CS162
Operating Systems and Systems Programming
Lecture 19

File Systems continued
Distributed Systems

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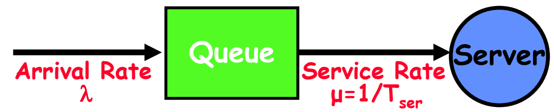
Review: A Little Queuing Theory: Some Results

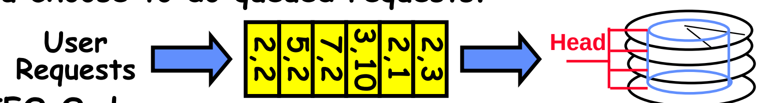
- Assumptions:
  - System in equilibrium; No limit to the queue
  - Time between successive arrivals is random and memoryless



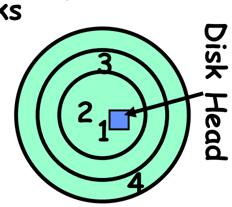
- Parameters that describe our system:
  - λ: mean number of arriving customers/second
  - T_{ser}: mean time to service a customer ("m1")
  - C: squared coefficient of variance = $\sigma^2/m1^2$
  - μ: service rate = $1/T_{ser}$
  - u: server utilization ($0 \le u \le 1$): $u = \lambda/\mu = \lambda \times T_{ser}$
- 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 ($C = 1$):
    - » Called M/M/1 queue: $T_q = T_{ser} \times u/(1 - u)$
  - General service distribution (no restrictions), 1 server:
    - » Called M/G/1 queue: $T_q = T_{ser} \times \frac{1}{2}(1+C) \times u/(1 - u))$

Review: Disk Scheduling

- 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



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

Goals for Today

- Finish Discussion of File Systems
  - Structure, Naming, Directories
- File Caching
- Data Durability
- Beginning of Distributed Systems Discussion

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from my lecture notes by Kubiatowicz.

Designing the File System: Access Patterns

- How do users access files?
  - Need to know type of access patterns user is likely to throw at system
- Sequential Access: bytes read in order ("give me the next X bytes, then give me next, etc")
  - Almost all file access are of this flavor
- Random Access: read/write element out of middle of array ("give me bytes i—j")
  - Less frequent, but still important. For example, virtual memory backing file: page of memory stored in file
  - Want this to be fast – don't want to have to read all bytes to get to the middle of the file
- Content-based Access: ("find me 100 bytes starting with KUBIATOWICZ")
  - Example: employee records – once you find the bytes, increase my salary by a factor of 2
  - Many systems don't provide this; instead, databases are built on top of disk access to index content (requires efficient random access)

Designing the File System: Usage Patterns

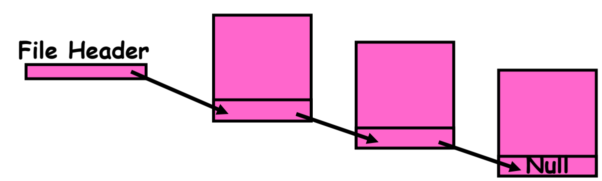
- Most files are small (for example, .login, .c files)
  - A few files are big – nachos, core files, etc.; the nachos executable is as big as all of your .class files combined
  - However, most files are small – .class's, .o's, .c's, etc.
- Large files use up most of the disk space and bandwidth to/from disk
  - May seem contradictory, but a few enormous files are equivalent to an immense # of small files
- Although we will use these observations, beware usage patterns:
  - Good idea to look at usage patterns: beat competitors by optimizing for frequent patterns
  - Except: changes in performance or cost can alter usage patterns. Maybe UNIX has lots of small files because big files are really inefficient?

How to organize files on disk

- Goals:
  - Maximize sequential performance
  - Easy random access to file
  - Easy management of file (growth, truncation, etc)
- First Technique: Continuous Allocation
  - Use continuous range of blocks in logical block space
    - » Analogous to base+bounds in virtual memory
    - » User says in advance how big file will be (disadvantage)
  - Search bit-map for space using best fit/first fit
    - » What if not enough contiguous space for new file?
  - File Header Contains:
    - » First sector/LBA in file
    - » File size (# of sectors)
  - Pros: Fast Sequential Access, Easy Random access
  - Cons: External Fragmentation/Hard to grow files
    - » Free holes get smaller and smaller
    - » Could compact space, but that would be *really* expensive
- Continuous Allocation used by IBM 360
  - Result of allocation and management cost: People would create a big file, put their file in the middle

