System Calls

Key concepts from previous lectures

- Control and status registers
- Memory-mapped I/O
- Interrupt and exception handling
- Privilege levels
- Memory protection

Recap: Manage Hardware

- Manage CPU: Control and Status Register (CSR)

3.1.12 Machine Trap-Vector Base-Address Register (mtvec)

The mtvec register is an XLEN-bit read/write register that holds trap vector configuration, consisting of a vector base address (BASE) and a vector mode (MODE).

XLEN-1 … 2	1 … 0
BASE[XLEN-1:2] (**WARL**)	MODE (**WARL**)
XLEN-2	2

```
void kernel() {
    ...
}

void os_init() {
    ...
    // Register kernel() as the
    // interrupt/exception handler.
    asm("csrw mtvec, %0" ::”r"(kernel));
    ...
}
```

Recap: Manage Hardware

- Manage IO: Memory-Mapped I/O (MMIO)
  - Timer
  - Software interrupt

mtimecmp_set() writes 8 bytes to → 0x2004000

mtime_get() reads 8 bytes from → 0x200bff8

Address	Width	Attr.	Description
0x2000000	4B	RW	msip for hart 0
0x2004008			Reserved
...			
0x200bff7			
0x2004000	8B	RW	mtimecmp for hart 0
0x2004008			Reserved
...			
0x200bff7			
0x200bff8	8B	RW	mtime
0x200c000			Reserved

Recap: Manage Hardware

- Manage IO: Memory-Mapped I/O (MMIO)
  - Timer
  - Software interrupt

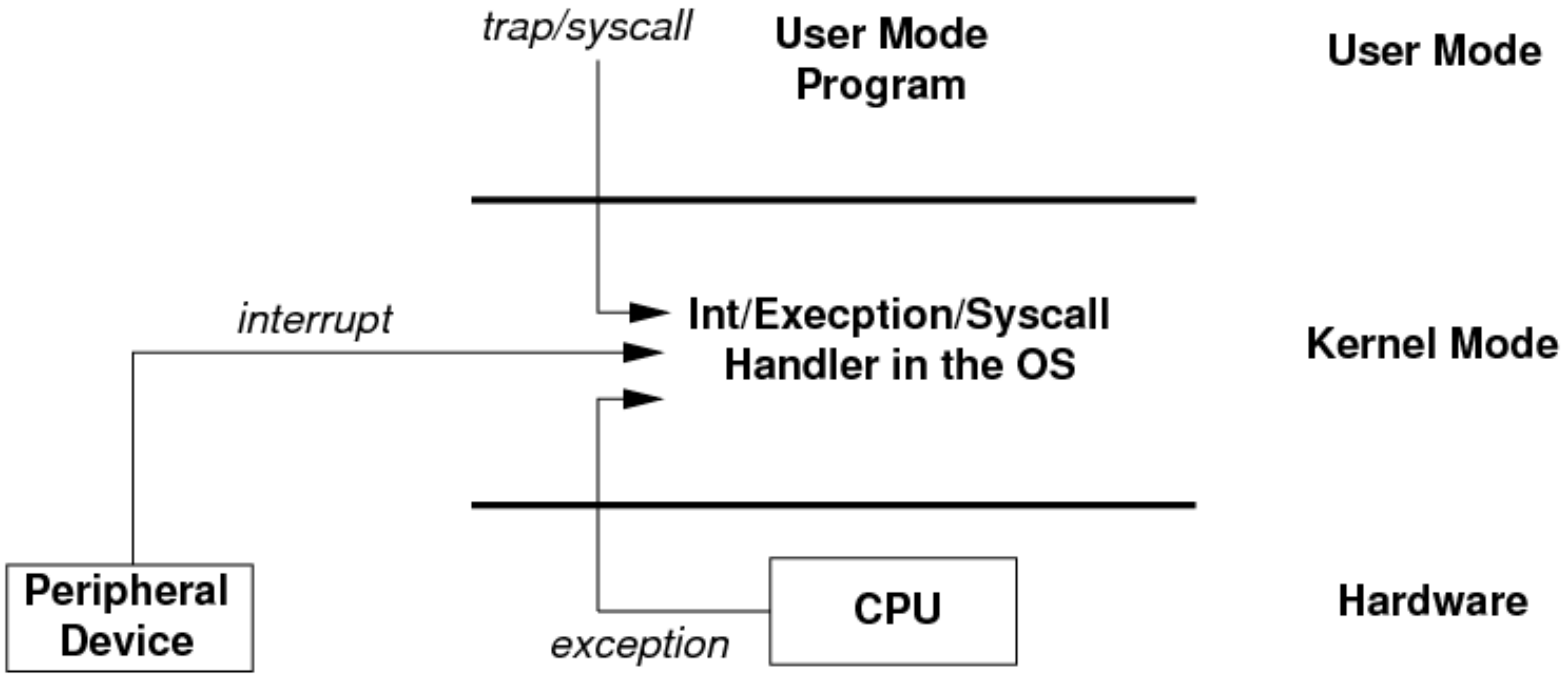
Address	Width	Attr.	Description	Notes
0x2000000	4B	RW	msip for hart 0	MSIP Registers (1 bit wide)
0x2004008			Reserved	
…				
0x200bff7				
0x2004000	8B	RW	mtimecmp for hart 0	MTIMECMP Registers
0x2004008			Reserved	
…				
0x200bff7				
0x200bff8	8B	RW	mtime	Timer Register
0x200c000			Reserved	

