Make your code faster by moving it out of the kernel

The anti-kernel

About this talk

- Old: OS principles
  - For doing things the OS wants you to do
  - Moving into the kernel
- New: User-land principles
  - For breaking the rules
  - Moving out of the kernel
  - That includes hardware drivers

What OS does for you

- Locks (spinlocks, mutexes)
- IPC
- Processes/threads/scheduling
- Memory allocation
- Security
- Network stack

What you can do for yourself in userland, better

- Locks (spinlocks, mutexes)
- IPC
- Processes/threads/scheduling
- Memory allocation
- Security
- Network stack

Q: Why is moving into the kernel faster?

- A: Cost of system calls
  - Function call = ~1.8 nanoseconds
  - System call = ~30ns to ~400ns
  - Security supervisory checks are expensive
- A: virtual memory vs. physical memory
  - Virtual addresses must be translated to physical addresses
  - TLB misses require page table walk

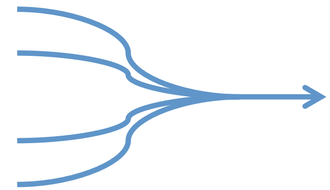
Q: So why is moving out of kernel better?

- A: because you can − even hardware drivers
- A: because you also avoid system calls and context switches
- A: because the cost of virtual memory can be mitigated

- A: because user-mode software is more robust, more secure, easier to debug

Multi-threading is not the same as multi-core

- Old: Multi-threading
  - Safety!
  - More than one thread per CPU core
  - Spinlock/mutex must therefore stop one thread to allow another to execute

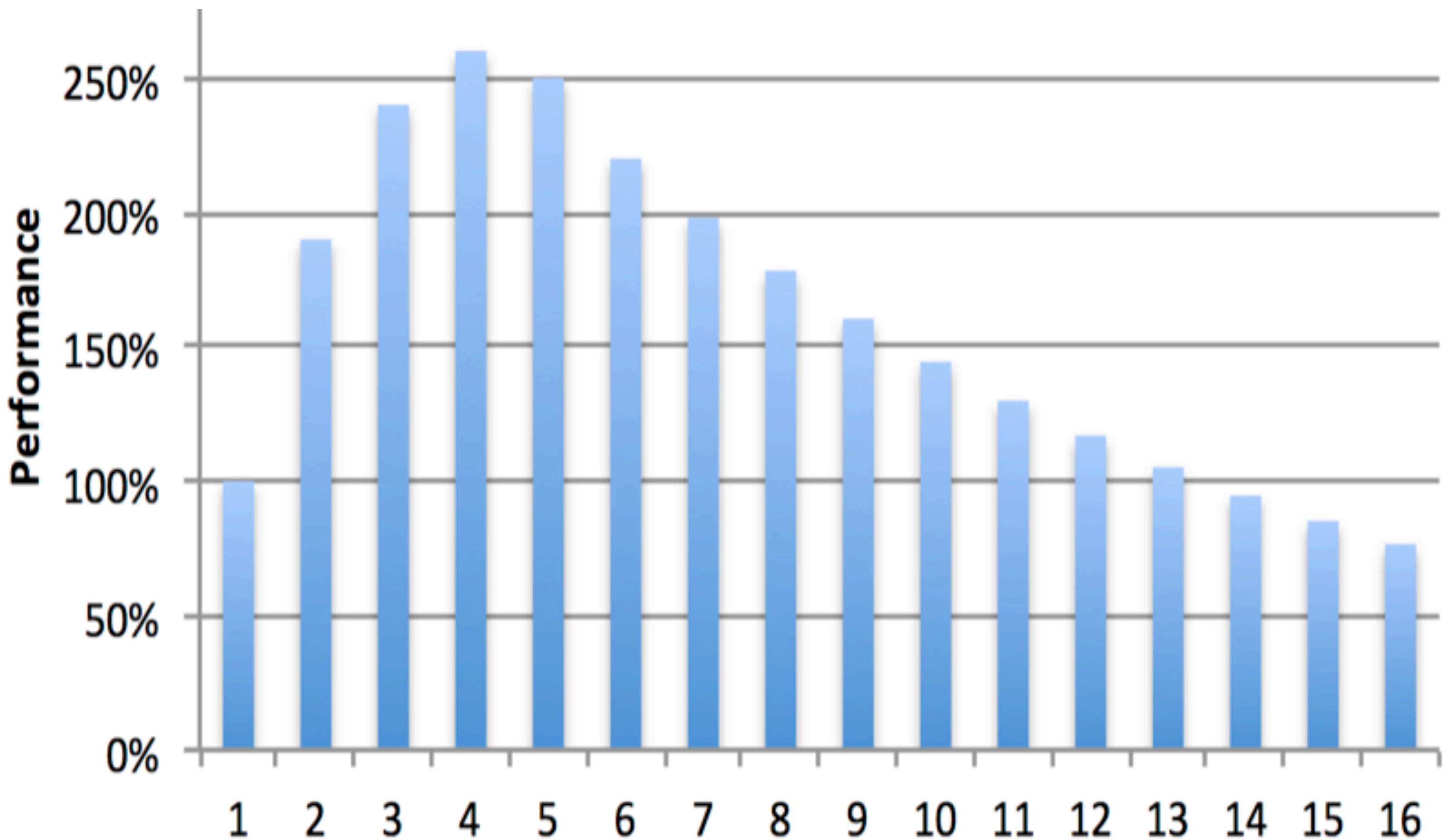


- New: Multi-core
  - Speed!
  - One thread per CPU core
  - When two threads/cores access the same data, they can't stop and wait for the other

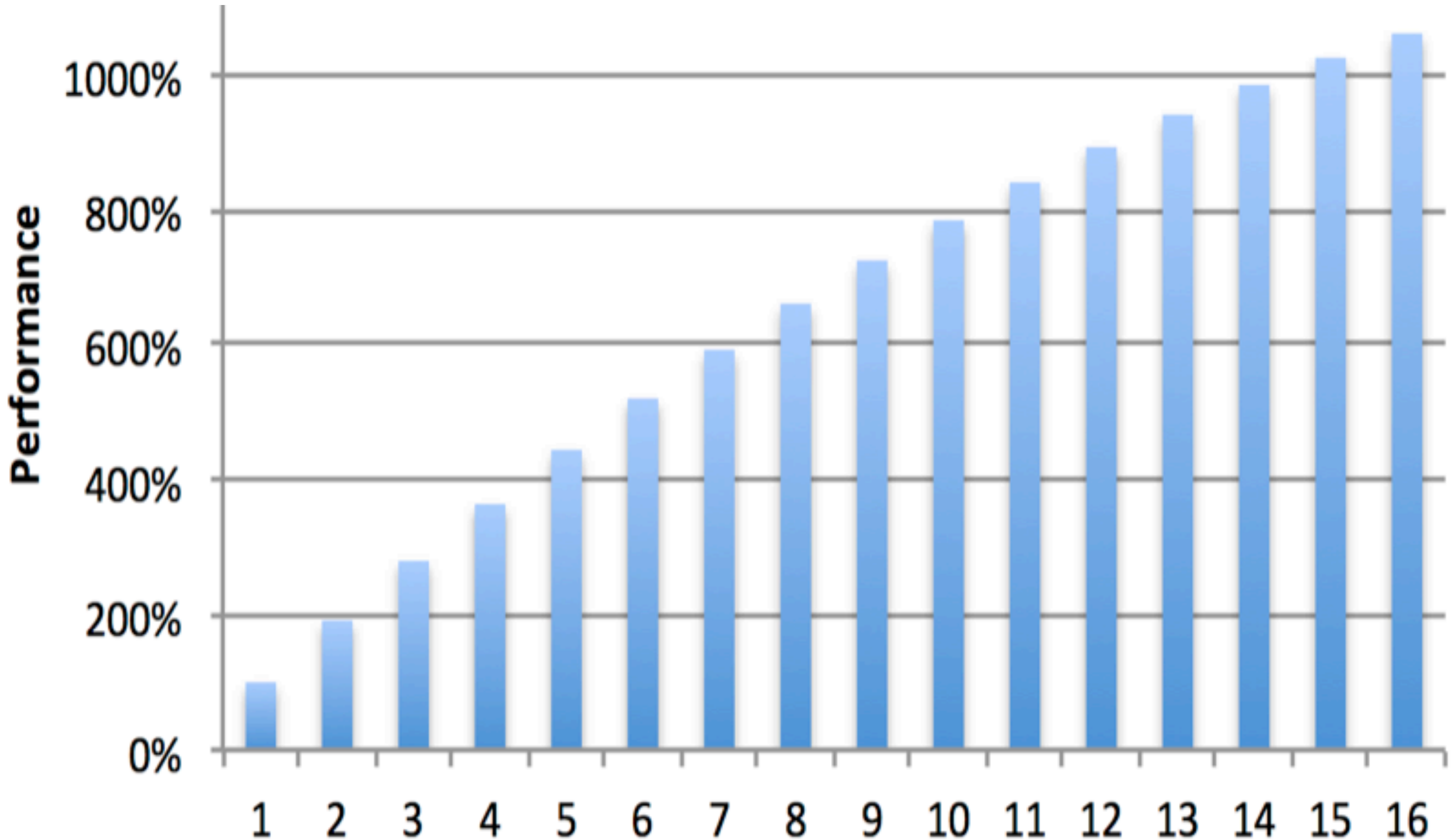
Contrast: spinlocks/mutexes

- What you were taught: better locks
- What you need to know: no locks
  - Linux kernel rapidly getting rid of spinlocks
  - Replacing with RCU and other lock-free/wait-free techniques

Most code doesn’t scale past 4 cores



At Internet scale, code needs to use all cores



Reads *or* writes are atomic

- Reading an aligned integer from memory is always an atomic operating
  - You'll never get a partial integer
  - On any CPU
- Same with writes

Example: network interface stats

```
john@bt:~$ ifconfig eth1
eth1      Link encap:Ethernet  HWaddr 00:0c:29:34:90:e7
          inet addr:172.16.134.128  Bcast:172.16.134.255  Mask:255.255.255.0
          inet6 addr: fe80::20c:29ff:fe34:90e7/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:201255 errors:0 dropped:0 overruns:0 frame:0
          TX packets:133251 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:101236165 (101.2 MB)  TX bytes:13531654 (13.5 MB)
          Interrupt:19 Base address:0x2000

john@bt:~$
```

Read-Copy-Update

- How it works
  - Make a copy of a data structure
  - Make all your changes
  - Replace the pointer, to your new one vs old one
  - Wait until all threads move forward
    - Now point to new data structure
  - Free old data structure
- Non-blocking
  - …for readers
  - …only one writer/changer at a time

Atomics

- Special hardware instructions
  - `cmpxchg16b`
  - `lock add`
  - `TSX`
- Intrinsics/libraries
  - __sync_add_and_fetch()
  - InterlockedExchangeAdd()

Non-blocking algorithms

- “Lock-free”
  - At least one thread makes forward progress
- “Wait free”
  - All threads make forward progress
  - Upper bound to number of steps any thread make make

Non-blocking algorithms

- Queues
- Hash-tables
- Ring-buffers
- Stacks, sets, etc.