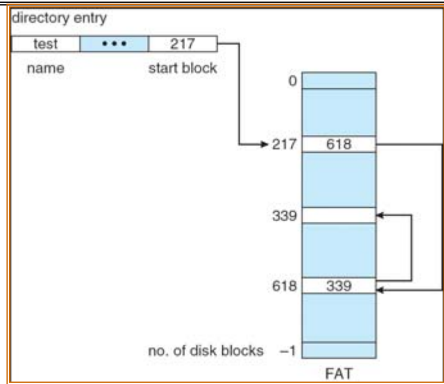
Linked List Allocation

- Second Technique: Linked List Approach
  - Each block, pointer to next on disk



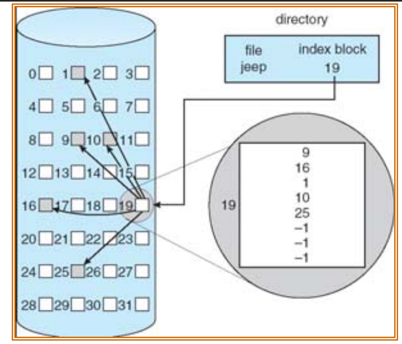
  - Pros: Can grow files dynamically, Free list same as file
  - Cons: Bad Sequential Access (seek between each block), Unreliable (lose block, lose rest of file)
  - Serious Con: Bad random access!!!!
  - Technique originally from Alto (First PC, built at Xerox)
    - » No attempt to allocate contiguous blocks

Linked Allocation: File-Allocation Table (FAT)



- MSDOS links pages together to create a file
  - Links not in pages, but in the File Allocation Table (FAT)
    - » FAT contains an entry for each block on the disk
    - » FAT Entries corresponding to blocks of file linked together
  - Access properies:
    - » Sequential access expensive unless FAT cached in memory
    - » Random access expensive always, but *really* expensive if FAT not cached in memory

Indexed Allocation



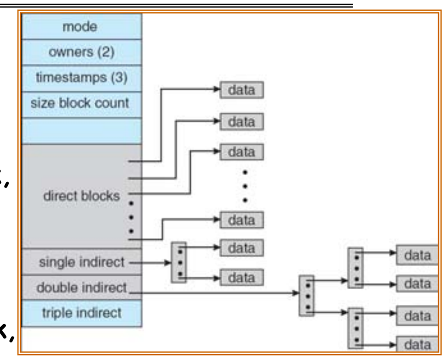
- Indexed Files (Nachos, VMS)
  - System Allocates file header block to hold array of pointers big enough to point to all blocks
    - » User pre-declares max file size;
  - Pros: Can easily grow up to space allocated for index
    Random access is fast
  - Cons: Clumsy to grow file bigger than table size
    Still lots of seeks: blocks may be spread over disk

Multilevel Indexed Files (UNIX BSD 4.1)

- Multilevel Indexed Files: Like multilevel address translation (from UNIX 4.1 BSD)
  - Key idea: efficient for small files, but still allow big files
  - File header 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
    - » Block 11 points to "indirect block" containing 256 blocks
    - » Block 12 points to "doubly indirect block" containing 256 indirect blocks for total of 64K blocks
    - » Block 13 points to a triply indirect block (16M blocks)
- Discussion
  - Basic technique places an upper limit on file size that is approximately 16Gbytes
    - » Designers thought this was bigger than anything anyone would need. Much bigger than a disk at the time…
    - » Fallacy: today, EOS producing 2TB of data per day
  - Pointers get filled in dynamically: need to allocate indirect block only when file grows > 10 blocks.
    - » On small files, no indirection needed

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

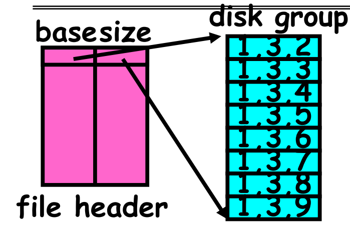


- UNIX 4.1 Pros and cons
  - Pros: Simple (more or less)
    Files can easily expand (up to a point)
    Small files particularly cheap and easy
  - Cons: Lots of seeks
    Very large files must read many indirect block (four I/Os per block!)

