
Remaining topics:

- networks
- concurrency / threads

Unix I/O

HW6 - due Friday 11/22

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Hello, world



```
#include <stdio.h>

// compile program with gcc -o hello hello.c
int main(void) {
    printf("Hello, world\n");
    return 0;
}
```

Where does the output go?

Hello, world



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Where does the output go?

To the terminal:

```
$ ./hello
Hello, world
```

To a file:

```
$ ./hello > hello.out
$ cat hello.out
Hello, world
```

File handles



C provides FILE* data type to represent a ‘‘file handle’’

- source of input and/or destination for output
- standard file handles: `stdin`, `stdout`, `stderr`
- can open named files/devices using `fopen`

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How do file handles work?

File descriptors



Unix-based systems such as Linux and MacOS use *file descriptors* to refer to

- files
- devices (e.g., terminals)
- other kinds of communication channels (e.g., network connections)
"sockets"
- a file descriptor is just an integer
- a C file handle (FILE*) is just a "wrapper" for a file descriptor

How can we write programs to work with file descriptors? (And why is it useful to do that?)

Files, Unix filesystem

Files



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Basic concept: file

Is a sequence of bytes: $b_0, b_1, b_2, \dots, b_{n-1}$

For all files, bytes can be read and written sequentially

For some files, random access is possible (reading or writing at arbitrary positions in the sequence)

depending on perm, file permission

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2. Any object or device that can be treated as a file (for reading bytes and/or writing bytes)

The first meaning is a special case of the second meaning.

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Lots of devices and objects in Unix are treated as files (in the second sense):

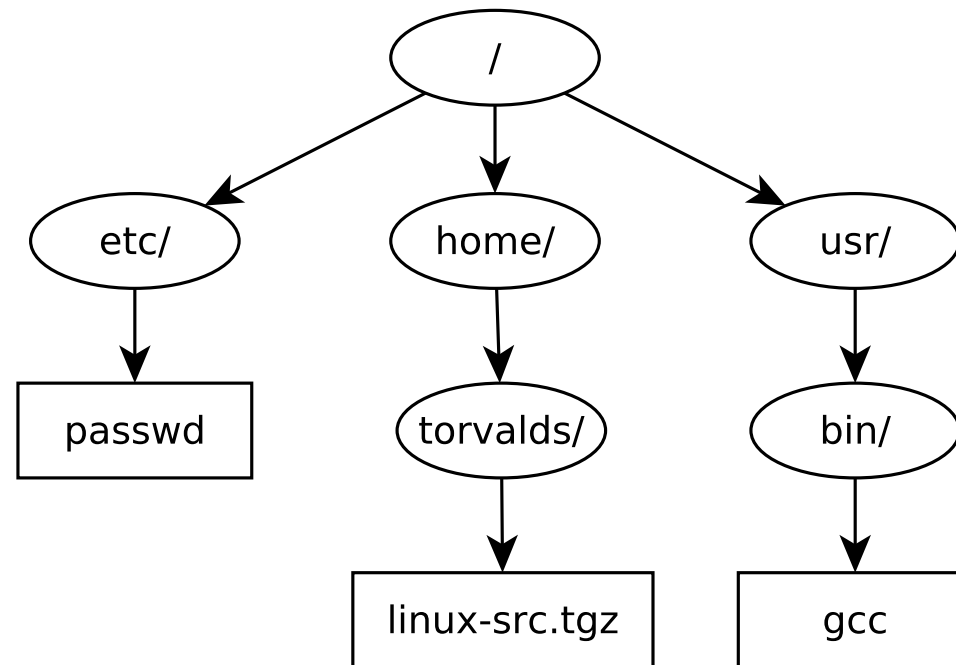
- Terminals
- Pipes (e.g., `cat myfile.txt | wc -l`)
- Network connections
- Peripheral devices
- And of course, files (in the first sense)

Filesystem



The Unix *filesystem* is a hierarchical namespace for files.

A *path* names the location of a file or directory in the namespace by describing how to find it, starting from the *root directory* (/), navigating through a sequence of zero or more intermediate directories.

