Background: I/O Concurrency

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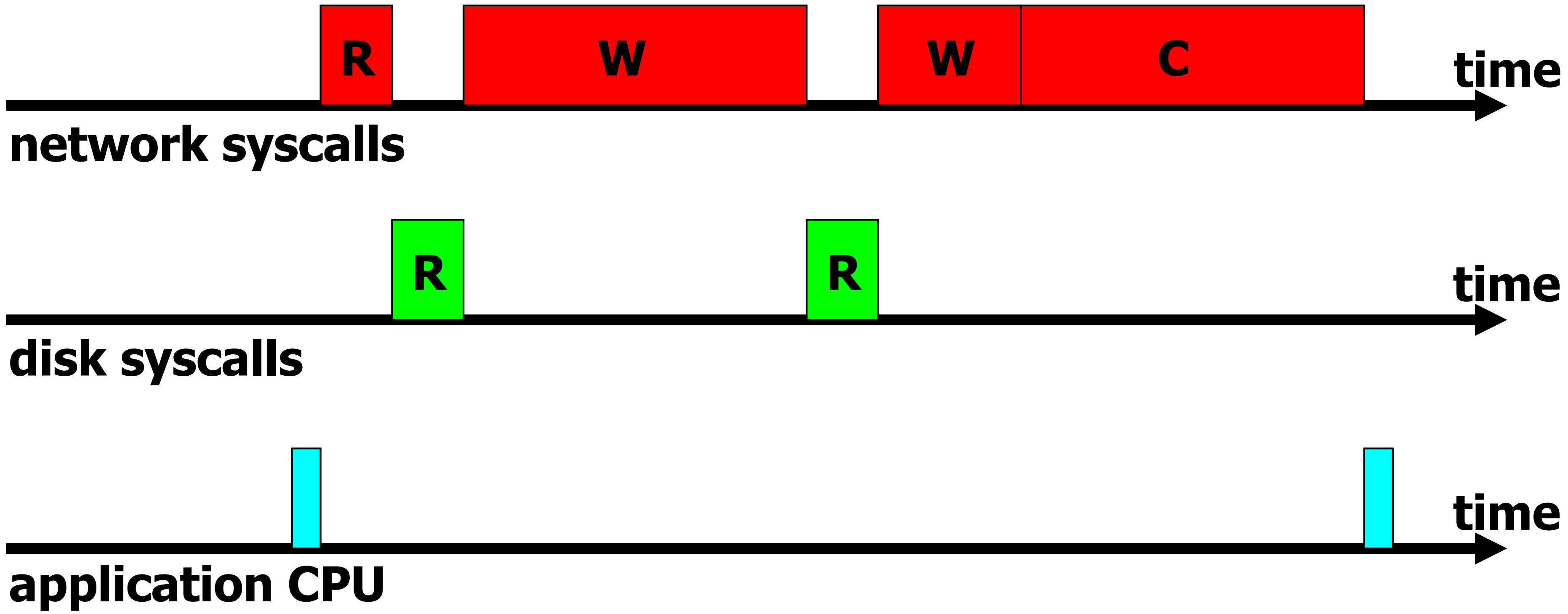
Outline

- "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)

