System I/O

15-213/18-243: Introduction to Computer Systems

20th Lecture, 1 April 2010

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Exam 2: 6 April

- **At your assigned lecture time**
- **Closed references, no calculators, open mind**
  - We will provide reference material (if necessary)
- **Covers:**
  - Lectures 10 - 19
  - Textbook
    - Chapter 5.1-5.12
    - Chapter 6.2-6.8
    - Chapter 8.1-8.7
    - Chapter 10.1-10.11, Wilson94 reading
  - Labs
    - Tshlab
    - Malloclab (through checkpoint 1)

Today

- **Memory related bugs**
- **System level I/O**
  - Unix I/O
  - Standard I/O
  - RIO (robust I/O) package
  - Conclusions and examples

Memory-Related Perils and Pitfalls

- Dereferencing bad pointers
- Reading uninitialized memory
- Overwriting memory
- Referencing nonexistent variables
- Freeing blocks multiple times
- Referencing freed blocks
- Failing to free blocks

Dereferencing Bad Pointers

- **Problem: Attempting to use a pointer to an unallocated space in virtual memory**
  - Attempting to use such a pointer results in protection exception
- **The classic `scanf` bug**

```
int val;

...

scanf("%d", val);
```

- **In the worst case, you won't get a protection exception!**

Reading Uninitialized Memory

- Problem: Heap memory is not initialized to zero (like .bss is)
- If you want zero'ed heap memory, use `calloc`

```
/* return y = Ax */
int *matvec(int **A, int *x) {
  int *y = (int *)Malloc(N*sizeof(int));
  int i, j;

  for (i=0; i<N; i++)
    for (j=0; j<N; j++)
      y[i] += A[i][j]*x[j];
  return y;
}
```

Overwriting Memory

- Allocating the (possibly) wrong sized object

```
int **p;

p = (int **)Malloc(N*sizeof(int));

for (i=0; i<N; i++) {
   p[i] = malloc(M*sizeof(int));
}
```

- Pointers and the objects they point to (int in this case) are not necessarily the same size!
-

Overwriting Memory

- Off-by-one error

```
int **p;

p = (int **)malloc(N*sizeof(int *));

for (i=0; i<=N; i++) {
   p[i] = malloc(M*sizeof(int));
}
```

- What data is likely one word after the allocated block?
- When will we likely discover the problem?

Overwriting Memory

- Not checking the max string size

```
char s[8];
int i;

gets(s);  /* reads "123456789" from stdin */
```

- Use `fgets` instead
- Basis for classic buffer overflow attacks
  - 1988 Internet worm
  - Modern attacks on Web servers
  - AOL/Microsoft IM war

Overwriting Memory

- Misunderstanding pointer arithmetic

```
int *search(int *p, int val) {

  while (*p && *p != val)
    p += sizeof(int);

  return p;
}
```

- Pointer math is based on units of the pointed-to type, not 1

Overwriting Memory

- Referencing a pointer instead of the object it points to

```
int *BinheapDelete(int **binheap, int *size) {
  int *packet;
  packet = binheap[0];
  binheap[0] = binheap[*size - 1];
  *size--; /* OOPS! Want heap size decremented */
  Heapify(binheap, *size, 0);
  return(packet);
}
```

Referencing Nonexistent Variables

- Forgetting that local variables disappear when a function returns

```
int *create_baffling_bug () {
  int val;

  return &val;
}
```

Freeing Blocks Multiple Times

- Nasty!

```
x = malloc(N*sizeof(int));
        <manipulate x>
free(x);

y = malloc(M*sizeof(int));
        <manipulate y>
free(x);
```

Referencing Freed Blocks

- Evil!

```
x = malloc(N*sizeof(int));
  <manipulate x>
free(x);
   ...
y = malloc(M*sizeof(int));
for (i=0; i<M; i++)
   y[i] = x[i]++;
```

Failing to Free Blocks (Memory Leaks)

- Slow, long-term killer!

```
void create_leak() {
    int *x = malloc(N*sizeof(int));
    ...
    return;
}
```

Failing to Free Blocks (Memory Leaks)

- Freeing only part of a data structure

```
struct list {
  int val;
  struct list *next;
};

void foo() {
  struct list *head = malloc(sizeof(struct list));
  head->val = 0;
  head->next = NULL;
  <create and manipulate the rest of the list>
   ...
  free(head);
  return;
}
```

Dealing With Memory Bugs

- **Conventional debugger (`gdb`)**
  - Good for finding bad pointer dereferences
  - Hard to detect the other memory bugs
- **Debugging `malloc` (UToronto CSRI `malloc`)**
  - Wrapper around conventional **`malloc`**
  - Detects memory bugs at **malloc** and **`free`** boundaries
    - Memory overwrites that corrupt heap structures
    - Some instances of freeing blocks multiple times
    - Memory leaks
  - Cannot detect all memory bugs
    - Overwrites into the middle of allocated blocks
    - Freeing block twice that has been reallocated in the interim
    - Referencing freed blocks

Dealing With Memory Bugs (cont.)

- **Some `malloc` implementations contain checking code**
  - Linux glibc malloc: **`setenv MALLOC_CHECK_ 2`**
  - FreeBSD: **`setenv MALLOC_OPTIONS AJR`**
- **Binary translator: valgrind (Linux), Purify**
  - Powerful debugging and analysis technique
  - Rewrites text section of executable object file
  - Can detect same errors as debugging **`malloc`**
  - Can also check each individual reference at runtime
    - Bad pointers
    - Overwriting
    - Referencing outside of allocated block
- **Garbage collection (Boehm-Weiser Conservative GC)**
  - Let the system free blocks instead of the programmer

Today

- Memory related bugs
- **System level I/O**
  - Unix I/O
  - Standard I/O
  - RIO (robust I/O) package
  - Conclusions and examples

Unix Files

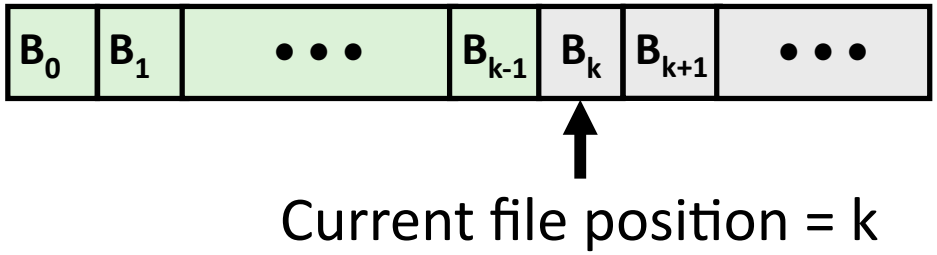
- **A Unix *file* is a sequence of *m* bytes**
  - $B_0, B_1, \ldots, B_k, \ldots, B_{m-1}$
- **All I/O devices are represented as files**
  - `/dev/sda2` (`/usr` disk partition)
  - `/dev/tty2` (terminal)
- **Even the kernel is represented as a file**
  - `/dev/kmem` (kernel memory image)
  - `/proc` (kernel data structures)

Unix File Types

- **Regular file**
  - File containing user/app data (binary, text, whatever)
  - OS does not know anything about the format
    - other than “sequence of bytes”, akin to main memory
- **Directory file**
  - A file that contains the names and locations of other files
- **Character special and block special files**
  - Terminals (character special) and disks (block special)
- **FIFO (named pipe)**
  - A file type used for inter-process communication
- **Socket**
  - A file type used for network communication between processes

Unix I/O

- **Key Features**
  - Elegant mapping of files to devices allows kernel to export simple interface
  - Important idea: All input and output is handled consistently and uniformly
- **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*** (seek)
    - indicates next offset into file to read or write
    - **`lseek()`**



Opening Files

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

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

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

- **Returns a small identifying integer *file descriptor***
  - `fd == -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

Closing Files

- Closing a file informs the kernel that you are finished accessing that file

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

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

- Closing an already closed file is a recipe for disaster in threaded programs (more on this later)
- Moral: Always check return codes, even for seemingly benign functions such as `close()`

Reading Files

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

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

/* Open fd and read up to 512 bytes */
if ((nbytes = read(fd, buf, sizeof(buf))) == -1) {
   perror("read");
   exit(1);
}
```

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

Writing Files

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

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

/* Open fd and write up to 512 bytes from buf */
if ((nbytes = write(fd, buf, sizeof(buf)) == -1) {
   perror("write");
   exit(1);
}
```

- **Returns number of bytes written from `buf` to file `fd`**
  - **`nbytes == -1`** indicates that an error occurred
  - As with reads, short counts are possible and are not errors!