Performance tradeoffs

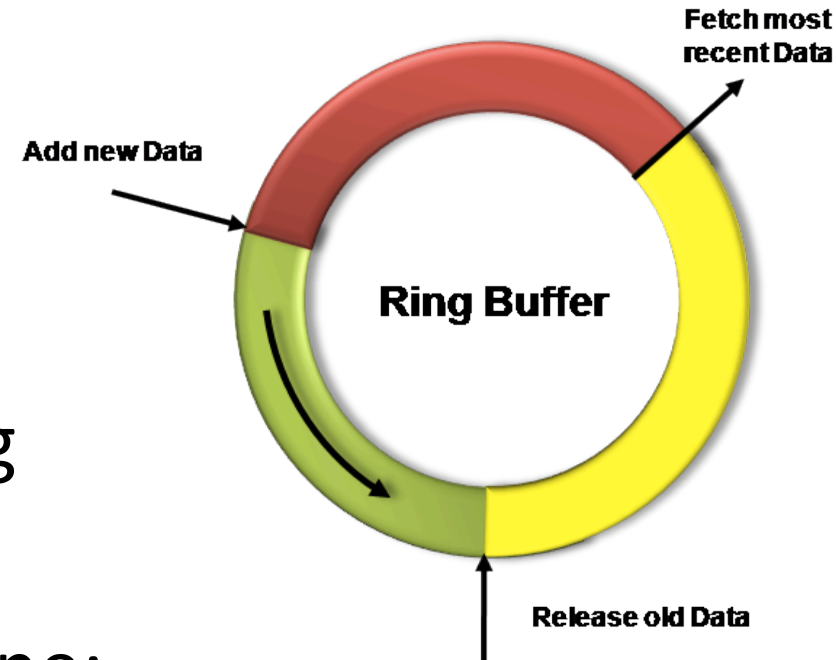
- You need to select the lock-free data structure that fits your needs
  - How frequent will contention be?
  - How many readers/writers?
  - Theoretical wait-free or lock-free?
- Sometimes the traditional spin lock is best
  - Especially for things with low contention

Most important synchronization issue

- Avoid more than one CPU changing data at the same time
- No amount of clever programming saves you if two CPUs are changing the same cache line on a frequent basis

Solution: lock-free ring-buffers Single reader, single writer

- No mutex/spinlock
- No syscalls
- Since head and tail are separate, no sharing of cache lines
- Measured on my machine:
  - 100-million msgs/second
  - ~10ns per msg



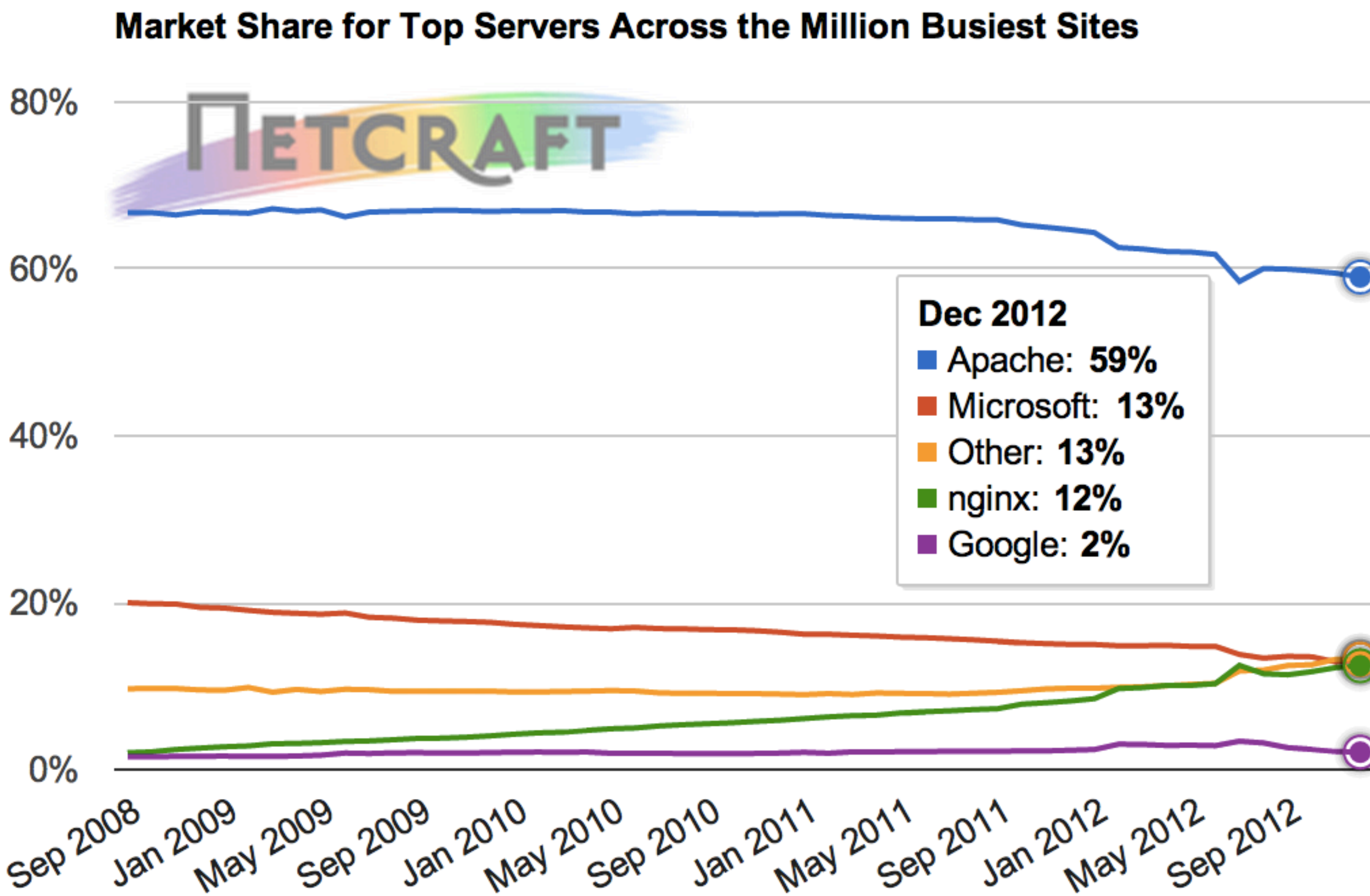
Contrast: Inter Process Communication

- Old school
  - Signals
  - Pipes
    - A hundred thousand messages/second
- New school
  - Shared memory
  - Lock-free queue
    - Millions of messages/second
  - Ring-buffer
    - Tens of millions of messages/second

Contrast: thread scheduler

- When you do this
  - When there are more processes/threads than CPUs
  - E.g. Apache with has one process/thread per TCP connection
    - For 10,000 connections
- When you don’t do this
  - When you are spreading a single task across many CPUs
  - E.g. Nginx which has one thread per CPU
    - For 1-million TCP connections

