Files & Directories

The File System Abstraction

- Presents applications with persistent, named data
- Two main components:
  - files
  - directories

The File

- A file is a named collection of data.
  - inode number: low-level name assigned to the file by the file system
  - path: human friendly string
    - must be mapped to inode number, somehow
  - file descriptor
    - dynamically designed handle used by processes to refer to inode
- A file has two parts
  - data – what a user or application puts in it
    - array of untyped bytes
  - metadata – information added and managed by the OS
    - size, owner, security info, modification time

The Directory

- A special file that stores mappings between human-friendly names of files and their inode numbers

```
ArgoX ls -i
2968458 Applications/      3123638 Dropbox (Old)/           4689728 Pictures/       4687176 gems/
2968461 Code/              3123878 Incompatible Software/    4687155 Public/         4687697 mercurial/
2968464 Desktop/           3123881 Library/                  4687159 Sites/          4687700 profiles.bin
2968978 Documents/         4687153 Mail/                     4687168 Synology/       4687701 src/
3121827 Downloads/         4689724 Movies/                   4687170 bin/            4689710 uninstall-mpi-cups.sh
3123562 Dropbox/           4689726 Music/                    4687175 fun/
ArgoX
```

  - Has its own inode, of course
  - Mapping may apply to human-friendly names of directories and their inodes
    - directory tree
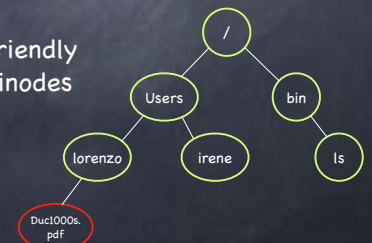
File System API

- Creating a file
  - int fd = open("foo", O_CREAT|O_RDWR|O_TRUNC, S_IRUSR|S_IWUSR);
    - path, flags, modes
  - returns a file descriptor, a per-process integer that grants process a capability to perform certain operations
  - int close(int fd); closes the file descriptor
- Reading/Writing
  - ssize_t read (int fd, void *buf, size_t count);
  - ssize_t write (int fd, void *buf, size_t count);
    - ▷ return number of bytes read/written
  - offt_t lseek (int fd, off_t offset, int whence);
    - ▷ repositions file's offset (initially 0, updates on reads and writes)
      - – to offset bytes (SEEK_SET)
      - – to offset bytes from current offset (SEEK_CUR)
      - – to offset bytes after the end of the file (SEEK_END)

File System API

- Writing synchronously
  - int fsynch (int fd);
  - flushes to disk all dirty data for file referred to by fd
  - if file is newly created, must fsynch also its directory!
- Getting file's metadata
  - stat() , fstat() — return a stat structure

```
struct stat {
    dev_t st_dev;      /* ID of device containing file */
    ino_t st_ino;      /* inode number */
    mode_t st_mode;    /* protection */
    nlink_t st_nlink;  /* number of hard links */
    uid_t st_uid;      /* user ID of owner */
    gid_t st_gid;      /* group ID of owner */
    dev_t st_rdev;     /* device ID (if special file) */
    off_t st_size;     /* total size, in bytes */
    blksize_t st_blksize; /* blocksize for filesystem I/O */
    blkcnt_t st_blocks; /* number of blocks allocated */
    time_t st_atime;   /* time of last access */
    time_t st_mtime;   /* time of last modification */
    time_t st_ctime;   /* time of last status change */
};
```

retrieved from file's inode
- on disk, per-file data structure
- may be cached in memory

File System API

- Writing synchronously
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    nlink_t st_nlink;  /* number of hard links */
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    gid_t st_gid;      /* group ID of owner */
    dev_t st_rdev;     /* device ID (if special file) */
    off_t st_size;     /* total size, in bytes */
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    blkcnt_t st_blocks; /* number of blocks allocated */
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    time_t st_ctime;   /* time of last status change */
};
```

retrieved from file's inode
- on disk, per-file data structure
- may be cached in memory

Old Friends

- Remember fork()?

