What Linux can learn from Solaris performance and vice-versa

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SCaLE12x
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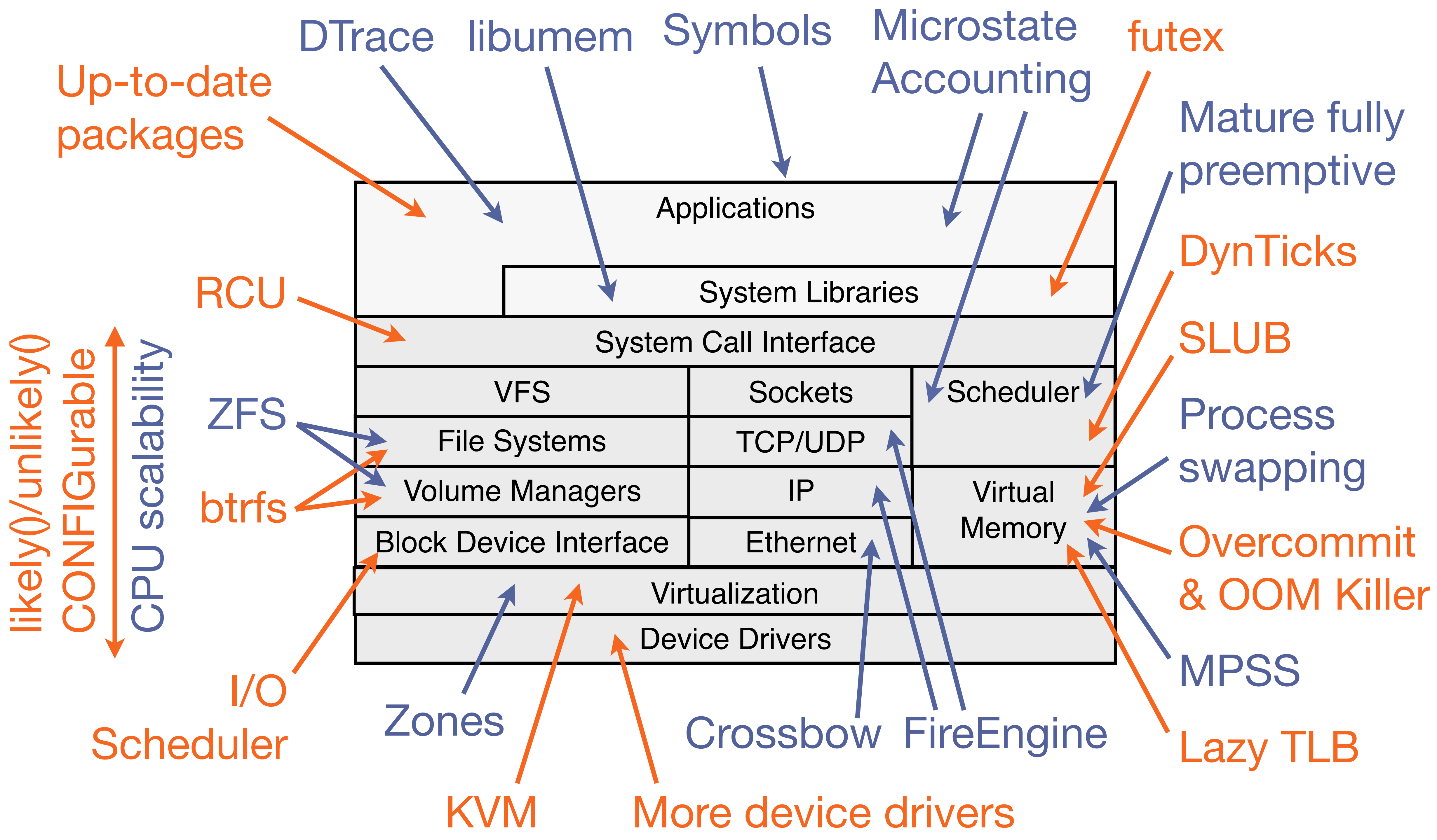
Linux vs Solaris Performance Differences



