CS162
Operating Systems and Systems Programming

Final Exam Review

May 4, 2012

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http://inst.eecs.berkeley.edu/~cs162

Final Exam

- Friday May 11 11:30-2:30 PM in 230 Hearst Gym
- Two double-sided handwritten pages of notes
- Closed book
- Comprehensive
  - All lectures, discussions, projects, readings, handouts,

Topics

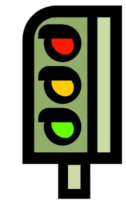
- Synchronization
  – Primitives, Deadlock
- Memory management
  – Address translation, Caches, TLBs, Demand Paging
- Distributed Systems
  – Naming, Security, Networking
- Filesystems
  – Disks, Directories
- Transactions

Synchronization Primitives

Definitions

- Synchronization: using atomic operations to ensure cooperation between threads
- Mutual Exclusion: ensuring that only one thread does a particular thing at a time
  - One thread *excludes* the other while doing its task
- Critical Section: piece of code that only one thread can execute at once
  - Critical section is the result of mutual exclusion
  - Critical section and mutual exclusion are two ways of describing the same thing

Semaphores



- Semaphores are a kind of generalized lock
  - First defined by Dijkstra in late 60s
  - Main synchronization primitive used in original UNIX
- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
  - P(): an atomic operation that waits for semaphore to become positive, then decrements it by 1
    - » Think of this as the wait() operation
  - V(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
    - » This of this as the signal() operation
  - Note that P() stands for "*proberen*" (to test) and V() stands for "*verhogen*" (to increment) in Dutch

Condition Variables

- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section
- Operations:
  - `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - `Signal()`: Wake up one waiter, if any
  - `Broadcast()`: Wake up all waiters
- Rule: Must hold lock when doing condition variable ops!

Mesa vs. Hoare monitors

- Hoare-style (most textbooks):
  - Signaler gives lock, CPU to waiter; waiter runs immediately
  - Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again
- Mesa-style (most real operating systems):
  - Signaler keeps lock and processor
  - Waiter placed on ready queue with no special priority
  - Practically, need to check condition again after wait

Deadlock

Four requirements for Deadlock

- Mutual exclusion
  - Only one thread at a time can use a resource.
- Hold and wait
  - Thread holding at least one resource is waiting to acquire additional resources held by other threads
- No preemption
  - Resources are released only voluntarily by the thread holding the resource, after thread is finished with it
- Circular wait
  - There exists a set $\{T_1, \ldots, T_n\}$ of waiting threads
    - » T_1 is waiting for a resource that is held by T_2
    - » T_2 is waiting for a resource that is held by T_3
    - » …
    - » T_n is waiting for a resource that is held by T_1

Banker's Algorithm for Preventing Deadlock

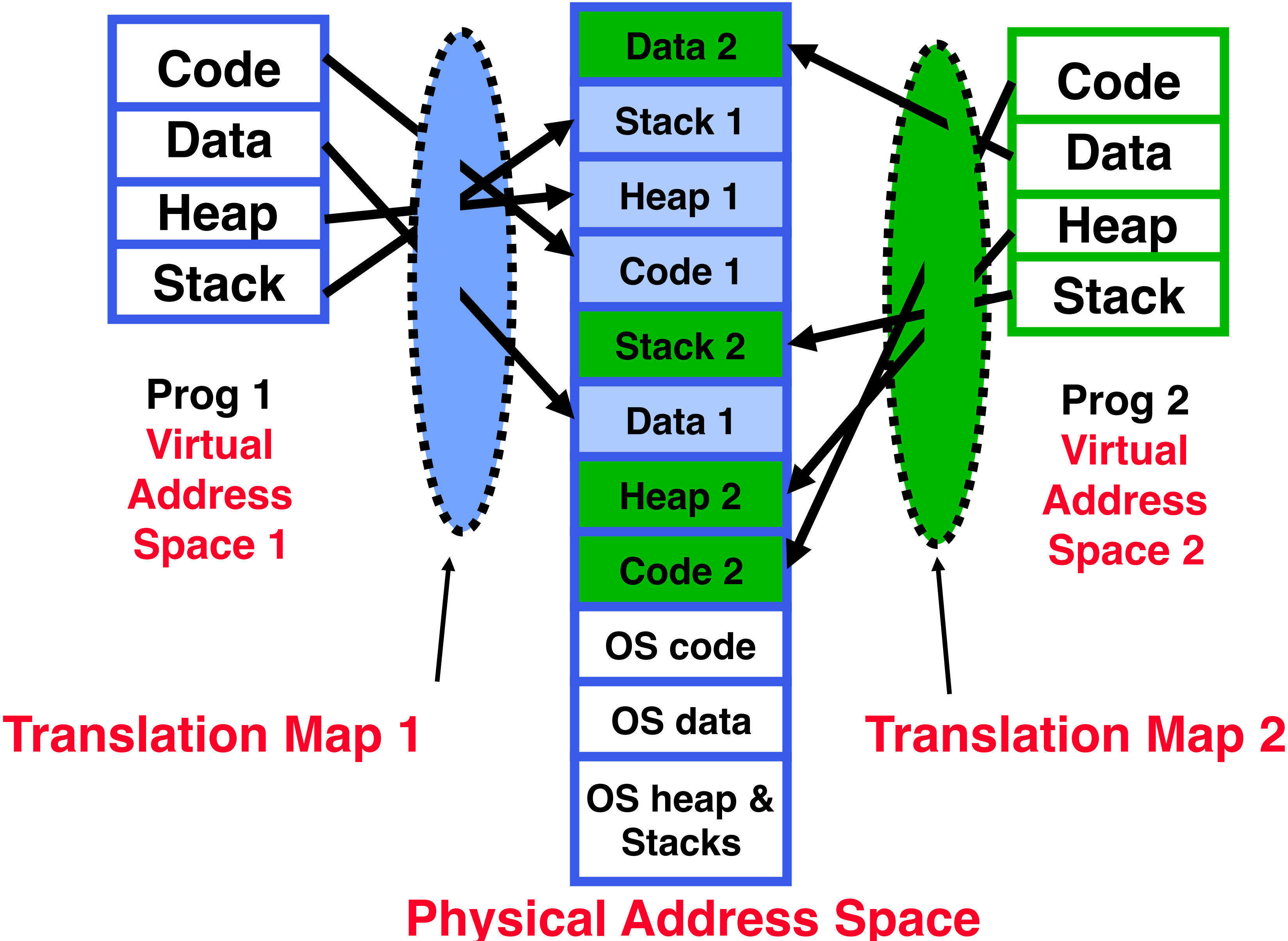
- Allocate resources dynamically
  - Evaluate each request and grant if some ordering of threads is still deadlock free afterward
  - Technique: pretend each request is granted, then run deadlock detection algorithm, substituting ($[Max_{node}]-[Alloc_{node}] \le [Avail]$) for ($[Request_{node}] \le [Avail]$) Grant request if result is deadlock free (conservative!)
  - Keeps system in a "SAFE" state, i.e. there exists a sequence $\{T_1, T_2, \ldots T_n\}$ with T_1 requesting all remaining resources, finishing, then T_2 requesting all remaining resources, etc..
- Algorithm allows the sum of maximum resource needs of all current threads to be greater than total resources

Memory Multiplexing, Address Translation

Important Aspects of Memory Multiplexing

- Controlled overlap:
  - Processes should not collide in physical memory
  - Conversely, would like the ability to share memory when desired (for communication)
- Protection:
  - Prevent access to private memory of other processes
    - » Different pages of memory can be given special behavior (Read Only, Invisible to user programs, etc).
    - » Kernel data protected from User programs
    - » Programs protected from themselves
- Translation:
  - Ability to translate accesses from one address space (virtual) to a different one (physical)
  - When translation exists, processor uses virtual addresses, physical memory uses physical addresses
  - Side effects:
    - » Can be used to avoid overlap
    - » Can be used to give uniform view of memory to programs

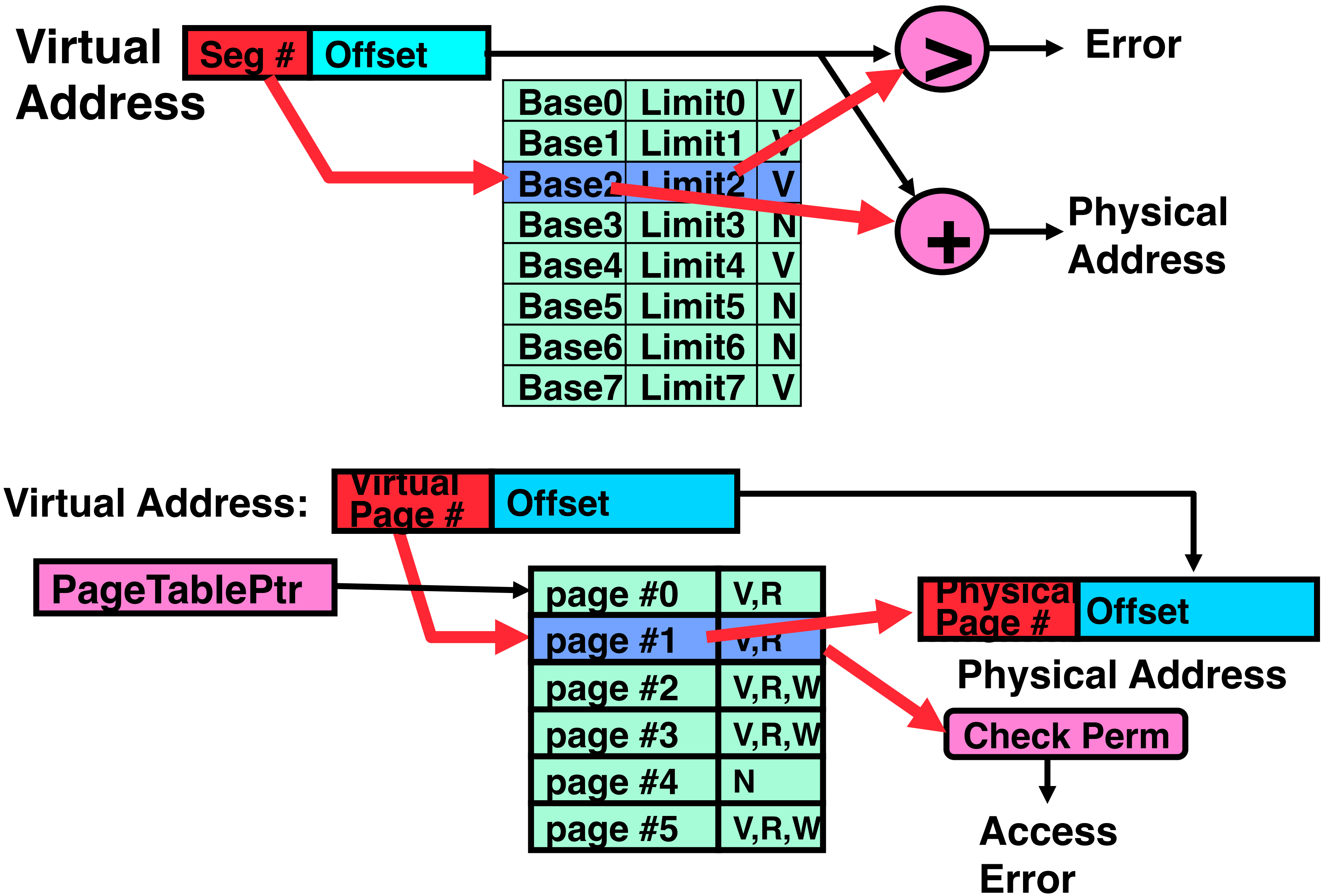
Why Address Translation?



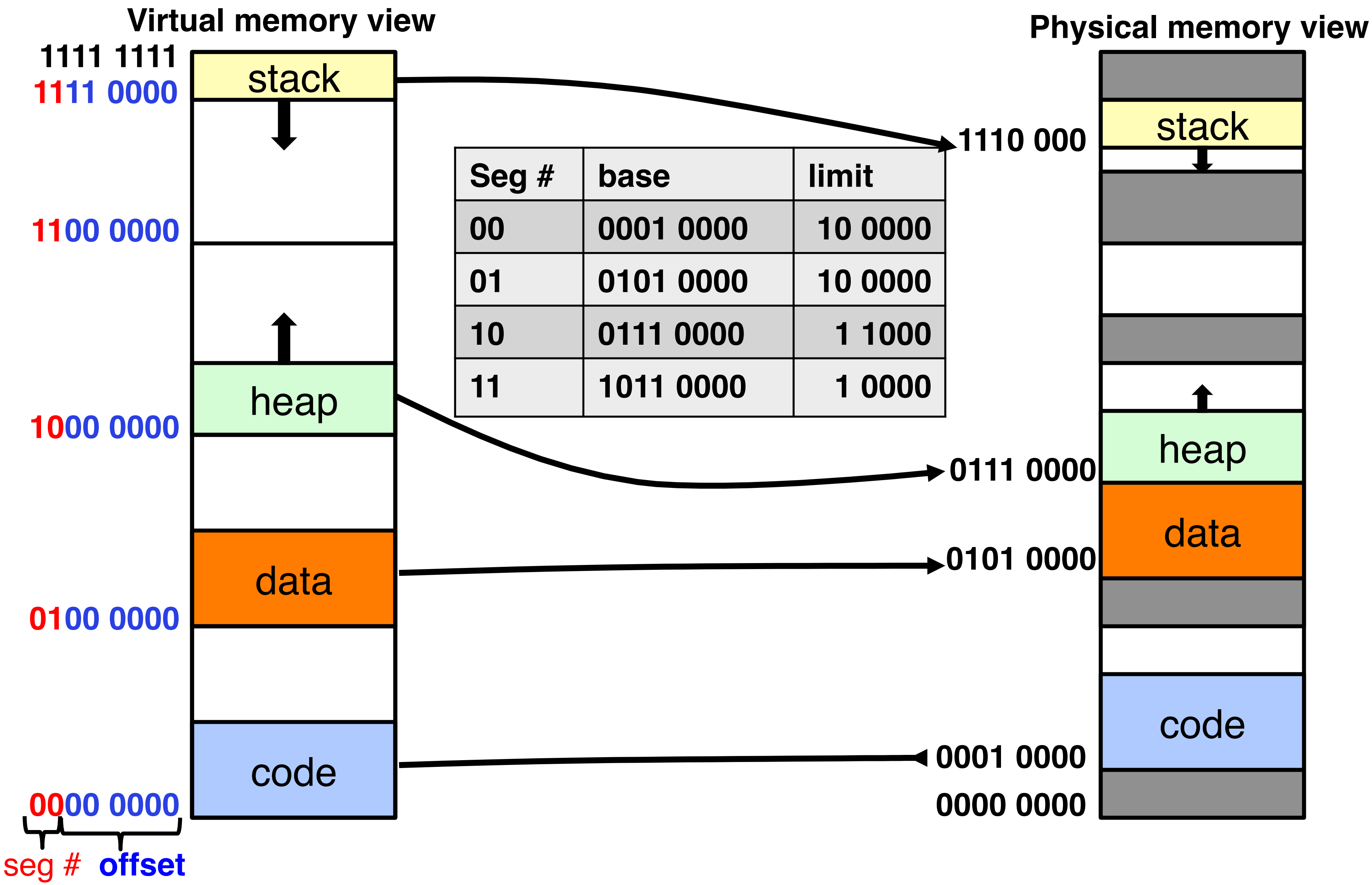
Dual-Mode Operation

- Can an application modify its own translation maps?
  - If it could, could get access to all of physical memory
  - Has to be restricted somehow
- To assist with protection, hardware provides at least two modes (Dual-Mode Operation):
  - "Kernel" mode (or "supervisor" or "protected")
  - "User" mode (Normal program mode)
  - Mode set with bits in special control register only accessible in kernel-mode
  - User→Kernel: System calls, Traps, or Interrupts

Addr. Translation: Segmentation vs. Paging

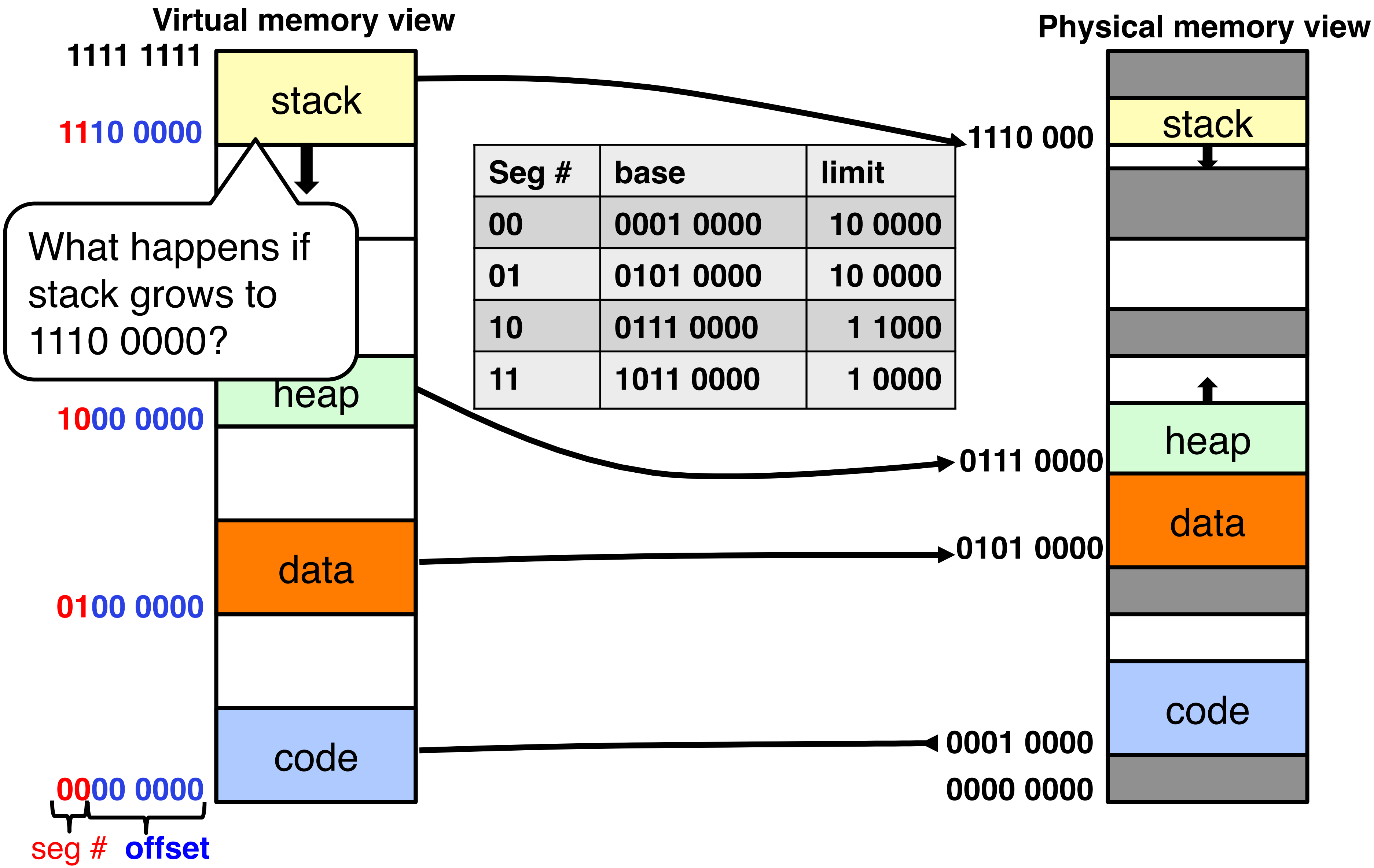


Review: Address Segmentation



Seg #	base	limit
00	0001 0000	10 0000
01	0101 0000	10 0000
10	0111 0000	1 1000
11	1011 0000	1 0000

Review: Address Segmentation



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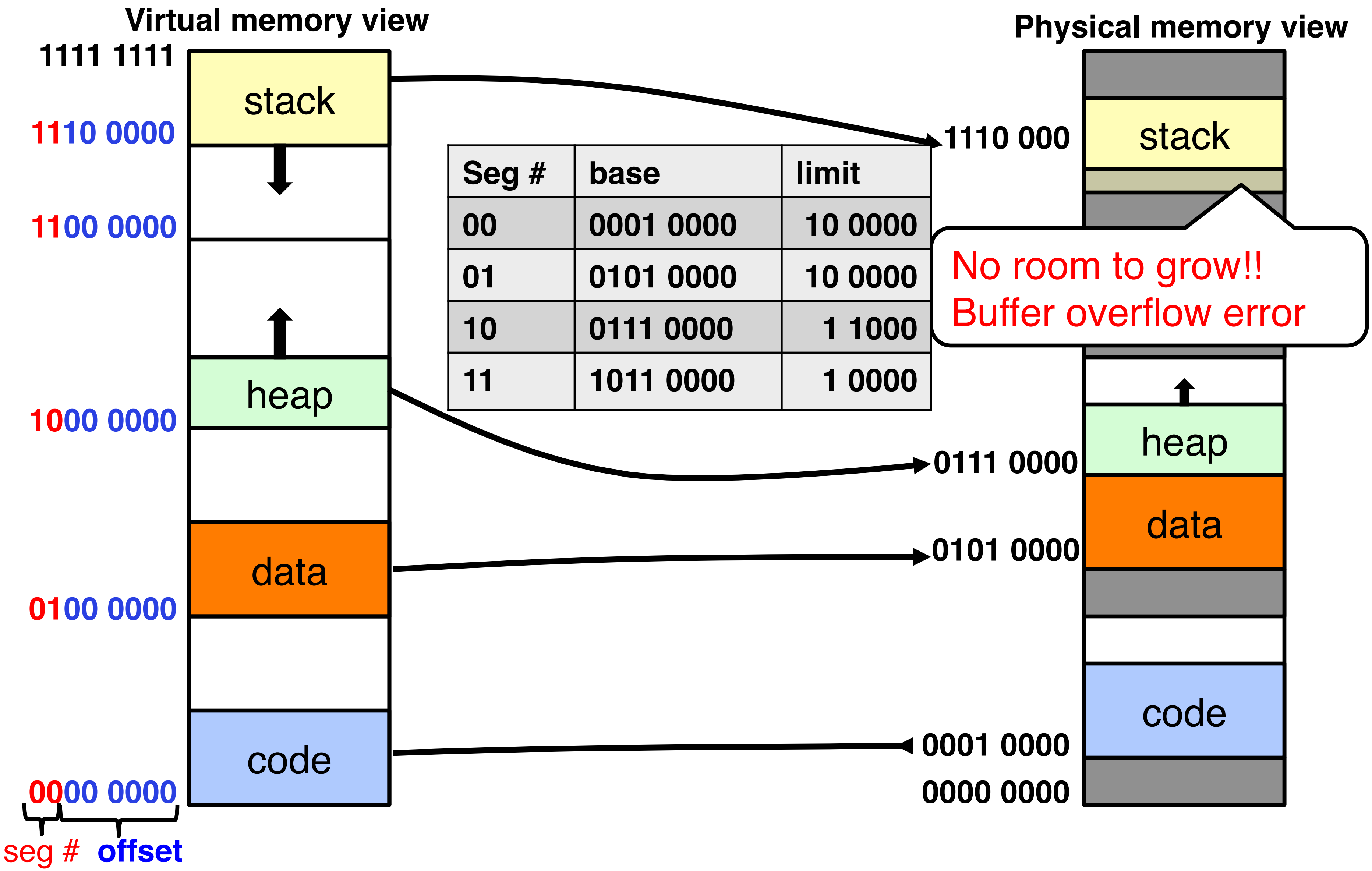

Seg #	base	limit
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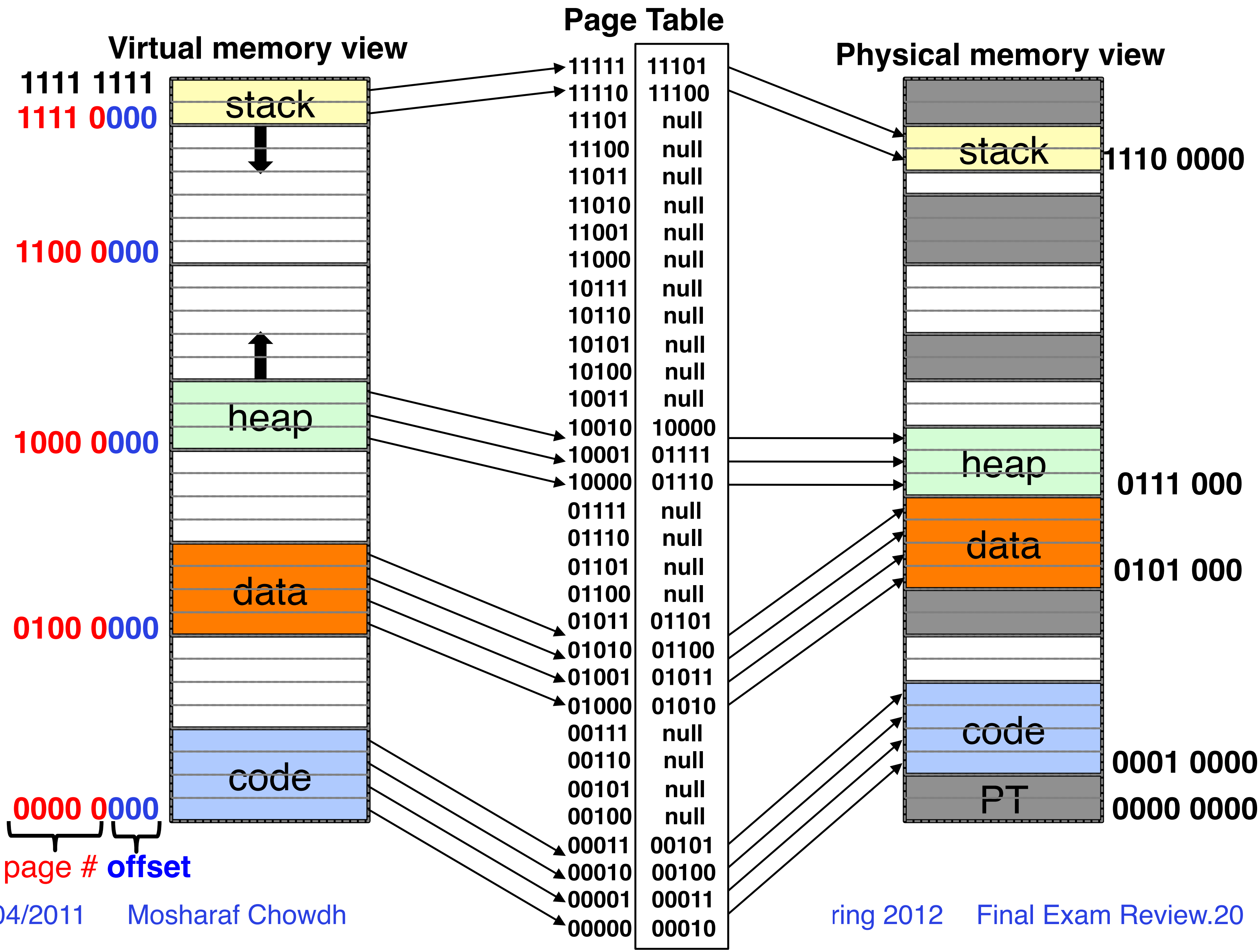
01	0101 0000	10 0000
10	0111 0000	1 1000
11	1011 0000	1 0000

Review: Page Tables



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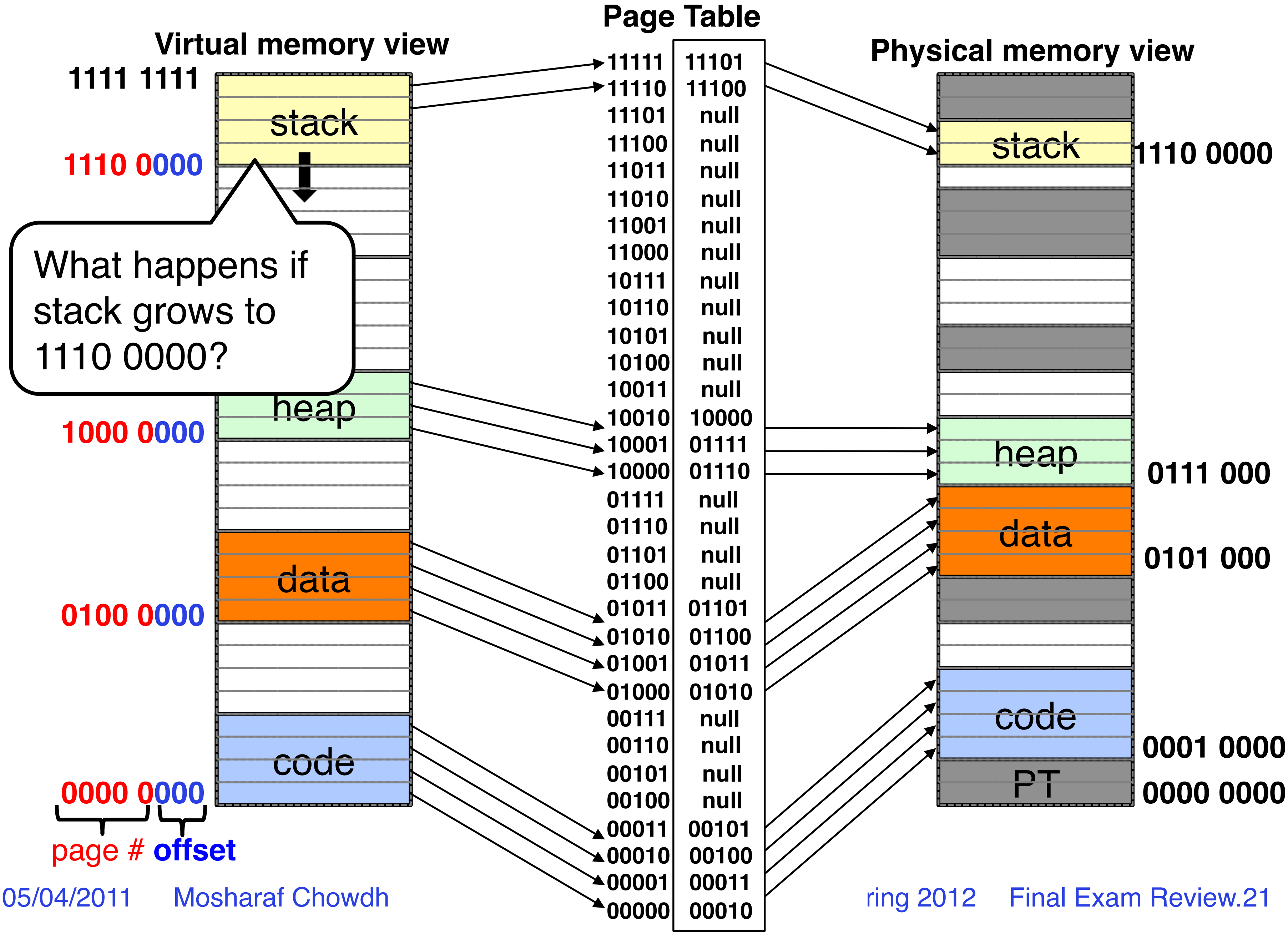

