CSCI-1680
Network Programming II

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Today

- **Network programming**
  - Programming Paradigms
  - Programming libraries
- **Final project**

Low-level Sockets

- **Address Family AF_PACKET**
  - Socket type: SOCK_RAW
    - See link-layer (Ethernet) headers. Can send broadcast on a LAN. Can get/create non-IP packets
  - Socket type: SOCK_DGRAM
    - See IP headers. Can get protocols other than TCP/UDP: ICMP, SCTP, DCCP, your own…
    - Can cook your own IP packets
  - Must have root privileges to play with these

Building High Performance Servers

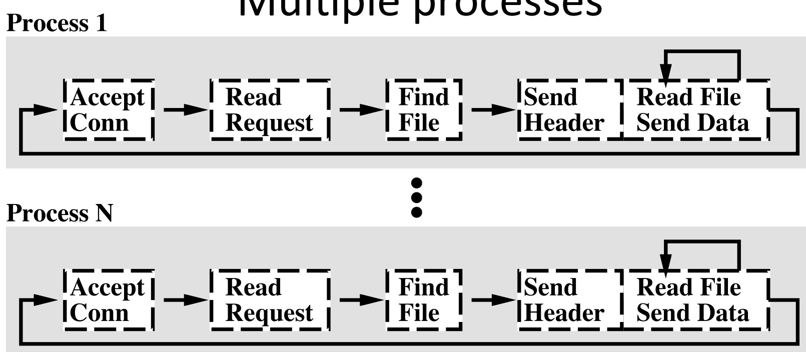
The need for concurrency

- **How to improve throughput?**
  - Decrease latency (throughput α 1/latency)
  - Hard to do!
    - Optimize code (this you should try!)
    - Faster processor (no luck here, recently)
    - Speed of light isn't changing anytime soon…
    - Disks have to deal with things like inertia!
  - Do multiple things at once
- **Concurrency**
  - Allows overlapping of computation and I/O
  - Allows use of multiple cores, machines