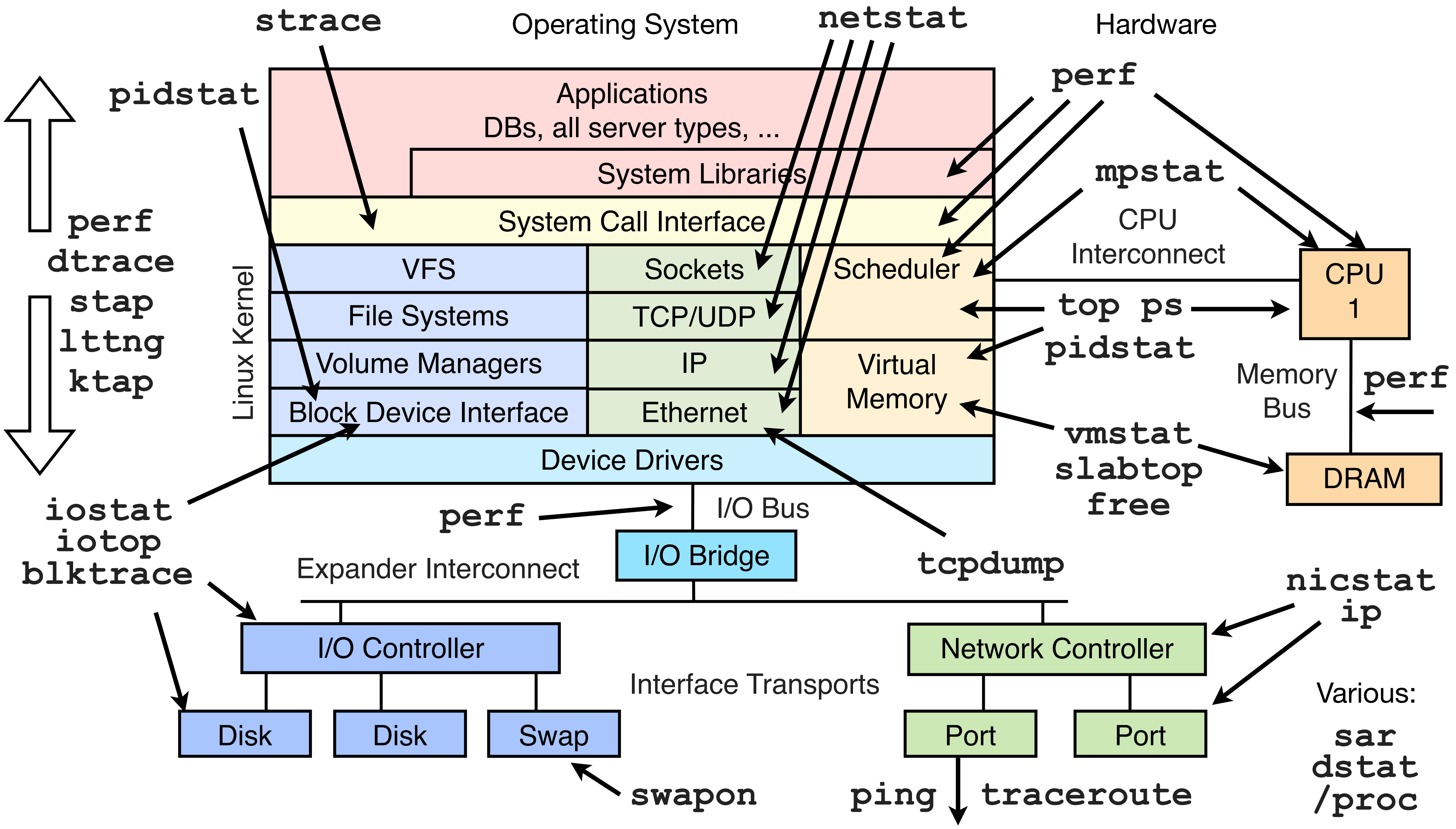
whoami

- Lead Performance Engineer at Joyent
    - Work on Linux and SmartOS performance
- Work/Research: tools, visualizations, methodologies
- Did kernel engineering at Sun Microsystems; worked on DTrace and ZFS

Joyent

- High-Performance Cloud Infrastructure
  - Compete on cloud instance/OS performance
- OS Virtualization for bare metal performance (Zones)
- Core developers of illumos/SmartOS and Node.js
- Recently launched Manta: a high performance object store
- KVM for Linux guests
  - Certified Ubuntu on Joyent cloud now available!

