File Descriptors

Unix philosophy: *everything is a file*

- **`main.c`**
- **`a.out`**
- **`/dev/sda1`** — the whole disk
- **`/dev/tty2`** — a terminal
- **`/proc/cpuinfo`** — CPU as deduced by the kernel
- unnamed channels of communincation

including input and output streams

A ***file descriptor*** is a handle to a file's input and/or output

represented as an **`int`**

Opening Files

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

int open(const char *path, int flags);
```

Open a file, where **`flags`** is typically **`O_RDONLY`**, **`O_WRONLY`**, or **`O_RDWR`**

Adding **`O_CREAT`** implies an extra argument

```
#include <unistd.h>

int close(int fd);
```

Closes a file descriptor

Reading and Writing

```
#include <unistd.h>

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

Reads from **`fd`**, putting up to **`n`** bytes into **`buf`**

```
#include <unistd.h>

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

Write to **`fd`**, using up to **`n`** bytes from **`buf`**

Result in either case is number of bytes read/written

or −1 for an error

Example: Reading a File

```
#include "csapp.h"

int main(int argc, char **argv) {
  int fd = Open(argv[0], O_RDONLY, 0);
  char buf[5];

  Read(fd, buf, 4);
  buf[4] = 0;

  printf("%s\n", buf+1);
  return 0;
}
```

Copy

Prints
`ELF`

Creating a Pipe

```
#include <unistd.h>

int pipe(int fds[2]);
```

Create an unnamed "file"

just in memory — not on a disk

- **`fds[0]`** is the read end
- **`fds[1]`** is the write end

Example: Data through a Pipe

```
#include "csapp.h"

int main(int argc, char **argv) {
  int fds[2];
  char buf[6];

  pipe(fds);

  Write(fds[1], "Hello", 5);

  Read(fds[0], buf, 5);
  buf[5] = 0;

  printf("%s\n", buf);
  return 0;
}
```

Copy

Prints
 `Hello`

Example: Pipe Read Waits on Write

```
#include "csapp.h"

int main(int argc, char **argv) {
  int fds[2];

  pipe(fds);

  if (Fork() == 0) {
    Sleep(1);
    Write(fds[1], "Hello", 5);
  } else {
    char buf[6];
    Read(fds[0], buf, 5);
    buf[5] = 0;
    printf("%s\n", buf);
  }

  return 0;
}
```

Copy

Prints
 `Hello`

after 1 second

Example: EOF Result

```
#include "csapp.h"

int main(int argc, char **argv) {
  int fds[2];
  char buf[6];

  pipe(fds);

  Write(fds[1], "Hello", 5);
  Write(fds[1], "World", 5);
  Close(fds[1]);

  while (1) {
    ssize_t n = Read(fds[0], buf, 3);
    if (n == 0) break;
    buf[n] = 0;
    printf("%s\n", buf);
  }

  return 0;
}
```

Copy

Prints

```
Hel
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orl
d
```
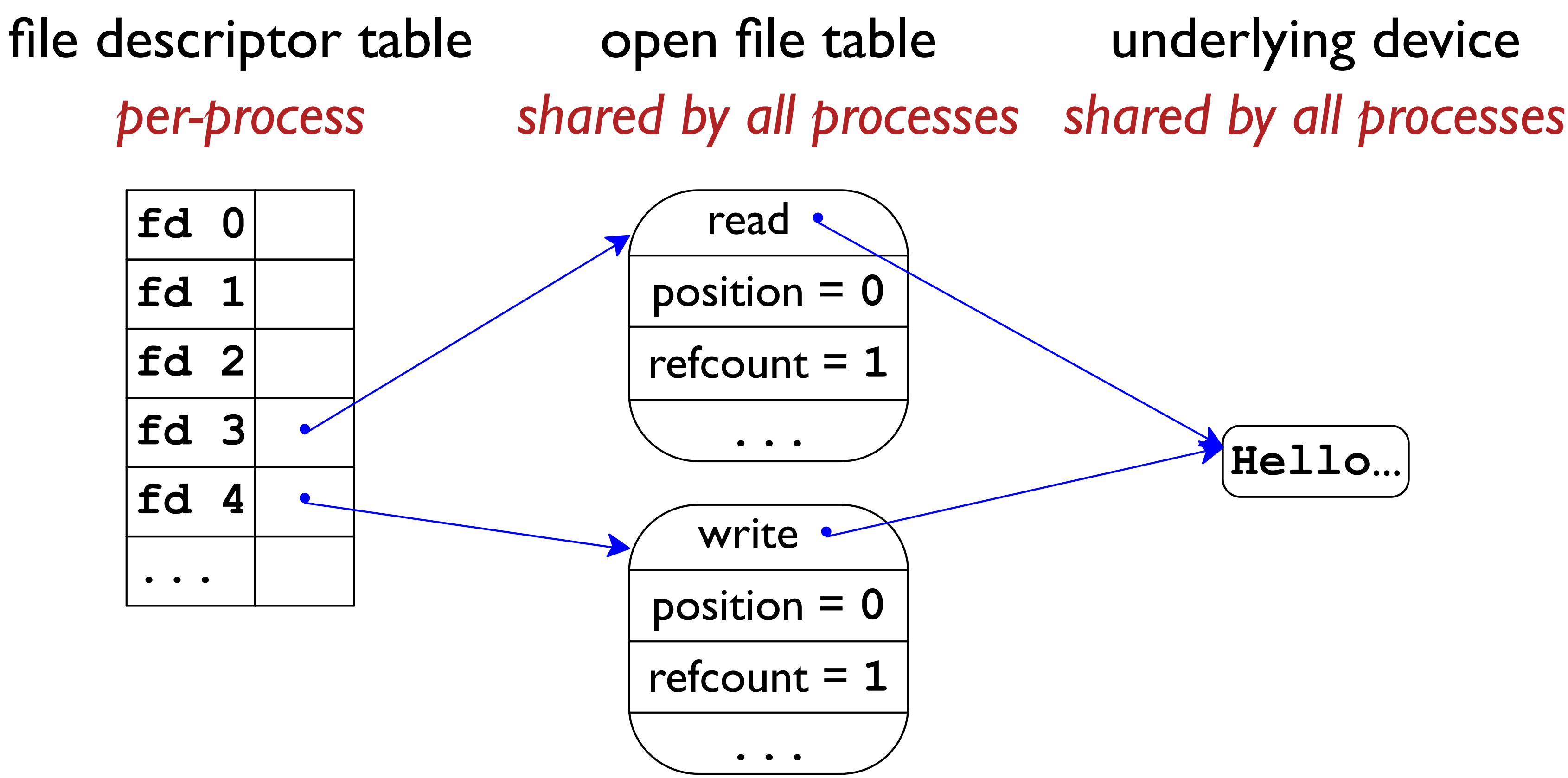

Example: Fork and Closing Pipes

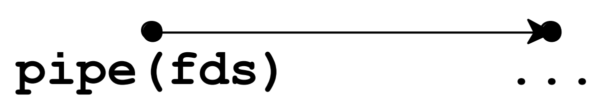
```
#include "csapp.h"

int main(int argc, char **argv) {
  int fds[2];
  pipe(fds);