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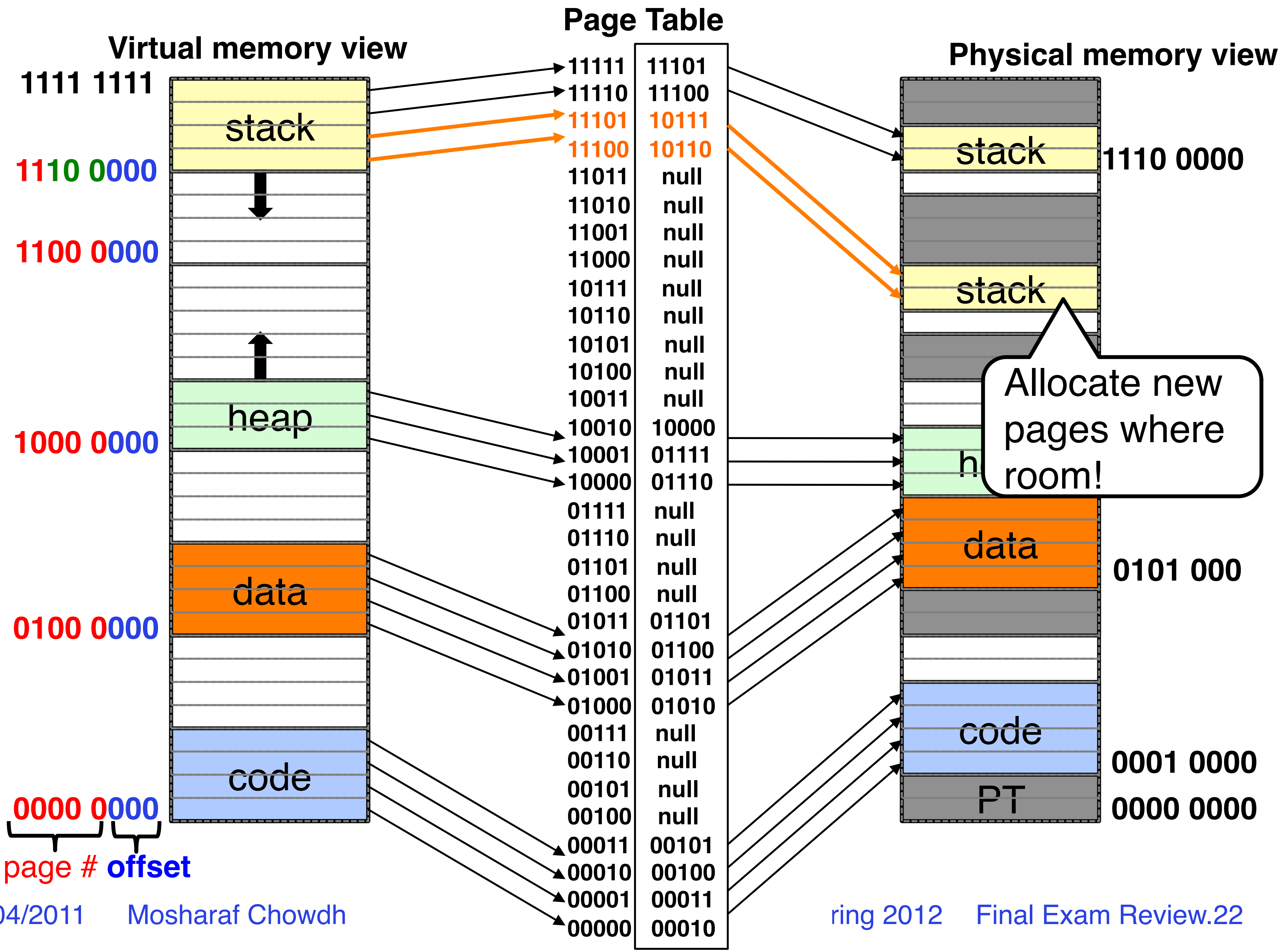
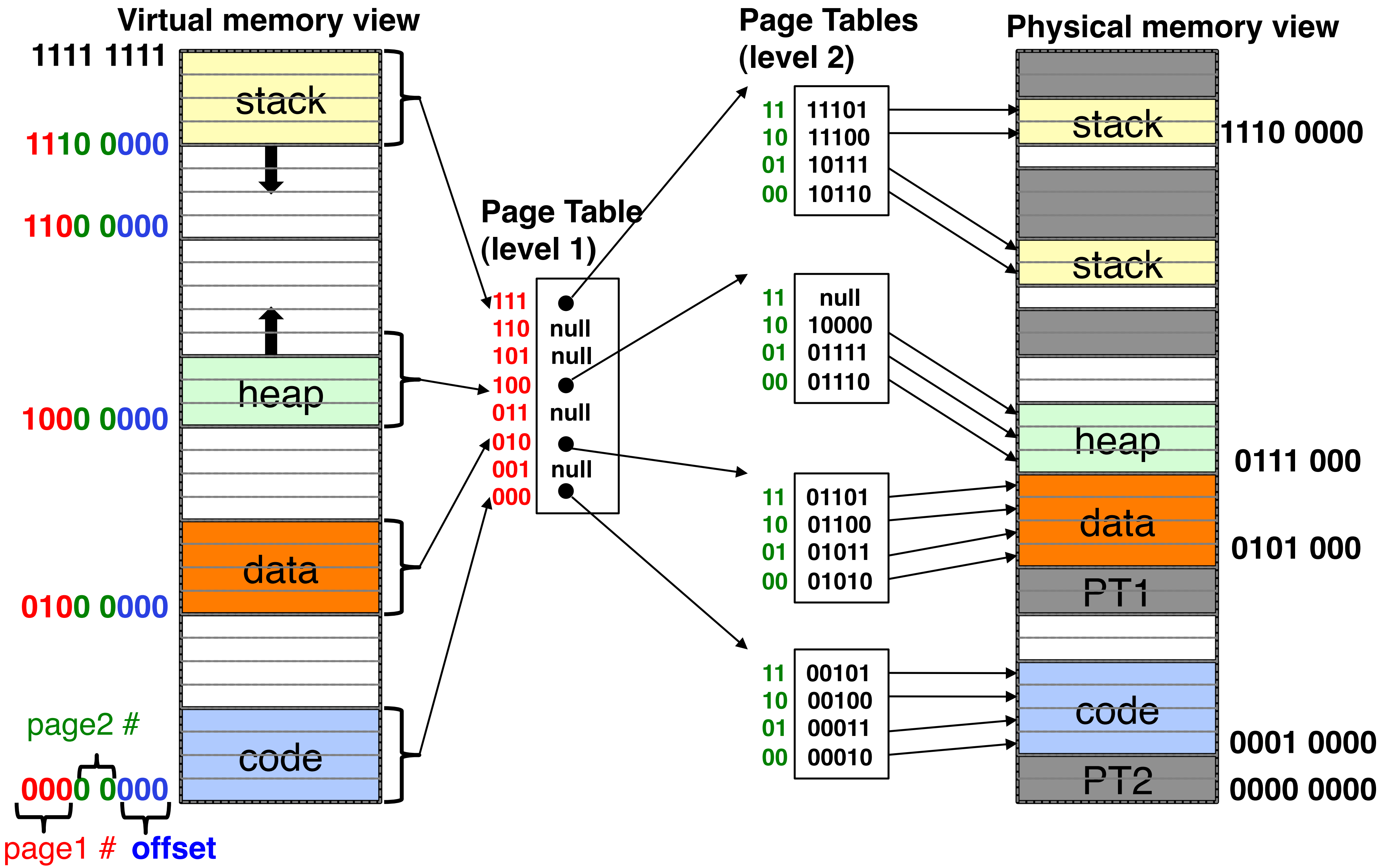


Review: Two-Level Page Tables



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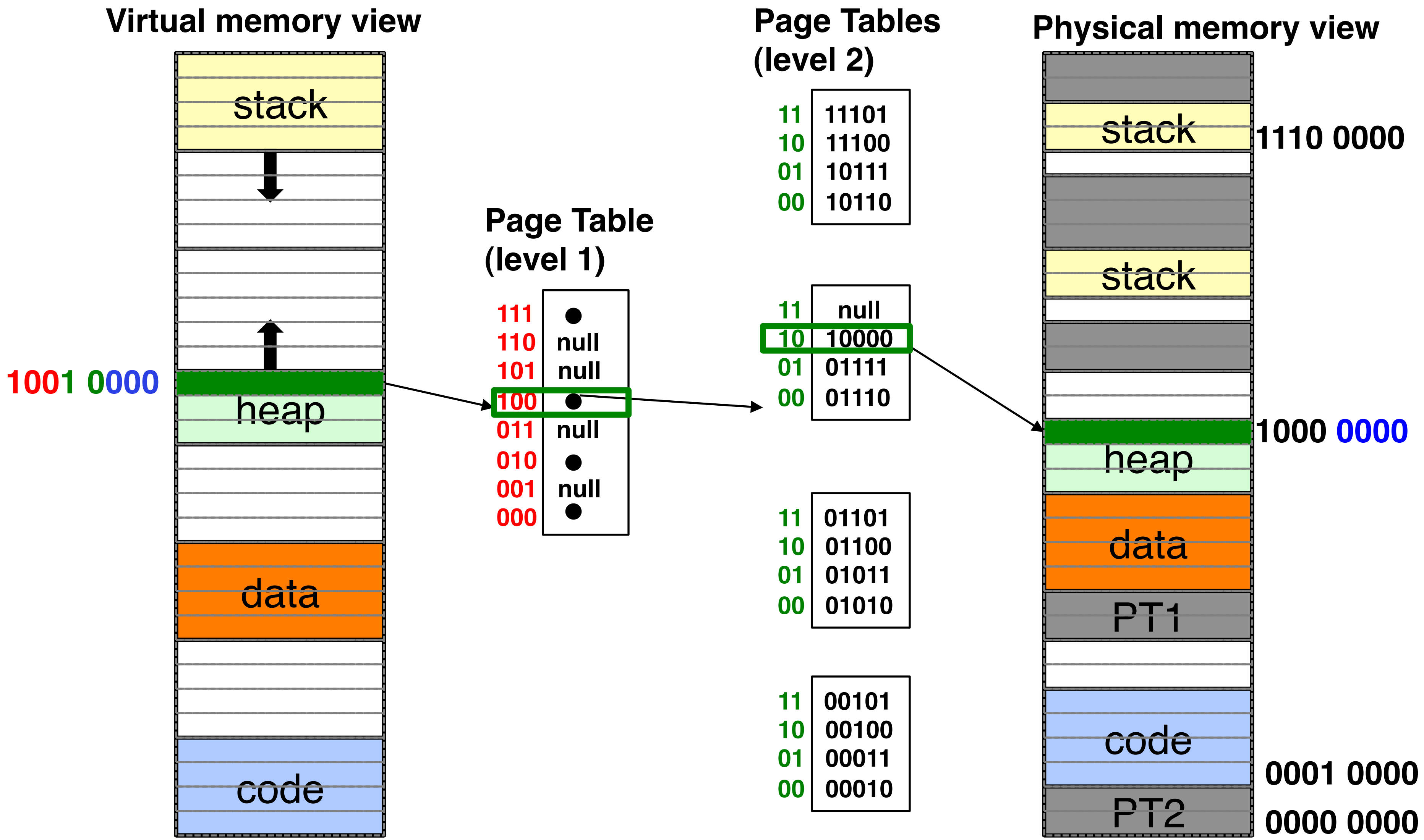
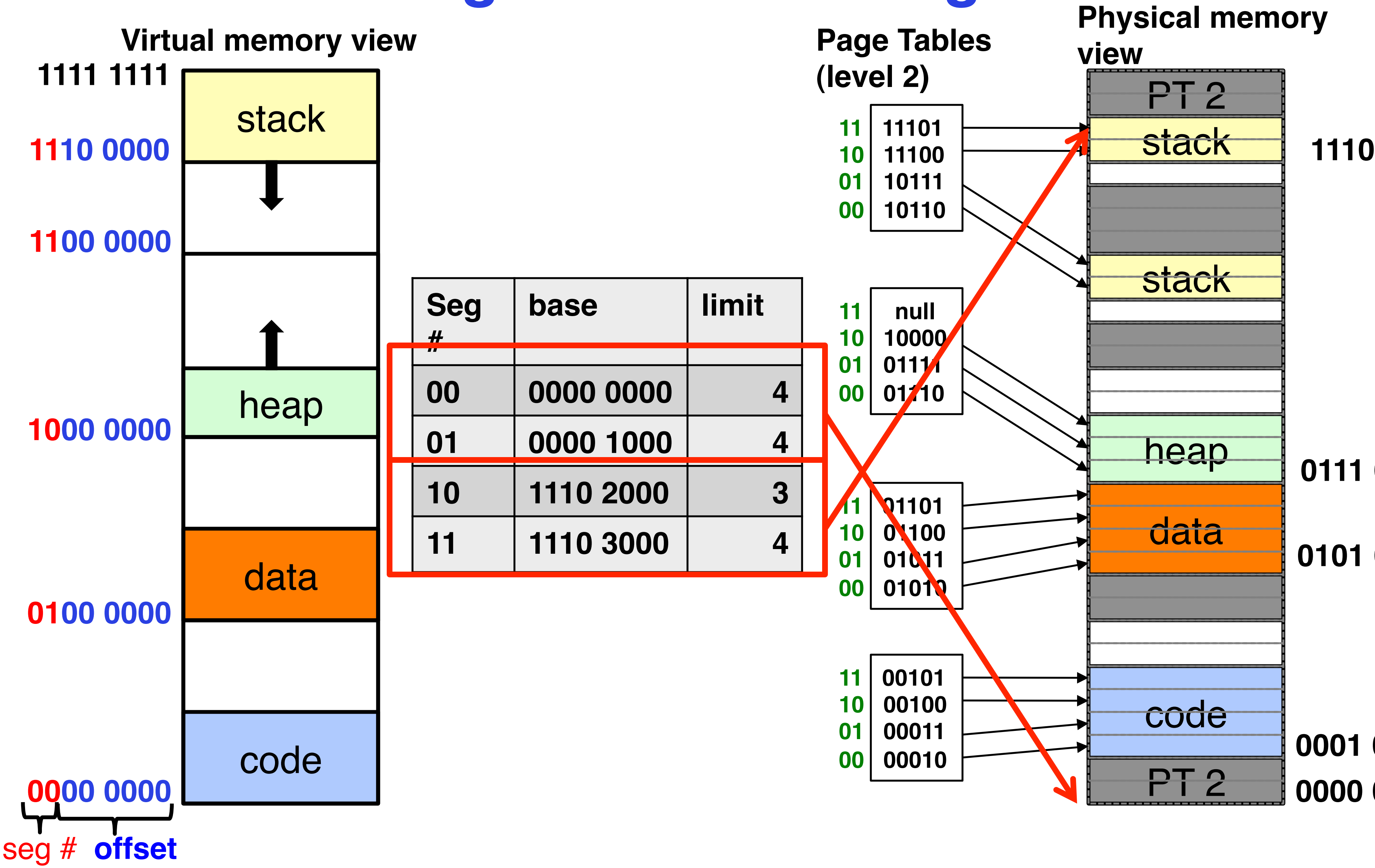
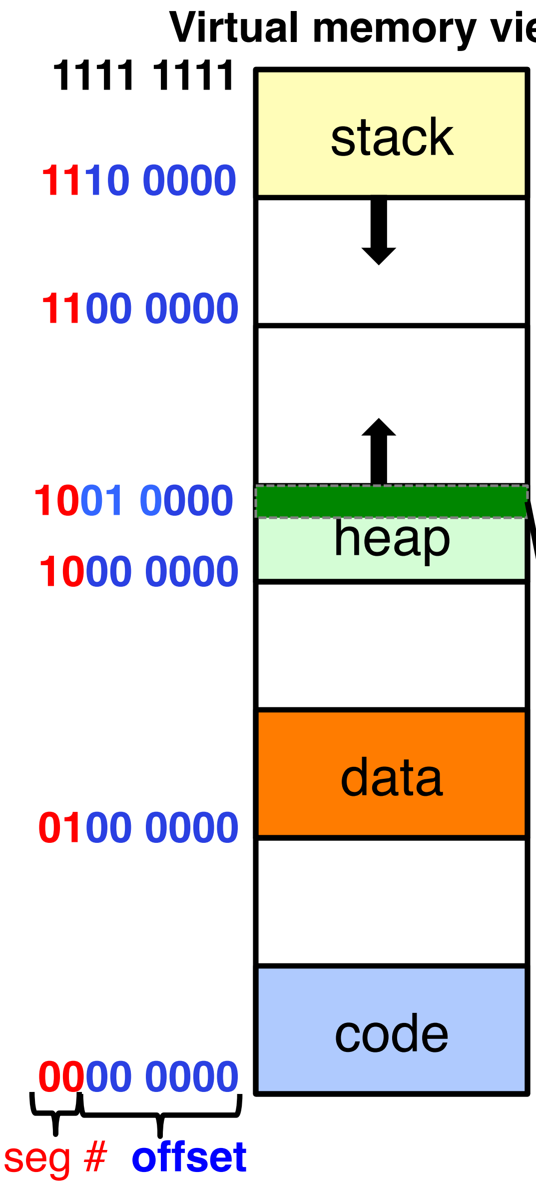


Review: Segmentation & Page Tables

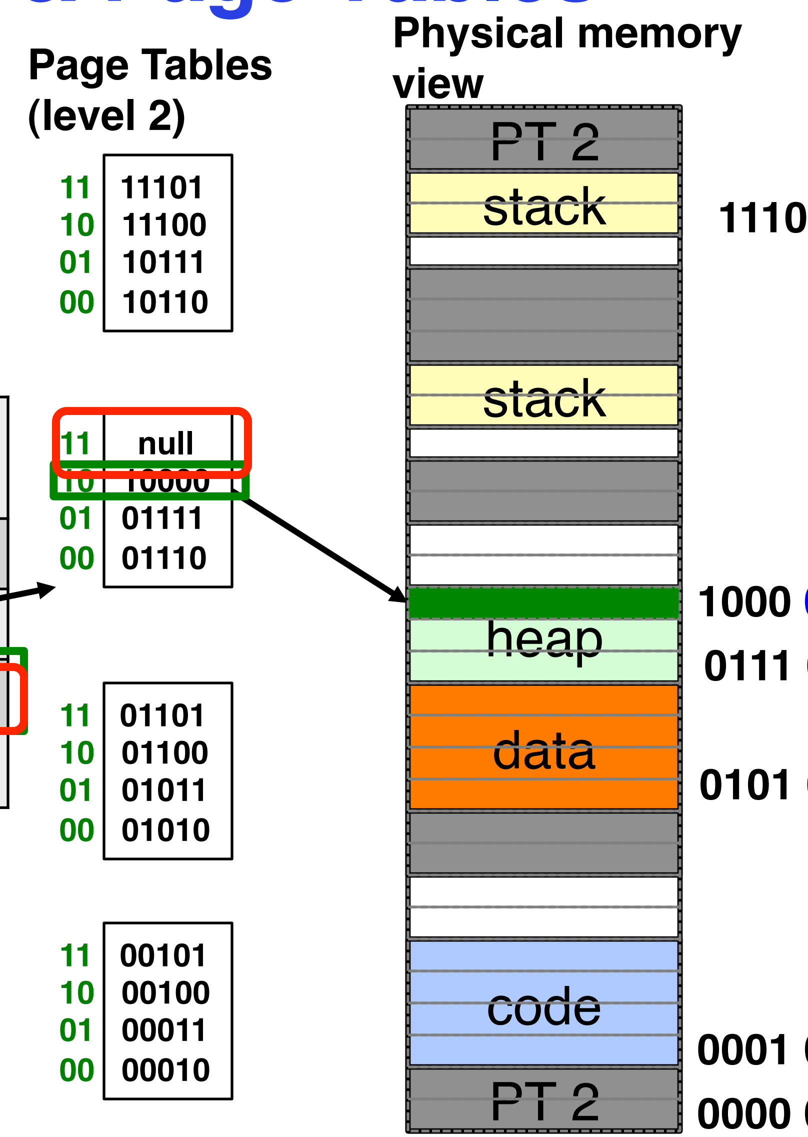


Seg #	base	limit
00	0000 0000	4
01	0000 1000	4
10	1110 2000	3
11	1110 3000	4

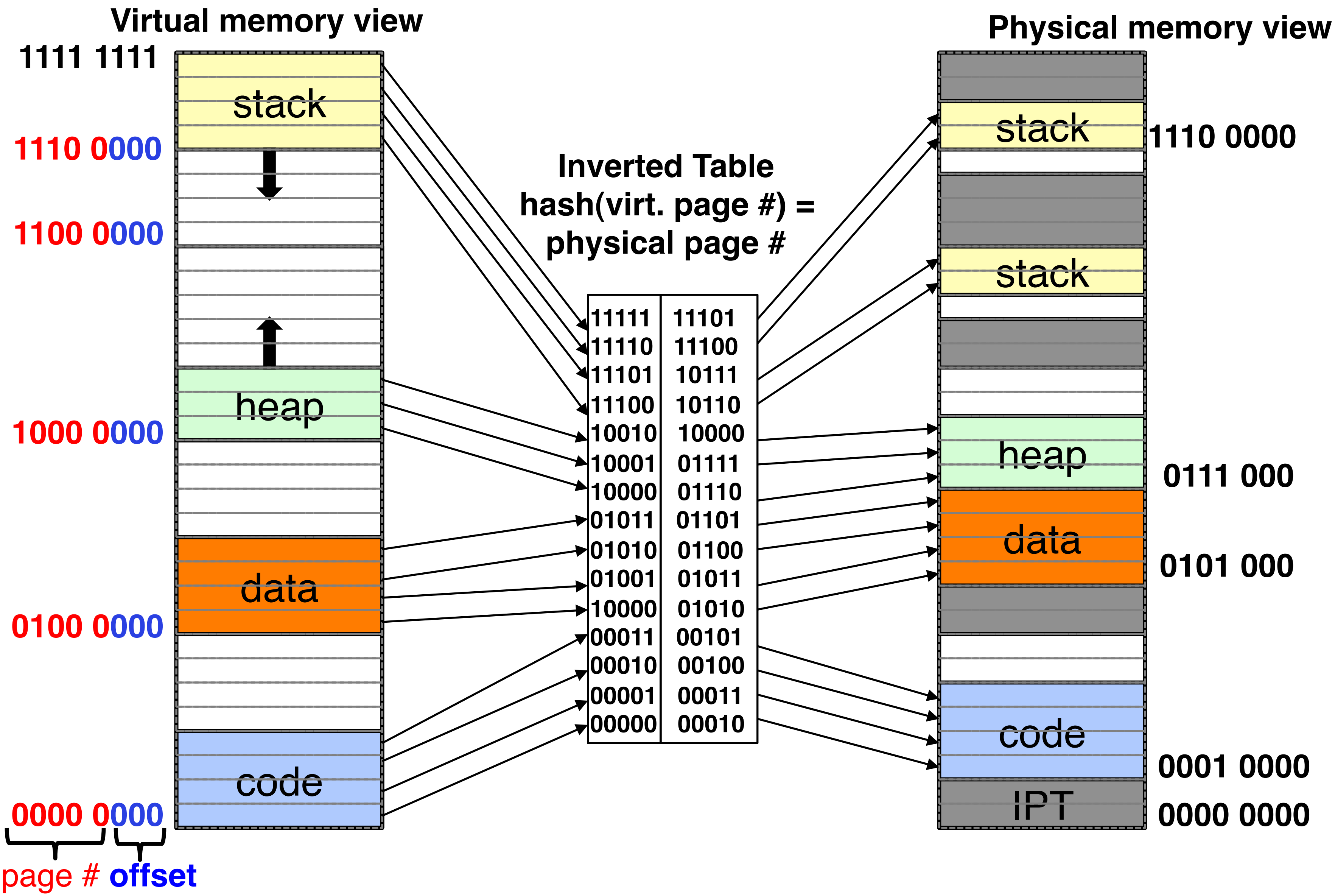
Review: Segmentation & Page Tables



Seg #	base	limit
00	0000 0000	4
01	0000 1000	4
10	1110 2000	3
11	1110 3000	4



Review: Inverted Page Table



Address Translation Comparison

<table>
<tr><th></th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Segmentation</td><td>Fast context switching: Segment mapping maintained by CPU</td><td>External fragmentation</td></tr>
<tr><td>Page Tables (single-level page)</td><td>No external fragmentation</td><td>•Large size: Table size ~ virtual memory
•Internal fragmentation</td></tr>
<tr><td>Page Tables& Segmentation</td><td rowspan="3">•No external fragmentation
•Table size ~ memory used by program</td><td rowspan="2">•Multiple memory references per page access
•Internal fragmentation</td></tr>
<tr><td>Two-level page tables</td></tr>
<tr><td>Inverted Table</td><td>Hash function more complex</td></tr>
</table>

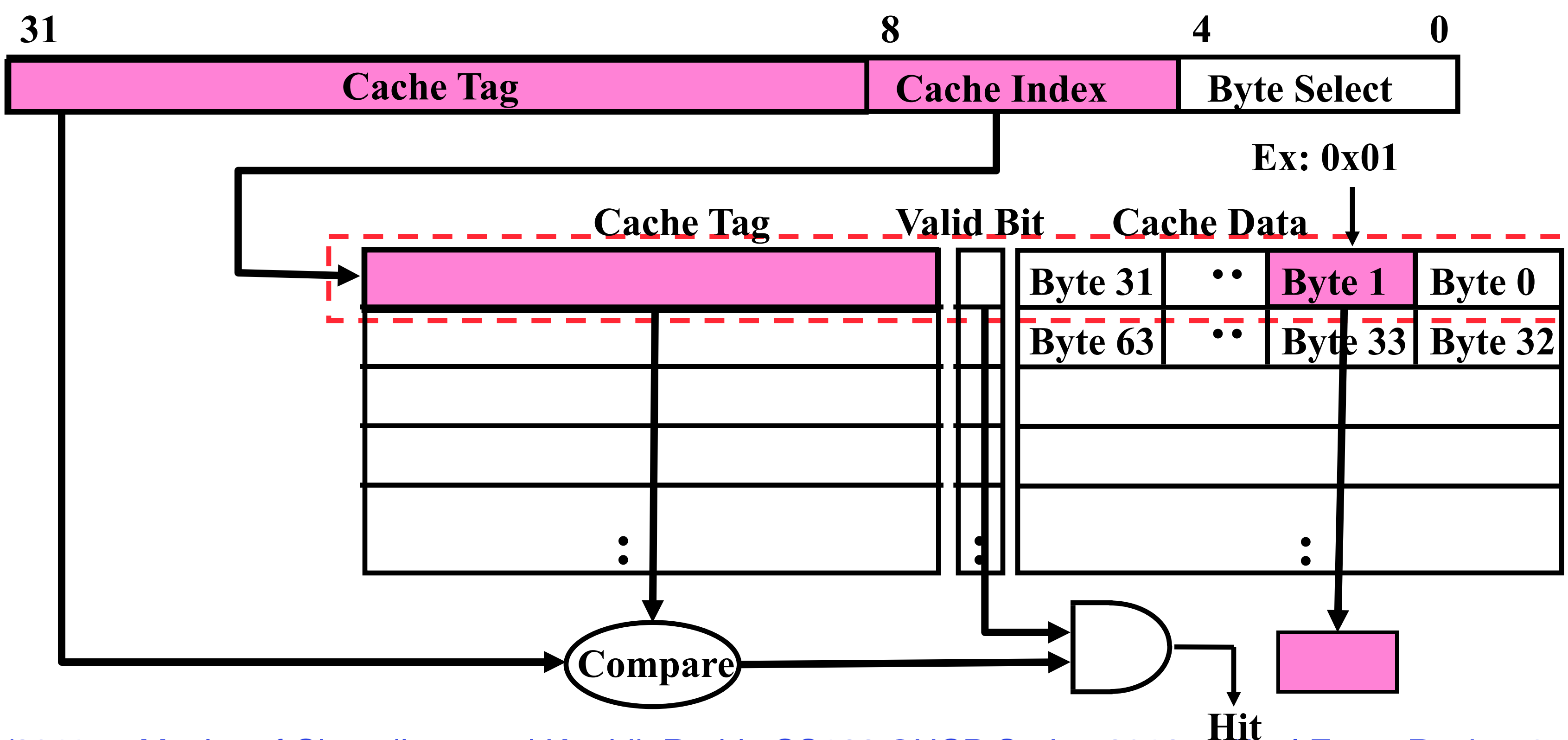
Caches, TLBs

Review: Sources of Cache Misses

- Compulsory (cold start): first reference to a block
  - "Cold" fact of life: not a whole lot you can do about it
  - Note: When running "billions" of instruction, Compulsory Misses are insignificant
- Capacity:
  - Cache cannot contain all blocks access by the program
  - Solution: increase cache size
- Conflict (collision):
  - Multiple memory locations mapped to same cache location
  - Solutions: increase cache size, or increase associativity
- Two others:
  - Coherence (Invalidation): other process (e.g., I/O) updates memory
  - Policy: Due to non-optimal replacement policy

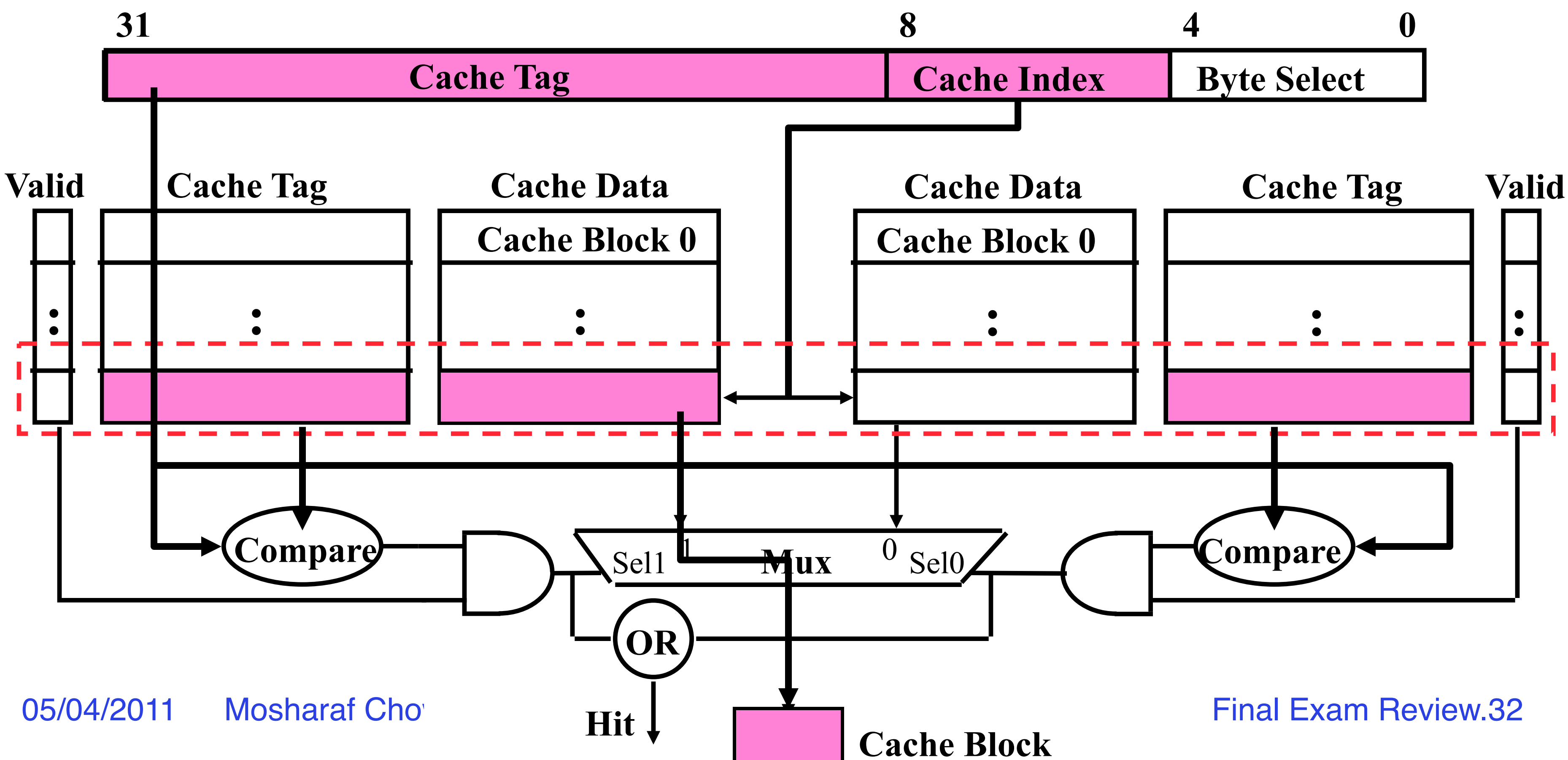
Direct Mapped Cache

- Cache index selects a cache block
- "Byte select" selects byte within cache block
  - Example: Block Size=32B blocks
- Cache tag fully identifies the cached data
- Data with same "cache index" shares the same cache entry
  - Conflict misses



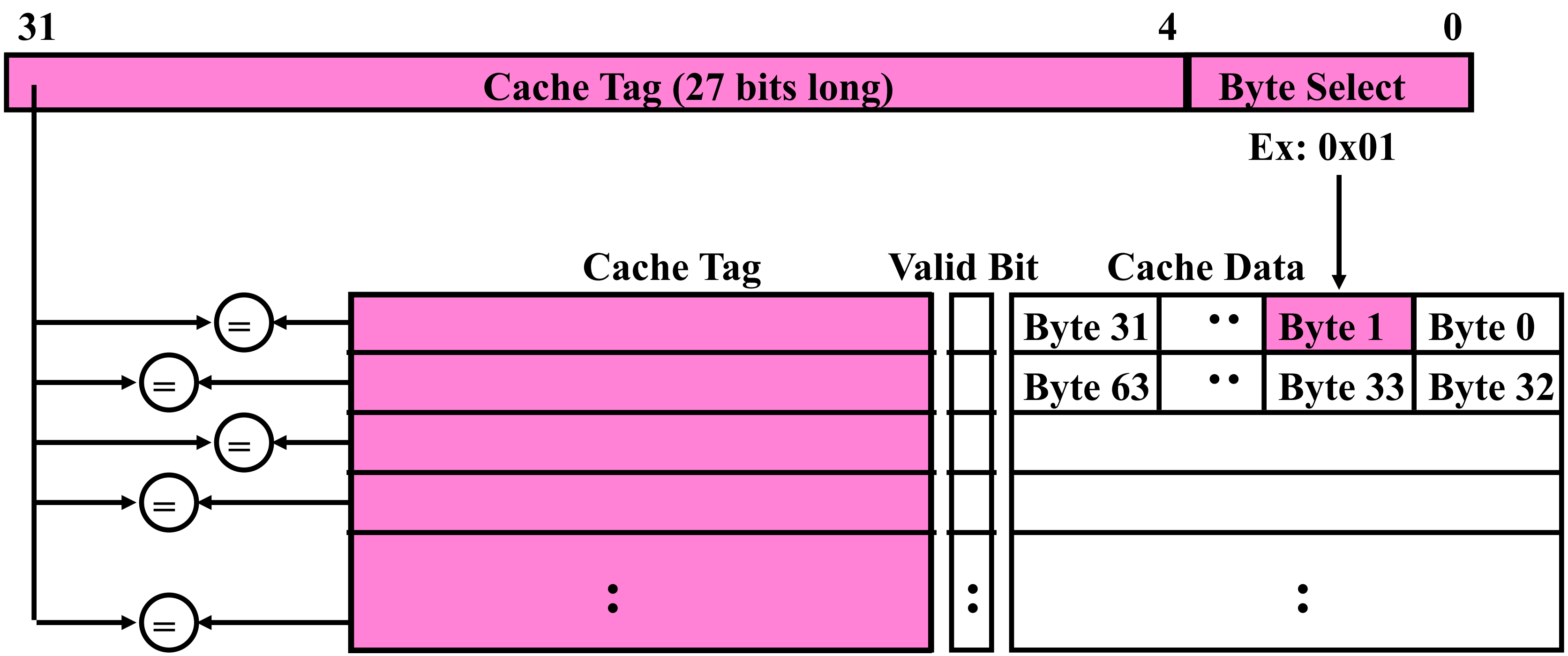
Set Associative Cache

- N-way set associative: N entries per Cache Index
  - N direct mapped caches operates in parallel
- Example: Two-way set associative cache
  - Two tags in the set are compared to input in parallel
  - Data is selected based on the tag result



Fully Associative Cache

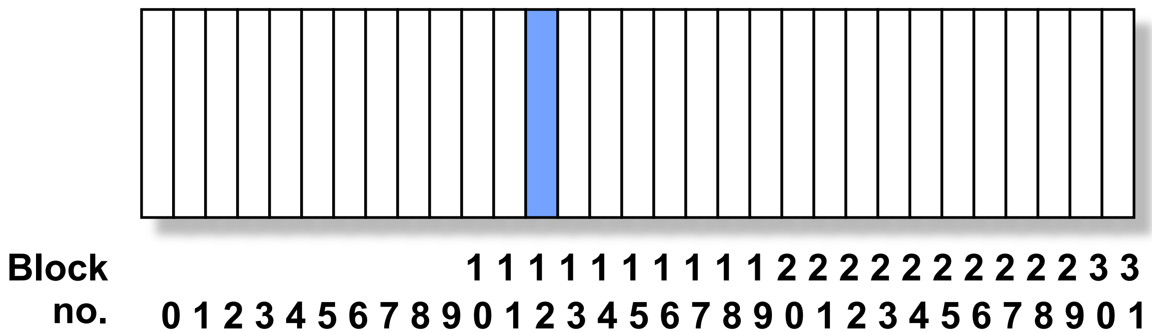
- Fully Associative: Every block can hold any line
  – Address does not include a cache index
  – Compare Cache Tags of all Cache Entries in Parallel
- Example: Block Size=32B blocks
  – We need N 27-bit comparators
  – Still have byte select to choose from within block



Where does a Block Get Placed in a Cache?

