File System (Internals)

Dave Eckhardt
de0u@andrew.cmu.edu

Synchronization

- P2 grading questions
  - Send us mail, expect to hear from your grader
- Today
  - Chapter 12 (not: Log-structured, NFS)

Outline

- File system code layers (abstract)
- Disk, memory structures
- Unix “VFS” layeringindirection
- 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, ...

Disk Structures

- Boot area (first block/track/cylinder)
- File system control block
  - Key parameters: #blocks, metadata layout
  - Unix: “superblock”
- Directories
- “File control block” (Unix: “inode”)
  - ownership/permissions
  - data location

Memory Structures

- In-memory partition tables
- 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

`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

vfs_read()

ufs_read()    procfs_read()

namei()       procfs_domem()

iget()  iput()
```

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)

Directories

- External interface
  - vnode2 = 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

Allocation – Linked

- Approach
  - File location defined as (start)
  - Each disk block contains pointer to next
- Motivation
  - Avoid fragmentation problems
  - Allow file growth

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, ...
- Linked allocation
- Links stored “out of band” in table
- 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.java	0
dir.c	1
sys.ini	4

Allocation - FAT

7
2
5
-1
3
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hello.java	0
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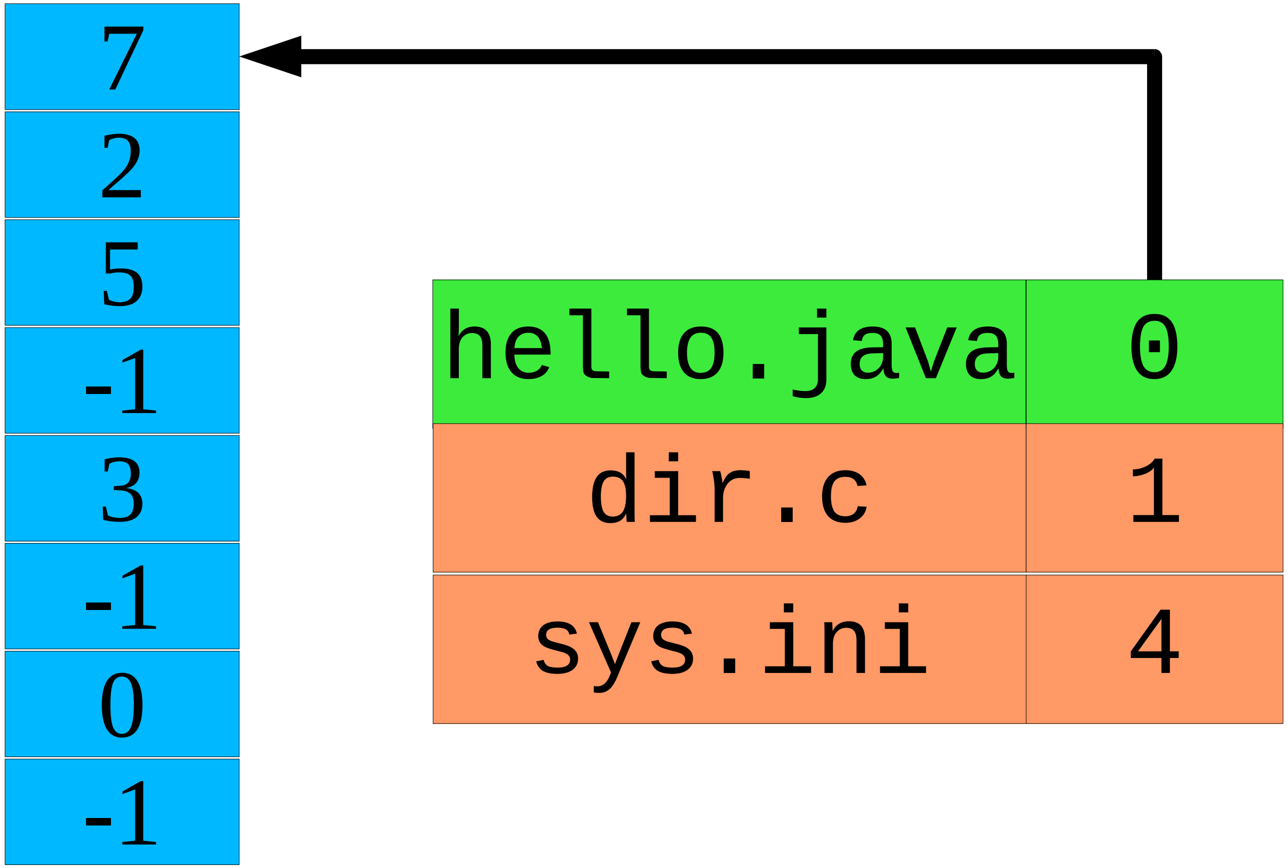
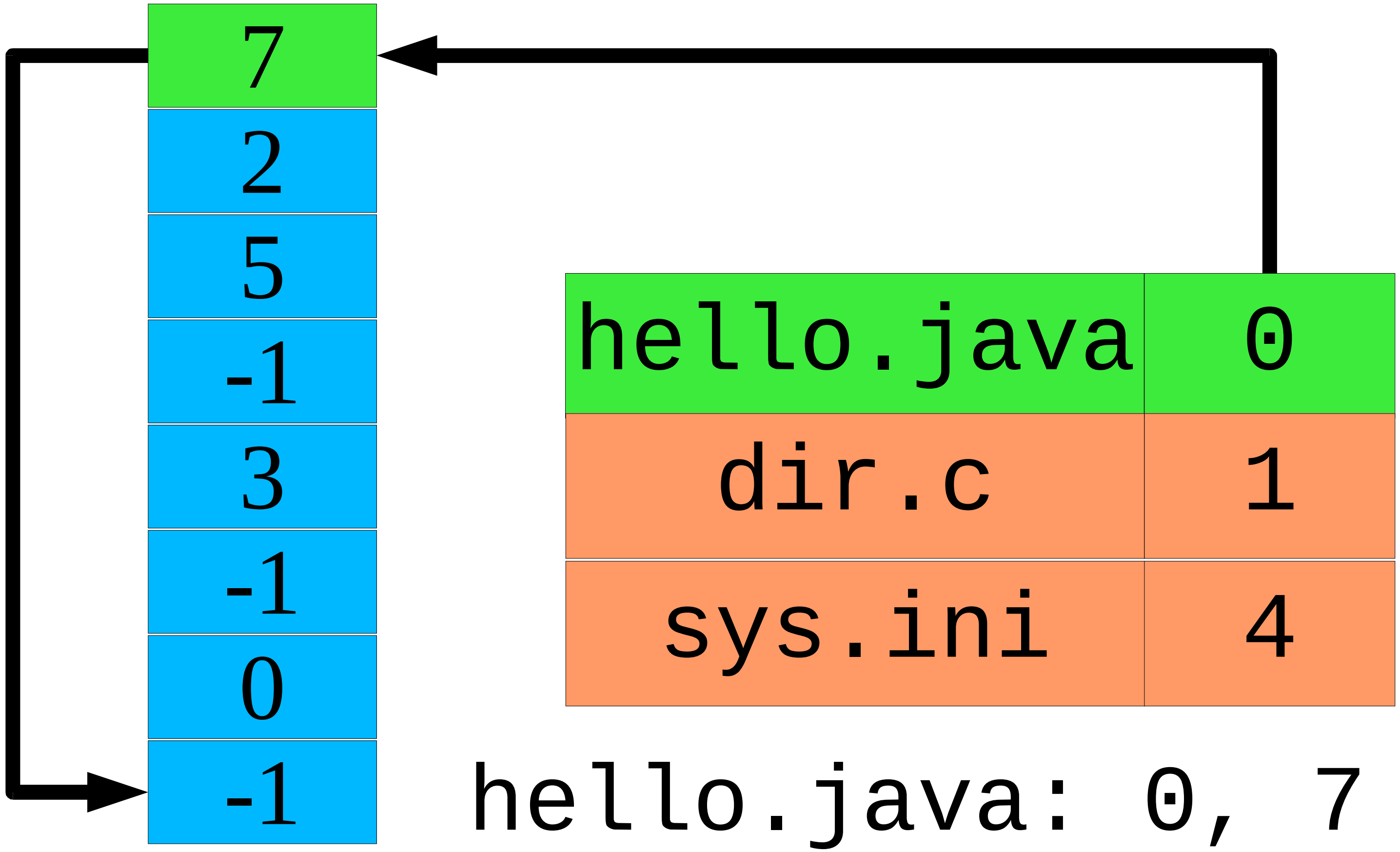
Allocation - FAT



Allocation - FAT



hello.java: 0, 7

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
