Threads vs Coroutines

Understanding the Concurrency Models of C++

CONOR SPILSBURY

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Understanding the Concurrency Models of C++

Bloomberg

Engineering

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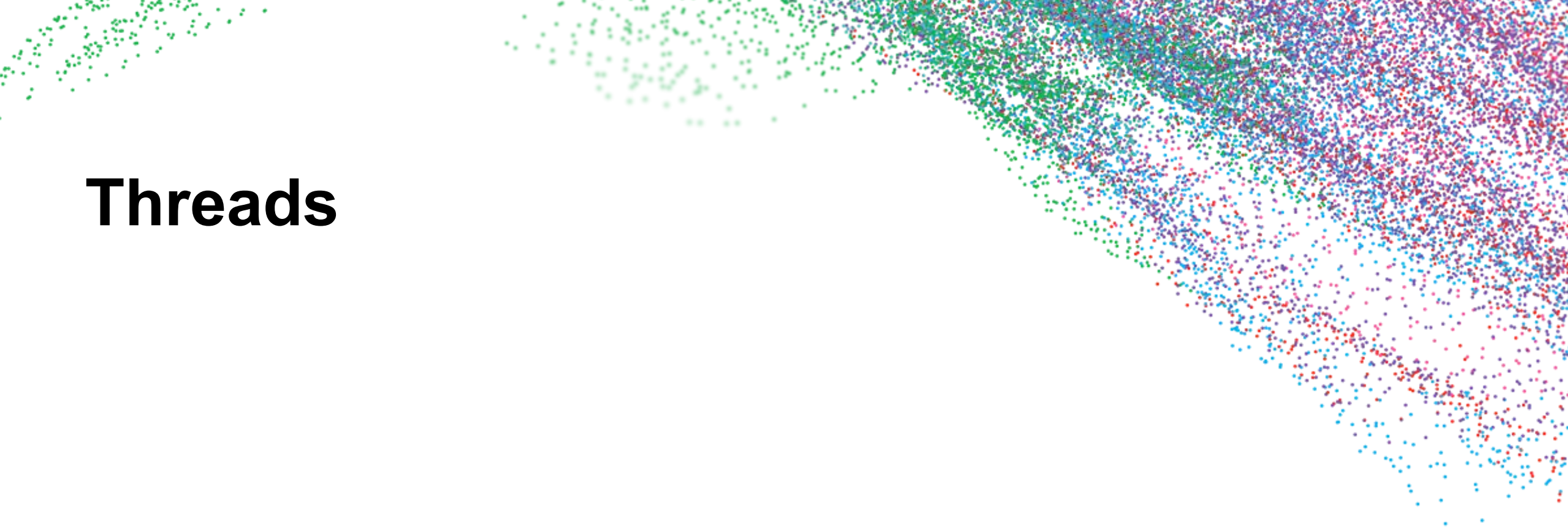
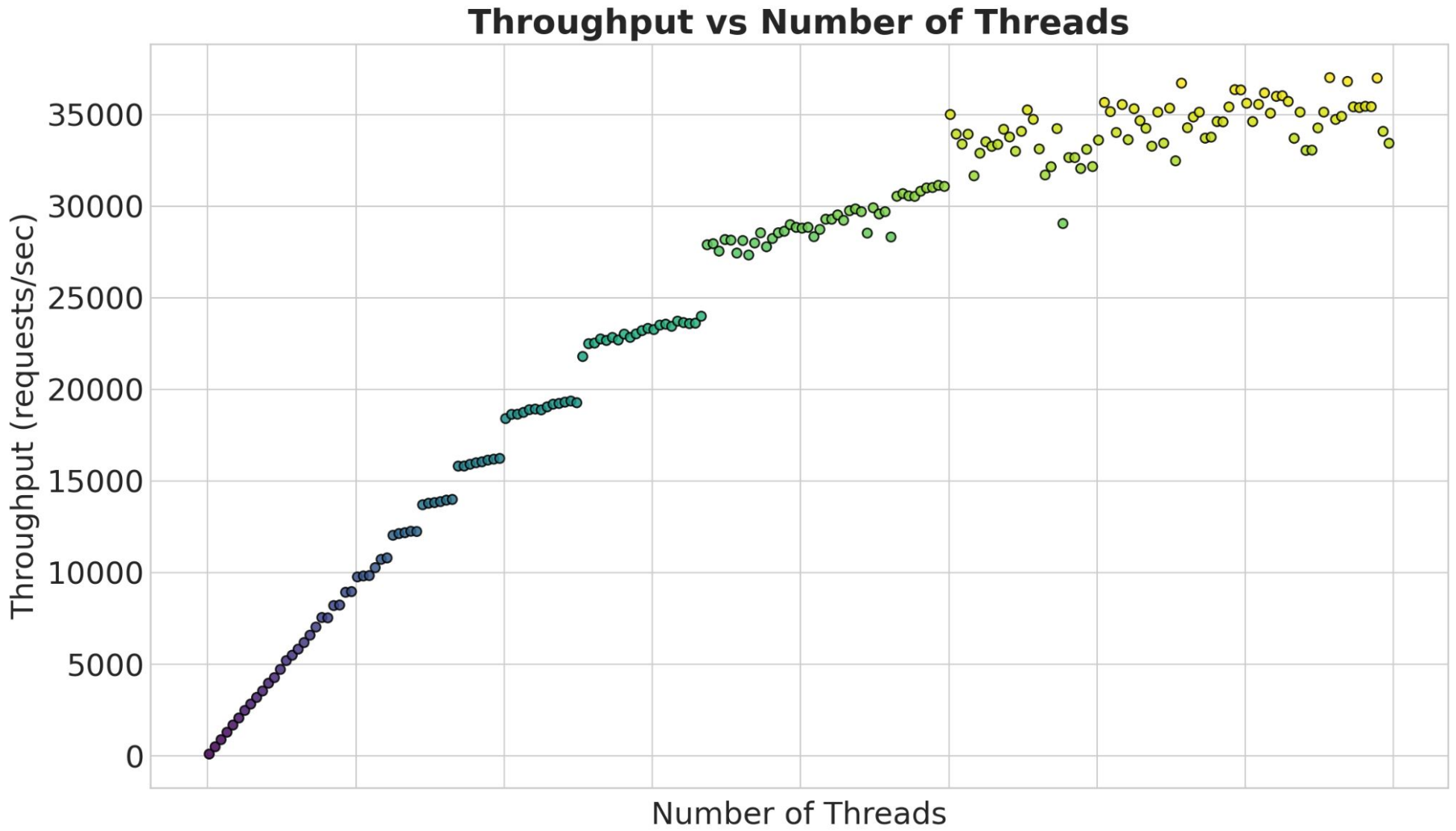
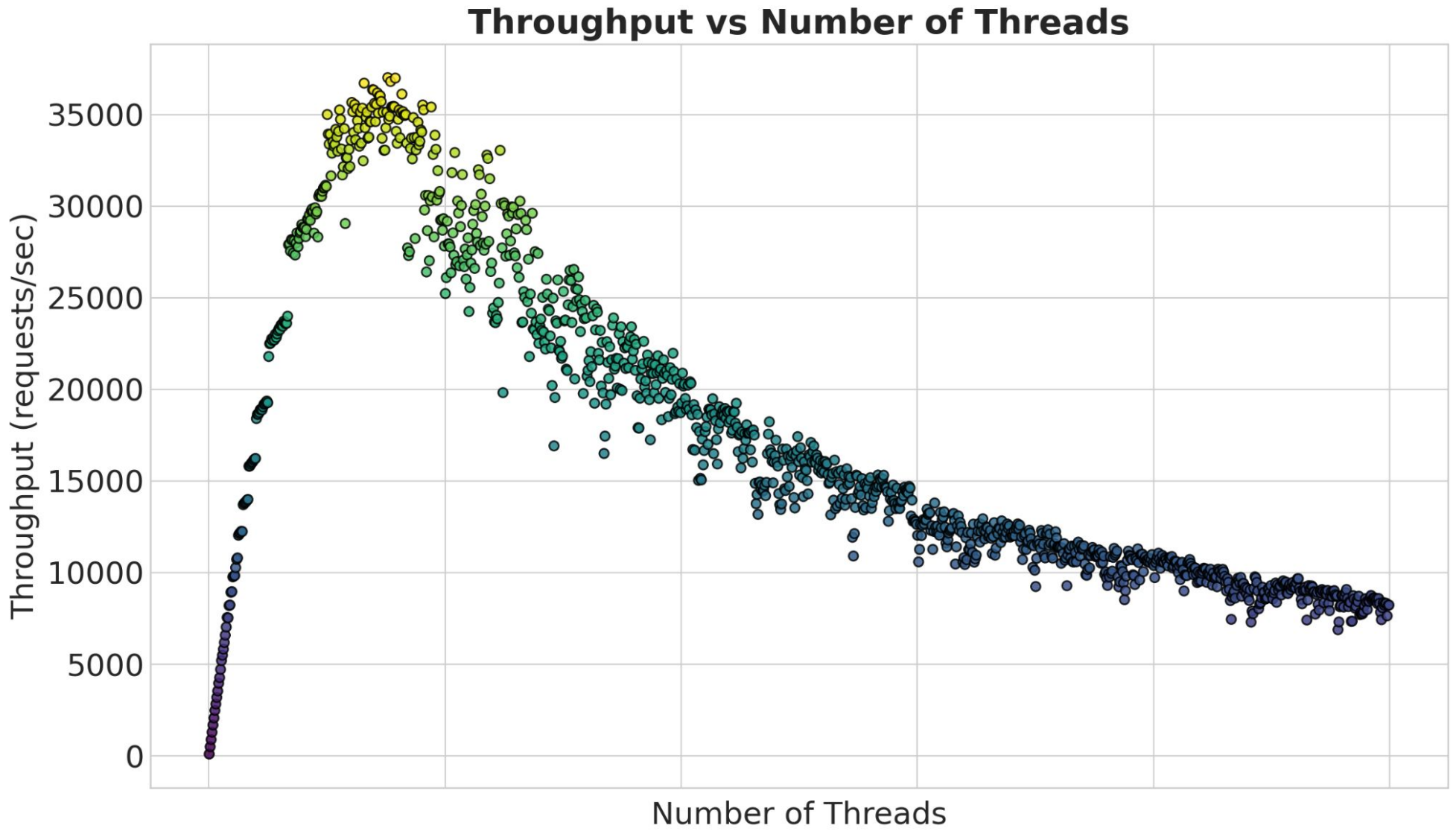
Design Decisions

- Application requirements shape concurrency decisions
- Threads vs. coroutines: limits of OS scheduling vs. cooperative scheduling
- Understand how to choose the right tool

Threads




Throughput vs Number of Threads
Throughput (requests/sec)
0
5000
10000
15000
20000
25000
30000
35000
Number of Threads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35000
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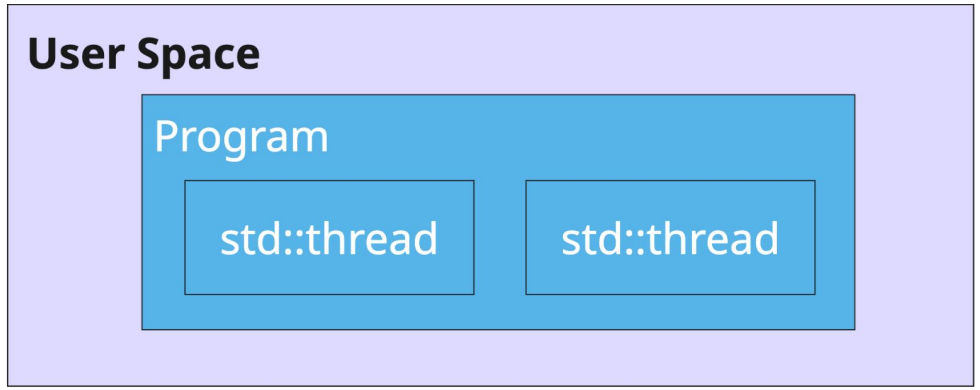
Number of Threads

What Are User and Kernel Space?



