Advanced Operating Systems
Lecture notes

Dr. Clifford Neuman

University of Southern California
Information Sciences Institute

CSci555: Advanced Operating Systems
Lecture 1 – August 26, 2011

Dr. Clifford Neuman

University of Southern California
Information Sciences Institute

Copyright © 1995-2009 Clifford Neuman - UNIVERSITY OF SOUTHERN CALIFORNIA - INFORMATION SCIENCES INSTITUTE

Administration

- Instructors
  - Dr. Clifford Neuman
    - csci555f11@clifford.neuman.name
    - Office hours – SAL 212
      - Friday 12:55 PM – 1:55 PM
- TA
  - Nam Ma
    - Namma at usc dot edu
    - Office Hours – TBD
- Class details
  - http://gost.isi.edu/555

Administration

- Class Home Page

  http://gost.isi.edu/555/
  - Announcements
  - Syllabus
  - Lecture Slides
  - Reading list

- Class e-mail: csci555@usc.edu

Administrative Information

- Reading list
  - ~65 papers and
  - ~20 book chapters
  - Concentrated toward the first half
- Text
  - Principles of Computer System Design
    - By Saltzer and Kaashoek
  - Also using second volume online

Administrative Information

- Assignments
  - 4 Reports,
    - Due 11 p.m. Wednesday nights
  - Research Paper
    - Due: last class
  - Exams
    - Mid-Term: Friday, in October
    - Final Exam: Friday, December 9

Administrative Information

- DEN site - Blackboard
  - Lecture webcast
  - Class forum on DEN
  - Grades
- Lecture notes to be posted before lecture
- Academic Integrity
  - READ IT – It applies to you

Academic Integrity

- I take Academic Integrity Seriously
  - Every year I have too many cases of cheating
  - Last year I assigned multiple F's for the class
  - Occasionally students leave USC
- What is and is not OK
  - I encourage you to work with others to learn the material
  - Do not to turn in the work of others
  - Do not give others your work to use as their own
  - Do not plagiarize from others (published or not)
  - Do not try to deceive the instructors
- See section on web site and assignments
  - More guidelines on academic integrity
  - Links to university resources
  - Don't just assume you know what is acceptable.

Administration

- Grading
  - 20%: Reading Reports
  - 20%: Midterm
  - 20%: Final
  - 30%: Research Paper
  - 10%: Class Participation & Quizes
    - Class forum participation
    - In class participation

How to survive?

- Read the survival guide
- How to read papers
  - Read the papers in advance
    - Be critical
  - At least skim through
- Build your own notes
- Study group

What you should learn in this course

- **You will gain a basic understanding of distributed system concepts.**
- **You will develop intuition for which approaches work, and which don't.**
- **You will develop the ability to sense where bottlenecks lie in system design.**
- **You will remember where to look for more information when you are faced with a distributed system problem.**
- **Above all, you will learn how to be critical of what you are told by system designers.**

Some things an operating system does (review)

- **Memory Management**
- **Scheduling / Resource management**
- **Communication**
- **Protection and Security**
- **File Management - I/O**
- **Naming**
- **Synchronization**
- **User Interface**

Progression of Operating Systems

Primary goal of a distributed system:

- **Sharing**

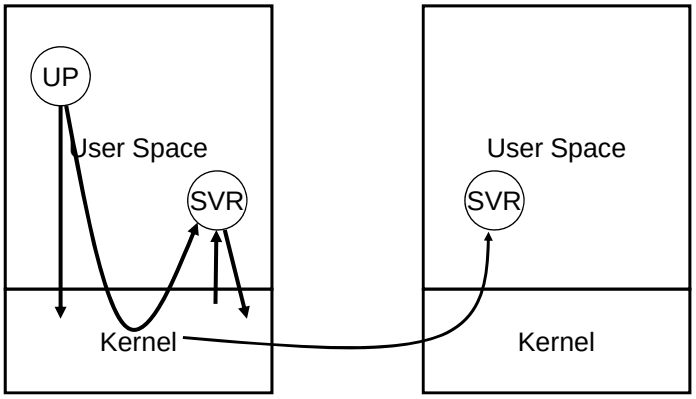
Progression over past years

- **Dedicated machines**
- **Batch Processing**
- **Time Sharing**
- **Workstations and PC's**
- **Distributed Systems**
- **Devices**

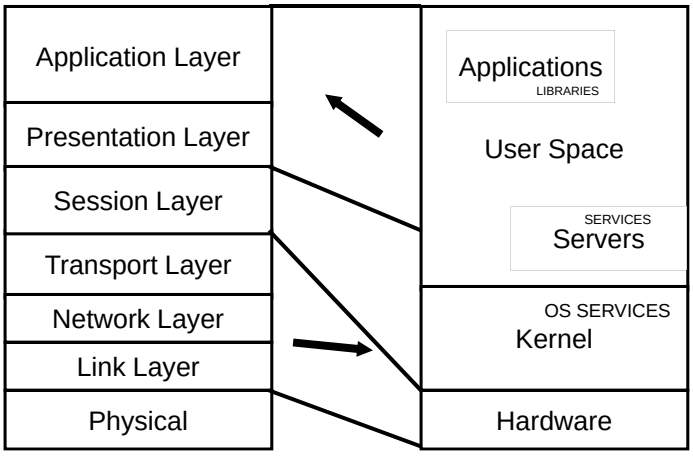
Structure of Distributed Systems

- **Kernel**
  - **Basic functionality and protection**
- **Application Level**
  - **Does the real work**
- **Servers**
  - **Service and support functions needed by applications**
  - **Many functions that used to be in Kernel are now in servers.**

Structure of Distributed Systems



Network vs. OS Layering
(No direct mapping, colors to stimulate discussion)



Characteristics of a Distributed System

- **Basic characteristics:**
  - **Multiple Computers**
  - **Interconnections**
  - **Shared State**

Why Distributed Systems are Hard

- **Scale:**
  - **Numeric**
  - **Geographic**
  - **Administrative**
- **Loss of control over parts of the system**
- **Unreliability of Messages**
- **Parts of the system down or inaccessible**
  - **Lamport:** You know you have a distributed system when the crash of a computer you have never heard of stops you from getting any work done.

End-to-End Argument

- **QUESTION: Where to place distributed systems functions?**
- **Layered system design:**
  - **Different levels of abstraction for simplicity.**
  - **Lower layer provides service to upper layer.**
  - **Very well defined interfaces.**

E2E Argument (continued)

- **E2E paper argues that functions should be moved closer to the application that uses them.**

E2E Argument (continued)

- **Rationale:**
  - **Some functions can only be completely and correctly implemented with application's knowledge.**
    - **Example:**
      - **Reliable message delivery, security**
      - **Encrypted e-mail**
      - **Streaming media vs. Banking**
  - **Applications that do not need certain functions should not have to pay for them.**

E2E Counter-Argument

- **Performance**
  - **Example: File transfer**
    - **Reliability checks at lower layers detect problems earlier.**
    - **Abort transfer and re-try without having to wait till whole file is transmitted.**
- **Abstraction**
  - **Less repetition across apps**

Bottom line: **"spread" functionality across layers.**

Lecture Transition

- **This concludes the slides for lecture1.**
- **The following slides are for lecture 2.**

CSci555: Advanced Operating Systems

Lecture 2 – September 2, 2011

Communication Models

Dr. Clifford Neuman

University of Southern California
Information Sciences Institute

COVERED LAST LECTURE

Outline: Communications Models

- **Communication Models:**
  - **General concepts.**
  - **Message passing.**
  - **Distributed shared memory (DSM).**
  - **Remote procedure call (RPC) [Birrel et al.]**
    - **Light-weight RPC [Bershad et al.]**
  - **DSM case studies**
    - **IVY [Li et al.]**
    - **Linda [Carriero et al.]**

COVERED LAST LECTURE

Communication Models

- **Support for processes to communicate among themselves.**
- **Traditional (centralized) OS's:**
  - **Provide local (within single machine) communication support.**
  - **Distributed OS's: must provide support for communication across machine boundaries.**
    - **Over LAN or WAN.**

COVERED LAST LECTURE

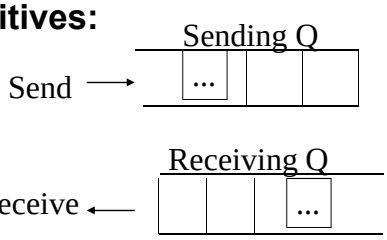
Communication Paradigms

- 2 paradigms
  - Message Passing (MP)
  - Distributed Shared Memory (DSM)
- Message Passing
  - Processes communicate by sending messages.
- Distributed Shared Memory
  - Communication through a "virtual shared memory".

COVERED LAST LECTURE

Message Passing

- Basic communication primitives:
  - Send message.
  - Receive message.



- Modes of communication:
  - Synchronous versus asynchronous.
- Semantics:
  - Reliable versus unreliable.

COVERED LAST LECTURE

Synchronous Communication

- **Blocking send**
  - **Blocks until message is transmitted**
  - **Blocks until message acknowledged**
- **Blocking receive**
  - **Waits for message to be received**
- **Process synchronization.**

COVERED LAST LECTURE

Asynchronous Communication

- **Non-blocking send: sending process continues as soon message is queued.**
- **Blocking or non-blocking receive:**
  - **Blocking:**
    - **Timeout.**
    - **Threads.**
  - **Non-blocking: proceeds while waiting for message.**
    - **Message is queued upon arrival.**
    - **Process needs to poll or be interrupted.**

COVERED LAST LECTURE

Reliability of Communication

- **Unreliable communication:**
  - **"best effort" - send and hope for the best**
  - **No ACKs or retransmissions.**
  - **Application must provide its own reliability.**
  - **Example: User Datagram Protocol (UDP)**
    - **Applications using UDP either don't need reliability or build their own (e.g., UNIX NFS and DNS (both UDP and TCP), some audio or video applications)**

COVERED LAST LECTURE

Reliability of Communication

- **Reliable communication:**
  - **Different degrees of reliability.**
  - **Processes have some guarantee that messages will be delivered.**
  - **Example: Transmission Control Protocol (TCP)**
  - **Reliability mechanisms:**
    - **Positive acknowledgments (ACKs).**
    - **Negative Acknowledgments (NACKs).**
  - **Possible to build reliability atop unreliable service (E2E argument).**

COVERED LAST LECTURE

Distributed Shared Memory

- **Motivated by development of shared-memory multiprocessors which do share memory.**
- **Abstraction used for sharing data among processes running on machines that do** not **share memory.**
- **Processes think they read from and write to a "virtual shared memory".**

COVERED LAST LECTURE

DSM 2

- **Primitives: read and write.**
- **OS ensures that all processes see all updates.**
  - **Happens transparently to processes.**

COVERED LAST LECTURE

DSM and MP

- **DSM is an abstraction!**
  - **Gives programmers the flavor of a centralized memory system, which is a well-known programming environment.**
  - **No need to worry about communication and synchronization.**
- **But, it is implemented atop MP.**
  - **No physically shared memory.**
  - **OS takes care of required communication.**

COVERED LAST LECTURE

Caching in DSM

- **For performance, DSM caches data locally.**
  - **More efficient access (locality).**
  - **But, must keep caches consistent.**
  - **Caching of pages for of page-based DSM.**
- **Issues:**
  - **Page size.**
  - **Consistency mechanism.**

COVERED LAST LECTURE

Approaches to DSM

- **Hardware-based:**
  - **Multi-processor architectures with processor-memory modules connected by high-speed LAN (E.g., Stanford's DASH).**
  - **Specialized hardware to handle reads and writes and perform required consistency mechanisms.**

COVERED LAST LECTURE

Approaches to DSM

- **Page-based:**
  - **Example: IVY.**
  - **DSM implemented as region of processor's virtual memory; occupies same address space range for every participating process.**
  - **OS keeps DSM data consistency as part of page fault handling.**

COVERED LAST LECTURE

Approaches to DSM

- **Library-based:**
  - **Or language-based.**
  - **Example: Linda.**
  - **Language or language extensions.**
  - **Compiler inserts appropriate library calls whenever processes access DSM items.**
  - **Library calls access local data and communicate when necessary.**

COVERED LAST LECTURE

DSM Case Studies: IVY

- **Environment:"loosely coupled" multiprocessor.**
  - **Memory is physically distributed.**
  - **Memory mapping managers (OS kernel):**
    - **Map local memories to shared virtual space.**
    - **Local memory as cache of shared virtual space.**
    - **Memory reference may cause page fault; page retrieved and consistency handled.**

COVERED LAST LECTURE

IVY

- Issues:
  - Read-only versus writable data.
  - Locality of reference.
  - Granularity (1 Kbyte page size).
    - Bigger pages versus smaller pages.

COVERED LAST LECTURE

IVY

- Memory coherence strategies:
  - Page synchronization
    - Invalidation
    - Write broadcast
  - Page ownership
    - Fixed: page always owned by same processor
    - Dynamic

IVY Page Synchronization

- **Invalidation:**
  - **On write fault, invalidate all copies; give faulting process write access; gets copy of page if not already there.**
  - **Problem: must update page on reads.**
- **Write broadcast:**
  - **On write fault, fault handler writes to all copies.**
  - **Expensive!**

IVY Memory Coherence

- **Paper discusses approaches to memory coherence in page-based DSM.**
  - **Centralized: single manager residing on a single processor managing all pages.**
  - **Distributed: multiple managers on multiple processors managing subset of pages.**

Linda

- DSM: tuple space.
- Basic operations:
  - out (data): data added to tuple space.
  - in (data): removes matching data from TS; destructive.
  - read (data): same as “in”, but tuple remains in TS (non-destructive).

Linda Primitives: Examples

- out (“P”, 5, false) : tuple (“P”, 5, false) added to TS.
  - “P” : name
  - Other components are data values.
  - Implementation reported on the paper: every node stores complete copy of TS.
  - out (data) causes data to be broadcast to every node.

Linda Primitives: Examples

- in ("P", int I, bool b): tuple ("P", 5, false) removed from TS.
  - If matching tuple found locally, local kernel tries to delete tuple on all nodes.

Remote Procedure Call

- Builds on MP.
- Main idea: extend traditional (local) procedure call to perform transfer of control and data across network.
- Easy to use: analogous to local calls.
- But, procedure is executed by a different process, probably on a different machine.
- Fits very well with client-server model.

RPC Mechanism

1. Invoke RPC.
2. Calling process suspends.
3. Parameters passed across network to target machine.
4. Procedure executed remotely.
5. When done, results passed back to caller.
6. Caller resumes execution.

Is this synchronous or asynchronous?

RPC Advantages

- Easy to use.
- Well-known mechanism.
- Abstract data type
  - Client-server model.
  - Server as collection of exported procedures on some shared resource.
  - Example: file server.
- Reliable.

