Events vs. Threads

COS 316: Principles of Computer System Design

Amit Levy & Wyatt Lloyd

Two Abstractions for Supporting Concurrency

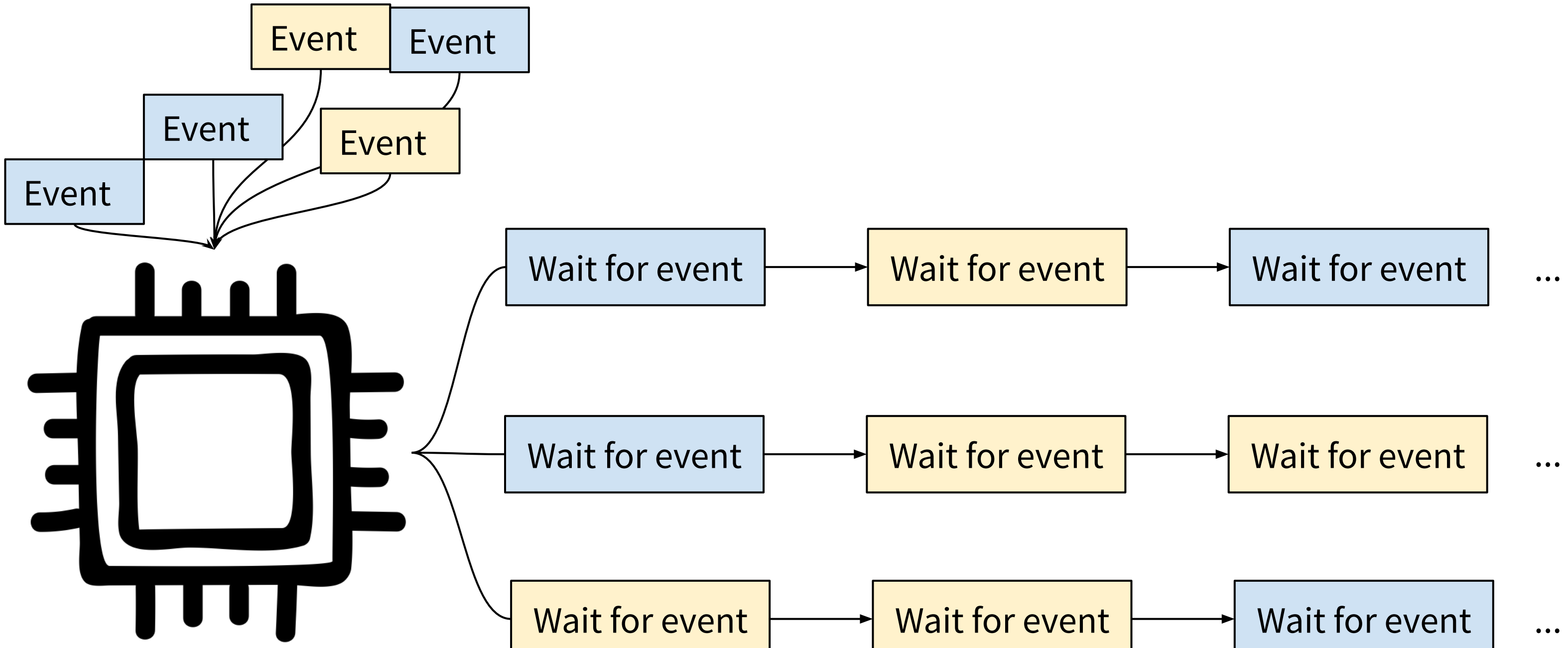
Problem: computationally light applications with large state-space

- How to support graphical interfaces with many possible interactions in each state?
- How to scale servers to handle many simultaneous requests?

Corollary: how do we best utilize the CPU in I/O-bound workloads?