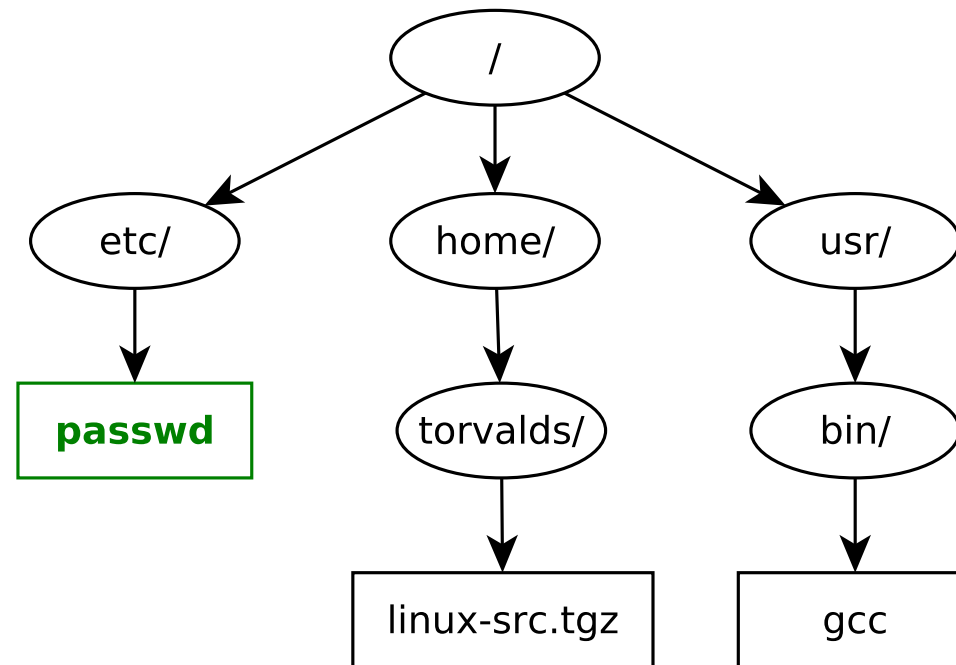


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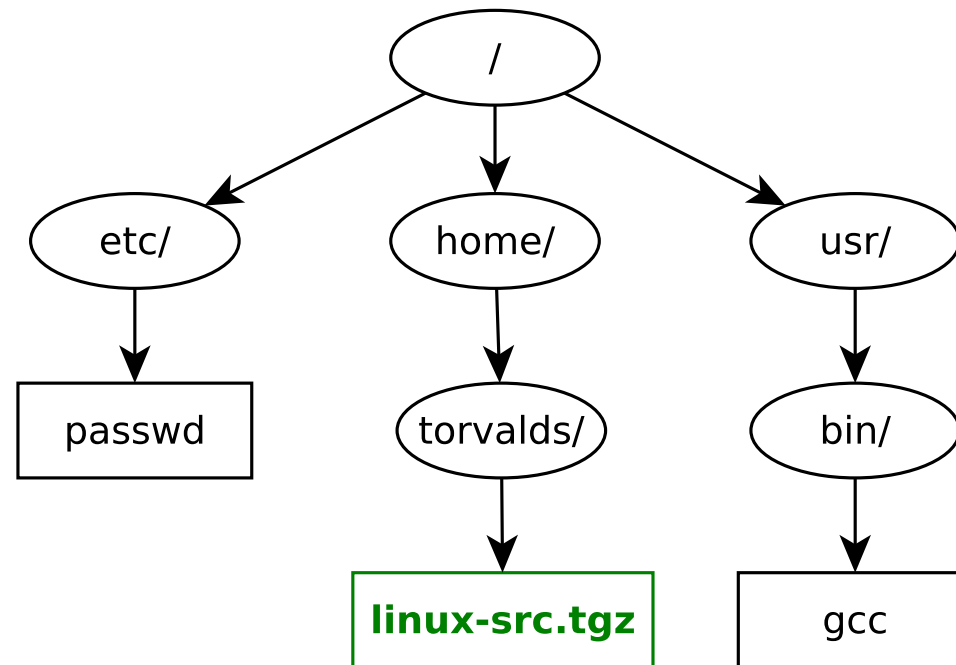
`/etc/passwd`