Table 24: CLINT Register Map

9.2 MSIP Registers

Machine-mode software interrupts are generated by writing to the memory-mapped control register msip. Each msip register is a 32-bit wide **WARL** register where the upper 31 bits are tied to

Recap: Privilege Levels



https://minnie.tuhs.org/CompArch/Lectures/week05.html

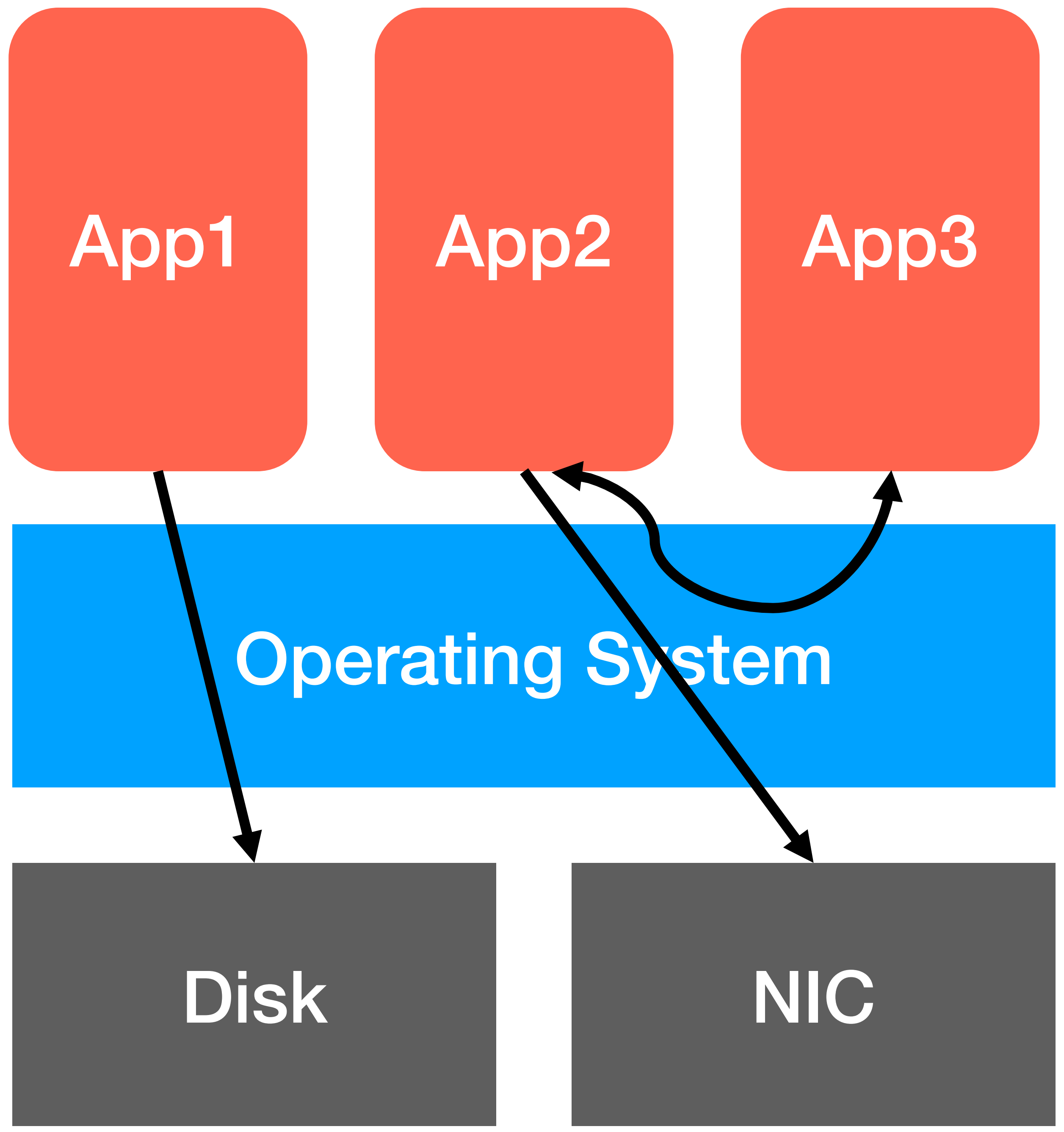
Recap: Memory Protection

- Memory region

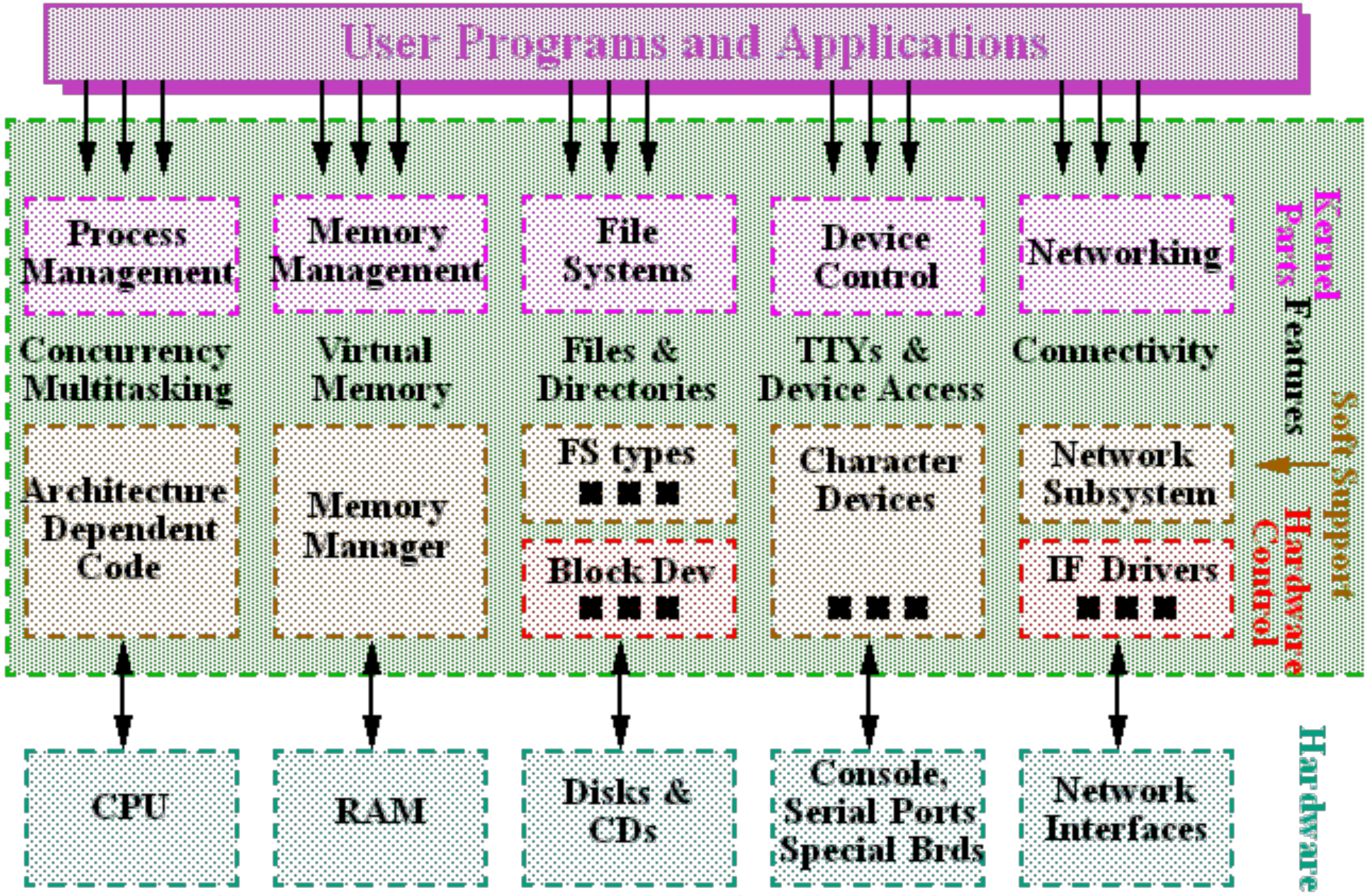
- Configuration
  - R/W/X
  - Address matching: TOR, NAPOT, etc

