File system

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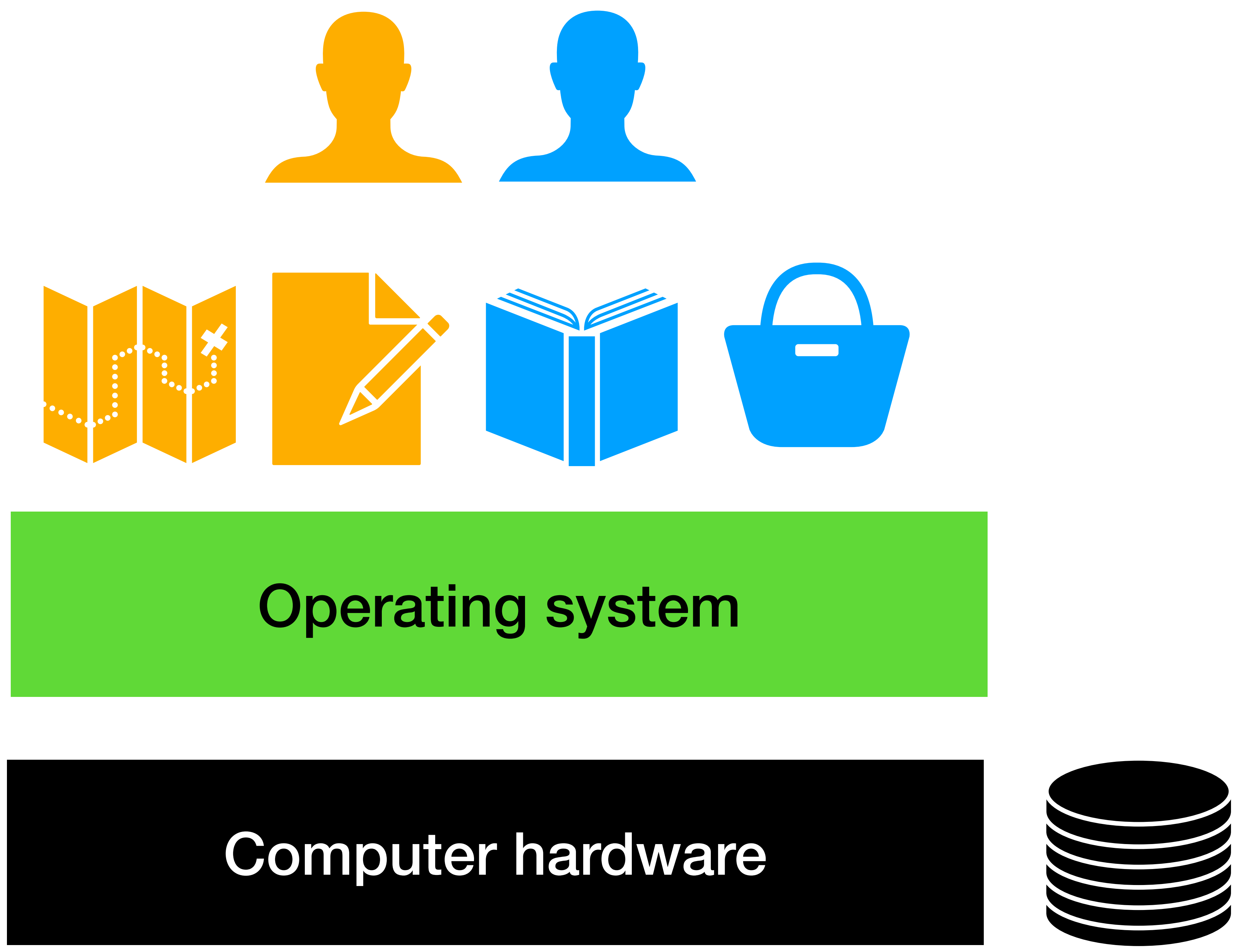
File system



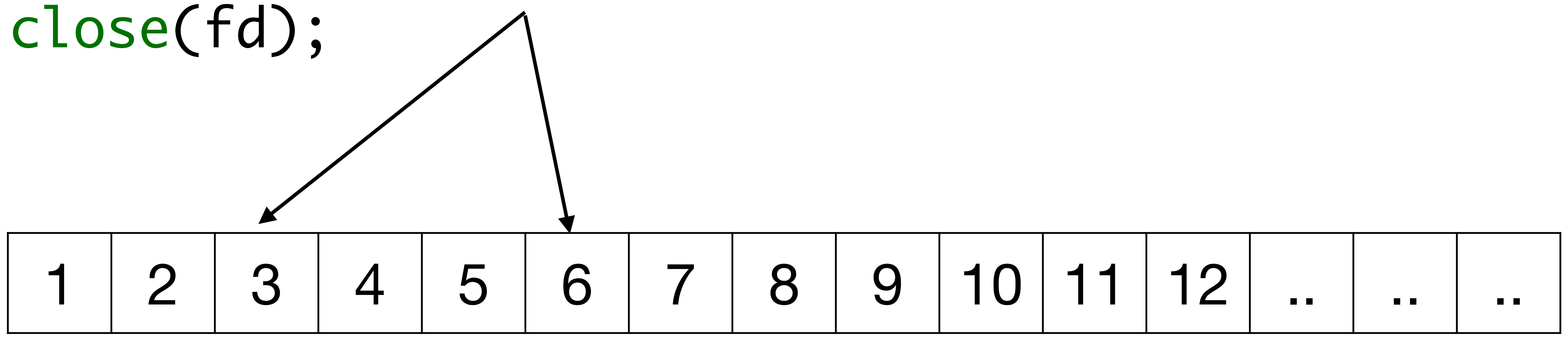
Example: io.c

Disk interface: List of blocks

File system OS interface: Folders and files.

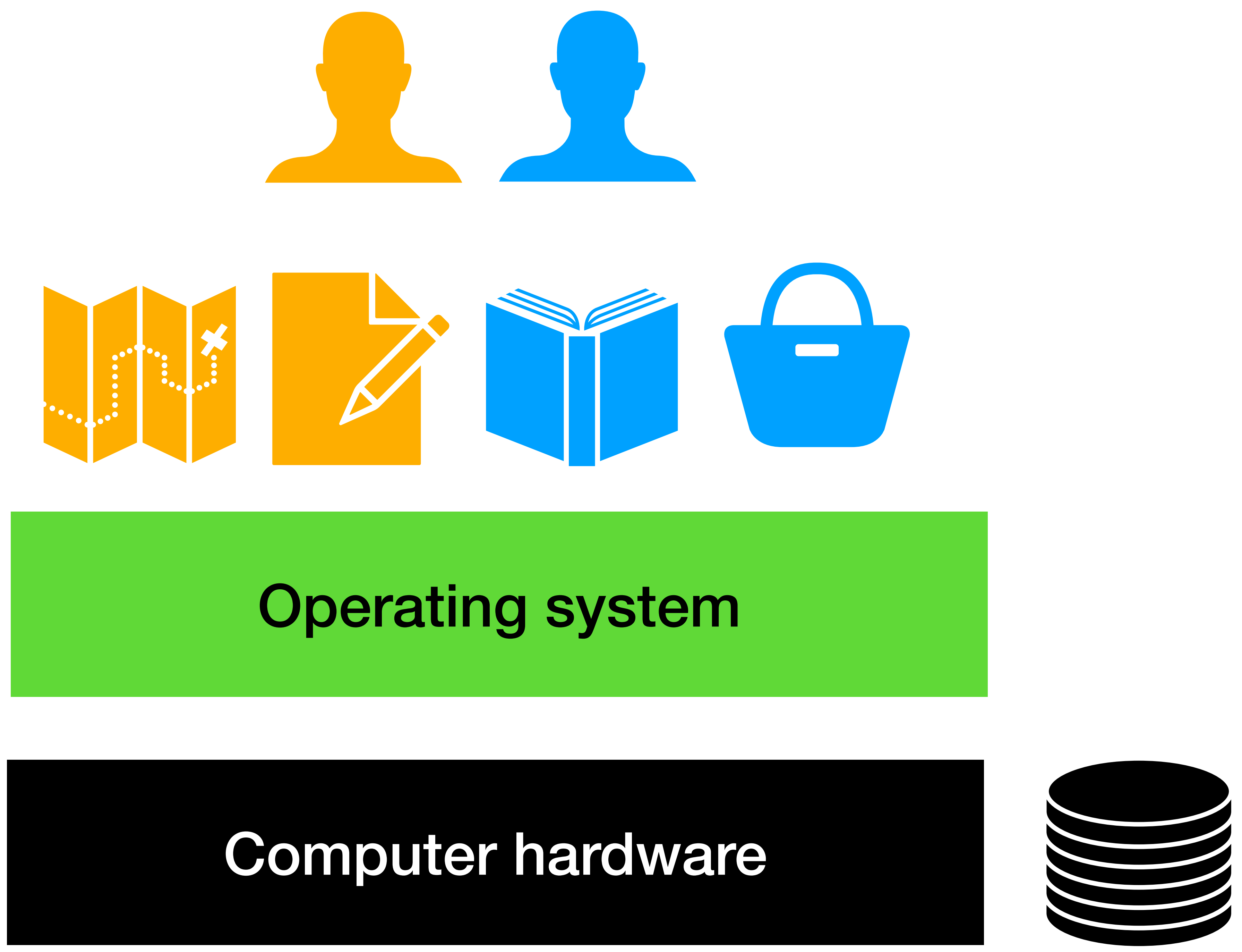
open, write, read, lseek, close, append,
permissions, truncation, file descriptor offset

```
int fd = open("/tmp/file", O_WRONLY | O_CREAT);
int rc = write(fd, "hello world\n", 12);
close(fd);
```

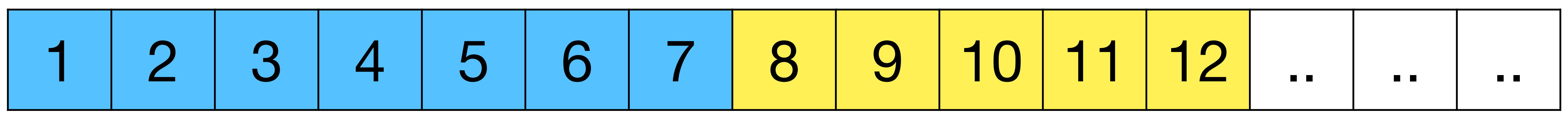


Why file system?

Why not just multiplex disk blocks like memory?



