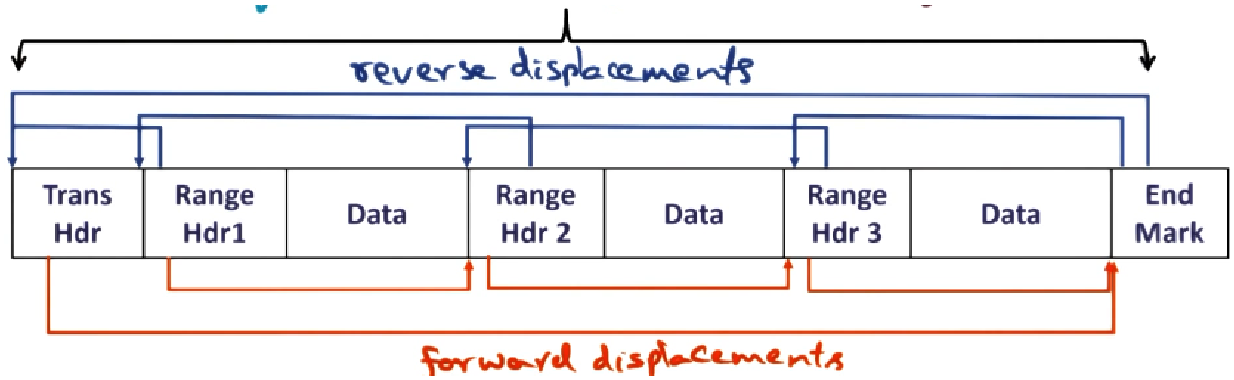
Failures and Recovery

Lightweight Recoverable Virtual Memory

1. Lightweight Recoverable Virtual Memory Introduction
    - How do we build systems that survive crashes?
        - Hardware, software, power failures
    - LRVM: Persistent memory layer in support of system services
2. Persistence
    - Why?
        - Need of OS subsystems (filesystem inodes)
        - Log memory to disk, but need to keep it consistent with changes in memory
    - How?
        - Make virtual memory persistent
        - All data structures contained in virtual memory become persistent
        - Subsystems don't have to worry about flushing to disk if it's handled by the OS
    - Who will use it?
        - Subsystem designers if it is performant
    - How to make it efficient?
        - Writing every change in memory to disk incurs signifcant overhead due to the latency of writing to disk (seek, rotational)
        - Use persistent logs to record changes to VM (similar to xFS)
        - Only write logs of the changes, buffer to save them all at once to solve the small write problem
3. Server Design
    - Distiguish between persistent metadata and normal data structures
    - Create external data segments to back persistent data structures
        - Applications manage their persistence needs
    - Designers can make regions of virtual memory to segments on disk
        - Designer's choice to use single or multiple data segments
    - Mapping from virtual address to external data segments is 1-to-1
        - No overlap in occupancy of virtual address space
        - Simplifies design
    - Application can map and unmap whenever needed
4. Recoverable Virtual Memory Primitiives
    - Initialization
        - initialize(options): Log segment to be used for persistent data
        - map(region, options): Virtual address to external data segments
        - unmap(region): Deletes a mapping
    - Body of server code (like a critical section)
        - begin_xact(tid, restore_mode): Start of changes to log
        - set_range(tid, addr, size): Only using a portion of address range
        - end_xact(tid, commit_mode): Log changes to log segment
        - abort_xact(tid): Discard changes to persistent data structures
    - GC to reduce log space (done by LRVM automatically)
        - flush(): Provided for application flexibility
        - truncate(): Provided for application flexibility
    - Miscellaneous
        - query_options(region)
        - set_options(options)
        - create_log(options, len, mode)
    - When a developer is making changes within a transaction, RVM commits the changes to a redo log in the log segment
        - These are only committed to disk if the transaction isn't aborted
        - Committing to disk happens at opportune times