MP Reliability of Communication

- **Unreliable communication:**
  - **"best effort" - send and hope for the best**
  - **No ACKs or retransmissions.**
  - **Application must provide its own reliability.**
  - **Example: User Datagram Protocol (UDP)**
    - **Applications using UDP either don't need reliability or build their own (e.g., UNIX NFS and DNS (both UDP and TCP), some audio or video applications)**

RPC Semantics 1

- **Delivery guarantees.**
- **"Maybe call":**
  - **Clients cannot tell for sure whether remote procedure was executed or not due to message loss, server crash, etc.**
  - **Usually not acceptable.**

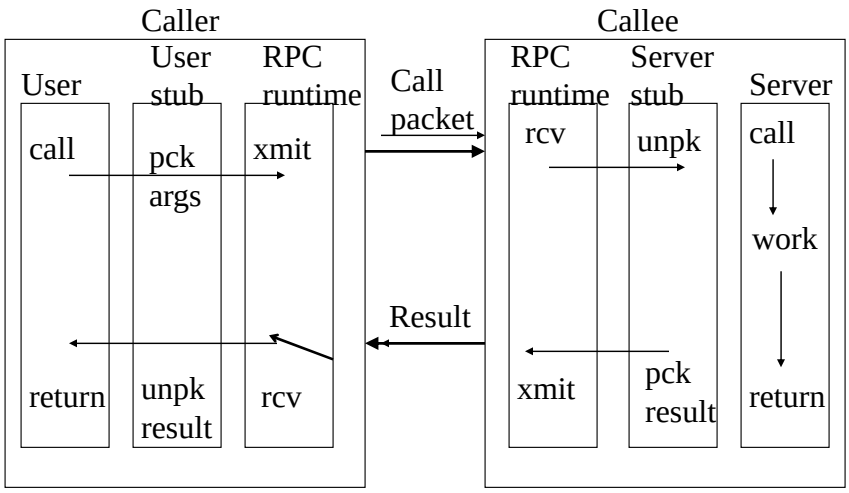
RPC Semantics 2

- "At-least-once" call:
  - Remote procedure executed at least once, but maybe more than once.
  - Retransmissions but no duplicate filtering.
  - Idempotent operations OK; e.g., reading data that is read-only.

RPC Semantics 3

- "At-most-once" call
  - Most appropriate for non-idempotent operations.
  - Remote procedure executed 0 or 1 time, ie, exactly once or not at all.
  - Use of retransmissions and duplicate filtering.
  - Example: Birrel et al. implementation.
    - Use of probes to check if server crashed.

RPC Implementation (Birrel et al.)



RPC Implementation 2

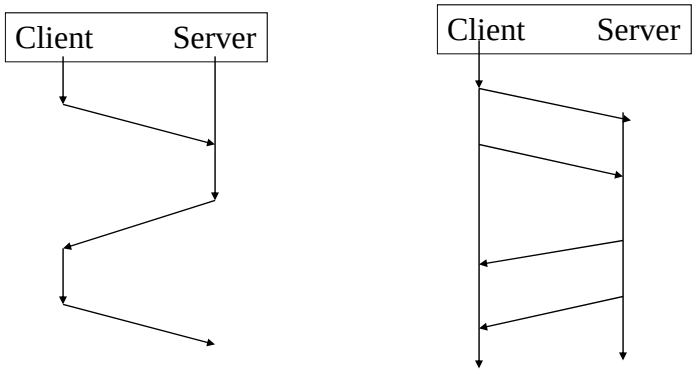
- **RPC runtime mechanism responsible for retransmissions, acknowledgments.**
- **Stubs responsible for data packaging and un-packaging;**
  - **AKA marshalling and un-marshalling: putting data in form suitable for transmission. Example: Sun's XDR.**

Binding

- How to determine where server is? Which procedure to call?
  - "Resource discovery" problem
    - Name service: advertises servers and services.
    - Example: Birrel et al. uses Grapevine.
- Early versus late binding.
  - Early: server address and procedure name hard-coded in client.
  - Late: go to name service.

Synchronous & Asynchronous RPC

Synchronous **Asynchronous**



RPC Performance

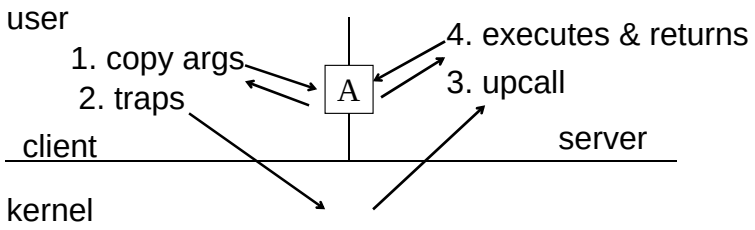
- Sources of overhead
  - data copying
  - scheduling and context switch.
- Light-Weight RPC
  - Shows that most invocations took place on a single machine.
  - LW-RPC: improve RPC performance for local case.
  - Optimizes data copying and thread scheduling for local case.

LW-RPC 1

- Argument copying
  - RPC: 4 times
  - copying between kernel and user space.
  - LW-RPC: common data area (A-stack) shared by client and server and used to pass parameters and results; access by client or server, one at a time.

LW-RPC 2

- **A-stack avoids copying between kernel and user spaces.**
- **Client and server share the same thread: less context switch (like regular calls).**



Lecture Transition

- **This concludes the slides for lecture2.**
- **The following slides are for lecture 3.**

CSci555: Advanced Operating Systems

Lecture 3 – Distributed Concurrency, Transactions, Deadlock
9 September 2011

Dr. Clifford Neuman
University of Southern California
Information Sciences Institute
(lecture slides written by Dr. Katia Obraczka)

COVERED LAST LECTURE

Concurrency Control and Synchronization

- **How to control and synchronize possibly conflicting operations on shared data by concurrent processes?**
- **First, some terminology.**
  - **Processes.**
  - **Light-weight processes.**
  - **Threads.**
  - **Tasks.**

COVERED LAST LECTURE

Processes

- **Text book:**
  - **Processing activity associated with an execution environment, ie, address space and resources (such as communication and synchronization resources).**

COVERED LAST LECTURE

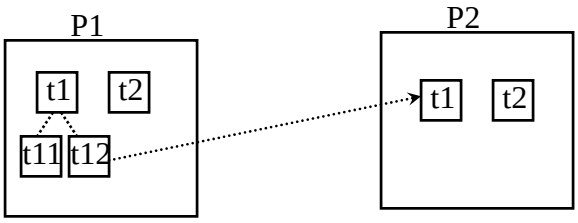
Threads

- **OS abstraction of an activity/task.**
  - **Execution environment expensive to create and manage.**
  - **Multiple threads share single execution environment.**
  - **Single process may spawn multiple threads.**
  - **Maximize degree of concurrency among related activities.**
  - **Example: multi-threaded servers allow concurrent processing of client requests.**

COVERED LAST LECTURE

Other Terminology

- **Process versus task/thread.**
  - **Process: heavy-weight unit of execution.**
  - **Task/thread: light-weight unit of execution.**



COVERED LAST LECTURE

Threads Case Study 1

- **Hauser et al.**
- **Examine use of user-level threads in 2 OS's:**
  - **Xerox Parc's Cedar (research).**
  - **GVX (commercial version of Cedar).**
- **Study dynamic thread behavior.**
  - **Classes of threads (eternal, worker, transient)**
  - **Number of threads.**
  - **Thread lifetime.**

COVERED LAST LECTURE

Thread Paradigms

- **Different categories of usage:**
  - **Defer work: thread does work not vital to the main activity.**
    - **Examples: printing a document, sending mail.**
  - **Pumps: used in pipelining; use output of a thread as input and produce output to be consumed by another task.**
  - **Sleepers: tasks that repeatedly wait for an event to execute; e.g., check for network connectivity every x seconds.**

COVERED LAST LECTURE

Synchronization

- **So far, how one defines/activates concurrent activities.**
- **But how to control access to shared data and still get work done?**
- **Synchronization via:**
  - **Shared data [DSM model].**
  - **Communication [MP model].**

COVERED LAST LECTURE

Synchronization by Shared Data

❖**Primitives**

structure ↓ flexibility ↑

- ❑ **Semaphores.**
- ❑ **Conditional critical regions.**
- ❑ **Monitors.**

COVERED LAST LECTURE

Synchronization by MP

❖**Explicit communication.**

❖**Primitives send and receive**

- ***Blocking send, blocking receive*: sender and receiver are blocked until message is delivered (redezvous)**
- ***Nonblocking send, blocking receive*: sender continues processing receiver is blocked until the requested message arrives**
- ***Nonblocking send, nonblocking receive*: messages are sent to a shared data structure consisting of queues (mailboxes)**

Deadlocks ?

- **Mailboxes one process sends a message to the mailbox and the other process picks up the message from the mailbox**

  Example:
  Send (mailbox, msg)
  Receive (mailbox, msg)

COVERED LAST LECTURE

Transactions

- **Database term.**
  - **Execution of program that accesses a database.**
- **In distributed systems,**
  - **Concurrency control in the client/server model.**
  - **From client's point of view, sequence of operations executed by server in servicing client's request in a single step.**

COVERED LAST LECTURE

Transaction Properties

- **ACID:**
  - **Atomicity: a transaction is an atomic unit of processing and it is either performed entirely or not at all**
  - **Consistency: a transaction's correct execution must take the database from one correct state to another**
  - **Isolation: the updates of a transaction must not be made visible to other transactions until it is committed**
  - **Durability: if transaction commits, the results must never be lost because of subsequent failure**

COVERED LAST LECTURE

Transaction Atomicity

- "All or nothing".
- Sequence of operations to service client's request are performed in one step, ie, either all of them are executed or none are.
- Start of a transaction is a continuation point to which it can roll back.
- Issues:
  - Multiple concurrent clients: "isolation".
    1. Each transaction accesses resources as if there were no other concurrent transactions.
    2. Modifications of the transaction are not visible to other resources before it finishes.
    3. Modifications of other transactions are not visible during the transaction at all.
  - Server failures: "failure atomicity".

COVERED LAST LECTURE

Transaction Features

- **Recoverability:** server should be able to "roll back" to state before transaction execution.
- **Serializability:** transactions executing concurrently must be interleaved in such a way that the resulting state is equal to some serial execution of the transactions
- **Durability:** effects of transactions are permanent.
  - A completed transaction is always persistent (though values may be changed by later transactions).
  - Modified resources must be held on persistent storage before transaction can complete. May not just be disk but can include battery-backed RAM.

COVERED LAST LECTURE

Concurrency Control

Maintain transaction serializability:

- **establish order of concurrent transaction execution**
- **Interleave execution of operations to ensure serializability**

❖ **Basic Server operations: read or write.**

❖ **3 mechanisms:**

- **Locks.**
- **Optimistic concurrency control.**
- **Timestamp ordering.**

COVERED LAST LECTURE

Locks

❖ **Lock granularity: affects level of concurrency.**

- **1 lock per shared data item.**
- **Shared Read**
  - **Exists when concurrent transactions granted READ access**
  - **Issued when transaction wants to read and exclusive lock not held on item**
- **Exclusive Write**
  - **Exists when access reserved for locking transaction**
  - **Used when potential for conflict exists**
  - **Issued when transaction wants to update unlocked data**

- **Many Read locks simultaneously possible for a given item, but only one Write lock**

- **Transaction that requests a lock that cannot be granted must wait**

COVERED LAST LECTURE

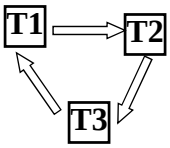
Lock Implementation

- **Server lock manager**
  - **Maintains table of locks for server data items.**
  - ***Lock* and *unlock* operations.**
  - **Clients *wait* on a lock for given data until data is released; then client is signalled.**
  - **Each client's request runs as separate server thread.**

COVERED LAST LECTURE

Deadlock

- **Use of locks can lead to deadlock.**
- **Deadlock: each transaction waits for another transaction to release a lock forming a wait cycle.**
- **Deadlock condition: cycle in the wait-for graph.**
- **Deadlock prevention and detection.**
  - **require all locks to be acquired at once**
    Problems?
  - **Ordering of data items: once a transaction locks an item, it cannot lock anything occurring earlier in the ordering**
- **Deadlock resolution: lock timeout.**



COVERED LAST LECTURE

Optimistic Concurrency Control 1

- **Assume that most of the time, probability of conflict is low.**
- **Transactions allowed to proceed in parallel until *close transaction* request from client.**
- **Upon *close transaction*, checks for conflict; if so, some transactions aborted.**

COVERED LAST LECTURE

Optimistic Concurrency 2

- **Read phase**
  - **Transactions have *tentative* version of data items it accesses.**
    - **Transaction reads data and stores in local variables**
    - **Any writes are made to local variables without updating the actual data**
  - ***Tentative* versions allow transactions to abort without making their effect permanent.**
- **Validation phase**
  - **Executed upon *close transaction*.**
  - **Checks serially equivalence.**
  - **If validation fails, conflict resolution decides which transaction(s) to abort.**

COVERED LAST LECTURE

Optimistic Concurrency 3

- **Write phase**
  - **If transaction is validated, all of its tentative versions are made permanent.**
  - **Read-only transactions commit immediately.**
  - **Write transactions commit only after their tentative versions are recorded in permanent storage.**

COVERED LAST LECTURE

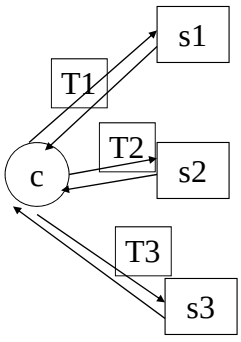
Timestamp Ordering

- **Uses timestamps to order transactions accessing same data items according to their starting times.**
- **Assigning timestamps:**
  - **Clock based: assign global unique time stamp to each transaction**
  - **Monotonically increasing counter.**
- **Some time stamping necessary to avoid "livelock": where a transaction cannot acquire any locks because of unfair waiting algorithm**

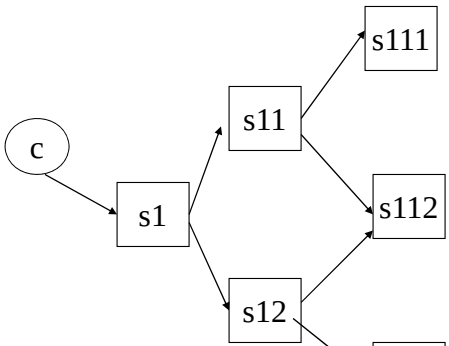
Local versus Distributed Transactions

- **Local transactions:**
  - **All transaction operations executed by single server.**
- **Distributed transactions:**
  - **Involve multiple servers.**
- **Both local and distributed transactions can be simple or nested.**
  - **Nesting: increase level of concurrency.**

Distributed Transactions 1



Simple Distributed Transaction



Nested Distributed Transaction

Distributed Transactions 2

- **Transaction coordinator**
  - **First server contacted by client.**
  - **Responsible for aborting/committing.**
  - **Adding *workers*.**
- **Workers**
  - **Other servers involved report their results to the coordinator and follow its decisions.**