  if (Fork() == 0) {
    Write(fds[1], "Hello", 5);
    Close(fds[1]);
  } else {
    // Close(fds[1]);
    while (1) {
      char buf[6];
      ssize_t n = Read(fds[0], buf, 3);
      if (n == 0) break;
      buf[n] = 0;
      printf("%s\n", buf);
    }
  }
  return 0;
}
```

Copy

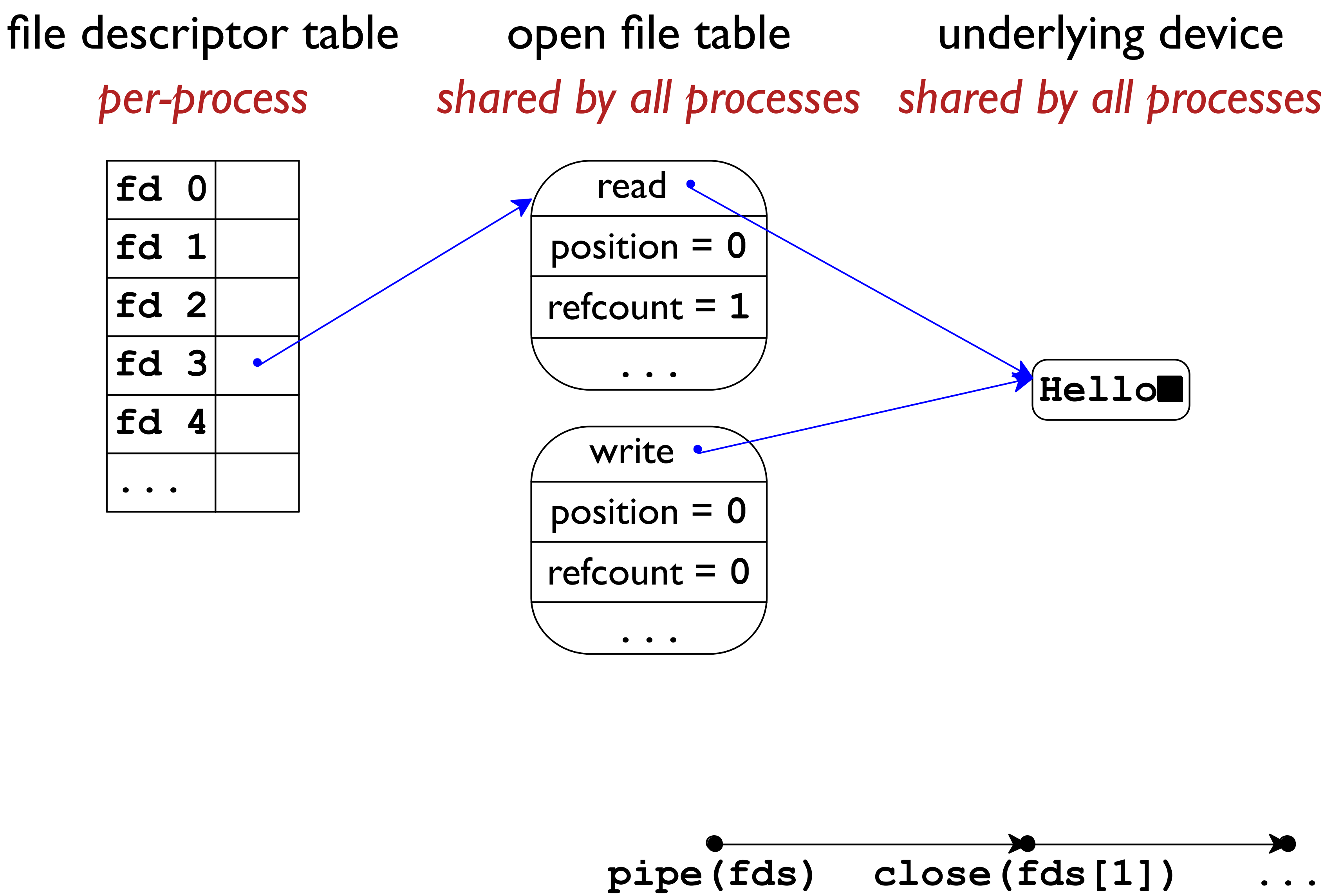
Gets stuck, unless the `Close` call is uncommented

File Descriptors and Open Files





File Descriptors and Open Files

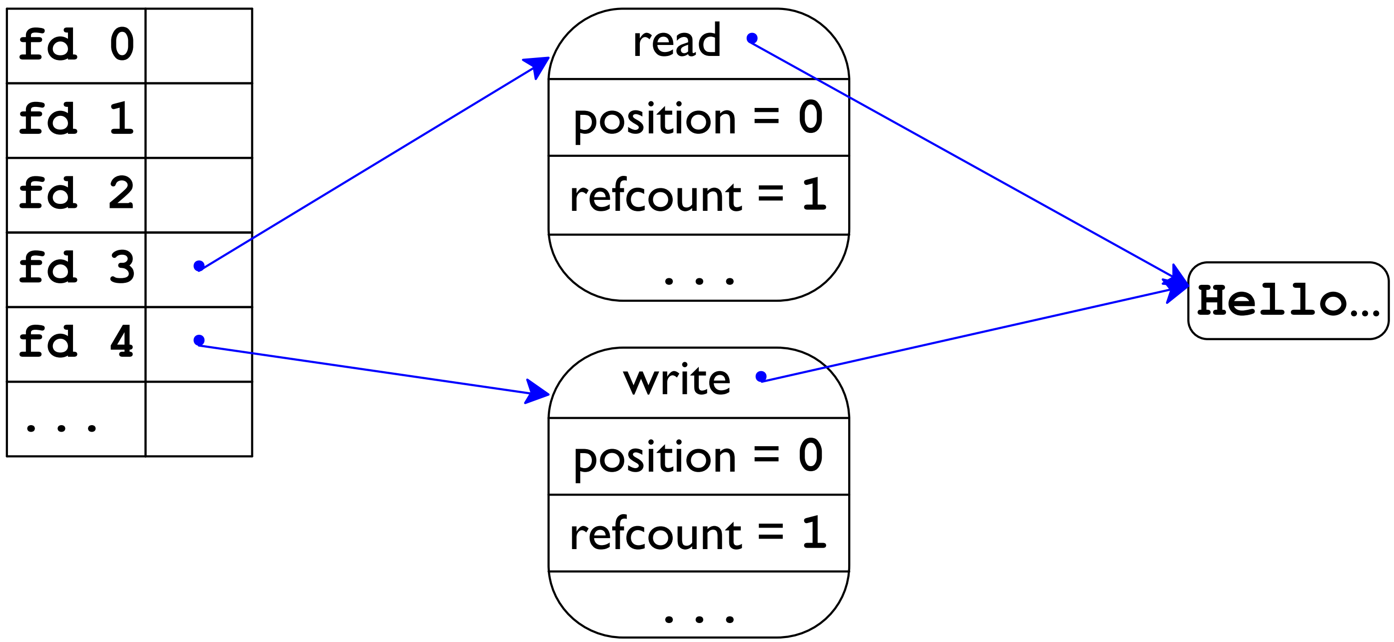


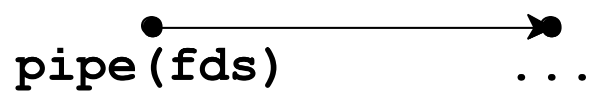