- Disk blocks live after programs exits, computer restarts
- Different programs read / write same file
    - vim writes io.c
    - gcc reads io.c, write io
    - We finally run io



Files as sequence of bytes

- Other options: Files have structured records
    - Can build structure on top
    - But may not optimise disk accesses
- Also expose raw disk blocks
    - Databases
    - File system checker (fsck)
    - Disk defragmenter

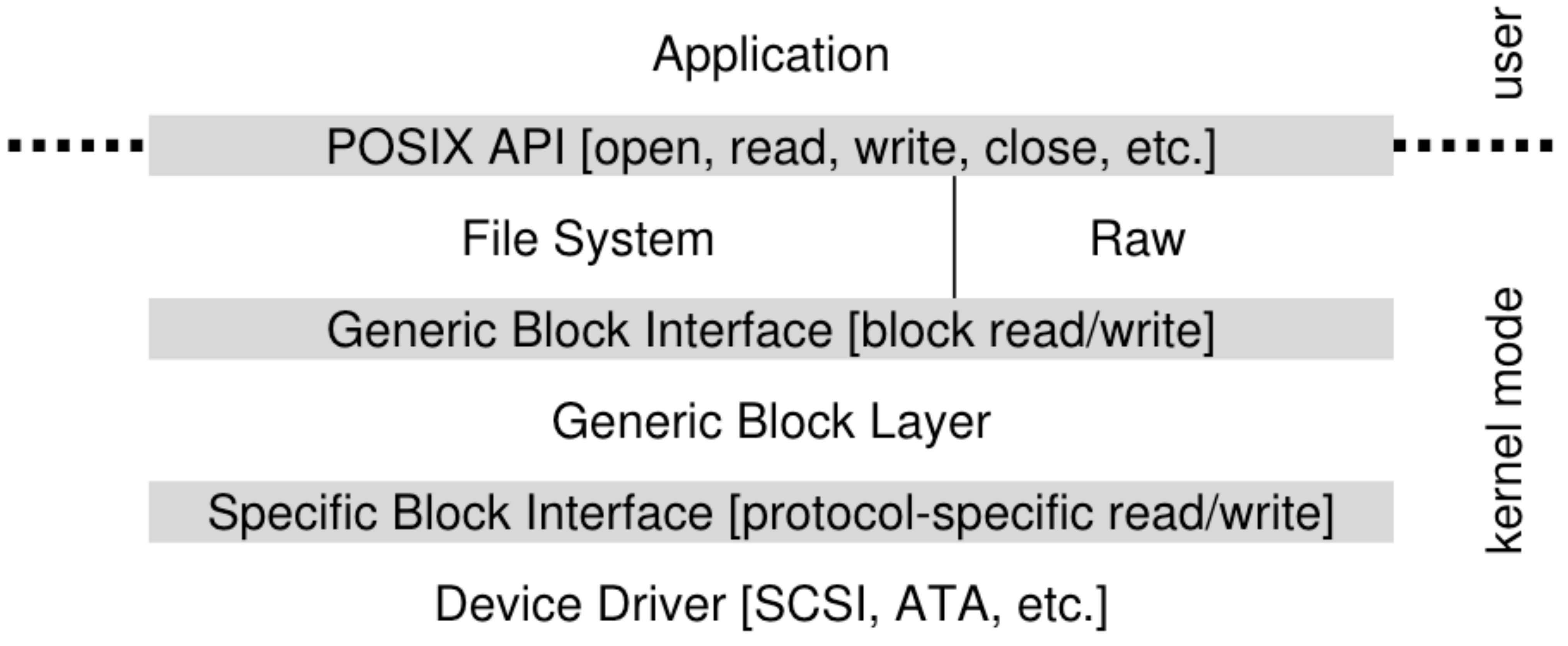


Figure 36.4: **The File System Stack**

Flexible abstraction

- Stitch multiple file systems into a common directory tree
    - `mount –t ext3 /dev/sda1 /home/abhilash/photos/`
    - `mount –t ext2 /dev/sdb1 /home/abhilash/docs/`
- /proc
- Run tty. cat <filename>
- /sys

Agenda

- Build a file system (OSTEP Ch. 40, xv6 Ch. 6)
  - On-disk data structure. Organize disk blocks to expose files and directories
- Optimizations (OSTEP Ch. 41)
- Crash consistency: Don’t lose data when computer restarts (OSTEP Ch. 42)

File system characteristics

- File system contains lots of files ~100K
- Most files are small ~2KB
- A few big files use most of the disk space
- Directories have typically < 20 files and directories

xv6 file system

File system implementation , OSTEP Ch.40, xv6 Ch. 6

How to store files?

Contiguous allocation

1	2	3	4	5	6	7	8	9	10	11	12

- “a.txt” -> (base = 1, size = 2)
- “b.txt” -> (base = 8, size = 2)

- Growth. “b.txt” wants to use 6 blocks. Need to copy to a new location.

- Fragmentation. Want to create a file “c.txt” with 6 blocks.

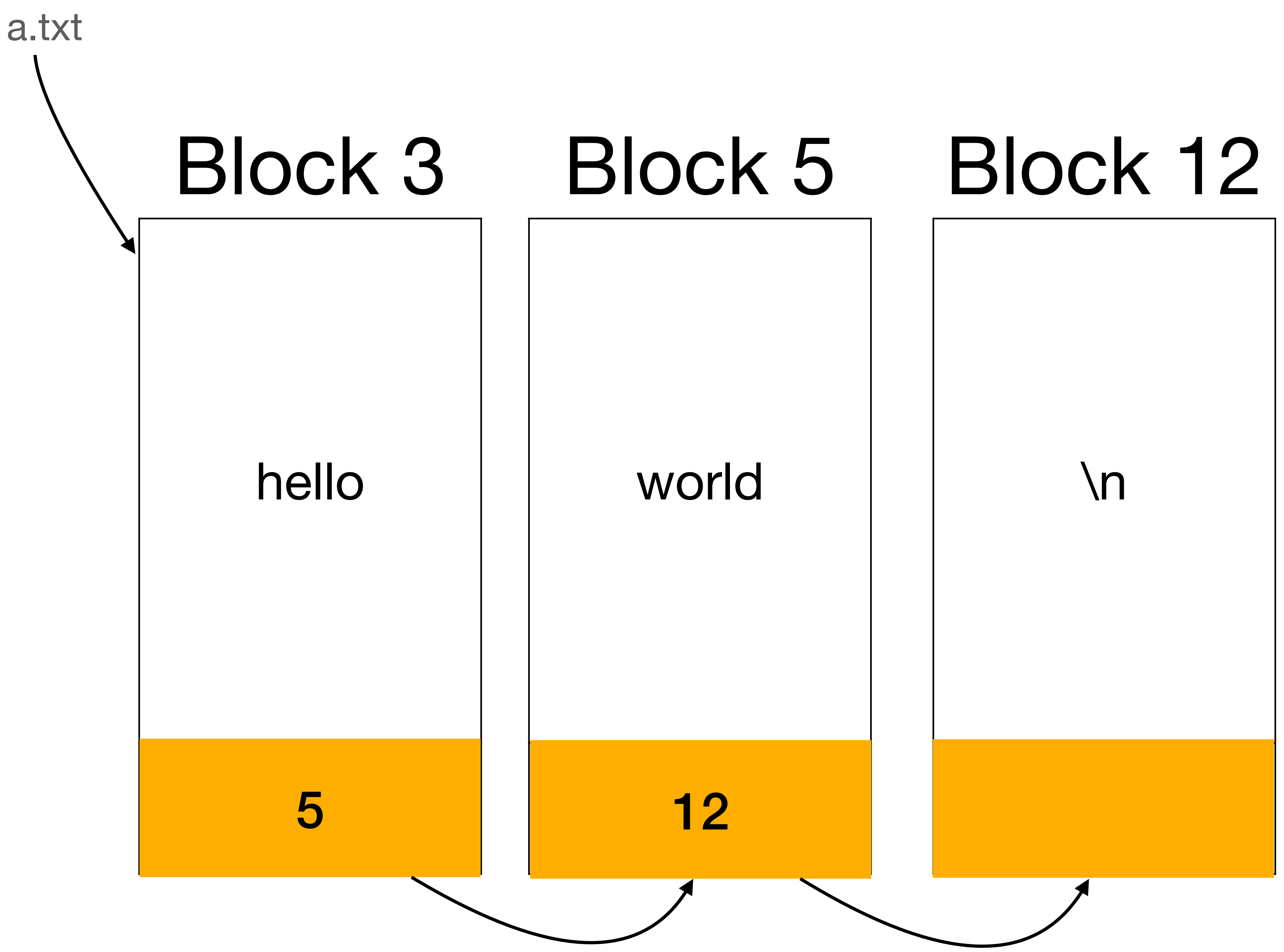
✓ Sequential file rw is sequential disk rw

How to store files?

Linked list of blocks

✓ Files can grow easily

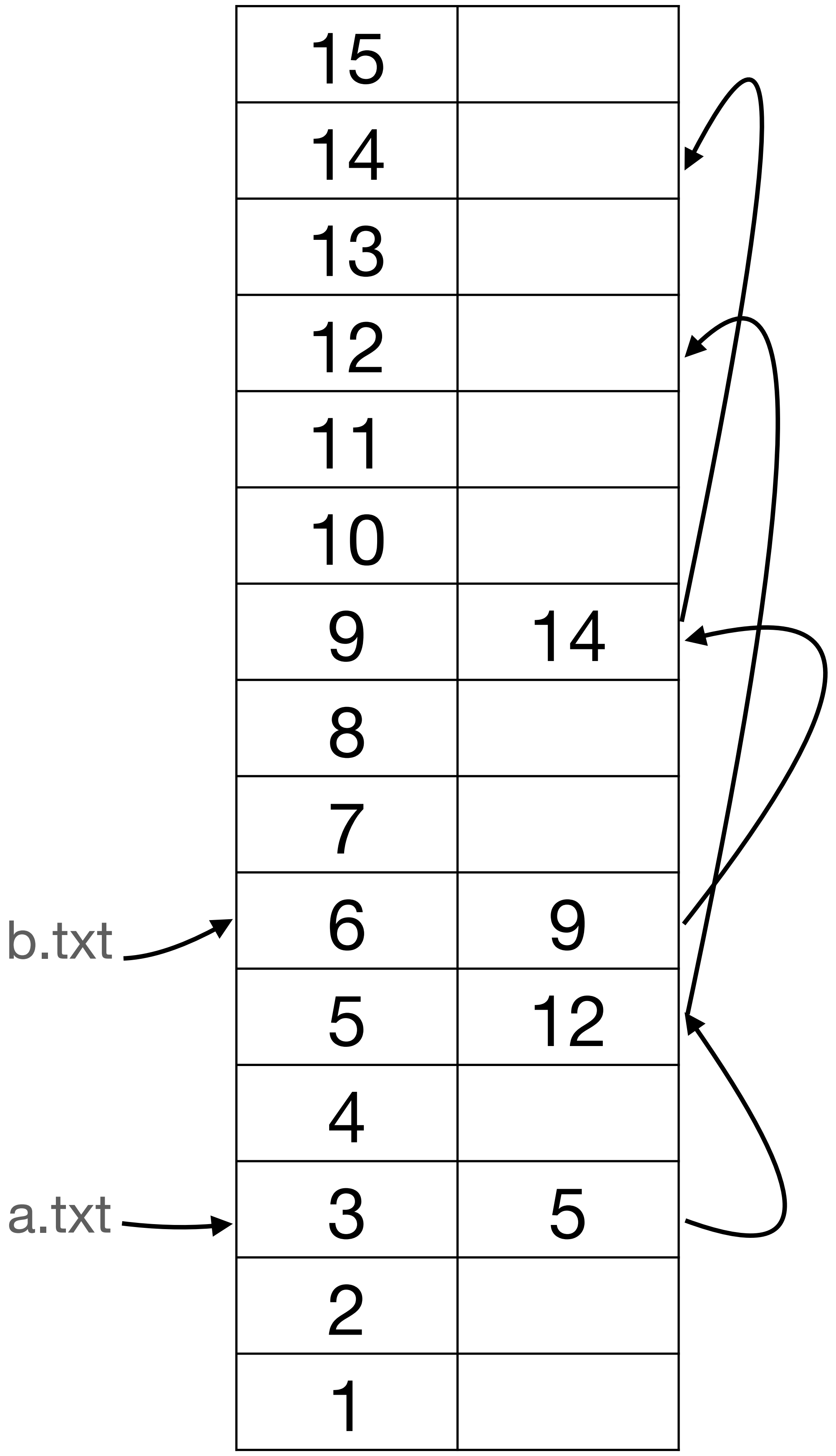
- Seeks / appends are terrible:
  - Need to read the whole file
- Sequential rws become random disk rws
  - Cannot send >1 in-flight IO requests. Lose disk scheduling potential.
- If one block gets corrupted, parts of the file is lost



How to store files?

