

Background: I/O Concurrency

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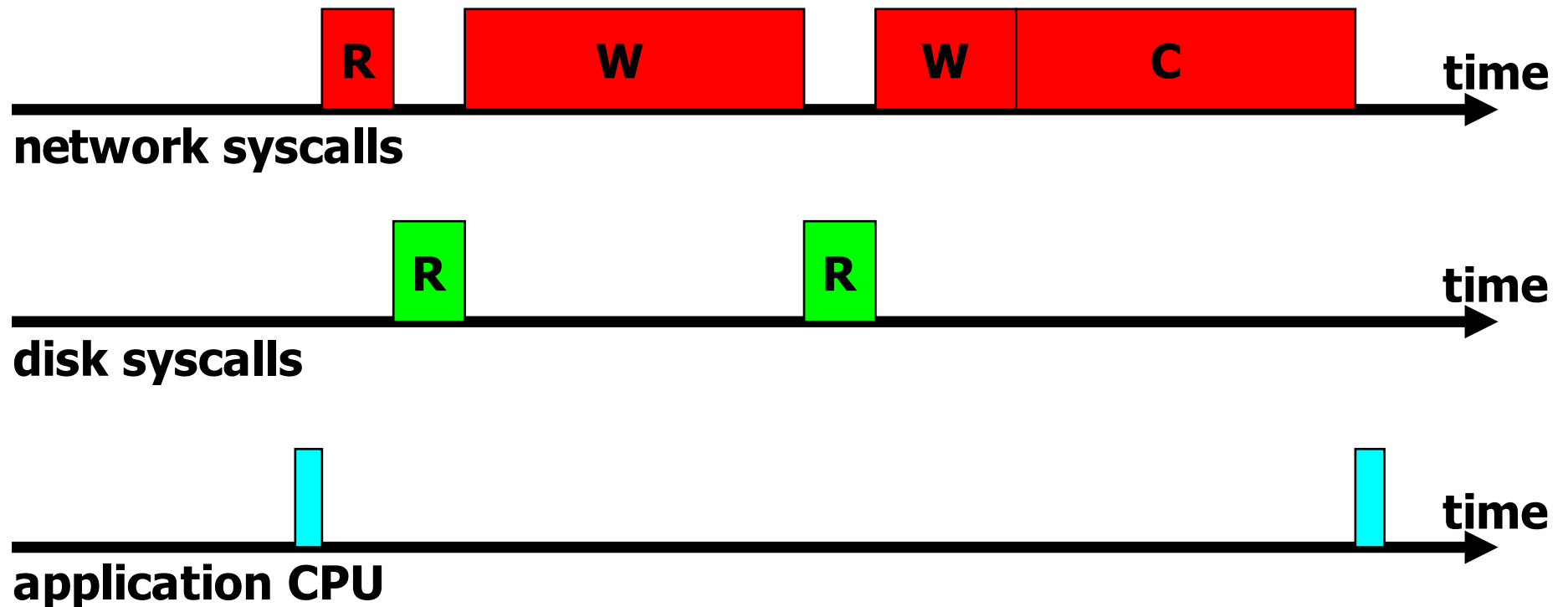
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Outline

- “Worse Is Better” and Distributed Systems
- Problem: Naïve single-process server leaves system resources idle; I/O **blocks**
 - Goal: **I/O concurrency**
 - Goal: **CPU concurrency**
- Solutions
 - **Multiple processes**
 - **One process, many threads**
 - Event-driven I/O (not in today’s lecture)

Review: How Do Servers Use Syscalls?

