File Systems: Introduction
CS 111
Operating Systems
Peter Reiher

Outline

- File systems:
  - Why do we need them?
  - Why are they challenging?
- Basic elements of file system design
- Designing file systems for disks
  - Basic issues
  - Free space, allocation, and deallocation

Introduction

- Most systems need to store data persistently
  - So it's still there after reboot, or even power down
- Typically a core piece of functionality for the system
  - Which is going to be used all the time
- Even the operating system itself needs to be stored this way
- So we must store some data persistently

Our Persistent Data Options

- Use raw disk blocks to store the data
  - Those make no sense to users
  - Not even easy for OS developers to work with
- Use a database to store the data
  - Probably more structure (and possibly overhead) than we need or can afford
- Use a file system
  - Some organized way of structuring persistent data
  - Which makes sense to users and programmers

File Systems

- Originally the computer equivalent of a physical filing cabinet
- Put related sets of data into individual containers
- Put them all into an overall storage unit
- Organized by some simple principle
  - E.g., alphabetically by title
  - Or chronologically by date
- Goal is to provide:
  - Persistence
  - Ease of access
  - Good performance

The Basic File System Concept

- Organize data into natural coherent units
  - Like a paper, a spreadsheet, a message, a program
- Store each unit as its own self-contained entity
  - A *file*
  - Store each file in a way allowing efficient access
- Provide some simple, powerful organizing principle for the collection of files
  - Making it easy to find them
  - And easy to organize them

File Systems and Hardware

- File systems are typically stored on hardware providing persistent memory
  - Disks, tapes, flash memory, etc.
- With the expectation that a file put in one "place" will be there when we look again
- Performance considerations will require us to match the implementation to the hardware
  - Remember seek time and rotational latency?
- But ideally, the same user-visible file system should work on any reasonable hardware

File Systems and OS Abstractions

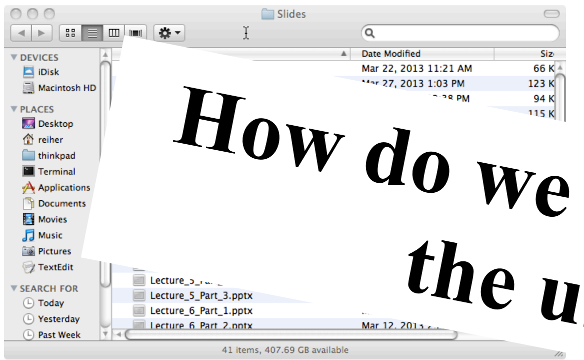
- Obviously a version of the basic memory abstraction
- So we'd expect `read()` and `write()` operations for it
- We could have a file system abstraction very close to the hardware reality
  - E.g., exposing disk cylinders or flash erase cycles
- But it's better to hide the messy details
  - Treat files as magically persistent memory

Data and Metadata

- File systems deal with two kinds of information
- *Data* – the information that the file is actually supposed to store
  - E.g., the instructions of the program or the words in the letter
- *Metadata* – Information about the information the file stores
  - E.g., how many bytes are there and when was it created
  - Sometimes called *attributes*
- Ultimately, both data and metadata must be stored persistently
  - And usually on the same piece of hardware

Bridging the Gap

We want something like . . .



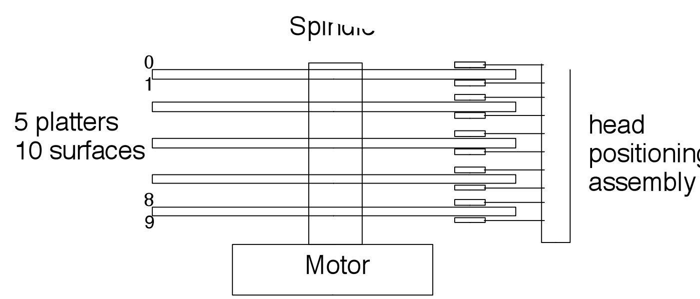
How do we get from the hardware to the useful abstraction?

But we've got something like . . .

Or . . .

Or at least

```
drwxr-xr-x    8 root  wheel    272 May  4  2010 X11
lrwxr-xr-x    1 root  wheel      3 May  4  2010 X11R6 -> X11
drwxr-xr-x  913 root  wheel  31042 Apr 21 12:21 bin
drwxr-xr-x  336 root  wheel  11424 Mar 17 09:13 lib
drwxr-xr-x  103 root  wheel   3502 Apr 21 12:23 libexec
drwxr-xr-x    7 root  wheel    238 Jan 16 23:00 local
drwxr-xr-x  238 root  wheel   8092 Mar 17 09:13 sbin
drwxr-xr-x   59 root  wheel   2006 Apr 21 12:21 share
drwxr-xr-x    4 root  wheel    136 May  4  2010 standalone
```



A Further Wrinkle

- We want our file system to be agnostic to the storage medium
- Same program should access the file system the same way, regardless of medium
  – Otherwise it's hard to write portable programs
- Should work the same for disks of different types
- Or if we use a RAID instead of one disk
- Or if we use flash instead of disks
- Or if even we don't use persistent memory at all
  – E.g., RAM file systems

Desirable File System Properties

- What are we looking for from our file system?
  - Persistence
  - Easy use model
    - For accessing one file
    - For organizing collections of files
  - Flexibility
    - No limit on number of files
    - No limit on file size, type, contents
  - Portability across hardware device types
  - Performance
  - Reliability
  - Suitable security

The Performance Issue

- How fast does our file system need to be?
- Ideally, as fast as everything else
  - Like CPU, memory, and the bus
  - So it doesn't provide a bottleneck
- But these other devices operate today at nanosecond speeds
- Disk drives operate at millisecond speeds
- Suggesting we'll need to do some serious work to hide the mismatch

The Reliability Issue

- Persistence implies reliability
- We want our files to be there when we check, no matter what
- Not just on a good day
- So our file systems must be free of errors
  - Hardware or software
- Remember our discussion of concurrency, race conditions, etc.?
  - Might we have some challenges here?

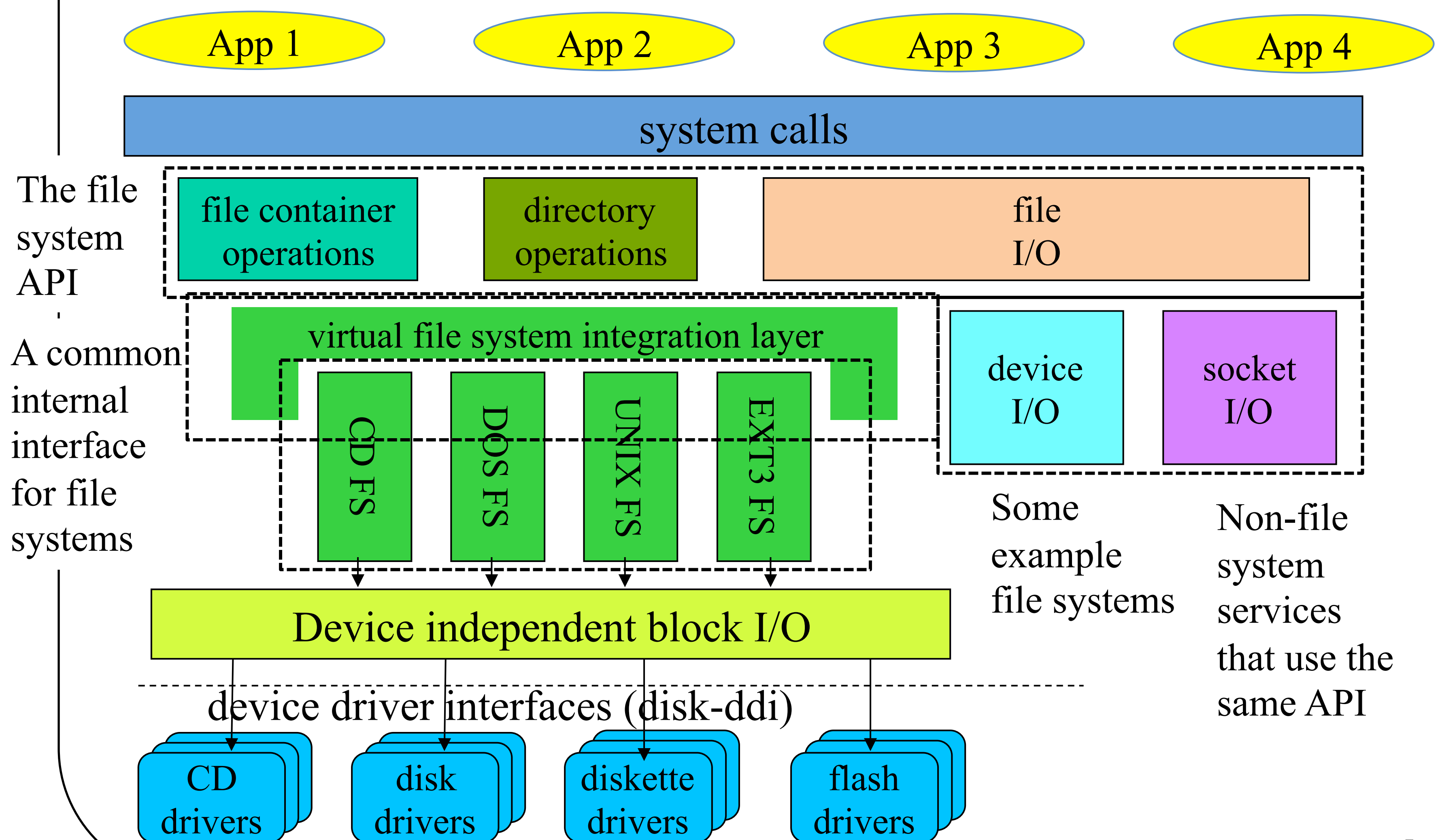
“Suitable” Security

- What does that mean?
- Whoever owns the data should be able to control who accesses it
  - Using some well-defined access control model and mechanism
- With strong guarantees that the system will enforce his desired controls
  - Implying we’ll apply complete mediation
  - To the extent performance allows