- Ideally, CPU should not be a bottleneck for saturating I/O

Threads


Event
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Wait for event
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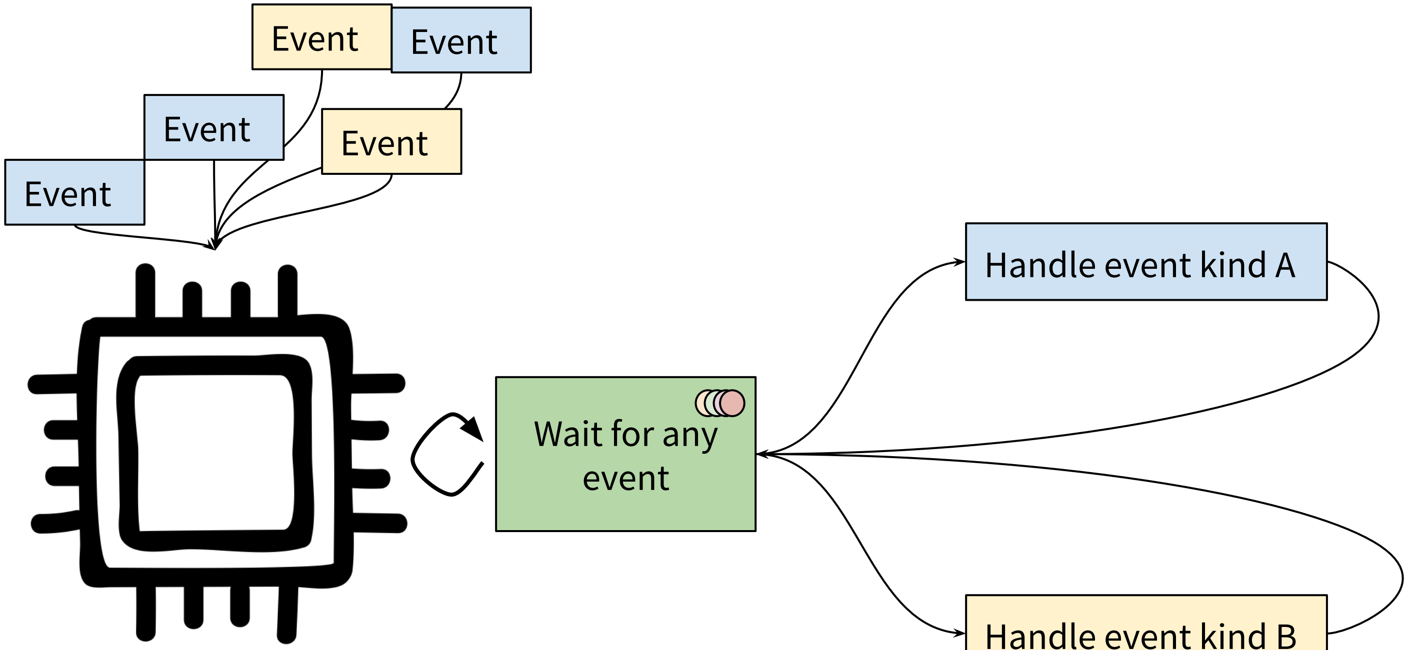
Threads

- One thread per sequence of related I/O operations
  - E.g. one thread per client TCP connection
- When next I/O isn't ready, block thread until it is
  - i.e. return to event handler instead of blocking for next event
- State machine is implicit in the sequential program
  - E.g., parse HTTP request, then send DB query, then read file from disk, then send HTTP response
- Only keeping track of relevant next I/O operations
- Any shared state must be synchronized
  - E.g. with locks, channels, etc
- In theory, scale by having a thread per connection

Events


Event
Event
Event
Event
Event
Event
Wait for any event
Handle event kind A
Handle event kind B

Events

- Single "event-loop" waits for the next event (of any kind)
- When event arrives, handle it "to completion"
  - i.e. return to event handler instead of blocking for next event
- Event loop keeps track of state machine explicitly
  - How to handle an event depends on which state I'm in
  - E.g. an HTTP parser will parse next incoming packet differently depending on what we've parsed so far
- In theory, one thread can handle infinite concurrent potential events
  - E.g. infinite number of client TCP connections
- In theory, no synchronization necessary
  - Each event handler has non-concurrent access to shared state
- In theory, scale by having an event-loop per CPU core

Which style should systems support?

