How **not** to write network applications

(and how not to use them correctly..)

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Overview

- A simple overview - including HTTP basics
- A few “bad” examples, notably from Squid/Apache - and what they’ve subsequently done
- An “ok” example - notably lighttpd
- “good” examples - memcached, varnish
- What is libevent ?

Overview (ctd)

- Latency, bandwidth delay product, and scheduling network IO
- Why does disk IO matter?
- Summary

Introduction

- Writing network applications is easy
- Writing efficient network applications is less easy
- Writing efficient, scalable network applications is even less easy
- Predicting your real-life workloads and handling that is difficult

Lessons learnt, #1

- High-performance network applications needs clue
  - Coding clue
    - Algorithm choices, structure
  - Hardware clue
    - How fast can you push what
    - Gathering/Interpreting profiling

Lessons learnt, #1

- Operating system clue
  - Best way to schedule stuff
  - Worst ways to schedule stuff
  - Profiling!
- Networking clue
  - “speed of light”
  - TCP/UDP behaviour

Lessons learnt, #1

- Protocol clue
  - How does the protocol work
  - Client <-> Server communication
  - Client behaviour, Server behaviour
  - How this ties into the network

An example: HTTP

- HTTP is .. strange
- A large variance in usage patterns, client/servers, traffic patterns, software versions, network behaviour..
- Small objects
  - < 64k
  - will never see TCP window size hit maximum during initial connection lifetime

An example: HTTP

- Large objects
  - Well, >64k really
  - Will start to hit congestion and back-off limits
  - Throughput variations are perceived by end-user
    - versus small objects - request/reply rate dictates perceived speed

An example: HTTP

- But there's more!
  - HTTP keepalives affect TCP congestion
  - HTTP pipelining influences perceived request speed on small objects
  - Clients and servers have differently tuned TCP stacks...
    - ..."download accelerators", anyone?

Apache: History!

- The pre-fork web server
- internals **should've** been clean because of this
- Handled high-reqrate poorly
- Handled high numbers of concurrent connections poorly
- Flexible enough to run a variety of processing modules - php, python, perl, java..

Apache: History!

- Why did it perform so poorly under load?
  - Memory use - each connection == 1 process; SSL/PHP/Python/etc overheads
  - .. even if the request didn’t require any of that
  - scheduling 30,000 concurrent processes == hard (Jeff: is it that bad nowdays?)
  - small amount of paging == death

Apache 2: Revolution

- Decided to abstract out the dispatching runtime - thread pool, pre-fork
  - To handle varying platform support, incl. Windows, Netware
- Abstracted out the socket polling where relevant - select, poll, kqueue, epoll, etc
- User can select which dispatcher (MPM) they wish to use at compile/install time

Apache 2: MPM

- Quite a few MPM modules for scheduling work
  - Traditional prefork
  - Process + thread worker module
  - Thread-only worker modules (Netware)
  - Something windows-specific

Apache 2: Performance

- Pre-fork: same as apache 1
- Worker thread models:
  - network IO only? It should be fast enough for you
  - Disk IO too? Things get scary: the worker thread pool begins to grow!
- thread seems to scale (as a proxy) to >10000 concurrent connections

Apache 2: Modern Use

- Split up different services - static, dynamic, application
- Configure a front apache (running thread MPM) as a proxy; "route" content to applicable backend
- Static content? Don't waste memory on PHP.
- PHP/etc content? Don't stall static content serving

Squid: History

- Squid: its been around a while
- Its not as bad as people make it out to be
- Its getting better as I find free time
- Compared to modern proxies, its slower..
  - .. but it handles a wide cross-section of traffic loads (except "lots of traffic"..)
  - .. lots of traffic defined at ~ 1000 req/sec and about 200mbit of mixed traffic

Squid: internals

- Single process/thread event loop for everything but disk IO
- Non-blocking network IO
- Has grown kqueue/epoll/etc support
- Uses threads/processes to parallelise blocking disk IO
- Attempts to mitigate overload conditions where humanly possible (ie: where I find them)

Squid: whats wrong?