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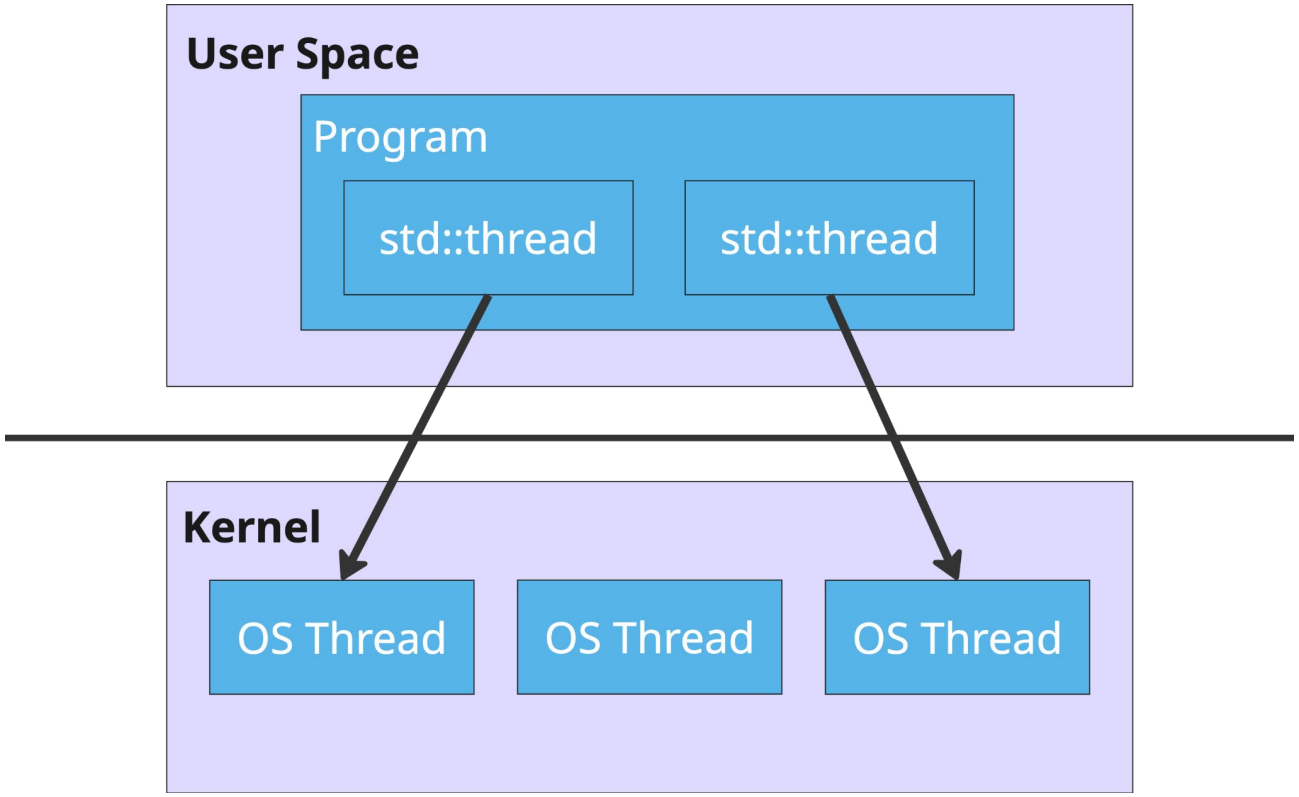

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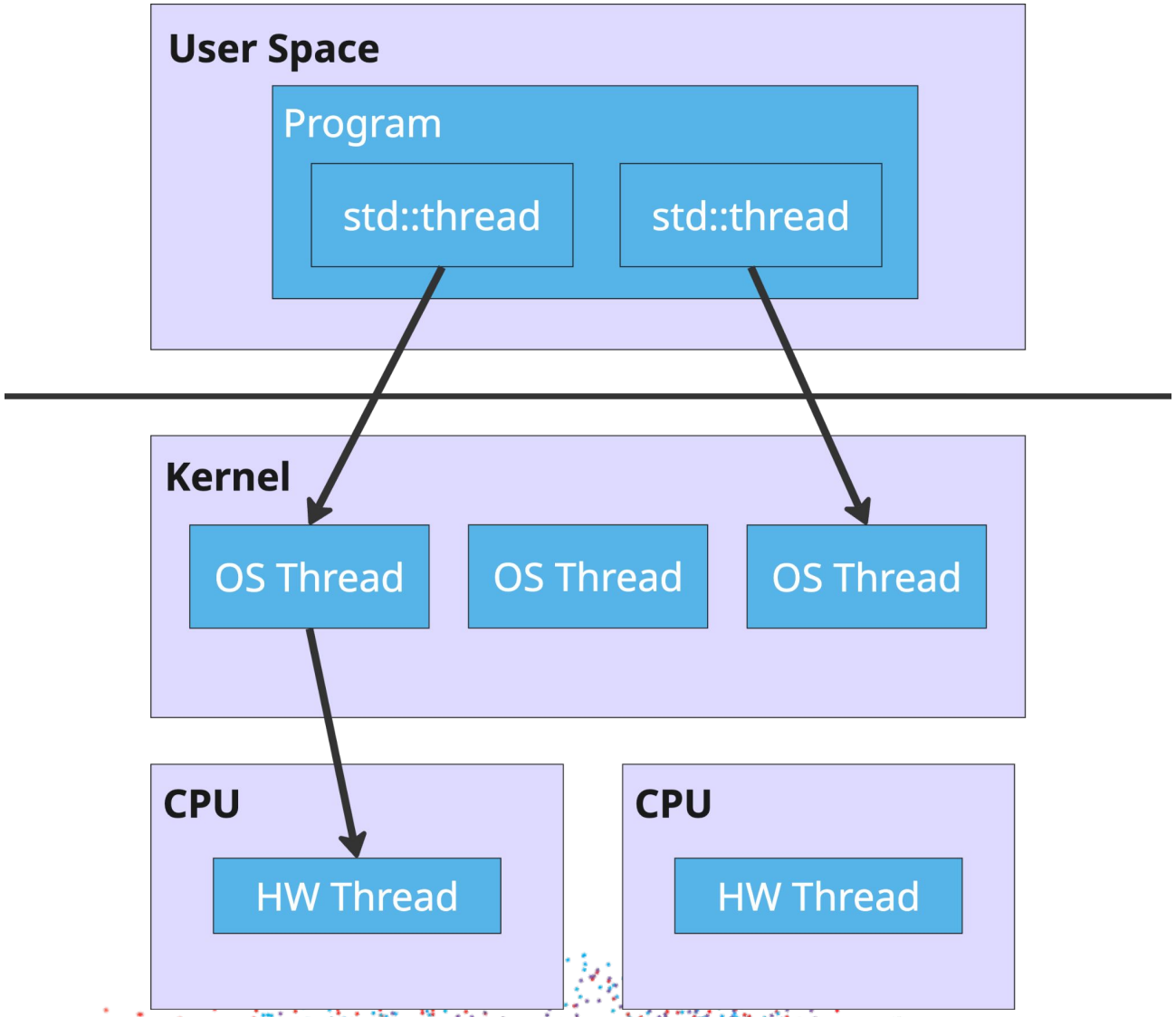

