The Gutenberg Operating System Kernel

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ABSTRACT

The Gutenberg system is a port-based, object-oriented operating system kernel designed to facilitate the design and structuring of distributed systems. This is achieved by providing primitives for controlling process interconnections and thereby controlling access to shared resources. Only shared resources are viewed as protected objects. Processes communicate with each other and access protected objects through the use of ports. Each port is associated with an abstract data type operation and can be created by a process only if the process possesses the privilege to execute that operation. Capabilities to create ports for requesting operations are contained in the capability directory which is a kernel object. At any time, each process is associated with a single subdirectory of the capability directory designated as its active directory.

This paper describes the design philosophy and the structure of the Gutenberg kernel. First, it discusses the principles and motivations behind the Gutenberg design. Then, it presents the structure, contents and operations of kernel objects and discusses their use in structuring access to protected user-defined objects. Also discussed are the salient aspects of the distributed Gutenberg kernel. A brief comparison with other related systems is given.

1 INTRODUCTION

Modern distributed operating systems must be designed to facilitate structuring distributed computations in an understandable and reliable manner that is suitable for validation. Experience in programming languages and in controlling complexity of large software systems has shown that the strongly typed object paradigm and its associated information hiding can be used to produce manageable and understandable systems. In large distributed systems, lack of a corresponding clean, well-structured interprocess communication paradigm leads to more complexity than is required by the nature of the distribution alone. This points to the need for an efficient mechanism which structures all interprocess communications along the abstract data type lines.

This paper deals with the design of such a mechanism, the distributed Gutenberg kernel [11,12,7,8]. The Gutenberg Operating System Kernel, currently being developed at the University of Massachusetts, takes a unique approach to interprocess communication, provides multiple programming language support, and attempts to minimize overheads. The following three salient features of Gutenberg provide for the controlled establishment of communication connections which serves the goal of understandability and verifiability, and should contribute to its better performance compared to previous communication schemes:

- the adoption of port-based communication, whereby interprocess communication is solely by means of ports, queue-like objects which are managed by the kernel;
- the adoption of non-uniform object-orientation, whereby only interprocess communication, but not module interconnections within a process, are structured and controlled by means of capabilities; and
- the use of a capability directory, which expresses all potential process interconnections in the system and is a distributed persistent object, maintained and manipulated only by the kernel.

Principles underlying the Gutenberg Kernel. The Gutenberg system evolved from the following series of design decisions concerning the nature of communication and protection in the system.

Limit the responsibilities of the kernel. Operating systems that support the definition and protection of arbitrary objects traditionally have had performance problems because of the maintenance of protection domains and the overhead of dynamic access checks, e.g. Hydra [16] and iMAX [4]. We hoped to restrict the overheads of the kernel by taking a non-uniform object orientation, in which only resources shared by different processes need to be structured as objects at the operating system level. We believe that conventional mechanisms for protecting unshared data (e.g., local variables) are adequate and desirable, from both a downward compatibility and an efficiency viewpoint. Conventional memory protection mechanisms (e.g. page tables) ensure that the local data of processes are not accessible to other processes. Gutenberg depends on programming languages to provide static type-checking for self-protection. Thus, although local data are not necessarily object-oriented (depending on the programming language), shared data are required to be object-oriented. An underlying assumption in Gutenberg is that the granularity of objects is medium to large, a size adequate to amortize the cost of the interprocess communication required to access the object.

Programming language independence. There should be no requirement that a specific programming language or that only
object-oriented languages run under the Gutenberg system kernel. In fact, non-object-oriented languages can achieve an object oriented view of other processes through the use of kernel primitives [11]. The system is designed to support applications implemented in any programming language.

Resources are directly manipulated by their managers. Managers are processes that synchronize the operations on an object (i.e., a shared resource). A process managing an object is the only subject able to directly manipulate the object. The process performs the operations, in part, by invoking kernel primitives for manipulating kernel objects.

Object sharing is via interprocess communication. Processes do not share address spaces. They can interact only through interprocess communication using explicit message passing. An operation can be performed on the object only as a result of a request from another process via interprocess communication. Processes are provided with communication primitives allowing both synchronous and asynchronous communication.

