Advanced Memory Management
Introduction to File Systems

Last Time

- Cache Replacement Policies
  - FIFO, MIN, LRU, LFU, Clock
- Memory-mapped files
- Demand-paged virtual memory

Main Points

- Applications of memory management
  - What can we do with ability to trap on memory references to individual pages?
- File systems and persistent storage
  - Goals
  - Abstractions
  - Interfaces

Address Translation Uses

- *Process isolation*
  - Keep a process from touching anyone else's memory, or the kernel's
- *Efficient interprocess communication*
  - Shared regions of memory between processes
- *Shared code segments*
  - E.g., common libraries used by many different programs
- *Program initialization*
  - Start running a program before it is entirely in memory
- *Dynamic memory allocation*
  - Allocate and initialize stack/heap pages on demand

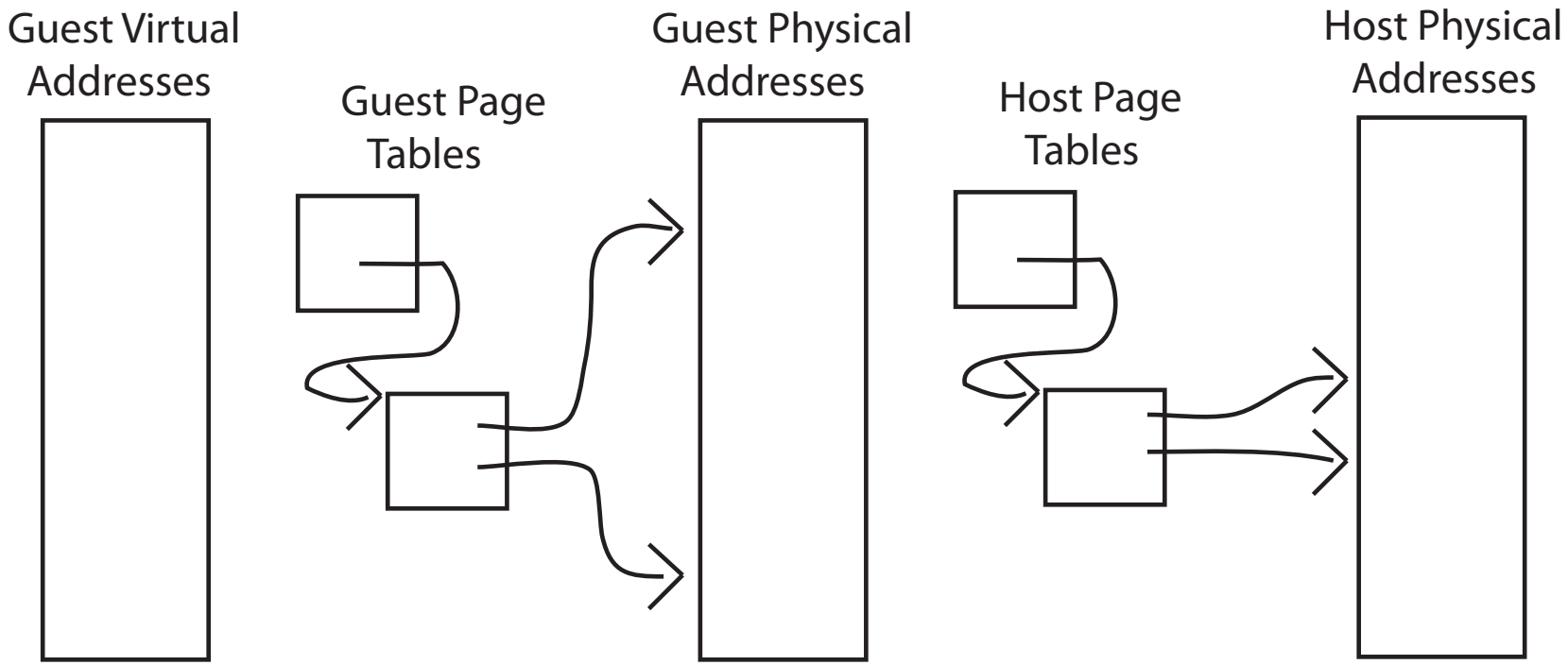
Address Translation (more)