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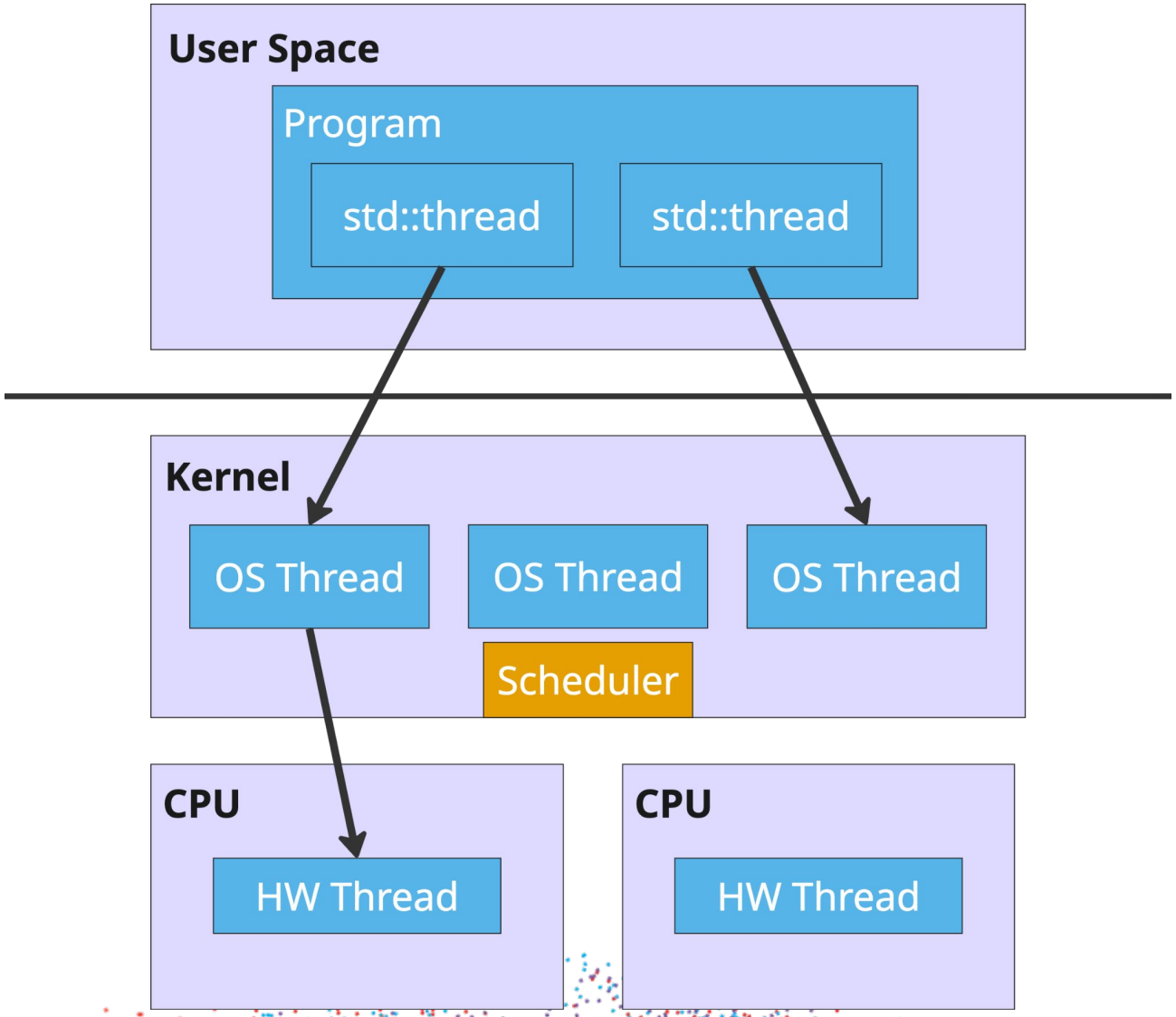
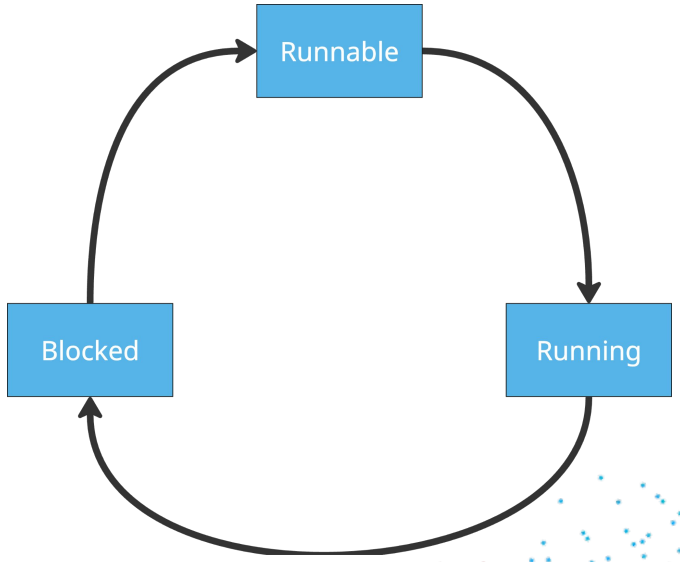
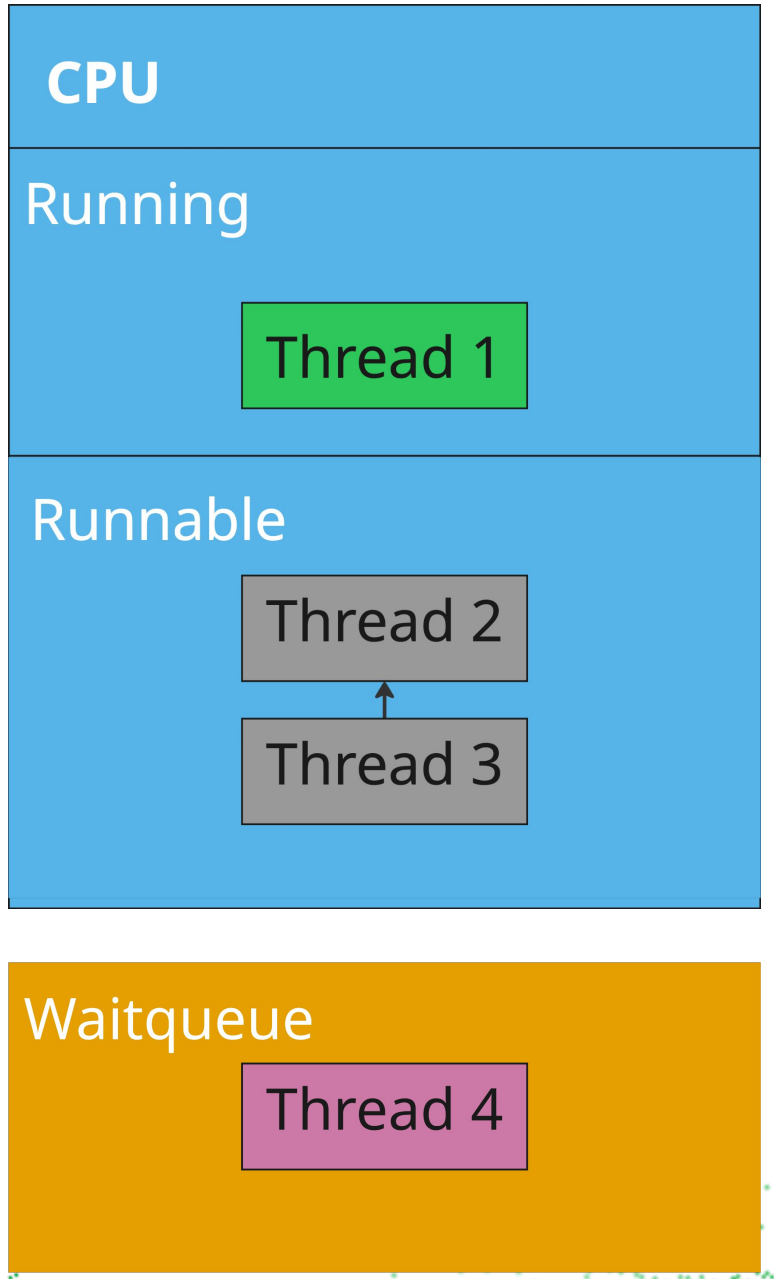


Thread State

At any moment, a thread is either:

- RUNNING on a CPU
- RUNNABLE, waiting to be scheduled
- BLOCKED, on a wait queue (I/O, futex, timers)





Thread Scheduling

- The *Scheduler* decides which thread runs on which core and for how long

```
std::thread a([](){ /* work a */ });
std::thread b([](){ /* work b */ });
```

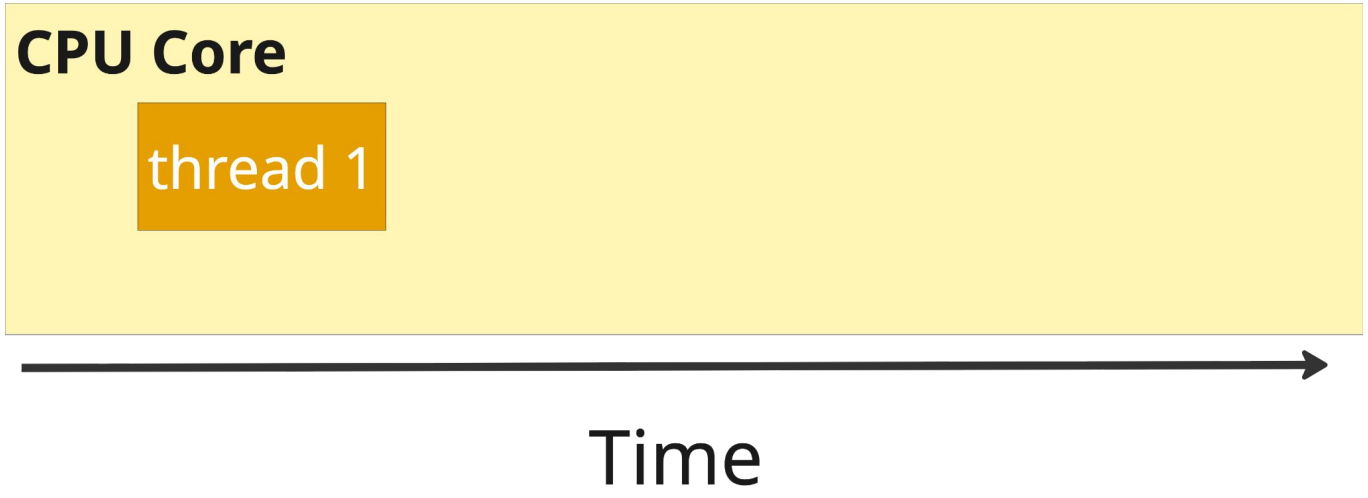
- Not deterministic as to whether a or b will run first
- Execution can be interleaved

Context Switches

- Involuntary (preemption)
- Voluntary (e.g., block on I/O)

