15-410

"...Does this look familiar?..."

File System (Internals)
Nov. 6, 2006

Dave Eckhardt

Bruce Maggs

Greg Hartman

Synchronization

Sun is recruiting kernel hackers

- Solaris Kernel Development at Sun Microsystems
  - Wednesday, November 8
  - Scaife Hall, Room 214
  - 6-8pm

Today

- Chapter 11 (not: Log-structured, NFS, WAFL)

Outline

File system code layers (abstract)

Disk, memory structures

Unix “VFS” layering indirection

Directories

Block allocation strategies, free space

Cache tricks

Recovery, backups

File System Layers

Device drivers

- read/write(disk, start-sector, count)

Block I/O

- read/write(partition, block) [cached]

File I/O

- read/write (file, block)

File system

- manage directories, free space

File System Layers

Multi-filesystem namespace

- **Partitioning, names for devices**
- **Mounting**
- **Unifying multiple file system *types***
  - **UFS, ext2fs, ext3fs, reiserfs, FAT, 9660, ...**

Shredding Disks

Split disk into *partitions*/slices/minidisks/...

- PC: 4 “partitions” –e.g., Windows, FreeBSD, Plan 9
- Mac: “volumes” –can do: OS 9, OS X, user files

Or: glue disks together into *volumes*/logical disks

Partition may contain...

- Paging area
  - Indexed by in-memory structures
  - “random garbage” when OS shuts down
- File system
  - Block allocation: file # ⇒ block list
  - Directory: name ⇒ file #

Shredding Disks

```
# fdisk -s
/dev/ad0: 993 cyl 128 hd 63 sec
Part          Start          Size Type Flags
   1:             63       1233729 0x06 0x00
   2:        1233792       6773760 0xa5 0x80
```

Shredding Disks

```
8 partitions:
#        size   offset   fstype  [fsize bsize bps/cpg]
  a:   131072        0   4.2BSD   2048 16384   101   # (Cyl.    0 - 16*)
  b:   393216   131072     swap                       # (Cyl.   16*- 65*)
  c:  6773760        0   unused      0     0         # (Cyl.    0 - 839)
  e:    65536   524288   4.2BSD   2048 16384   104   # (Cyl.   65*- 73*)
  f:  6183936   589824   4.2BSD   2048 16384    89   # (Cyl.   73*- 839*)

Filesystem  1K-blocks    Used  Avail Capacity  Mounted on
/dev/ad0s2a     64462   55928   3378    94%    /
/dev/ad0s2f   3043806 2608458 191844    93%    /usr
/dev/ad0s2e     32206    7496  22134    25%    /var
procfs              4       4      0   100%    /proc

(FreeBSD 4.7 on ThinkPad 560X)
```

Disk Structures

Boot area (first block/track/cylinder)

- Interpreted by hardware bootstrap ("BIOS")
- May include partition table

File system control block

- Key parameters: #blocks, metadata layout
- Unix: "superblock"

"File control block" (Unix: "inode")

- ownership/permissions
- data location

Possibly a freespace map as well

Memory Structures

In-memory partition tables

- Sanity check file system I/O in correct partition

Cached directory information

System-wide open-file table

- In-memory file control blocks

Process open-file tables

- Open mode (read/write/append/...)
- “Cursor” (read/write position)

