TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Informatik Institut für Systemarchitektur, Professur für Betriebssysteme

INFLUENTIAL WORK ON FILE SYSTEMS

CARSTEN WEINHOLD

OUTLINE

Introduction and Terminology

A Fast File System for UNIX

Marshall Kirk McKusick, William N. Joy, Samuel J. Leffer, Robert S. Fabry
ACM Transactions on Computer Systems (TOCS), Vol. 2 Issue 3, Aug. 1984

Soft Updates: A Technique for Eliminating Most Synchronous Writes in the Fast Filesystem

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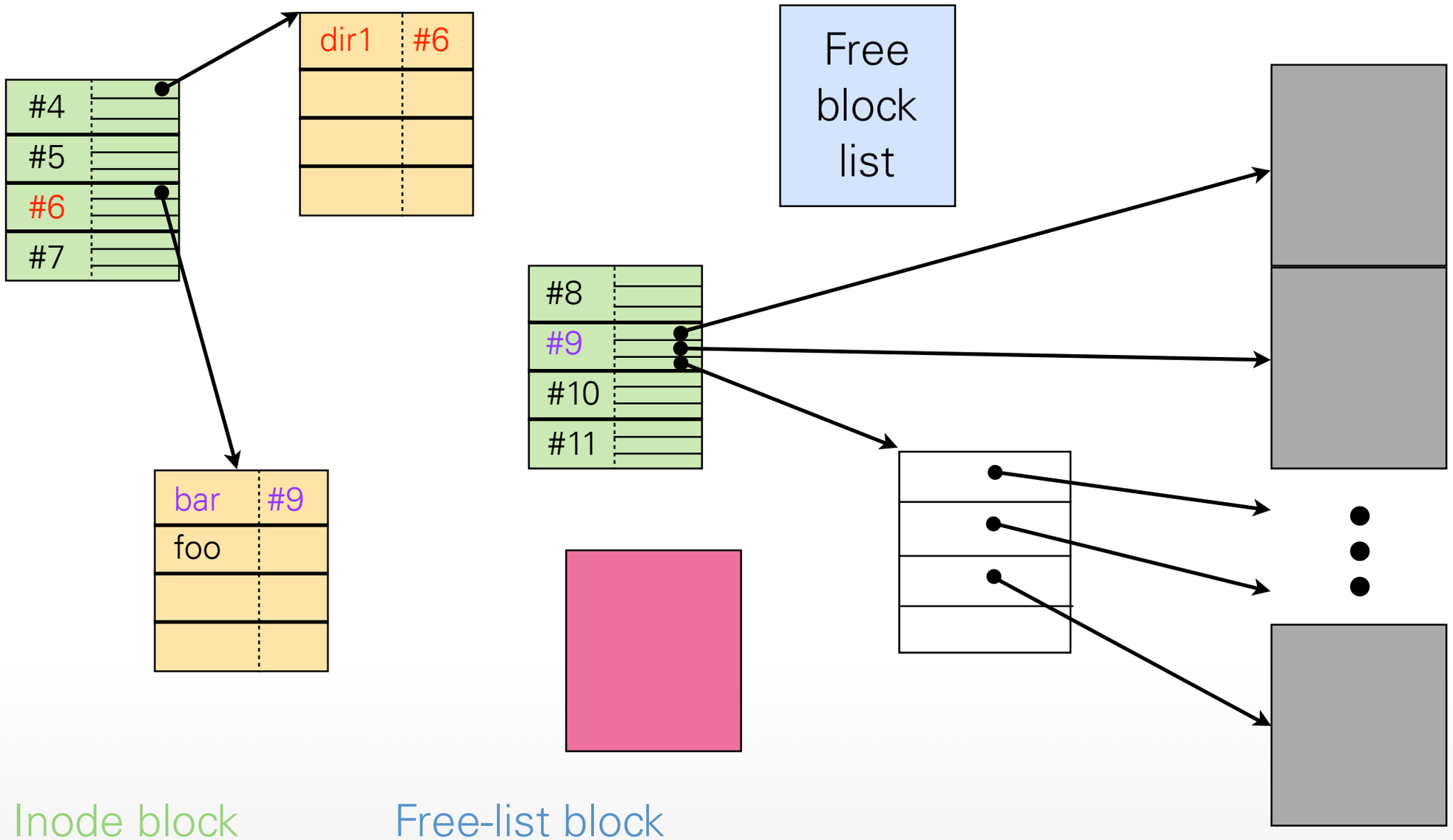
FILE SYSTEMS

- Mapping of high-level objects (files) to storage locations (blocks)
- Mapping encoded in metadata:
  - Hierarchy of directories: directory entries map filenames to inodes
  - Inodes contain file attributes and pointers
  - Pointers specify blocks with file content
  - Status of inodes and blocks: free / in use
  - Metadata is stored in blocks as well

BASIC DATA STRUCTURES

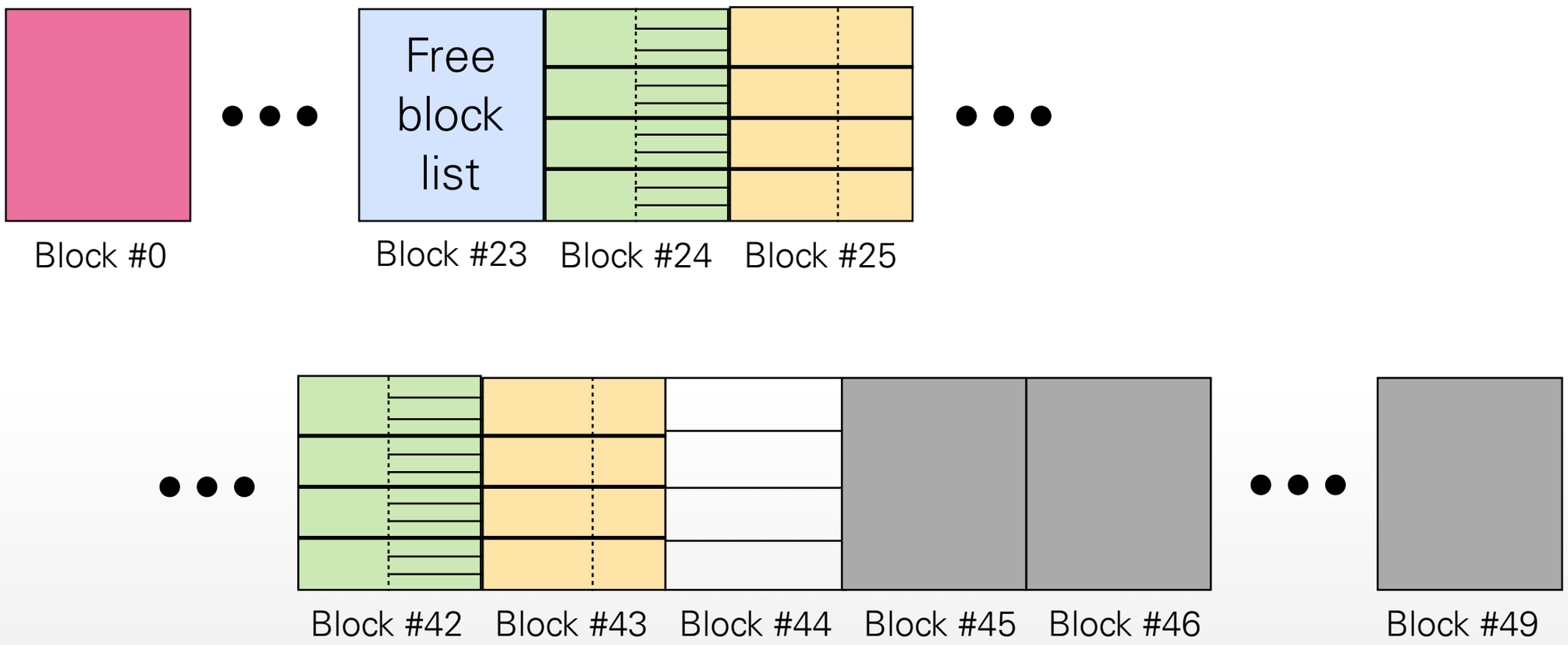


Inode block
Directory block
Indirect block
Free-list block
Data block
Super block