Simple Unix I/O example

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

```
int main(void)
{
  char c;

  while ((len = read(0 /*stdin*/, &c, 1)) == 1) {
    if (write(1 /*stdout*/, &c, 1) != 1)
      exit(20);

    if (len == -1) {
      perror ("read from stdin failed");
      exit (10);
    }
  }
  exit(0);
}
```

File Metadata

- ***Metadata*** **is data about data, in this case file data**
- **Per-file metadata maintained by kernel**
  - accessed by users with the **`stat`** and **`fstat`** functions

```
/* Metadata returned by the stat and fstat functions */
struct stat {
    dev_t         st_dev;      /* device */
    ino_t         st_ino;      /* inode */
    mode_t        st_mode;     /* protection and file type */
    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 type (if inode device) */
    off_t         st_size;     /* total size, in bytes */
    unsigned long st_blksize;  /* blocksize for filesystem I/O */
    unsigned long 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 change */
};
```

Example of Accessing File Metadata

```
/* statcheck.c - Querying and manipulating a file's meta data */
#include "csapp.h"

int main (int argc, char **argv)
{
    struct stat stat;
    char *type, *readok;

    Stat(argv[1], &stat);
    if (S_ISREG(stat.st_mode))
        type = "regular";
    else if (S_ISDIR(stat.st_mode))
        type = "directory";
    else
        type = "other";

    if ((stat.st_mode & S_IRUSR)) /* OK to read?*/
        readok = "yes";
    else
        readok = "no";

    printf("type: %s, read: %s\n", type, readok);
    exit(0);
}
```

```
unix> ./statcheck statcheck.c
type: regular, read: yes
unix> chmod 000 statcheck.c
unix> ./statcheck statcheck.c
type: regular, read: no
unix> ./statcheck ..
type: directory, read: yes
unix> ./statcheck /dev/kmem
type: other, read: yes
```