- Program debugging
  - Data breakpoints when address is accessed
- Zero-copy I/O
  - Directly from I/O device into/out of user memory
- *Memory mapped files*
  - Access file data using load/store instructions
- *Demand-paged virtual memory*
  - Illusion of near-infinite memory, backed by disk or memory on other machines

Address Translation (even more)

- Checkpoint/restart
  - Transparently save a copy of a process, without stopping the program while the save happens
- Persistent data structures
  - Implement data structures that can survive system reboots
- Process migration
  - Transparently move processes between machines
- Information flow control
  - Track what data is being shared externally
- Distributed shared memory
  - Illusion of memory that is shared between machines

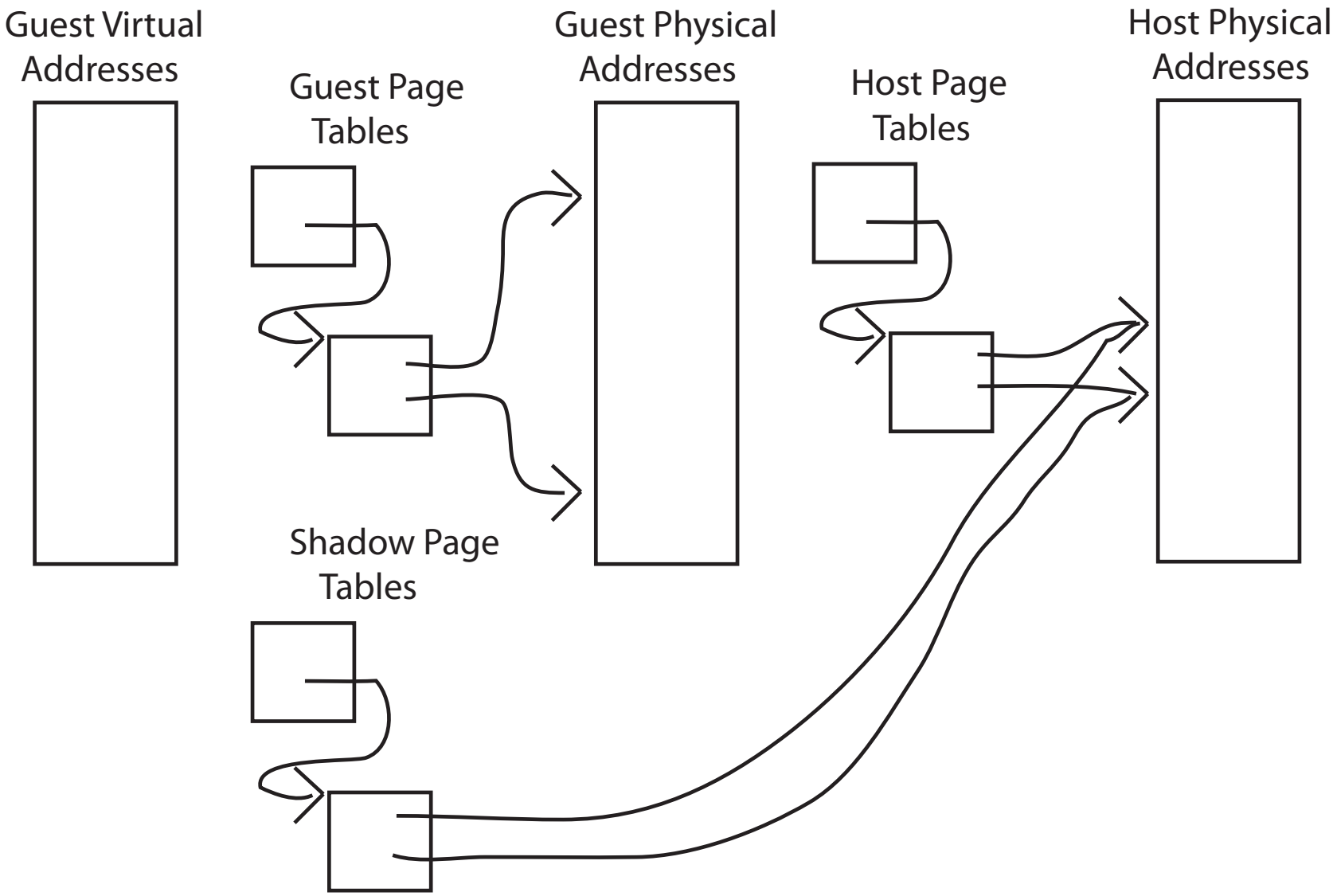
Virtual Machines and Virtual Memory



Segment Table		Page Table A		Page Table B	
0	Page Table A	0	0002	0	0001
1	Page Table B	1	0006	1	0004
x	(rest invalid)	2	0000	2	0003
		3	0005	x	(rest invalid)
		x	(rest invalid)		

Segment Table		Page Table K	
0	Page Table K	0	BEEF
x	(rest invalid)	1	F000
		2	CAFE
		3	3333
		4	(invalid)
		5	BA11
		6	DEAD
		7	5555
		x	(rest invalid)