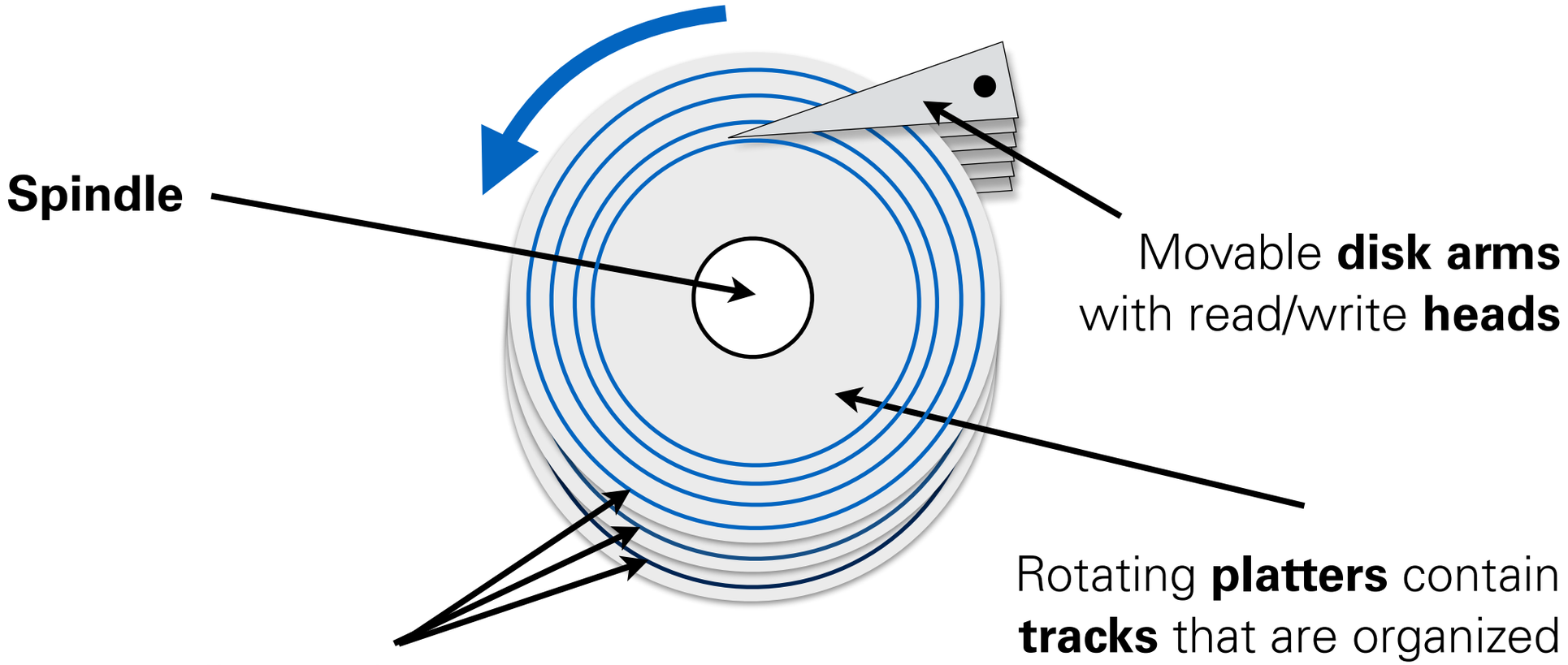
BASIC DATA STRUCTURES

Blocks on disk are adressed by block number

Data transfers of file-system data structures is done in blocks

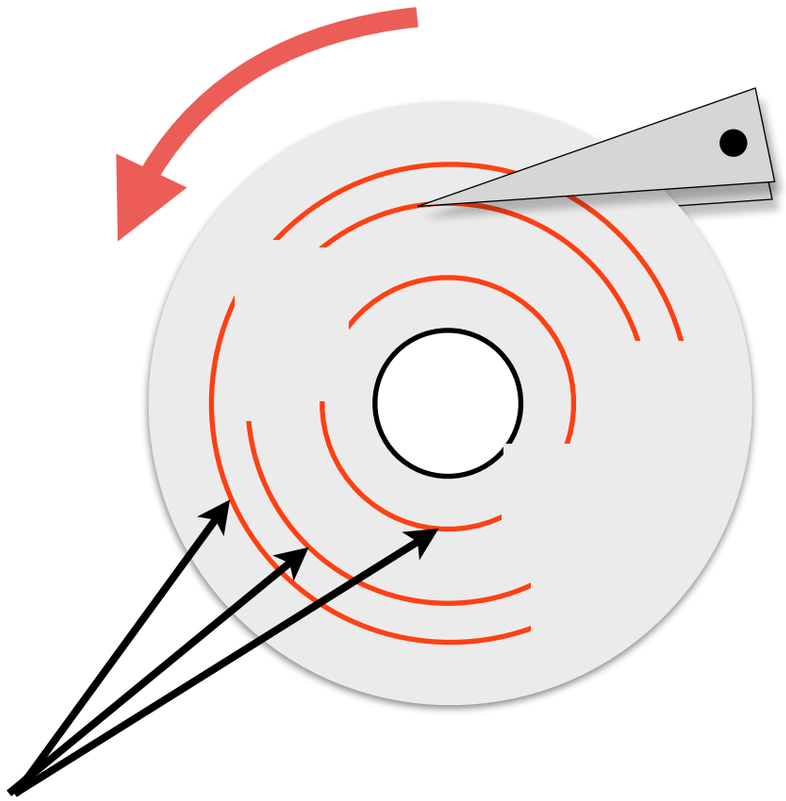


DISK ORGANIZATION



Disk space can also be **partitioned** into consecutive groups of cylinders (each partition can host one file system)

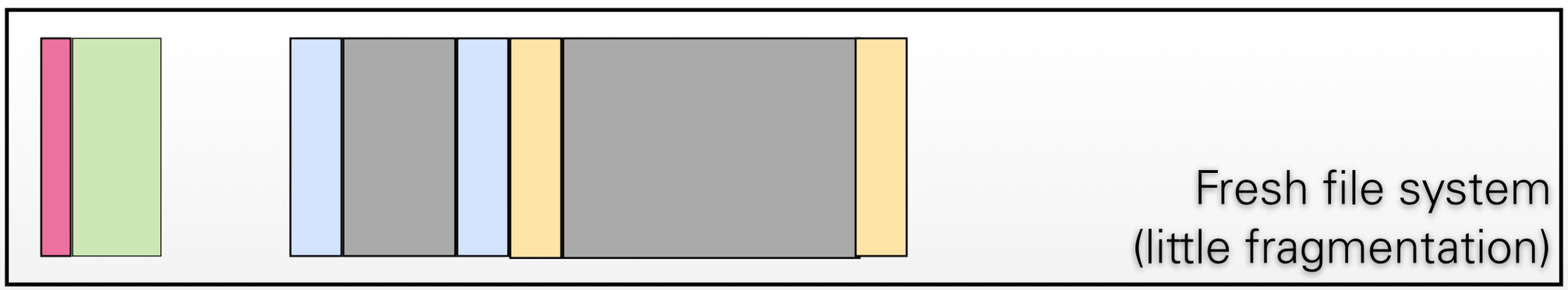
DATA ORGANIZATION



- **Inter-dependent data** and **metadata** often spread across different sectors, tracks, or cylinders
- **Read** and **write operations** can cause **disk-arm movement** to position **heads** over tracks
- **Rotational delay** until requested sectors pass under head

"OLD" UNIX FILE SYSTEM

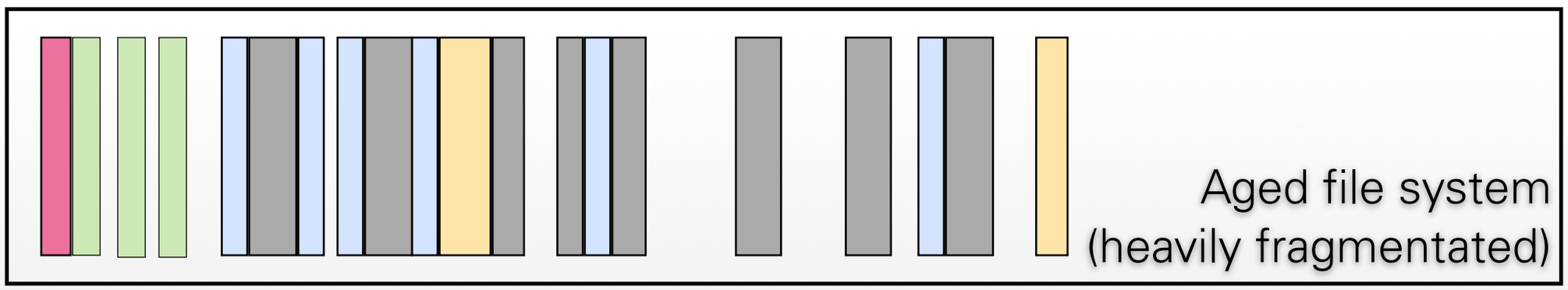
- Small block size (512 bytes, later 1024 bytes[1])
- Free-block tracking based on linked list
- Fixed inode area at start of partition (e.g., first 4 MB of 150 MB partition reserved for inodes)



Super Block / Inode / Directory block / Free-block linked list / Data Block

PERFORMANCE ISSUES[1]

- Fragmentation: 80 percent performance loss
- Long seeks between inode and blocks
- Inodes of files in same dir not grouped
- Small block size causes low throughput



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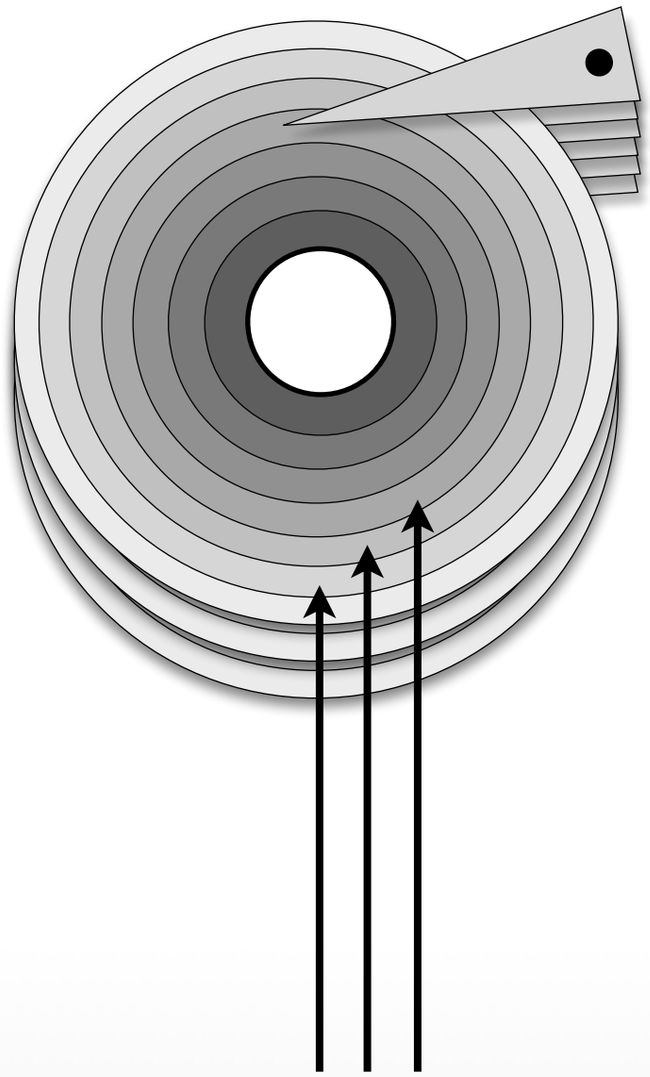
FAST FILE SYSTEM (FFS)

- Goals and achievements of FFS:
  - Stable performance also for aged file systems
  - Parameterization to adapt to different hardware
  - New functionality
- Lives on in *BSD (still named UFS)
- Linux Ext2 is an incompatible clone of FFS

CYLINDER GROUPS

- FFS used **larger block size** (configurable, min. 4096 bytes)
- FFS introduced **cylinder groups:**
  - Much smaller than partition
  - Less potentially long seeks:
    - **Array of inodes**, closer to data
    - **Allocation bitmap** for blocks (cylinder group is preferred location for files in same dir)
- Redundant **bookkeeping** information on **different platters**



Cylinder groups

LARGE BLOCK SIZES

- Larger blocks and inodes in each cylinder group enable faster throughput
- Problem to avoid: internal fragmentation (small files may not fill up entire blocks)