- Example: Block 12 placed in 8 block cache

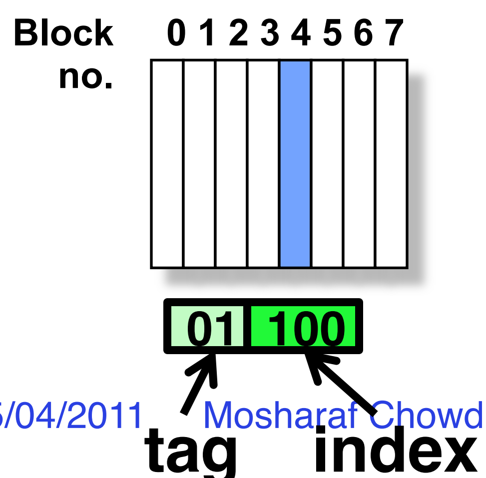
32-Block Address Space:

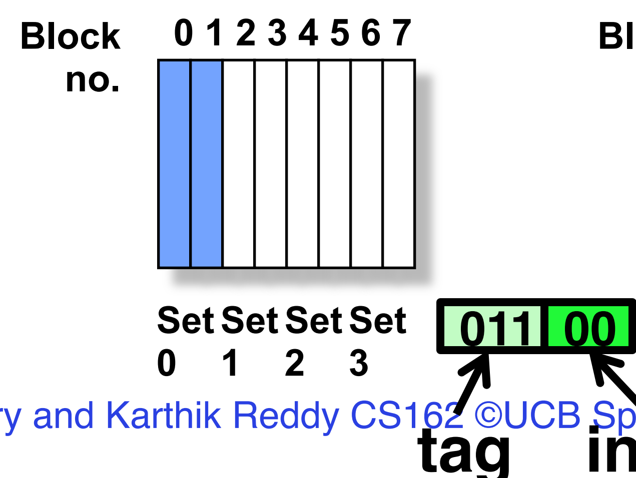


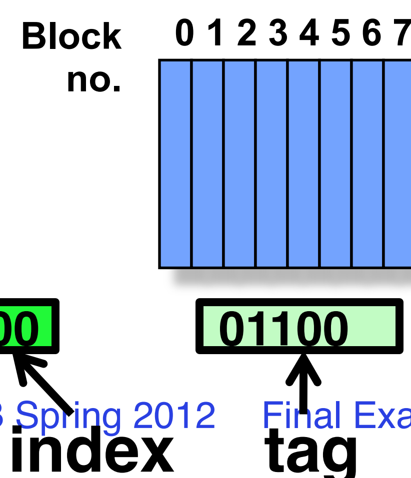
Direct mapped:
block 12 (01100) can go only into block 4 (12 mod 8)

Set associative:
block 12 can go anywhere in set 0 (12 mod 4)

Fully associative:
block 12 can go anywhere

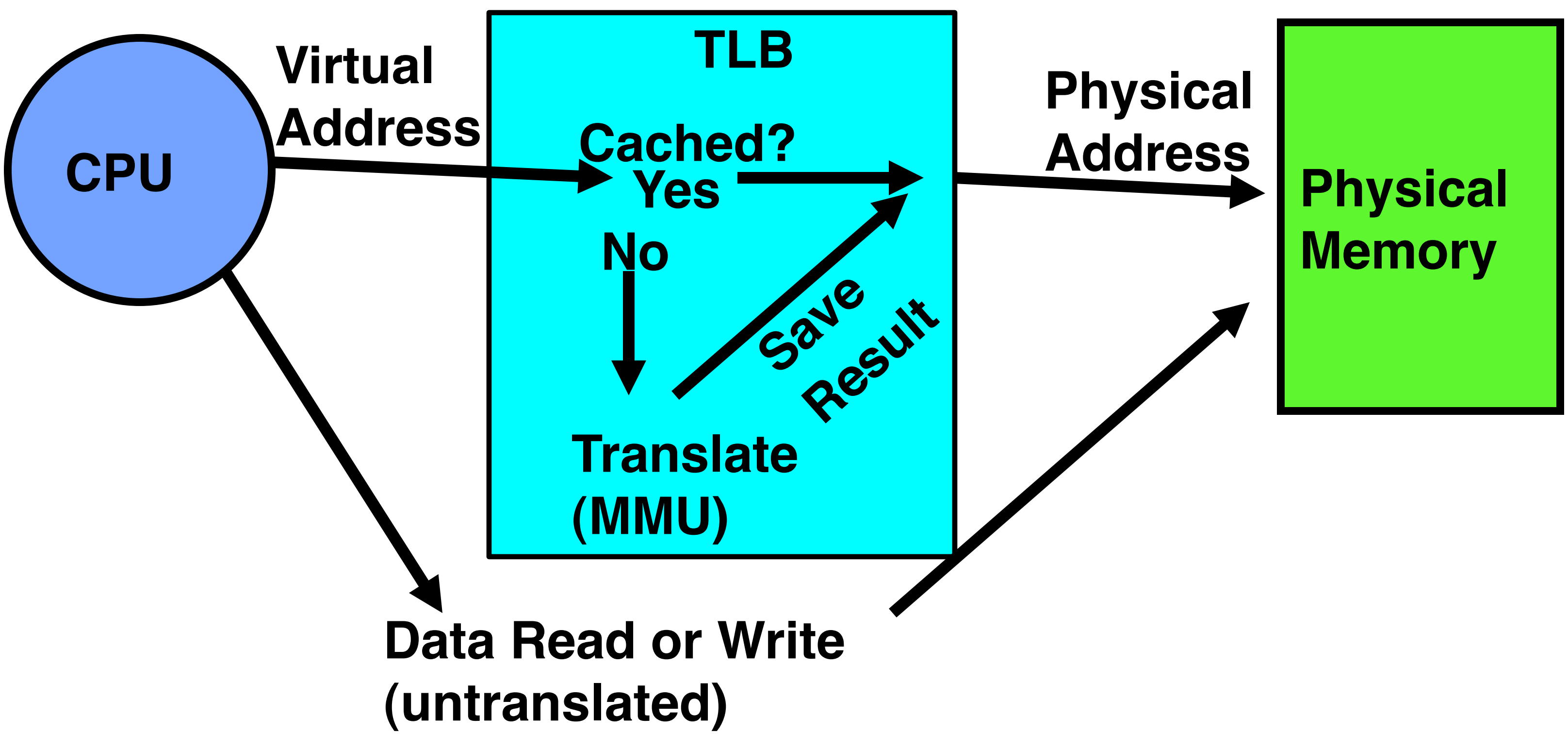






Review: Caching Applied to Address Translation

- Problem: address translation expensive (especially multi-level)
- Solution: cache address translation (TLB)
  - Instruction accesses spend a lot of time on the same page (since accesses sequential)
  - Stack accesses have definite locality of reference
  - Data accesses have less page locality, but still some…

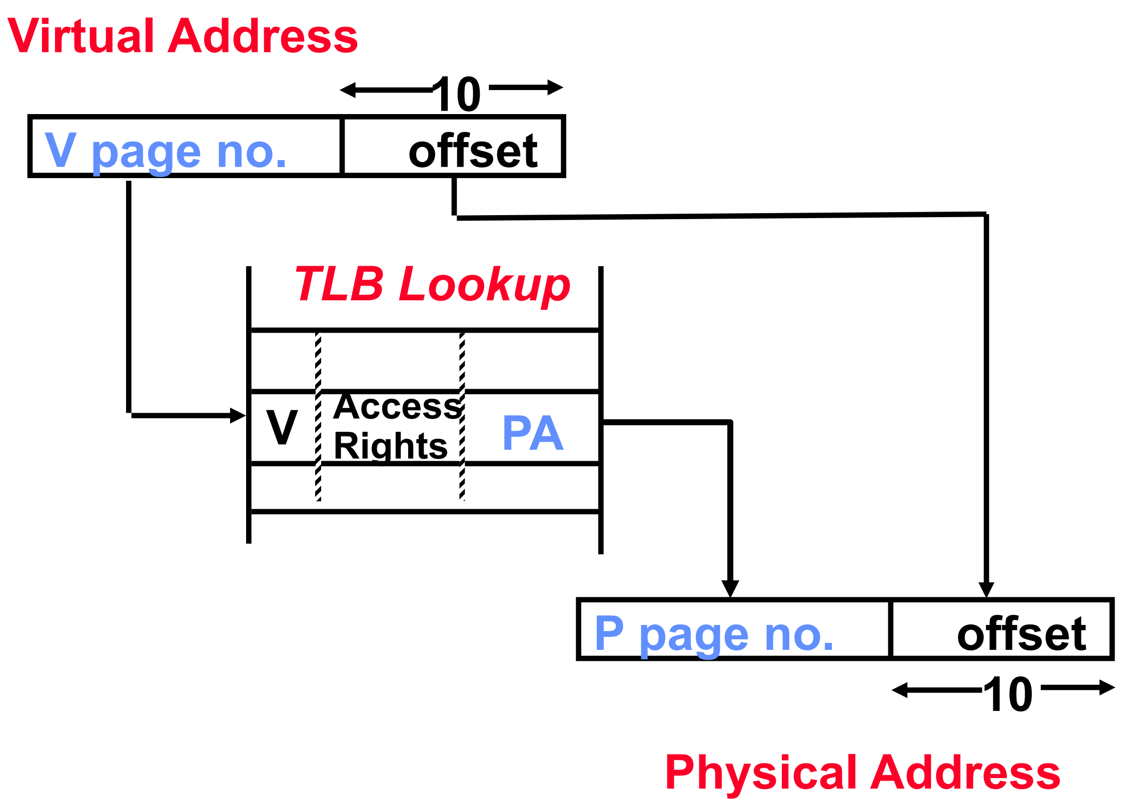


TLB organization

- How big does TLB actually have to be?
  - Usually small: 128-512 entries
  - Not very big, can support higher associativity
- TLB usually organized as fully-associative cache
  - Lookup is by Virtual Address
  - Returns Physical Address
- What happens when fully-associative is too slow?
  - Put a small (4-16 entry) direct-mapped cache in front
  - Called a "TLB Slice"
- When does TLB lookup occur?
  - Before cache lookup?
  - In parallel with cache lookup?

Reducing translation time further

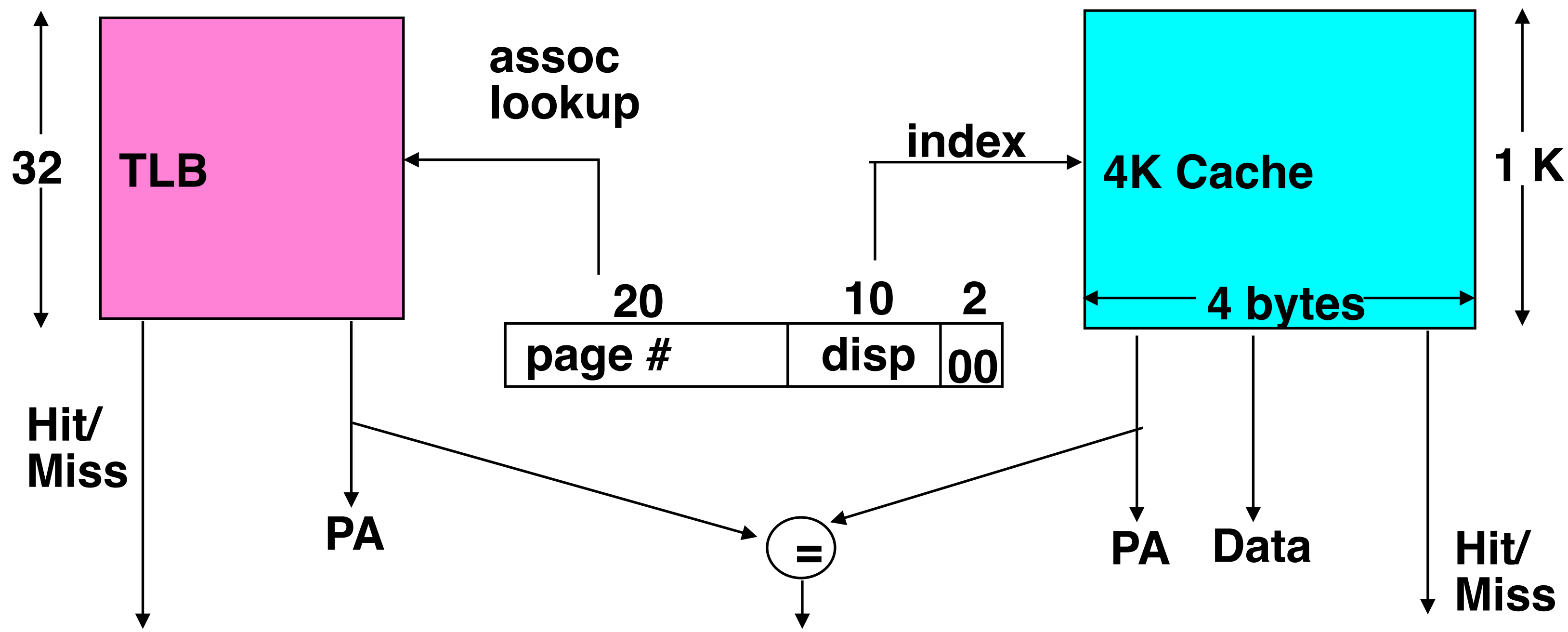
- As described, TLB lookup is in serial with cache lookup:



- Machines with TLBs go one step further: they overlap TLB lookup with cache access.
  – Works because offset available early

Overlapping TLB & Cache Access

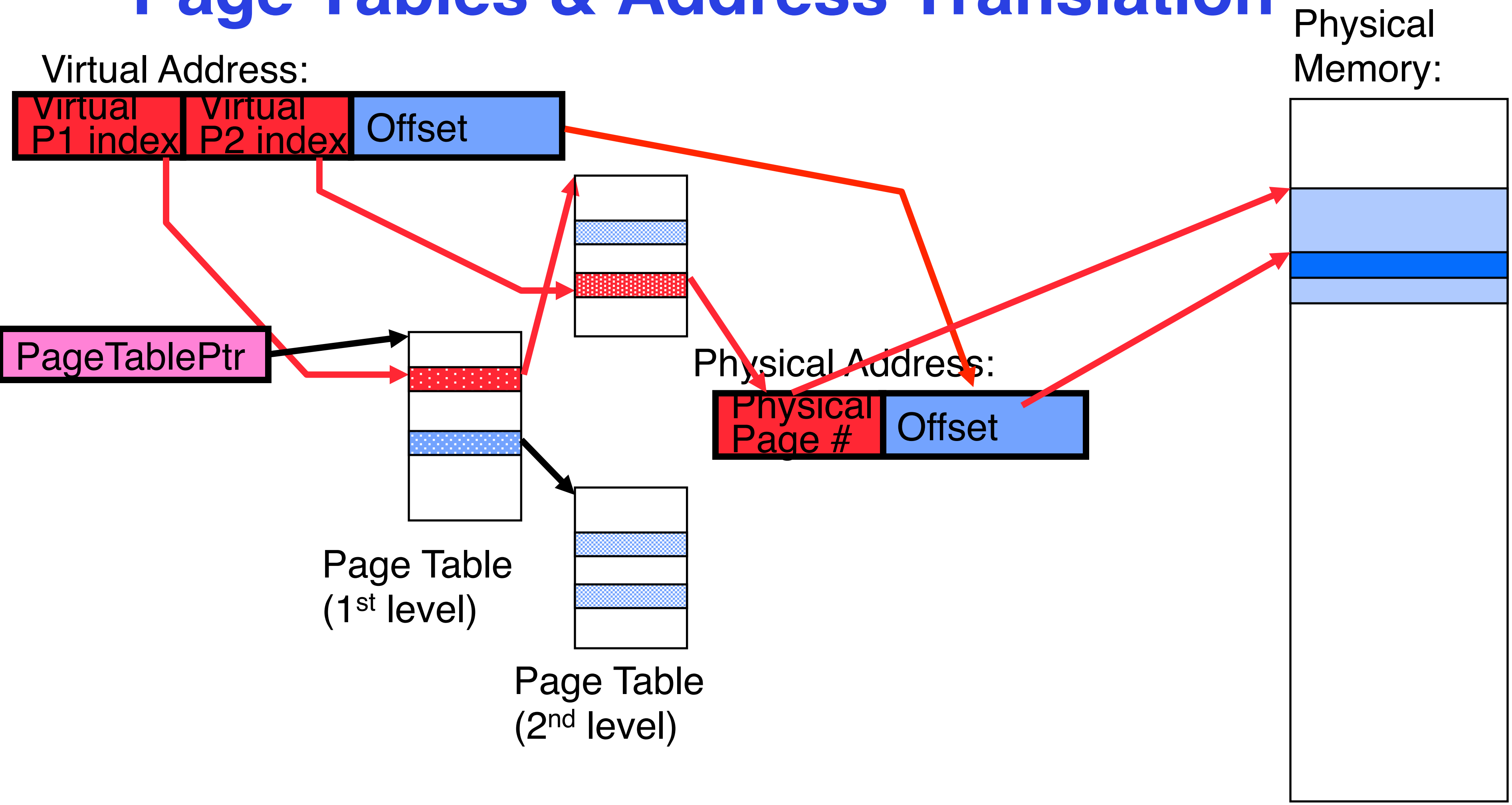
- Here is how this might work with a 4K cache:



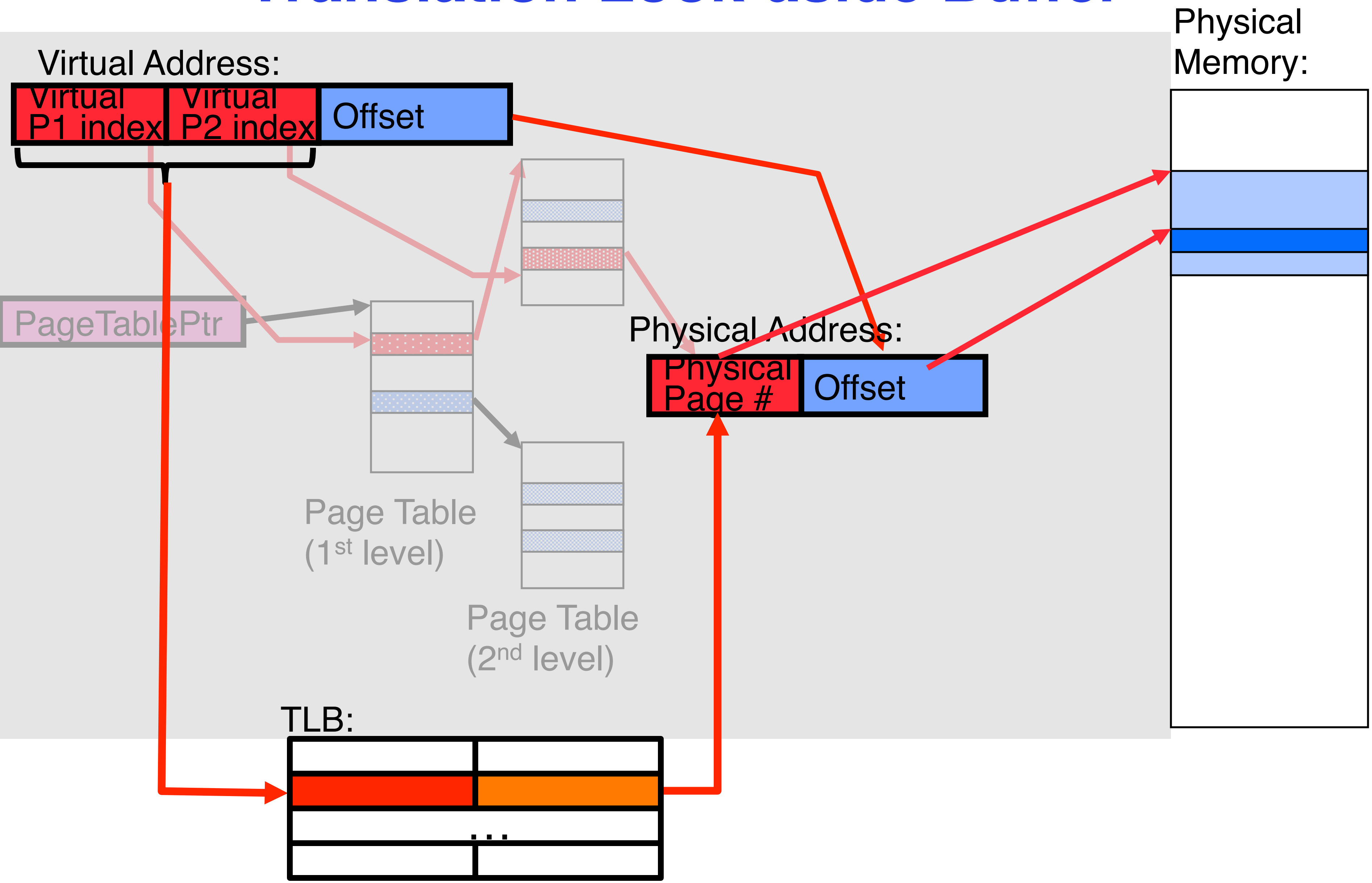
- What if cache size is increased to 8KB?
  - Overlap not complete
  - Need to do something else. See CS152/252
- Another option: Virtual Caches
  - Tags in cache are virtual addresses
  - Translation only happens on cache misses

Putting Everything Together

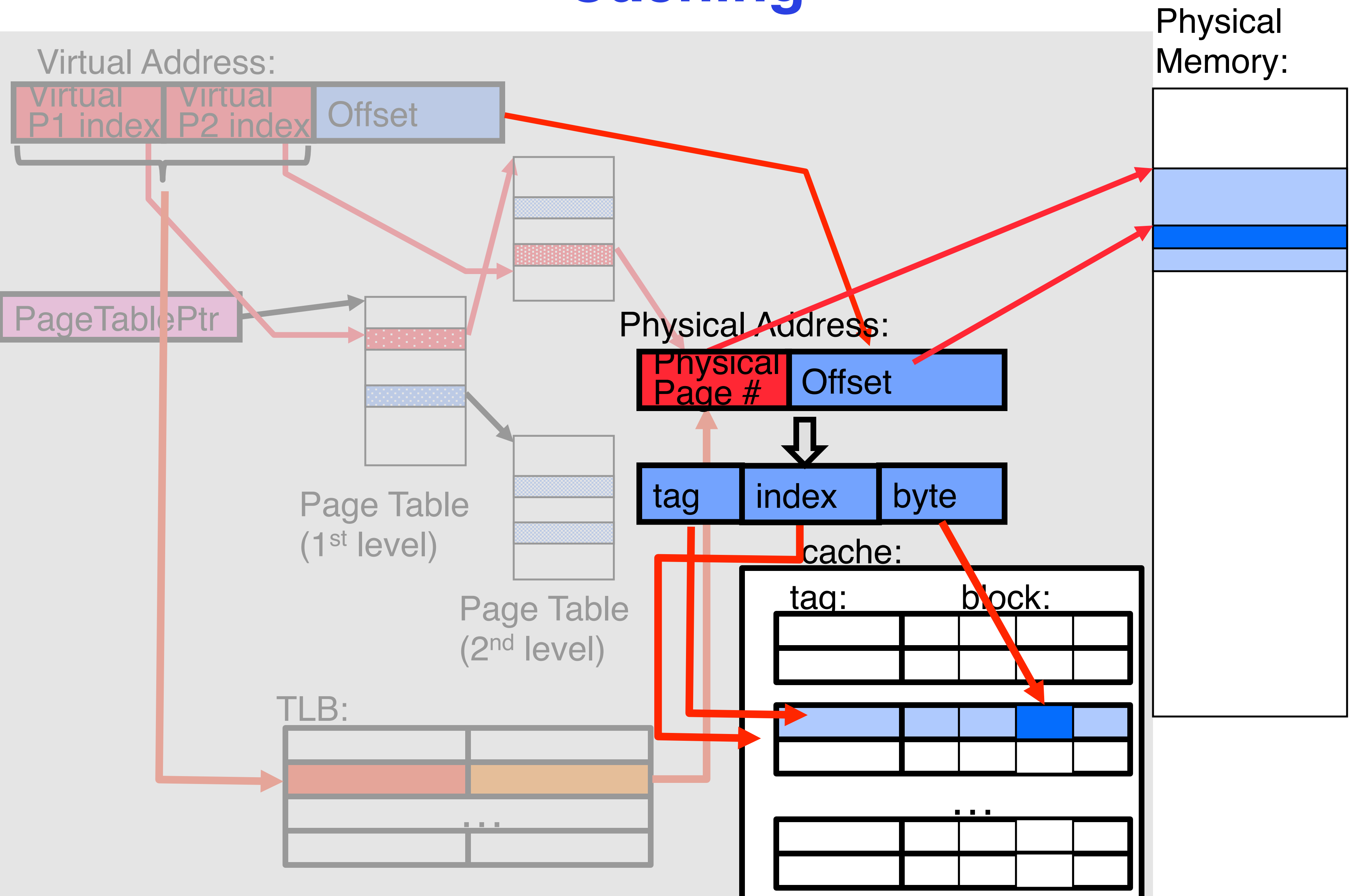
Page Tables & Address Translation



Translation Look-aside Buffer



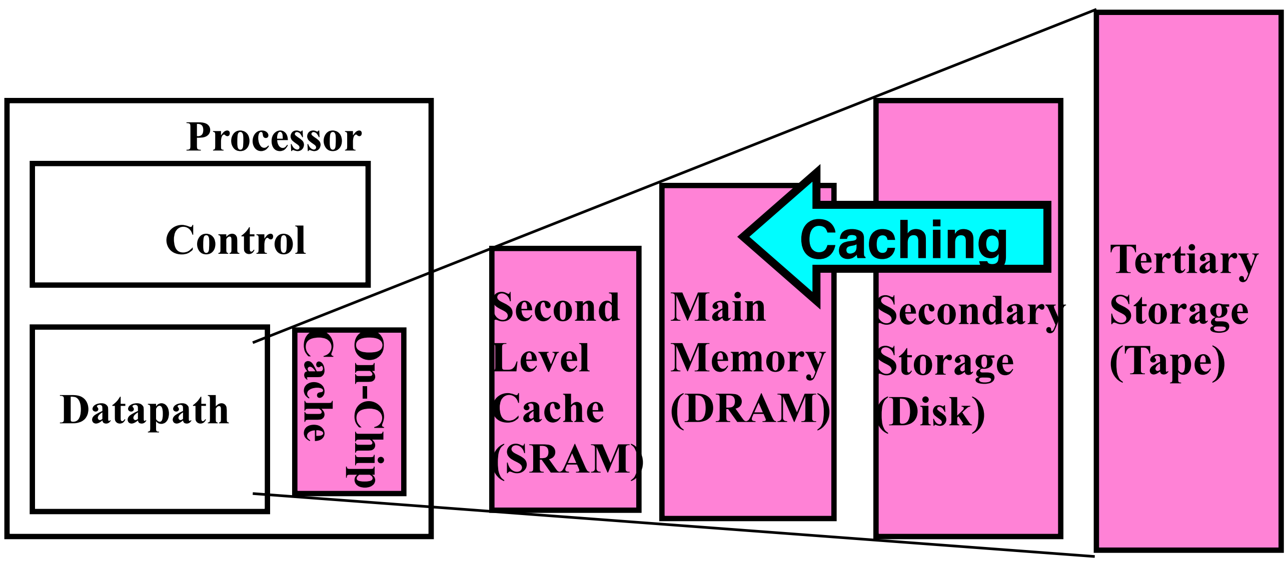
Caching


Physical
Memory:
Virtual Address:
Virtual P1 index
Virtual P2 index
Offset
PageTablePtr
Page Table
(1st level)
Page Table
(2nd level)
TLB:
...
Physical Address:
Physical Page #
Offset
tag
index
byte
cache:
tag:
block:
...