    - Truncation: Throwing away the redo log after it's committed
    - Developer can explicitly manage its redo log as a way to optimize the use of disk space
  - Small set of primitives that are easy to use and performant
  - Transaction: Intended for recovery management, doesn't need all of the properties associated with typical database transactions (ACID)
    - Atomicity
    - Consistency
    - Isolation
    - Durability
  - RVM doesn't allow for nested transactions or support concurrency control
    - Developer must implement at a higher level if needed
5. How the Server Uses the Primitives
  - Initialize address space from external segments
  - begin_xact(tid, mode);
    - set_range(tid, base_addr, #bytes);
    - write metadata m1; // contained in range
    - write metadata m2; // contained in range
  - end_xact(tid, mode); // can also be abort
  - When developer calls set_range, LRVM creates an undo record
    - Copy of virtual address space for the specified number of bytes
  - Mode specifier allows user to specify to RVM whether transaction will ever abort
    - If developer is certain transaction won't abort, can specify a no_restore mode so RVM knows not to create an undo record
  - When the application is writing metadata, no action is needed by LRVM
    - Changes happen directly to the virtual address space of that particular process where the in-memory copy of the persistent data structures are living
6. Transaction Optimizations
  - No-restore mode in begin_xact
    - No need to create in-memory undo record
  - No-flush mode in end_xact
    - No need to do synchronous flush redo log to disk
    - Lazy persistence (will be persistent, but not at the point of end_xact)
    - There's a period of vulnerability between end_xact and flush, but this provides improved speed by removing synchronous I/O
    - "Transactional systems perform well when you don't use transactions"
  - Use transactions as insurance
7. Implementation
  - Lightweight in terms of transactional properties
  - No undo/redo value logging
    - Undo log: Creating an undo record of changes only in memory, not on disk (only for duration of transaction)
    - Redo log: All changes to different regions between begin_xact and end_xact (also in memory, then flushed to disk)
  - On commit: Replace old value record in virtual memory with new value records (automatic based on how RVM works)
    - Must undo changes if a transaction aborts
  - Creating the undo log is optional if the developer guarantees that the transaction won't abort
  - Writing the redo log to disk can be done lazily (don't block on call to end_xact)
    - Gives a window of vulnerability where data can be lost
  - Can traverse redo log in both directions to provide flexibility



RVM Implementation

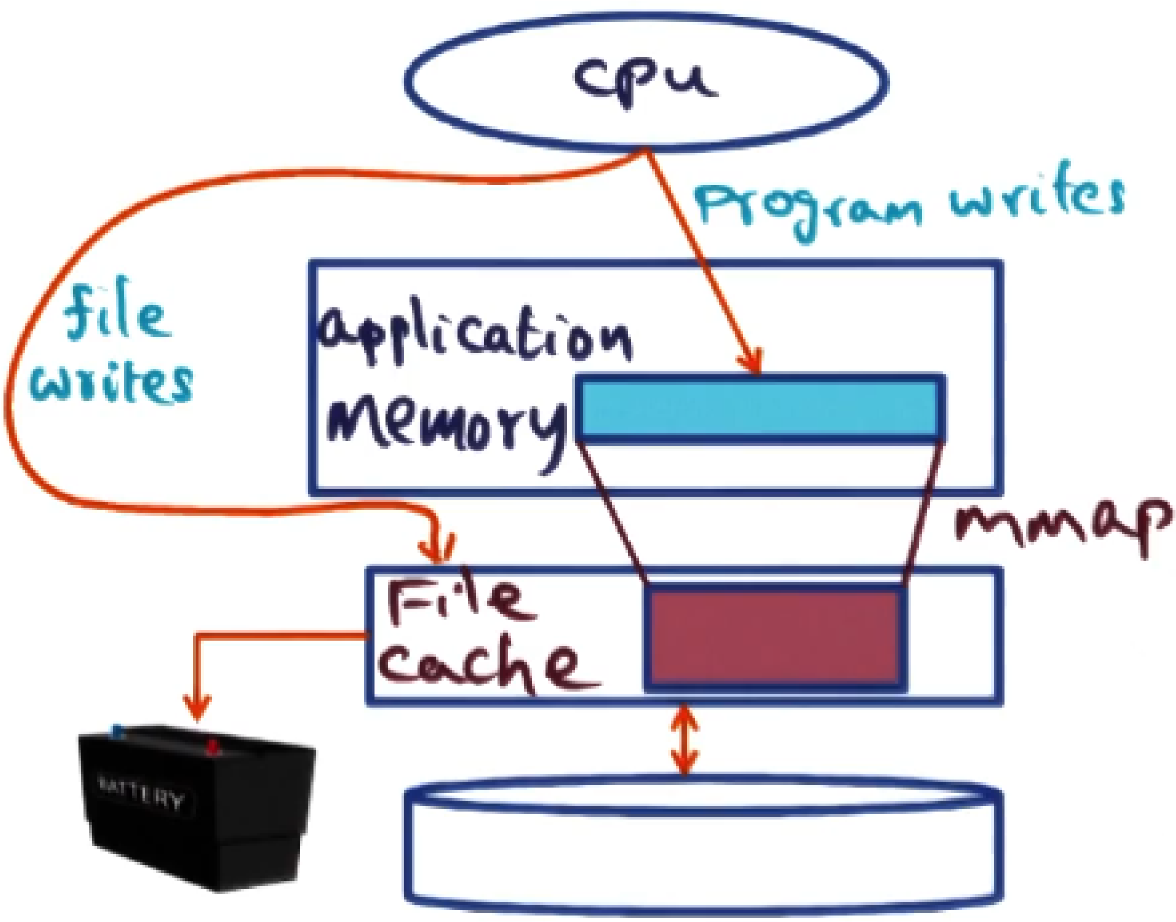
8. Crash Recovery
   - Redo log has transaction header
     - Between transaction header and end mark contains all of the changes that have been made by a critical section
   - Resume from crash
     - Read redo log from disk
     - Apply to external data segments in memory
   - All of the needed information is contained in the redo log
9. Log Truncation
   - If time between crashes is long (as we hope), log segments build up
     - Redo log will also build up
   - When a crash happens, apply to redo log to disk to clear it
     - Clogging disk space, unnecessary overhead
   - Truncating the log: Read logs from disk and apply to external data segments so the logs can be discarded
     - Simply apply crash recovery algorithm (same logic)
     - Read redo logs into memory and apply to data segment
   - Log truncation: Perform in parallel with forward processing
     - LRVM splits log record into epochs
     - Truncation epoch: Crash recovery is using this
     - Current epoch: Server is using this
   - Biggest challenge in LRVM is log truncation code
     - So much coordination involved
10. Lightweight Recoverable Virtual Memory Conclusion
    - LRVM is classic systems research example
      - Understand pain point and create a solution
    - Pain point: Managing persistence of critical data structures
    - Solution: Lightweight transactions without typical ACID properties