Administrivia

- Project zero-sum game:
  - In the end, we decide how to distribute points to partners
    - » Normally, we are pretty even about this
    - » But, under extreme circumstances, may take points from non-working members and give to working members
  - This is a zero-sum game!
- Make sure to do your project evaluations
  - This is supposed to be an individual evaluation, not done together as a group
  - This is part of the information that we use to decide how to distributed points
  - We will give 0 (ZERO) to people who don't fill out evals
- Midterm II
  - December 5th
- In the News: Google in the OS business?
  - Google talking about offering an operating system for mobile phones
  - Rumor has it that Wind-River Systems may contribute

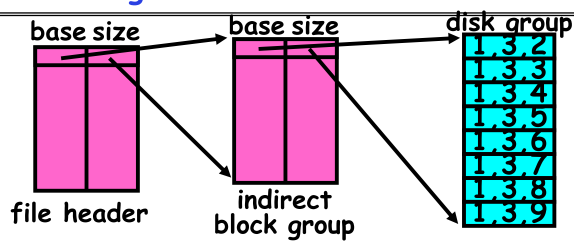
File Allocation for Cray-1 DEMOS



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)

How to keep DEMOS performing well?

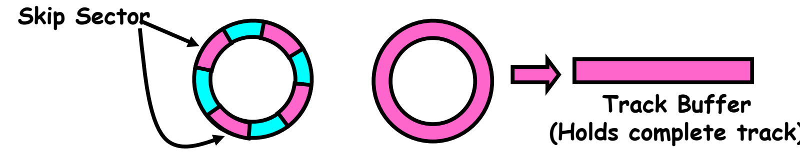
- In many systems, disks are always full
  - CS department growth: 300 GB to 1TB in a year
    - » That's 2GB/day! (Now at 6 TB?)
  - How to fix? Announce that disk space is getting low, so please delete files?
    - » Don't really work: people try to store their data faster
  - Sidebar: Perhaps we are getting out of this mode with new disks… However, let's assume disks full for now
    - » (Rumor has it that the EECS department has 60TB of spinning storage just waiting for use…)
- Solution:
  - Don't let disks get completely full: reserve portion
    - » Free count = # blocks free in bitmap
    - » Scheme: Don't allocate data if count < reserve
  - How much reserve do you need?
    - » In practice, 10% seems like enough
  - Tradeoff: pay for more disk, get contiguous allocation
    - » Since seeks so expensive for performance, this is a very good tradeoff

UNIX BSD 4.2

- Same as BSD 4.1 (same file header and triply indirect blocks), except incorporated ideas from DEMOS:
  - Uses bitmap allocation in place of freelist
  - Attempt to allocate files contiguously
  - 10% reserved disk space
  - Skip-sector positioning (mentioned next slide)
- Problem: When create a file, don't know how big it will become (in UNIX, most writes are by appending)
  - How much contiguous space do you allocate for a file?
  - In Demos, power of 2 growth: once it grows past 1MB, allocate 2MB, etc
  - In BSD 4.2, just find some range of free blocks
    - » Put each new file at the front of different range
    - » To expand a file, you first try successive blocks in bitmap, then choose new range of blocks
  - Also in BSD 4.2: store files from same directory near each other
- Fast File System (FFS)
  - Allocation and placement policies for BSD 4.2

Attack of the Rotational Delay

- Problem 2: Missing blocks due to rotational delay
  - Issue: Read one block, do processing, and read next block. In meantime, disk has continued turning: missed next block! Need 1 revolution/block!



  - Solution1: Skip sector positioning ("interleaving")
    - » Place the blocks from one file on every other block of a track: give time for processing to overlap rotation
  - Solution2: Read ahead: read next block right after first, even if application hasn't asked for it yet.
    - » This can be done either by OS (read ahead)
    - » By disk itself (track buffers). Many disk controllers have internal RAM that allows them to read a complete track
- Important Aside: Modern disks+controllers do many complex things "under the covers"
  - Track buffers, elevator algorithms, bad block filtering

How do we actually access files?