Atomicity in Distributed Transactions

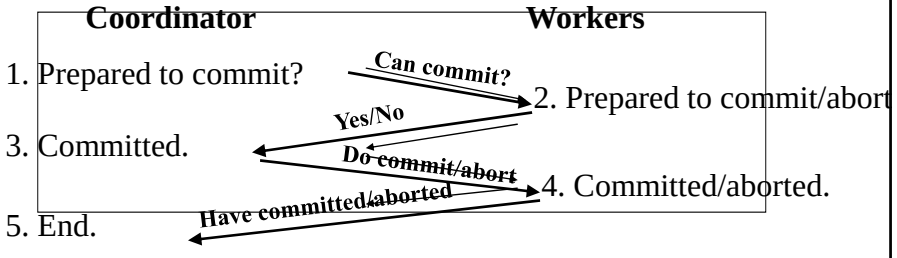
- **Harder: several servers involved.**
- **Atomic commit protocols**
  - **1-phase commit**
    - **Example: coordinator sends "commit" or "abort" to workers; keeps re-broadcasting until it gets ACK from all of them that request was performed.**
    - **Inefficient.**
    - **How to ensure that all of the servers vote + that they all reach the same decision. It is simple if no errors occur, but the protocol must work correctly even when server fails, messages are lost, etc.**

2-Phase Commit 1

- **First phase: voting**
  - **Each server votes to commit or abort transaction.**
- **Second phase: carrying out joint decision.**
  - **If any server votes to abort, joint decision is to abort.**

2-Phase Commit 2

- **Phase I**:
  - **Each participant votes for the transaction to be committed or aborted.**
  - **Participants must ensure to carry out its part of commit protocol. (prepared state).**
  - **Each participant saves in permanent storage all of the objects that it has altered in transaction to be in 'prepared state'.**
- **Phase II**:
  - **Every participant in the transaction carries out the joint decision.**
  - **If any one participant votes to abort, then the decision is to abort.**
  - **If all participants vote to commit, then the decision is to commit.**



Concurrency Control in Distributed Transactions 1

- **Locks**
  - **Each server manages locks for its own data.**
  - **Locks cannot be released until transaction committed or aborted on all servers involved.**
  - **Lock managers in different servers set their locks independently, there are chances of different transaction orderings.**
  - **The different ordering lead to cyclic dependencies between transactions and a distributed deadlock situation.**
  - **When a deadlock is detected, a transaction is aborted to resolve the deadlock**

Concurrency Control in Distributed Transactions 2

- **Timestamp Ordering**
  - **Globally unique timestamps.**
    - **Coordinator issues globally unique TS and passes it around.**
    - **TS: <server id, local TS>**
  - **Servers are jointly responsible for ensuring that they performed in a serially equivalent manner.**
  - **Clock synchronization issues**

Concurrency Control in Distributed Transactions 3

- **Optimistic concurrency control**
  - **Each transaction should be validated before it is allowed to commit.**
  - **The validation at all servers takes place during the first phase of the 2-Phase Commit Protocol.**

Camelot [Spector et al.]

- **Supports execution of distributed transactions.**
- **Specialized functions:**
  - **Disk management**
    - **Allocation of large contiguous chunks.**
  - **Recovery management**
    - **Transaction abort and failure recovery.**
  - **Transaction management**
    - **Abort, commit, and nest transactions.**

Distributed Deadlock 1

- When locks are used, deadlock can occur.
- Circular wait in wait-for graph means deadlock.
- Centralized deadlock detection, prevention, and resolutions schemes.
  - Examples:
    - Detection of cycle in wait-for graph.
    - Lock timeouts: hard to set TO value, aborting unnecessarily.

Distributed Deadlock 2

- Much harder to detect, prevent, and resolve. Why?
  - No global view.
  - No central agent.
  - Communication-related problems
    - Unreliability.
    - Delay.
    - Cost.

Distributed Deadlock Detection

- **Cycle in the** global **wait-for graph.**
- **Global graph can be constructed from local graphs: hard!**
  - **Servers need to communicate to find cycles.**

Distributed Deadlock Detection Algorithms 1

- **[Chandy et al.]**
- **Message sequencing is preserved.**
- **Resource versus communication models.**
  - **Resource model**
    - **Processes, resources, and controllers.**
    - **Process requests resource from controller.**
  - **Communication model**
    - **Processes communicate directly via messages (request, grant, etc) requesting resources.**

Resource versus Communication Models

- In resource model, controllers are deadlock detection agents; in communication model, processes.
- In resource model, process cannot continue until all requested resources granted; in communication model, process cannot proceed until it can communicate with at least one process it's waiting for.
- Different models, different detection alg's.

Distributed Deadlock Detection Schemes

- Graph-theory based.
- Resource model: deadlock when cycle among dependent processes.
- Communication model: deadlock when knot (all vertices that can be reached from *i* can also reach *i*) of waiting processes.

Deadlock Detection in Resource Model

- **Use probe messages to follow edges of wait-for graph (aka edge chasing).**
- **Probe carries transaction wait-for relations representing path in global wait-for graph.**

Deadlock Detection Example

1. **Server 1 detects transaction T is waiting for U, which is waiting for data from server 2.**
2. **Server 1 sends probe T->U to server 2.**
3. **Server 2 gets probe and checks if U is also waiting; if so (say for V), it adds V to probe T->U->V. If V is waiting for data from server 3, server 2 forwards probe.**
4. **Paths are built one edge at a time.**

Before forwarding probe, server checks for cycle (e.g., T->U->V->T).

5. **If cycle detected, a transaction is aborted.**

Replication

Replication requires synchronization

- **Keep more than one copy of data item.**
- **Technique for improving performance in distributed systems.**
- **In the context of concurrent access to data, replicate data for increase availability.**
  - **Improved response time.**
  - **Improved availability.**
  - **Improved fault tolerance.**

Replication 2

- **But nothing comes for free.**
- **What's the tradeoff?**
  - **Consistency maintenance.**
- **Consistency maintenance approaches:**
  - **Lazy consistency (gossip approach).**
    - An operation call is executed at just one replica; updating of other replicas happens by lazy exchange of "gossip" messages.
  - **Quorum consensus is based on voting techniques.**
  - **Process group.**

Stronger consistency

Quorum Consensus

- Goal: prevent partitions from from producing inconsistent results.
- Quorum: subgroup of replicas whose size gives it the right to carry out operations.
- Quorum consensus replication:
  - Update will propagate successfully to a subgroup of replicas.
  - Other replicas will have outdated copies but will be updated off-line.

Weighted Voting [Gifford] 1

- Every copy assigned a number of votes (weight assigned to a particular replica).
- Read: Must obtain *R* votes to read from any up-to-date copy.
- Write: Must obtain write quorum of *W* before performing update.

Weighted Voting 2

- W > 1/2 total votes, R+W > total votes.
- Ensures non-null intersection between every read quorum and write quorum.
- Read quorum guaranteed to have current copy.
- Freshness is determined by version numbers.

Weighted Voting 3

- On read:
  - Try to find enough copies, ie, total votes no less than R. Not all copies need to be current.
  - Since it overlaps with write quorum, at least one copy is current.
- On write:
  - Try to find set of up-to-date replicas whose votes no less than W.
  - If no sufficient quorum, current copies replace old ones, then update.

Time in Distributed Systems

- Notion of time is critical.
- "Happened before" notion.
  - Example: concurrency control using TSs.
  - "Happened before" notion is not straightforward in distributed systems.
    - No guarantees of synchronized clocks.
    - Communication latency.

Event Ordering

- Lamport defines partial ordering ($\rightarrow$):
  1. If X and Y events occurred in the same process, and X comes before Y, then $X \rightarrow Y$.
  2. Whenever X sends a message to Y, then $X \rightarrow Y$.
  3. If $X \rightarrow Y$ and $Y \rightarrow Z$, then $X \rightarrow Z$.
  4. X and Y are concurrent if $X \not\rightarrow Y$ and $Y \not\rightarrow Z$

Causal Ordering

- "Happened before" also called causal ordering.
- In summary, possible to draw happened-before relationship between events if they happen in same process or there's chain of messages between them.

Logical Clocks

- Monotonically increasing counter.
- No relation with real clock.
- Each process keeps its own logical clock Cp used to timestamp events.

Causal Ordering and Logical Clocks

1. ***Cp* incremented before each event.**
   ***Cp=Cp+1*.**
2. **When *p* sends message *m*, it piggybacks *t=Cp*.**
3. **When q receives *(m, t),* it computes:**
   ***Cq=max(Cq, t)* before timestamping message receipt event.**

Example: text book page 398.

Total Ordering

- **Extending partial to total order.**
- **Global timestamps:**
  - **(T_a, p_a), where T_a is local TS and p_a is the process id.**
  - **(T_a, p_a) < (T_b, p_b) iff $T_a < T_b$ or $T_a=T_b$ and $p_a<p_b$**
  - **Total order consistent with partial order.**

Virtual Time [Jefferson]

- Time warp mechanism.
- May or may not have connection with real time.
- Uses optimistic approach, i.e., events and messages are processed in the order received: “look-ahead”.

Local Virtual Clock

- Process virtual clock set to TS of next message in input queue.
- If next message’s TS is in the past, rollback!
  - Can happen due to different computation rates, communication latency, and unsynchronized clocks.

Rolling Back

- Process goes back to TS(last message).
- Cancels all intermediate effects of events whose TS > TS(last message).
- Then, executes forward.
- Rolling back is expensive!
  - Messages may have been sent to other processes causing them to send messages, etc.

Anti-Messages 1

- For every message, there is an anti-message with same content but different *sign*.
- When sending message, message goes to receiver input queue and a copy with "-" sign is enqueued in the sender's output queue.
- Message is retained for use in case of roll back.

Anti-Message 2

- **Message + its anti-message = 0 when in the same queue.**
- **Processes must keep log to "undo" operations.**

Implementation

- **Local control.**
- **Global control**
  - **How to make sure system as a whole progresses.**
  - **"Committing" errors and I/O.**
  - **Avoid running out of memory.**

Global Virtual Clock

- Snapshot of system at given real time.
- Minimum of all local virtual times.
- Lower bound on how far processes rollback.
- Purge state before GVT.
- GVT computed concurrently with rest of time warp mechanism.
  - Tradeoff?

ISIS 1

- Goal: provide programming environment for development of distributed systems.
- Assumptions:
  - DS as a set of processes with disjoint address spaces, communicating over LAN via MP.
  - Processes and nodes can crash.
  - Partitions may occur.

ISIS 2

- Distinguishing feature: group communication mechanisms
  - Process group: processes cooperating in implementing task.
  - Process can belong to multiple groups.
  - Dynamic group membership.

Virtual Synchrony

- Real synchronous systems
  - Events (e.g., message delivery) occur in the same order everywhere.
  - Expensive and not very efficient.
- Virtual synchronous systems
  - Illusion of synchrony.
  - Weaker ordering guarantees when applications allow it.

Atomic Multicast 1

- All destinations receive a message or none.
- Primitives:
  - ABCAST: delivers messages atomically and in the same order everywhere.
  - CBCAST: causally ordered multicast.
    - "Happened before" order.
    - Messages from given process in order.
  - GBCAST
    - used by system to manage group addressing.

Other Features

- Process groups
  - Group membership management.
- Broadcast and group RPC
  - RPC-like interface to CBCAST, ABCAST, and GBCAST protocols.
  - Delivery guarantees
    - Caller indicates how many responses required.
      - No responses: asynchronous.
      - 1 or more: synchronous.

Implementation

- Set of library calls on top of UNIX.
- Commercially available.
- In the paper, example of distributed DB implementation using ISIS.
- HORUS: extension to WANs.

CSci555: Advanced Operating Systems

Lecture 4 – September 16 2011

Naming and Binding

Dr. Clifford Neuman
University of Southern California
Information Sciences Institute

COVERED LAST LECTURE

Naming Concepts

- **Name**
  - **What you call something**
- **Address**
  - **Where it is located**
- **Route**
  - **How one gets to it**

  What is http://www.isi.edu/~bcn ?
- **But it is not that clear anymore, it depends on perspective. A name from one perspective may be an address from another.**
  - **Perspective means layer of abstraction**

COVERED LAST LECTURE

What are the things we name

- **Users**
  - **To direct, and to identify**
- **Hosts (computers)**
  - **High level and low level**
- **Services**
  - **Service and instance**
- **Files and other "objects"**
  - **Content and repository**
- **Groups**
  - **Of any of the above**

COVERED LAST LECTURE

How we name things

- Host-Based Naming
  - Host-name is required part of object name
- Global Naming
  - Must look-up name in global database to find address
  - Name transparency
- User/Object Centered Naming
  - Namespace is centered around user or object
- Attribute-Based Naming
  - Object identified by unique characteristics
  - Related to resource discovery / search / indexes

COVERED LAST LECTURE

Namespace

- A name space maps:

$$\Sigma^* \rightarrow X \in O$$

At a particular point in time.

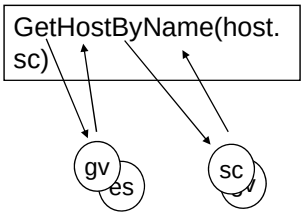
- The rest of the definition, and even some of the above, is open to discussion/debate.
- What is a "flat namespace"
  - Implementation issue

Case Studies

- **Host Table**
  - **Flat namespace (?)**
  - **Global namespace (?)**

```
GetHostByName(usc.arpa){
   scan(host file);
   return(matching entry);
   }
```

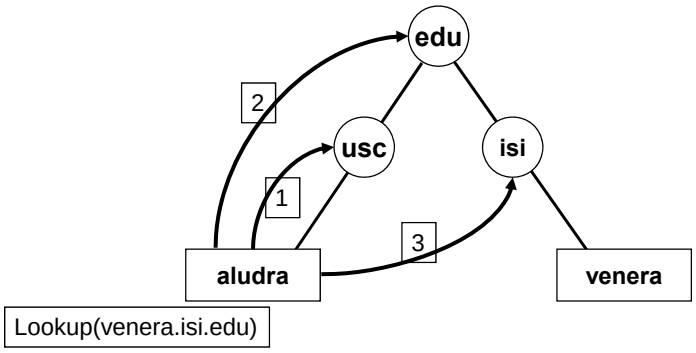
- **Grapevine**
  - **Two-level, iterative lookup**
  - **Clearinghouse 3 level**



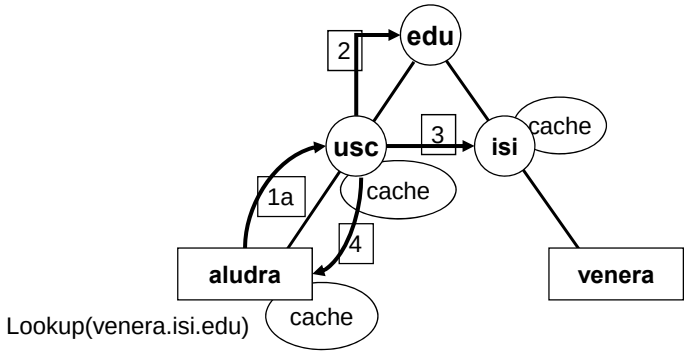
- **Domain name system**
  - **Arbitrary depth**
  - **Iterative or recursive(chained) lookup**
  - **Multi-level caching**

Domain Name System

Iterative query



Chained query



Scalability of naming

- **Scalability**
  - **Ability to continue to operate efficiently as a system grows large, either numerically, geographically, or administratively.**
- **Affected by**
  - **Frequency of update**
  - **Granularity**
  - **Evolution/reconfiguration**
- **DNS characteristics**
  - **Multi-level implementation**
  - **Replication of root and other servers**
  - **Multi-level caching**

Closure

- Closure binds an object to the namespace within which names embedded in the object are to be resolved.
  - "Object" may as small as the name itself
    - GNS binds the names to namespaces
    - Prospero binds enclosing object to multiple namespaces
    - Tilde and quicksilver bind users to namespaces
    - NFS mount table constructs system centered namespace
  - Movement of objects can cause problems
    - When closure is associated with wrong entity

Other implementations of naming

- Broadcast
  - Limited scalability, but faster local response
- Prefix tables
  - Essentially a form of caching
- Capabilities
  - Combines security and naming
  - Traditional name service built over capability based addresses

Advanced Name Systems

- DEC's Global Naming
  - Support for reorganization the key idea
  - Little coordination needed in advance
- Half Closure
  - Names are all tagged with namespace identifiers
    - DID - Directory Identifier
    - Hidden part of name - makes it global
    - Upon reorganization, new DID assigned
    - Old names relative to old root
  - But the DID's must be unique - how do we assign?