```
int main(int argc, char *argv[]){
    int fd = open("file.txt", O_RD_ONLY);
    assert (fd >= 0);
    int rc = fork();
    if (rc ==0) {
        rc = lseek(fd, 10, SEEK_SET);
        printf("child: offset %d\n", rc);
    } else if (rc > 0) {
        (void) wait(NULL);
        printf("parent: offset %d\n",
            (int) lseek(fd, 10, SEEK_CUR));
    }
    retur(n 0;
}
```

What does this code print?

Parent and child each have an independent file descriptor

Though independent, both correspond to the same integer (e.g., 3)

They both point to the same entry in the OS's Open File Table

An entry in that table looks like

```
struct file {
    int ref;
    char readable;
    char writable;
    struct inode *ip
    uint off
}
```

The reference count for file.txt would be 2!

The Directory

- The directory holds instances of two types of mappings:
  - Hard links
    - map a file's human-friendly name (its local path) to the corresponding inode number
  - Symbolic (soft) links
    - maps a file's human-friendly name (its local path) to the number of an inode that contains the path name of a different file
      - you can think of it as a hard link for a special file, that indeed OS treats differently

Hard links

- Creating file foo adds a hard link for file foo in the file's directory
- int link(const char *oldpath, const char *newpath)
  - adds a hard link mapping path newpath to the inode number currently also mapped to file oldpath
  - invoked executing ln at the command line
- Removing a file through the rm [file] command invokes a call to int unlink(const char *pathname)
  - removes from directory the hard link between pathname and corresponding inode number
- Link count maintained in file's inode
  - inode reclaimed (file deleted) only when link count = 0; if file opened, wait to reclaim until file is closed

Hard link No-Nos

- Creating a hard link to a directory
  - may create a cycle in the directory tree!
- Creating a hard link to files in other volumes
  - inode numbers are unique only within a single file system

```
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ ls
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .   391230414 ..
```
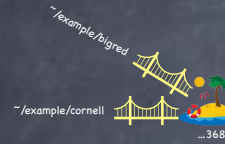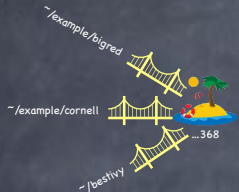
Example

Example (slide 1)

```
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ ls
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..
la13@en-cs-cisugcl10:~/example$ echo ezra > cornell
la13@en-cs-cisugcl10:~/example$ cat cornell
ezra
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..  392852368 cornell
```

~/example/cornell   inode   ...368
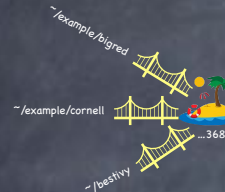
Example (slide 2)

```
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ ls
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..
la13@en-cs-cisugcl10:~/example$ echo ezra > cornell
la13@en-cs-cisugcl10:~/example$ cat cornell
ezra
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..  392852368 cornell
la13@en-cs-cisugcl10:~/example$ ln cornell bigred
la13@en-cs-cisugcl10:~/example$ cat bigred
ezra
la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
```

~/example/bigred   ~/example/cornell   ...368

Example (slide 3)

```
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ ls
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..
la13@en-cs-cisugcl10:~/example$ echo ezra > cornell
la13@en-cs-cisugcl10:~/example$ cat cornell
ezra
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..  392852368 cornell
la13@en-cs-cisugcl10:~/example$ ln cornell bigred
la13@en-cs-cisugcl10:~/example$ cat bigred
ezra
la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
la13@en-cs-cisugcl10:~/example$ ln bigred ../bestivy
la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
la13@en-cs-cisugcl10:~/example$ cd ..
la13@en-cs-cisugcl10:~$ cat bestivy
ezra
la13@en-cs-cisugcl10:~$ ls -i
392852368 bestivy  398842589 CS4410-2020sp-A4  392852366 example
```

~/example/bigred   ~/example/cornell   ~/bestivy   ...368

Example (slide 4)

```
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ ls
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..
la13@en-cs-cisugcl10:~/example$ echo ezra > cornell
la13@en-cs-cisugcl10:~/example$ cat cornell
ezra
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..  392852368 cornell
la13@en-cs-cisugcl10:~/example$ ln cornell bigred
la13@en-cs-cisugcl10:~/example$ cat bigred
ezra
la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
la13@en-cs-cisugcl10:~/example$ ln bigred ../bestivy
la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
la13@en-cs-cisugcl10:~/example$ cd ..
la13@en-cs-cisugcl10:~$ cat bestivy
ezra
la13@en-cs-cisugcl10:~$ ls -i
392852368 bestivy  398842589 CS4410-2020sp-A4  392852366 example
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ rm cornell
la13@en-cs-cisugcl10:~/example$ rm bigred
la13@en-cs-cisugcl10:~/example$ ls -i
la13@en-cs-cisugcl10:~/example$ cd ..
```

~/example/bigred   ~/example/cornell   ~/bestivy   ...368

Example

