CS162
Operating Systems and Systems Programming
Lecture 18

Queueing Theory, Disk scheduling & File Systems

April 2nd, 2020

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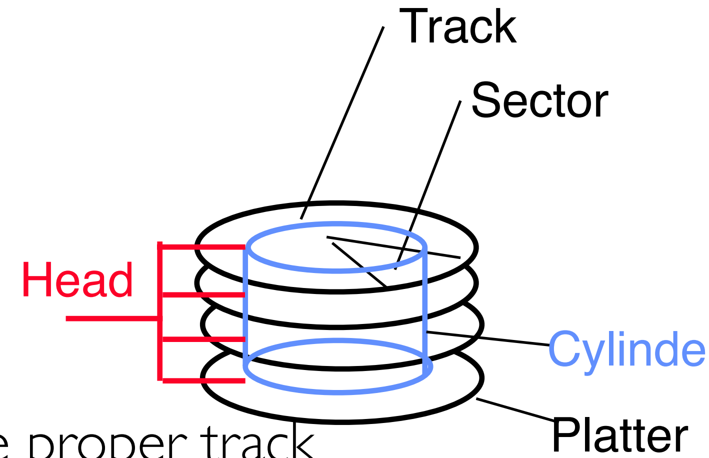
Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

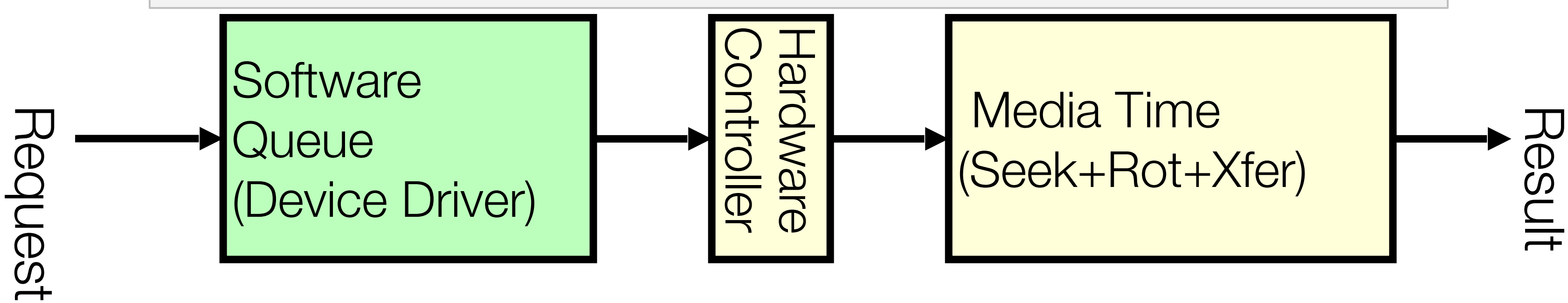
Review: Magnetic Disks

- Cylinders: all the tracks under the head at a given point on all surface

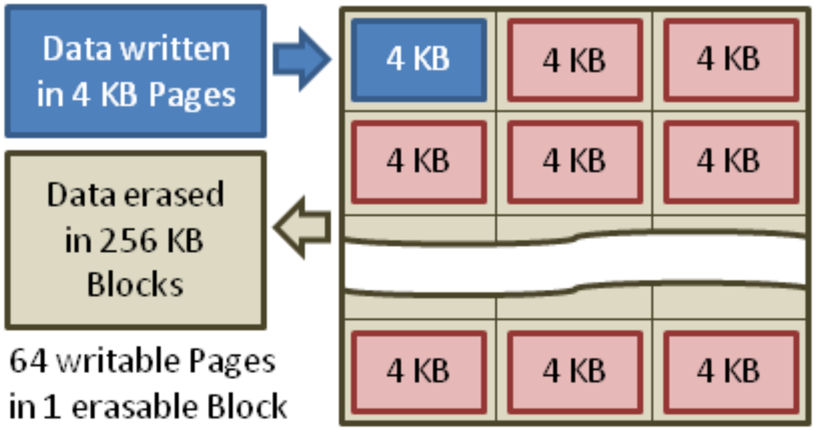


- Read/write data is a three-stage process:
  - Seek time: position the head/arm over the proper track
  - Rotational latency: wait for desired sector to rotate under r/w head
  - Transfer time: transfer a block of bits (sector) under r/w head

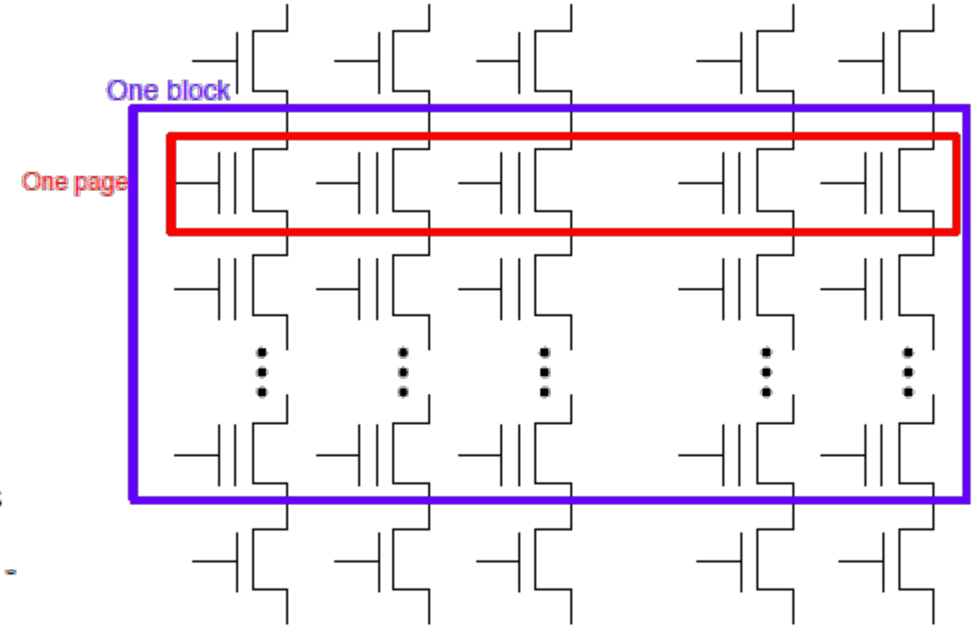
Disk Latency = Queueing Time + Controller time + Seek Time + Rotation Time + Xfer Time



Flash Memory (Con't)



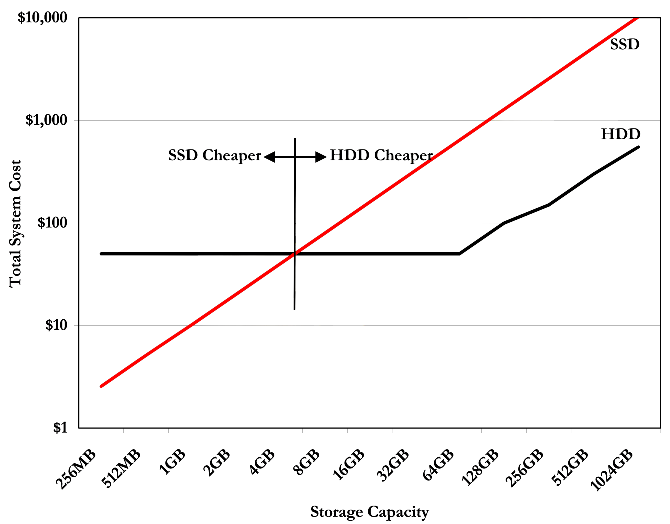
Typical NAND Flash Pages and Blocks



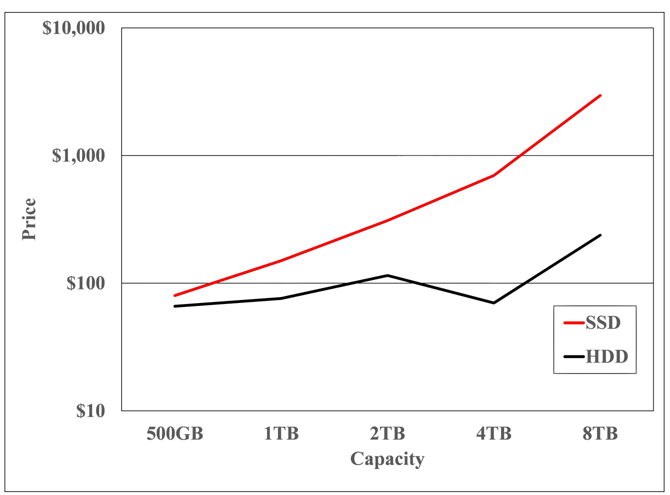
- Data read and written in page-sized chunks (e.g. 4K)
  – Cannot be addressed at byte level
  – Random access at block level for reads (no locality advantage)
  – Writing of new blocks handled in order (kinda like a log)
- Before writing, must be *erased* (256K block at a time)
  – Requires free-list management
  – CANNOT write over existing block (Copy-on-Write is normal case)

Recall: SSD Summary

- Pros (vs. hard disk drives):
  - Low latency, high throughput (eliminate seek/rotational delay)
  - No moving parts:
    - » Very light weight, low power, silent, very shock insensitive
  - Read at memory speeds (limited by controller and I/O bus)
- Cons
  - Small storage (0.1-0.5x disk), expensive (3-20x disk)
    - » Hybrid alternative: combine small SSD with large HDD
  - Wear-out happens because of writing

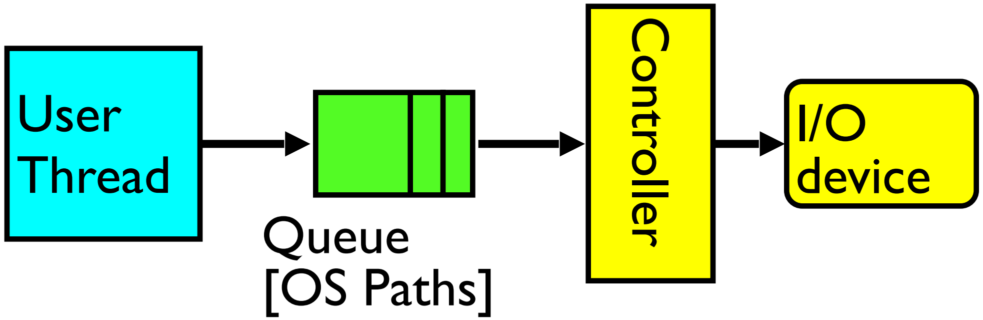


2007 perspective (Storage Newsletter)