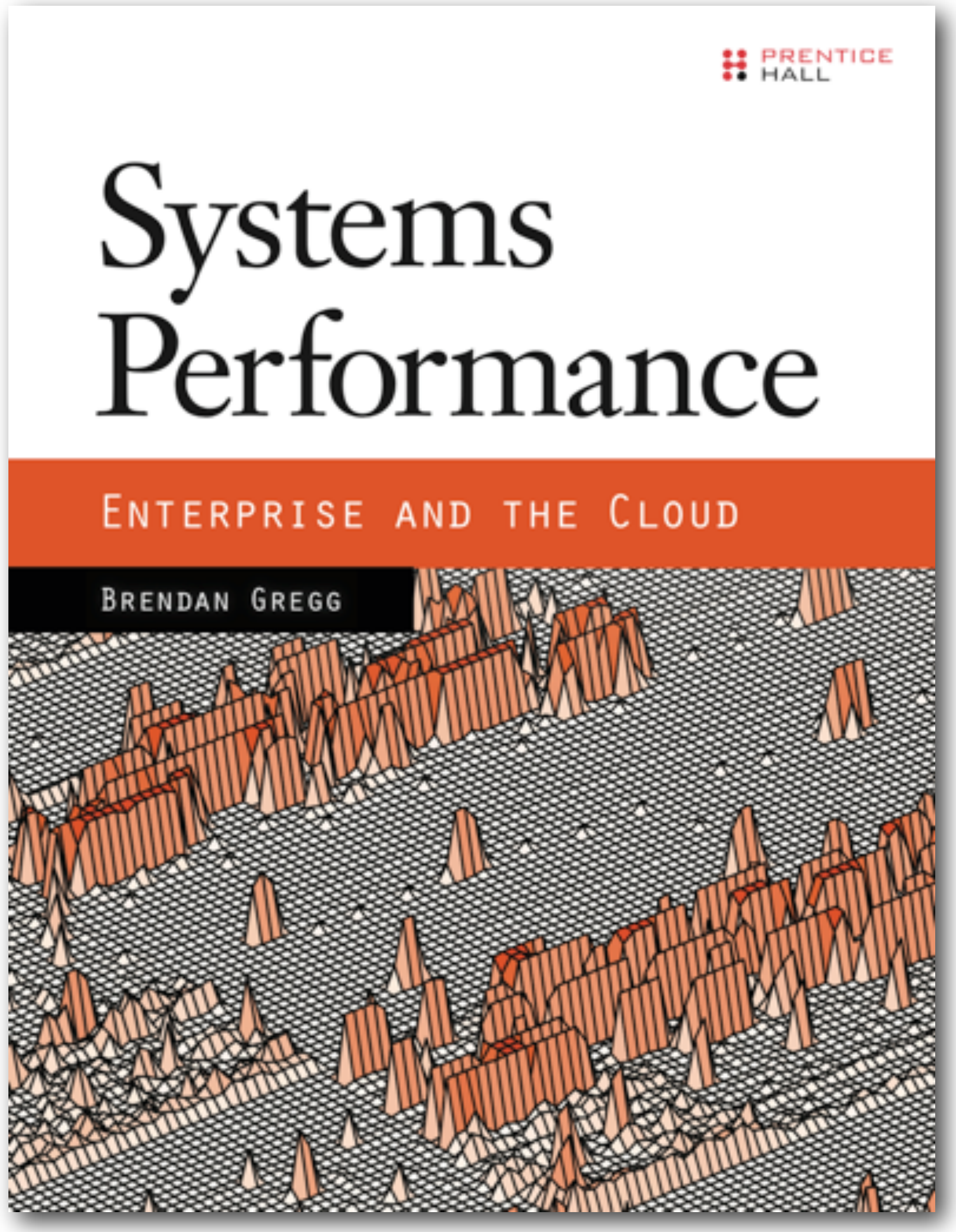
SCaLE11x: Linux Performance Analysis



Latest version: http://www.brendangregg.com/linuxperf.html

SCaLE12x: Linux and Solaris Performance

- Also covered in my new book, Systems Performance (Prentice Hall, 2013)
- Focus is on understanding systems and the methodologies to analyze them. Linux and Solaris are used as examples



