Design and Engineering of Computer Systems

Lecture 14: File system and memory

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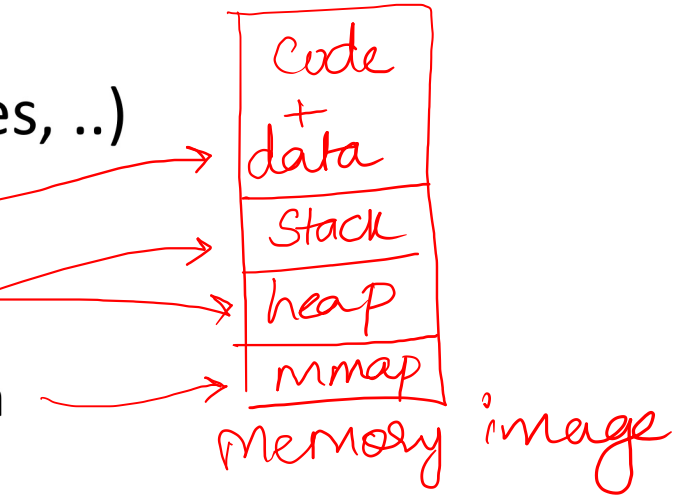
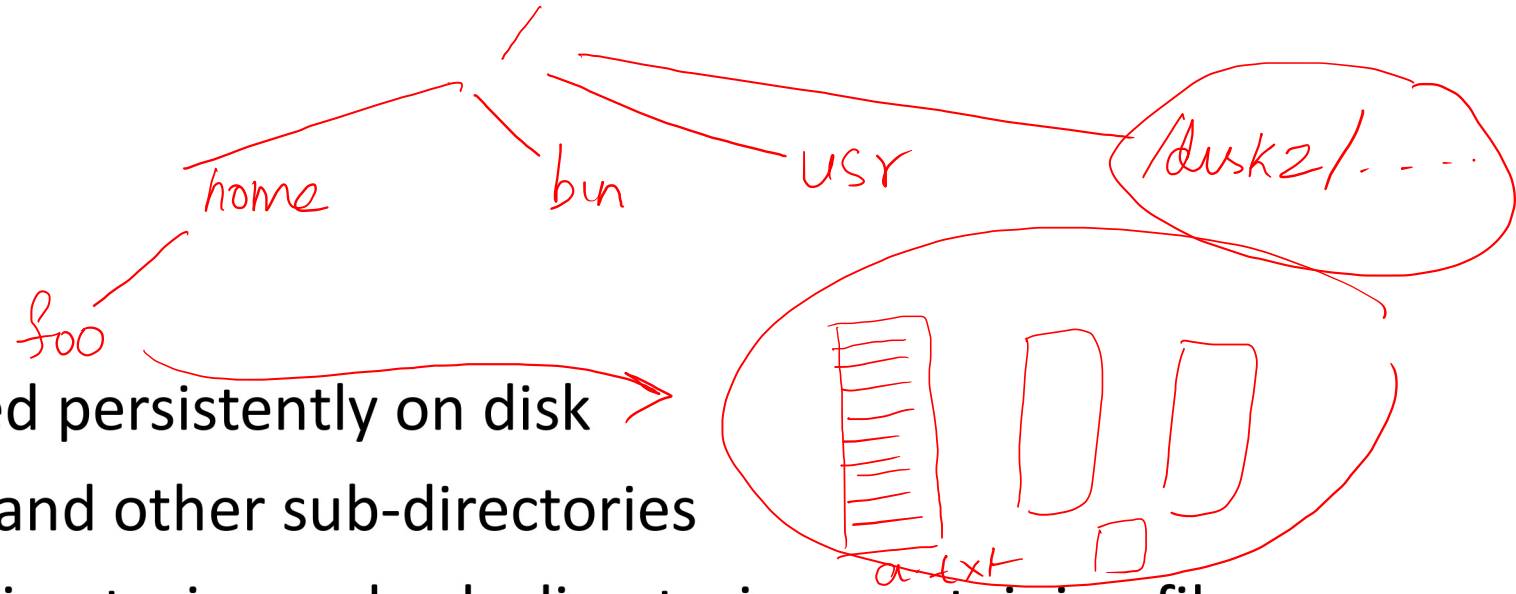
Storing program data