RioVista

1. RioVista Introduction
   - Synchronous I/O makes transactions heavyweight in LRVM even though the semantics of transactions have been simplified considerably
   - RioVista's goal is performance-conscious design of persistent memory
2. System Crash
   - Two problems concerning failure
     - Power failure: Can we throw some hardware at the problem and make it disappear? (UPS)
     - Software crash: Reserve a portion of main memory that survives crashes

- RioVista is only concerned with software crashes
  - Makes transactions cheaper

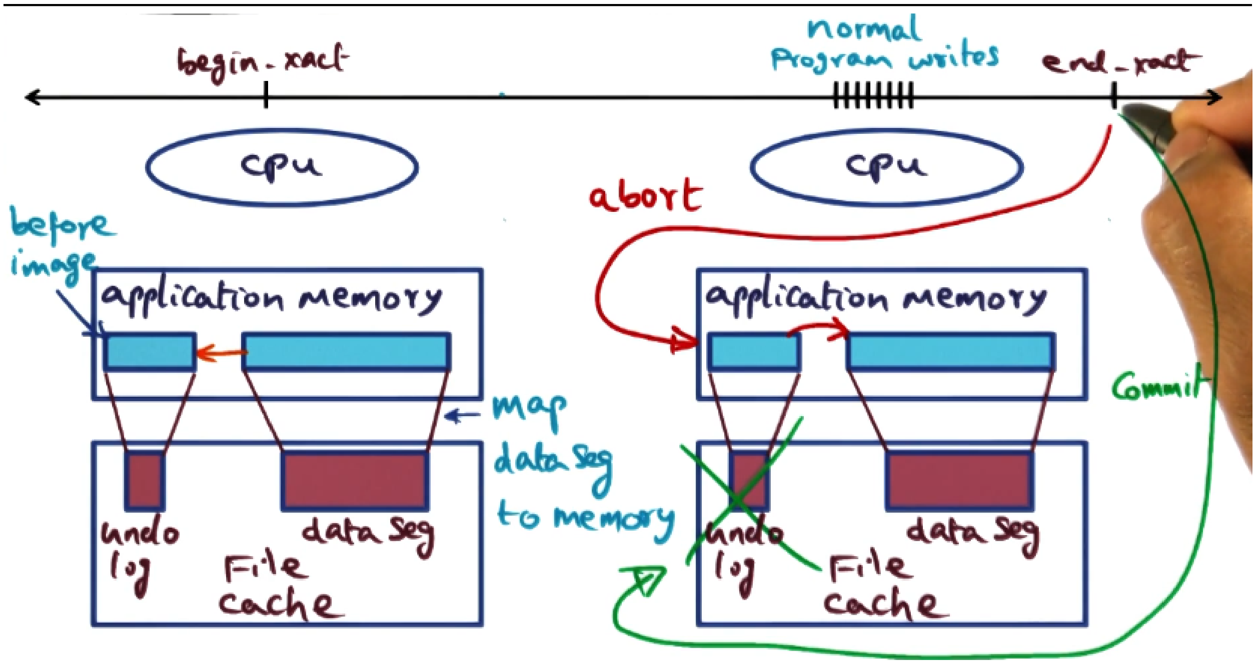
3. LRVM Revisited
   - begin_xact: Memory copy of portion of memory by LRVM
   - body: Normal program writes
   - end_xact: Disk copy by LRVM, get rid of undo logs
   - log truncation: Redo logs -> data, get rid of redo logs by LRVM
   - Upshot: 3 copies by LRVM to persist data
     - Biggest vulnerability is power failure if using no-flush option
4. Rio File Cache
   - Rio: Using battery-backed DRAM to implement a persistent file cache
     - File system uses file cache holds data brought from disk
     - Persistent: Use UPS to persist file cache data
   - OS buffers writes to DRAM and writes to disk at opportune times
     - User has to use fsync to force writes to disk
   - mmap: Normal application memory becomes persistent
     - Backed by battery
   - Using battery-backed DRAM means no synchronous writes are required