Repeated Slide: Opening Files

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

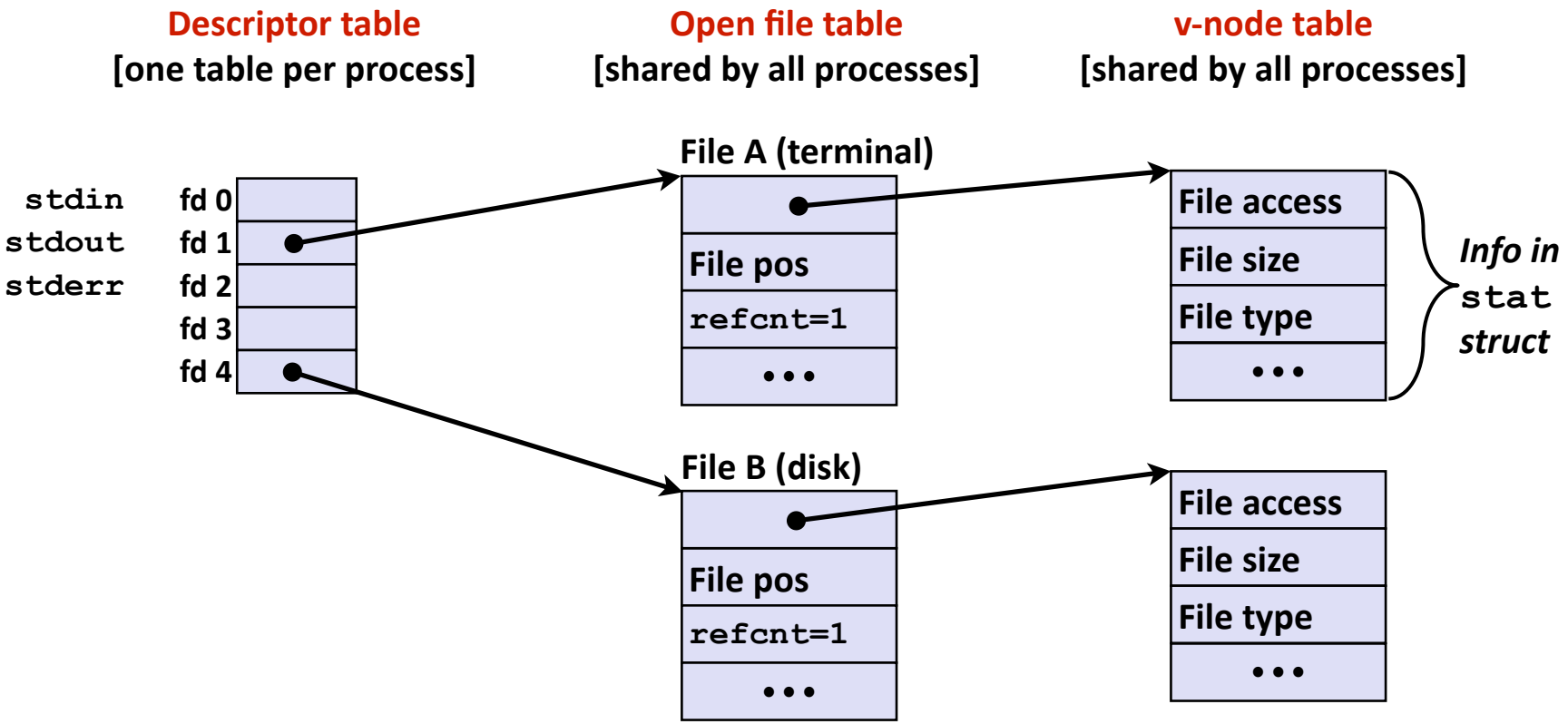
```
int fd;    /* file descriptor */

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

- **Returns a small identifying integer *file descriptor***
  - `fd == -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

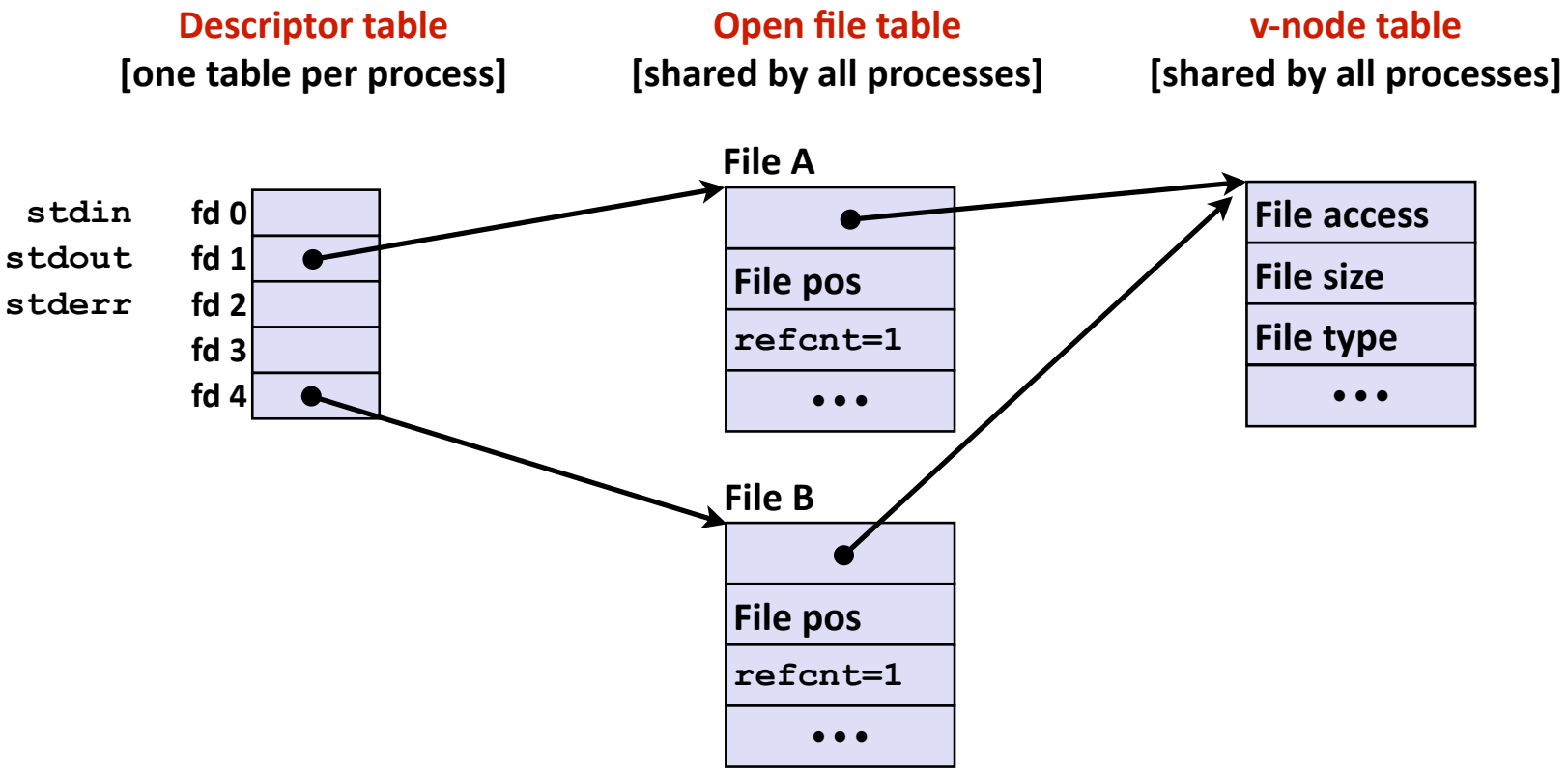
How the Unix Kernel Represents Open Files

- Two descriptors referencing two distinct open disk files. Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file



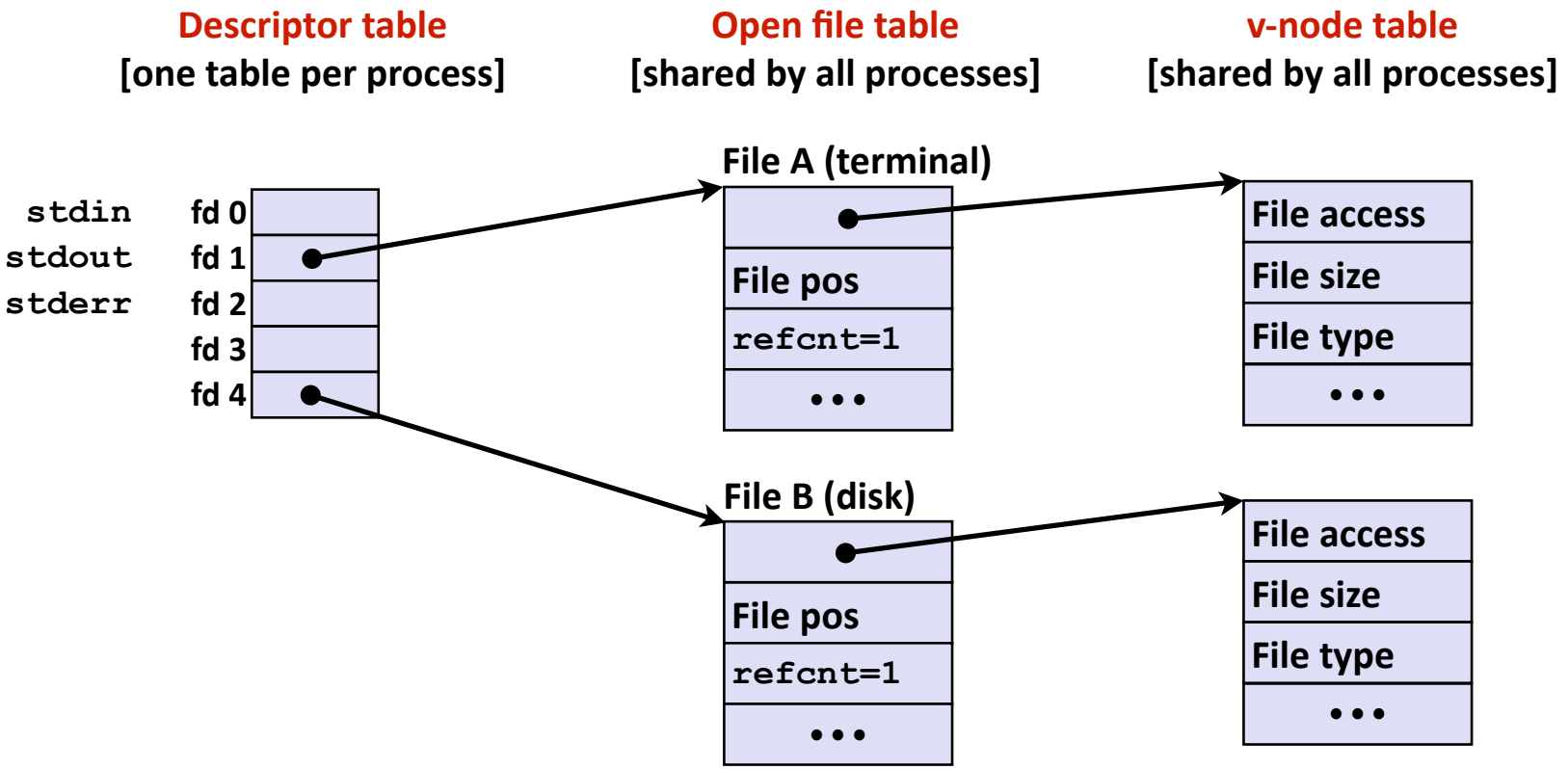
File Sharing

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



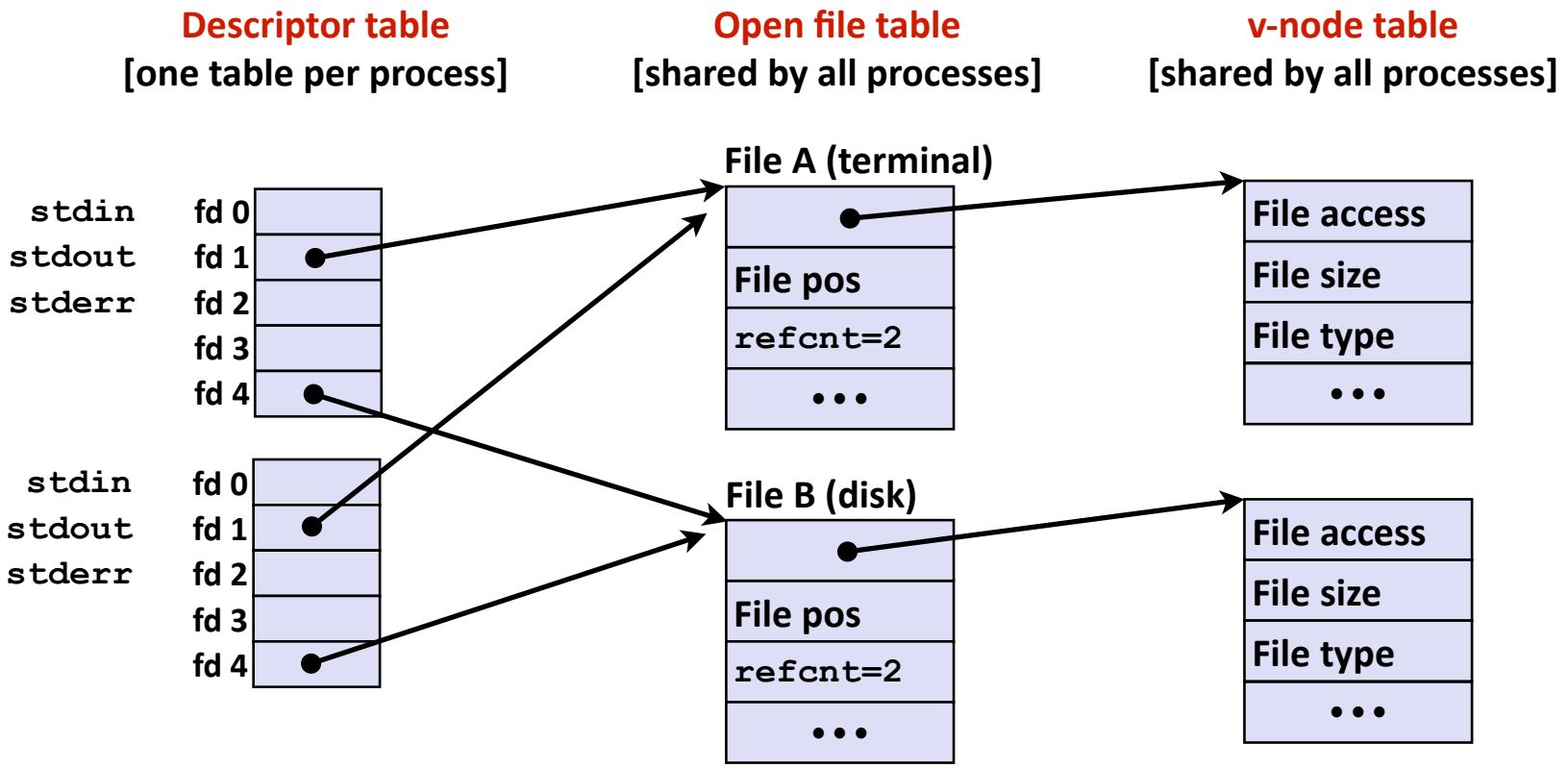
How Processes Share Files: Fork()

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