History of the Debate

- 1978 - Lauer & Needham
  - "procedure-oriented" and "message-oriented" systems are duals
- 1995 - Ousterhout: "Why Threads Are A Bad Idea"
- 2001/2002 - Matt Welch builds SEDA
- 2002 - Adya et al. "Cooperative Task Management without Manual Stack Management"
- 2003 - Behrer, Condit, Brewer: "Why Events Are A Bad Idea"
- 2009/10 - NodeJS & ***Golang***
- 2012 - Linux addresses non-blocking I/O performance issues with `epoll`
- 2020 - is the debate still relevant?
  - Spoiler alert: I think it is!

How do Threads and Events Compare?

Some of the debate has been around usability---which is easier to program.

Much of the debate has focused on “object” measures:

1. Performance
2. Control Flow
3. Synchronization
4. State Management
5. Scheduling

Performance

Threads

- Heavier weight *abstraction* of hardware
  - Blocking I/O naturally translates to polling, but that's not what we want
- Context switching can be expensive
- System ops for threads often O(n)
  - But this is not fundamental!

Events

- Abstraction maps neatly to most hardware
  - With interrupts turned off, a CPU-core is basically an event system
- Result: easier to implement efficiently
- Why: complexity is deferred to applications
  - This can be good for apps!
- Operations can be O(n) in event types
  - Fixed in the last decade

Control Flow

Threads

- Linear control flow implied
  - Do this I/O, then this I/O, then this I/O
  - This is the *most* common control flow
- Simple to support
  - Call/return
  - Parallel calls
  - Pipelines
- More complex flows don’t fit well
  - Dynamic fan-in or fan-out

Events

- No particular control-flow implied
  - Call/return
  - Parallel
  - Pipelines
  - Fan-in/fan-out
- In practice, complex control-flows are uncommon
- Simple control-flows are “harder” to program
  - Ousterhout disagrees!
  - Notably hard: exceptions & error handling

Synchronization

Threads

- Synchronization across threads is hard
  - Locks, condition variables, channels
  - Difficult to reason about
  - ***Very*** difficult to test
- Synchronization necessary even when not fundamental
  - E.g. on a uniprocessor

Events

- Synchronization for “free”
  - Single thread of execution means no need to synchronize on shared state
- Well… only true for uniprocessors
  - Lots of applications are single-core
  - Scalable servers typically multi-core
  - Multi-core event-loops still need explicit synchronization

State Management

Threads

- State encapsulated on the stack
- Programmer doesn't need to think about what state to track between I/O
  - Implied in local variables, etc
- State-machine implied in linear flow of program
- Need a stack for each frame
  - How big should the stack be?
  - Too small? Stack overflow
  - Too big? Memory waste

Events

- Programmer tracks state explicitly
  - Called "Stack ripping"
- Global, shared variables
- Can make state difficult to track
  - Particularly if state-space is large
- No need for separate stacks
- Memory usage (can be) optimal

Scheduling

Threads

- Typically: threads scheduled *preemptively* by system
- Provides performance isolation
  - Threads with long-running computation don't starve other threads
- Programmer doesn't have to think about scheduling
- Requires worst-case context switching
- Scheduling decisions can be sub-optimal for application

Events

- Cooperatively scheduled
  - Event handlers yield by returning to event loop
  - Next event handler runs only when previous completes
- Scheduling decisions deferred to application
  - E.g. event loop can prioritize advantageous events
  - Only true if you write your own event loop
- Hard to achieve fairness
  - Hard to debug and test fairness regressions

Which style should systems support?