VFS layer

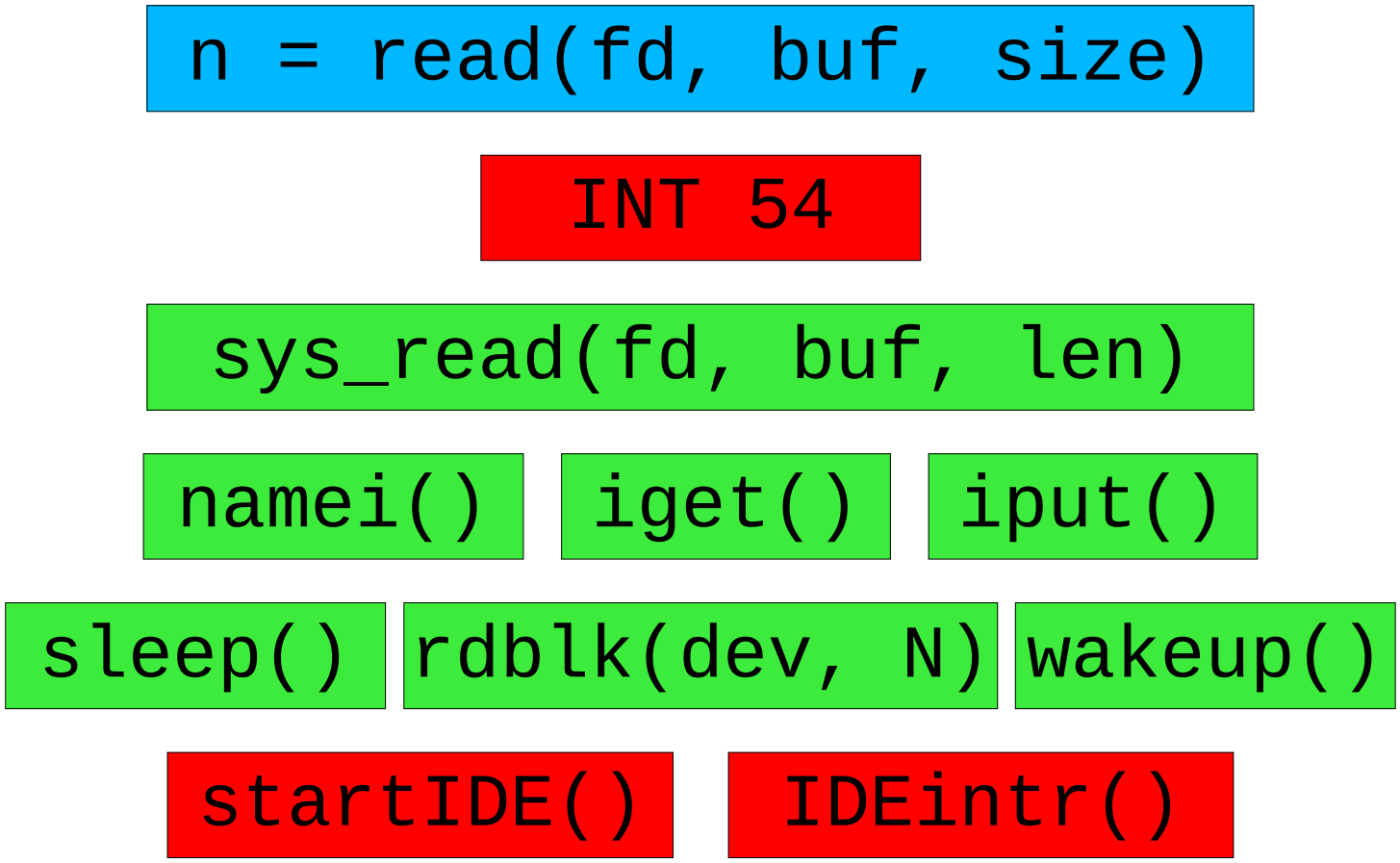
Goal

- Allow one machine to use multiple file system *types*
  - Unix FFS
  - MS-DOS FAT
  - CD-ROM ISO9660
  - Remote/distributed: NFS/AFS
- Standard system calls should work transparently

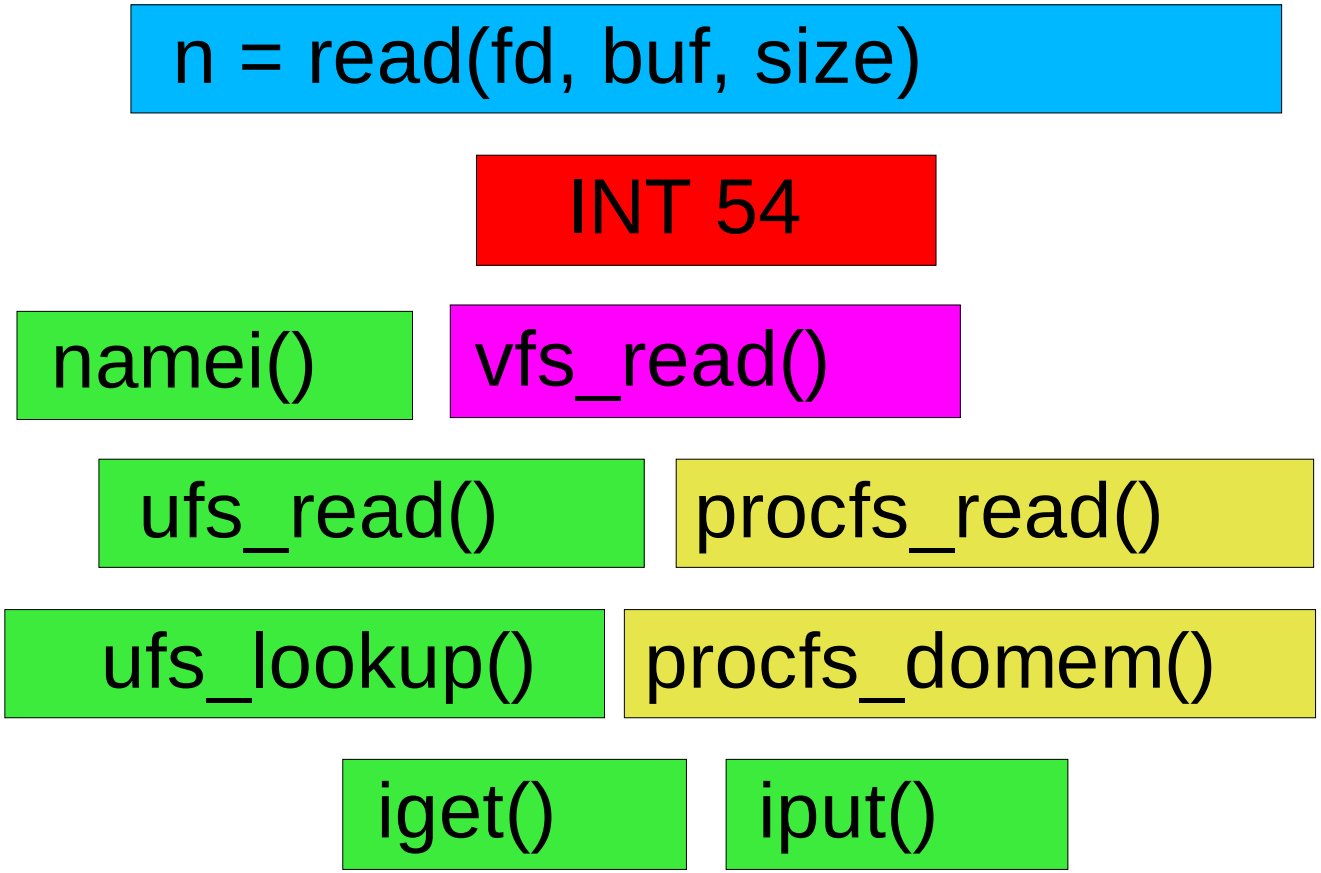
Solution

- Insert a level of indirection!