Q: Why?
A: Scale


Market Share for Top Servers Across the Million Busiest Sites
80%
60%
40%
20%
0%
NETCRAFT
Dec 2012
Apache: 59%
Microsoft: 13%
Other: 13%
nginx: 12%
Google: 2%
Sep 2008
Jan 2009
May 2009
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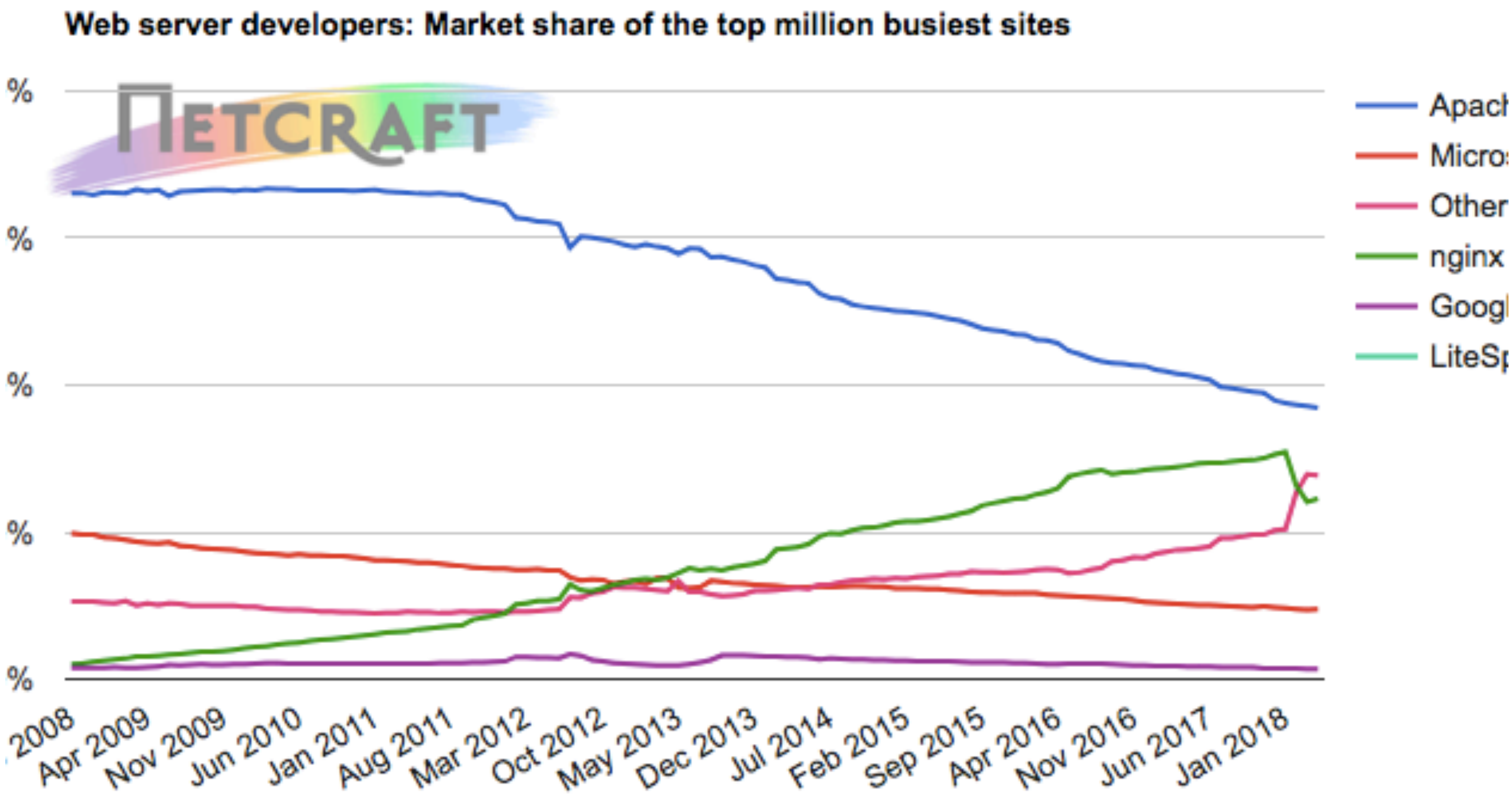
Jan 2012
May 2012
Sep 2012

Scalable solutions



Asynchronous programing (one thread per CPU)

- API
  - Epoll, kqueue, completion-ports
- Examples
  - Libuv, libev, libevent
  - Nginx
  - NodeJS
    - Bare-metal programming with JavaScript

“User-mode threads”

- Co-operative multitasking
  - Old: read() context switches in kernel
  - New: read() is function call return
- Examples
  - Coroutines in Lua
  - Goroutines in Go
  - Java green threads
  - Windows ‘fibers’

Case study: Erlang programming language

- Everything is a user-mode “process”
- No memory sharing…
- …message passing between processes instead

Case study: go

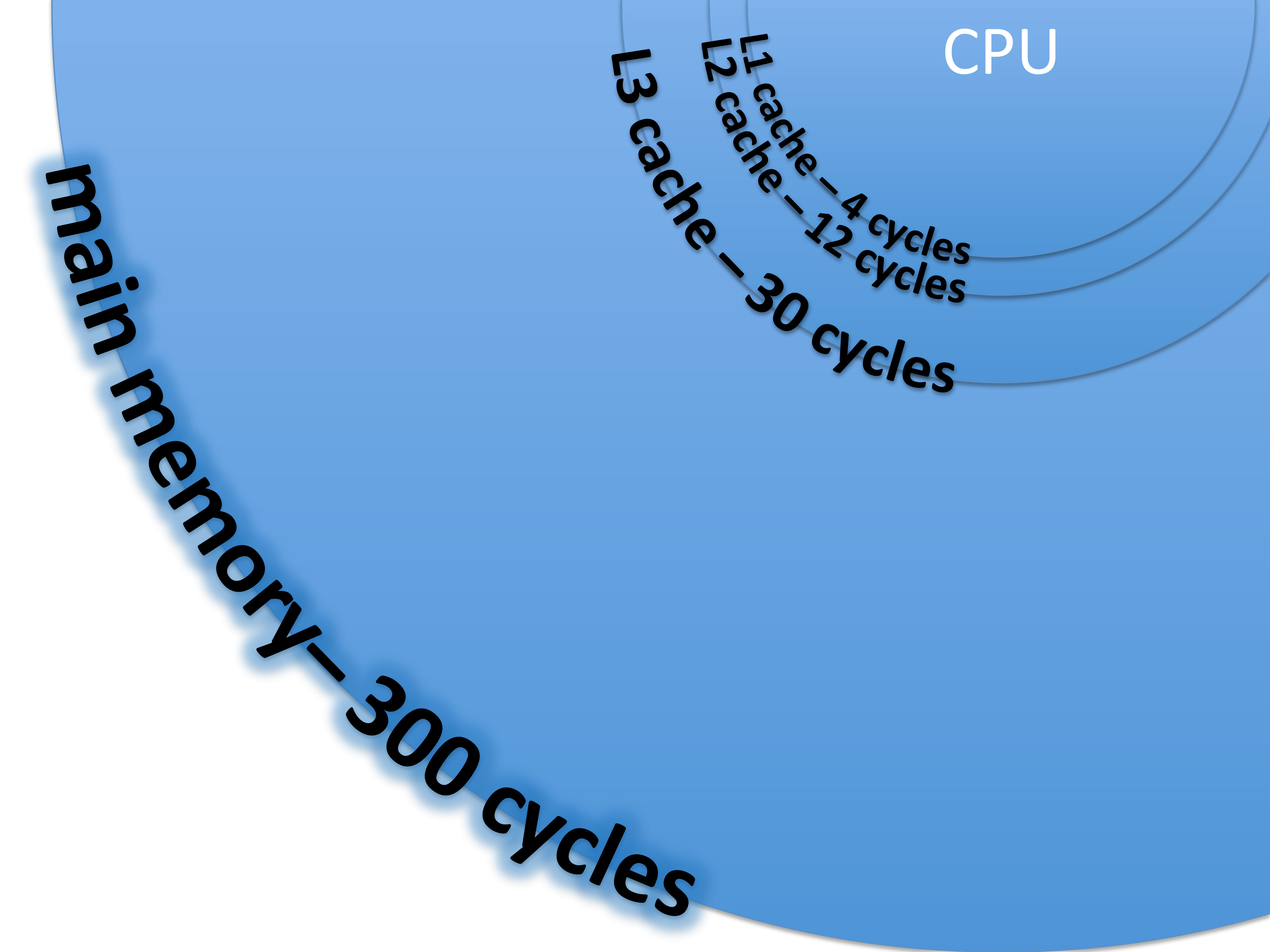
- Massive use of ‘goroutines’
- Message passing via ‘channels’ between goroutines