File Allocation Table (FAT filesystem)

- Fast seeks/appends
  - Bring table into memory, do pointer chasing in memory
- Size of block: 2KB to 32KB.
  - FAT16
    - 2^16 entries. Maximum disk size: 2^16 * 2KB = 128 MB
    - Size of table = 2^16*(2 bytes) = 128KB
  - FAT32
    - 2^28 entries. Maximum disk size: 2^28 * 2KB = 512 GB
    - Size of table = 2^28 * (4 bytes) = 1GB
- Reliability:
  - Lose file system if we lose FAT table. Keep two copies.

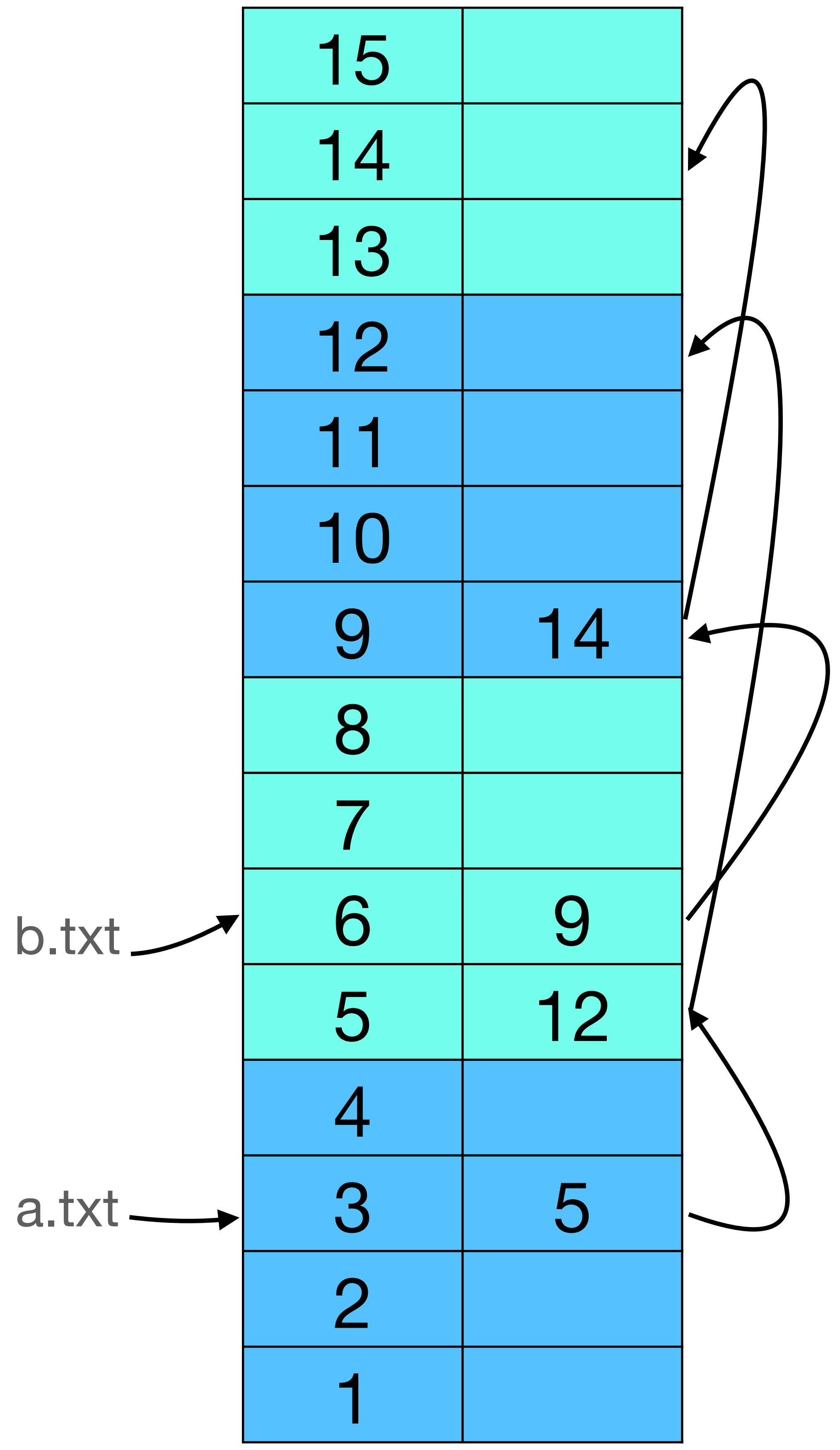


Block size in FAT

- Large block size:
  - ✓ Support larger disks
  - ✓ Reduced random IO
  - ✓ Reduced Metadata overhead. FAT32 overhead: 4 bytes / 2KB ~ 0.2%; 4 bytes / 32KB ~ 0.01%
  - Increased internal fragmentation: minimum file size is block size
  - Increase buffer cache pressure: lesser number of blocks can be cached

Performance

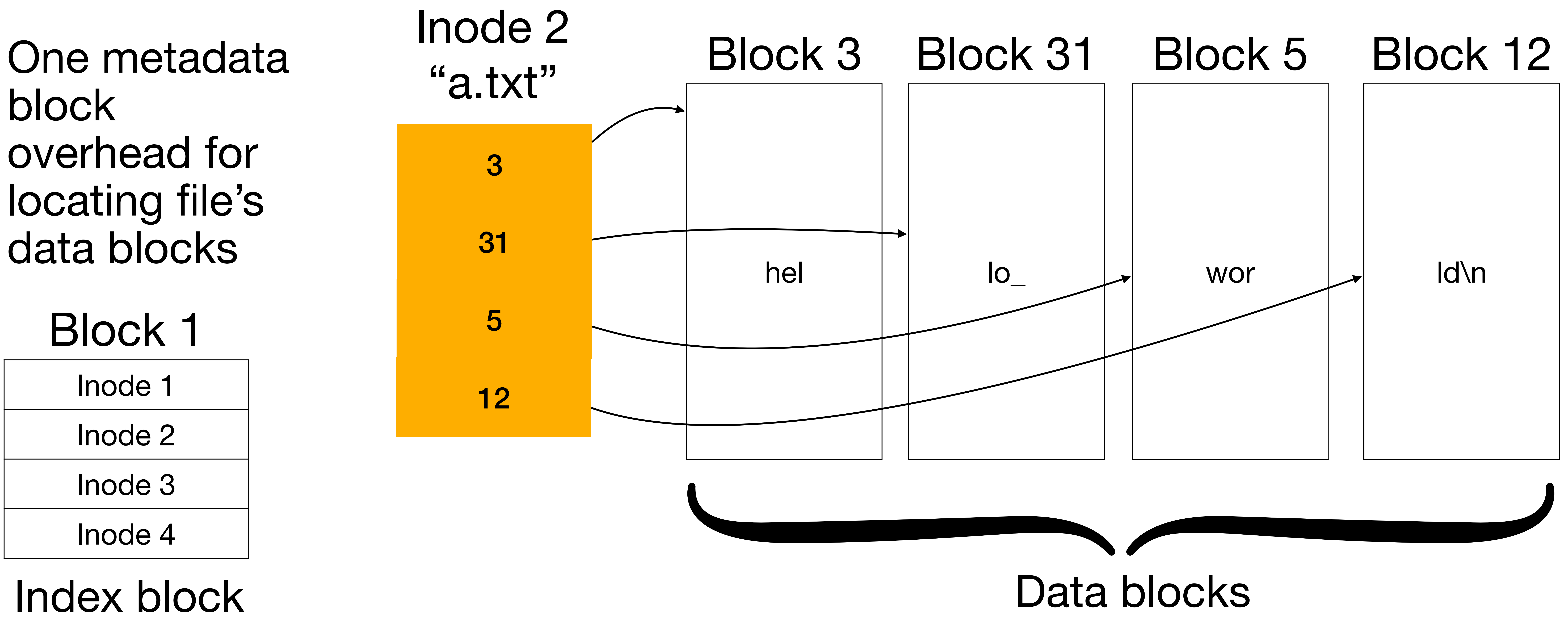
- Sequential IO
    - Better than linked list. Can find the list of blocks apriori and send requests. Disk controller can schedule them.
    - Worse than contiguous allocation since it did only 1 seek.
- Random IO
    - As fast as it can be. Find the block in memory and send disk request
- Use buffer cache for FAT table when it does not fit in memory (1GB for FAT-32)
    - To locate file's blocks, we might have to read many metadata blocks



How to store files?