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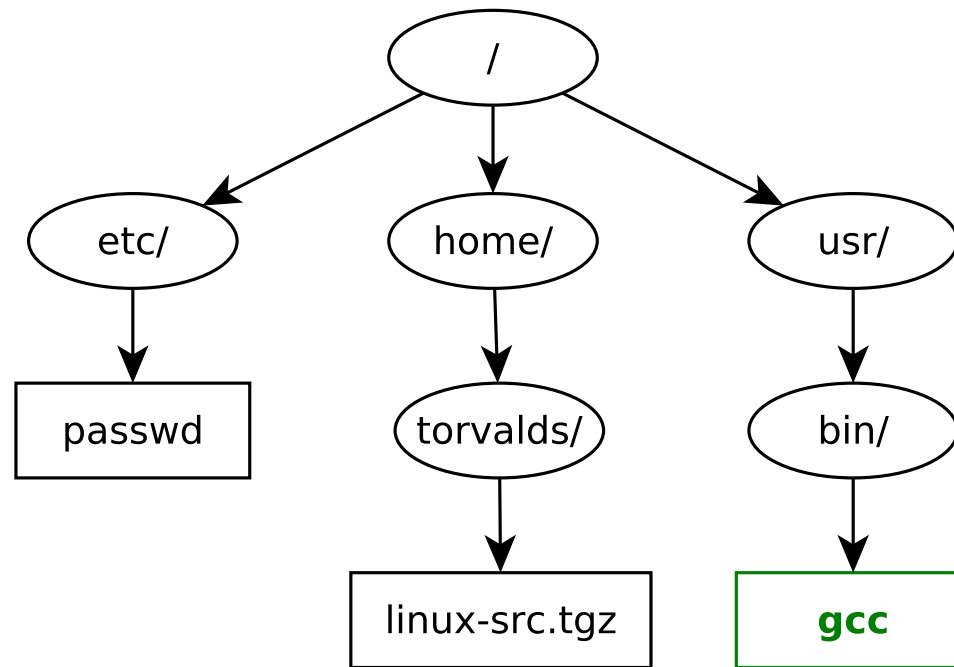


`/home/torvalds/linux-src.tgz`

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`/usr/bin/gcc`



System calls, Unix I/O

System calls

A *system call* is a mechanism allowing a process (running program) to request a service from the operating system.

To the program, system calls are just function calls. (They are typically implemented using software interrupts.)

System calls are typically very low-level. Most programming languages provide a *run-time library* with higher-level functions.

For example:

- open, read, write: system calls
- fopen, fread, fwrite: run-time library functions

System calls and signals

Signals are a Unix mechanism for asynchronous notification.

They are similar to hardware interrupts, but are delivered to processes (running programs). The program can register a *signal handler* function to receive them.

Example signals:

- SIGSEGV: segmentation violation (ever gotten this? 😊)
- SIGINT: interruption (sent when you type control-C in the terminal)
- SIGALRM: software timer

Issue: system calls can be interrupted if a signal is received.

Opening files

open system call:

```
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

int open(const char *pathname, int flags, mode_t mode);
```

Used for opening a *named* file (one that has a path in the filesystem.)
Returns file descriptor (or -1 to indicate error.)

flags: one of O_RDONLY, O_WRONLY, or O_RDWR, bitwise-or'ed
with (optionally) O_CREAT, O_TRUNC, and/or O_APPEND

mode: access permission bits (only significant when flags
contains O_CREAT, can omit otherwise)

Closing files

close system call:

```
#include <unistd.h>

int close(int fd);
```

Closes file named by specified file descriptor (fd).

Reading data

read system call:

```
#include <unistd.h>

ssize_t read(int fd, void *buf, size_t n);
```

Read n bytes from specified file descriptor, placing data read in `buf`. Returns number of bytes read, or -1 on error.

Short read: fewer than n bytes might be read because

- end of file was reached
- some data is not available yet (e.g., reading from a network connection)
- line buffering by terminal

Must check return value!

Dealing with short reads

```
// Try to read n bytes from fd.
// Returns number of bytes read, or -1 on error.
// Returns fewer than n bytes only if EOF is reached.
ssize_t read_fully(int fd, void *buf, size_t n) {
    char *p = buf;
    while (p < (char *) buf + n) {
        size_t remaining = p - (char *) buf;
        ssize_t rc = read(fd, p, remaining);
        if (rc == 0) {
            break; // reached end of file
        } else if (rc > 0) {
            p += rc; // read data successfully
        } else if (errno != EINTR) {
            return -1; // an error occurred
        }
    }
    return (ssize_t) (p - (char *) buf);
}
```

Writing data

write system call:

```
#include <unistd.h>

ssize_t write(int fd, const void *buf, size_t n);
```

Write n bytes from `buf` to specified file descriptor.
Returns number of bytes written, or `-1` on error.

Like `read`, can also return a short write (fewer than n bytes written.)

Exercise for reader: implement a `write_fully` function.