Agenda

- Why systems differ
- Specific differences
- What Solaris could learn from Linux
- What Linux could learn from Solaris
- What both can learn
- Results

Terminology

- For convenience in this talk:
- Linux = an operating system distribution which uses the Linux kernel. eg, Ubuntu.
- Solaris = a distribution from the family of operating systems whose kernel code originated from Sun Solaris.
- SmartOS = a Solaris-family distribution developed by Joyent, based on the illumos kernel, which was based on the OpenSolaris kernel, which was based on the Solaris kernel
- System = everything you get when you pick a Linux or Solaris distribution: the kernel, libraries, tools, and package repos
- Opinions in this presentation are my own, and I do not represent Oracle Solaris. I'll actually be talking about SmartOS.

Why Systems Differ

Why Systems Differ

- Does the system even matter?
- Will your application perform the same on Linux and Solaris?

Example

- Let's start with this simple program:

```
perl -e 'for ($i = 0; $i < 100_000_000; $i++) { $s = "SCaLE12x" }'
```

- This counts to 100,000,000, setting a variable
- To simplify this further, we're only interested in performance of the loop, which dominates runtime, not program startup.

Example Results

- One of these is Linux, the other SmartOS. Same hardware:

```
systemA$ time perl -e 'for ($i = 0; $i < 100_000_000; $i++) { $s = "SCaLE12x" }'

real	0m18.534s
user	0m18.450s
sys	0m0.018s

systemB$ time perl -e 'for ($i = 0; $i < 100_000_000; $i++) { $s = "SCaLE12x" }'

real    0m16.253s
user    0m16.230s
sys     0m0.010s
```

- One system is 14% slower
- Imagine that's *your* system – you'd want to know why
- I recently had a customer with a complex performance issue try a one-liner like this, as a simple test, and with a similar result. It's an interesting tour of some system differences

Possible Differences: Versioning

- Different versions of Perl
  - Applications improve performance from release to release
  - Linux and SmartOS distributions use entirely different package repos; different software versions are common
- Different compilers used to build Perl
  - Compilers come from package repos, too. I've seen 50% performance improvements by gcc version alone
- Different compiler options used to build Perl
  - Application Makefile: #ifdef Linux -O3 #else -O0. ie, the performance difference is due to a Makefile decision
  - 32-bit vs 64-bit builds

Possible Differences: OS

- Different system libraries
  - If any library calls are used. eg: strcmp(), malloc(), memcpy(), ... These implementations vary between Linux and Solaris, and can perform very differently
  - Robert Mustacchi enhanced libumem to provide improved malloc() performance on SmartOS. This can make a noticeable difference for some workloads
- Different background tasks
  - Runtime could be perturbed by OS daemons doing async housekeeping. These differ between Linux and Solaris

Possible Differences: Observability

- Can the 14% be root caused?
  - Observability tools differ. These don't cause the 14%, but can make the difference as to whether you can diagnose and fix it – or not.
  - DTrace has meant that anything can be solved; without an equivalent on Linux, you may have to live with that 14%
  - Although, Linux observability is getting much better...

Possible Differences: Kernel

- Can the kernel make a difference? ... As a reminder:

```
perl -e 'for ($i = 0; $i < 100_000_000; $i++) { $s = "SCaLE12x" }'
```

- The program makes no system calls during the loop

Possible Differences: Kernel, cont.