File Descriptors and Open Files

file descriptor table — *per-process*

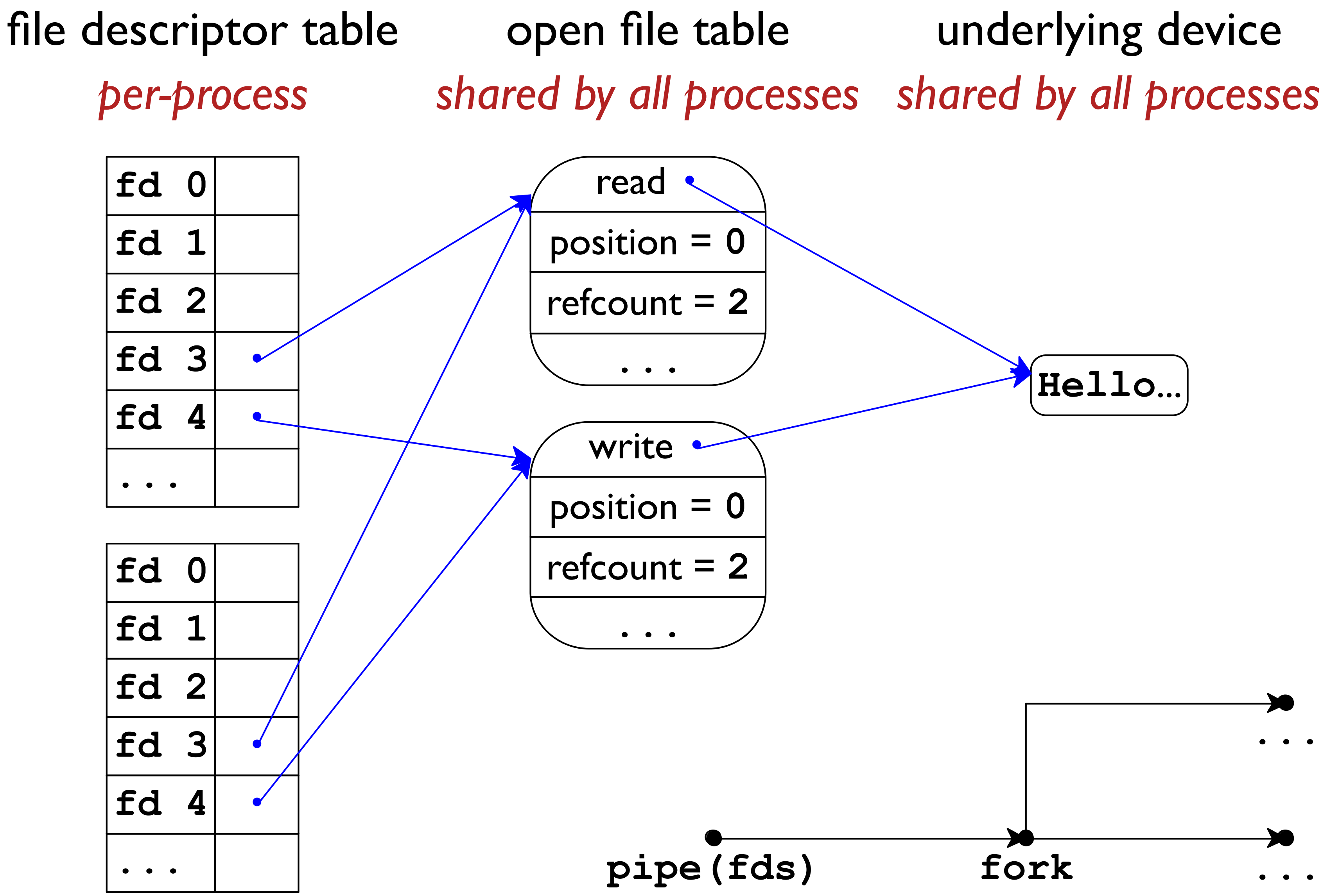
open file table — *shared by all processes*

underlying device — *shared by all processes*

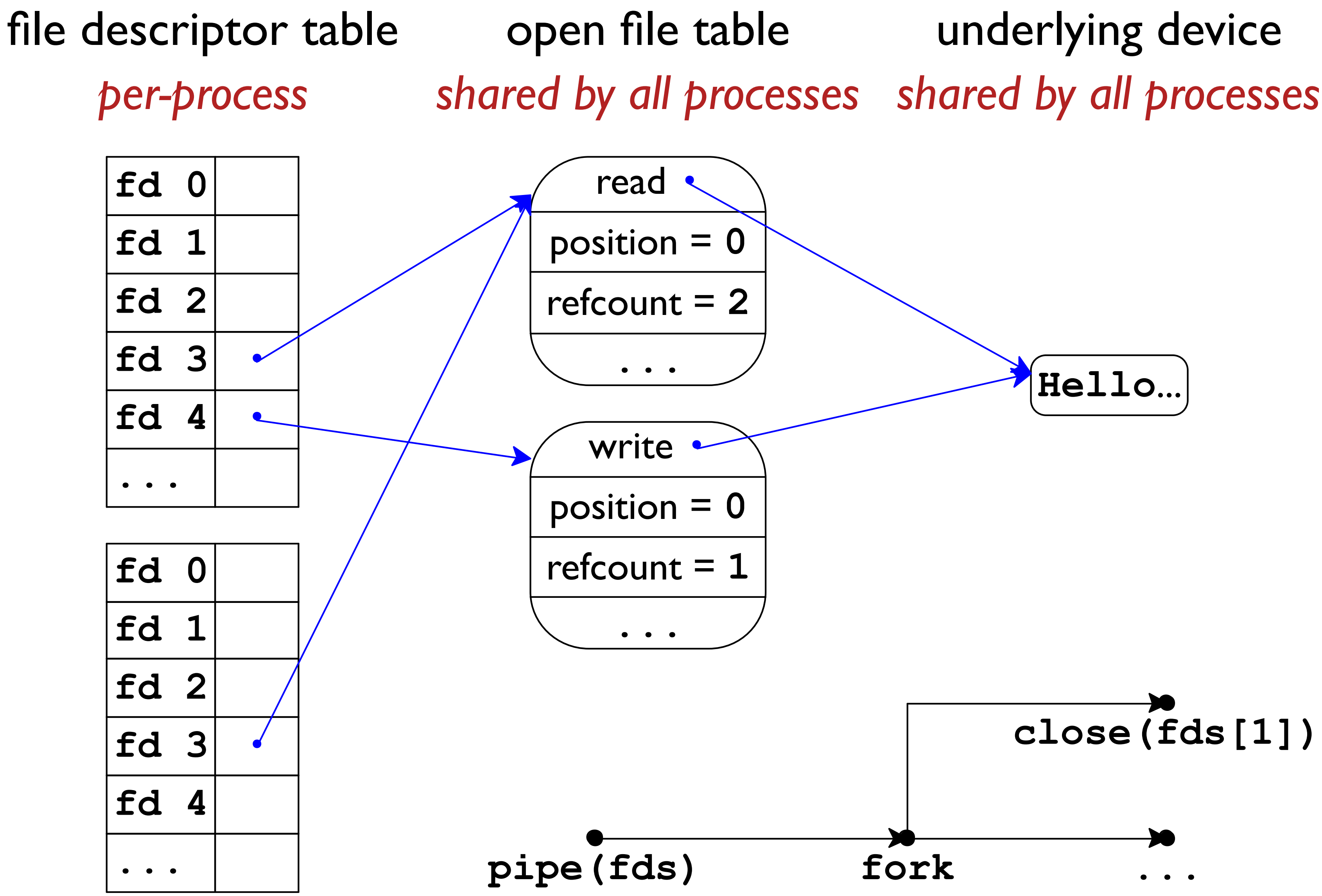




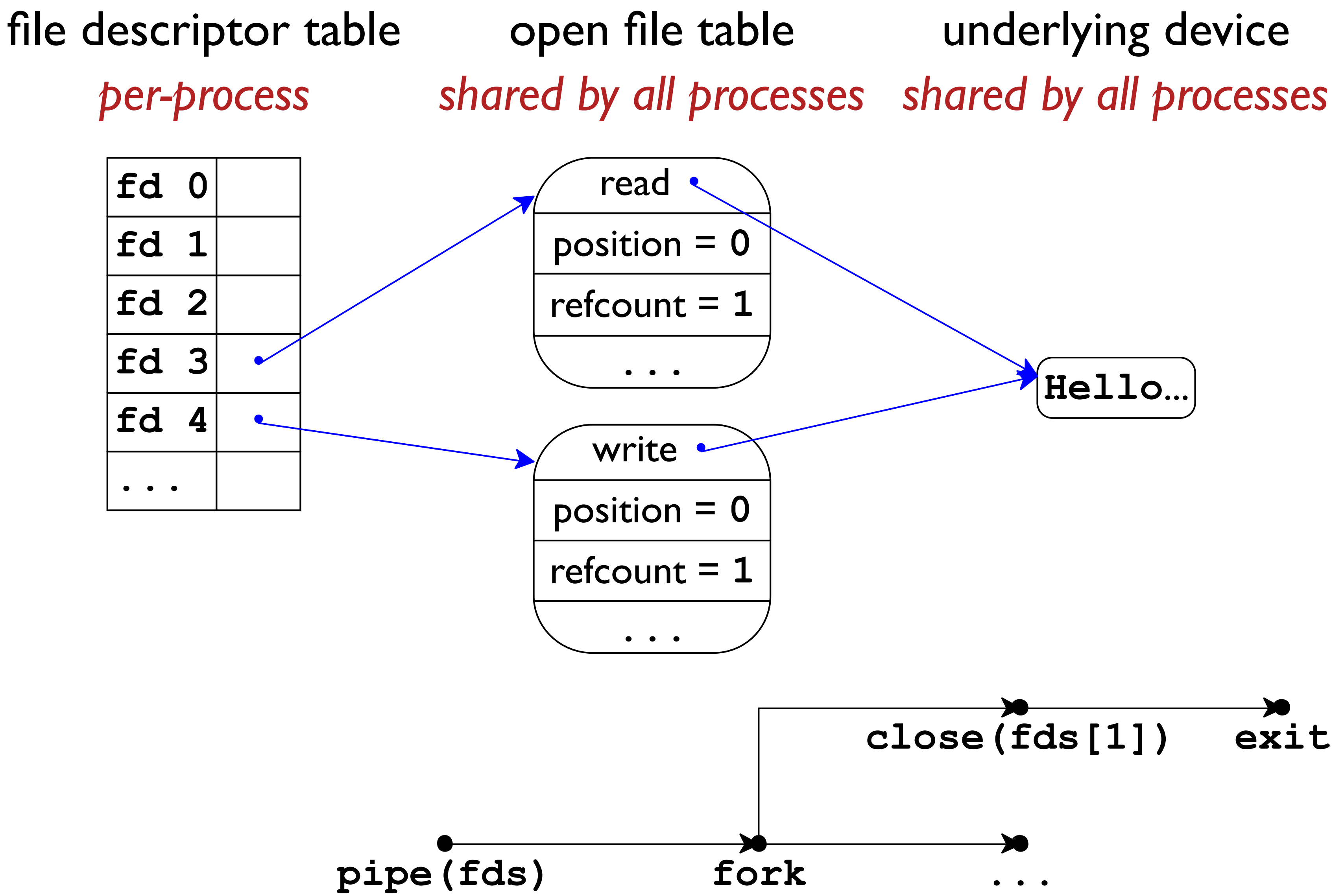
File Descriptors and Open Files



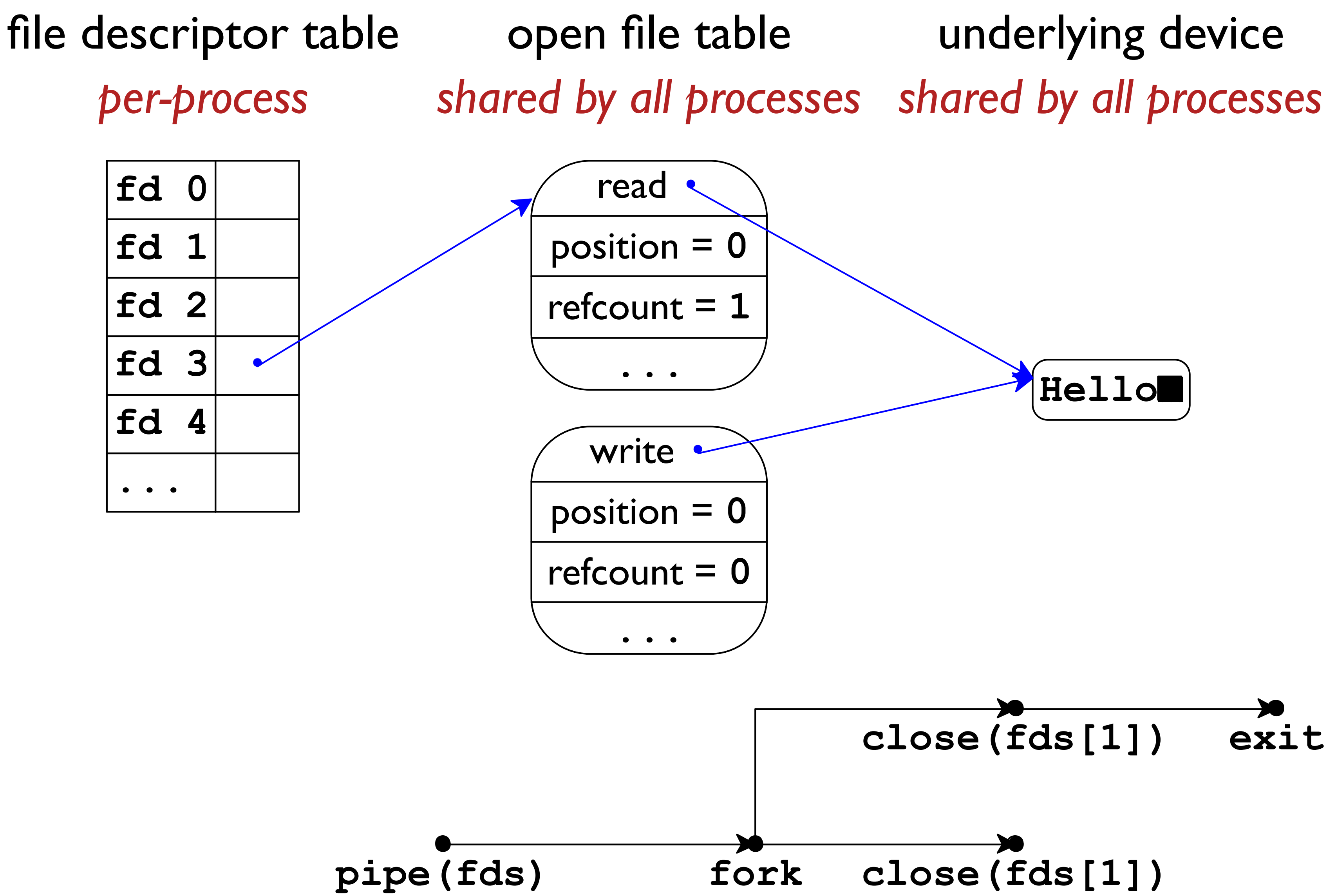
File Descriptors and Open Files



File Descriptors and Open Files



File Descriptors and Open Files



Example: Pipe Write Can Wait on Read