Single File System



VFS “Virtualization”



VFS layer –file system operations

```
struct vfsops {
  char *name;
  int (*vfs_mount)();
  int (*vfs_statfs)();
  int (*vfs_vget)();
  int (*vfs_unmount)();
  ...
}
```

VFS layer –file operations

Each VFS provides an array of methods

- **VOP_LOOKUP(vnode, new_vnode, name)**
- **VOP_CREATE(vnode, new_vnode, name, attributes)**
- **VOP_OPEN(vnode, mode, credentials, process)**
- **VOP_READ(vnode, uio, readwrite, credentials)**

Operating system provides fs-independent code

- **Validating system call parameters**
- **Moving data from/to user memory**
- **Thread sleep/wakeup**
- **Caches (data blocks, name ⇒ inode mappings)**

Directories

namei() ⇒ fs interface

- vnode2 = VOP_LOOKUP(vnode1, name)

Traditional Unix FFS directories

- List of (name,inode #) - not sorted!
- Names are variable-length
- Lookup is linear
  - How long does it take to delete N files?

Common alternative: hash-table directories

Allocation / Mapping

Allocation problem

- Where do I put the next block of this file?
- Near the previous block?

Mapping problem

- Where is block 32 of this file?
- Similar to virtual memory
  - Multiple large “address spaces” *specific to each file*
  - Only one underlying “address space” of blocks
  - Source address space may be sparse!

Allocation –Contiguous

Approach

- File location defined as (start, length)

Motivation

- Sequential disk accesses are cheap
- Bookkeeping is easy

Issues

- Dynamic storage allocation (fragmentation, compaction)
- Must pre-declare file size at creation
- This should sound familiar

Allocation –Linked

Approach

- File location defined as (start)
- Each disk block contains pointer to next

Motivation

- Avoid fragmentation problems
- Allow file growth

Issues?

Allocation –Linked

Issues

- 508-byte blocks don't match memory pages
- In general, one seek per block read/written - *slow!*
- *Very* hard to access file blocks at random
  - lseek(fd, 37 * 1024, SEEK_SET);

Benefit

- Can recover files even if directories destroyed

Common modification

- Linked multi-block *clusters*, not blocks

Allocation –FAT

Used by MS-DOS, OS/2, Windows

- Digital cameras, GPS receivers, printers, PalmOS, ...

Semantically same as linked allocation

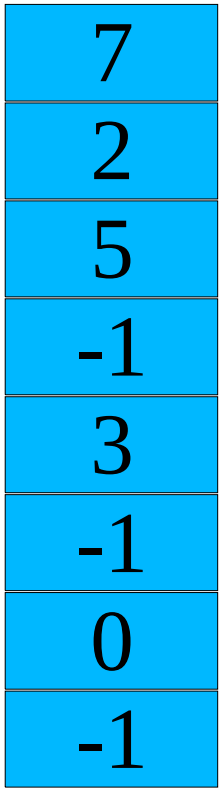
Links stored “out of band” in table

- Result: nice 512-byte sectors for data

Table at start of disk

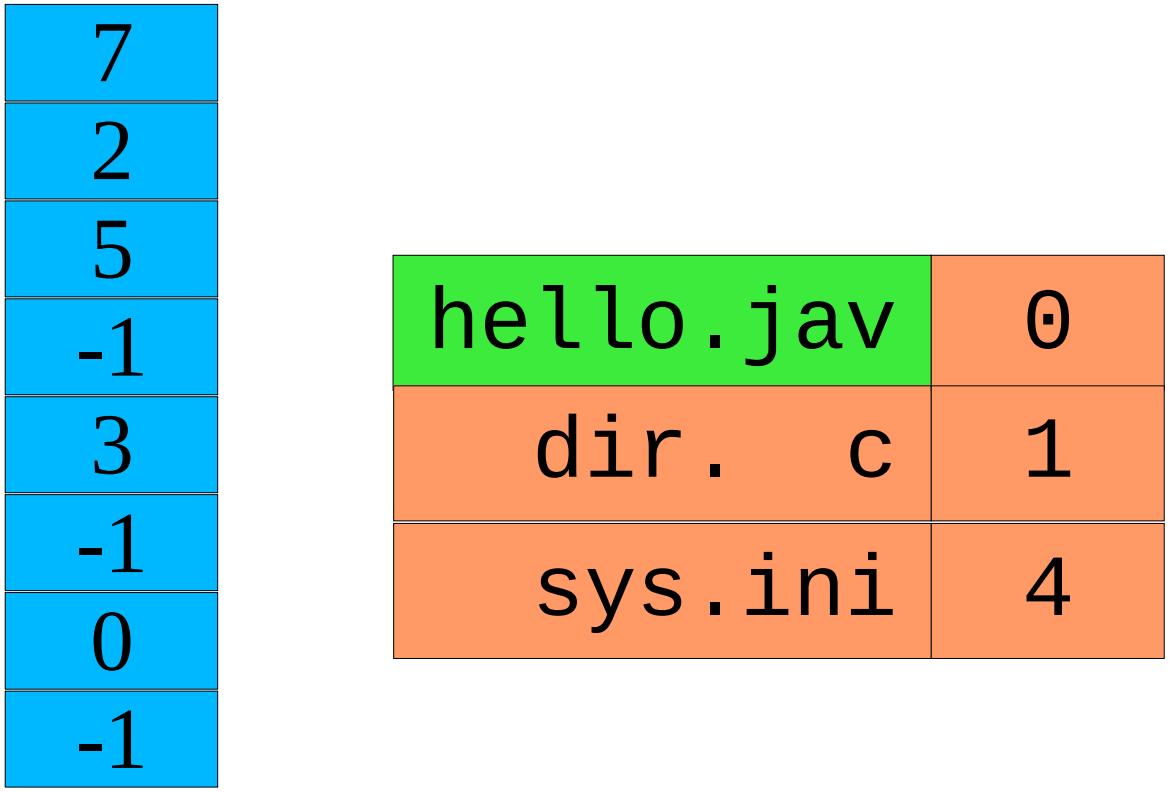
- Next-block pointer array
- Indexed by block number
- Next=0 means “free”