Basics of File System Design

- Where do file systems fit in the OS?
- File control data structures

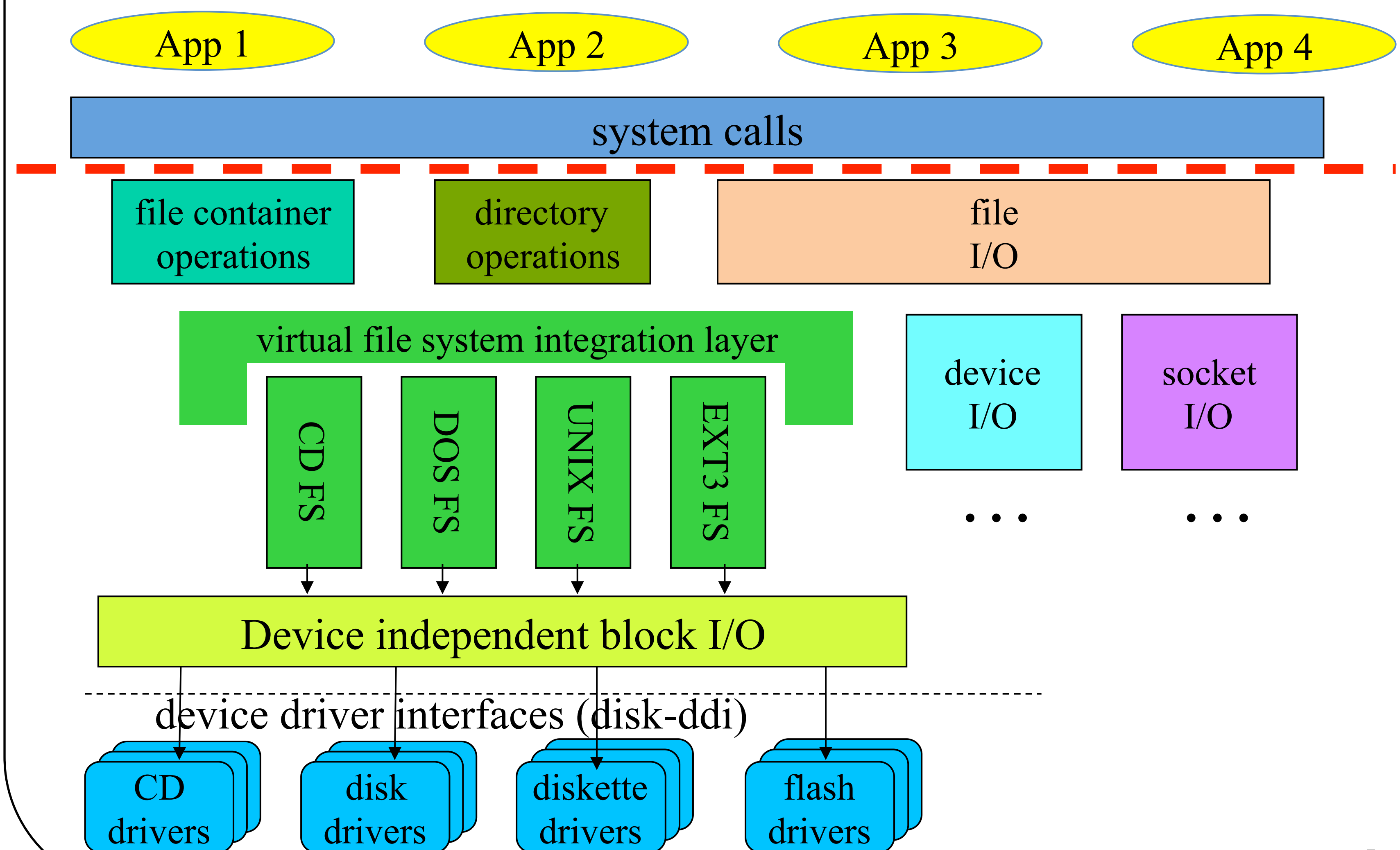
File Systems and the OS



File Systems and Layered Abstractions

- At the top, apps think they are accessing files
- At the bottom, various block devices are reading and writing blocks
- There are multiple layers of abstraction in between
- Why?
- Why not translate directly from application file operations to devices' block operations?

The File System API



The File System API

- Highly desirable to provide a single API to programmers and users for all files
- Regardless of how the file system underneath is actually implemented
- A requirement if one wants program portability
  – Very bad if a program won't work because there's a different file system underneath
- Three categories of system calls here
  1. File container operations
  2. Directory operations
  3. File I/O operations

File Container Operations

- Standard file management system calls
  - Manipulate files as objects
  - These operations ignore the contents of the file
- Implemented with standard file system methods
  - Get/set attributes, ownership, protection ...
  - Create/destroy files and directories
  - Create/destroy links
- Real work happens in file system implementation

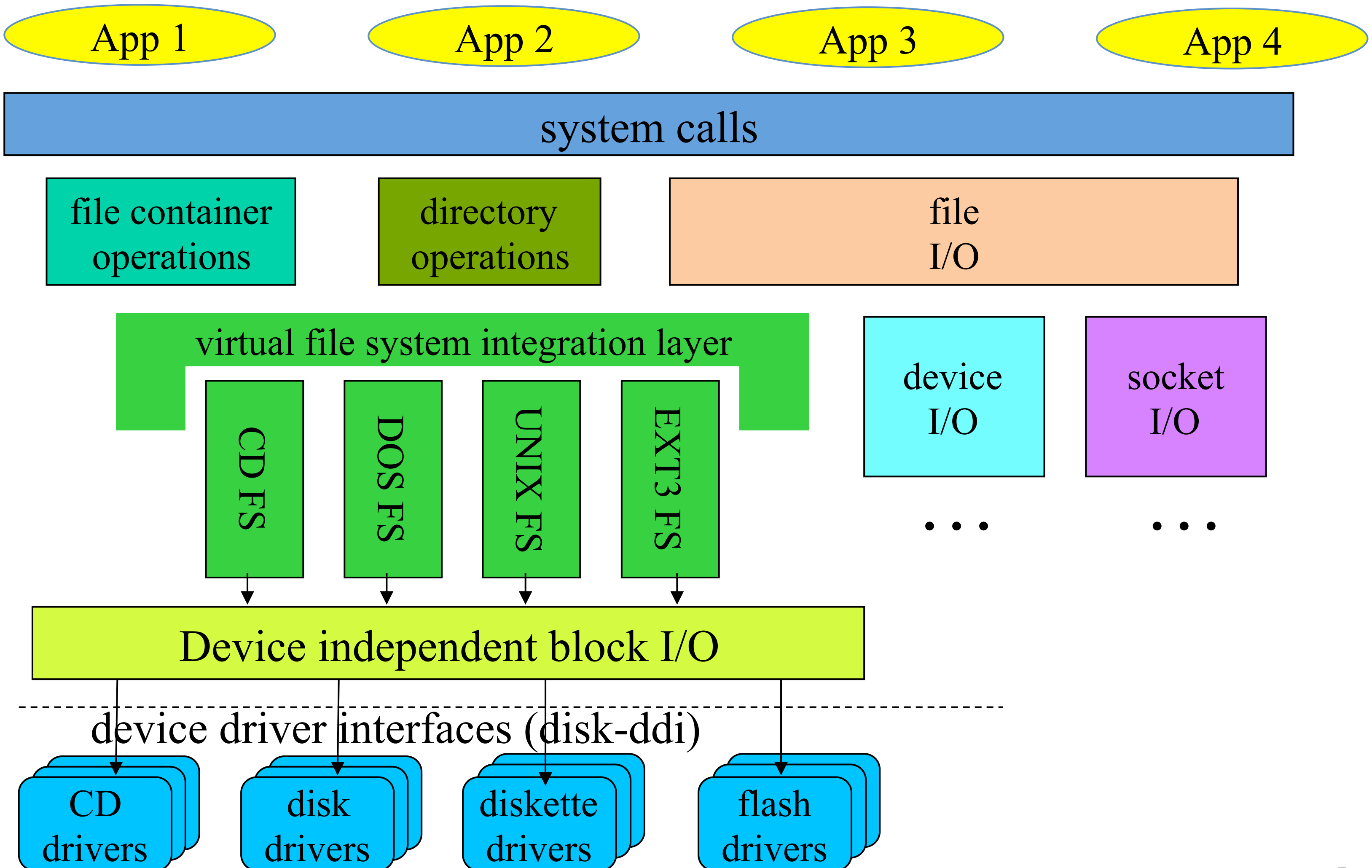
Directory Operations

- Directories provide the organization of a file system
  - Typically hierarchical
  - Sometimes with some extra wrinkles
- At the core, directories translate a name to a lower-level file pointer
- Operations tend to be related to that
  - Find a file by name
  - Create new name/file mapping
  - List a set of known names