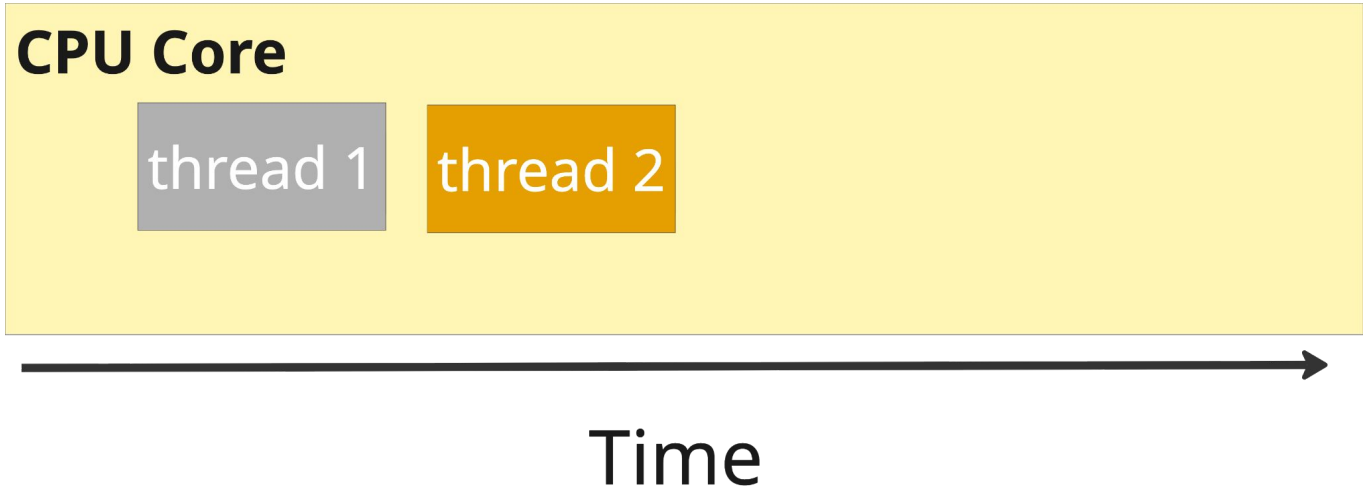
Preemption

- Time Slicing



Preemption

- Time Slicing



Preemption

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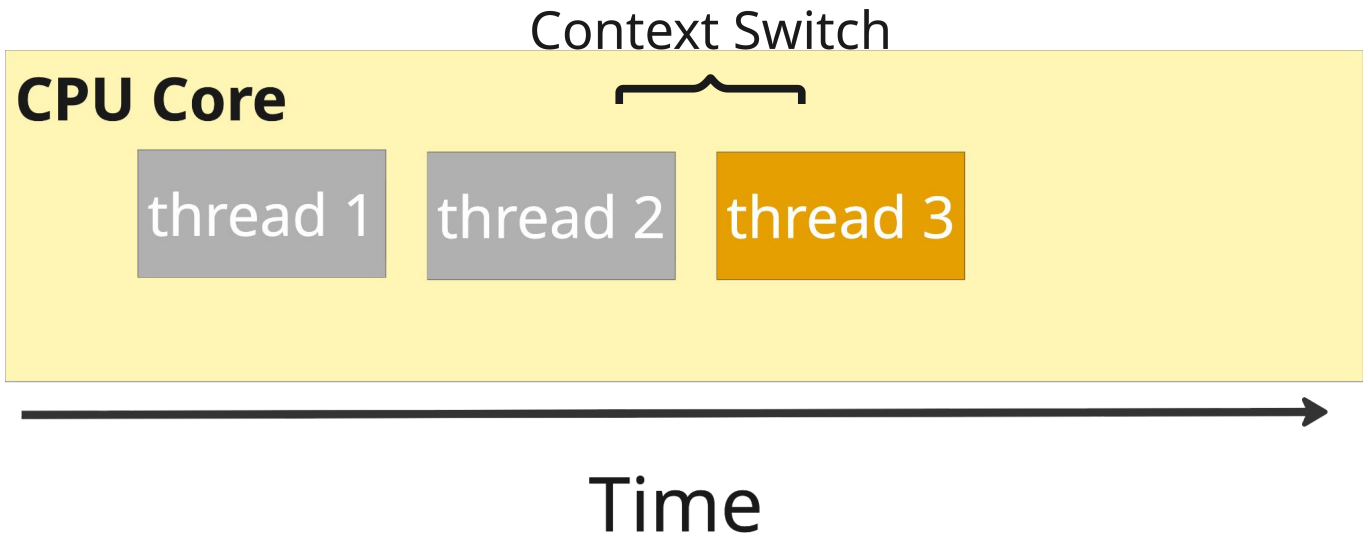
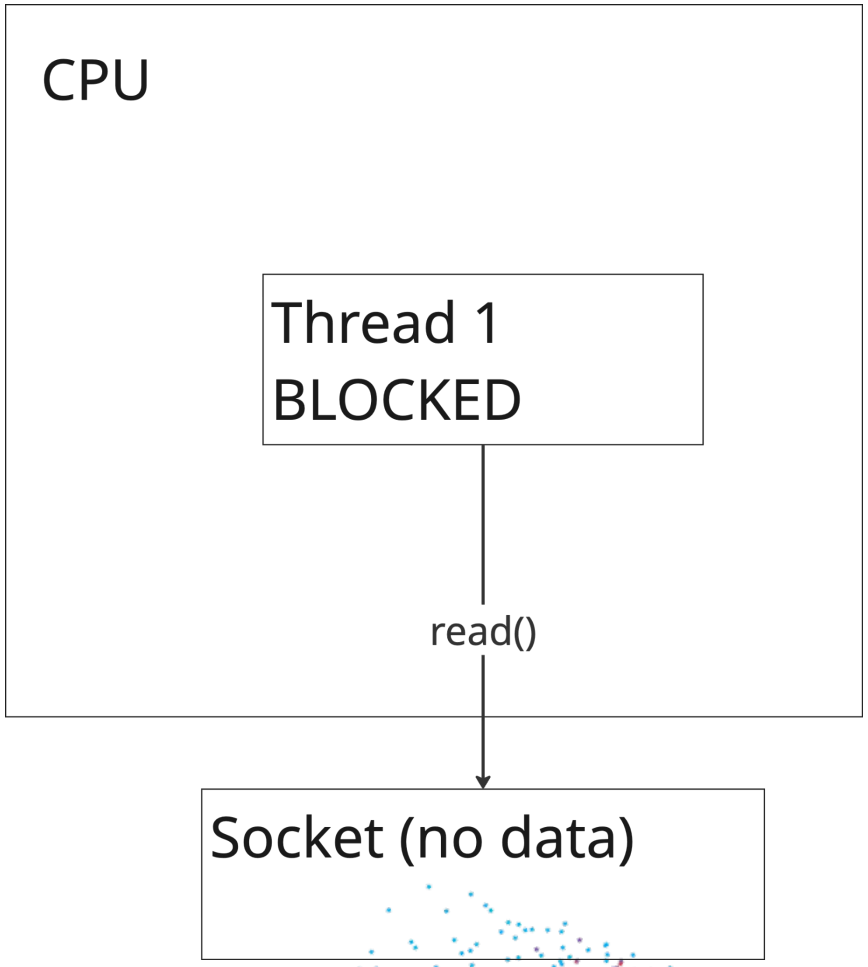


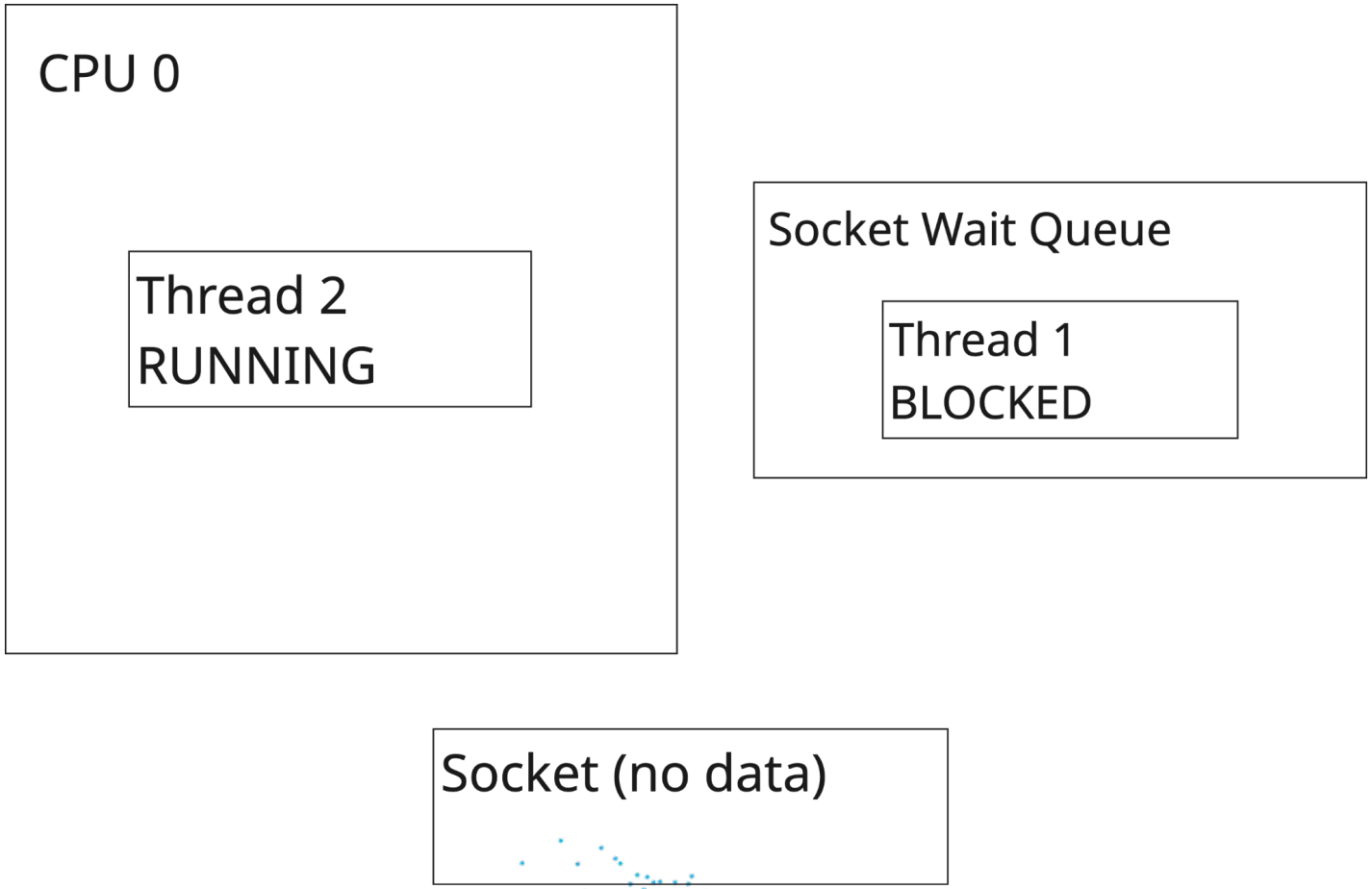
Blocking on I/O

```
int result = read(fd, buffer, sizeof(buffer));
```

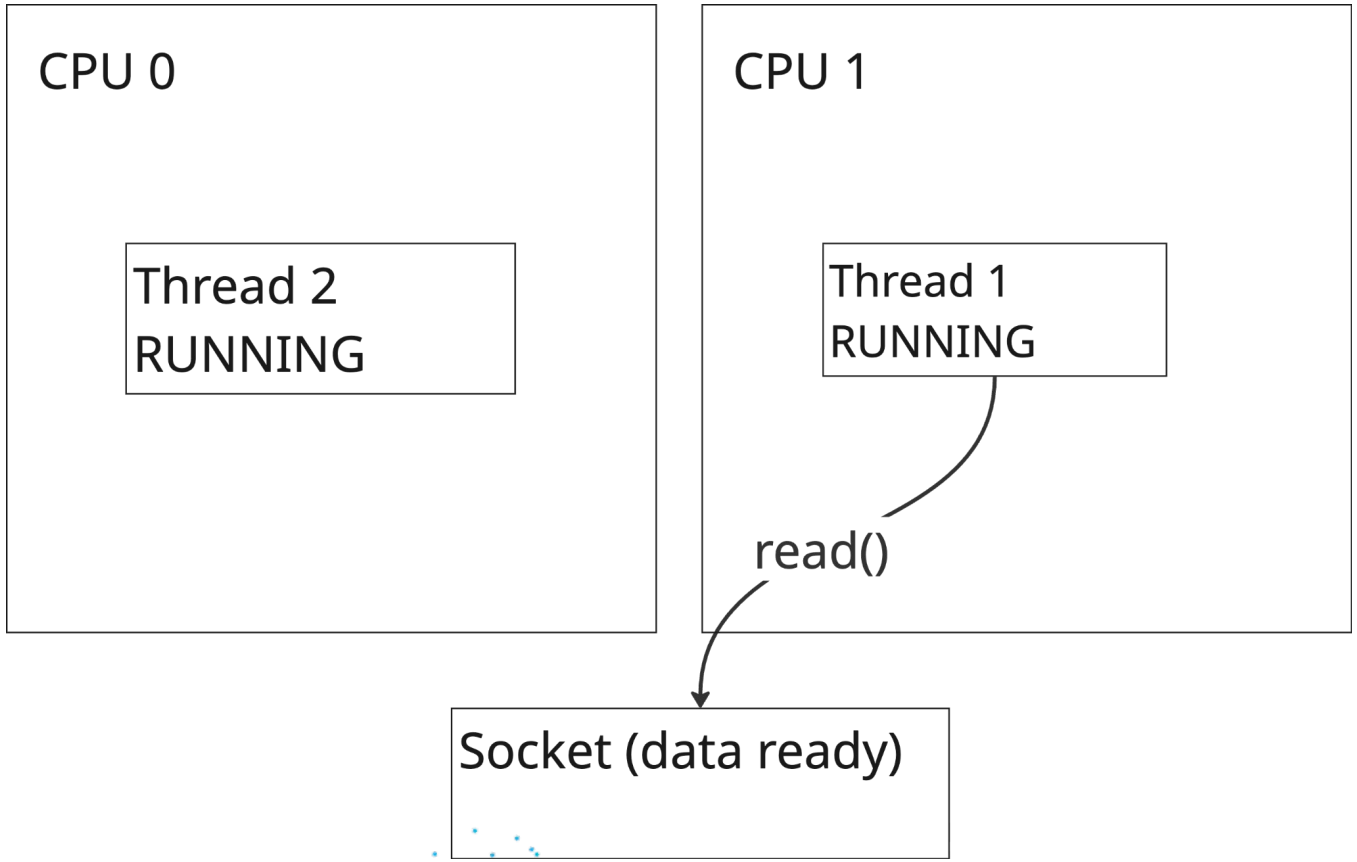
Blocking on I/O (what happens to the thread)