- User applications deal with data (variables, data structures, ..)
  - Global/static variables are in program executable
  - Memory allocated via malloc stored on heap
  - Function variables and arguments stored on stack
  - Can request one or more pages from OS via mmap to store data
- All of these mechanisms do not store data persistently
  - Data in main memory is lost when power is turned off
- How to store program data persistently?
  - Use files on secondary storage (hard disk and other such storage media)
- In this lecture: interaction of files with main memory
  - Next week: more details on filesystem, how file operations are done



File abstraction



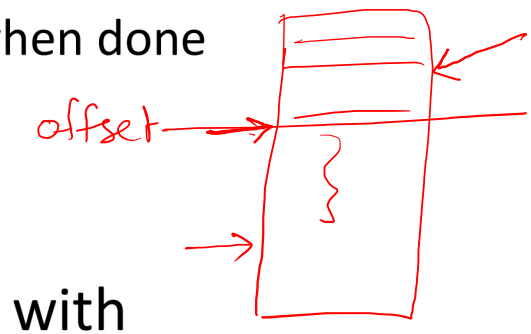
- File: sequence of bytes, stored persistently on disk
- Directory: container for files and other sub-directories
- Directory tree: hierarchy of directories and sub-directories, containing files
  - Root file system: directory tree starting at root (“/”)
  - Directory trees on disk can be mounted at various locations of root filesystem
- Containers have different root file system view on the same OS
- Steps to access a file
  - Open a file using system call, get a file descriptor
  - File descriptor is a handle to refer to file for read/write
  - Close file when done accessing it

```
fd = open(“/home/foo/a.txt”)
read(fd, ..)
write(fd, ..)
close(fd)
```

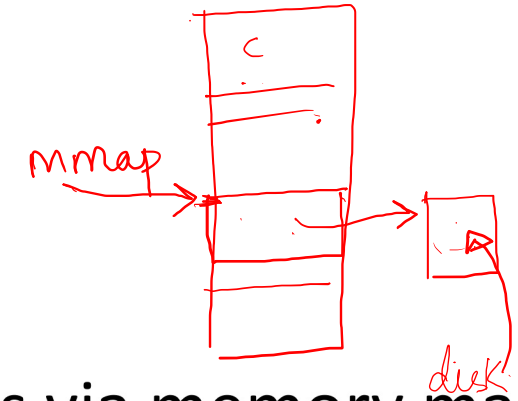
Reading and writing a file

```
fd = open("/home/foo/a.txt")
char buf[64]
n = read(fd, buf, 64)
buf[0] = …
n = write(fd, buf, 64)
```

- After opening a file, process can read/write to a file as a stream
  - File descriptor used as handle to refer to the open file stream
  - Read system call reads specified number of bytes into a user-defined buffer, returns number of bytes read
  - Write system call writes specified number of bytes from a user-defined buffer, returns number of bytes written
- Implemented by commands to disk controller via device driver in OS
  - Device driver gives command, data transfer via DMA, device raises interrupt when done
- Read and write system calls update the offset into a file
  - After reading N bytes, next read will return the next set of bytes
  - Can also update the offset from which to read/write using a seek system call
- Every open file descriptor will read/write file as independent stream, with independent offsets
  - Exception: parent and child processes share same offset after fork



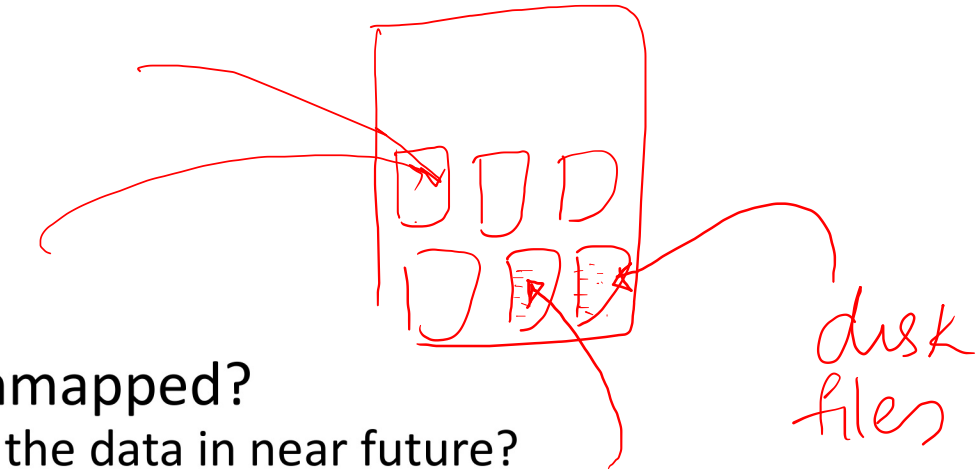
Memory mapping a file




```
fd = open("/home/foo/a.txt")
char *buf = mmap(fd, size, ..)
buf[0] = …
buf[1] = …
munmap(..)
```

