Concurrency: Processes and Events

CSE 333 Autumn 2019

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About how long did Exercise 17 take?

A. 0-1 Hours
B. 1-2 Hours
C. 2-3 Hours
D. 3-4 Hours
E. 4+ Hours
F. I prefer not to say

Administrivia

- No more exercises!

- HW4 due on Thursday (12/05) !!!
  - You can use at most ONE late day

- Guest lecture on Wednesday (12/04)
  - Albert J. Wong, Google: threat modeling and system design

Administrivia

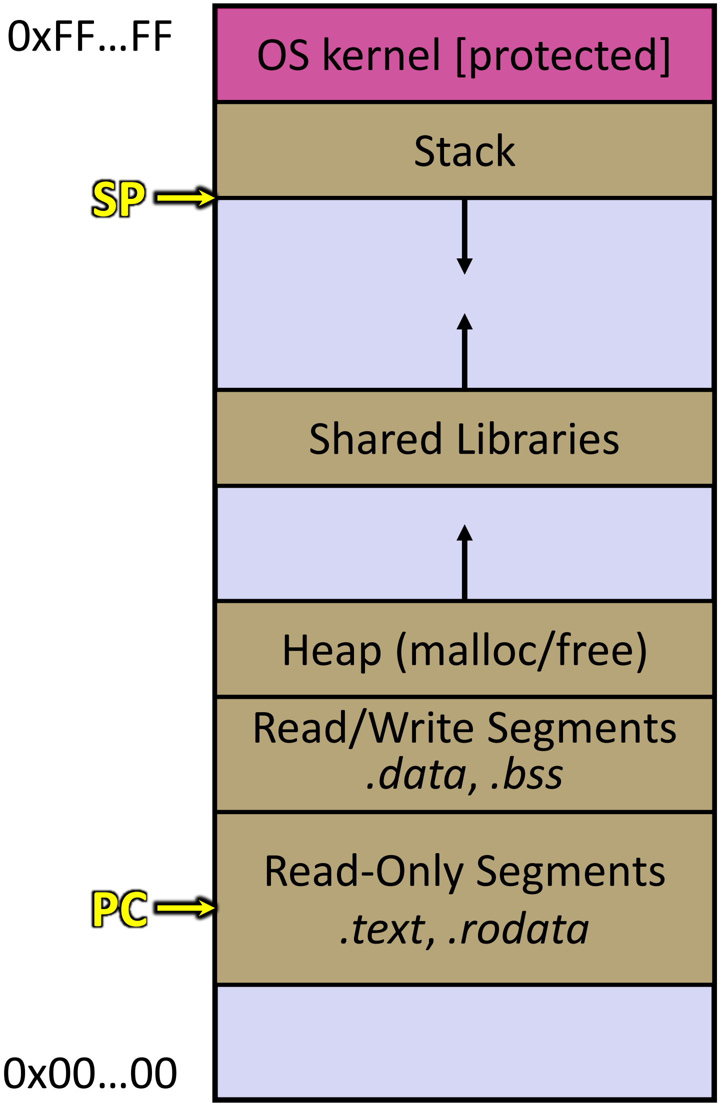
- Final exam on Wednesday (12/11)
  - Final review sessions this weekend!
- Course evals
  - Please fill them out! Your feedback is extremely valuable to us
  - Comments are helpful!
  - Your honesty is even more helpful!

Lecture Outline

- Processes
  - `fork()` and `wait()`
  - Concurrency using Processes
  - Threads vs. Processes: A Story of Efficiency
- Event-based Concurrency
- Concurrency Wrapup

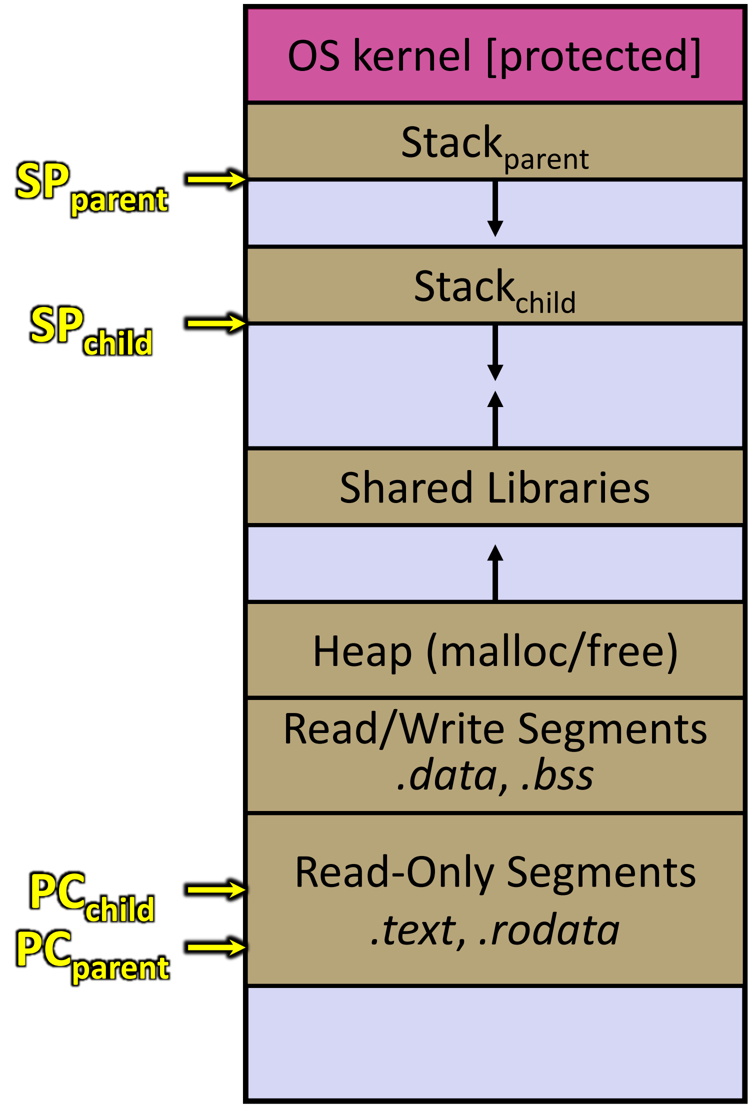
Review: Address Spaces

- A process executes within an *address space*
  - Includes segments for different parts of memory
  - Process tracks its current state using the stack pointer (SP) and program counter (PC)