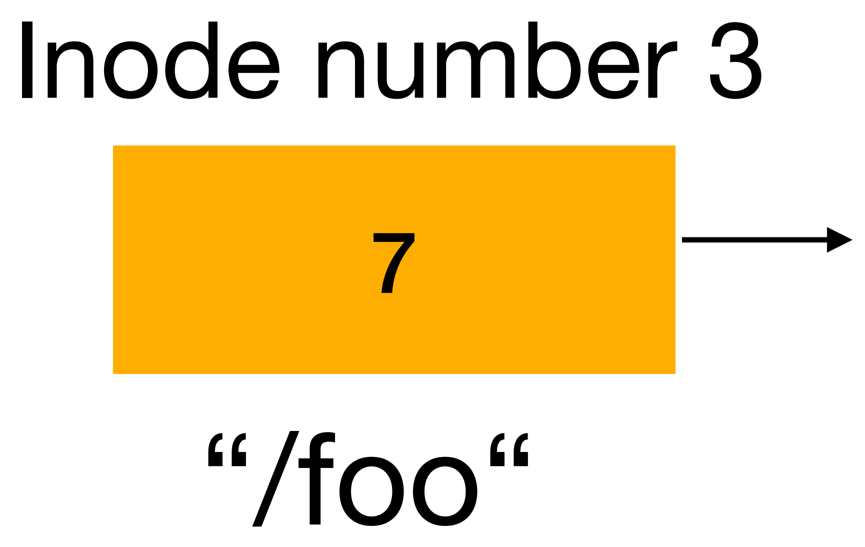
Index and data blocks

- One metadata block overhead for locating file's data blocks



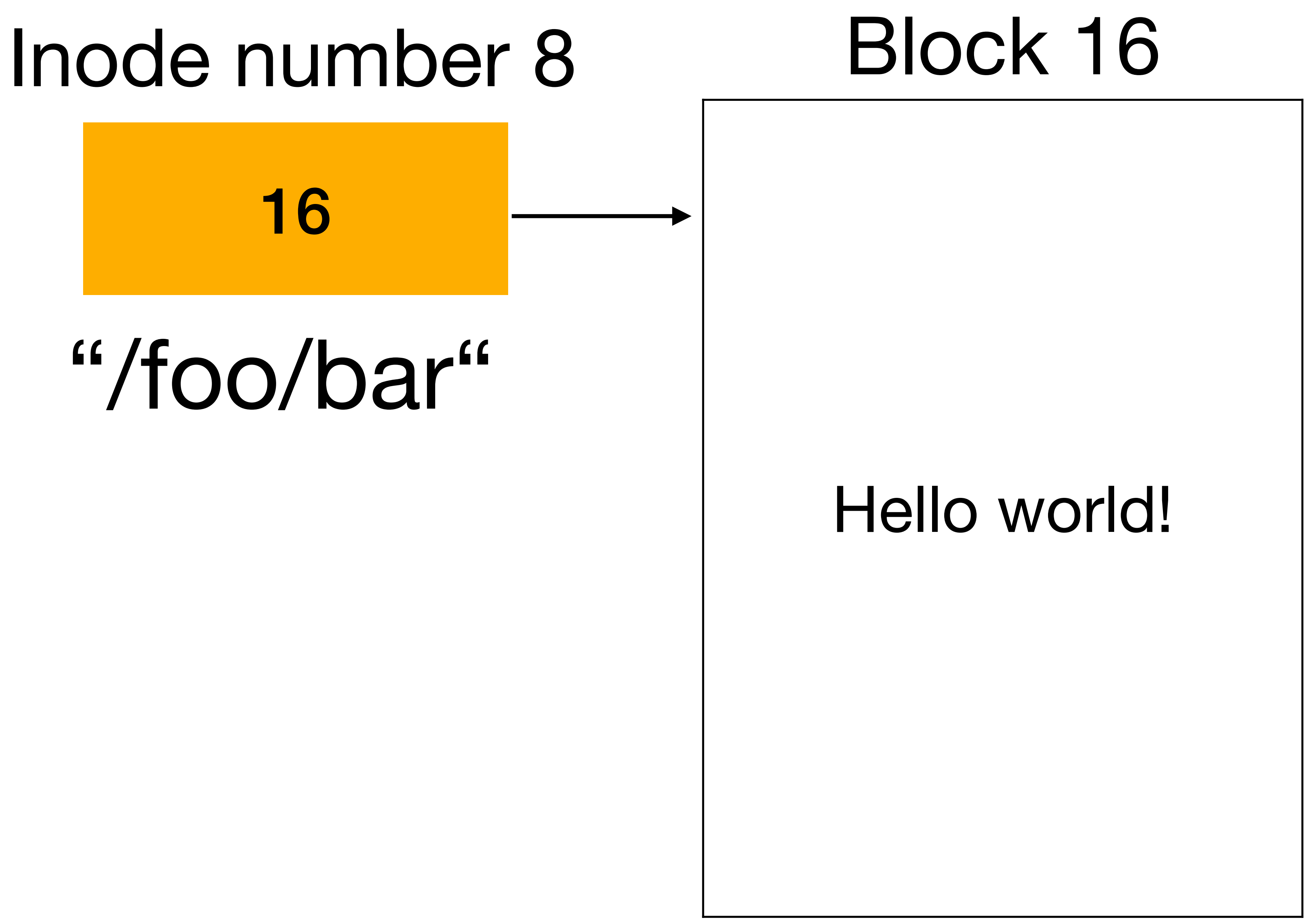
How to store directories?

/foo/bar



Block 7

File/directory name	Inode number
.	3
..	1
bar	8
…	…



- In xv6, each directory entry is 16 bytes. 32 (=512/16) directory entries in one data block
- Directories have typically < 20 files and directories

Other things in inode

```
stat /tmp/file

  File: /tmp/file
  Size: 14         Blocks: 8          IO Block: 4096   regular file
Device: 803h/2051d Inode: 22414820    Links: 1
Access: (0600/-rw-------)  Uid: ( 1000/    dell)   Gid: ( 1000/    dell)
Access: 2024-01-24 06:29:51.395609006 +0530
Modify: 2024-01-24 06:29:51.395609006 +0530
Change: 2024-01-24 06:29:51.395609006 +0530
 Birth: -


Modify time: last time when data nodes were changed
Change time: last time when inode was changed
```

Type = directory
Size
Accessed Time
Created time
Modified time
Owner user ID
Owner group ID
rwx mode
nlinks
3

File system layout

Example: /foo/bar

Inode = 1 “/“

Type = directory
Size
2

Block 2

File/directory name	Inode number
.	1
foo	8

Inode = 8 “/foo“

Type = directory
Size
16

Block 16

File/directory name	Inode number
.	8
..	1
bar	9

Inode = 9 “/foo/bar”

Type = file
Size
3
31
5
12

Block 3	Block 31	Block 5	Block 12
hel	lo	wor	ld

Reading a file

Example: /foo/bar

```
char buf[10];
fd = open("/foo/bar", O_RDONLY)

while(read(fd, &buf, 10) > 0) {
    // print buf etc.
}
close(fd);
```

Inode = 1 "/"

	Type = directory
	Size
	Access time
1	2

Block 2

	File/directory name	Inode number
	.	1
2	foo	8

Inode = 8 "/foo"

	Type = directory
	Size
	Access time
3	16

Block 16

	File/directory name	Inode number
	.	8
	..	1
4	bar	9

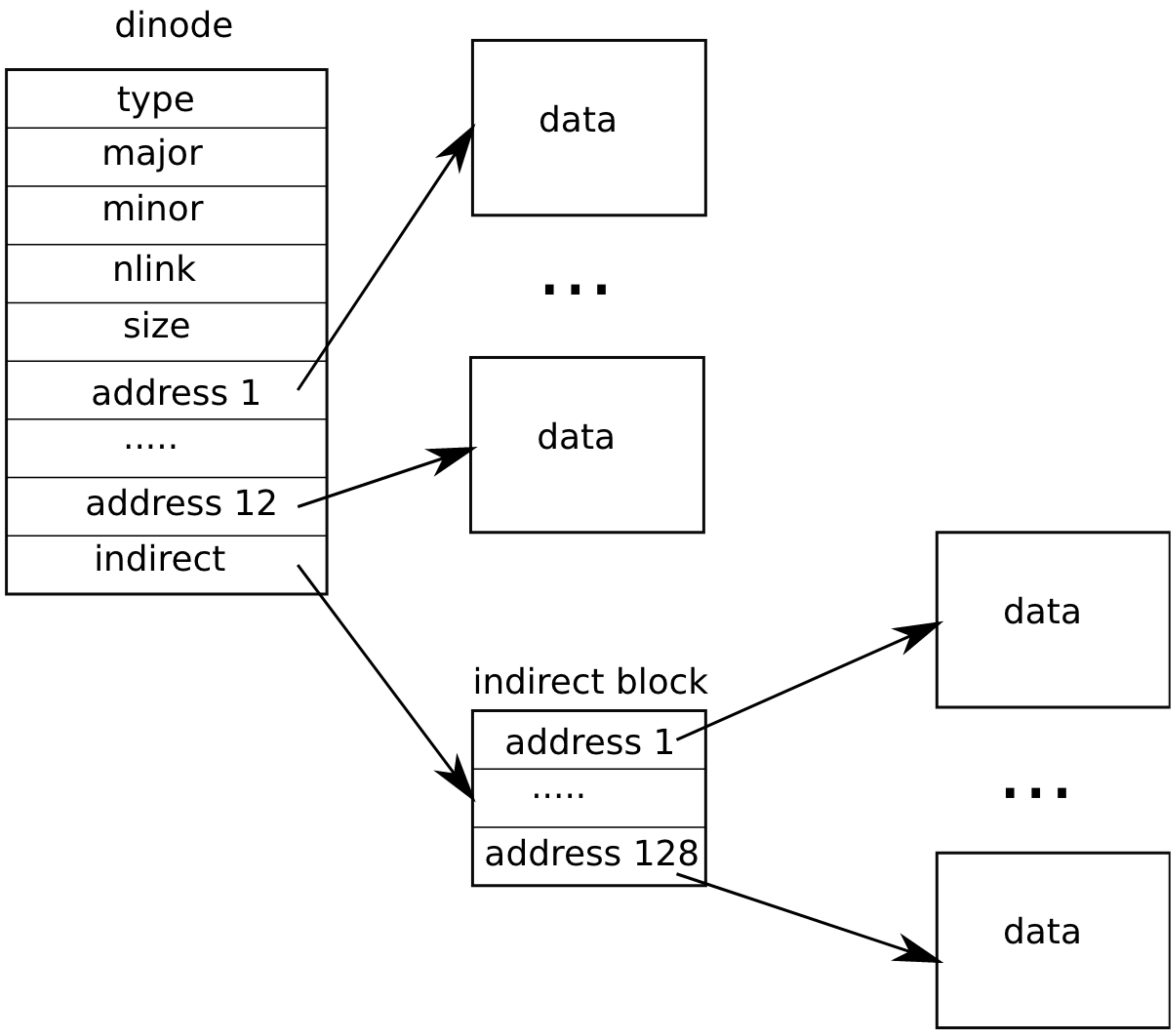
Inode = 9 "/foo/bar"

	Type = file	
	Size	
	Access time	13
5	3	
	31	7
9	5	
	12	11

Block 3	Block 31	Block 5	Block 12
6	8	10	12
hel	lo	wor	ld

Storing large files

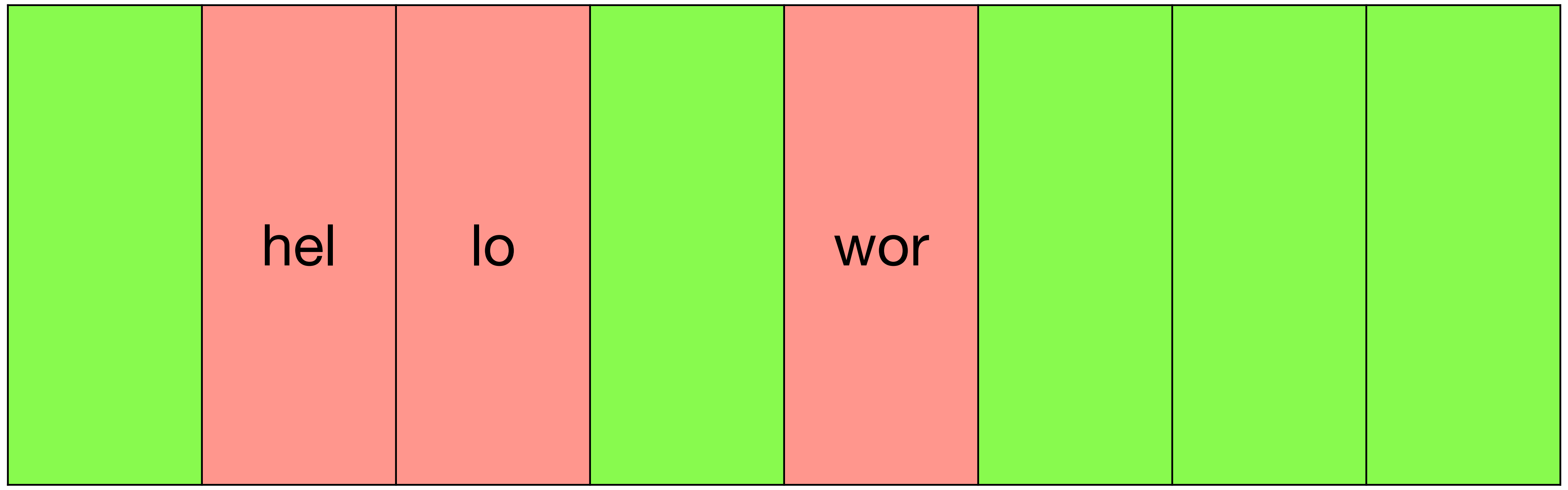
- Keep inodes of fixed size (64 bytes) for simplicity
- 8 inodes in a 512 byte block
- Most files are < 2KB
- 12*512 bytes = 6KB
- Most files do not need indirect block



How to track free blocks?