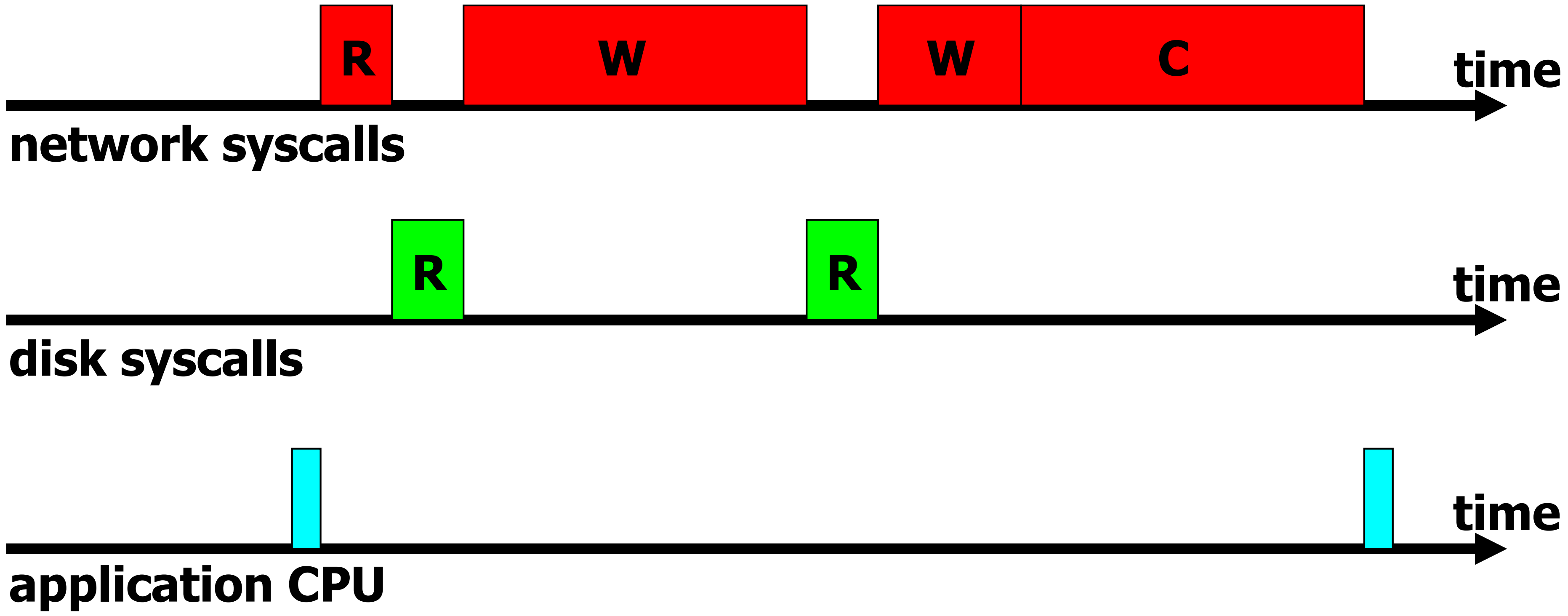


Review: How Do Servers Use Syscalls?

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!)