Review: Multi-threaded Address Spaces

- After creating a thread
  - *Two* threads of execution running in the address space
    - Original thread (parent) and new thread (child)
    - New stack created for child thread
    - Child thread has its own *values* of the PC and SP
  - Both threads share the other segments (code, heap, globals)
    - They can cooperatively modify shared data



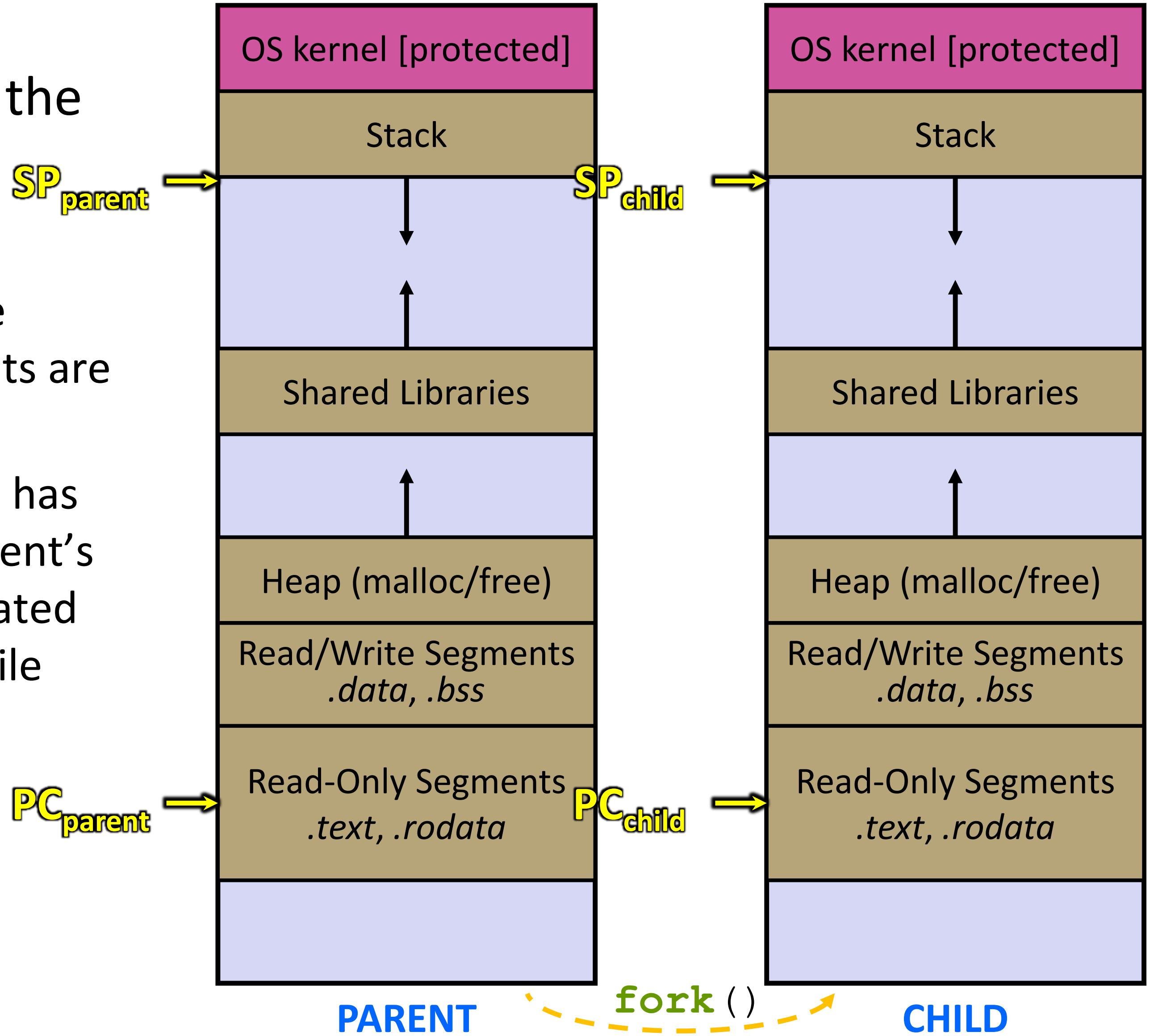
Creating New Processes

- `pid_t fork(void);`
  - Creates a new process (the “child”) that is an *exact clone** of the current process (the “parent”)
    - Variables, file descriptors, open sockets, the virtual address space (code, globals, heap, stack), etc.
    - *Everything is cloned *except* threads

- Primarily used in two patterns:
  - Servers: fork a child to handle a connection
  - Shells: fork a child that then exec’s a new program

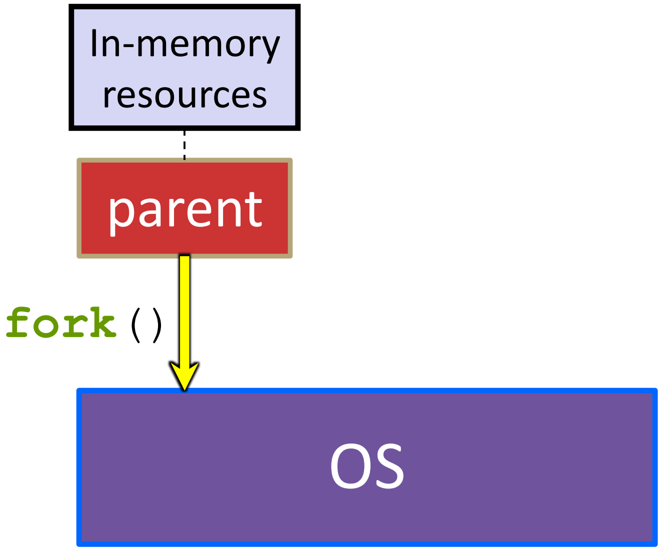
fork() and Address Spaces

- fork() causes the OS to clone the address space
  - The *copies* of the memory segments are (nearly) identical
  - The new process has *copies* of the parent's data, stack-allocated variables, open file descriptors, etc.



fork()

- **fork**() has peculiar semantics
  - The parent invokes **fork**()
  - The OS clones the parent
  - *Both* the parent and the child return from fork
    - Parent receives child's pid
    - Child receives a 0