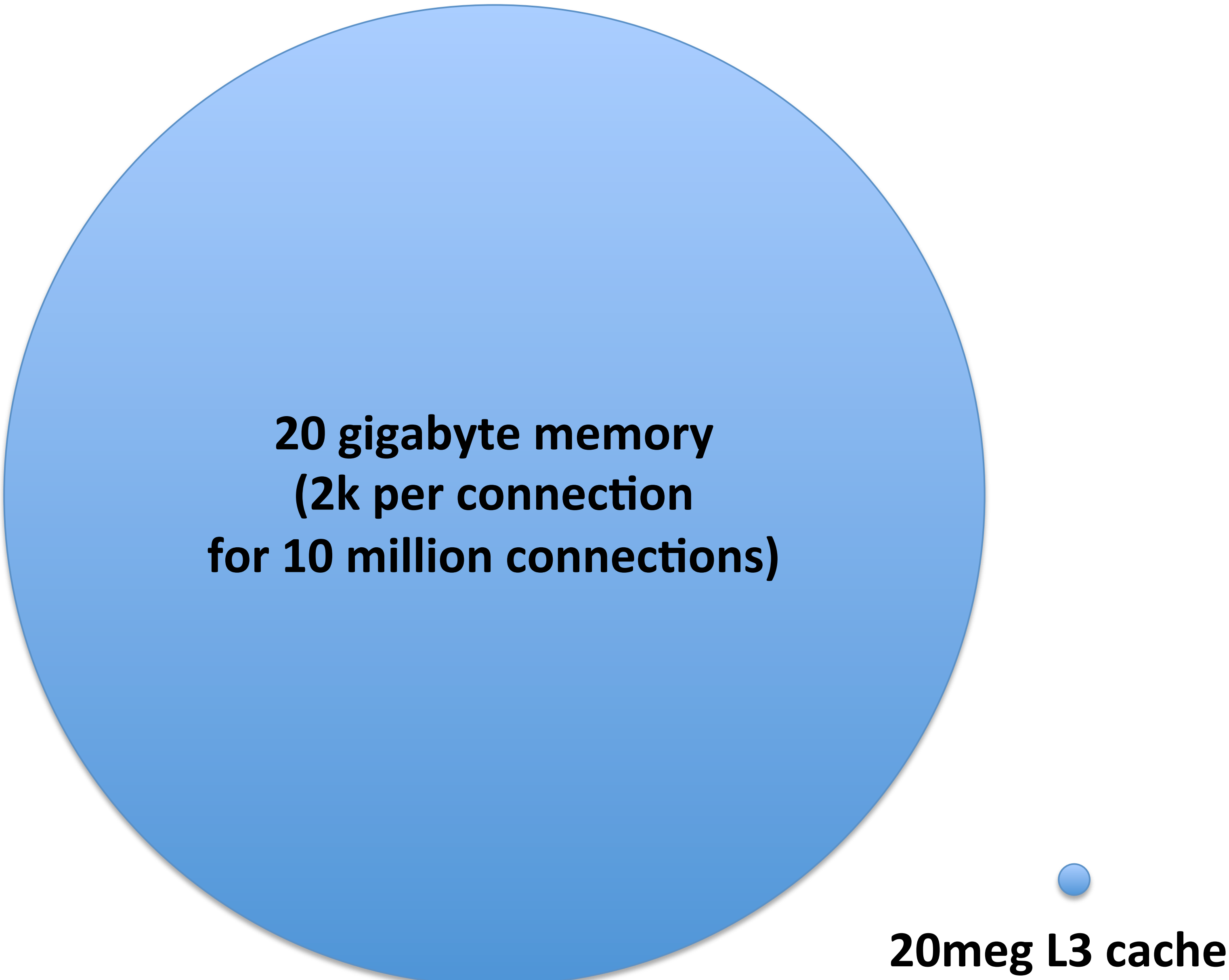
Case study: OpenResty

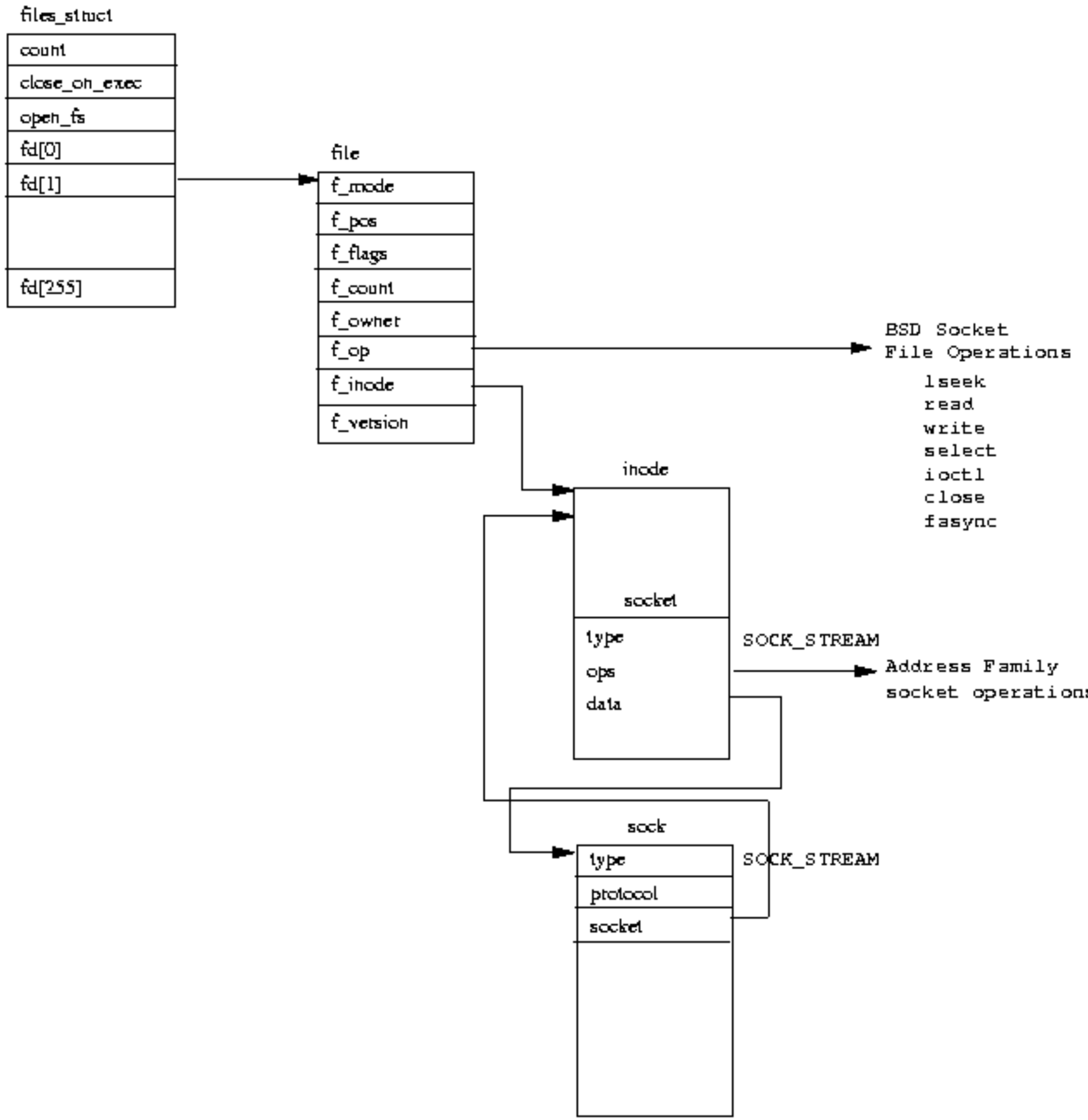
- Lua within nginx
- Lowest cost coroutines per TCP connection

Contrast: dealing with memory

- Old school
  - Many processes
  - All doing moderate memory
  - Fairness
- New school
  - One process (dedicated appliance)
  - Allocating most all the memory in a system
  - Unfairness


CPU
L1 cache – 4 cycles
L2 cache – 12 cycles
L3 cache – 30 cycles
main memory– 300 cycles


20 gigabyte memory
(2k per connection
for 10 million connections)
20meg L3 cache


files_stuct
count
close_on_exec
open_fs
fd[0]
fd[1]
fd[255]
file
f_mode
f_pos
f_flags
f_count
f_owner
f_op
f_inode
f_version
BSD Socket
File Operations
lseek
read
write
select
ioctl
close
fasync
inode
socket
type
ops
data
SOCK_STREAM
Address Family
socket operations
sock
type
protocol
socket
SOCK_STREAM

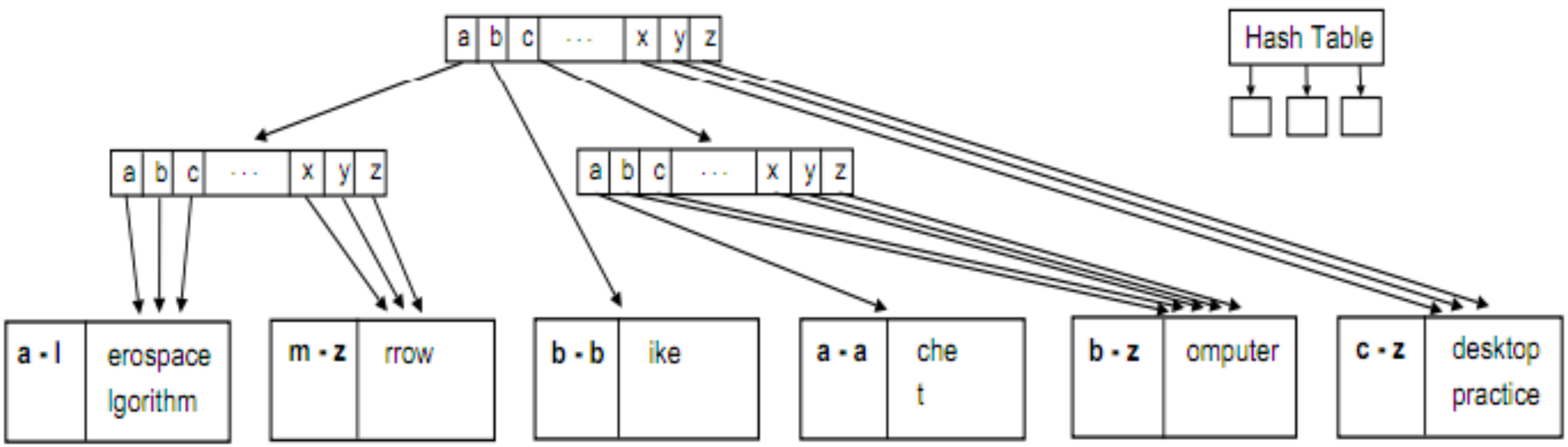
co-locate data

- Don't: data structures all over memory connected via pointers
  - Each time you follow a pointer it'll be a cache miss
  - [Hash pointer] -> [TCB] -> [Socket] -> [App]
- Do: all the data together in one chunk of memory
  - [TCB | Socket | App]

compress data

- Bit-fields instead of large integers
- Indexes (one, two byte) instead of pointers (8-bytes)
- Get rid of padding in data structures

