System-Level I/O

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1

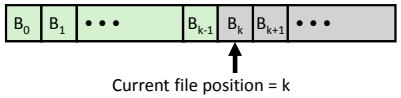
I/O Overview

- Data input-from/output-to external devices (disk storage, network, terminal …)
- I/O is privileged (must be managed by the operating system)
- Our study
  - Focus on the application interface
  - A bit of behind-the-scene look to help our understanding
  - Much more in OS and networking courses later
- Outline:
  - Operating system I/O (taking Unix as an example)
  - User-level runtime library (C language runtime)
  - Internal representation, sharing, and redirection

2

Unix I/O and Files

- Data organization is at the center of I/O.
- A Unix *file* is a sequence of *m* bytes:
  - $B_0, B_1, \ldots, B_k, \ldots, B_{m-1}$
  - "unstructured" data object
- Basic Unix I/O operations (system calls):
  - Opening and closing files: **`open()`** and **`close()`**
  - Reading and writing a file: **`read()`** and **`write()`**
  - Changing the ***current file position***: **`lseek()`**



3

Unix "File" Types

- Regular files
  - File containing user/app data (binary, text, whatever)
- Directory files
  - A file that contains the names and locations of other files
- Device files
  - Terminals (character device) and disks (block device)
- Unix pipes for inter-process communication
- Sockets for network communications
- **`/proc:`** An convenient way to access kernel information

→ "File" is an object/target for I/O.

4

Opening Files

- Opening a file informs the OS kernel that you are getting ready to access that file

```
int fd;   /* file descriptor */

if ((fd = open("/etc/hosts", O_RDONLY)) < 0) {
   perror("open");
   exit(1);
}
```

- Returns an identifying integer *file descriptor*
  - Returns **-1** indicates that an error occurred
- Each process created by a Unix shell begins life with three open files associated with a terminal:
  - 0: standard input
  - 1: standard output
  - 2: standard error

5

Closing Files

- Closing a file informs the kernel that you are finished accessing that file, so resources can be freed

```
int fd;     /* file descriptor */
int retval; /* return value */

if ((retval = close(fd)) < 0) {
   perror("close");
   exit(1);
}
```

- OS will close all unclosed files when a process terminates
- Always check return codes, even for seemingly benign functions such as **`close()`**

6

Reading Files

- Reading a file copies bytes from the current file position to memory, and then updates file position

```
char buf[512];
int fd;       /* file descriptor */
int nbytes;   /* number of bytes read */

/* Open file fd ...  */
/* Then read up to 512 bytes from file fd */
if ((nbytes = read(fd, buf, sizeof(buf))) < 0) {
   perror("read");
   exit(1);
}
```

- Returns number of bytes read from file **`fd`** into **`buf`**
  - Return type **`ssize_t`** is signed integer
  - Returns **`-1`** indicates that an error occurred
  - ***Short counts*** (**`nbytes < sizeof(buf)`**) are possible and are not necessarily errors.

7

Short Counts

- Short counts can occur in these situations:
  - Encountering (end-of-file) EOF on reads
  - Reading text lines from a terminal
  - Reading and writing network sockets or Unix pipes
- Deal with short counts:
  - Check return count. Don't assume you've read/written all.
  - To reach desired count, you may need to read/write again & again.

8

Simple Unix I/O example

- Copying standard in to standard out, one byte at a time

```
#include "csapp.h"

int main(void)
{
    char c;

    while(read(STDIN_FILENO, &c, 1) != 0)
        write(STDOUT_FILENO, &c, 1);
    exit(0);
}
```

- Works but not efficient.

9

Buffered I/O: Motivation

- Applications sometimes read/write one(few) byte(s) at a time
- Implementing as Unix I/O calls expensive
  - **`read`** and **`write`** require OS kernel calls
    - 10,000 clock cycles
- Solution: Buffered read
  - Use Unix **`read`** to grab block of bytes
  - User input functions take one byte at a time from buffer
    - Refill buffer when empty

- Buffered write
  - First write to a temporary buffer, then do Unix **`write`** in a batch

10

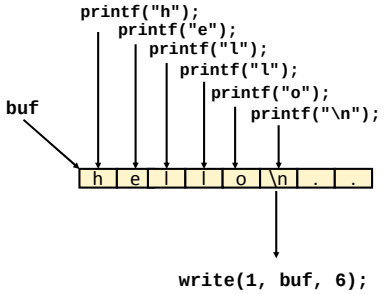
C Utility I/O Functions

- The C library (**`libc.so`**) contains a collection of higher-level *I/O* functions
- Examples of standard I/O functions:
  - Opening and closing files (**`fopen`** and **`fclose`**)
  - Reading and writing bytes (**`fread`** and **`fwrite`**)
  - Reading and writing text lines (**`fgets`** and **`fputs`**)
  - Formatted reading and writing (**`fscanf`** and **`fprintf`**)
- I/O models open files as *streams*
  - Abstraction for a file descriptor and a buffer in memory.