Interprocess communication connections are established using functional addressing [12]. Processes use communication channels called ports to request operations on objects. A port can be used to request an operation only if it was created for that purpose. Ports are created by indicating the function of the port (viz., to request an operation), not by identifying a particular process.

The kernel controls access to shared objects by controlling interprocess communication. An operation may be requested only by transmitting the operation request over a port to the object's manager. By limiting the use of ports and constraining their use to request a specific operation on a specific object, access to the object is controlled.

Details of the implementation of the communication mechanism are hidden from the processes using it. Ports are themselves objects with a small set of operations defined on them. They are managed by the kernel. The representation of ports is the port primitive.

Privileges persist in a single kernel-managed structure. Gutenberg recognizes that privileges need to persist in the system independent of the execution of processes. Rather than allowing privileges to be placed on secondary storage in user objects (hidden from the view of the kernel), privileges that are not dependent on the existence of a process are stored in a kernel-managed structure called the capability directory. This directory is shared by the processes in the system. Being physically distributed, it can be designed to ensure availability and reliable access despite communication and node failures. However, since it is logically unified, i.e., appears as a single globally addressable entity, the physical distribution will be transparent to its users.

Transient capabilities of a process, i.e., capabilities that exist only as long as the process is active, are kept in the process' capability directory.

The above design principles made it possible to use Gutenberg as the basis for a distributed operating system for the following reasons. The use of resource managers is a common approach to structuring software in distributed systems. Second, the logical separation of process address spaces in Gutenberg corresponds to the physical realization of processes in a distributed system. Third, the close association of communication and protection contributes to decentralized access authorization.

The rest of the paper is structured as follows: Section 2 introduces the structure and the contents of the kernel objects. User-defined objects, type creation, and manager instantiation are the subject of section 3. Issues related to the dynamic control of interprocess communication are also discussed in section 3. The distributed kernel is examined in section 4. Section 5 contains a brief comparison of Gutenberg with related systems. We conclude with a section summarizing our approach and future work.

2 GUTENBERG KERNEL OBJECTS

The Gutenberg kernel itself is structured as a set of cooperative abstract data type managers. Furthermore, the kernel is viewed by the processes as an abstract data type manager of kernel objects with the kernel primitives as the corresponding abstract data type operations. There are four types of kernel objects: processes, ports, capability directory and transient capabilities.

2.1 Processes

A process is an independently schedulable unit of computation with the ability to communicate with other processes. Each process is represented by a unique process control block, abbreviated PCB, which resides within the kernel address space. Processes can communicate only through explicit message exchanges over communication channels called ports. As a result, processes do not share address spaces, eliminating the need for synchronization in memory access and generalizing the process interactions in a distributed system.

2.2 Ports

A port is a kernel object that processes manipulate by invoking kernel primitives. It is a communication channel between a pair of processes in one-to-one topology connecting just one pair of processes at a time. Typically, one process has the privilege to place messages on the port, which behaves as a queue of messages awaiting delivery. The other has the privilege to remove messages. This communication can be either synchronous or asynchronous.

The basic interprocess communication of the Gutenberg system is based on the client/server model, in which the creator of a port, called the client, communicates with the port server, the manager of some shared object, for the purpose of requesting an operation on the object. A port is established with functional addressing. A client creates a port by naming the service it would like to request using the port rather than by identifying the server process. As a result, the server process does not have to be in existence prior to the creation of the port.

The advantage of this strategy is that it allows the dynamic creation of server processes. In fact, in Gutenberg, process creation and destruction are byproducts of port operations. There are no primitives for process creation and destruction; processes are hidden from the programmers, the lowest level of abstraction being the level of operations on the ports.

Therefore, the only way a process can request an operation on a shared object is to create a port and execute a kernel primitive on that port. The possible kernel primitives on ports to a client are SEND, RECEIVE, and SEND-RECEIVE (to receive the result of an operation based on the parameters sent).

In order to restrict the use of ports to the functionality for which they have been created, a port is typed as either a Send, Receive, or Send-Receive port. This typing specifies the directionality of the port and the kernel primitives used by the client to transmit messages through it. Consequently, it specifies the kernel primitives that the server of the port may use. Figure 1 shows the port primitives used by clients and servers for each port type. Send and Receive ports are unidirectional. Send-Receive ports are bidirectional, allowing the port's client to send a message and receive a response from the port's server.