Space used	% waste	Organization
775.2 Mb	0.0	Data only, no separation between files
807.8 Mb	4.2	Data only, each file starts on 512 byte boundary
828.7 Mb	6.9	Data + inodes, 512 byte block UNIX file system
866.5 Mb	11.8	Data + inodes, 1024 byte block UNIX file system
948.5 Mb	22.4	Data + inodes, 2048 byte block UNIX file system
1128.3 Mb	45.6	Data + inodes, 4096 byte block UNIX file system

Disk space used for real file system on a (back then) contemporary time-sharing system [1]

BLOCKS AND FRAGMENTS

- FFS introduces **fragments:**
  - Split blocks into smaller units (512, 1024, … bytes)
  - Free space in cylinder group tracked at fragment level using bitmap:

Bits in map	XXXX	XXOO	OOXX	OOOO
Fragment numbers	0-3	4-7	8-11	12-15
Block numbers	0	1	2	3

Allocation bits (example from [1])

  - **In example:** block 3 available, block 1 and 2 hold fragments only
- Also: **fewer, larger blocks** require **fewer pointers** in intermediate blocks

INODE ALLOCATION

- **Inode allocation:**
  - Directory inodes: distribute across cylinder groups
  - File inode: same cylinder group as parent dir
- **Clustering** reduces I/O:
  - At most 16 disk transfers for maximum of 2048 inodes per cylinder group
  - Old Unix file system: one disk request for each inode in the worst case

BLOCK ALLOCATION

- **Global layout policy:**
  - Put blocks in same cylinder group as inode
  - Large files: after first indirect block (and then after each MB) put blocks into other cylinder group
- **Local layout policy:**
  1) Rotationally closest block location, same cylinder (skip over *n* blocks to minimize rotational delay, e.g., due to slow CPU, interrupt handling, …)
  2) Same cylinder group
  3) Other cylinder group (find via quadratic hashing)
  4) Exhaustive search in all cylinder groups
- **Reduce fragmentation:** 5% block reserve (super user only)

PERFORMANCE (IN 1984)

Type of File System	Processor and Bus Measured	Read Speed	Read Bandwidth	% CPU
old 1024	750/UNIBUS	29 Kbytes/sec	29/983 3%	11%
new 4096/1024	750/UNIBUS	221 Kbytes/sec	221/983 22%	43%
new 8192/1024	750/UNIBUS	233 Kbytes/sec	233/983 24%	29%
new 4096/1024	750/MASSBUS	466 Kbytes/sec	466/983 47%	73%
new 8192/1024	750/MASSBUS	466 Kbytes/sec	466/983 47%	54%

Read performance of FFS vs its predecessor [1]

Type of File System	Processor and Bus Measured	Write Speed	Write Bandwidth	% CPU
old 1024	750/UNIBUS	48 Kbytes/sec	48/983 5%	29%
new 4096/1024	750/UNIBUS	142 Kbytes/sec	142/983 14%	43%
new 8192/1024	750/UNIBUS	215 Kbytes/sec	215/983 22%	46%
new 4096/1024	750/MASSBUS	323 Kbytes/sec	323/983 33%	94%
new 8192/1024	750/MASSBUS	466 Kbytes/sec	466/983 47%	95%

Write performance of FFS vs its predecessor [1]

"NEW" FEATURES IN FFS

- **Long filenames:** variable-length dentries, think `struct { int inode; int size; int nlen; char name[0]; }`
- **Advisory file locking**
- **Symbolic links**
- **Rename**
- **Quotas**

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DEPENDENCIES

- FFS in 1984: **asynchronous writes**[1], but …
- … **Interdependencies** in file system structures:
  - Directory entries point to inodes
  - Inodes point to data blocks or indirect blocks
  - Bitmaps mark inodes or blocks as free / in use
- High-level operations often require multi-block updates (e.g., inode, dentry, bitmap, …)
- Partial updates can cause inconsistencies

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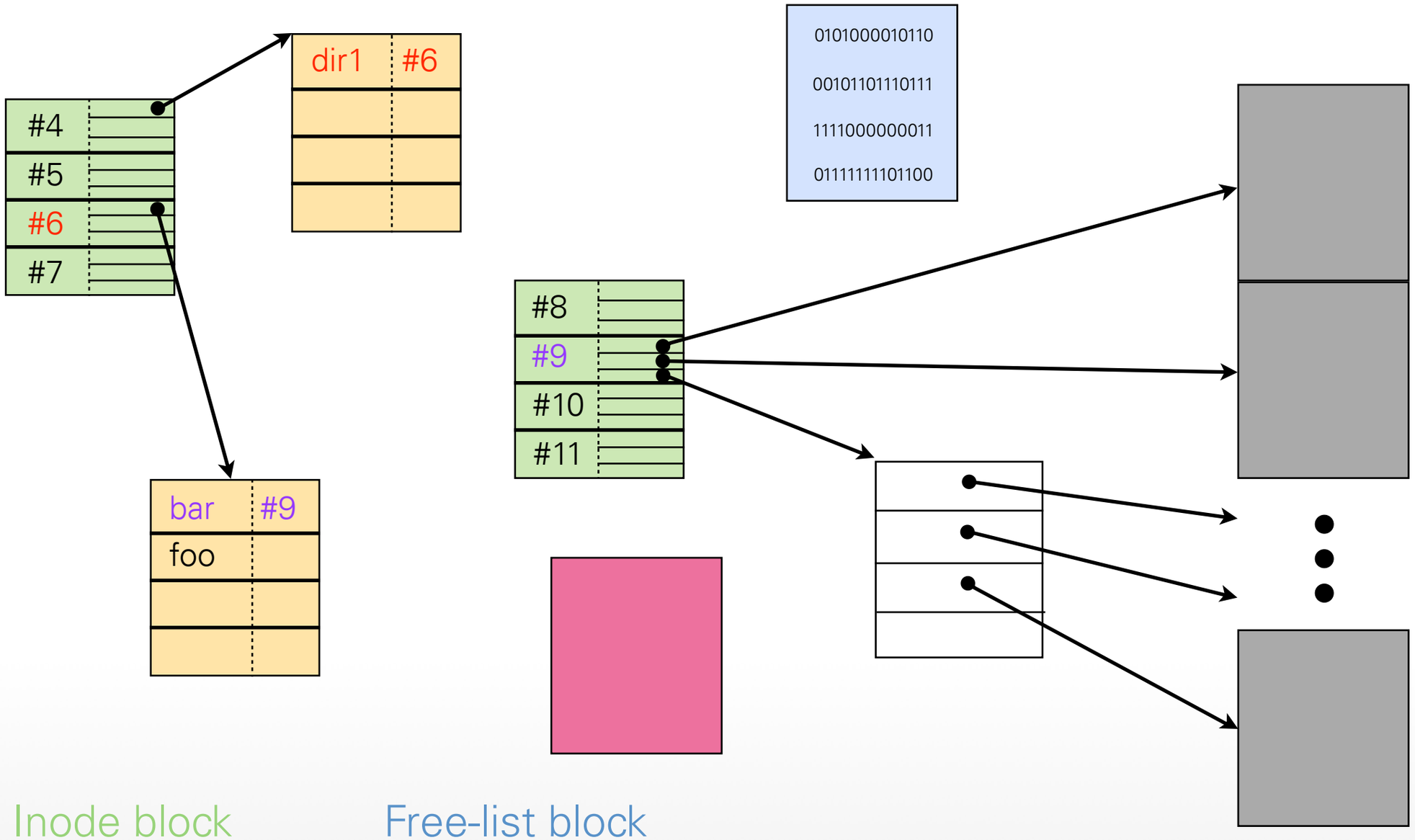
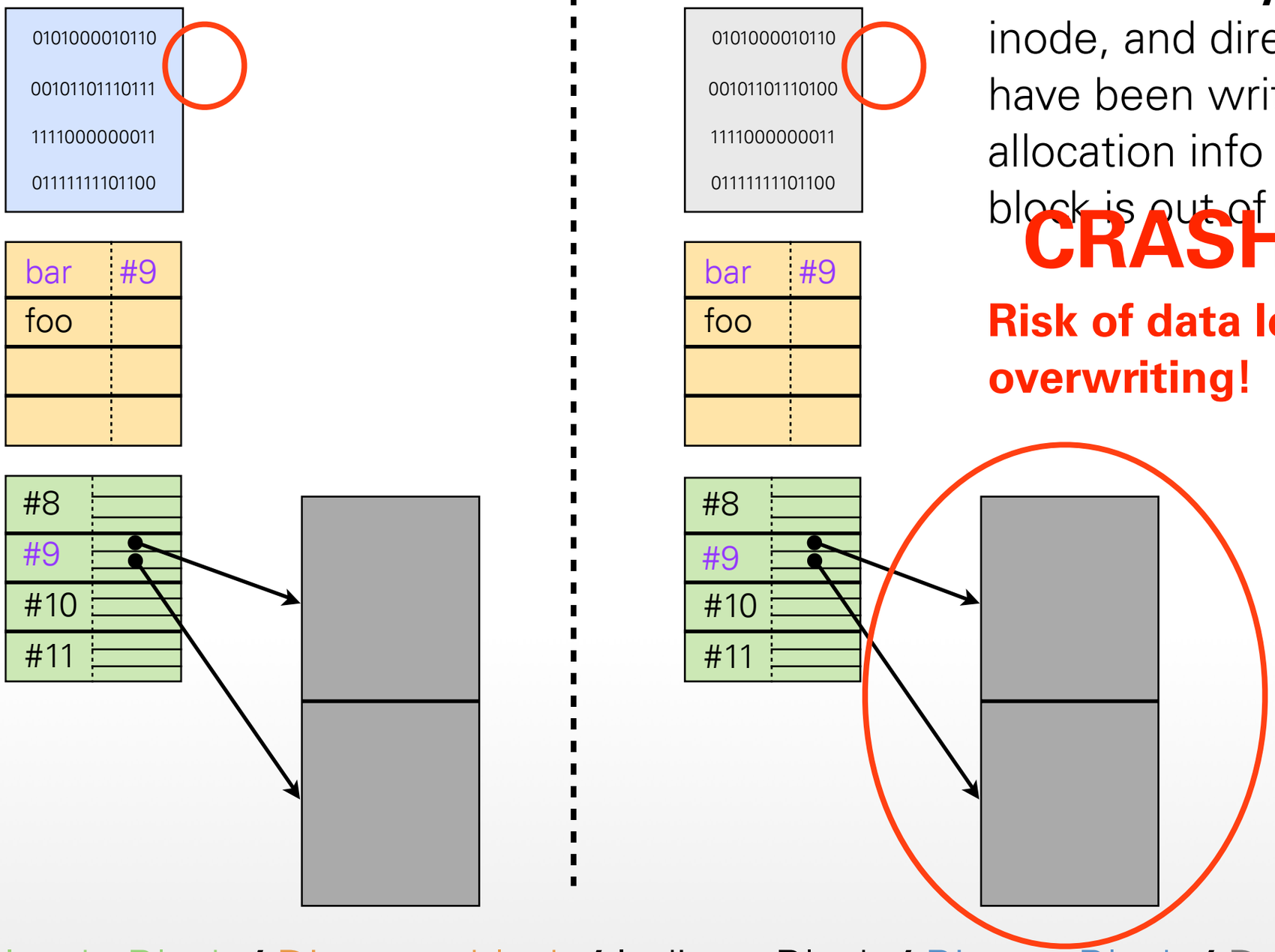