Prospero Directory Service

- Multiple namespace centered around a "root" node that is specific to each namespace.
  - Closure binds objects to this "root" node.
- Layers of naming
  - User level names are "object" centered
  - Objects still have an address which is global
  - Namespaces also have global addresses
- Customization in Prospero
  - Filters create user level derived namespaces on the fly
  - Union links support merging of views

Resource Discovery

- Similar to naming
  - Browsing related to directory services
  - Indexing and search similar to attribute based naming
- Attribute based naming
  - Profile
  - Multi-structured naming
- Search engines
- Computing resource discovery

The Web

- Object handles
  - Uniform Resource Identifier (URI's)
  - Uniform Resource Locators (URL's)
  - Uniform Resource Names (URN's)
- XML
  - Definitions provide a form of closure
    - Conceptual level rather than the "namespace" level.

LDAP

- Manage information about users, services
  - Lighter weight than X.500 DAP
    - Heavier than DNS
  - Applications have conventions on where to look
    - Often data is duplicated because of multiple conventions
  - Performance enhancements not as well defined
    - Caching harder because of less constrained patterns of access

CSci555: Advanced Operating Systems

Lecture 5 – September 23 2011

Ubiquitous and Mobile Computing

Dr. Clifford Neuman

University of Southern California

Information Sciences Institute

COVERED LAST LECTURE

New Computing Environments

- Ubiquitous and Pervasive Computing
  - Including Sensor Nodes
  - Managing Devices
- Mobile computing
  - Portable Devices

COVERED LAST LECTURE

Characteristics

- Low power availability
- Constrained resources
- Transient relationships
- Ad-hoc deployment
- Peer to Peer relationships
- Weakly managed
- Context aware

COVERED LAST LECTURE

Ubiquitous computing

- **According to Mark Weiser at Xerox:**
  - **Transparent computing is the ultimate goal**
  - **Computers should disappear into the background**
  - **Computation becomes part of the environment**

COVERED LAST LECTURE

Ubiquitous Computing

- **Computing everywhere**
  - **Desktop, Laptop, Palmtop**
  - **Cars, Cell phones**
  - **Shoes, Clothing, Walls (paper / paint)**
- **Connectivity everywhere**
  - **Broadband**
  - **Wireless**
- **Mobile everywhere**
  - **Users move around**
  - **Disposable devices**

COVERED LAST LECTURE

Ubiquitous Computing

- **Structure**
  - **Resource and service discovery critical**
  - **User location an issue**
  - **Interface discovery**
  - **Disconnected operation**
  - **Ad-hoc organization**
- **Security**
  - **Small devices with limited power**
  - **Intermittent connectivity**
- **Agents**
- **Sensor Networks**

Mobile Computing

- **Often managed devices**
  - **Cell phones**
  - **PDA's**
  - **Subscription Services**

Ad-hoc Networking

- Peer-to-peer of network routing
- Transient devices
- Issues:
  - Discovery
  - Security
  - Power
- Examples:
  - Many Sensor Networks

Source: ISI & DARPA PAC/C Program

Communication/Computation Technology Projection

	1999 (Bluetooth Technology)	2004
Communication	(150nJ/bit)	(5nJ/bit)
	1.5mW*	50uW
Computation		~ 190 MOPS
		(5pJ/OP)

Assume: 10kbit/sec. Radio, 10 m range.

Large cost of communications relative to computation continues

(source – talk by Deborah Estrin)

Active Badges

- Provides location information and one or more buttons
  - Beacons
- Simple interface
  - Controlled access
  - Carries context
    - Two way, device knows where your are, and your location knows you are present
    - Moves your environment

Today's Mobile Devices

- Smart Phones
  - Communication
    - Wifi, 3G, 4G
    - Mostly infrastructure based
  - Location Services & Power
    - GPS, Cell Tower, Beacons, Inertial Navigation

In-Network Processing

- Communication is expensive, computing less-so, so pre-process to reduce data sent.
- Send information, not-data.
- Requires more knowledge at the edges so that query can be distributed.
- Intermediate nodes correlate and agregate results.

Directed Diffusion

- Publish/Subscribe model
- Data named, not nodes
- But what are the implications
  - discussion

A Taxonomy

- Approaches/Products/Devices differ by placement/nature of:
  - Management
  - Storage
  - Computing
  - Communication
  - Context maintenance
  - Authority

Classes

- Mobile Terminals
- Passive devices
- Personal Devices
- Remote Sensors/Actuators
- Communicating Devices
- Sensor Networks

Examples

- Cell Phones
- i-phone
- PDA
- Home automation
- Proximity cards
- Laptop computer
- In Vehicle networks
- Active Badges

CSci555: Advanced Operating Systems
Lecture 6 – September 30, 2011

Security Concepts, Distributed Systems

Dr. Clifford Neuman
University of Southern California
Information Sciences Institute

COVERED LAST LECTURE

Security Goals

- **Confidentiality**
  - **inappropriate information is not disclosed**
- **Integrity**
  - **Authenticity of document**
  - **That it hasn't changed**
- **Availability**
  - **the ability of authorized entities to use the information or resource**

COVERED LAST LECTURE

System Security: Terminology

- ***vulnerability*** **is a weakness in the system that might be exploited to cause loss or harm.**
- ***threat*** **is a potential violation of security and includes a capability to exploit a vulnerability.**
- ***attack*** **is the actual attempt to violate security. It is the manifestation of the threat**
  - Interception
  - Modification
  - Disruption
- ***security policy*** **defines what is and is not allowed**
- ***security mechanism*** **is a method or tool for enforcing security policy**
  - Prevention
  - Detection
  - Reaction

COVERED LAST LECTURE

Basic Security Services

Protection
Authentication
Access Control, Authorization
Accounting
Payment
Audit
Assurance
Privacy
Policy

COVERED LAST LECTURE

Security Models

- **Discretionary Access Control**
  - **Users have complete control over his/her resources**
- **Mandatory Access Control**
  - **Administrators decide what you have access to as well as what you can give access to (as opposed to discretionary access control).**
  - **Users must deal with not having control over how they use their own resources.**

COVERED LAST LECTURE

Security Policy

- **Access Matrix**

Subject	OBJ1	OBJ2
bcn	RW	R
gost-group	RW	-
obraczka	R	RW
tyao	R	R
Csci555	R	-

  - **implemented as:**
    - **Capabilities or**
    - **Access Control list**

COVERED LAST LECTURE

Access Control Lists

- **Advantages**
  - **Easy to see who has access**
  - **Easy to change/revoke access**
- **Disadvantages**
  - **Time consuming to check access**
- **Extensions to ease management**
  - **Groups**
  - **EACLs**

COVERED LAST LECTURE

Extended Access Control Lists

- **Conditional authorization**
  - **Implemented as restrictions on ACL entries and embedded as restrictions in authentication and authorization credentials**

Principal	*Rights*	*Conditions*
bcn	RW	HW-Authentication Retain Old Items
gost-group	RW	TIME: 9AM-5PM
authorization server	R	Delegated-Access
*	R	Load Limit 8 Use: Non-Commercial
*	R	Payment: $Price

COVERED LAST LECTURE

Example Conditions

- **Authentication method** specifies mechanisms suitable for authentication.
- **Payment** specifies currency and amount.
- **Time** time periods expressed as time of day or days of week when access is granted.
- **Location** access is granted to principals connecting from specific hosts.
- **Notification** enables automatic generation of notification messages.
- **Audit** enables automatic generation of application level audit data.
- **System Threat Level** specifies system threat level, e.g., high, medium or low.

COVERED LAST LECTURE

Capabilities

- **Advantages**
  - **Easy and efficient to check access**
  - **Easily propagated**
- **Disadvantages**
  - **Hard to protect capabilities**
  - **Easily propagated**
  - **Hard to revoke**
- **Hybrid approach**
  - **EACL's/proxies**

COVERED LAST LECTURE

Protecting capabilities

- **Stored in TCB**
  - **Only protected calls manipulate**
- **Limitations ?**
  - **Works in centralized systems**
- **Distributed Systems**
  - **Tokens with random or special coding**
  - **Possibly protect through encryption**
  - **How does Amoeba do it? (claimed)**

COVERED LAST LECTURE

Network Threats

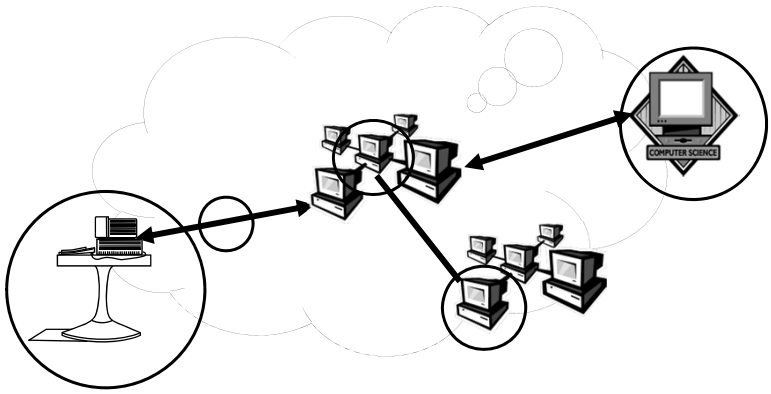
- Unauthorized release of data
- Unauthorized modification of data
- Impersonation (spurious association initiation)
- Denial of use
- Traffic analysis

❖ Attacks may be

- Active or passive

COVERED LAST LECTURE

Likely points of attack (location)



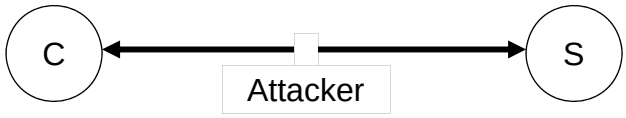
COVERED LAST LECTURE

Likely points of attack (module)

- **Against the protocols**
  - **Sniffing for passwords and credit card numbers**
  - **Interception of data returned to user**
  - **Hijacking of connections**
- **Against the server**
  - **The commerce protocol is not the only way in**
  - **Once an attacker is in, all bets are off**
- **Against the client's system**
  - **You have little control over the client's system**

COVERED LAST LECTURE

Network Attacks



Eavesdropping

Listening for passwords or credit card numbers

Message stream modification

Changing links and data returned by server

Hijacking

Killing client and taking over connection

COVERED LAST LECTURE

Network Attack Countermeasures

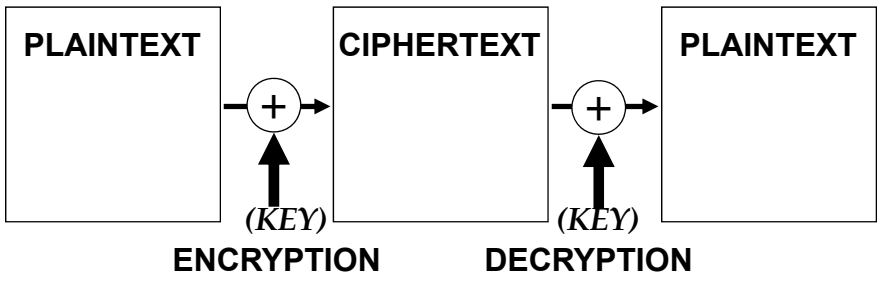
Don't send anything important
- Not everything needs to be protected

Encryption
- For everything else
- Mechanism limited by client side software

COVERED LAST LECTURE

Encryption for confidentiality and integrity

❖**Encryption used to scramble data**

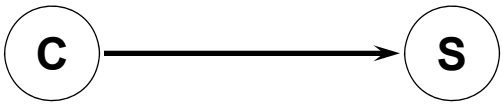


COVERED LAST LECTURE

Authentication

- **Proving knowledge of encryption key**
  - **Nonce = Non repeating value**

$\{Nonce\ or\ timestamp\}K_c$



COVERED LAST LECTURE

Today's security deployment

- **Most of the deployment of security services today handles the easy stuff, implementing security at a single point in the network, or at a single layer in the protocol stack:**
  - **Firewalls, VPN's**
  - **IPSec**
  - **SSL**
- **Unfortunately, security isn't that easy. It** must **be better integrated with the application.**
  - **At the level at which it must ultimately be specified, security policies pertain to application level objects, and identify application level entities (users).**

COVERED LAST LECTURE

Conclusion: Integration is hard to do

- **The majority of applications were not being modified to use security services.**
  - **In fact, the only widespread interoperable integration of security services with applications was SSL integration with the web, and SSL is used primarily as a confidentiality mechanism and only rarely for user authentication.**

COVERED LAST LECTURE

Conclusion: Integration is hard to do

- **The reason**
  - **Integration with applications involved many changes:**
    - **Multiple calls to GSS-API or other authentication interfaces**
    - **Calls to decide what the user is authorized to do**
      - **Home grown policy databases or protocol extensions requiring even more calls to complete.**
    - **Custom integration with other security services**
      - **Confidentiality, integrity, payment, audit**