“cache efficient” data structures

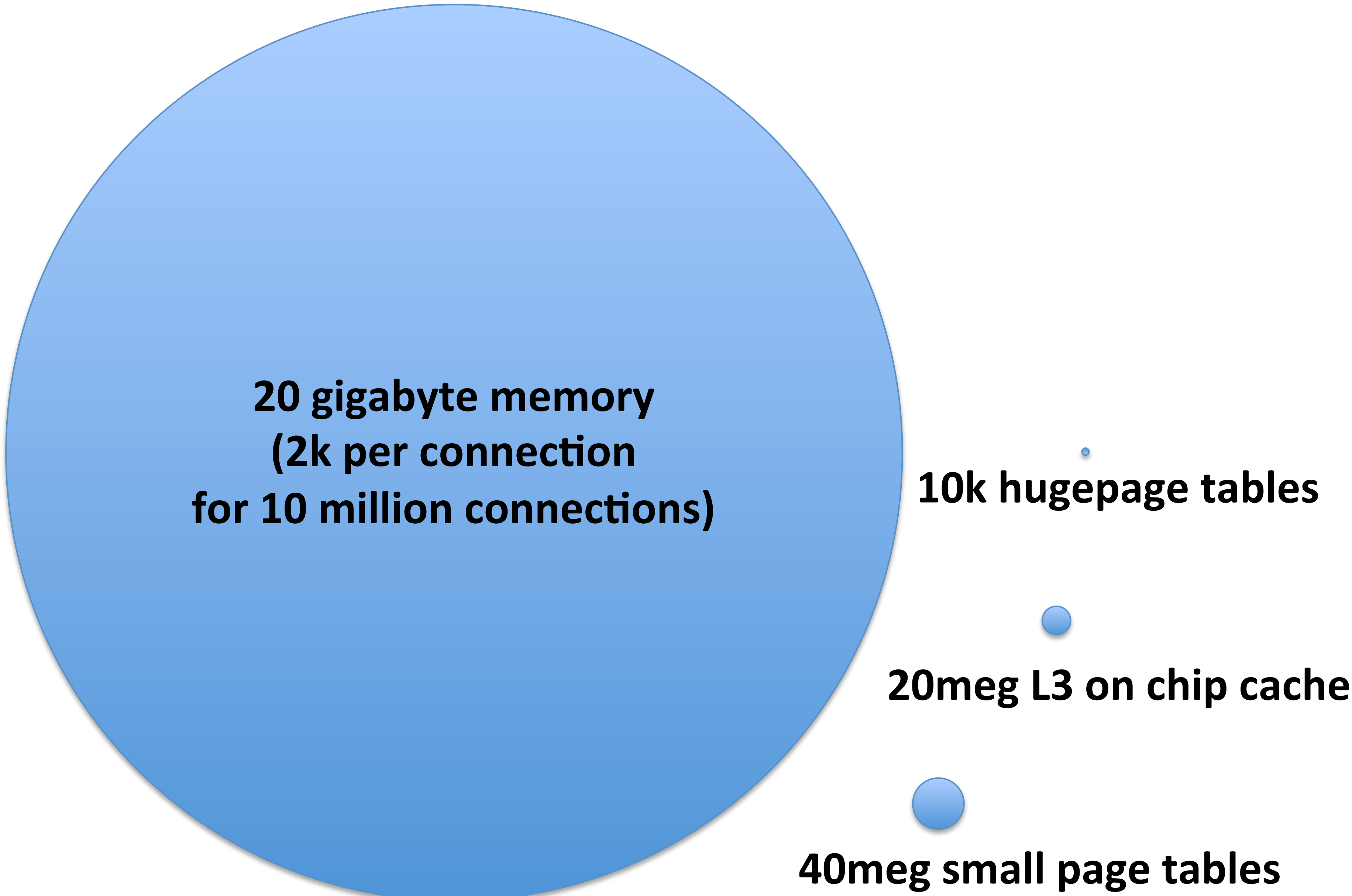


Virtual memory (aka. memory address translation)

- Review why moving code to kernel faster
  - Avoid system call
  - Avoid virtual to physical memory address translation
- Spectre/Meltdown
  - Has made this cost much worse
  - Old: kernel memory was mapped into user-memory, memory cache is the same
  - New: cache flushes a lot on each system call

“huge pages”

- What is it?
  - 2 megabyte pages instead of 4 kilobytes
  - (a chunk of 512 smaller pages)
- At scale page tables won’t be in cache
  - Thus, uncached memory lookups require two memory lookups
  - It’s a big reason why kernel code (no virtual memory) is faster than user-mode
    - That, and no transitions
- Linux auto-hugepage
  - Linux now automatically gives huge pages underneath


20 gigabyte memory
(2k per connection
for 10 million connections)
10k hugepage tables
20meg L3 on chip cache
40meg small page tables

Contrast

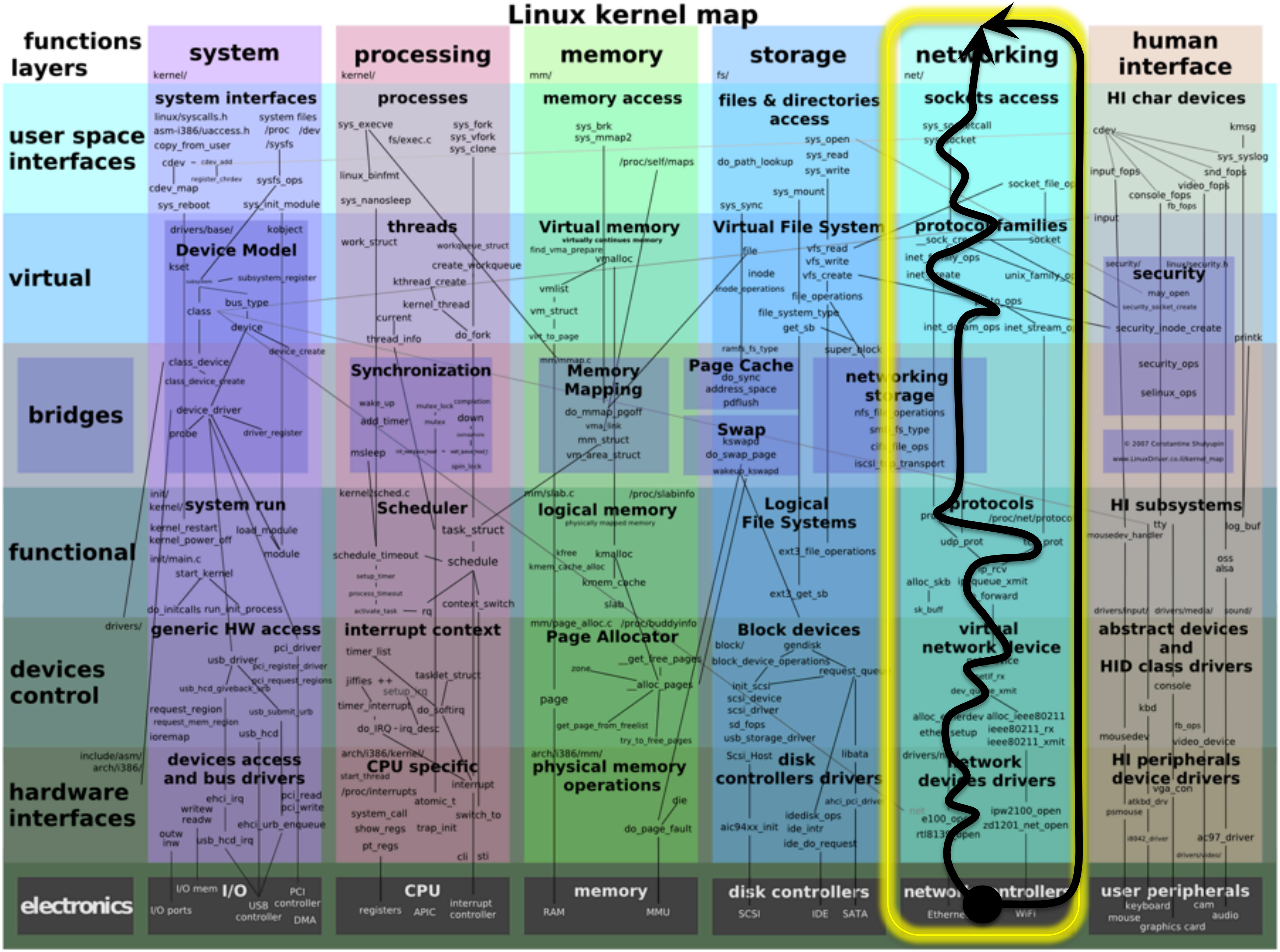
- Old school
  - Many users on the same system
- New school
  - Appliance dedicated to a single task
  - Any security you'll have to do yourself
  - E.g. CloudFlare revealing uninitialized memory

Review: system call speed

- System calls require security check on every call
- Unnecessary for dedicated appliances
- Application code still needs to do network security checks

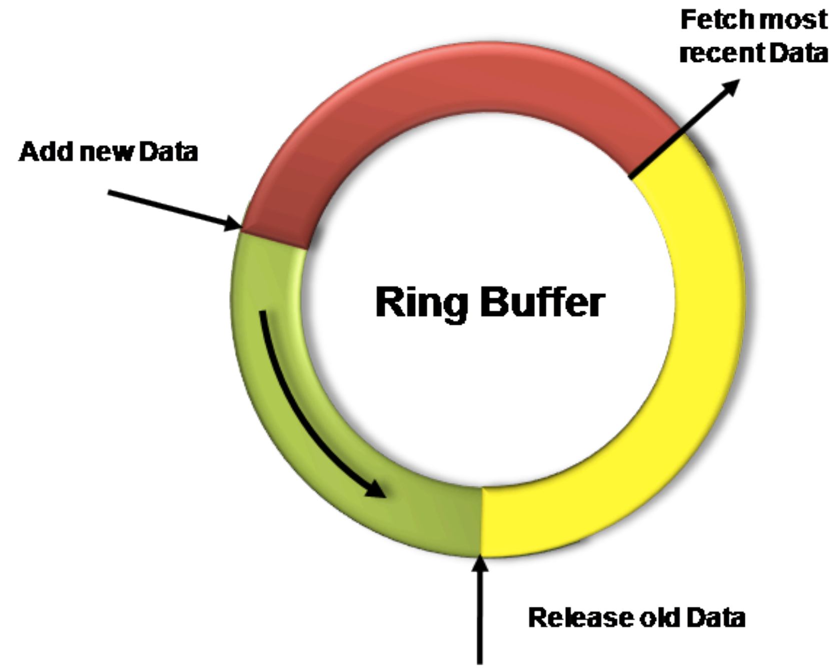
Contrast: network

- Old school
  - A network stack for many processes
- New school
  - Your own network stack, not shared with others
  - Yes, even hardware drivers, especially hardware drivers