File I/O Operations

- Open – map name into an open instance
- Read data from file and write data to file
  - Implemented using logical block fetches
  - Copy data between user space and file buffer
  - Request file system to write back block when done
- Seek
  - Change logical offset associated with open instance
- Map file into address space
  - File block buffers are just pages of physical memory
  - Map into address space, page it to and from file system

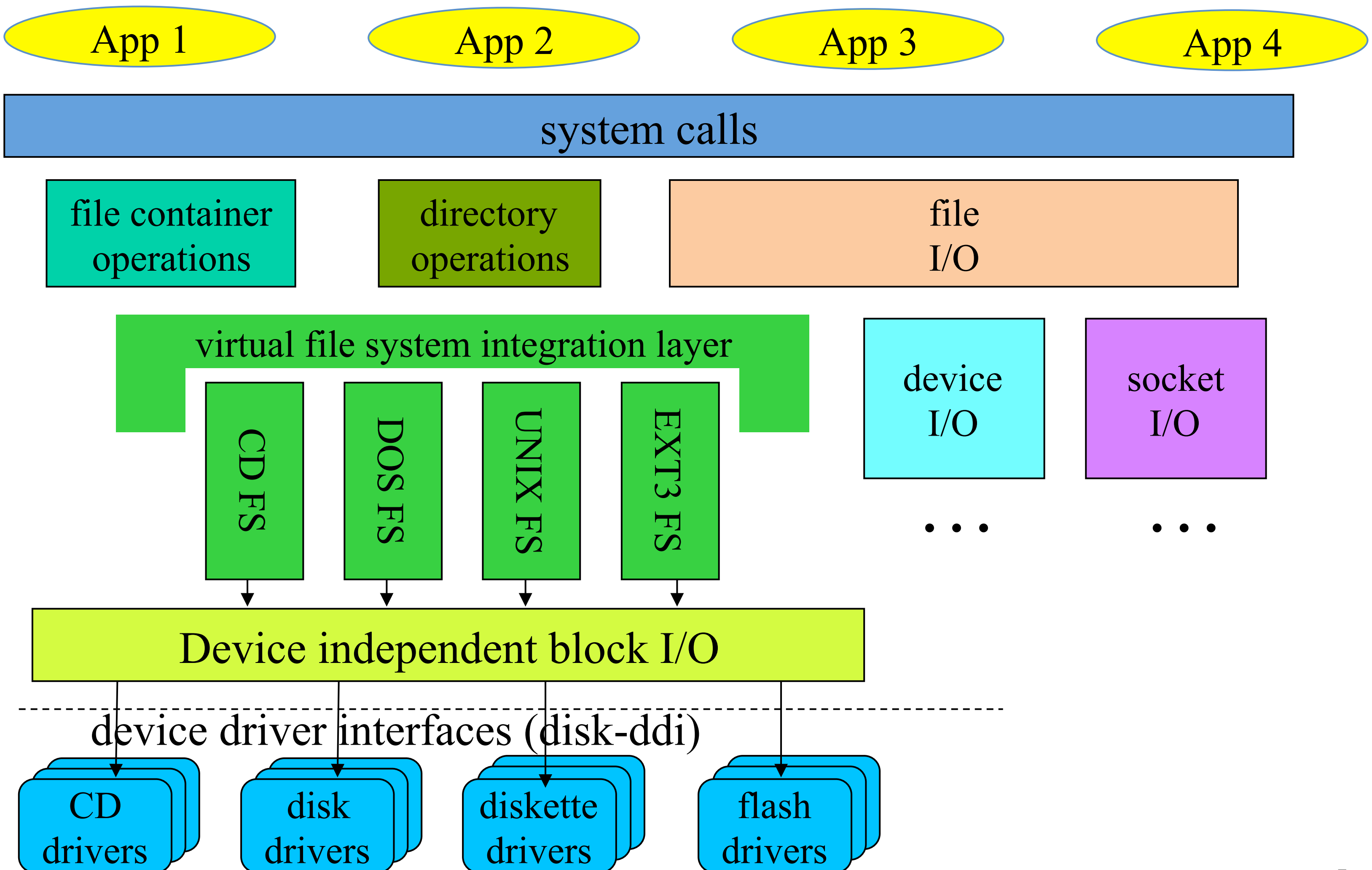
The Virtual File System Layer



The Virtual File System (VFS) Layer

- Federation layer to generalize file systems
  - Permits rest of OS to treat all file systems as the same
  - Support dynamic addition of new file systems
- Plug-in interface or file system implementations
  - DOS FAT, Unix, EXT3, ISO 9660, network, etc.
  - Each file system implemented by a plug-in module
  - All implement same basic methods
    - Create, delete, open, close, link, unlink,
    - Get/put block, get/set attributes, read directory, etc.
- Implementation is hidden from higher level clients
  - All clients see are the standard methods and properties

The File System Layer



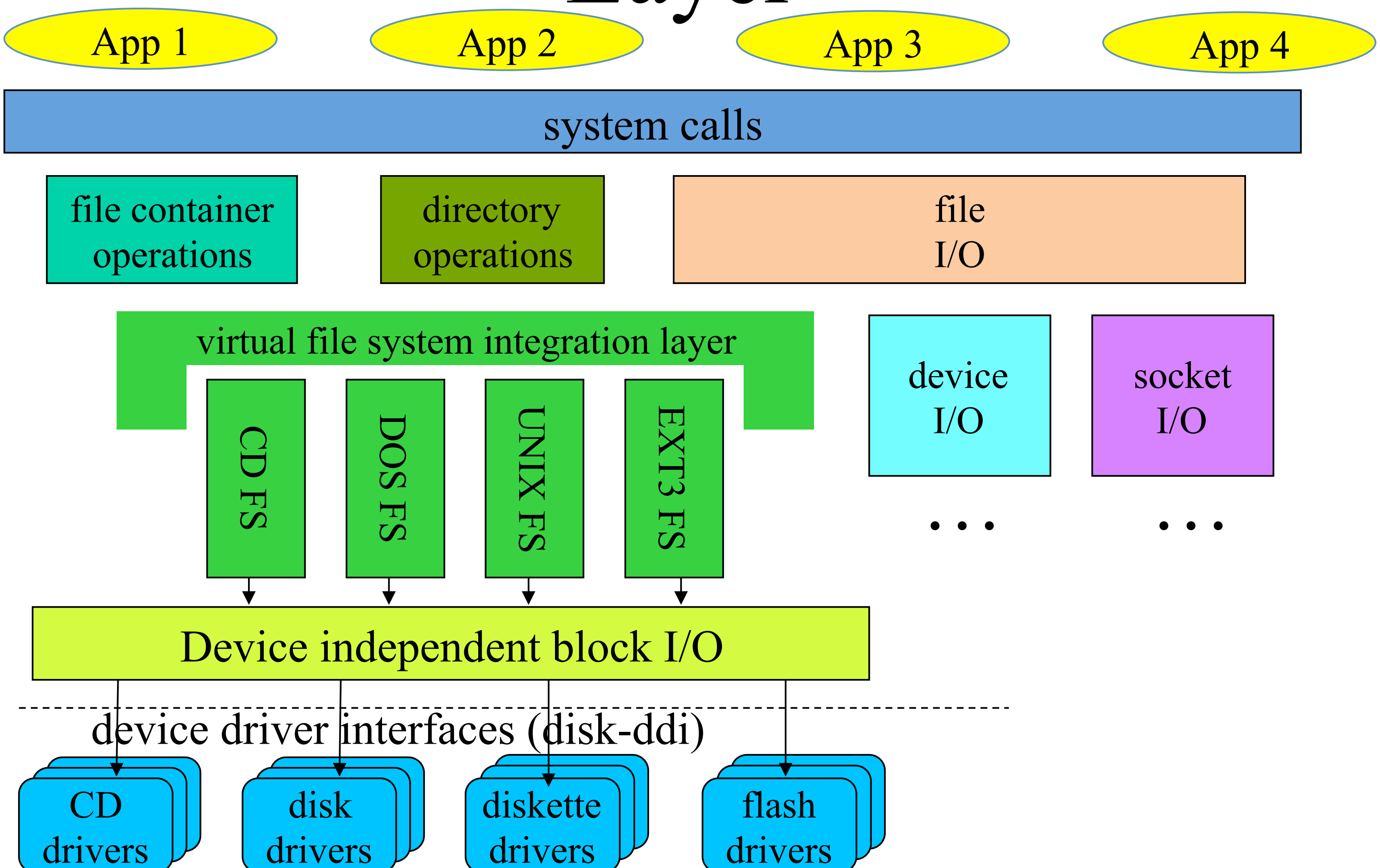
The File Systems Layer

- Desirable to support multiple different file systems
- All implemented on top of block I/O
  - Should be independent of underlying devices
- All file systems perform same basic functions
  - Map names to files
  - Map <file, offset> into <device, block>
  - Manage free space and allocate it to files
  - Create and destroy files
  - Get and set file attributes
  - Manipulate the file name space

Why Multiple File Systems?