```
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ ls
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..
la13@en-cs-cisugcl10:~/example$ echo ezra > cornell
la13@en-cs-cisugcl10:~/example$ cat cornell
ezra
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..  392852368 cornell
la13@en-cs-cisugcl10:~/example$ ln cornell bigred
la13@en-cs-cisugcl10:~/example$ cat bigred
ezra
la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
la13@en-cs-cisugcl10:~/example$ ln bigred ../bestivy
la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
la13@en-cs-cisugcl10:~/example$ cd ..
la13@en-cs-cisugcl10:~$ cat bestivy
ezra
la13@en-cs-cisugcl10:~$ ls -i
392852368 bestivy  398842589 CS4410-2020sp-A4  392852366 example
```

Example

```
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ ls
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392852366 .  391230414 ..
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392852366 .  391230414 ..  392852368 cornell
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392852368 bigred  392852368 cornell
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la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
la13@en-cs-cisugcl10:~/example$ cd ..
la13@en-cs-cisugcl10:~$ cat bestivy
ezra
la13@en-cs-cisugcl10:~$ ls -i
392852368 bestivy  398842589 CS4410-2020sp-A4  392852366 example
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ rm cornell
la13@en-cs-cisugcl10:~/example$ rm bigred
la13@en-cs-cisugcl10:~/example$ ls -i
la13@en-cs-cisugcl10:~/example$ cd ..
la13@en-cs-cisugcl10:~$ cat bestivy
ezra
la13@en-cs-cisugcl10:~$ ls -i
392852368 bestivy  398842589 CS4410-2020sp-A4  392852366 example
la13@en-cs-cisugcl10:~$
```

Symbolic (Soft) links

- More flexible than hard links
  - can link to a directory
  - can link to files in another volume

- A map between pathnames
  - to link newpathname to existingpathname for file inode1:
    - create a hard link between newpathname and new file inode2
    - store in inode2 the existingpathname for inode1
  - so, a symbolic link is really a file (inode2 in our example) of a third type
    - neither a regular file nor a directory

- Created using ln, but with the –s flag

Example

Example

```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
```

Example

```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
la13@en-cs-cisugcl05:~/example$ ln cornell bigred
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 bigred  392852367 cornell
```

Example

```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
la13@en-cs-cisugcl05:~/example$ ln cornell bigred
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 bigred  392852367 cornell
la13@en-cs-cisugcl05:~/example$ cd ..
la13@en-cs-cisugcl05:~$ ln example/cornell bestivy
la13@en-cs-cisugcl05:~$ ln -s example/cornell highabove
la13@en-cs-cisugcl05:~$ ls -i
392852367 bestivy  398842589 CS4410-2020sp-A4  392852366 example  392971138 highabove
```

Example

```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
la13@en-cs-cisugcl05:~/example$ ln cornell bigred
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 bigred  392852367 cornell
la13@en-cs-cisugcl05:~/example$ cd ..
la13@en-cs-cisugcl05:~$ ln example/cornell bestivy
la13@en-cs-cisugcl05:~$ ln -s example/cornell highabove
la13@en-cs-cisugcl05:~$ ls -i
392852367 bestivy  398842589 CS4410-2020sp-A4  392852366 example  392971138 highabove
la13@en-cs-cisugcl05:~$ ls -l
total 8
-rw-r--r-- 3 la13 pug-la13     5 Apr 28 23:03 bestivy
drwxr-sr-x 4 la13 pug-la13 4096 Apr 27 11:55 CS4410-2020sp-A4
drwxr-sr-x 2 la13 pug-la13 4096 Apr 28 23:03 example
lrwxrwxrwx 1 la13 pug-la13    15 Apr 28 23:04 highabove -> example/cornell
```

Example

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la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
la13@en-cs-cisugcl05:~/example$ ln cornell bigred
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392852367 bigred   392852367 cornell
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la13@en-cs-cisugcl05:~$ ln example/cornell bestivy
la13@en-cs-cisugcl05:~$ ln -s example/cornell highabove
la13@en-cs-cisugcl05:~$ ls -i
392852367 bestivy  398842589 CS4410-2020sp-A4  392852366 example  392971138 highabove
la13@en-cs-cisugcl05:~$ ls -l
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la13@en-cs-cisugcl05:~$ cat bestivy
ezra
la13@en-cs-cisugcl05:~$ cat highabove
ezra
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392852367 cornell
la13@en-cs-cisugcl05:~/example$ ln cornell bigred
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 bigred   392852367 cornell
la13@en-cs-cisugcl05:~/example$ cd ..
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la13@en-cs-cisugcl05:~$ ln -s example/cornell highabove
la13@en-cs-cisugcl05:~$ ls -i
392852367 bestivy  398842589 CS4410-2020sp-A4  392852366 example  392971138 highabove
la13@en-cs-cisugcl05:~$ ls -l
total 8
-rw-r--r-- 3 la13 pug-la13    5 Apr 28 23:03 bestivy
drwxr-sr-x 4 la13 pug-la13 4096 Apr 27 11:55 CS4410-2020sp-A4
drwxr-sr-x 2 la13 pug-la13 4096 Apr 28 23:03 example
lrwxrwxrwx 1 la13 pug-la13   15 Apr 28 23:04 highabove -> example/cornell
la13@en-cs-cisugcl05:~$ cat bestivy
ezra
la13@en-cs-cisugcl05:~$ cat highabove
ezra
la13@en-cs-cisugcl05:~$ rm example/cornell
```

