Persistent Storage

Persistent storage

just like memory, only different

- Just like diamonds
    - last forever (?)
        - memory is volatile
    - very dense
        - 1 TByte of storage fits here 
- ...but much cheaper
    - 1 TByte is less than $100 on Amazon
        - way cheaper than 

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance		
Named data		
Controlled Sharing		
Reliability		

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance	Large cost to initiate I/O	
Named data		
Controlled Sharing		
Reliability		

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance	Large cost to initiate I/O	Organize storage to access data in large sequential units Use caching
Named data		
Controlled Sharing		
Reliability		

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance	Large cost to initiate I/O	Organize storage to access data in large sequential units Use caching
Named data	Large capacity Survives crashes Shared across programs	
Controlled Sharing		
Reliability		

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance	Large cost to initiate I/O	Organize storage to access data in large sequential units Use caching
Named data	Large capacity Survives crashes Shared across programs	Support files and directories with meaningful names
Controlled Sharing		
Reliability		

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance	Large cost to initiate I/O	Organize storage to access data in large sequential units Use caching
Named data	Large capacity Survives crashes Shared across programs	Support files and directories with meaningful names
Controlled Sharing	Device may store data from many users	
Reliability		

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance	Large cost to initiate I/O	Organize storage to access data in large sequential units Use caching
Named data	Large capacity Survives crashes Shared across programs	Support files and directories with meaningful names
Controlled Sharing	Device may store data from many users	Include with files metadata for access control
Reliability		

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance	Large cost to initiate I/O	Organize storage to access data in large sequential units Use caching
Named data	Large capacity Survives crashes Shared across programs	Support files and directories with meaningful names
Controlled Sharing	Device may store data from many users	Include with files metadata for access control
Reliability	Crash can occur during updates Storage devices can fail Flash memory wears out	

How persistent storage affects OS Design

Goal	Physical Characteristics	Design Implication
High performance	Large cost to initiate I/O	Organize storage to access data in large sequential units Use caching
Named data	Large capacity Survives crashes Shared across programs	Support files and directories with meaningful names
Controlled Sharing	Device may store data from many users	Include with files metadata for access control
Reliability	Crash can occur during updates Storage devices can fail Flash memory wears out	Use transactions Use redundancy to detect and correct failures Migrate data to even the wear

How persistent storage affects applications

- Example: Word processor with auto-save feature
- If file is large and developer is naive
  - poor performance
    - may have to overwrite entire file to write a few bytes!
      - clever doc format may transform updates in appends
  - corrupt file
    - crash while overwriting file
  - lost file
    - crash while copying new file to old file location

The File System abstraction

- Presents applications with persistent, named data
- Two main components:
  - ☐ files
  - ☐ directories

The File

- A file is a named collection of data.
- A file has two parts
  - data – what a user or application puts in it
    - array of untyped bytes (in MacOS HFS, multiple streams per file)
  - metadata – information added and managed by the OS
    - size, owner, security info, modification time

The Directory

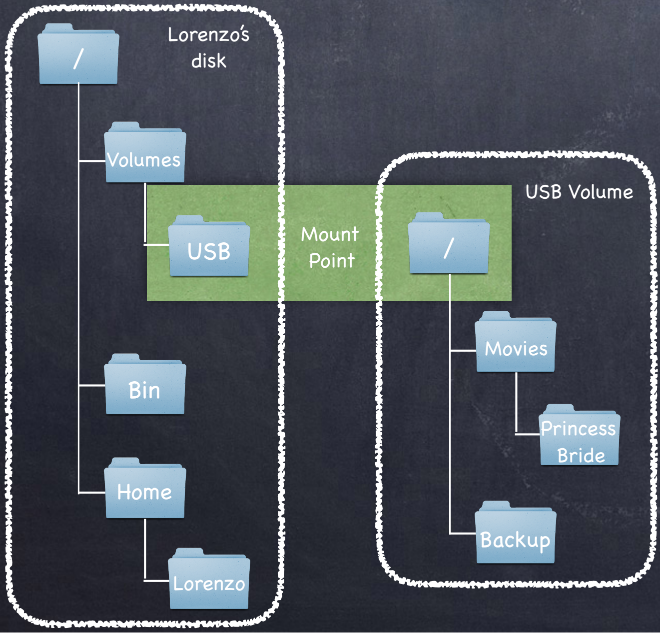
- The directory provides names for files
  - a list of human readable names
  - a mapping from each name to a specific underlying file or directory (hard link)
  - a soft link is instead a mapping from a file name to another file name
    - alias: a soft link that continues to remain valid when the (path of) the target file name changes

Path and Volume

- path: string that identifies a file or directory
    - absolute (if it stats with "/", the root directory)
    - relative (w.r.t. the current working directory)
- volume: a collection of physical storage resources forming a logical storage device

Mount

- mount: allows multiple file systems on multiple volumes to form a single logical hierarchy
  - a mapping from some path in existing file system to the root directory of the mounted file system



File system API

- Creating and deleting files
  - `create()` creates 1) a new file with some metadata and 2) a name for the file in a directory
  - `link()` creates a hard link–a new name for the same underlying file
  - `unlink()` removes a name for a file from its directory. If last link, file itself and resources it held are deleted
- Open and close
  - `open()` provides caller with a file descriptor to refer to file
    - permissions checked at open() time (a capability!)
    - creates per-file data structure, referred to by file descriptor
      - file ID, R/W permission, pointer to process position in file
  - `close()` releases data structure
- File access
  - `read()`, `write()`, `seek()`
    - but can use `mmap()` to create a mapping between region of file and region of memory
  - `fsync()` does not return until data is written to persistent storage

File systems: What's so hard?

- Just map keys (file name & offset) to values (block numbers on a device)!

File systems: What's so hard?

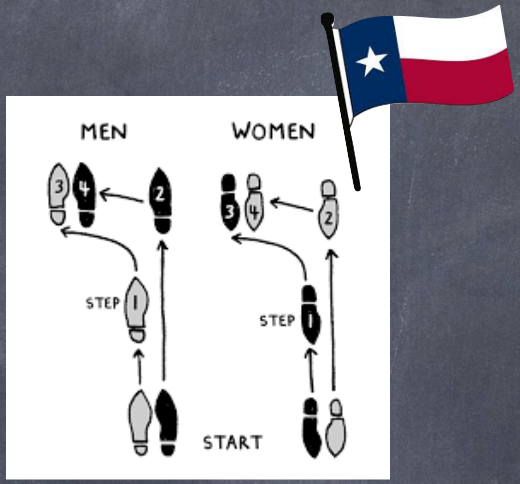
- Just map keys to values !
  file name & offset → keys; block numbers on a device → values

file name
& offset

block numbers
on a device

- Just map keys to values !
- Not so fast!
  - Performance
    - spatial locality
  - Flexibility
    - must handle diverse workloads
  - Reliability
    - must handle OS crashes and HW malfunctions

Implementation: key ideas



- Directories
  - file name → file number
- Index structures
  - file number → block
- Free space maps
  - find a free block; actually, find a free block nearby
- Locality heuristics
  - policies enabled by above mechanisms
    - group directories
    - make writes sequential
    - defragment

Directory

- A file that contains a collection of mapping from file name to file number

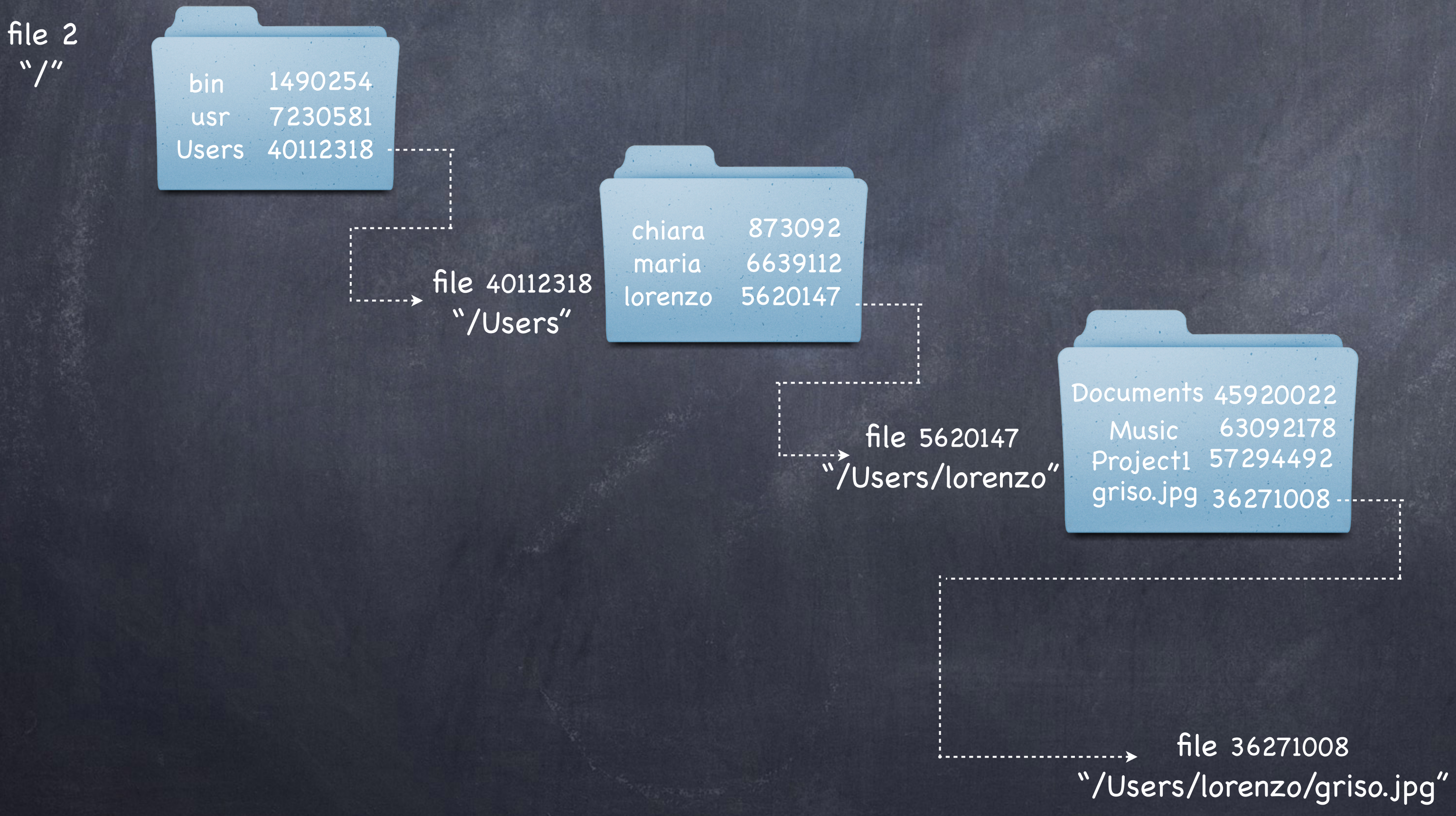
/Users/lorenzo

Documents	45920022
Music	63092178
Project1	57294492
griso.jpg	36271008

- To look up a file, find the directory that contains the mapping to the file number
- To find that directory, find the parent directory that contains the mapping to that directory's file number...
- Good news: root directory has well-known number (2)

Looking up a file

- Find file /Users/lorenzo/griso.jpg



file 2
"/"

bin	1490254
usr	7230581
Users	40112318

file 40112318
"/Users"

chiara	873092
maria	6639112
lorenzo	5620147

file 5620147
"/Users/lorenzo"

Documents	45920022
Music	63092178
Project1	57294492
griso.jpg	36271008

file 36271008
"/Users/lorenzo/griso.jpg"

Finding data

- **Index structure** provides a way to locate each of the file's blocks
  - usually implemented as a tree for scalability
- **Free space map** provides a way to allocate free blocks
  - often implemented as a bitmap
- **Locality heuristics** group data to maximize access performance

Case studies

- FAT late 70s; Microsoft
  - key idea: linked list
  - Today: flash sticks
- Unix FFS mid 80's
  - key idea: tree-based multi-level index
  - Today: Linux ext2 and ext3
- NTFS early 1990s; Microsoft.
  - Key idea: variable size extents instead of fixed size blocks
  - Today: Windows 7, Linux ext4, Apple HFS
- ZFS early 2000; open source.
  - Key idea: copy on write (COW)

FAT File system

Microsoft, late 70s

- File Allocation Table (FAT)
  - ☐ started with MSDOS
  - ☐ in FAT-32, supports 2^{28} blocks and files of 2^{32}-1 bytes

Index Structures

File Allocation Table (FAT)

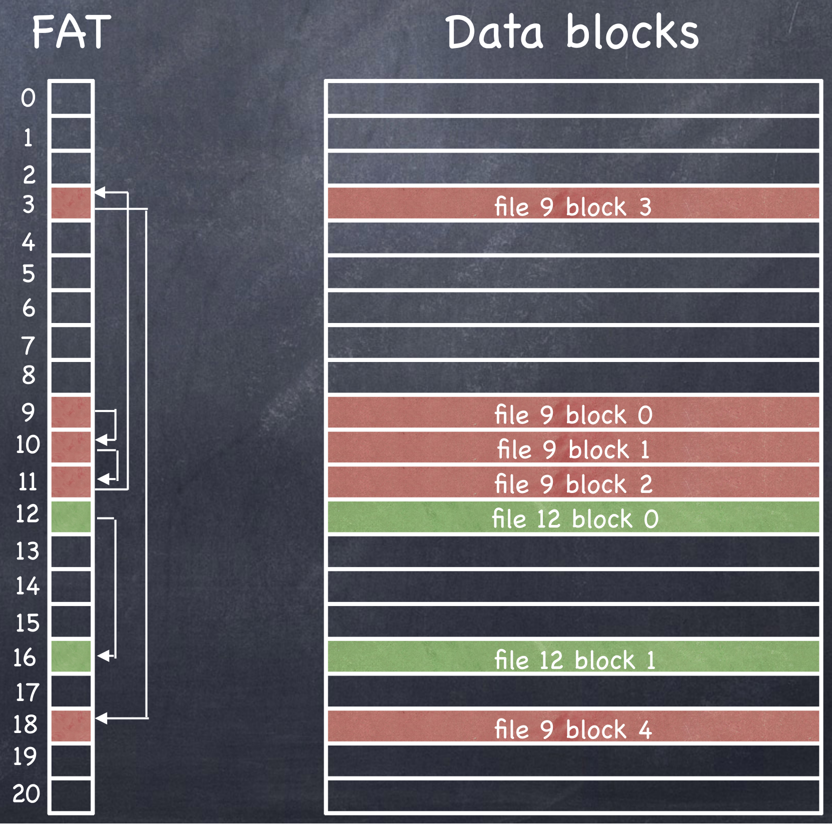
- array of 32-bit entries
- file represented as a linked list of FAT entries
- file # = index of first FAT entry

Free space map

- If data block i is free, then FAT[i] = 0
- find free blocks by scanning MFT

Locality heuristics

- As simple as next fit:
  - ☐ scan sequentially from last allocated entry and return next free entry
- Can be improved through defragmentation



FAT File system

Microsoft, late 70s

- File Allocation Table (FAT)
  - started with MSDOS
  - in FAT-32, supports 2^{28} blocks and files of 2^{32}-1 bytes

Advantages

- simple!
  - used in many USB flash keys
  - used even within MS Word!