Blocking on I/O (what happens to the thread)

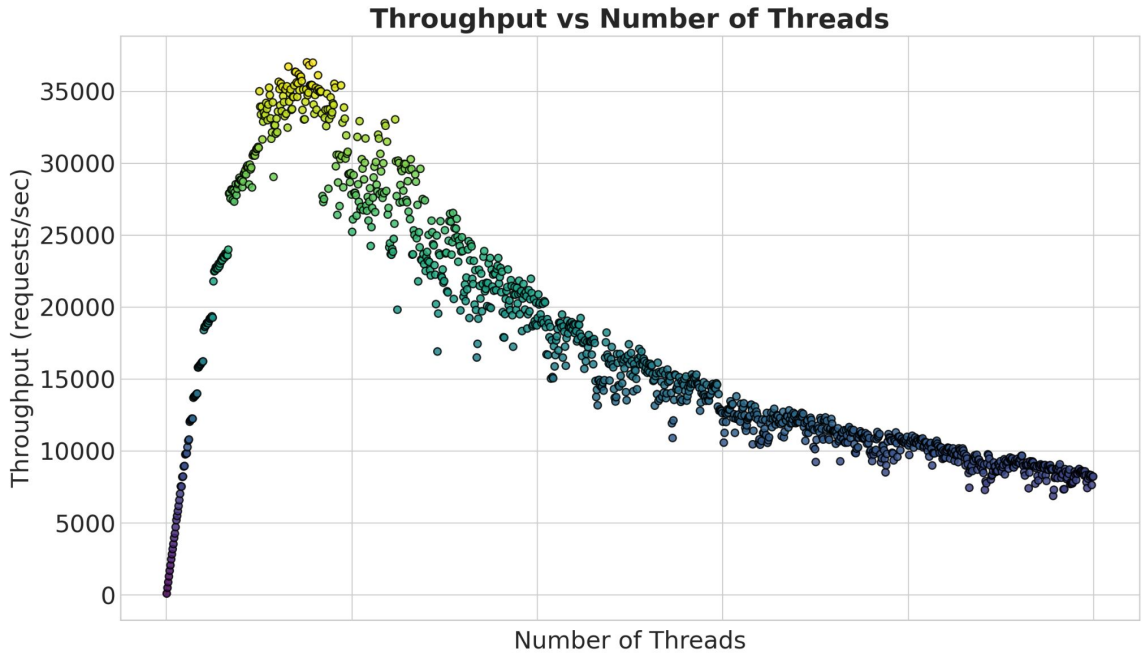


Blocking on I/O (what happens to the thread)



Where the cost really comes from

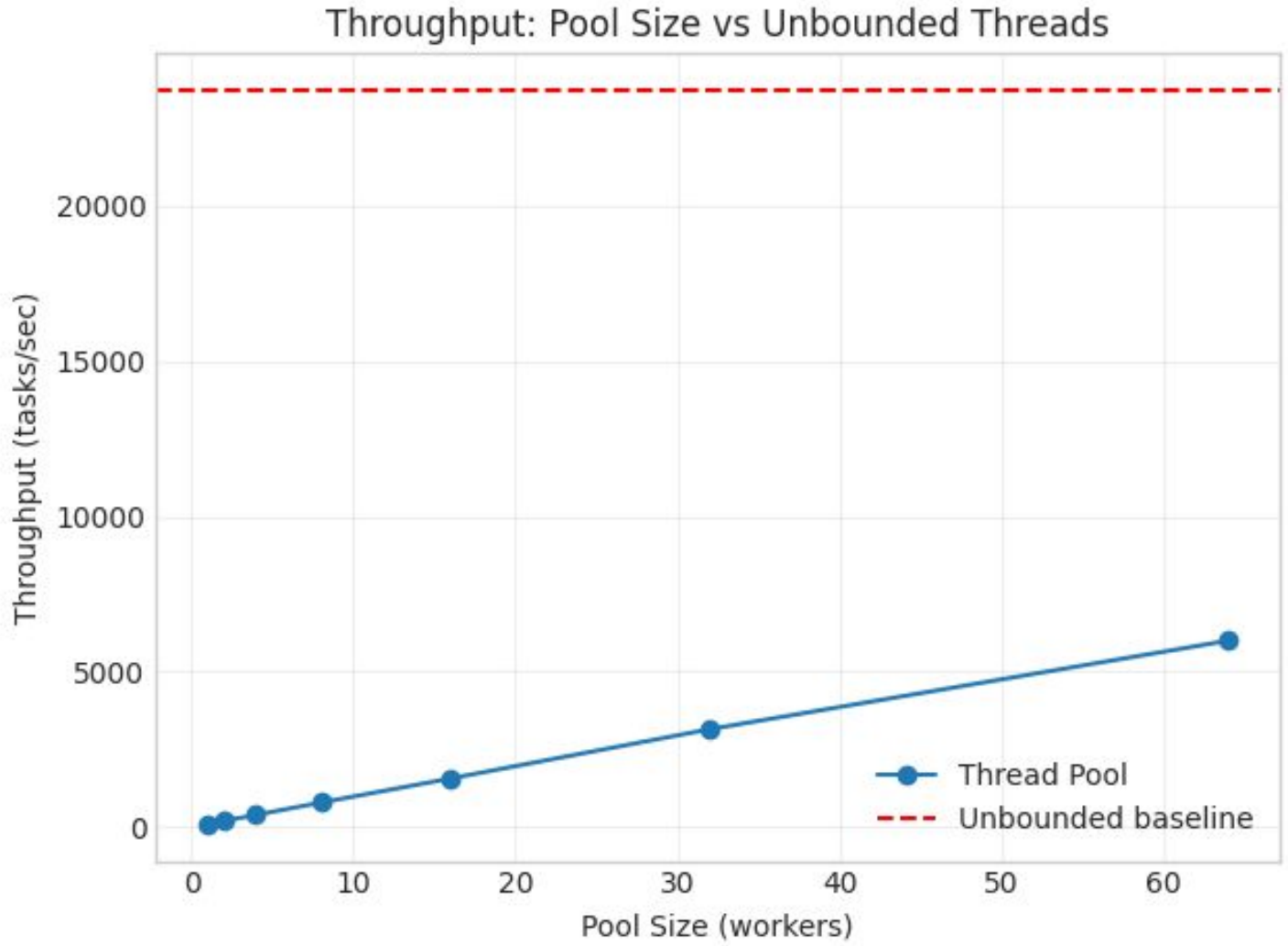
- Context switches prevent thread from completing its work until it is next scheduled
- The more threads, the more the scheduler tries to enforce fairness
- Oversubscription



Thread Pools

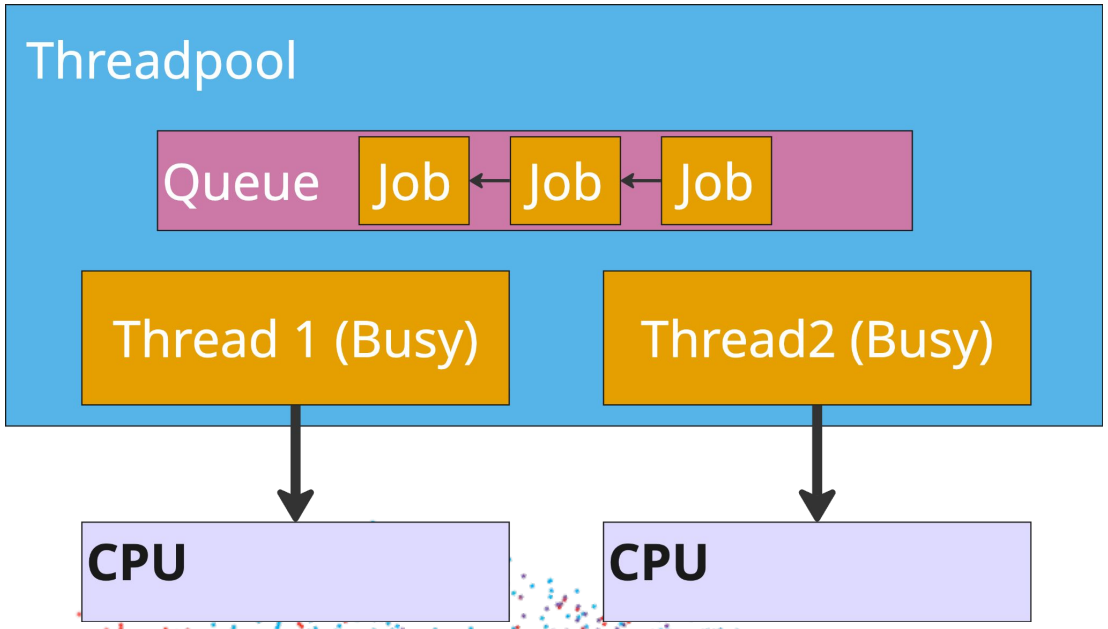
- Limit the number of threads
- Push work items into a queue
- Worker threads in pool pick up work and execute it

Thread Pools



Thread Pools

- *Parallelism* equal to the number of threads in our pool
- But each thread runs to completion, no interleaving
- Jobs are sitting in the queue to our pool
- Now limiting our *concurrency*
- Does not solve problem of blocking



Parallelism vs. Concurrency

Parallelism: Multiple tasks running at the exact same time

Concurrency: Multiple tasks in progress during the same time period, but not necessarily running at the same instant.