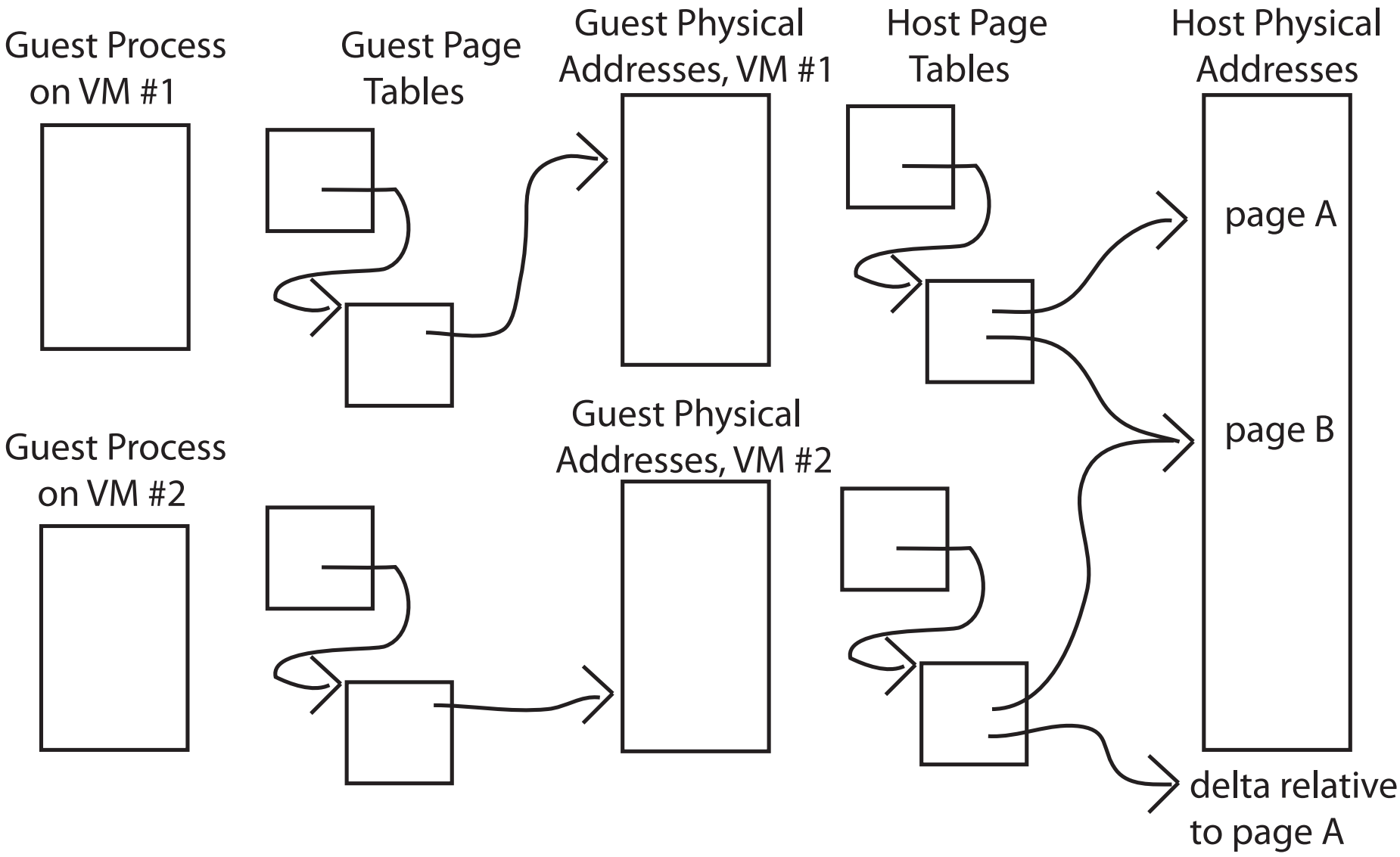
Shadow Page Tables



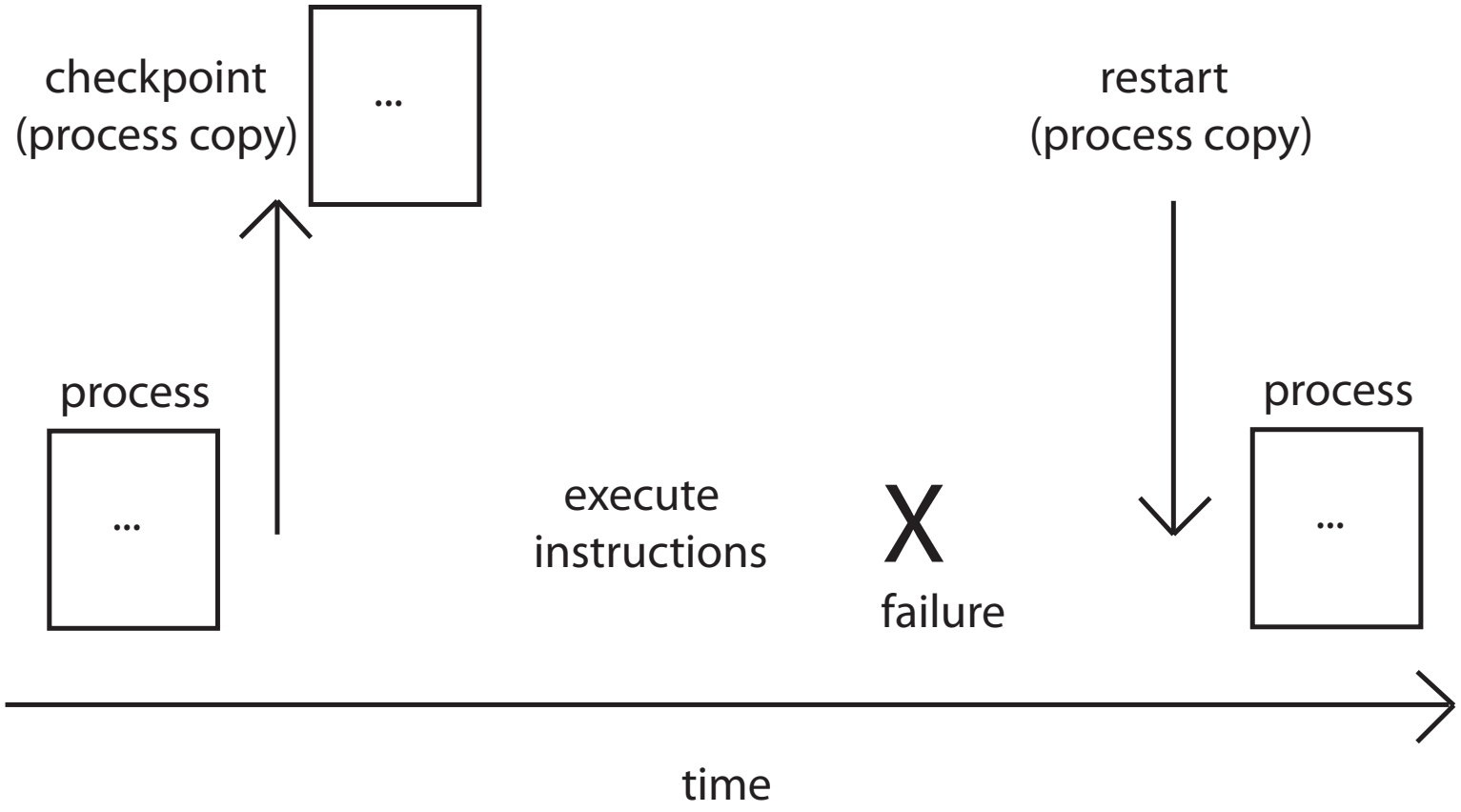
Hardware Support for Virtual Machines

- x86 recently added hardware support for running virtual machines at user level
- Operating system kernel initializes two sets of translation tables
  - One for the guest OS
  - One for the host OS
- Hardware translates address in two steps
  - First using guest OS tables, then host OS tables
  - TLB holds composition