Rio File Cache

5. Vista RVM on Top of Rio

- Vista: RVM library on top of Rio
- Semantics are identical to LRVM semantics, but the implementation takes advantage of the fact that it's sitting on top of Rio
- When mapping virtual memory to a data segment, it's mapped to the file cache which is already guaranteed to be persistent
- Specify address range to be persistent at the point of begin_xact
  - Create an in-memory copy of the memory to be modified, which serves as the undo log
  - Undo log is mapped to file cache (persistent by definition)
  - Changes during the body of the critical section are already persistent
- At end_xact, changes are committed
  - In Vista, changes are already committed because they're in persistent memory
  - Faster because there's no need to write to disk synchronously
- If the transaction aborts, the undo record created at the beginning of the transaction is simply copied back to memory
- Rio+Vista is fast because there's no disk I/O
  - Everything is memory resident and can be written back to disk asynchronously



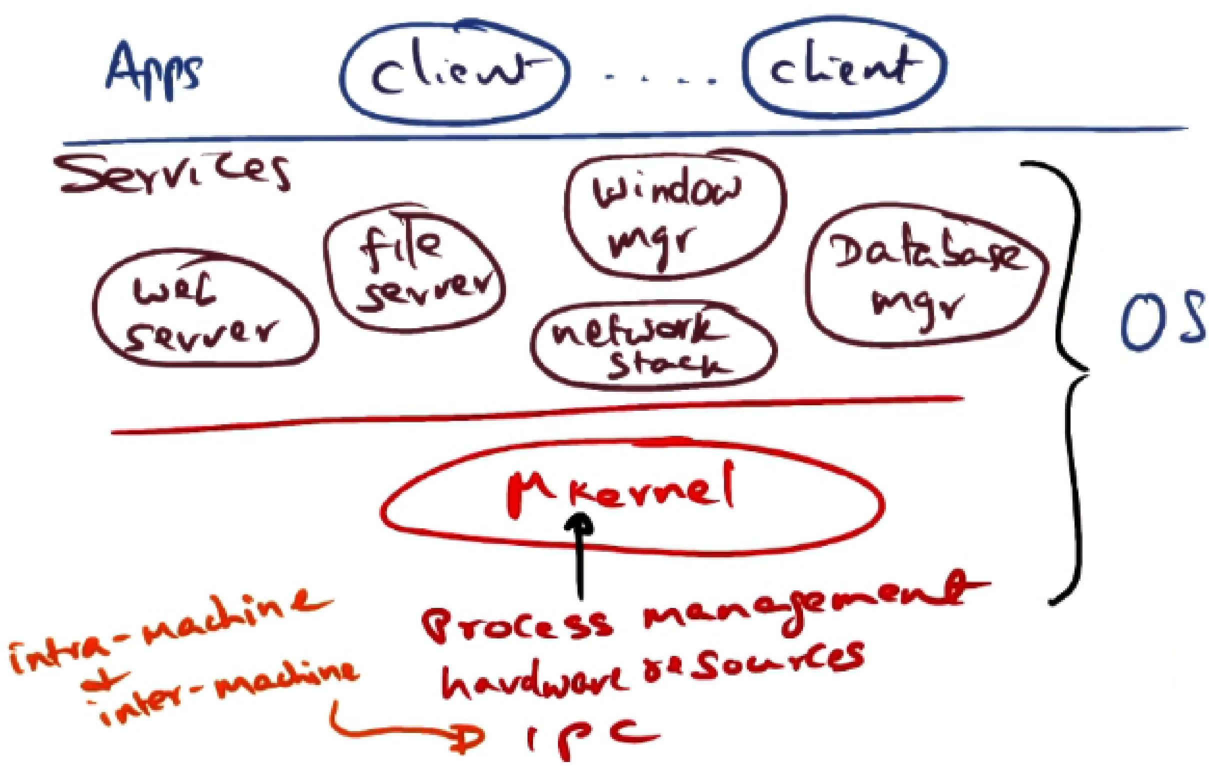
Vista Recoverable Virtual Memory

6. Crash Recovery
   - Treat like an abort
     - Recover old image from undo log (survives crashes since it's in Rio file cache)
   - Crash during crash recovery?
     - Idempotency of recovery, so there's no issue
7. Vista Simplicity
   - 700 lines of code in Vista compared to 10000 in LRVM
     - Performs three orders of magnitude better than LRVM (no disk I/O)
   - Simpler
     - No redo logs or truncation code