```
#include "csapp.h"

int main(int argc, char **argv) {
  int fds[2];

  pipe(fds);

  if (Fork() == 0) {
    char buf[6];
    Sleep(2);
    while (Read(fds[0], buf, 6) > 1) { }
  } else {
    int i;
    for (i = 0; i < 20000; i++)
      Write(fds[1], "Hello", 5);
    printf("done\n");
  }

  return 0;
}
```

Copy

Prints
 `done`
after ~2 seconds

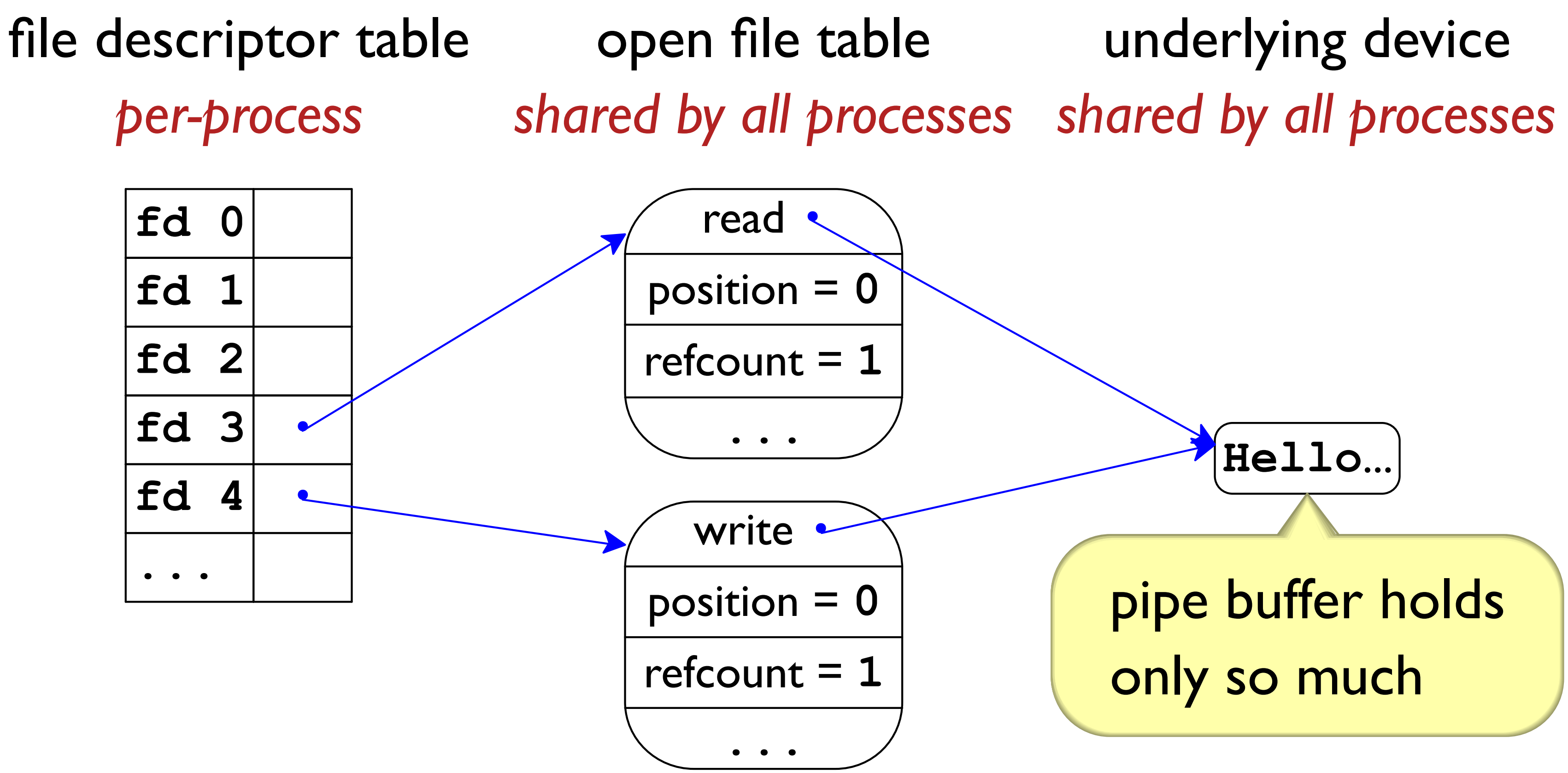
`Sleep(1)`

⇒ ~1 second

fewer iterations

⇒ ~0 seconds

Pipe Buffer Size



Input, Output, and Error

Every process starts with at least 3 file descriptors:

- **`0`** = standard input (read)
- **`1`** = standard output (write)
- **`2`** = standard error (write)

Using Standard File Descriptors

```
#include "csapp.h"

int main() {
  char buffer[32];
  int n;

  Write(1, "Your name? ", 11);

  n = Read(0, buffer, 32);

  Write(2, "Unknown: ", 9);
  Write(2, buffer, n);

  return 0;
}
```

Copy

Writes to output, reads from input, writes to error

Setting Standard File Descriptors

`fork` creates a process with the same ports as the parent

A shell needs a way to redirect input, output, and errors

```
#include <unistd.h>

int dup2(int oldfd, int newfd);
```

Makes `newfd` refer to the same open file as `oldfd`

if `newfd` is already used, closes it first

Capturing Child Output

```
#include "csapp.h"

int main() {
  pid_t pid;
  int fds[2], n;

  Pipe(fds);