VMM Memory Compression



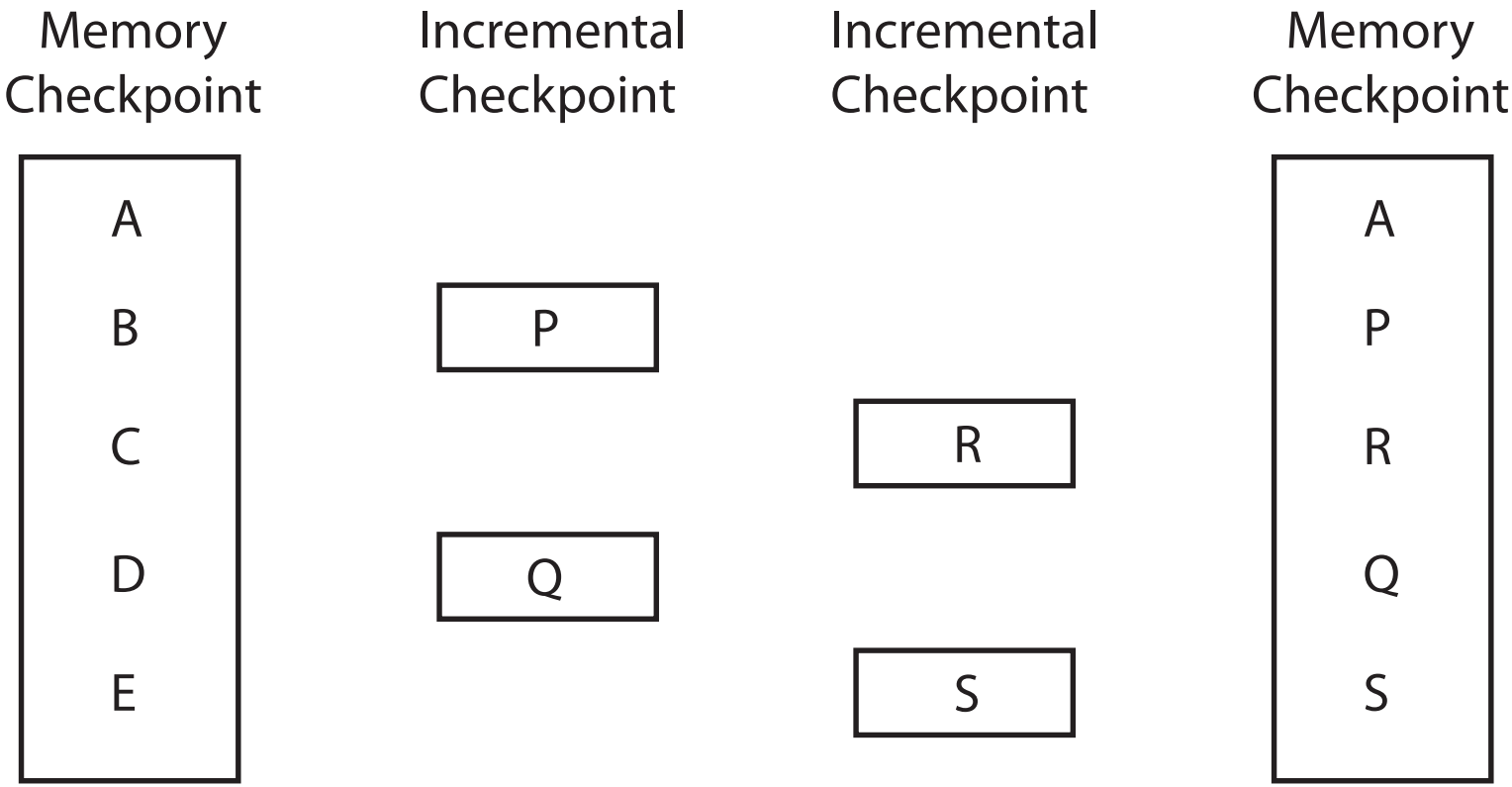
Transparent Checkpoint



Question

- At what point can we resume the execution of a checkpointed program?
  - When the checkpoint starts?
  - When the checkpoint is entirely on disk?

Incremental Checkpoint



Deterministic Debugging

- Can we precisely replay the execution of a multi-threaded process?
  - If process does not have a memory race
- From a checkpoint, record:
  - All inputs and return values from system calls
  - All scheduling decisions
  - All synchronization operations
    - Ex: which thread acquired lock in which order

Process Migration

- What if we checkpoint a process and then restart it on a different machine?
  - Process migration: move a process from one machine to another
  - Special handling needed if any system calls are in progress
    - Where does the system call return to?

Cooperative Caching

- Can we demand page to memory on a different machine?
  - Remote memory over LAN much faster than disk
  - On page fault, look in remote memory first before fetching from disk

Distributed Virtual Memory

- Can we make a network of computers appear to be a shared-memory multiprocessor?
  - Read-write: if page is cached only on one machine
  - Read-only: if page is cached on several machines
  - Invalid: if page is cached read-write on a different machine
- On read page fault:
  - Change remote copy to read-only
  - Copy remote version to local machine
- On write page fault (if cached):
  - Change remote copy to invalid
  - Change local copy to read-write

Recoverable Virtual Memory

- Data structures that survive failures
  - Want a consistent version of the data structure
  - User marks region of code as needing to be atomic
    - Begin transaction, end transaction
  - If crash, restore state before or after transaction

Recoverable Virtual Memory

- On begin transaction:
  - Snapshot data structure to disk
  - Change page table permission to read-only
- On page fault:
  - Mark page as modified by transaction
  - Change page table permission to read-write
- On end transaction:
  - Log changed pages to disk