INVALID BLOCK BITMAP



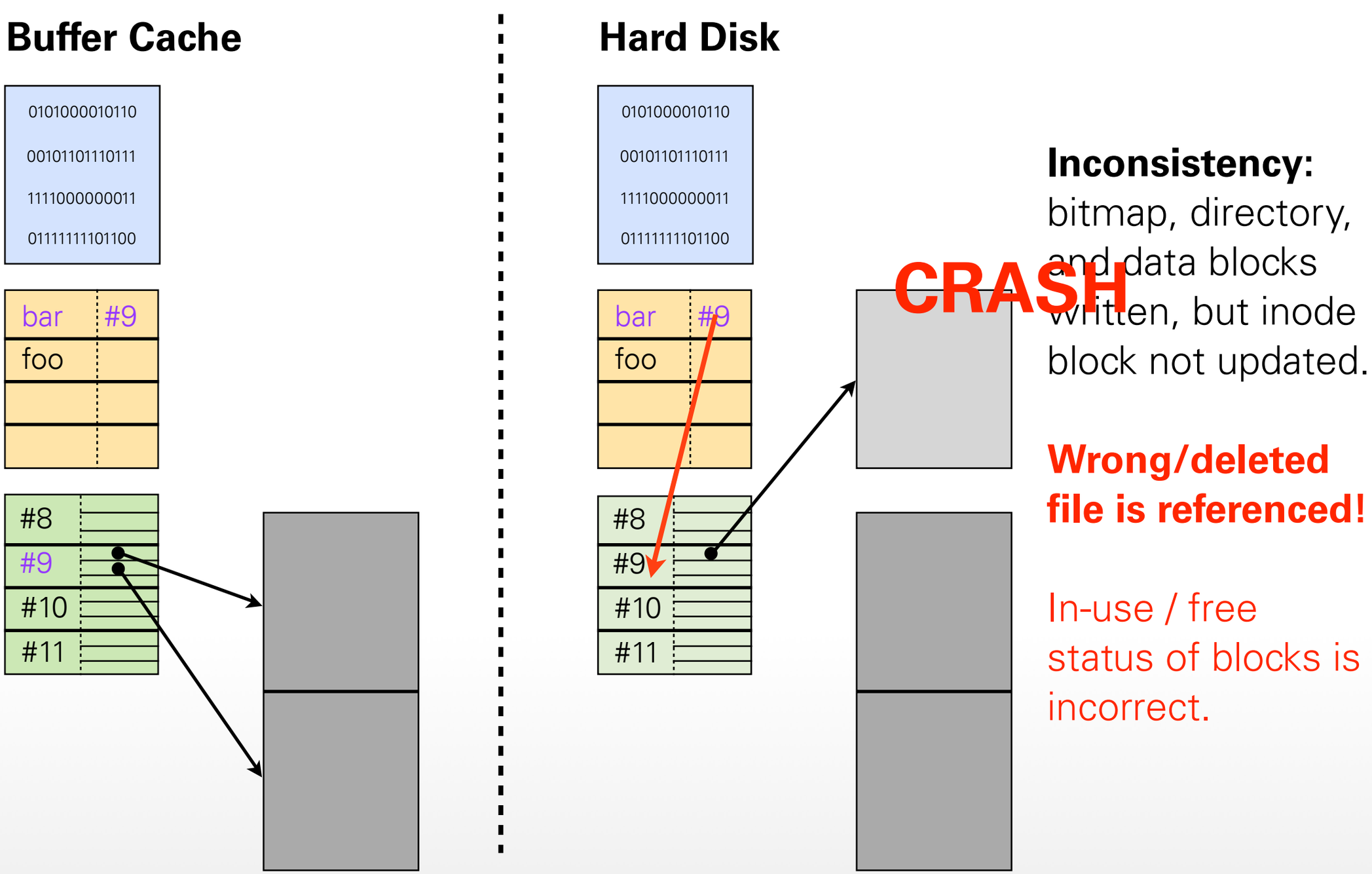
Inconsistency: data blocks, inode, and directory block have been written, but allocation info in bitmap block is out of data

CRASH

Risk of data loss due to overwriting!

Inode Block / Directory block / Indirect Block / Bitmap Block / Data Block

INVALID POINTERS



Inconsistency: bitmap, directory, and data blocks written, but inode block not updated.

Wrong/deleted file is referenced!

In-use / free status of blocks is incorrect.

Inode Block / Directory block / Indirect Block / Bitmap Block / Data Block

TYPES OF ERRORS

- **Critical:** loss of previously existing data
  - Pointers to wrong inodes or data blocks containing data of other (or deleted) files
  - Used block or inode marked as free
  - Inode's reference counter too small
- **Non-critical:** temporary resource leaks
  - Free block or inode marked as used
  - Inode's reference counter too high
  - Data block *(or inode)* already persistent, but block pointer *(or directory entry)* not written yet

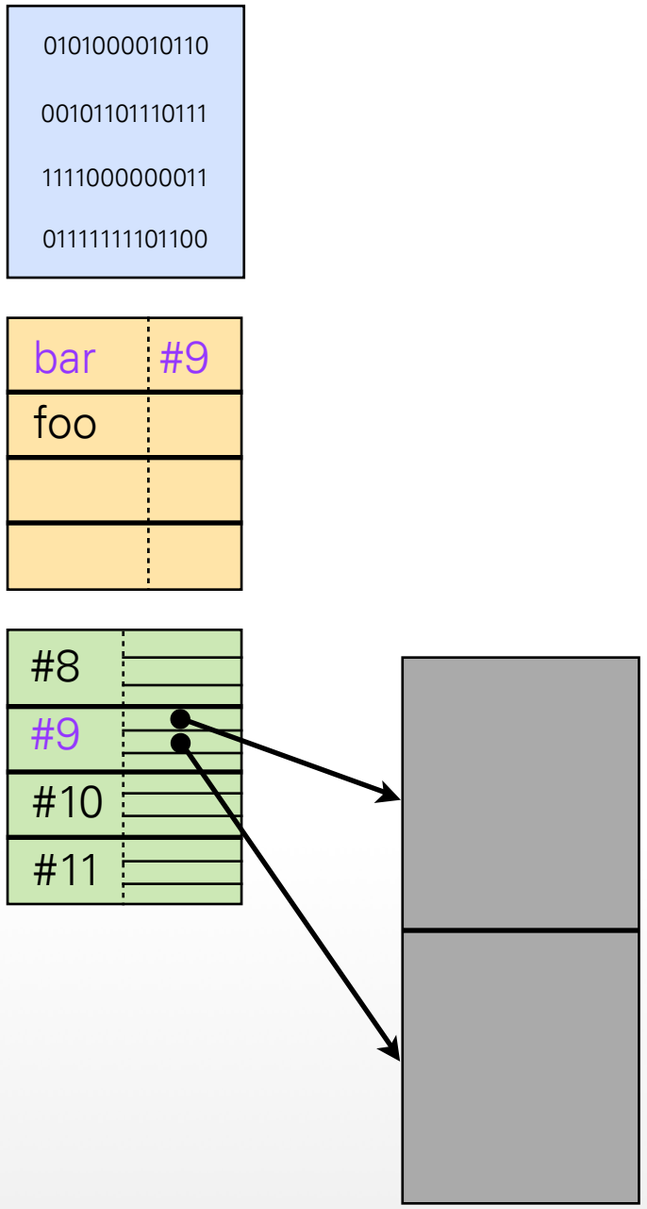
RULES OF CONSISTENCY

- **Valid pointers:** do not point to a data structure that has not been initialized yet
- **Reuse:** do not reuse a data structure, unless all old pointers to it have been invalidated
- **Reachability:** do not invalidate a pointer to a valid resource, before a new pointer to it has been set

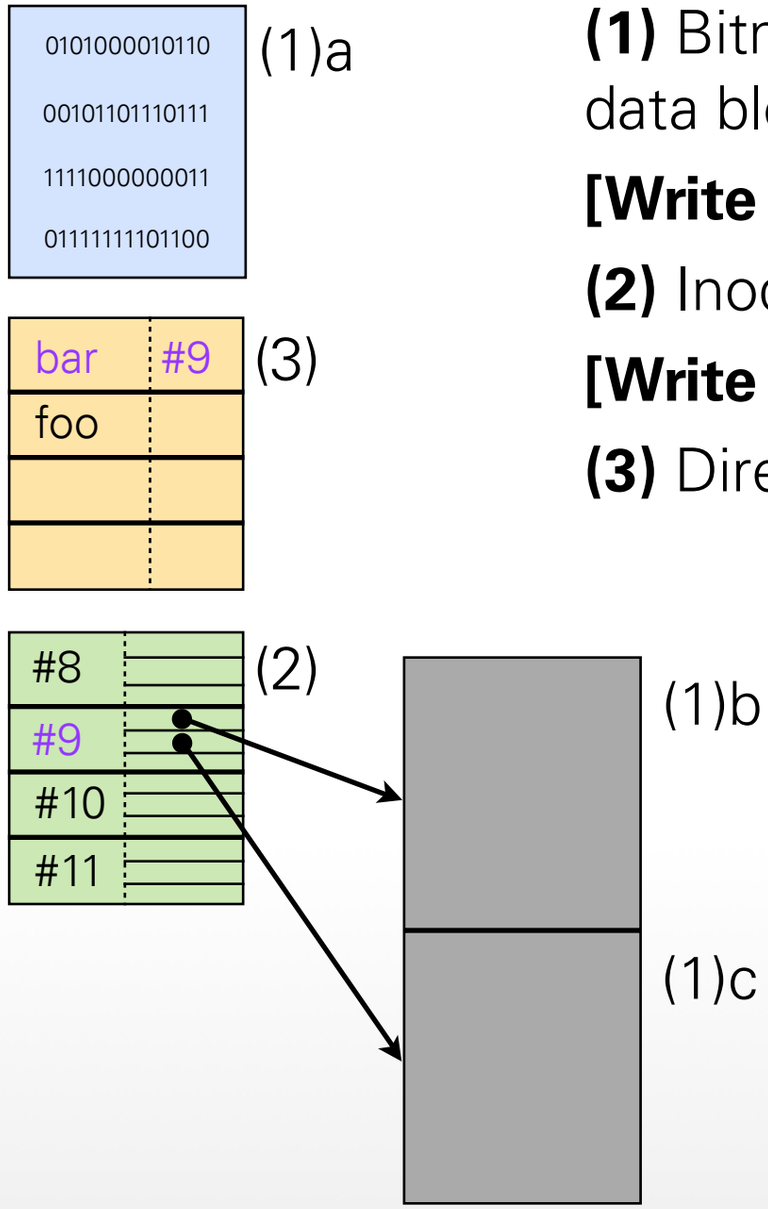
Source: [2]