11

Buffering in C Utility I/O

- Standard I/O functions use buffered I/O

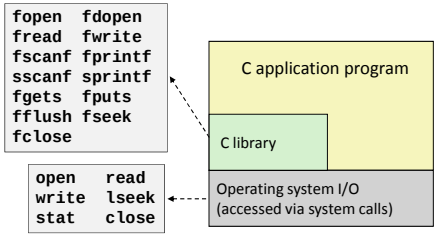


- Buffer flushed to output fd on "\n" or **`fflush()`** call
- But may lose more data when the machine crashes

12

Unix I/O vs. C Utility I/O

- C Utility I/O is implemented using low-level Unix I/O



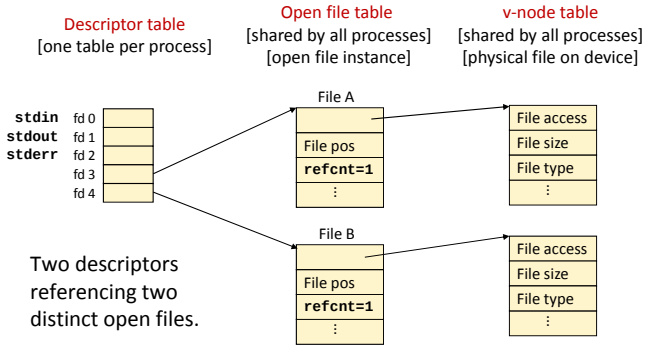
- Which ones should you use in your programs?

Unix I/O vs. C Utility I/O

- Pros for Unix I/O
  - Unix I/O is the most general and lowest raw overhead form of I/O.
    - All other I/O packages are implemented using Unix I/O functions.
  - Unix I/O provides functions for accessing file metadata.
  - Unix I/O functions are async-signal-safe and can be used safely in signal handlers.
- Pros for C Utility I/O
  - Buffering increases efficiency by decreasing the number of **`read`** and **`write`** system calls
  - Short counts are handled automatically

How the Unix Kernel Represents Open Files?

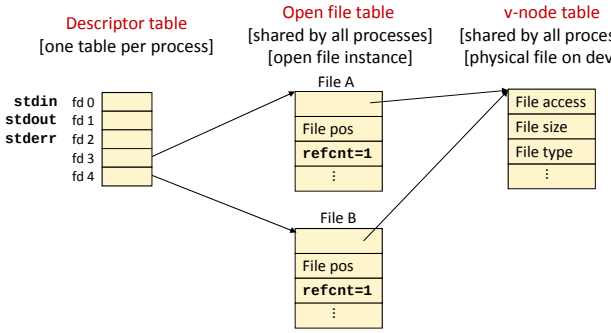
- File descriptors, open files, and v-nodes.



Two descriptors referencing two distinct open files.

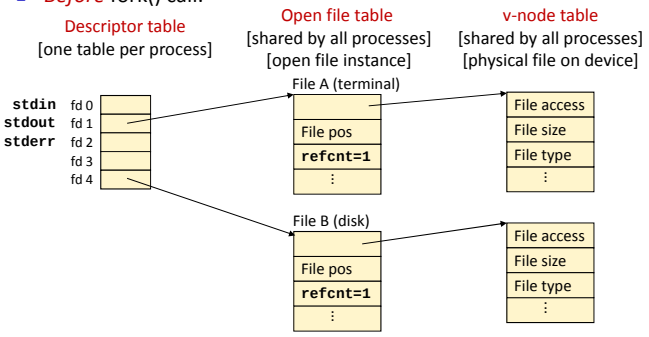
File Sharing

- Two distinct descriptors sharing the same physical file through two distinct open file table entries
  - E.g., Calling **`open`** twice with the same **`filename`** argument



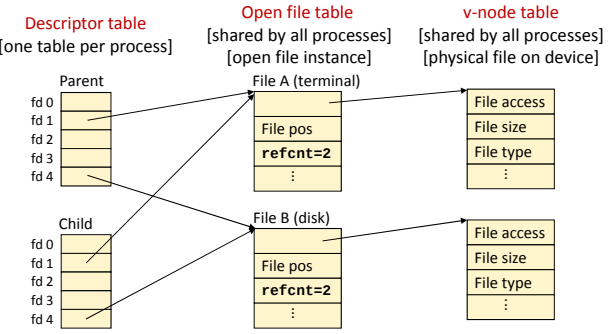
How Processes Share Files: Fork()