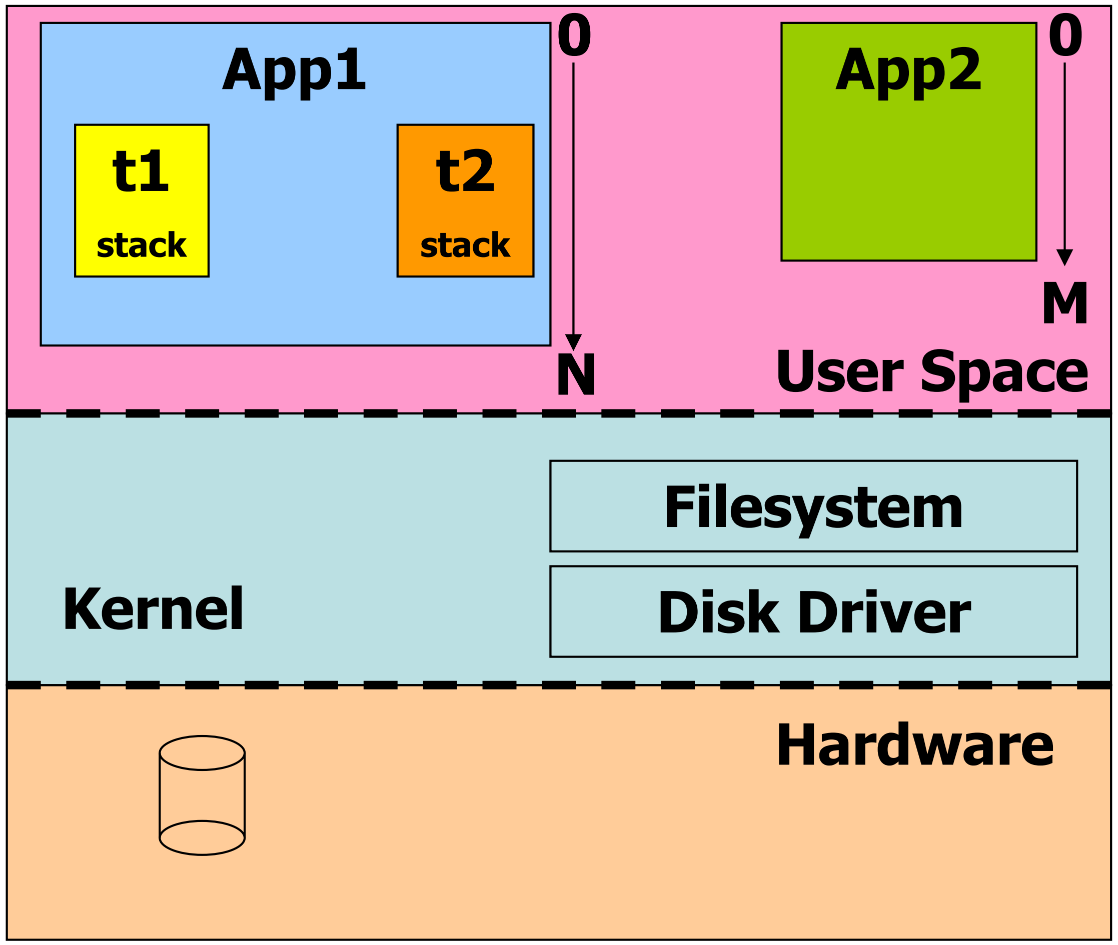
Problems with Multiple Processes

- 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



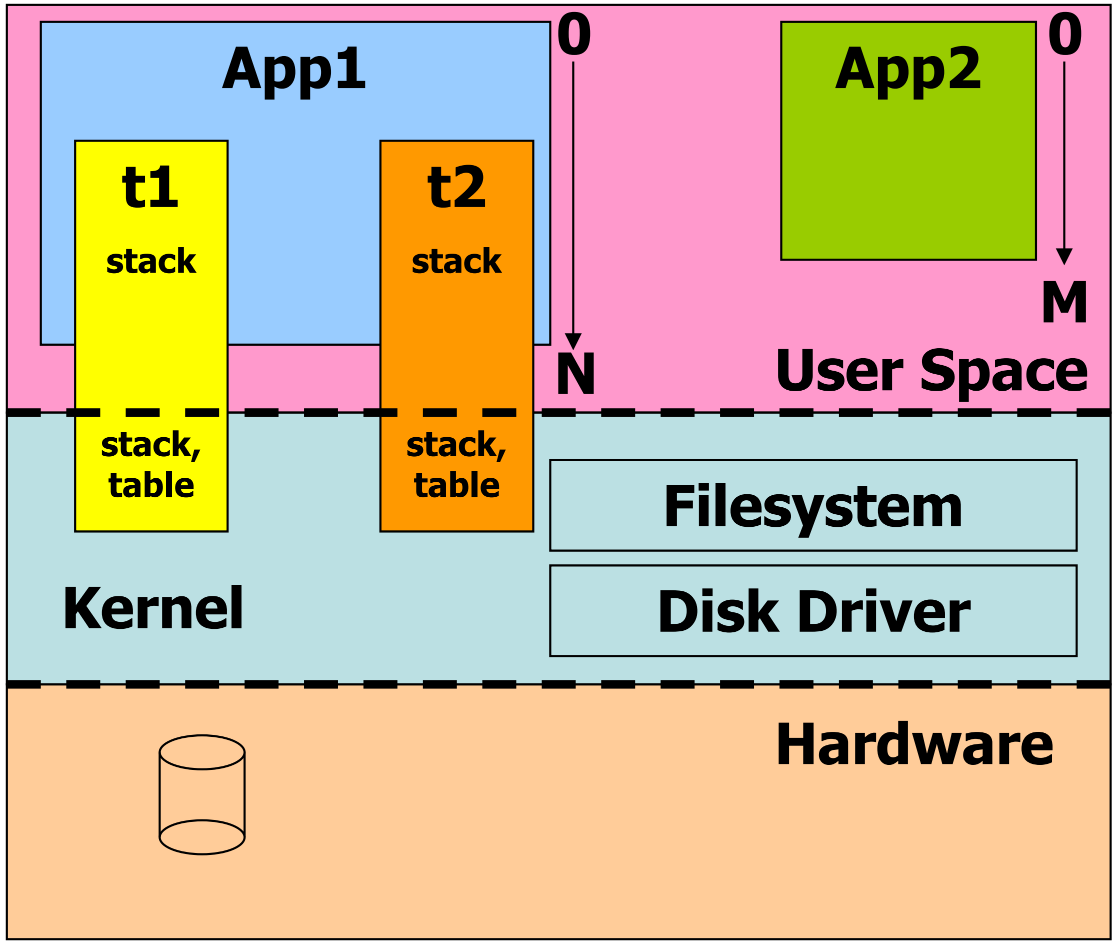
Threads: Low-Level Details Are Hard!