Disadvantages

- Poor locality
  - next fit? seriously?
- Poor random access
  - needs sequential traversal
- Limited access control
  - no file owner or group ID metadata
  - any user can read/write any file
- No support for hard links
  - metadata stored in directory entry
- Volume and file size are limited
  - FAT entry is 32 bits, but top 4 are reserved
  - no more than 2^{28} blocks
  - with 4kB blocks, at most 1TB volume
  - file no bigger than 4GB
- No support for transactional updates

FFS: Fast File System

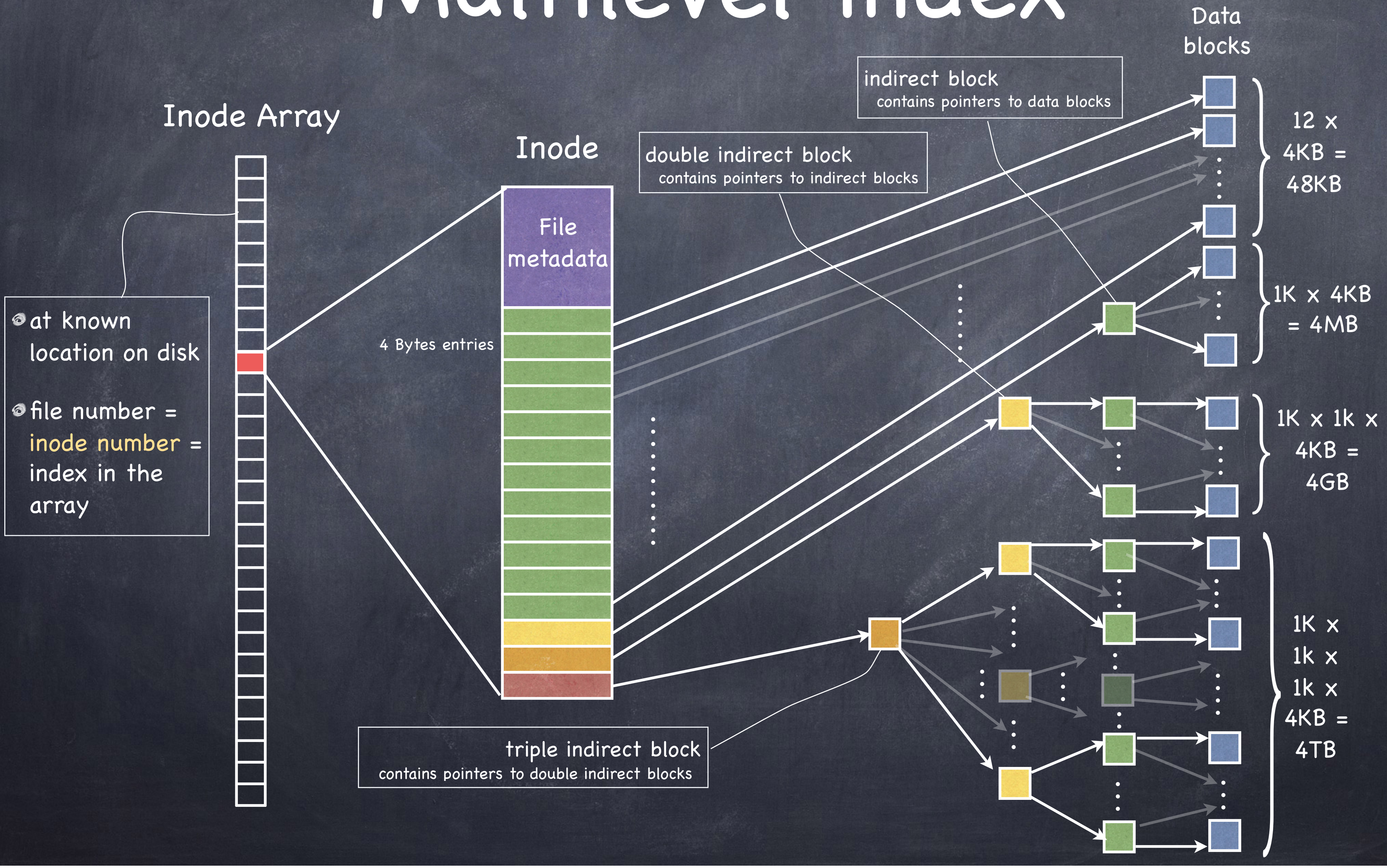
Unix, 80s

- Smart index structure
  - multilevel index allows to locate all blocks of a file
    - efficient for both large and small files
- Smart locality heuristics
  - block group placement
    - optimizes placement for when a file data and metadata, and other files within same directory, are accessed together
  - reserved space
    - gives up about 10% of storage to allow flexibility needed to achieve locality

File structure

- Each file is a fixed, asymmetric tree, with fixed size data blocks (e.g. 4KB) as its leaves
- The root of the tree is the file's inode
  - contains file's metadata
    - owner, permissions (rwx for owner, group other), directory?, etc
    - setuid: file is always executed with owner's permission
      - add flexibility but can be dangerous
    - setgid: like setuid for groups
  - contains a set of pointers
    - typically 15
    - first 12 point to data block
    - last three point to intermediate blocks, themselves containing pointers
      - 13: indirect pointer
      - 14: double indirect pointer
      - 15: triple indirect pointer

Multilevel index



Inode Array

- at known location on disk
- file number = inode number = index in the array

Inode

File metadata

4 Bytes entries

indirect block
contains pointers to data blocks

double indirect block
contains pointers to indirect blocks

triple indirect block
contains pointers to double indirect blocks

Data blocks

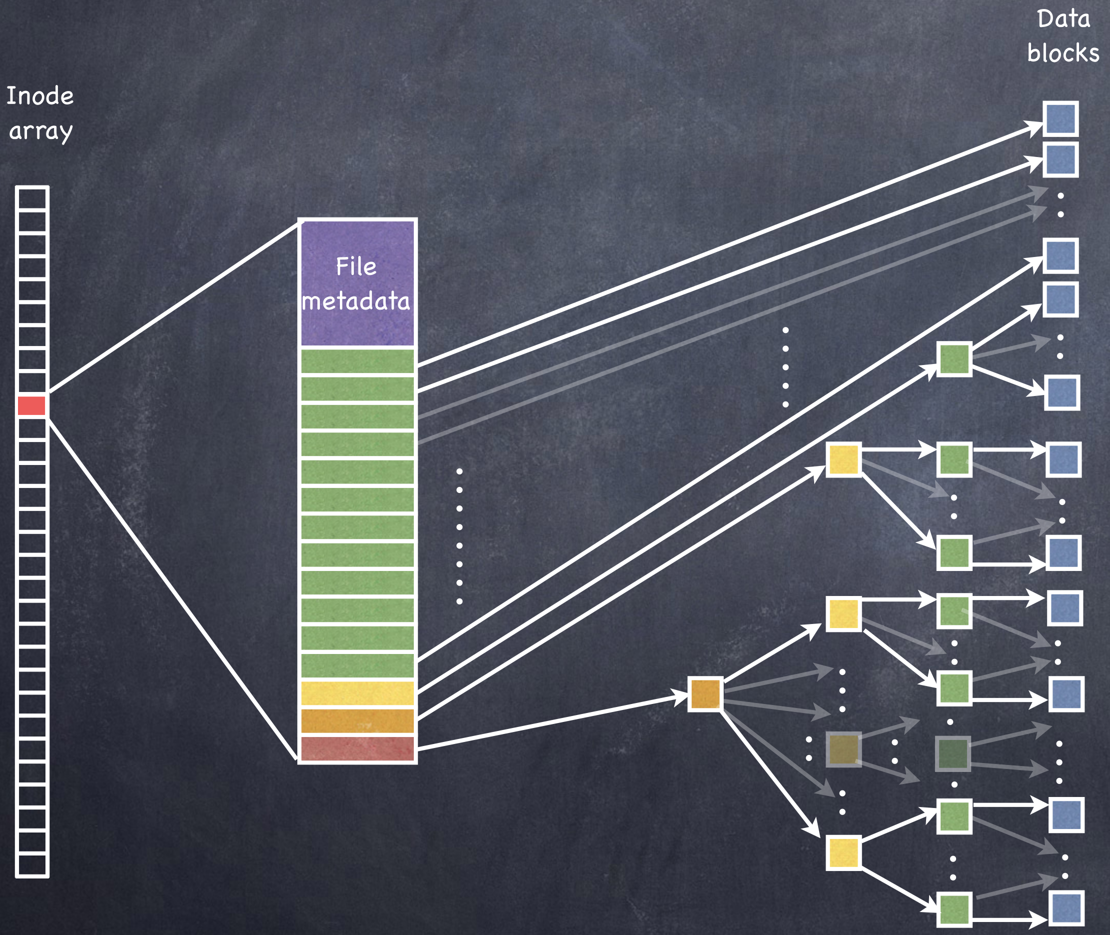
12 x 4KB = 48KB

1K x 4KB = 4MB

1K x 1k x 4KB = 4GB

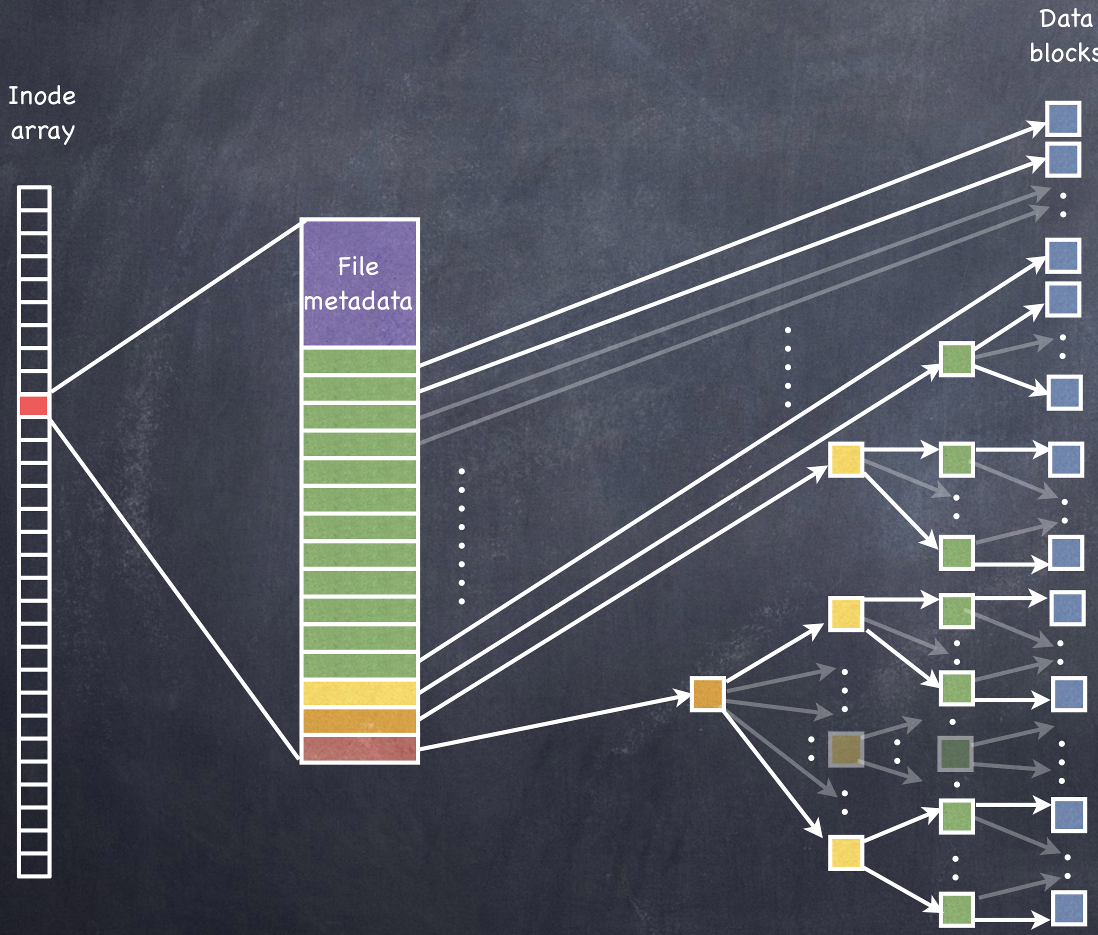
1K x 1k x 1k x 4KB = 4TB

Multilevel index: key ideas



- Tree structure
  - efficient in finding blocks
- High degree
  - efficient in sequential reads
    - once an indirect block is read, can read 100s of data block
- Fixed structure
  - simple to implement
- Asymmetric
  - supports efficiently files big and small

Example: variations on the FFS theme



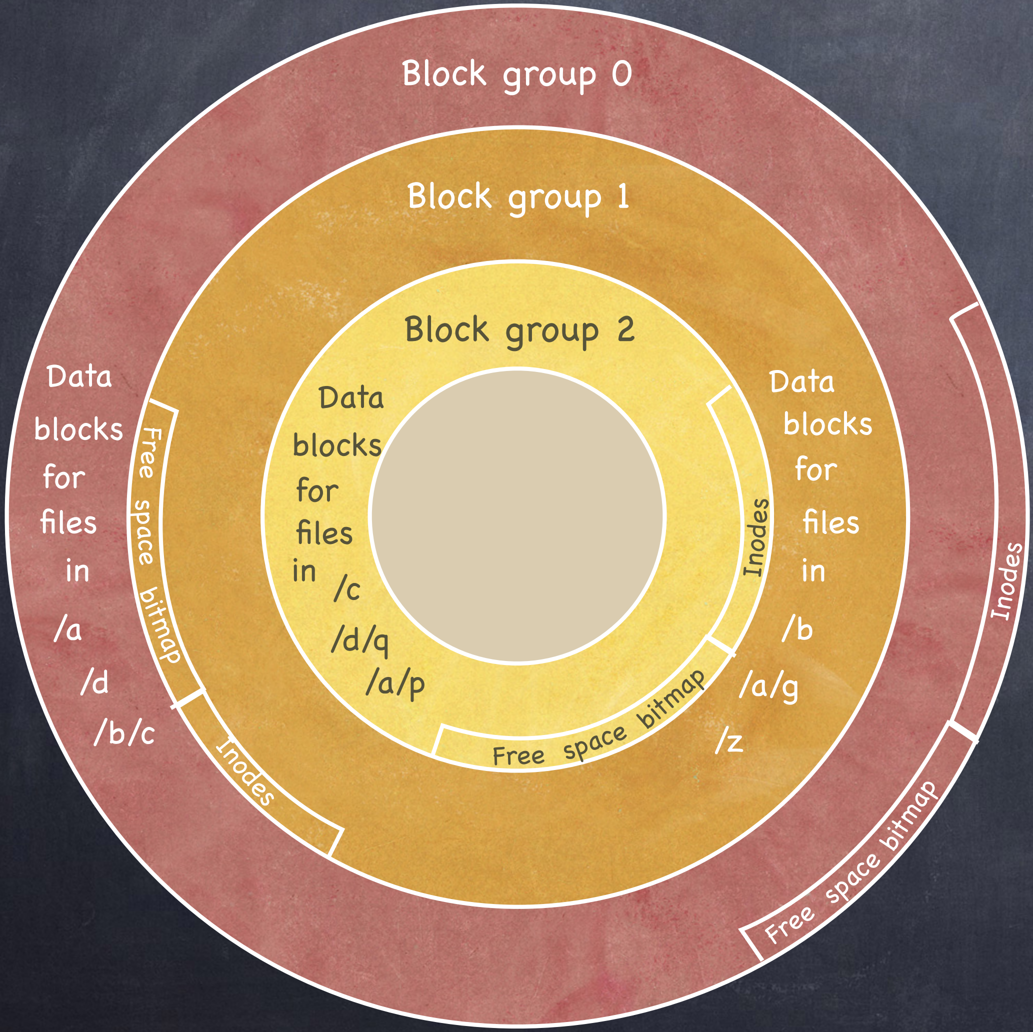
- In BigFS an inode stores
- 4kb blocks, 8 byte pointers
  - 12 direct pointers
  - 1 indirect pointer
  - 1 double indirect
  - 1 triple indirect
  - 1 quadruple indirect
- What is the maximum size of a file?
  - Through direct pointers
    - 12 x 4kb = 48KB
  - Indirect pointer
    - 512 x 4kb = 2MB
  - Double indirect pointer
    - 512^2 x 4kb = 1GB
  - Triple indirect pointer
    - 512^3 x 4kb = 512GB
  - Quadruple indirect pointer
    - 512^4 x 4kb = 256TB

Total = $(256 + .5 + 10^{-6} + 2 \times 10^{-9} + 4.8 \times 10^{-11}) \approx 256.5$ TB