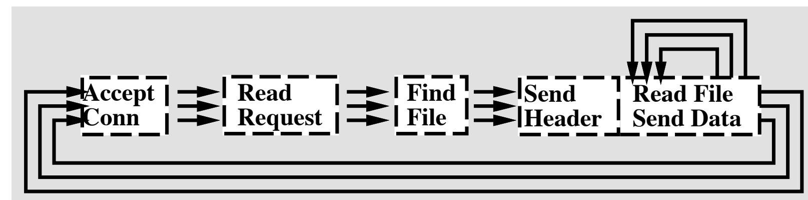
High-performance Servers

Common Patterns

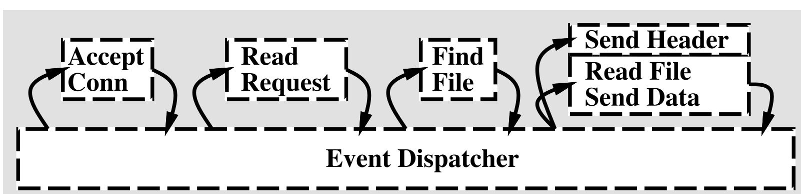
Multiple processes



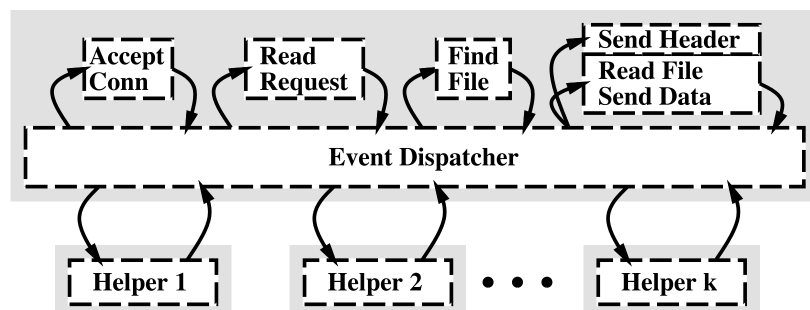
Multiple Threads



Single Process Event Driven



Single Process Event Driven with Helpers

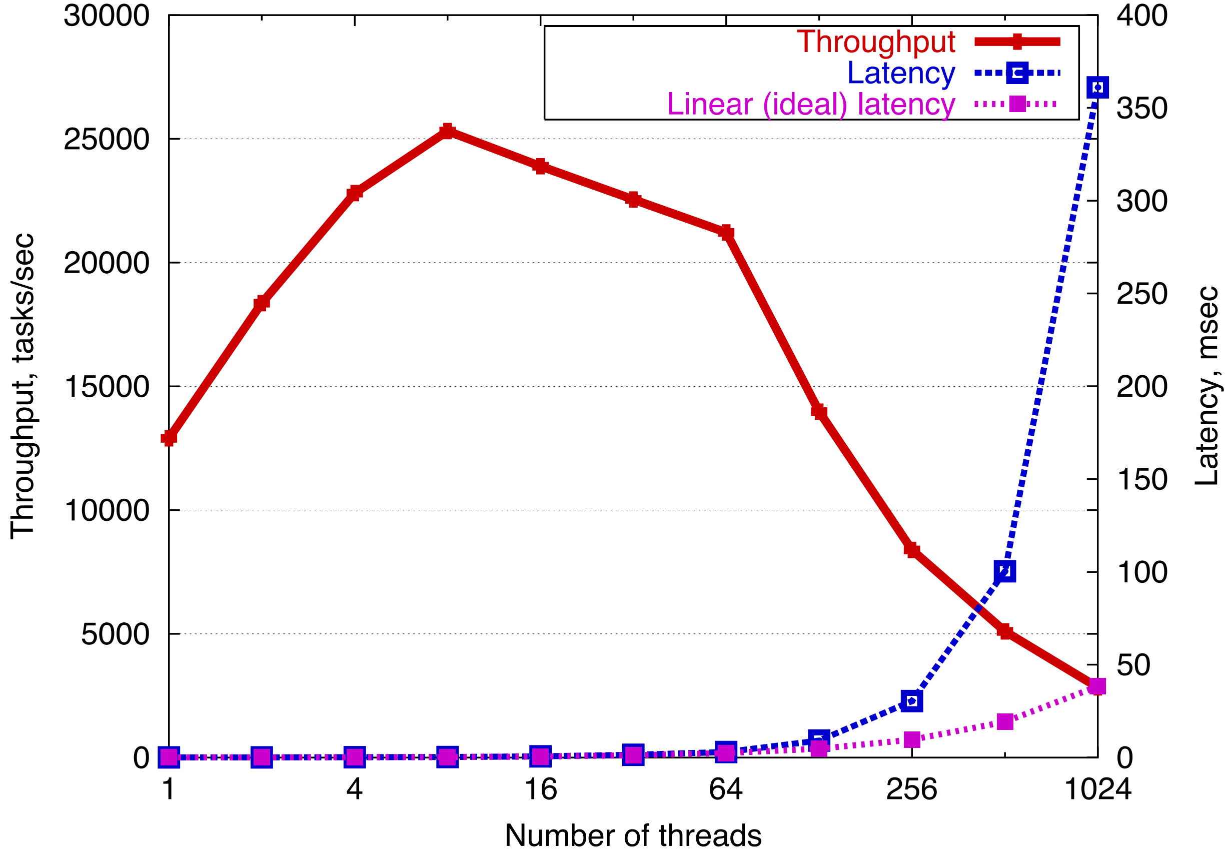


Figures from Pai, et al., 1999 “Flash: An efficient and portable Web server”

Threads

- **Usual model for achieving concurrency**
- **Uniform abstraction for single and multiple cores**
- **Concurrency with locks/mutexes**
  - Threads may block, hold locks for long time
- **Easy to reason about**
  - Each thread has own stack
- **Strong support from OS, libraries, debuggers**
- **Traditionally, problems with more than a few 100 threads**
  - Memory overhead, O(n) operations