- 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



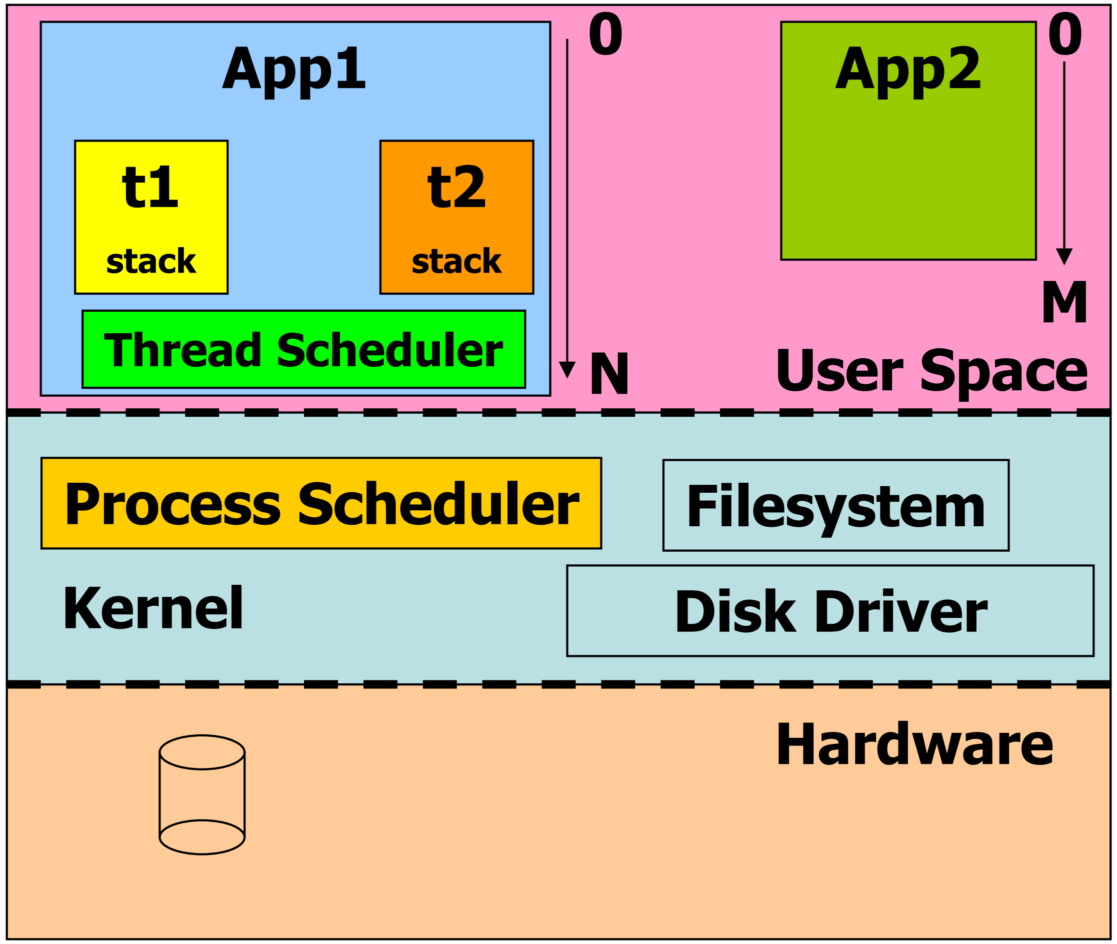
Kernel Threads: Trade-Offs

- 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…
- …though practically all modern OSes now include a kernel thread implementation!

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);
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Non-blocking System Calls: Hard to Implement

- Typical syscall implementation, inside the kernel,

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```
    wait_for_disk(i);
```

Problem: Keeping state for complex, multi-step operations

```
    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

User-Threads: Implementation Choices

- Live with only partial support for user-level

But why bother with user-level threads now that kernels all support kernel threads?

Performance. High-performance servers now process packets in user space. Don't want to have to trap to kernel to switch between handling different packets. (This is an area of ongoing systems research!)

  - 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