  pid = Fork();
  if (pid == 0) {
    Dup2(fds[1], 1);
    printf("Hello!");
  } else {
    char buffer[32];
    Close(fds[1]);
    Waitpid(pid, NULL, 0);
    n = Read(fds[0], buffer, 31);
    buffer[n] = 0;
    printf("Got: %s\n",buffer);
  }
  return 0;
}
```

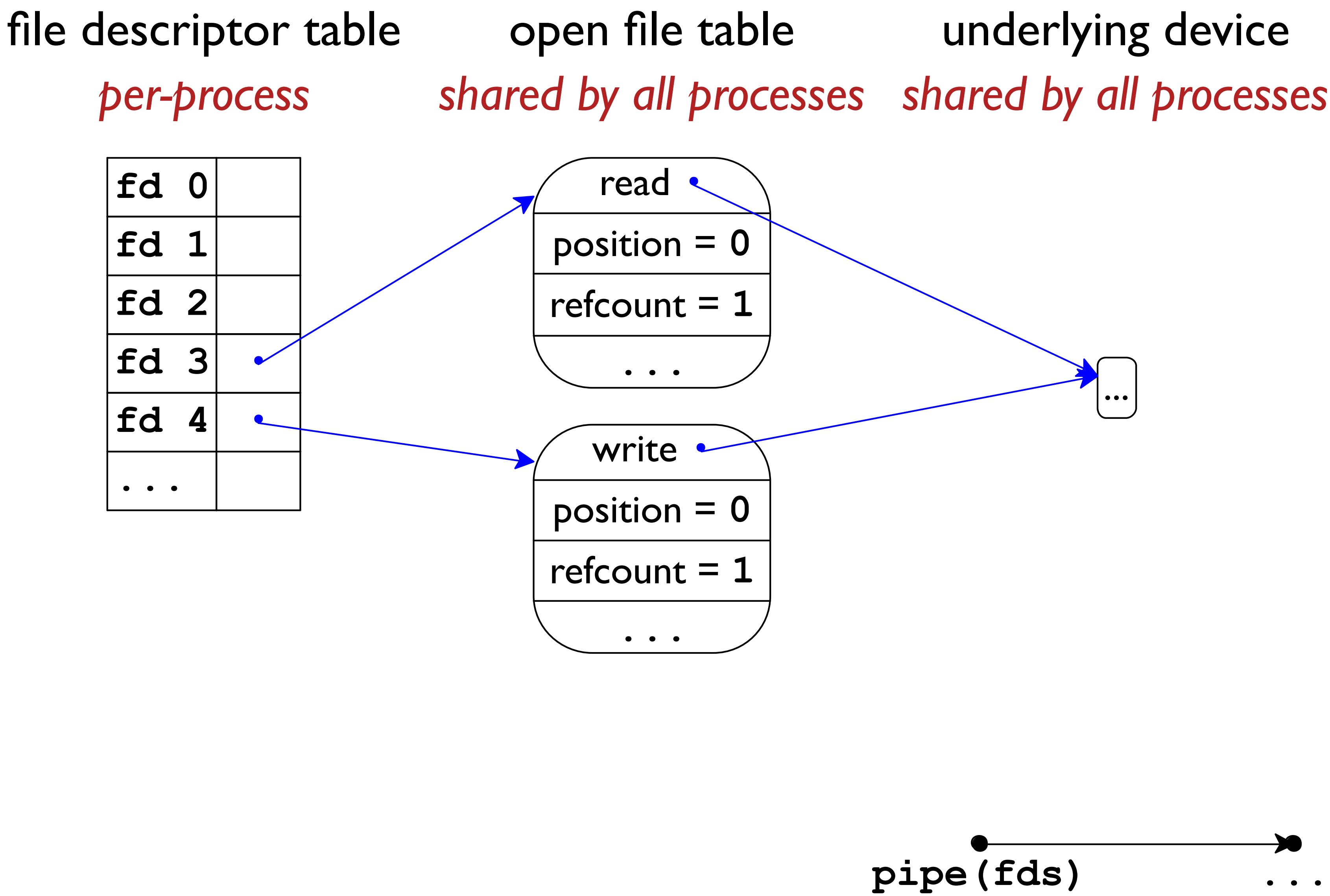
Copy

Prints

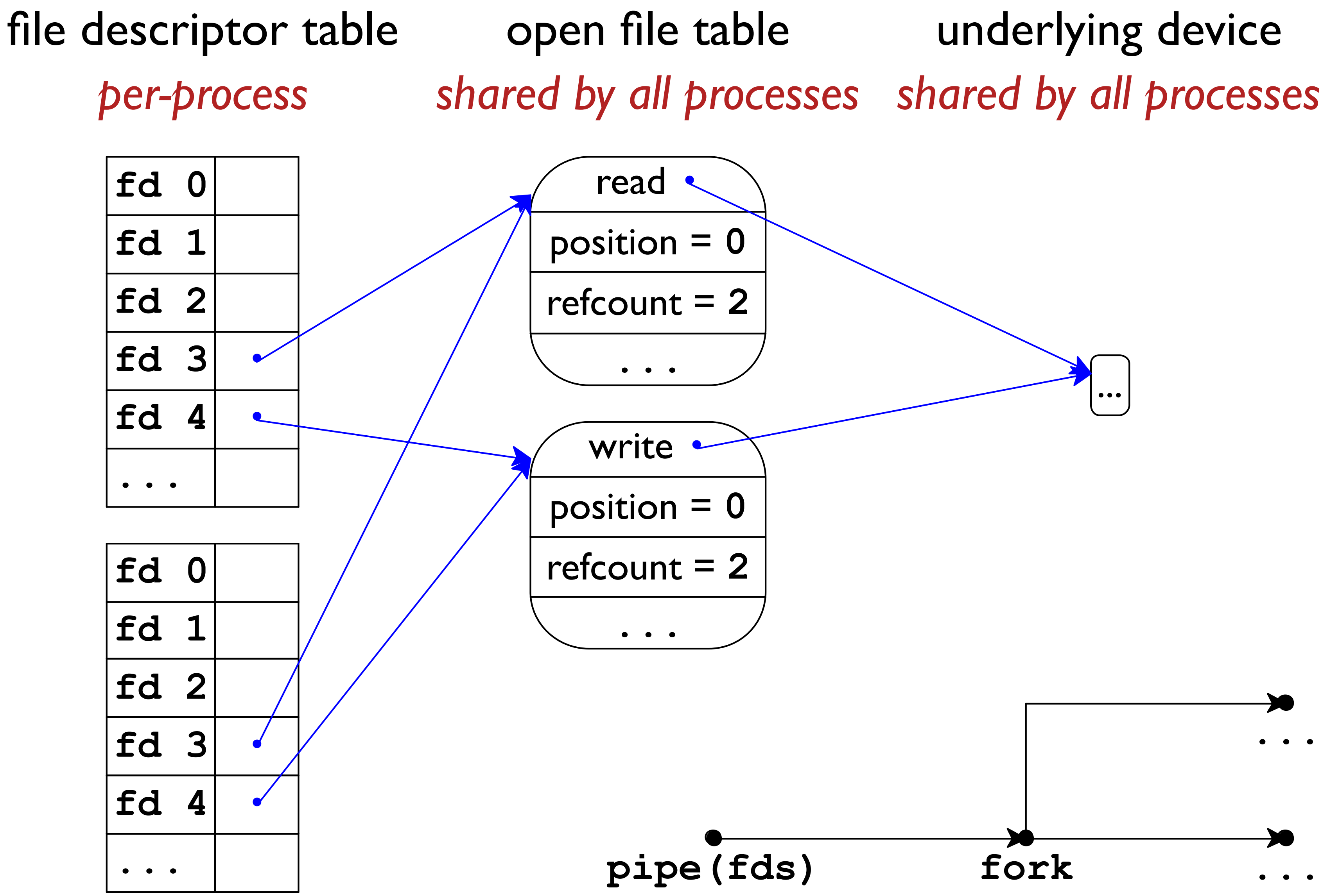
`Got: Hello!`

because **`printf`** writes to **`1`**

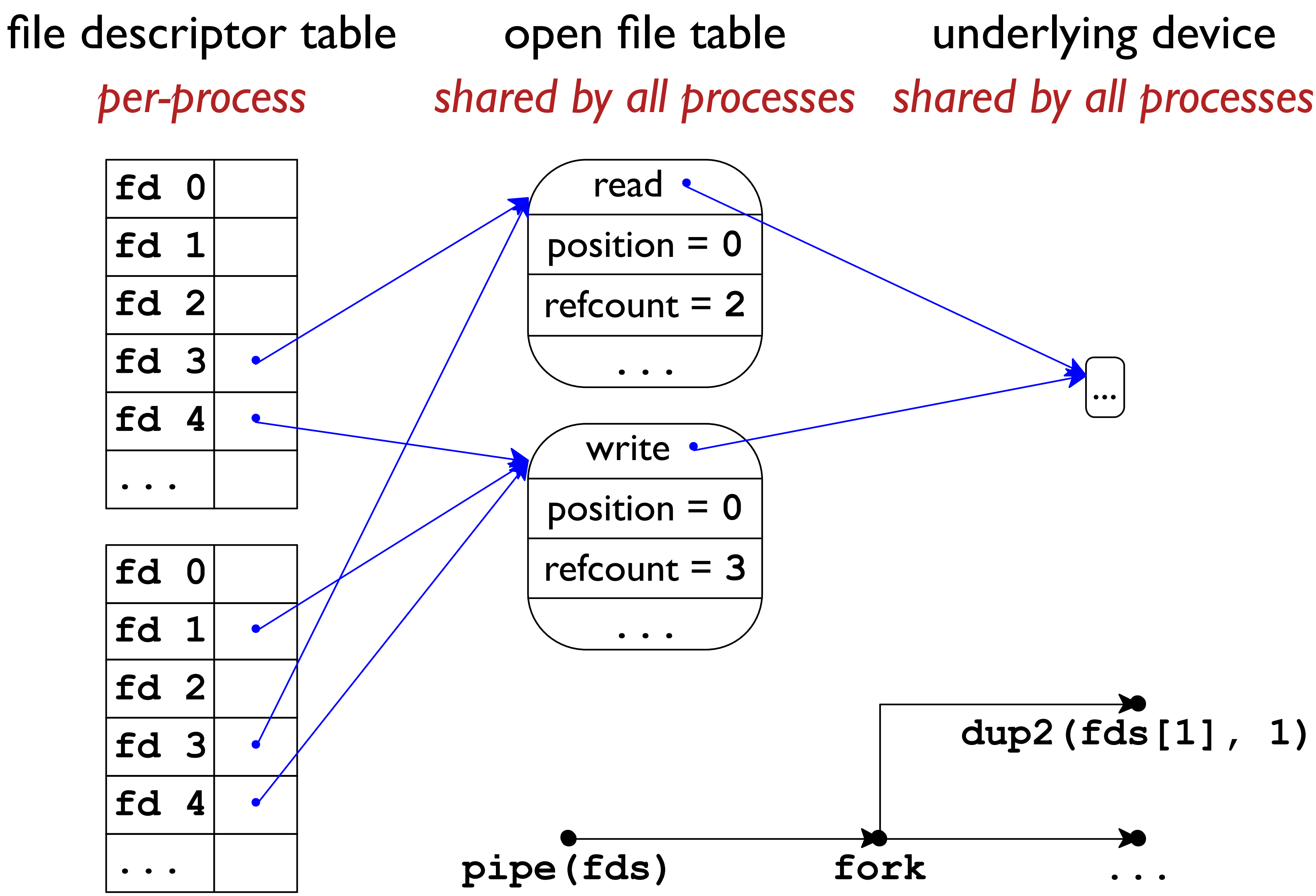
Redirecting File Descriptors



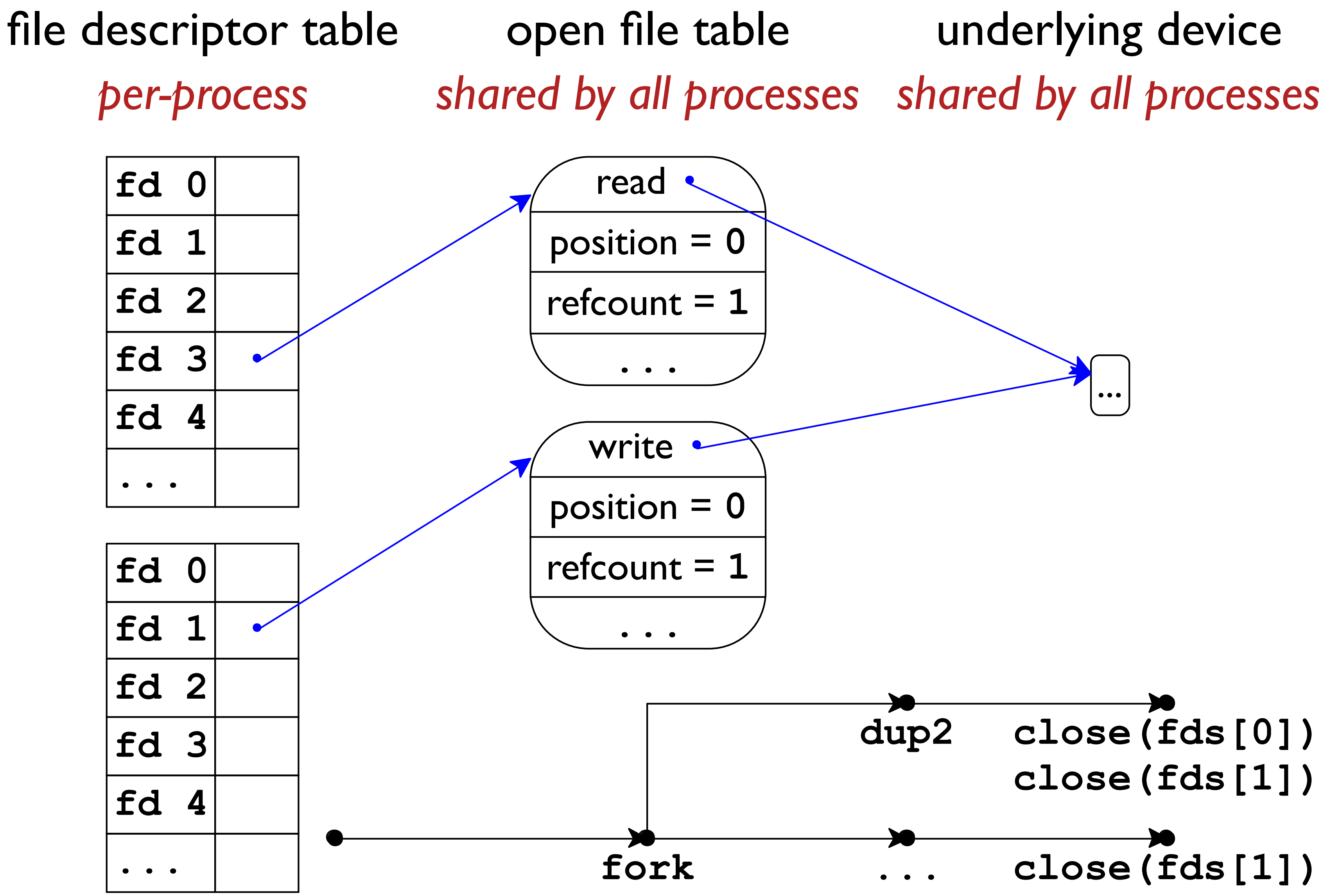
Redirecting File Descriptors



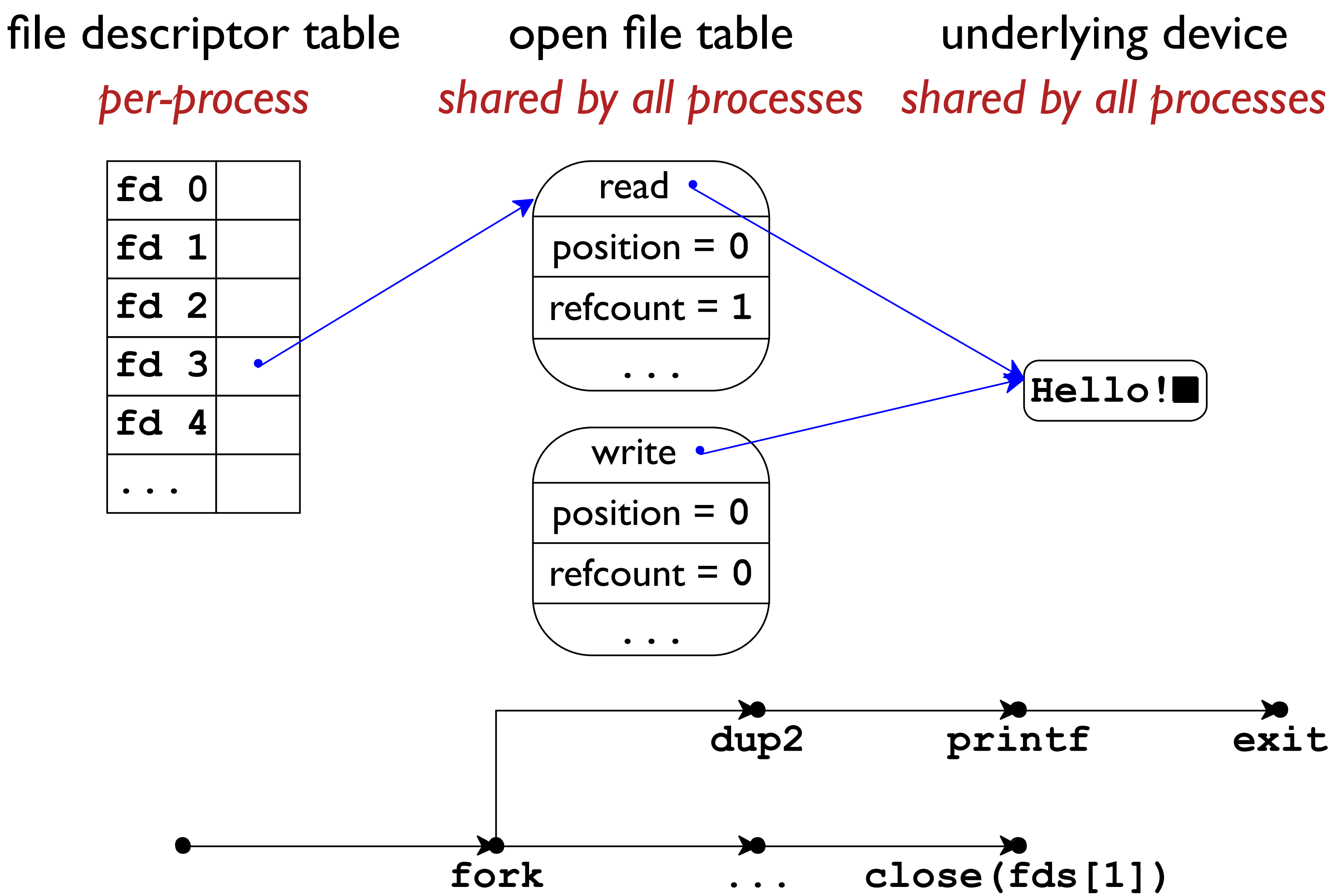
Redirecting File Descriptors



Redirecting File Descriptors



Redirecting File Descriptors



Shell Pipeline