Allocation –FAT

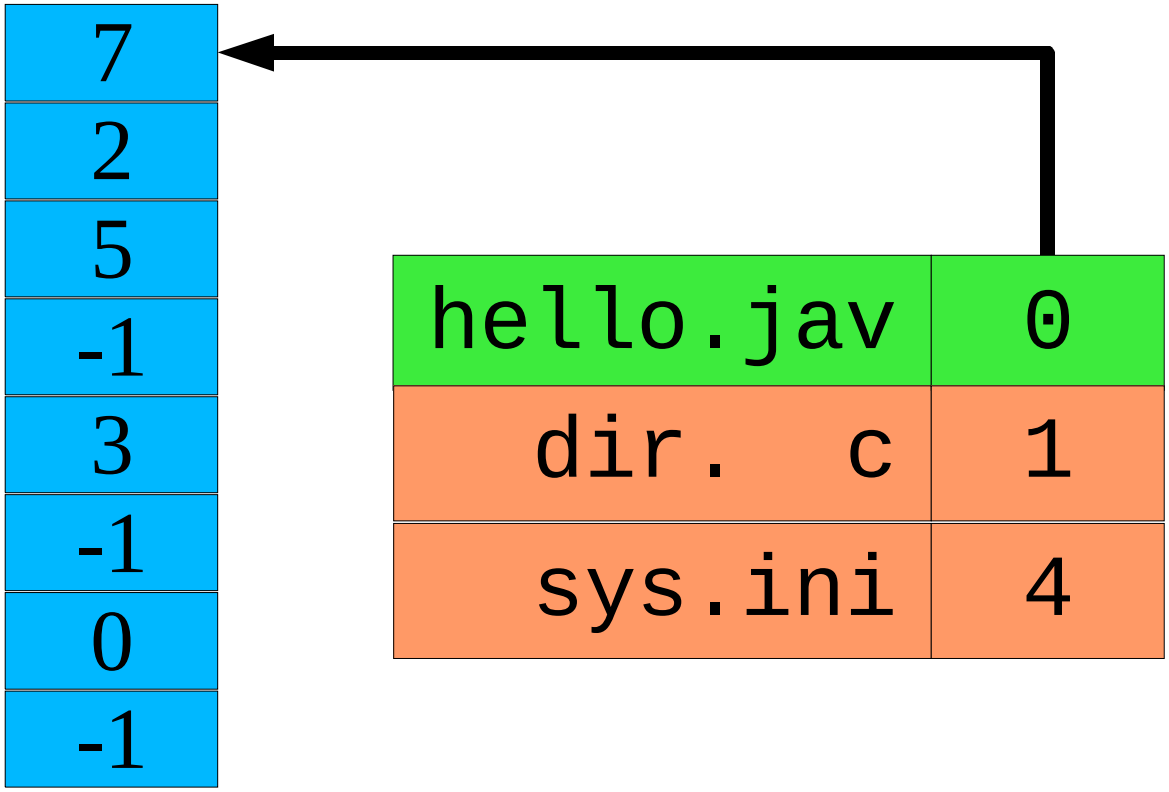


hello.jav	0
dir. c	1
sys.ini	4

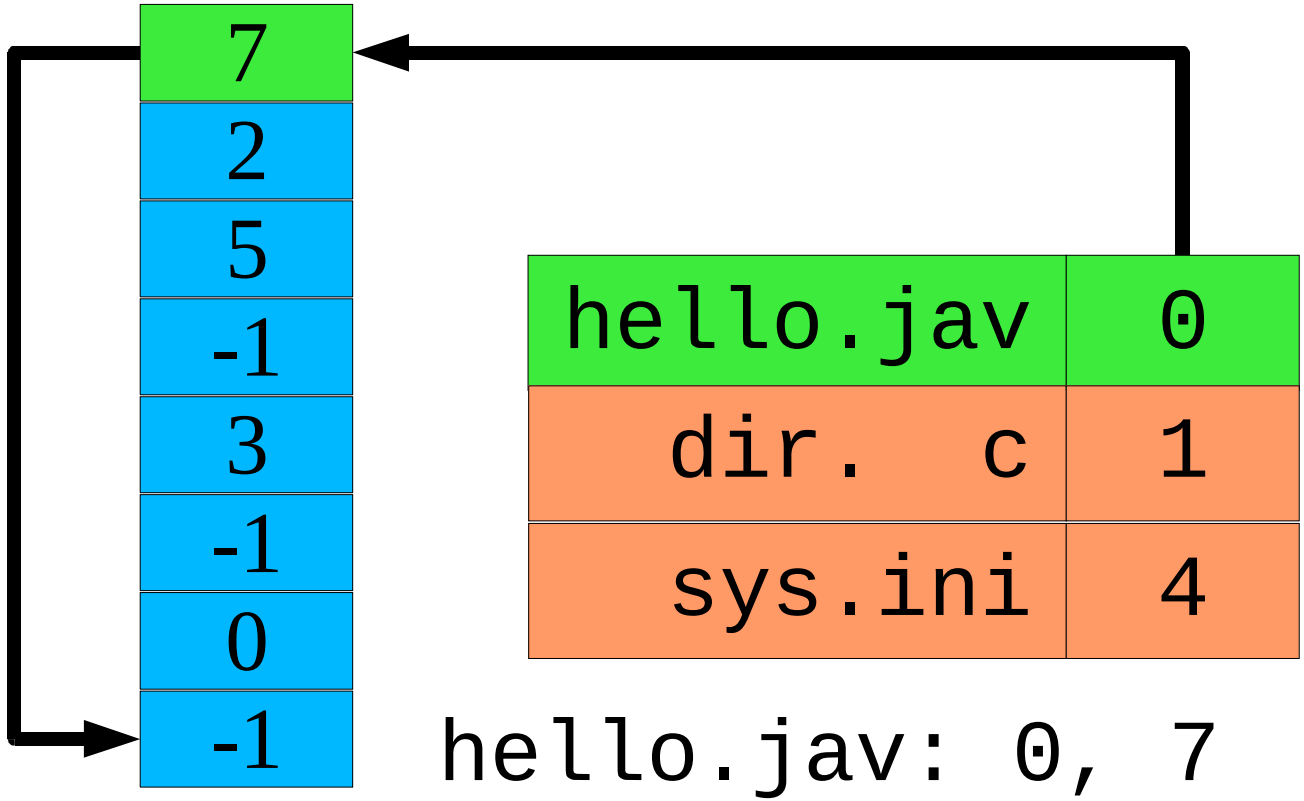
Allocation - FAT



Allocation - FAT



Allocation - FAT



Allocation –FAT

Issues

- Damage to FAT scrambles entire disk
  - Solution: backup FAT
- Generally *two* seeks per block read/write
  - Seek to FAT, read, seek to actual block (repeat)
  - Unless FAT can be cached well in RAM
- Still *very* hard to access random file blocks
  - Linear time to walk through FAT

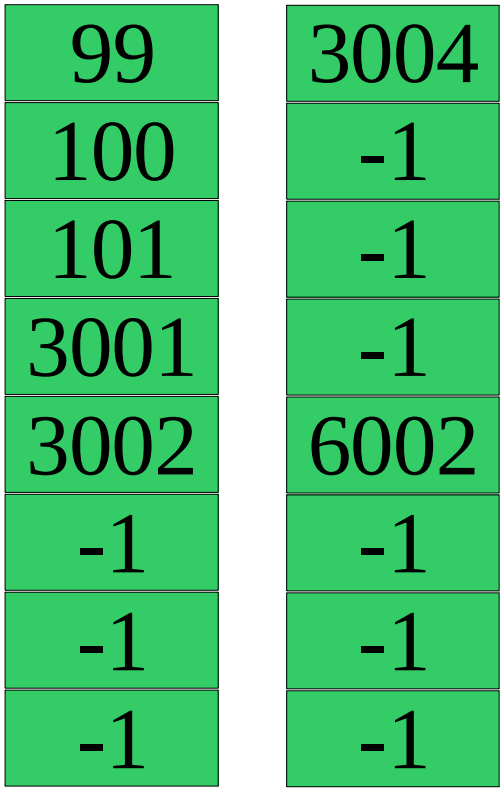