- Consider server_1() web server (in handout)

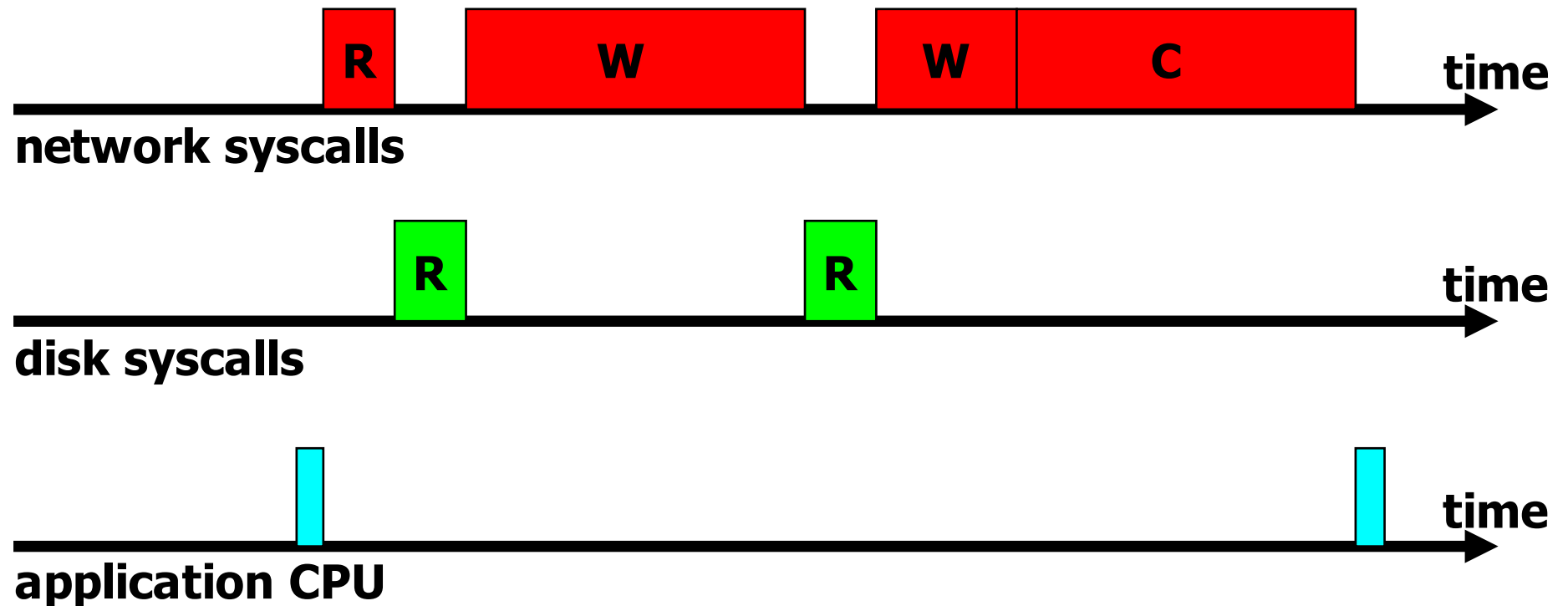


Review: How Do Servers Use Syscalls?

Server waits for each resource in turn

Each resource largely idle

What if there are many clients?



Performance and Concurrency

- Under heavy load, server_1():
 - Leaves resources idle
 - ...and has a lot of work to do!
- Why?
 - Software poorly structured!
 - What would a better structure look like?

Solution: I/O Concurrency

- Can we overlap I/O with other useful work? Yes:
 - Web server: if files in disk cache, I/O wait spent mostly **blocked on write to network**
 - Networked file system client: could **compile first part of file while fetching second part**
- Performance benefits potentially huge
 - Say one client causes disk I/O, **10 ms**
 - **If other clients' requests in cache, could serve 100 other clients during that time!**

One Process May Be Better Than You Think

- OS provides I/O concurrency to application transparently when it can, e.g.,
 - Filesystem does **read-ahead** into disk buffer cache; **write-behind** from disk buffer cache
 - Networking code copies arriving packets into application's kernel socket buffer; copies app's data into kernel socket buffer on write()

I/O Concurrency with Multiple Processes

- Idea: start new UNIX process for each client connection/request
- Master process assigns new connections to child processes
- Now plenty of work to keep system busy!
 - One process blocks in syscall, others can process arriving requests
- Structure of software still simple
 - See `server_2()` in `webserver.c`
 - `fork()` after `accept()`
 - Otherwise, software structure unchanged!