How Processes Share Files: Fork()

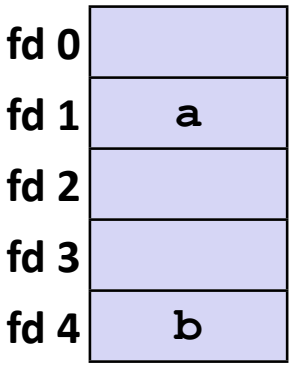
- A child process inherits its parent's open files
- *After* fork():
  - Child's table same as parents, and +1 to each `refcnt`



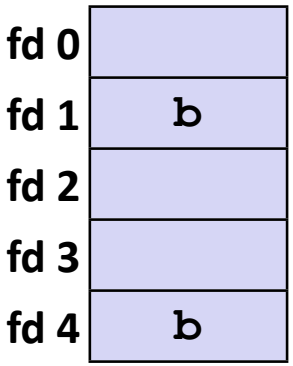
I/O Redirection

- **Question: How does a shell implement I/O redirection?**
  - `unix> ls > foo.txt`
- **Answer: By calling the `dup2(oldfd, newfd)` function**
  - Copies (per-process) descriptor table entry `oldfd` to entry `newfd`

Descriptor table *before* `dup2(4,1)`

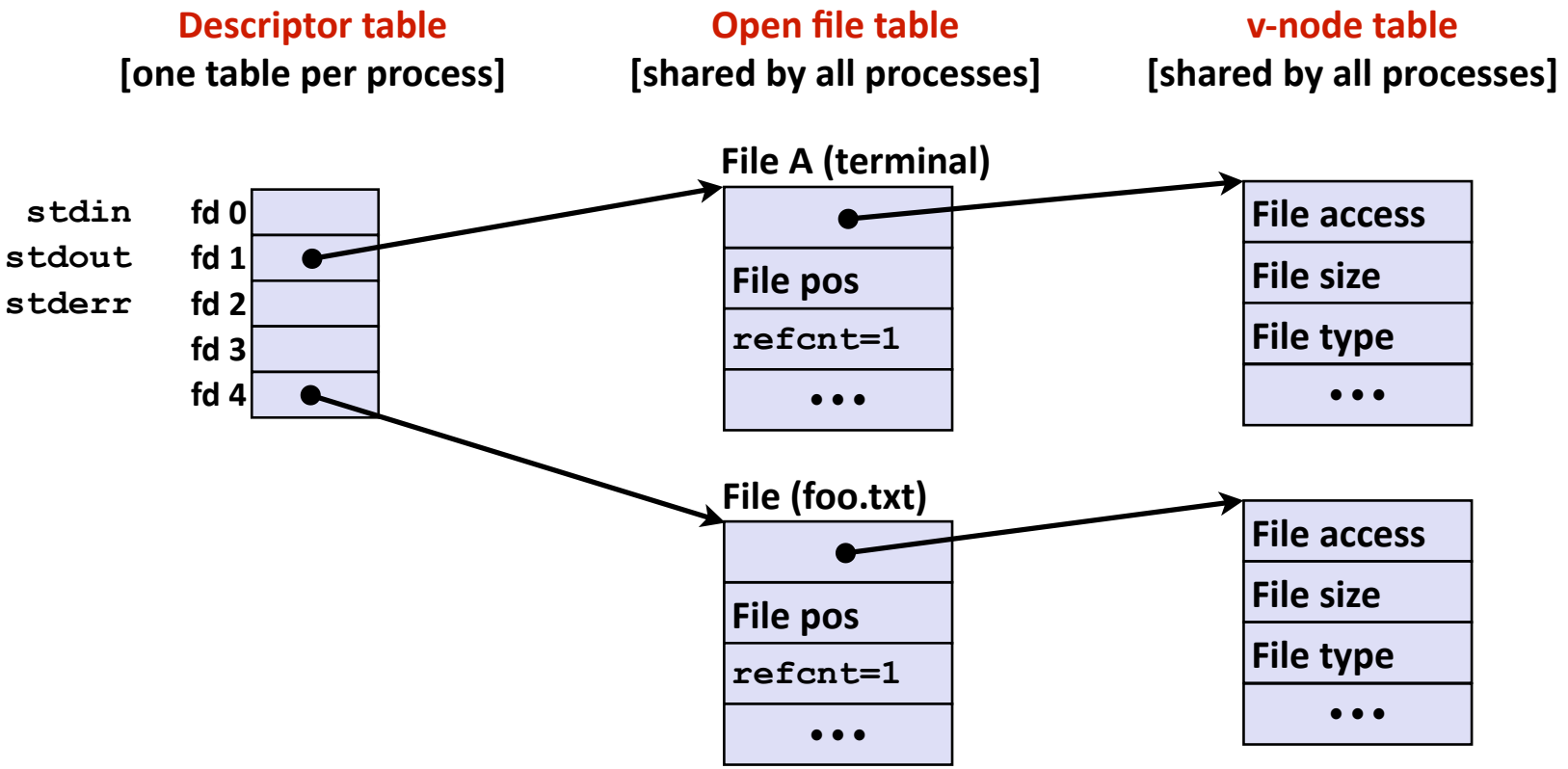


Descriptor table *after* `dup2(4,1)`



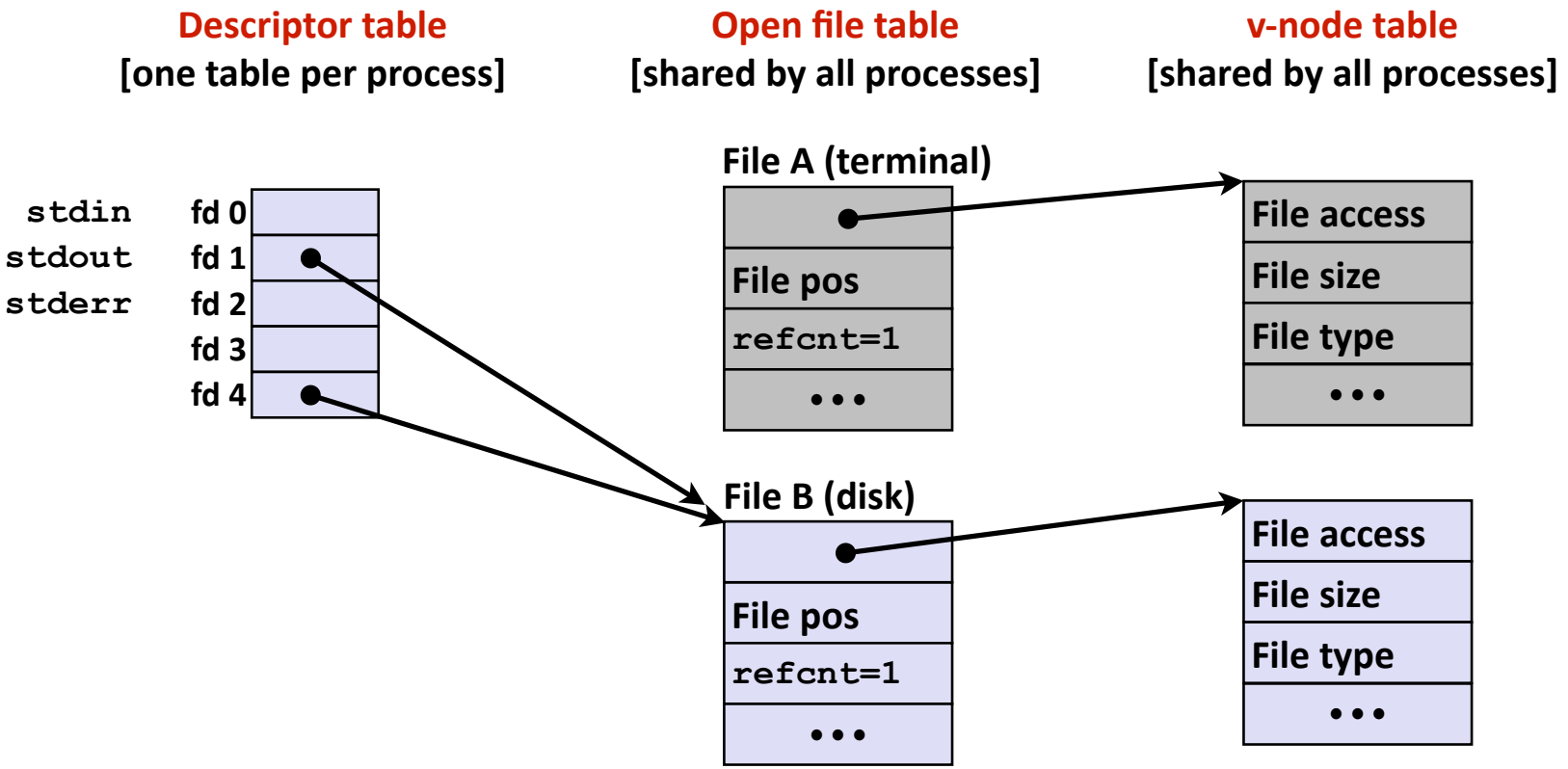
I/O Redirection Example

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



I/O Redirection Example (continued)