Demand Paging

Demand Paging

- Modern programs require a lot of physical memory
  – Memory per system growing faster than 25%-30%/year
- But they don't use all their memory all of the time
  – 90-10 rule: programs spend 90% of their time in 10% of their code
  – Wasteful to require all of user's code to be in memory
- Solution: use main memory as cache for disk

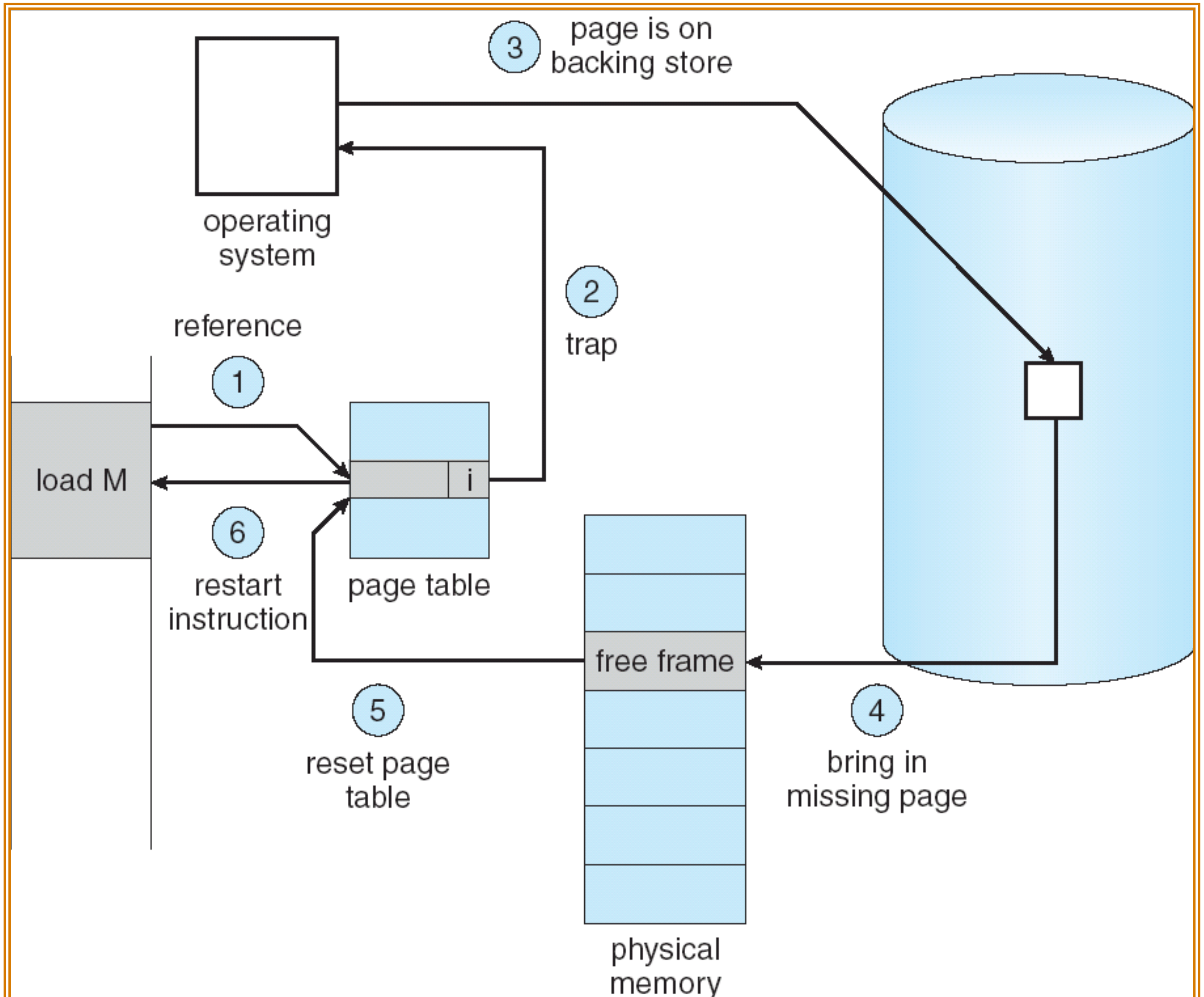


Demand Paging Mechanisms

- PTE helps us implement demand paging
  - Valid ⇒ Page in memory, PTE points at physical page
  - Not Valid ⇒ Page not in memory; use info in PTE to find it on disk when necessary
- Suppose user references page with invalid PTE?
  - Memory Management Unit (MMU) traps to OS
    - » Resulting trap is a "Page Fault"

  - What does OS do on a Page Fault?:
    - » Choose an old page to replace
    - » If old page modified ("D=1"), write contents back to disk
    - » Change its PTE and any cached TLB to be invalid
    - » Load new page into memory from disk
    - » Update page table entry, invalidate TLB for new entry
    - » Continue thread from original faulting location
  - TLB for new page will be loaded when thread continued!
  - While pulling pages off disk for one process, OS runs another process from ready queue
    - » Suspended process sits on wait queue

Steps in Handling a Page Fault



Page Replacement Policies

- FIFO (First In, First Out)
  – Throw out oldest page. Be fair – let every page live in memory for same amount of time.
  – Bad, because throws out heavily used pages instead of infrequently used pages
- MIN (Minimum):
  – Replace page that won't be used for the longest time
  – Great, but can't really know future…
  – Makes good comparison case, however
- LRU (Least Recently Used):
  – Replace page that hasn't been used for the longest time
  – Programs have locality, so if something not used for a while, unlikely to be used in the near future.
  – Seems like LRU should be a good approximation to MIN.

Example: FIFO

- Suppose we have 3 page frames, 4 virtual pages, and following reference stream:
  - A B C A B D A D B C B
- Consider FIFO Page replacement:

Ref: Page:	A	B	C	A	B	D	A	D	B	C	B
1	A					D				C	
2		B					A				
3			C						B		

  - FIFO: 7 faults.
  - When referencing D, replacing A is bad choice, since need A again right away

Example: MIN

- Suppose we have the same reference stream:
  - A B C A B D A D B C B
- Consider MIN Page replacement:

Ref: / Page:	A	B	C	A	B	D	A	D	B	C	B
1	A									C	
2		B									
3			C			D					

  - MIN: 5 faults
  - Look for page not referenced farthest in future.
- What will LRU do?
  - Same decisions as MIN here, but won't always be true!

When will LRU perform badly?

- Consider the following: A B C D A B C D A B C D
- LRU Performs as follows (same as FIFO here):

Ref: Page:	A	B	C	D	A	B	C	D	A	B	C	D
1	A			D			C			B		
2		B			A			D			C	
3			C			B			A			D

  – Every reference is a page fault!
- MIN Does much better:

Ref: Page:	A	B	C	D	A	B	C	D	A	B	C	D
1	A									B		
2		B					C					
3			C	D								

Adding Memory Doesn't Always Help Fault Rate

- Does adding memory reduce number of page faults?
  - Yes for LRU and MIN
  - Not necessarily for FIFO! (Belady's anomaly)

Page:	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E					
2		B			A					C		
3			C			B					D	

Page:	A	B	C	D	A	B	E	A	B	C	D	E
1	A						E				D	
2		B						A				E
3			C						B			
4				D						C		

- After adding memory:
  - With FIFO, contents can be completely different
  - In contrast, with LRU or MIN, contents of memory with X pages are a subset of contents with X+1 Page

Implementing LRU & Second Chance

- Perfect:
  - Timestamp page on each reference
  - Keep list of pages ordered by time of reference
  - Too expensive to implement in reality for many reasons

- Second Chance Algorithm:
  - Approximate LRU
    - » Replace an old page, not the oldest page
  - FIFO with "use" (reference) bit

- Details
  - A "use" bit per physical page
  - On page fault check page at head of queue
    - » If use bit=1 → clear bit, and move page at tail (give the page second chance!)
    - » If use bit=0 → replace page
  - Moving pages to tail still complex

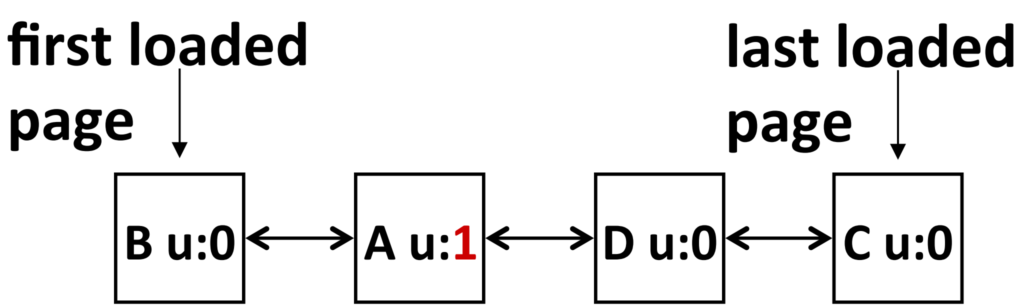
Clock Algorithm

- Clock Algorithm: more efficient implementation of second chance algorithm
  – Arrange physical pages in circle with single clock hand
- Details:
  – On page fault:
    » Advance clock hand (not real time)
    » Check use bit: 1→used recently; clear and leave it alone
    0→selected candidate for replacement
  – Will always find a page or loop forever?

- What if hand moving slowly?
  – Good sign or bad sign?
    » Not many page faults and/or find page quickly
- What if hand is moving quickly?
  – Lots of page faults and/or lots of reference bits set

Second Chance Illustration

- Max page table size 4
  - Page B arrives
  - Page A arrives
  - Access page A
  - Page D arrives
  - Page C arrives



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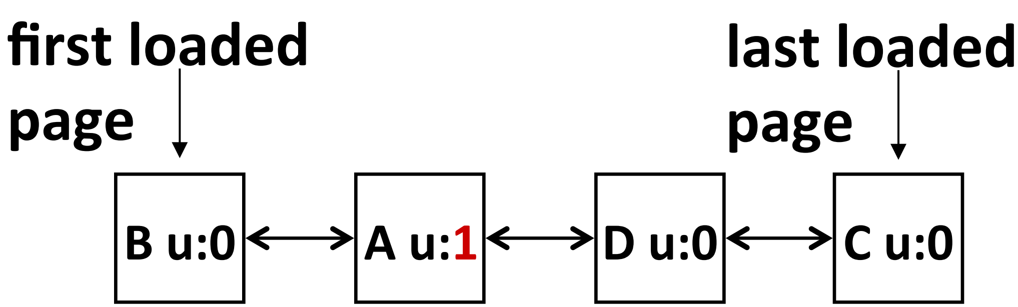

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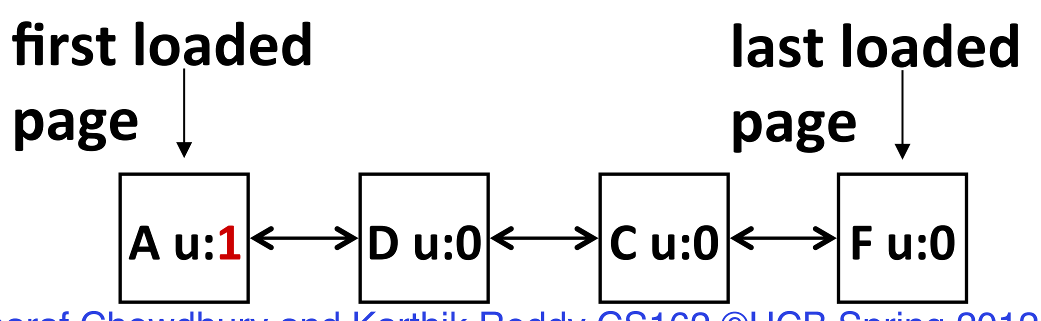

Second Chance Illustration

- Max page table size 4
  - Page B arrives
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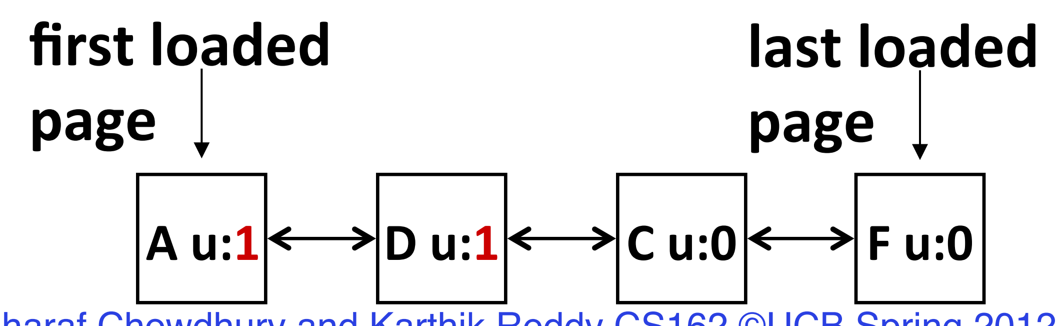
  - Page D arrives
  - Page C arrives
  - Page F arrives
  - Access page D
  - Page E arrives



Second Chance Illustration

- Max page table size 4
  - Page B arrives
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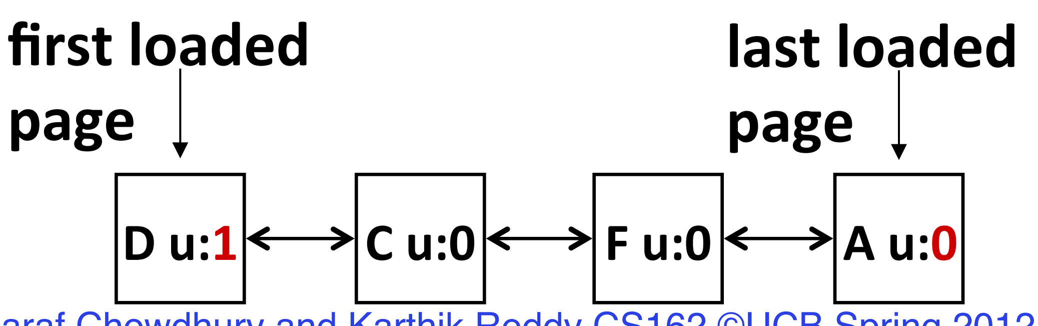

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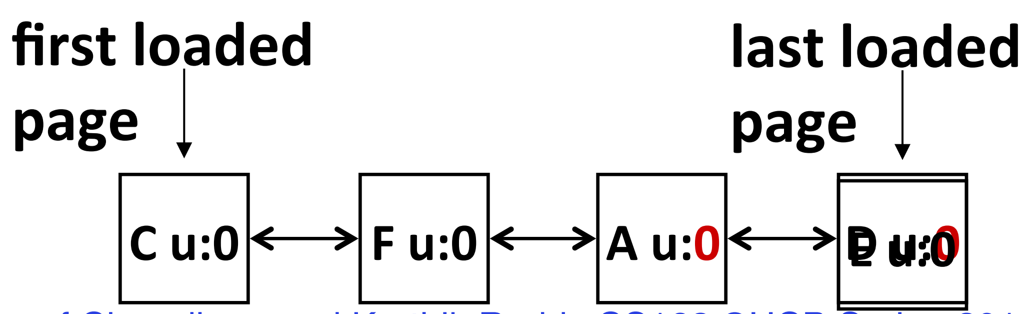
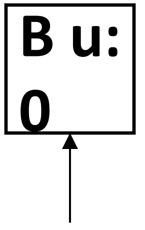


Clock Replacement Illustration

- Max page table size 4
- Invariant: point at oldest page
  - Page B arrives



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- Invariant: point at oldest page

  - Page B arrives
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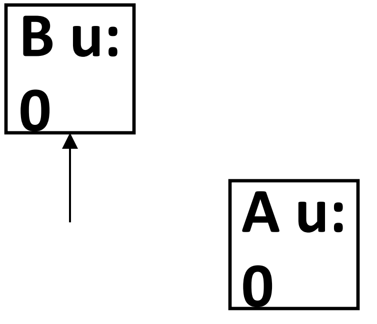

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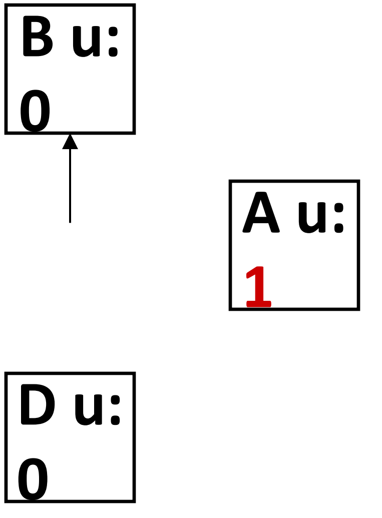

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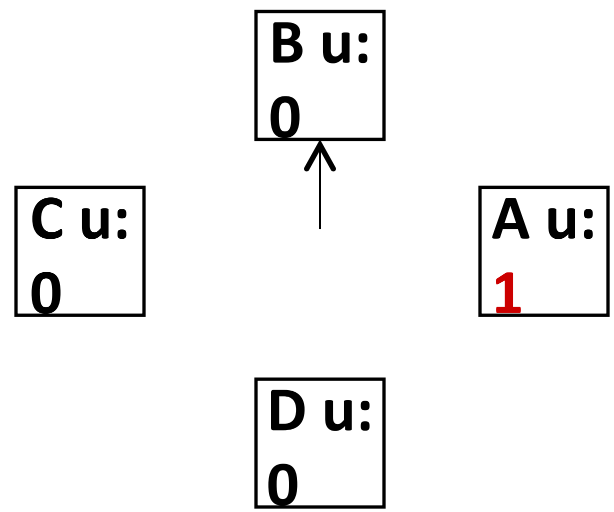

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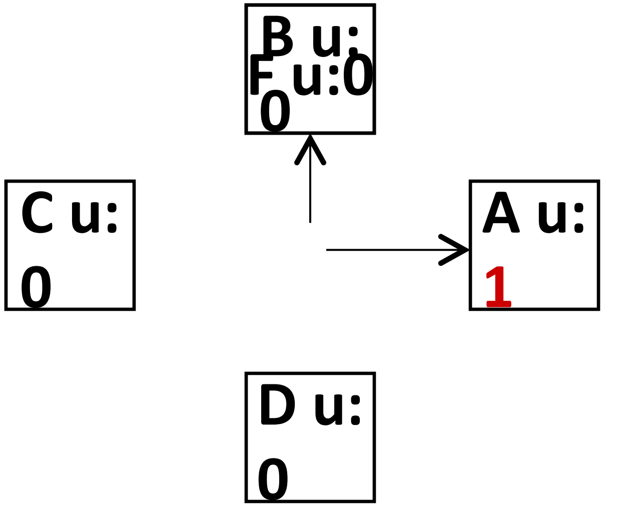

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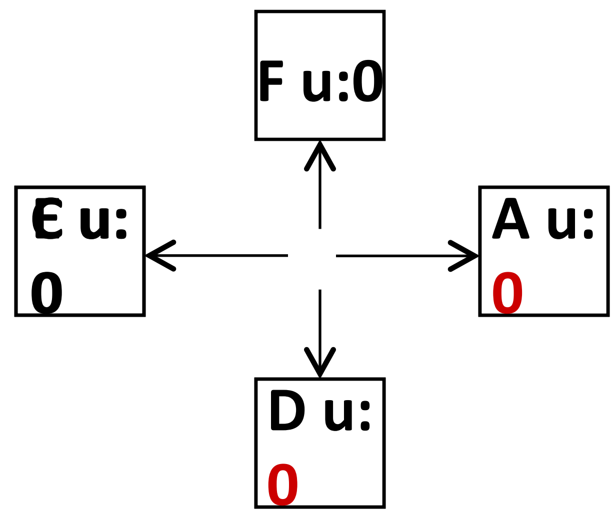
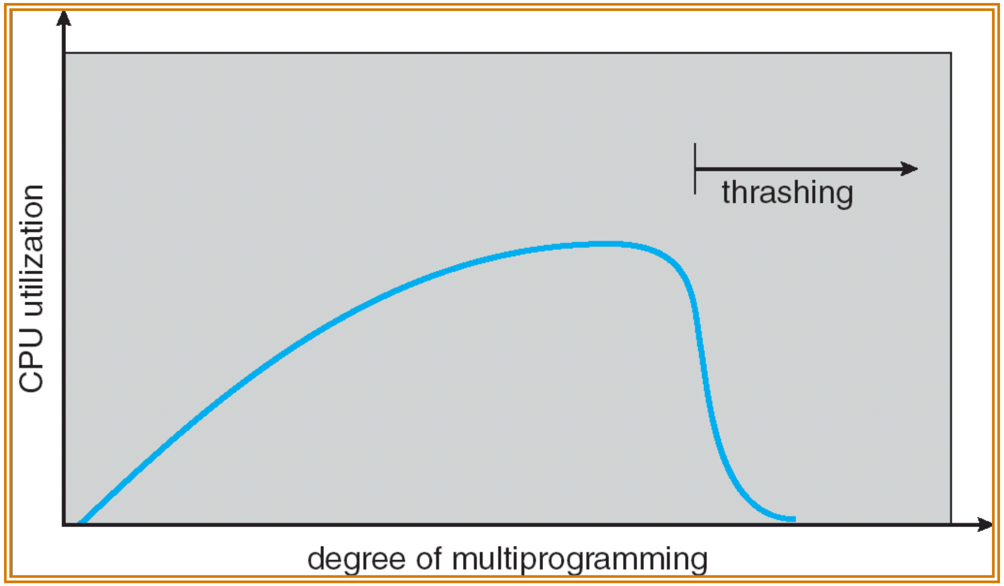


N^{th} Chance version of Clock Algorithm

- N^{th} chance algorithm: Give page N chances
  - OS keeps counter per page: # sweeps
  - On page fault, OS checks use bit:
    - » 1⇒clear use and also clear counter (used in last sweep)
    - » 0⇒increment counter; if count=N, replace page
  - Means that clock hand has to sweep by N times without page being used before page is replaced
- How do we pick N?
  - Why pick large N? Better approx to LRU
    - » If N ~ 1K, really good approximation
  - Why pick small N? More efficient
    - » Otherwise might have to look a long way to find free page
- What about dirty pages?
  - Takes extra overhead to replace a dirty page, so give dirty pages an extra chance before replacing?
  - Common approach:
    - » Clean pages, use N=1
    - » Dirty pages, use N=2 (and write back to disk when N=1)

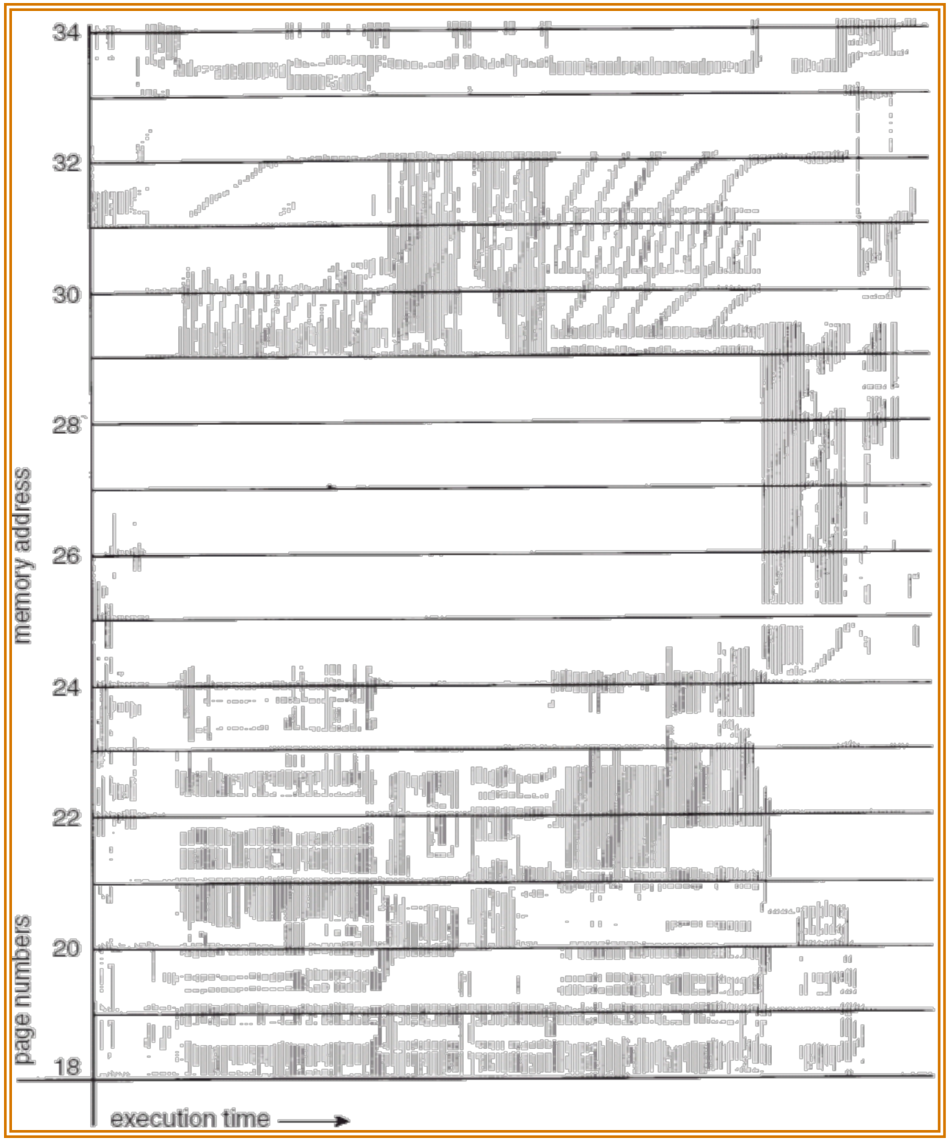
Thrashing



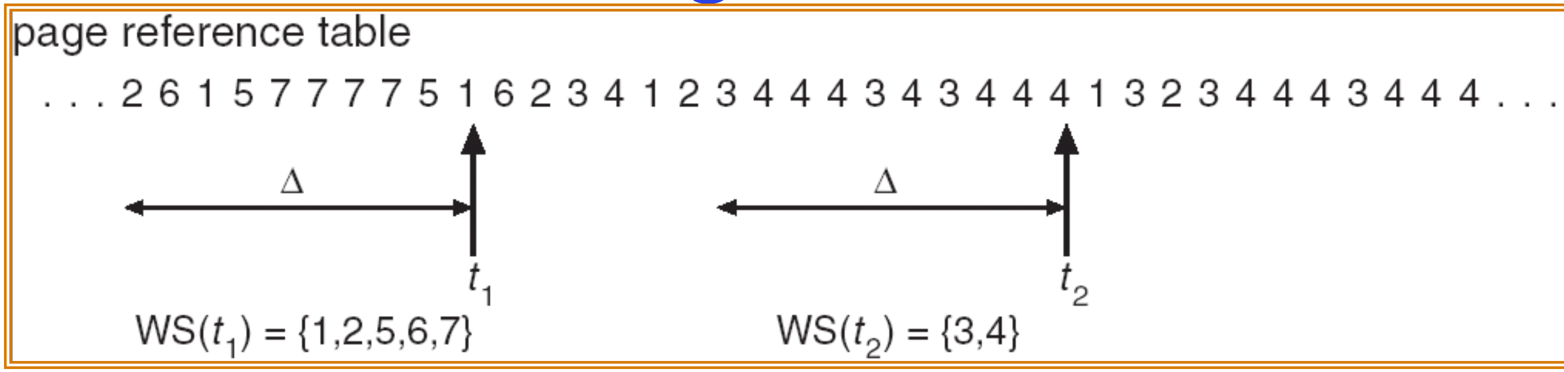
- If a process does not have "enough" pages, the page-fault rate is very high. This leads to:
  - low CPU utilization
  - operating system spends most of its time swapping to disk
- Thrashing ≡ a process is busy swapping pages in and out
- Questions:
  - How do we detect Thrashing?
  - What is best response to Thrashing?

Locality In A Memory-Reference Pattern

- Program Memory Access Patterns have temporal and spatial locality
  - Group of Pages accessed along a given time slice called the "Working Set"
  - Working Set defines minimum number of pages needed for process to behave well
- Not enough memory for Working Set⇒Thrashing
  - Better to swap out process?



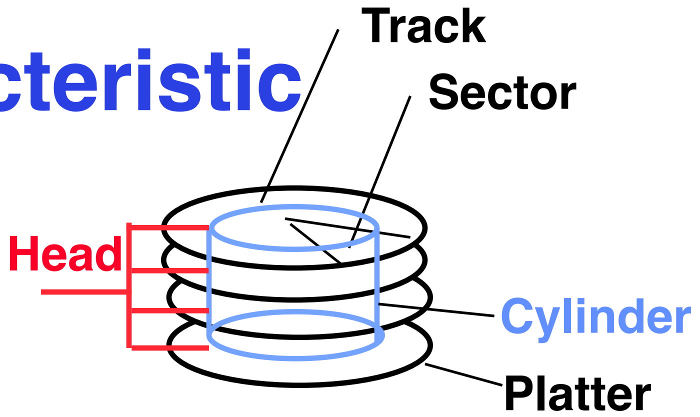
Working-Set Model



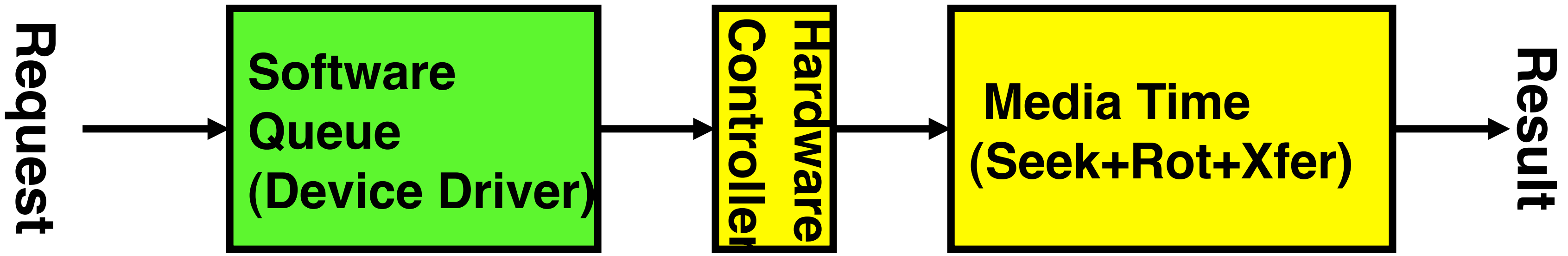
- Δ ≡ working-set window ≡ fixed number of page references
  – Example: 10,000 instructions
- WS_i (working set of Process P_i) = total set of pages referenced in the most recent Δ (varies in time)
  – if Δ too small will not encompass entire locality
  – if Δ too large will encompass several localities
  – if Δ = ∞ ⇒ will encompass entire program
- $D = \Sigma|WS_i| \equiv$ total demand frames
- if $D >$ *memory* ⇒ Thrashing
  – Policy: if $D >$ memory, then suspend/swap out processes
  – This can improve overall system behavior by a lot!

File Systems

Review: Magnetic Disk Characteristic



- Cylinder: all the tracks under the head at a given point on all surface
- Read/write data is a three-stage process:
  - Seek time: position the head/arm over the proper track (into proper cylinder)
  - Rotational latency: wait for the desired sector to rotate under the read/write head
  - Transfer time: transfer a block of bits (sector) under the read-write head
- Disk Latency = Queuing Time + Controller time + Seek Time + Rotation Time + Xfer Time



- Highest Bandwidth:
  - transfer large group of blocks sequentially from one track

Building a File System

- File System: OS layer that transforms block interface of disks into Files, Directories, etc.