COVERED LAST LECTURE

Focus on Authorization

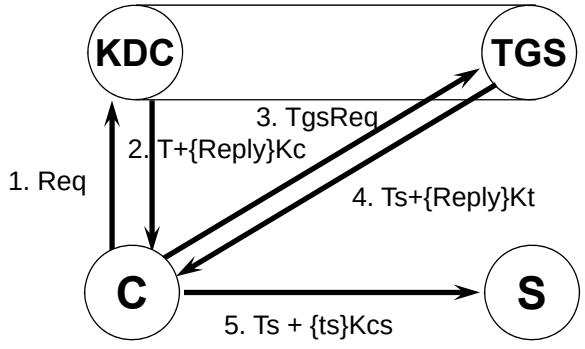
- **Focusing on authorization and the management of policies used in the authorization decision.**
  - **Not really new - this is a reference monitor.**
  - **Applications shouldn't care about authentication or identity.**
    - **Separate policy from mechanism**
  - **Authorization may be easier to integrate with applications.**
  - **Hide the calls to the key management and authentication functions.**

COVERED LAST LECTURE

Kerberos

Third-party authentication service

- **Distributes session keys for authentication, confidentiality, and integrity**



COVERED LAST LECTURE

Global Authentication Service

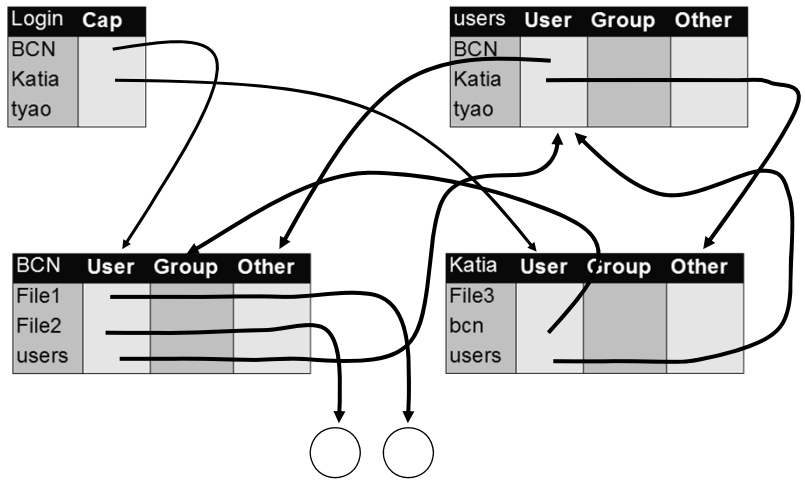
- **Pair-wise trust in hierarchy**
  - **Name is derived from path followed**
  - **Shortcuts allowed, but changes name**
  - Exposure of path is important for security
- **Compared to Kerberos**
  - **Transited field in Kerberos - doesn't change name**
- **Compared with X.509**
  - **X.509 has single path from root**
  - **X.509 is for public key systems**
- **Compared with PGP**
  - **PGP evaluates path at end, but may have name conflicts**

Capability Based Systems - Amoeba

"Authentication not an end in itself"

- **Theft of capabilities an issue**
  - **Claims about no direct access to network**
  - **Replay an issue**
- **Modification of capabilities a problem**
  - **One way functions provide a good solution**
- **Where to store capabilities for convenience**
  - **In the user-level naming system/directory**
  - **3 columns**
- **Where is authentication in Amoeba**
  - **To obtain initial capability**

Capability Directories in Amoeba



Distributed Authorization

- **It must be possible to maintain authorization information separate from the end servers**
  - **Less duplication of authorization database**
  - **Less need for specific prior arrangement**
  - **Simplified management**
- **Based on restricted proxies which support**
  - **Authorization servers**
  - **Group Servers**
  - **Capabilities**
  - **Delegation**

Security Architectures

- **DSSA**
  - **Delegation is the important issue**
    - **Workstation can act as user**
    - **Software can act as workstation - if given key**
    - **Software can act as developer - if checksum validated**
  - **Complete chain needed to assume authority**
  - **Roles provide limits on authority - new sub-principal**
- **Proxies - Also based on delegation**
  - **Limits on authority explicitly embedded in proxy**
  - **Works well with access control lists**

Next Generation Secure Computing Base -> Longhorn -> Vista

- **Secure booting provides known hardware and OS software base.**
- **Security Kernel in OS provides assurance about the application.**
- **Security Kernel in application manages credentials granted to application.**
- **Security servers enforce rules on what software they will interact with.**

Hardware Requirements for Trusted Computing

- **How do we know what software is running?**
  - **Exercise: Suppose a virus infected our application.**
  - **Suppose we were running a hacked kernel.**
  - **Suppose we were running in a virtual machine.**
  - **Suppose someone replaced our hardware with something similar, but with special operations.**

A basis step for trust

- **The Hardware must be secure.**
  - **And it must be able to prove that it has not been modified or replaced.**
  - **This requires special keys accessible only to the hardware.**
  - **It requires tamper resistance that destroys the key if someone tries to open the chip.**
  - **(we also need validation of the hardware implementation)**

But this is an OS class

- **The OS must be secure**
  - **And it must be able to prove that it has not been modified or replaced.**
  - **This requires special keys accessible to OS.**
    - **These keys are provided when booted.**
    - **They are bound to a checksum.**
    - **They may be managed in hardware or by the OS itself.**
  - **What does this protect against?**

What does the OS do

- **The OS must perform special functions**
  - **Must provide certified keys for the applications (as the HW did for the OS).**
  - **The OS must protect itself, and its own keys – so that malware or other users can not act as the OS.**
  - **The OS must protect process from one another. Some functions may require stronger separation than typically provided today.**
  - **The Trusted Applications themselves must similarly apply application specific protections to the data they manipulate.**

OS Concepts

- Trusted computing base
- Trusted path
- Separation of processes

The Trusted Computing Bases (TCB)

- That part of the system which is critical for security.
  - Vulnerability of the TCB affects the core security of the system.
  - Trusted Computing Extends the TCB across physical system boundaries.
    - Allows remote components to be part of the TCB for a particular function.

Trusted Path

- Provides attestation of the system to the user.
  - Requires confidence in the hardware by the user.
  - Requires training of the user on how to invoke trusted path.

Separation of Processes

- Allows process that are trusted to run without interference from other processes.
  - Requires isolation that is provided by lower level trusted modules.
  - Include hardware support, much of which is already standard in chips, but some which is not.

Vista Security Technologies

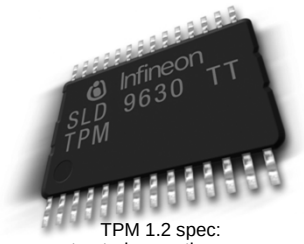
- **Summary of some of the support for trusted computing in Vista (on the following slides)**

Trusted Platform Module (TPM)?

Smartcard-like module

on the motherboard that:

- **Performs cryptographic functions**
  - **RSA, SHA-1, RNG**
  - **Meets encryption export requirements**
- **Can create, store and manage keys**
  - **Provides a unique Endorsement Key (EK)**
  - **Provides a unique Storage Root Key (SRK)**
- **Performs digital signature operations**
- **Holds Platform Measurements (hashes)**
- **Anchors chain of trust for keys and credentials**
- **Protects itself against attacks**



TPM 1.2 spec:
www.trustedcomputinggroup.org

Slide From Steve Lamb at Microsoft

Why Use A TPM?

- **Trusted Platforms use Roots-of-Trust**
  - **A TPM is an implementation of a Root-of-Trust**
- **A hardware Root-of-Trust has distinct advantages**
  - **Software can be hacked by Software**
    - **Difficult to root trust in software that has to validate itself**
  - **Hardware can be made to be robust against attacks**
    - **Certified to be tamper resistant**
  - **Hardware and software combined can protect root secrets better than software alone**
- **A TPM can ensure that keys and secrets are only available for use when the environment is appropriate**
  - **Security can be tied to specific hardware and software configurations**

Slide From Steve Lamb at Microsoft

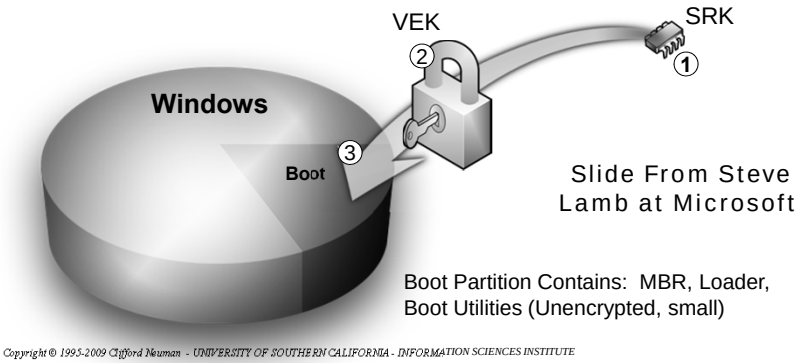
Disk Layout & Key Storage

Windows Partition Contains

- Encrypted OS
- Encrypted Page File
- Encrypted Temp Files
- Encrypted Data
- Encrypted Hibernation File

Where's the Encryption Key?

1. *SRK* (Storage Root Key) contained in TPM
2. *SRK* encrypts *VEK* (Volume Encryption Key) protected by TPM/PIN/Dongle
3. *VEK* stored (encrypted by *SRK*) on hard drive in Boot Partition



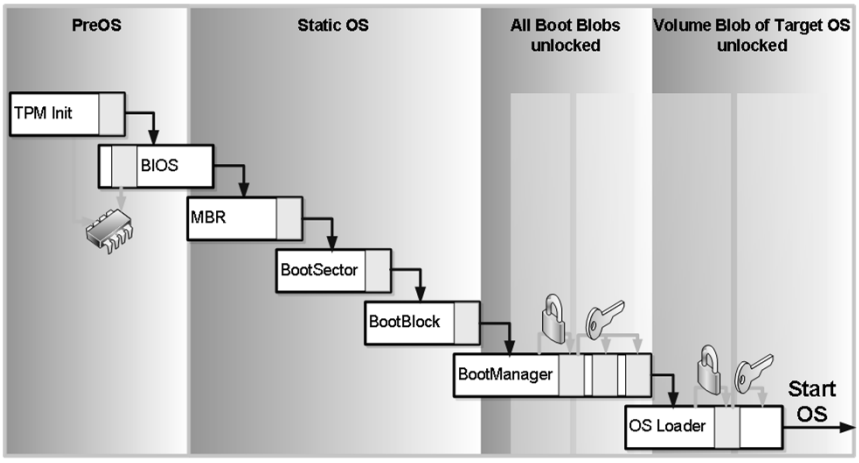
Slide From Steve Lamb at Microsoft

Boot Partition Contains: MBR, Loader, Boot Utilities (Unencrypted, small)

BitLocker™ Architecture

Static Root of Trust Measurement of early boot components

Slide From Steve Lamb at Microsoft



Hardware Requirements for Trusted Computing

- **How do we know what software is running?**
  - **Exercise: Suppose a virus infected our application.**
  - **Suppose we were running a hacked kernel.**
  - **Suppose we were running in a virtual machine.**
  - **Suppose someone replaced our hardware with something similar, but with special operations.**

This helps to contain breaches

- **But it doesn't prevent breaches.**
  - **A buggy OS can still be compromised.**
  - **Bugs in applications still leave vulnerabilities.**
  - **But one can at least be more sure about what version of software one is communicating with.**

Virtualization and Trusted Computing

- **The separation provided by virtualization may be just what is needed to keep data managed by trusted applications out of the hands of other processes.**
- **But a trusted Guest OS would have to make sure the data is protected on disk as well.**

CSci555: Advanced Operating Systems

Lecture 7 – October 7 2011

Virtualization

Dr. Clifford Neuman
University of Southern California
Information Sciences Institute

COVERED LAST LECTURE

Virtualization and Trusted Computing

- **The separation provided by virtualization may be just what is needed to keep data managed by trusted applications out of the hands of other processes.**
- **But a trusted Guest OS would have to make sure the data is protected on disk as well.**

COVERED LAST LECTURE

Protecting Data Within an OS

- **Trusted computing requires protection of processes and resources from access or modification by untrusted processes.**
  - **Don't allow running of untrusted processes**
    - **Limits the usefulness of the OS**
    - **But OK for embedded computing**
  - **Provide strong separation of processes**
    - **Together with data used by those processes**
  - **Protection of data as stored**
    - **Encryption by OS / Disk**
    - **Encryption by trusted application**
    - **Protection of hardware, and only trusted boot**

COVERED LAST LECTURE

Protection by the OS

- **The OS provides**
  - **Protection of its own data, keys, and those of other applications.**
    - **The OS protect process from one another. Some functions may require stronger separation than typically provided today, especially from "administrator".**
  - **The trusted applications themselves must similarly apply application specific protections to the data they manipulate.**

COVERED LAST LECTURE

Strong Separation

- OS Support
  - Ability to encrypt parts of file system
  - Access to files strongly mediated
  - Some protections enforced against even "Administrator"
- Mandatory Access Controls
  - Another form of OS support
  - Policies are usually simpler
- Virtualization

COVERED LAST LECTURE

Virtualization

- Operating Systems are all about virtualization
  - One of the most important function of a modern operating system is managing virtual address spaces.
  - But most operating systems do this for applications, not for other OSs.

COVERED LAST LECTURE

Virtualization of the OS

- Some have said that all problems in computer science can be handled by adding a later of indirection.
  - Others have described solutions as reducing the problem to a previously unsolved problem.
- Virtualization of OS's does both.
  - It provides a useful abstraction for running guest OS's.
  - But the guest OS's have the same problems as if they were running natively.

COVERED LAST LECTURE

What is the benefit of virtualization

- Management
  - You can running many more "machines" and create new ones in an automated manner.
  - This is useful for server farms.
- Separation
  - "Separate" machines provide a fairly strong, though coarse grained level of protection.
  - Because the isolation can be configured to be almost total, there are fewer special cases or management interfaces to get wrong.

COVERED LAST LECTURE

Is Virtualization Different?

- **Same problems**
  - **Most of the problems handled by hypervisors are the same problems handled by traditional OS's**
- **But the Abstractions are different**
  - **Hypervisors present a hardware abstraction.**
    - **E.g. disk blocks**
  - **OS's present and application abstraction.**
    - **E.g. files**

COVERED LAST LECTURE

Virtualization

- **Running multiple operating systems simultaneously.**
  - **OS protects its own objects from within**
  - **Hypervisor provides partitioning of resources between guest OS's.**

Managing Virtual Resource

- Page faults typically trap to the Hypervisor (host OS).
  - Issues arise from the need to replace page tables when switching between guest OS's.
  - Xen places itself in the Guest OS's first region of memory so that the page table does not need to be rewitten for traps to the Hypervisor.
- Disks managed as block devices allocated to guest OS's, so that the Xen code to protect disk extents can be as simple as possible.

Virtualization

- Operating Systems are all about virtualization
  - One of the most important functions of a modern operating system is managing virtual address spaces.
  - But most operating systems do this for applications, not for other OSs.

Virtualization of the OS

- Some have said that all problems in computer science can be handled by adding a layer of indirection.
  - Others have described solutions as reducing the problem to a previously unsolved problem.
- Virtualization of OS's does both.
  - It provides a useful abstraction for running guest OS's.
  - But the guest OS's have the same problems as if they were running natively.