Buffered I/O

A program

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <unistd.h>

int main(int argc, char **argv) {
    int fd = open(argv[1], O_RDONLY);
    char *buf = malloc(100000000);
    for (int i = 0; i < 100000000; i++) {
        if (read(fd, buf + i, 1) != 1) {
            fprintf(stderr, "failed read?\n");
            return 1;
        }
    }
    close(fd);
    return 0;
}
```

```
$ gcc -Wall -O2 -o r1 r1.c
$ time ./r1 largefile.mp3

real 0m5.334s
user 0m2.204s
sys 0m3.128s
```

Another program

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```
#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <unistd.h>

int main(int argc, char **argv) {
    int fd = open(argv[1], O_RDONLY);
    char *buf = malloc(100000000);
    if (read(fd, buf, 100000000) != 100000000) {
        fprintf(stderr, "failed read?\n");
        return 1;
    }
    close(fd);
    return 0;
}
```

```
$ gcc -Wall -O2 -o r2 r2.c
$ time ./r2 largefile.mp3

real 0m0.010s !
user 0m0.000s
sys 0m0.010s
```

System call overhead



System calls (such as `read`) are not like ordinary function calls. They require a call into operating system kernel (typically via a software interrupt). This requires:

- saving and restoring registers
- switching processor privilege levels
- checking system call arguments
- carrying out the system call (I/O, data transfer to/from program buffer)

This overhead can add up.

Buffering

read and write system calls can be made less frequent using *buffering*:

- Writing: store data in a buffer in memory, flush (write to actual file) when buffer has become full or before closing file
- Reading: read large chunks of data into buffer infrequently, retrieve data from the buffer when requested

FILE* objects (C file handles) have an internal buffer, so, e.g.

- fgetc doesn't call read each time
- fputc doesn't call write each time

A third program

```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char **argv) {
    FILE *in = fopen(argv[1], "rb");
    char *buf = malloc(100000000);
    for (int i = 0; i < 100000000; i++) {
        int c = fgetc(in);
        if (c < 0) {
            fprintf(stderr, "fgetc failed?\n");
            return 1;
        }
        buf[i] = (char) c;
    }
    fclose(in);
    return 0;
}
```

```
$ gcc -Wall -O2 -o r3 r3.c
$ time ./r3 largefile.mp3

real 0m0.042s
user 0m0.038s
sys 0m0.004s
```

Downsides of buffered I/O
- inconsistency



Files and processes

What is a file descriptor?

A *file descriptor* is a small integer value identifying an open file.

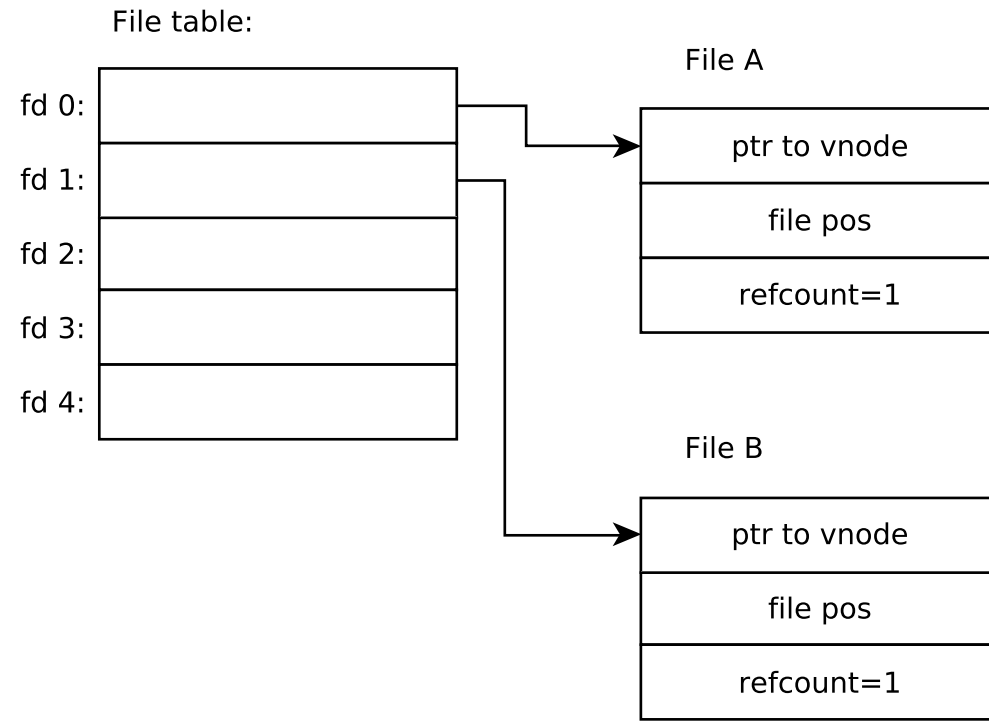
Really, it's an index into a *file table* belonging to the process. The file table is a kernel data structure (not directly accessible to the program.)