     - Checkpointing and recovery code is simplified
     - No group commit optimizations
   - Upshot: Simple like LRVM but performance efficient
8. RioVista Conclusion

- Shows that by changing the starting assumptions of the problem, you can arrive at a completely different solution

Quicksilver

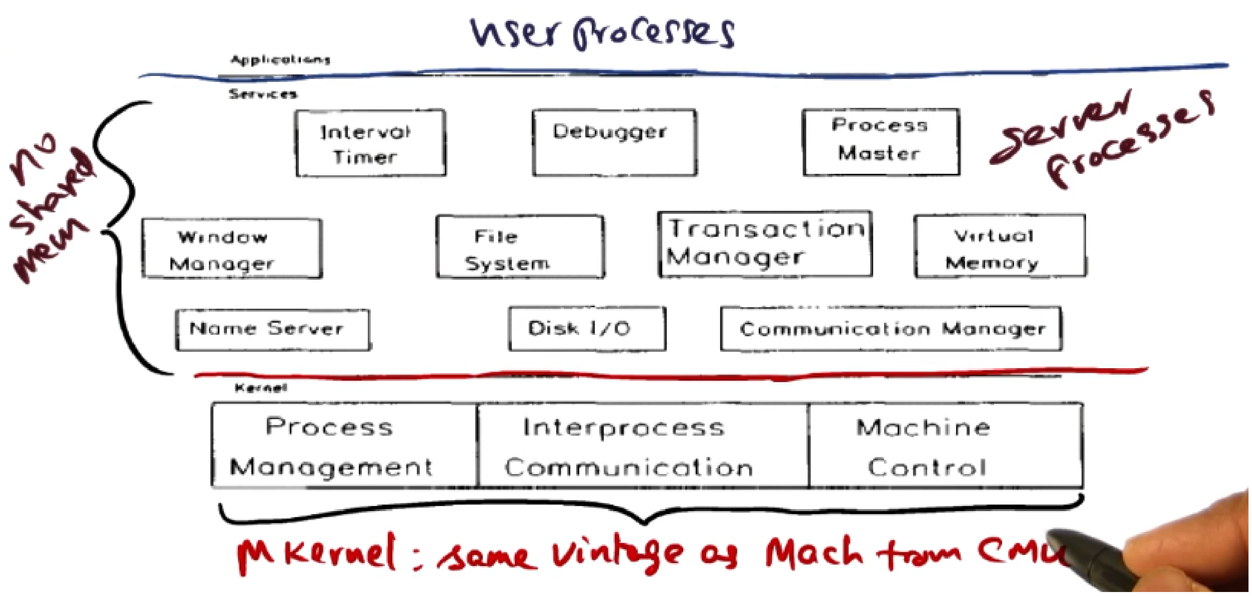
1. Quicksilver Introduction
    - Making recovery a first class citizen in an OS design, not an afterthought
    - Performance and reliability are generally considered to be opposing concerns
    - Quicksilver's approach is that if recovery is taken seriously at the initial design, you can have both
2. Cleaning up State Orphan Processes
    - "Not responding" windows come from programs not being hygenic
    - When an application closes, it needs to clean up any resources it was using
    - LRVM and RioVista only target state that needs to be persisted across system crashes
    - NFS is stateless; server doesn't maintain any state pertaining to the clients
        - The server cannot know about what state the client is reliant on when a transaction aborts. This state may live forever if a client application crashes
3. Quicksilver
    - Quicksilver identifies many problems that we face with our everyday computing with orphan windows and such
    - Built by IBM in the early 80s
4. Distributed System Structure
    - Applications interact with system services, which interact directly with the microkernel
    - Structure provides extensibility and high performance