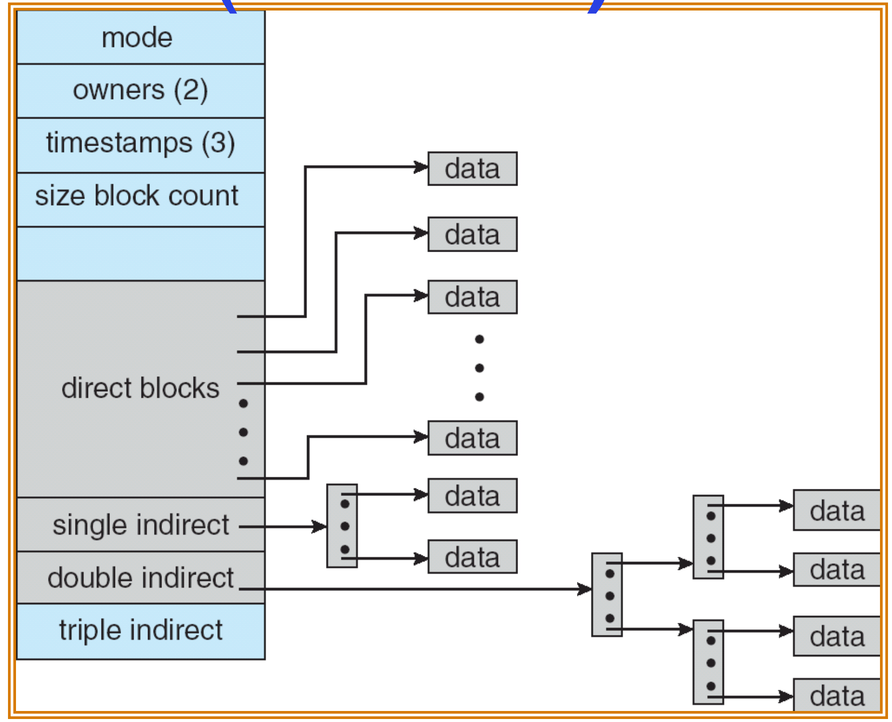
- File System Components
  - Disk Management: collecting disk blocks into files
  - Naming: Interface to find files by name, not by blocks
  - Protection: Layers to keep data secure
  - Reliability/Durability

- How do users access files?
  - Sequential Access: bytes read in order (most file accesses)
  - Random Access: read/write element out of middle of array

- Goals:
  - Maximize sequential performance
  - Easy random access to file
  - Easy management of file (growth, truncation, etc)

Multilevel Indexed Files (UNIX 4.1)

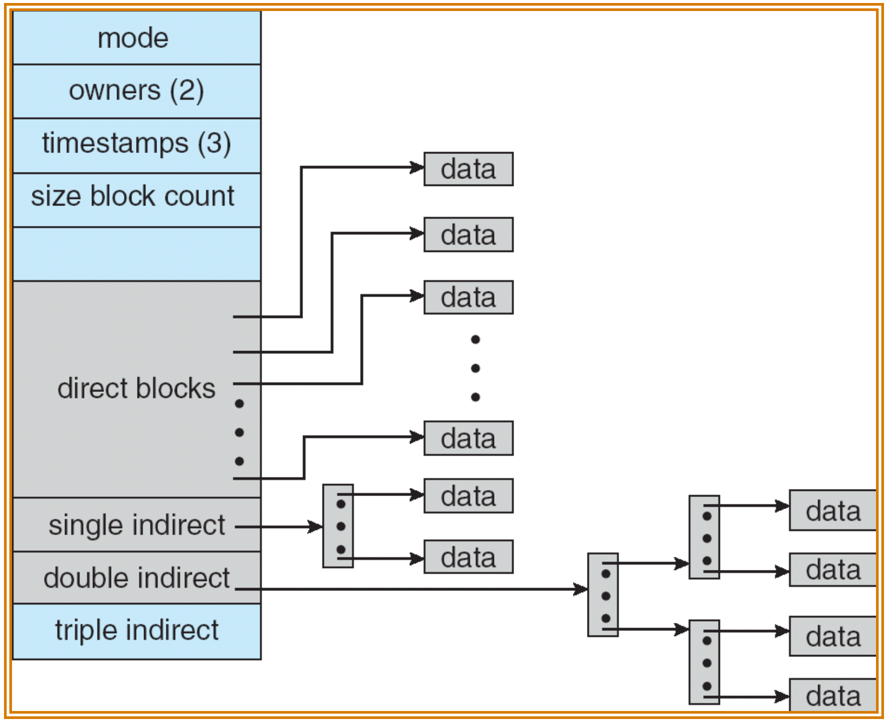
- Multilevel Indexed Files: (from UNIX 4.1 BSD)
  – Key idea: efficient for small files, but still allow big files



- File hdr contains 13 pointers
  – Fixed size table, pointers not all equivalent
  – This header is called an "inode" in UNIX
- File Header format:
  – First 10 pointers are to data blocks
  – Ptr 11 points to "indirect block" containing 256 block ptrs
  – Pointer 12 points to "doubly indirect block" containing 256 indirect block ptrs for total of 64K blocks
  – Pointer 13 points to a triply indirect block (16M blocks)

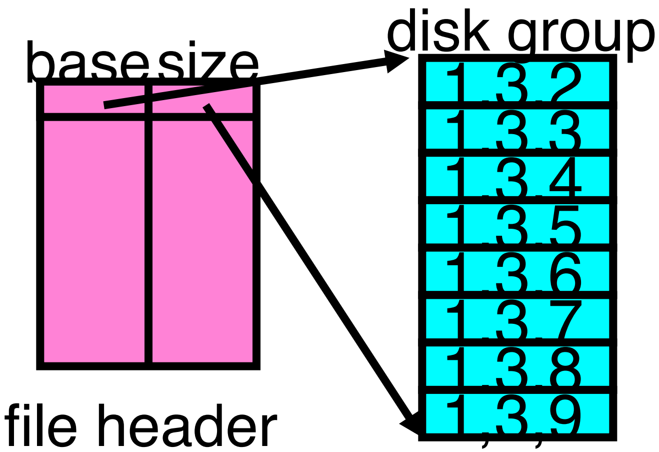
Example of Multilevel Indexed Files

- Sample file in multilevel indexed format:
  - How many accesses for block #23? (assume file header accessed on open)?
    - » Two: One for indirect block, one for data
  - How about block #5?
    - » One: One for data
  - Block #340?
    - » Three: double indirect block, indirect block, and data



- UNIX 4.1 Pros and cons
  - Pros: Simple (more or less)
    Files can easily expand (up to a point)
    Small files particularly cheap and easy
  - Cons: Lots of seeks
    Very large files must read many indirect blocks (four I/O's per block!)

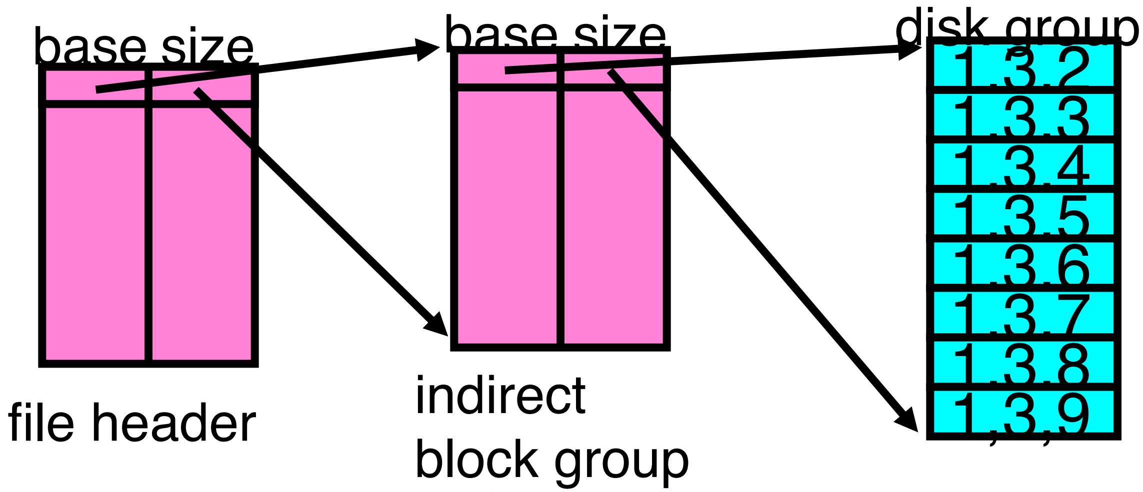
File Allocation for Cray-1 DEMOS



Basic Segmentation Structure:
Each segment contiguous on disk

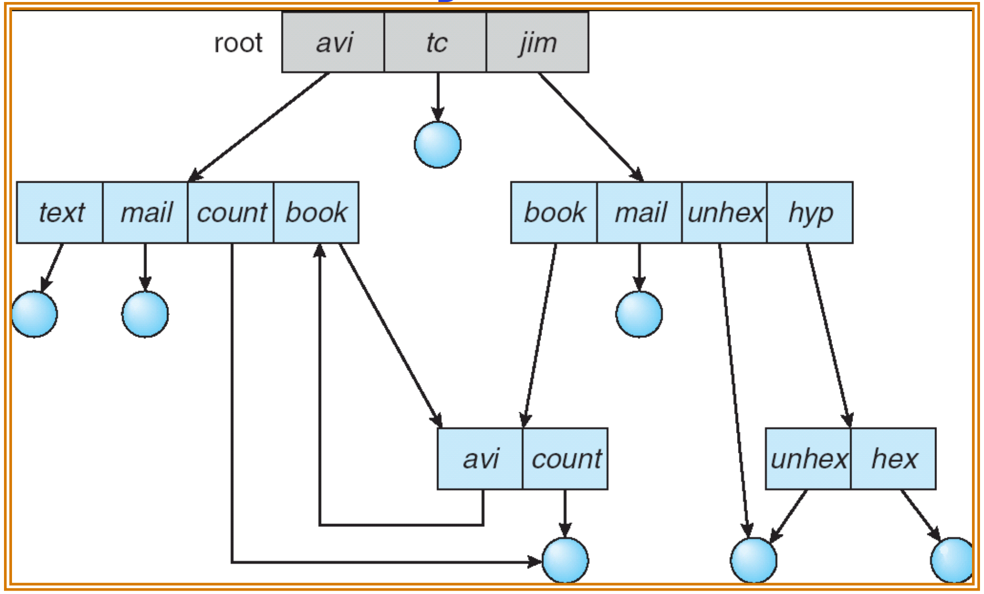
- DEMOS: File system structure similar to segmentation
  - Idea: reduce disk seeks by
    - » using contiguous allocation in normal case
    - » but allow flexibility to have non-contiguous allocation
  - Cray-1 had 12ns cycle time, so CPU:disk speed ratio about the same as today (a few million instructions per seek)
- Header: table of base & size (10 "block group" pointers)
  - Each block chunk is a contiguous group of disk blocks
  - Sequential reads within a block chunk can proceed at high speed – similar to continuous allocation
- How do you find an available block group?
  - Use freelist bitmap to find block of 0's.

Large File Version of DEMOS



- What if need much bigger files?
  - If need more than 10 groups, set flag in header: BIGFILE
    - » Each table entry now points to an indirect block group
  - Suppose 1000 blocks in a block group ⇒ 80GB max file
    - » Assuming 8KB blocks, 8byte entries⇒ (10 ptrs×1024 groups/ptr×1000 blocks/group)*8K =80GB
- Discussion of DEMOS scheme
  - Pros: Fast sequential access, Free areas merge simply
    Easy to find free block groups (when disk not full)
  - Cons: Disk full ⇒ No long runs of blocks (fragmentation), so high overhead allocation/access
  - Full disk ⇒ worst of 4.1BSD (lots of seeks) with worst of continuous allocation (lots of recompaction needed)

Directory Structure



- Not really a hierarchy!
  - Many systems allow directory structure to be organized as an acyclic graph or even a (potentially) cyclic graph
  - Hard Links: different names for the same file
    - » Multiple directory entries point at the same file
  - Soft Links: “shortcut” pointers to other files
    - » Implemented by storing the logical name of actual file
- Name Resolution: The process of converting a logical name into a physical resource (like a file)
  - Traverse succession of directories until reach target file
  - Global file system: May be spread across the network

Networking

How Does a Client Communicate with Servers?

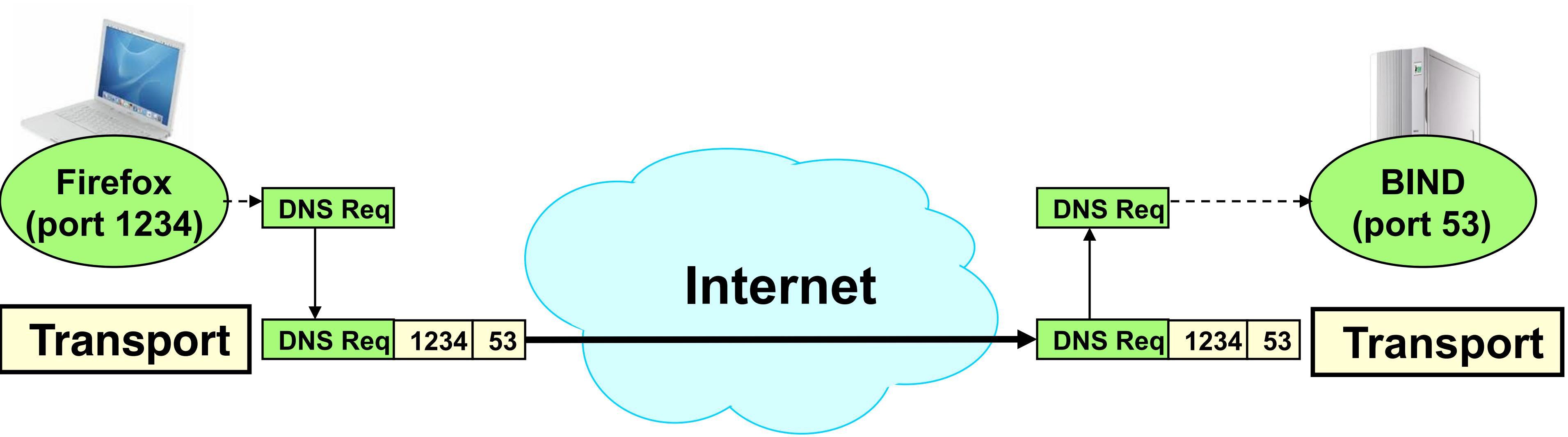
- A: Via **transport** protocol (e.g., UDP, TCP, …)

- Transport protocol in a nutshell:
  - Allow two application end-points to communicate
    - » Each application identified by a port number on the machine it runs
  - Multiplexes/demultiplexes packets from/to different processes using port numbers
  - Can provide reliability, flow control, congestion control

- Two main transport protocols in the Internet
  - **User datagram protocol (UDP):** just provide multiplexing/ demultiplexing, no reliability
  - **Transport Control Protocol (TCP):** provide reliability, flow control, congestion control

Transport Layer

- DNS server runs at a specific port number, i.e., 53
  – Most popular DNS server: BIND (Berkeley Internet Name Domain)
  – Assume client (browser) port number 1234



How do UDP packets Get to Destination?

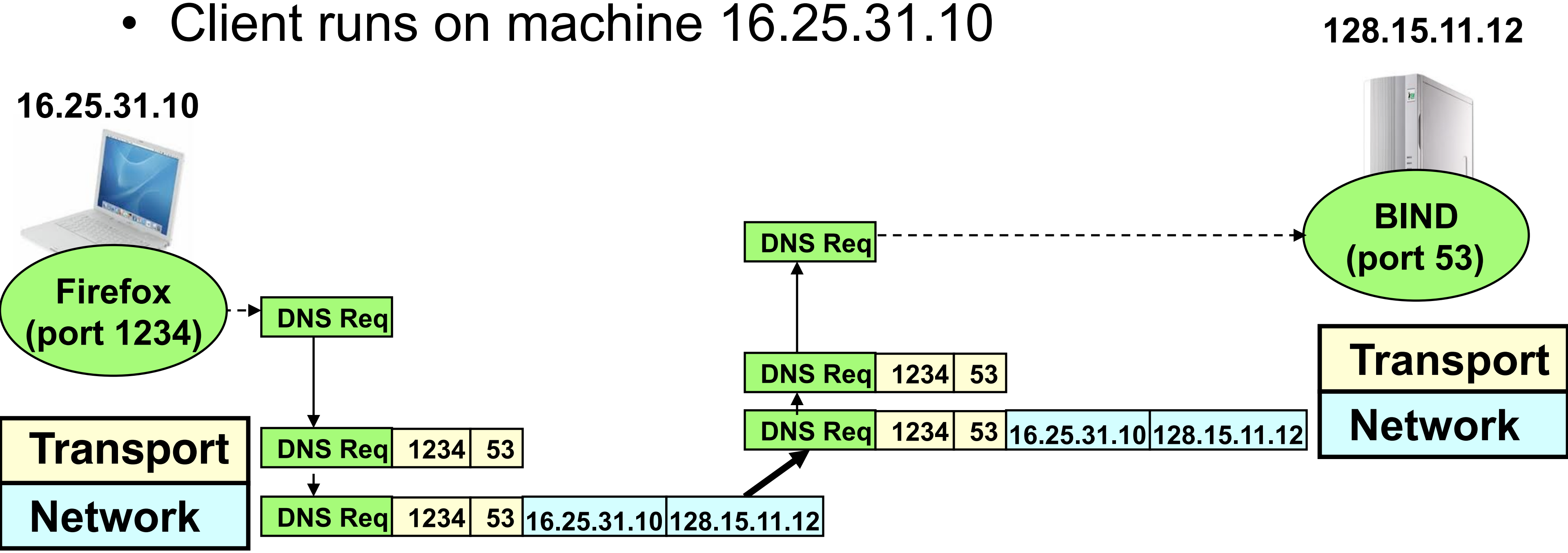
- A: Via network layer, i.e., Internet Protocol (IP)

- Implements datagram packet switching
  - Enable two end-hosts to exchange packets
    - » Each end-host is identified by an IP address
    - » Each packets contains destination IP address
    - » **Independently** routes each packet to its destination

  - **Best effort service**
    - » No deliver guarantees
    - » No in-order delivery guarantees

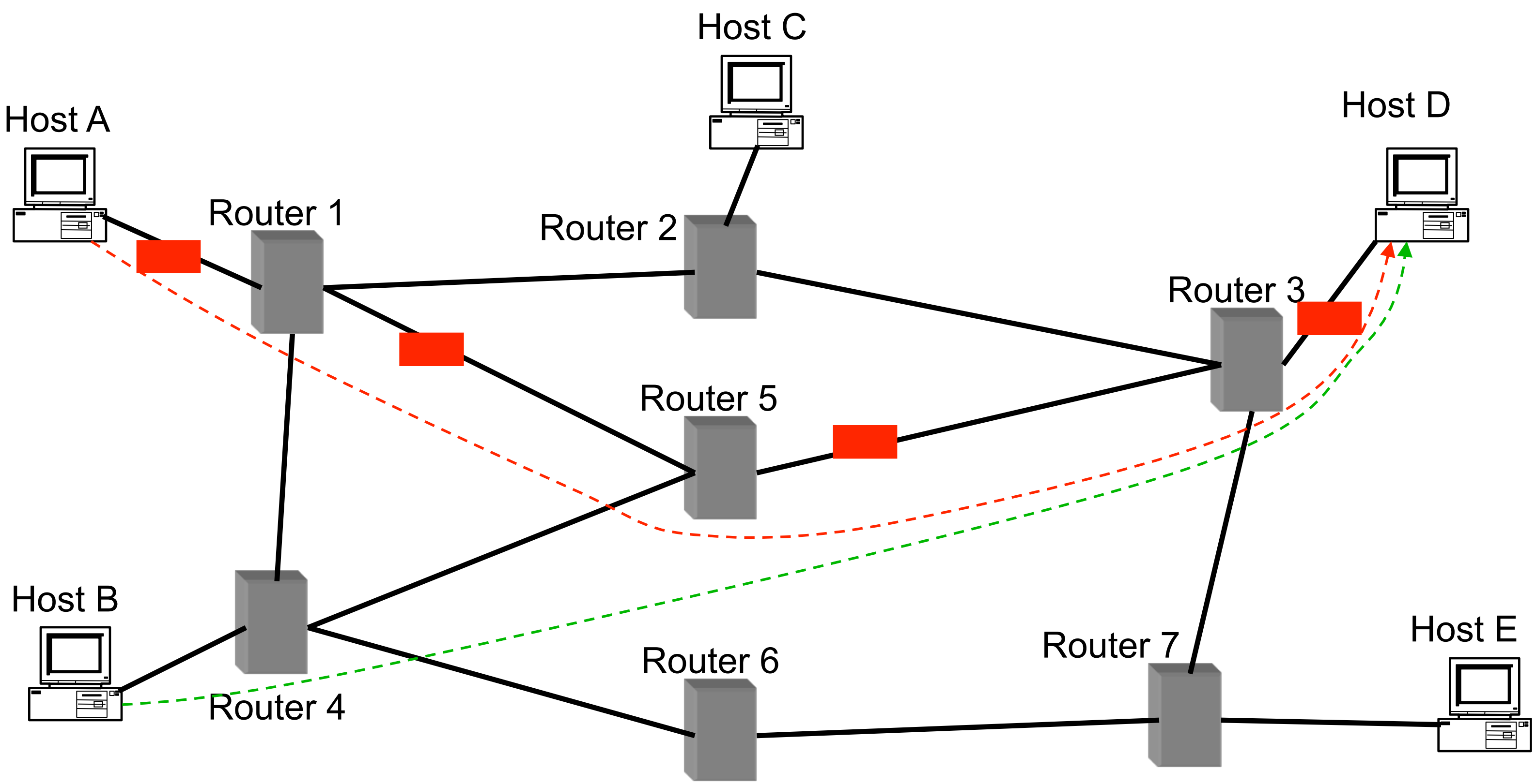
Network (IP) Layer (cont'd)

- Assume DNS server runs on machine 128.15.11.12
  - Client configured with DNS server IP address
- Client runs on machine 16.25.31.10



IP Packet Routing

- Each packet is individually routed



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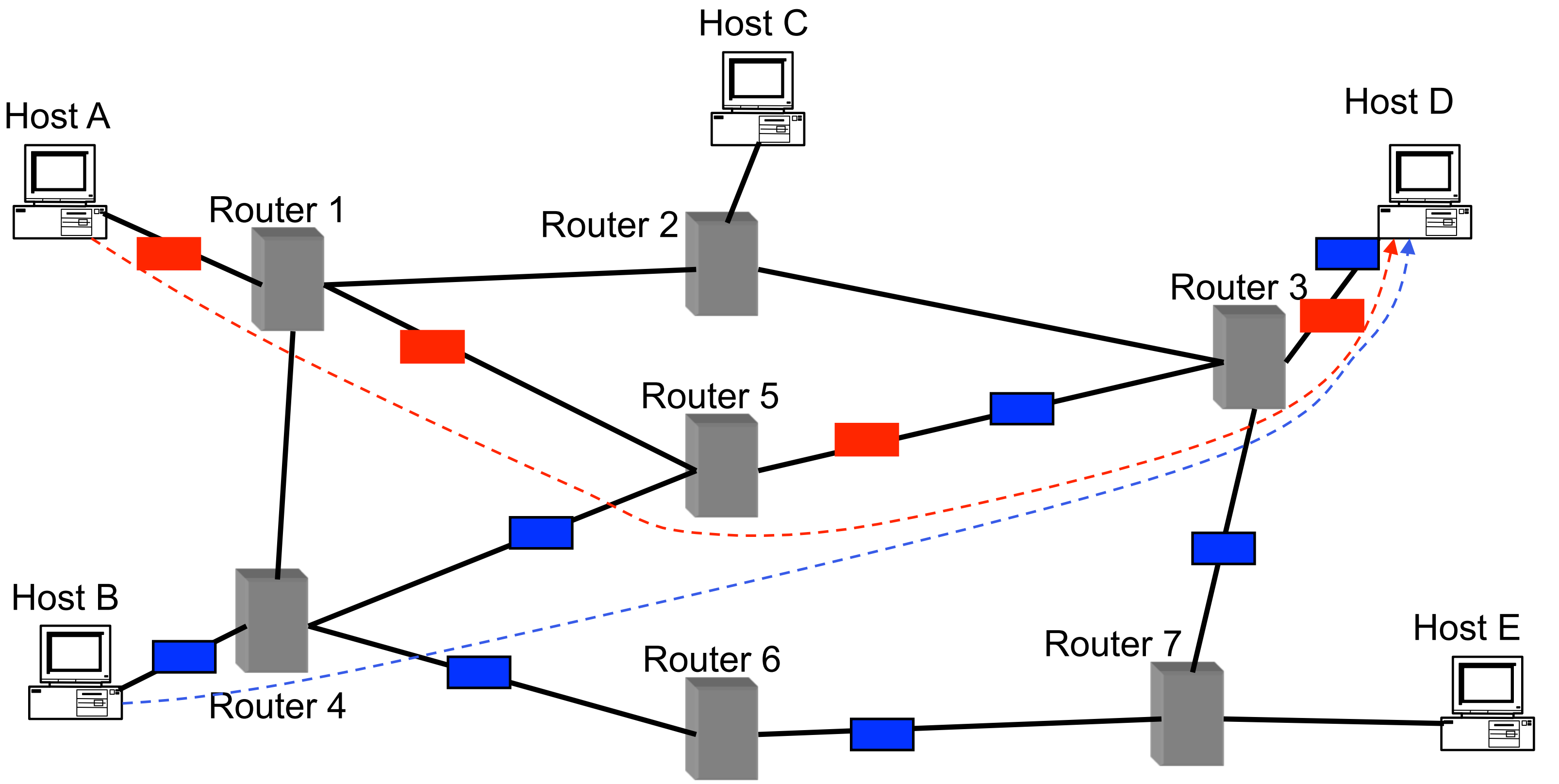
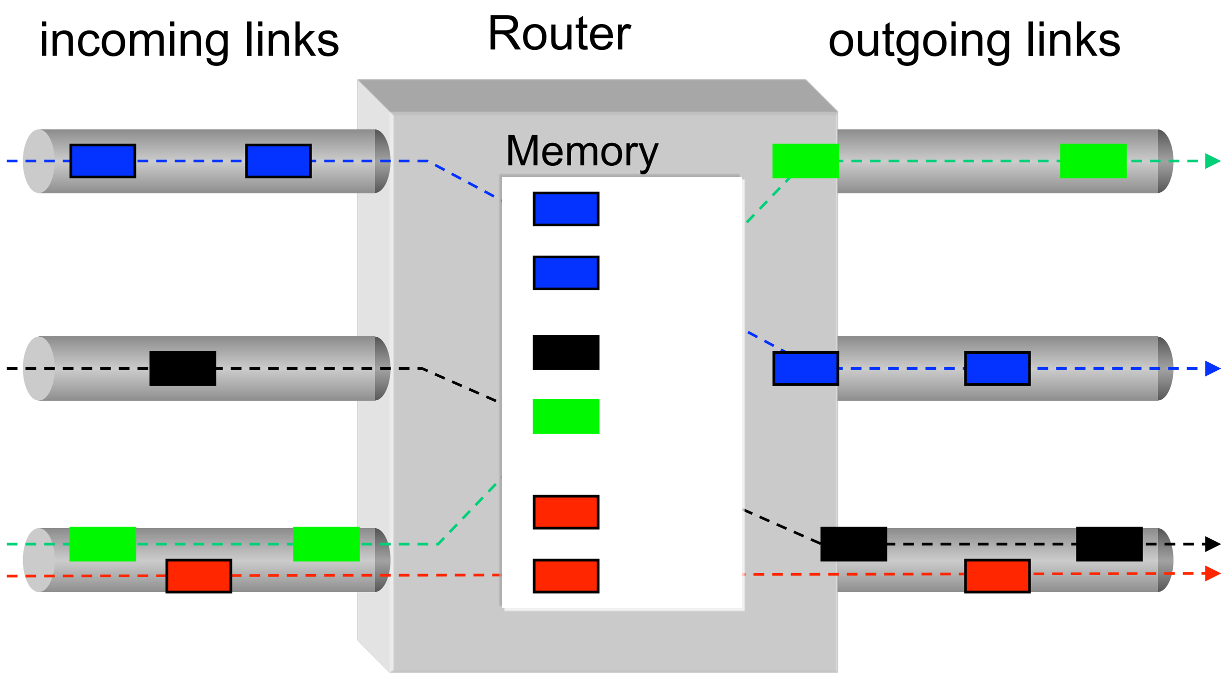


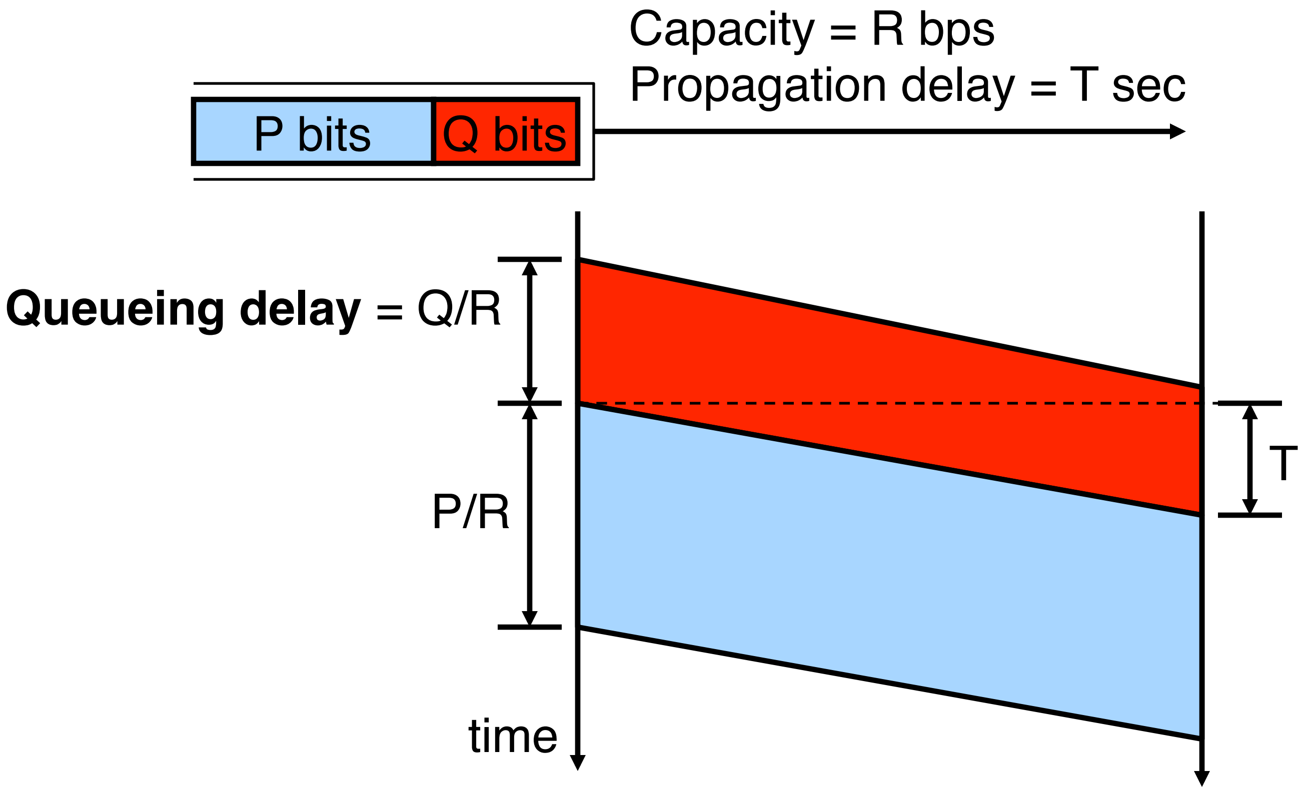
Packet Forwarding

- Packets are first stored before being forwarded
  - Why?