Free space management

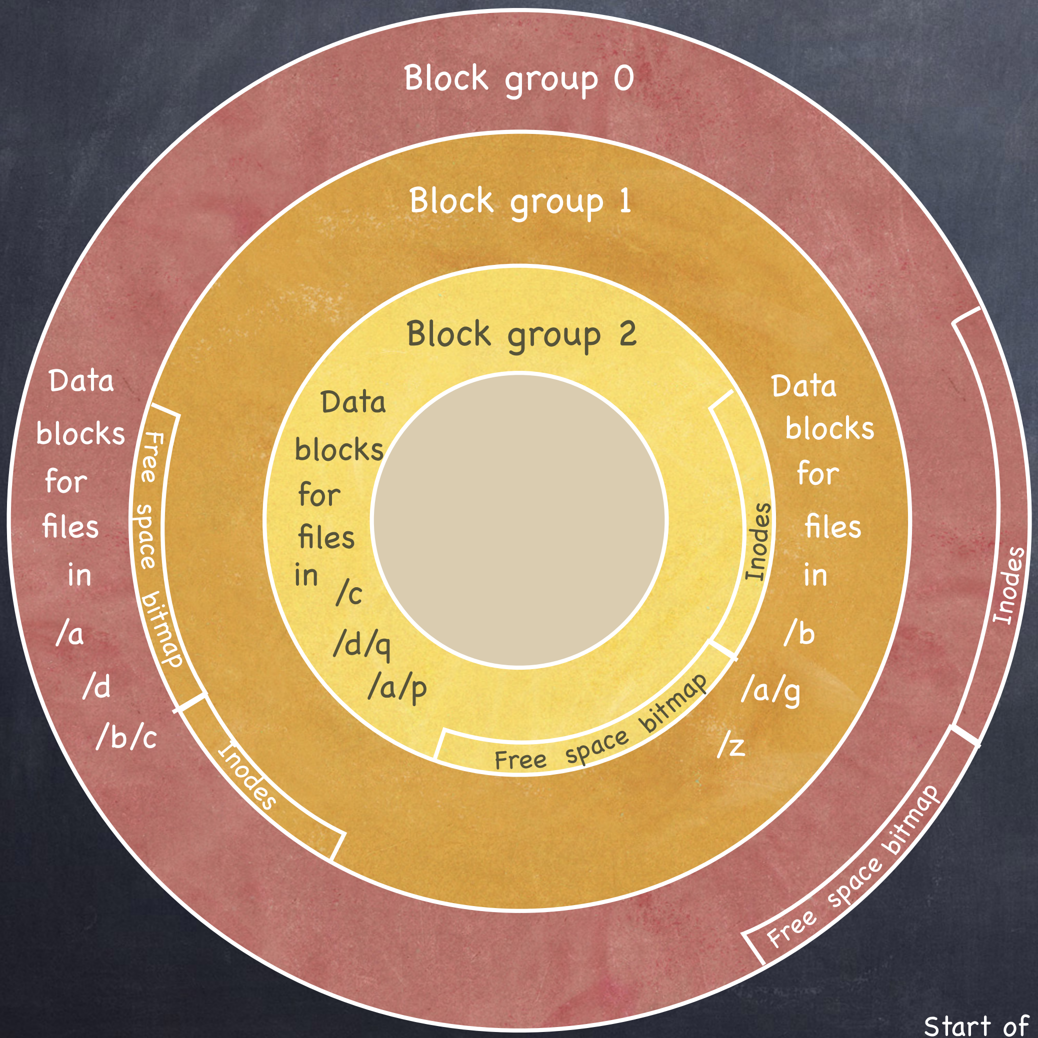
- Easy
  - a bitmap with one bit per storage block
  - bitmap location fixed at formatting time
  - i-th bit indicates whether i-th block is used or free

Locality heuristics: block group placement

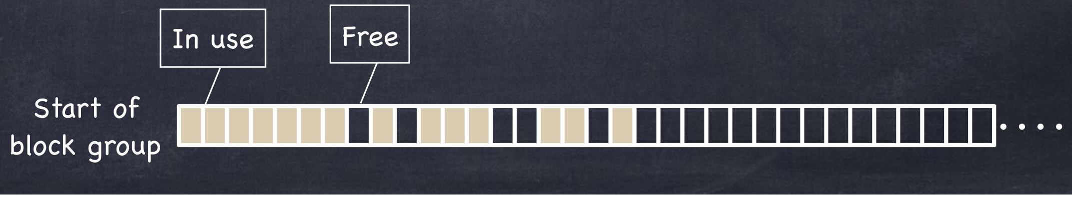


- Divide disk in block groups
  - ☐ sets of nearby tracks
- Distribute metadata
  - ☐ old design: free space bitmap and inode map in a single contiguous region
    - lots of seeks when going from reading metadata to reading data
  - ☐ FFS: distribute free space bitmap and inode array among block groups
- Place file in block group
  - ☐ when a new file is created, FFS looks for inodes in the same block as the file's directory
  - ☐ when a new directory is created, FFS palces it in a different block from the parent's directory
- Place data blocks
  - ☐ first free heuristics
  - ☐ trade short term for long term locality

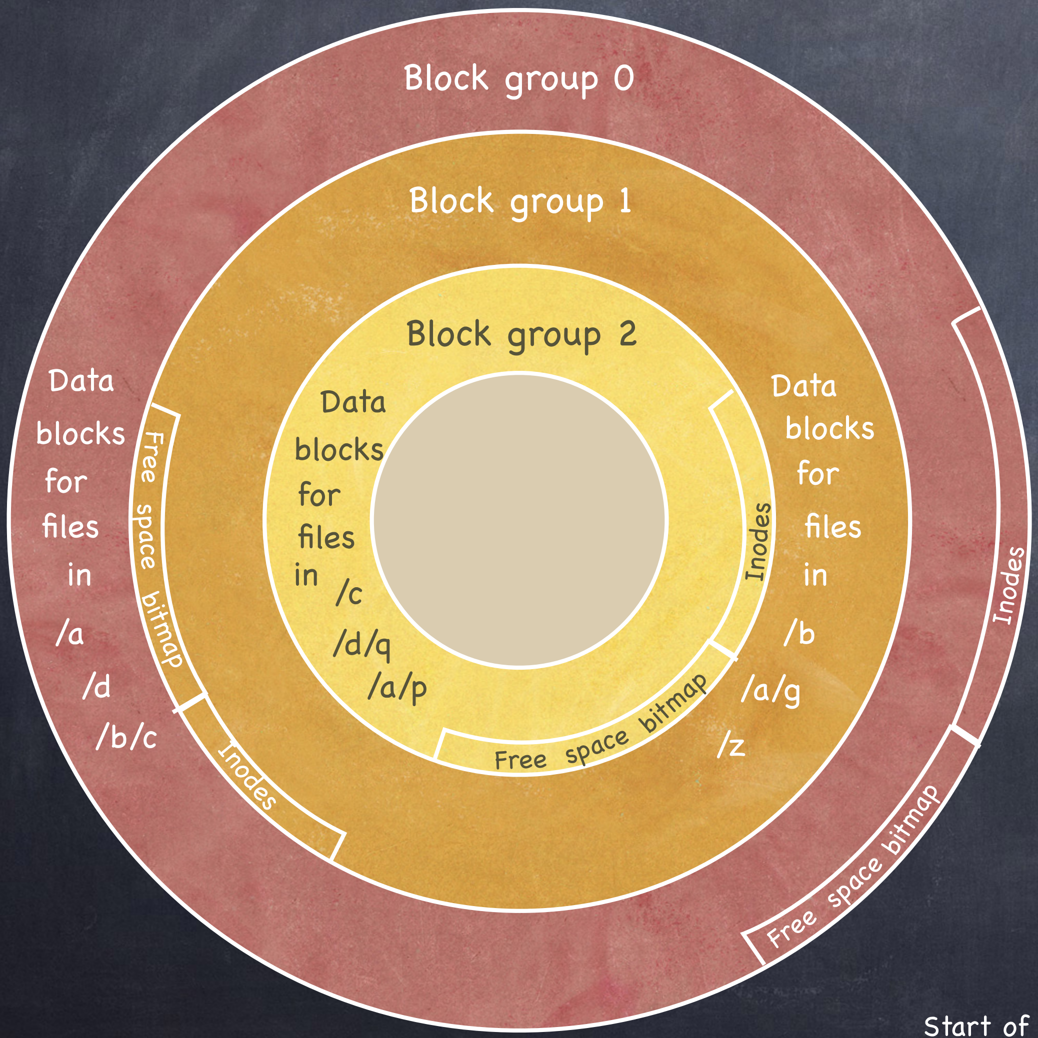
Locality heuristics: block group placement



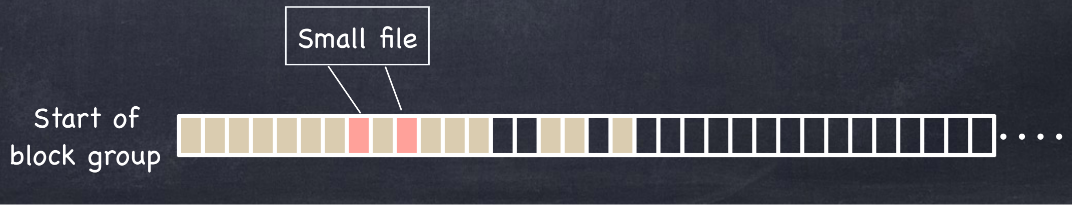
- Divide disk in block groups
  - sets of nearby tracks
- Distribute metadata
  - old design: free space bitmap and inode map in a single contiguous region
    - lots of seeks when going from reading metadata to reading data
  - FFS: distribute free space bitmap and inode array among block groups
- Place file in block group
  - when a new file is created, FFS looks for inodes in the same block as the file’s directory
  - when a new directory is created, FFS palces it in a different block from the parent’s directory
- Place data blocks
  - first free heuristics
  - trade short term for long term locality



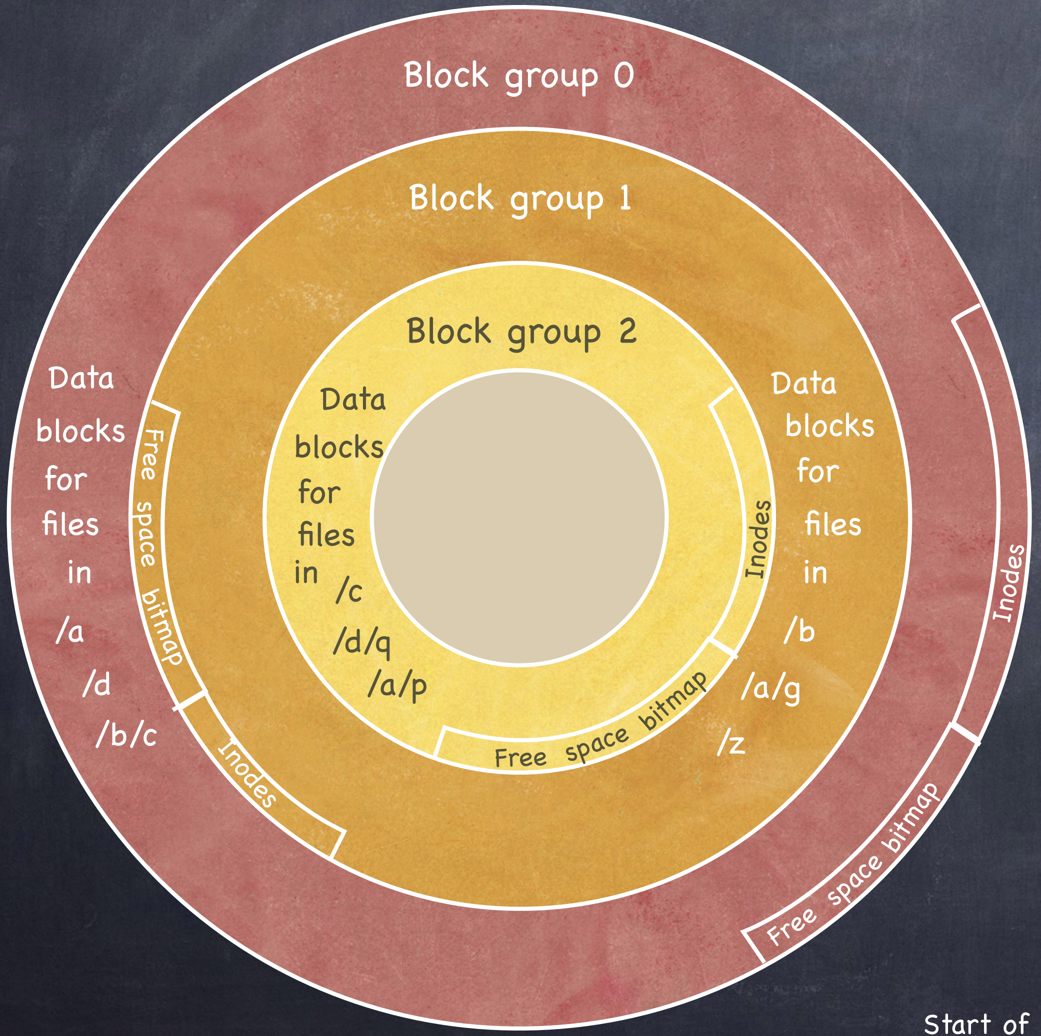
Locality heuristics: block group placement



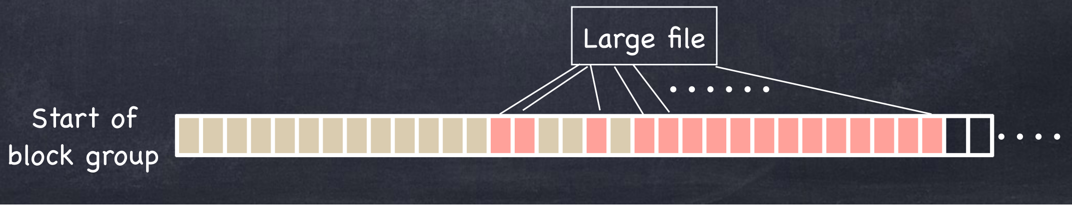
- Divide disk in block groups
  - sets of nearby tracks
- Distribute metadata
  - old design: free space bitmap and inode map in a single contiguous region
    - lots of seeks when going from reading metadata to reading data
  - FFS: distribute free space bitmap and inode array among block groups
- Place file in block group
  - when a new file is created, FFS looks for inodes in the same block as the file's directory
  - when a new directory is created, FFS palces it in a different block from the parent's directory
- Place data blocks
  - first free heuristics
  - trade short term for long term locality



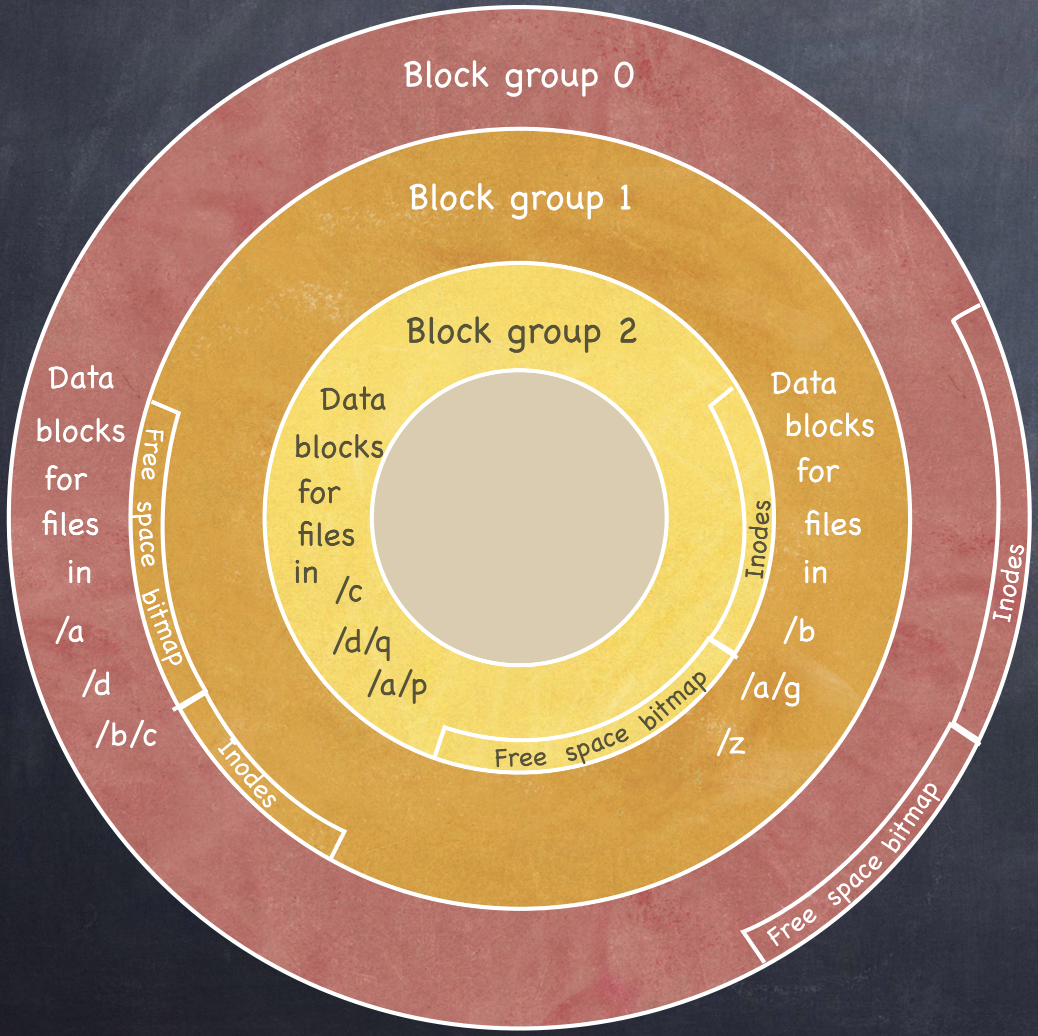
Locality heuristics: block group placement