Unifying Events and Threads

Behrer, Condit & Brewer: "Why Events Are A Bad Idea (for high-concurrency servers)" HotOS 2003

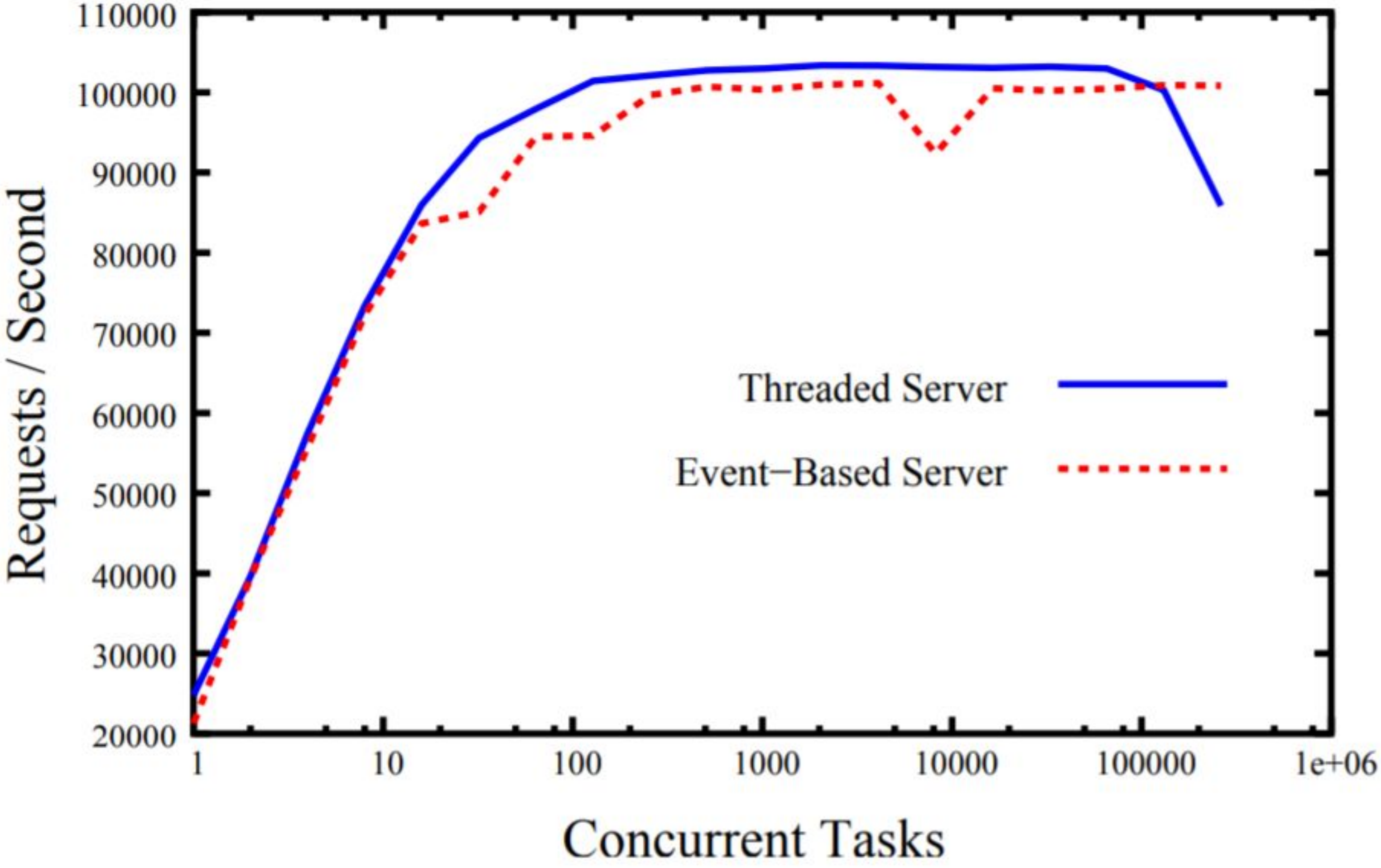
Premise: threads are easier to program than events

- This is probably not true for GUIs, games, etc
- It’s at least closest to what we learn in 126

Key idea: better implementations and the compiler can (and should!) address the problems with threads