Ver 0.6, 1/1/2008

All drivers use packet ring buffers



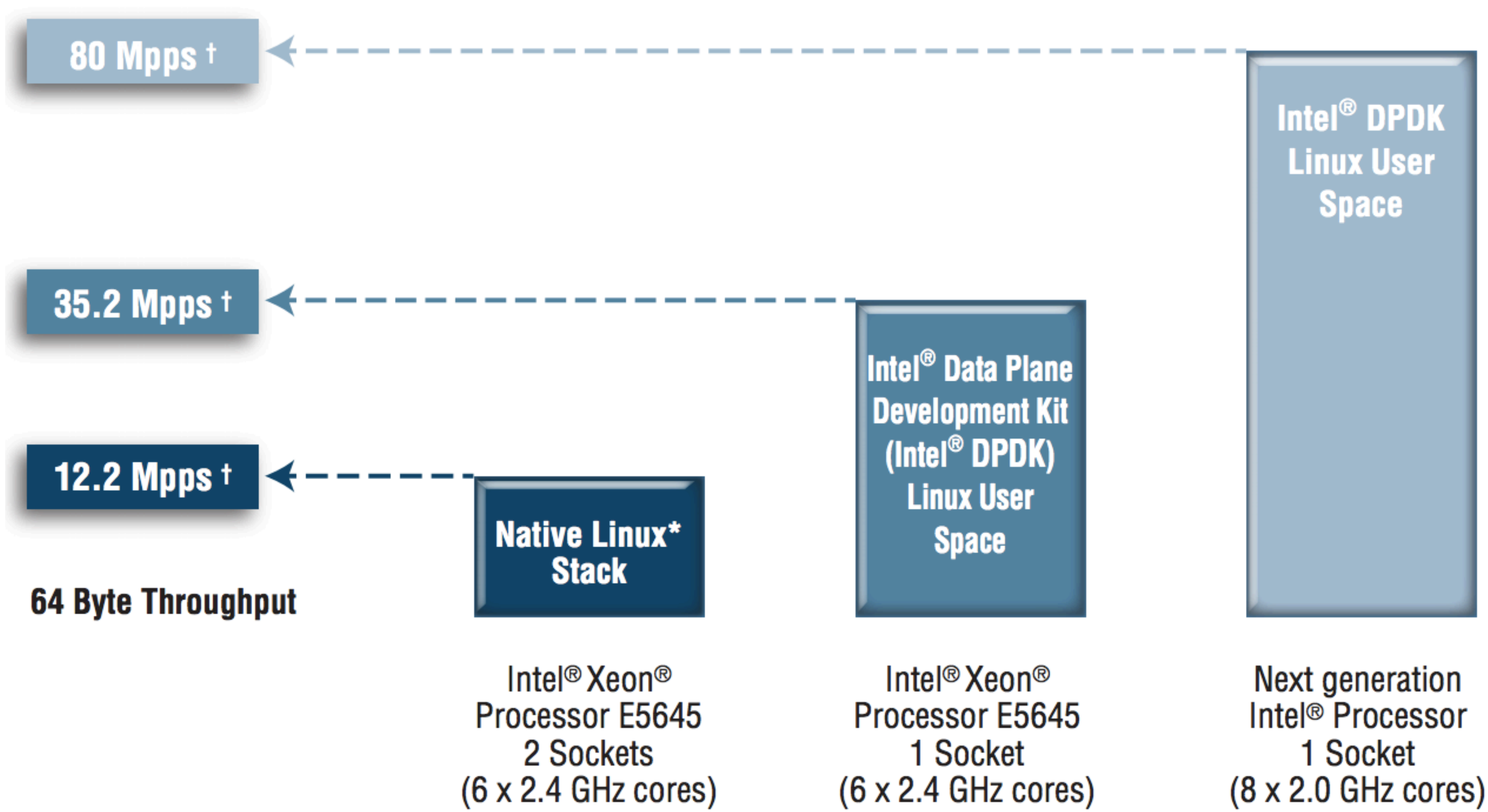
Trick

- Memory map ring buffer into user-mode
- User-mode cost
  - ~100 clock cycles to mark buffer as free
  - Packet parsed in-place inside the ring buffer
- Kernel cost
  - Must move packet out of ring buffer before processed
  - Because many apps may be using the network
  - Must either copy or alloc new buffer to replace old one
  - ~1000s clock cycles per packet

Where can I get some?

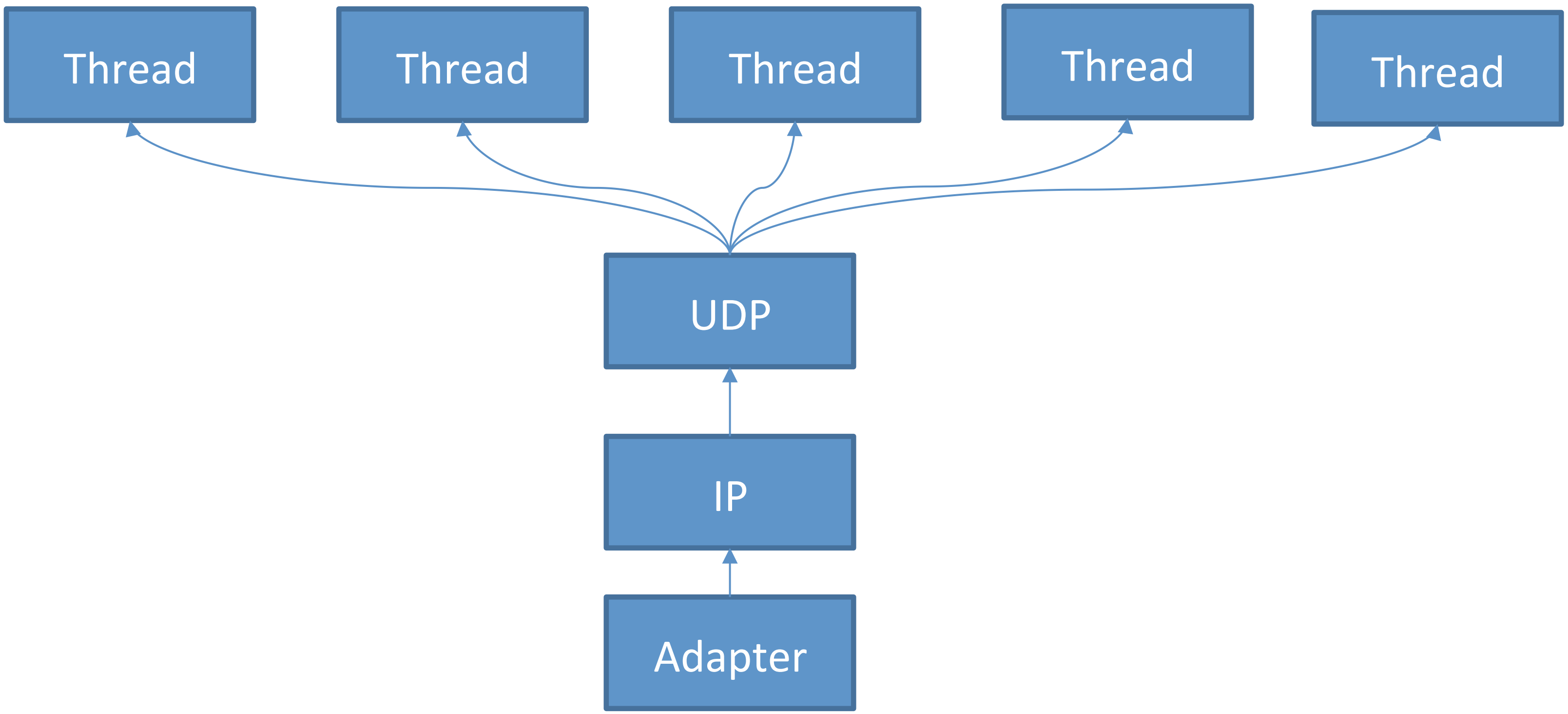
- PF_RING
  - Linux
  - open-source
- Netmap
  - FreeBSD
  - open-source
- Intel DPDK
  - Linux
  - License fees
  - Third party support
    - 6WindGate