- Divide disk in block groups
    - sets of nearby tracks
- Distribute metadata
    - old design: free space bitmap and inode map in a single contiguous region
        - lots of seeks when going from reading metadata to reading data
    - FFS: distribute free space bitmap and inode array among block groups
- Place file in block group
    - when a new file is created, FFS looks for inodes in the same block as the file's directory
    - when a new directory is created, FFS palces it in a different block from the parent's directory
- Place data blocks
    - first free heuristics
    - trade short term for long term locality



Locality heuristics: reserved space



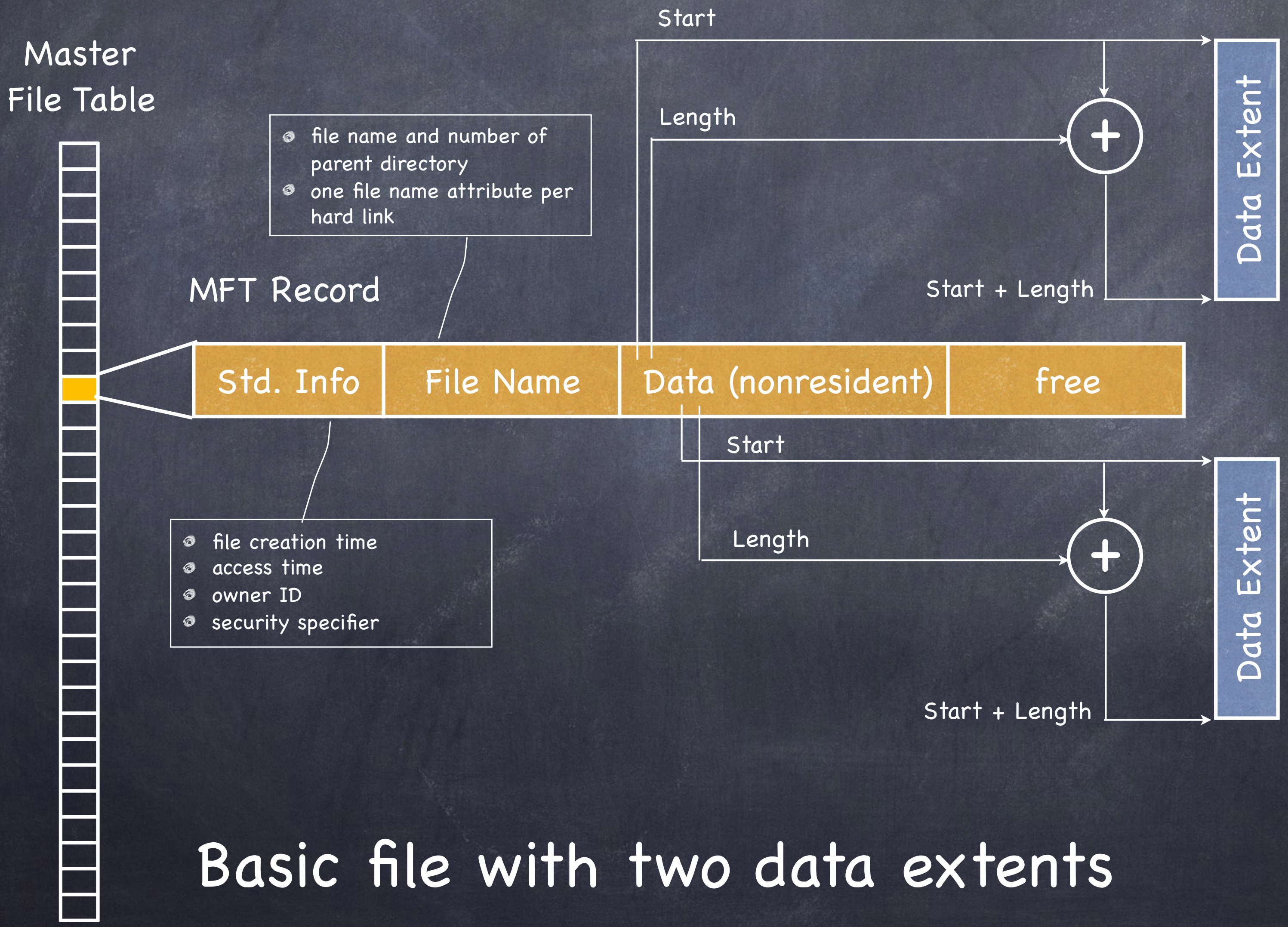
- When a disk is full, hard to optimize locality
  - ☐ file may end up scattered through disk
- FFS presents applications with a smaller disk
  - ☐ about 10% smaller
  - ☐ user write that encroaches on reserved space fails
  - ☐ super user still able to allocate inodes to clean things up

NTFS: flexible tree with extents

Microsoft, 93s

- Index structure: extents and flexible tree
  - extents
    - track ranges of contiguous blocks rather than single blocks
  - flexible tree
    - file represented by variable depth tree
      - large file with few extents can be stored in a shallow tree
  - MFT (Master File Table)
    - array of 1 KB records holding the trees' roots
    - similar to inode table (but 1 file can have multiple MFT entries)
    - each record stores sequence of variable-sized attribute records
      - both data and metadata are attributes
      - attributes can be resident (fits in the record) or nonresident

Example of NTFS index structure

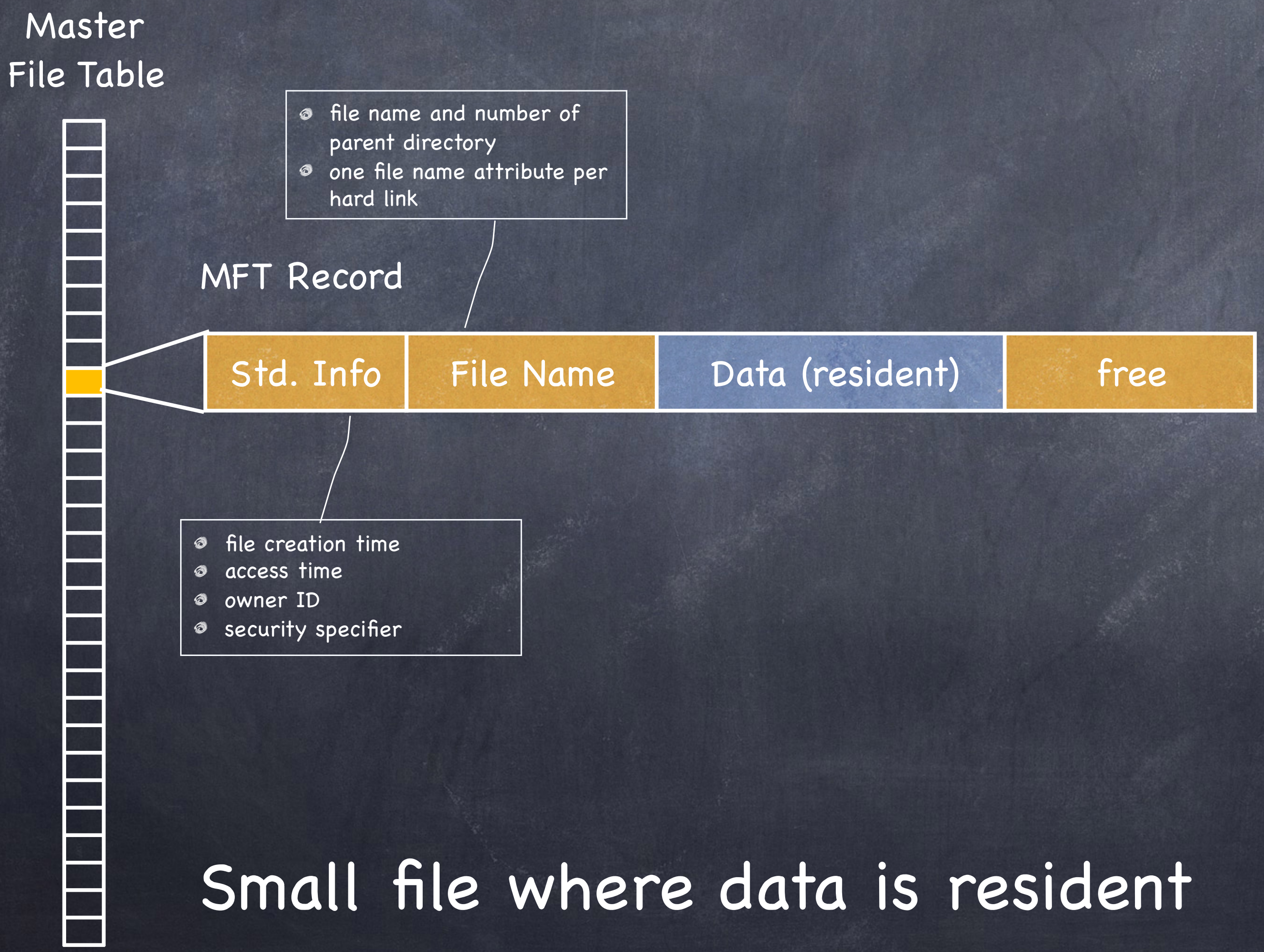


- file name and number of parent directory
- one file name attribute per hard link

- file creation time
- access time
- owner ID
- security specifier

Basic file with two data extents

Example of NTFS index structure



Master File Table

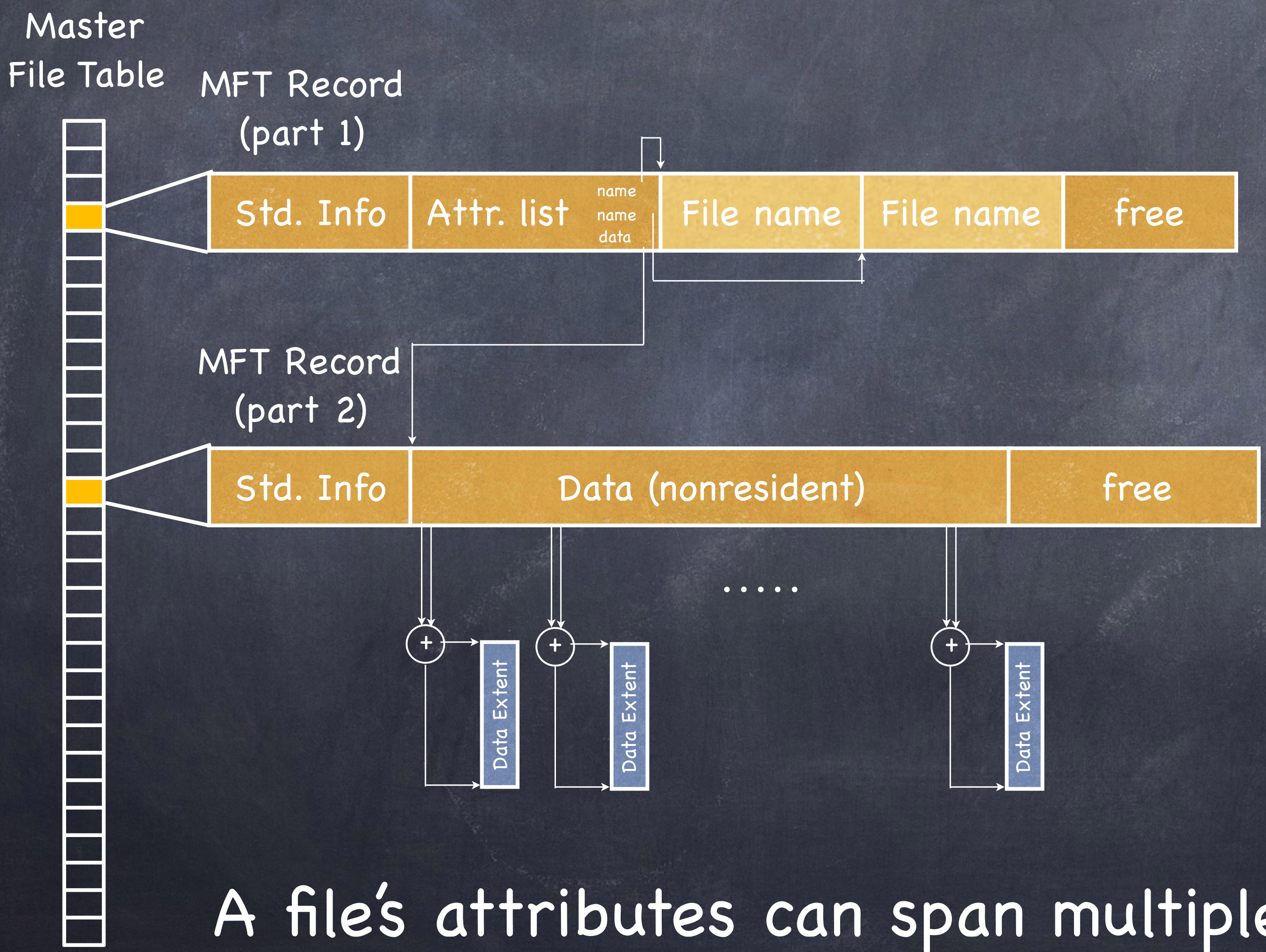
- file name and number of parent directory
- one file name attribute per hard link

MFT Record

- file creation time
- access time
- owner ID
- security specifier

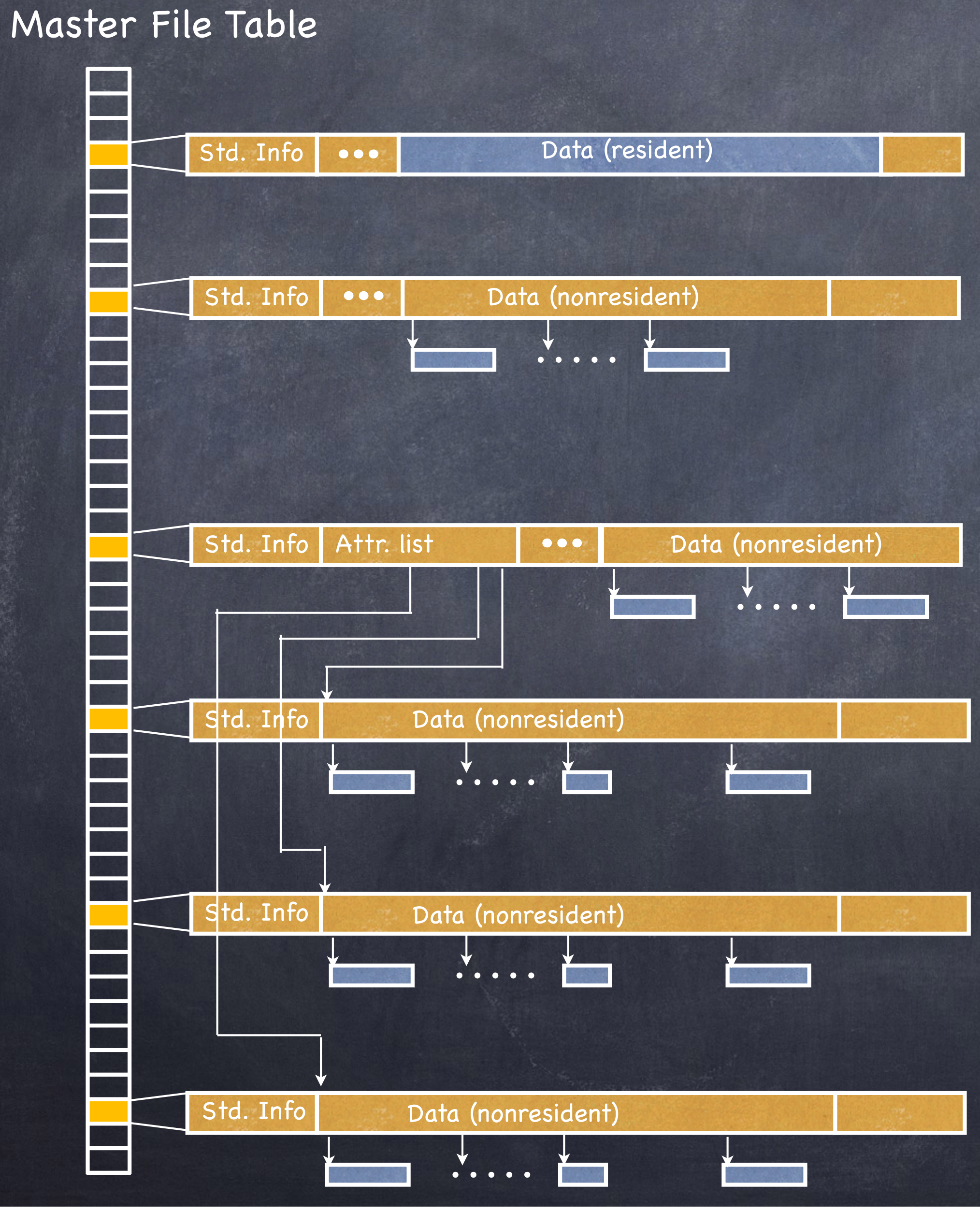
Small file where data is resident

Example of NTFS index structure



A file's attributes can span multiple records

Small, normal, and big files



...and for really huge (or really badly fragmented) files, even the attribute list can become nonresident!