SAFE WRITE ORDER

Buffer Cache



Hard disk



Order of writes:

(1) Bitmap and data blocks (a-c)

[Write Barrier]

(2) Inode block

[Write Barrier]

(3) Directory block

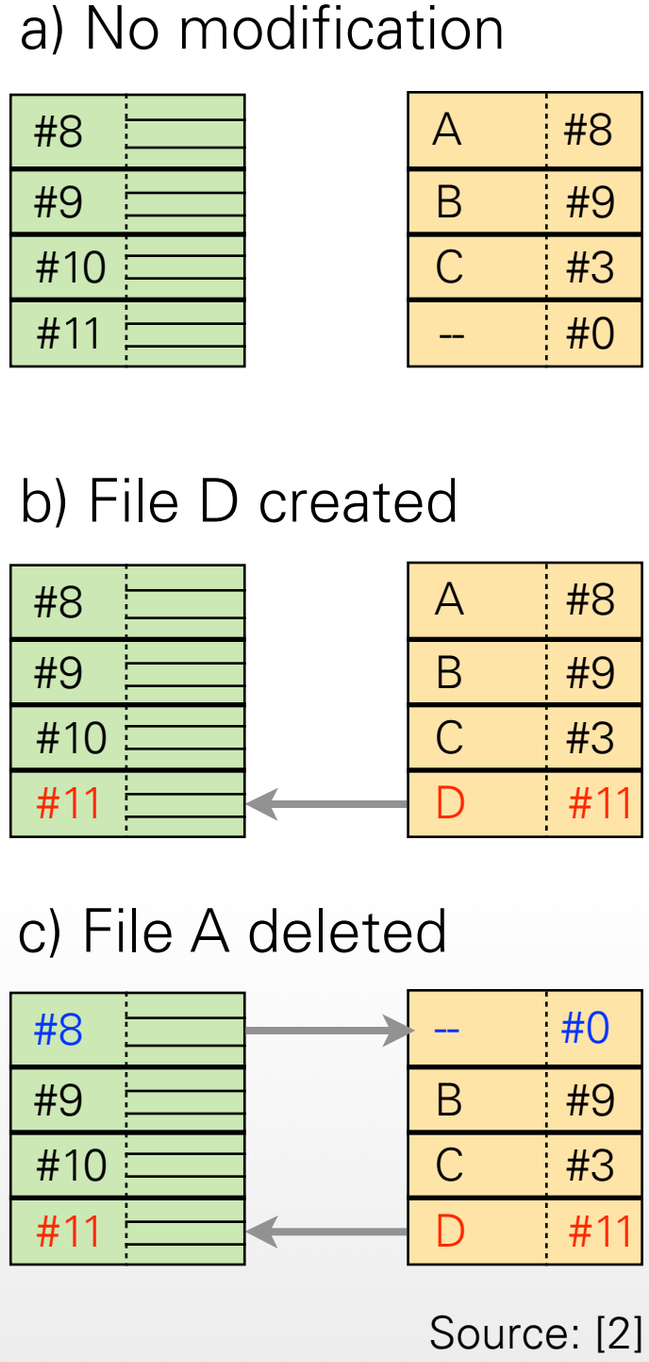
Inode Block / Directory block / Indirect Block / Bitmap Block / Data Block

SOFT UPDATES

- **Idea:** group individual phases of large number of safe-write sequences into large batches
  - Accumulate modifications in buffer cache
  - When writing, takes all dependencies among blocks into account (serialize writes into batches)
- **Implementation:**
  - Dependency structures for each cache block
    - Metadata (e.g., directory -> inode)
    - Data (inode / indirect block -> data block)
  - Problem: cycles in dependency graph

CYCLIC DEPENDENCIES

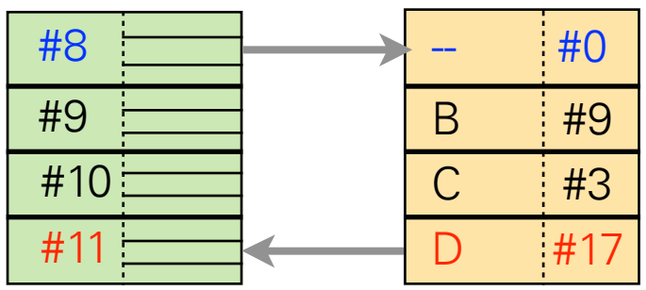
- State of inode and directory blocks in buffer cache:
  a) No dependency
  b) Inode block must be initialized before writing directory block
  c) Inode pointer in directory entry must be invalidated before inode can be freed
- Cyclic dependency!



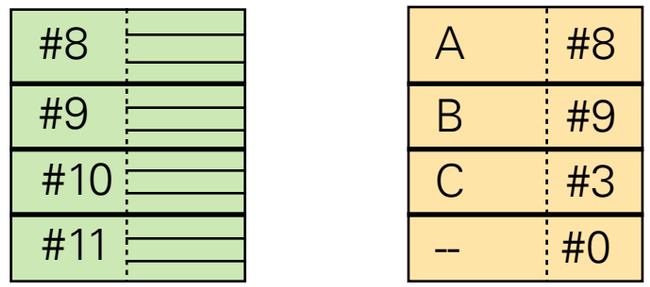
Source: [2]

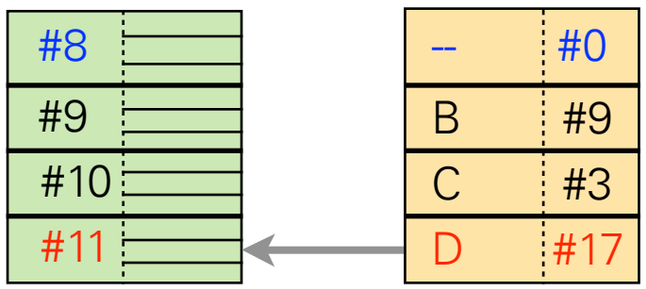
BREAKING THE CYLCLE

Buffer Cache **Hard disk**

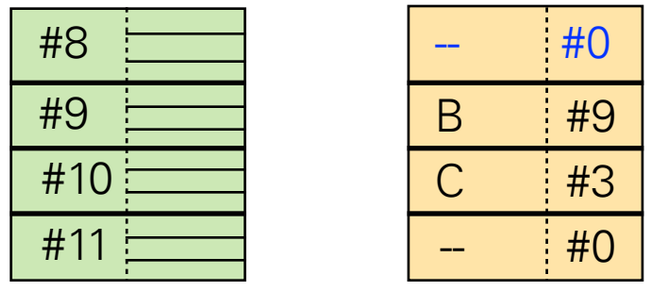


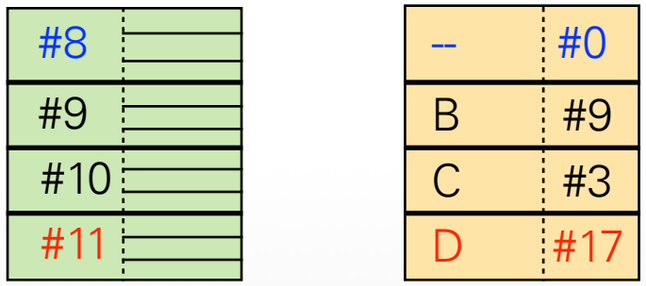
a) Metadata blocks modified in cache



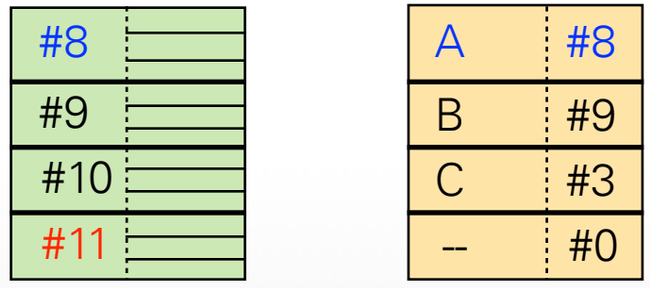


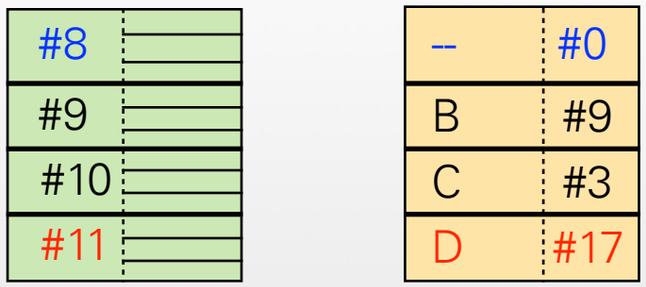
b) Directory block written (but without new dir entry for D)