Port typing also determines the format of messages that may be placed in the port and the object operation associated with this, which identifies the operation that will be requested via the port. Each port is represented by a unique channel control block, abbreviated CCB, which resides within the kernel address space. CCB contains the port type along with information about the
DESTROY-PORT (only a client primitive) destroys a port. The creator of a port becomes the initial owner of the port. As part of the sharing mechanism supported by the Gutenberg system, a process may transfer part of its privileges, including port privileges, to another, over ports.

Ownership represents the privilege to destroy the port. The choice of these primitives during system design was based on the desire to keep their number and complexity to a minimum while providing users a set of primitives for building systems of communicating processes in arbitrary topologies with reasonable ease. Thus, we have added to the basic SEND and RECEIVE primitives the bidirectional SEND-RECEIVE and its receiving reciprocal GETDETAILS in order to allow such functions as reading a record with a given key (the key being sent as request details) or a remote procedure call (the procedure's parameters being sent as request details) to be implemented by a single primitive. However, it should be noted that the asynchronous mode makes the SEND-RECEIVE operation more robust and flexible than a remote procedure call semantics.

### 2.3 Capability Directory

Gutenberg controls the creation and use of ports through the use of capabilities. All capabilities for accessing potentially sharable objects are maintained in a logically unified structure called the capability directory. Thus, the capability directory expresses all potential process interconnections in the system. This is similar to the UNIX file directory [10] which provides uniform treatment of files, devices and interprocess communication. The capability directory is a stable structure in that its existence does not depend on the existence of any process. It is also shared since more than one process may concurrently access the same segment of the directory. It should be noted that no portion of the directory is owned by any process at any time.

#### 2.3.1 Capability Directory Nodes

Capabilities within the capability directory are further organized into groups called the capability directory nodes, abbreviated cd-nodes. They are identified by both a system-wide unique name created by and visible only to the kernel, and by user-specified names. In general, cd-nodes contain other information along with capabilities. Cd-nodes are linked to other cd-nodes through capabilities. The same cd-node may be linked to several cd-nodes under possibly different user-specified names. All capabilities pointing to a cd-node have equal status. That is, cd-nodes are unique and are not contained within other cd-nodes. A cd-node exists independently of any other cd-node and disappears along with the last capability link to it, if it is not explicitly destroyed. In this way the capability directory is structured as a graph in which nodes (each node corresponds to a cd-node) are connected by edges corresponding to capabilities.

![Figure 1: Port primitives used by clients and servers for each port type](image)

<table>
<thead>
<tr>
<th>Port Type</th>
<th>Client Primitives</th>
<th>Server Primitives</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>SEND</td>
<td>RECEIVE</td>
</tr>
<tr>
<td></td>
<td>REVOKE</td>
<td>REFUSE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EXAMINE</td>
</tr>
<tr>
<td>R</td>
<td>RECEIVE</td>
<td>SEND</td>
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<tr>
<td></td>
<td>EXAMINE</td>
<td>REFUSE</td>
</tr>
<tr>
<td>SR</td>
<td>SEND-RECEIVE</td>
<td>GETDETAILS</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td>EXAMINE</td>
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</tbody>
</table>

REFUSE rejects a client's request for service as unsatisfiable and notifies the requester by setting a status. REVOKE revokes privileges sent as part of request details by a SEND-RECEIVE or in a SEND message up to receipt of the message.

A scheme for revoking transferred capabilities anytime after the transfer is discussed in [8].
Capabilities in cd-nodes inherit all the properties of the capability directory in that they are stable and sharable but are not owned by processes. These capabilities are called stable capabilities and can only reside in the capability directory.

Capabilities in Gutenberg consist of three parts: a specific kernel primitive, a list of parameters for the primitive, and a list of primitives that can be used to manipulate the capability itself, which are called capcaps, for capabilities on a capability.

