15-410

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

File System (Internals)
Nov. 6, 2015

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Synchronization

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, zfs, FAT, 9660, ...**

Shredding Disks

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

- MBR (PC): 4 “partitions” – Windows, FreeBSD, Plan 9, ...
- APM (Mac): “volumes” – can split: OS 9, OS X, user files
- GPT (new, multi-platform) - many partitions, long names

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

A partition (of a disk or of a volume) 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
```

```
(A 4-gigabyte disk)
```

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 free-space map as well

Memory Structures

In-memory partition tables

- Sanity check file system I/O fits 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

Goals

- **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?

VFS layer

Goals

- **Allow one machine to use multiple file system *types***
  - **Unix FFS**
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  - **CD-ROM ISO9660**
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- **Standard system calls should work transparently**

Solution

- **Insert a level of indirection!**

Single File System

```
n = read(fd, buf, size)
```

```
INT 54
```

```
sys_read(fd, buf, len)
```

```
namei()    iget()    iput()
```

```
sleep()    rdblk(dev, N)    wakeup()
```

```
startIDE()    IDEintr()
```

VFS "Virtualization"

n = read(fd, buf, size)

INT 54

namei() vfs_read()

ufs_read() procfs_read()

ufs_lookup() procfs_domem()

ufs_iget() ufs_iput()

VFS layer – file system operations

These operate on file *systems*, not individual files

```
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 per-file 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 ⇒ vnode mappings)

Directories

Old: one namei() ⇒ VFS: fs-provided vnode method

- 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" is not a bad idea
  - Beyond that, it gets complicated

Mapping problem

- Where was block 32 of this file previously put?
- 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 / Mapping

- **Contiguous**
- **Linked**
- **FAT**
- **Indexed**
  - **Linked**
  - **Multi-level**
  - **Unix (index tree)**

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 block

Motivation

- Avoids fragmentation problems
- Allows 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

- Link multi-block *clusters*, not blocks

Allocation – FAT

Used by MS-DOS, OS/2, Windows

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

Semantically the same as linked allocation

But next-block links stored "out of band" in a 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