- atribute list split in separate extents

Metadata files

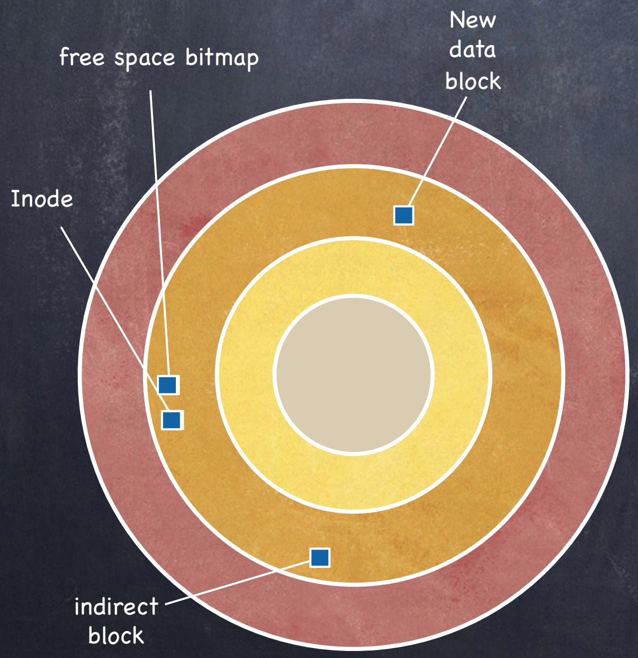
- NTFS stores most metadata in ordinary files with well-known numbers
  - 5 (root directory); 6 (free space bitmap); 8 (list of bad blocks)
- $Secure (file no. 9)
  - stores access control list for every file
  - indexed by fixed-length key
  - files store appropriate key in their MFT record
- $MFT (file no. 0)
  - stores Master File Table
  - to read MFT, need to know first entry of MFT
    - a pointer to it stored in first sector of NTFS
  - MFT can start small and grow dynamically
  - To avoid fragmentation, part of start of volume reserved to MFT expansion
    - when full, halves reserved MFT area

Locality heuristics

- Best fit
  - finds smallest region large enough to fit file
  - NTFS caches allocation status for a small area of disk
    - writes that occur together in time get clustered together
  - `SetEnfOfFile()` lets specify expected length of file at creation

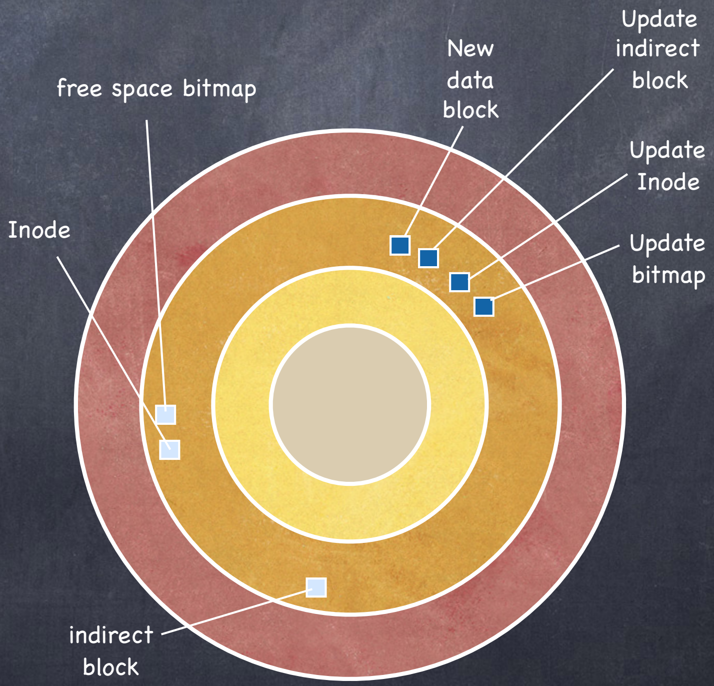
COW File Systems (copy-on-write)

- Data and metadata not updated in place, but written to new location
  - transforms random writes into sequential writes



Traditional

Adding a block to a file

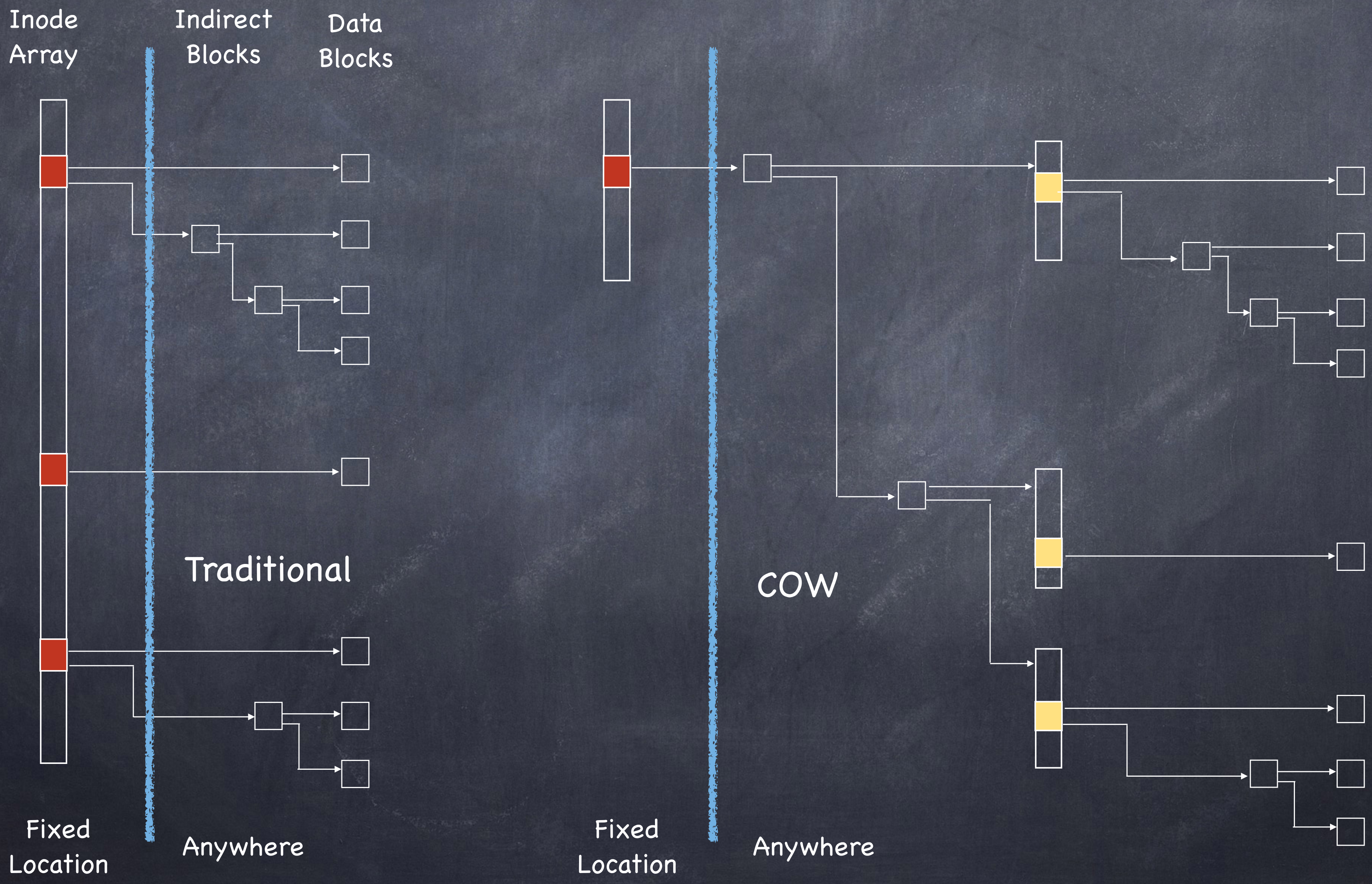


COW

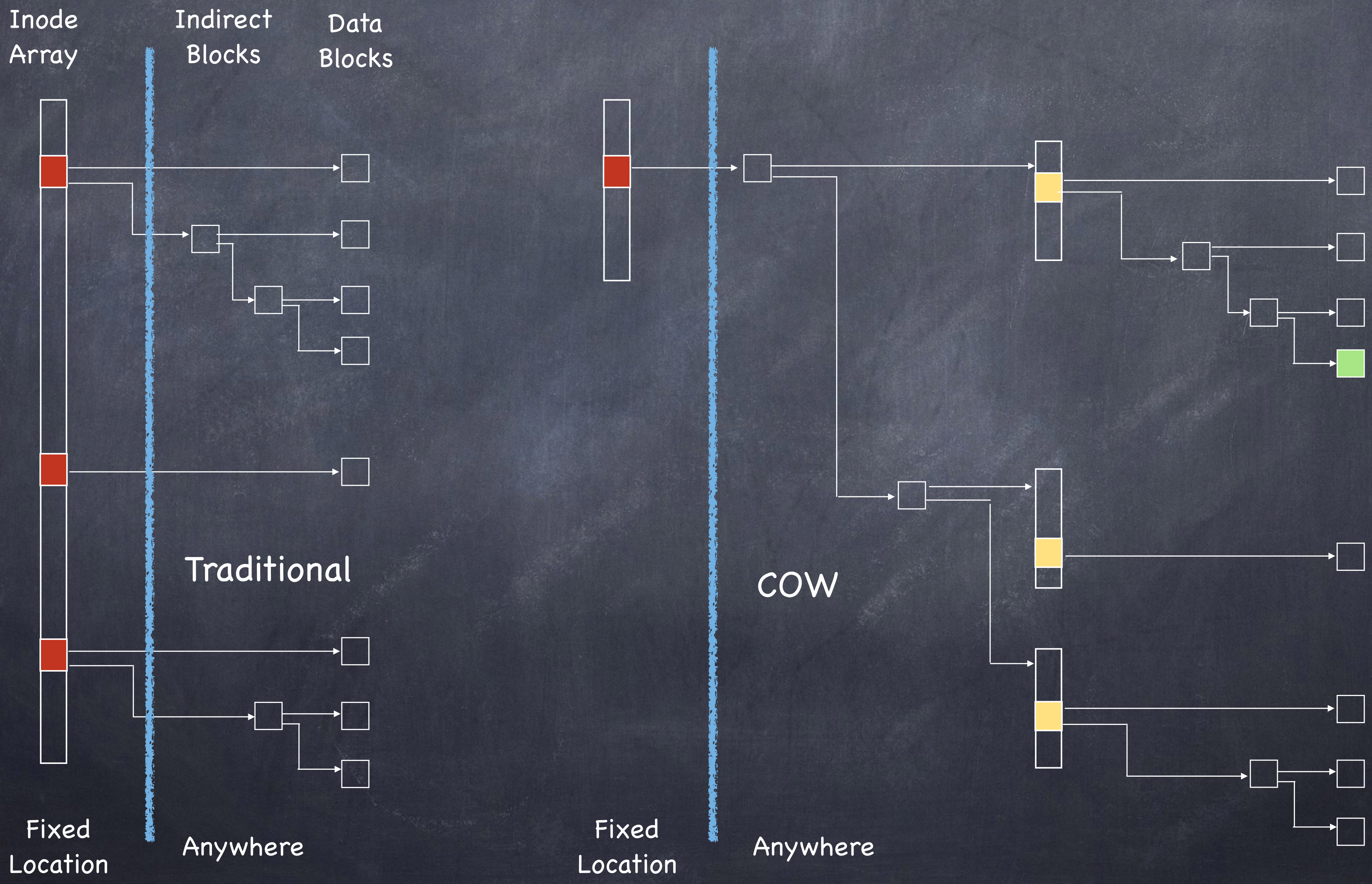
COW File Systems
Why?

- Small writes are expensive
- Small writes are expensive on RAID
  - expensive to update a single block (4 disk I/O) but efficient for entire stripes
- Caches filter reads
- Widespread adoption of flash storage
  - wear leveling, which spreads writes across all cells, important to maximize flash life
  - COW techniques used to virtualize block addresses and redirect writes to cleared erasure blocks
- Large storage capacities enable versioning
  - versioning is easy with COW!