- Can the kernel make a difference? ... As a reminder:

```
perl -e 'for ($i = 0; $i < 100_000_000; $i++) { $s = "SCaLE12x" }'
```

- The program makes no system calls during the loop
- Yes, for a number of reasons:
  - Setting the string involves memory I/O, and the kernel controls memory placement. Allocating nearby memory in a NUMA system can significantly improve performance
  - The kernel may also control the CPU clock speed (eg, Intel SpeedStep), and vary it for temp or power reasons
  - The program could be perturbed by interrupts: eg, network I/O (although the performance effect should be small).

Possible Differences: Kernel, cont.

- During a perturbation, the kernel CPU scheduler may migrate the thread to another CPU, which can hurt performance (cold caches, memory locality)
- Sure, but would that happen for this simple Perl program?

Possible Differences: Kernel, cont.

- During a perturbation, the kernel CPU scheduler may migrate the thread to another CPU, which can hurt performance (cold caches, memory locality)
- Sure, but would that happen for this simple Perl program?

```
# dtrace -n 'profile-99 /pid == $target/ { @ = lquantize(cpu, 0, 16, 1); }' -c ...
           value  ------------- Distribution ------------- count
             < 0 |                                         0
               0 |                                         1
               1 |@@@@@                                    483
               2 |                                         1
               3 |@@@@@@@                                  663
               4 |                                         2
               5 |@@@                                      276
               6 |                                         0
               7 |@@@@@@                                   512
               8 |                                         1
               9 |@@@                                      288
              10 |                                         0
              11 |@@@@@@                                   576
              12 |                                         0
              13 |@@@@@                                    442
              14 |                                         2
              15 |@@@                                      308
              16 |                                         0
```

Yes, a lot!

This shows the CPUs Perl ran on. It should stay put, but instead runs across many.

We've been fixing this in SmartOS

Kernel Myths and Realities

- Myth: "The kernel gets out of the way for applications"
    - The only case where the kernel gets out of the way is when your software calls halt() or shutdown()
    - The performance difference between kernels may be small, eg, 5% – but I have already seen a 5x difference this year

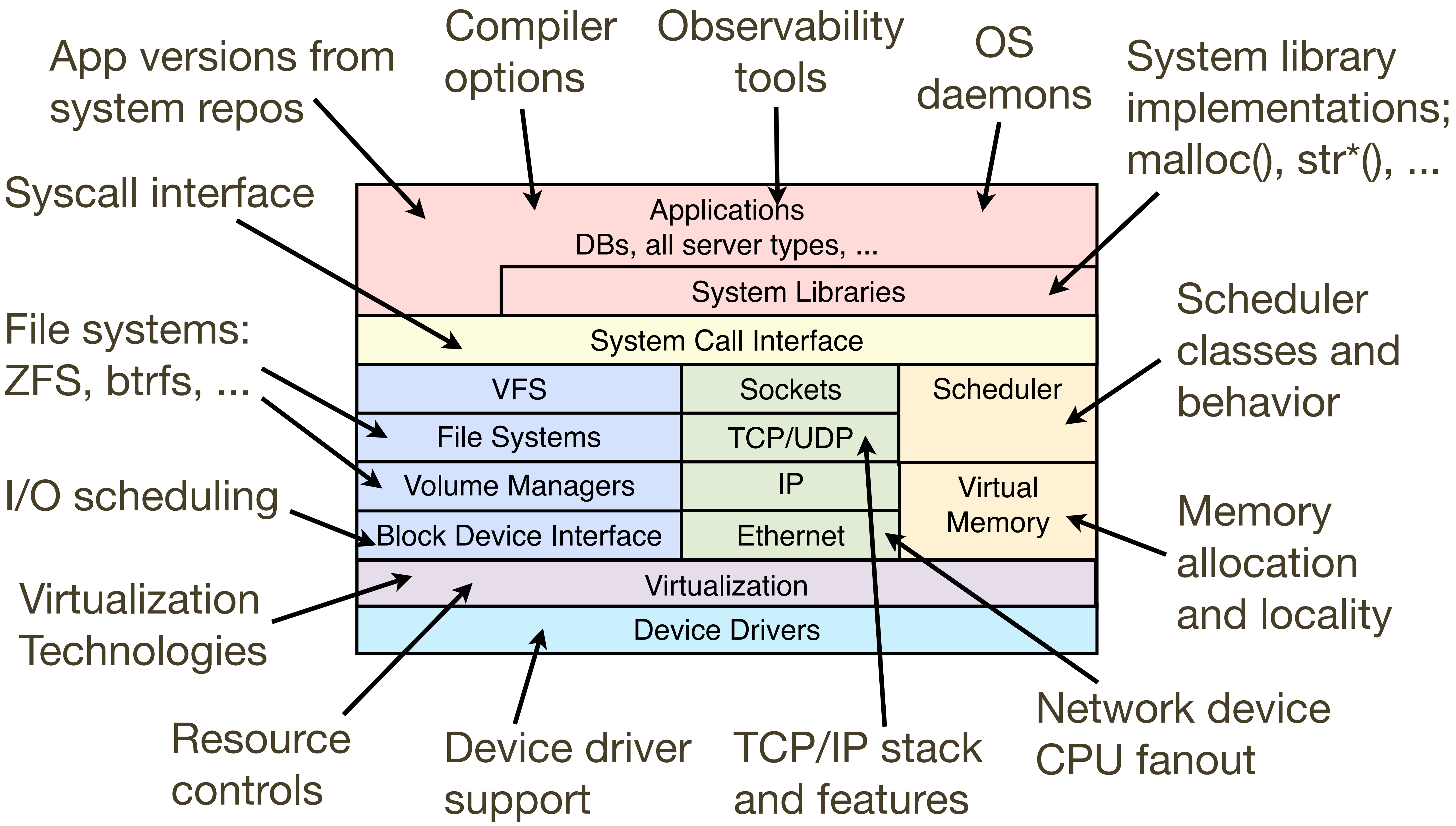
```
arch/ia64/kernel/smp.c:
void
cpu_die(void)
{
        max_xtp();
        local_irq_disable();
        cpu_halt();
        /* Should never be here */
        BUG();
        for (;;);
}
```