- Why not instead choose one “good” one?
- There may be multiple storage devices
  - E.g., hard disk and flash drive
  - They might benefit from very different file systems
- Different file systems provide different services, despite the same interface
  - Differing reliability guarantees
  - Differing performance
  - Read-only vs. read/write
- Different file systems used for different purposes
  - E.g., a temporary file system

Device Independent Block I/O Layer



File Systems and Block I/O Devices

- File systems typically sit on a general block I/O layer
- A generalizing abstraction – make all disks look same
- Implements standard operations on each block device
  - Asynchronous read (physical block #, buffer, bytecount)
  - Asynchronous write (physical block #, buffer, bytecount)
- Map logical block numbers to device addresses
  - E.g., logical block number to <cylinder, head, sector>
- Encapsulate all the particulars of device support
  - I/O scheduling, initiation, completion, error handlings
  - Size and alignment limitations

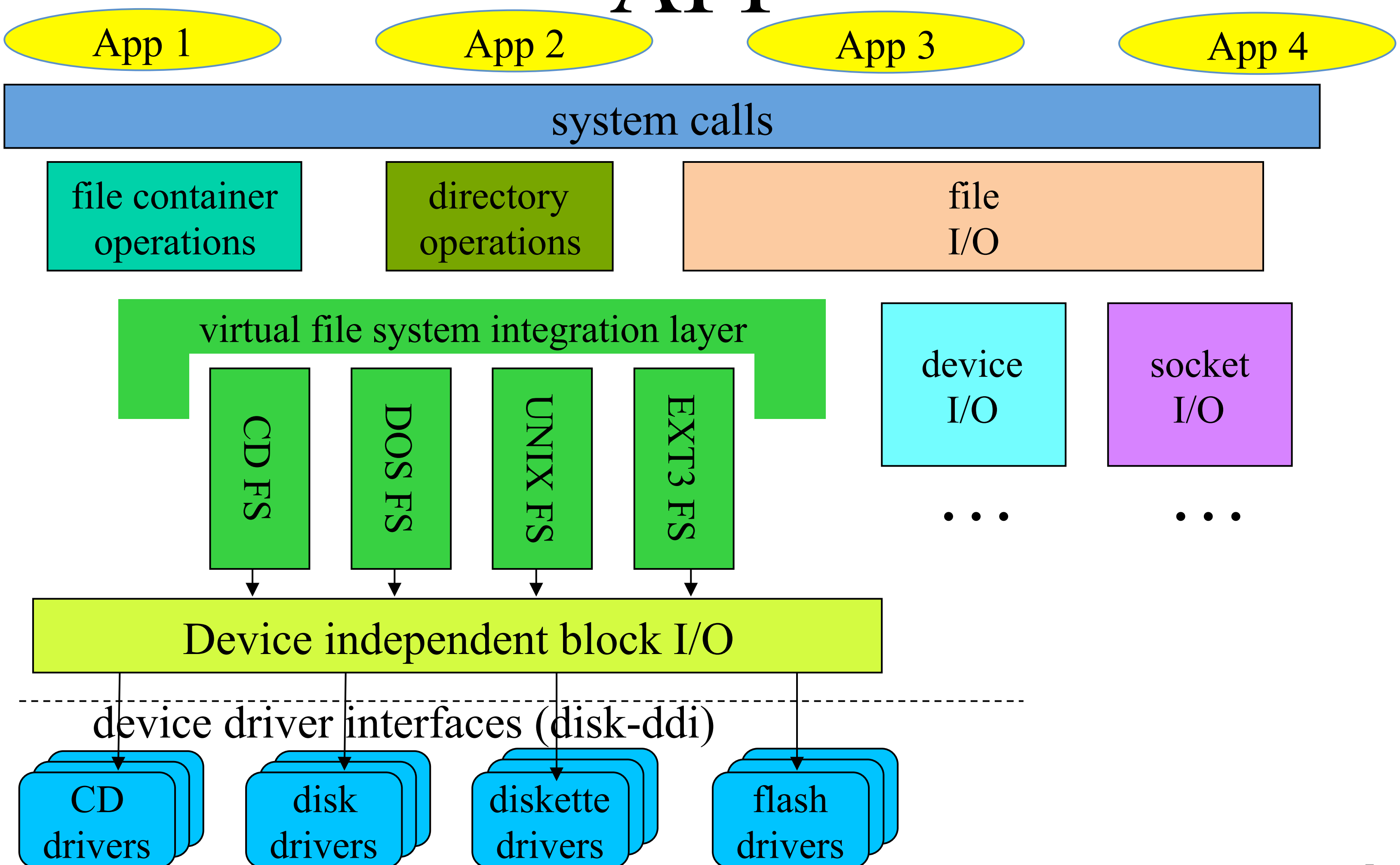
Why Device Independent Block I/O?

- A better abstraction than generic disks
- Allows unified LRU buffer cache for disk data
  - Hold frequently used data until it is needed again
  - Hold pre-fetched read-ahead data until it is requested
- Provides buffers for data re-blocking
  - Adapting file system block size to device block size
  - Adapting file system block size to user request sizes
- Handles automatic buffer management
  - Allocation, deallocation
  - Automatic write-back of changed buffers

Why Do We Need That Cache?

- File access exhibits a high degree of reference locality at multiple levels:
  – Users often read and write a single block in small operations, reusing that block
  – Users read and write the same files over and over
  – Users often open files from the same directory
  – OS regularly consults the same meta-data blocks
- Having common cache eliminates many disk accesses, which are slow

Devices, Sockets and File System API



Device and Socket I/O

- Devices are, well, devices
- Sockets are an IPC mechanism
- What are they doing in this description of file systems?
- Unix systems typically abstract them using the file interface
  - Which allows file-type operations to be performed on them

File Systems Control Structures

- A file is a named collection of information
- Primary roles of file system:
  - To store and retrieve data
  - To manage the media/space where data is stored
- Typical operations:
  - Where is the first block of this file?
  - Where is the next block of this file?
  - Where is block 35 of this file?
  - Allocate a new block to the end of this file
  - Free all blocks associated with this file

Finding Data On Disks

- Essentially a question of how you managed the space on your disk
- Space management on disk is complex
  - There are millions of blocks and thousands of files
  - Files are continuously created and destroyed
  - Files can be extended after they have been written
  - Data placement on disk has performance effects
  - Poor management leads to poor performance
- Must track the space assigned to each file
  - On-disk, master data structure for each file

On-Disk File Control Structures

- On-disk description of important attributes of a file
  - Particularly where its data is located
- Virtually all file systems have such data structures
  - Different implementations, performance & abilities
  - Implementation can have profound effects on what the file system can do (well or at all)
- A core design element of a file system
- Paired with some kind of in-memory representation of the same information

The Basic File Control Structure Problem

- A file typically consists of multiple data blocks
- The control structure must be able to find them
- Preferably able to find any of them quickly
  - I.e., shouldn't need to read the entire file to find a block near the end
- Blocks can be changed
- New data can be added to the file
  - Or old data deleted
- Files can be sparsely populated

The In-Memory Representation

- There is an on-disk structure pointing to disk blocks (and holding other information)
- When file is opened, an in-memory structure is created
- Not an exact copy of the disk version
  – The disk version points to disk blocks
  – The in-memory version points to RAM pages
    - Or indicates that the block isn't in memory
  – Also keeps track of which blocks are dirty and which aren't