```
$ cat *.c | grep fork | wc -l
```

- **`pipe(fdsA)`** for a **`cat`**-to-**`grep`** connection
- **`pipe(fdsB)`** for a **`grep`**-to-**`wc`** connection
- **`fork`** three times; in those children:
  - ```
    dup2(fdsA[1], 1)
    exec("/bin/cat", ...)
    ```
  - ```
    dup2(fdsA[0], 0)
    dup2(fdsB[1], 1)
    exec("/bin/grep", ...)
    ```
  - ```
    dup2(fdsB[0], 0)
    exec("/bin/wc", ...)
    ```
    ```

Shell Pipeline

```
$ cat *.c | grep fork | wc -l
```

- `pipe(fdsA)` for a `cat`-to-`grep` connection
- `pipe(fdsB)` for a `grep`-to-`wc` connection
- `fork` three times; in those children:
  - ```
    dup2(fdsA[1], 1)
    exec("/bin/cat", ...)
    ```
  - ```
    dup2(fdsA[0], 0)
    dup2(fdsB[1], 1)
    exec("/bin/grep", ...)
    ```
  - ```
    dup2(fdsB[0], 0)
    exec("/bin/wc", ...)
    ```

Before `exec`, plus parent:

```
close(fdsA[0])
close(fdsA[1])
close(fdsB[0])
close(fdsB[1])
```
```

Shell Pipeline

```
$ cat *.c | grep fork | wc -l
```

Pipe buffer limit keeps **`cat`** from getting too far ahead of **`grep`**

Unix I/O vs. C Library I/O

- Unix
  - file descriptors as **`int`**
  - **`open`**, **`read`**, **`write`**, ...

- Standard C
  - file handles as **`FILE*`**
  - **`fopen`**, **`fread`**, **`fwrite`**, ...

Convert from file descriptor to **`FILE*`** using **`fdopen`**

Predefined:

- **`stdin`** = **`fdopen(0, "r")`**
- **`stdout`** = **`fdopen(1, "w")`**
- **`stderr`** = **`fdopen(2, "w")`**

Unix I/O vs. C Library I/O

```c
#include "csapp.h"

#define ITERS 1000000

int main() {
  int fds[2];
  int i;

  Pipe(fds);
  if (Fork() == 0) {
    for (i = 0; i < ITERS; i++)
      Write(fds[1], "Hello", 5);
  } else {
    char buffer[5];
    int n = 0;
    for (i = 0; i < ITERS; i++)
      n += Read(fds[0], buffer, 5);
    printf("%d\n", n);
  }
  return 0;
}
```

Copy

```c
#include "csapp.h"

#define ITERS 1000000

int main() {
  int fds[2];
  int i;

  Pipe(fds);
  if (Fork() == 0) {
    FILE *out = fdopen(fds[1], "w");
    for (i = 0; i < ITERS; i++)
      fwrite("Hello", 1, 5, out);
  } else {
    FILE *in = fdopen(fds[0], "r");
    char buffer[5];
    int n = 0;
    for (i = 0; i < ITERS; i++)
      n += fread(buffer, 1, 5, in);
    printf("%d\n", n);
  }
  return 0;
}
```

Copy

Unix I/O vs. C Library I/O

```
#include "csapp.h"

#define ITERS 1000000

int main() {
  int fds[2];
  int i;

  Pipe(fds);
  if (Fork() == 0) {
    for (i = 0; i < ITERS; i++)
      Write(fds[1], "Hello", 5);
  } else {
    char buffer[5];
    int n = 0;
    for (i = 0; i < ITERS; i++)
      n += Read(fds[0], buffer, 5);
    printf("%d\n", n);
  }
  return 0;
}
```

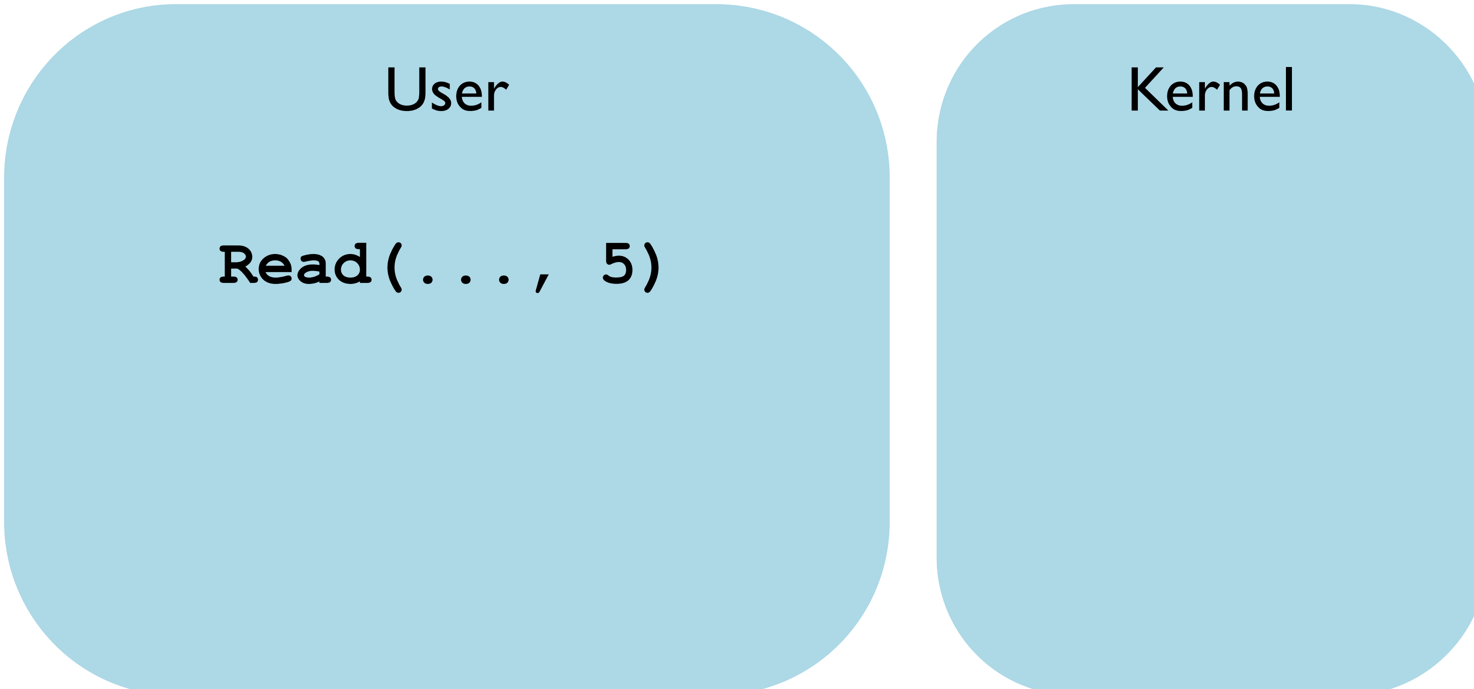
Copy

```
#include "csapp.h"

#define ITERS 1000000

int main() {
  int fds[2];
  int i;

  Pipe(fds);
  if (Fork() == 0) {
    FILE *out = fdopen(fds[1], "w");
    for (i = 0; i < ITERS; i++)
      fwrite("Hello", 1, 5, out);
  } else {
    FILE *in = fdopen(fds[0], "r");
    char buffer[5];
    int n = 0;
    for (i = 0; i < ITERS; i++)
      n += fread(buffer, 1, 5, in);
    printf("%d\n", n);
  }
  return 0;
}
```