unintentional kernel humor...

Other Differences

- The previous example was simple. Any applications that do I/O (ie, everything) encounter more differences:
  - Different network stack implementations, including support for different TCP/IP features
  - Different file systems, storage I/O stacks
  - Different device drivers and device feature support
  - Different resource control implementations
  - Different virtualization technologies
  - Different community support: stackoverflow, meetups, ...

Types of Differences



Specific Differences

Specific Differences

- Comparing systems is like comparing countries
    - I'm often asked: how's Australia different from the US?
    - Where do I start!?
- I'll categorize performance differences into big or small, based on their engineering cost, not their performance effect
- If one system is 2x faster than another for a given workload, the real question for the slower system is:
    - Is this a major undertaking to fix?
    - Is there a quick fix or workaround?
- Using **SmartOS** for specific examples...

Big Differences

- Major bodies of perf work and other big differences, include:
- Linux
    - up-to-date packages, large community, more device drivers, futex, RCU, btrfs, DynTicks, SLUB, I/O scheduling classes, overcommit & OOM killer, lazy TLB, likely()/unlikely(), CONFIGurable
- SmartOS
    - Mature: Zones, ZFS, DTrace, fully pre-emptable kernel
    - Microstate accounting, symbols by default, CPU scalability, MPSS, libumem, FireEngine, Crossbow, binary /proc, process swapping

Big Differences: Linux

Up-to-date packages	Latest application versions, with the latest performance fixes
Large community	Weird perf issue? May be answered on stackoverflow, or discussed at meetups
More device drivers	There can be better coverage for high performing network cards or driver features
futex	Fast user-space mutex
RCU	Fast-performing read-copy updates
btrfs	Modern file system with pooled storage
DynTicks	Dynamic ticks: tickless kernel, reduces interrupts and saves power
SLUB	Simplified version of SLAB kernel memory allocator, improving performance

Big Differences: Linux, cont.