Performance, Thread-based server



From Welsh, et al., SOSP 2001 "SEDA: An Architecture for Well-Conditioned, Scalable Internet Services

Events

- **Small number of threads, one per CPU**
- **Threads do one thing:**

```
while(1) {
    get event from queue
    Handle event to completion
}
```

- **Events are network, I/O readiness and completion, timers, signals**
  - Remember select()?
- **Assume event handlers never block**
  - Helper threads handle blocking calls, like disk I/O

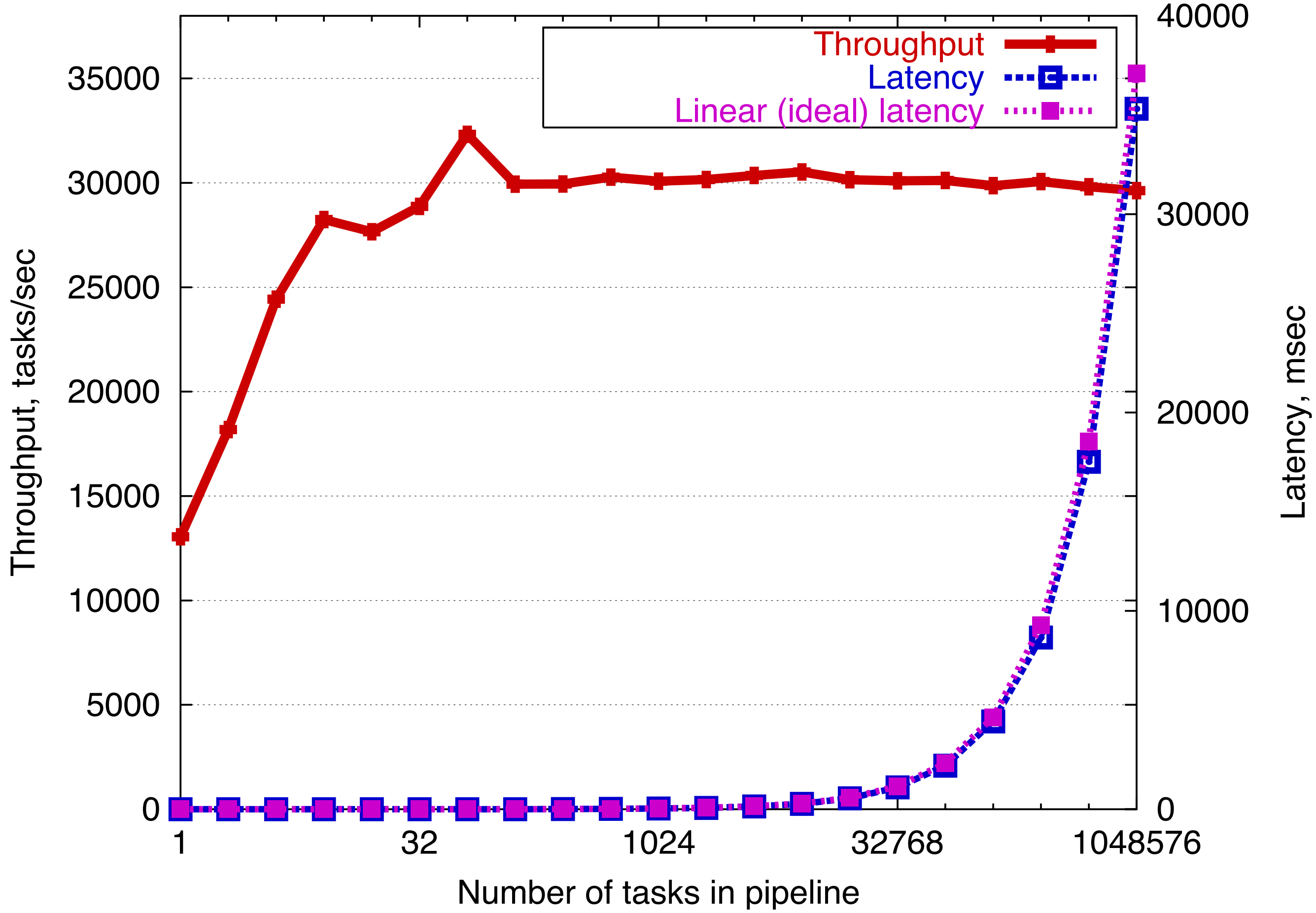
Events

- **Many works in the early 2000's claimed that events are needed for high performance servers**
  - E.g., Flash, thttpd, Zeus, JAWS web servers
- **Indeed, many of today's fastest servers *are* event-driven**
  - E.g., OKCupid, lighttpd, nginx, tornado

Lighttpd: "Its event-driven architecture is optimized for a large number of parallel connections"

Tornado: "Because it is non-blocking and uses epoll, it can handle thousands of simultaneous standing connections"

Performance, Event-Driven Web server



From Welsh, et al., SOSP 2001 "SEDA: An Architecture for Well-Conditioned, Scalable Internet Services

Flash Web Server

- **Pai, Drushel, Zwaenepoel, 1999**
- **Influential work**