- Far too much code ..
  - ~ 25 functions account for 40% of CPU
  - ~ 500 functions account for the other 60% of CPU (userland)
- IO done in small amounts
  - Disk IO - 4k
  - Network IO - 16k
  - This isn’t as bad as you think.. read on

Squid: whats wrong?

```
CPU: Core 2, speed 2194.48 MHz (estimated)
Counted CPU_CLK_UNHALTED events (Clock cycles when not halted) with a unit mask
of 0x00 (Unhalted core cycles) count 100000
samples % image name symbol name
216049 6.5469 libc-2.7.so memcpy
115581 3.5024 libc-2.7.so _int_malloc
103345 3.1316 libc-2.7.so vfprintf
85197 2.5817 squid memPoolAlloc
64652 1.9591 libc-2.7.so memchr
60720 1.8400 libc-2.7.so strlen
```

Squid: whats wrong?

- Codebase has grown organically
- Squid-cluey programmers were hired by Akamai, etc - suddenly no-one was working on performance
- Ten + years of features added on top of poor structural base, and HTTP/1.1 still hasn't appeared..
- .. but the poor structure is now looking better

Squid: network IO?

(ACCELERATOR)
HTTP I/O
number of reads: 19463301
Read Histogram:

1-	1:	5194	0%
2-	2:	4675	0%
3-	4:	1588	0%
5-	8:	10412	0%
9-	16:	351771	2%
17-	32:	89452	0%
33-	64:	63398	0%
65-	128:	81808	0%
129-	256:	337836	2%
257-	512:	412245	2%
513-	1024:	928914	5%
1025-	2048:	14296942	73%
2049-	4096:	1731657	9%
4097-	8192:	808069	4%
8193-	16384:	205358	1%
16385-	32768:	60013	0%