Today: System Call

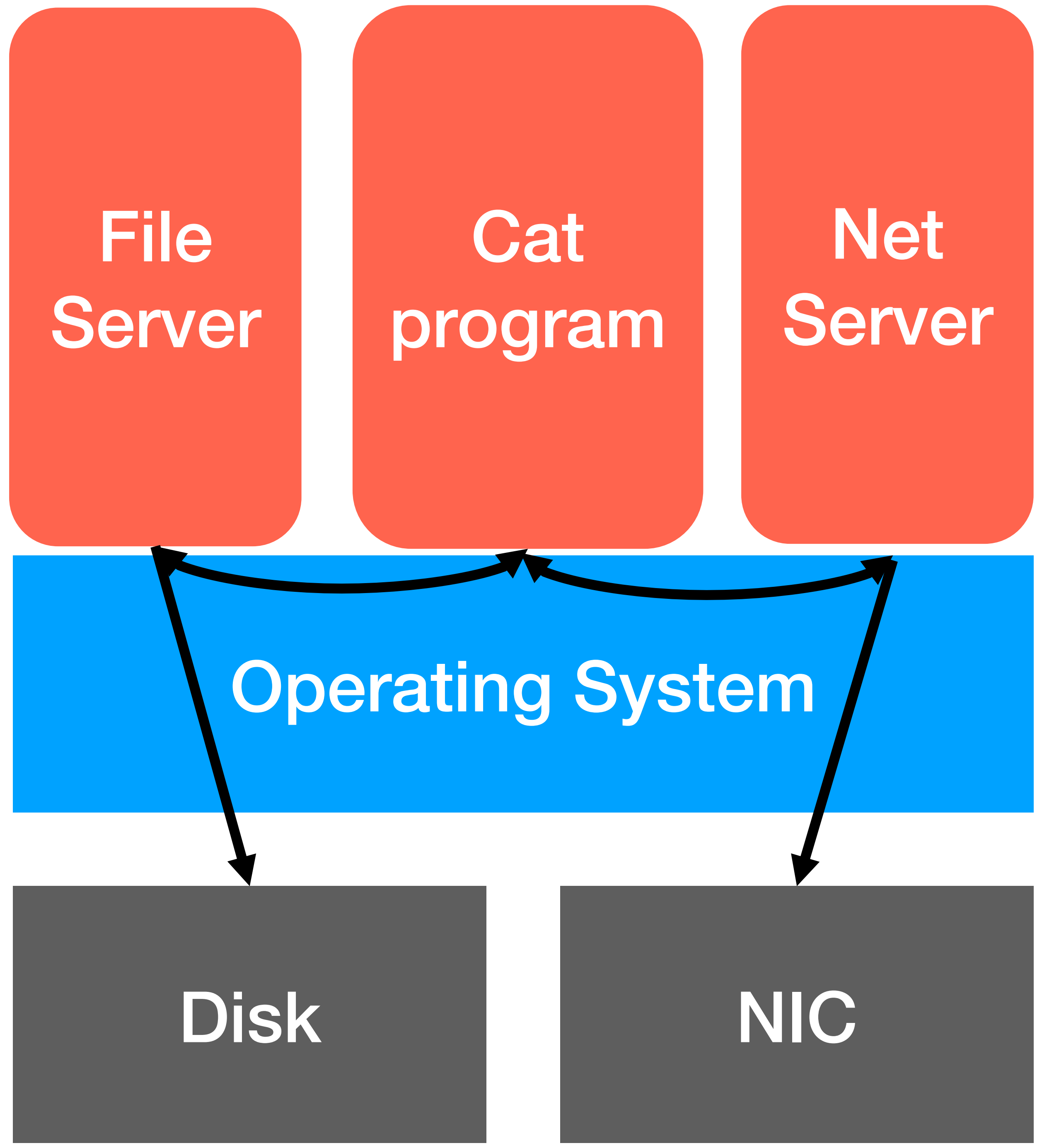
- A way for applications to request **services** from the OS.
  - E.g., read/write disks, access NICs, inter-process communication (IPC)
- How
  - Invoke OS kernel by SWI or ECALL



Monolithic kernel vs Microkernel



https://ece-research.unm.edu/jimp/310/slides/linux_driver1.html



EGOS

Agenda

- A high-level picture of system calls
- A concrete implementation of system calls
- Starting P2: Invoking system calls with ecall

apps/user/cat.c

make qemu ⌥⌘2

```
[INFO] App file size: 0x00002770 bytes
[INFO] App memory size: 0x00002fc8 bytes
[SUCCESS] Enter kernel process GPID_FILE
[INFO] sys_proc receives: Finish GPID_FILE initialization
[INFO] Load kernel process #3: sys_dir
[INFO] App file size: 0x00000fa4 bytes
[INFO] App memory size: 0x00001bb0 bytes
[SUCCESS] Enter kernel process GPID_DIR
[INFO] sys_proc receives: Finish GPID_DIR initialization
[INFO] Load kernel process #4: sys_shell
[INFO] App file size: 0x000006d0 bytes
[INFO] App memory size: 0x00000ed0 bytes
[CRITICAL] Welcome to the egos-2000 shell!
➜ /home/yunhao cat README
With only 2000 lines of code, egos-2000 implements boot loader, microSD driver,
tty driver, memory paging, address translation, interrupt handling, process sche
duling and messaging, system call, file system, shell, 7 user commands and the `
mkfs/mkrom` tools.
➜ /home/yunhao
```