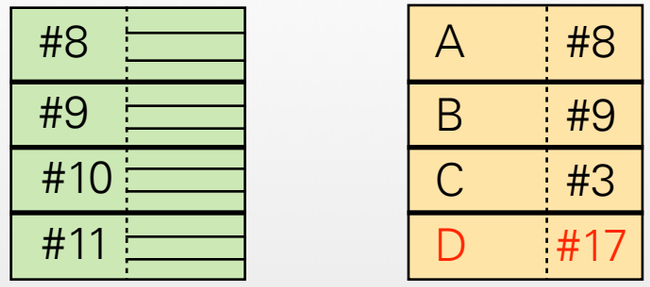


c) Inode block written





d) Directory block written again, this time including D



Source: [2]

TRACKING DEPENDENCIES

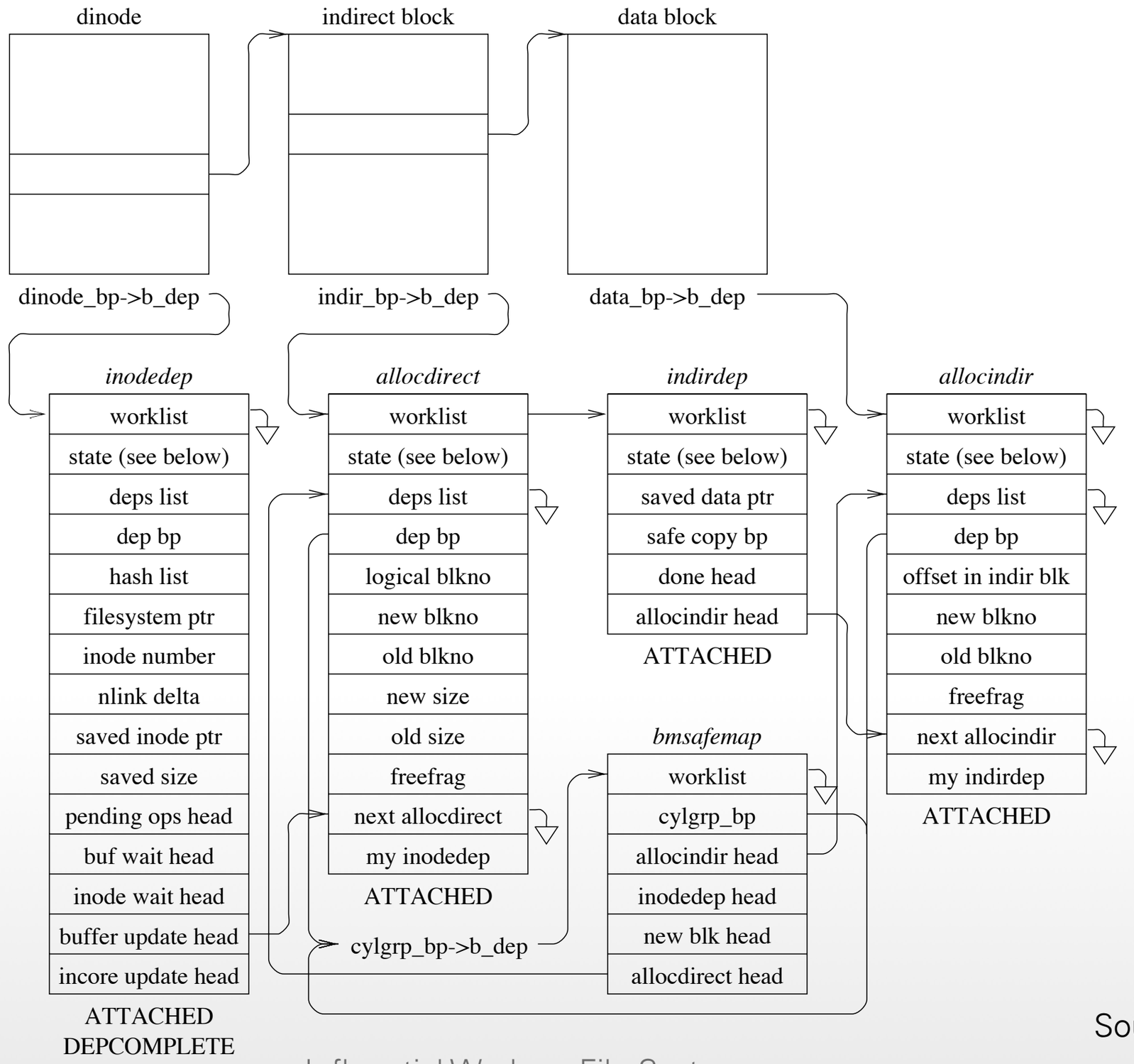
- Goal: can write modified blocks at any time
- Soft-updates code inspects dependency structures before write operation:
  - Consistent / isolated modifications can be written immediately without side effects
  - Modifications with unsatisfied dependencies are rolled back temporarily for block-write operation
  - When consistent version of block is been written, re-apply temporarily removed modifications
- There is a dependency structure for each block modification (chained up in list linked at buffer head)

TRACKING DEPENDENCIES

Name	Function	Associated Structures
bmsafemap	track bitmap dependencies (points to lists of dependency structures for recently allocated blocks and inodes)	cylinder group block
inodedep	track inode dependencies (information and list head pointers for all inode-related dependencies, including changes to the link count, the block pointers, and the file size)	inode block
allocdirect	track inode-referenced block (linked into lists pointed to by an inodedep and a bmsafemap to track inode's dependence on the block and bitmap being written to disk)	data block or indirect block or directory block
indirdep	track indirect block dependencies (points to list of dependency structures for recently-allocated blocks with pointers in the indirect block)	indirect block
allocindir	track indirect block-referenced block (linked into lists pointed to by an indirdep and a bmsafemap to track the indirect block's dependence on that block and bitmap being written to disk)	data block or indirect block or directory block
pagedep	track directory block dependencies (points to lists of diradd and dirrem structures)	directory block
diradd	track dependency between a new directory entry and the referenced inode	inodedep and directory block
mkdir	track new directory creation (used in addition to standard diradd structure when doing a mkdir)	inodedep and directory block
dirrem	track dependency between a deleted directory entry and the unlinked inode	first pagedep then tasklist
freefrag	tracks a single block or fragment to be freed as soon as the corresponding block (containing the inode with the now-replaced pointer to it) is written to disk	first inodedep then tasklist
freeblks	tracks all the block pointers to be freed as soon as the corresponding block (containing the inode with the now-zeroed pointers to them) is written to disk	first inodedep then tasklist
freefile	tracks the inode that should be freed as soon as the corresponding block (containing the inode block with the now-reset inode) is written to disk	first inodedep then tasklist

Source: [2]

UPDATE DEPENDENCIES

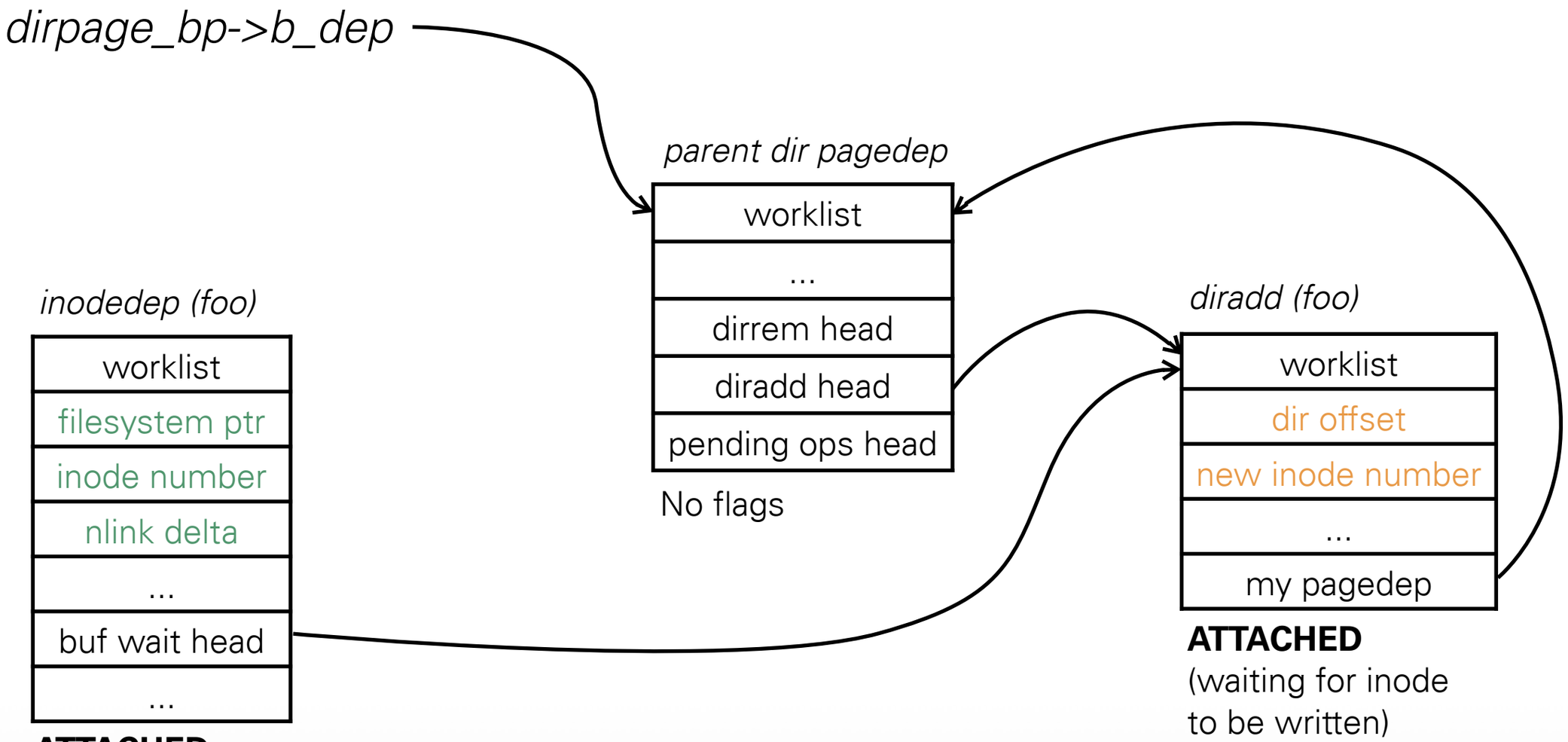


Source: [2]

DEPENDENCY STATES

- **ATTACHED:**
  - Buffer is not being written at the moment
  - For rollback: clear ATTACHED flag to indicate that modification must be re-applied after write
- **DEPCOMPLETE:**
  - Modification safe for writing, no need to roll back
- **COMPLETE:**
  - Modification has been written to disk
- Deallocation: only after all flags are set