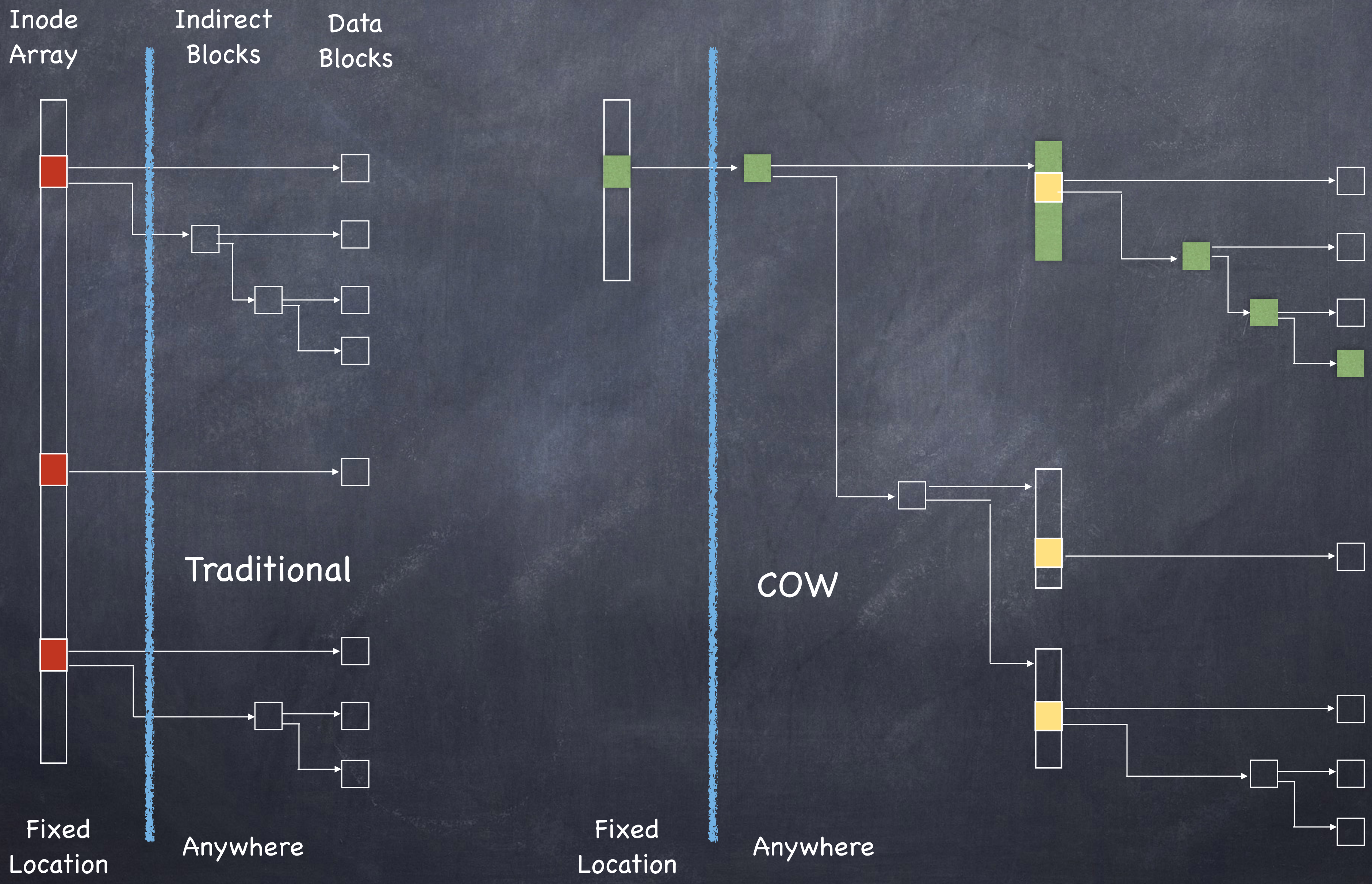
The core idea



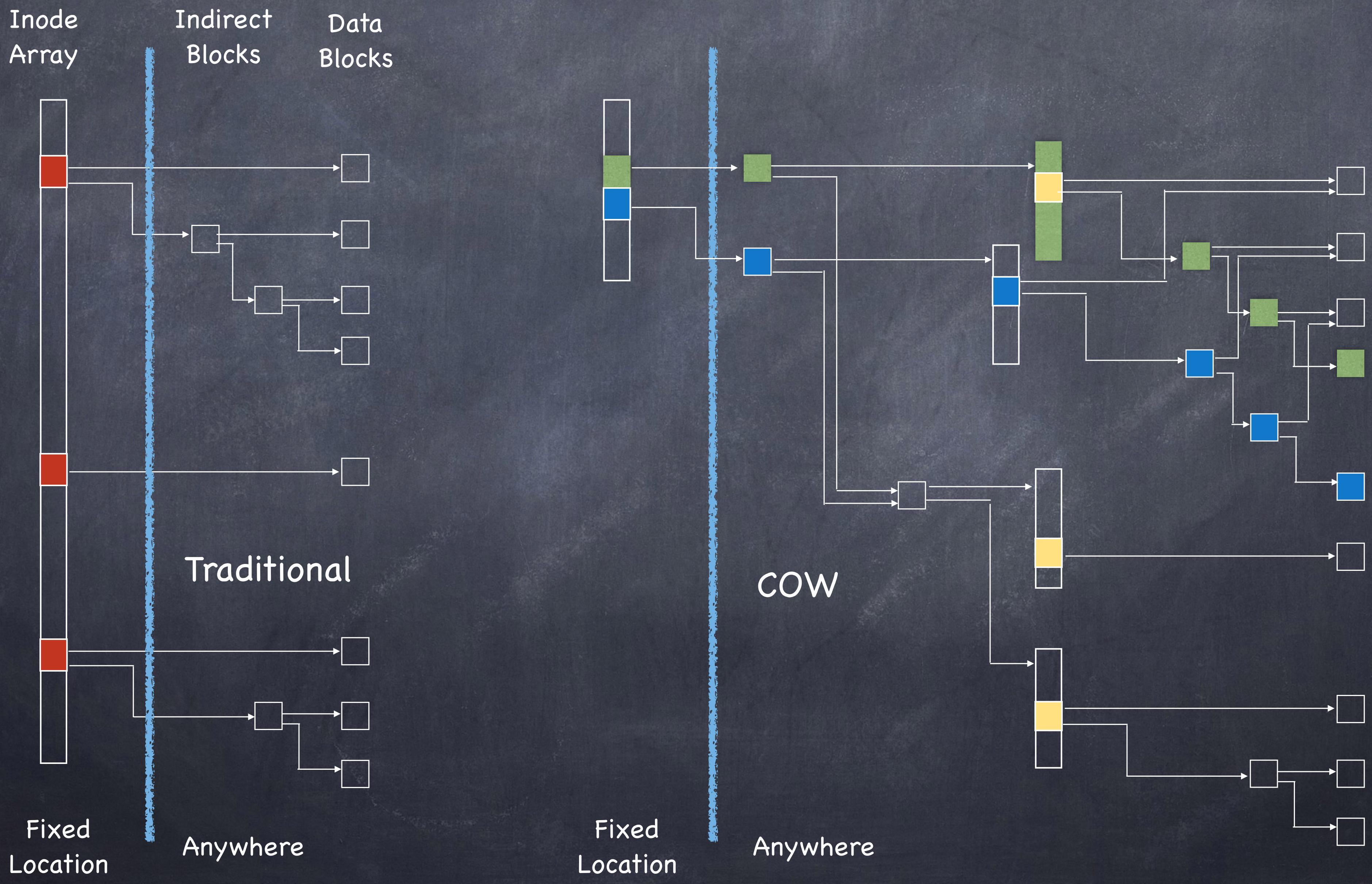
The core idea



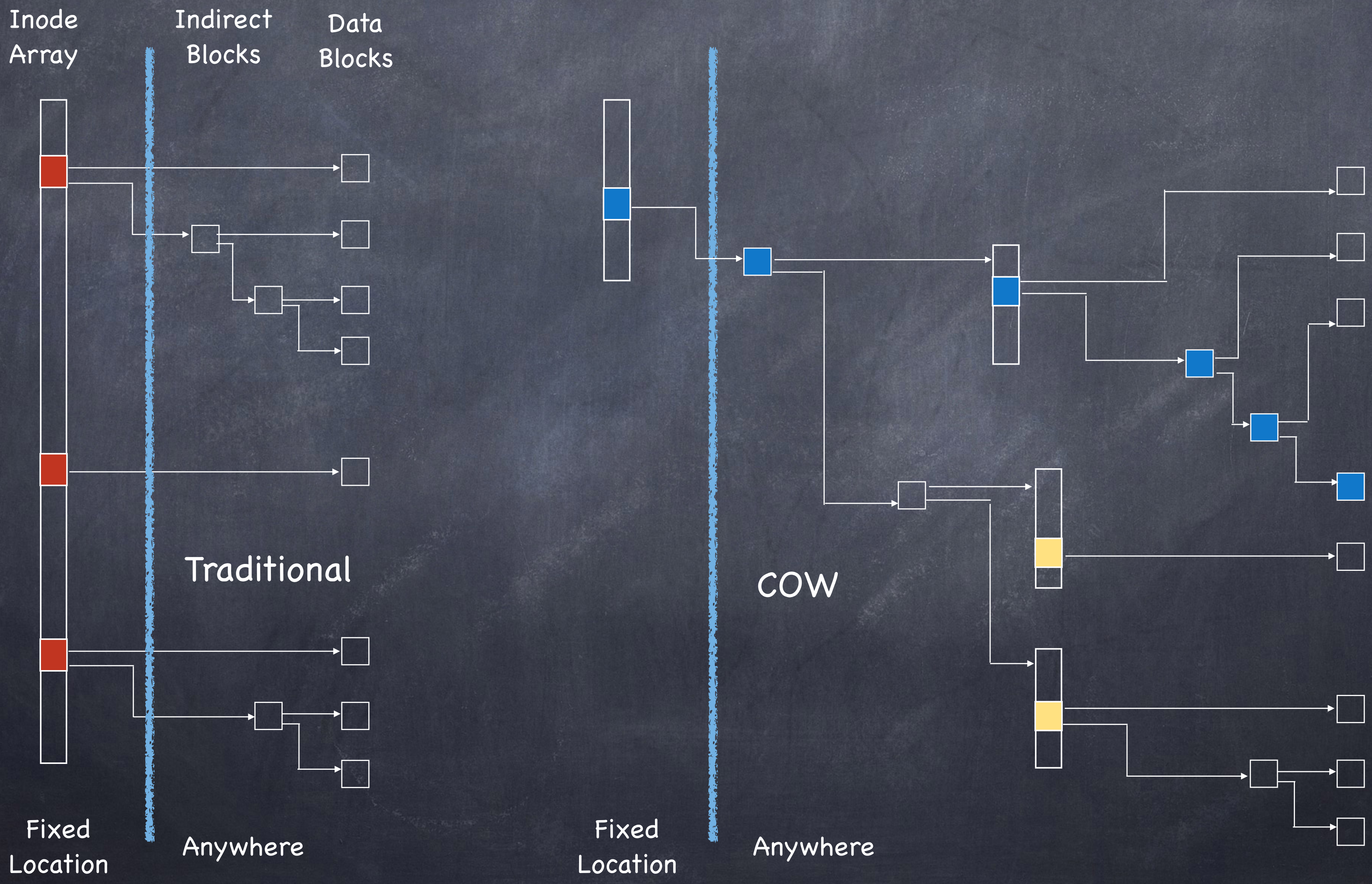
The core idea



The core idea



The core idea



File access in FFS

- What it takes to read /Users/lorenzo/wisdom.txt
    - Read Inode for "/" (root) from a fixed location
    - Read first data block for root
    - Read Inode for /Users
    - Read first data block of /Users
    - Read Inode for /Users/lorenzo
    - Read first data block for /Users/lorenzo
    - Read Inode for /Users/lorenzo/wisdom.txt
    - Read data blocks for /Users/lorenzo/wisdom.txt

"A cache is a man's best friend"

Caching and consistency

- File systems maintain many data structures
  - bitmap of free blocks
  - bitmap of inodes
  - directories
  - inodes
  - data blocks
- Data structures cached for performance
  - works great for read operations...
  - ...but what about writes?
- Solutions:
  - write-back caches: delay writes for higher performance at the cost of potential inconsistencies
  - write through caches: write synchronously but poor performance
    - do we get consistency at least?

Example: a tiny ext2

- 6 blocks, 6 inodes

inode bitmap

0	1	0	0	0	0

data bitmap

0	0	0	0	1	0

i-nodes

-- Iv1 -- -- -- --

data blocks

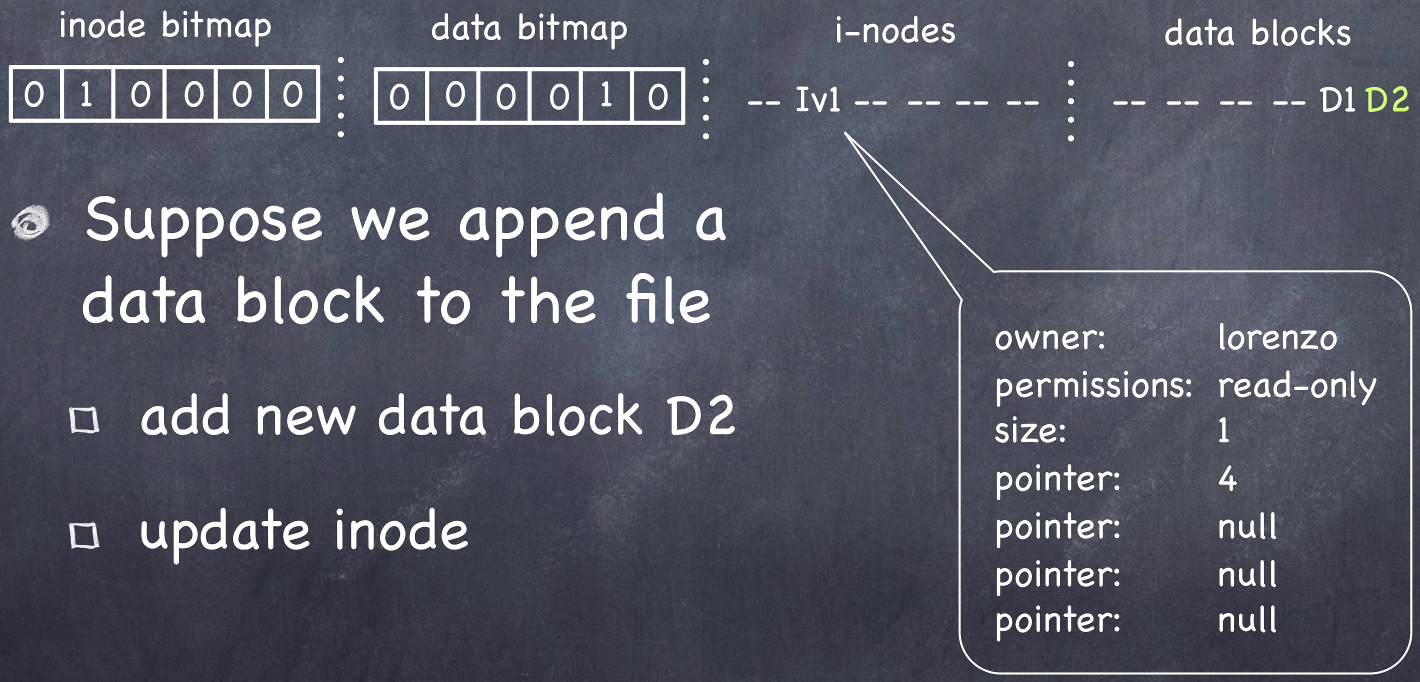
-- -- -- -- D1 --

- Suppose we append a data block to the file
  - add new data block D2

owner:	lorenzo
permissions:	read-only
size:	1
pointer:	4
pointer:	null
pointer:	null
pointer:	null

Example: a tiny ext2

- 6 blocks, 6 inodes



owner: lorenzo
permissions: read-only
size: 1
pointer: 4
pointer: null
pointer: null
pointer: null

- Suppose we append a data block to the file
    - add new data block D2
    - update inode

Example: a tiny ext2

- 6 blocks, 6 inodes

inode bitmap

0	1	0	0	0	0

data bitmap

0	0	0	0	1	0

i-nodes

-- Iv2 -- -- -- --

data blocks

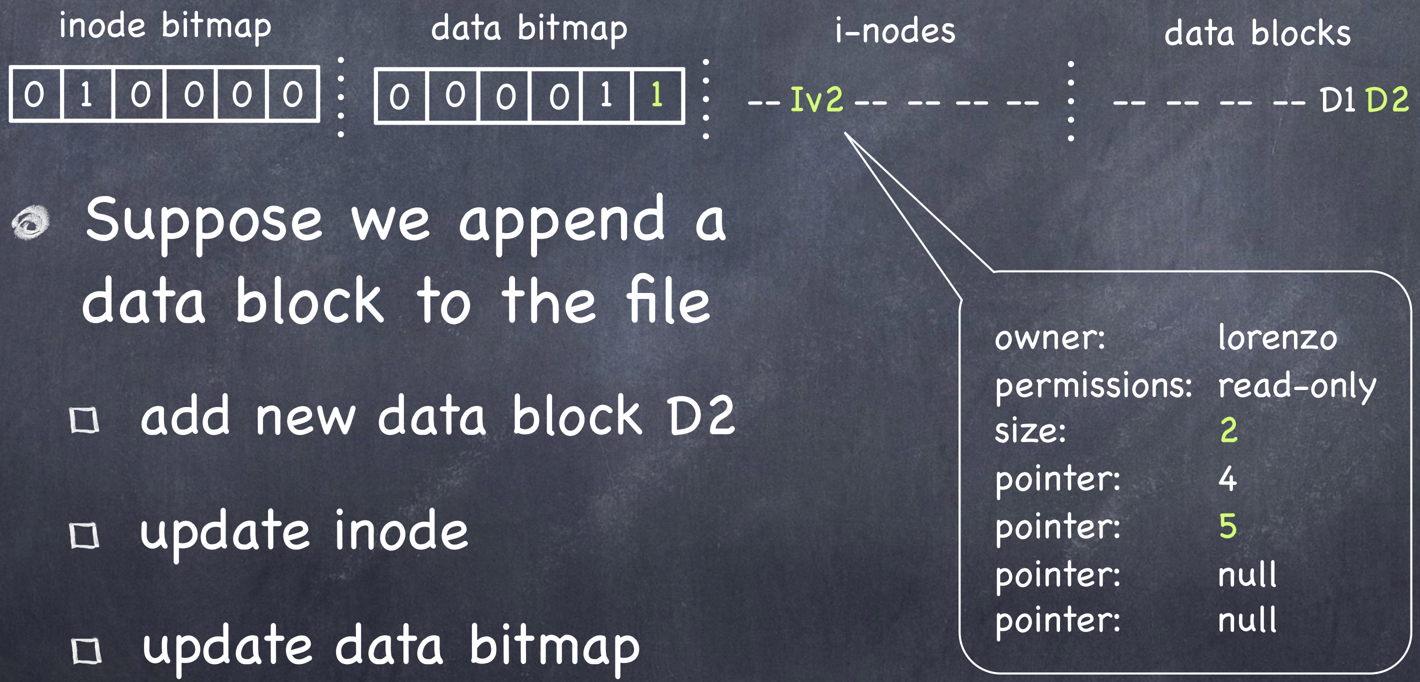
-- -- -- -- D1 D2

- Suppose we append a data block to the file
  - ☐ add new data block D2
  - ☐ update inode
  - ☐ update data bitmap

owner:	lorenzo
permissions:	read-only
size:	2
pointer:	4
pointer:	5
pointer:	null
pointer:	null

Example: a tiny ext2

- 6 blocks, 6 inodes



inode bitmap

0	1	0	0	0	0

data bitmap

0	0	0	0	1	1

i-nodes

-- Iv2 -- -- -- --

data blocks

-- -- -- -- D1 D2

owner:	lorenzo
permissions:	read-only
size:	2
pointer:	4
pointer:	5
pointer:	null
pointer:	null

- Suppose we append a data block to the file
  - add new data block D2
  - update inode
  - update data bitmap

What if a crash or power outage occurs between writes?