7
2
5
-1
3
-1
0
-1

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

Allocation - FAT

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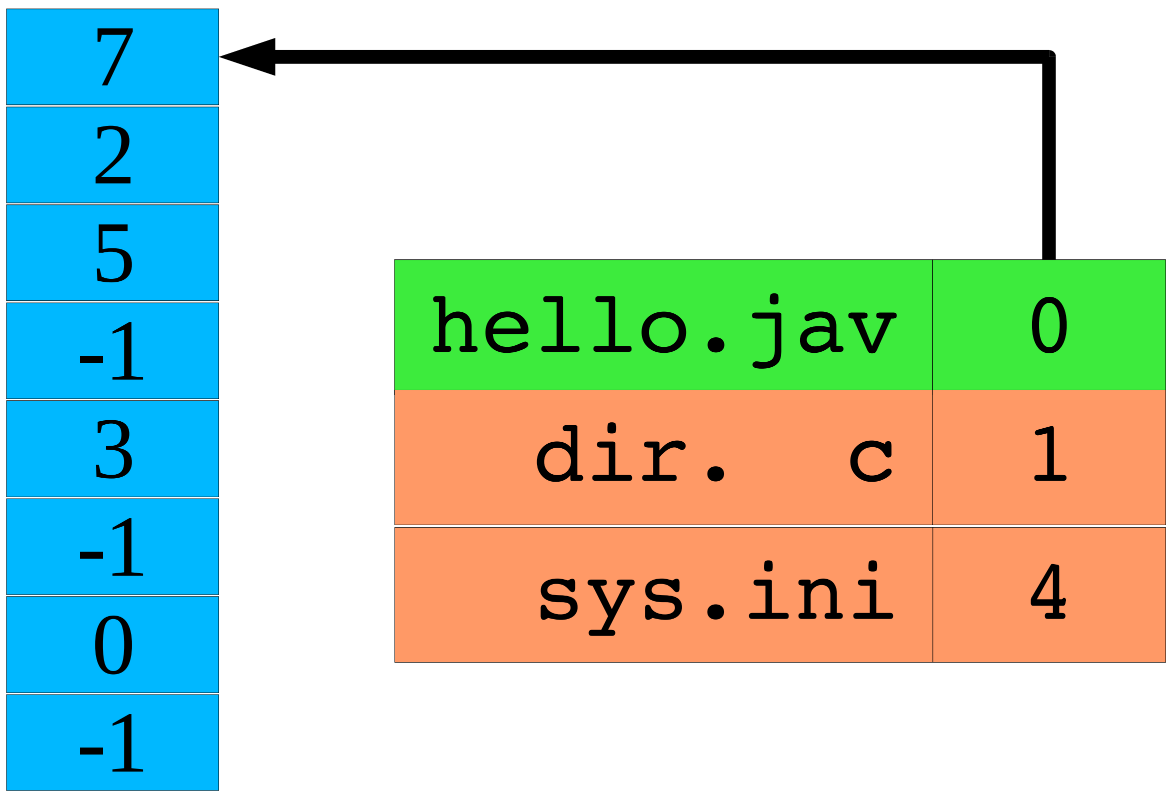
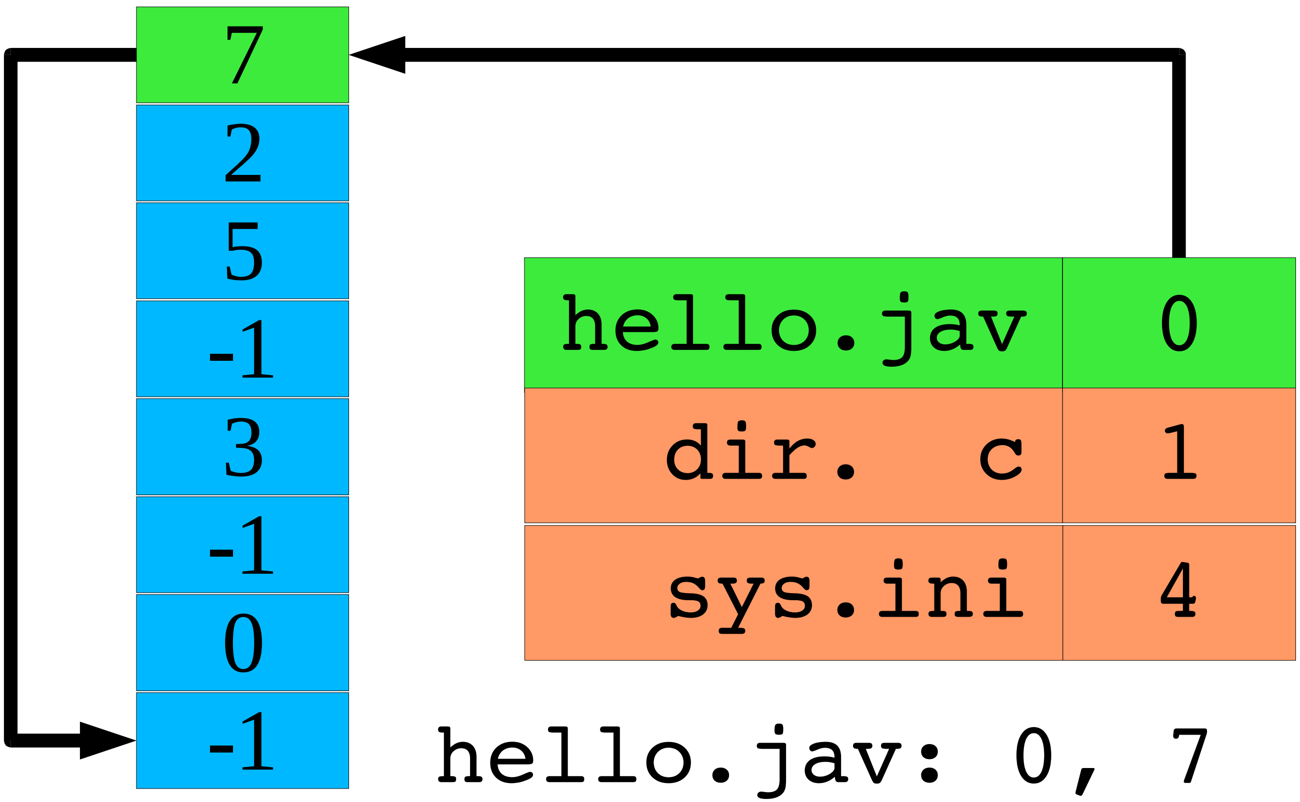
Allocation - FAT