Allocation –Indexed

Motivation

- **Avoid fragmentation problems**
- **Allow file growth**
- *Improve random access*

Approach

- *Per-file* **block array**



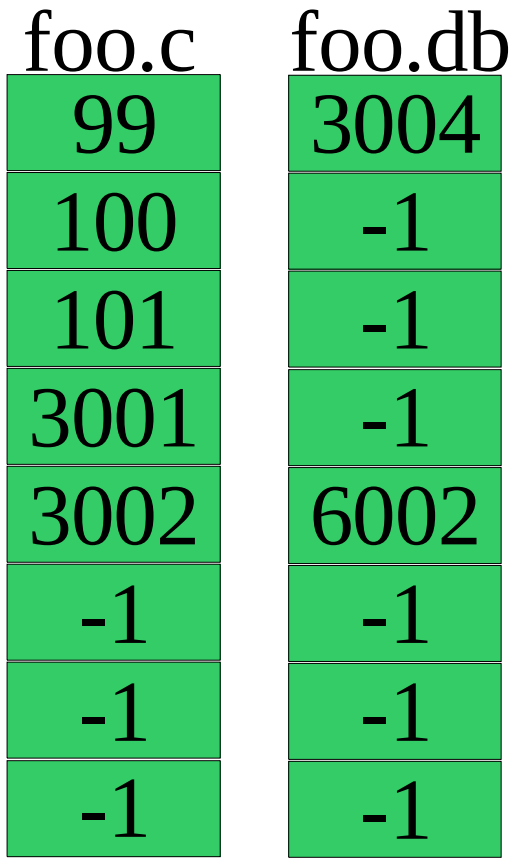
Allocation –Indexed

Allows "holes"

- foo.c is sequential
- foo.db, blocks 1..3 ⇒ -1
  - logically "blank"

"sparse allocation"

- a.k.a. "holes"
- read() returns nulls
- write() requires alloc
- file "size" ≠ file "size"
  - `ls -l` index of last byte
  - `ls -s` number of blocks



Allocation –Indexed

How big should index block be?