A capability permits a process which possesses it to invoke the specific kernel primitive it contains. This primitive is also called primary kernel primitive in order to distinguish it from

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**Figure 2: Example of Capability Directory Segment**

This is a sample capability directory of a basic mail system. The Mail Maintenance Directory which contains the Mail System Manager Definition is created by the creator of the system and stored in the System Maintenance Directory. The two operations defined on the Mail System, namely the Mail and Read, are contained in the login process subdirectory. Each user gets capabilities for these operations during the login procedure. In the default subdirectory of the Mail System, operations on the File Manager exist that permit access to files.

The active directory of a process is one component of a process protection domain. The other component is its current set of transient capabilities; this is discussed later. A process may dynamically switch from one protection domain to another by changing to a new active directory or changing the contents of its current active directory, if it has the privilege to do so.

Manager definitions constitute one of the novel features of the Gutenberg system. All processes in the system are instantiated from manager definitions. Thus, a manager definition provides information necessary for instantiating the manager process, as, for example, a capability for the file containing the executable image (object module) of the process, and the initiation protocol (see section 3.2) for determining the manner in which ports are connected to manager processes. It also includes a capability for a subdirectory containing the privileges that all processes instantiated from the manager definition will initially possess.

One other component of a manager definition node is a set of port descriptors. This set corresponds to the set of operations defined within the manager. Each port description contains a generic operation name (a name specified by the user at manager creation time), and the type of port through which a user requests this operation.

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**Subdirectory cd-node**

Contains a set of capabilities, and has the following attributes:

- **subdirectory id**: system-wide unique identifier of the subdirectory.
- **use count**: the number of stable and transient subdirectory capabilities (including those in manager definition cd-nodes) pointing to this cd-node.
- **active directory count**: the number of processes having this cd-node as their active directory.

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**Manager Definition Node**

Provides information necessary for instantiating a manager process. The manager definition cd-node has nine attributes.

- **manager id**: system-wide unique identifier of the manager cd-node.
- **initial active directory**: a subdirectory capability pointing to the subdirectory cd-node that will become the active directory of the manager process when it is initiated.
- **initial process image**: a privilege (represented by a cooperation class capability) for a file containing the object code to be executed when the process is initiated.
- **manager dependency**: indicates whether the existence of a manager process is dependent on the existence of ports connected to it.
- **initiation protocol**: indicates when a new manager process is created or an existing one is connected to when a port to the manager is created.
- **port descriptors**: the list of (port type, generic operation name) pairs for operation capabilities that may be linked to this manager cd-node. The port type specifies whether it is a Send, Receive or Send-Receive port as well as the format of the arguments that may be passed over the port as part of a message or request details.
- **manager use count**: the number of manager capabilities pointing to this cd-node.
- **operation use count**: the number of operation capabilities linked to this cd-node.
- **port use count**: the number of ports associated with this cd-node.

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**Figure 3: Attributes of Capability Directory Node**

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Operation Capability Provides the privilege to create ports. Operation capabilities have six attributes:

- **operation name** user-specified name of the operation. This name becomes the object operation of created ports. This name also serves to identify the operation capability.
- **generic operation name** name of the corresponding operation defined in the manager definition cd-node. This name can be the same as or different from the operation name.
- **port type** specifies the port type for this operation that may be linked to the corresponding manager definition cd-node. The port type can either be Send (S), Receive (R), or Send-Receive (SR).
- **message format** specifies the arguments that may be passed over the port as part of the message, and the request-details in case of Send-Receive port type.
- **cooperation class(es)** restrict how the port will be connected to a manager process.
- **manager id** a pointer, global name, to the manager to which this operation capability is linked.

The capabilities of the operation capability are: COPY, TRANSFER, REGISTER, REMOVE, HOLD, MERGE, MODIFY-CAP, MODIFY-CAPCAP, and VIEW CAP.

Manager Definition Capability Provides the privilege to create operation capabilities. The manager definition capability has the following attributes:

- **manager definition name** user-specified name used to identify the manager definition cd-node to which the created operation capabilities are linked to. This name also serves to identify the manager definition capability.
- **cooperation class(es)** restrict who may create operation capabilities linked to the definition manager. Possession of one of the specified cooperation class capabilities is required when exercising the Create-operation primitive.
- **manager id** a pointer, global name, to the manager definition cd-node corresponding to this capability.