Allocation - FAT



Allocation – FAT

Issues

- Damage to FAT scrambles entire file system
  - Solution: mirror the 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 *somewhat* hard to access random file blocks
  - Linear time to walk through FAT
- FAT may be a “hot spot” (everybody needs to access it)
- Lots of FAT updates (near beginning of disk)
  - Even if files being modified are far away

Allocation – Indexed

Motivation

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

Approach

- *Per-file* **block array**
- **File block number indexes into table, yields disk block number**
- **No O(n) sequential steps**

99	3004
100	-1
101	-1
3001	-1
3002	6002
-1	-1
-1	-1
-1	-1

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

foo.c	foo.db
99	3004
100	-1
101	-1
3001	-1
3002	6002
-1	-1
-1	-1
-1	-1

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**

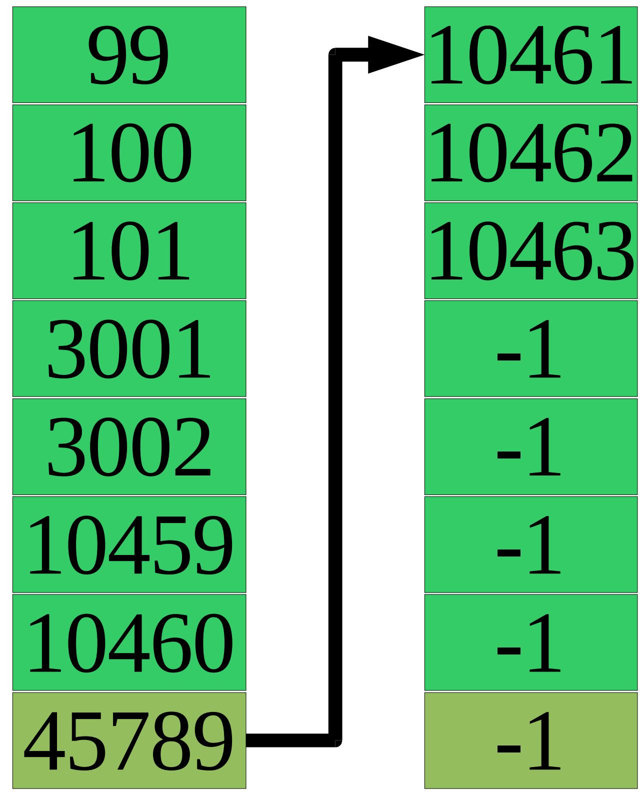
Linked Index Blocks

Last pointer indicates next index block

Simple

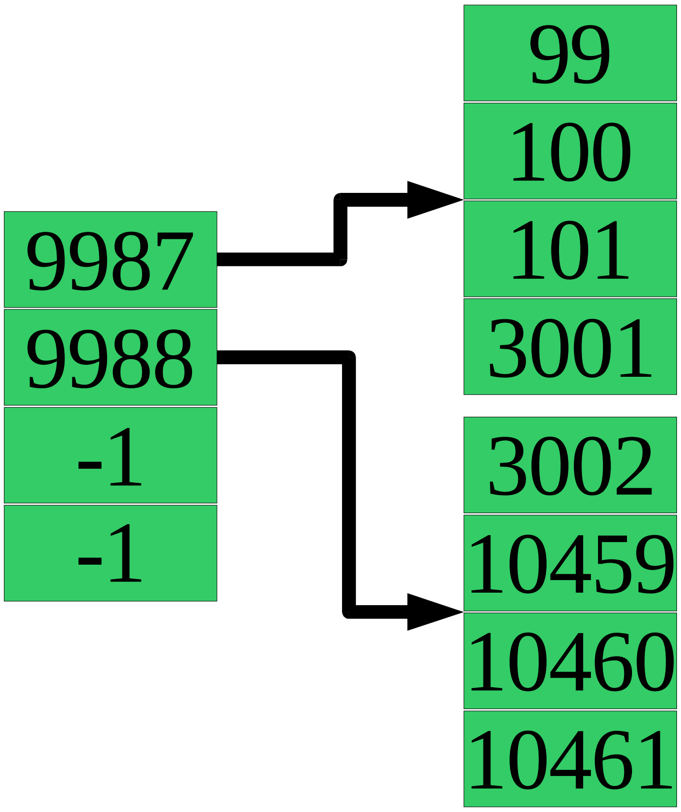
Access is not-so-random

- 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* (gigabytes... maybe terabytes!)

How do we solve this problem?

- We are computer scientists!

Unix Index Blocks

Intuition

- *Many* files are small
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How do we solve this problem?

- We are computer scientists!
  - So we realize when 57 levels of indirection would be slow!!!

Unix Index Blocks

Intuition

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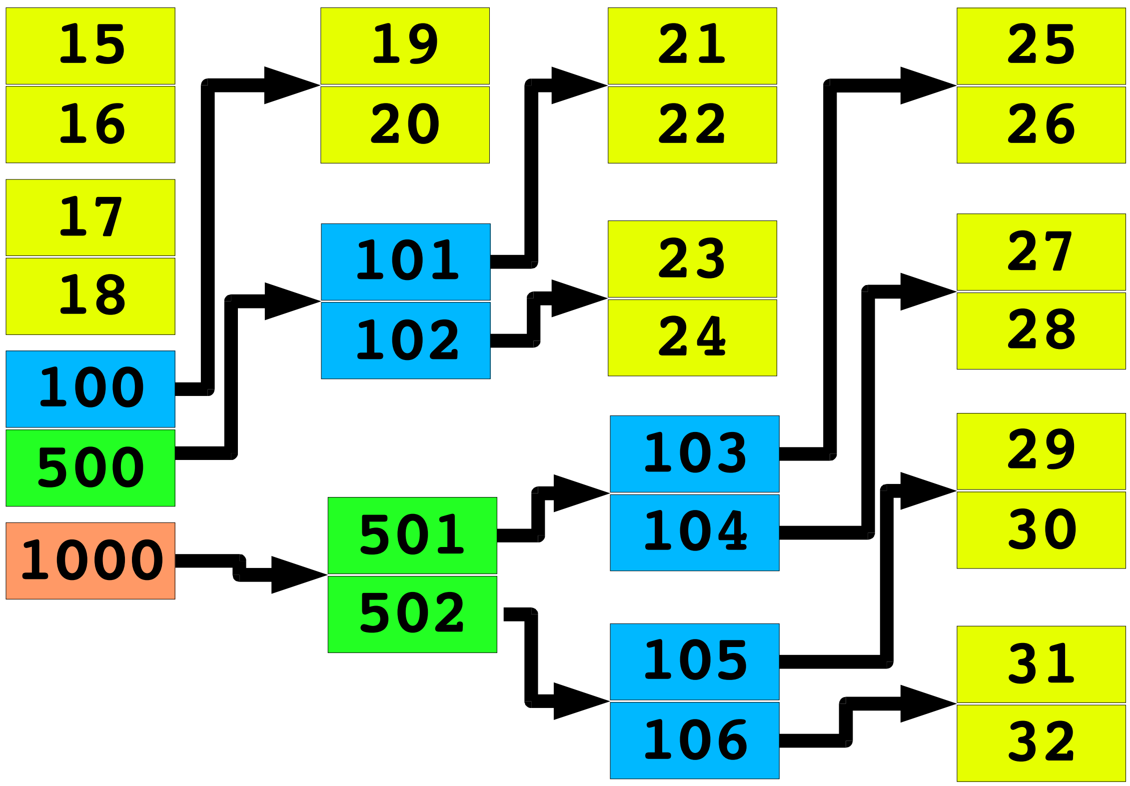
"Clever heuristic" in Unix FFS inode