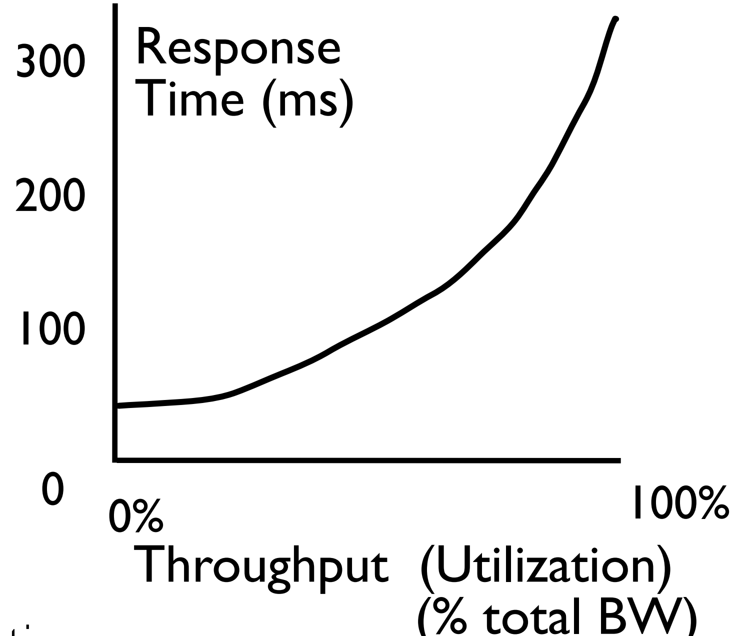


2019 perspective

Recall: I/O Performance

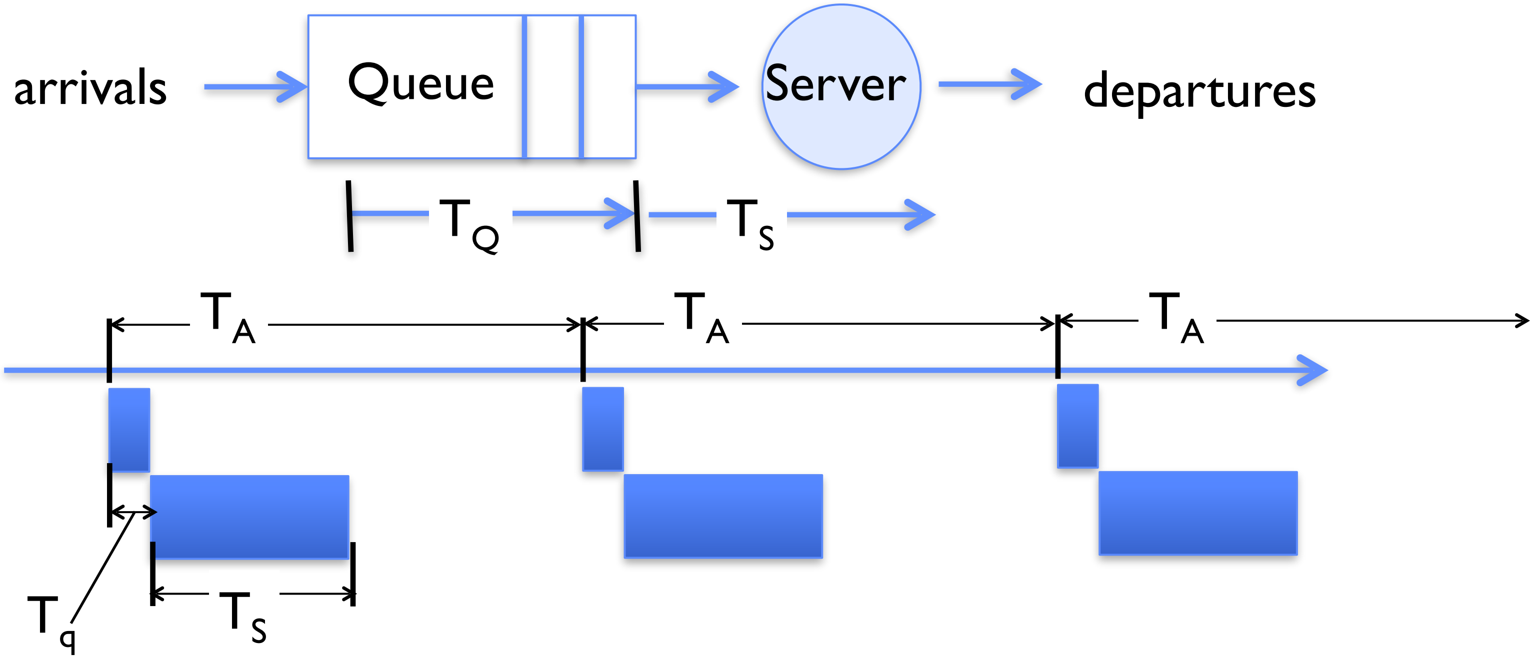


Response Time = Queue + I/O device service time



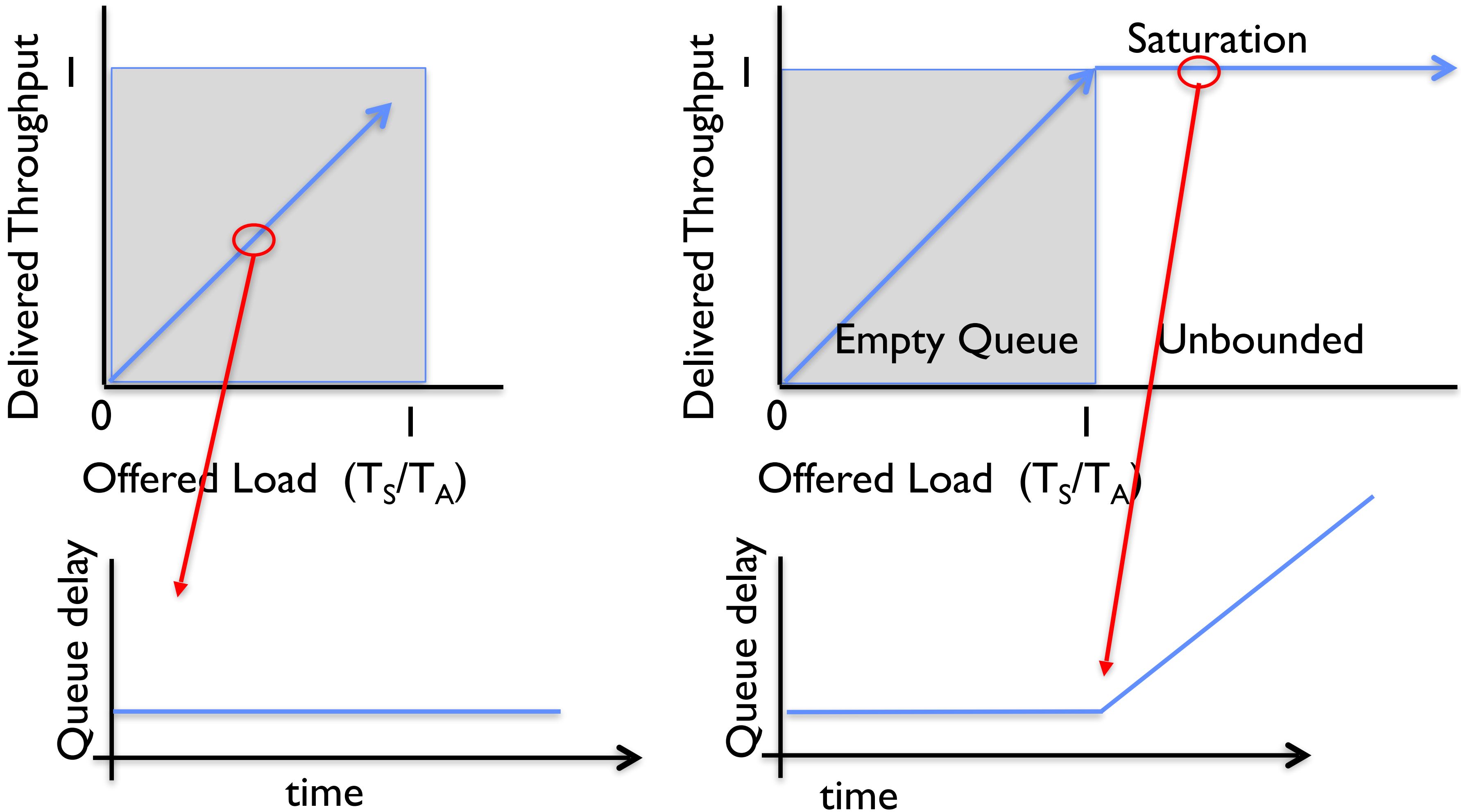
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » EffBW(n) = n / (S + n/B) = B / (1 + SB/n)
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller
    - » I/O device service time
- Queuing behavior:
  - Can lead to big increases of latency as utilization increases
  - Solutions?

A Simple Deterministic World



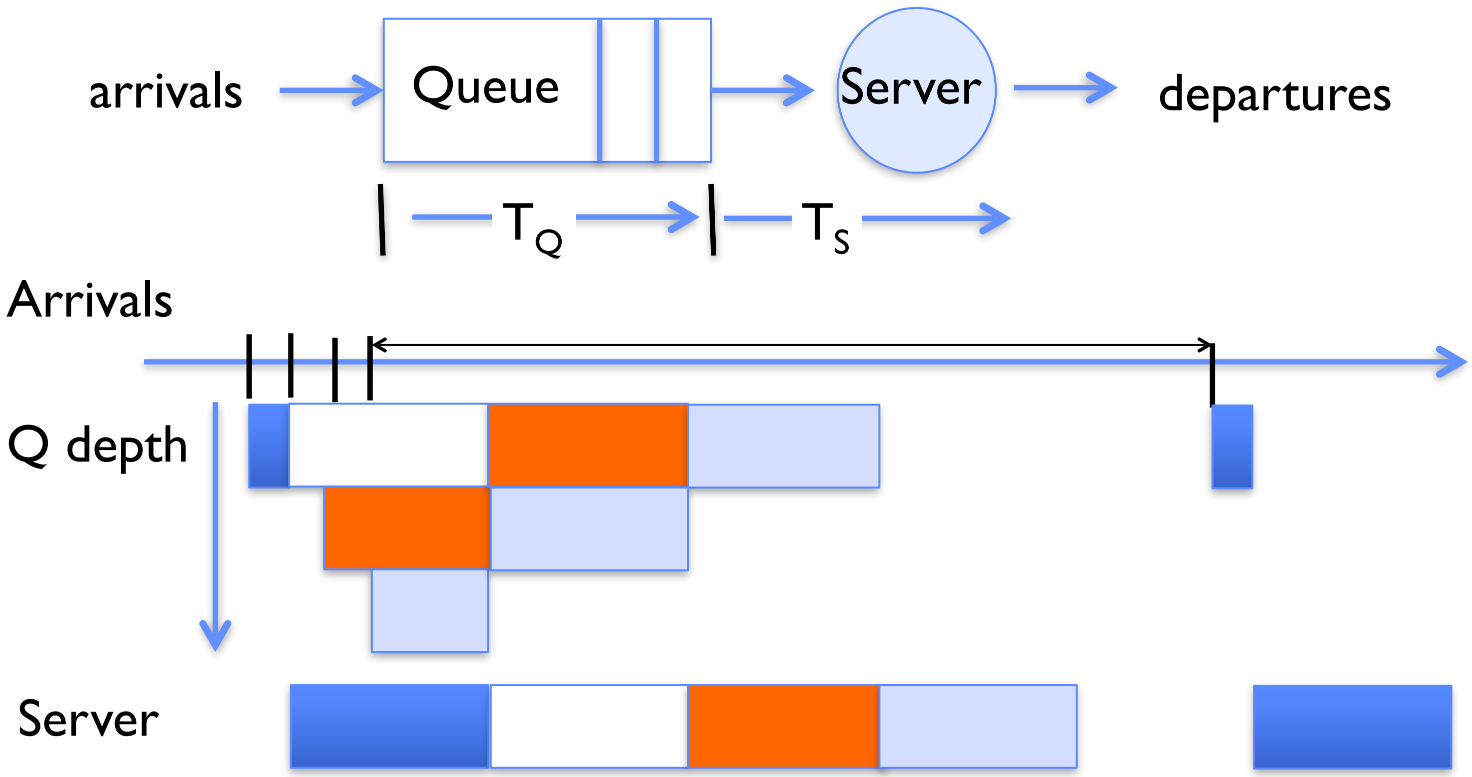
- Assume requests arrive at regular intervals, take a fixed time to process, with plenty of time between …
- Service rate ($\mu = 1/T_S$) - operations per second
- Arrival rate: ($\lambda = 1/T_A$) - requests per second
- Utilization: $U = \lambda/\mu$, where $\lambda < \mu$

A Ideal Linear World



- What does the queue wait time look like during overload?
  - Grows unbounded at a rate ~ (T_S/T_A) till request rate subsides

Reality: A Bursty World



- Requests arrive in a burst, must queue up till served
- Same average arrival time, but:
  - Almost all of the requests experience large queue delays
  - Even though average utilization is low!

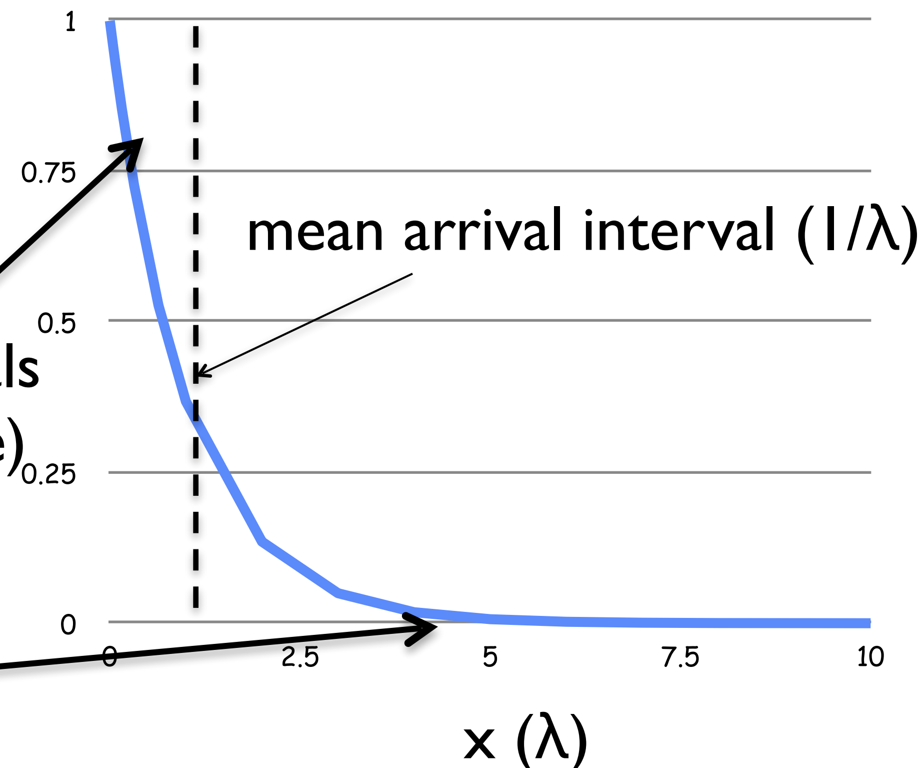
So how do we model the burstiness of arrival?