- **Too small: limits file size**
- **Too big: lots of wasted pointers**

Combining index blocks

- **Linked**
- **Multi-level**
- **What Unix actually does**

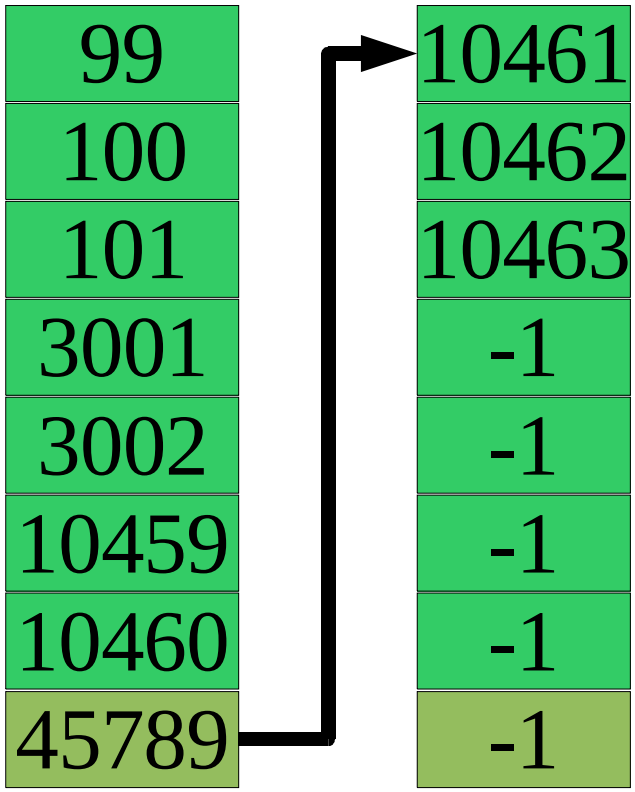
Linked Index Blocks

Last pointer indicates next index block

Simple

Access is not-so-random

- **O(n/c) is still O(n)**
- **O(n) *disk transfers***

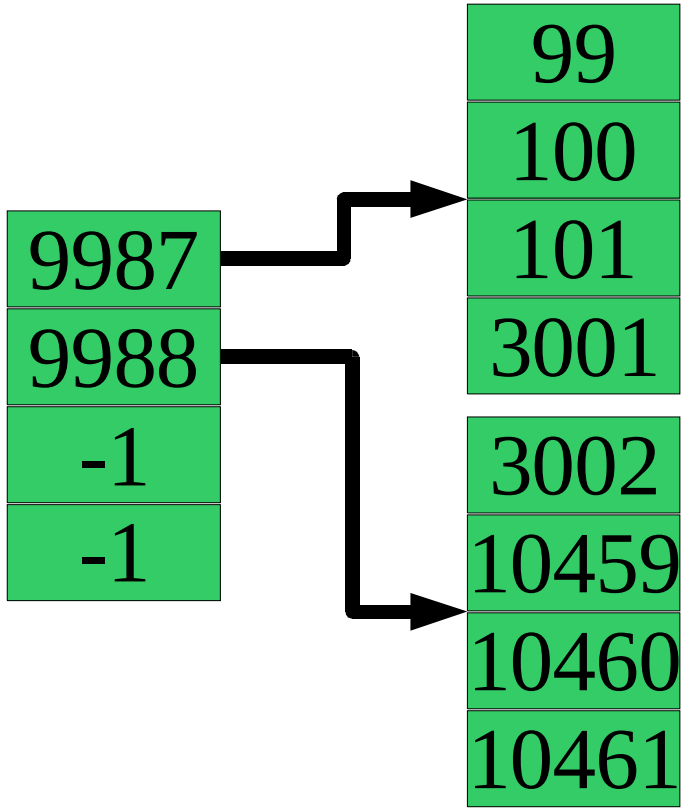


Multi-Level Index Blocks

Index blocks of index blocks

Does this look familiar?

Allows *big* holes



Unix Index Blocks

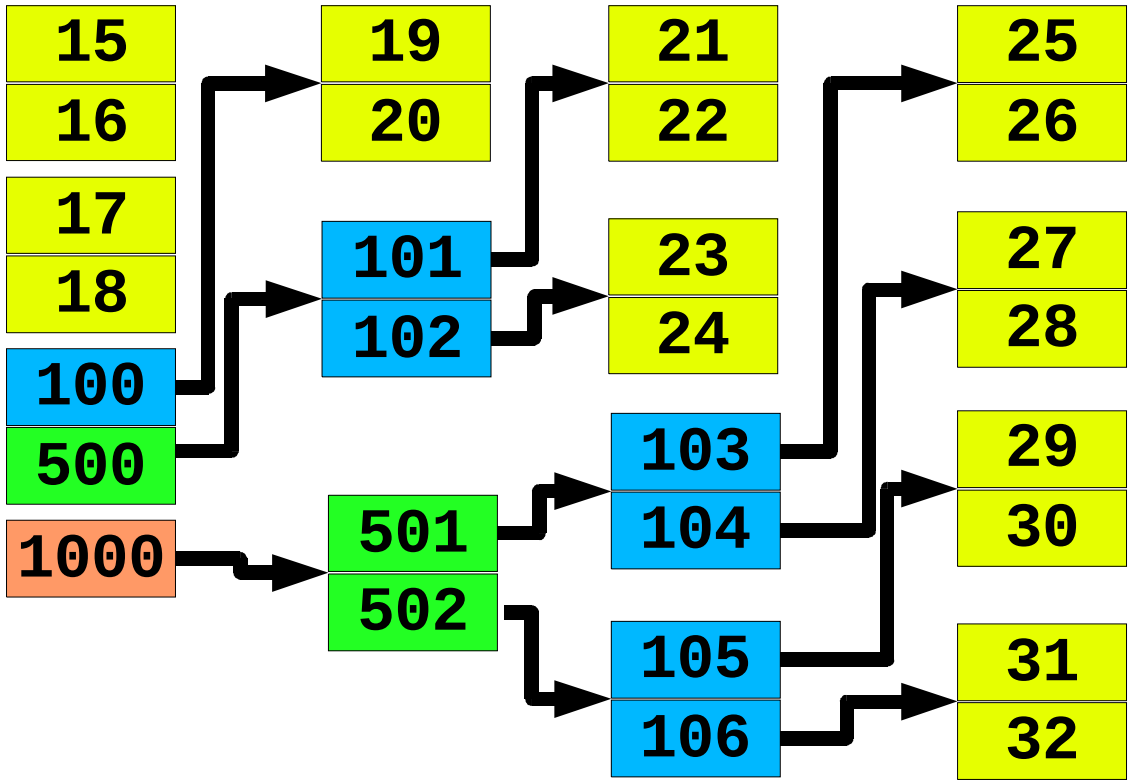
Intuition

- *Many* files are small
  - Length = 0, length = 1, length < 80, ...
- Some files are *huge* (3 gigabytes)