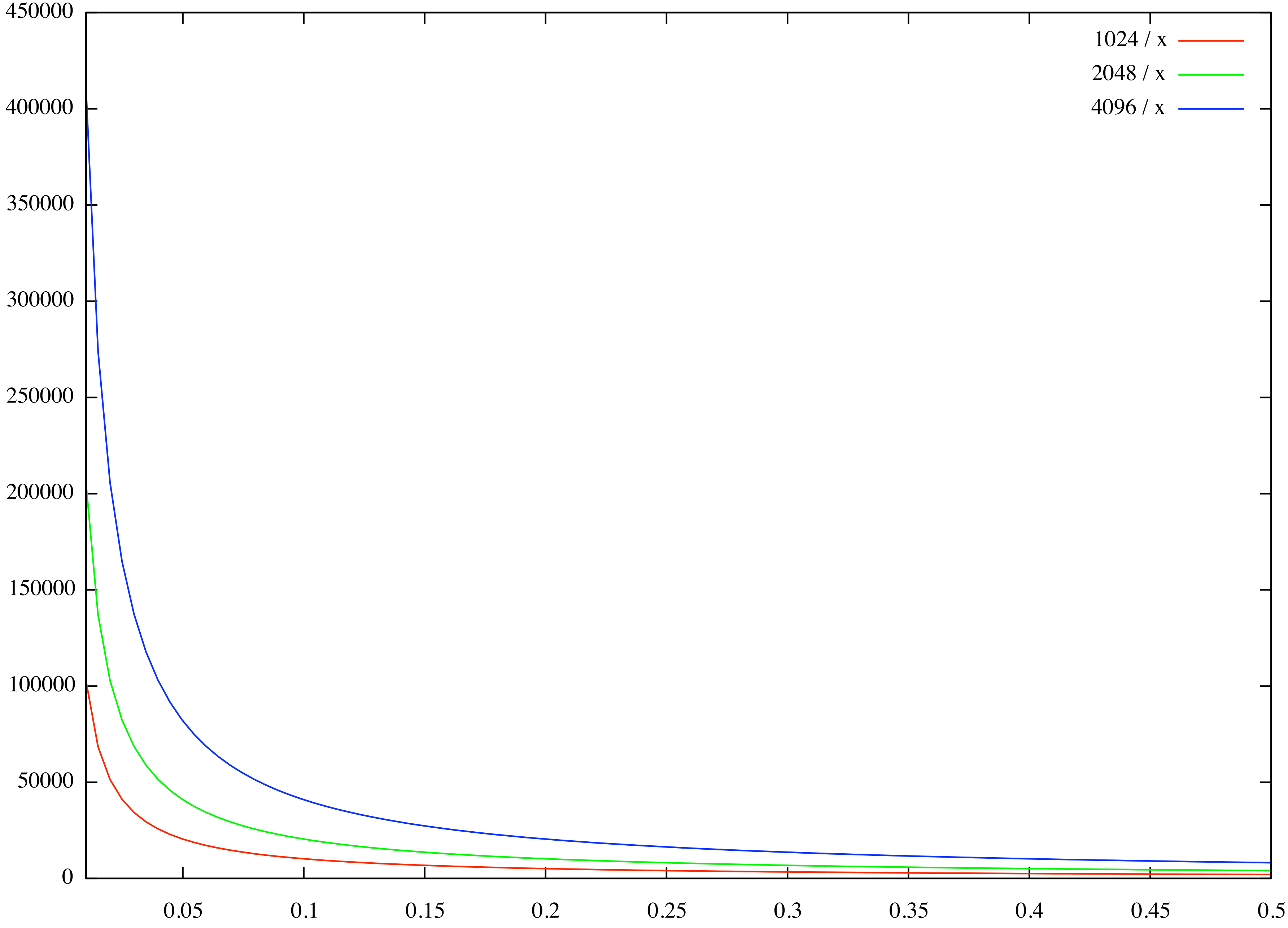
(PROXY)
HTTP I/O
number of reads: 3087754
Read Histogram:

1-	1:	11327	0%
2-	2:	208	0%
3-	4:	1211	0%
5-	8:	617	0%
9-	16:	1421	0%
17-	32:	3400	0%
33-	64:	6079	0%
65-	128:	14680	0%
129-	256:	20808	1%
257-	512:	57378	2%
513-	1024:	2931775	95%
1025-	2048:	25183	1%
2049-	4096:	3767	0%
4097-	8192:	4061	0%
8193-	16384:	5839	0%
16385-	32768:	0	0%