- Elegant mathematical framework if you start with *exponential distribution*
  - Probability density function of a continuous random variable with a mean of $1/\lambda$
  - $f(x) = \lambda e^{-\lambda x}$
  - *"Memoryless"*

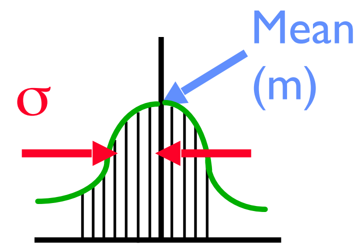
Likelihood of an event occurring is independent of how long we've been waiting

Lots of short arrival intervals (i.e., high instantaneous rate)

Few long gaps (i.e., low instantaneous rate)

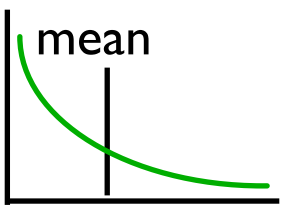


- Server spends variable time (T) with customers
  - Mean (Average) $m = \Sigma p(T) \times T$
  - Variance (stddev^2) $\sigma^2 = \Sigma p(T) \times (T-m)^2 = \Sigma p(T) \times T^2 - m^2$
  - Squared coefficient of variance: $C = \sigma^2/m^2$
    Aggregate description of the distribution



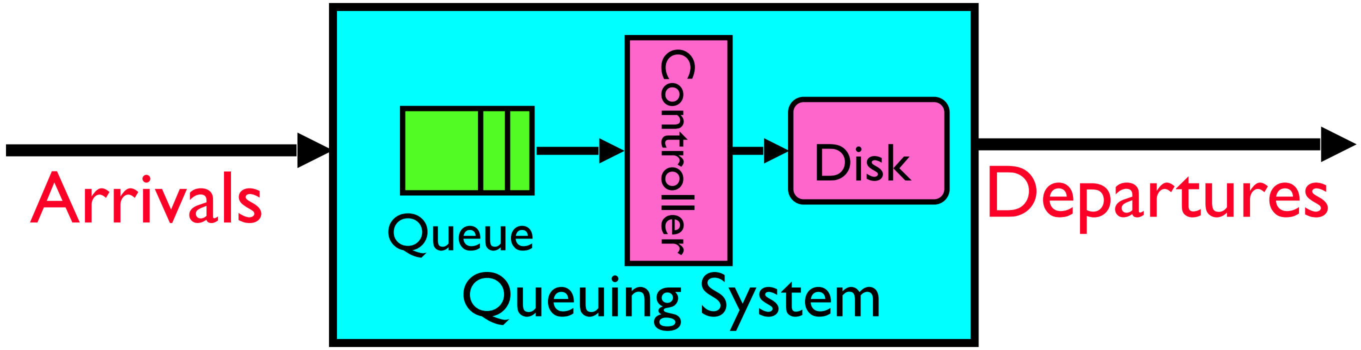
Distribution of service times

- Important values of C:
  - No variance or deterministic $\Rightarrow$ $C=0$
  - "Memoryless" or exponential $\Rightarrow$ $C=1$
    - » Past tells nothing about future
    - » Poisson process – *purely* or *completely* random process
    - » Many complex systems (or aggregates) are well described as memoryless
  - Disk response times $C \approx 1.5$ (majority seeks < average)



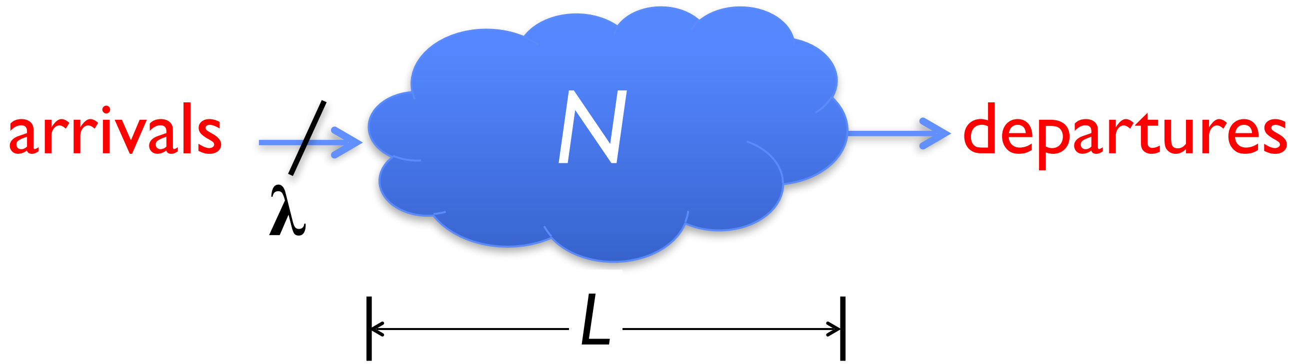
Memoryless

Introduction to Queuing Theory



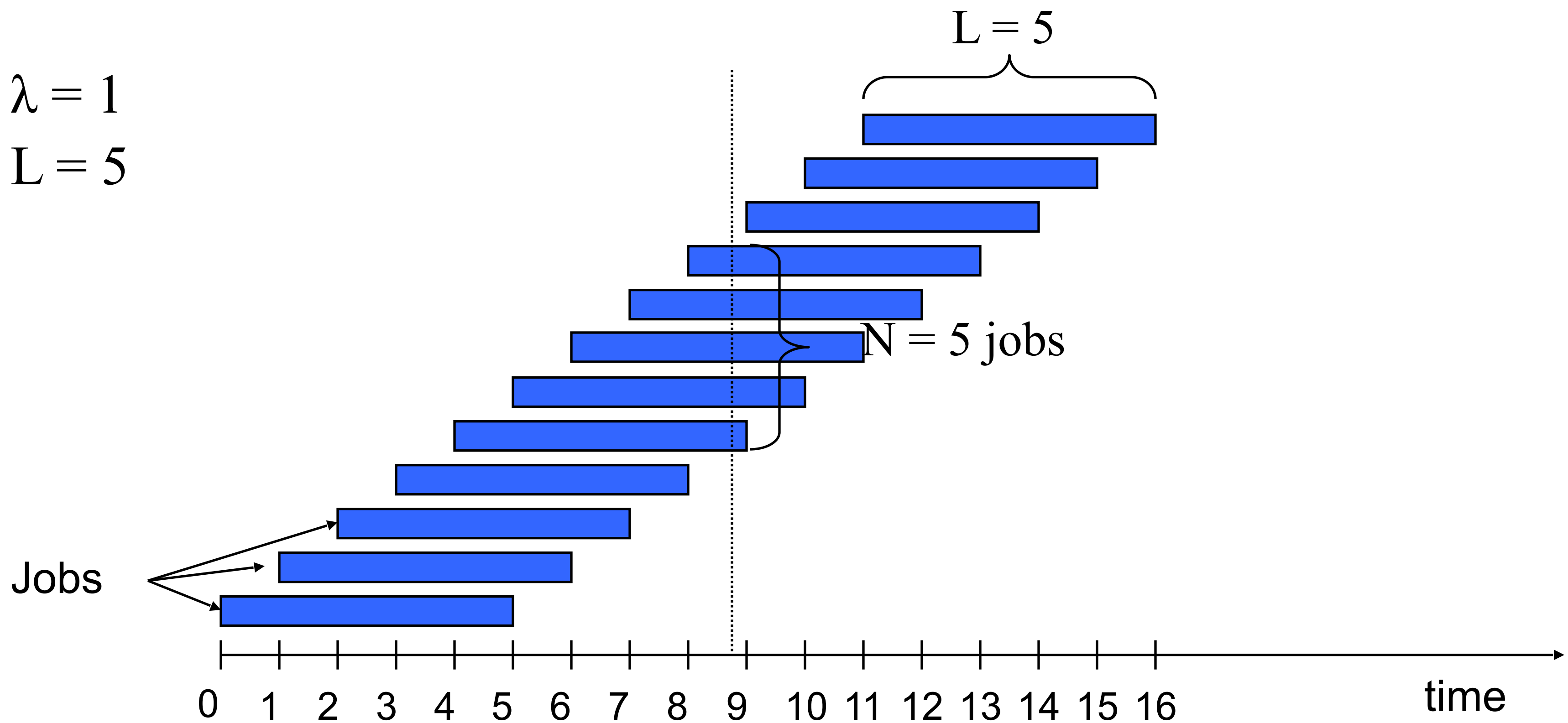
- What about queuing time??
  - Let's apply some queuing theory
  - Queuing Theory applies to long term, steady state behavior ⇒ Arrival rate = Departure rate
- Arrivals characterized by some probabilistic distribution
- Departures characterized by some probabilistic distribution

Little's Law



- In any *stable* system
  - Average arrival rate = Average departure rate
- The average number of jobs/tasks in the system (*N*) is equal to arrival time / throughput (λ) times the response time (*L*)
  - *N (jobs) = λ (jobs/s) x L (s)*
- Regardless of structure, bursts of requests, variation in service
  - Instantaneous variations, but it washes out in the average
  - Overall, requests match departures

Example

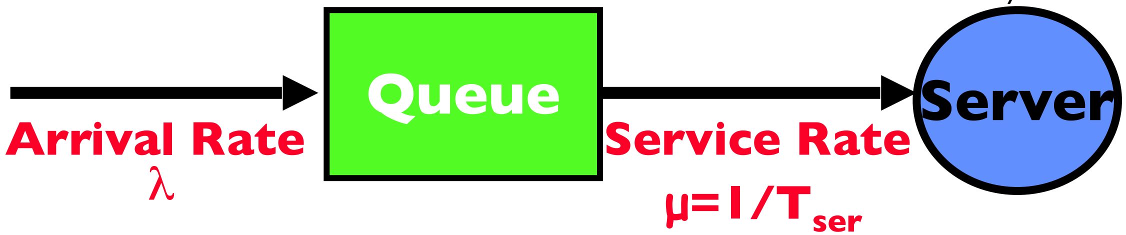


A: $N = \lambda \times L$

- E.g., $N = \lambda \times L = 5$

A Little Queuing Theory: Some Results

- Assumptions:
  - System in equilibrium; No limit to the queue
  - Time between successive arrivals is random and memoryless



- Parameters that describe our system:
  - λ: mean number of arriving customers/second
  - T_{ser}: mean time to service a customer ("m1")
  - C: squared coefficient of variance = $\sigma^2/m1^2$
  - μ: service rate = $1/T_{ser}$
  - u: server utilization ($0 \le u \le 1$): $u = \lambda/\mu = \lambda \times T_{ser}$
- Parameters we wish to compute:
  - T_q: Time spent in queue
  - L_q: Length of queue = $\lambda \times T_q$ (by Little's law)
- Results:
  - Memoryless service distribution (C = 1): (an "M/M/1 queue"):
    - » $T_q = T_{ser} \times u/(1 - u)$
  - General service distribution (no restrictions), 1 server (an "M/G/1 queue"):
    - » $T_q = T_{ser} \times ½(1+C) \times u/(1 - u)$

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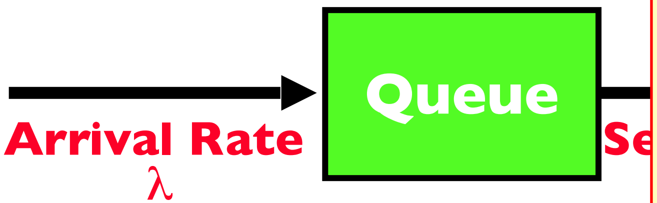
  - System in equilibrium; No limit to the q
  - Time between successive arrivals is ranc



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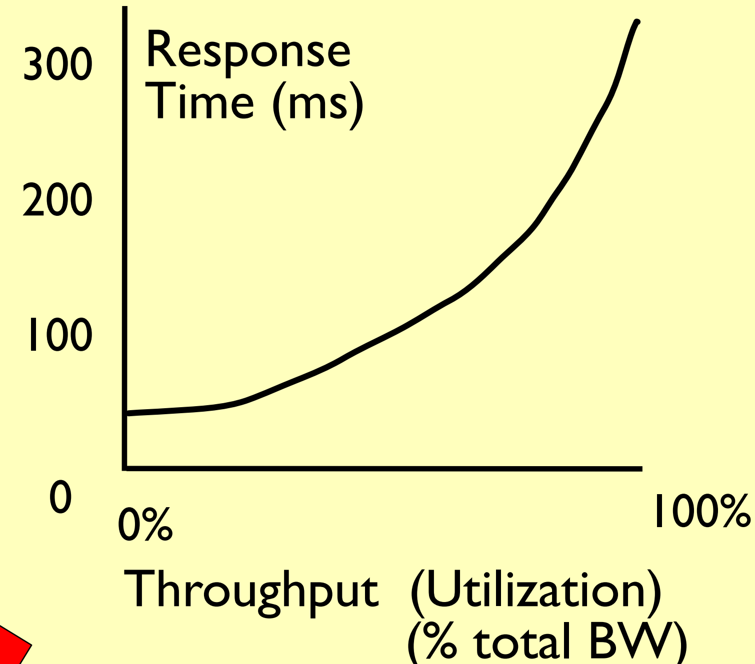
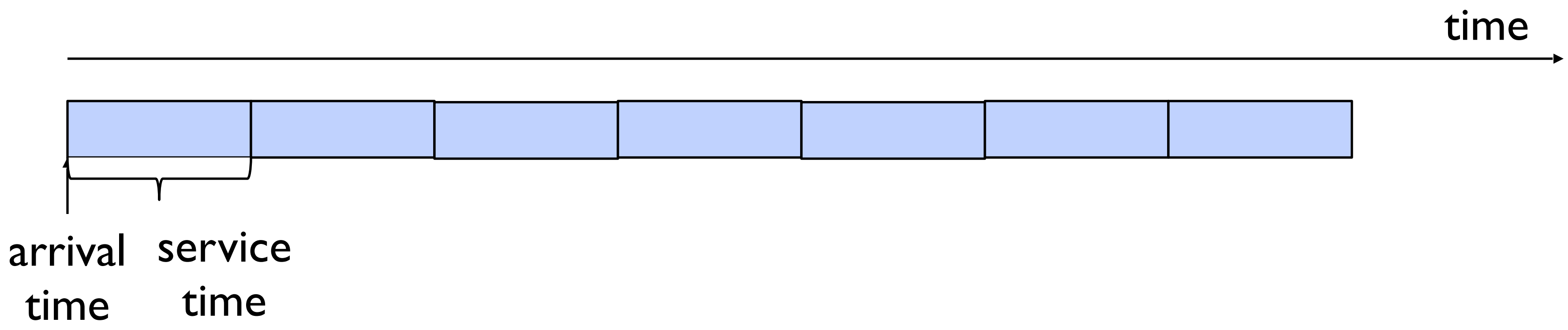
Why does response/queueing delay grow unboundedly even though the utilization is < 1 ?



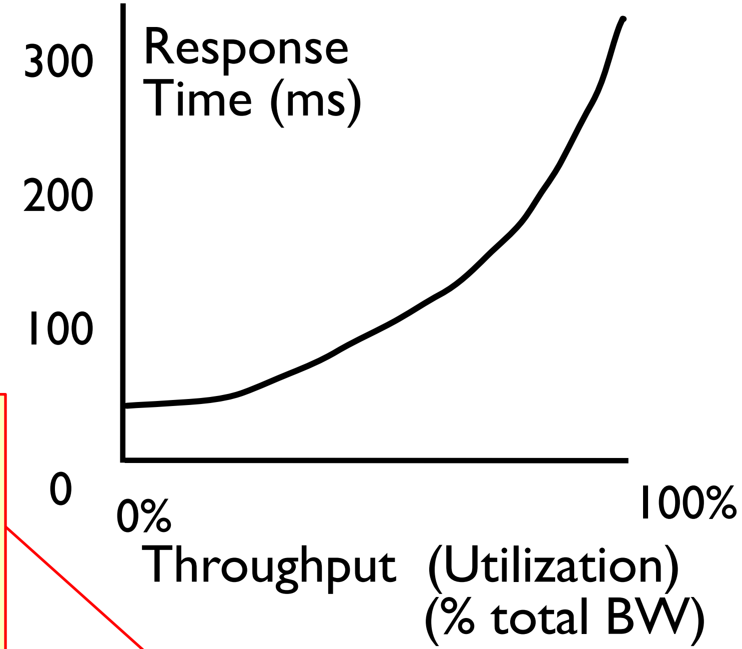
Why unbounded response time?