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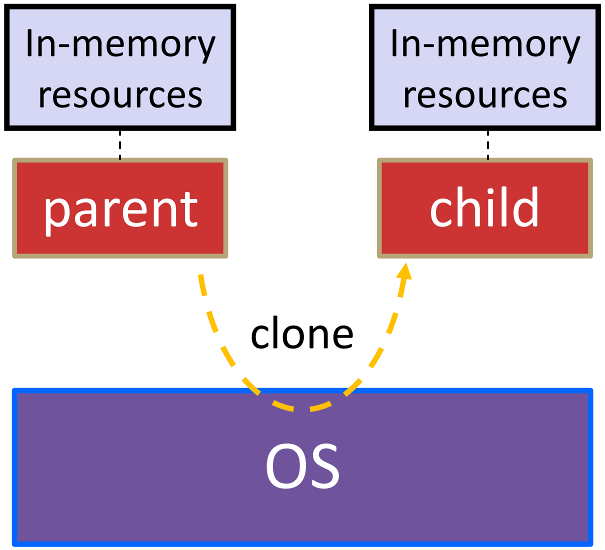

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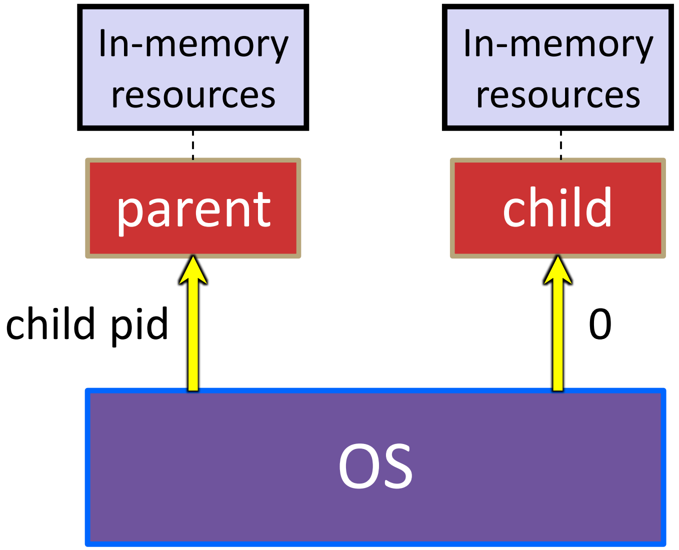

- Remember that processes become "zombies" after death

waitpid()

```
pid_t waitpid(pid_t pid, int *status,
                        int options);
```

- *Block* until the passed-in process has changed state (usually terminated)
  - Detailed process status available in `status` output parameter.

I need a `fork()`ing demo!

- See `fork_example.cc`

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Multi-processes Search Engine: Architecture

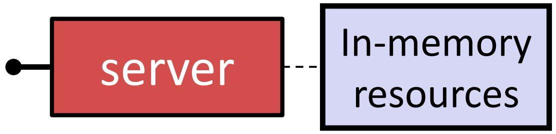
- The **parent** process blocks on `accept()`, waiting for a new client to connect
  - When a new connection arrives, the parent calls `fork()` to create a **child** process
  - The child process handles that new connection and subsequent I/O, calls `exit()`'s when the connection terminates

Double-fork Trick

- There is no "process version" of `pthread_detach()`
  - How do we tell the OS to clean up the process when it's dead?

- Remember that processes become "zombies" after death
  - Option A: Parent calls `waitpid()` to "reap" children
  - Option B: Parent terminates, causing children to be "adopted" by the root process ("`init`" or "`systemd`")

Multi-process Search Engine: Request Flow



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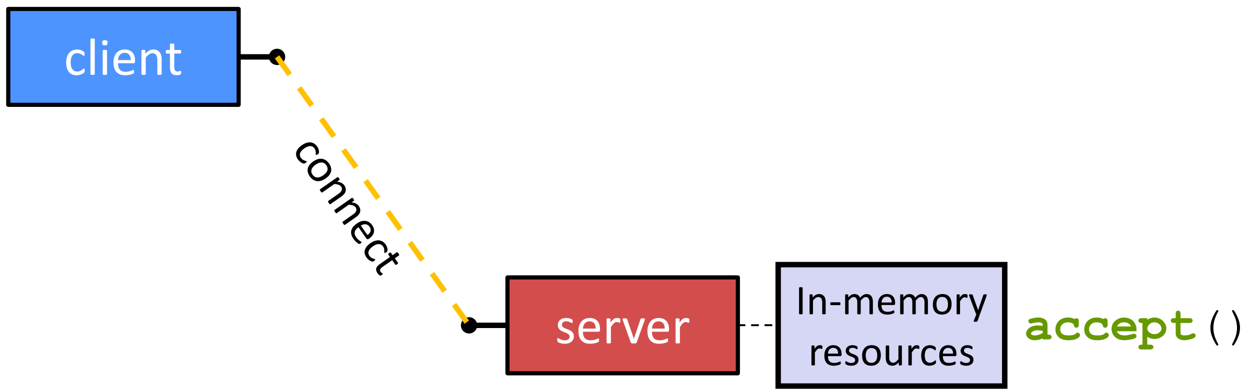

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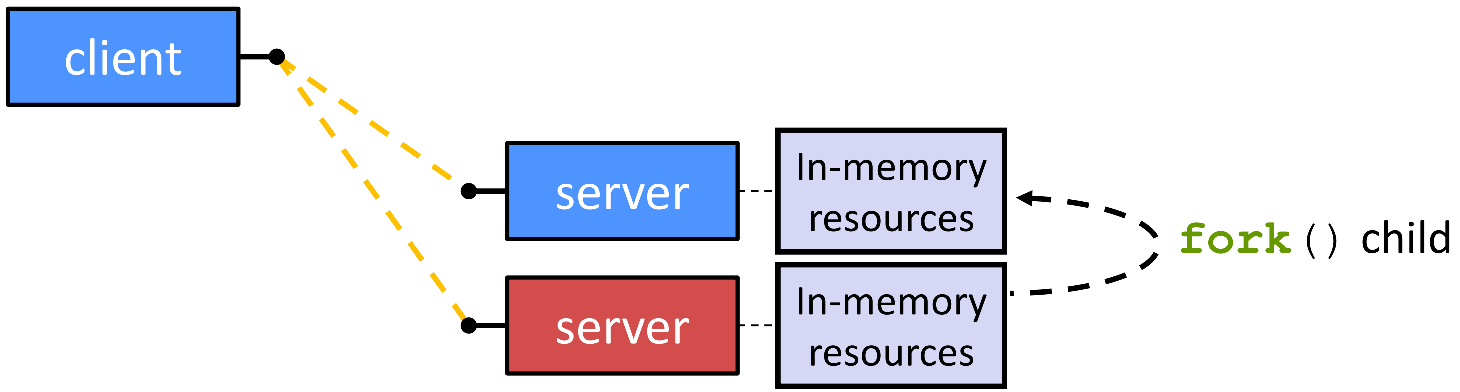