Distributed System Structure

5. Quicksilver System Architecture
    - Quicksilver was architected to be very similar to modern day designs

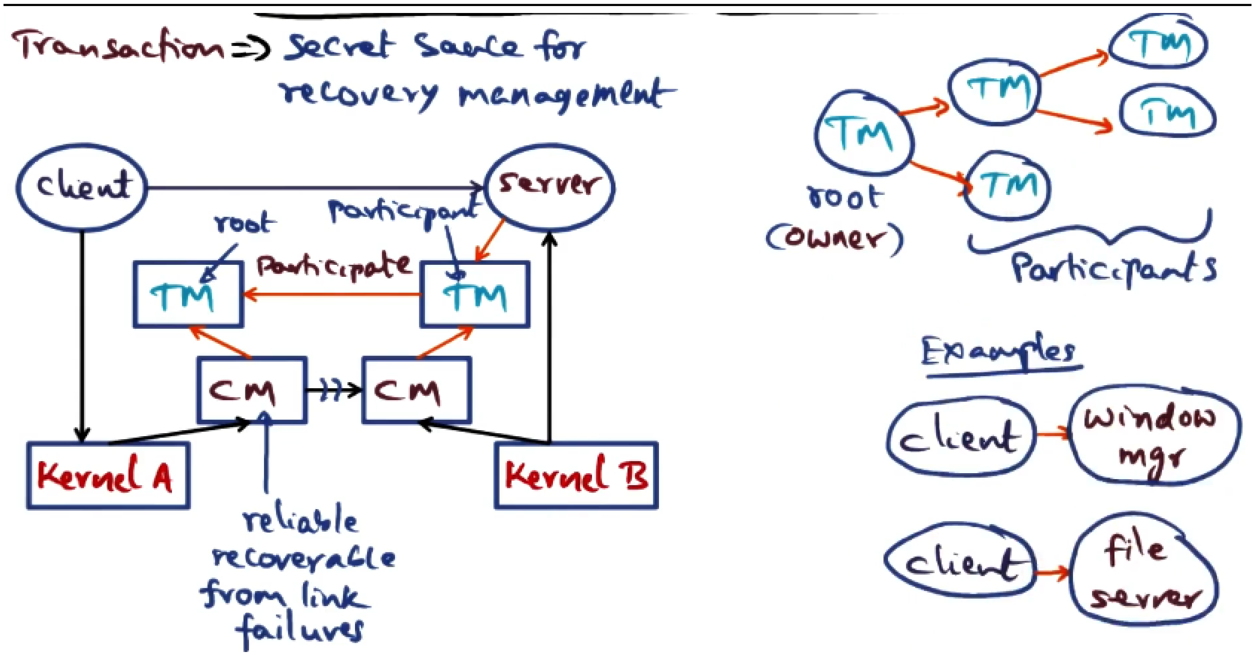
  - No shared memory
  - Server processes all sit above microkernel
  - Microkernel; same vintage as Mach from CMU
- 80s were moving from CRTs and mainframe to desktop computers
- Quicksilver proposes transaction as a unifying concept for recovery management of the servers
  - Transaction manager is service provided by OS to manage this