Packet Forwarding Timing

- The queue has Q bits when packet arrives → packet has to wait for the queue to drain before being transmitted



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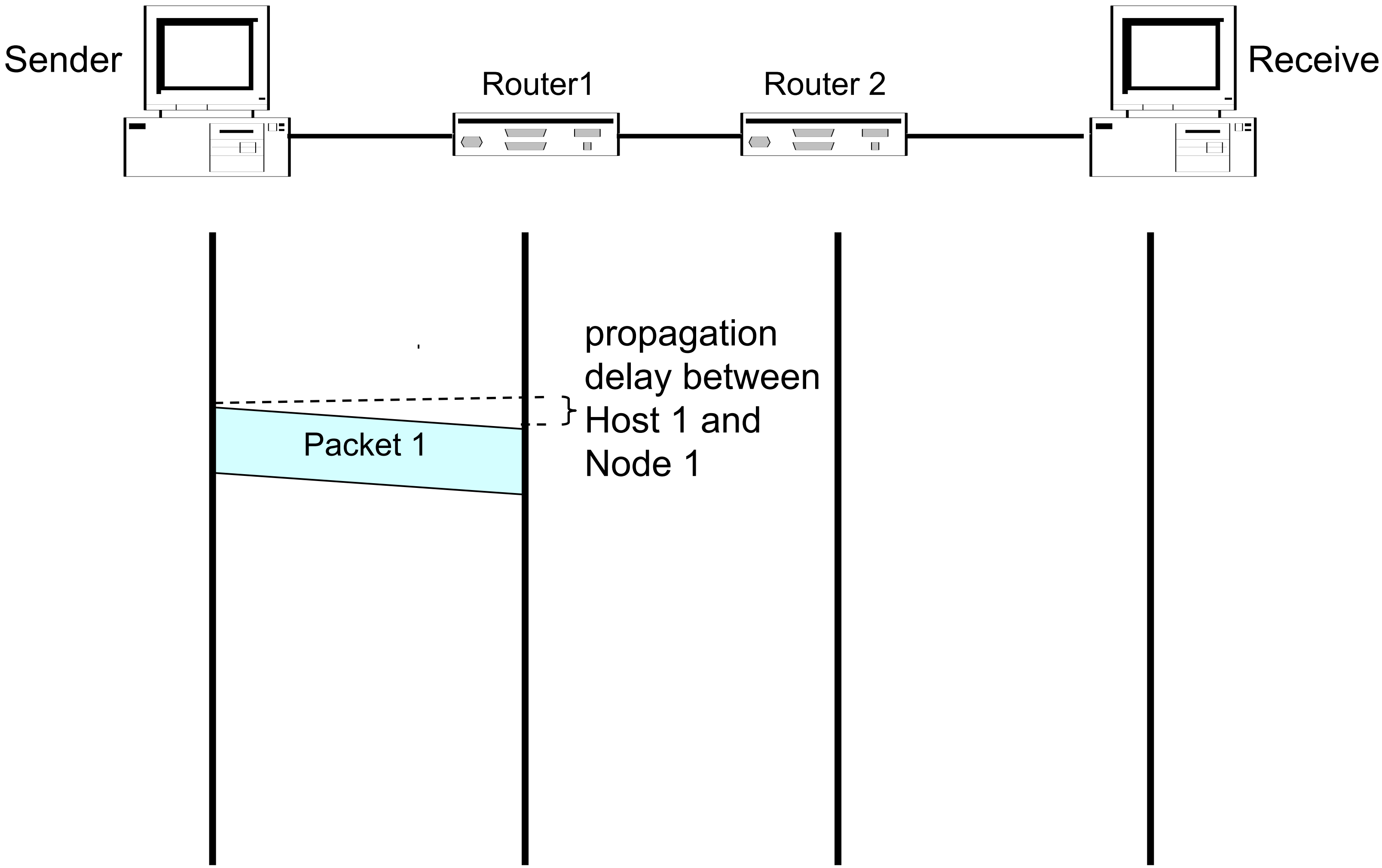

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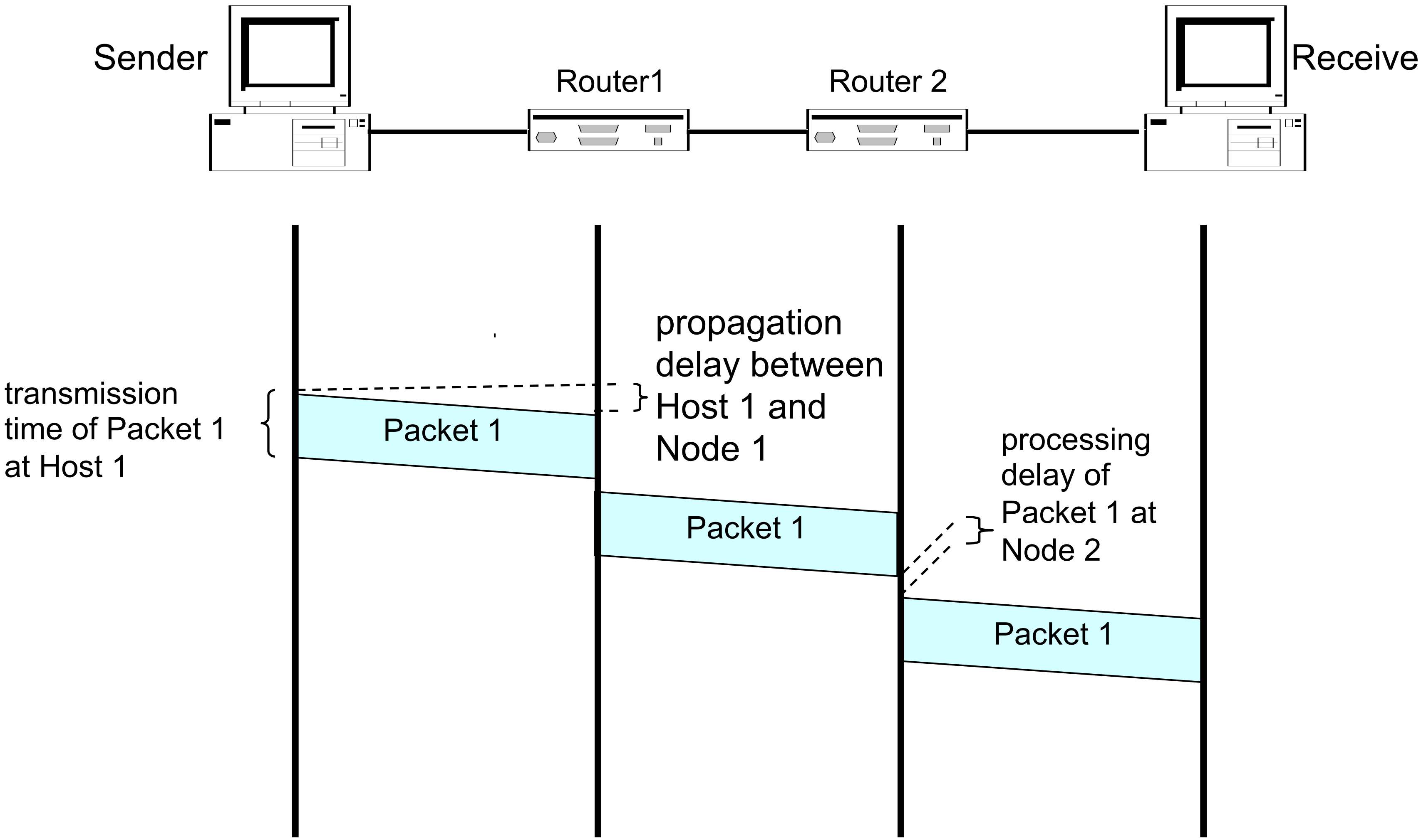

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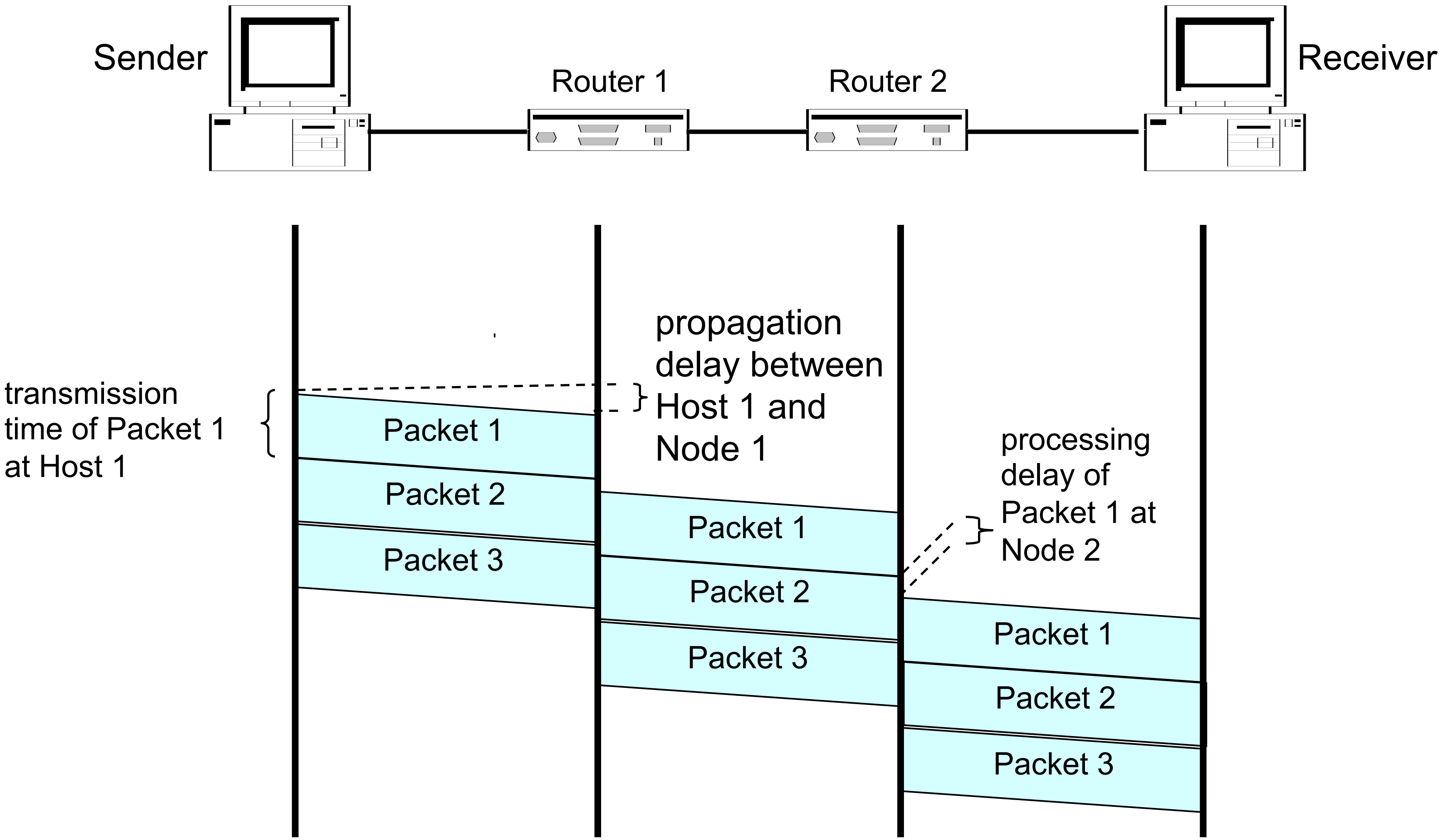
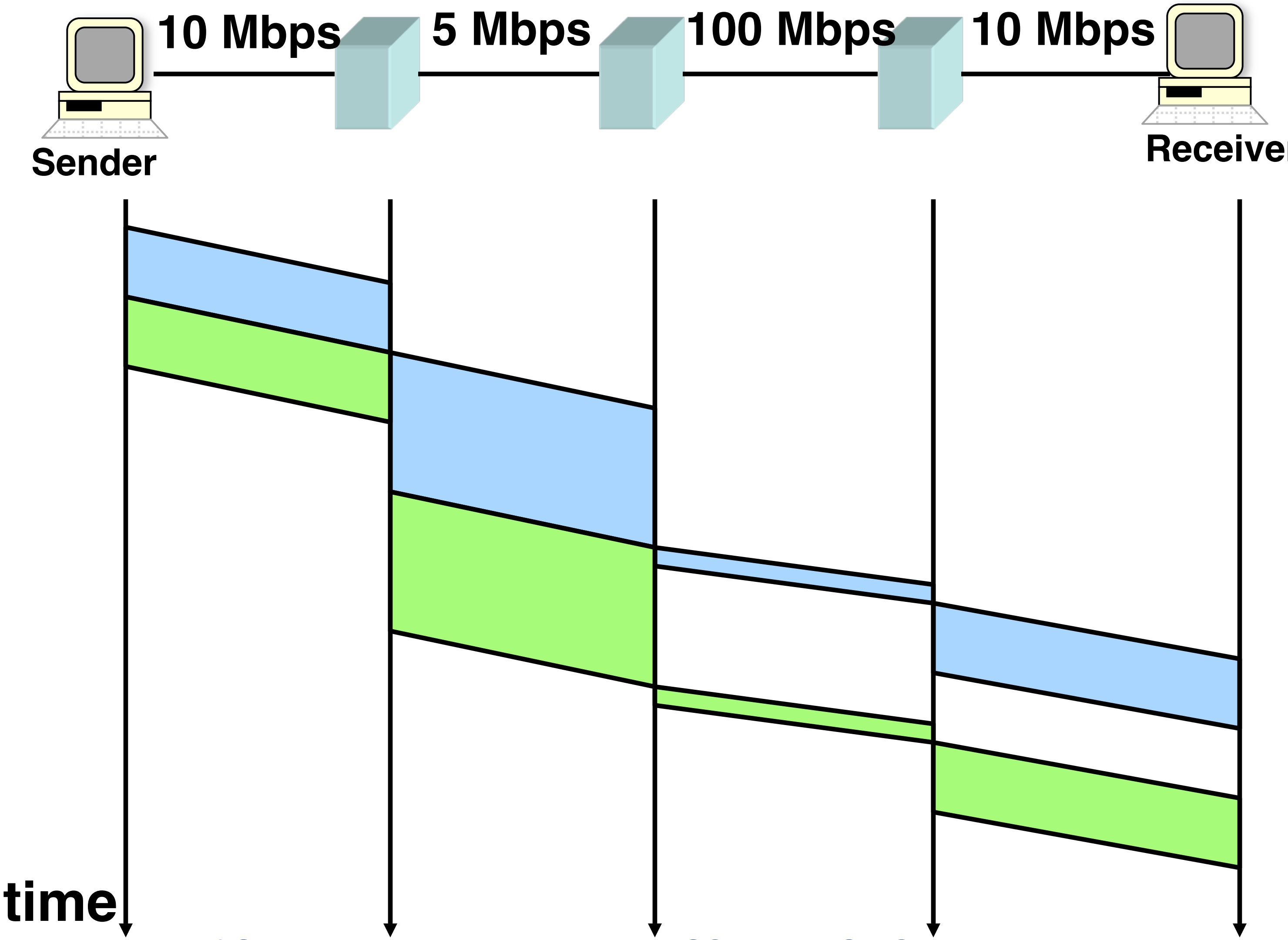
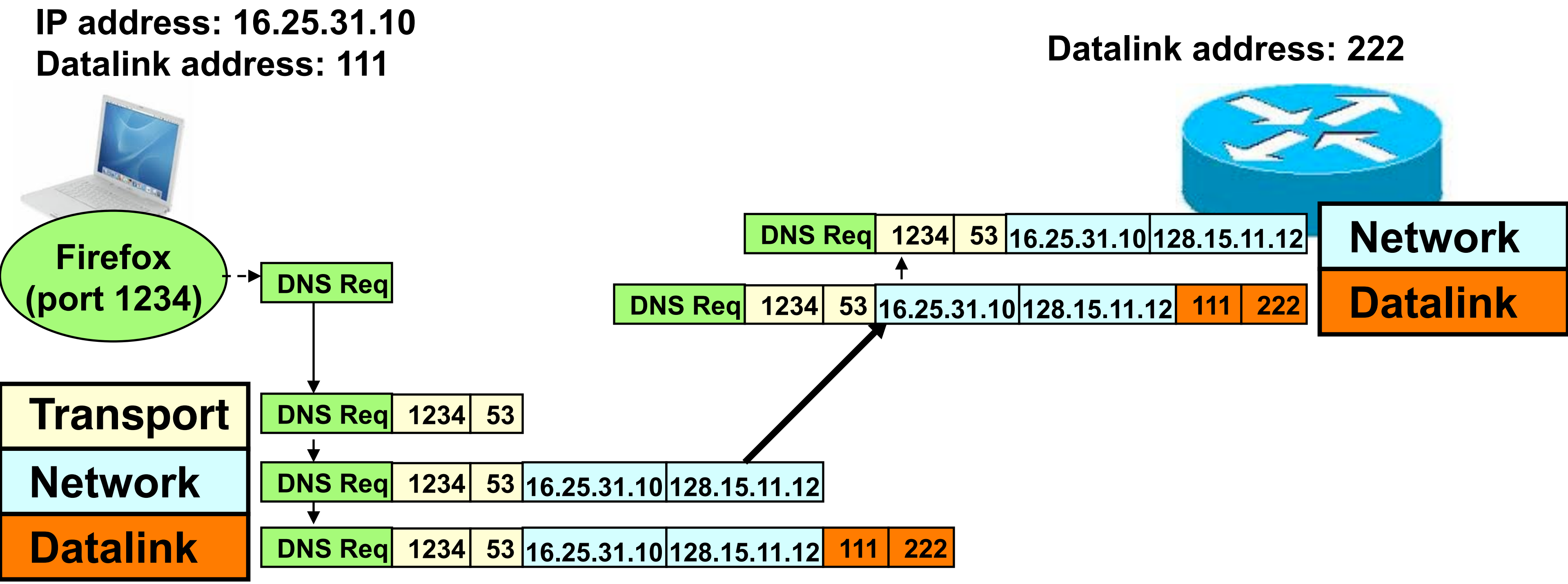


Packet Forwarding Timing: Packets of Different Lengths



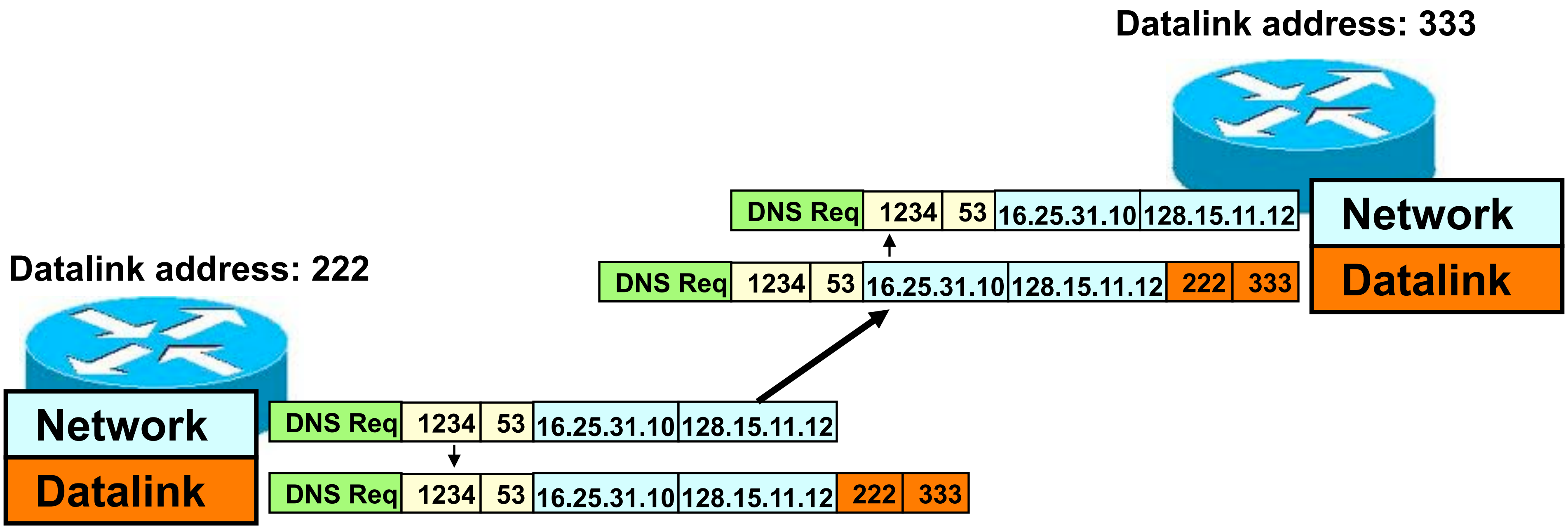
Datalink Layer

- Enable nodes (e.g., hosts, routers) connected by **same link** to exchange packets (frames) with each other
  - Every node/interface has a datalink layer address (e.g., 6 bytes)
  - No need to route packets, as each node on same link receives packets from everyone else on that link (e.g., WiFi, Ethernet)



Datalink Layer

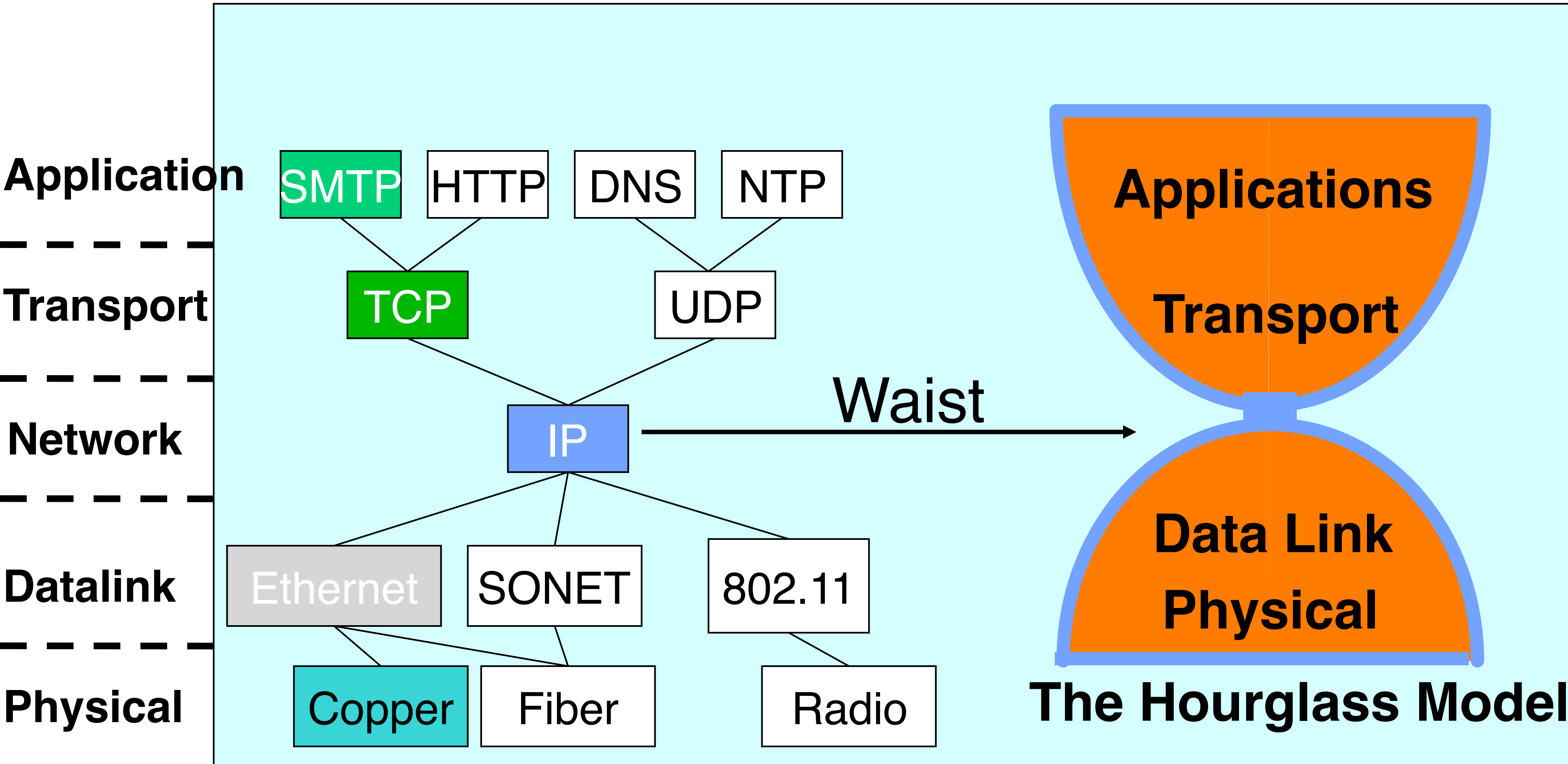
- Enable nodes (e.g., hosts, routers) connected by **same link** to exchange packets (frames) with each other
  - Every node/interface has a datalink layer address (e.g., 6 bytes)
  - **Network layer** picks the next router for the packet towards destination based on its destination IP address



Physical Layer

- Move bits of information between two systems connected by a physical link
- Specifies how bits are represented (encoded), such as voltage level, bit duration, etc
- Examples: coaxial cable, optical fiber links; transmitters, receivers

The Internet *Hourglass*



There is just one network-layer protocol, **IP**
The “narrow waist” facilitates interoperability

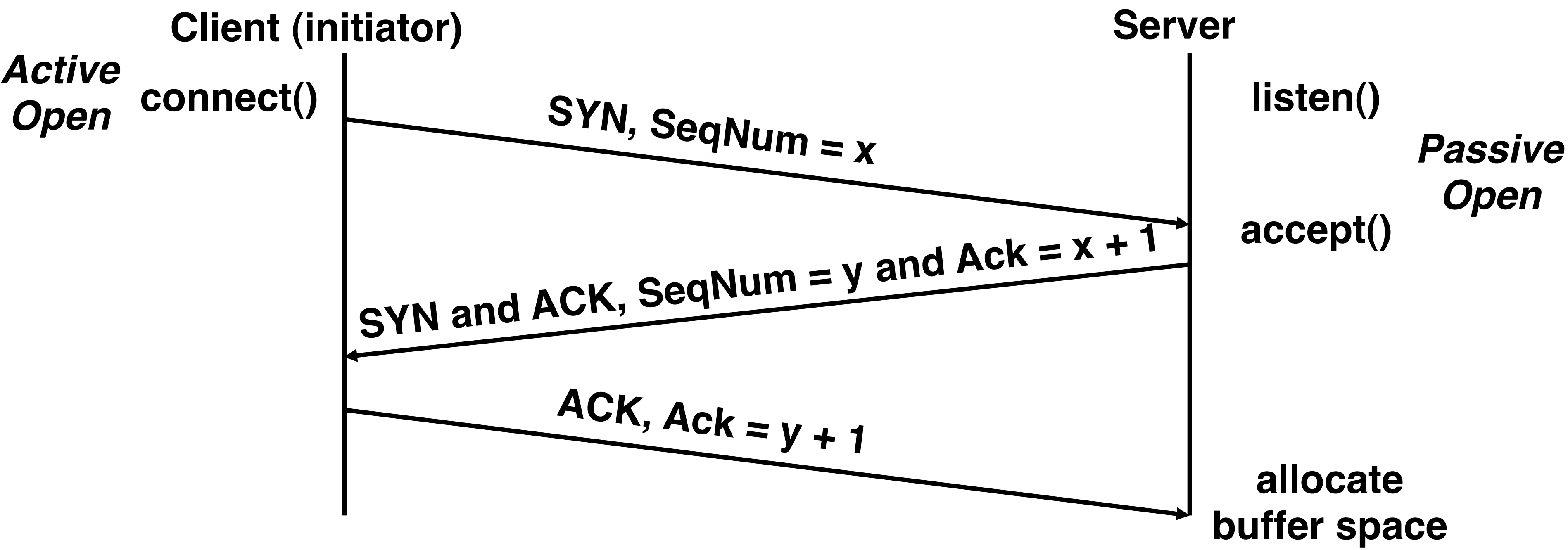
Implications of Hourglass & Layering

Single Internet-layer module (**IP**):

- Allows arbitrary networks to interoperate
  - Any network technology that supports IP can exchange packets
- Allows applications to function on all networks
  - Applications that can run on IP can use any network technology
- Supports simultaneous innovations above and below IP
  - But changing IP itself, i.e., **IPv6**, very involved

TCP Open Connection: 3-Way Handshaking

- Goal: agree on a set of parameters: the start sequence number for each side
  - Starting sequence numbers are random



TCP Flow Control & Reliability

- Sliding window protocol at byte (not packet) level
  - Receiver tells sender how many more bytes it can receive without overflowing its buffer (i.e., AdvertisedWindow)
- Reliability
  - The ack(nowledgement) contains sequence number N of next byte the receiver expects, i.e., receiver has received all bytes in sequence up to and including N-1
  - Go-back-N: TCP Tahoe, Reno, New Reno
  - Selective acknowledgement: TCP Sack
- We didn't learn about congestion control (two lectures in ee122)

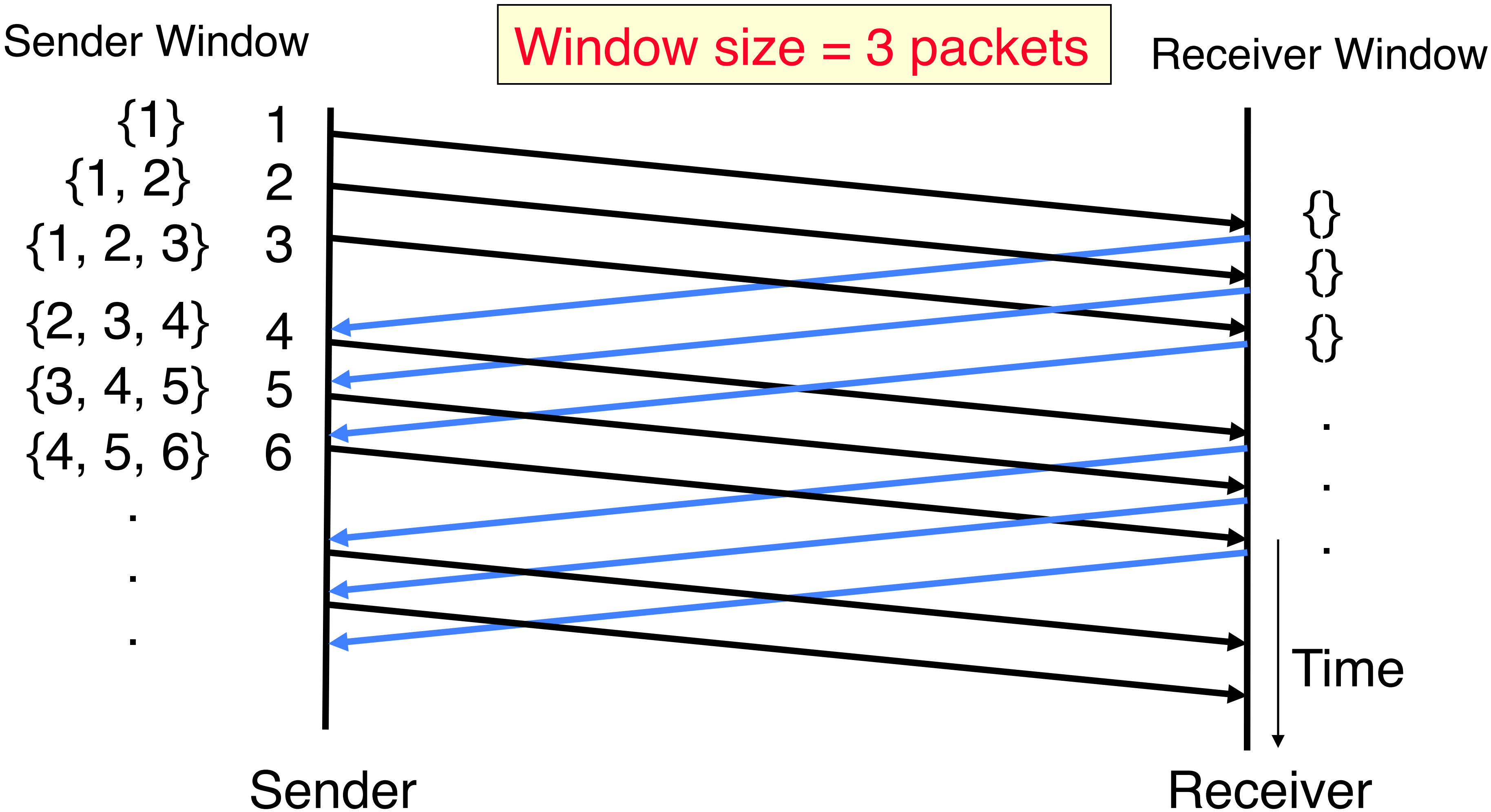
Sliding Window

- *window* = set of adjacent sequence numbers
- The size of the set is the *window size*
- Assume window size is n
- Let A be the last ack'd packet of sender without gap; then window of sender = {A+1, A+2, …, A+n}
- Sender can send packets in its window
- Let B be the last received packet without gap by receiver, then window of receiver = {B+1,…, B+n}
- Receiver can accept out of sequence, if in window

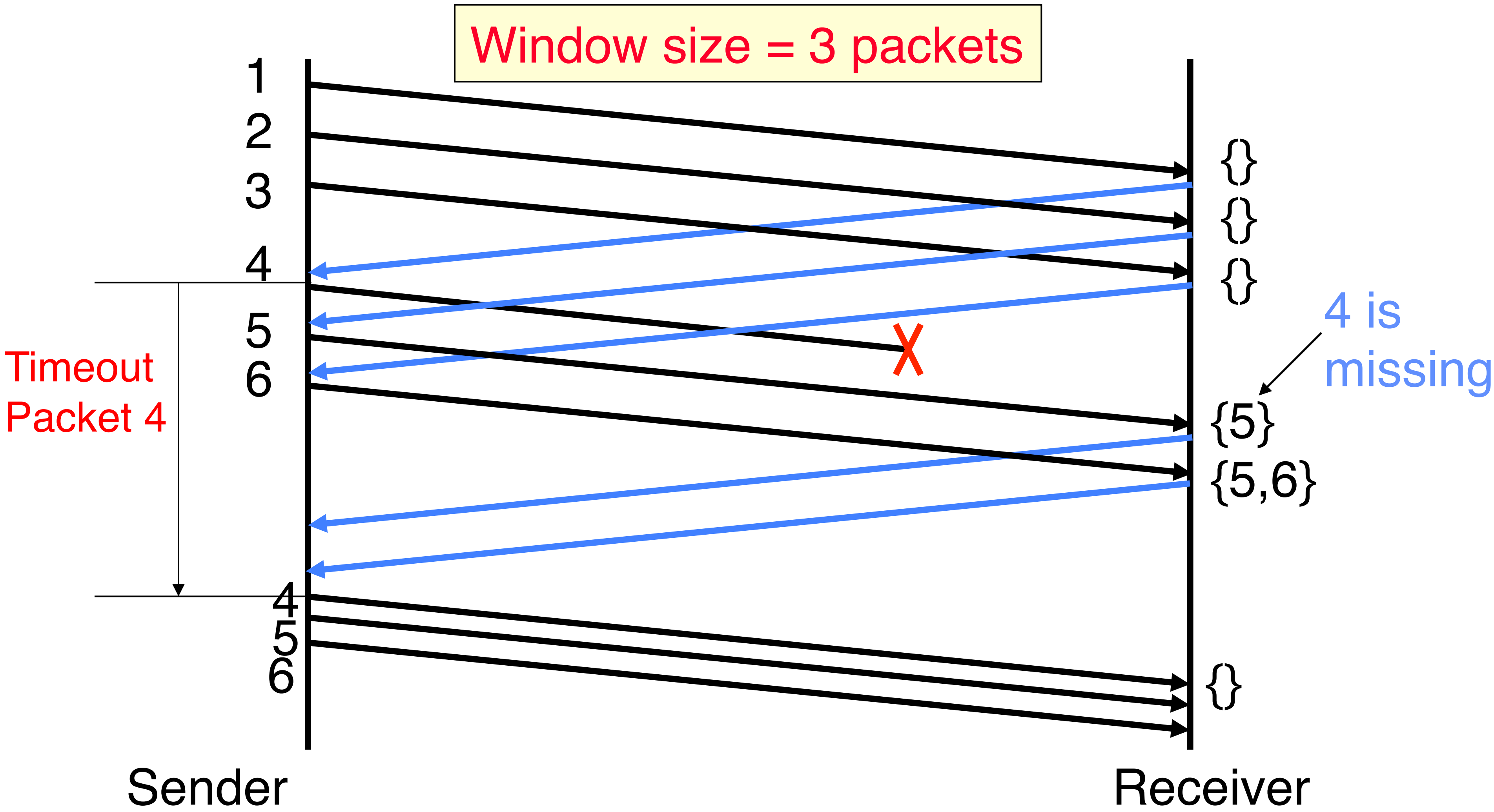
Go-Back-n (GBN)

- Transmit up to *n* unacknowledged packets
- If timeout for ACK(*k*), retransmit *k*, *k+1*, …

GBN Example w/o Errors



GBN Example with Errors



Observations

- With sliding windows, it is possible to fully utilize a link, provided the window size is large enough. Throughput is ~ (n/RTT)
  – Stop & Wait is like n = 1.
- Sender has to buffer all unacknowledged packets, because they may require retransmission
- Receiver may be able to accept out-of-order packets, but only up to its buffer limits

Security

How do You Secure your Credit Card?