Multiple Processes: More Benefits

- Isolation
 - Bug while processing one client's request leaves other clients/requests unaffected
 - Processes do interact, but OS arbitrates (e.g., "lock the disk request queue")
- CPU concurrency for "free"
 - If more than one CPU in box, each process may run on one CPU

CPU Concurrency

- Single machine may have multiple CPUs, one shared memory
 - Symmetric Multiprocessor (SMP) PCs
 - Intel Core Duo
- I/O concurrency tools often help with CPU concurrency
 - But way more work for OS designer!
- Generally, CPU concurrency way less important than I/O concurrency
 - Factor of 2X, not 100X
 - Very hard to program to get good scaling
 - Easier to buy 2 machines (see future lectures!)

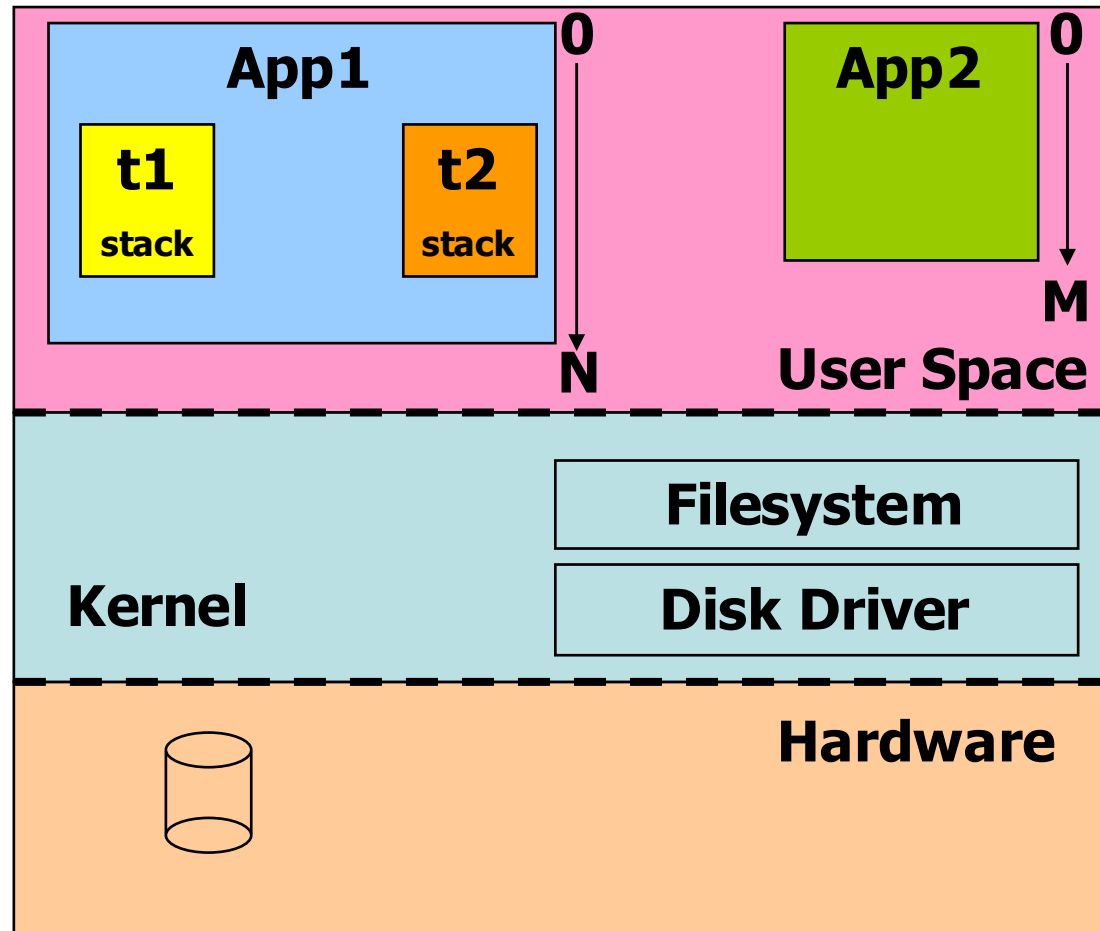
Problems with Multiple Processes

- fork() may be expensive
 - Memory for new address space
 - 300 us minimum on modern PC running UNIX
- Processes fairly **isolated** by default
 - Memory not shared
 - How do you build web cache on server visible to all processes?
 - How do you simply keep statistics?