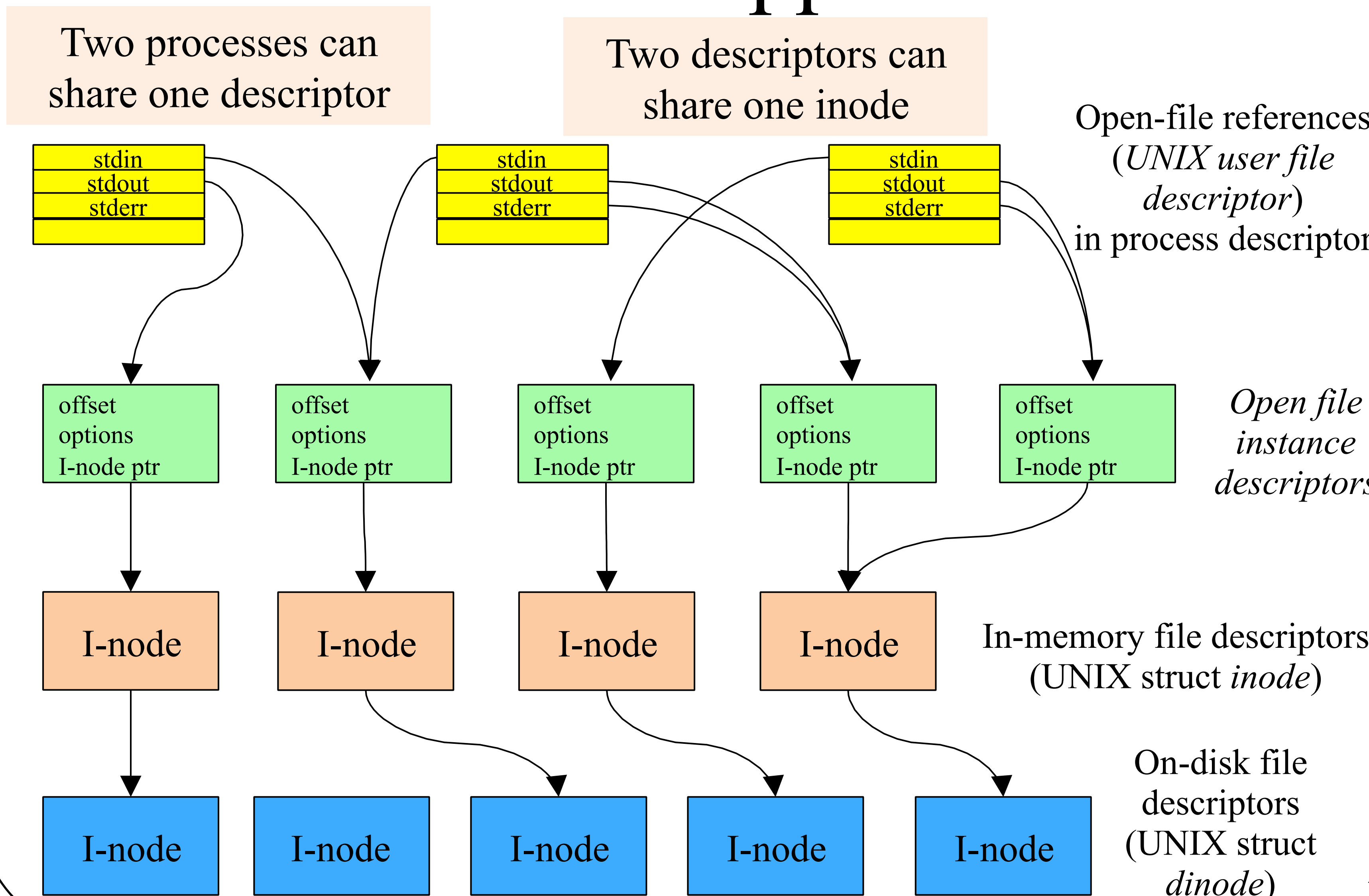
In-Memory Structures and Processes

- What if multiple processes have a given file open?
- Should they share one control structure or have one each?
- In-memory structures typically contain a cursor pointer
  - Indicating how far into the file data has been read/ written
- Sounds like that should be per-process . . .

Per-Process or Not?

- What if cooperating processes are working with the same file?
  – They might want to share a cursor
- And how can we know when all processes are finished with an open file?
  – So we can reclaim space used for its in-memory descriptor
- Implies a two-level solution
  1. A structure shared by all
  2. A structure shared by cooperating processes

The Unix Approach



File System Structure

- How do I organize a disk into a file system?
  - Linked extents
    - The DOS FAT file system
  - File index blocks
    - Unix System V file system

Basics of File System Structure

- Most file systems live on disks
- Disk volumes are divided into fixed-sized blocks
  - Many sizes are used: 512, 1024, 2048, 4096, 8192 ...
- Most blocks will be used to store user data
- Some will be used to store organizing “meta-data”
  - Description of the file system (e.g., layout and state)
  - File control blocks to describe individual files
  - Lists of free blocks (not yet allocated to any file)
- All operating systems have such data structures
  - Different OSes and file systems have very different goals
  - These result in very different implementations

The Boot Block

- The 0th block of a disk is usually reserved for the boot block
  - Code allowing the machine to boot an OS
- Not usually under the control of a file system
  - It typically ignores the boot block entirely
- Not all disks are bootable
  - But the 0th block is usually reserved, "just in case"
- So file systems start work at block 1

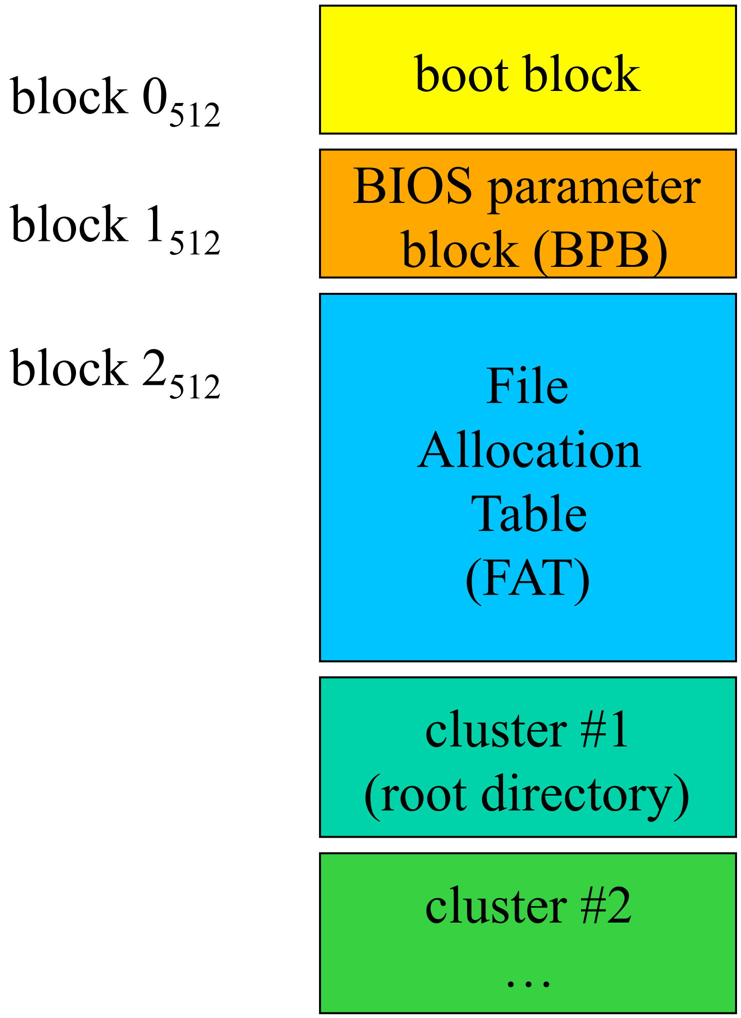
Managing Allocated Space

- A core activity for a file system, with various choices
- What if we give each file same amount of space?
  – Internal fragmentation ... just like memory
- What if we allocate just as much as file needs?
  – External fragmentation, compaction ... just like memory
- Perhaps we should allocate space in “pages”
  – How many chunks can a file contain?
- The file control data structure determines this
  – It only has room for so many pointers, then file is “full”
- So how do we want to organize the space in a file?

Linked Extents

- A simple answer
- File control block contains exactly one pointer
  - To the first chunk of the file
  - Each chunk contains a pointer to the next chunk
  - Allows us to add arbitrarily many chunks to each file
- Pointers can be in the chunks themselves
  - This takes away a little of every chunk
  - To find chunk N, you have to read the first N-1 chunks
- Pointers can be in auxiliary "chunk linkage" table
  - Faster searches, especially if table kept in memory

The DOS File System



Cluster size and FAT length are specified in the BPB

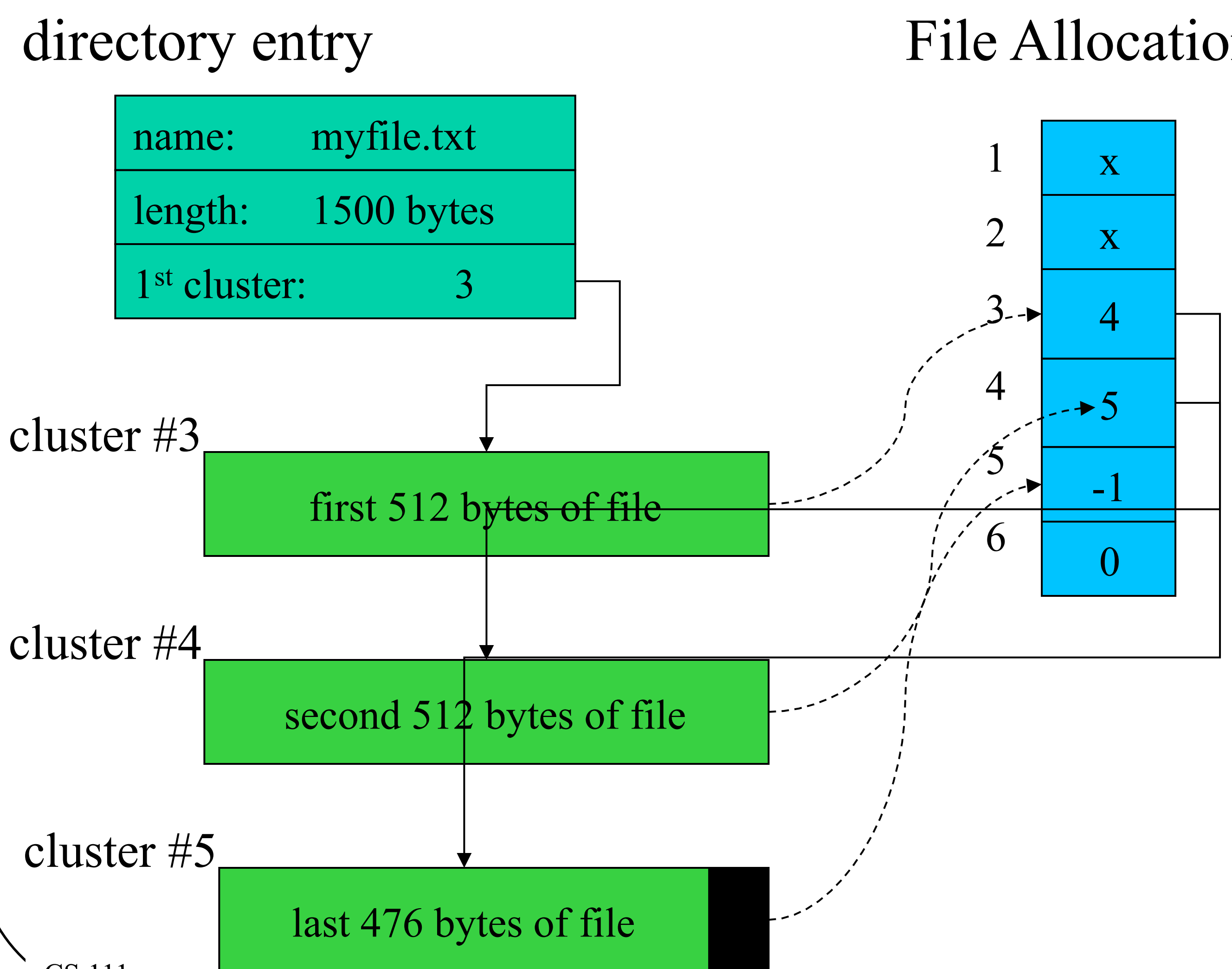
Data clusters begin immediately after the end of the FAT