- 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
- inode struct also contains 3 indirect block pointers
  - single-indirect, double-indirect, triple-indirect

Unix Index Blocks



Summary

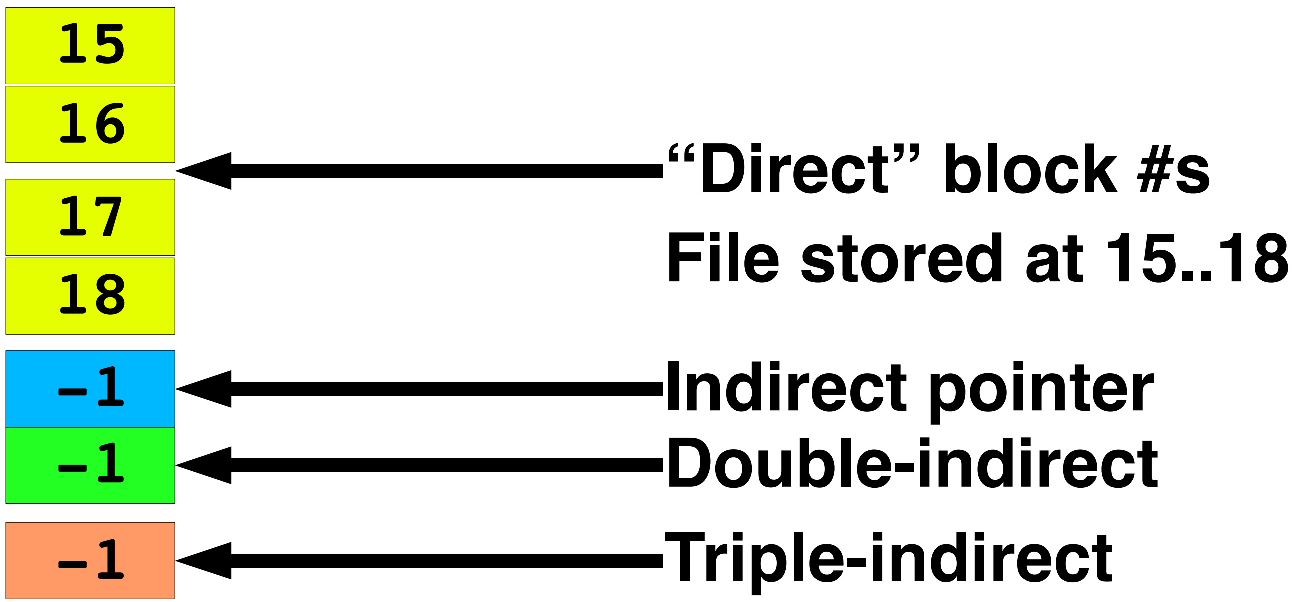
Block-mapping problem

- 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