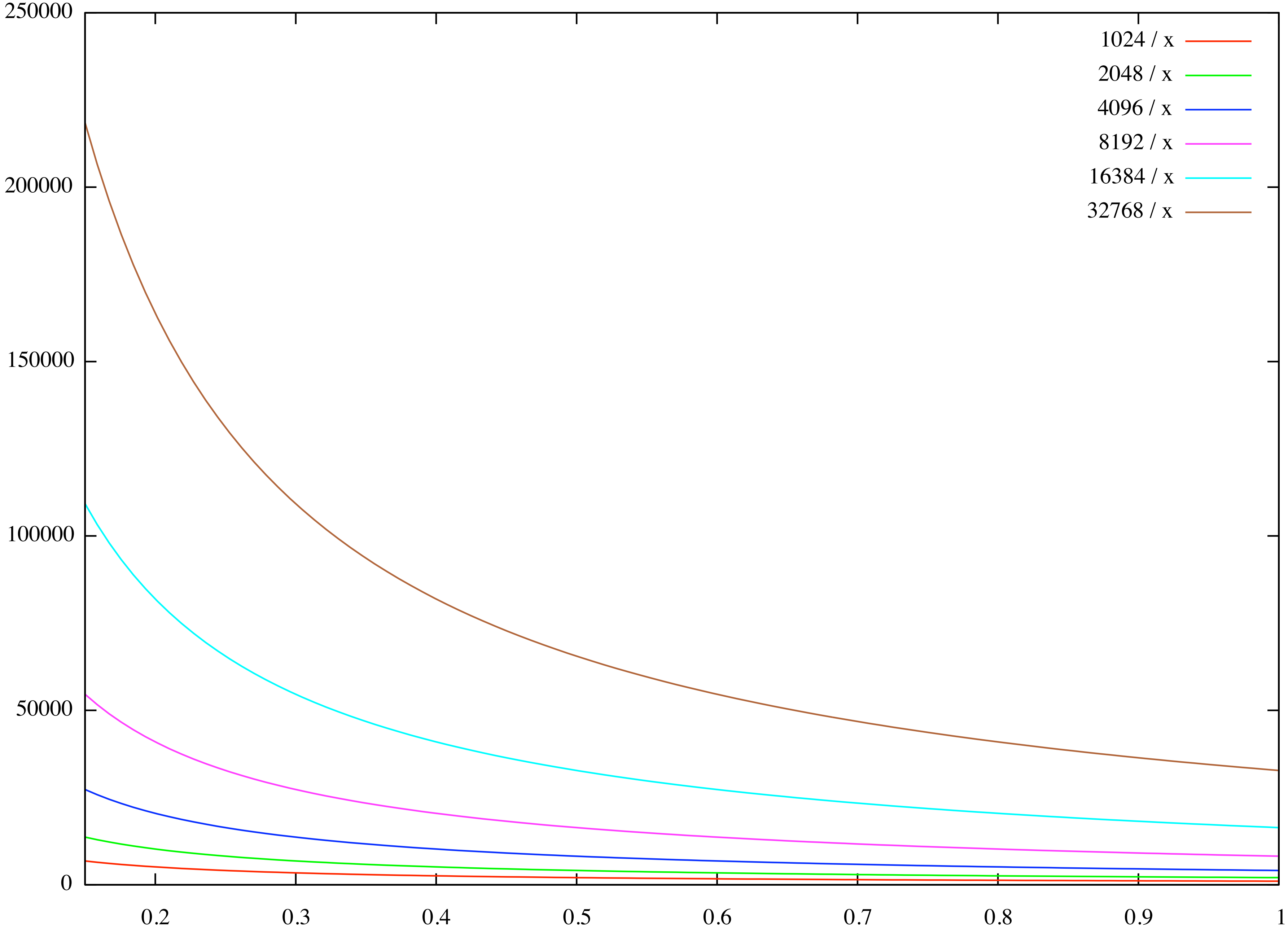
Squid: Network IO?

- Talking over a LAN != Talking over a WAN
- Larger socket buffers == faster throughput
  - But only up until bandwidth delay!
- Larger socket buffers also == wasted RAM
- Choose socket buffer size based on required throughput **and** concurrency, based on **client delay**.
  - .. which can vary, so its tricky ..

Theoretical: <= 4k bufs



Theoretical: <= 32k bufs



Socket buffers (again)

- So socket buffer sizes are a tradeoff
  - eg: 10,000 4k socket buffers: 40 megabytes
  - eg 10,000 32k socket buffers: 320 megabytes
  - Double that (at least) if the application buffers in-flight data until the kernel says its sent!

Squid: Disk IO

- Don't use one-file-per-object for small, frequently accessed files
  - If you do, at least pretend to dump related objects in the same directory
  - open/close metadata overheads are high
  - If you're unlucky, >2 seeks to open a file that isn't in VM/buffer cache
    - .. and then the IO is done in 4k chunks

Squid: 4k disk IO?