Root directory begins in the first data cluster

DOS File System Overview

- DOS file systems divide space into "clusters"
  - Cluster size (multiple of 512) fixed for each file system
  - Clusters are numbered 1 though N
- File control structure points to first cluster of a file
- File Allocation Table (FAT), one entry per cluster
  - Contains the number of the next cluster in file
  - A 0 entry means that the cluster is not allocated
  - A -1 entry means "end of file"
- File system is sometimes called "FAT," after the name of this key data structure

DOS FAT Clusters



Each FAT entry corresponds to a cluster, and contains the number of the next cluster.

-1 = End of File

0 = free cluster

DOS File System Characteristics

- To find a particular block of a file
  - Get number of first cluster from directory entry
  - Follow chain of pointers through File Allocation Table
- Entire File Allocation Table is kept in memory
  - No disk I/O is required to find a cluster
  - For very large files the search can still be long
- No support for “sparse” files
  - Of a file has a block *n*, it must have all blocks < *n*
- Width of FAT determines max file system size
  - How many bits describe a cluster address
  - Originally 8 bits, eventually expanded to 32

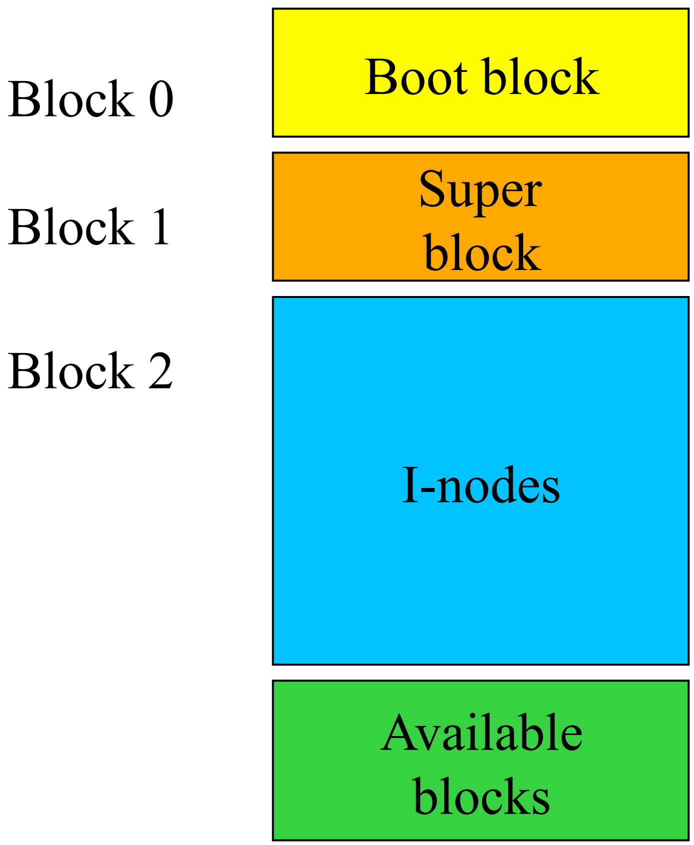
File Index Blocks

- A different way to keep track of where a file's data blocks are on the disk
- A file control block points to all blocks in file
  - Very fast access to any desired block
  - But how many pointers can the file control block hold?
- File control block could point at extent descriptors
  - But this still gives us a fixed number of extents

Hierarchically Structured File Index Blocks

- To solve the problem of file size being limited by entries in file index block
- The basic file index block points to blocks
- Some of those contain pointers which in turn point to blocks
- Can point to many extents, but still a limit to how many
  - But that limit might be a very large number
  - Has potential to adapt to wide range of file sizes

Unix System V File System

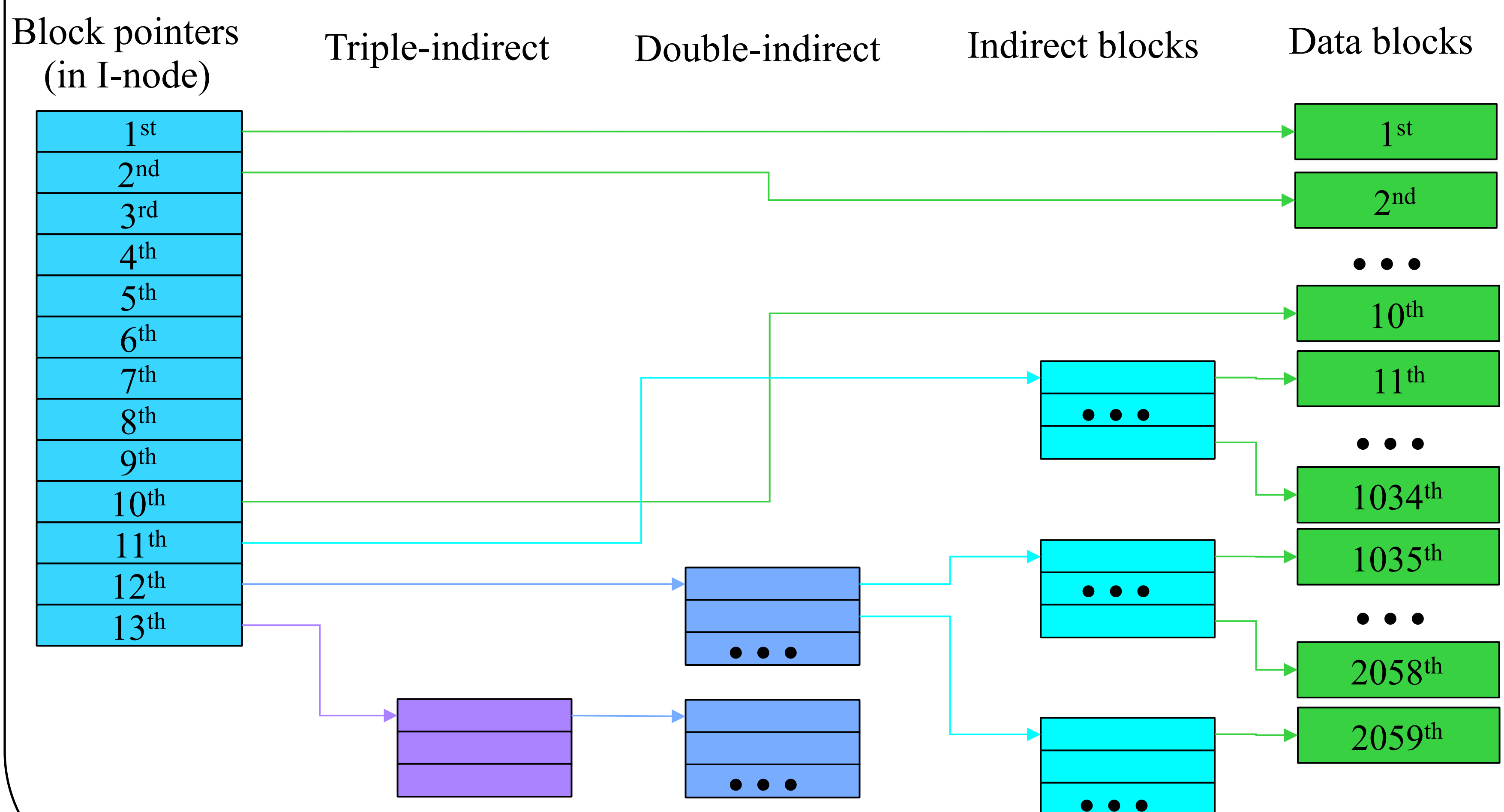


Block size and number of I-nodes are specified in super block

I-node #1 (traditionally) describes the root directory

Data blocks begin immediately after the end of the I-nodes.

Unix Inodes and Block Pointers



Why Is This a Good Idea?