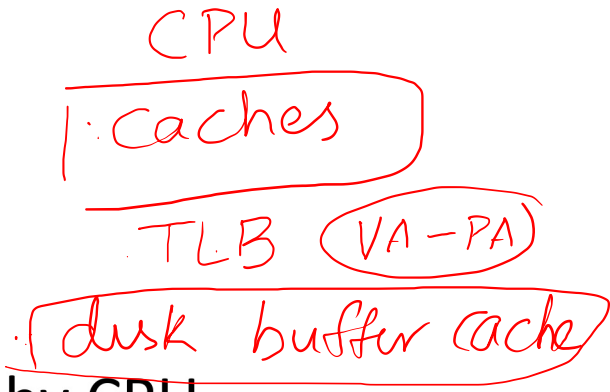
- Alternate ways to read/write a file is via memory mapping
  - mmap system call takes the file descriptor, size of data to memory map, and other arguments, returns the starting virtual address of mmap region
  - File data is read into one or more physical memory frames, which are mapped at free addresses in the process virtual address space (new page table entries)
  - Can access memory mapped file data like any other memory region
  - With demand paging, physical frames can be assigned on-demand only when mmap region accessed
- File can be memory mapped in private or shared mode
  - Shared mode: changes to file are written to disk immediately, seen by others
  - Private mode: changes to file are written to disk when memory unmapped

Disk buffer cache

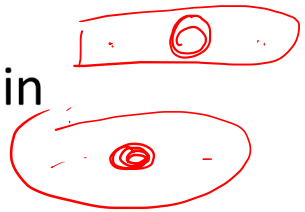


- What happens after memory mapped file is unmapped?
  - Why erase file data, if some other process requires the data in near future?
- File data that is read from hard disk is retained in memory for some time in the disk buffer cache = memory pages that cache recently read disk data
  - Both mmap files and files read via read/write syscalls are cached
- Any changes to disk data (via write or mmap) is made in the cached copy of disk buffer cache first, then written to disk later
  - Write-through cache: changes written to disk immediately (synchronous writes)
  - Write-back cache: changes written to disk after some delay (asynchronous writes)
  - Write-back cache has better performance, but can lose data in case of power failure
- Benefits of disk buffer cache
  - Improved performance due to fewer disk accesses
  - Merge changes when multiple processes modify same file data
- Most OS allocate unused physical memory to disk buffer cache
  - Some applications doing their own optimizations can bypass cache