- Assume deterministic arrival process and service time
  - Possible to sustain utilization = 1 with bounded response time!

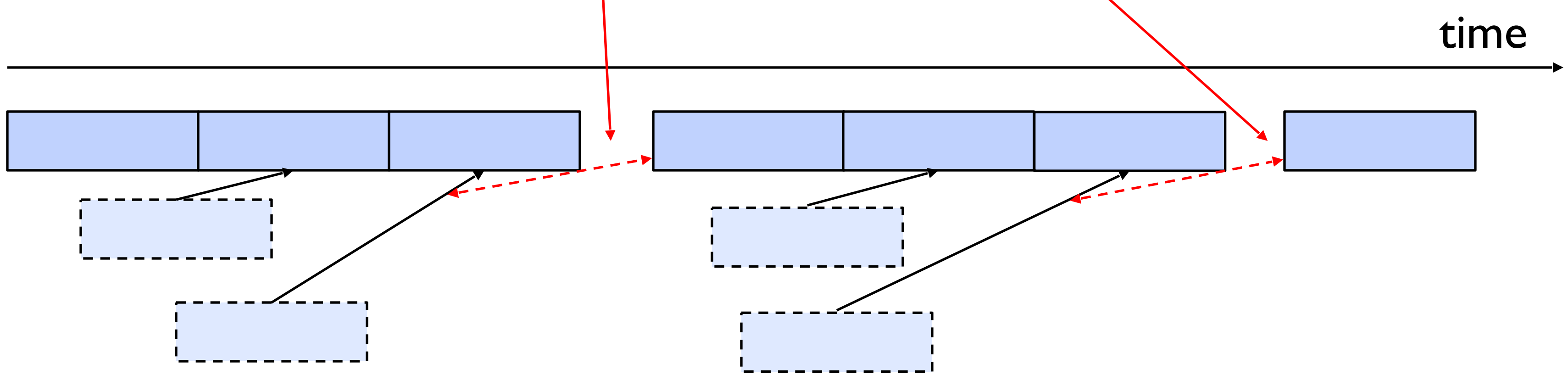


Why unbounded response time?

- Assume stochastic arrival process (and service time)
  - No longer possible to achieve utilization = 1



This wasted time can never be reclaimed!
So cannot achieve u = 1!



A Little Queuing Theory: An Example

- Example Usage Statistics:
  - User requests 10 x 8KB disk I/Os per second
  - Requests & service exponentially distributed (C=1.0)
  - Avg. service = 20 ms (From controller+seek+rot+trans)
- Questions:
  - How utilized is the disk?
    - » Ans: server utilization, $u = \lambda T_{ser}$
  - What is the average time spent in the queue?
    - » Ans: T_q
  - What is the number of requests in the queue?
    - » Ans: L_q
  - What is the avg response time for disk request?
    - » Ans: $T_{sys} = T_q + T_{ser}$
- Computation:

λ (avg # arriving customers/s) = 10/s

T_{ser} (avg time to service customer) = 20 ms (0.02s)

u (server utilization) = $\lambda \times T_{ser}$ = 10/s × .02s = 0.2

T_q (avg time/customer in queue) = $T_{ser} \times u/(1 - u)$
= 20 x 0.2/(1-0.2) = 20 x 0.25 = 5 ms (0 .005s)

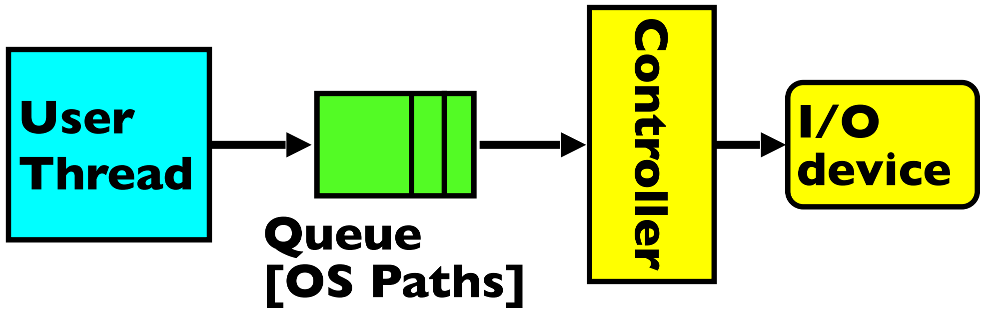
L_q (avg length of queue) = $\lambda \times T_q$ = 10/s x .005s = 0.05

T_{sys} (avg time/customer in system) = $T_q + T_{ser}$ = 25 ms

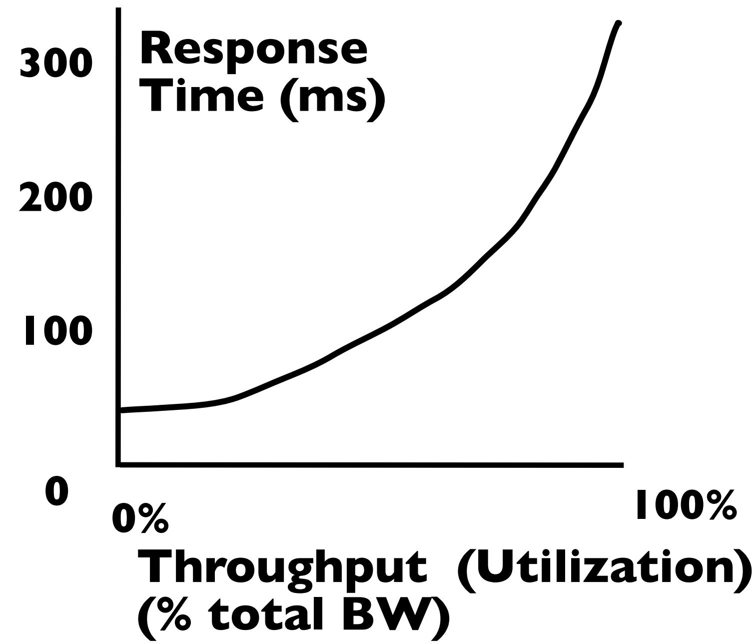
Queuing Theory Resources

- Resources page contains Queueing Theory Resources (under Readings):
  - Scanned pages from Patterson and Hennessy book that gives further discussion and simple proof for general equation: https://cs162.eecs.berkeley.edu/static/readings/patterson_queue.pdf
  - A complete website full of resources: http://web2.uwindsor.ca/math/hlynka/qonline.html

Optimize I/O Performance



Response Time = Queue + I/O device service time



- How to improve performance?
  - Make everything faster ☺
  - More Decoupled (Parallelism) systems
    - » multiple independent buses or controllers
  - Optimize the bottleneck to increase service rate
    - » Use the queue to optimize the service
  - Do other useful work while waiting
- Queues absorb bursts and smooth the flow
- Admissions control (finite queues)
  - Limits delays, but may introduce unfairness and livelock

I/O Scheduling Discussion

- What happens when two processes are accessing storage in different regions of the disk ?
- What can the driver do?
- How can buffering help?
- What about non-blocking I/O?
- Or threads with blocking I/O?
- What limits how much reordering the OS can do?

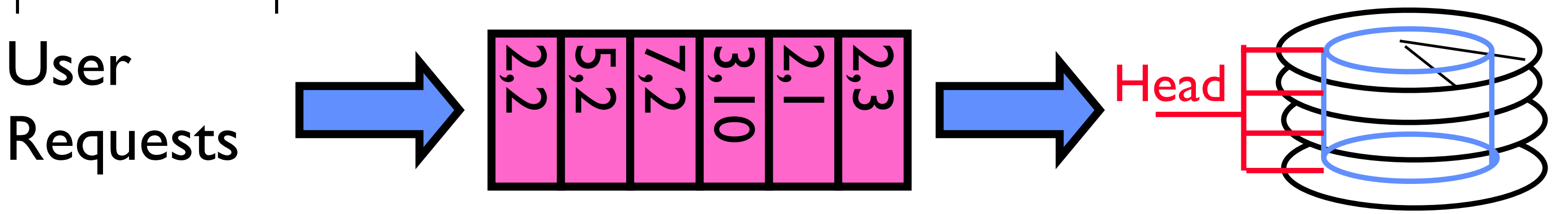
When is Disk Performance Highest?

- When there are big sequential reads, or
- When there is so much work to do that they can be piggy backed (reordering queues—one moment)

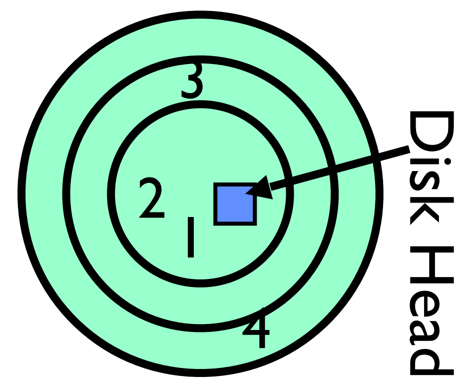
- OK to be inefficient when things are mostly idle
- Bursts are both a threat and an opportunity
- <your idea for optimization goes here>
  - Waste space for speed?

Disk Scheduling (1/2)

- Disk can do only one request at a time; What order do you choose to do queued requests?

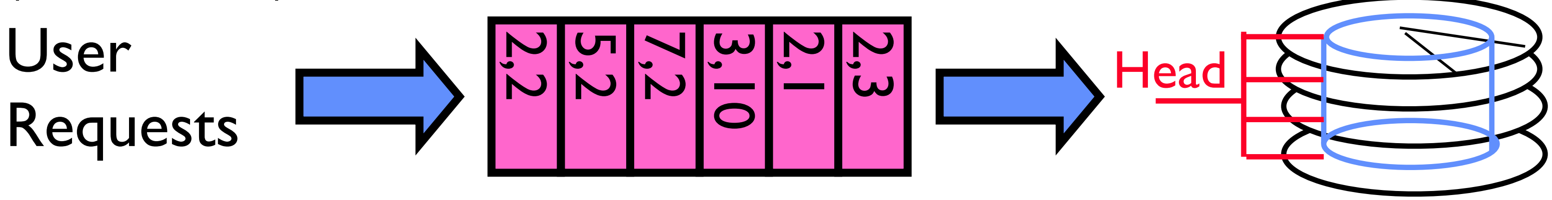


- FIFO Order
  - Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  - Pick the request that's closest on the disk
  - Although called SSTF, today must include rotational delay in calculation, since rotation can be as long as seek
  - Con: SSTF good at reducing seeks, but may lead to starvation

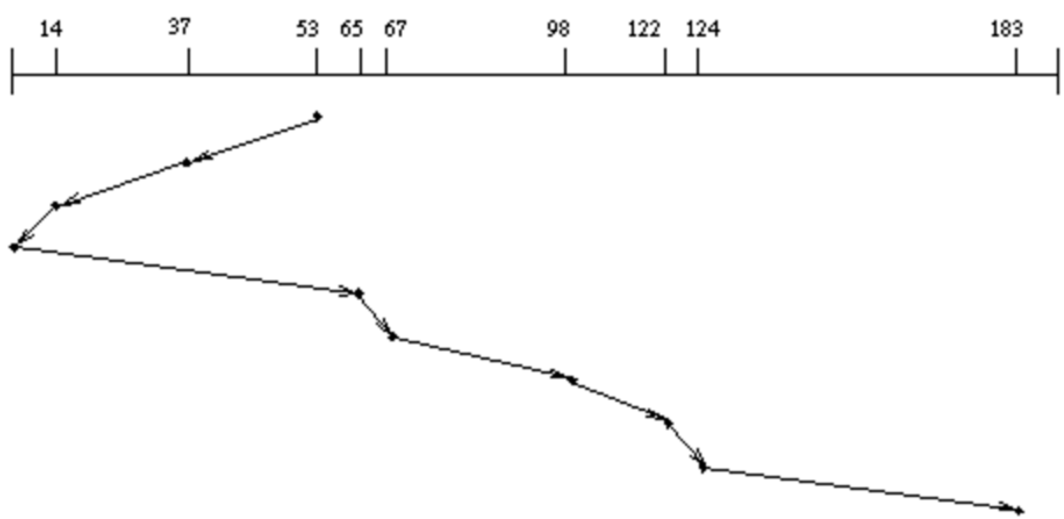


Disk Scheduling (2/2)

- Disk can do only one request at a time; What order do you choose to do queued requests?



- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  - No starvation, but retains flavor of SSTF



Disk Scheduling (2/2)

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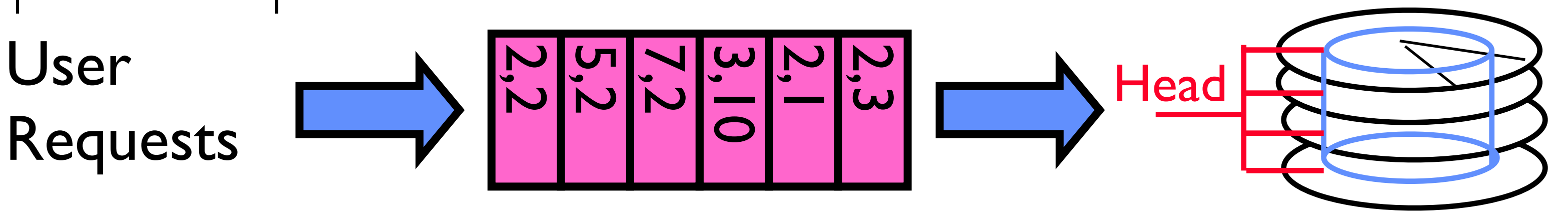
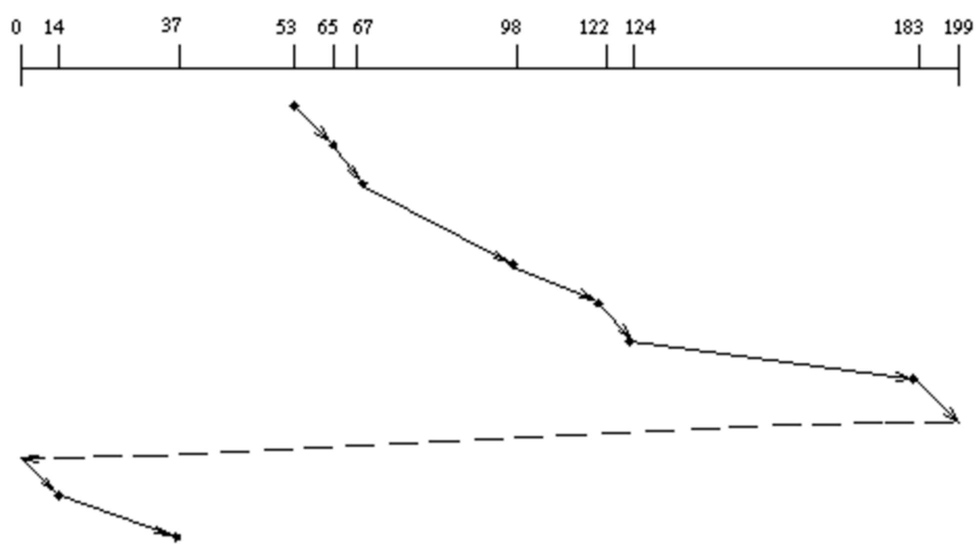


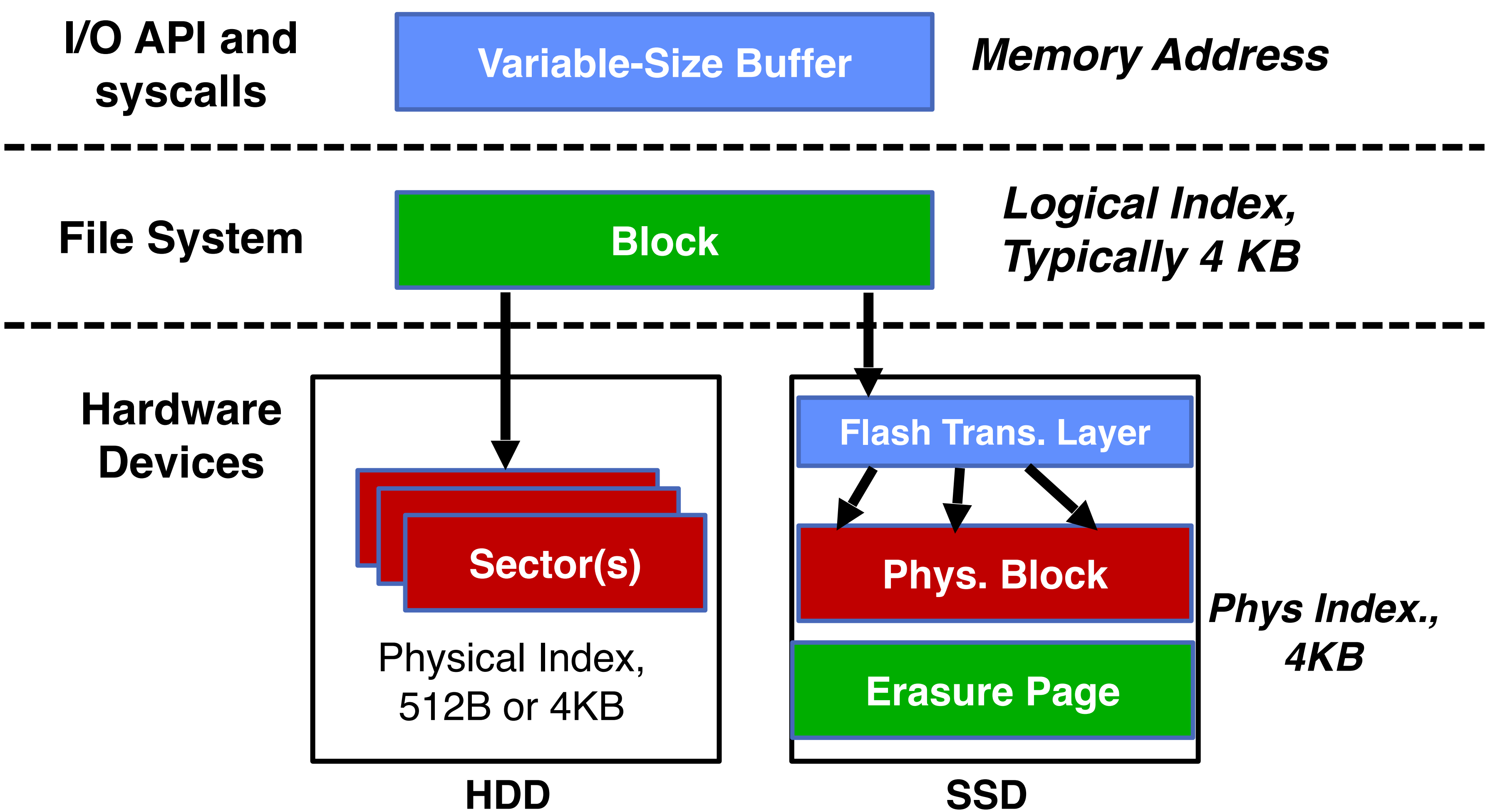
- C-SCAN: Circular-Scan: only goes in one direction
  – Skips any requests on the way back
  – Fairer than SCAN, not biased towards pages in middle



Recall: How do we Hide I/O Latency?

- Blocking Interface: "Wait"
  - When request data (e.g., read() system call), put process to sleep until data is ready
  - When write data (e.g., write() system call), put process to sleep until device is ready for data
- Non-blocking Interface: "Don't Wait"
  - Returns quickly from read or write request with count of bytes successfully transferred to kernel
  - Read may return nothing, write may write nothing
- Asynchronous Interface: "Tell Me Later"
  - When requesting data, take pointer to user's buffer, return immediately; later kernel fills buffer and notifies user
  - When sending data, take pointer to user's buffer, return immediately; later kernel takes data and notifies user

From Storage to File Systems

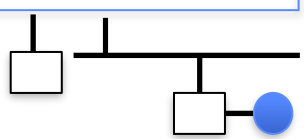


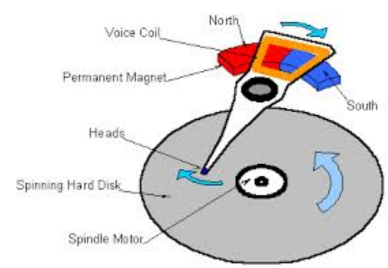
I/O & Storage Layers

Operations, Entities and Interface

Application / Service

High Level I/O	*streams*
Low Level I/O	*handles*
Syscall	*registers*
	`file_open, file_read, … on struct file * & void *`
File System	*descriptors* ← **we are here …**
I/O Driver	*Commands and Data Transfers*
	Disks, Flash, Controllers, DMA





Recall: C Low level I/O

- Operations on File Descriptors – as OS object representing the state of a file
  - User has a "handle" on the descriptor

```
#include <fcntl.h>
#include <unistd.h>
#include <sys/types.h>

int open (const char *filename, int flags [, mode_t mode])
int create (const char *filename, mode_t mode)
int close (int filedes)
```

Bit vector of:
- Access modes (Rd, Wr, …)
- Open Flags (Create, …)
- Operating modes (Appends, …)

Bit vector of Permission Bits:
- User|Group|Other X R|W|X

http://www.gnu.org/software/libc/manual/html_node/Opening-and-Closing-Files.html

Recall: C Low Level Operations

```
ssize_t read (int filedes, void *buffer, size_t maxsize)
 - returns bytes read, 0 => EOF, -1 => error
ssize_t write (int filedes, const void *buffer, size_t size)
 - returns bytes written
off_t lseek (int filedes, off_t offset, int whence)
 - set the file offset
   * if whence == SEEK_SET: set file offset to "offset"
   * if whence == SEEK_CRT: set file offset to crt location +
"offset"
   * if whence == SEEK_END: set file offset to file size + "offse
int fsync (int fildes)
 – wait for i/o of filedes to finish and commit to disk
void sync (void) – wait for ALL to finish and commit to disk
```

- When write returns, data is on its way to disk and can be read, but it may not actually be permanent!

Building a File System

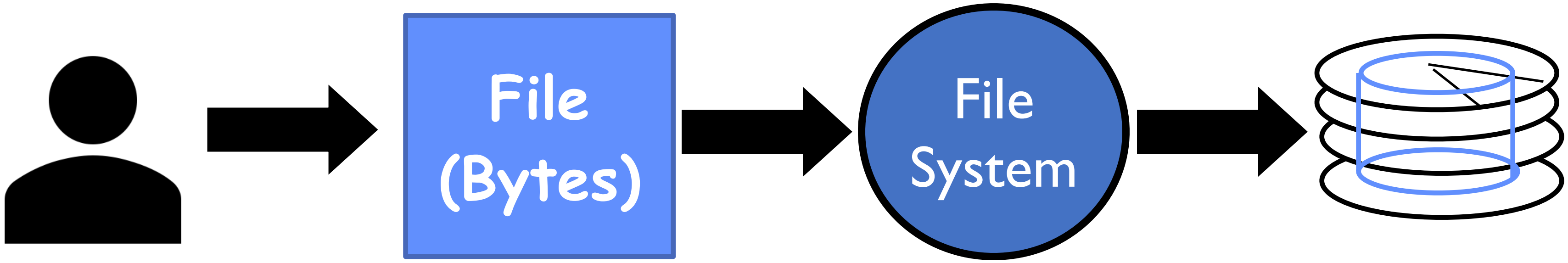
- **File System**: Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.

- File System Components
  - **Naming**: Interface to find files by name, not by blocks
  - **Disk Management**: collecting disk blocks into files
  - **Protection**: Layers to keep data secure
  - **Reliability/Durability**: Keeping of files durable despite crashes, media failures, attacks, etc.

Recall: User vs. System View of a File

- User's view:
  - Durable Data Structures
- System's view (system call interface):
  - Collection of Bytes (UNIX)
  - Doesn't matter to system what kind of data structures you want to store on disk!
- System's view (inside OS):
  - Collection of blocks (a block is a logical transfer unit, while a sector is the physical transfer unit)
  - Block size ≥ sector size; in UNIX, block size is 4KB

Translating from User to Systems View



- What happens if user says: "give me bytes 2 – 12?"
  – Fetch block corresponding to those bytes
  – Return just the correct portion of the block
- What about writing bytes 2 – 12?
  – Fetch block, modify relevant portion, write out block
- Everything *inside* file system in terms of whole-size blocks
  – Actual disk I/O happens in blocks
  – read/write smaller than block size needs to translate and buffer

Disk Management Policies

- Basic entities on a disk:
  - File: user-visible group of blocks arranged sequentially in logical space
  - Directory: user-visible index mapping names to files

- Access disk as linear array of sectors. Two Options:
  - Identify sectors as vectors [cylinder, surface, sector], sort in cylinder-major order, not used anymore
  - Logical Block Addressing (LBA): Every sector has integer address from zero up to max number of sectors
  - Controller translates from address ⇒ physical position
    - » First case: OS/BIOS must deal with bad sectors
    - » Second case: hardware shields OS from structure of disk

What does the file system need?

- Track free disk blocks
  - Need to know where to put newly written data
- Track which blocks contain data for which files
  - Need to know where to read a file from
- Track files in a directory
  - Find list of file's blocks given its name
- Where do we maintain all of this?
  - Somewhere on disk