What if only a single write succeeds?

- Just the data block (D2) is written to disk
    - data is written, but no way to get to it - in fact, D2 still appears as a free block
    - as if write never occurred
- Just the updated inode (Iv2) is written to disk
    - if we follow the pointer, we read garbage
    - file system inconsistency: data bitmap says block is free, while inode says it is used. Must be fixed
- Just the updated bitmap is written to disk
    - file system inconsistency: data bitmap says data block is used, but no inode points to it.
    - No idea which file the data block was to belong to!

What if two writes succeed?

- Inode and data bitmap updates succeed
  - file system is consistent
  - but reading new block returns garbage
- Inode and data block updates succeed
  - file system inconsistency. Must be fixed
- Data bitmap and data block succeed
  - file system inconsistency
  - no idea to which file data block should belong to!

The Consistent Update problem

- Several file systems operations update multiple data structures
  - Move a file between directories
    - delete file from old directory
    - add file to new directory
  - Create new file
    - update inode bitmap and data bitmap
    - write new inode
    - add new file to directory file
- Even with write through we have a problem!

Ad hoc solutions: metadata consistency

- Synchronous write through for metadata
- Updates performed in a specific order
  - File create
    - write data block
    - update inode
    - update inode bitmap
    - update data bitmap
    - update directory
    - if directory grew: 1) update data bitmap; 2) update directory inode
- On file crash
  - fsck
    - scans entire disk for inconsistencies, starting with superblock
    - scans inodes, indirect blocks, double indirect, etc tu understand which blocks are allocated
    - uses scan results to update bitmaps
    - file created but not in any directory: delete file
- Issues
  - need to get ad-hoc reasoning exactly right
  - synchronous writes lead to poor performance
  - recovery is sloooow: must scan entire disk

Ad hoc solutions: user data consistency

- Asynchronous write back
  - forced after a fixed interval (e.g. 30 sec)
  - can lose up to 30 sec of work
- Rely on metadata consistency
  - updating a file in vi
    - delete old file
    - write new file

Ad hoc solutions: user data consistency

- Asynchronous write back
    - forced after a fixed interval (e.g. 30 sec)
    - can lose up to 30 sec of work
- Rely on metadata consistency
    - updating a file in vi
        - write new version to temp
        - move old version to other temp
        - move new version to real file
        - unlink old version
            - if crash, look in temp area and send “there may be a problem” email to user

Ad hoc solutions: implementation tricks

- Block I/O Barriers
  - allow a block device user to enforce ordering among I/O issued to that block device
  - client need not block waiting for write to complete
  - instead, OS builds a dependency graph
    - no write goes to disk unless all writes it depends on have

A principled approach: Transactions

- Group together actions so that they are
  - Atomic: either all happen or none
  - Consistent: maintain invariants
  - Isolated: serializable (schedule in which transactions occur is equivalent to transactions executing sequentially
  - Durable: once completed, effects are persistent
- Critical sections are ACI, but not Durable
- Transaction can have two outcomes:
  - Commit: transaction becomes durable
  - Abort: transaction never happened
    - may require appropriate rollback

Journaling (write ahead logging)

- Turns multiple disk updates into a single disk write
    - "write ahead" a short note to a "log", specifying changes about to be made to the FS data structures
    - if a crash occurs while updating the FS data structure, consult log to determine what to do
        - no need to scan entire disk!

Data Jounaling: an example

- We start with

inode bitmap	data bitmap	i-nodes	data blocks
0 1 0 0 0 0	0 0 0 0 1 0	-- Iv1 -- -- -- --	-- -- -- -- D1 --

- We want to add a new block to the file
- Three easy steps
  - Write to the log 5 blocks: TxBegin | Iv2 | B2 | D2 | TxEnd
    - write each record to a block, so it is atomic
  - Write the blocks for Iv2, B2, D2 to the FS proper
  - Mark the transaction free in the journal
- What happens if we crash before the log is updated?
  - no commit, nothing to disk - ignore changes!
- What happens if we crash after the log is updated?
  - replay changes in log back to disk

Journaling and Write Order

- Issuing the 5 writes to the log TxBegin | Iv2 | B2 | D2 | TxEnd sequentially is slow
- Issue at once, and transform in a single sequential write
- Problem: disk can schedule writes out of order
  - first write TxBegin, Iv2, B2, TxEnd

Disk loses power →

  - then write D2
- Log contains: TxBegin | Iv2 | B2 | ?? | TxEnd
  - syntactically, transaction log looks fine, even with nonsense in place of D2!
- Set a Barrier before TxEnd
  - TxEnd must block until data on disk

What about performance?

- All data is written twice… surely it is horrible?
- 100 1KB random writes vs. log + write-back
    - Direct write: 100 x T_{rw} ≈ 100 x 10ms ≈ 1s
    - Pessimistic log
        - $100 \times T_{sw} + 100 \times T_{rw} \approx 100/(50 \times 10^3) + 1s = 2ms + 1s$
    - Realistic (write-back performed in the background)
        - more opportunities for disk scheduling
        - 100 random writes may take less time than in direct write case

Back to

The early 90s

- Growing memory sizes
  - file systems can afford large block caches
  - most reads can be satisfied from block cache
  - performance dominated by write performance
- Growing gap in random vs sequential I/O performance
  - transfer bandwidth increases 50%-100% per year
  - seek and rotational delay decrease by 5%-10% per year
  - using disks sequentially is a big win
- Existing file system perform poorly on many workloads
  - 6 writes to create a new file of 1 block
    - new inode | inode bitmap | directory data block that includes file | directory inode (if necessary) | new data block storing content of new file | data bitmap
  - lots of short seeks

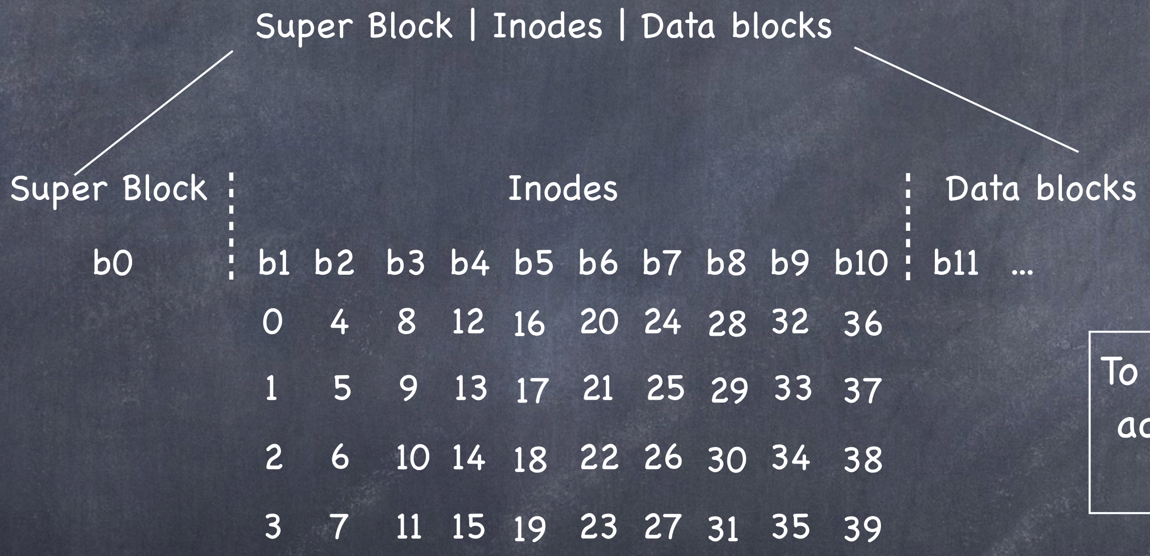
Log structured file systems

- Use disk as a log
  - buffer all updates (including metadata!) into a segment
  - when segment is full, write to disk in a long sequential transfer to unused part of disk
- Virtually no seeks
  - much improved disk throughput
- But how does it work?
  - suppose we want to add a new block to a 0-sized file
  - LFS paces both data block and inode in its in-memory segment

Fine.
But how do we find the inode?

Finding inodes

- in UFS, just index into inode array



Super Block | Inodes | Data blocks

Super Block	Inodes									Data blocks	
b0	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11 …
	0	4	8	12	16	20	24	28	32	36	
	1	5	9	13	17	21	25	29	33	37	
	2	6	10	14	18	22	26	30	34	38	
	3	7	11	15	19	23	27	31	35	39	

512 bytes/block
128 bytes/inode

To find address inode 11:
addr(b1)+ #inode x
size(inode)

- Same in FFS (but Inodes are at divided (at known locations) between block groups

Finding inodes in LFS

- inode map: a table indicating where each inode is on disk
  - inode map blocks written as part of the segment
  - … so need not seek to write to imap
- but how do we find the inode map?
  - table in a fixed checkpoint region
    - updated periodically (every 30 seconds)
- The disk then looks like


CR

seg1

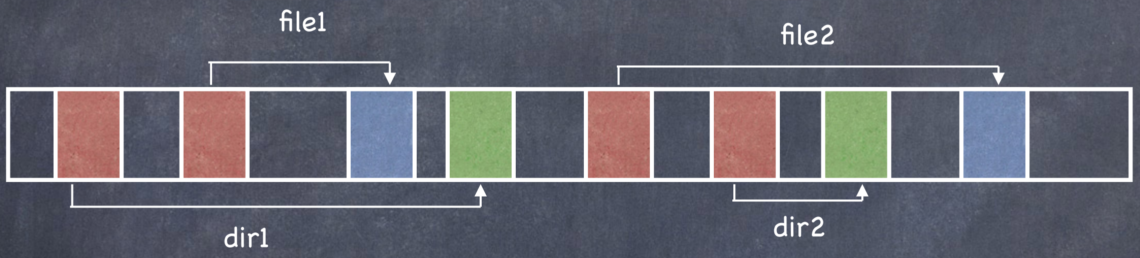
free

seg2

seg3

free

LFS vs UFS

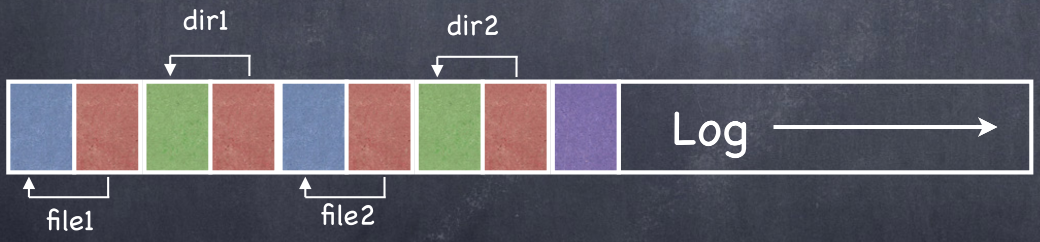

file1

file2

dir1

dir2

Unix File System


dir1

dir2

Log

file1

file2

Log-structured File System

🟥 inode

🟩 directory

🟦 data

🟪 inode map

Blocks written to create two 1-block files: dir1/file1 and dir2/file2 in UFS and LFS

Reading from disk in LFS

- Suppose nothing in memory…
  - read checkpoint region
  - from it, read and cache entire inode map
  - from now on, everything as usual
    - read inode
    - use inode's pointers to get to data blocks
- When the imap is cached, LFS reads involve virtually the same work as reads in traditional file systems

modulo an
imap lookup

Garbage collection

- As old blocks of files are replaced by new, segment in log become fragmented
- Cleaning used to produce contiguous space on which to write
  - compact M fragmented segments into N new segments, newly written to the log
  - free old M segments
- Cleaning mechanism:
  - How can LFS tell which segment blocks are live and which dead?
- Cleaning policy
  - How often should the cleaner run?
  - How should the cleaner pick segments?

Segment summary block

- For each data block, stores
  - the file it belongs (inode#)
  - the offset (block#) within file
- During cleaning
  - allows to determine whether data block D is live
    - use inode# to find in imap where inode is currently on disk
    - read inode (if not already in memory)
    - check whether pointer for block block# refers to D's address
  - allows to update file's inode with correct pointer if D is live and compacted to new segment

Which segments to clean, and when?

- When?
  - periodically
  - when you have nothing better to do
  - when disk is full
- Which segments?
  - utilization: how much it is gained by cleaning
    - segment usage table tracks how much live data in segment
  - age: how likely is the segment to change soon
    - better to wait on cleaning a hot block

Crash recovery

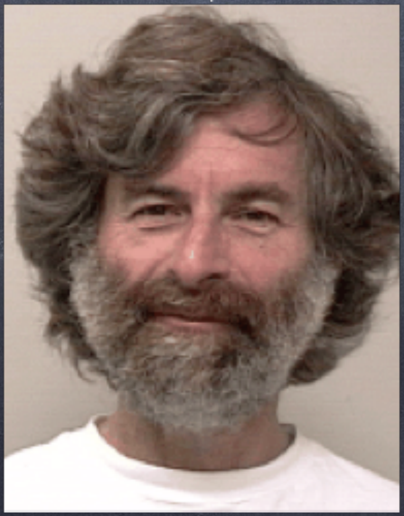
- The journal is the file system!
- On recovery
  - read checkpoint region
    - may be out of date (written periodically)
    - may be corrupted
      - 1) two CR blocks at opposite ends of disk / 2) timestamp blocks before and after CR
      - use CR with latest consistent timestamp blocks
  - roll forward
    - start from where checkpoint says log ends
    - read through next segments to find valid updates not recorded in checkpoint
      - when a new inode is found, update imap
      - when a data block is found that belongs to no inode, ignore

Towards
Distributed Systems

What is a distributed system?

“A distributed system is one in which the failure of a computer you didn’t even know existed can render your own computer unusable.”

Leslie Lamport



The Client/Server paradigm

- Server
  - offers some service (e.g., file server)
  - may exist in more than one node
- Client
  - uses the service
- The basic pattern
  - clients binds (i.e., connects) to the server
  - client sends request (with paramenters) to perform services
  - server returns response

How to communicate?