The capabilities of the manager definition capability are: COPY, TRANSFER, REGISTER, REMOVE, DESTROY-NODE, MERGE, MODIFY-CAP, MODIFY-NODE, MODIFY-CAPCAP, VIEW-CAP, and VIEW-NODE.
Cooperation class capability. In effect, such processes become responding primary primitive to the processes which possess the capability. In this way cooperation class capabilities complement the capability is associated with either a subdirectory or a manager definition capability, it restricts the invocation of the cooperation class capability may be associated with an operation capability, for example a communication with a manager of a shared object. Here, the cooperation class capability can be used as a synchronization token or to identify either an instance of a manager or a particular instance of an object. It could also be used to identify a transaction, a file, or a process. It can be used to classify the users in the system into groups and divisions for administrative reasons. New cooperation class capabilities can be created, on request, by the kernel.

2.4 Transient Capabilities

Port capabilities and copies of stable capabilities from the capability directory are the transient capabilities. Two features distinguish the transient capabilities from the stable capabilities: they are owned by a single process, and therefore cannot be shared, and their existence is dependent on the existence of the process that owns them. All the transient capabilities a process owns exist only for the duration of the existence of the process and are destroyed when the process terminates. The transient capabilities possessed by a process are stored in the process' capability list, or c-list. Capabilities in the c-list, as previously stated, together with the active directory of a process, form the protection domain of the process. Thus, a process, in addition to the capabilities in its active directory, may exercise the capabilities in its c-list.

A transient capability comes into existence when a process moves or copies a capability from its active directory into its c-list. The c-list contains two features: it contains transient capabilities, which cannot be shared or copied. However, either the client or the server process may transfer its port capability to another process. The transferring may be either temporary (the capability is transferred to, say, a port, and then it is destroyed when the port is destroyed). In the last instance, two port capabilities are generated to access the created port, one for the client of the port and the other for the server of the port. A process moves a capability in its active directory into its c-list in order not to lose the capability when it changes its active directory to another subdirectory.

The part of the c-list in which the kernel maintains the port capabilities of a process is called the p-list. The port capabilities are exclusive, and such port capabilities are inherently transient, cannot be shared or copied. However, either the client or the server process may transfer its port capability to another process. The transferring may be either temporary (the semantics of a port is to keep the ownership retained) or permanent with the SEND-RECEIVE primitive. The latter case, the ownership of the port is transferred along with the port capability.

The only capcap associated with a port capability is transfer. The transfer capability in the client's port capability is set to the value of the corresponding transfer capcap in the operation capability used. If the used operation capability is stable, then the transfer right of the client's active directory is also taken into consideration. The transfer capability in the server's port capability is always enabled. A server process may transfer a port that it serves, to another server as long as the port functionality is preserved. This is essential for supporting the implementation of load balancing algorithms and realizing a hierarchy of object managers, features which can improve the performance, flexibility and reliability of a distributed system. A common example of a hierarchy of managers is a manager structured based on the master/slave model, in which a process can only create a port for requesting an operation to the master process. The master process decides which slave process should service the request and passes the port capability to it. A process may reset the transfer capcap of the port capability when it passes the capability to another process, to prevent further transferring.
Transient capabilities contribute to the flexible use of capabilities in Gutenberg without compromising the security of the system because the c-list is saved in the PCB and may only be manipulated through kernel primitives.

The kernel primitives that manipulate the capabilities both within a c-list and an active directory, fall into two classes: generic and special primitives. Generic primitives are further classified into constructive in that they do not affect the participating capabilities, and destructive. Constructive primitives are designated by the ending -C attached to their names. Recall that a number of capcaps and rights correspond to each primitive, and must be active in the capability on which the primitive is invoked, and must be allowed by the rights of the active directory of the invoking process.

The eleven generic kernel primitives are: Create, Register, Register-C, Remove, Hold, Hold-C, Drop, View, Modify, Merge, Merge-C. Here is a brief description of their functionality (Details concerning the primitives may be found in [3]).

Create These primitives create a capability. Create-port, and Create-operation are instances of this generic primitive. A Create always creates a transient capability which may then be registered or transferred with all or part of its privileges retained. Creating an operation capability requires a manager capability, and creating a port capability requires an operation capability. Other Create primitives require no privilege.