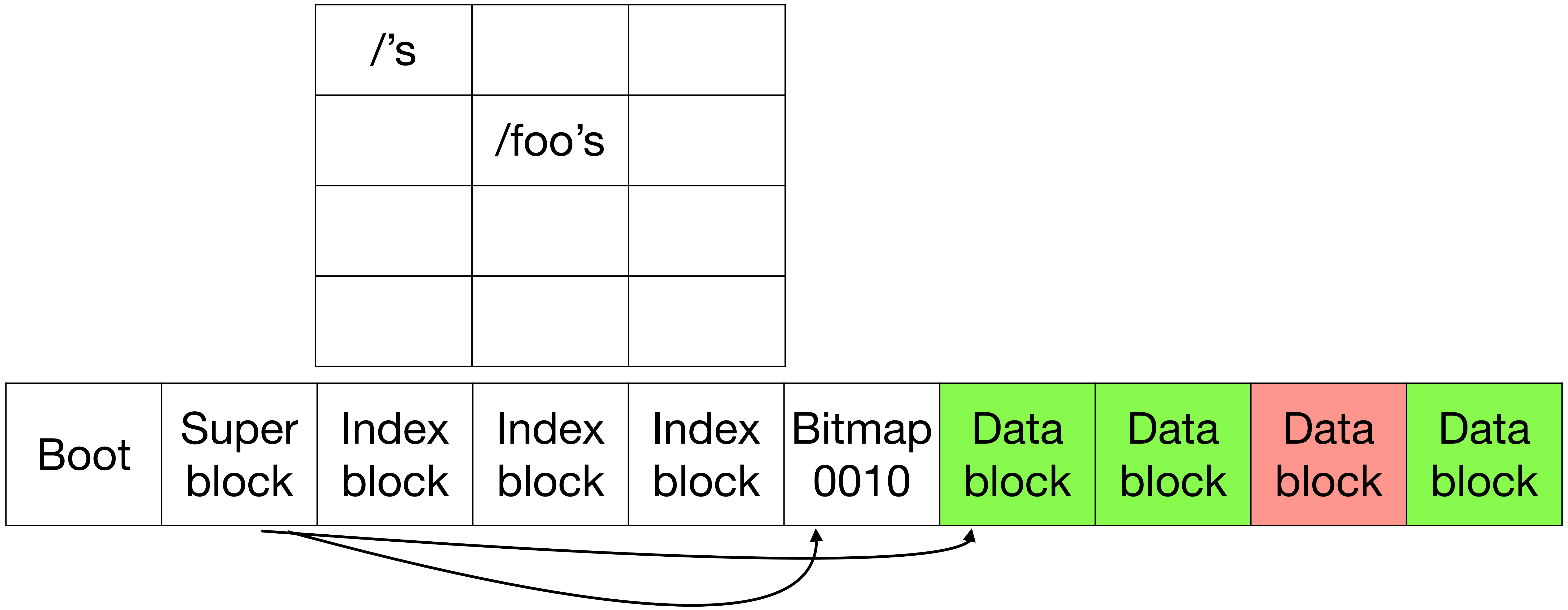
- Keep bitmap in another block

10010111



Putting it all together: xv6 FS organisation

- Data region contains actual file and directory data
- File system structure is maintained via nodes stored in index blocks
- Superblock contains file system metadata:
  - how many inodes are in system, etc



Writing a file
Example: /foo/bar

```
fd = open("/foo/bar", O_CREATE)
write(fd, "hello world\n", 12);
close(fd);
```

Inode = 1 "/"

Type = directory
Size
2

Block 2

File/directory name	Inode number
.	1
foo	8

Inode = 8 "/foo"

Type = directory
Size
16

Block 16

File/directory name	Inode number
.	8
..	1
bar	2

Inode = 2 "/foo/bar"

Type = file
Size
Modified time
3
5
7
12

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 3	Block 5	Block 7	Block 12
hel	lo	wor	ld

Xv6 code walkthrough

p8-read-fs

- fs.h
  - ROOTINO=1: root folder is at the first inode
  - struct superblock
  - NDIRECT: 12 direct pointers. NINDIRECT: Number of pointers that can fit in the second-level pointer node (128).
  - MAXFILE: maximum number of data blocks (140). Max file size is 70 KB
  - struct dinode (16 bytes). IPB = 32.
  - struct dirent. 16 bytes. 32 directory entries in one data block of directory
- Makefile, mkfs.c creates a disk image with the file system containing one “/welcome.txt” file
- main.c reads and prints contents from welcome.txt

File System Optimizations

OSTEP Ch.41

Performance problems

- Fragmentation
- Poor locality
- Poor use of the buffer cache
- Minimal disk scheduling opportunities

Fragmentation problem

- Over time, a file's data blocks get spread all over the disk
  - Disk head(s) need to go back and forth to read files sequentially

A1	A2	B1	B2	C1	C2	C3	D1				
A1	A2	B1	B2	C1	C2	C3	D1	A3			
A1	A2	B1	B2	C1	C2	C3		A3			
A1	A2	B1	B2	C1	C2	C3	E1	A3			
A1	A2			C1	C2	C3	E1	A3			
A1	A2	E2		C1	C2	C3	E1	A3			

Fragmentation problem

Defragmentation

- Defragmenter rearranges data blocks
    - Also updates data block pointers in file's inode
- Modern FS such as ext4 do defragmentation in background: without making FS unavailable

A1	A2	E2		C1	C2	C3	E1	A3			

A1	A2	A3	C1	C2	C3	E1	E2				

Fragmentation problem

Pre-allocate blocks

- Disks have grown bigger
  - Ext3 pre-allocates 8 blocks at file creation
- Reduce metadata lookup overhead by keeping extents