What is the benefit of virtualization

- Management
  - You can run many more "machines" and create new ones in an automated manner.
  - This is useful for server farms.
- Separation
  - "Separate" machines provide a fairly strong, though coarse grained level of protection.
  - Because the isolation *can be* configured to be almost total, there are fewer special cases or management interfaces to get wrong.

What makes virtualization hard

- Operating systems are usually written to assume that they run in privileged mode.
- The Hypervisor (the OS of OS's) manages the guest OS's as if they are applications.
- Some architecture provide more than two "Rings" which allows the guest OS to reside between the two states.
  - But there are still often assumptions in coding that need to be corrected in the guest OS.

Managing Virtual Resource

- Page faults typically trap to the Hypervisor (host OS).
  - Issues arise from the need to replace page tables when switching between guest OS's.
  - Xen places itself in the Guest OS's first region of memory so that the page table does not need to be rewritten for traps to the Hypervisor.
- Disks managed as block devices allocated to guest OS's, so that the Xen code protects disk extents and is as simple as possible.

Partitioning of Resources

- Fixed partitioning of resources makes the job of managing the Guest OS's easier, but it is not always the most efficient way to partition.
  - Resources unused by one OS (CPU, Memory, Disk) are not available to others.
- But fixed provisioning prevents use of resources in one guest OS from effecting performance or even denying service to applications running in other guest OSs.

The Security of Virtualization

- +++ Isolation and protection between OS's can be simple (and at a very coarse level of granularity).
- +++ This coarse level of isolation may be an easier security abstraction to conceptualize than the finer grained policies typically encountered in OSs.
- --- Some malware (Blue pill) can move the real OS into a virtual machine from within which the host OS (the Malware) can not be detected.

Virtualization and Trusted Computing

- The separation provided by virtualization may be just what is needed to keep data managed by trusted applications out of the hands of other processes.
- But a trusted Guest OS would have to make sure the data is protected on disk as well.

Examples of Virtualization

- VMWare
  - Guest OS's run under host OS
  - Full Virtualization, unmodified Guest OS
- Xen
  - Small Hypervisor as host OS
  - Para-virtualization, modified guest OS
- Terra
  - A Virtual Machine-Based TC platform
- Denali
  - Optimized for application sized OS's.

Arun Viswanathan
(Slides primarily from XEN website
http://www.cl.cam.ac.uk/research/srg/netos/xen/architecture.html)

XEN Hypervisor Intro

- An x86 virtual machine monitor
- Allows multiple commodity operating systems to share conventional hardware in a safe and resource managed fashion,
- Provides an idealized virtual machine abstraction to which operating systems such as Linux, BSD and Windows XP, can be *ported*
  with minimal effort.
- Design supports 100 virtual machine instances simultaneously on a modern server.

Arun Viswanathan
(Slides primarily from XEN website
http://www.cl.cam.ac.uk/research/srg/netos/xen/architecture.html)

Para-Virtualization in Xen

- Xen extensions to x86 arch
  - Like x86, but Xen invoked for privileged ops
  - Avoids binary rewriting
  - Minimize number of privilege transitions into Xen
  - Modifications relatively simple and self-contained
- Modify kernel to understand virtualised env.
  - Wall-clock time vs. virtual processor time
    - Desire both types of alarm timer
  - Expose real resource availability
    - Enables OS to optimise its own behaviour

Arun Viswanathan
(Slides primarily from XEN website
http://www.cl.cam.ac.uk/research/srg/netos/xen/architecture.html)

Xen System

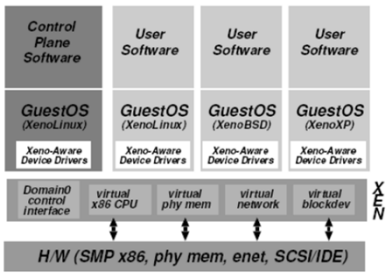
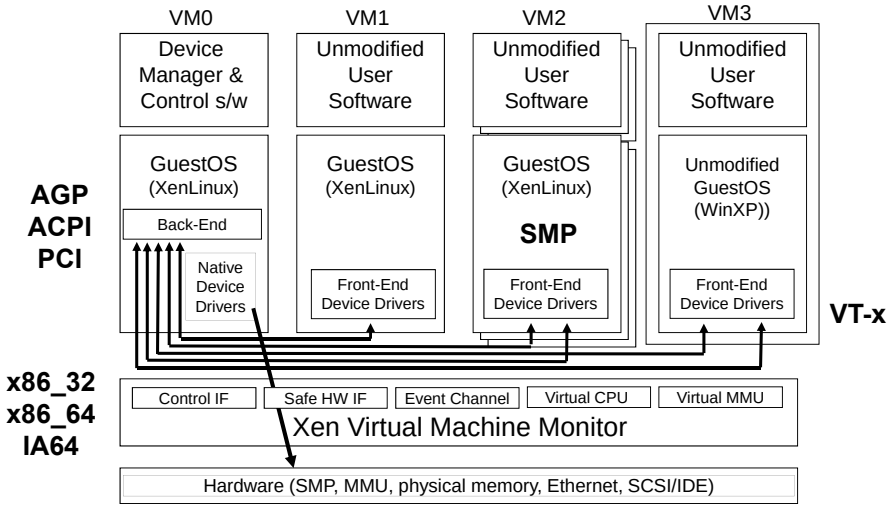


Figure 1: The structure of a machine running the Xen hypervisor, hosting a number of different guest operating systems, including *Domain0* running control software in a XenoLinux environment.

Arun Viswanathan
(Slides primarily from XEN website
http://www.cl.cam.ac.uk/research/srg/netos/xen/architecture.html)

Xen 3.0 Architecture



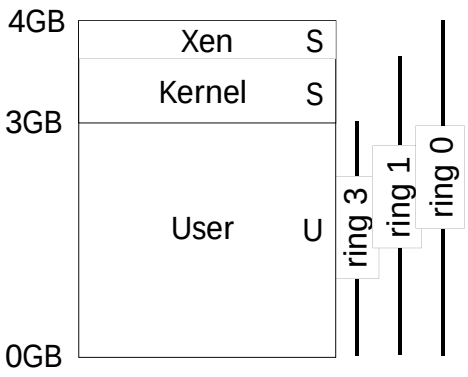
Arun Viswanathan
(Slides primarily from XEN website
http://www.cl.cam.ac.uk/research/srg/netos/xen/architecture.html)

Paravirtualized x86 interface

Memory Management	
Segmentation	Cannot install fully-privileged segment descriptors and cannot overlap with the top end of the linear address space.
Paging	Guest OS has direct read access to hardware page tables, but updates are batched and validated by the hypervisor. A domain may be allocated discontiguous machine pages.
CPU	
Protection	Guest OS must run at a lower privilege level than Xen.
Exceptions	Guest OS must register a descriptor table for exception handlers with Xen. Aside from page faults, the handlers remain the same.
System Calls	Guest OS may install a 'fast' handler for system calls, allowing direct calls from an application into its guest OS and avoiding indirecting through Xen on every call.
Interrupts	Hardware interrupts are replaced with a lightweight event system.
Time	Each guest OS has a timer interface and is aware of both 'real' and 'virtual' time.
Device I/O	
Network, Disk, etc.	Virtual devices are elegant and simple to access. Data is transferred using asynchronous I/O rings. An event mechanism replaces hardware interrupts for notifications.

Arun Viswanathan
(Slides primarily from XEN website
http://www.cl.cam.ac.uk/research/srg/netos/xen/architecture.html)

x86_32



- Xen reserves top of VA space
- Segmentation protects Xen from kernel
- System call speed unchanged
- Xen 3 now supports PAE for >4GB mem

Arun Viswanathan
(Slides primarily from XEN website
http://www.cl.cam.ac.uk/research/srg/netos/xen/architecture.html)

x86 CPU virtualization

- Xen runs in ring 0 (most privileged)
- Ring 1/2 for guest OS, 3 for user-space
  - GPF if guest attempts to use privileged instr
- Xen lives in top 64MB of linear addr space
  - Segmentation used to protect Xen as switching page tables too slow on standard x86
- Hypercalls jump to Xen in ring 0
- Guest OS may install 'fast trap' handler
  - Direct user-space to guest OS system calls
- MMU virtualisation: shadow vs. direct-mode

Arun Viswanathan
(Slides primarily from XEN website
http://www.cl.cam.ac.uk/research/srg/netos/xen/architecture.html)

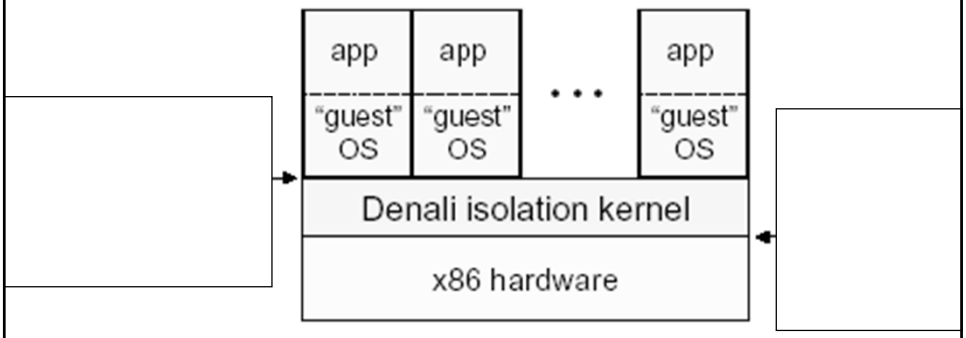
Para-Virtualizing the MMU

- Guest OSes allocate and manage own PTs
  - Hypercall to change PT base
- Xen must validate PT updates before use
  - Allows incremental updates, avoids revalidation
- Validation rules applied to each PTE:
  1. Guest may only map pages it owns*
  2. Pagetable pages may only be mapped RO
- Xen traps PTE updates and emulates, or 'unhooks' PTE page for bulk updates

Denali

- Whitaker, Shaw, Gribble at University of Washington
  - Observation is that conventional Operating Systems do not provide sufficient isolation between processes.
- So, Denali focuses on use of virtualization to provide strong isolation:
  - Content and information
  - Performance
- Resource sharing itself is not the focus.

Denali



Denali Philosophy

- Run each service in a separate VM
  - Much easier to provide isolation than to use traditional OS functions which are deigned more for sharing.
  - Approximation of separate hardware
  - Only low level abstractions
    - Fewer bugs or overlooked issues

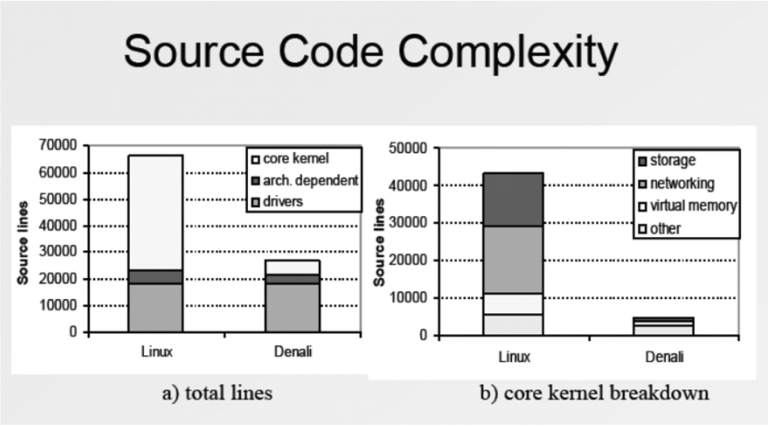
Isolation Kernel

- Goes beyond, but does less than Virtual Machine Monitor
  - Don't emulate physical hardware
  - Leave namespace isolation, hardware API running on hardware
- Isolation Kernel provides
  - Isolated resource management

How they do it

- Eliminate unnecessary parts of "hardware architecture" in the isolation kernel.
  - Segmentation, Rings, BIOS
- Change others
  - Interrupts, Memory Management
- Simplify some
  - Ethernet only supports send and receive

Comparison to Linux



From 2002 OSDI Talk, Andrew Whitaker

Observation on Denali

- **Small overhead for virtualization**
  - **Most costs are in network stack and physical devices**
  - **Ability to support huge number of virtual (guest) OS's.**
    - **This means it is OK to run individual applications in separate OS.**
- **At time of OSDI paper, Guest OS was only a library, with no simulated protection boundary.**
  - **Supports a POSIX subset.**

Figure by Carl Waldspurger - VMWARE

VMWare

- **Goals - provide ability to run multiple operating systems, and to run untrusted code safely.**
  - **Isolation primarily from guest OS to the outside.**
  - **This can provide isolation between guest OS's**
  - **Often configured to run inside a larger host OS, but also support a VMM layer as an option.**

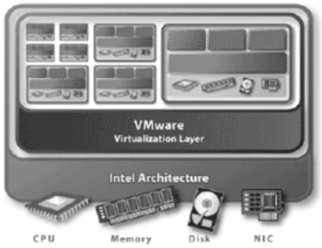
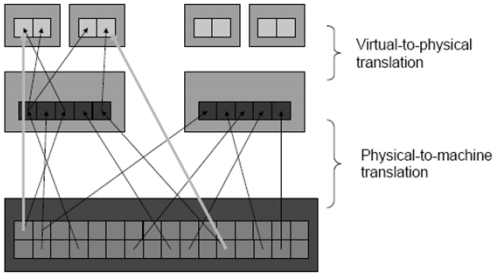


Figure by Carl Waldspurger - VMWARE

VMWare Memory Virtualization

- Intercepts MMU manipulating functions such as functions that change page table or TLB
- Manages shadow page tables with VM to Machine Mappings
- Kept in sync using physical to page mappings of VMM.