Unifying Events and Threads

- Scheduling: threads can be cooperatively scheduled too!
  - Key idea in Go's goroutines
- Performance: existence proof of a lightweight thread system
  - Many previous examples, especially from language runtimes (ML, Erlang)
- Control-flow: not really a problem
- Synchronization: compiler analysis can reduce/eliminate occurrence of concurrency bugs
  - Haskell, Rust languages take this to extreme
- State management
  - Dynamic stack growth: start with a small stack and dynamically allocate more as necessary
    - Go, Haskell
  - Compiler can purge unnecessary stack variables


110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
Requests / Second
1
10
100
1000
10000
100000
1e+06
Concurrent Tasks
Threaded Server
Event−Based Server

Two Paths: Node.js & Go

- Around 2009, it seemed time for new runtimes for building servers
  - Java was showing its age
  - C++ perceived as unnecessarily hard
  - Popular languages not “fast enough” (PHP, Python, Ruby)
    - Note that most performance sensitive code in these languages actually in C
  - Cool kids don’t want to use good languages for some reason (ML, Lisp, Haskell etc)
- Node.js:
  - Chrome made JavaScript fast with V8’s just-in-time compiler
  - Everyone already knows JavaScript!
  - Events are faster than threads!
- Go:
  - Write a language and compiler from scratch targeted specifically at building scalable servers
  - I’m Ken “f&#*$ing” Thompson and I don’t have to care what language you already know!
  - Threads are easier to program, and we can make them just as fast!

Goroutines

- Threaded programming model
  - I/O operations are blocking
  - Spawn a goroutine per-connection, request, etc
- Lightweight:
  - Dynamically sized stacks (starts at 2KB, grows based on compiler analysis)
  - Context switching in language runtime, only save minimal CPU state
- Cooperatively scheduled
  - Uses implied save-points to yield:
    - Function calls
    - I/O operations
    - Recently, loop iterations
- M:N threading model: schedule M goroutines onto N CPU cores (kernel threads)

The State of Events vs. Threads in 2020

- General-purpose operating systems have converged on…. both
  - Posix Threads on Linux (LinuxThreads) continue to improve in performance
  - epoll solves bottlenecks in previous event system calls
  - Most highly-concurrent servers use multiple threads, each running an event-loop
- Switch to 64-bit address space & dramatic increase in RAM have circumvented the stack consumption problem on servers
  - 64-bit virtual addresses means it's easy to allocate many virtually unbounded stacks
  - Lots of memory means that overallocated unused memory isn't so bad (on the order of MBs)
- Most common language runtimes just use Posix Threads
  - Python, Ruby, Java, Rust
  - Turns out to be fine in the vast majority of applications

The State of Events vs. Threads in 2020

Some back of the envelope math:

- Facebook has millions of servers
- Facebook has ~1.5 billion users
- If every user established a TCP connection at the same time
  - 1,500,000,000 / 1,000,000 = 1,500 connections/server
  - 1,500 threads * 4MB/thread = ~6GB of RAM
- Most applications are not Facebook

Maybe it’s just not that important anymore. Whatever is most natural to program…

Not all Systems in 2020 are Network Servers

- Embedded "Internet of Things" systems have very low memory
  - 16KB to, at most, 1MB
  - 32-bit addresses and often no virtual memory
  - Even with Golang's small goroutine stacks, we could only have 4
- Real-time systems
  - Both threads and events can make it hard to estimate compute time
  - Threads: task switching modulates block I/O time
  - Events: can't reliably ensure event progress without preemption
- Performance isolation
  - When running untrusted code, we might *need* preemption to ensure performance isolation

Takeaways

- Often, there are no clear answers to system design questions
  - Are threads or events easier to program? How would you measure?
  - Are threads or events more performant? How to disentangle from implementation details?
- True not just for events vs. threads:
  - Garbage collection vs. manual memory management
  - Asynchronous messaging vs RPC
  - Hardware vs. software fault isolation
  - As we'll see, access control: mandatory vs. discretionary access control, capabilities vs. information flow control
- Measuring performance of an actual system is the best way to get a concrete answer to this question

You should always plan to build *at least* two systems from scratch. You will throw away the first one once you learn what are the hard problems.