I/O scheduling classes	Block I/O classes: deadline, anticipatory, ...
Overcommit & OOM killer	Doing more with less main memory
Lazy TLB	Higher performing munmap()
likely()/unlikely()	Kernel is embedded with compiler information for branch prediction, improving runtime perf
CONFIGurable	Lightweight kernels possible by disabling features

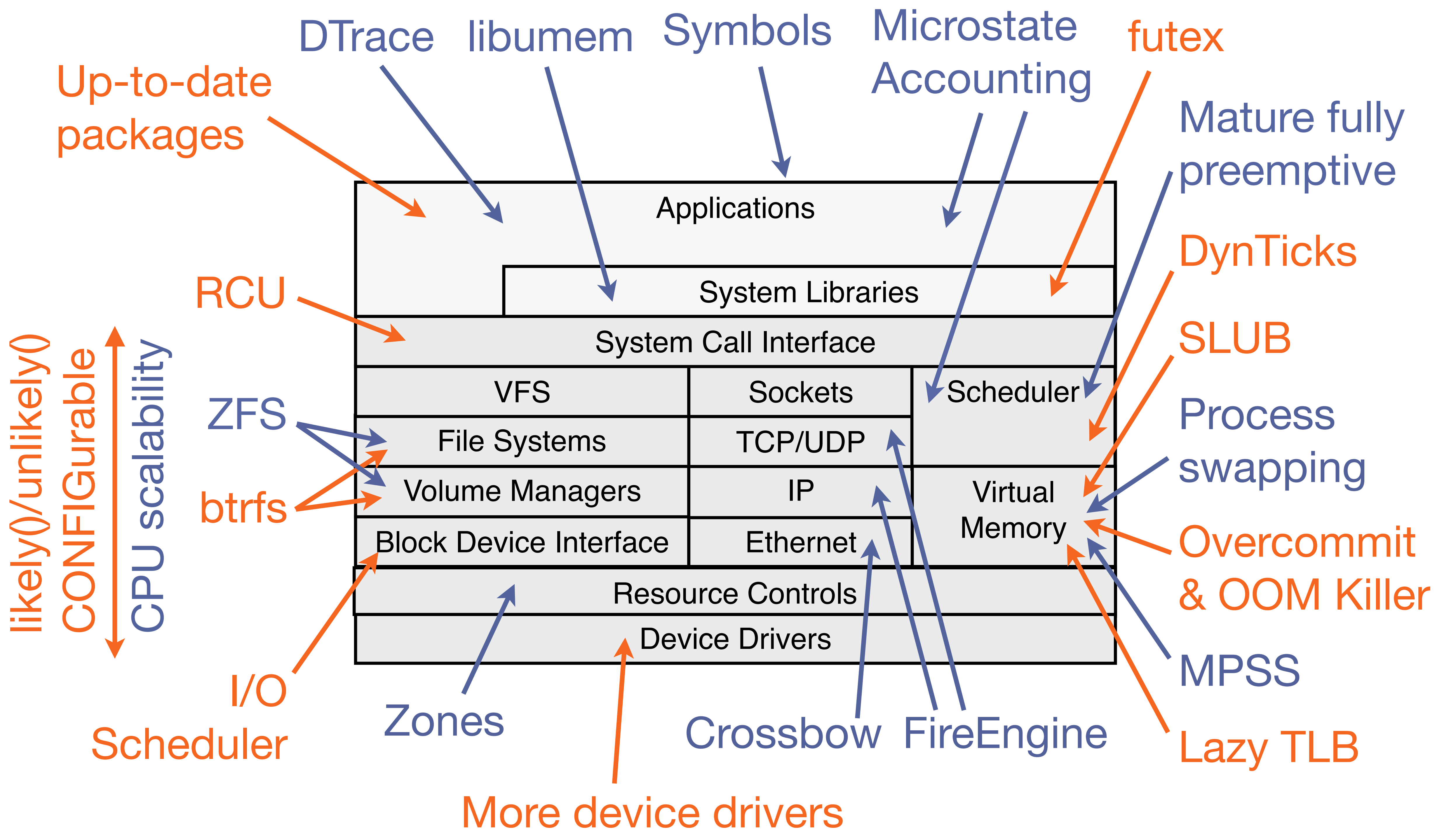
Big Differences: SmartOS

Mature Zones	OS virtualization for high-performing server instances
Mature ZFS	Fully-featured and high-performing modern integrated file system with pooled storage
Mature DTrace	Programmable dynamic and static tracing for performance analysis
Mature fully pre-emptable kernel	Support for real-time systems was an early Sun differentiator
Microstate accounting	Numerous high-resolution thread state times for performance debugging
Symbols	Symbols available for profiling tools by default
CPU scalability	Code is often tested, and bugs fixed, for large SMP servers (mainframes)
MPSS	Multiple page size support (not just hugepages)

Big Differences: SmartOS, cont.

libumem	High-performing memory allocation library, with per-thread CPU caches
FireEngine	High-performing TCP/IP stack enhancements, including vertical perimeters and IP fanout
Crossbow	High-performing virtualized network interfaces, as used by OS virtualization
binary /proc	Process statistics are binary (slightly more efficient) by default
Process swapping	Apart from paging (what Linux calls swapping), Solaris can still swap out entire processes

Big Differences: Linux vs SmartOS



Small Differences

- Smaller performance-related differences, tunables, bugs
- Linux
    - glibc, better TCP defaults, better CPU affinity, perf stat, a working sar, htop, splice(), fadvise(), ionice, /usr/bin/time, mpstat %steal, voluntary preemption, swappiness, various accounting frameworks, tcp_tw_reuse/recycle, TCP tail loss probe, SO_REUSEPORT, ...
- SmartOS
    - perf tools by default, kstat, vfsstat, iostat -e, ptime -m, CPU-only load averages, some STREAMS leftovers, ZFS SCSI cache flush by default, different TCP slow start default, ...

Small Differences, cont.

- Small differences change frequently: a feature is added to one kernel, then the other a year later; a difference may only exist for a short period of time.