Cat invokes `file_read()`

```c
int main(int argc, char** argv) {
  if (argc == 1) {
    INFO("usage: cat [FILE]");
    return -1;
  }

  /* Get the inode number of the file */
  int file_ino = dir_lookup(grass->workdir_ino, argv[1]);
  if (file_ino < 0) {
    INFO("cat: file %s not found", argv[1]);
    return -1;
  }

  /* Read and print the first block of the file */
  char buf[BLOCK_SIZE];
  file_read(file_ino, 0, buf);
  printf("%s", buf);
  if (buf[strlen(buf) - 1] != '\n') printf("\r\n");

  return 0;
}
```

Step1. File server waits for requests

Process #1

apps/system/sys_file.c `main()`

↓

grass/syscall.c `sys_recv()`

Step2. Cat sends a request for file content

Process #2

Apps/user/cat.c `main()`

↓

library/servers/servers.c `file_read()`

↓

grass/syscall.c `sys_send()`

Step3. Kernel handles the IPC

Process #1 (sys_file)

main()

sys_recv()

Receive:
Read from **X** file

Process #2 (cat)

main()

file_read()

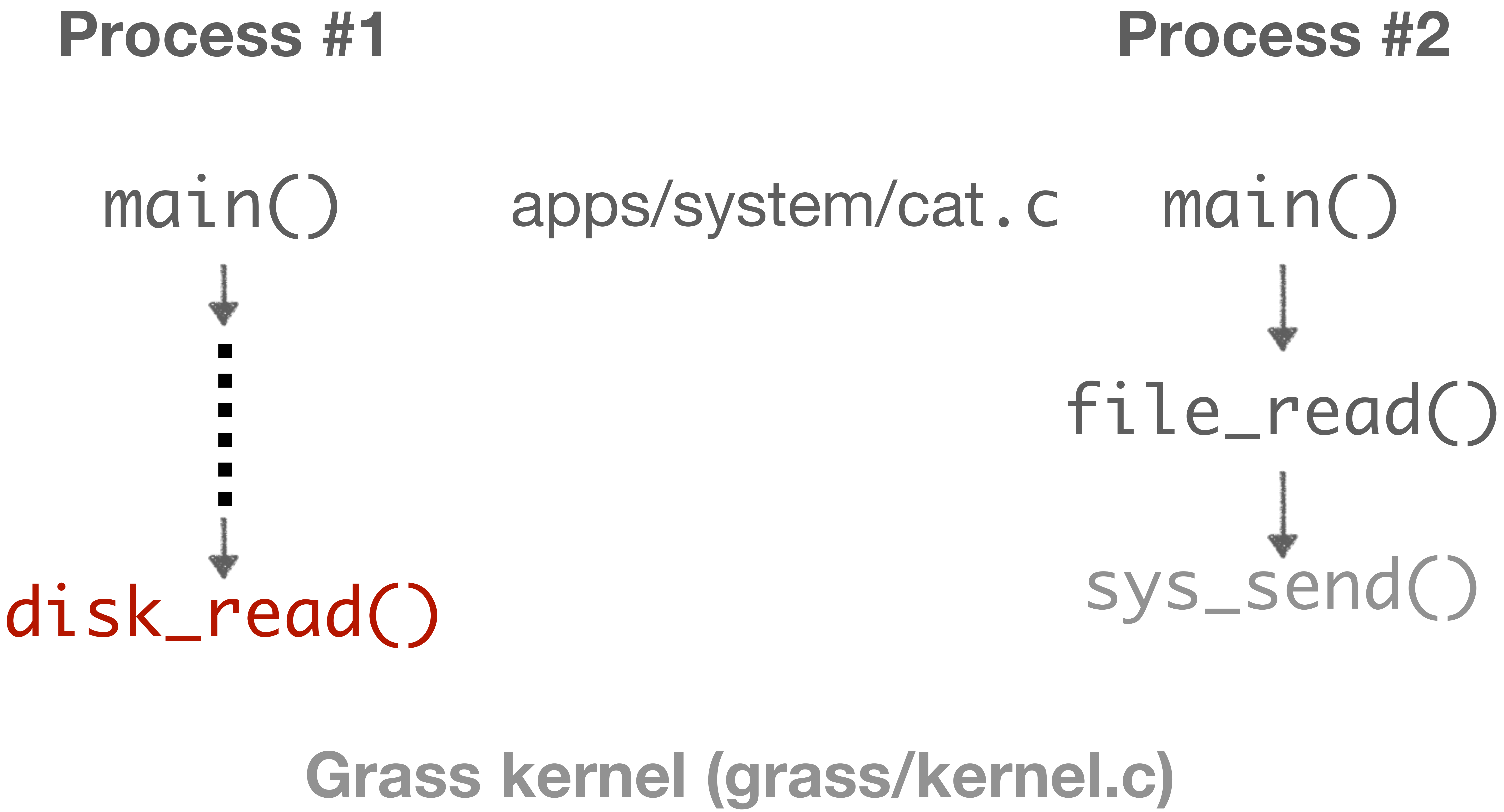
sys_send()