- All information about a file contained in its file header
  - UNIX calls this an "inode"
    - » Inodes are global resources identified by index ("inumber")
  - Once you load the header structure, all the other blocks of the file are locatable
- Question: how does the user ask for a particular file?
  - One option: user specifies an inode by a number (index).
    - » Imagine: open("14553344")
  - Better option: specify by textual name
    - » Have to map name→inumber
  - Another option: Icon
    - » This is how Apple made its money. Graphical user interfaces. Point to a file and click.
- Naming: The process by which a system translates from user-visible names to system resources
  - In the case of files, need to translate from strings (textual names) or icons to inumbers/inodes
  - For global file systems, data may be spread over globe⇒need to translate from strings or icons to some combination of physical server location and inumber

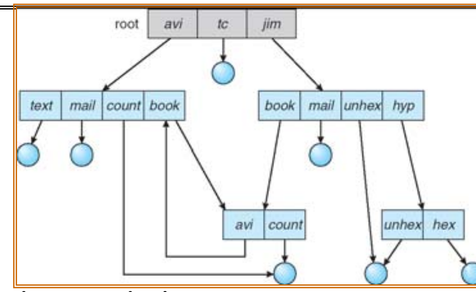
Directories

- Directory: a relation used for naming
  - Just a table of (file name, inumber) pairs
- How are directories constructed?
  - Directories often stored in files
    - » Reuse of existing mechanism
    - » Directory named by inode/inumber like other files
  - Needs to be quickly searchable
    - » Options: Simple list or Hashtable
    - » Can be cached into memory in easier form to search
- How are directories modified?
  - Originally, direct read/write of special file
  - System calls for manipulation: `mkdir`, `rmdir`
  - Ties to file creation/destruction
    - » On creating a file by name, new inode grabbed and associated with new file in particular directory

Directory Organization

- Directories organized into a hierarchical structure
  - Seems standard, but in early 70's it wasn't
  - Permits much easier organization of data structures
- Entries in directory can be either files or directories
- Files named by ordered set (e.g., /programs/p/list)

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

Directory Structure (Con't)

- 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")

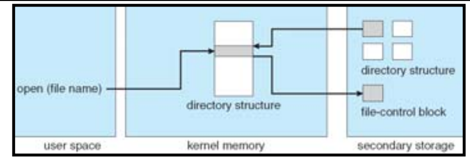
Where are inodes stored?

- In early UNIX and DOS/Windows' FAT file system, headers stored in special array in outermost cylinders
  - Header not stored near the data blocks. To read a small file, seek to get header, seek back to data.
  - Fixed size, set when disk is formatted. At formatting time, a fixed number of inodes were created (They were each given a unique number, called an "inumber")

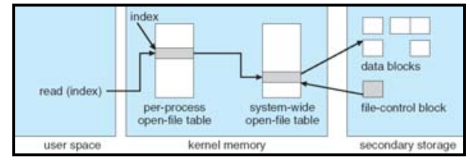
Where are inodes stored?

- Later versions of UNIX moved the header information to be closer to the data blocks
  - Often, inode for file stored in same "cylinder group" as parent directory of the file (makes an ls of that directory run fast).
  - Pros:
    - » UNIX BSD 4.2 puts a portion of the file header array on each cylinder. For small directories, can fit all data, file headers, etc in same cylinder⇒no seeks!
    - » File headers much smaller than whole block (a few hundred bytes), so multiple headers fetched from disk at same time
    - » Reliability: whatever happens to the disk, you can find many of the files (even if directories disconnected)
  - Part of the Fast File System (FFS)
    - » General optimization to avoid seeks

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



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

File System Caching

- Key Idea: Exploit locality by caching data in memory
  - Name translations: Mapping from paths→inodes
  - Disk blocks: Mapping from block address→disk content
- Buffer Cache: Memory used to cache kernel resources, including disk blocks and name translations
  - Can contain "dirty" blocks (blocks yet on disk)
- Replacement policy? LRU
  - Can afford overhead of timestamps for each disk block
  - Advantages:
    - » Works very well for name translation
    - » Works well in general as long as memory is big enough to accommodate a host's working set of files.
  - Disadvantages:
    - » Fails when some application scans through file system, thereby flushing the cache with data used only once
    - » Example: `find . -exec grep foo {} \;`
- Other Replacement Policies?
  - Some systems allow applications to request other policies
  - Example, 'Use Once':
    - » File system can discard blocks as soon as they are used

File System Caching (con't)