Each entry in the table points to a *file object*.

The file object contains:

- Pointer to a *vnode* (“virtual node”)
- File position (offset of next byte to be read or written, only relevant for random-access files)
- Reference count

File table example



What is a vnode?

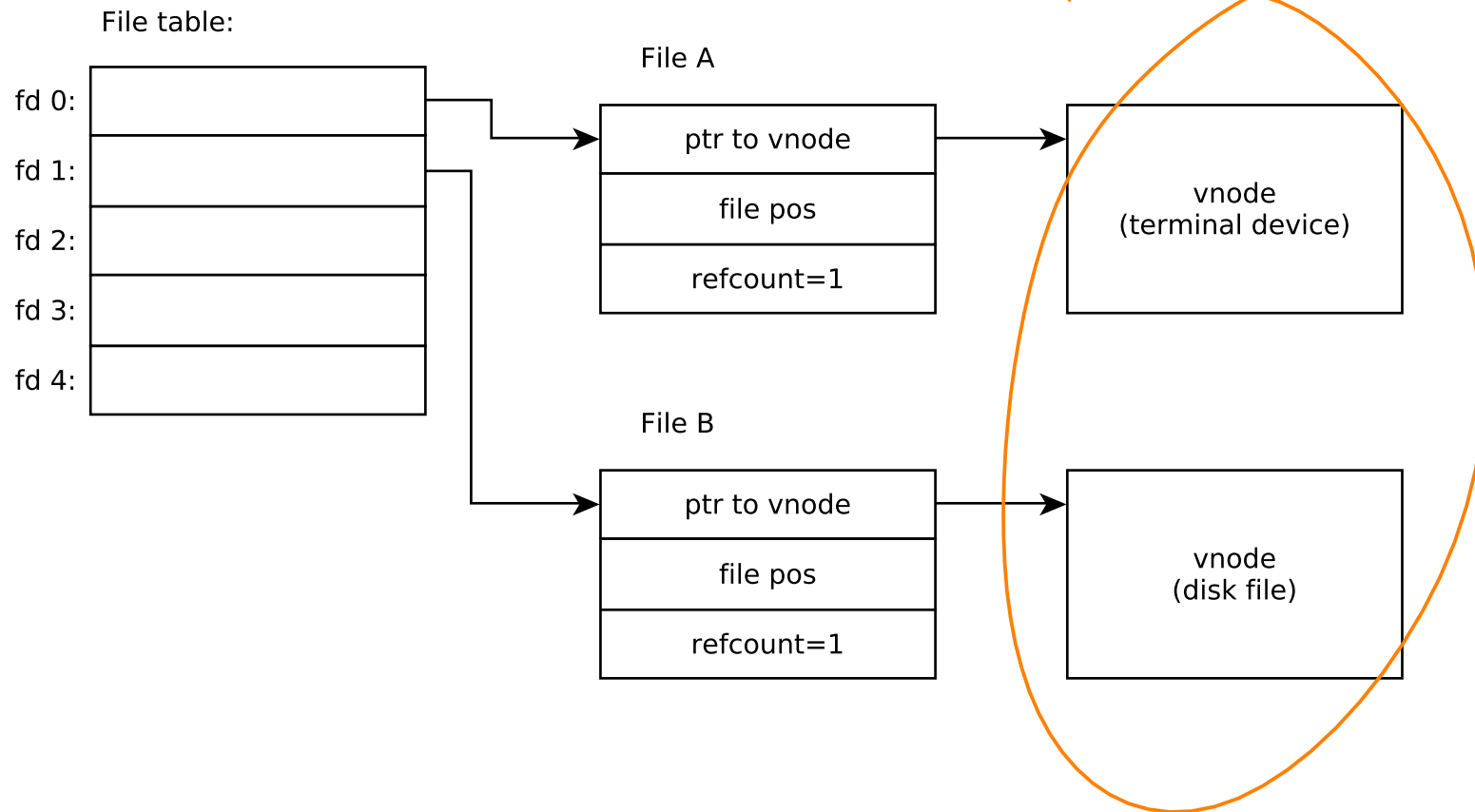
A *vnode* is an object representing the actual file data, in whatever its ‘‘true’’ form is

- file on disk or SSD
- terminal device
- pipe
- network connection
- etc.