Send to FileServer:
Read from **X** file

Inter-process Communication (IPC)

Grass kernel (grass/kernel.c)

Step4a. File server reads file from disk



Step4b. Cat waits for the file content

Process #1

Process #2

main()

apps/system/cat.c

main()

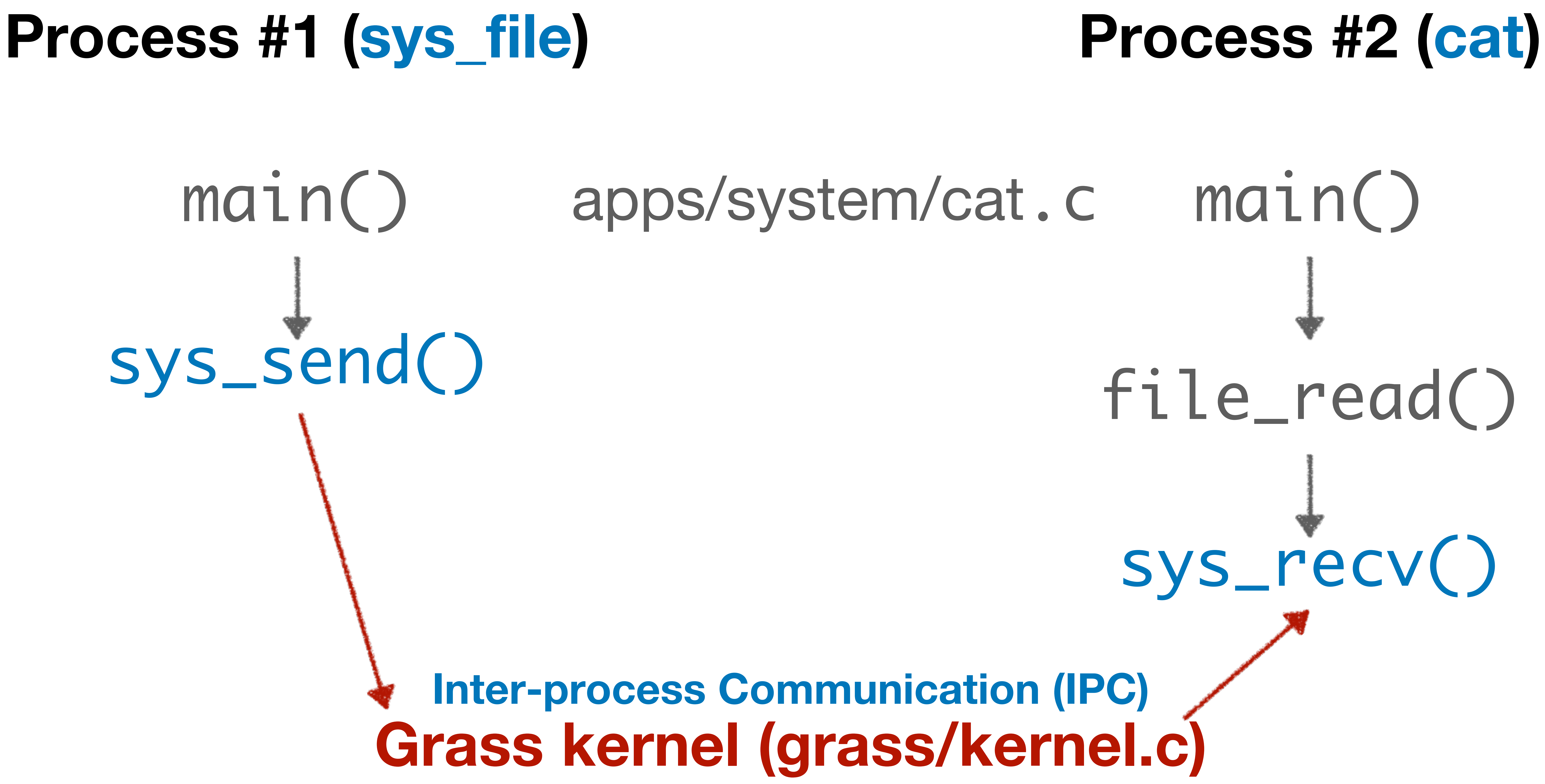
file_read()

sys_recv()

disk_read()

Grass kernel (grass/kernel.c)

Step5. File server returns the file content



- A high-level picture of system calls

➡ A concrete implementation of system calls

- Starting P2: Invoking system calls with ecall

Data structures for system calls

```c
struct syscall {
    enum syscall_type type;
    struct sys_msg msg;
    int retval;
};
```

```c
enum syscall_type {
        SYS_UNUSED,
        SYS_RECV,
        SYS_SEND,
        SYS_NCALLS
};
```