Register and Register-C These primitives make a transient capability, or one derived from transient capabilities, stable. A process may reset part of the capcaps and/or rights of a capability, when it registers the capability. The purpose of these primitives is to allow a process to store a capability for future reference in another session; and, to allow a process to share a capability with other processes which are not currently instantiated, but share access to a subdirectory.

Remove These primitives delete a stable capability from the active directory.

Drop These primitives delete a transient capability from the c-list.

Hold and Hold-C These primitives make a stable capability, or one derived from stable capabilities, transient. A process may reset part of the capcaps and/or rights of a capability, when it holds the capability. The purpose of these primitives is to allow a process to retain a capability from its active directory when it changes its active directory to another subdirectory.

View These primitives bring a copy of a transient or stable capability, or a cd-node into the address space of a process. Partial views are also facilitated in the case of a subdirectory; it is possible to bring capabilities of a specified type into the address space of the process. The purpose of these primitives is to allow a process to examine capabilities it possesses, and, if desired, use this information to modify or create new capabilities.

Modify These primitives allow a process to modify an existing transient or stable capability, or a cd-node.

Merge and Merge-C These primitives allow a process to merge two compatible capabilities to obtain another. Two capabilities are compatible if they are of the same type and have identical non-modifiable attributes (attributes whose values cannot be changed with the Modify primitive).

As has previously been discussed, the manager definition and subdirectory capabilities are slightly different from other capabilities. These capabilities contain pointers to manager definition and subdirectory cd-nodes, respectively. When one of these capabilities is created with the Create primitive, the cd-node is created as well. These cd-nodes exist in the system until either they are explicitly destroyed by using the proper Destroy primitives, or all of the capabilities that point to them are deleted using the Remove or Drop primitives.

The kernel uses the c-list and the active directory of a process to check whether it has a legitimate privilege for executing a primitive it has requested. Therefore, the consistency and availability of the capability directory is fundamental to the correct operation of the protection mechanism. As is commonly done with resources in distributed systems, the capability directory is physically distributed, though still logically unified, across the distributed system as we discuss below.

3 USER-DEFINED OBJECTS

Recall that the Gutenberg kernel is not involved in the protection of objects that are purely local to a process. User-defined objects are those objects managed by one process but accessible by other processes via operations requested using ports. Here, we discuss how user-defined objects are created, shared, and protected.

3.1 Type Creation

User-defined types in Gutenberg are represented by manager definition cd-nodes (figure 3). A manager definition is created by a process invoking the Create-manager primitive. Recall that no special privilege is required to invoke this primitive.

In invoking the primitive, a process must provide five parameters: A cooperation class capability identifying the file containing the executable image for the process; a subdirectory capability identifying the default directory, the subdirectory which becomes the active directory of any process instantiated from this manager definition; the operation list, the specification of the operations that are implemented by the manager; the manager initiation protocol, indicating how manager processes are instantiated; and, the manager dependency indicating whether a manager process will be destroyed when all ports connected to it are destroyed.

Upon successful execution of the Create-manager primitive, the kernel places a manager definition capability, pointing at the new manager definition and containing its name, in the process’s c-list. After the manager definition and the corresponding manager definition capability are created, the process may use the manager capability to invoke the Create-operation primitive to create the operation capabilities for the type. These operation capabilities can then be stored in the capability directory or distributed over ports to processes wishing to use the type.

3.2 Manager Initiation Protocols

The manager initiation protocol specified when creating a manager definition determines the manner in which ports are connected to the manager processes instantiated from the definition. It specifies whether all the object instances of a type are managed by one process or each object is managed by different processes. There are three initiation protocols in Gutenberg: conservative, creative and class conservative. In the conservative manager initiation protocol, a manager process is instantiated from the manager definition only if there is no other manager process executing in the system which was instantiated using this manager definition. If such a process already exists, the port be-
The capability directory is partitioned and replicated to ensure availability and reliability. Manager definitions are replicated only at the sites in which manager processes from these can possibly be instantiated. Subdirectories are replicated in locations where they are expected to be used and in a number of other locations in a manner that meet the resiliency requirement and balance the distribution of local directory storage space. The site where a cd-node is created has a copy of that cd-node and also keeps track of which sites have copies of that cd-node. The set of capabilities and cd-nodes from the capability directory that resides on a site forms that site's local directory. The site's local directory dynamically expands and contracts to accommodate the needs of any process executing on the site. Dynamic adjustments pertain only to the migration of subdirectories; modifications to manager definitions are expected to be relatively rare to justify their migration. A subdirectory is migrated only when processes make repetitive use of the capabilities associated with that subdirectory.