A
1
2
3
4

A
1, 4

A1	A2		B1	B2		C1	C2		D1		

A1	A2	A3	B1	B2		C1	C2		D1		

A1	A2	A3	B1	B2		C1	C2				

A1	A2	A3	B1	B2		C1	C2		E1		

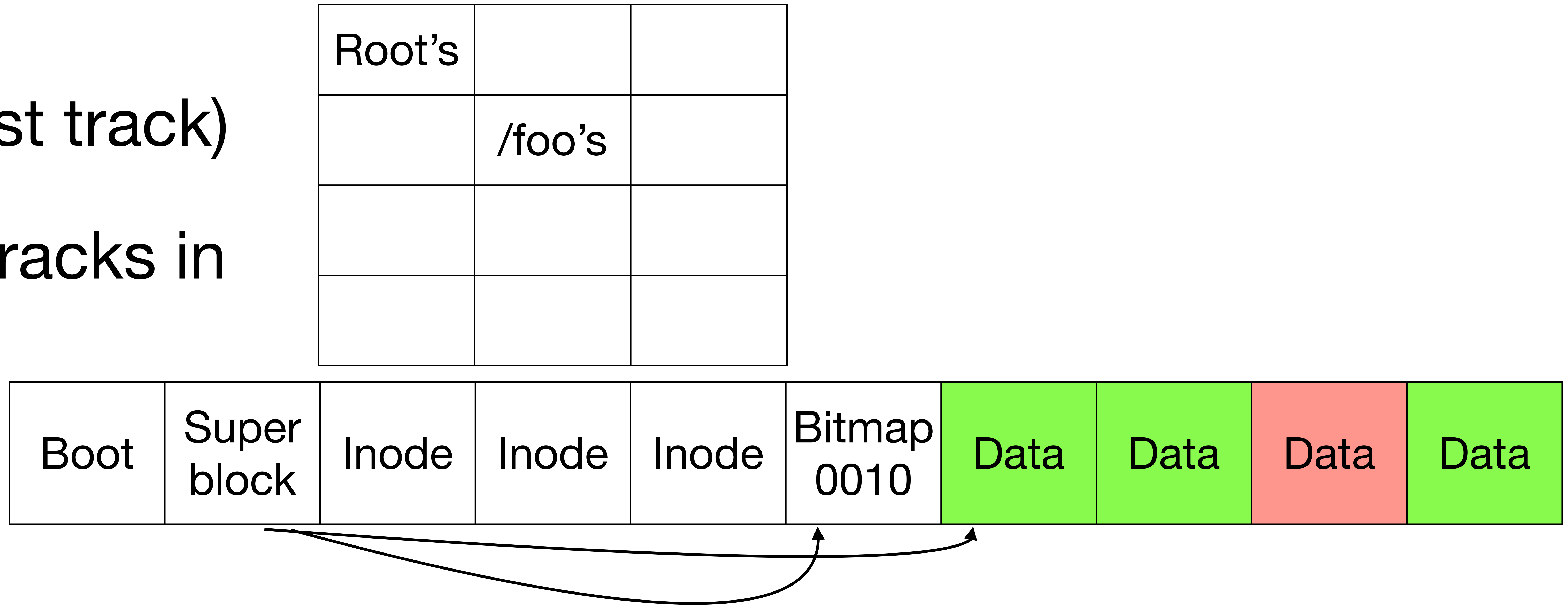
A1	A2	A3				C1	C2		E1		

A1	A2	A3				C1	C2		E1	E2	

A1	A2	A3	A4			C1	C2		E1	E2	

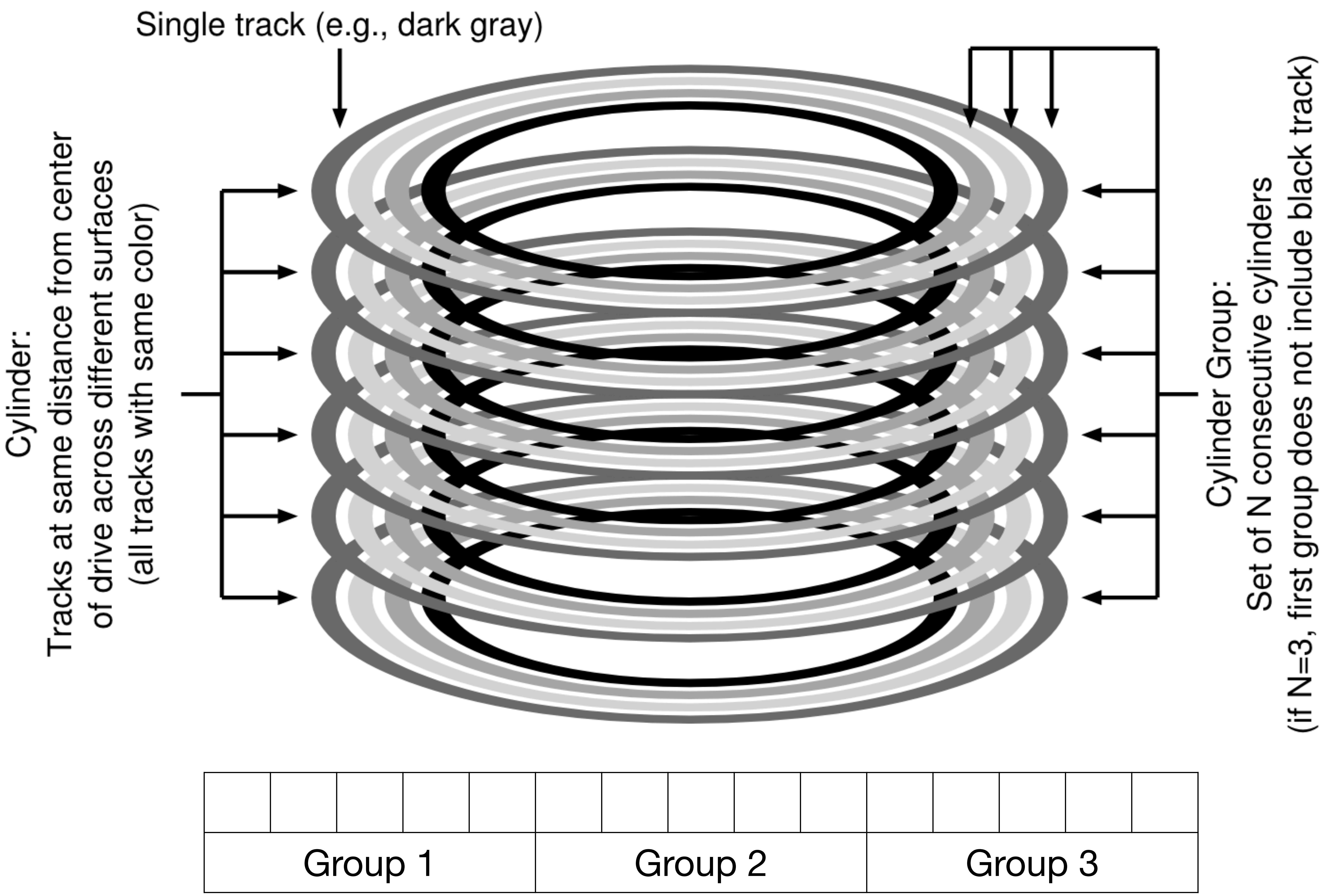
Locality problem

- Fast `ls`: just lookup inodes
- inodes and data blocks are far apart: slow file reads
- Back and forth disk head movement at write time:
    - inodes, bitmap (inner most track)
    - data blocks (outer most tracks in worst case)



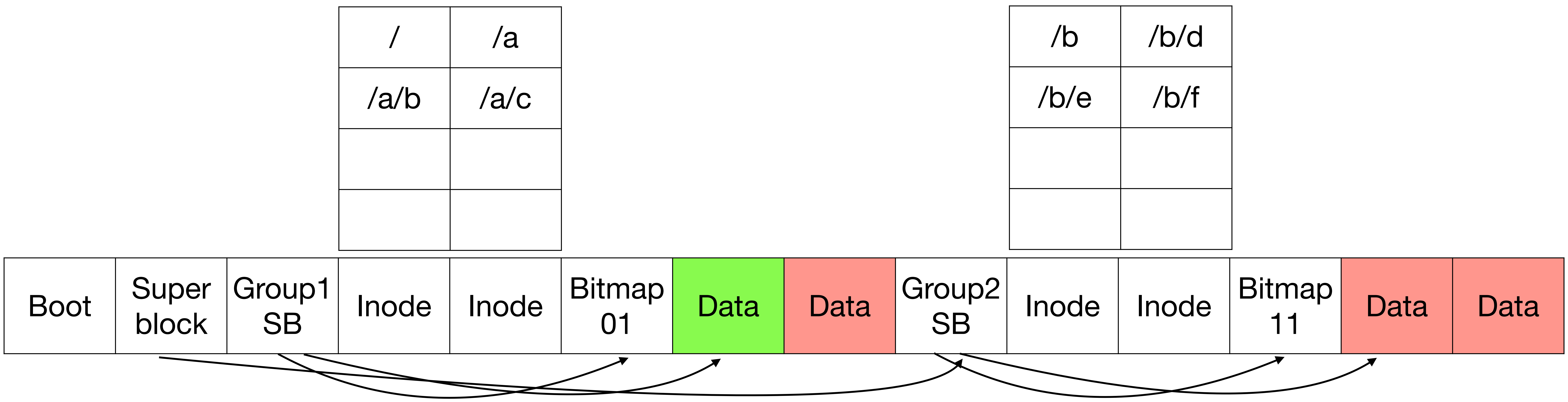
Break disk into locality groups

- Data on the same cylinder require no seek
- Break disk into "cylinder groups"
- Try to keep accesses limited within a group



Locality-aware file system

- Principle: Keep related stuff together



Greedy allocation

- Keep inode and data blocks of each file/directory in the same group.
- Allocate new files and directories on the most empty group
- /a, /a/c, /a/d, /a/e, /b, /b/f
- Very slow
  - `ls -l /a`
  - Linking /a/c, /a/d, /a/e to create an executable

Group	inodes	Data blocks
1	/_______	/__________
2	a_______	a__________
3	b_______	b__________
4	c_______	cc_________
5	d_______	dd_________
6	e_______	ee_________
7	f_______	ff_________
8	________	___________

Keeping related stuff together

- /a, /a/c, /a/d, /a/e
- /b, /b/f

Group	inodes	Data blocks
1	/_______	/__________
2	acde____	accddeee___
3	bf______	bff_________
4	_______	___________
5	_______	___________
6	_______	___________
7	_______	___________
8	_______	___________

What about large files?

- /a, /a/c, /a/d, /a/e
- /b, /b/f
- /a/d, /a/e got separated from /a

Group	inodes	Data blocks
1	/_______	/__________
2	ac______	accccccccccc
3	bf______	bff_________
4	_______	ccccccccc__
5	de_____	ddee_______
6	_______	___________
7	_______	___________
8	_______	___________

What about large files?

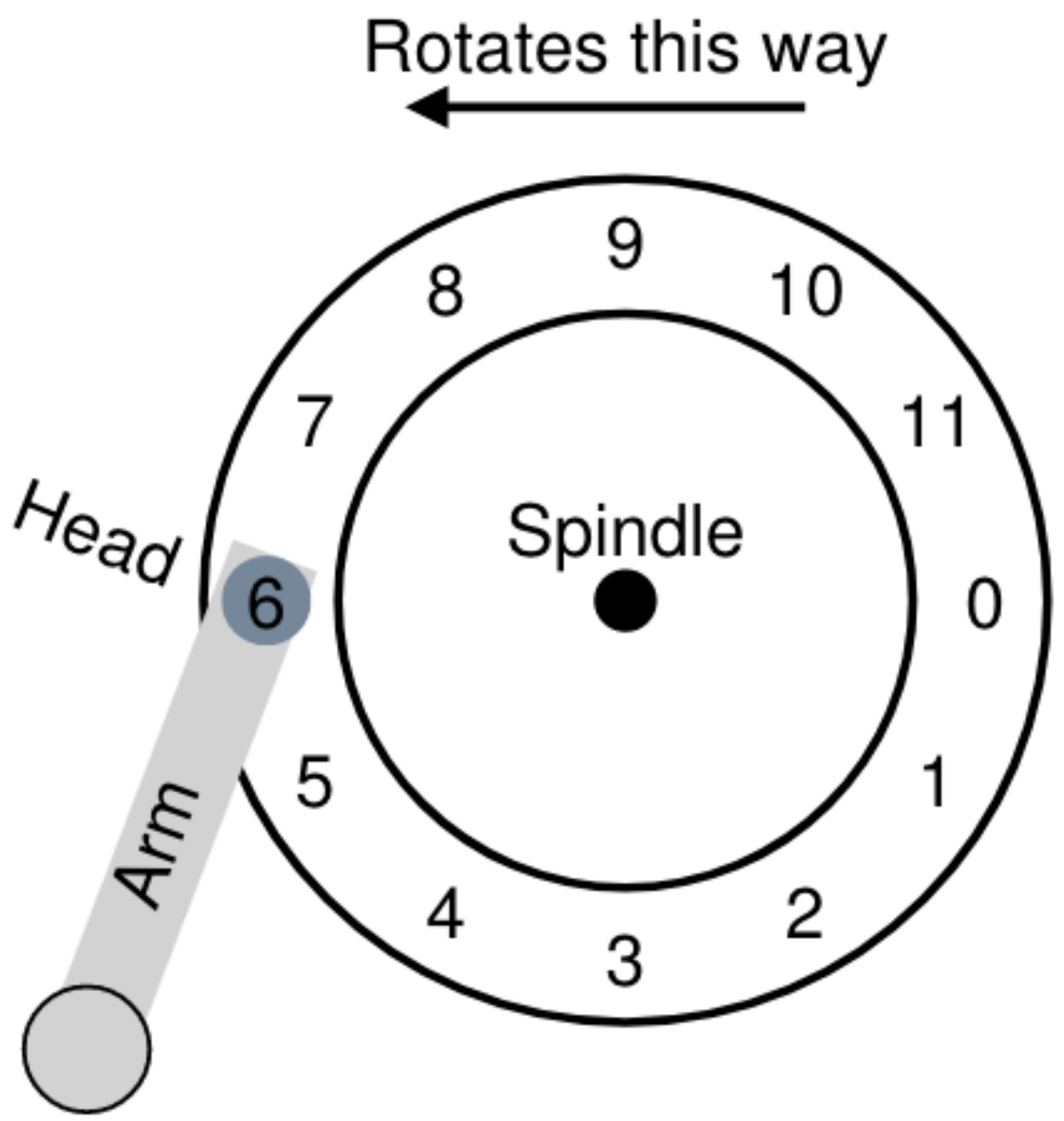
- /a, /a/c, /a/d, /a/e
- /b, /b/f
- Keep the data block of direct pointers within the group