- **Compared four architectures**
  - Multi-process servers
  - Multi-threaded servers
  - Single-process event-driven
  - Asymmetric Multi-process event driven
- **AMPED was the fastest**

Events (cont)

- **Highly efficient code**
  - Little or no switching overhead
  - Easy concurrency control
- **Common complaint: hard to program and reason about**
  - For people and tools
- **Main reason: *stack ripping***

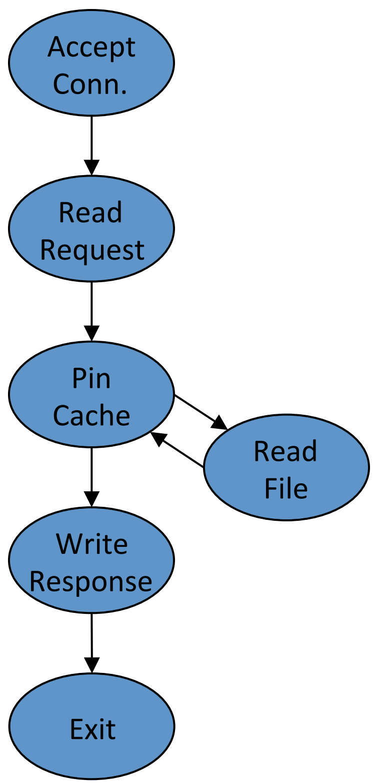
Events criticism: control flow

- **Events obscure control flow**
  - For programmers *and* tools

Threads	*Events*

thread_main(int sock) {
    struct session s;
    accept_conn(sock, &s);
    read_request(&s);
    pin_cache(&s);
    write_response(&s);
    unpin(&s);
}
 	
pin_cache(struct session *s) {
    pin(&s);
    if(!in_cache(&s))
        read_file(&s);
}
	CacheHandler(struct session *s) {
	    pin(s);
	    if(!in_cache(s)) ReadFileHandler.enqueue(s);
	    else ResponseHandler.enqueue(s);
	}
	RequestHandler(struct session *s) {
	    …; CacheHandler.enqueue(s);
	}
	. . .
	ExitHandlerr(struct session *s) {
	    …; unpin(&s); free_session(s);
	}
	AcceptHandler(event e) {
	    struct session *s = new_session(e);
	    RequestHandler.enqueue(s); }