See header file grass/syscall.h

File server invoking sys_recv

```
char buf[SYSCALL_MSG_LEN];

while (1) {
    int sender, r;
    struct file_request *req = (void*)buf;
    r = grass->sys_recv(&sender, buf, SYSCALL_MSG_LEN);

    switch (req->type) {
    case FILE_READ:
        ... // read a file from disk
    case FILE_WRITE:
        ... // write to a file on disk
    }
}
```

File server invoking sys_recv

```
static void sys_invoke() {
    *((int*)0x2000000) = 1;  // Trigger a software interrupt
}                            // which is interrupt #3

int sys_recv(int* sender, char* buf, int size) {
    if (size > SYSCALL_MSG_LEN) return -1;

    sc->type = SYS_RECV;
    sys_invoke();
    memcpy(buf, sc->msg.content, size);
    if (sender) *sender = sc->msg.sender;
    return sc->retval;
}
```

Kernel calls system call handler

```
void kernel() {
    int mcause;
    __asm__ volatile("csrr %0, mcause" : "=r"(mcause));

    int id = mcause & 0x3ff;
    if (mcause & (1 << 31)) {
        if (id == 3) { syscall_handler(); }
        if (id == 7) { timer_handler(); }
    } else {
        fault_handler();
    }
}
```

Kernel blocks the file server process

```
void syscall_handler() {
    ...
    // If SYS_RECV
    // Block the file server process
    // until it receives a message,
    // which is similar to sema_dec() in P1.
    ...
}
```

App invoking sys_send

```
static struct syscall *sc = (struct syscall*)SYSCALL_ARG;

static void sys_invoke() {
    *((int*)0x2000000) = 1;
}

int sys_send(int receiver, char* msg, int size) {
    if (size > SYSCALL_MSG_LEN) return -1;
    // Prepare the system call data structure
    sc->type = SYS_SEND;
    sc->msg.receiver = receiver;
    memcpy(sc->msg.content, msg, size);
    sys_invoke();
    return sc->retval;
}
```

App invoking sys_send

```
static struct syscall *sc = (struct syscall*)SYSCALL_ARG;

static void sys_invoke() {
    *((int*)0x2000000) = 1;  // Trigger a software interrupt
}                            // which is interrupt #3

int sys_send(int receiver, char* msg, int size) {
    if (size > SYSCALL_MSG_LEN) return -1;

    sc->type = SYS_SEND;
    sc->msg.receiver = receiver;
    memcpy(sc->msg.content, msg, size);
    sys_invoke();
    return sc->retval;
}
```

Kernel calls system call handler

```
void kernel() {
    int mcause;
    __asm__ volatile("csrr %0, mcause" : "=r"(mcause));

    int id = mcause & 0x3ff;
    if (mcause & (1 << 31)) {
        if (id == 3) { syscall_handler(); }
        if (id == 7) { timer_handler(); }
    } else {
        fault_handler();
    }
}
```

Kernel unblocks the file server process

```
void syscall_handler() {
    ...
    // If SYS_SEND
    // Copy the message from the memory
    // of cat to the memory of sys_file.
    // Then unblock the file server process.
    ...
}
```

File server is unblocked

```
static struct syscall *sc = (struct syscall*)SYSCALL_ARG;

int sys_recv(int* sender, char* buf, int size) {
    if (size > SYSCALL_MSG_LEN) return -1;

    sc->type = SYS_RECV;
    sys_invoke();
    memcpy(buf, sc->msg.content, size);
    if (sender) *sender = sc->msg.sender;
    return sc->retval;
}
```

Parse the message as a request

```
char buf[SYSCALL_MSG_LEN];

while (1) {
    int sender, r;
    struct file_request *req = (void*)buf;
    r = grass->sys_recv(&sender, buf, SYSCALL_MSG_LEN);

    switch (req->type) {
    case FILE_READ:
        ... // read a file from disk
    case FILE_WRITE:
        ... // write to a file on disk
    }
}
```

File server handles the request

```
char buf[SYSCALL_MSG_LEN];

while (1) {
    int sender, r;
    struct file_request *req = (void*)buf;
    r = grass->sys_recv(&sender, buf, SYSCALL_MSG_LEN);

    switch (req->type) {
    case FILE_READ:
        ... // read a file from disk (project P3 & P4)
    case FILE_WRITE:
        ... // write to a file on disk (project P3 & P4)
    }
}
```

- A high-level picture of system calls
- A concrete implementation of system calls

➔ P2: Invoking system calls with ecall

Modify sys_invoke

```
// Previously
static void sys_invoke() {
    *((int*)0x2000000) = 1;  // Trigger a software interrupt
}                            // which is interrupt #3

// Now
static void sys_invoke() {
    asm("ecall");            // Trigger an ecall exception
}                            // which is exception #8 / #11
```