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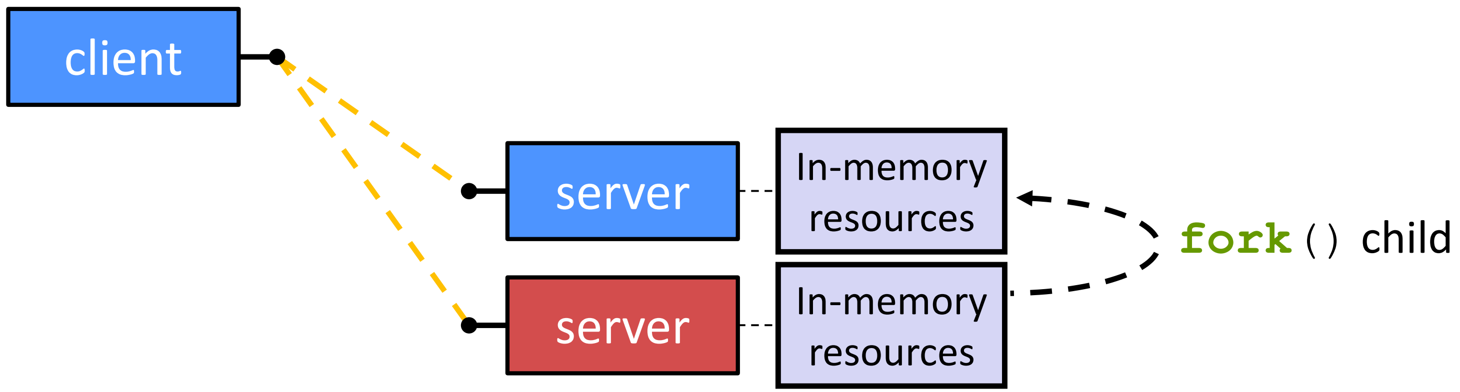

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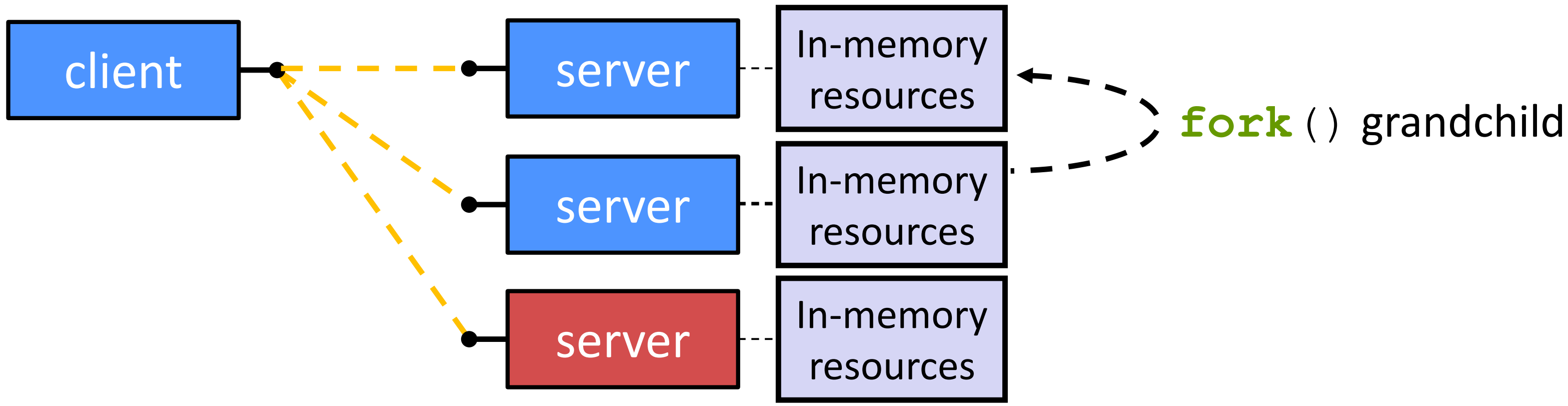

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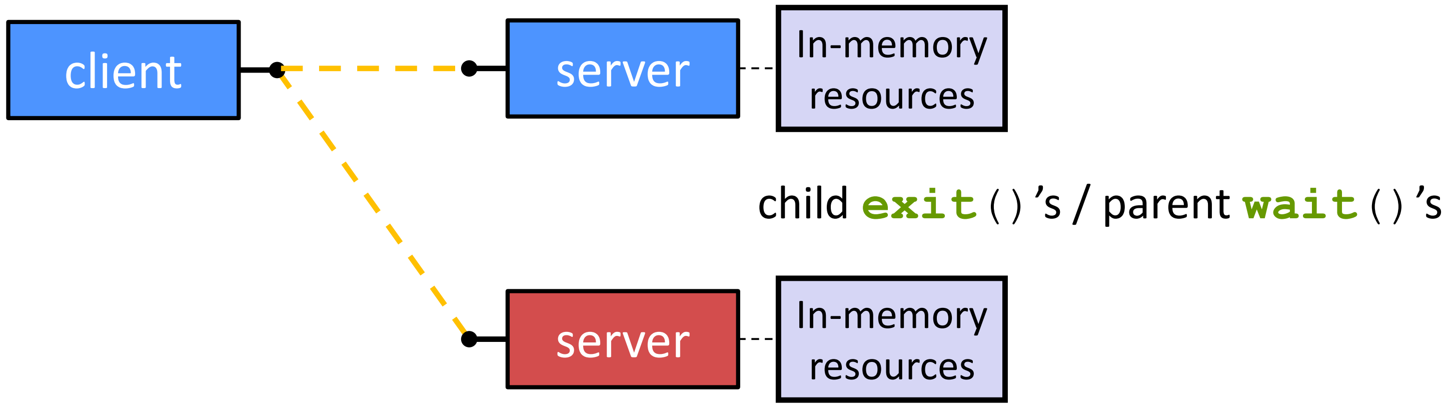