Web Server



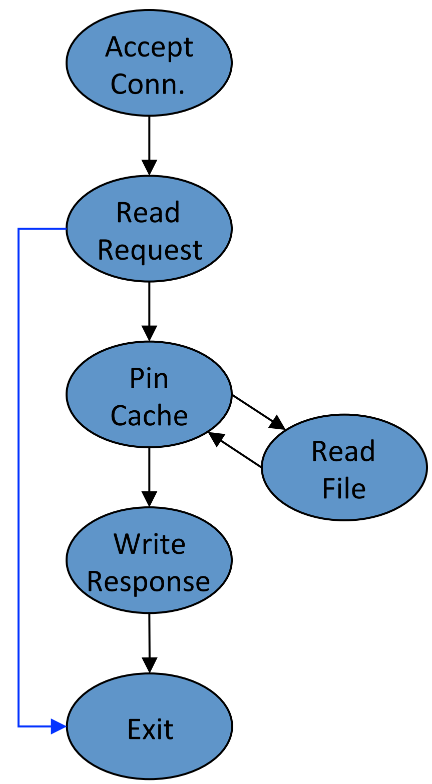
Events criticism: Exceptions

- **Exceptions complicate control flow**
  - Harder to understand program flow
  - Cause bugs in cleanup code

Threads	*Events*

<pre>thread_main(int sock) {
    struct session s;
    accept_conn(sock, &s);
    if(!read_request(&s))
        return;
    pin_cache(&s);
    write_response(&s);
    unpin(&s);
}
 	
pin_cache(struct session *s) {
    pin(&s);
    if(!in_cache(&s))
        read_file(&s);
}</pre>
	<pre>CacheHandler(struct session *s) {
	    pin(s);
	    if(!in_cache(s)) ReadFileHandler.enqueue(s);
	    else ResponseHandler.enqueue(s);
	}
	RequestHandler(struct session *s) {
	    ...; if(error) return; CacheHandler.enqueue(s);
	}
	. . .
	ExitHandlerr(struct session *s) {
	    ...; unpin(&s); free_session(s);
	}
	AcceptHandler(event e) {
	    struct session *s = new_session(e);
	    RequestHandler.enqueue(s); }</pre>

Web Server



Events criticism: State Management

- **Events require manual state management**
- **Hard to know when to free**
  - Use GC or risk bugs

Threads	*Events*

Threads

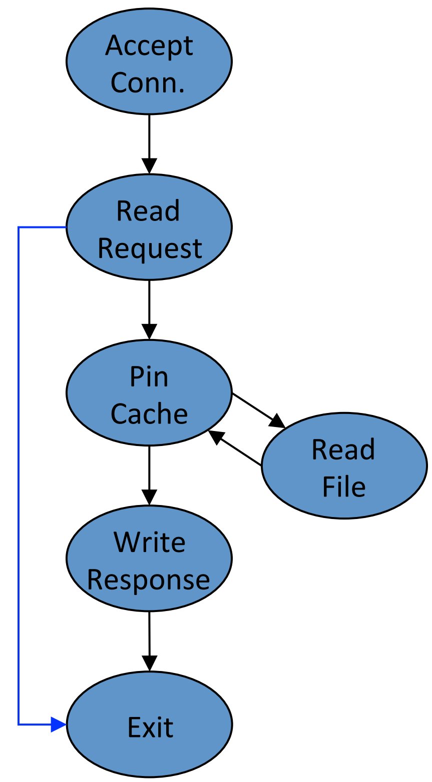
```
thread_main(int sock) {
    struct session s;
    accept_conn(sock, &s);
    if( !read_request(&s) )
        return;
    pin_cache(&s);
    write_response(&s);
    unpin(&s);
}

pin_cache(struct session *s) {
    pin(&s);
    if( !in_cache(&s) )
        read_file(&s);
}
```

Events

```
CacheHandler(struct session *s) {
    pin(s);
    if( !in_cache(s) )  ReadFileHandler.enqueue(s);
    else                ResponseHandler.enqueue(s);
}
RequestHandler(struct session *s) {
    …; if( error ) return;  CacheHandler.enqueue(s);
}
. . .
ExitHandlerr(struct session *s) {
    …;  unpin(&s);  free_session(s);
}
AcceptHandler(event e) {
    struct session *s = new_session(e);
    RequestHandler.enqueue(s); }
```