- Transfer rate at 32k (18gig 10krpm SCSI)
  Runtime: 41.32 seconds, Op rate: 247.84 ops/sec, Avg transfer rate: 8121367.38 bytes/sec
- Transfer rate at 4k (18gig 10krpm SCSI)
  Runtime: 32.27 seconds, Op rate: 317.28 ops/sec, Avg transfer rate: 1299566.81 bytes/sec
- ops/sec drop by 22%; transfer rate up by 6x
- need to squeeze small objects into larger blocks on disk **and** increase IO size

Squid: logging

- It **did** use stdio calls for logging
- .. which may block on buffer flush
  - anecdotally, topping out the logging performance at ~ 300 req/sec
- Current logging code: log to memory buffer; send buffer over pipe() to helper process
- Later plans will turn this into a thread
- Limited by Squid: can log ~ 4000 req/sec to disk with no service impact

Squid: reply sizes

- Like the object histogram, actual reply sizes (and the time length to serve them) varies greatly
  - Forward proxy: mix of small and large
  - Accelerator: may be a mix; may be just small, may be just large, may be both
- If you're clever, you can handle all of these cases efficiently enough
- .. or you can assume everyone is local..

Squid: reply sizes

- Sample 1: Forward proxy
- < 8k - 314871
  < 64k - 2448235
  < 256k - 333
  <1M - 6761
  < 32M - 20874
  > 32M - 3132
- Most requests are < 64k; with a secondary small peak between 1M / 32M

Squid: reply sizes

- Sample 2: (last.fm; used with permission)
- < 8k - 3249802
< 64k - 5618618
< 256k -1357
< 1M - 33407
< 32M - 88592
> 32M - 11511
- Again, most are <64k; ~ 100k (~1.2%) are >32M
- What are the implications of these?

Squid: reply sizes

- Those large replies will be streaming replies, either from disk or from another server
- Much more data transmitted!
- Long-held connections, potentially filled TX socket buffer
- Transmitting these should not interfere with small object replies
- .. and for the most part, Squid handles that dichotomy fine

Squid: load shedding

- At some point you'll receive more requests then you can handle
- You need to gracefully(ish) handle this so the service doesn't spiral into death
- Squid does this in a number of places
  - Too many connections? Stop accept()'ing
  - Too much disk IO? Stop disk HITs; fail to MISSes

Squid: accept() rates

- Balance accepting new connections and handling existing connections
- More difficult with poll()! (Ie, how often to run poll() over the incoming vs all sockets)
- In the past - full accept queue -> ignore new requests
- Currently (AFAICT) - full accept queue -> RST new requests
- Impacts service; impacts SLB logic

Squid: Disk IO

- Overloaded disk IO queue?
  - First: Turn object creates into create fails; limit hits to memory only
  - Then: Turn object reads into fails; limit hits to memory only - generally turn into temporary MISS -> backend fetch
  - Problem: increased backend load
    - .. and this can also cause your service to spiral down into death

Lighttpd: New Stuff

- The Ruby crowd loves this thing for some reason
- Isn't a HTTP server so much as a "HTTP content router"
- Save a few things (eg static, flv); all complicated stuff is done via fastcgi back-ends
- Attempted to handle sendfile() where appropriate

lighttpd: internals

- Again - select/kqueue/poll/epoll style event loop with callbacks
- Monolithic process - SMP implemented as simply running >1 process
  - Which works very well for what lighttpd does
- Attempts to schedule "IO operations" internally which map to a variety of options
  - read, readv or sendfile, for example

lighttpd: whats right

- The majority of complicated behaviour is implemented through fast-cgi modules
  - Ie, lighttpd doesn't run PHP, etc in its own process
- This frees up lighttpd to be a HTTP content router to "other" things locally and/or over the network
- It just happens that it also serves static content quite well

lighttpd: whats wrong

- “Chunk” interface - A list of “chunks” to write to the client
- A “chunk” could be memory, disk, another network socket
- “disk” chunks would be read/sendfile ()’ed as needed..
    - .. and the whole process stopped if the read needed to block.
- Apparently fixed in later versions!