  - 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

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, block 1 ⇒-1
- “sparse allocation”
  - read() returns nulls
  - write() requires alloc

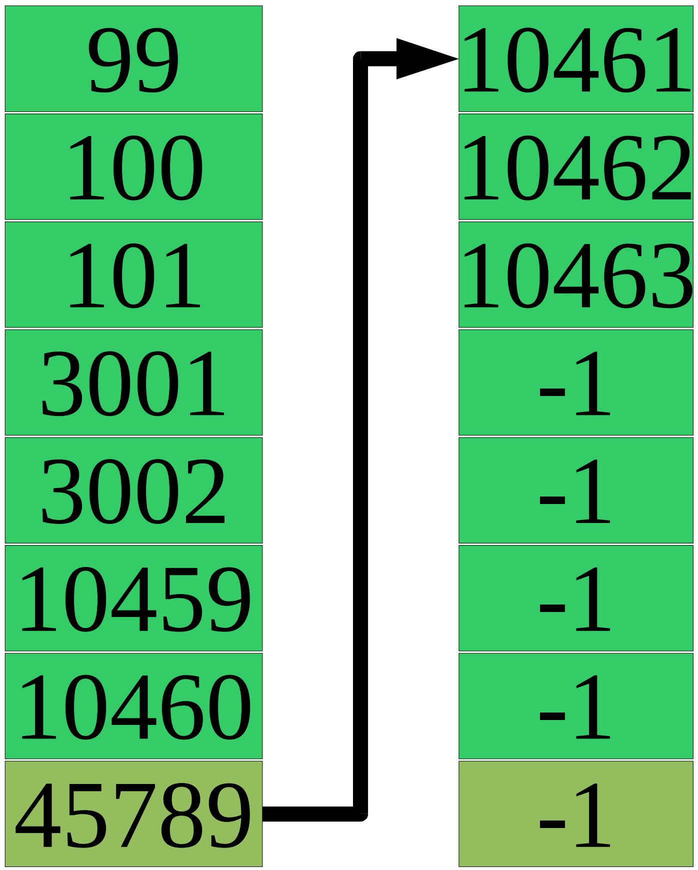
foo.c	foo.db
99	3004
100	-1
101	-1
3001	-1
3002	6002
-1	-1
-1	-1
-1	-1

Allocation – Indexed

- How big should index block be?
  - Too big: lots of wasted pointers
  - Too small: limits file size
- Combining index blocks
  - Linked
  - Multi-level
  - What Unix actually does

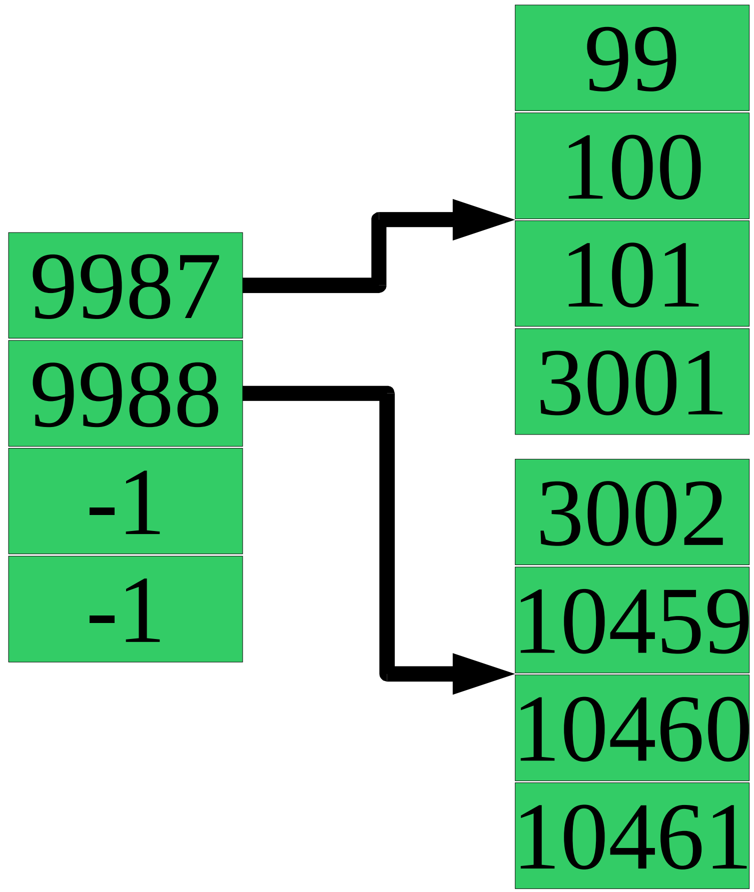
Linked Index Blocks

- Last pointer indicates next index block
- Simple
- Access is not-so-random



Multi-Level Index Blocks

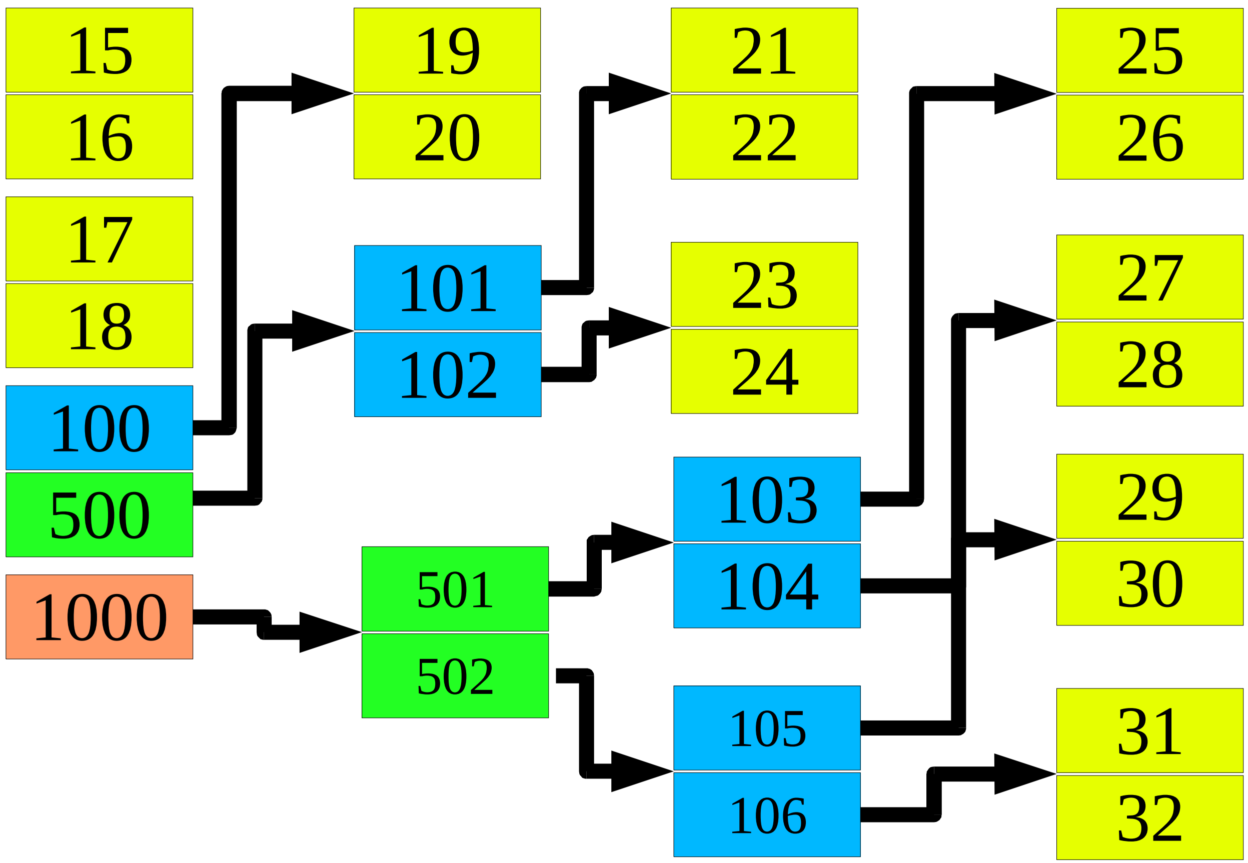
- Index blocks of index blocks
- Does this look familiar?
- Allows ***big*** holes



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
  - 12 (direct) block pointers: 12 * 8 KB = 96 KB
  - 3 indirect block pointers
    - single, double, triple

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
  - FAT approach provides free-block list "for free"
- Keep free-***extent*** lists
  - (block,count)

Unified Buffer Cache

- Some memory frames back virtual pages
- Some memory frames cache file blocks
- Observation
  - In-memory virtual pages may be backed by disk
  - Why not have just one cache?
    - Some of RAM is virtual memory
    - Some of RAM is disk blocks
    - Mix varies according to load

Cache tricks

- Read-ahead

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

  - System observes sequential reads
    - can pipeline reads to overlap "computation", read latency
- 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???

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