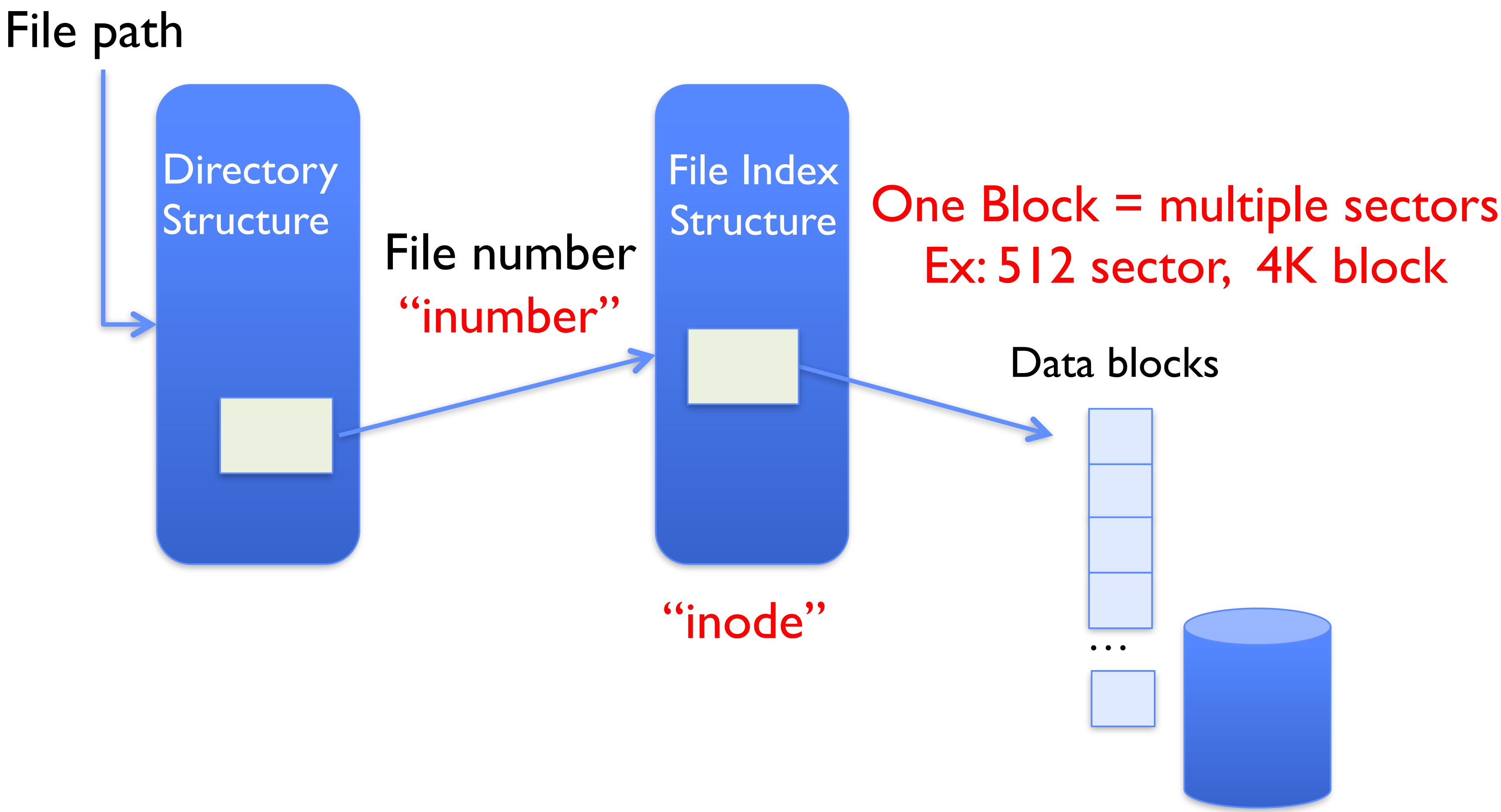
Data Structures on Disk

- Different than data structures in memory
- Access a block at a time
  - Can't efficiently read/write a single word
  - Have to read/write full block containing it
  - Ideally want sequential access patterns
- Durability
  - Ideally, file system is in meaningful state upon shutdown
  - This obviously isn't always the case…

Designing a File System …

- What factors are critical to the design choices?
- Durable data store => it's all on disk
- (Hard) Disks Performance !!!
  - Maximize sequential access, minimize seeks
- Open before Read/Write
  - Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  - Can write to expand the file
  - Start small and grow, need to make room
- Organized into directories
  - What data structure (on disk) for that?
- Need to allocate / free blocks
  - Such that access remains efficient

Components of a File System

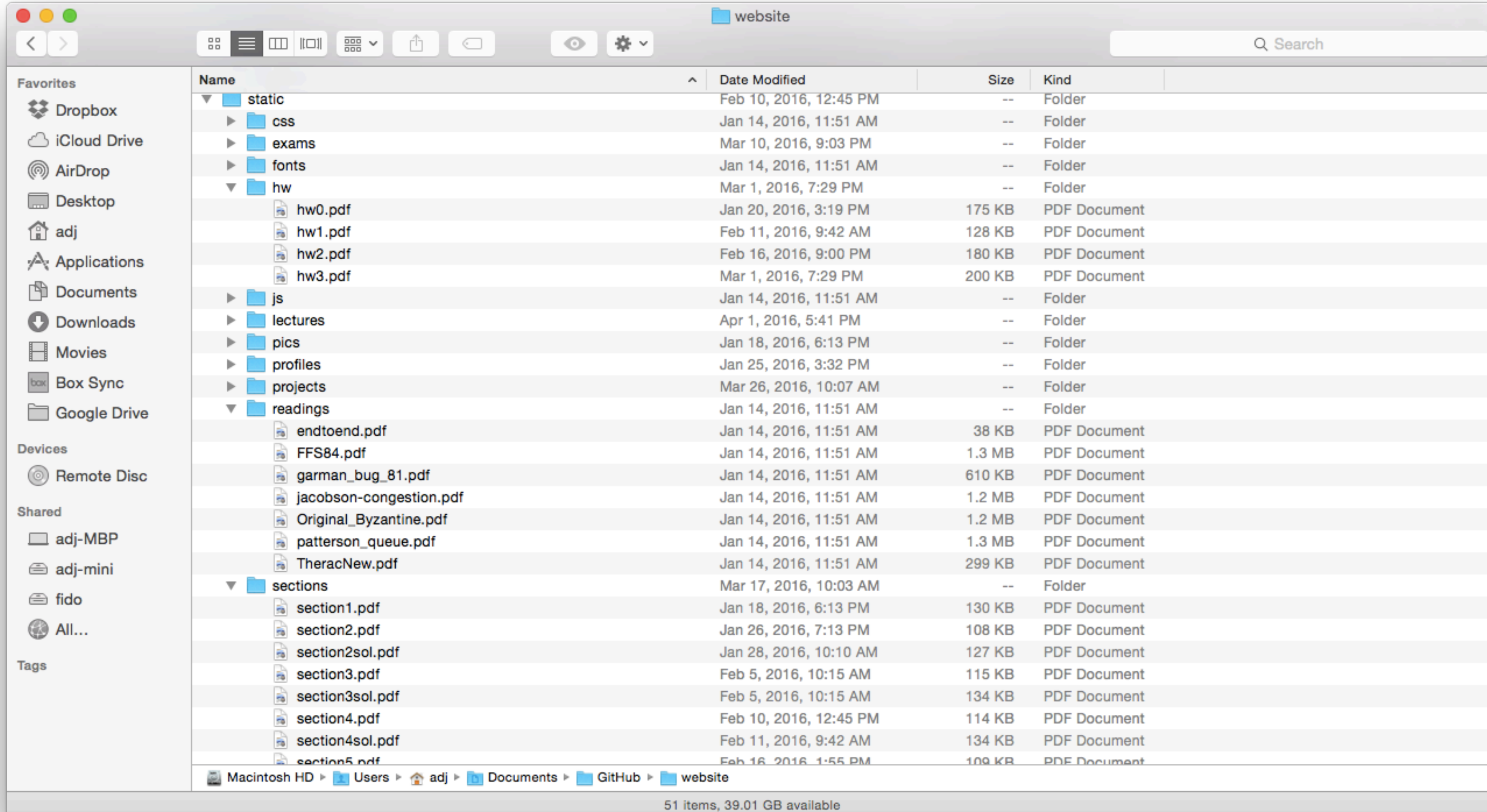


Components of a file system

file name *offset* —directory→ *file number* *offset* —Index structure→ *Storage block*

- Open performs *Name Resolution*
  - Translates pathname into a "file number"
    - » Used as an "index" to locate the blocks
  - Creates a file descriptor in PCB within kernel
  - Returns a "handle" (another integer) to user process
- Read, Write, Seek, and Sync operate on handle
  - Mapped to file descriptor and to blocks

Directories



Directory

- Basically a hierarchical structure

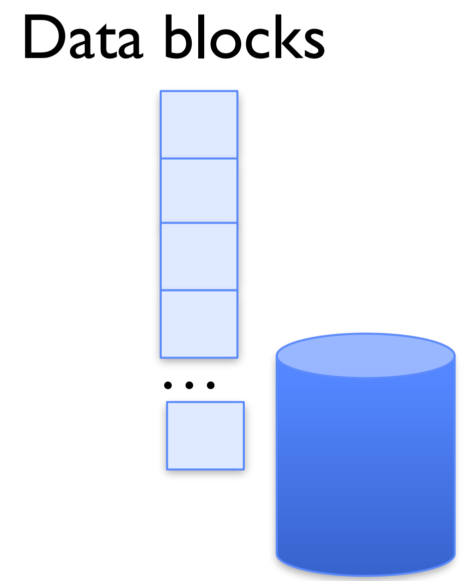
- Each directory entry is a collection of
  - Files
  - Directories
    - » A link to another entries

- Each has a name and attributes
  - Files have data

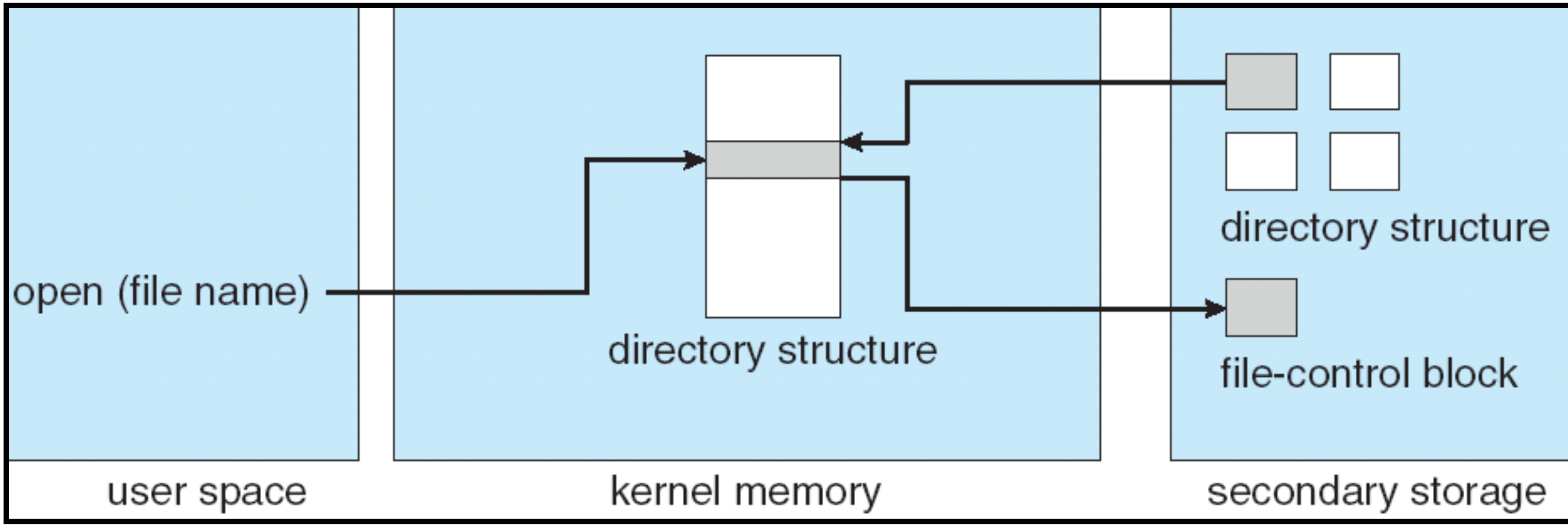
- Links (hard links) make it a DAG, not just a tree
  - Softlinks (aliases) are another name for an entry

File

- Named permanent storage
- Contains
  - – Data
    - » Blocks on disk somewhere
  - – Metadata (Attributes)
    - » Owner, size, last opened, …
    - » Access rights
      - R, W, X
      - Owner, Group, Other (in Unix systems)
      - Access control list in Windows system

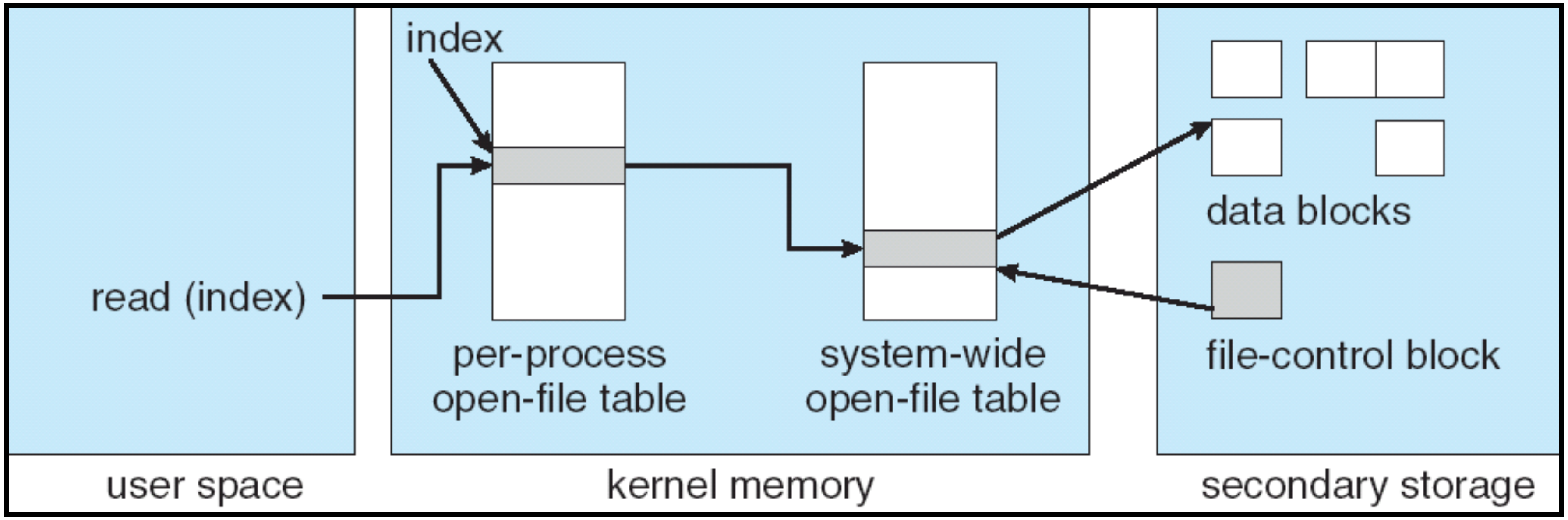


In-Memory File System Structures



- Open system call:
  – Resolves file name, finds file control block (inode)
  – Makes entries in per-process and system-wide tables
  – Returns index (called "file handle") in open-file table