Example

```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
la13@en-cs-cisugcl05:~/example$ ln cornell bigred
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 bigred   392852367 cornell
la13@en-cs-cisugcl05:~/example$ cd ..
la13@en-cs-cisugcl05:~$ ln example/cornell bestivy
la13@en-cs-cisugcl05:~$ ln -s example/cornell highabove
la13@en-cs-cisugcl05:~$ ls -i
392852367 bestivy  398842589 CS4410-2020sp-A4  392852366 example  392971138 highabove
la13@en-cs-cisugcl05:~$ ls -l
total 8
-rw-r--r-- 3 la13 pug-la13    5 Apr 28 23:03 bestivy
drwxr-sr-x 4 la13 pug-la13 4096 Apr 27 11:55 CS4410-2020sp-A4
drwxr-sr-x 2 la13 pug-la13 4096 Apr 28 23:03 example
lrwxrwxrwx 1 la13 pug-la13   15 Apr 28 23:04 highabove -> example/cornell
la13@en-cs-cisugcl05:~$ cat bestivy
ezra
la13@en-cs-cisugcl05:~$ cat highabove
ezra
la13@en-cs-cisugcl05:~$ rm example/cornell
la13@en-cs-cisugcl05:~$ cat bestivy
ezra
```

Example

```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
la13@en-cs-cisugcl05:~/example$ ln cornell bigred
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 bigred   392852367 cornell
la13@en-cs-cisugcl05:~/example$ cd ..
la13@en-cs-cisugcl05:~$ ln example/cornell bestivy
la13@en-cs-cisugcl05:~$ ln -s example/cornell highabove
la13@en-cs-cisugcl05:~$ ls -i
392852367 bestivy  398842589 CS4410-2020sp-A4  392852366 example  392971138 highabove
la13@en-cs-cisugcl05:~$ ls -l
total 8
-rw-r--r-- 3 la13 pug-la13    5 Apr 28 23:03 bestivy
drwxr-sr-x 4 la13 pug-la13 4096 Apr 27 11:55 CS4410-2020sp-A4
drwxr-sr-x 2 la13 pug-la13 4096 Apr 28 23:03 example
lrwxrwxrwx 1 la13 pug-la13   15 Apr 28 23:04 highabove -> example/cornell
la13@en-cs-cisugcl05:~$ cat bestivy
ezra
la13@en-cs-cisugcl05:~$ cat highabove
ezra
la13@en-cs-cisugcl05:~$ rm example/cornell
la13@en-cs-cisugcl05:~$ cat bestivy
ezra
la13@en-cs-cisugcl05:~$ cat highabove
cat: highabove: No such file or directory
la13@en-cs-cisugcl05:~$
```

Permission Bits

```
la13@en-cs-cisugcl05:~$ ls -l
total 8
-rw-r--r-- 3 la13 pug-la13     5 Apr 28 23:03 bestivy
drwxr-sr-x 4 la13 pug-la13 4096 Apr 27 11:55 CS4410-2020sp-A4
drwxr-sr-x 2 la13 pug-la13 4096 Apr 28 23:03 example
lrwxrwxrwx 1 la13 pug-la13    15 Apr 28 23:04 highabove -> example/cornell
```

- File bestivy
  - leading - says bestiviy is a regular file
    - d is for directory; l is for soft link
  - Next nine characters are permission bits
    - rwx for owner, group, everyone
      - owner can read and write; group and others can just read
      - x set in a regular file means means file can be executed
      - x set in a directory that user/group/everybody is allow to cd to that directory
    - can be set using chmod

Mount

- Mount: allows multiple file systems on multiple volumes to form a single logical hierarchy

  - a mapping from some path in existing file system to the root directory of the mounted file system