Group	inodes	Data blocks
1	/_______	/__________
2	acde____	accddee____
3	bf______	bff_________
4	_______	ccccccccccc
5	_______	cccccc_____
6	_______	___________
7	_______	___________
8	_______	___________

Disk cache

Disk rotation

- By the time, FS could give command to read block 7, disk has already rotated
  - Disk controller caches sectors on the entire track



Buffer cache

Write-through cache

- Example: untar create and write 100 files

Directory data block

.	3
a.txt	4
b.txt	5

Inode bitmap

0	0	0	0	0	1	1	1

Data bitmap

0	0	0	0	0	0	0	0

aaaa

aaaa

bbbb

bbbb

Buffer cache

Write-back cache

- Absorb multiple writes into single write
- Better disk scheduling opportunity

Directory data block

.	3
a.txt	4
b.txt	5

Inode bitmap

0	0	0	0	0	1	1	1

Data bitmap

0	0	0	0	0	0	0	0

aaaa

aaaa

bbbb

bbbb

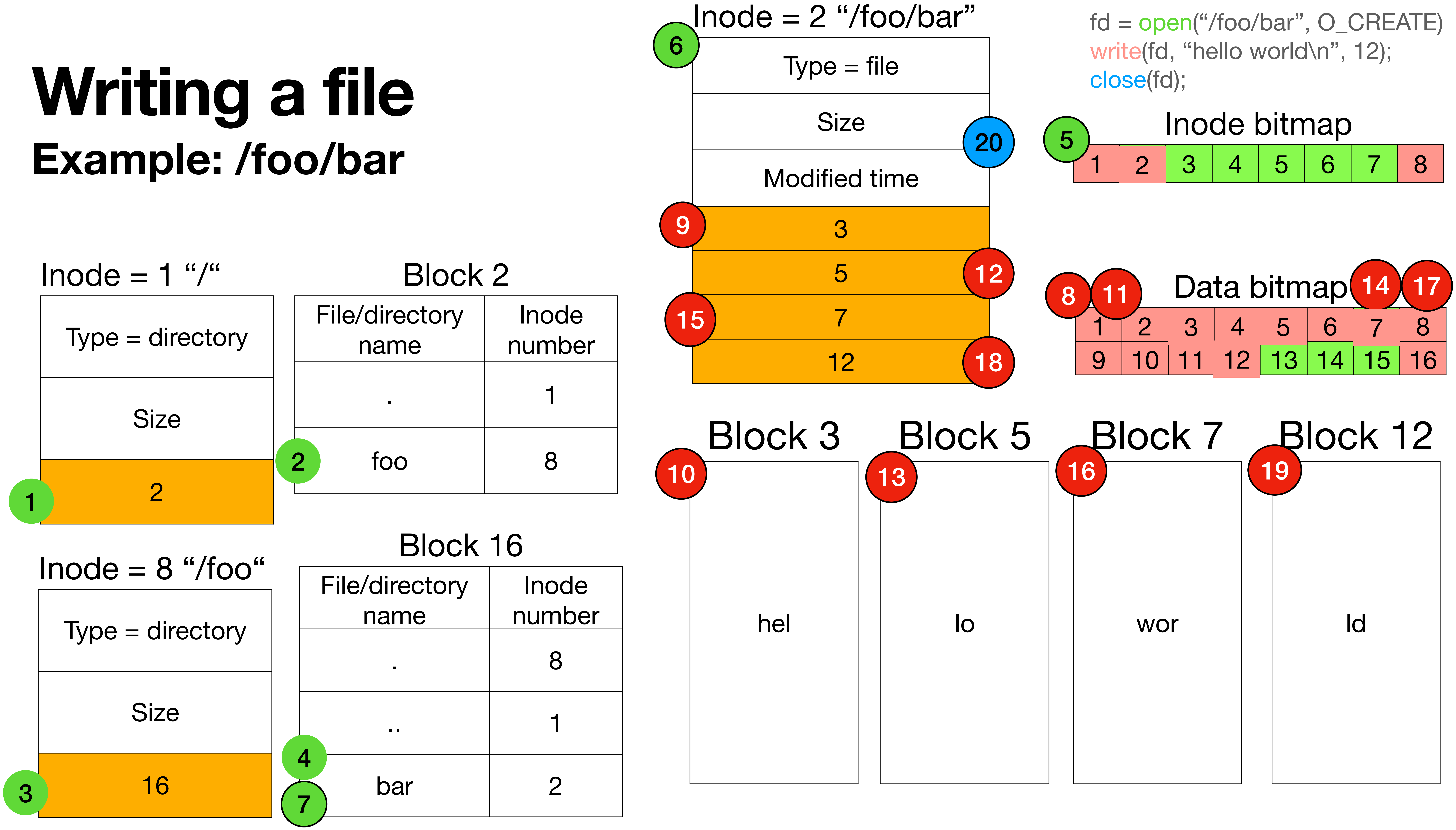
Crash consistency

OSTEP Ch.42

Writing a file

Example: /foo/bar

```
fd = open("/foo/bar", O_CREATE)
write(fd, "hello world\n", 12);
close(fd);
```



Crash problem

- Sending all the requests in parallel for better write throughput (disk scheduling)
- Crash can happen at any time => only a subset of blocks may get written

Inode = 2 “/foo/bar”

Type = file
Size
Modified time
3
5
7
12

```
fd = open(“/foo/bar”, O_CREATE)
write(fd, “hello world\n”, 12);
close(fd);
```

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 16

File/directory name	Inode number
.	8
..	1
bar	2

Block 3	Block 5	Block 7	Block 12
hel	lo	wor	ld

What can go wrong?

Missed data blocks

- File now contains garbage data

```
fd = open("/foo/bar", O_CREATE)
write(fd, "hello world\n", 12);
close(fd);
```

Inode = 2 "/foo/bar"

Type = file
Size
Modified time
3
5
7
12

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 16

File/directory name	Inode number
.	8
..	1
bar	2

Block 3	Block 5	Block 7	Block 12
xaw	1234	?.pw	.ELF

What can go wrong?

Missed data bitmap

- File initially looks ok
- Data blocks can get overwritten later by contents of another file

Inode = 2 “/foo/bar”

Type = file
Size
Modified time
3
5
7
12

```
fd = open(“/foo/bar”, O_CREATE)
write(fd, “hello world\n”, 12);
close(fd);
```

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 16

File/directory name	Inode number
.	8
..	1
bar	2

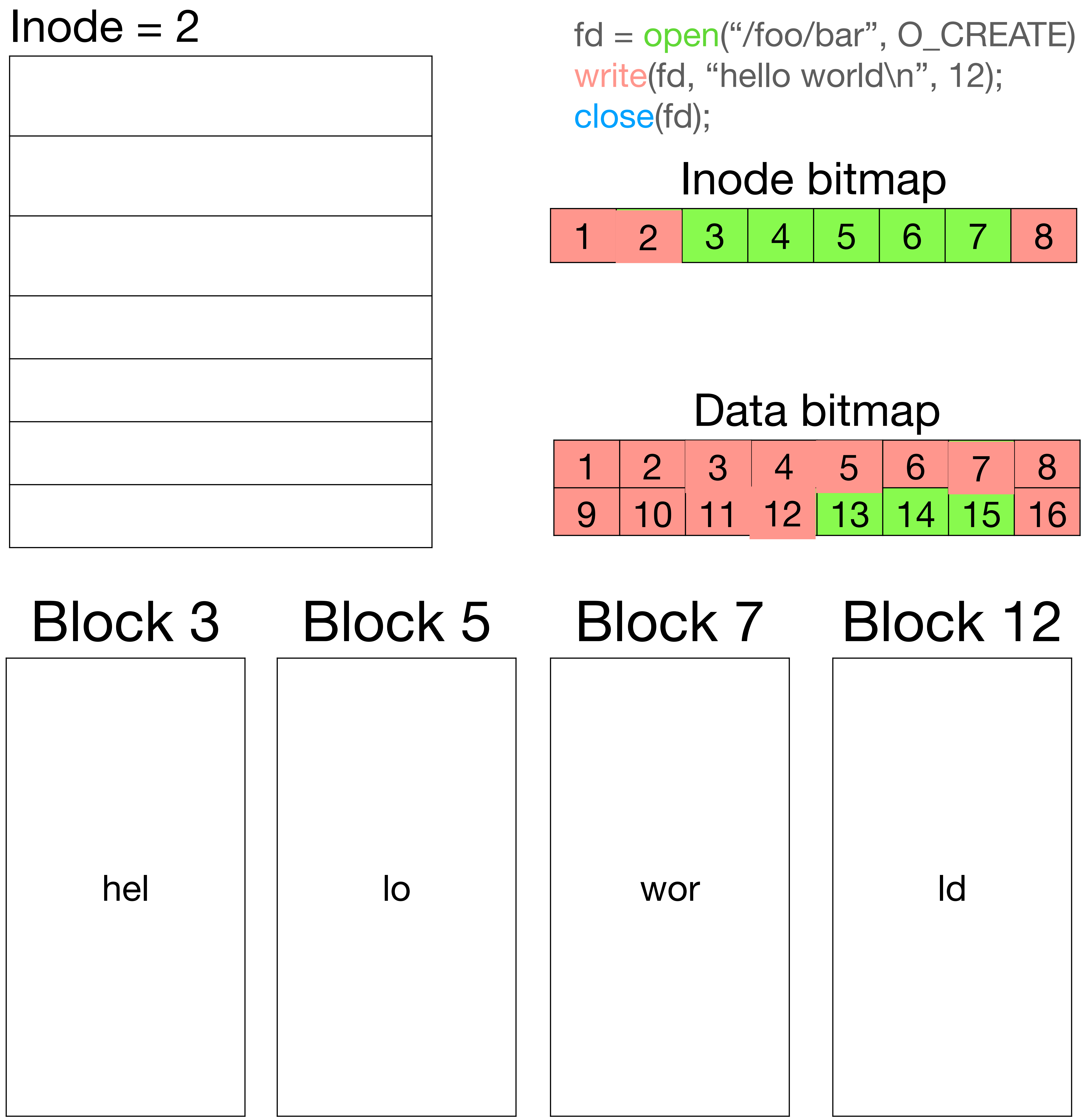
Block 3	Block 5	Block 7	Block 12
hel	lo	wor	ld

What can go wrong?

Missed file's inode block

- File data is present but not accessible via any file
- Leaked data blocks

```
fd = open("/foo/bar", O_CREATE)
write(fd, "hello world\n", 12);
close(fd);
```



Block 16

File/directory name	Inode number
.	8
..	1
bar	2

What can go wrong?

Missed file’s inode block

- Directory points to a deleted file. Leaked sensitive information

Inode = 2 “/pass”

Type = file
Size
Modified time
14

```
fd = open(“/foo/bar”, O_CREATE)
write(fd, “hello world\n”, 12);
close(fd);
```

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 16

File/directory name	Inode number
.	8
..	1
bar	2

Block 3	Block 5	Block 7	Block 12
hel	lo	wor	ld

What can go wrong?