- Cache Size: How much memory should the OS allocate to the buffer cache vs virtual memory?
  - Too much memory to the file system cache ⇒ won't be able to run many applications at once
  - Too little memory to file system cache ⇒ many applications may run slowly (disk caching not effective)
  - Solution: adjust boundary dynamically so that the disk access rates for paging and file access are balanced
- Read Ahead Prefetching: fetch sequential blocks early
  - Key Idea: exploit fact that most common file access is sequential by prefetching subsequent disk blocks ahead of current read request (if they are not already in memory)
  - Elevator algorithm can efficiently interleave groups of prefetches from concurrent applications
  - How much to prefetch?
    - » Too many imposes delays on requests by other applications
    - » Too few causes many seeks (and rotational delays) among concurrent file requests

File System Caching (con't)

- Delayed Writes: Writes to files not immediately sent out to disk
  - Instead, `write()` copies data from user space buffer to kernel buffer (in cache)
    - » Enabled by presence of buffer cache: can leave written file blocks in cache for a while
    - » If some other application tries to read data before written to disk, file system will read from cache
  - Flushed to disk periodically (e.g. in UNIX, every 30 sec)
  - Advantages:
    - » Disk scheduler can efficiently order lots of requests
    - » Disk allocation algorithm can be run with correct size value for a file
    - » Some files need never get written to disk! (e..g temporary scratch files written /tmp often don't exist for 30 sec)
  - Disadvantages
    - » What if system crashes before file has been written out?
    - » Worse yet, what if system crashes before a directory file has been written out? (lose pointer to inode!)

Important "ilities"

- Availability: the probability that the system can accept and process requests
  - Often measured in "nines" of probability. So, a 99.9% probability is considered "3-nines of availability"
  - Key idea here is independence of failures
- Durability: the ability of a system to recover data despite faults
  - This idea is fault tolerance applied to data
  - Doesn't necessarily imply availability: information on pyramids was very durable, but could not be accessed until discovery of Rosetta Stone
- Reliability: the ability of a system or component to perform its required functions under stated conditions for a specified period of time (IEEE definition)
  - Usually stronger than simply availability: means that the system is not only "up", but also working correctly
  - Includes availability, security, fault tolerance/durability
  - Must make sure data survives system crashes, disk crashes, other problems

How to make file system durable?

- Disk blocks contain Reed-Solomon error correcting codes (ECC) to deal with small defects in disk drive
  - Can allow recovery of data from small media defects
- Make sure writes survive in short term
  - Either abandon delayed writes or
  - use special, battery-backed RAM (called non-volatile RAM or NVRAM) for dirty blocks in buffer cache.
- Make sure that data survives in long term
  - Need to replicate! More than one copy of data!
  - Important element: independence of failure
    - » Could put copies on one disk, but if disk head fails…
    - » Could put copies on different disks, but if server fails…
    - » Could put copies on different servers, but if building is struck by lightning….
    - » Could put copies on servers in different continents…
- RAID: Redundant Arrays of Inexpensive Disks
  - Data stored on multiple disks (redundancy)
  - Either in software or hardware
    - » In hardware case, done by disk controller; file system may not even know that there is more than one disk in use

Log Structured and Journaled File Systems

- Better reliability through use of log
  - All changes are treated as *transactions*
  - A transaction is *committed* once it is written to the log
    - » Data forced to disk for reliability
    - » Process can be accelerated with NVRAM
  - Although File system may not be updated immediately, data preserved in the log
- Difference between "Log Structured" and "Journaled"
  - In a Log Structured filesystem, data stays in log form
  - In a Journaled filesystem, Log used for recovery
- For Journaled system:
  - Log used to asynchronously update filesystem
    - » Log entries removed after used
  - After crash:
    - » Remaining transactions in the log performed ("Redo")
    - » Modifications done in way that can survive crashes
- Examples of Journaled File Systems:
  - Ext3 (Linux), XFS (Unix), etc.

Conclusion

- Cray DEMOS: optimization for sequential access
  - Inode holds set of disk ranges, similar to segmentation
- 4.2 BSD Multilevel index files
  - Inode contains pointers to actual blocks, indirect blocks, double indirect blocks, etc
  - Optimizations for sequential access: start new files in open ranges of free blocks
  - Rotational Optimization
- Naming: act of translating from user-visible names to actual system resources
  - Directories used for naming for local file systems
- Important system properties
  - Availability: how often is the resource available?
  - Durability: how well is data preserved against faults?
  - Reliability: how often is resource performing correctly?