P2 – Three Tasks

- Use **ecall** to handle system calls
- Assign privilege level to processes
- Add memory protect to four memory regions

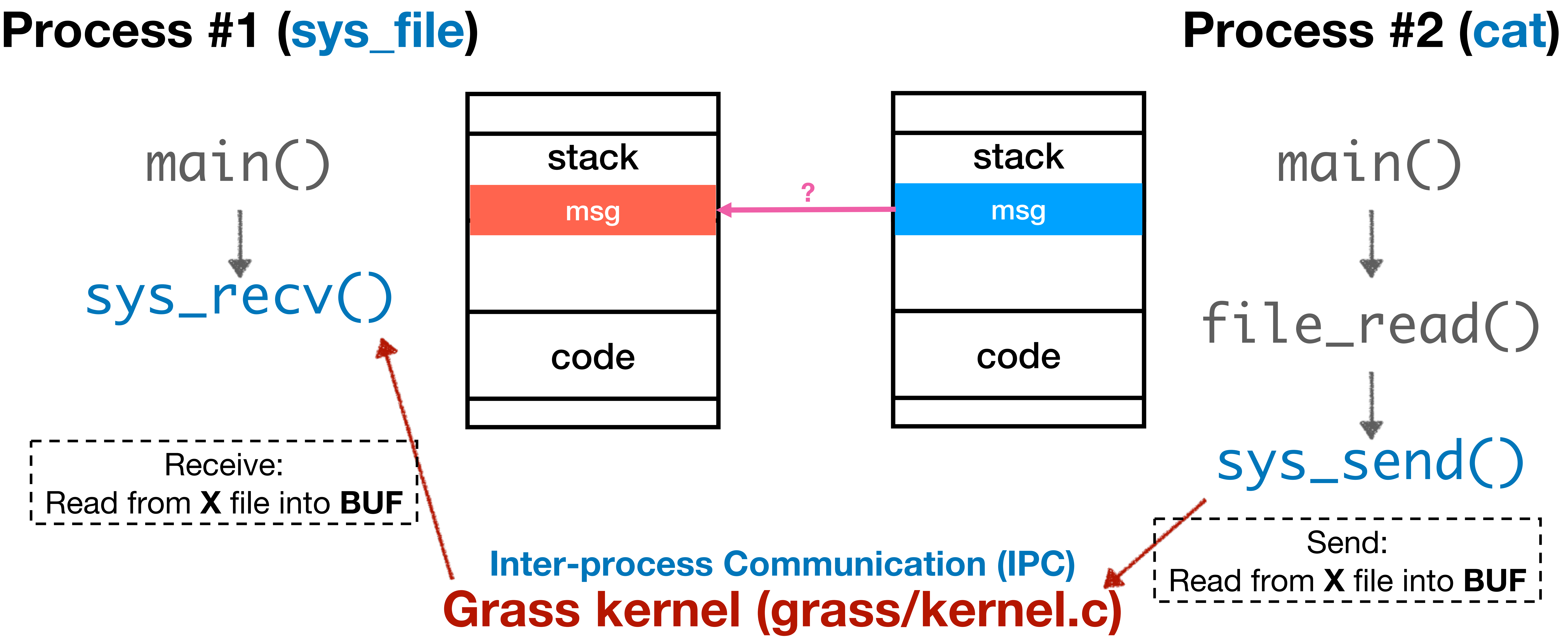
Virtual Memory

- What: allowing multiple processes to use the same (virtual) address
  - Both Cat and FileServer can use address 0xaabb
- How

1. OS buffers memory for application processes

2. Page table

Back to our Cat & SysFile



Software TLB

```
static void proc_send(struct syscall *sc) {
    ...
    /* Copy message from sender to kernel stack */
    struct sys_msg tmp;
    earth->mmu_switch(curr_pid);
    memcpy(&tmp, &sc->msg, sizeof(tmp));

    /* Copy message from kernel stack to receiver */
    earth->mmu_switch(receiver);
    memcpy(&sc->msg, &tmp, sizeof(tmp));

    /* Set receiver process as runnable */
    proc_set_runnable(receiver);
    ...
}
```

```
int soft_tlb_switch(int pid) {
    ...
    /* Unmap curr_vm_pid from the user address space */
    for (int i = 0; i < NFRAMES; i++)
        if (table[i].use && table[i].pid == curr_vm_pid)
            paging_write(i, table[i].page_no);

    /* Map pid to the user address space */
    for (int i = 0; i < NFRAMES; i++)
      if (table[i].use && table[i].pid == pid)
          memcpy((void*)(table[i].page_no << 12), paging_read(i, 0), PAGE_SIZE);
    ...
}
```

Homework

- P2 is due on March 15th.
- Please remember to fill up the mid-term evaluation!
- Come to office hours for help.