UPDATE DEPENDENCIES



Example: dependencies for creating a new directory entry (simplified version of presentation in [2])

PERFORMANCE

Software development benchmark:

- 75 percent fewer writes
- 21 percent shorter run time

Filesystem Configuration	Disk Writes		Running Time
	Sync	Async	
Normal	162,410	39,924	2hr, 12min
Asynchronous	0	38,262	1hr, 44min
Soft Updates	1124	48,850	1hr, 44min

Time to build and install FreeBSD [2]

Filesystem Configuration	Disk Writes	
	Sync	Async
Normal	1,877,794	1,613,465
Soft Updates	118,102	946,519

Mail server operation [2]

Mail server workload:

- Writes per second dropped from 40 to 12 per send
- Mail-handling capacity tripled

SOFT UPDATES IN USE

- Soft updates were introduced in 4.4BSD
- Huge improvement over synchronous writes
- Still in use today:
  - FreeBSD
  - OpenBSD

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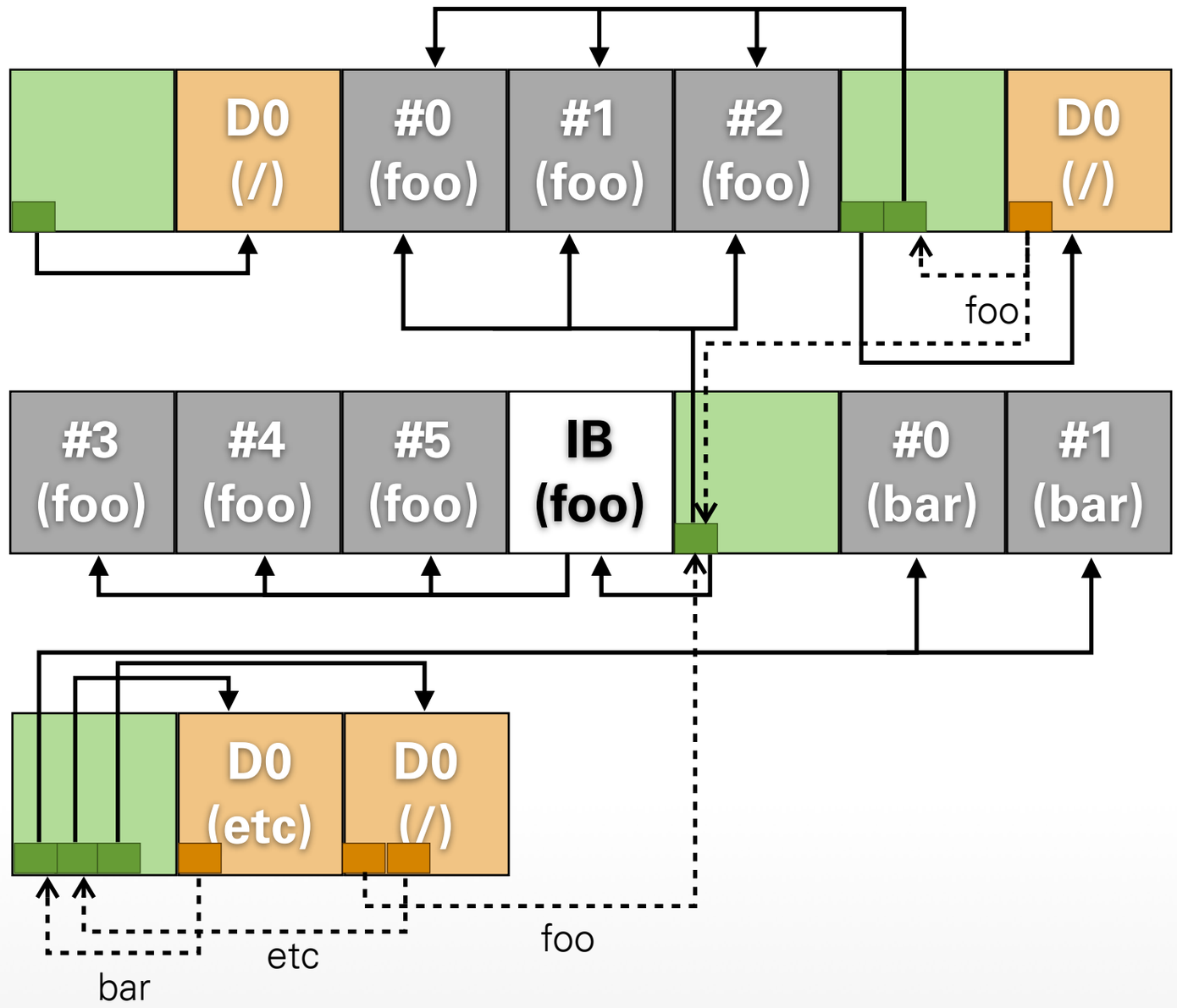
NEW PARADIGM: LFS

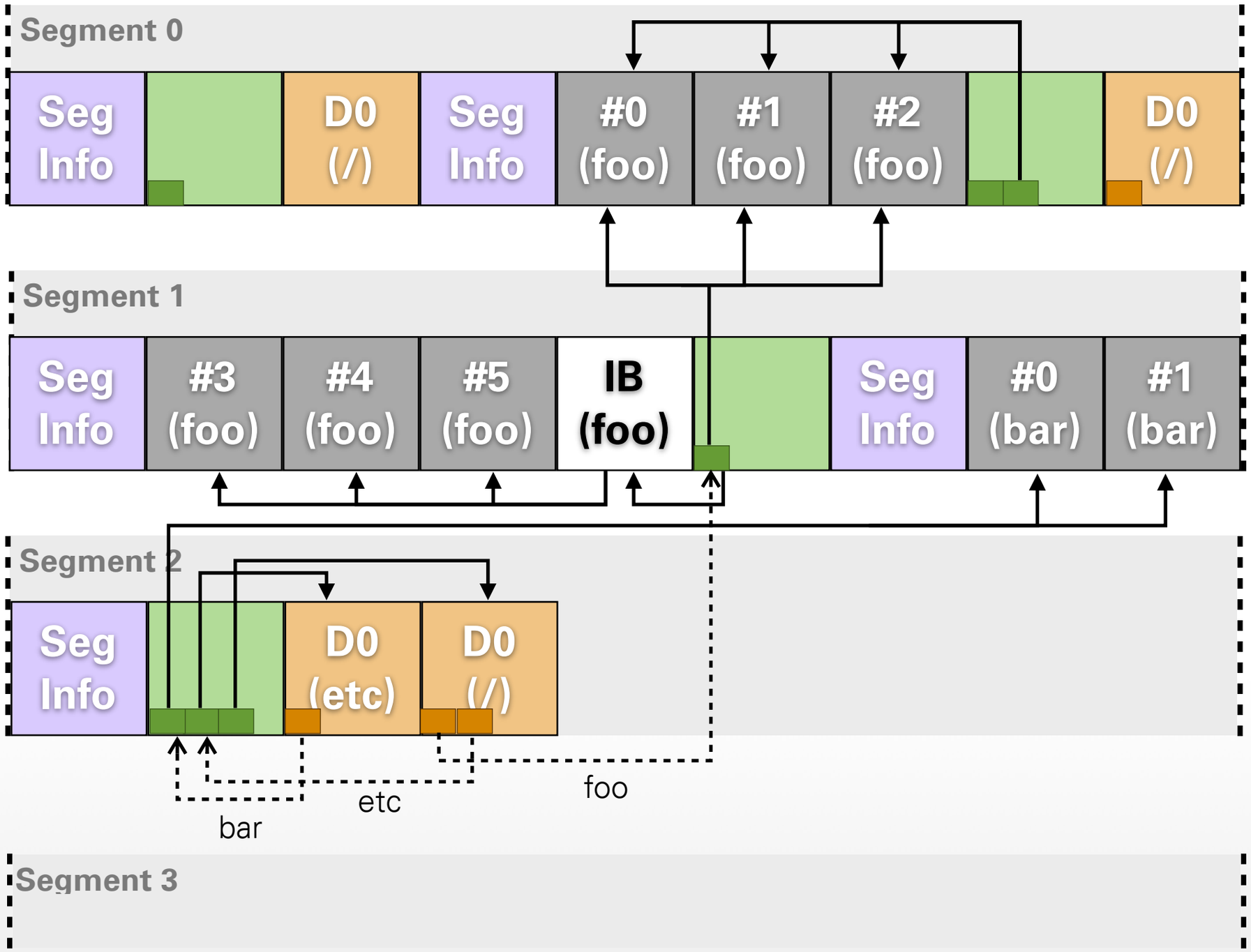
- **Idea:** treat entire file system as a log
  - Write data and metadata blocks linearly
  - No overwriting, append new block versions to log
  - Newest versions of all blocks contain latest file-system state
- Additional features:
  - Log contains consistent versions of old file-system state
  - Multiple snapshots of file-system state possible

LFS OPERATION



Inode Block / Directory Block / Indirect Block / Data Block

SEGMENTS IN AN LFS



Inode Block / Directory Block / Indirect Block / Data Block / Summary Block

SEGMENT INFORMATION

- Block address space portioned into **segments**
- Segments contain **data** and **metadata** blocks
- **Summary blocks** describe block types:
  - File / directory blocks: **(Inode,Block#)**
  - **Inode blocks:** new / modified inodes
  - **Inode-map blocks:** pointers to inodes in log
- Inode map **decouples** inode pointers in directory entries from physical location in log (prevents trickle-up effect up to root directory)

CHECKPOINTS

- All data and metadata in log ... **but:** full scan of entire log too expensive
- **Better:** regularly checkpoint current state of metadata in compact form
- **2 checkpoint areas** at fixed position:
  - Consistent version of all blocks from inode map + segment usage table
  - Timestamp + pointer to last written segment
  - Checksum to validate consistency and completeness of checkpoint area