In Gutenberg, process interconnections can change dynamically through the transfer of capabilities on ports. There are three ways in which one process can transfer some of its capabilities linked to the manager definition to another process. First, the transferring process can copy a reference to the capability object to a destination port on the receiving process. This allows the receiving process to use an operation capability in the active directory or c-list of the requesting process. Second, the transferring process can transfer a defensive manager definition to the manager definition directory. This allows the receiving process to use an operation capability in the active directory or c-list of the receiving's process c-list. Since the kernel is the manager of the capabilities and ports, it monitors the transfer of capabilities between processes.

The third protocol is the transfer of an operation capability. This protocol allows a process to create a port to a new process under all situations. This protocol allows a process to isolate the newly created manager in order to ensure that the kernel cannot leak information. However, it cannot support multi-port interconnections between a specific client and a specific server.

4 DISTRIBUTED GUTENBERG KERNEL

An instance of the Gutenberg kernel is running on each site in the system. From the objects that the kernel maintains only the capability directory needs to be distributed. The other three objects, namely processes, ports and transient capabilities, are naturally distributed since processes always execute on a single site, and ports and transient capabilities can only be used by the process which possesses them.

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The capability directory is partitioned and replicated to ensure availability and reliability. Manager definitions are replicated only at the sites in which manager processes from these can possibly be instantiated. Subdirectories are replicated in locations where they are expected to be used and in a number of other locations in a manner that meet the resiliency requirement and balance the distribution of local directory storage space. The site where a cd-node is created has a copy of that cd-node and also keeps track of which sites have copies of that cd-node. The set of capabilities and cd-nodes from the capability directory that resides on a site forms that site's local directory. The site's local directory dynamically expands and contracts to accommodate the needs of any process executing on the site. Dynamic adjustments pertain only to the migration of subdirectories; modifications to manager definitions are expected to be relatively rare to justify their migration. A subdirectory is migrated only when processes make repetitive use of the capabilities associated with that subdirectory.

In Gutenberg, process interconnections can change dynamically through the transfer of capabilities on ports. There are three ways in which one process can transfer some of its capabilities linked to the manager definition to another process. First, the transferring process can copy a reference to the capability object to a destination port on the receiving process. This allows the receiving process to use an operation capability in the active directory or c-list of the requesting process. Second, the transferring process can transfer a defensive manager definition to the manager definition directory. This allows the receiving process to use an operation capability in the active directory or c-list of the receiving's process c-list. Since the kernel is the manager of the capabilities and ports, it monitors the transfer of capabilities between processes.

The third protocol is the transfer of an operation capability. This protocol allows a process to create a port to a new process under all situations. This protocol allows a process to isolate the newly created manager in order to ensure that the kernel cannot leak information. However, it cannot support multi-port interconnections between a specific client and a specific server.

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A Privilege in Gutenberg is represented by capabilities which have two levels of persistence, transient for those capabilities which persist only as long as an owning process exists, and stable for those capabilities in the capability directory, whose existence is independent of processes. Gutenberg has mechanisms for achieving transfer of privileges represented by both transient and stable capabilities. Some of the highlights of these mechanisms include:

- Using both unidirectional and bidirectional communication primitives and associating them with permanent (unidirectional) and temporary (bidirectional) granting of privileges in order to provide flexibility in privilege granting while keeping the kernel simple.
- Typing ports with respect to the ability to transfer privileges on them in order to expedite communication in cases where no privilege transfer can be made.
- Restricting ports to connecting one client process with one server process in order to simplify interprocess communication in general and the transfer of privileges in particular.

Design and implementation of a Gutenberg kernel (built on top of UNIX) is currently nearing completion. Experimentation with this kernel should provide qualitative evaluation of the advantages of the Gutenberg approach.

References