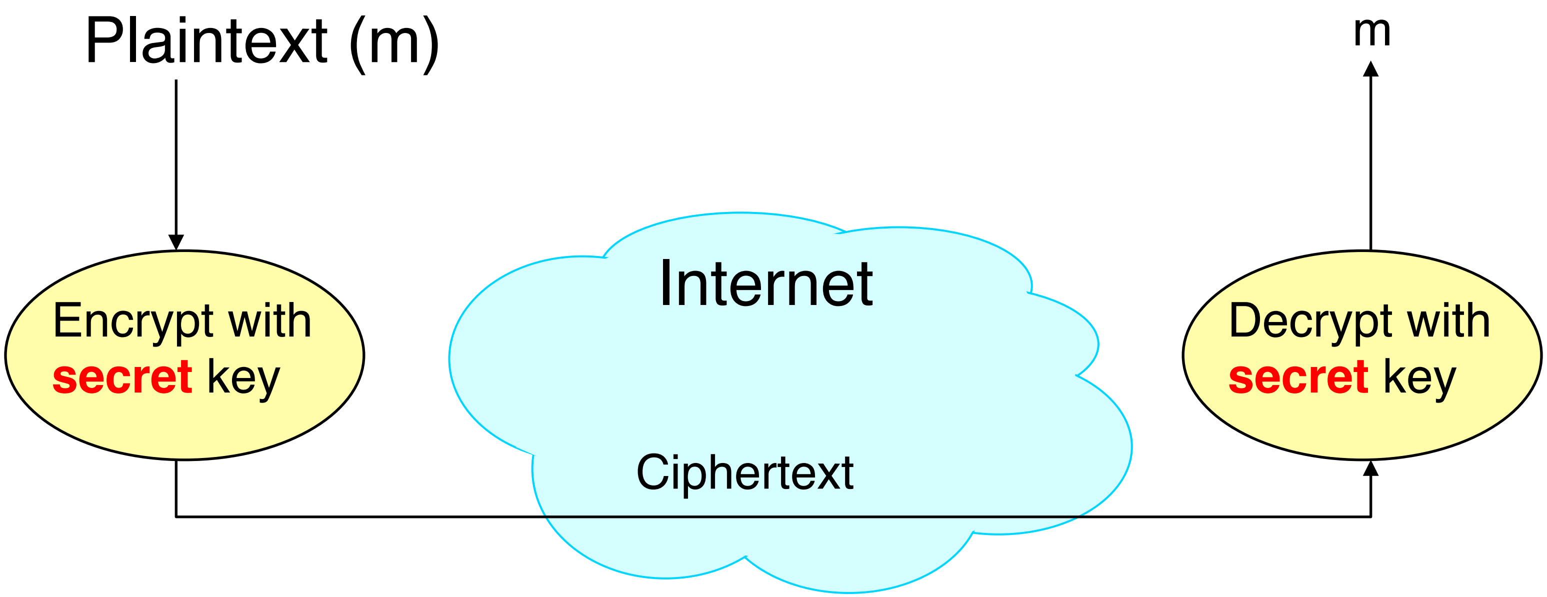
- Use a secure protocol, e.g., HTTPS

- Need to ensure three properties:
  - Confidentiality: an adversary cannot snoop the traffic
  - Authentication: make sure you indeed talk with Amazon
  - Integrity: an adversary cannot modify the message
    - » Used for improving authentication performance

- Cryptography based solution:
  - General premise: there is a key, possession of which allows decoding, but without which decoding is infeasible
    - » Thus, key must be kept secret and not guessable

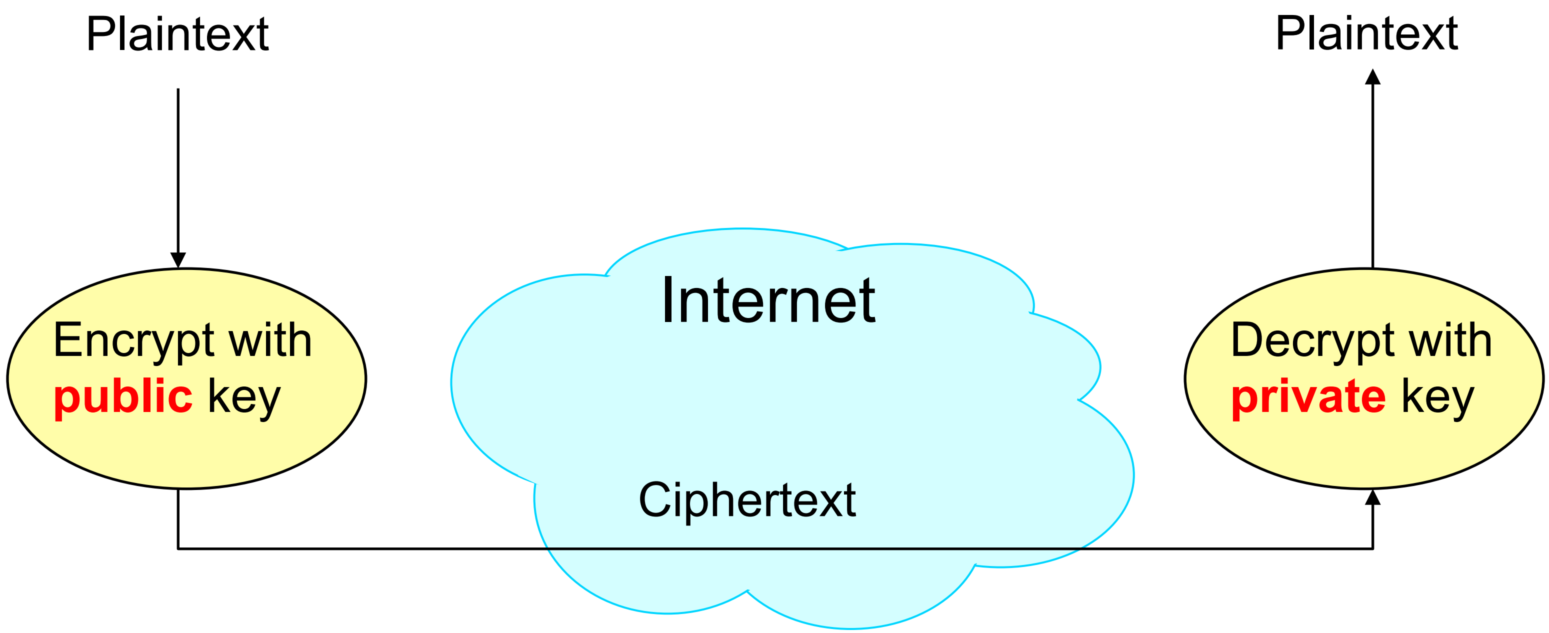
Symmetric Keys

- Sender and receiver use the same key for encryption and decryption
- Examples: AES128, DES, 3DES



Public Key / Asymmetric Encryption

- Sender uses receiver's public key
  - Advertised to everyone
- Receiver uses complementary private key
  - Must be kept secret
- Example: RSA



Symmetric vs. Asymmetric Cryptography

- Symmetric cryptography
  - + Low overhead, fast
  - – Need a secret channel to distribute key

- Asymmetric cryptography
  - + No need for secret channel; public key known by everyone
  - + Provable secure
  - – Slow, large keys (e.g., 1024 bytes)

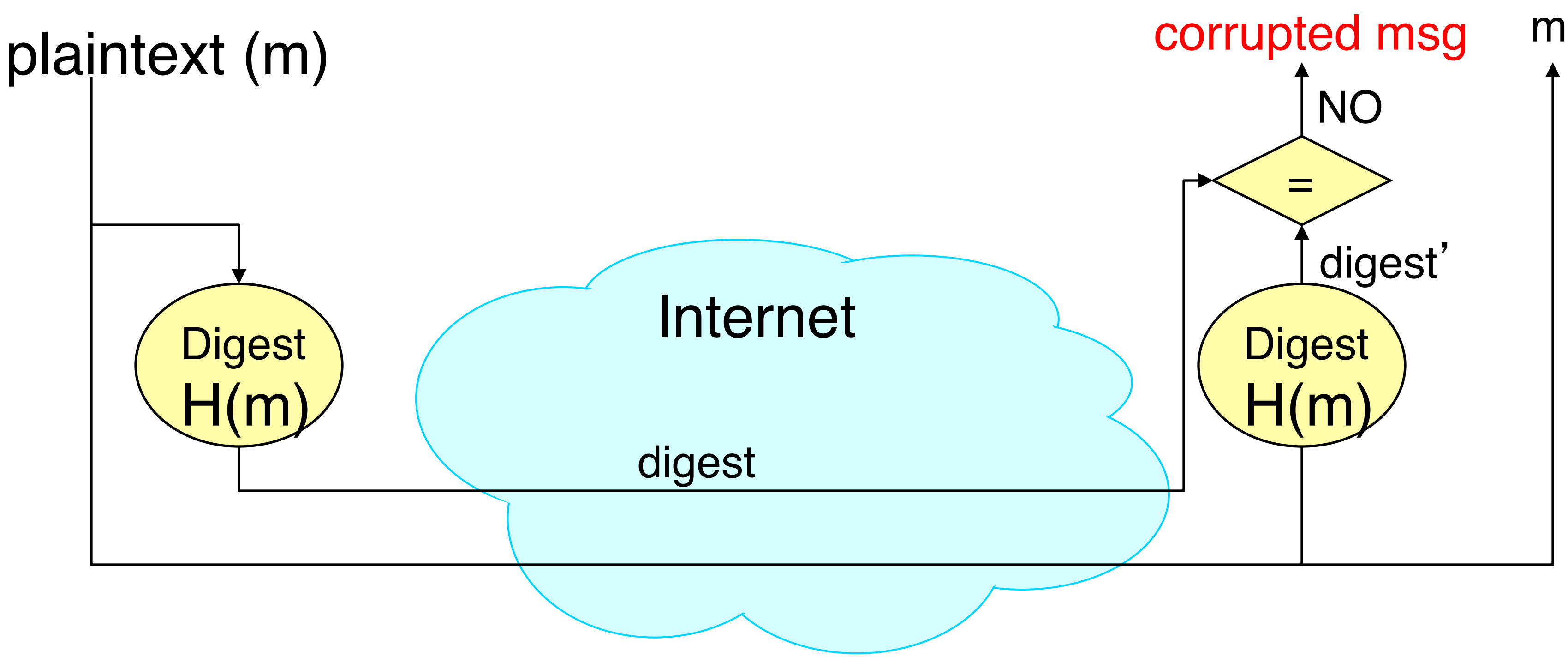
Integrity

- Basic building block for integrity: *hashing*
  – Associate hash with byte-stream, receiver verifies match
    » Assures data hasn't been modified, either accidentally - or maliciously

- Approach:
  - Sender computes a *digest* of message m, i.e., H(m)
    » H() is a publicly known *hash function*
  - Send digest (d = H(m)) to receiver in a secure way, e.g.,
    » Using another physical channel
    » Using encryption (e.g., Asymmetric Key)
  - Upon receiving m and d, receiver re-computes H(m) to see whether result agrees with d

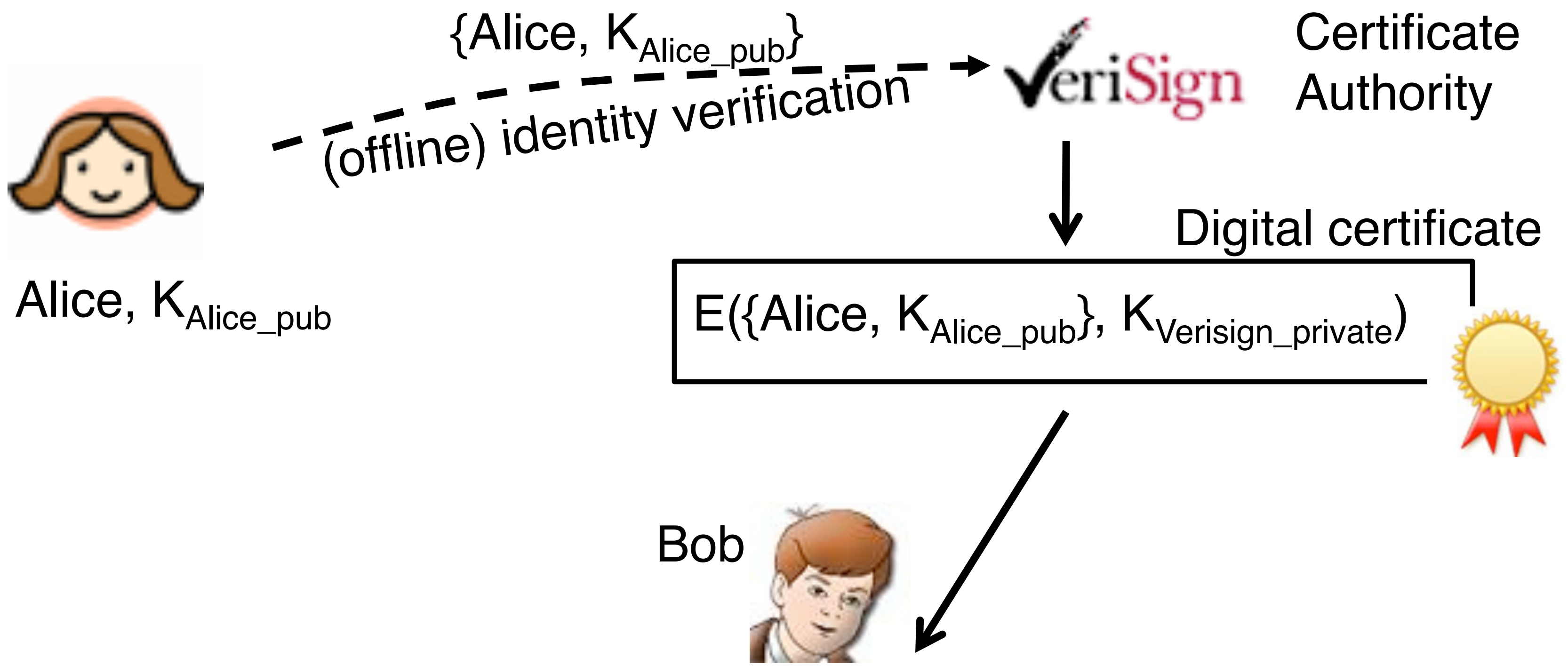
- Examples: ~~MD5~~, SHA1

Operation of Hashing for Integrity



Digital Certificates

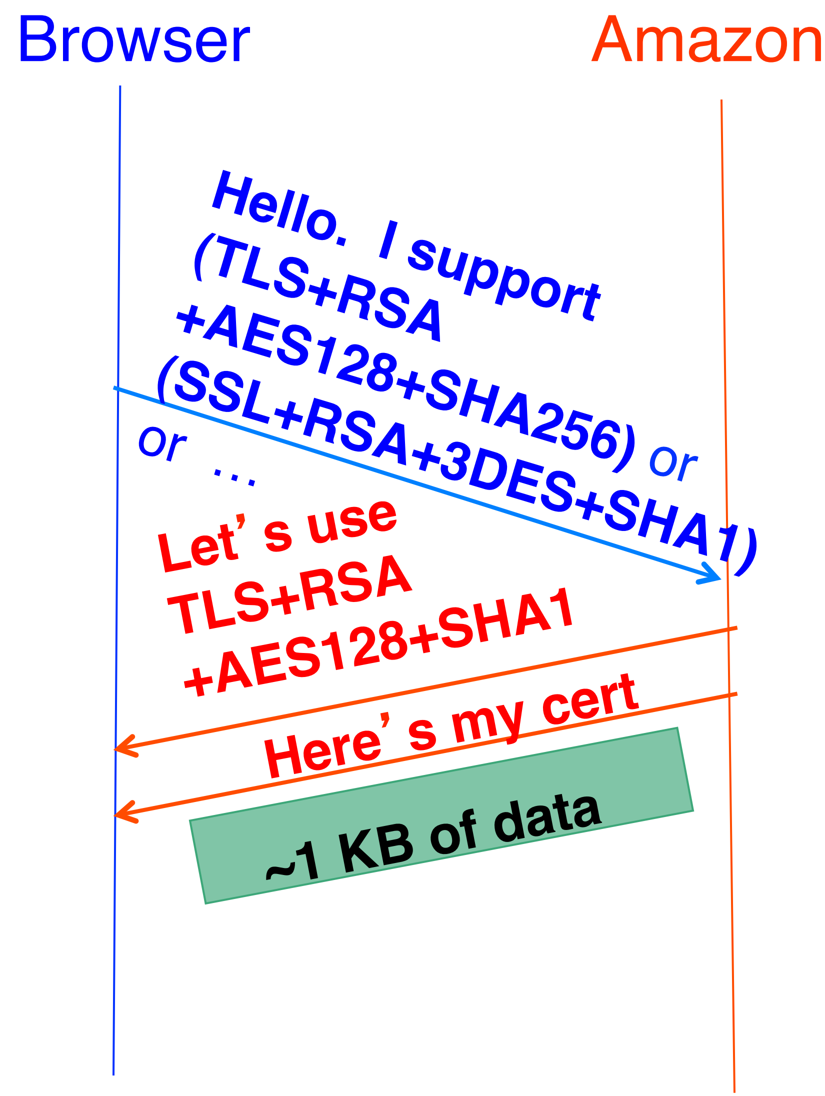
- How do you know $\mathbf{K_{Alice\_pub}}$ is indeed **Alice**'s public key?
- Main idea: trusted authority signing binding between Alice and its private key



$$D(E(\{Alice, K_{Alice\_pub}\}, K_{Verisign\_private}), K_{Verisign\_public}) = \{Alice, K_{Alice\_pub}\}$$

HTTPS Connection (SSL/TLS)

- Browser (client) connects via TCP to Amazon's HTTPS server
- Client sends over list of crypto protocols it supports
- Server picks protocols to use for this session
- Server sends over its certificate
- (all of this is in the clear)



Inside the Server's Certificate

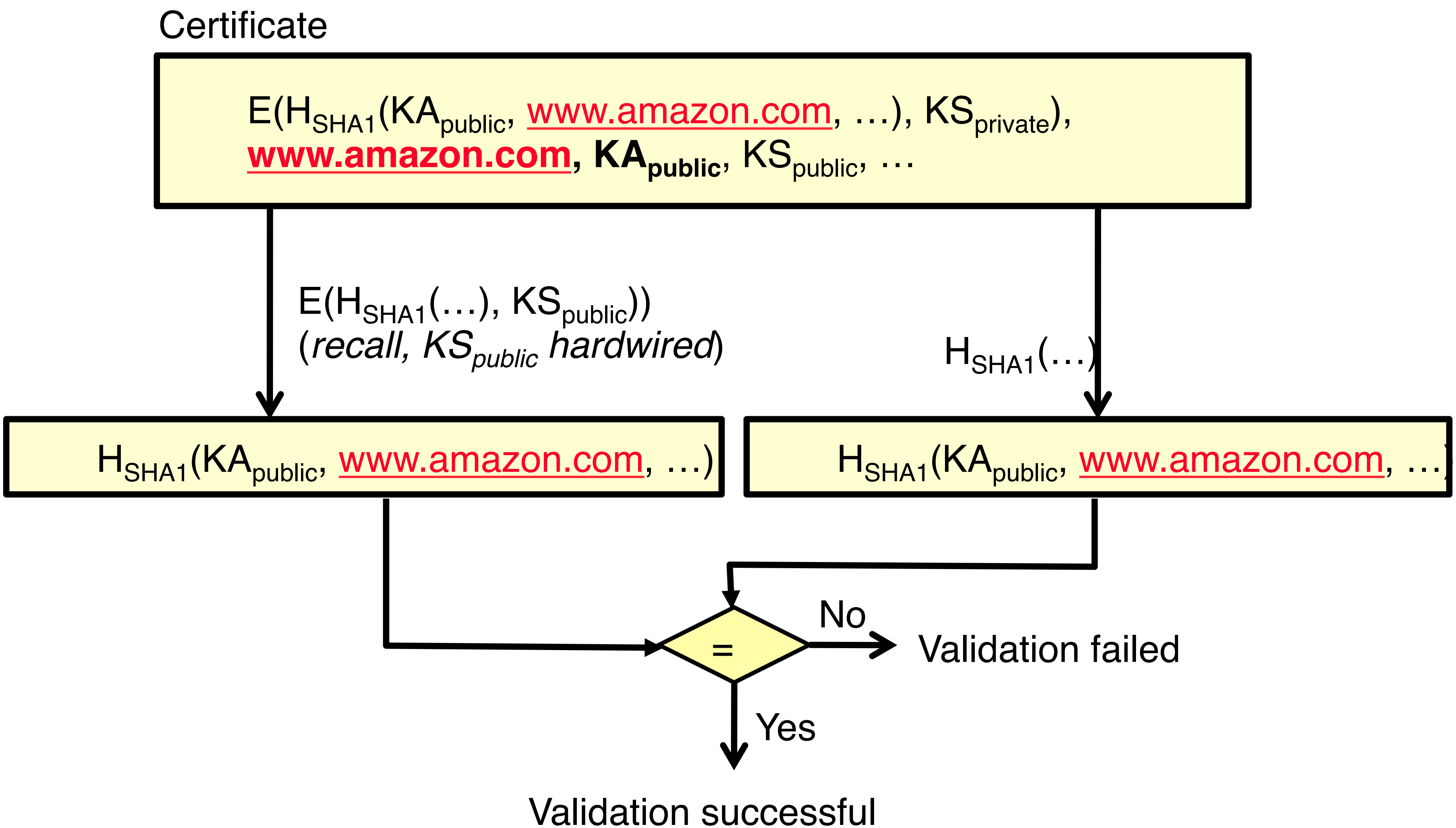
- Name associated with cert (e.g., Amazon)
- Amazon's RSA public key
- A bunch of auxiliary info (physical address, type of cert, expiration time)
- Name of certificate's signatory (who signed it)
- A public-key signature of a hash (SHA1) of all this
  - Constructed using the signatory's private RSA key, i.e.,
  - Cert = $E(H_{SHA1}(KA_{public}$, www.amazon.com, …), $KS_{private})$
    - » KA_{public}: Amazon's public key
    - » $KS_{private}$: signatory (certificate authority) public key
- …

Validating Amazon's Identity

- How does the browser authenticate certificate signatory?
  - Certificates of few certificate authorities (e.g., Verisign) are hardwired into the browser
- If it can't find the cert, then warns the user that site has not been verified
  - And may ask whether to continue
  - Note, can still proceed, just without authentication
- Browser uses public key in signatory's cert to decrypt signature
  - Compares with its own SHA1 hash of Amazon's cert
- Assuming signature matches, now have high confidence it's indeed Amazon …
  - … assuming signatory is trustworthy

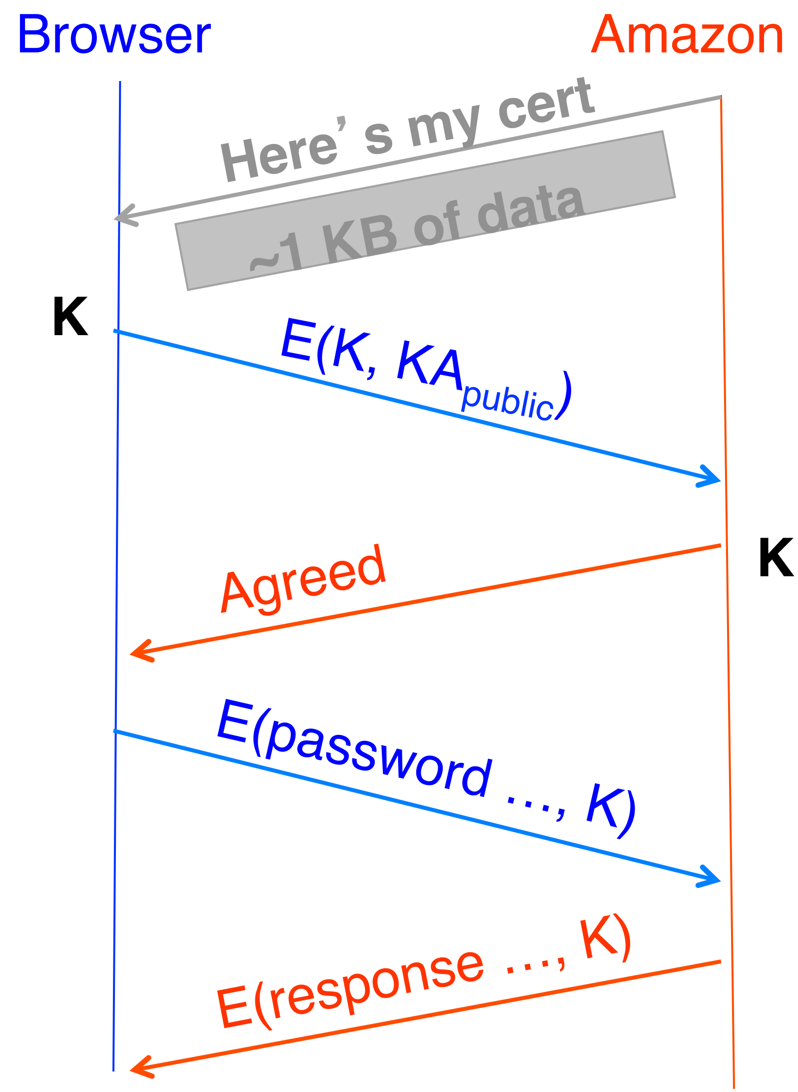
Certificate Validation

- You (browser) want to make sure that KA_{public} is indeed the public key of www.amazon.com



HTTPS Connection (SSL/TLS), con't

- Browser constructs a random *session (symmetric) key* K
- Browser encrypts K using Amazon's public key
- Browser sends E(K, KA_{public}) to server
- Browser displays 
- All subsequent communication encrypted w/ symmetric cipher (e.g., AES128) using key K
  - E.g., client can authenticate using a password



Two-Phase Locking (2PL)

Concurrent Execution & Transactions

- Concurrent execution essential for good performance
  - Disk slow, so need to keep the CPU busy by working on several user programs concurrently
- DBMS only concerned about what data is read/written from/ to the database
  - Not concerned about other operations performed by program on data
- **Transaction** – DBMS's abstract view of a user program, i.e., a sequence of reads and writes.

Transaction - Example

```
BEGIN;     --BEGIN TRANSACTION
 UPDATE accounts SET balance = balance -
   100.00 WHERE name = 'Alice';

 UPDATE branches SET balance = balance -
   100.00 WHERE name = (SELECT branch_name
   FROM accounts WHERE name = 'Alice');

 UPDATE accounts SET balance = balance +
   100.00 WHERE name = 'Bob';

 UPDATE branches SET balance = balance +
   100.00 WHERE name = (SELECT branch_name
   FROM accounts WHERE name = 'Bob');

COMMIT;     --COMMIT WORK
```

The ACID properties of Transactions

- **Atomicity:** all actions in the transaction happen, or none happen
- **Consistency:** if each transaction is consistent, and the DB starts consistent, it ends up consistent
- **Isolation:** execution of one transaction is isolated from that of all others
- **Durability:** if a transaction commits, its effects persist

Transaction Scheduling

- **Serial schedule:** A schedule that does not interleave the operations of different transactions
  – Transactions run serially (one at a time)

- **Equivalent schedules:** For any database state, the effect (on the database) and output of executing the first schedule is identical to the effect of executing the second schedule

- **Serializable schedule:** A schedule that is equivalent to some serial execution of the transactions
  – Intuitively: with a serializable schedule you only see things that could happen in situations where you were running transactions one-at-a-time.

Conflict Serializable Schedules

- Two operations **conflict** if they
  - Belong to different transactions
  - Are on the same data
  - At least one of them is a write.