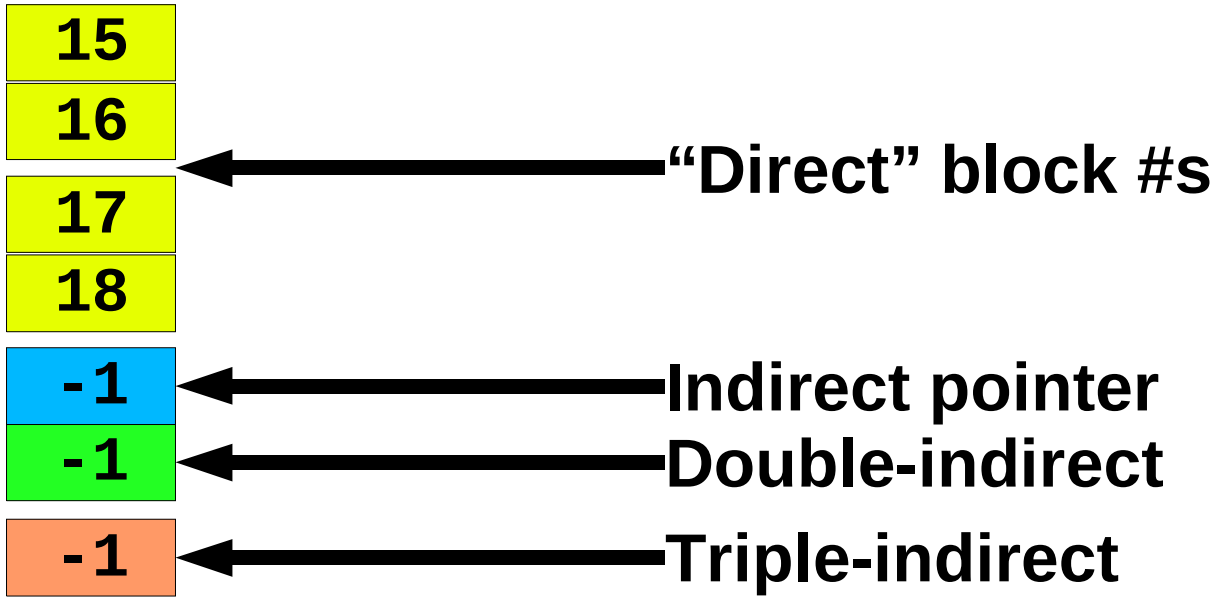
"Clever heuristic" in Unix FFS inode

- inode struct contains 12 "direct" block pointers
  - 12 block numbers * 8 KB/block = 96 KB
  - Availability is "free" - must read inode to open() file anyway
- 3 indirect block pointers
  - single, double, triple