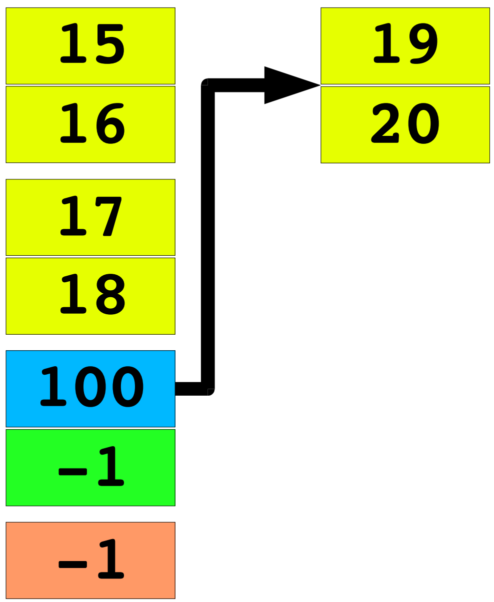
“Insert a level of indirection”

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

Unix Index Blocks



Unix Index Blocks



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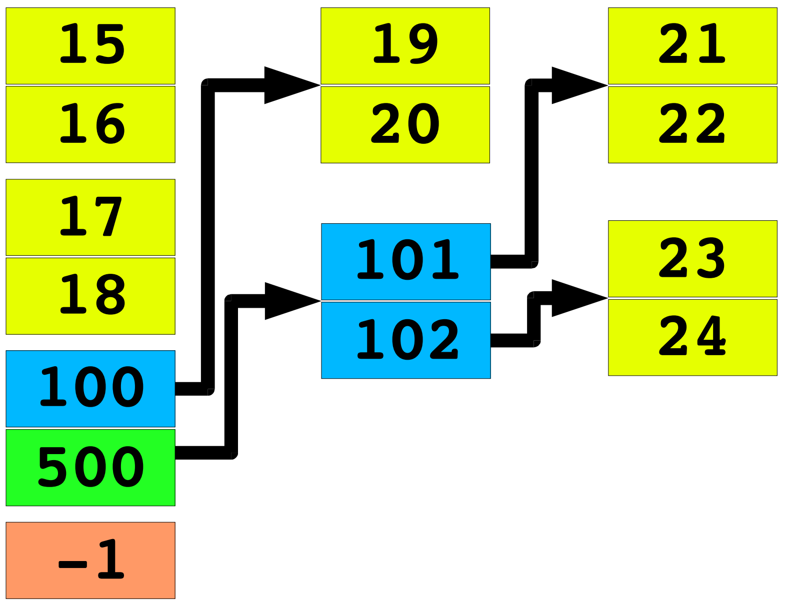
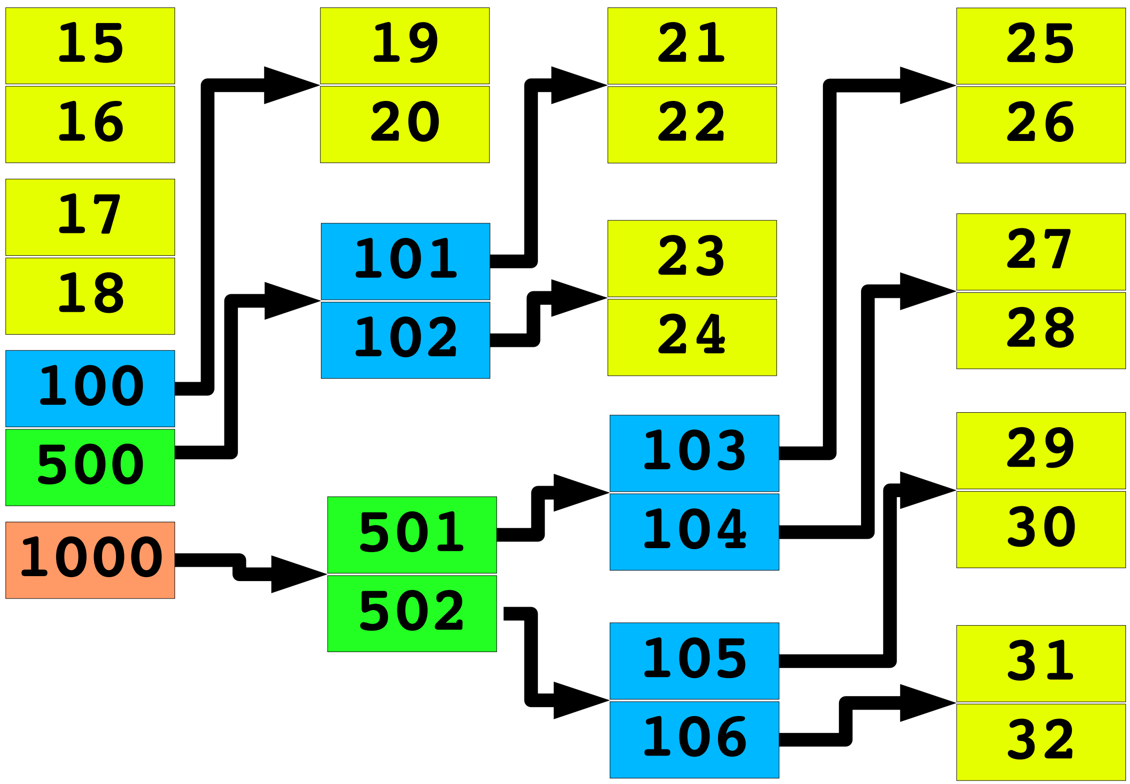