- Two schedules are **conflict equivalent** iff:
  - Involve same operations of same transactions
  - Every pair of **conflicting** operations is ordered the same way

- Schedule S is **conflict serializable** if S is conflict equivalent to some serial schedule

Conflict Equivalence – Intuition

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**
- Example:

```
T1:R(A),W(A),          R(B),W(B)
T2:          R(A),W(A),         R(B),W(B)
```

⇓

```
T1:R(A),W(A),     R(B),     W(B)
T2:          R(A),     W(A),    R(B),W(B)
```

⇓

```
T1:R(A),W(A),R(B),          W(B)
T2:               R(A),W(A),    R(B),W(B)
```

Conflict Equivalence – Intuition (cont'd)

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**
- Example:

```
T1:R(A),W(A),R(B),                    W(B)
T2:                  R(A),W(A),    R(B),W(B)
```

⇩

```
T1:R(A),W(A),R(B),          W(B)
T2:                  R(A),          W(A),R(B),W(B)
```

⇩

```
T1:R(A),W(A),R(B),W(B)
T2:                          R(A), W(A),R(B),W(B)
```

Conflict Equivalence – Intuition (cont'd)

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**

- Is this schedule serializable?

```
T1:R(A),                W(A)
T2:      R(A),W(A),
```

Dependency Graph

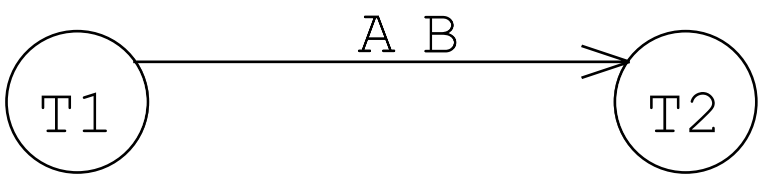
- **Dependency graph:**
  - Transactions represented as nodes
  - Edge from Ti to Tj:
    - » an operation of Ti conflicts with an operation of Tj
    - » Ti appears earlier than Tj in the schedule

- **Theorem:** Schedule is conflict serializable if and only if its dependency graph is acyclic

Example

- Conflict serializable schedule:

```
T1:R(A),W(A),                   R(B),W(B)
T2:            R(A),W(A),                 R(B),W(B)
```



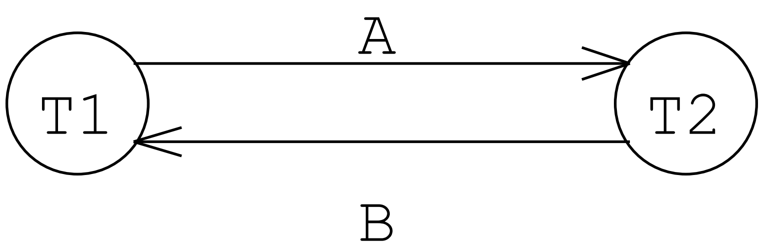
Dependency graph

- No cycle!

Example

- Conflict that is *not* serializable:

```
T1:R(A),W(A),                          R(B),W(B)
T2:          R(A),W(A),R(B),W(B)
```



Dependency graph

- Cycle: The output of T1 depends on T2, and vice-versa

Notes on Conflict Serializability

- Conflict Serializability doesn't allow all schedules that you would consider correct
  – This is because it is strictly *syntactic* - it doesn't consider the meanings of the operations or the data

- In practice, Conflict Serializability is what gets used, because it can be done efficiently
  – Note: in order to allow more concurrency, some special cases do get implemented, such as for travel reservations, …

- Two-phase locking (2PL) is how we implement it

Locks

- "Locks" to control access to data

- Two types of locks:
  - shared (S) lock – multiple concurrent transactions allowed to operate on data
  - exclusive (X) lock – only one transaction can operate on data at a time

Lock Compatibility Matrix

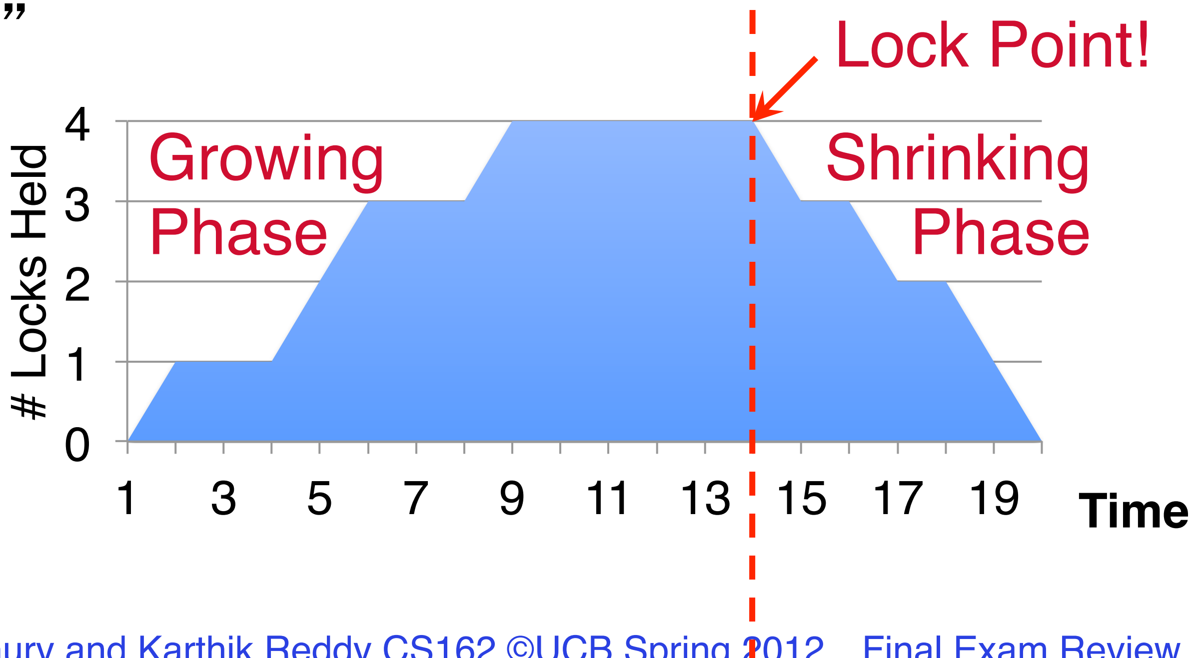
	S	**X**
S	√	–
X	–	–

Two-Phase Locking (2PL)

1) Each transaction must obtain:
   - S (*shared*) or X (exclusive) lock on data before reading,
   - X (*exclusive*) lock on data before writing

2) A transaction can not request additional locks once it releases any locks.

Thus, each transaction has a "growing phase" followed by a "shrinking phase"



Two-Phase Locking (2PL)

- 2PL guarantees conflict serializability

- Doesn't allow dependency cycles; Why?
- Answer: a cyclic dependency cycle leads to deadlock
  - Edge from Ti to Tj means that Ti acquires lock first and Tj needs to wait
  - Edge from Ti to Tj means that Ti acquires lock first and Tj needs to wait
  - Thus, both T1 and Tj wait for each other → deadlock

- Schedule of conflicting transactions is conflict equivalent to a serial schedule ordered by "lock point"

Deadlock Prevention

- Assign priorities based on timestamps. Assume Ti wants a lock that Tj holds. Two policies are possible:
  - Wait-Die: If Ti is older, Ti waits for Tj; otherwise Ti aborts
  - Wound-wait: If Ti is older, Tj aborts; otherwise Ti waits

- If a transaction re-starts, make sure it gets its original timestamp
  - Why?

Example

- T1 transfers $50 from account A to account B

```
T1:Read(A),A:=A-50,Write(A),Read(B),B:=B+50,Write(B)
```

- T2 outputs the total of accounts A and B

```
T2:Read(A),Read(B),PRINT(A+B)
```

- Initially, A = $1000 and B = $2000

- What are the possible output values?

Is this a 2PL Schedule?

Lock_X(A) <granted>	
Read(A)	Lock_S(A)
A: = A-50	
Write(A)	
Unlock(A)	<granted>
	Read(A)
	Unlock(A)
	Lock_S(B) <granted>
Lock_X(B)	
	Read(B)
<granted>	Unlock(B)
	PRINT(A+B)
Read(B)	
B := B +50	
Write(B)	
Unlock(B)	

No, and it is not serializable

Is this a 2PL Schedule?

Lock_X(A) <granted>	
Read(A)	Lock_S(A)
A: = A-50	↓
Write(A)	↓
Lock_X(B) <granted>	↓
Unlock(A)	<granted>
	Read(A)
	Lock_S(B)
Read(B)	↓
B := B +50	↓
Write(B)	↓
Unlock(B)	<granted>
	Unlock(A)
	Read(B)
	Unlock(B)
	PRINT(A+B)

Yes, so it is serializable

Cascading Aborts

- Example: T1 aborts
  - Note: this is a 2PL schedule

```
T1:R(A),W(A),              R(B),W(B), Abort
T2:             R(A),W(A)
```

- Rollback of T1 requires rollback of T2, since T2 reads a value written by T1

- Solution: **Strict Two-phase Locking (Strict 2PL)**: same as 2PL except
  - All locks held by a transaction are released only when the transaction completes

Strict 2PL (cont'd)

- All locks held by a transaction are released only when the transaction completes

- In effect, "shrinking phase" is delayed until:
  a) Transaction has committed (commit log record on disk), or
  b) Decision has been made to abort the transaction (then locks can be released after rollback).

Is this a Strict 2PL schedule?

Lock_X(A) <granted>	
Read(A)	Lock_S(A)
A: = A-50	
Write(A)	
Lock_X(B) <granted>	
Unlock(A)	<granted>
	Read(A)
	Lock_S(B)
Read(B)	
B := B +50	
Write(B)	
Unlock(B)	<granted>
	Unlock(A)
	Read(B)
	Unlock(B)
	PRINT(A+B)

No: Cascading Abort Possible

Is this a Strict 2PL schedule?

Lock_X(A) <granted>	
Read(A)	Lock_S(A)
A: = A-50	
Write(A)	
Lock_X(B) <granted>	
Read(B)	
B := B +50	
Write(B)	
Unlock(A)	
Unlock(B)	<granted>
	Read(A)
	Lock_S(B) <granted>
	Read(B)
	PRINT(A+B)
	Unlock(A)
	Unlock(B)

Two-Phase Commit (2PC)

Two Phase (2PC) Commit

- 2PC is a distributed protocol
- High-level problem statement
  - If no node fails and all nodes are ready to commit, then all nodes **COMMIT**
  - Otherwise **ABORT** at all nodes
- Developed by Turing award winner Jim Gray (first Berkeley CS PhD, 1969)

Detailed Algorithm

Coordinator Algorithm

Coordinator sends **VOTE-REQ** to all workers

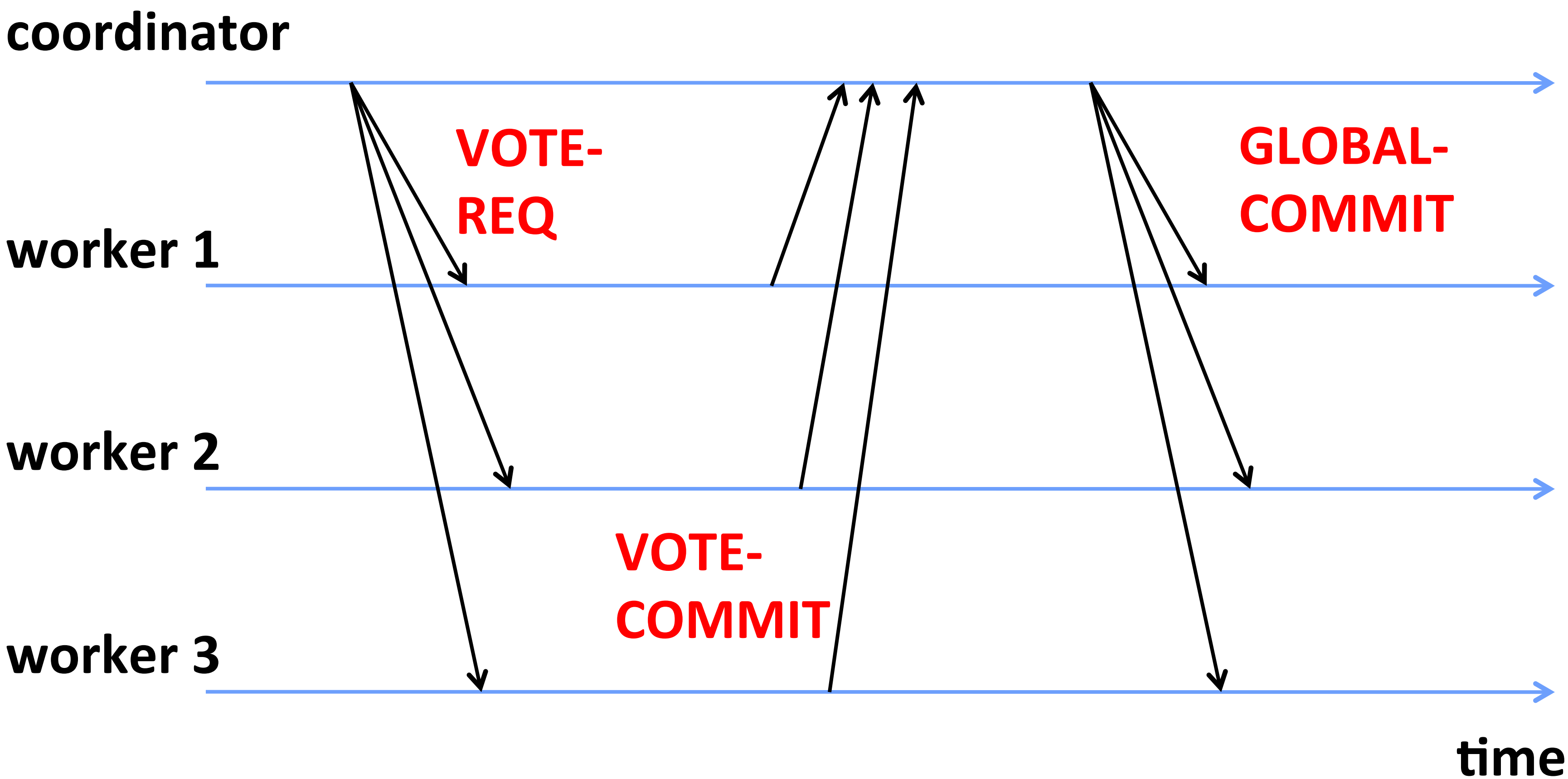
- If receive VOTE-COMMIT from all N workers, send GLOBAL-COMMIT to all workers
- If doesn't receive VOTE-COMMIT from all N workers, send GLOBAL-ABORT to all workers

Worker Algorithm

- Wait for **VOTE-REQ** from coordinator
- If ready, send **VOTE-COMMIT** to coordinator
- If not ready, send **VOTE-ABORT** to coordinator
  - And immediately abort

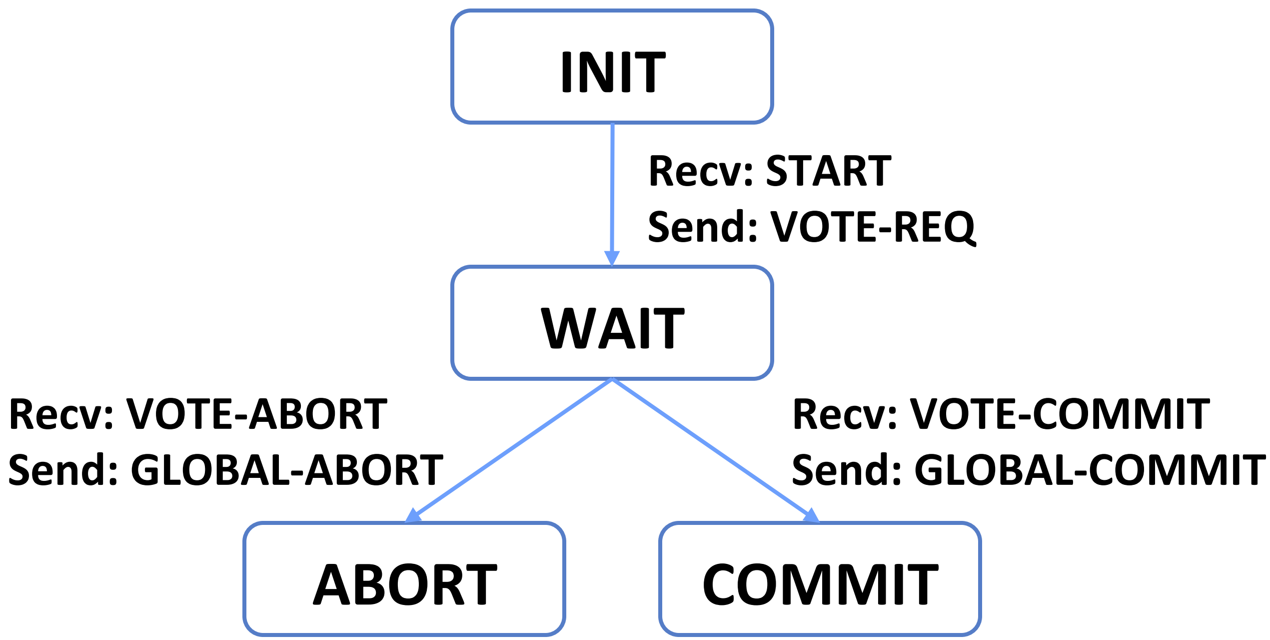
- If receive GLOBAL-COMMIT then commit
- If receive GLOBAL-ABORT then abort

Failure Free Example Execution

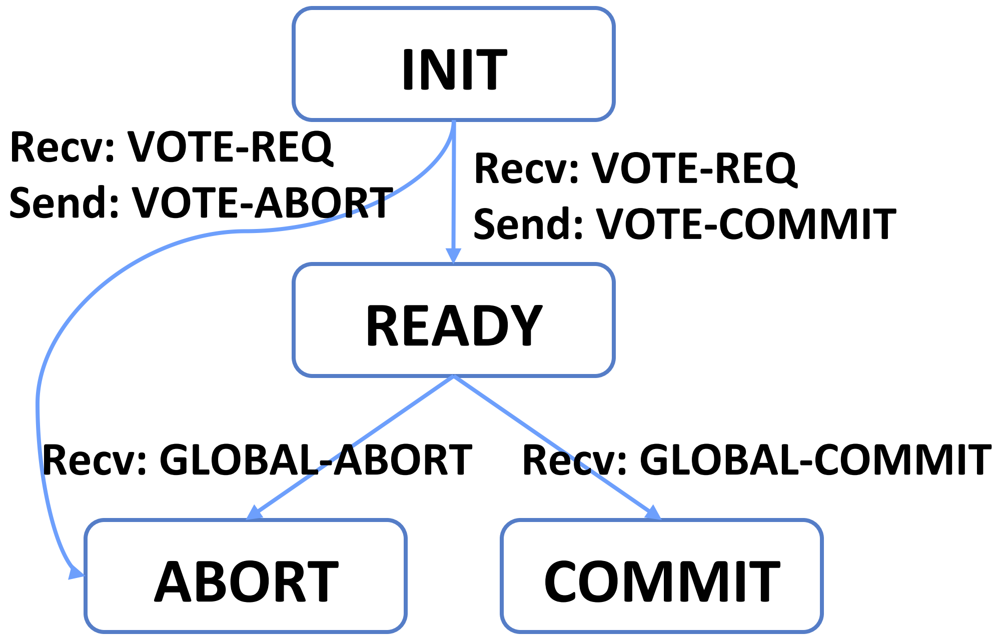


State Machine of Coordinator

- Coordinator implements simple state machine

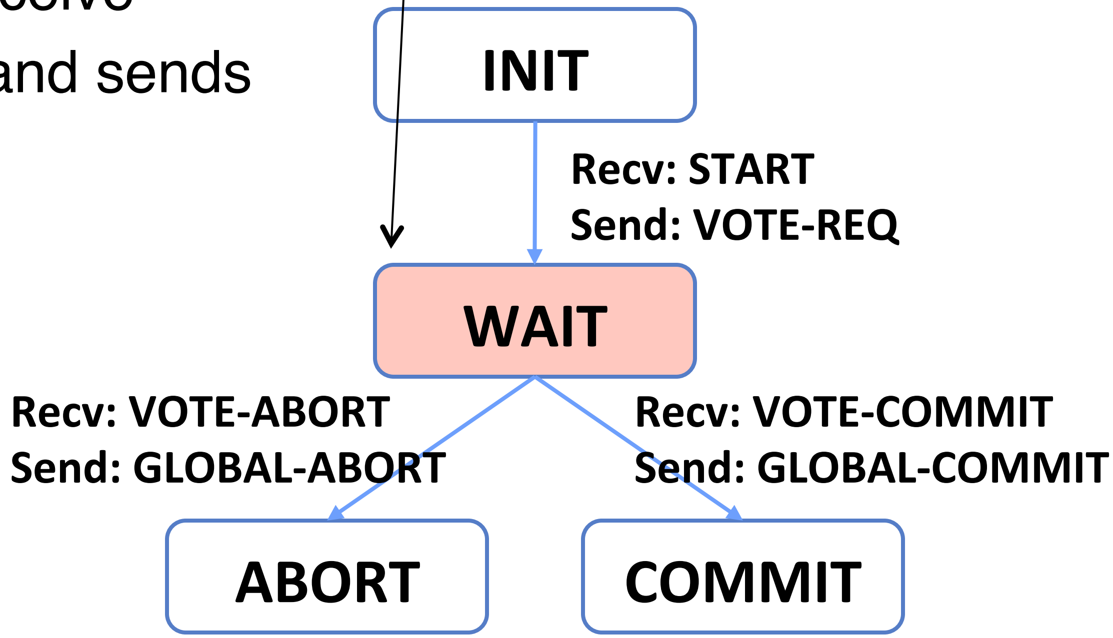


State Machine of workers



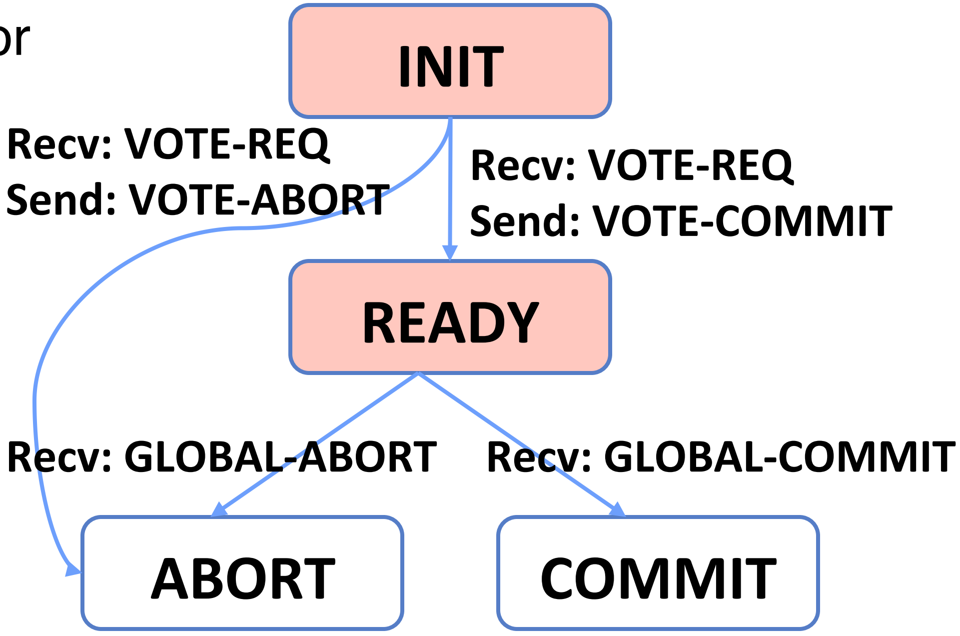
Dealing with Worker Failures

- How to deal with worker failures?
  - Failure only affects states in which the node is waiting for messages
  - Coordinator only waits for votes in "WAIT" state
  - In WAIT, if doesn't receive N votes, it times out and sends GLOBAL-ABORT

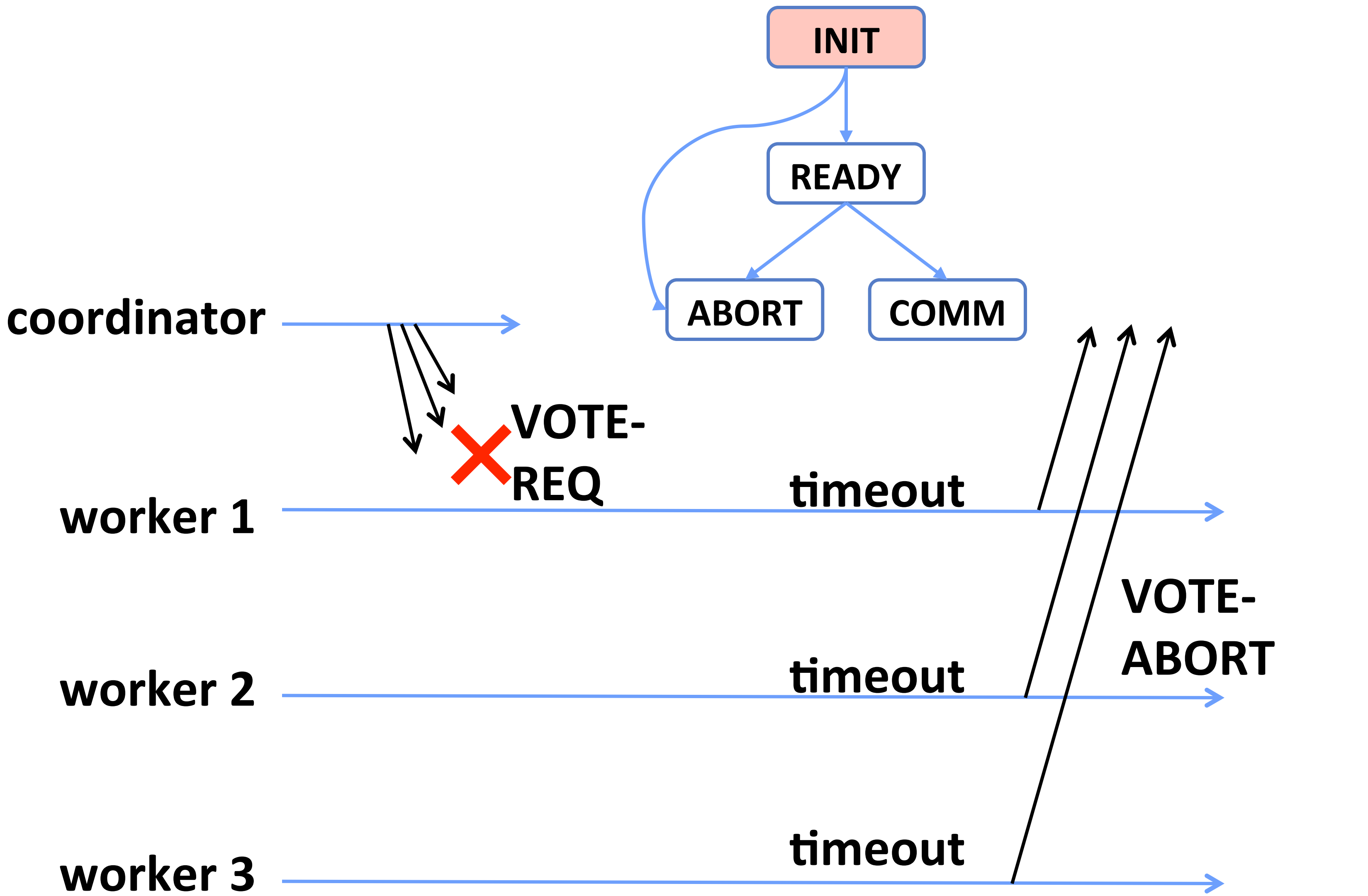


Dealing with Coordinator Failure

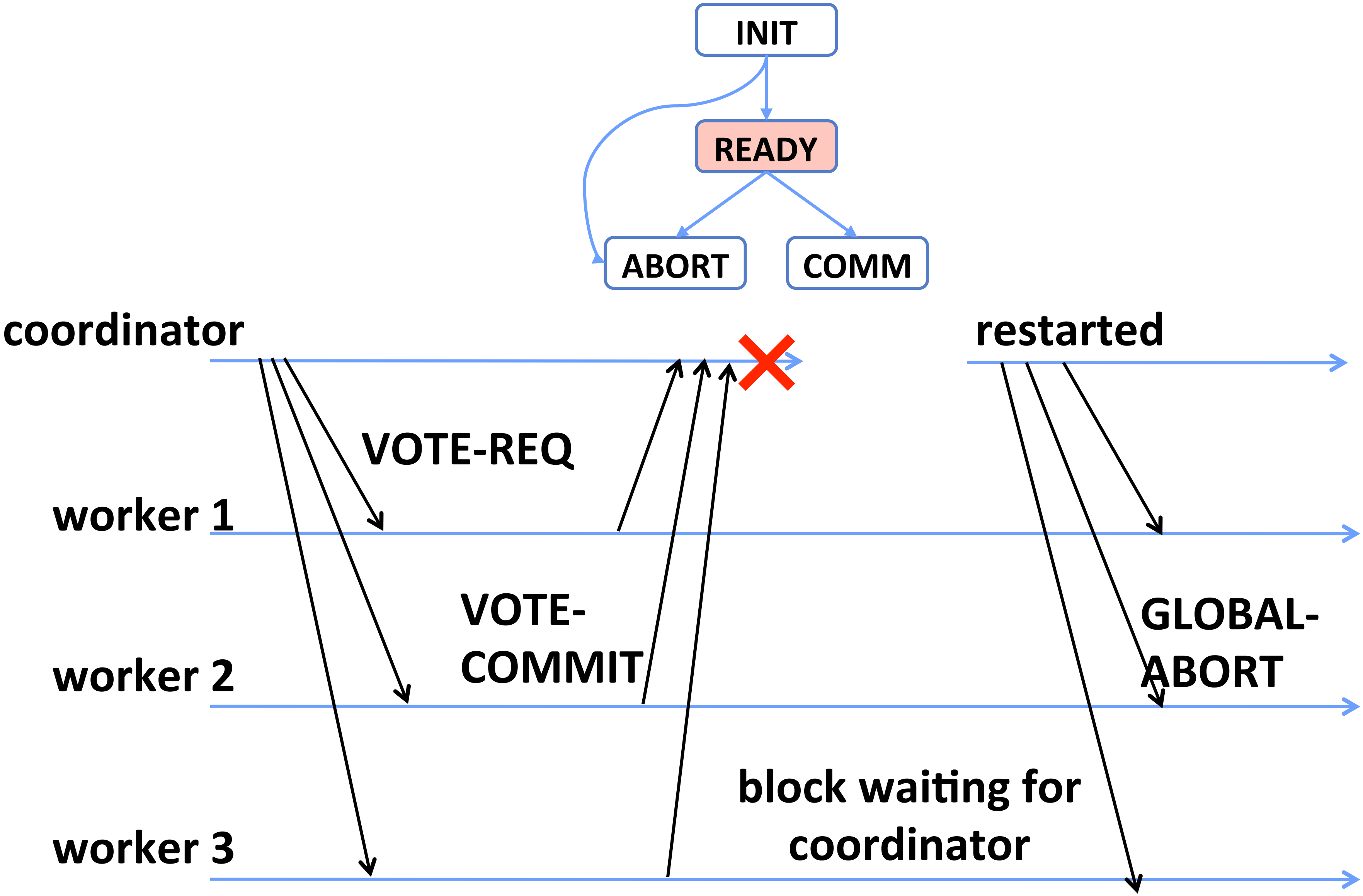
- How to deal with coordinator failures?
  - worker waits for VOTE-REQ in INIT
    - » Worker can time out and abort (coordinator handles it)
  - worker waits for GLOBAL-* message in READY
    - » If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send GLOBAL_* message



Example of Coordinator Failure #1



Example of Coordinator Failure #2



Remembering Where We Were

- All nodes use stable storage to store which state they were in

- Upon recovery, it can restore state and resume:
  – Coordinator aborts in INIT, WAIT, or ABORT
  – Coordinator commits in COMMIT
  – Worker aborts in INIT, READY, ABORT
  – Worker commits in COMMIT

Blocking for Coordinator to Recover

- A worker waiting for global decision can ask fellow workers about their state
  - If another worker is in ABORT or COMMIT state then coordinator must have sent GLOBAL-*
  - Thus, worker can safely abort or commit, respectively
  - If another worker is still in INIT state then both workers can decide to abort
  - If all workers are in ready, need to **BLOCK** (don't know if coordinator wanted to abort or commit)