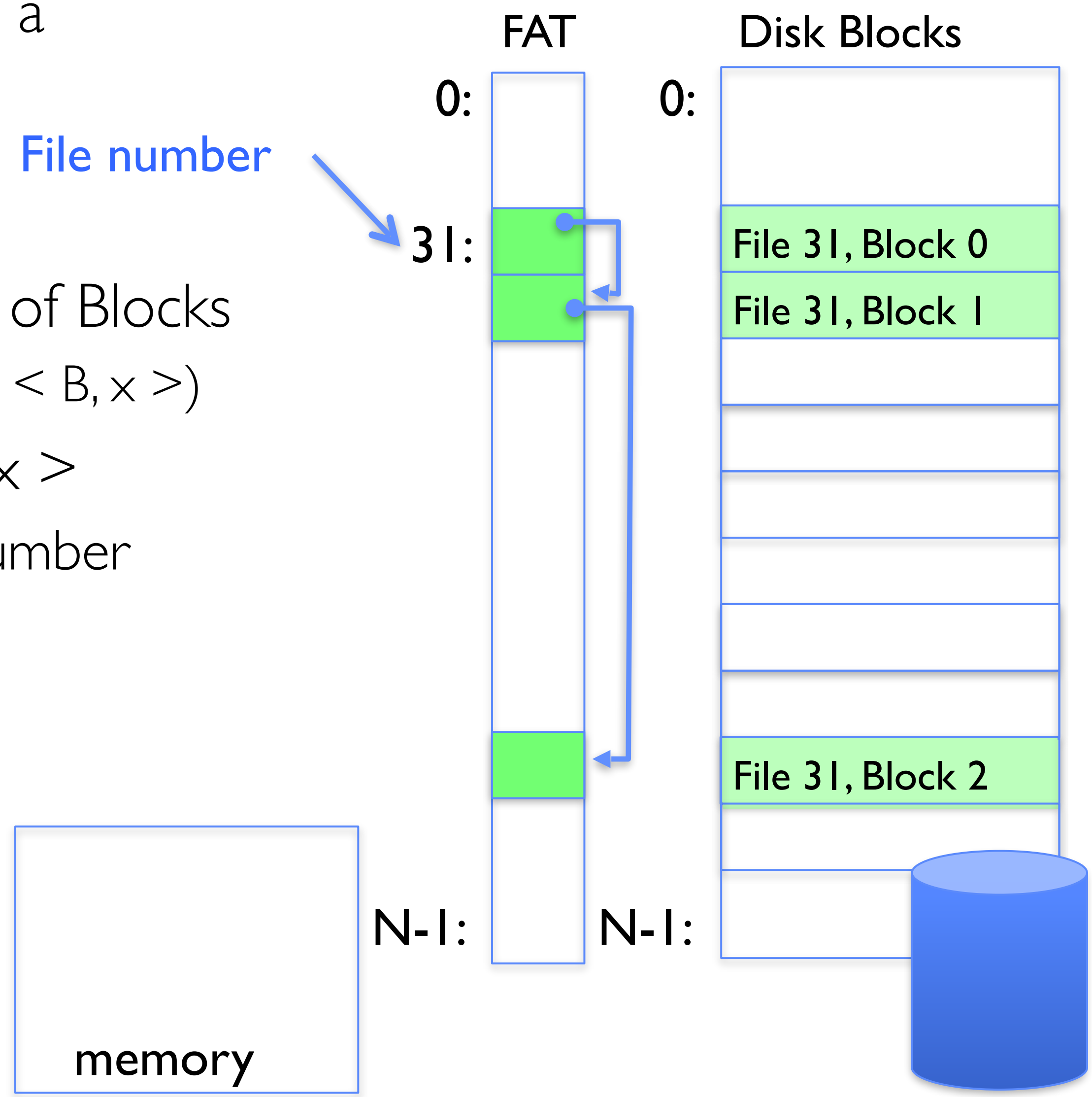
In-Memory File System Structures



- Read/write system calls:
  - Use file handle to locate inode
  - Perform appropriate reads or writes

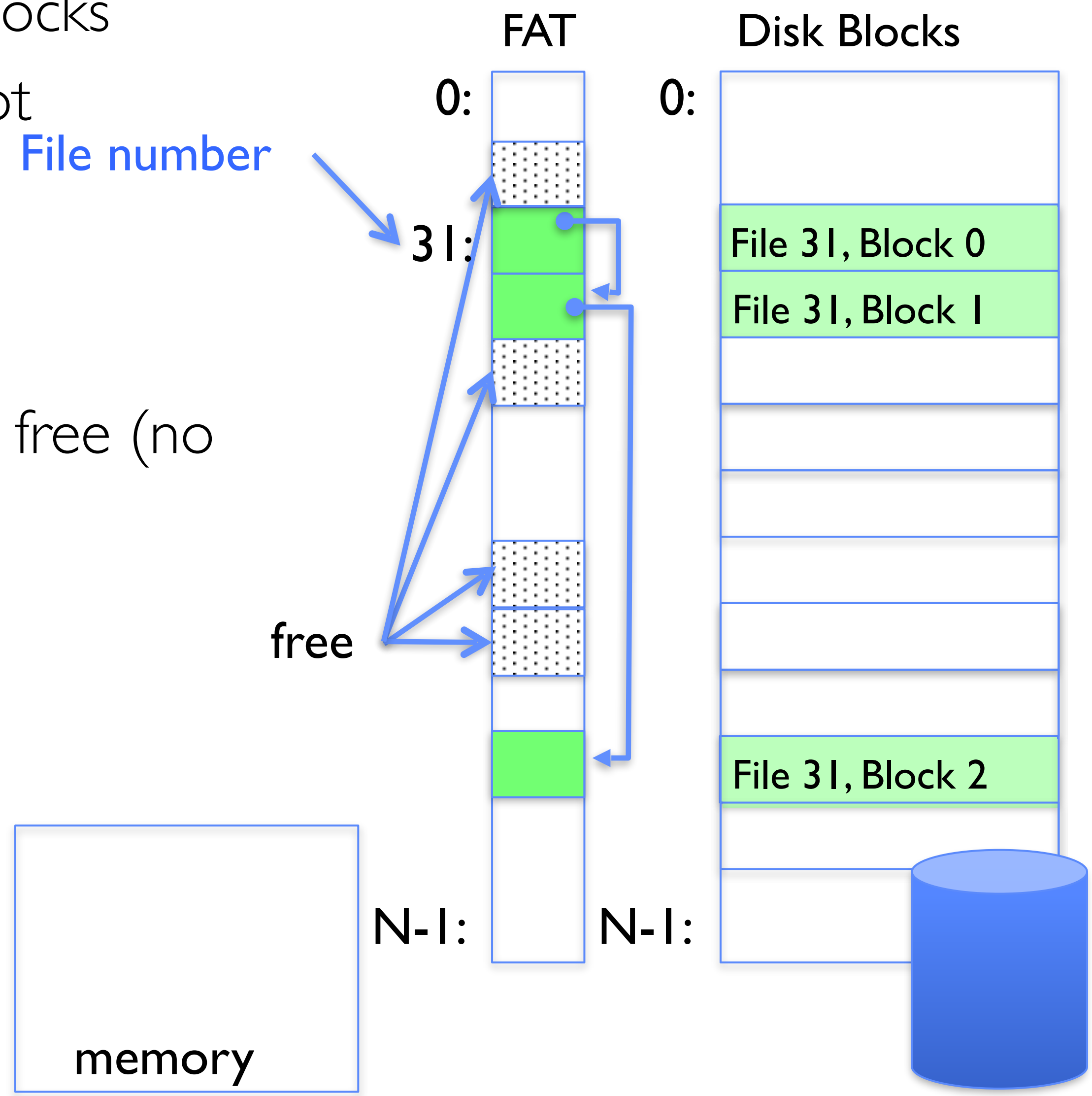
Our first filesystem: FAT (File Allocation Table)

- The most commonly used filesystem in the world!
- Assume (for now) we have a way to translate a path to a "file number"
  – i.e., a directory structure
- Disk Storage is a collection of Blocks
  – Just hold file data (offset o = < B, x >)
- Example: file_read 31, < 2, x >
  – Index into FAT with file number
  – Follow linked list to block
  – Read the block from disk into memory



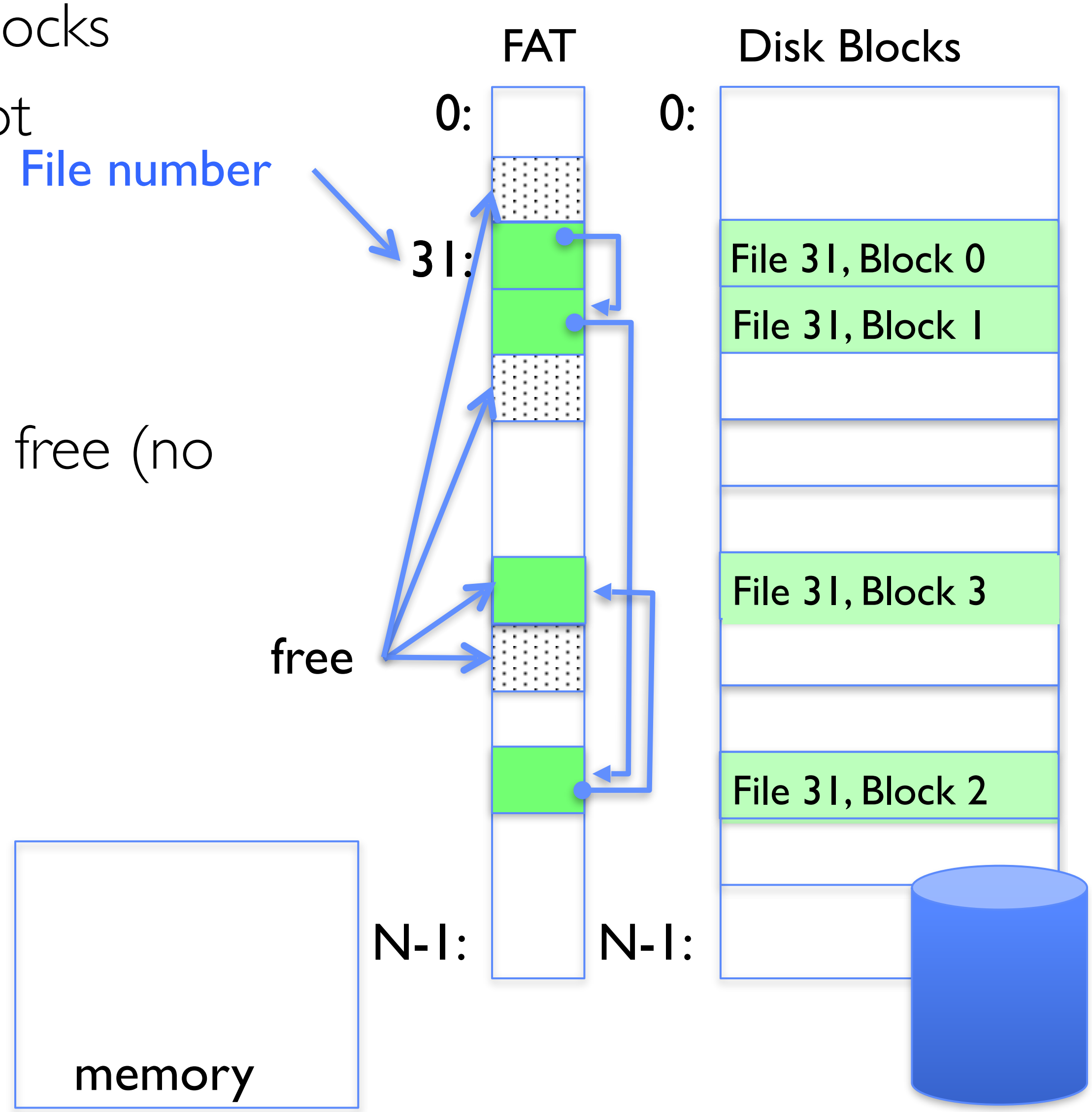
FAT Properties

- File is collection of disk blocks
- FAT is linked list 1-1 with blocks
- File Number is index of root of block list for the file
- File offset (o = < B, x >)
- Follow list to get block #
- Unused blocks ⇔ Marked free (no ordering, must scan to find)