Unix Index Blocks



Triple indirect can address >> 2^{32} bytes

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

Traditional two-cache approach

- Page cache, file-system cache often totally independent
  - Page cache chunks according to hardware page size
  - File cache chunks according 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 / replace-behind

- Discard buffer from cache when next is requested
- Good for large files
- “Anti-LRU” (evict “MRU” instead of “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 lecture material)

Backups

Incremental "Towers of Hanoi" approach - traditional

- **Monthly: dump entire file system**
- **Weekly: dump changes since last monthly**
- **Daily: dump changes since last weekly**
- **Restore a file?**
  - **Most-recent "monthly" tape definitely has a copy**
    - **May be stale, so...**
  - **Any one of the "weekly" tapes might have a copy (scan all)**
  - **Any one of the "daily" tapes might have a copy (scan all)**

Backups

Merge approach ("TiBS") - www.teradactyl.com

- Something special about tape drives
- They run *much* faster when they're "streaming" (continuous full speed, no start/stop)
- Collect changes since yesterday
  - Scan file system by modification time
- "Output" tape drive has a blank tape
- "Input" tape drive streams yesterday's dump in
  - Some files are un-changed: stream to output tape
  - Some files are stale: replace them in output stream
- Keep as many tapes as you want to, recycle the rest
- Restoring is fast (stream *one* tape onto disks)
- Files stored (very) redundantly – good for reliability

Backups

Snapshot approach

- **At midnight, stop writing into file system**
- **New writes go into a new file system**
  - **Mostly pointers to yesterday's data**
  - **Changes stored in the live file system**
    - **Maybe entire files (copy-on-write)**
    - **Maybe just new data blocks**
- **Great for users**
  - **Old snapshots can be mounted (read-only)**
  - **Accidentally delete a file? Get it from yesterday!**
  - **AFS supports a simple version (see “OldFiles”)**

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- Grow your block-allocation map
- ...

Further Reading

Journaling

- Prabhakaran et al., Analysis and Evolution of Journaling File Systems (USENIX 2005)

Something cool which isn't journaling

- McKusick & *Ganger*: "Soft Updates: A Technique for Eliminating Most Synchronous Writes in the Fast Filesystem" (USENIX 1999)

Both papers appear in the "filesystem reliability" book report paper track