Missed parent’s inode block

- File exists but cannot be reached
- Leaks file inode and data blocks

```
fd = open(“/foo/bar”, O_CREATE)
write(fd, “hello world\n”, 12);
close(fd);
```

Inode = 2 “/foo/bar”

Type = file
Size
Modified time
3
5
7
12

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 3	Block 5	Block 7	Block 12
hel	lo	wor	ld

Block 16

File/directory name	Inode number
.	8
..	1

What can go wrong?

Missing inode bitmap

- Inode gets overwritten by another file => Lose file.
- Parent points to another file.
- Leaked data blocks.

```
fd = open("/foo/bar", O_CREATE)
write(fd, "hello world\n", 12);
close(fd);
```

Inode = 2 "/foo/bar"

Type = file
Size
Modified time
3
5
7
12

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 16

File/directory name	Inode number
.	8
..	1
bar	2

Block 3	Block 5	Block 7	Block 12
hel	lo	wor	ld

Crash consistency

- Make writes atomic with respect to power failures / kernel crashes
- Either all the blocks are written or none of the blocks are written
- Challenge: Disk only writes one block at a time

```
fd = open("/foo/bar", O_CREATE)
write(fd, "hello world\n", 12);
close(fd);
```

Inode = 2 "/foo/bar"

Type = file
Size
Modified time
3
5
7
12

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 16

File/directory name	Inode number
.	8
..	1
bar	2

Block 3	Block 5	Block 7	Block 12
hel	lo	wor	ld

Durability guarantees

```
write(fd, ...) {
    begin_txn(..);
    bwrite( .. );
    bwrite( .. );
    bwrite( .. );
    end_txn(..);
}
```

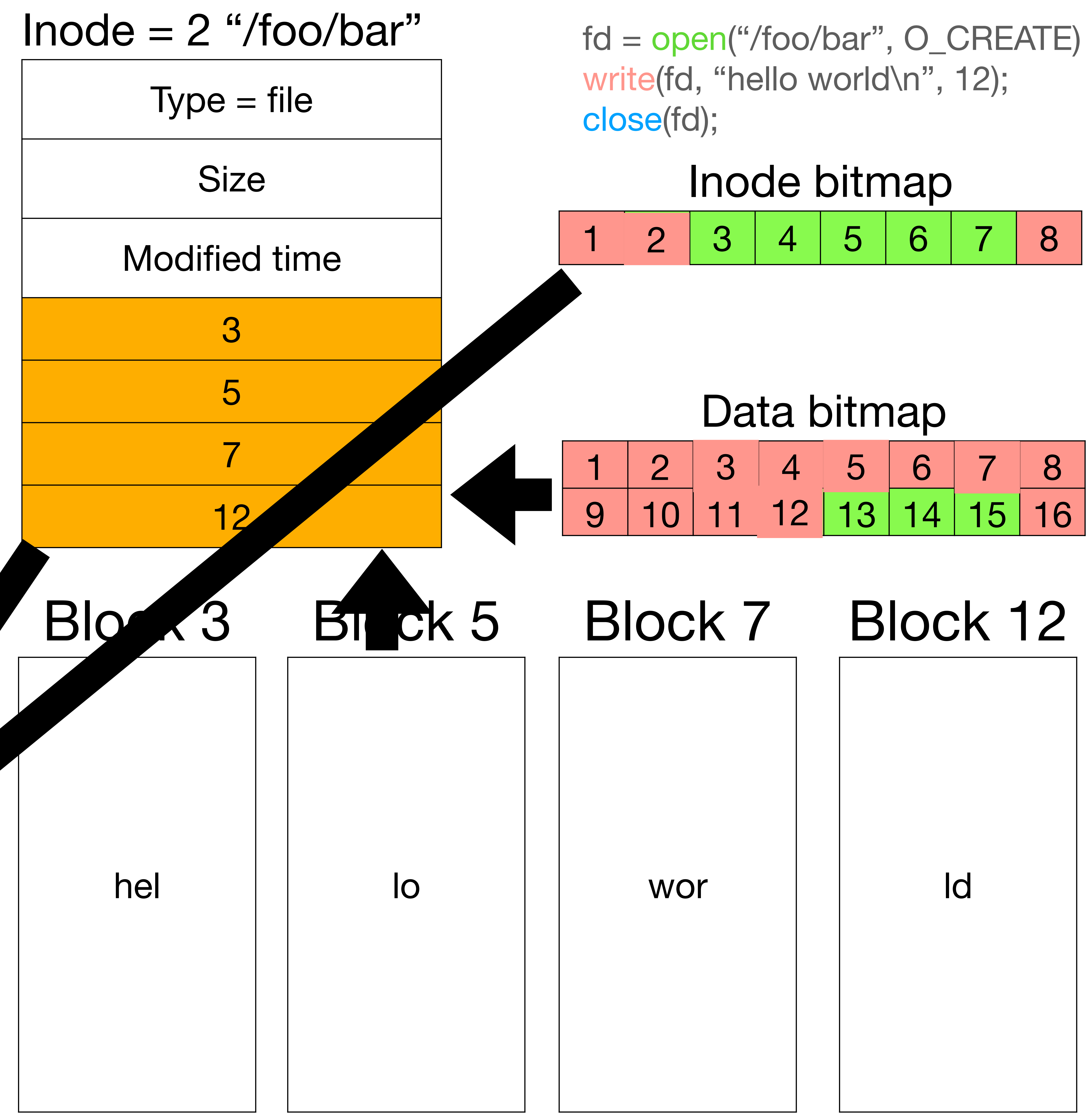
```
fd = open("/foo/bar", O_CREATE)
write(fd, ...);
write(fd, ...);
write(fd, ...);
close(fd);
```

- At every write call. Most conservative.
    - Buffer cache is write-through. Terrible performance
- At close. Example: network file systems.
    - Long file operations increase risk of loss. Writing many small files is slow.
- At some point in the future (within 5 to 30 seconds)
    - Most performant. Buffer cache is write-back.
    - One transaction contains several operations
    - fsync to ensure that write is on disk. time ./fsync

```
write(fd, ...) {
    begin_op(..);
    bwrite( .. );
    bwrite( .. );
    bwrite( .. );
    end_op(..);
}
```

Order writes

- Dangling pointers are very bad! Can live with space leaks.
- Avoid dangling pointers by ordering writes. First write child, then parent
- Modern disks allow specifying ordering.



Block 16

File/directory name	Inode number
.	8
..	1
bar	2

What about deletes?

- Truncate

```
fd = open("/foo/bar", O_CREATE)
write(fd, "hello world\n", 12);
close(fd);
```

Inode = 2 "/foo/bar"

Type = file
Size
Modified time
3
5
~~7~~
~~12~~

Inode bitmap

1	2	3	4	5	6	7	8

Data bitmap

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16

Block 3

hel

Block 5

lo

Block 7

wor

Block 12

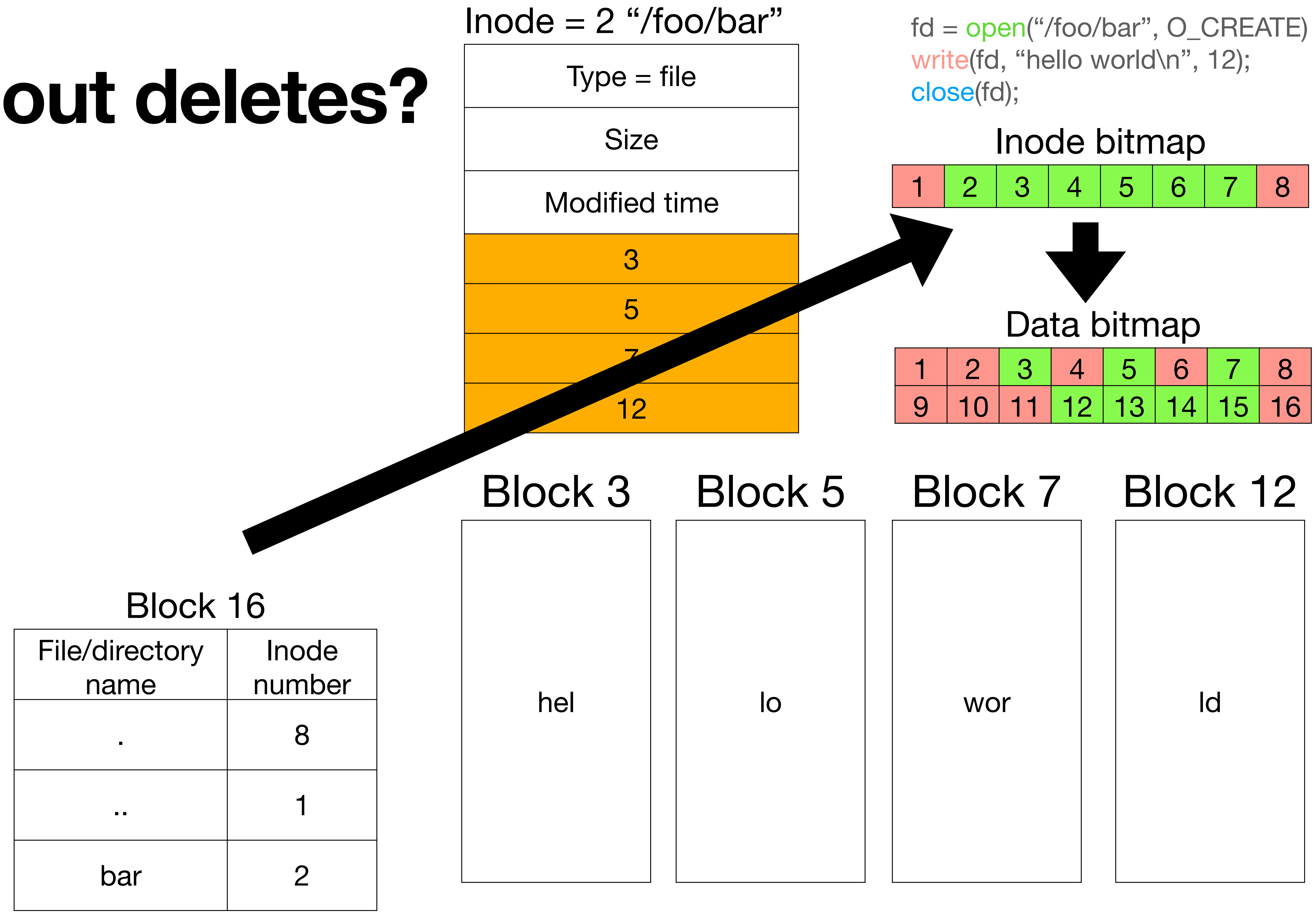
ld

Block 16

File/directory name	Inode number
.	8
..	1
bar	2

What about deletes?

- Unlink



What about moves?

mv a/foo b/

“a” data block

File/directory name	Inode number
foo	2

“b” data block

File/directory name	Inode number
bar	36

Operations in a transaction can create circular dependencies

mv a/foo b/; mv b/bar a/;

- Detect cycles before happening.
- Close the transaction. Flush to disk.

“a” data block

File/directory name	Inode number
foo	2

“b” data block

File/directory name	Inode number
bar	36