200 CPU clocks per packet

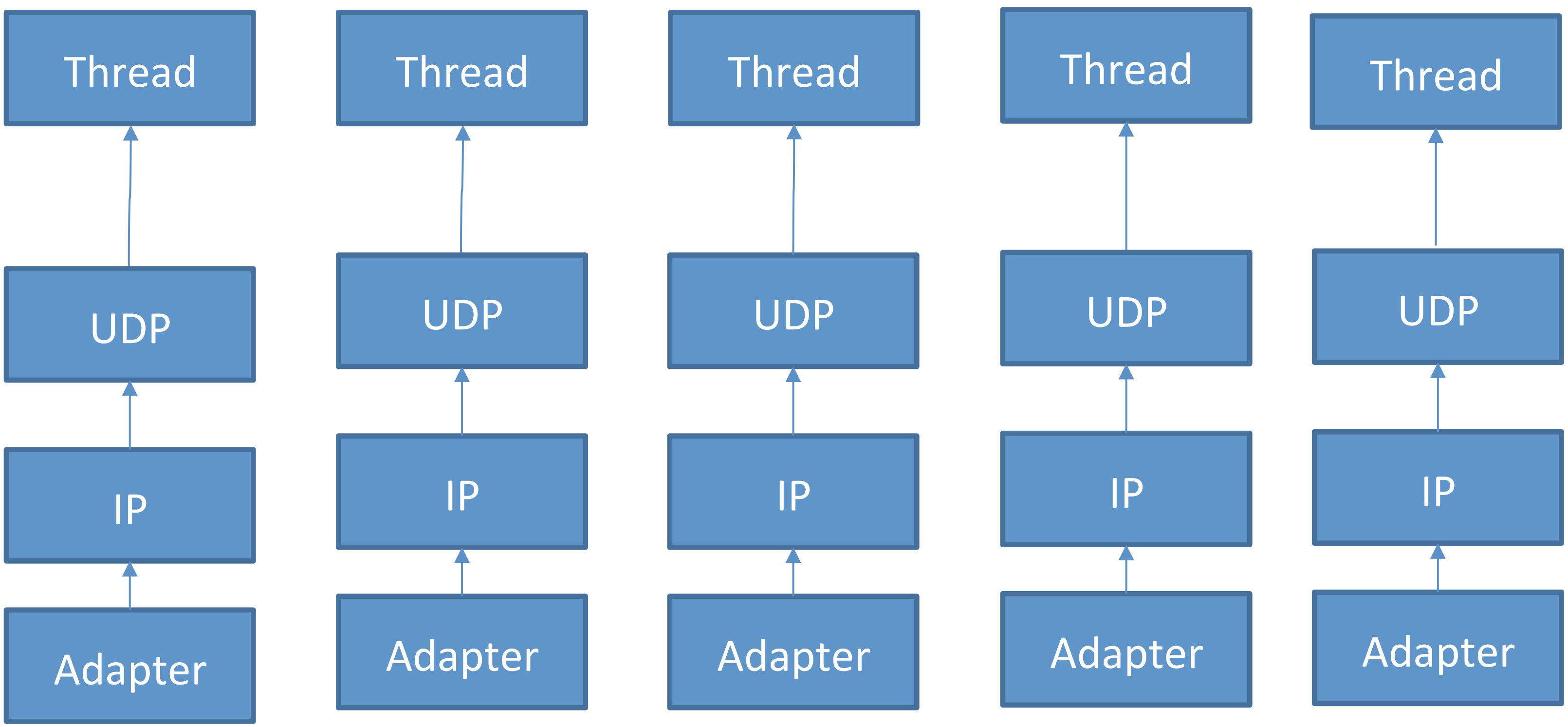


http://www.intel.com/content/dam/www/public/us/en/documents/solution-briefs/communications-packet-processing-brief.pdf

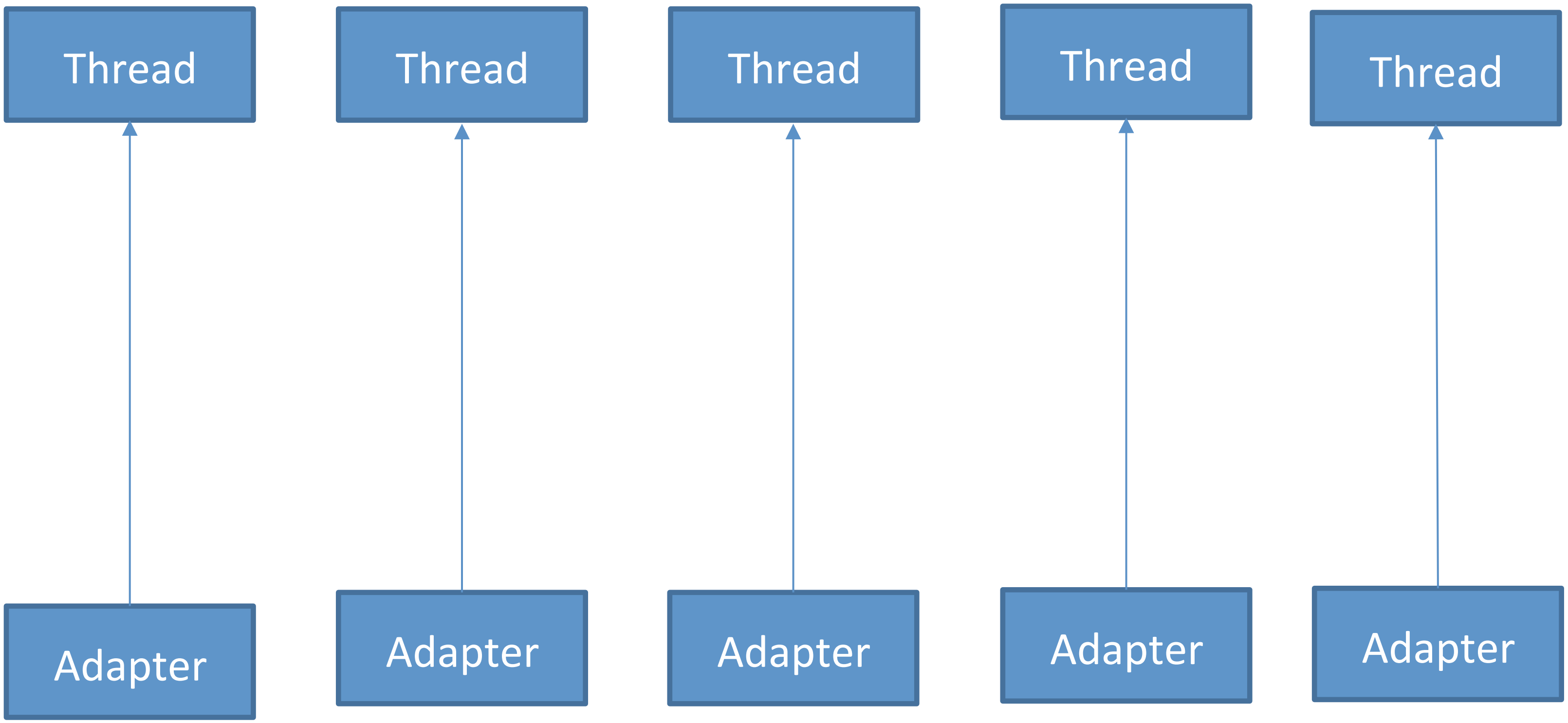
Old UDP: 500 kpps



UDP + receive queues + SO_REUSEPORT = 3 mpps



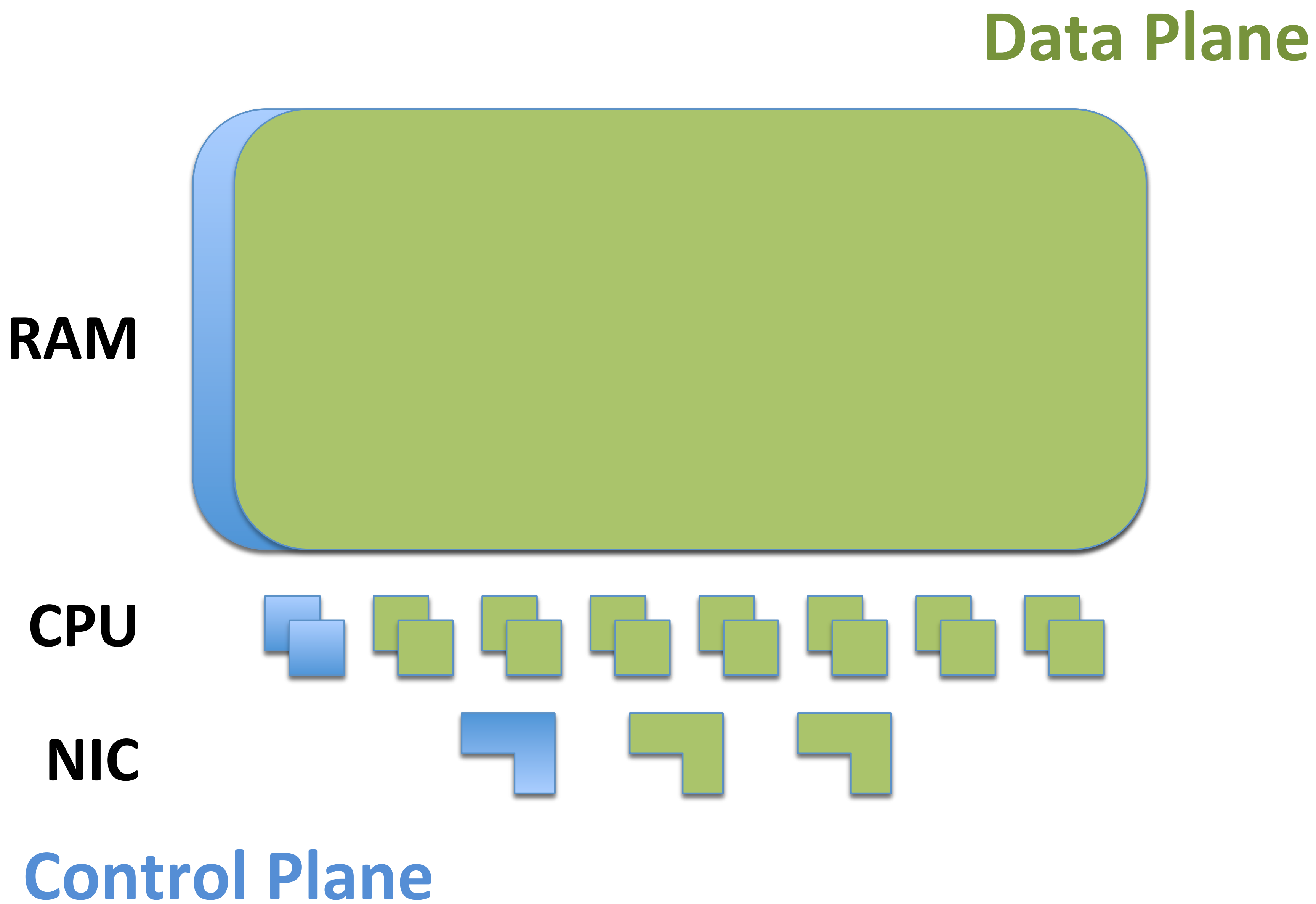
Custom = 30 mpps



User-mode network stacks

- PF_RING/DPDK get you raw packets without a stack
  - Great for apps like IDS or root DNS servers
- For TCP, there are commercial stacks available
  - 6windgate is the best known commercial stack, working well with DPDK
  - Also, some research stacks
  - Requires change in your software to exploit them, such as asynchronous

Control plane vs. Data plane


Data Plane
RAM
CPU
NIC
Control Plane

Case study: masscan

- What is…
  - Ports scans entire Internet
  - Like nmap, but more scalable
- Transmits 30-million packets/second
  - PF_RING user-mode ring-buffer
- Pointer to TCB, then TCB, containing all data
- Has it’s own IP address(s)
  - Even when shared with machine