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



Today

- Memory related bugs
- **System level I/O**
  - Unix I/O
  - **Standard I/O**
  - RIO (robust I/O) package
  - Conclusions and examples

Standard I/O Functions

- **The C standard library (`libc.a`) contains a collection of higher-level *standard I/O* functions**
  - Documented in Appendix B of K&R

- **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`**)

Standard I/O Streams

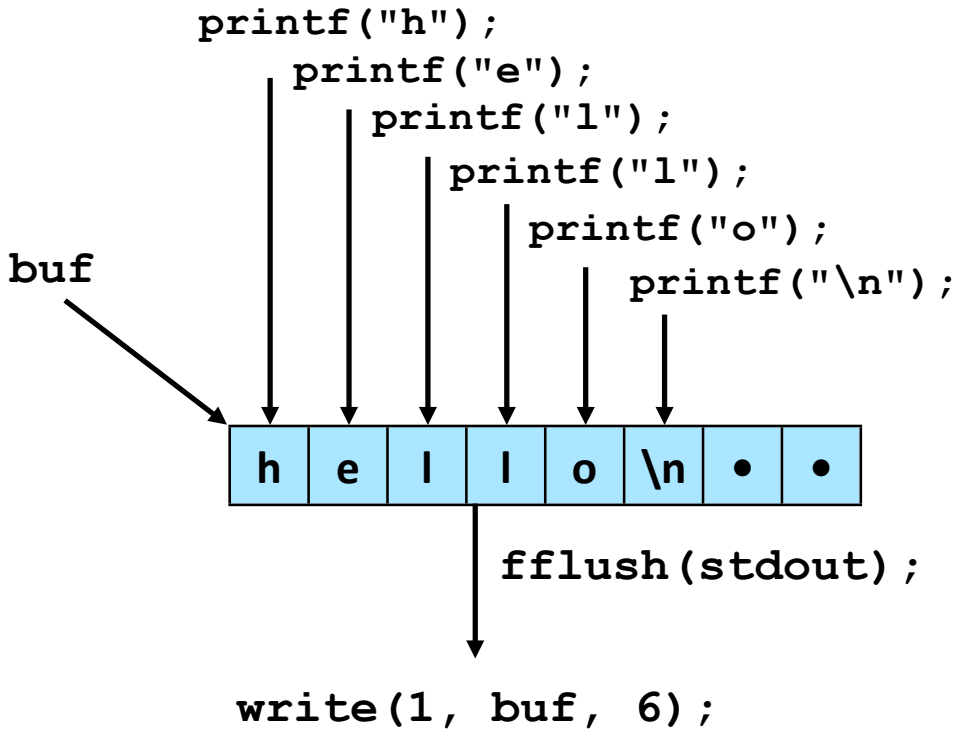
- **Standard I/O models open files as *streams***
  - Abstraction for a file descriptor and a buffer in memory
  - Similar to buffered RIO (later)
- **C programs begin life with three open streams (defined in `stdio.h`)**
  - **`stdin`** (standard input)
  - **`stdout`** (standard output)
  - **`stderr`** (standard error)