Example on next slide: fd 0 (standard output) is a terminal, fd 1 (standard input) is a file on disk

vnode example

polymorphism!



Duplication of file descriptors

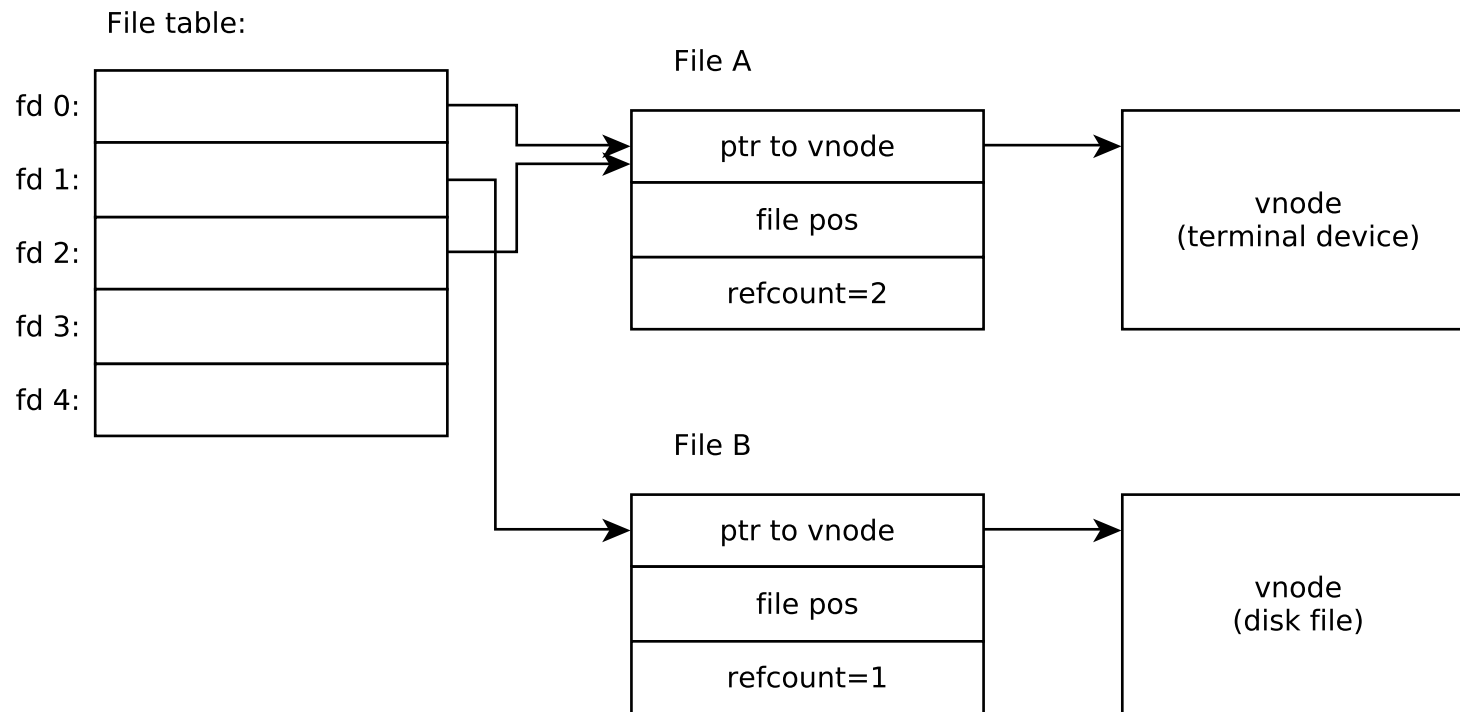


More than one file descriptor (file table entry) can refer to the same file object.

The `dup` and `dup2` system calls create a new file descriptor pointing to the same file object as an existing file descriptor.

Example on next slide: `fd 2` (standard error) also goes to terminal.

Duplicated file descriptor



Shared file objects

When a process creates a child process using the fork system call, the parent process's file table is inherited by the child.

This results in file objects being shared between parent and child.

Example on next slide: fd 0 and fd 1 in parent and child processes are shared following fork system call.

Shared file descriptor example