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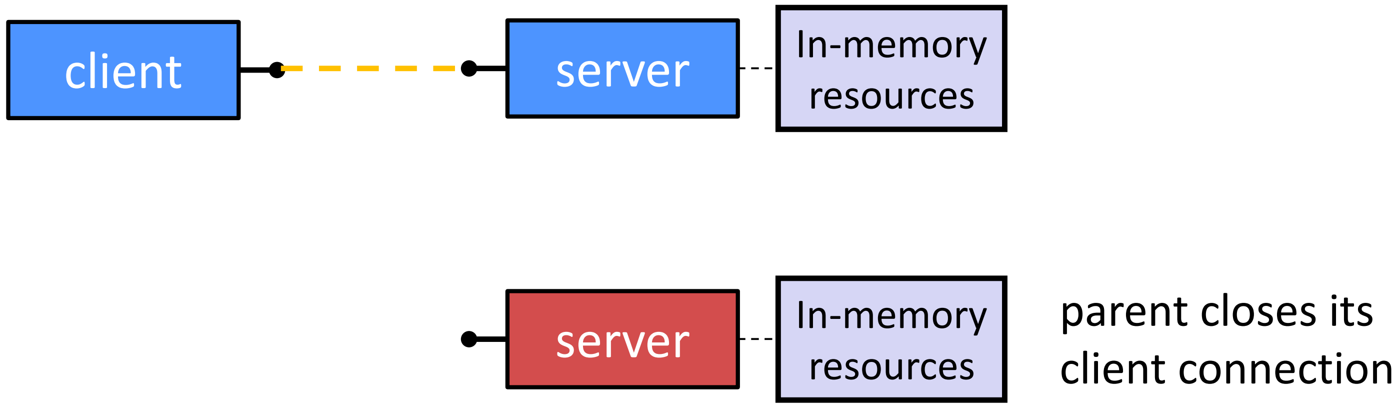

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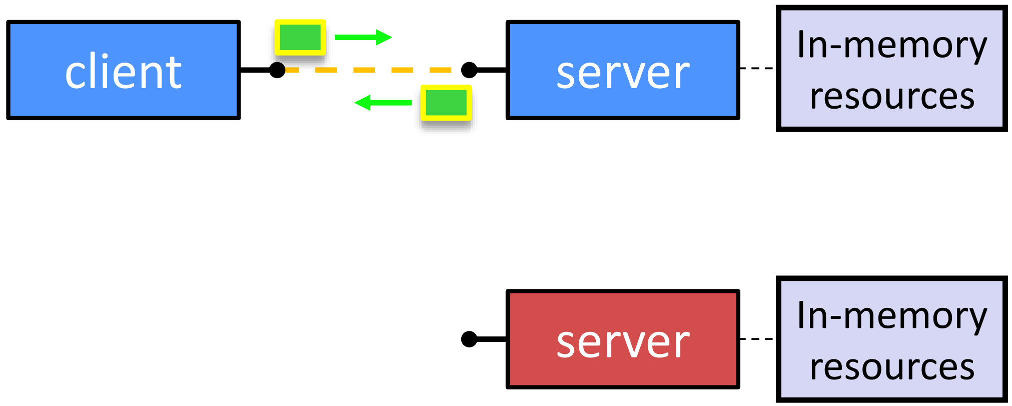

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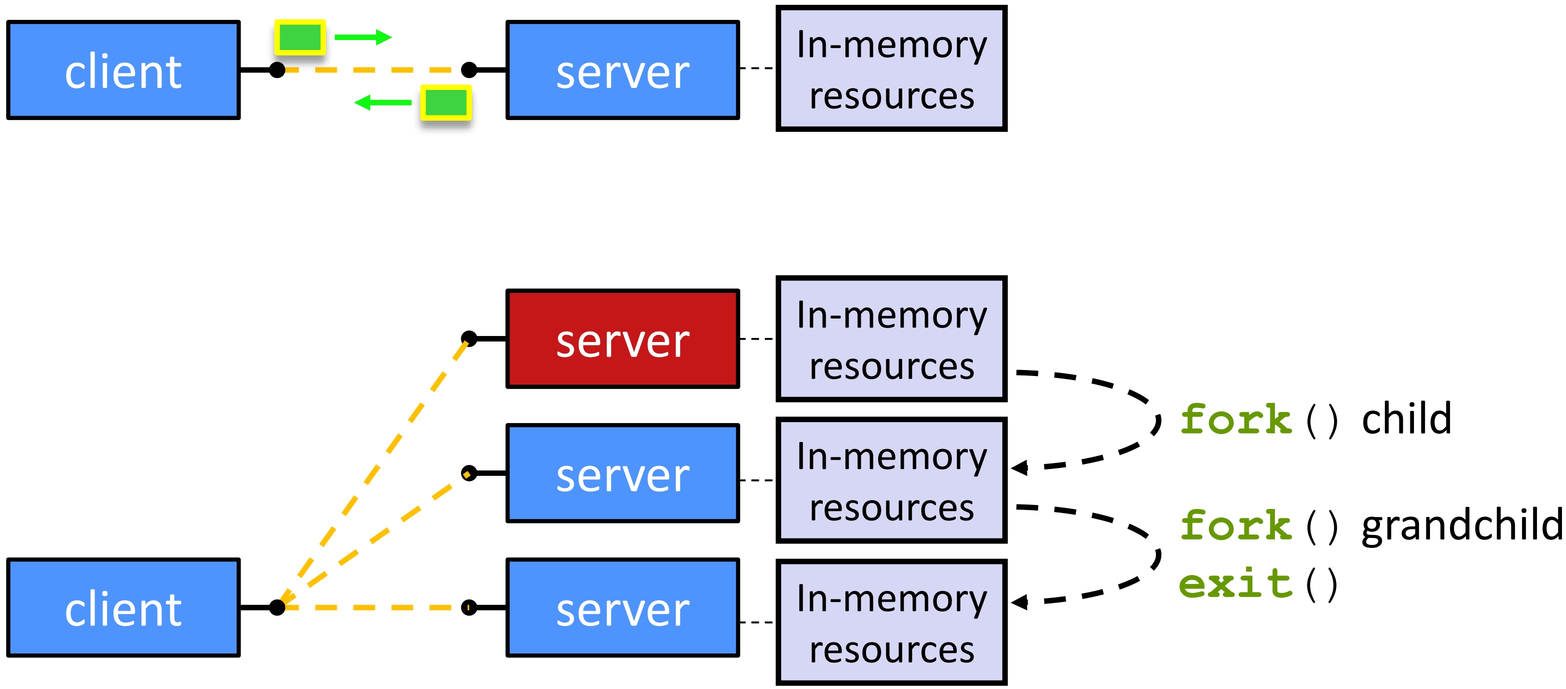