Web Server

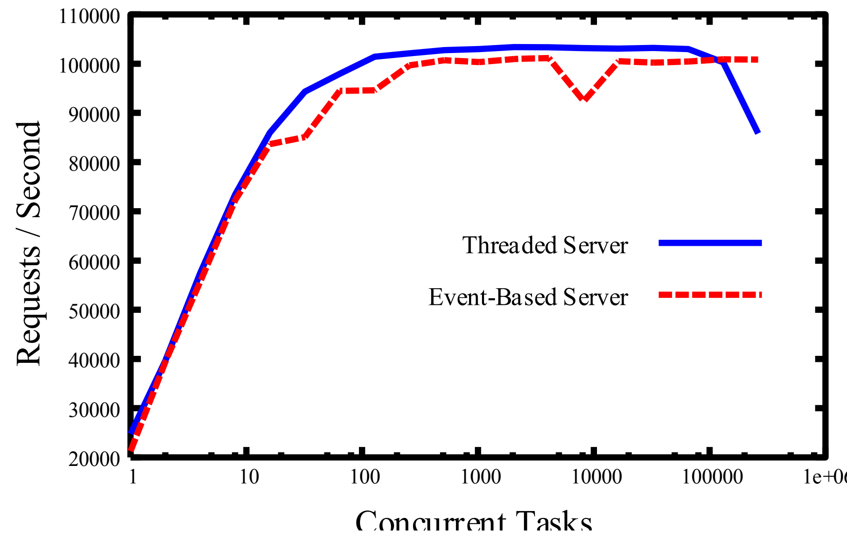


Usual Arguments

- **Events:**
  - Hard to program (stack ripping)
  - Easy to deal with concurrency (cooperative task management)
    - Shared state is more explicit
  - High performance (low overhead, no switching, no blocking)
- **Threads**
  - Easy to reason about flow, state (automatic stack management)
  - Hard to deal with concurrency (preemptive task management)
    - Everything is shared
  - Lower performance (thread switching cost, memory overhead)

Capriccio (2003)

- **Showed threads can perform as well as events**
  - Avoid O(n) operations
  - Cooperative lightweight user-level threads
    - (still one kernel thread per core)
  - Asynchronous I/O
    - Handled by the library
  - Variable-length stacks
  - The thread library runs an event-based system underneath!



Artificial Dichotomy!

- **Old debate! Lauer and Needham, 78**
  - Duality between process-based and message-passing
  - Updated by the Capriccio folks, 2003

Threads	*Events*
Monitors	Event handler & queue
Exported functions	Events accepted
Call/return and fork/join	Send message / await reply
Wait on condition variable	Wait for new messages

- **Performance should be similar**
  - No inherent reason for threads to be worse
  - Implementation is key

Artificial Dichotomy

- **Threads**
  - Preemptive multitasking
  - Automatic stack management
- **Events**
  - Cooperative multitasking
  - Manual stack management (stack ripping)
- **Adya, 2002: you can choose your features!**
  - They show that you can have cooperative multitasking with automatic stack managment

Adya, A. et al., 2002. "Cooperative Task Management without Manual Stack Managementor, Event-driven Programming is Not the Opposite of Threaded Programming

Threads vs. Events

- **Today you still have to mostly choose either style (complete packages)**
  - Thread-based servers very dependent on OS, threading libraries
- **Some promising directions!**
  - TAME allows you to write sequential C++ code (with some annotations), converts it into event-based
  - Scala (oo/functional language that runs on the JVM) makes threaded and event-based code look almost identical

Popular Event-Based Frameworks

- **libevent**
- **libasync (SFS, SFS-light)**
- **Javascript**
  - All browser code
  - Node.js at the server side
- **GUI programming**