```
#include <stdio.h>
extern FILE *stdin;  /* standard input  (descriptor 0) */
extern FILE *stdout; /* standard output (descriptor 1) */
extern FILE *stderr; /* standard error  (descriptor 2) */

int main() {
    fprintf(stdout, "Hello, world\n");
}
```

Buffering in Standard I/O

- Standard I/O functions use buffered I/O



- Buffer flushed to output fd on "\n" or `fflush()` call

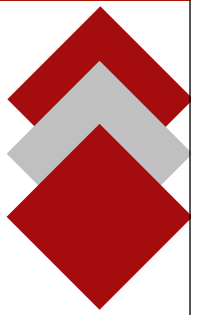
Standard I/O Buffering in Action

- You can see this buffering in action for yourself, using the always fascinating Unix `strace` program:

```
#include <stdio.h>

int main()
{
  printf("h");
  printf("e");
  printf("l");
  printf("l");
  printf("o");
  printf("\n");
  fflush(stdout);
  exit(0);
}
```

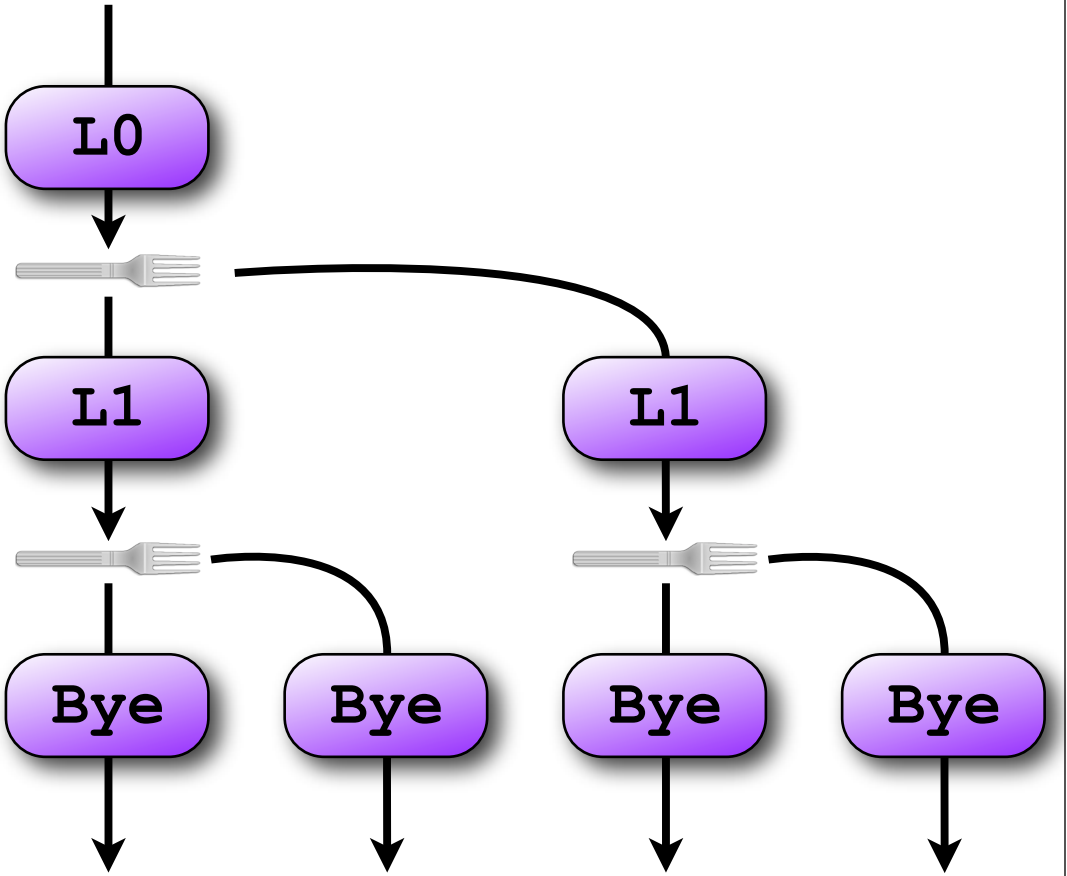
```
linux> strace ./hello
execve("./hello", ["hello"], [/* ... */]).
...
write(1, "hello\n", 6...)                = 6
...
_exit(0)                                 = ?
```



Fork Example #2 (Earlier Lecture)

- Both parent and child can continue forking

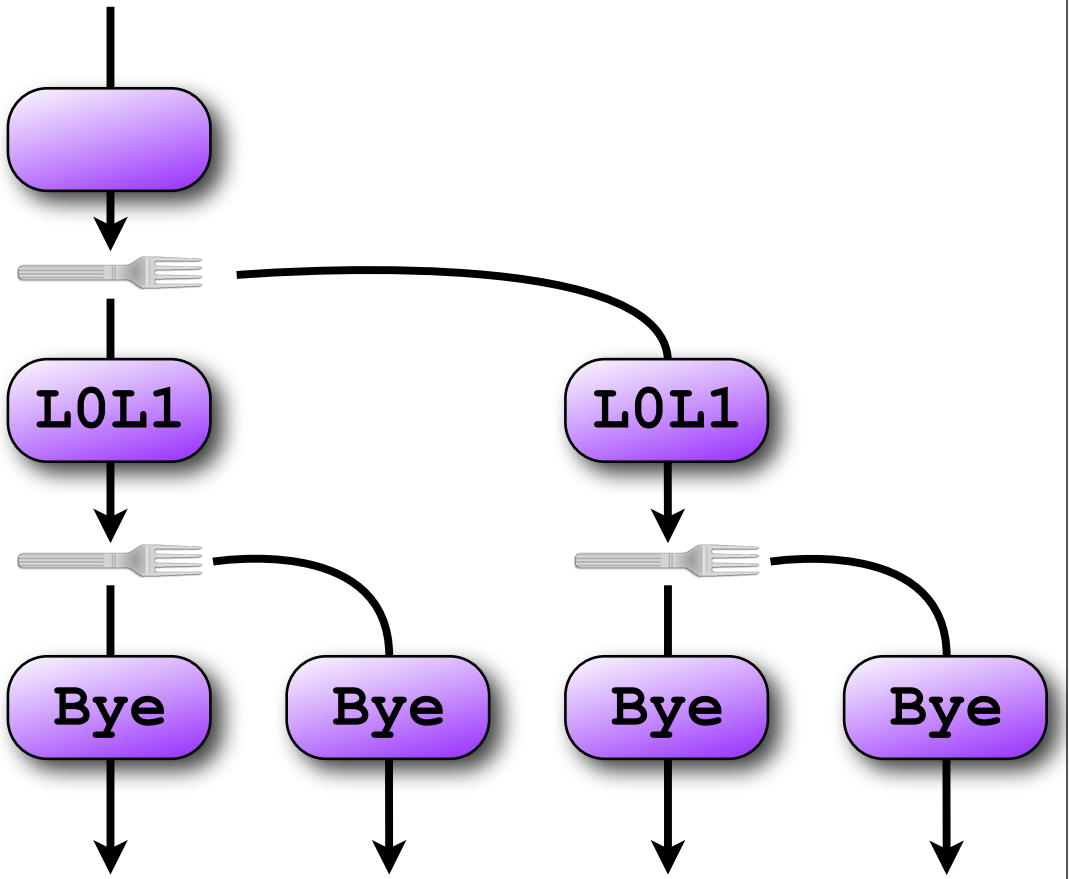
```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #2 (Modified)