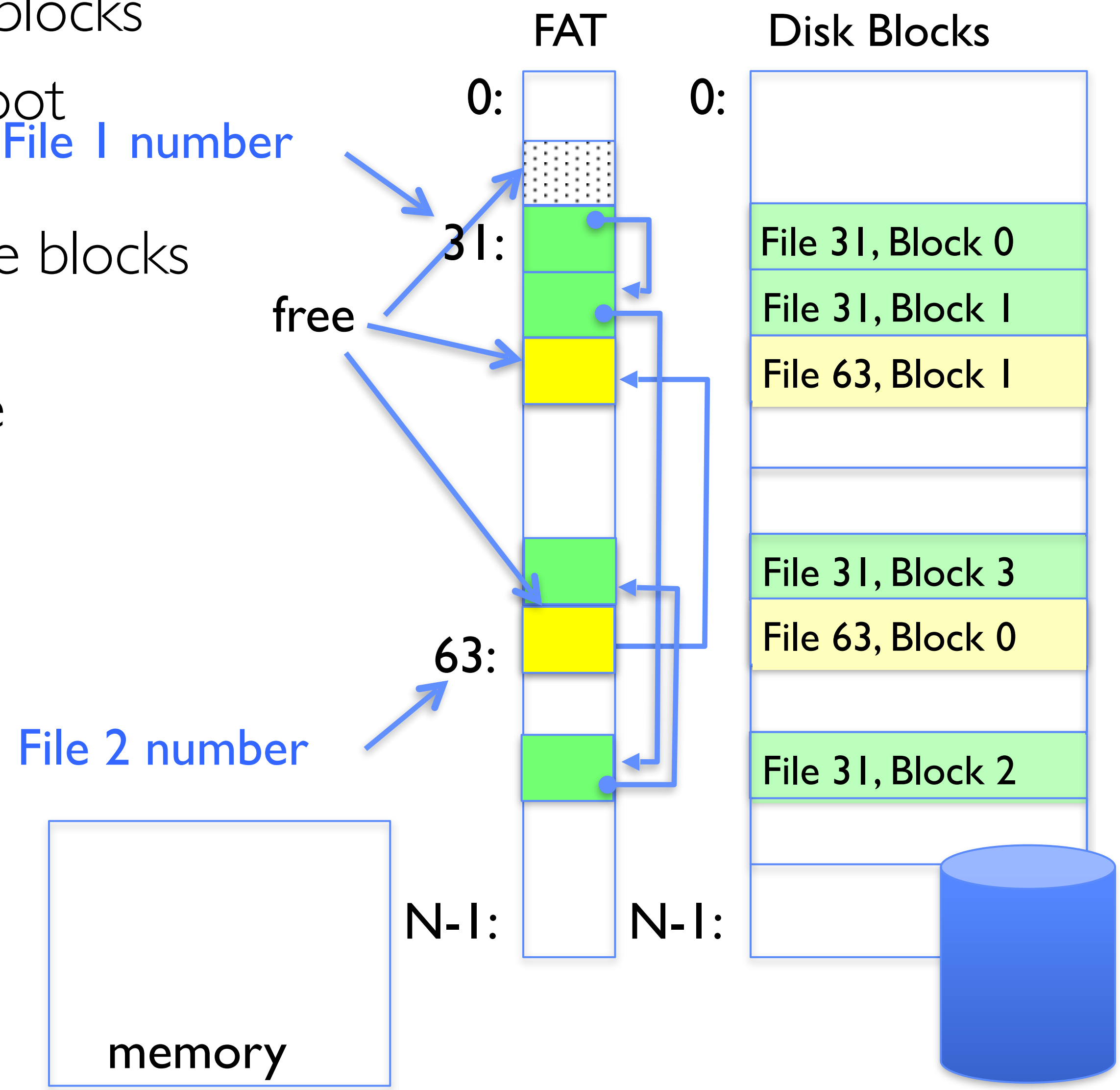
FAT Properties

- File is collection of disk blocks
- FAT is linked list 1-1 with blocks
- File Number is index of root of block list for the file
- File offset (o = < B, x >)
- Follow list to get block #
- Unused blocks ⇔ Marked free (no ordering, must scan to find)
- Ex: file_write(31, < 3, y >)
  - Grab free block
  - Linking them into file



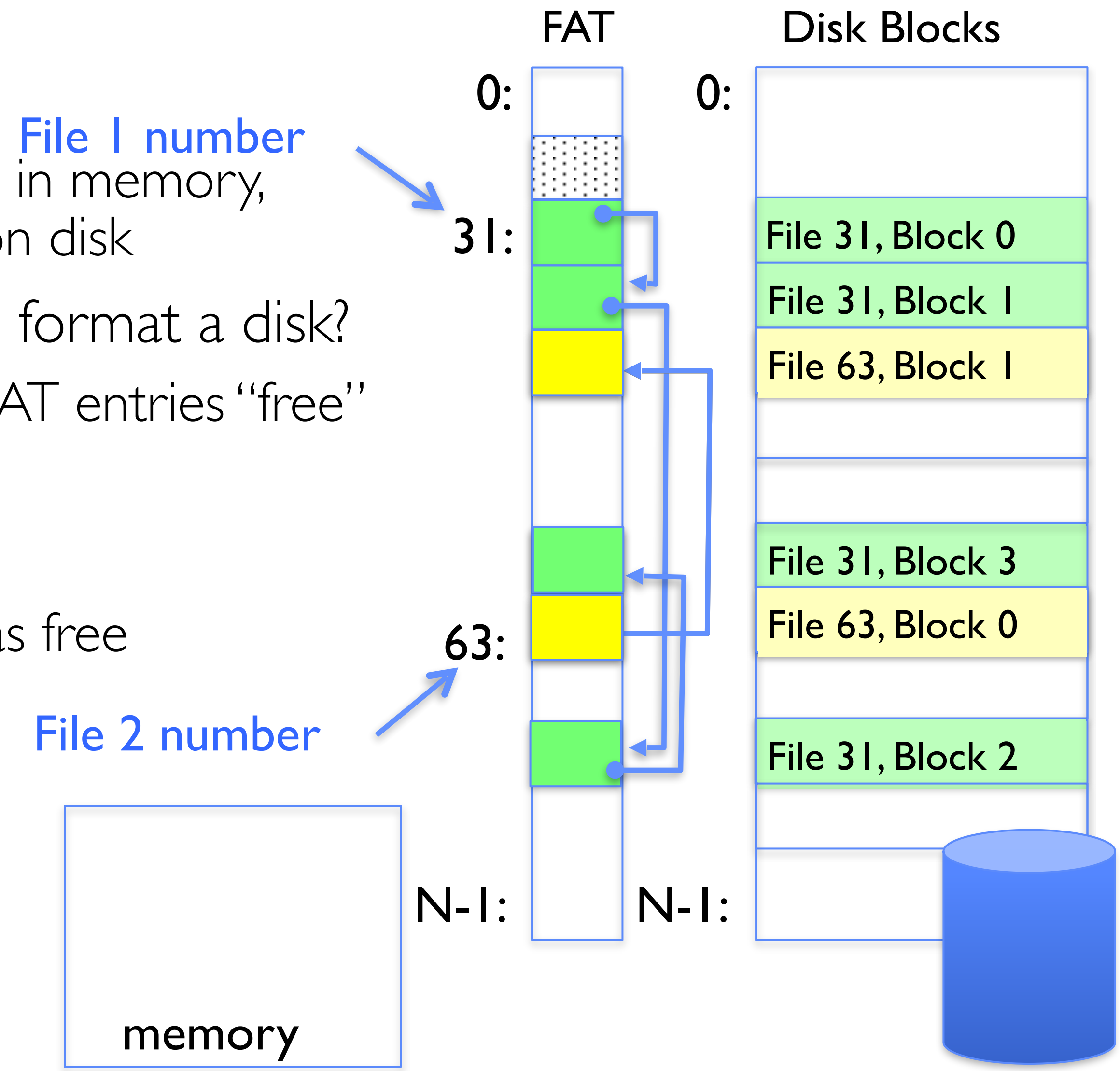
FAT Properties

- File is collection of disk blocks
- FAT is linked list 1-1 with blocks
- File Number is index of root of block list for the file
- Grow file by allocating free blocks and linking them in
- Ex: Create file, write, write



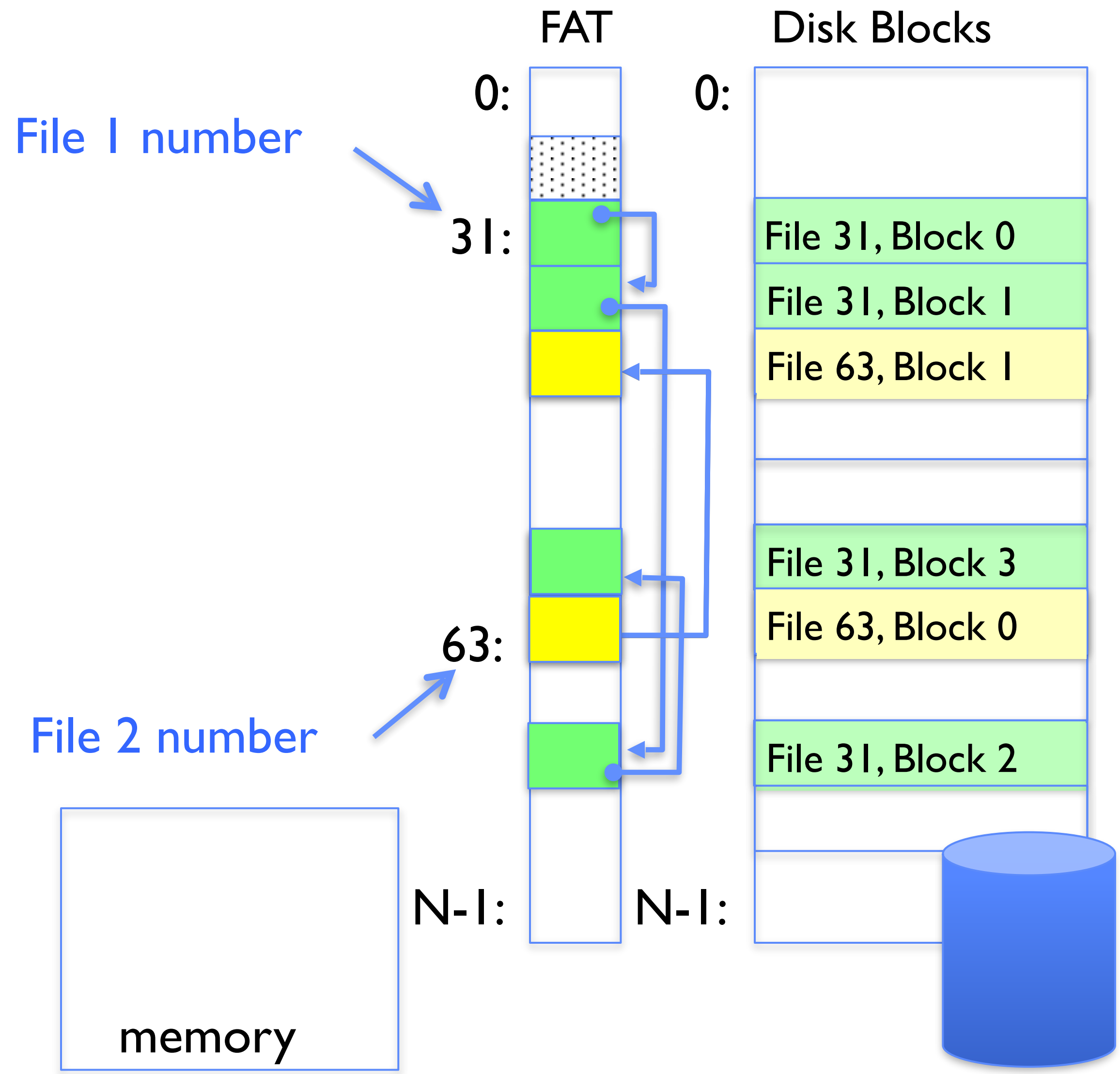
FAT Assessment

- *FAT32 (32 instead of 12 bits) used in Windows, USB drives, SD cards, …*
- Where is FAT stored?
  - On Disk, on boot cache in memory, second (backup) copy on disk
- What happens when you format a disk?
  - Zero the blocks, Mark FAT entries "free"
- What happens when you quick format a disk?
  - Mark all entries in FAT as free
- *Simple*
  - Can implement in device firmware

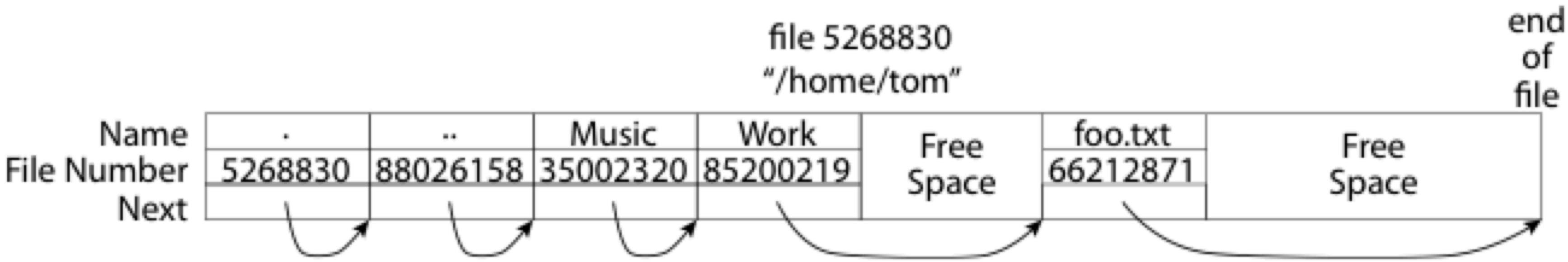


FAT Assessment – Issues

- Time to find block (large files) ??
- Block layout for file ???
- Sequential Access ???
- Random Access ???
- Fragmentation ???
  - MSDOS defrag tool
- Small files ???
- Big files ???



What about the Directory?



- Essentially a file containing
  <file_name: file_number> mappings
- Free space for new entries
- In FAT: file attributes are kept in directory (!!!)
- Each directory a linked list of entries
- Where do you find root directory ("/")?

Directory Structure (cont'd)

- How many disk accesses to resolve "/my/book/count"?
  - Read in file header for root (fixed spot on disk)
  - Read in first data block for root
    - » Table of file name/index pairs. Search linearly – ok since directories typically very small
  - Read in file header for "my"
  - Read in first data block for "my"; search for "book"
  - Read in file header for "book"
  - Read in first data block for "book"; search for "count"
  - Read in file header for "count"
- Current working directory: Per-address-space pointer to a directory (inode) used for resolving file names
  - Allows user to specify relative filename instead of absolute path (say CWD="/my/book" can resolve "count")

Many Huge FAT Security Holes!

- FAT has no access rights
- FAT has no header in the file blocks
- Just gives an index into the FAT
  - (file number = block number)

Summary

- Bursts & High Utilization introduce queuing delays
- Queuing Latency:
  - M/M/1 and M/G/1 queues: simplest to analyze
  - As utilization approaches 100%, latency → ∞

$$T_q = T_{ser} \times \frac{1}{2}(1+C) \times u/(1-u))$$

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for access and usage patterns
  - Maximize sequential access, allow efficient random access
- File (and directory) defined by header, called "inode"
- File Allocation Table (FAT) Scheme
  - Linked-list approach
  - Very widely used: Cameras, USB drives, SD cards
  - Simple to implement, but poor performance and no security
- Look at actual file access patterns – many small files, but large files take up all the space!