Some available libraries

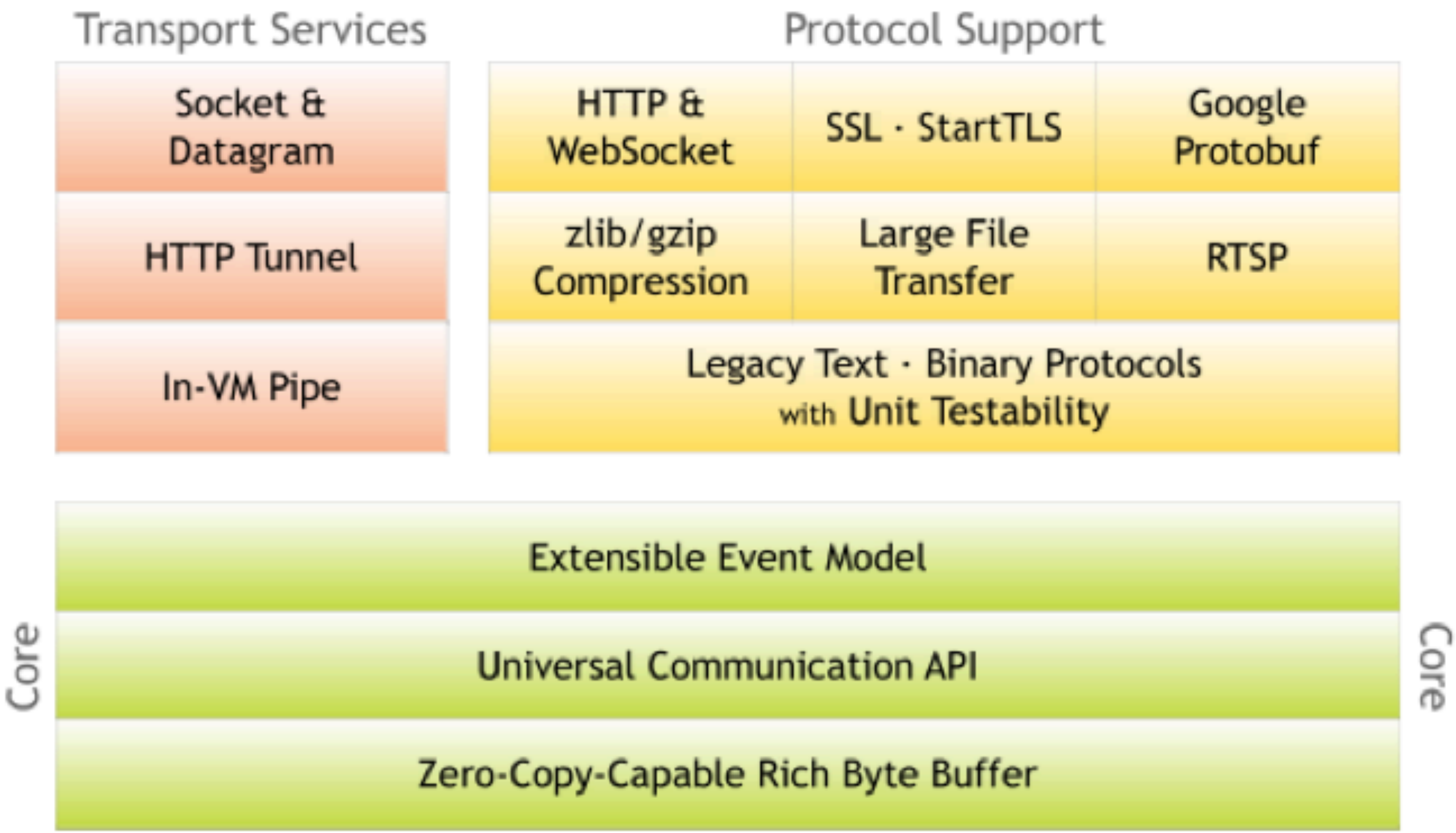
With material from Igor Ganichev

Python

- **Rich standard library**
  - url/http/ftp/pop/imap/smtp/telnet
  - SocketServer, HTTPServer, DocXMLRPCServer, etc
- **Twisted**
  - Very popular
  - Has *a lot* of stuff, but quite modular
  - Event-driven, many design patterns. Steep learning curve…
  - Well maintained and documented