Concurrency with Threads

- Similar to multiple processes
- Difference: one address space
 - All threads share same process' memory
 - One stack per thread, inside process
- Seems simple: single-process structure!
- Programmer needs to use locks
- One thread can corrupt another (i.e., no cross-request isolation)

Concurrency with Threads



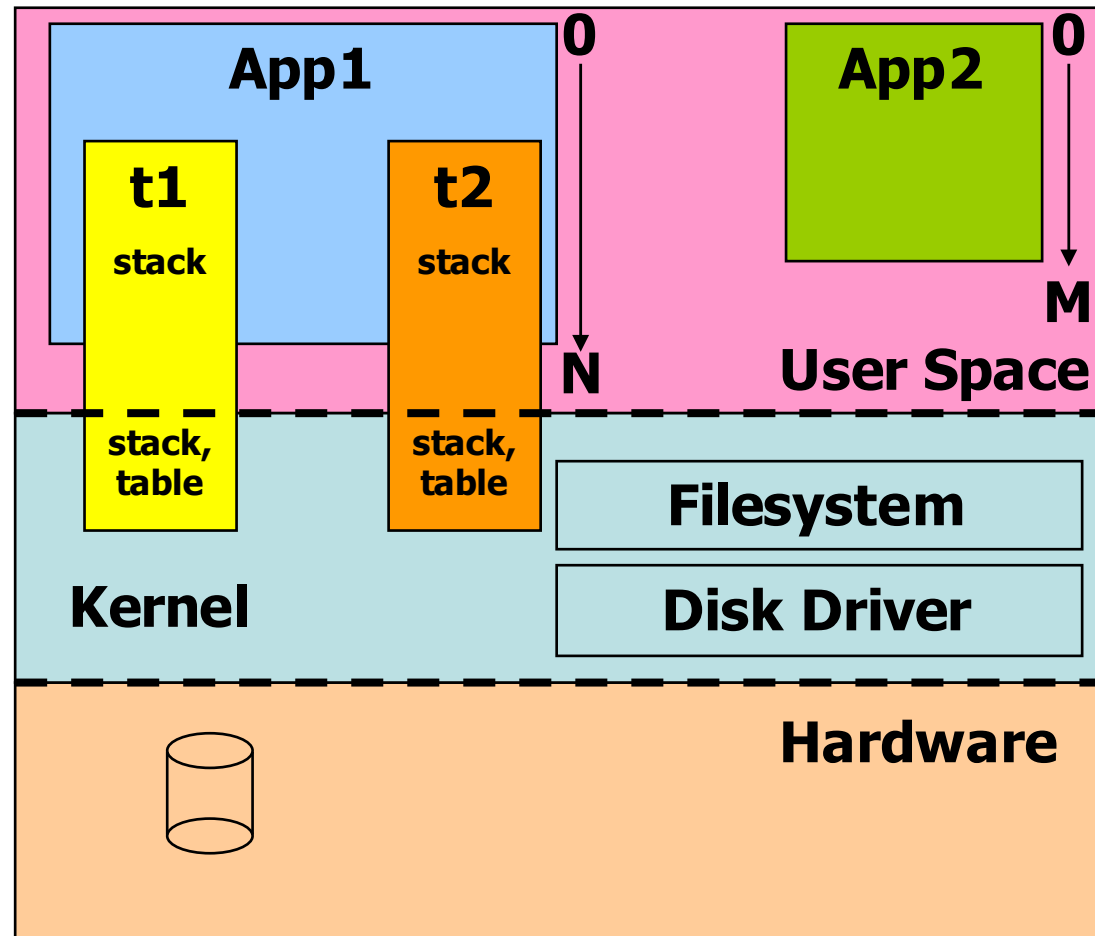
Threads: Low-Level Details Are Hard!