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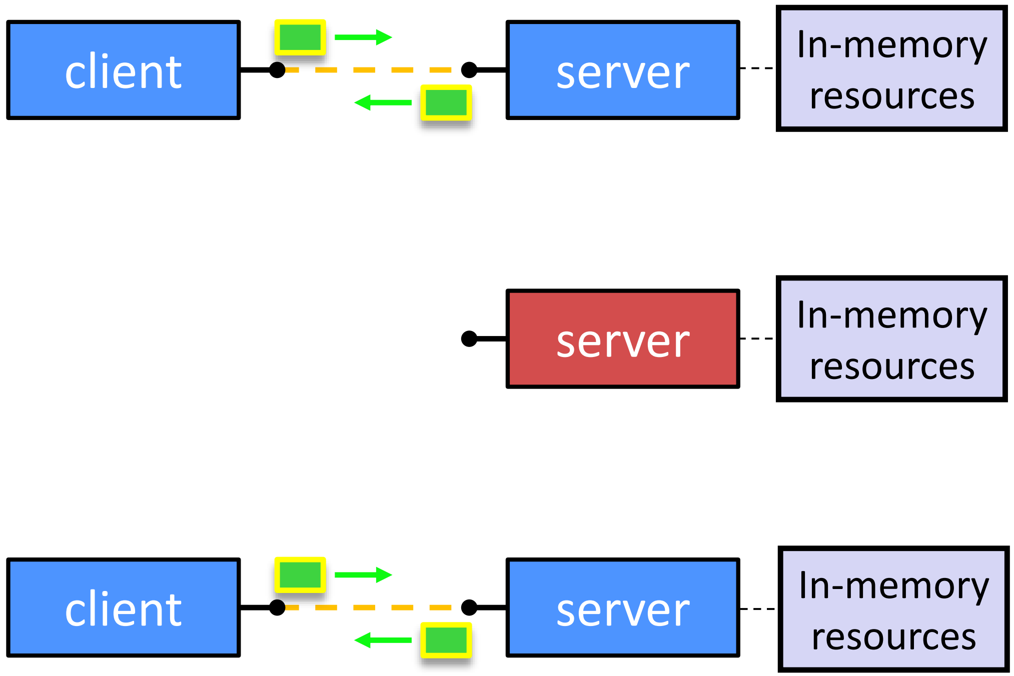

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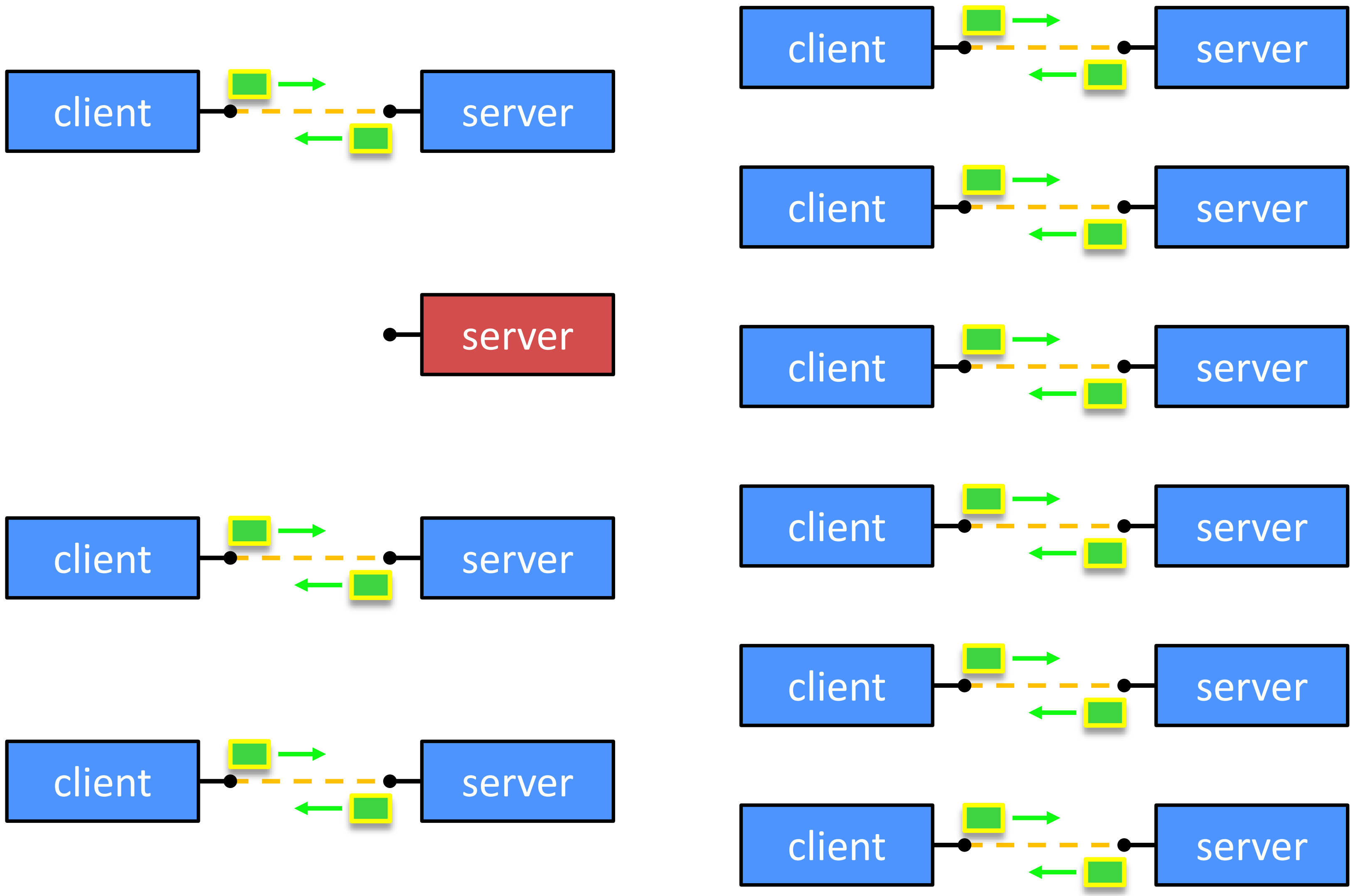

Poll Everywhere

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What happens when a grandchild process finishes?