Domain Knowledge

- The domain knowledge lives in our application
- The OS does not know what is needed
- We know what behaviour we want to see
- Let’s start to improve what we have control over

Event Loops

- One thread

- Single loop for:
  - Wait for event
  - Dispatch event to handler

Event Loops (Slide code example)

```
class EventLoop {
 std::mutex mutex_;
 std::condition_variable cv_;
 std::queue<Task> ready_queue_;

 void run() {
   while (!runq.empty()) {
     auto task = ready_queue_.pop()
     task();  // do small, non-blocking work
   }
   cv_.wait();
 }
}
```

Non-Blocking

- Don’t wait for the work to be finished
- Need some way to figure out if it is finished
- Kernel has select/poll/epoll

…But

- The code gets more challenging
- Fixes how we wait, but not how we write the waiting code

Coroutines

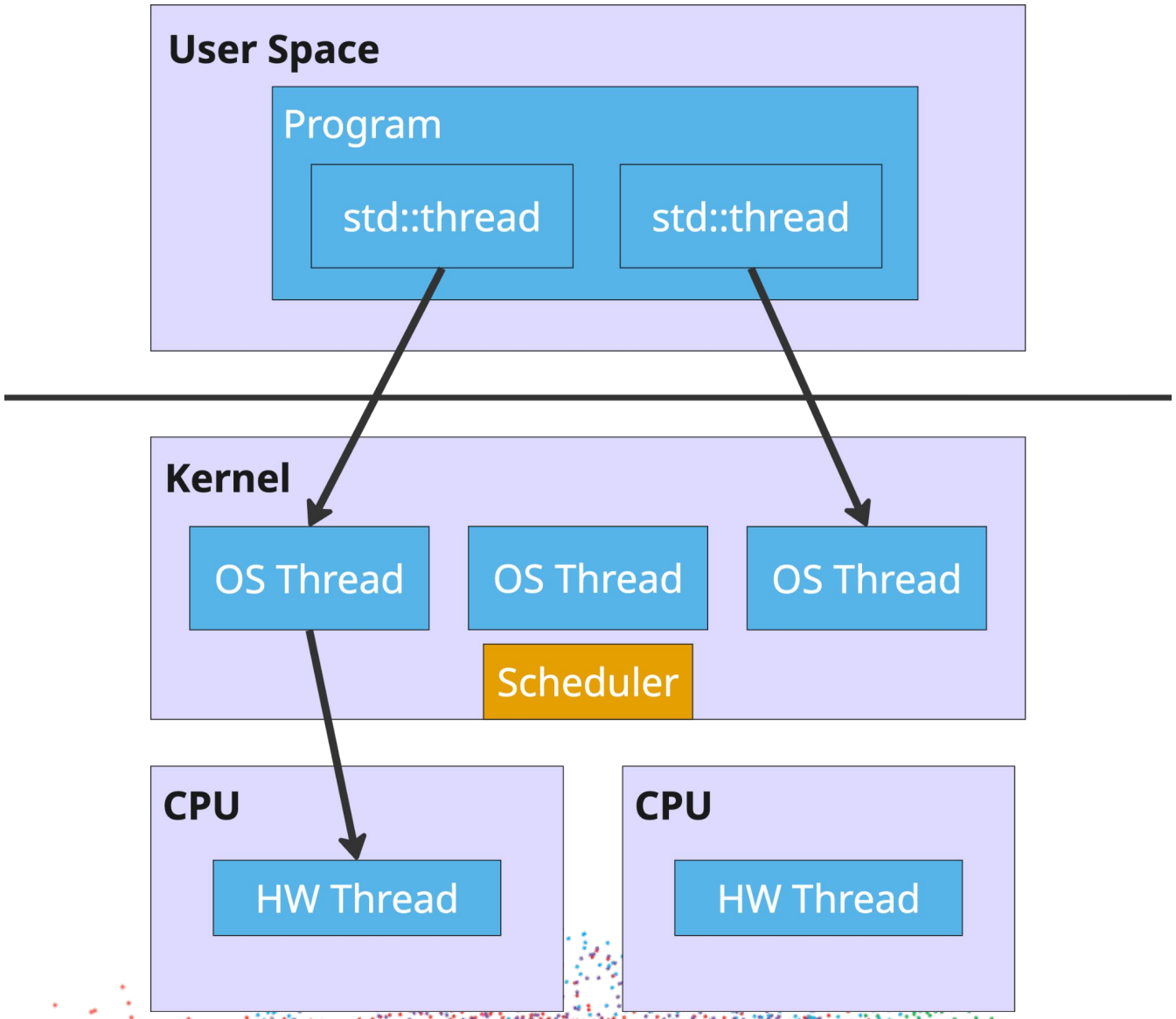
What is a Coroutine?

- A function that can suspend itself (and be resumed)

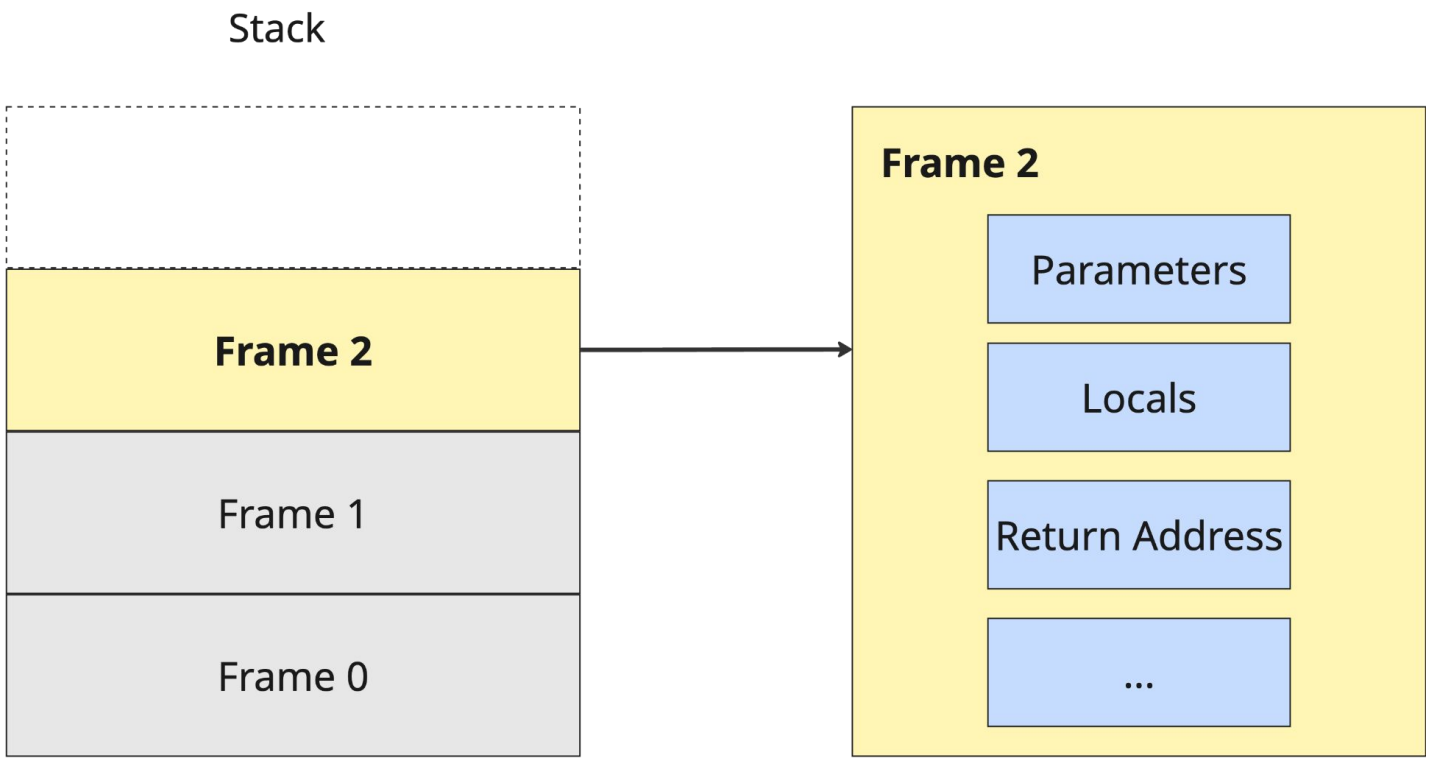
```
co_await async_read();
```

- Suspends function until there is a result from “async_read”