- **Removed the "\n" from the first `printf`**
  - "L0" gets printed twice
  - fork duplicated stream buffer

```
void fork2_mod()
{
    printf("L0");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



Dealing with 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
- **Short counts never occur in these situations:**
  - Reading from disk files (except for EOF)
  - Writing to disk files
- **One way to deal with short counts in your code:**
  - Use the RIO (Robust I/O) package from your textbook's csapp.c file (Appendix B)

Today

- Memory related bugs
- **System level I/O**
  - Unix I/O
  - Standard I/O
  - **RIO (robust I/O) package**
  - Conclusions and examples

The RIO Package

- **RIO is a set of wrappers that provide efficient and robust I/O in apps, such as network programs that are subject to short counts**

- **RIO provides two different kinds of functions**
  - Unbuffered input and output of binary data
    - **`rio_readn`** and **`rio_writen`**
  - Buffered input of binary data and text lines
    - **`rio_readlineb`** and **`rio_readnb`**
    - Buffered RIO routines are ***thread-safe*** and can be interleaved arbitrarily on the same descriptor
- **Download from**

  `csapp.cs.cmu.edu/public/ics/code/src/csapp.c`

  `csapp.cs.cmu.edu/public/ics/code/include/csapp.h`

Unbuffered RIO Input and Output

- Same interface as Unix `read` and `write`
- Especially useful for transferring data on network sockets

```
#include "csapp.h"

ssize_t rio_readn(int fd, void *usrbuf, size_t n);
ssize_t rio_writen(int fd, void *usrbuf, size_t n);
```

Return: num. bytes transferred if OK, 0 on EOF (rio_readn only), -1 on error

  - **`rio_readn`** returns short count only if it encounters EOF
    - Only use it when you know how many bytes to read
  - **`rio_writen`** never returns a short count
  - Calls to **`rio_readn`** and **`rio_writen`** can be interleaved arbitrarily on the same descriptor

Implementation of `rio_readn`

```
/*
 * rio_readn - robustly read n bytes (unbuffered)
 */
ssize_t rio_readn(int fd, void *usrbuf, size_t n)
{
  size_t nleft = n;
  ssize_t nread;
  char *bufp = usrbuf;

  while (nleft > 0) {
    if ((nread = read(fd, bufp, nleft)) < 0) {
      if (errno == EINTR) /* interrupted by sig handler return */
        nread = 0;        /* and call read() again */
      else
        return -1;        /* errno set by read() */
    }
    else if (nread == 0)
      break;              /* EOF */
    nleft -= nread;
    bufp += nread;
  }
  return (n - nleft);     /* return >= 0 */
}
```

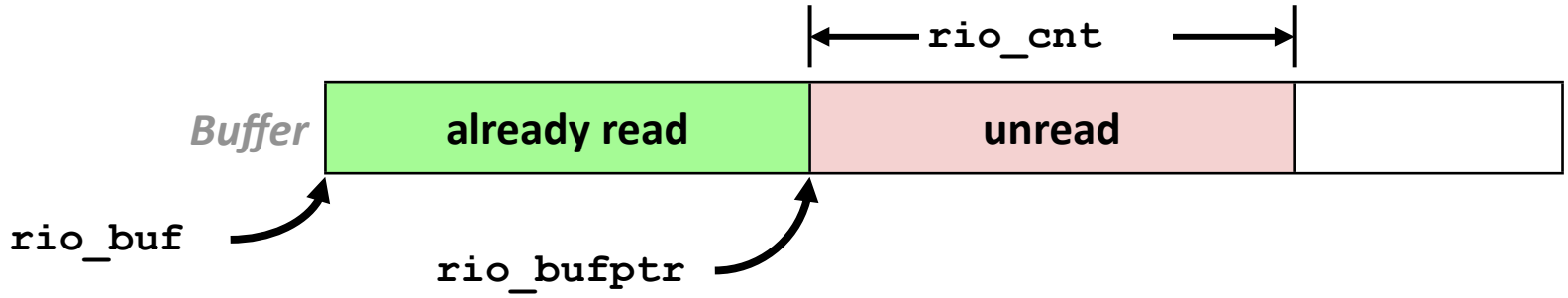
Buffered I/O: Motivation

- **I/O Applications Read/Write One Character at a Time**
  - getc, putc, ungetc
  - gets
    - Read line of text, stopping at newline
- **Implementing as Calls to Unix I/O Expensive**
  - Read & Write involve require Unix kernel calls
    - > 10,000 clock cycles

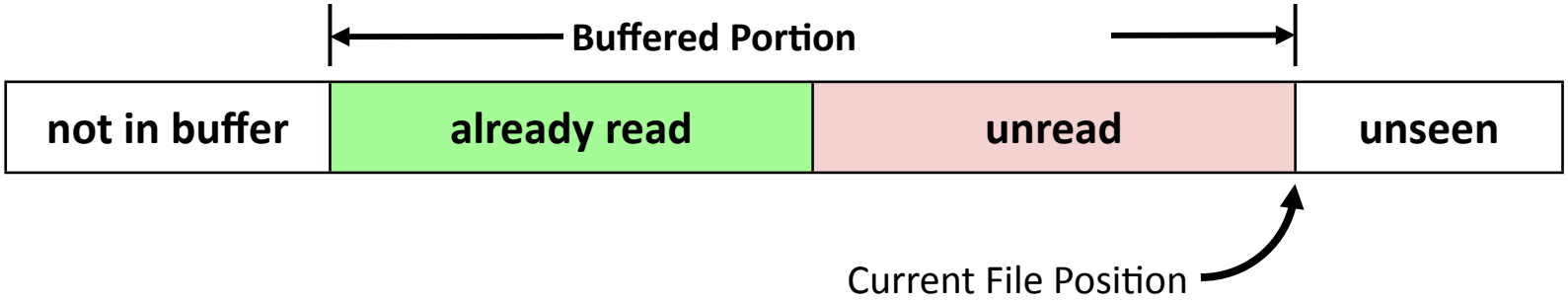
- **Buffered Read**
  - Use Unix read() to grab block of bytes
  - User input functions take one byte at a time from buffer
    - Refill buffer when empty

Buffered I/O: Implementation

- For reading from file
- File has associated buffer to hold bytes that have been read from file but not yet read by user code

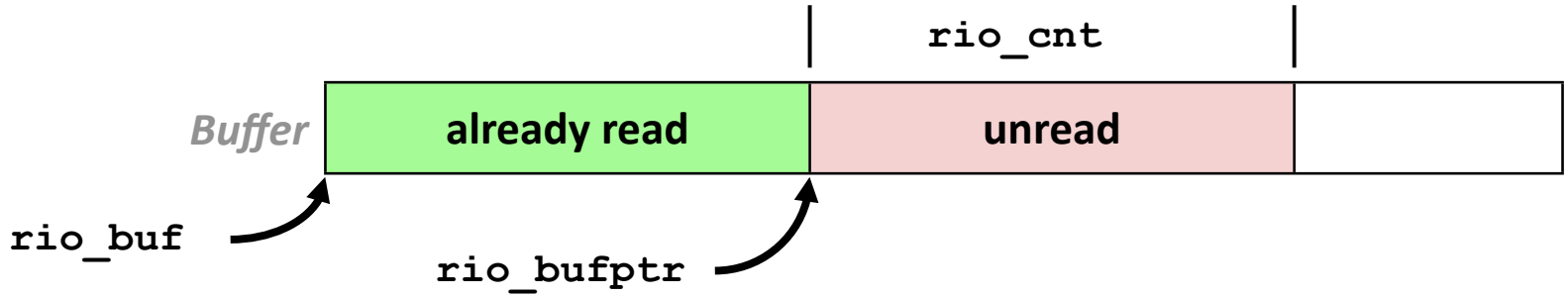


- Layered on Unix File



Buffered I/O: Declaration

- All information contained in struct