Quicksilver Architecture

6. IPC Fundamental to System Services
   - Service-q used to handle IPC; client adds a request to service-q and initiates an upcall to the server. Server executes request, completion goes back to service-q, and OS gives control back to client
     - Created by server
     - Any process can connect and any server can service requests
     - No loss of requests or duplicate requests
     - Service-q is globally unique, so client doesn't need to know where in the network the requests is being serviced
     - Supports synchronous and asynchronous requests
     - Very similar to RPC (invented around the same time)
   - Recovery mechanism is intimately tied to RPC
     - Client/server interactions must use IPC
     - Binds recovery with IPC to make it cheaper
   - Quicksilver created in early 1980s, paper not published until 1988
     - Industry only published when the system was finished
     - Nowadays, everybody publishes often
7. Bundling Distributed IPC and Transctions
   - Transaction: Secret sauce for recovery management
     - Lightweight, not heavyweight notion associated with databases
     - LRVM took their ideas for transactions from Quicksilver
   - IPC calls are tagged with transaction headers
     - Want all failures to be recoverable, clean up state from clients, servers, communication manager, etc.
   - Communication manager: One per node, handles IPC
     - Transaction data is piggybacked on top of regular IPC so there's no additional overhead

- Transaction manager: One per node, handles tracking local changes to commit/abort as part of a transaction later
  - Creator of transaction is default owner of transaction, coordinator for transaction tree that is being established (might go through several calls to other servers)
- Transactions need to clean up windows started by a window manager, file pointers opened by the filesystem, any additional state
  - Transaction manager needs to track this state across an entire transaction tree



Quicksilver IPC and Transactions

8. Transaction Management
   - Coordinator can be different from owner
   - Client makes a call to a filesystem, filesystem makes call to data server
     - Client is owner of transaction tree, filesystem and data server are participants
     - Owner can delegate ownership to someone else
     - Clients are most fickle; clean up will become difficult if client crashes, so it might delegate to another node
   - Heavy lifting done by Quicksilver is facilitating recovery management through the transaction tree
9. Distributed Transaction
   - Transactions are inherently distributed
   - Results in a graph structure of the transaction tree
   - Different types of failures
     - Client crashes
     - Connection failure
     - Subordinate transaction manager failed to report
   - Transaction manager logs periodically to a persistent store to create checkpoint records for the client
     - Useful for recovery of work
   - When a transaction manager terminates a transaction, all of the nodes must clean up all of their state
10. Commit Initiated by Coordinator
    - When a transaction completes, the transaction tree is traversed to clean up any resources created to satisfy the request

- Initiated by coordinator for commit or abort
- Down the tree (initiated by coordinator)
  - Vote request
  - Abort request
  - End commit/abort
- Up the tree
  - Response commensurate with request
- If the transaction tree is representing the client/server relationship for opening a window…
  - If client crashes, coordinator will send an abort. Window manager will clear window since it's volatile
- If the transaction tree is representing the client/server relationship a writing to a file…
  - If client crases, coordinator will send an abort. File system will undo changes to disk using checkpoints

11. Upshot of Bundling IPC and Recovery
    - Reclaim resources: Service can safely collect all breadcrumbs left behind by failed clients and servers
      - Have a tree of all of the state changes to undo
    - No extra communication due to piggybacking off of IPC
    - Examples
      - Memory
      - File handles
      - Communication handles
      - Orphan windows
    - Only mechanism in OS, policy up to service
      - Low overhead mechanisms for simple services (window manager)
      - Weighty mechanisms for services (file system)
    - In memory logs are written to disk by transaction manager
      - Frequency is a performance consideration
      - Can be more opportunistic if failures are infrequent
12. Implementation Notes
    - Log maintainence
      - Transaction manager write log records for recovering to persistent state
      - Frequency of "log force" impacts performance
    - Services have to choose mechanisms commensurate with their recovery requirements
      - Can impact all clients due to synchronous I/O requirements
13. Quicksilver Conclusion
    - Ideas of transactions as a fundamental OS mechanism to bundle in state recovery of OS services found resurgence in the 90s with LRVM
      - In 2010, used to provide safeguard against system vulnerability and malicious attacks on a system in a research OS called Texas
    - Commercial OS are always focused on performance
      - Reliability takes a back seat
      - Writing to a file is only in memory until it's flushed to disk
    - Storage class memory
      - Nonvolatile, but with latency properties similar to DRAM