- Suppose thread calls `read()` (or other blocking syscall)
 - Does whole process block until I/O done?
 - If so, no I/O concurrency!
- Two solutions:
 - Kernel-supported threads
 - User-supported threads

Kernel-Supported Threads

- OS kernel aware of each thread
 - Knows if thread blocks, e.g., disk read wait
 - Can schedule another thread
- Kernel requirements:
 - Per-thread kernel stack
 - Per-thread tables (e.g., saved registers)
- Semantics:
 - Per-process: address space, file descriptors
 - Per-thread: user stack, kernel stack, kernel state

Kernel-Supported Threads



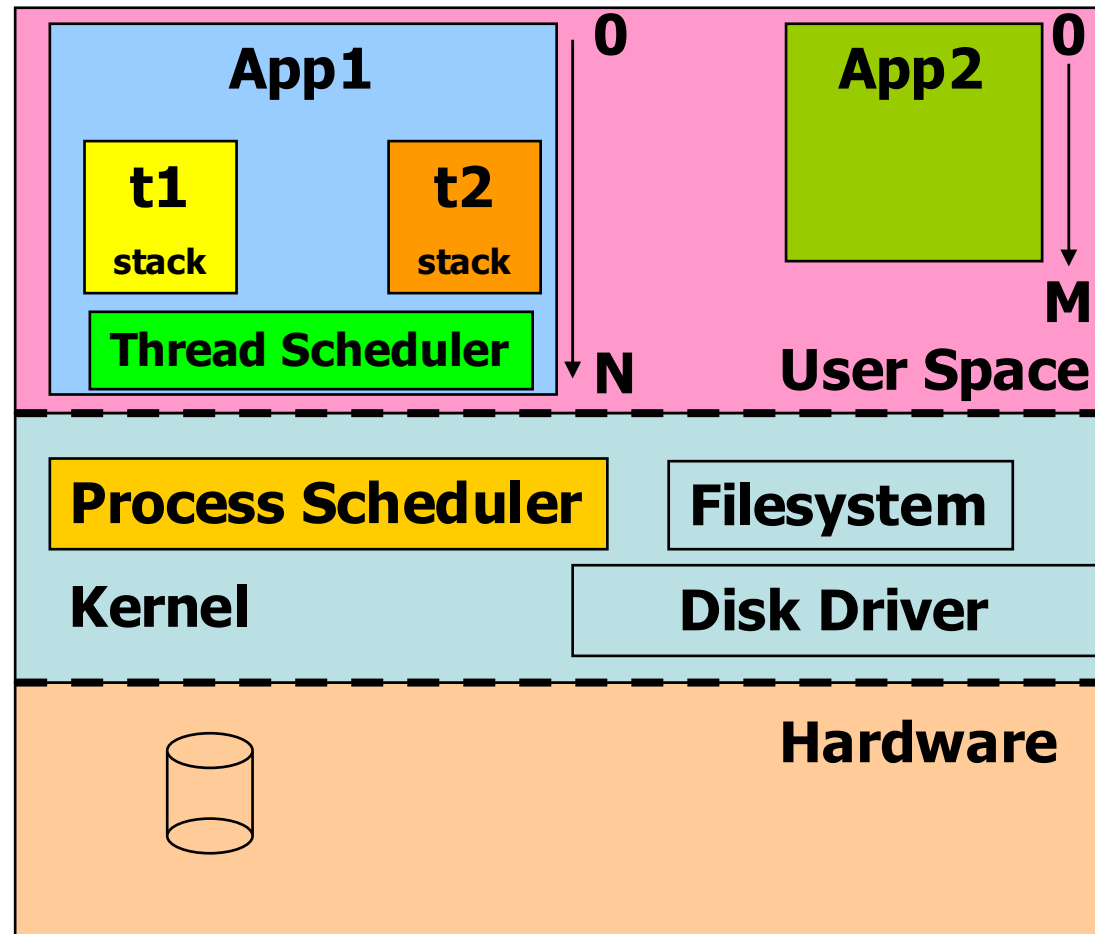
Kernel Threads: Trade-Offs

- Kernel can schedule one thread per CPU
 - Fits our goals well: both CPU and I/O concurrency
- But kernel threads **expensive**, like processes:
 - Kernel must help create each thread
 - Kernel must help with thread context switch!
 - Which thread took a page fault?
 - Lock/unlock must invoke kernel, but heavily used
- Kernel threads **not portable**; implementation heavily tailored to each OS