- A child process inherits its parent's open files
  - Note: situation unchanged by **exec** functions
- *Before* fork() call:



How Processes Share Files: Fork()

- A child process inherits its parent's open files
- *After* fork():
  - Child's table same as parent's, and +1 to each refcnt

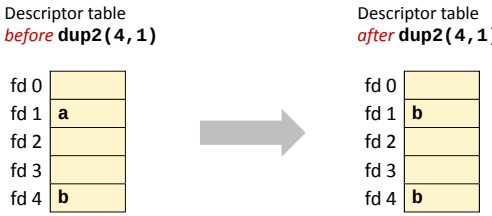


I/O Redirection

- How does a shell implement I/O redirection? Not required for your assignment!

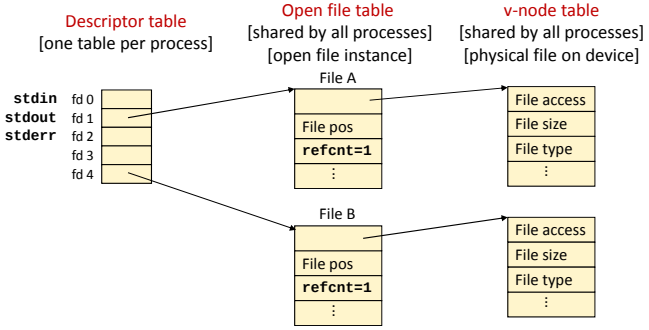
```
unix> ls > foo.txt
```

- Answer: By calling the **dup2(oldfd, newfd)** function
  - Copies (per-process) descriptor table entry **oldfd** to entry **newfd**



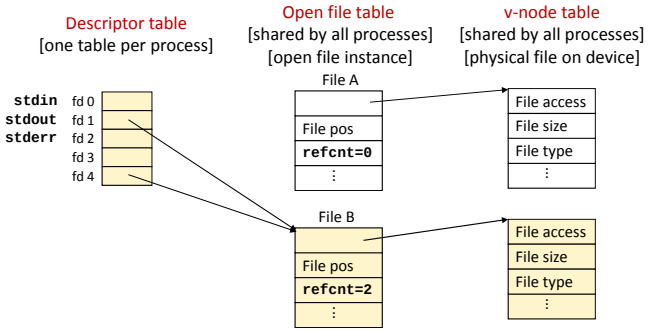
I/O Redirection Example

- Step #1: open file to which stdout should be redirected
  - Happens in child executing shell code, before **exec**



I/O Redirection Example (cont.)

- Step #2: call **dup2(4,1)**
  - cause fd=1 (stdout) to refer to disk file pointed at by fd=4



21

Fun with File Descriptors

```
int main(int argc, char *argv[]) {
    int fd1, fd2, fd3;
    char c1, c2, c3;
    char *fname = argv[1];
    fd1 = open(fname, O_RDONLY, 0);
    fd2 = open(fname, O_RDONLY, 0);
    fd3 = open(fname, O_RDONLY, 0);
    dup2(fd2, fd3);
    read(fd1, &c1, 1);
    read(fd2, &c2, 1);
    read(fd3, &c3, 1);
    printf("c1 = %c, c2 = %c, c3 = %c\n", c1, c2, c3);
    return 0;
}
```

- **Must check return code of system calls in your code!!!**
- What would this program print for file containing "abcde"?
  - c1 = a, c2 = a, c3 = b

22

Fun with File Descriptors (2)

```
int main(int argc, char *argv[]) {
    int fd;
    char c1, c2;
    char *fname = argv[1];
    fd1 = open(fname, O_RDONLY, 0);
    read(fd, &c1, 1);
    if (fork()) { /* Parent */
        read(fd, &c2, 1);
        printf("Parent: c1 = %c, c2 = %c\n", c1, c2);
    } else { /* Child */
        sleep(1);
        read(fd, &c2, 1);
        printf("Child: c1 = %c, c2 = %c\n", c1, c2);
    }
    return 0;
}
```

- What would this program print for file containing "abcde"?

23

Disclaimer

These slides were adapted from the CMU course slides provided along with the textbook of "Computer Systems: A programmer's Perspective" by Bryant and O'Hallaron. The slides are intended for the sole purpose of teaching the computer organization course at the University of Rochester.

24