lighttpd: anecdotally

- Feedback from various teams inside a large content provider
- Lighttpd doing straight static replies:
  - ~ 1k: ~10,000 req/sec per CPU
  - ~ 2k: ~8000 req/sec per CPU
  - ~ 4k: ~5000 req/sec per CPU
  - > 8k: about the same speed as Squid
    - 4k, 5000 req/sec => 200mbit / sec

Varnish

- (Hi PHK!)
- Initially I had a lot to talk about, but my data has fallen through from third parties

Varnish

- A good example of how far you can push hardware and software
- A bit workload-specific : handles small objects well; much larger objects not so well
- Anecdotal evidence about handling lots of slow clients poorly (this is what I wanted data about!)

Varnish: internals

- (Insert PHK's slides from last year here)
- Pool of worker threads
- Network/VM IO done sync, not async
- Parallelism through worker threads
- Good pthread locking, efficient parsing, efficient data exchange, doesn't abuse memory allocator, VCL is shiny

Varnish: internals

- Instead of complicated hard-coded rules (a la Squid and most other things), forwarding and caching logic is implemented in VCL
- Which is translated into C and inserted into varnish at runtime
- Reliant on scatter-gather IO (good!) and VM system (not so good, see below)

Varnish: in production

- Works great for some
  - Hot workload fits in RAM; small objects? Fantastic
- Anecdotally, doesn’t work great for others
  - Slow backend w/ popular objects? Not so good. (Squid -> “collapsed forwarding”)
  - Slow clients/servers -> not so good

Varnish: VM?

- Varnish uses the VM system quite extensively
- The VM system is great at the average, but needs to be “taught” about HTTP access patterns to optimise disk throughput
- Eg: pack small objects into contiguous pages
- Eg: do IO in larger parts to save on disk ops

Varnish: the “good”

- Scales well across multiple CPUs
- Handles its workload very well
  - (Ie, puts other proxies to shame)
- Does stuff “differently” (in a good way)
  - Eg - logging, statistics reporting
  - VCL - don’t hard-code your application logic!

Memcached

- Or, as I like to call it, "mysqlcached"
- A memory object cache for storing and retrieving "stuff"
- "stuff" is generally SQL queries, but can be whatever the heck you want

Memcached: Internals

- Started as a Squid-like single process async event loop
- First time I saw it: it used libevent
- A couple years ago? - threaded
  - N threads, one per CPU
  - One thread handles incoming connections
  - All threads: handle actual work

Memcached: scaling

- It scales quite well..
- .. but it isn't a complicated program!
- Memcached scaling is generally limited by OS parallelism - FDs, socket, TCP, UDP, IP
- Doesn't need to schedule disk IO; all operations are memory based

Memcache: issues

- Similar to Squid/Varnish: small objects pack badly
- Apparently(!) Memcache tries to pack objects using 32 bit pointers in 64 bit environment
- Squid - 160 byte StoreEntry, 70 odd byte MD5; 30 odd byte MemObject; 4k object granularity
  - Memory wastage on small objects

Libevent?

- Libevent is a simple(!) library for scheduling network IO events across UNIX platforms
- Implements poll, select, kqueue, epoll, /dev/poll, solaris event ports
    - (and Windows; but thats a different story)
- Basic threading support - run multiple event queues, one per thread

How is libevent used?

- Create queue - event_base * event_init();
- Run the queue - event_base_loop (event_base *);
- Setup events - event_set(event *, fd, what, callback, data)
- Throw event into a queue - event_base_set ()
- Schedule event - event_add(event *, timeval *)

Does libevent scale?

- Scales well across multiple CPUs - each libevent queue runs seperately
- Event registration isn't O(1) - uses trees for registering timer/immediate events in priority/order
    - A "derivative" libevent tries to avoid this overhead

Trouble with Libevent

- Standard UNIX problem - inter-thread communication
- Thread sleeps on poll/select/kqueue/etc; how does another thread wake it?
- “portable” method - create pipe; write byte to “wake” up destination thread to check message queue
- Each UNIX has a different way of solving this!