A. Zombie until ~~gran~~dparent exits
B. Zombie until grandparent reaps
C. Zombie until `systemd` reaps
D. ZOMBIE FOREVER!!!
E. I'm not sure…

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How Fast is `fork()`?

- See `forklatency.cc`

- ~ **0.500 ms** per fork*
  - ∴ maximum of (1000/0.50) = 2,000 connections/sec/core
  - ~175 million connections/day/core
    - This is fine for most servers
    - Too slow for super-high-traffic front-line web services
      - Facebook served ~ 750 billion page views per day in 2013! Would need 3-6k cores just to handle **`fork`**`()`, *i.e.* without doing any work for each connection

- *Past measurements are not indicative of future performance – depends on hardware, OS, software versions, …

How Fast is `pthread_create()`?

- See `threadlatency.cc`

- ~**0.070 ms** per thread creation*
  - ~10x faster than `fork()`
  - ∴ maximum of (1000/0.036) = 28,000 connections/sec
  - ~2.4 billion connections/day/core

- Mush faster, but writing safe multithreaded code can be serious voodoo

- *Past measurements are not indicative of future performance – depends on hardware, OS, software versions, …, but will typically be an order of magnitude faster than fork()

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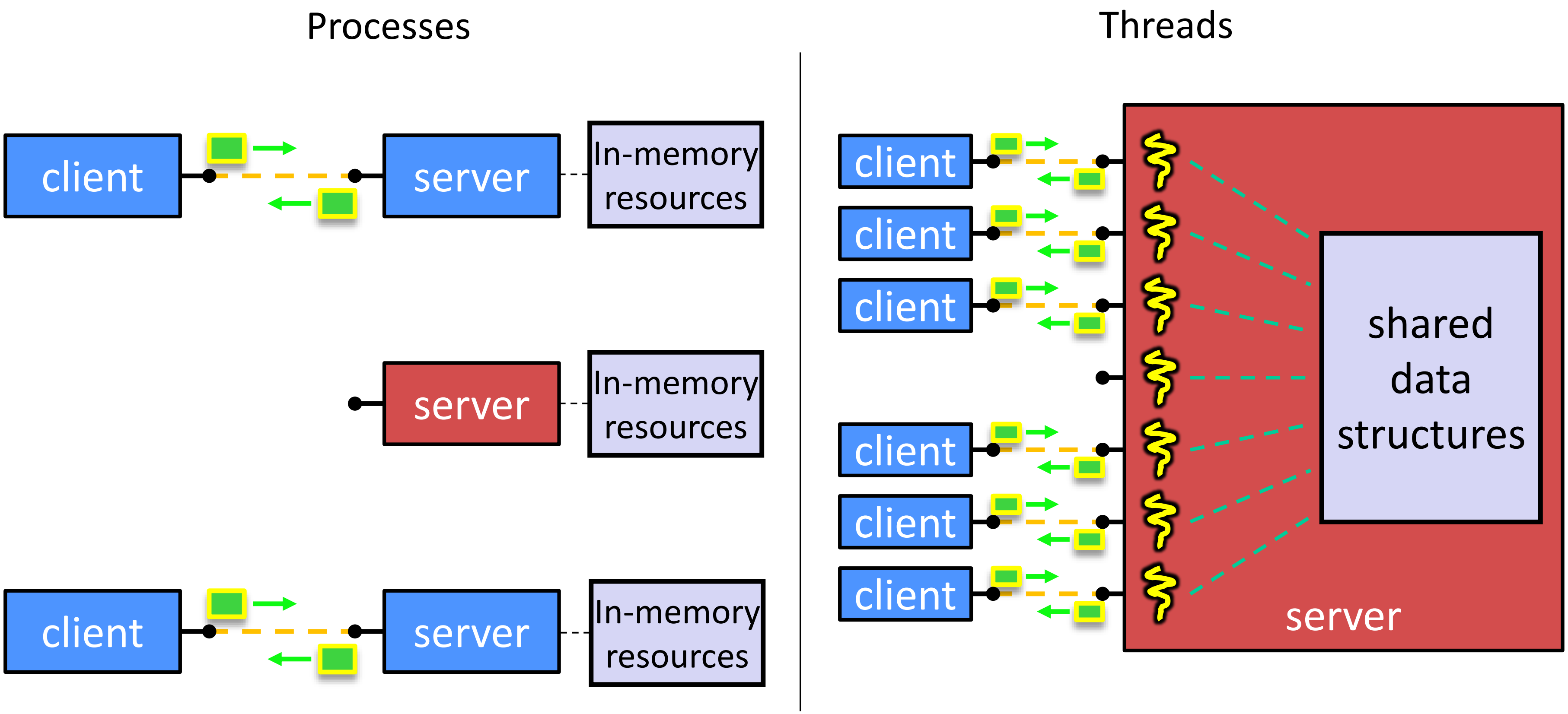
Review: Multi-“worker” Search Engine



“The child process/thread handles that new connection ***and subsequent I/O****, then calls* `exit()`*/*`pthread_exit()` *when the connection terminates”*

Event-Driven Programming

- Your program is structured as an *event-loop* consisting of (mostly) independent, stateless tasks executing in any order

any necessary state is held outside of your event handler

```
void ProcessOneTask(state) {
  query_words = state.buffer;
  for (idx : state.indices) {
    ...
  }
  ...
}

while (1) {
  event = OS.GetNextEvent();
  state = GetState(event);
  ProcessOneTask(state);
}
```

your application code ("event handler"). Typically a dispatcher into more specialized sub-handlers

typically framework code ("event loop")

One Way to Think About It

- Threaded code:
  - OS and thread scheduler switch between threads for you
  - Each thread executes its task sequentially, and per-task state is naturally stored in the thread's stack