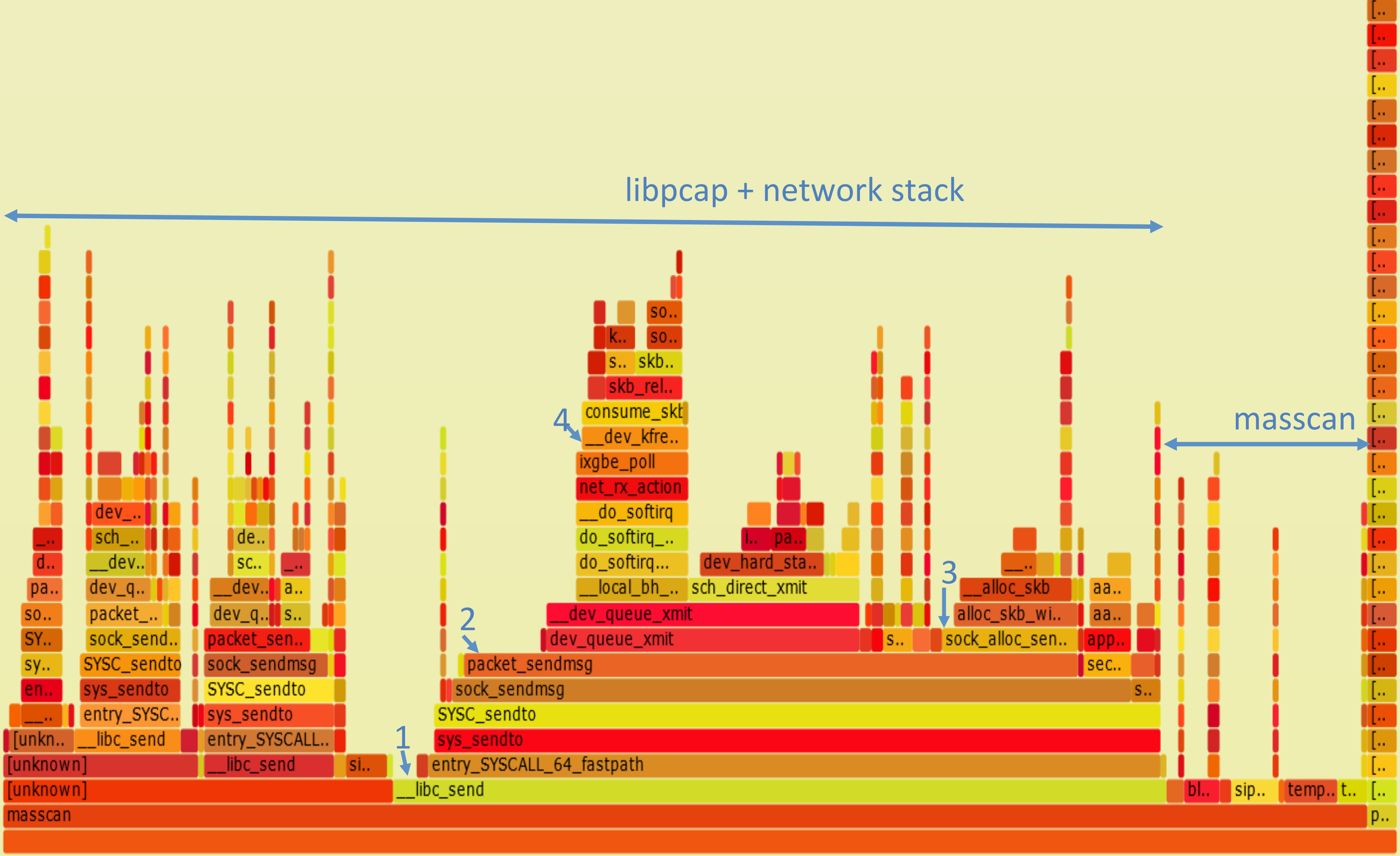
masscan

- Quad-core Sandy Bridge 3.0 GHz

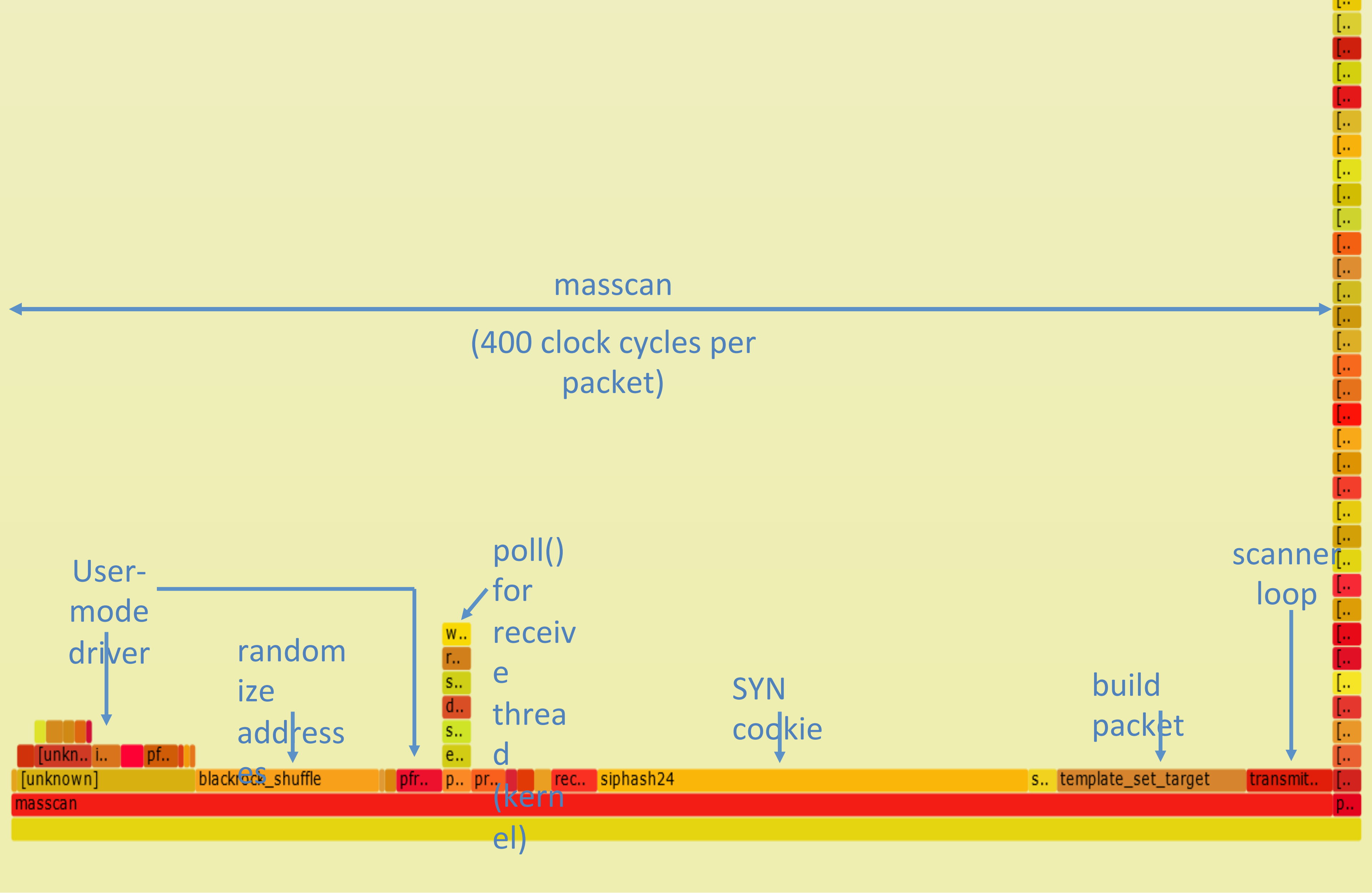
root@supermicro1: ~/masscan

```
root@supermicro1:~/masscan# bin/masscan 0.0.0.0/0 -p80 --max-rate 30000000 --pfring
/etc/masscan/exclude.txt: excluding 3880 ranges from file

Starting masscan 1.0 (http://bit.ly/14GZzcT) at 2013-09-14 22:59:14 GMT
 -- forced options: -sS -Pn -n --randomize-hosts -v --send-eth
Initiating SYN Stealth Scan
Scanning 3508758232 hosts [1 port/host]
rate:25011.09-kpps, 56.72% done,   0:00:49 remaining, 0-tcbs,
```



libpcap + network stack
masscan
1
2
3
4
so..
k..
s..
skb..
skb_rel..
consume_skb
__dev_kfre..
ixgbe_poll
net_rx_action
__do_softirq
do_softirq_..
do_softirq...
__local_bh_..
sch_direct_xmit
dev_hard_sta..
i..
pa..
__alloc_skb
alloc_skb_wi..
sock_alloc_sen..
aa..
app..
sec..
__dev_queue_xmit
dev_queue_xmit
packet_sendmsg
sock_sendmsg
SYSC_sendto
sys_sendto
entry_SYSCALL_64_fastpath
__libc_send
[unknown]
masscan
bl..
sip..
temp..
t..
p..
dev_..
sch_..
__dev..
dev_q..
packet_..
sock_send..
entry_SYSC..
[unkn..
de..
sc..
a..
packet_sen..
entry_SYSCALL..
si..
so..
SY..
sy..
en..
pa..
d..


masscan
(400 clock cycles per packet)
User-mode driver
randomize addresses
poll() for receive thread (kernel)
SYN cookie
build packet
scanner loop
[unkn..
i..
pf..
[unknown]
blackrock_shuffle
pfr..
p..
pr..
rec..
siphash24
s..
template_set_target
transmit..
masscan
p..
w..
r..
s..
d..
s..
e..

Conclusion

- Questions?
- @ErrataRob
- https://blog.erratasec.com
- https://github.com/robertdavidgraham/masscan