- Messages
  - very flexible
  - leave programmers to worry about
    - message format
    - how to pack and unpack messages
    - how to decode at the server
    - error handling
- Procedure calls
  - an old friend!
  - server is a module that exports a set of procedures

Remote Procedure Call

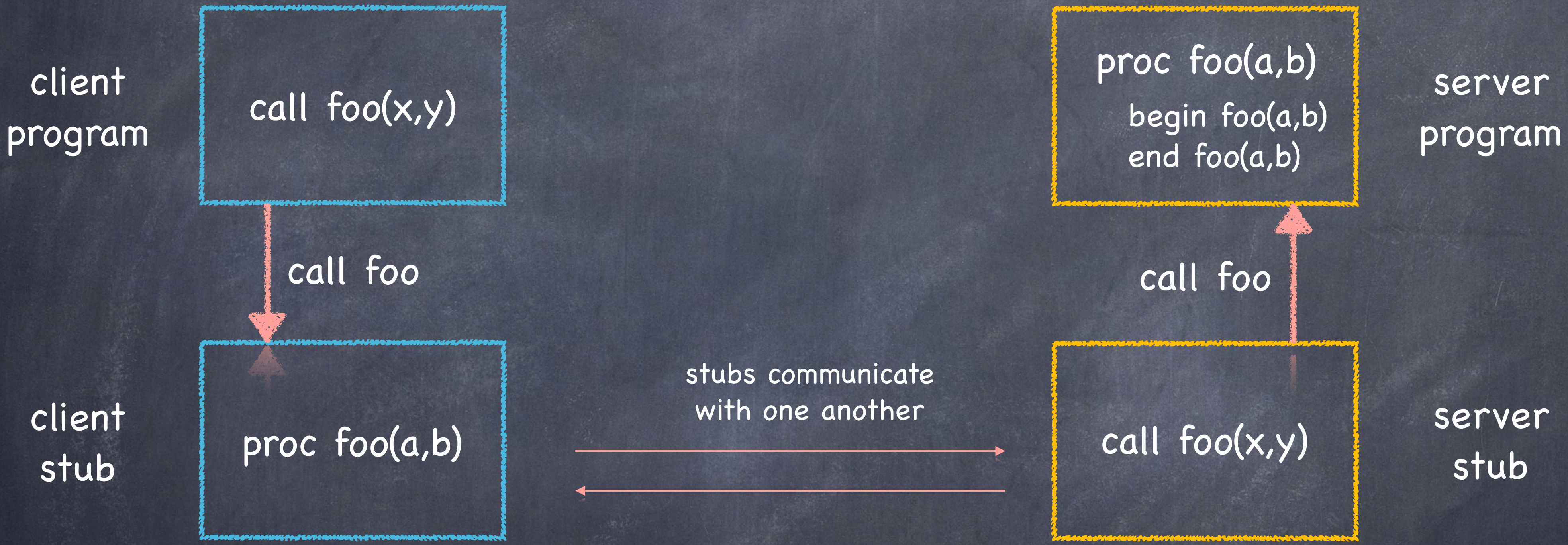
Birrell & Nelson, Xerox PARC, ‘80s

- Procedure calls as basis for distributed communication
- How can we make RPC look like LPC?
  - how can we make it invisible to the programmer?
  - what are the semntics of parameter passing?
  - how do we locate the server (binding)?
  - how do we support heterogeneity (OS, architecture, programming language)?
- Three-part solution
  - user program (client or server)
  - set of stub procedures
  - runtime support

Building a server

- Define server's interface in an interface definition language (IDL)
    - specifies names, paramenters, and types for all server procedures that clients can invoke
- Stubs compiler
    - reads IDL
    - produces a client and a server stub for each server procedure
        - manage all details of remote client-server communication
- Server and client developers link their code to respective stub

RPC Stubs



client program

call foo(x,y)

call foo

client stub

proc foo(a,b)

stubs communicate with one another

proc foo(a,b)

begin foo(a,b)
end foo(a,b)

server program

call foo

call foo(x,y)

server stub

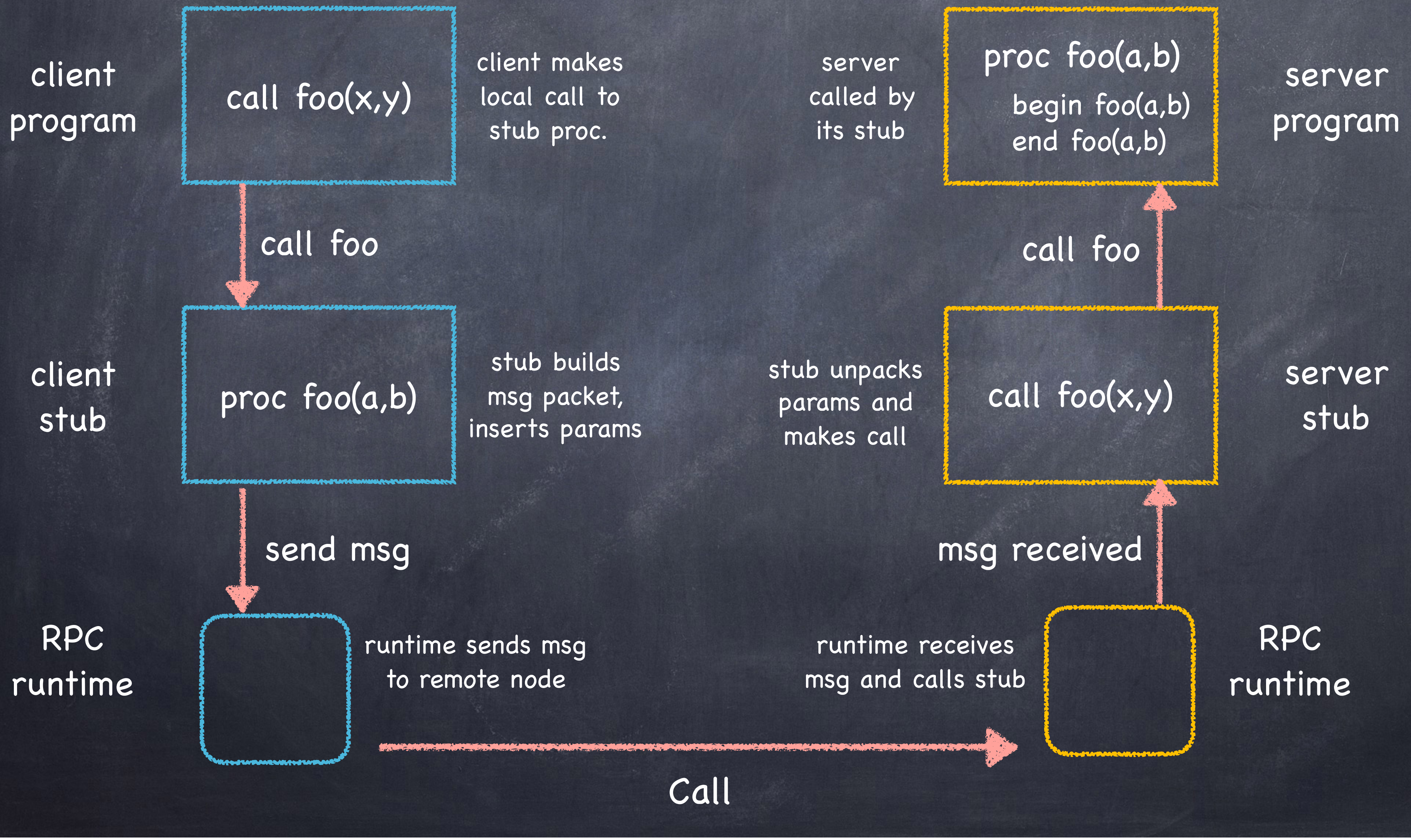
Client-side stub

- Looks to client as callable server procedure
- Client program thinks it is calling the server

Server-side stub

- Server program thinks it is called by client
- foo actually called by server's stub

RPC Stubs



client program

call foo(x,y)

client makes local call to stub proc.

call foo

client stub

proc foo(a,b)

stub builds msg packet, inserts params

send msg

RPC runtime

runtime sends msg to remote node

Call

runtime receives msg and calls stub

RPC runtime

msg received

stub unpacks params and makes call

call foo(x,y)

server stub

call foo

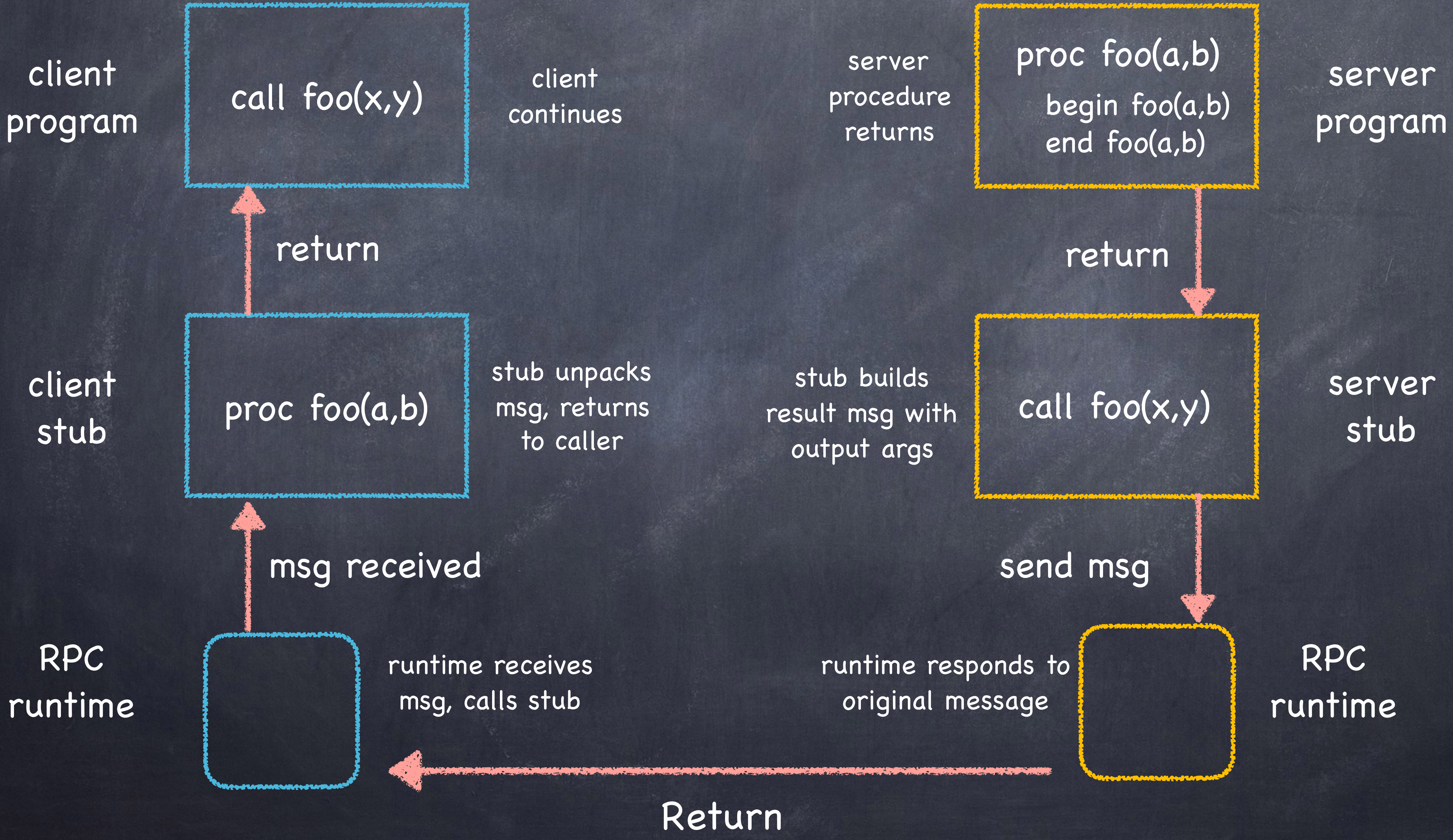
server called by its stub

proc foo(a,b)

begin foo(a,b)
end foo(a,b)

server program

RPC Stubs



client program

call foo(x,y)

client continues

return

client stub

proc foo(a,b)

stub unpacks msg, returns to caller

msg received

RPC runtime

runtime receives msg, calls stub

server procedure returns

proc foo(a,b)

begin foo(a,b)
end foo(a,b)

server program

return

stub builds result msg with output args

call foo(x,y)

server stub

send msg

runtime responds to original message

RPC runtime

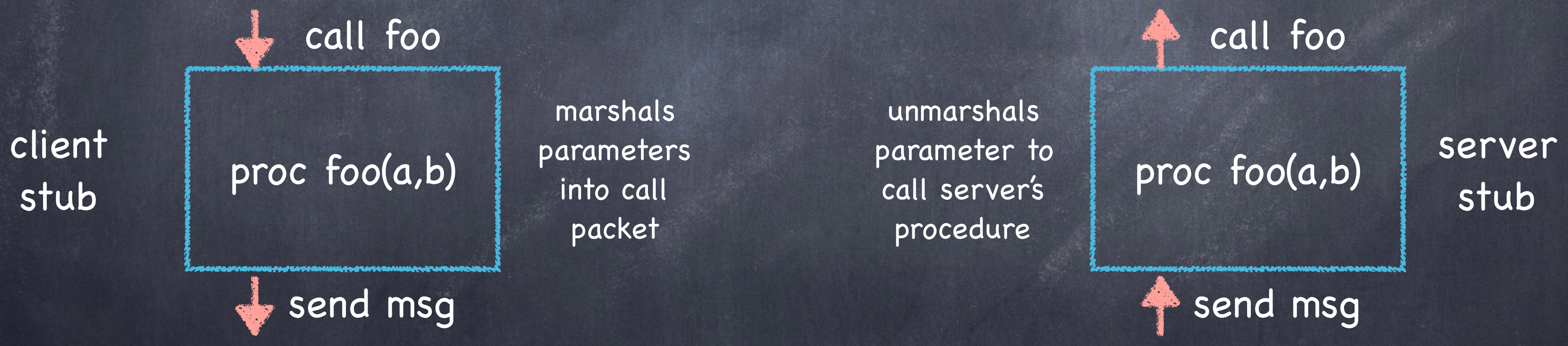
Return

RPC Binding

- Server at startup exports its interface
  - identifies itself to a network name server
  - tells local runtime address of the dispatch routine that will perform requested services
- Client, before issuing calls, imports server
  - RPC runtime looks up service though network name server
  - contacts server to set up a connection
- Import and export are explicit calls in the code

RPC Marshalling

- Packing of procedure parameters in a message packet
  - notion close to pickling (Python), serialization (Java)
- RPC stubs call type-specific procedures to marshal/unmarshal call parameters



client stub

call foo

proc foo(a,b)

send msg

marshals parameters into call packet

unmarshals parameter to call server's procedure

call foo

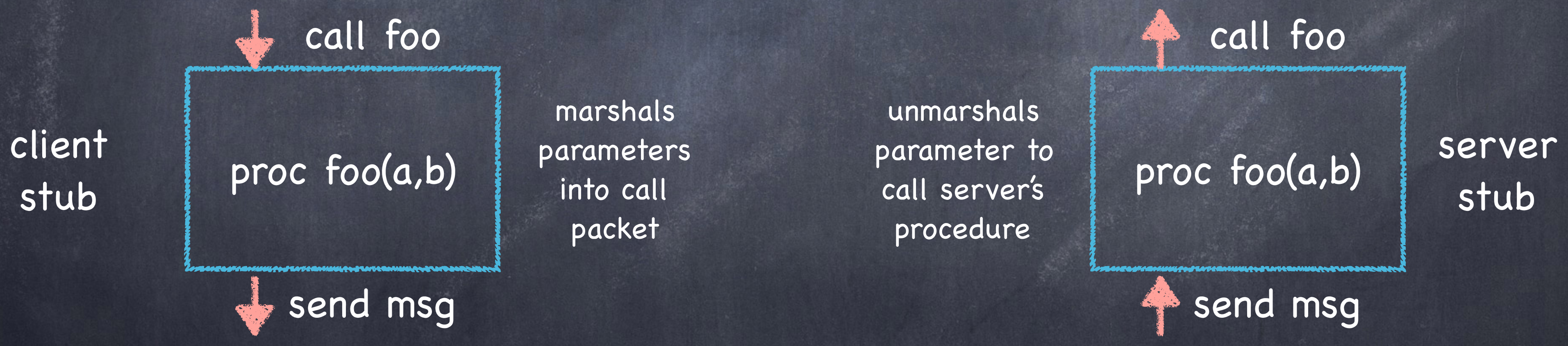
proc foo(a,b)

send msg

server stub

RPC Marshalling

- Packing of procedure parameters in a message packet
    - notion close to pickling (Python), serialization (Java)
- RPC stubs call type-specific procedures to marshal/ unmarshal call parameters



client stub

call foo

proc foo(a,b)

send msg

marshals parameters into call packet

unmarshals parameter to call server's procedure

call foo

proc foo(a,b)

send msg

server stub

- Roles reverse on return
    - server stub,marshals return parameters; client stub unmarshals