User, Kernel, and CPUs revisited



Function Calling



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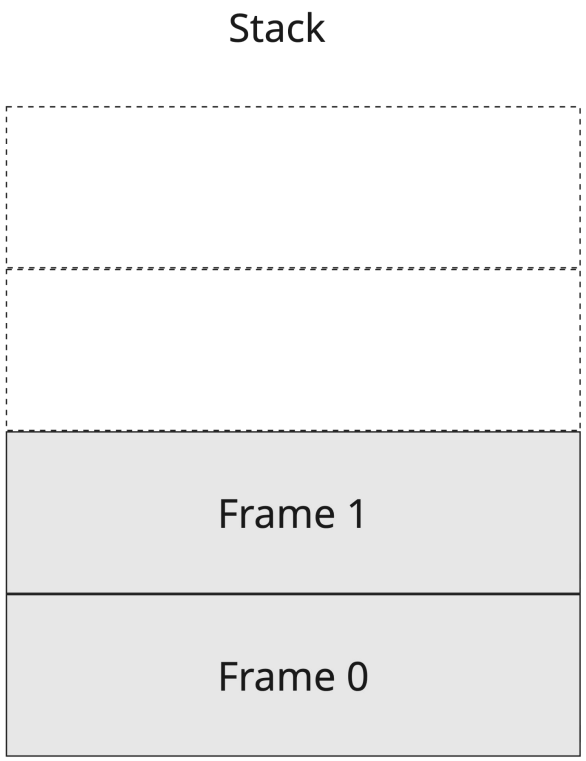
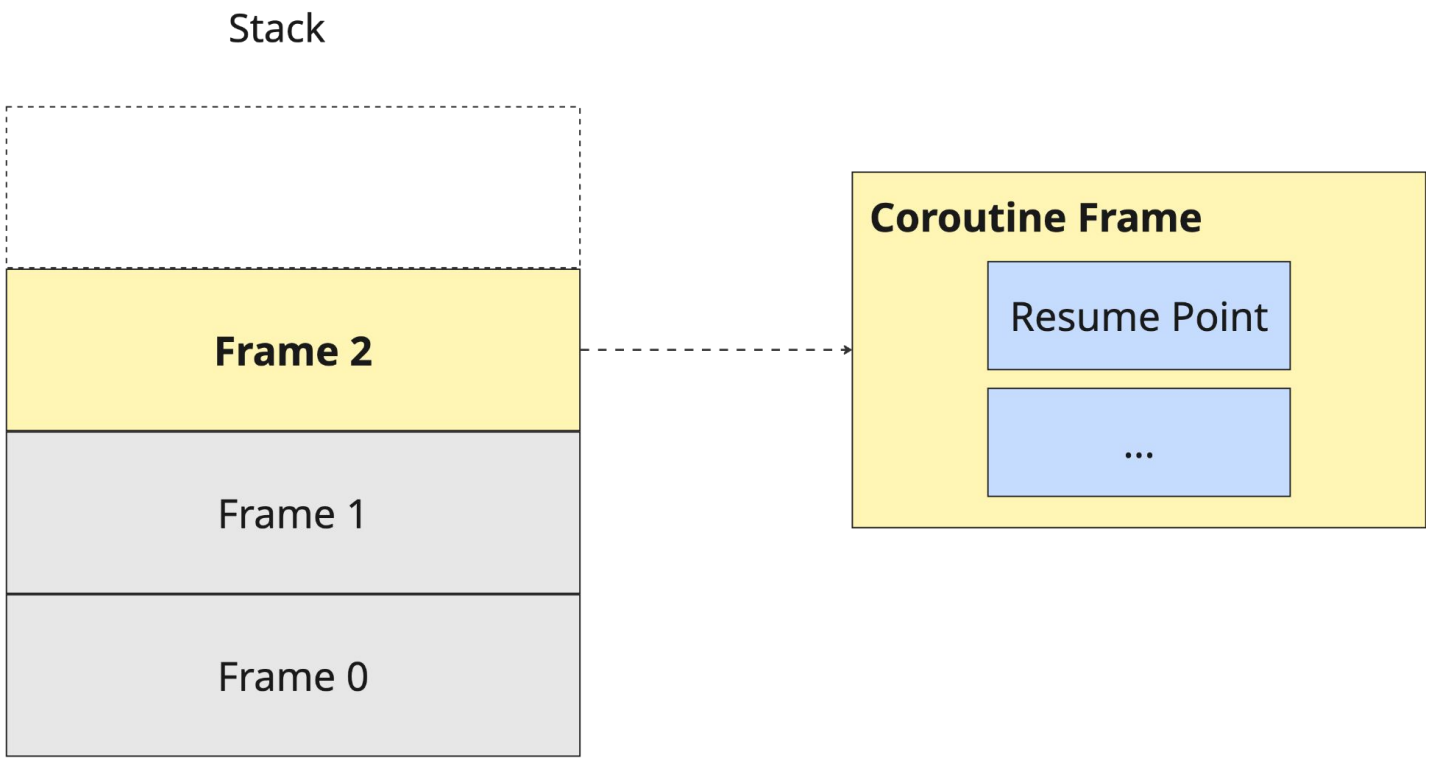
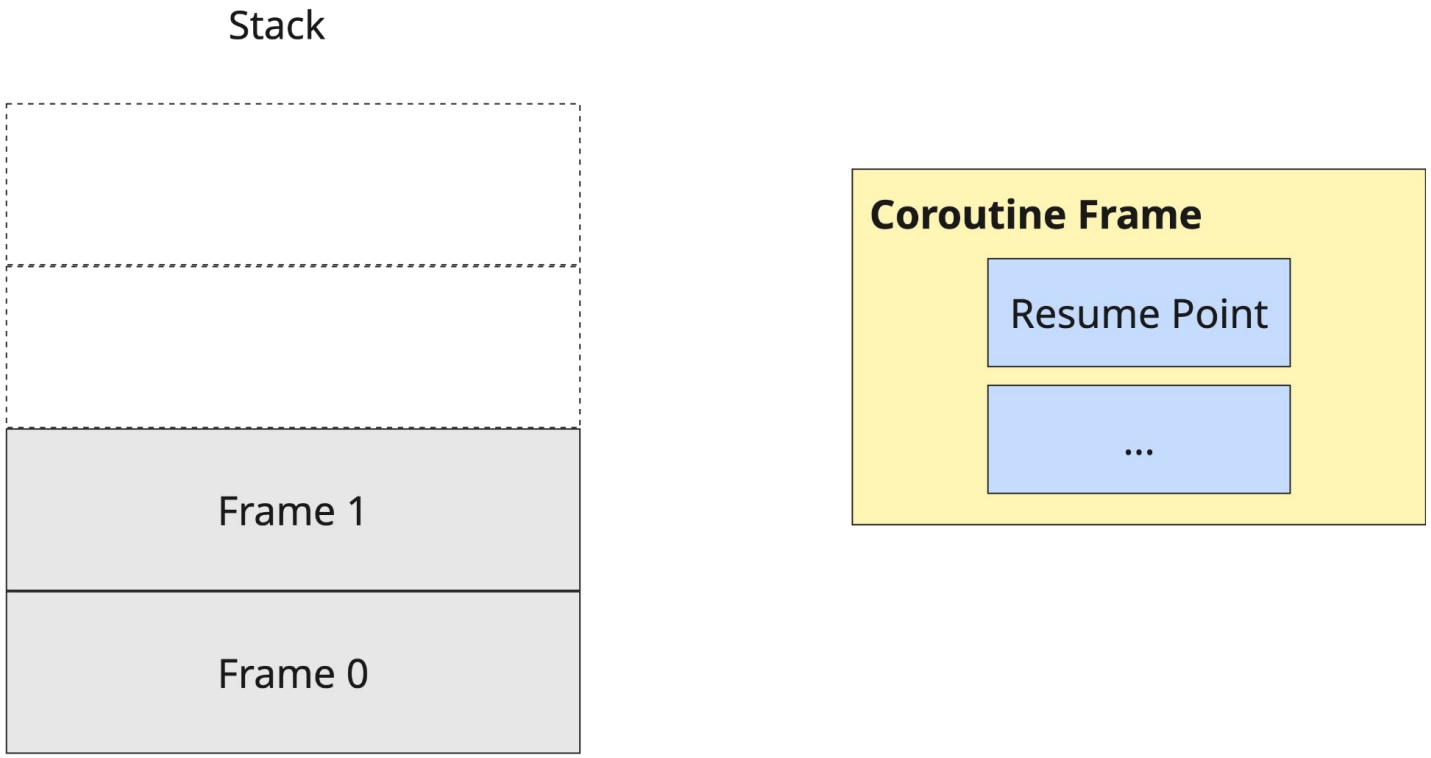


Coroutine Frames

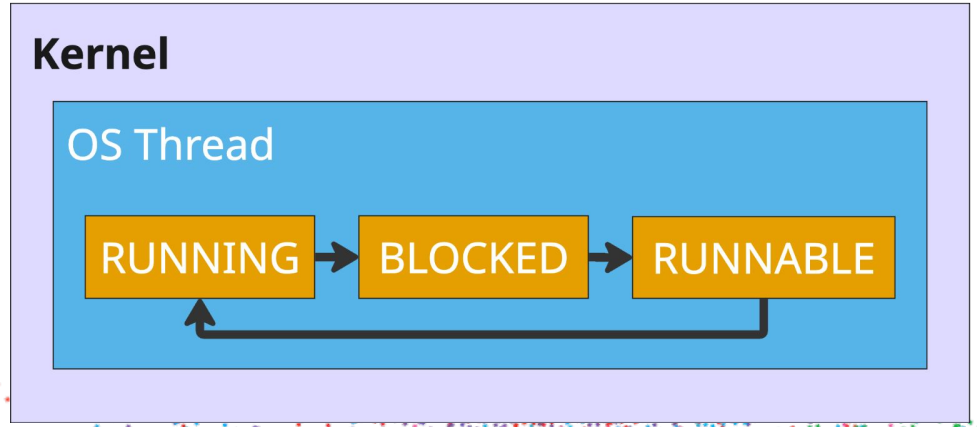


Coroutine Frames



The switching is in User Space!

- Compiler generates state machine
- Cost of “Context Switching” comparable to function call
- Our application chooses when to run it



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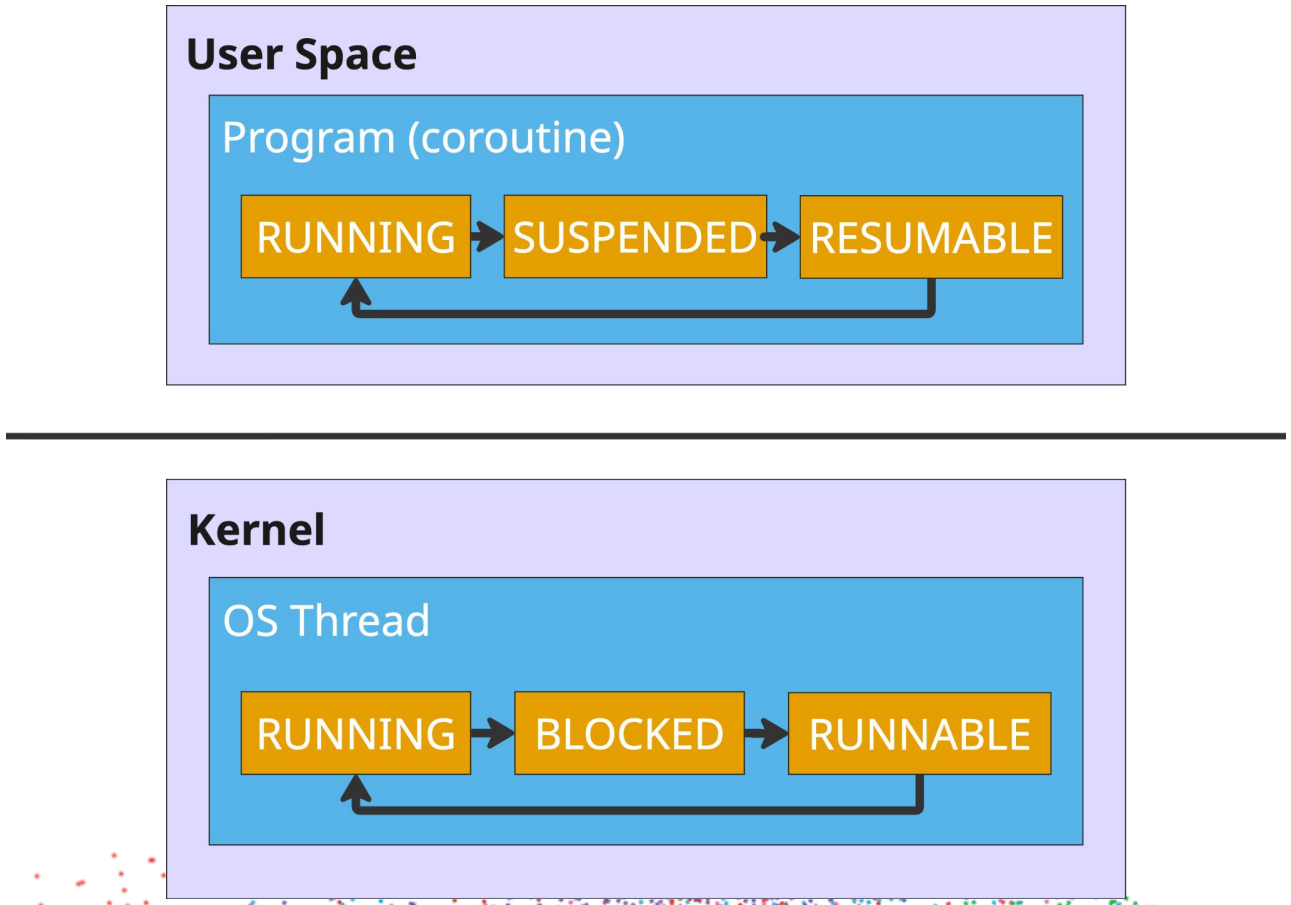