  - Commit transaction when all mods are on disk
- Recovery:
  - Read last snapshot + logged changes, if committed

File Systems

- Abstraction on top of persistent storage
  - Magnetic disk
  - Flash memory (e.g., USB thumb drive)
- Devices provide
  - Storage that (usually) survives across machine crashes
  - Block level (random) access
  - Large capacity at low cost
  - Relatively slow performance
    - Magnetic disk read takes 10-20M processor instructions

File System as Illusionist: Hide Limitations of Physical Storage

- Persistence of data stored in file system:
  - Even if crash happens during an update
  - Even if disk block becomes corrupted
  - Even if flash memory wears out
- Naming:
  - Named data instead of disk block numbers
  - Directories instead of flat storage
  - Byte addressable data even though devices are block-oriented
- Performance:
  - Cached data
  - Data placement and data structure organization
- Controlled access to shared data

File System Abstraction

- File system: persistent, named data
- File: named collection of data in file system
  - UNIX: linear sequence of bytes
  - Windows/MacOS: collection of linear sequences
    - Example: a Word file might contain text, pictures, spreadsheets, formatting templates, …
- File consists of
  - Metadata
    - Access permissions, creation date
  - Data
    - File contents

File System Abstraction

- Directory
  - Group of named files or subdirectories
  - Mapping from file name to file metadata location
- Path
  - String that uniquely identifies file or directory
  - Ex: /cse/www/education/courses/cse451/12au
- Links
  - Hard link: link from name to metadata location
  - Soft link: link from name to alternate name
- Mount
  - Mapping from name in one file system to root of another

UNIX File System API

- create, link, unlink, createdir, rmdir
  - Create file, link to file, remove link
  - Create directory, remove directory
- open, close, read, write, seek
  - Open/close a file for reading/writing
  - Seek resets current position
- fsync
  - File modifications can be cached
  - fsync forces modifications to disk (like a memory barrier)