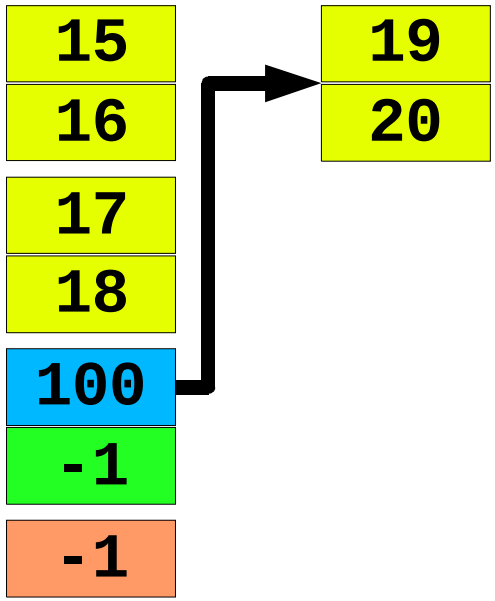
Unix Index Blocks



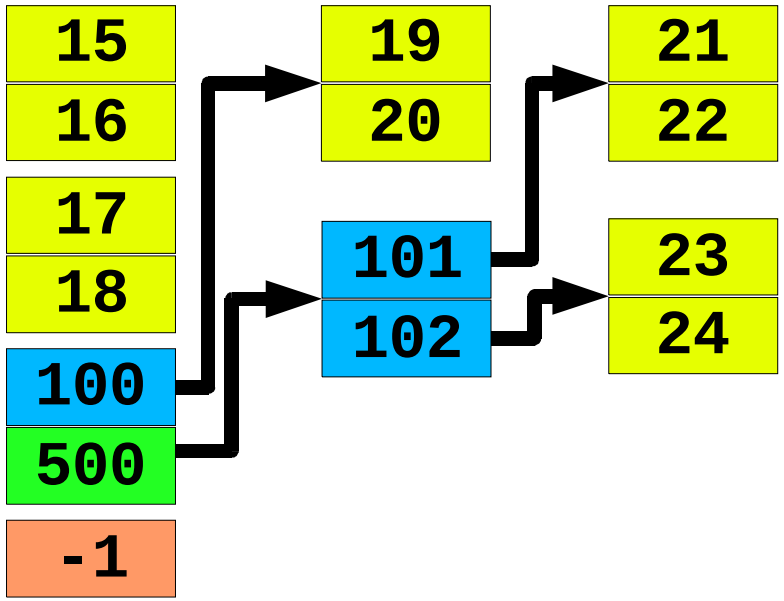
Unix Index Blocks



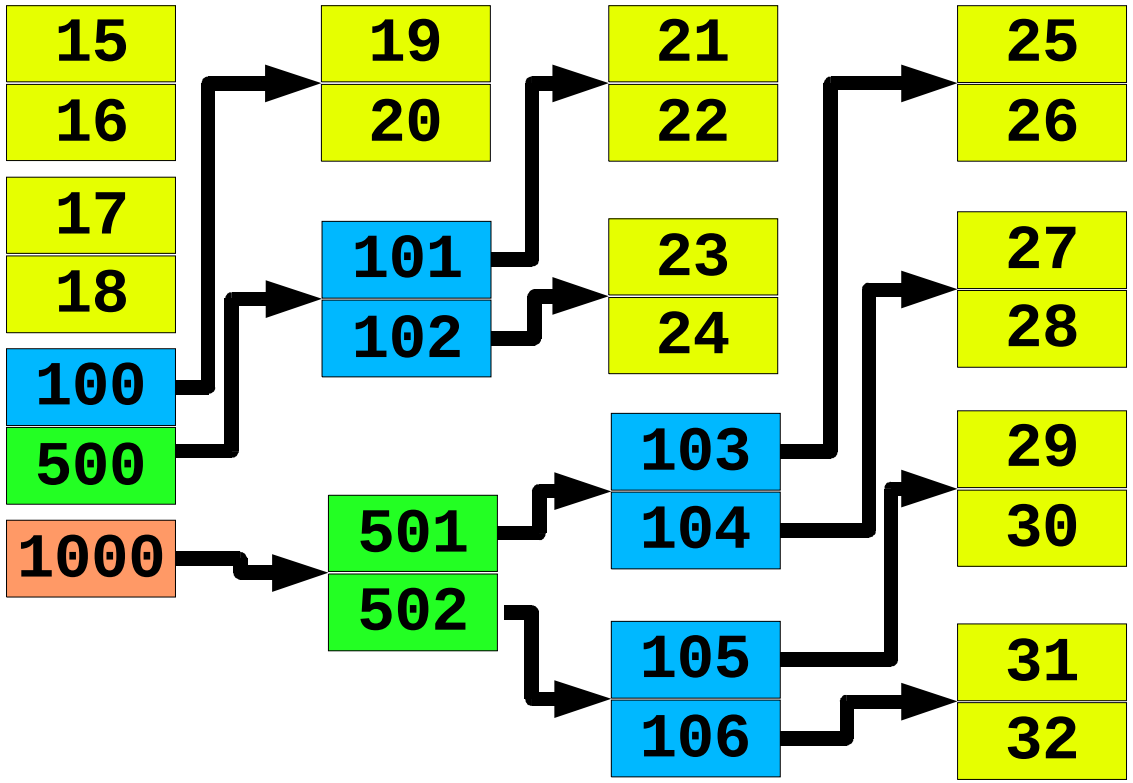
Unix Index Blocks



Unix Index Blocks



Unix Index Blocks



Tracking Free Space

Bit-vector

- 1 bit per block: boolean “free”
- Check each word vs. 0
- Use “first bit set” instruction
- Text example
  - 1.3 GB disk, 512 B sectors: 332 KB bit vector

Need to keep (much of) it in RAM

Tracking Free Space

Linked list

- Superblock points to first free block
- Each free block points to next

Cost to allocate N blocks is linear

- Free block can point to *multiple* free blocks
  - 512 bytes = 128 (4-byte) block numbers
- FAT approach provides free-block list "for free"

Keep free-*extent* lists

- (block,sequential-block-count)

Unified Buffer Cache

Seems silly to double-cache vmem pages

- Page cache, file-system cache often totally independent
  - Page cache chunks according to hardware page size
  - File cache chunks accoding to “file system block” size
  - Different code, different RAM pools
- How much RAM to devote to each one?

Observation

- Why not have just one cache?
  - Mix automatically varies according to load
    - » “cc” wants more disk cache
    - » Firefox wants more VM cache

Unified Buffer Cache - Warning!

"Virtual memory architecture in SunOS"

Gingell, Moran, & Shannon

USENIX 1987 Summer Conference

"The work has consumed approximately four man-years of effort over a year and a half of real time. A surprisingly large amount of effort has been drained by efforts to interpose the VM system as the logical cache manager for the file systems…"

Cache tricks

Read-ahead

```
for (i = 0; i < filesize; ++i)
  putc(getc(infile), outfile);
```

- System observes sequential reads
  - File block 0, 1, 2, ...
  - Can pipeline reads to overlap “computation”, read latency
    - » Request for block 2 triggers disk read of block 3

Free-behind

- Discard buffer from cache when next is requested
- Good for large files
- “Anti-LRU”

Recovery

System crash...now what?

- Some RAM contents were lost
- Free-space list on disk may be wrong
- Scan file system
  - Check invariants
    - » Unreferenced files
    - » Double-allocated blocks
    - » Unallocated blocks
  - Fix problems
    - » Expert user???

Modern approach

- "Journal" changes (see upcoming Transactions lecture)

Backups

Incremental approach

- Monthly: dump entire file system
- Weekly: dump changes since last monthly
- Daily: dump changes since last weekly

Merge approach - www.teradactyl.com

- Collect changes since yesterday
  - Scan file system by modification time
- Two tape drives merge yesterday's tape, today's delta

Summary

Block-mapping problem

- Similar to virtual-to-physical mapping for memory
- Large, often-sparse “address” spaces
  - “Holes” not the common case, but not impossible
- Map any “logical address” to any “physical address”
- Key difference: file maps often don't fit in memory

“Insert a level of indirection”

- Multiple file system types on one machine
- Grow your block-allocation map
- ...