Java

- **Mature RPC library: RMI**
- **River: RMI + service discovery, mobile code**
- **Java.NIO**
  - High-level wrapping of OS primitives
    - Select -> Selector . Socket -> Channel
  - Good, efficient buffer abstraction
- **Jetty**
  - Extensible, event-driven framework
  - High-performance
  - Avoid unnecessary copies
  - Other side doesn't have to be in Java


Transport Services
Protocol Support
Socket & Datagram
HTTP & WebSocket
SSL · StartTLS
Google Protobuf
HTTP Tunnel
zlib/gzip Compression
Large File Transfer
RTSP
In-VM Pipe
Legacy Text · Binary Protocols with Unit Testability
Extensible Event Model
Universal Communication API
Zero-Copy-Capable Rich Byte Buffer
Core
Core

C

- **Sockets!**
- **Direct access to what the OS provides**
- **Libevent**
  - Simple, somewhat portable abstraction of select() with uniform access to events: I/O, timers, signals
  - Supports /dev/poll, kqueue(2), event ports, select(2), poll(2) and epoll(4).
  - Well maintained, actively developed
  - Behind many very high-performance servers
    - Memcached

C++

- **Boost.ASIO**
  - Clean, lightweight, portable abstraction of sockets and other features
  - Not a lot of higher-level protocol support
  - Has support for both synchronous and asynchronous operations, threads (from other parts of Boost)
- **Others: ACE, POCO**

ICE

- **Cross-language middleware + framework**
  - Think twisted + protocol buffers
- **Open source but owned by a company**
- **SSL, sync/async, threads, resource allocation, firewall traversal, event distribution, fault tolerance**
- **Supports many languages**
  - C++, Java, .NET-languages (such as C# or Visual Basic), Objective-C, Python, PHP, and Ruby

Other "cool" approaches

- **Erlang, Scala, Objective C**
  - Support the Actor model: program is a bunch of actors sending messages to each other
  - Naturally extends to multi-core and multiple machines, as sending messages is the same
- **Go**
  - Built for concurrency, uses 'Goroutines', no shared state
  - "Don't share memory to communicate, communicate to share memory"

Node.js

- Javascript server framework
- Leverages highly efficient Chrome V8 Javascript JIT runtime
- Completely event-based
- Many high-level libraries

```
var http = require('http');
http.createServer(function (req, res) {
  res.writeHead(200, {'Content-Type': 'text/plain'});
  res.end('Hello World\n');
}).listen(8124, "127.0.0.1");
console.log('Server running at http://127.0.0.1:8124/');
```

Final Assignment

Final Project

- **Tethering IP over 3G**
- **Problem: Laptop in need of internet, no Wi-Fi available.**
- **On hand: Smartphone with 3G connection.**
- **Native applications don't always allow custom network programming.**
  - iOS App Store guidelines.

Custom Tethering Solution

- **Websockets to the rescue!**
  - Implemented in browsers.
  - Bi-directional, full-duplex connection over a single TCP socket.
  - Modern smartphone browsers have implemented websockets.

Implementation

Some questions

- How to connect phone to laptop?
- How to encode data?
- Virtual interfaces: TUN or TAP?
- Client: setting up routes
- Server: what to do with the packets you receive?

Some Resources

- **TUN/TAP Interfaces**
  - TunTap package for Mac OSX
- **Websocket Server**
  - Twisted
- **NAT**
  - Scapy
- **Base64 Encoding**
  - http://www.ietf.org/rfc/rfc3548.txt