Garfinkel, Pfaff, Chow, Rosenblum, Boneh, 2003

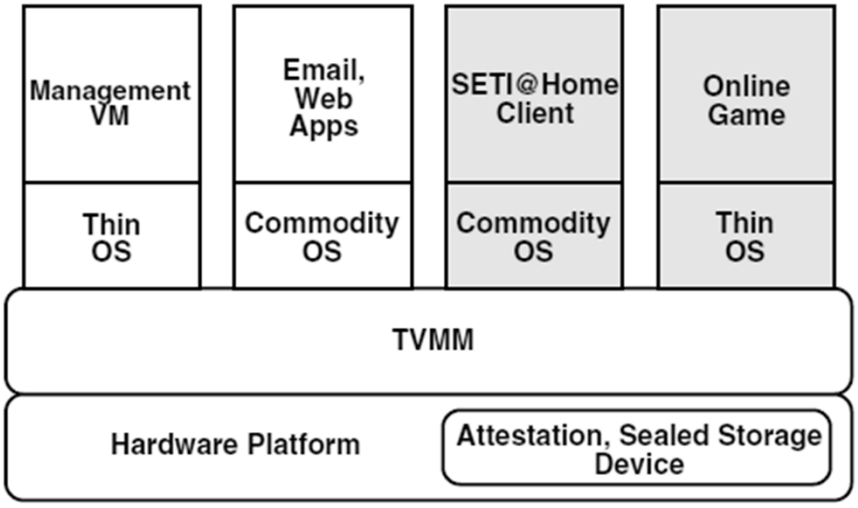
Terra: A Virtual Machine-Based Platform for Trusted Computing

- Similar to 2004 NGSCB architecture, supports multiple, isolated compartments
  - Terra supports an arbitrary number of user-defined VMs, more flexible than NGSCB
- Provides both "open-" and "closed-box" environments
- Implemented on VMware but didn't actually use TPM

Slide by Michael LeMay – University of Illinois

Garfinkel, Pfaff, Chow, Rosenblum, Boneh, 2003

Terra Architecture



Garfinkel, Pfaff, Chow, Rosenblum, Boneh, 2003

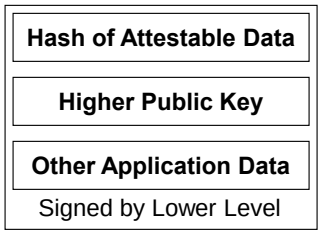
Terra Approach

- **TVMM: Trusted Virtual Machine Monitor**
- **Open-box VMs:**
  - **Just like current GP systems, no protection**
- **Closed-box VMs:**
  - **VM protected from modification, inspection**
  - **Can attest to remote peer that VM is protected**
  - **Behaves like true closed-box, but with cost and availability benefits of open-box**

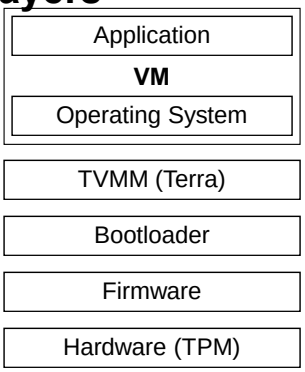
Slide by Michael LeMay – University of Illinois

TVMM Attestation

- **Each layer of software has a keypair**
- **Lower layers certify higher layers**
- **Enables attestation of entire stack**



Certificate



Layers

Slide by Michael LeMay – University of Illinois

Terra - Additional Benefits

- **Software stack can be tailored on per-application basis**
  - **Game can run on thin, high-performance OS**
  - **Email client can run on highly-secure, locked-down OS**
  - **Regular applications can use standard, full-featured and permissively-configured OS**
- **Applications are isolated and protected from each other**
  - **Reduces effectiveness of email viruses and spyware against system as a whole**
- **Low-assurance applications can automatically be transformed into medium-assurance applications, since they are protected from external influences**

Terra Example

- Online gaming: Quake
- Players often modify Quake to provide additional capabilities to their characters, or otherwise cheat
- Quake can be transformed into a closed-box VM and distributed to players
- Remote attestation shows that it is unmodified
- Very little performance degradation
- Covert channels remain, such as frame rate statistics

CSci555: Advanced Operating Systems
Lecture 8 – October 14, 2011
File Systems

Dr. Clifford Neuman
University of Southern California
Information Sciences Institute

COVERED LAST LECTURE

File Systems

- **Provide set of primitives that abstract users from details of storage access and management.**

COVERED LAST LECTURE

Distributed File Systems

- **Promote sharing across machine boundaries.**
- **Transparent access to files.**
- **Make diskless machines viable.**
- **Increase disk space availability by avoiding duplication.**
- **Balance load among multiple servers.**

COVERED LAST LECTURE

Sun Network File System 1

- De facto standard:
  - Mid 80's.
  - Widely adopted in academia and industry.
- Provides transparent access to remote files.
- Uses Sun RPC and XDR.
  - NFS protocol defined as set of procedures and corresponding arguments.
  - Synchronous RPC

COVERED LAST LECTURE

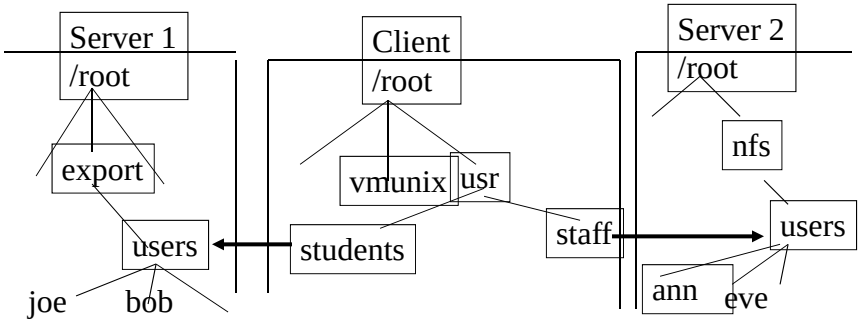
Sun NFS 2

- Stateless server:
  - Remote procedure calls are self-contained.
  - Servers don't need to keep state about previous requests.
    - Flush all modified data to disk before returning from RPC call.
  - Robustness.
    - No state to recover.
    - Clients retry.

COVERED LAST LECTURE

Location Transparency

- **Client's file name space includes remote files.**
  - **Shared remote files are *exported* by server.**
  - **They need to be *remote-mounted* by client.**



COVERED LAST LECTURE

Achieving Transparency 1

- **Mount service.**
  - **Mount remote file systems in the client's local file name space.**
  - **Mount service process runs on each node to provide RPC interface for mounting and unmounting file systems at client.**
  - **Runs at system boot time or user login time.**

COVERED LAST LECTURE

Achieving Transparency 2

- **Automounter.**
  - **Dynamically mounts file systems.**
  - **Runs as user-level process on clients (daemon).**
  - **Resolves references to unmounted pathnames by mounting them on demand.**
  - **Maintains a table of mount points and the corresponding server(s); sends probes to server(s).**
  - **Primitive form of replication**

COVERED LAST LECTURE

Transparency?

- **Early binding.**
  - **Mount system call attaches remote file system to local mount point.**
  - **Client deals with host name once.**
  - **But, mount needs to happen before remote files become accessible.**

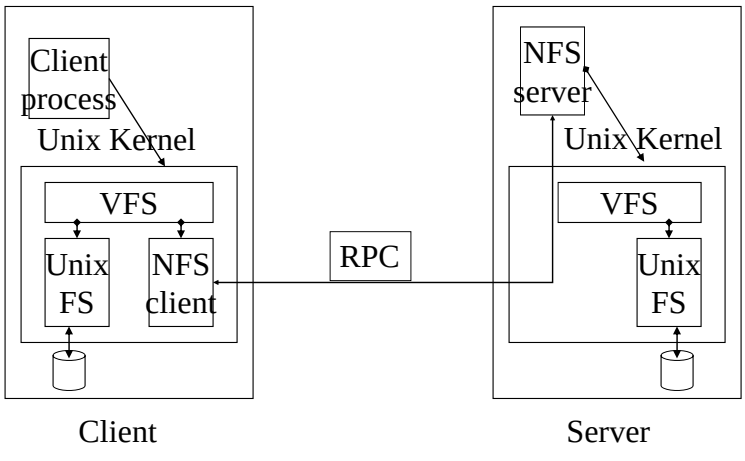
COVERED LAST LECTURE

Other Functions

- **NFS file and directory operations:**
  - **read, write, create, delete, getattr, etc.**
- **Access control:**
  - **File and directory access permissions.**
- **Path name translation:**
  - **Lookup for each path component.**
  - **Caching.**

COVERED LAST LECTURE

Implementation



COVERED LAST LECTURE

Virtual File System

- **VFS added to UNIX kernel.**
  - **Location-transparent file access.**
  - **Distinguishes between local and remote access.**
- **@ client:**
  - **Processes file system system calls to determine whether access is local (passes it to UNIX FS) or remote (passes it to NFS client).**
- **@ server:**
  - **NFS server receives request and passes it to local FS through VFS.**

COVERED LAST LECTURE

VFS

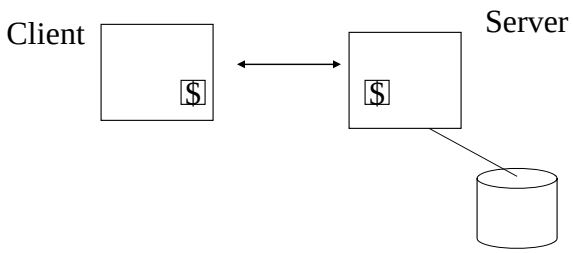
- **If local, translates file handle to internal file id's (in UNIX i-nodes).**
- **V-node:**
  - **If file local, reference to file's i-node.**
  - **If file remote, reference to file handle.**
- **File handle: uniquely distinguishes file.**

File system id	I-node #	I-node generation #

COVERED LAST LECTURE

NFS Caching

- File contents and attributes.
- Client versus server caching.



COVERED LAST LECTURE

Server Caching

- Read:
  - Same as UNIX FS.
  - Caching of file pages and attributes.
  - Cache replacement uses LRU.
- Write:
  - Write through (as opposed to delayed writes of conventional UNIX FS). Why?
  - [Delayed writes: modified pages written to disk when buffer space needed, sync operation (every 30 sec), file close].

COVERED LAST LECTURE

Client Caching 1

- Timestamp-based cache invalidation.
- Read:
  - (T-T*c* < *TTL*) V (T*m*c=T*m*s)
  - Cached entries have TS with last-modified time.
  - Blocks assumed to be valid for TTL.
    - TTL specified at mount time.
    - Typically 3 sec for files.

COVERED LAST LECTURE

Client Caching 1

- Timestamp-based cache validation.
- Read:
  - Validity condition:

    (T-T*c* < *TTL*) V (T*m*c=T*m*s)

- Write:
  - Modified pages marked and flushed to server at file close or sync.

COVERED LAST LECTURE

Client Caching 2

- **Consistency?**
  - **Not always guaranteed!**
  - **e.g., client modifies file; delay for modification to reach servers + 3-sec (TTL) window for cache validation from clients sharing file.**

COVERED LAST LECTURE

Cache Validation

- **Validation check performed when:**
  - **First reference to file after TTL expires.**
  - **File open or new block fetched from server.**
- **Done for all files, even if not being shared.**
  - **Why?**
- **Expensive!**
  - **Potentially, every 3 sec get file attributes.**
  - **If needed invalidate all blocks.**
  - **Fetch fresh copy when file is next accessed.**

COVERED LAST LECTURE

The Sprite File System

- Main memory caching on both client and server.
- Write-sharing consistency guarantees.
- Variable size caches.
  - VM and FS negotiate amount of memory needed.
  - According to caching needs, cache size changes.

COVERED LAST LECTURE

Sprite

- Sprite supports concurrent writes by disabling caching of write-shared files.
  - If file shared, server notifies client that has file open for writing to write modified blocks back to server.
  - Server notifies all client that have file open for read that file is no longer cacheable; clients discard all cached blocks, so access goes through server.

COVERED LAST LECTURE

Sprite

- Sprite servers are stateful.
  - Need to keep state about current accesses.
  - Centralized points for cache consistency.
    - Bottleneck?
    - Single point of failure?
- Tradeoff: consistency versus performance/robustness.

COVERED LAST LECTURE

Andrew

- Distributed computing environment developed at CMU.
- Campus wide computing system.
  - Between 5 and 10K workstations.
  - 1991: ~ 800 workstations, 40 servers.

COVERED LAST LECTURE

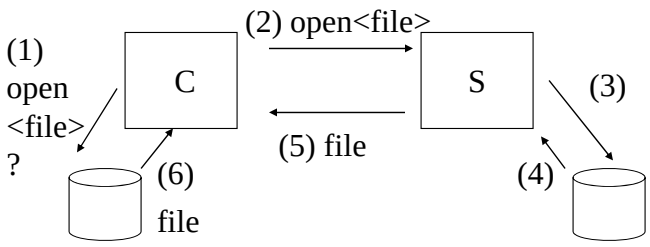
Andrew FS

- **Goals:**
  - **Information sharing.**
  - **Scalability.**
    - **Key strategy: caching of** whole **files at client.**
    - **Whole file serving**
      - **Entire file transferred to client.**
    - **Whole file caching**
      - **Local copy of file cached on client's local disk.**
      - **Survive client's reboots and server unavailability.**

COVERED LAST LECTURE

Whole File Caching

- **Local cache contains several most recently used files.**



- Subsequent operations on file applied to local copy.
- On close, if file modified, sent back to server.

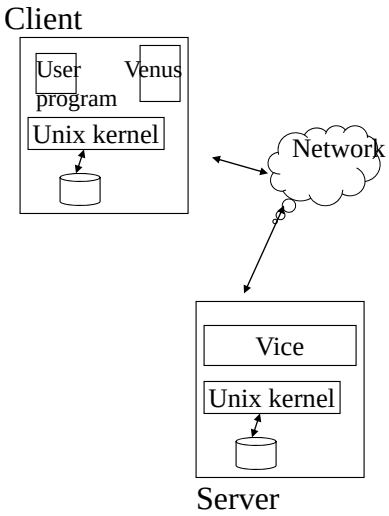
COVERED LAST LECTURE

Implementation 1

- **Network of workstations running Unix BSD 4.3 and Mach.**
- **Implemented as 2 user-level processes:**
  - **Vice: runs at each Andrew server.**
  - **Venus: runs at each Andrew client.**

COVERED LAST LECTURE

Implementation 2



- **Modified BSD 4.3 Unix kernel.**
  - **At client, intercept file system calls (open, close, etc.) and pass them to Venus when referring to shared files.**
- **File partition on local disk used as cache.**
- **Venus manages cache.**
  - **LRU replacement policy.**
  - **Cache large enough to hold 100's of average-sized files.**

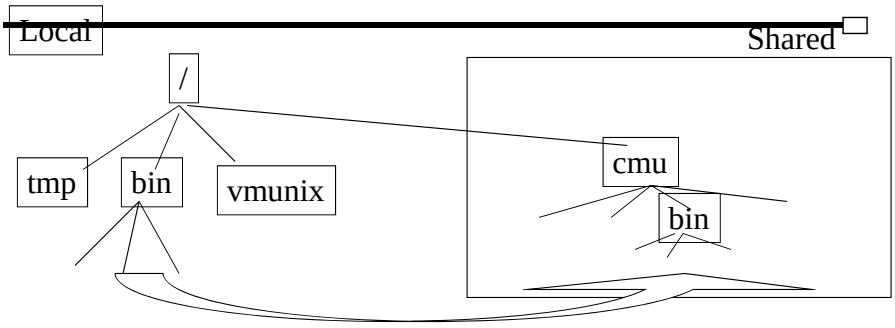
COVERED LAST LECTURE

File Sharing

- **Files are *shared* or *local*.**
  - **Shared files**
    - **Utilities (/bin, /lib): infrequently updated or files accessed by single user (user's home directory).**
    - **Stored on servers and cached on clients.**
    - **Local copies remain valid for long time.**
  - **Local files**
    - **Temporary files (/tmp) and files used for start-up.**
    - **Stored on local machine's disk.**

COVERED LAST LECTURE

File Name Space



- **Regular UNIX directory hierarchy.**
- **"cmu" subtree contains shared files.**
- **Local files stored on local machine.**
- **Shared files: symbolic links to shared files.**

COVERED LAST LECTURE

AFS Caching

- AFS-1 uses timestamp-based cache invalidation.
- AFS-2 and 3 use *callbacks*.
  - When serving file, Vice server promises to notify Venus client when file is modified.
  - Stateless servers?
  - Callback stored with cached file.
    - Valid.
    - Canceled: when client is notified by server that file has been modified.