How low can you go?

- A simple libevent-based TCP proxy
  - accept() connection, connect() to another; shuffle data
- CPU parallelism by using one thread per CPU
- Core 2 Duo desktop: E2200
- Variable socket sizes; variable concurrency
- How far can things be pushed?

TCP Proxy: One thread

- One userland thread
- One kernel thread for network device IO
    - Can split that into device/netisr threads
- Throughput: ~4kbyte objects; ~400mbit/sec; 12000 req/sec - 24,000 sockets/sec
- One CPU maxed userland; other CPU mostly maxed doing device/netisr

TCP Proxy: two threads

- Two userland threads
- Same setup
- Only incremental improvement - 500mbit; slightly more requests/sec
- Both CPUs at 100%
- Why?

TCP Proxy: contention

- One particular area of contention:
  - TCP PCB processing
  - Robert/Kris will be working on this
- Userland CPU breakdown:
  - <5% userland CPU both CPUs; so the userland is fine
  - Is it "doing" things efficiently?

TCP Proxy: buffer size

- What happens if you up the socket buf size?
- (And what happens if you up the transaction size?)
  - Transaction size: higher throughput; approaching 800mbit FDX
  - Socket buffer size: no appreciable difference on LAN
  - Need to model WAN traffic a little better!

Bandwidth Delay

- .. this isn't just a problem on the WAN
- LAN's have similar issues with gige/10ge pipesize
- In summary - you end up having to pipeline
- .. why would you need to pipeline on a **LAN ?**
- (eg - NFS)

NFS and Delay

- Say, 4k transactions over the wire
- How can you get gigabit speed with 4k transactions?
  - 100 megabytes/sec / 4kbyte/sec => ~25k packets a second
  - Each transaction: 0.00004 sec (0.04 msec)
- If your transaction for 4k block > 0.04msec, you won't saturate gigabit ethernet

NFS, Delay, real-world

- Comptuational cluster serving data over NFS
- Legacy fortran code, ~ 1kbyte data chunking
- Bad throughput!
  - CPU wasn't maxed
  - Disks weren't maxed
  - Network wasn't maxed
  - ... ?

NFS, Delay, Real world

- Problem is due to NFS transaction latency!

Disk IO ..?

- Lots of applications do disk IO to push out to the network
- Think about latency on disk IO + latency on network IO -> effective transfer rates
- UNIX network IO - traditionally sync
  - POSIX AIO makes this less painful
  - Faked using Threads/Processes

Scheduling Disk IO

- How its done in Squid:
  - aio_read(fd, buf, size, callback, cbdata)
  - ... buffer is returned
  - .. event_add(socket write event, timeout)
  - .. socket is ready
  - write(sockfd, buf, size)

Scheduling disk IO

- The problems!
  - Standard UNIX read/write involves a kernel copyin/copyout, which takes quite a bit of time
  - POSIX AIO in FreeBSD should make this much less painful - shouldn't copy disk data
  - Prefetching or no-prefetching?

Disk IO: prefetching?

- How much data can you pre-fetch?
  - Balance between reading slightly more data from disk, and how much RAM in your box (and buffer cache)
- mmap() ?
  - Again, potentially blocking!
  - You have to manually lock pages or they may even be removed underneath you..

Disk IO: sendfile

- Sendfile is a "pretty word"
- In essence - glue together a disk fd and a socket fd; ask kernel to do the heavy lifting for you without copying
- You avoid two trips user->kernel for the disk read, then the socket write
- Traditionally: blocking only; so you need threads to run the sendfile context()
- (ie, one reason varnish is what it is..)

Summary

- Writing efficient, scalable network applications is hard
- Understand what you're trying to do
- Understand how you can do it
- Understand your protocol, hardware, software
- And above all - assume users will do dirty things with it that you don't expect!

Questions?

Thankyou!

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