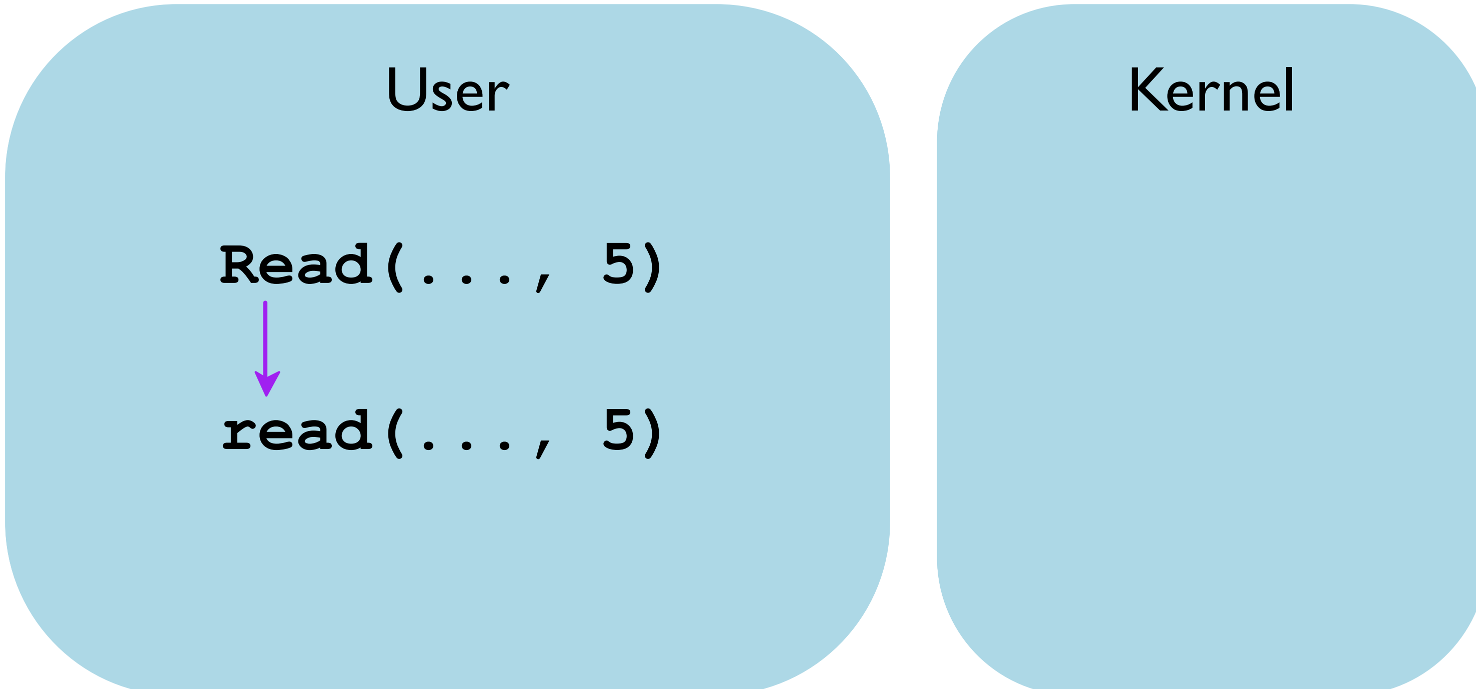
Copy

10x faster!