- Event-driven code:
  - ***You*** (or your framework) are the scheduler
    - You (or your framework) also manages scheduling-related resources, such as the connection
  - You have to bundle up task state into *continuations* (data structures describing what-to-do-next); tasks do not have their own stacks

the "state" in our pseudocode

Multi-Step Event-Driven Programming

- Each step is a brand-new event
  - Task state must include information about which step we're on

dispatches into specialized sub-handlers

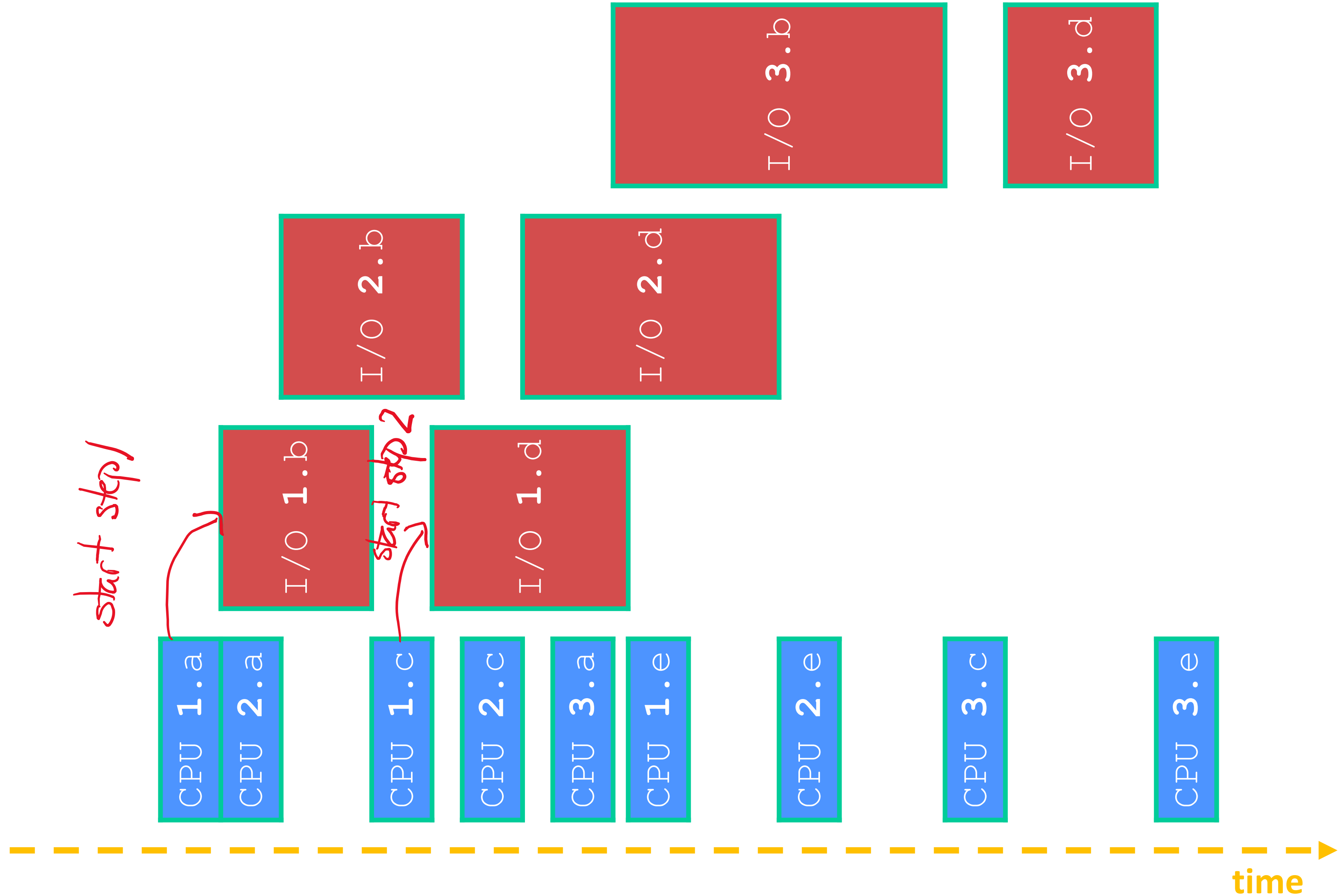
```
void dispatch(task, event) {
  switch (task.state) {
    case READING_FROM_CONSOLE:
      query_words = event.query;
      async_read(index, query_words[0]);
      task.state = READING_FROM_INDEX;
      return;
    case READING_FROM_INDEX:
      results = event.results;
      ...
  }
}

while (1) {
  event = OS.GetNextEvent();
  task = lookup(event);
  dispatch(task, event);
}
```

step 1

step 2

step N

Multi-Step, Event-Driven w/Async I/O



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Aside: Thread Pools

- In real servers, we'd like to avoid overhead needed to create a new thread or process for every request
- Idea: Thread Pools
  - Create a fixed set of worker threads or processes on server startup and put them in a queue
  - When a request arrives, remove the first worker thread from the queue and assign it to handle the request
  - When a worker is done, it places itself back on the queue and then sleeps until dequeued and handed a new request
- Pairs naturally with event-based programming (but also works with "traditional" threaded programming)

Why Sequential?

- Advantages:
  - Simple to write, maintain, debug
  - The default. Supported everywhere!

- Disadvantages:
  - Depending on application, poor performance
    - One slow client will cause *all* others to block
    - Poor utilization of resources (CPU, network, disk)

Why Concurrent Threads?

- Advantages:
  - Almost as simple to code as sequential
  - Concurrent execution with good CPU and network utilization
  - Threads can run in parallel if you have multiple CPUs/cores
  - Shared-memory communication is possible

- Disadvantages:
  - Need language and OS support for threads
  - If threads share data, you need locks or other synchronization
  - Threads can introduce overhead (technical + cognitive)
  - Threads have a "shared fate" (eg, "rogue" thread, shared limits)

Why Concurrent Processes?

- Advantages:
  - Almost as simple to code as sequential
  - Concurrent execution with good CPU and network utilization
  - Processes almost certainly run in parallel thanks to OS time-sharing
  - No need to synchronize access to in-memory structures

- Disadvantages:
  - Processes are heavyweight
    - Relatively slow to fork and context switching latency is high
  - Communication between processes is complicated – no shared memory
  - Fewer things to synchronize – but when you do need to synchronize, it's hard! – eg, disk based locks? Shared "master" to hold lock?

Why Events?

- Advantages:
  - For some kinds of programs – those with mostly-stateless, simple responses – leads to very simple and intuitive program
    - Eg, GUIs: one event handler for each UI event

- Disadvantages:
  - Can lead to very complex structure for some programs
    - Sequential logic gets broken up into a jumble of small event handlers
    - You have to package up all task state between handlers