- The UNIX pointer structure seems ad hoc and complicated
- Why not something simpler?
  - E.g., all block pointers are triple indirect
- File sizes are not random
  - The majority of files are only a few thousand bytes long
- Unix approach allows us to access up to 40Kbytes (assuming 4K blocks) without extra I/Os
  - Remember, the double and triple indirect blocks must themselves be fetched off disk

How Big a File Can Unix Handle?

- The on-disk inode contains 13 block pointers
  - First 10 point to first 10 blocks of file
  - 11th points to an indirect block (which contains pointers to 1024 blocks)
  - 12th points to a double indirect block (pointing to 1024 indirect blocks)
  - 13th points to a triple indirect block (pointing to 1024 double indirect blocks)
- Assuming 4k bytes per block and 4-bytes per pointer
  - 10 direct blocks = 10 * 4K bytes = 40K bytes
  - Indirect block = 1K * 4K = 4M bytes
  - Double indirect = 1K * 4M = 4G bytes
  - Triple indirect = 1K * 4G = 4T bytes
  - At the time system was designed, that seemed impossibly large
  - But . . .

Unix Inode Performance Issues

- The inode is in memory whenever file is open
- So the first ten blocks can be found with no extra I/O
- After that, we must read indirect blocks
  - The real pointers are in the indirect blocks
  - Sequential file processing will keep referencing it
  - Block I/O will keep it in the buffer cache
- 1-3 extra I/O operations per thousand pages
  - Any block can be found with 3 or fewer reads
- Index blocks can support "sparse" files
  - Not unlike page tables for sparse address spaces

Free Space and Allocation Issues

- How do I keep track of a file system's free space?
- How do I allocate new disk blocks when needed?
  - And how do I handle deallocation?

The Allocation/Deallocation Problem

- File systems usually aren't static
- You create and destroy files
- You change the contents of files
  - Sometimes extending their length in the process
- Such changes convert unused disk blocks to used blocks (or visa versa)
- Need correct, efficient ways to do that
- Typically implies a need to maintain a free list of unused disk blocks

Creating a New File

- Allocate a free file control block
  - For UNIX
    - Search the super-block free I-node list
    - Take the first free I-node
  - For DOS
    - Search the parent directory for an unused directory entry
- Initialize the new file control block
  - With file type, protection, ownership, ...
- Give new file a name
  - Naming issues will be discussed in the next lecture

Extending a File

- Application requests new data be assigned to a file
  - May be an explicit allocation/extension request
  - May be implicit (e.g., write to a currently non-existent block – remember sparse files?)
- Find a free chunk of space
  - Traverse the free list to find an appropriate chunk
  - Remove the chosen chunk from the free list
- Associate it with the appropriate address in the file
  - Go to appropriate place in the file or extent descriptor
  - Update it to point to the newly allocated chunk

Deleting a File

- Release all the space that is allocated to the file
  - For UNIX, return each block to the free block list
  - DOS does not free space
    - It uses garbage collection
    - So it will search out deallocated blocks and add them to the free list at some future time
- Deallocate the file control lock
  - For UNIX, zero inode and return it to free list
  - For DOS, zero the first byte of the name in the parent directory
    - Indicating that the directory entry is no longer in use

Free Space Maintenance

- File system manager manages the free space
- Getting/releasing blocks should be fast operations
  - They are extremely frequent
  - We'd like to avoid doing I/O as much as possible
- Unlike memory, it matters what block we choose
  - Best to allocate new space in same cylinder as file's existing space
  - User may ask for contiguous storage
- Free-list organization must address both concerns
  - Speed of allocation and deallocation
  - Ability to allocate contiguous or near-by space

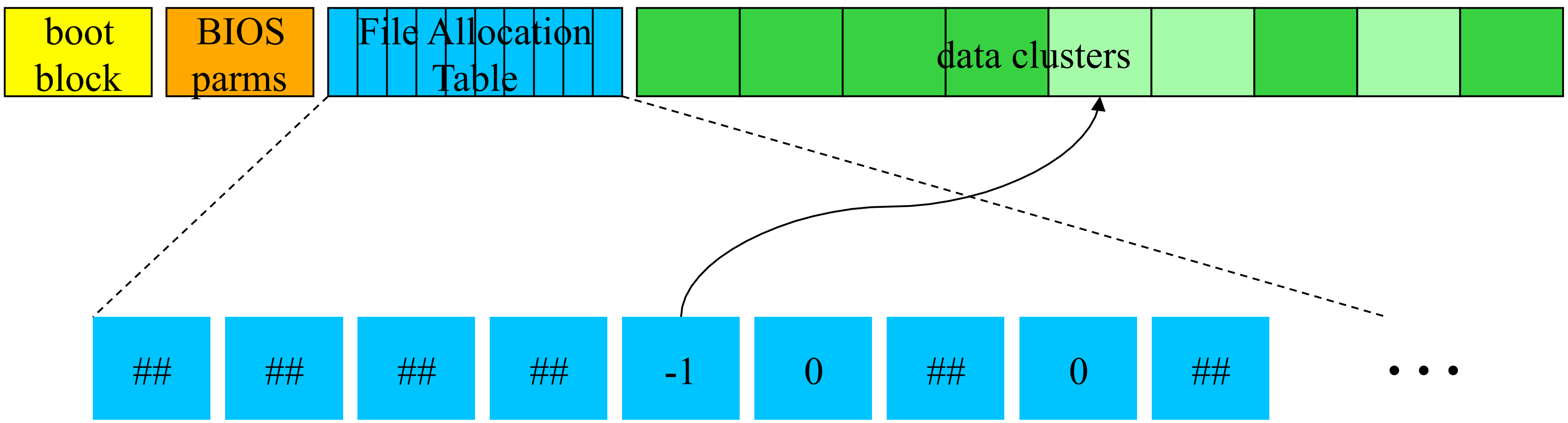
DOS File System Free Space Management

- Search for free clusters in desired cylinder
  - We can map clusters to cylinders
    - The BIOS Parameter Block describes the device geometry
  - Look at first cluster of file to choose the desired cylinder
  - Start search at first cluster of desired cylinder
  - Examine each FAT entry until we find a free one
- If no free clusters, we must garbage collect
  - Recursively search all directories for existing files
  - Enumerate all of the clusters in each file
  - Any clusters not found in search can be marked as free
  - This won't be fast . . .

Extending a DOS File

- Note cluster number of current last cluster in file
- Search the FAT to find a free cluster
  – Free clusters are indicated by a FAT entry of zero
  – Look for a cluster in the same cylinder as previous cluster
  – Put -1 in its FAT entry to indicate that this is the new EOF
  – This has side effect of marking the new cluster as "not free"
- Chain new cluster on to end of the file
  – Put the number of new cluster into FAT entry for last cluster

DOS Free Space



Each FAT entry corresponds to a cluster, and contains the number of the next cluster.

A value of zero indicates a cluster that is not allocated to any file, and is therefore free.

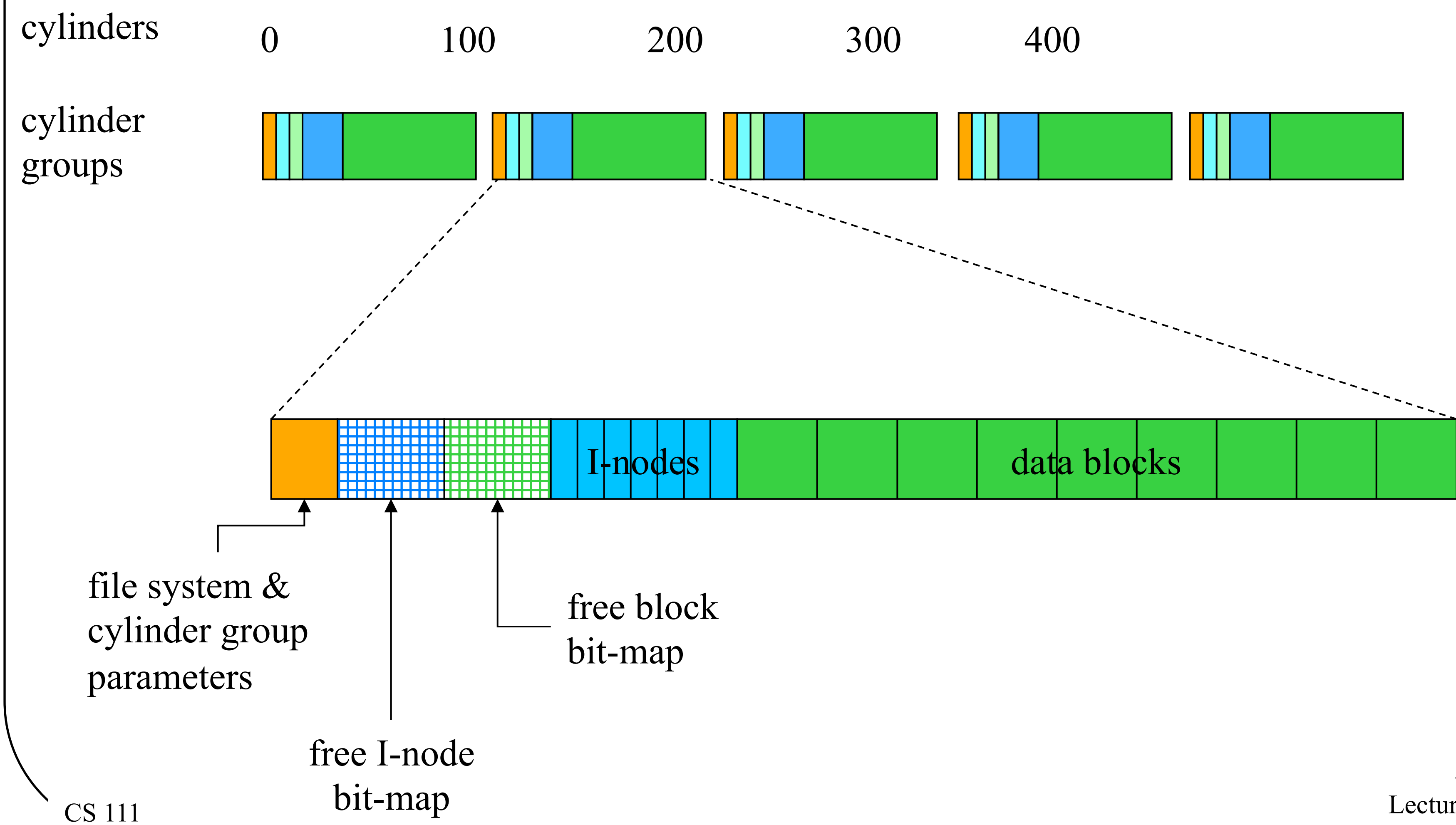
The BSD File System Free Space Management