User-Level Threads

- Purely inside user process; kernel oblivious
- Scheduler within user process for process' own threads
 - In addition to kernel's process scheduler
- User-level scheduler must
 - Know when thread makes blocking syscall
 - Not block process; switch to another thread
 - Know when I/O done, to wake up original thread

User-Level Thread Implementation



User-Level Threads: Details

- Apps linked against **thread library**
- Library contains “fake” read(), write(), accept(), &c. syscalls
- Library can start **non-blocking** syscall operations
- Library marks threads as **waiting**, switches to **runnable** thread
- Kernel notifies library of I/O completion and other events; library marks **waiting** thread **runnable**

User-Level Threads: read() Example

```
read() {  
    tell kernel to start read;  
    mark thread waiting for read;  
    sched();  
}  
sched() {  
    ask kernel for I/O completion events;  
    mark corresponding threads runnable;  
    find runnable thread;  
    restore registers and return;  
}
```

User-Level Threads: Event Notification

- Events thread library needs from kernel:
 - new network connection
 - data arrived on socket
 - disk read completed
 - socket ready for further write()s
- Resembles miniature OS inside process!
- Problem: user-level threads demand significant kernel support:
 - non-blocking system calls
 - uniform event delivery mechanism

Event Notification in Typical OSes

- Usually, event notification only partly supported; e.g., in UNIX:
 - new TCP connections, arriving TCP/pipe/tty data: YES
 - filesystem operation completion: NO
- Similarly, not all syscalls can be started without waiting, e.g., in UNIX:
 - connect(), read()/write() on socket
 - open(), stat(): NO
 - read() from disk: SOMETIMES (e.g., aio_read())

Non-blocking System Calls: Hard to Implement

- Typical syscall implementation, inside the kernel, e.g., for read() (sys_read.c):

```
sys_read(fd, user_buffer, n) {  
    // read the file's i-node from disk  
    struct inode *i = alloc_inode();  
    start_disk(..., i);  
    wait_for_disk(i);  
    // the i-node tells us where the data are; read it.  
    struct buf *b = alloc_buf(i->...);  
    start_disk(..., b);  
    wait_for_disk(b);  
    copy_to_user(b, user_buffer);  
}
```

Non-blocking System Calls: Hard to Implement

- Typical syscall implementation, inside the kernel,

Why not just return to user program instead of calling wait_for_disk()?

How will kernel know where to continue?

In user space? In kernel?

```
wait_for_disk(i);  
// the i-node tells us where the data are; read it.  
struct buf *b = alloc_buf(i->...);  
start_disk(..., b);  
wait_for_disk(b);  
copy_to_user(b, user_buffer);
```

```
}
```

Non-blocking System Calls: Hard to Implement

- Typical syscall implementation, inside the kernel,

Why not just return to user program instead of calling `wait_for_disk()`?

How will kernel know where to continue?

In user space? In kernel?

```
wait_for_disk(i);
```

Problem: Keeping state for complex, multi-step operations

```
wait_for_disk(a);  
wait_for_disk(b);  
copy_to_user(b, user_buffer);  
}
```

User-Threads: Implementation Choices

- Live with **only partial support for user-level threads**
- New operating system with **totally different syscall interface**
 - One syscall per non-blocking “sub-operation”
 - Kernel doesn’t need to keep state across multiple steps
 - e.g., `lookup_one_path_component()`
- Microkernel: no system calls, just messages to servers, with non-blocking communication

Threads: Programming Difficulty

- Sharing of data structures in one address space
- Even on single CPU, thread model necessitates CPU concurrency
 - Locks often needed for mutual exclusion on data structures
 - May only have wanted to overlap I/O wait!
- Events usually occur one-at-a-time
 - Can we do CPU sequentially, and overlap only wait for I/O?
 - Yes: event-driven programming

Event-Driven Programming

- Foreshadowed by user-level threads implementation
 - Organize software around event arrival
- Write software in state-machine style
 - “When event X occurs, execute this function.”
- Library support for registering interest in events (e.g., data available to read())
- Desirable properties:
 - Serial nature of events preserved
 - Programmer sees only one event/function at a time