Scheduling

Return to our event loop from earlier.

```
void work_func() { /* work */ }


int main() {
 EventLoop loop;
 loop.post(work_func);
 loop.run();
}
```

Scheduling

Return to our event loop from earlier.

```
Task coroutine(EventLoop& loop) {
 co_await Awaitable{loop}; // suspends coroutine, event loop keeps running
}

int main() {
 EventLoop loop;
 coroutine(loop); // call our coroutine function
 loop.run();
}
```

What is wrong with this?

```
Task coroutine(...) {
  …
  BlockingRead(...);
  …
}
```

What is wrong with this?

```
Task coroutine(...) {
  co_await BlockingRead(...);
}
```

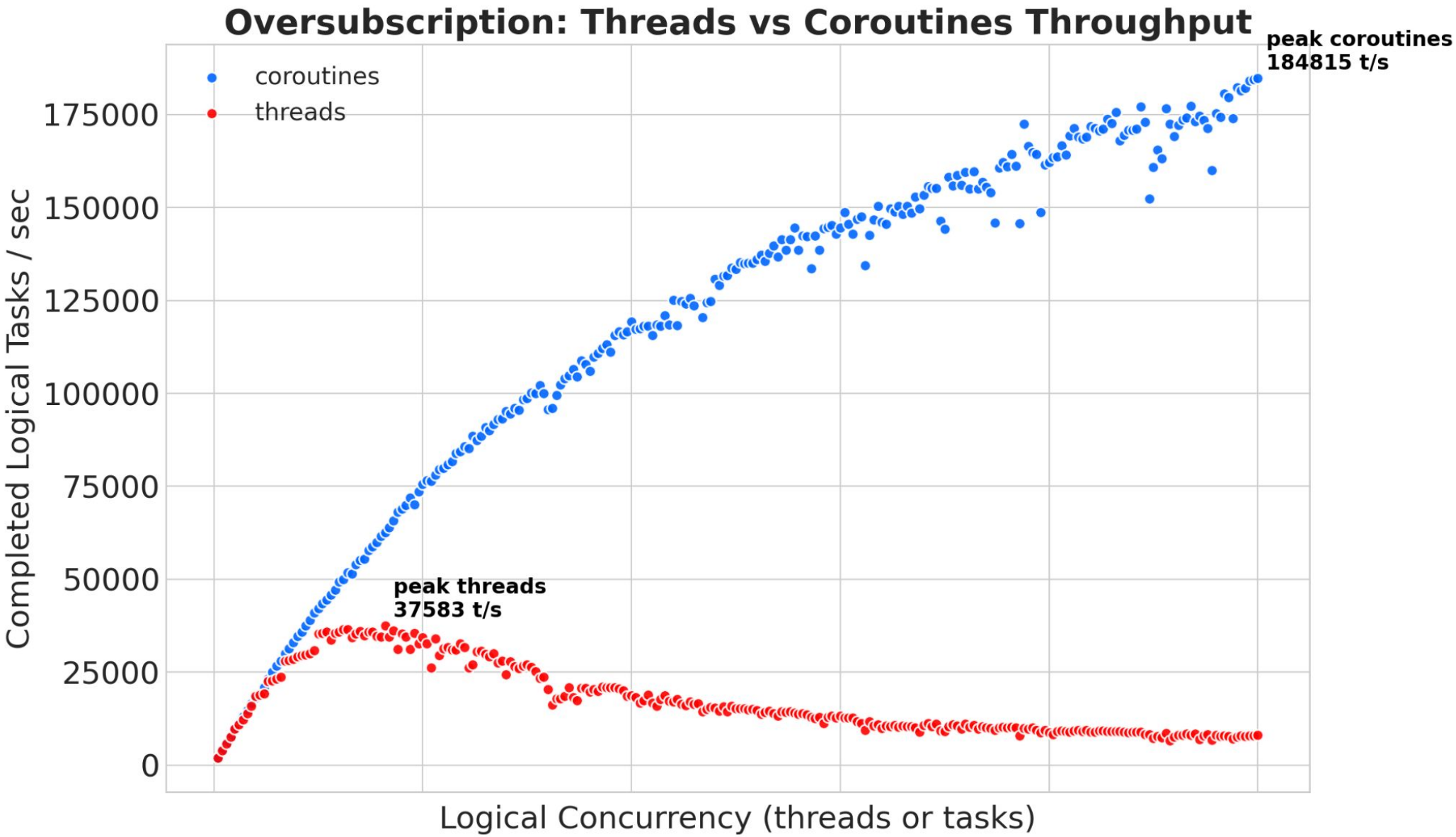
- Starvation!
- **Cooperative** multitasking: everyone must play nice!

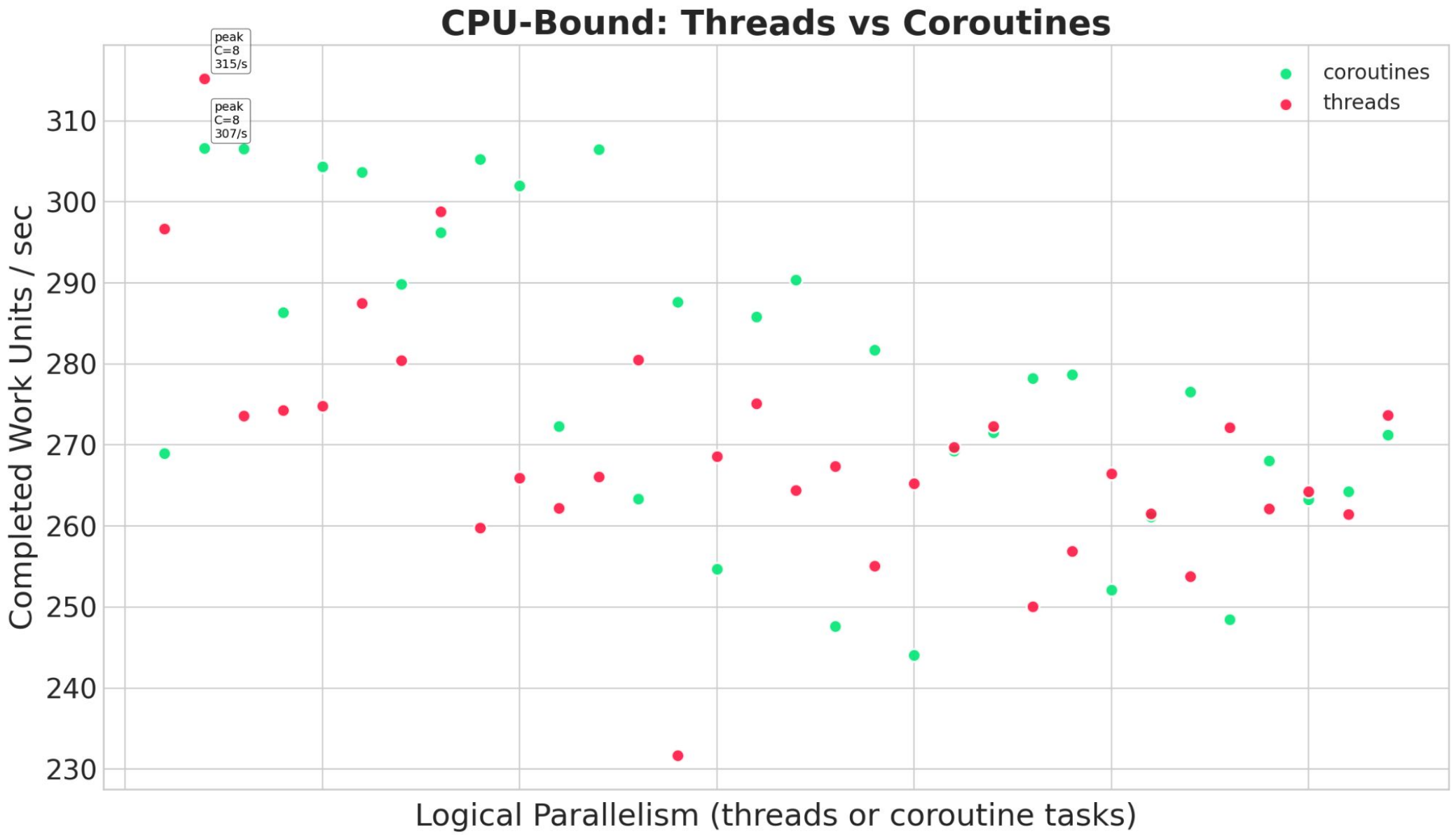
The type of work matters

- The application we are building is doing “work”
- I/O bound work?
- CPU bound work?

I/O Bound and Non-Blocking Work

- Bottleneck is *waiting for data* from outside the CPU
- I/O bound work involves a lot of waiting
- Coroutines can suspend cheaply while waiting
- Leaves the CPU to do other things
- E.g. reading/writing from a socket, waiting for a database query to complete, calling a remote API over the network.


Oversubscription: Threads vs Coroutines Throughput
coroutines
threads
peak coroutines
184815 t/s
peak threads
37583 t/s
Completed Logical Tasks / sec
175000
150000
125000
100000
75000
50000
25000
0
Logical Concurrency (threads or tasks)


CPU-Bound: Threads vs Coroutines
peak
C=8
315/s
peak
C=8
307/s
coroutines
threads
Completed Work Units / sec
310
300
290
280
270
260
250
240
230
Logical Parallelism (threads or coroutine tasks)

CPU Bound Work

- Threads (and threadpools) if bottleneck is computation
- Program already has the data, no waiting involved
- Examples: working with large in-memory datasets, or parsing or compressing a large file

Combination

- Coroutines can orchestrate I/O between stage
- Hand off any CPU work to the thread pool

```
Task handle_request(...) {
    auto data = co_await async_read(...); // I/O wait
    auto result = co_await schedule_on(cpu, process(data)); // CPU work
    co_await async_write(..., result); // I/O again
}
```

C++ 26 and std::execution

- Composable building blocks:
  - “what to do” (your work)
  - “where to do it” (the scheduler/executor)
- Make the *I/O-bound vs CPU-bound* distinction explicit

```
auto task = async_read(s)
          | stdexec::on(io)     // wait for I/O
          | stdexec::then(process)
          | stdexec::on(cpu)    // crunch numbers
          | stdexec::then(async_write);
```

Summing Up

- **Threads**
  - OS decides which thread runs on which CPU
  - Neccessary for parallelism up to N cores, concurrency beyond that
  - Preemptive, does not scale
  - Expensive (stack, kernel state)
- **Coroutines:**
  - Scheduled in user space
  - Cooperative: ensure tasks yield
  - Executors/Schedulers

Thank you!

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TechAtBloomberg: “Meet the C++ Guild” article