COVERED LAST LECTURE

AFS Caching

- Callbacks implemented using RPC.
- When accessing file, Venus checks if file exists and if callback valid; if canceled, fetches fresh copy from server.
- Failure recovery:
  - When restarting after failure, Venus checks each cached file by sending validation request to server.
  - Also periodic checks in case of communication failures.

COVERED LAST LECTURE

AFS Caching

- At file close time, Venus on client modifying file sends update to Vice server.
- Server updates its own copy and sends callback cancellation to all clients caching file.
- Consistency?
- Concurrent updates?

AFS Replication

- Read-only replication.
  - Only read-only files allowed to be replicated at several servers.

Coda

- Evolved from AFS.
- Goal: constant data availability.
  - Improved replication.
    - Replication of read-write volumes.
  - Disconnected operation: mobility.
    - Extension of AFS's whole file caching mechanism.
- Access to shared file repository (servers) versus relying on local resources when server not available.

Replication in Coda

- Replication unit: file volume (set of files).
- Set of replicas of file volume: volume storage group (VSG).
- Subset of replicas available to client: AVSG.
  - Different clients have different AVSGs.
  - AVSG membership changes as server availability changes.
  - On write: when file is closed, copies of modified file broadcast to AVSG.

Optimistic Replication

- **Goal is availability!**
- **Replicated files are allowed to be modified even in the presence of partitions or during disconnected operation.**

Disconnected Operation

- **AVSG = { }.**
- **Network/server failures or host on the move.**
- **Rely on local cache to serve all needed files.**
- **Loading the cache:**
  - **User intervention: list of files to be cached.**
  - **Learning usage patterns over time.**
- **Upon reconnection, cached copies validated against server's files.**

Normal and Disconnected Operation

- **During normal operation:**
  - **Coda behaves like AFS.**
  - **Cache miss transparent to user; only performance penalty.**
  - **Load balancing across replicas.**
  - **Cost: replica consistency + cache consistency.**
- **Disconnected operation:**
  - **No replicas are accessible; cache miss prevents further progress; need to load cache before disconnection.**

Replication and Caching

- **Coda integrates server replication and client caching.**
  - **On cache hit and valid data: Venus does not need to contact server.**
  - **On cache miss: Venus gets data from an AVSG server, i.e., the preferred server (PS).**
    - **PS chosen at random or based on proximity, load.**
  - **Venus also contacts other AVSG servers and collect their versions; if conflict, abort operation; if replicas stale, update them off-line.**

Next File Systems Topics

- **Leases**
  - **Continuum of cache consistency mechanisms.**
- **Log Structured File System and RAID.**
  - **FS performance from the storage management point of view.**

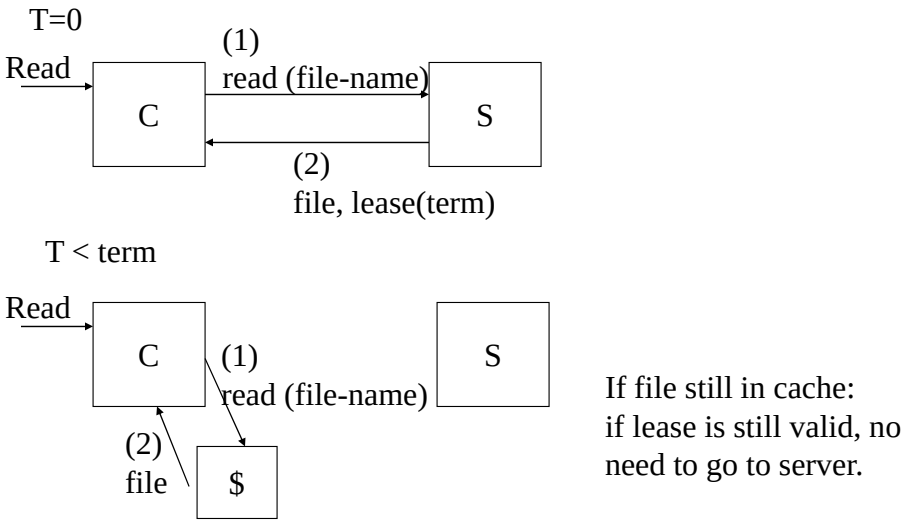
Caching

- **Improves performance in terms of response time, availability during disconnected operation, and fault tolerance.**
- **Price: consistency**
  - **Methods:**
    - **Timestamp-based invalidation**
      - **Check on use**
    - **Callbacks**

Leases

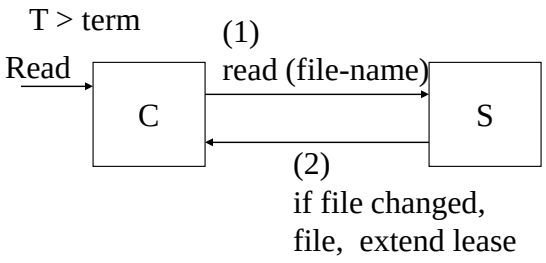
- **Time-based cache consistency protocol.**
- **Contract between client and server.**
  - **Lease grants holder control over writes to corresponding data item** during lease term**.**
  - **Server must obtain approval from holder of lease before modifying data.**
  - **When holder grants approval for write, it invalidates its local copy.**

Protocol Description 1

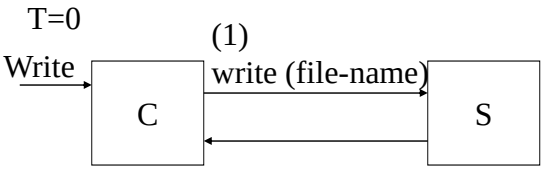


If file still in cache:
if lease is still valid, no need to go to server.

Protocol Description 2



On writes:



Server defers write request till: approval from lease holder(s) or lease expires.

Considerations

- **Unreachable lease holder(s)?**
- **Leases and callbacks.**
  - **Consistency?**
  - **Lease term**

Lease Term

- **Short leases:**
  - **Minimize delays due to failures.**
  - **Minimize impact of false sharing.**
  - **Reduce storage requirements at server (expired leases reclaimed).**
- **Long leases:**
  - **More efficient for repeated access with little write sharing.**

Lease Management 1

- **Client requests lease extension before lease expires in anticipation of file being accessed.**
  - **Performance improvement?**

Lease Management 2

- Multiple files per lease.
  - Performance improvement?
  - Example: one lease per directory.
  - System files: widely shared but infrequently written.
  - False sharing?
  - Multicast lease extensions periodically.

Lease Management 3

- Lease term based on file access characteristics.
  - Heavily write-shared file: lease term = 0.
  - Longer lease terms for distant clients.

Clock Synchronization Issues

- Servers and clients should be roughly synchronized.
  - If server clock advances too fast or client's clock too slow: inconsistencies.

Next...

- Papers on file system performance from storage management perspective.
- Issues:
  - Disk access time >>> memory access time.
  - Discrepancy between disk access time improvements and other components (e.g., CPU).
- Minimize impact of disk access time by:
  - Reducing # of disk accesses or
  - Reducing access time by performing parallel access.

Log-Structured File System

- Built as extension to Sprite FS (Sprite LFS).
- New disk storage technique that tries to use disks more efficiently.
- Assumes main memory cache for files.
- Larger memory makes cache more efficient in satisfying reads.
  - Most of the working set is cached.
- Thus, most disk access cost due to writes!

Main Idea

- Batch multiple writes in file cache.
  - Transform many small writes into 1 large one.
  - Close to disk's full bandwidth utilization.
- Write to disk in one write in a contiguous region of disk called *log*.
  - Eliminates seeks.
  - Improves crash recovery.
    - Sequential structure of log.
    - Only most recent portion of log needs to be examined.

LSFS Structure

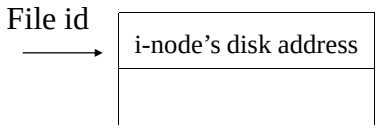
- **Two key functions:**
  - **How to retrieve information from log.**
  - **How to manage free disk space.**

File Location and Retrieval 1

- **Allows random access to information in the log.**
  - **Goal is to match or increase read performance.**
  - **Keeps indexing structures with log.**
- **Each file has i-node containing:**
  - **File attributes (type, owner, permissions).**
  - **Disk address of first 10 blocks.**
  - **Files > 10 blocks, i-node contains pointer to more data.**

File Location and Retrieval 2

- **In UNIX FS:**
  - **Fixed mapping between disk address and file i-node: disk address as function of file id.**
- **In LFS:**
  - **I-nodes written to log.**
  - **I-node map keeps current location of each i-node.**



  - **I-node maps usually fit in main memory cache.**

Free Space Management

- **Goal: maintain large, contiguous free chunks of disk space for writing data.**
- **Problem: fragmentation.**
- **Approaches:**
  - **Thread around used blocks.**
    - **Skip over active blocks and thread log through free extents.**
  - **Copying.**
    - **Active data copied in compacted form at head of log.**
    - **Generates contiguous free space.**
    - **But, expensive!**

Free Space Management in LFS

- Divide disk into large, fixed-size segments.
  - Segment size is large enough so that transfer time (for read/write) >>> seek time.
- Hybrid approach.
  - Combination of threading and copying.
  - Copying: segment cleaning.
  - Threading between segments.

Segment Cleaning

- Process of copying "live" data out of segment before rewriting segment.
- Number of segments read into memory; identify live data; write live data back to smaller number of clean, contiguous segments.
- Segments read are marked as "clean".
- Some bookkeeping needed: update files' i-nodes to point to new block locations, etc.

Crash Recovery

- When crash occurs, last few disk operations may have left disk in inconsistent state.
  - E.g., new file written but directory entry not updated.
- At reboot time, OS must correct possible inconsistencies.
- Traditional UNIX FS: need to scan whole disk.

Crash Recovery in Sprite LFS 1

- Locations of last disk operations are at the end of the log.
  - Easy to perform crash recovery.
- 2 recovery strategies:
  - Checkpoints and roll-forward.
- Checkpoints:
  - Positions in the log where everything is consistent.

Crash Recovery in Sprite LFS 2

- **After crash, scan disk backward from end of log to checkpoint, then scan forward to recover as much information as possible: *roll forward*.**

More on LFS

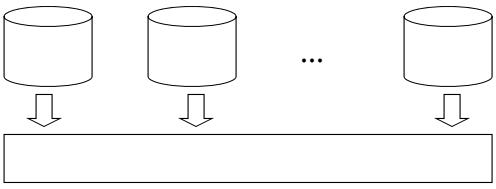
- **Paper talks about their experience implementing and using LFS.**
- **Performance evaluation using benchmarks.**
- **Cleaning overhead.**

Redundant Arrays of Inexpensive Disks (RAID)

- **Improve disk access time by using arrays of disks.**
- **Motivation:**
  - **Disks are getting inexpensive.**
  - **Lower cost disks:**
    - **Less capacity.**
    - **But cheaper, smaller, and lower power.**
- **Paper proposal: build I/O systems as arrays of inexpensive disks.**
  - **E.g., 75 inexpensive disks have 12 * I/O bandwidth of expensive disks with same capacity.**

RAID Organization 1

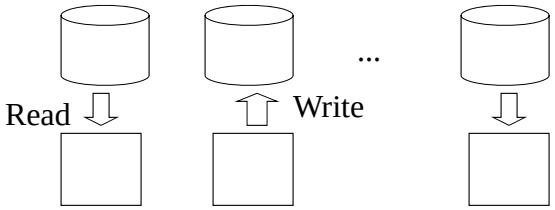
- **Interleaving disks.**
  - **Supercomputing applications.**
  - **Transfer of large blocks of data at high rates.**



Grouped read: single read spread over multiple disks

RAID Organization 2

- Independent disks.
  - Transaction processing applications.
  - Database partitioned across disks.
  - Concurrent access to independent items.



Problem: Reliability

- Disk unreliability causes frequent backups.
- What happens with 100*number of disks?
  - MTTF becomes prohibitive
  - Fault tolerance otherwise disk arrays are too unreliable to be useful.
- RAID: use of extra disks containing redundant information.
  - Similar to redundant transmission of data.

RAID Levels

- Different levels provide different reliability, cost, and performance.
- MTTF as function of total number of disks, number of data disks in a group (G), number of check disks per group (C), and number of groups.
- C determined by RAID level.

First RAID Level

- Mirrors.
  - Most expensive approach.
  - All disks duplicated (G=1 and C=1).
  - Every write to data disk results in write to check disk.
  - Double cost and half capacity.

Second RAID Level

- Hamming code.
- Interleave data across disks in a group.
- Add enough check disks to detect/correct error.
- Single parity disk detects single error.
- Makes sense for large data transfers.
- Small transfers mean all disks must be accessed (to check if data is correct).

Third RAID Level

- Lower cost by reducing C to 1.
  - Single parity disk.
- Rationale:
  - Most check disks in RAID 2 used to detect which disks failed.
  - Disk controllers do that.
  - Data on failed disk can be reconstructed by computing the parity on remaining disks and comparing it with parity for full group.

Fourth RAID Level

- Try to improve performance of small transfers using parallelism.
- Transfer units stored in single sector.
  - Reads are independent, i.e., errors can be detected without having to use other disks (rely on controller).
  - Also, maximum disk rate.
  - Writes still need multiple disk access.

Fifth RAID Level

- Tries to achieve parallelism for writes as well.
- Distributes data as well as check information across all disks.

The Google File System

- Focused on special cases:
  - Permanent failure normal
  - Files are huge – aggregated
  - Few random writes – mostly append
  - Designed together with the application
    - And implemented as library

The Google File System

- Some requirements
  - Well defined semantics for concurrent append.
  - High bandwidth (more important than latency)
  - Highly scalable
    - Master handles meta-data (only)

The Google File System

- Chunks
  - Replicated
    - Provides location updates to master
- Consistency
  - Atomic namespace
  - Leases maintain mutation order
  - Atomic appends
  - Concurrent writes can be inconsistent

Outline for Mid-Term Review

- Overview of Distributed Systems
  - End-to-end argument
- Communication models
  - Message passing
  - RPC
  - Distributed Share memory plus others
- Concurrency
  - Transactions – ACID
  - Synchronization and deadlock

Outline for Mid-Term Review

- **Naming and Binding**
  - **Types of names**
  - **Closure**
  - **Performance of Naming - DNS**
- **Security**
  - **Trusted Computing Base**
  - **Policy – ACL vs Capabilities**
  - **Authentication**
  - **Trusted Computing**
- **Virtualization**