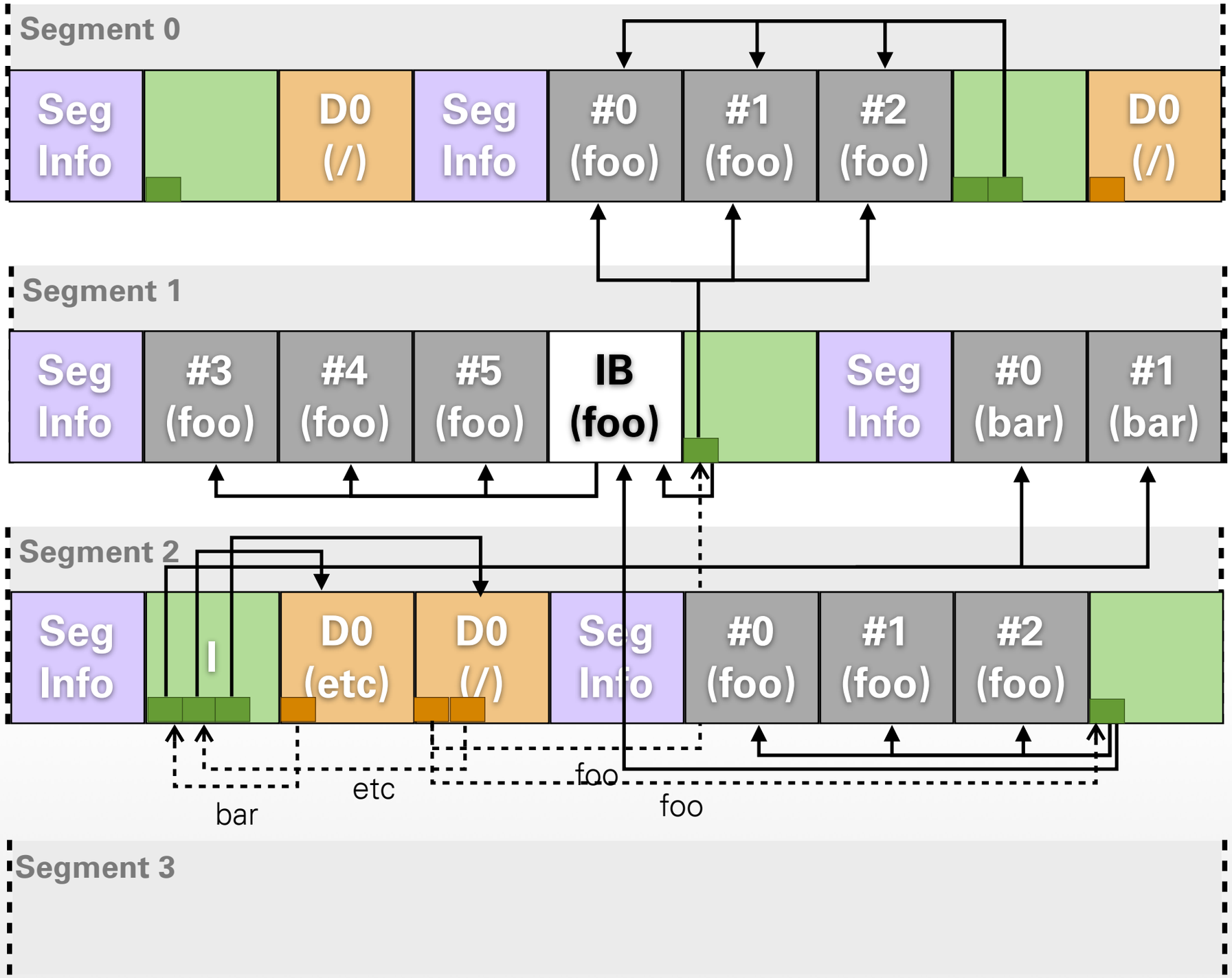
MOUNT / CRASH RECOVERY

- **Replay from last checkpoint**
  1. Choose latest consistent checkpoint area
  2. Reinitialize inode map in kernel memory
  3. Determine position of last segment written before checkpoint
  4. Roll-forward from last pre-checkpoint segment, redo all changes as found in log
  5. Latest consistent file system has been recovered

GARBAGE COLLECTION

- **Problem:** Log cannot grow indefinitely
- **Solution 1:** free old blocks, thread into log
  - (+) Simple and fast free operation
  - (-) Fragmentation grows
- **Solution 2:** clean complete segment
  - (+) Fragmention does not increase
  - (-) Live blocks in segment must be copied into new segment
- LFS as described in [3] implements solution 2

SEGMENT CLEANING



GARBAGE COLLECTION

- **Cleaner process** searches for partially live segments in background
- Starts and stops based on thresholds (low / high watermark of free segments)
- There is no block-allocation table or free list; how to identify obsolete blocks?
  1. **Find pointer** to block in inode or indirect block
  2. **No valid pointer found** -> block is **obsolete**
- Validation efficiency?

SEGMENT USAGE TABLE

- LFS keeps statistics about each segment:
  - **Versions** of blocks stored in segment
  - Last **modification time** of any block in segment
  - Number of **live bytes** (utilization)
- Blocks containing segment-usage table are written to log (positions put in checkpoint area)
- **Versions numbers:**
  - Compare to inode versions to find obsolete blocks, still need to check indirect blocks
  - Inode versions recorded in inode map

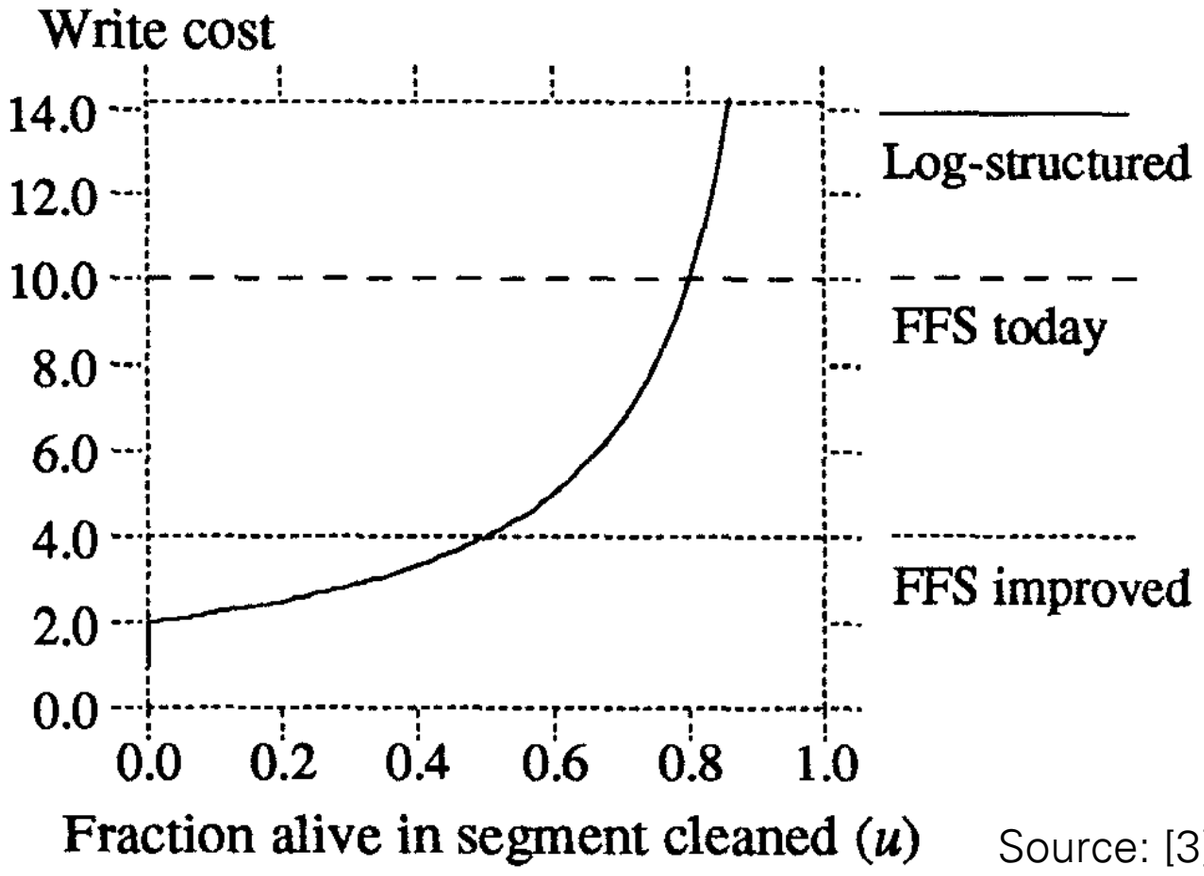
CLEANING POLICY

- Segment-usage table helps with cost-benefit cleaning policy
- **Age** + **utilization** of segment enable classification into **hot** and **cold** segments
- Surprising result:
  - Clean cold segments even with high utilization (e.g., 75%)
  - Leave hot segments alone until utilization drops to much lower value (e.g., 15%)
- Details and simulation results in [3]

SMALL-FILE WRITE COST

Garbage collection must be factored into write cost

Worst case: steady state where garbage collection is constantly required



Source: [3]

$$\text{write cost} = \frac{\text{total bytes read and written}}{\text{new data written}} = \frac{\text{read segs} + \text{write live} + \text{write new}}{\text{new data written}} = \frac{N + N^*u + N^*(1-u)}{N^*(1-u)} = \frac{2}{1-u}$$

Source: [3]

Variables:

- **N** … number of segments
- **u** … utilization of segments
- **N*(1-u)** … free space generated, maximum amount of new data that can be written

LFS IN PRACTICE

- Suitability for different types of storage:
  - **Rotating disks:**
    - Excellent write performance with sufficient amount of clean segments on a minority of storage systems with rotating disks
    - Prone to fragmentation, can hurt read performance
  - **Solid-state / flash-based storage:**
    - Highly suitable, fragmentation has little impact
    - Does not require sophisticated flash-translation layer
- Real-world usage:
  - YAFFS2, JFFS, NILFS2, F2FS, … for flash
  - Similar algorithms exist in flash translation layers

SOURCES

[1] *"A Fast File System for UNIX"*, Marshall Kirk McKusick, William N. Joy, Samuel J. Leffer, Robert S. Fabry, ACM Transactions on Computer Systems (TOCS), Vol. 2 Issue 3, Aug. 1984

[2] "*Soft updates: a Technique for Eliminating Most Synchronous Writes in the Fast Filesystem"*, Marshall Kirk McKusick und Gregory R. Ganger, ATEC '99 Proceedings of the annual conference on USENIX Annual Technical Conference, 1999

[3] "*The Design and Implementation of a Log-Structured File System"*, Mendel Rosenblum und John K. Ousterhout, ACM Transactions on Computer Systems (TOCS) Volume 10 Issue 1, Februar 1992