Understand various layers of caches

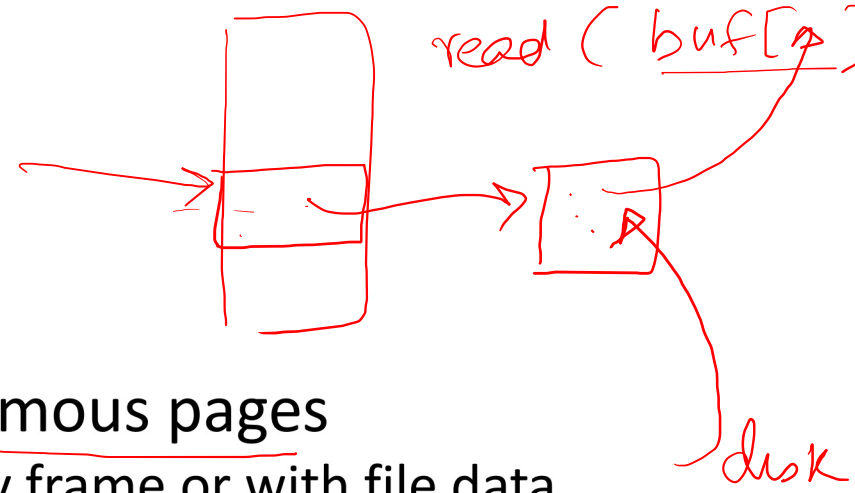


- CPU caches: stores recent memory instructions/data accessed by CPU
- TLB: stores recent virtual to physical address mappings done by MMU
- Disk buffer cache: stores recently accessed filesystem data in memory
- CPU cache and disk buffer cache store actual data, TLB stores mappings
  - TLB hit avoids only page table walk, not actual memory access
- All caches use locality of reference to avoid extra work in future
  - Temporal locality of reference: data accessed in recent past will be likely used again
  - Spatial locality of reference: data around current access will be likely used again



- All caches use some variant of LRU (least recently used) policy for evicting old entries when cache is full

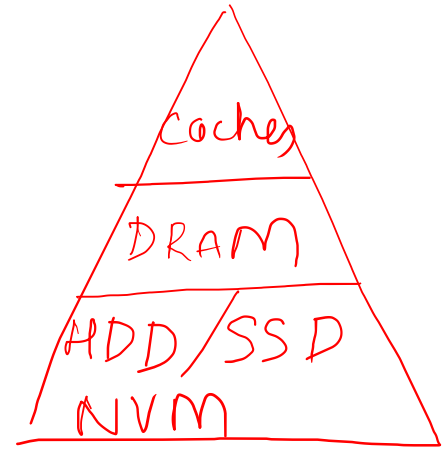
mmap vs. read/write syscalls

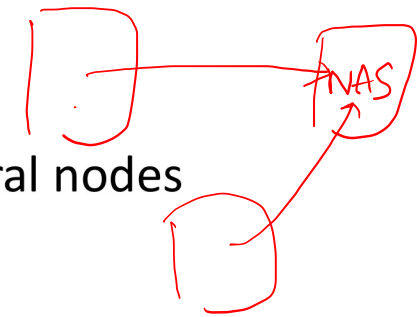


- mmap can be used for file-backed as well as anonymous pages
  - Physical frame mapped into address space can be empty frame or with file data
- Memory mapping a file is an easy way to read file data
  - Executable code, shared library code are memory mapped into virtual address space
- Memory mapping a file avoids extra data copies
  - Read/write system calls read data first into memory (disk buffer cache), then copy from disk buffer cache into user provided buffer
  - Memory mapping a file copies file data into free physical frames, which are directly accessed by user using virtual addresses
- Memory mapping allows reading disk data in large page-sized chunks
  - Useful when reading/writing large amounts of data from file
  - Not very efficient when reading files in small chunks

Data storage options in real applications

- Local storage: store data on local physical machine
  - CPU caches (SRAM) – fast, expensive, small memory close to CPU (~1-10 ns)
  - Main memory (DRAM) – random access memory for volatile storage (~100 ns)
  - Hard disk drive (HDD) – traditional magnetic disk, stores file data in blocks (~ms)
  - Solid State Drive (SSD) – faster option than HDD for files, common today
  - Non-volatile memory (NVM) – persistent memory, faster than hard disk
- Remote storage: storage accessible over the network in the cloud
  - Network Attached Storage (NAS) – store data in reliable file storage appliances
  - Databases – relational databases to store relational data durably
  - In-memory key-value stores – stores data in key-value format, distributed over several nodes
  - Distributed file systems – file storage built over a distributed system of nodes
  - Remote memory – DRAM-like memory accessible over the network
- Real computer systems use some combination of local and remote storage to achieve the functional and non-functional (performance, reliability) goals of applications





Summary

- In this lecture:
  - Storing program data in memory, files
  - Accessing file data using read/write vs. mmap syscalls
  - Disk buffer cache
- Look up the amount of main memory in your system, and find out how much of it is used as the disk buffer cache
  - The “free” command in Linux will show you the total memory available in your system, how much of it is used for the cache, and how much is free
- Programming exercise: practice accessing file data using read/write system calls as well as using mmap