- BSD is another version of Unix
- The details of its inodes are similar to those of Unix System V
  - As previously discussed
- Other aspects are somewhat different
  - Including free space management
  - Typically more advanced
- Uses bit map approach to managing free space
  - Keeping cylinder issues in mind

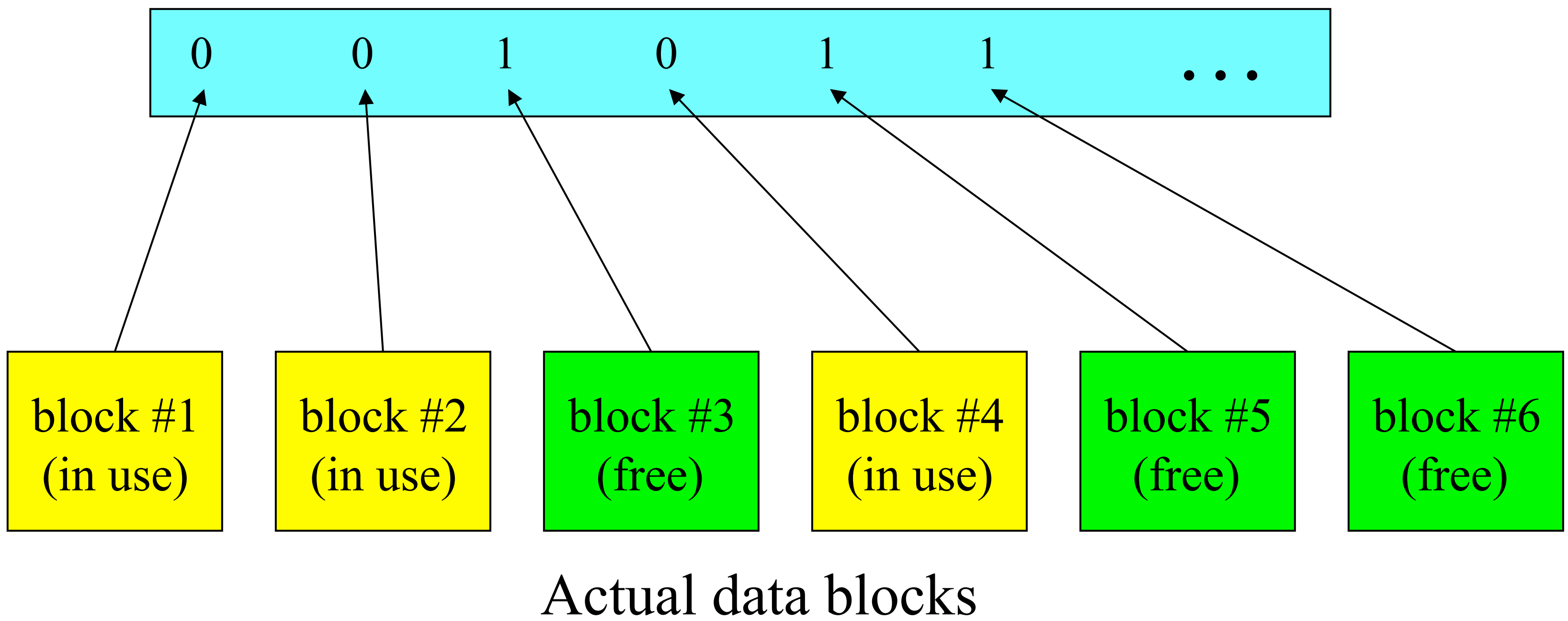
The BSD Approach

- Instead of all control information at start of disk,
- Divide file system into cylinder groups
  - Each cylinder group has its own control information
    - The *cylinder group summary*
  - Active cylinder group summaries are kept in memory
  - Each cylinder group has its own inodes and blocks
  - Free block list is a bit-map in cylinder group summary
- Enables significant reductions in head motion
  - Data blocks in file can be allocated in same cylinder
  - Inode and its data blocks in same cylinder group
  - Directories and their files in same cylinder group

BSD Cylinder Groups and Free Space



Bit Map Free Lists



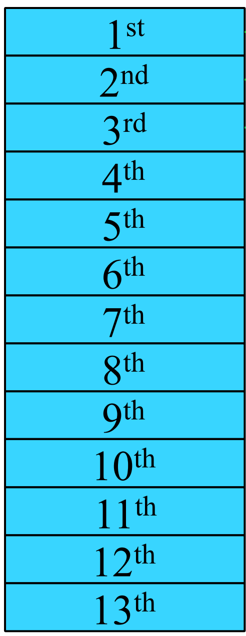
BSD Unix file systems use bit-maps to keep track of both free blocks and free I-nodes in each cylinder group

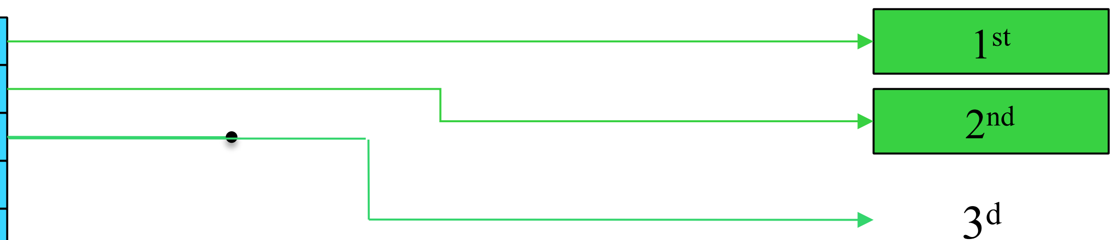
Extending a BSD/Unix File

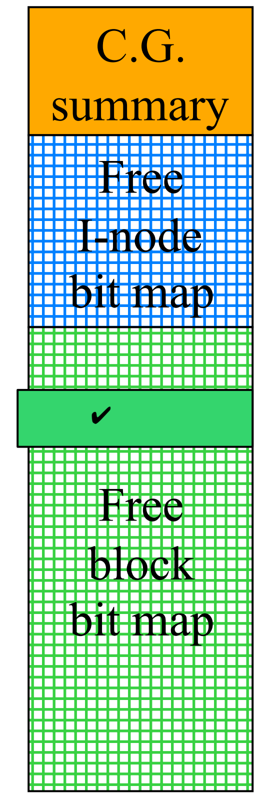
- Determine the cylinder group for the file's inode
  - Calculated from the inode's identifying number
- Find the cylinder for the previous block in the file
- Find a free block in the desired cylinder
  - Search the free-block bit-map for a free block in the right cylinder
  - Update the bit-map to show the block has been allocated
- Update the inode to point to the new block
  - Go to appropriate block pointer in inode/indirect block
  - If new indirect block is needed, allocate/assign it first
  - Update inode/indirect to point to new block

Unix File Extension

block pointers
(in I-node)







1. Determine cylinder group and get its information
2. Consult the cylinder group free block bit map to find a good block
3. Allocate the block to the file
   3.1 Set appropriate block pointer to it
   3.2 Update the free block bit map

Compaction and Defragmentation

- File I/O can be efficient if file extents are contiguous
  - Easy if free space is well distributed in large chunks
- With use, the free space becomes fragmented
  - And file I/O involves more head motion
- Periodic in-place compaction and defragmentation
  - Move the most popular files to the inner-most cylinders
  - Copy all files into contiguous extents
  - Leave the free-list with large contiguous extents
- Has the potential to significantly speed up file I/O

Compaction/Defragmentation in Real Systems

- Often done using a special utility
  - DOS file system
  - Unix XFS file system
- Good allocation strategies can limit the need
  - Most Linux systems don’t do it at all
- If your disk is big enough not to ever fill up, not a problem
  - Often the case in modern consumer computers
  - But not for many types of servers