```
typedef struct {
    int rio_fd;                /* descriptor for this internal buf */
    int rio_cnt;               /* unread bytes in internal buf */
    char *rio_bufptr;          /* next unread byte in internal buf */
    char rio_buf[RIO_BUFSIZE]; /* internal buffer */
} rio_t;
```

Buffered RIO Input Functions

- **Efficiently read text lines and binary data from a file partially cached in an internal memory buffer**

```
#include "csapp.h"

void rio_readinitb(rio_t *rp, int fd);

ssize_t rio_readlineb(rio_t *rp, void *usrbuf, size_t maxlen);
```

Return: number of bytes read if OK, 0 on EOF, -1 on error

- **`rio_readlineb` reads a text line of up to `maxlen` bytes from file `fd` and stores the line in `usrbuf`**
  - Especially useful for reading text lines from network sockets
- **Stopping conditions**
  - **`maxlen`** bytes read
  - EOF encountered
  - Newline ('**`\n`**') encountered

Buffered RIO Input Functions (cont)

```
#include "csapp.h"

void rio_readinitb(rio_t *rp, int fd);

ssize_t rio_readlineb(rio_t *rp, void *usrbuf, size_t maxlen);
ssize_t rio_readnb(rio_t *rp, void *usrbuf, size_t n);
```

Return: number of bytes read if OK, 0 on EOF, -1 on error

- **`rio_readnb` reads up to `n` bytes from file `fd`**
- **Stopping conditions**
  - **`maxlen`** bytes read
  - EOF encountered
- **Calls to `rio_readlineb` and `rio_readnb` can be interleaved arbitrarily on the same descriptor**
  - Warning: Don't interleave with calls to **`rio_readn`**

RIO Example

- Copying the lines of a text file from standard input to standard output

```
#include "csapp.h"

int main(int argc, char **argv)
{
  int n;
  rio_t rio;
  char buf[MAXLINE];

  Rio_readinitb(&rio, STDIN_FILENO);
  while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0)
    Rio_writen(STDOUT_FILENO, buf, n);
  exit(0);
}
```

Today

- Memory related bugs
- **System level I/O**
  - Unix I/O
  - Standard I/O
  - RIO (robust I/O) package
  - **Conclusions and examples**

Choosing I/O Functions

- **General rule: use the highest-level I/O functions you can**
  - Many C programmers do all of their work using standard I/O functions
- **When to use standard I/O**
  - When working with disk or terminal files
- **When to use raw Unix I/O**
  - When you need to fetch file metadata
  - In rare cases when you need absolute highest performance
- **When to use RIO**
  - When you are reading and writing network sockets or pipes
  - Never use standard I/O or raw Unix I/O on sockets or pipes

For Further Information

- **The Unix bible:**
  - W. Richard Stevens & Stephen A. Rago, ***Advanced Programming in the Unix Environment***, 2nd Edition, Addison Wesley, 2005
    - Updated from Stevens' 1993 book
- **Stevens is arguably the best technical writer ever**
  - Produced authoritative works in:
    - Unix programming
    - TCP/IP (the protocol that makes the Internet work)
    - Unix network programming
    - Unix IPC programming
- **Tragically, Stevens died Sept. 1, 1999**

Fun with File Descriptors (1)

```
#include "csapp.h"
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;
}
```

- What would this program print for file containing “abcde”?

Fun with File Descriptors (2)

```
#include "csapp.h"

int main(int argc, char *argv[])
{
  int fd1;
  int s = getpid() & 0x1;
  char c1, c2;
  char *fname = argv[1];
  fd1 = Open(fname, O_RDONLY, 0);
  Read(fd1, &c1, 1);
  if (fork()) { /* Parent */
    sleep(s);
    Read(fd1, &c2, 1);
    printf("Parent: c1 = %c, c2 = %c\n", c1, c2);
  } else { /* Child */
    sleep(1-s);
    Read(fd1, &c2, 1);
    printf("Child: c1 = %c, c2 = %c\n", c1, c2);
  }
  return 0;
}
```

- What would this program print for file containing “abcde”?

Fun with File Descriptors (3)

```
#include "csapp.h"
int main(int argc, char *argv[])
{
  int fd1, fd2, fd3;
  char *fname = argv[1];
  fd1 = Open(fname, O_CREAT|O_TRUNC|O_RDWR, S_IRUSR|S_IWUSR);
  Write(fd1, "pqrs", 4);
  fd3 = Open(fname, O_APPEND|O_WRONLY, 0);
  Write(fd3, "jklmn", 5);
  fd2 = dup(fd1);  /* Allocates descriptor */
  Write(fd2, "wxyz", 4);
  Write(fd3, "ef", 2);
  return 0;
}
```

- What would be the contents of the resulting file?

Accessing Directories

- **Only recommended operation on a directory: read its entries**
  - dirent structure contains information about a directory entry
  - DIR structure contains information about directory while stepping through

```
#include <sys/types.h>
#include <dirent.h>

{
  DIR *directory;
  struct dirent *de;
  ...
  if (!(directory = opendir(dir_name)))
      error("Failed to open directory");
  ...
  while (0 != (de = readdir(directory))) {
      printf("Found file: %s\n", de->d_name);
  }
  ...
  closedir(directory);
}
```

Unix I/O Key Characteristics

Classic Unix/Linux I/O

- **I/O operates on linear streams of bytes**
  - Can reposition insertion point and extend file at end
- **I/O tends to be synchronous**
  - Read or write operation block until data has been transferred
- **Fine grained I/O**
  - One key-stroke at a time
  - Each I/O event is handled by the kernel and an appropriate process

Mainframe I/O

- **I/O operates on structured records**
  - Functions to locate, insert, remove, update records
- **I/O tends to be asynchronous**
  - Overlap I/O and computation within a process
- **Coarse grained I/O**
  - Process writes “channel programs” to be executed by the I/O hardware
  - Many I/O operations are performed autonomously with one interrupt at completion

Pros and Cons of Unix I/O

- **Pros**
  - Unix I/O is the most general and lowest 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

- **Cons**
  - Dealing with short counts is tricky and error prone
  - Efficient reading of text lines requires some form of buffering, also tricky and error prone
  - Both of these issues are addressed by the standard I/O and RIO packages

Pros and Cons of Standard I/O

- **Pros:**
  - Buffering increases efficiency by decreasing the number of **`read`** and **`write`** system calls
  - Short counts are handled automatically
- **Cons:**
  - Provides no function for accessing file metadata
  - Standard I/O is not appropriate for input and output on network sockets
    - There are poorly documented restrictions on streams that interact badly with restrictions on sockets

Working with Binary Files

- **Binary File Examples**
  - Object code
  - Images (JPEG, GIF)
  - Arbitrary byte values

- **Functions you shouldn't use**
  - Line-oriented I/O
    - **`fgets`**, **`scanf`**, **`printf`**, **`rio_readlineb`**
    - Interprets byte value **`0x0A`** ('**`\n`**') as special
    - Use **`rio_readn`** or **`rio_readnb`** instead
  - String functions
    - **`strlen`**, **`strcpy`**
    - Interprets byte value **`0x00`** as special

Summary

- Memory Related Bugs
- System level I/O

- Next Time: Exam2