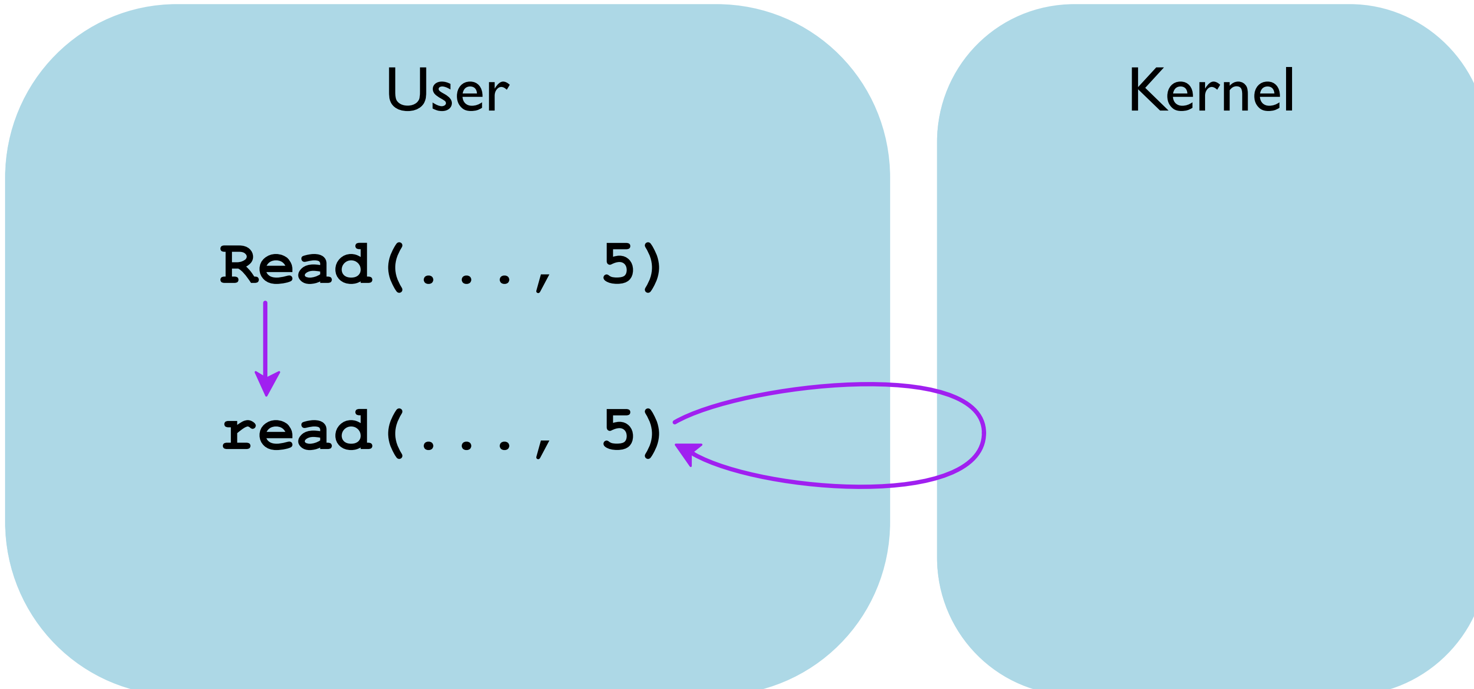
Unix I/O vs. C Library I/O



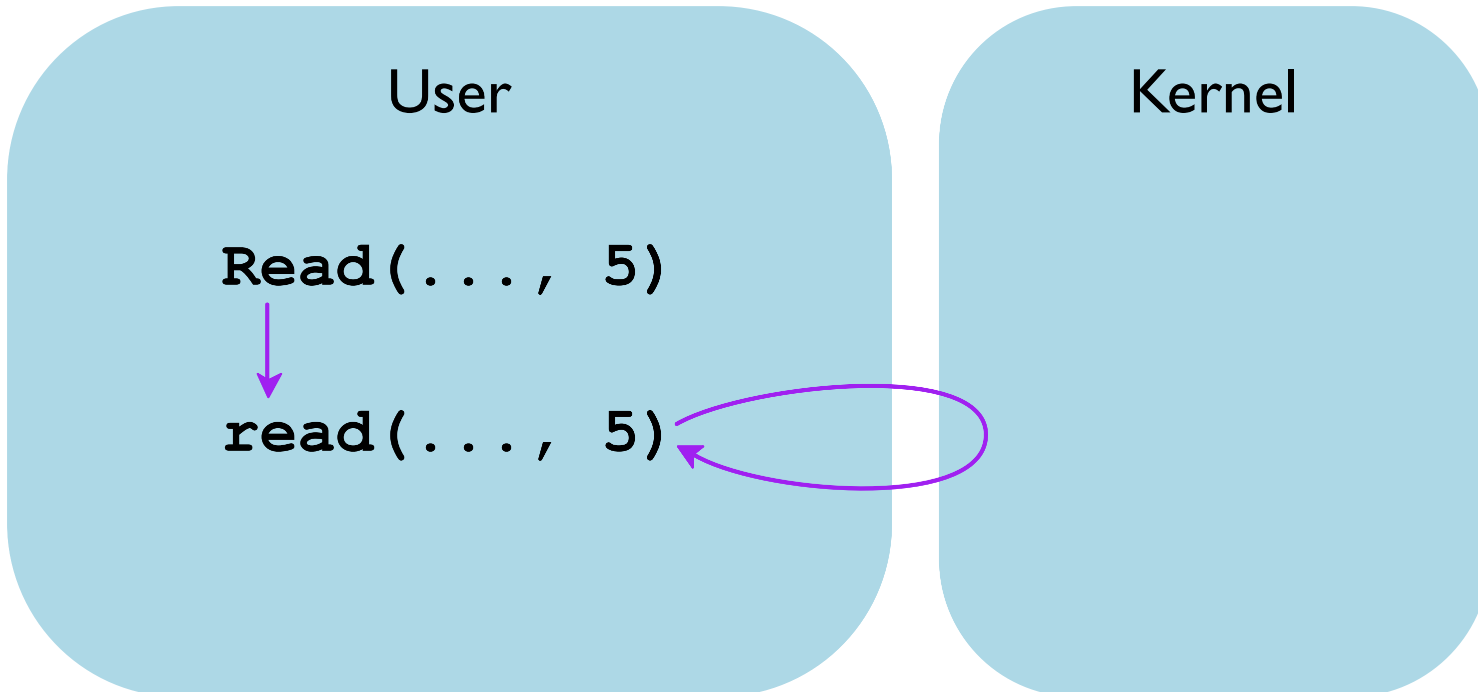
Unix I/O vs. C Library I/O



Unix I/O vs. C Library I/O



Unix I/O vs. C Library I/O



System call through kernel every time

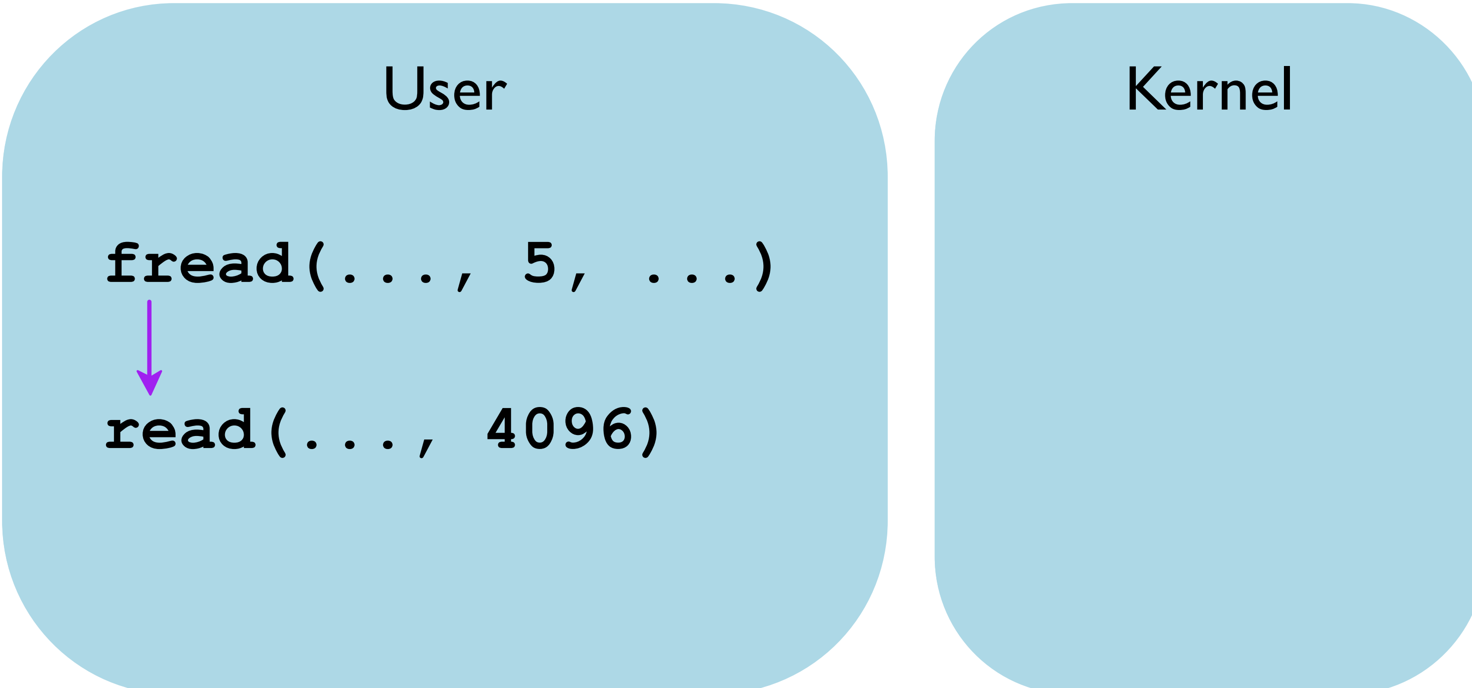
Unix I/O vs. C Library I/O

User

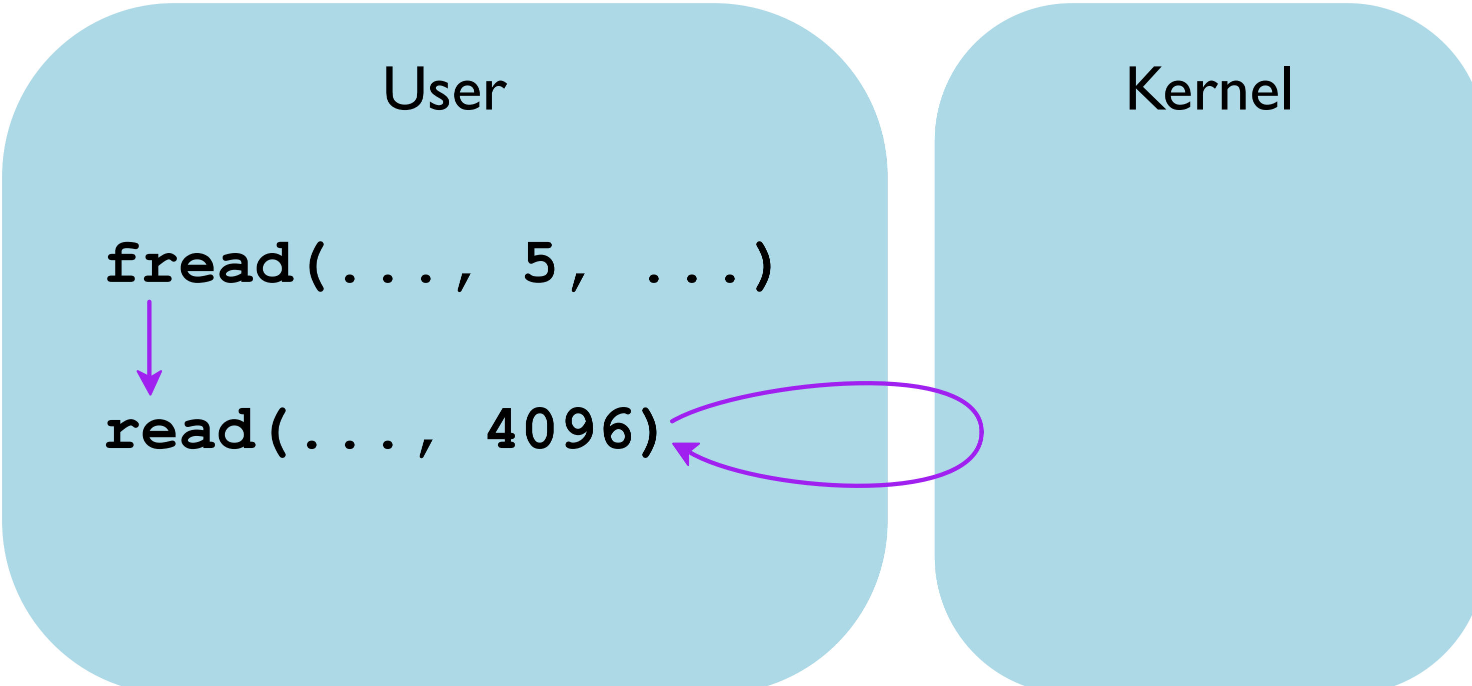
```
fread(..., 5, ...)
```

Kernel

Unix I/O vs. C Library I/O

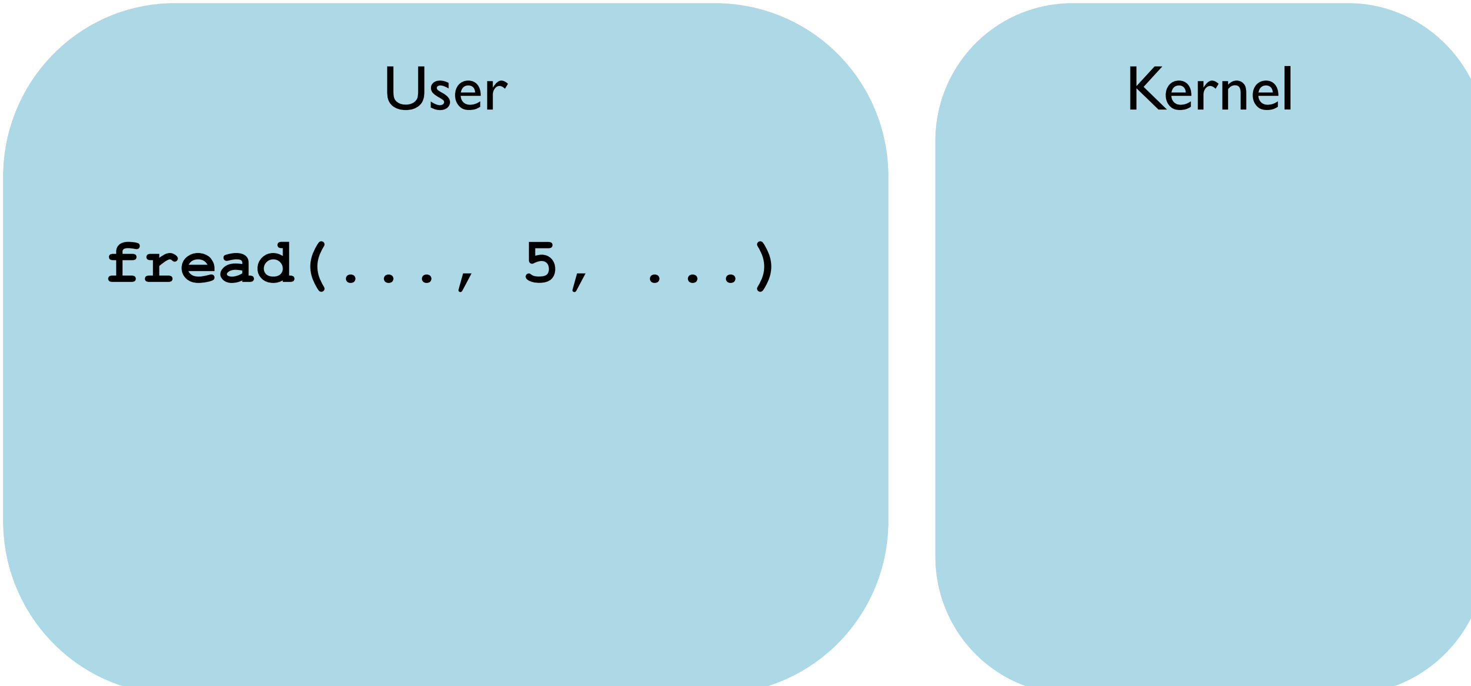


Unix I/O vs. C Library I/O



Extra bytes are stored in the **`FILE`** record

Unix I/O vs. C Library I/O



Extra bytes are stored in the **`FILE`** record

Unix I/O vs. C Library I/O

User

```
fread(..., 5, ...)
memcpy(...)
```

Kernel

Extra bytes are stored in the **`FILE`** record

Fast when buffered bytes are available

I/O Options

Unix I/O

+ Precise control

− Slow for small transfers

− Partial reads/write possible due to limits or signals

Standard C

+ Fast via buffering

+ Many conveniences

− Less control

From **`csapp.c`**:

- **`sio_...`**: convenience around Unix I/O
- **`rio_...`**: partial-handling wrapper around Unix I/O