- These small kernel differences may still make a significant performance difference, but are classified as "small" based on engineering cost.

System Similarities

- It's important to note that many performance-related features are roughly equivalent:
  - Both are Unix-like systems: processes, kernel, syscalls, time sharing, preemption, virtual memory, paged virtual memory, demand paging, ...
  - Similar modern features: unified buffer cache, memory mapped files, multiprocessor support, CPU scheduling classes, CPU sets, 64-bit support, memory locality, resource controls, PIC profiler, epoll, ...

Non Performance Differences

- Linux
  - Open source (vs Oracle Solaris), "everyone knows it", embedded Linux, popular and well supported desktop/ laptop use...
- SmartOS
  - SMF/FMA, contracts, privileges, mdb (postmortem debugging), gcore, crash dumps by default, ...

WARNING

The next sections are not suitable for those suffering
Not Invented Here (NIH) syndrome,
or those who are easily trolled

What Solaris can learn from Linux performance

What Solaris can learn from Linux performance

- Packaging
- Community
- Compiler Options
- likely()/unlikely()
- Tickless Kernel
- Process Swapping
- Overcommit & OOM Killer
- SLUB
- Lazy TLB
- TIME_WAIT Recycling
- sar
- KVM

- Either learning what to do, or learning what not to do...

Packaging

- Linux package repositories are often well stocked and updated
- Convenience aside, this can mean that users run newer software versions, along with the latest perf fixes
- They find "Linux is faster", but the real difference is the version of: gcc, openssl, mysql, ... Solaris is unfairly blamed

Packaging, cont.

- Packaging is important and needs serious support
    - Dedicated staff, community
- eg, Joyent has dedicated staff for the SmartOS package repo, which is based on pkgsrc from NetBSD
- It's not just the operating system that matters; it's the ecosystem

Community

- A large community means:
  - Q/A sites have performance tips: stackoverflow, ...
  - Conference talks on performance (this one!), slides, video
  - Weird issues more likely found and fixed by someone else
  - More case studies shared: what tuning/config worked
- A community helps people hear about the latest tools, tuning, and developments, and adopt them

Community, cont.

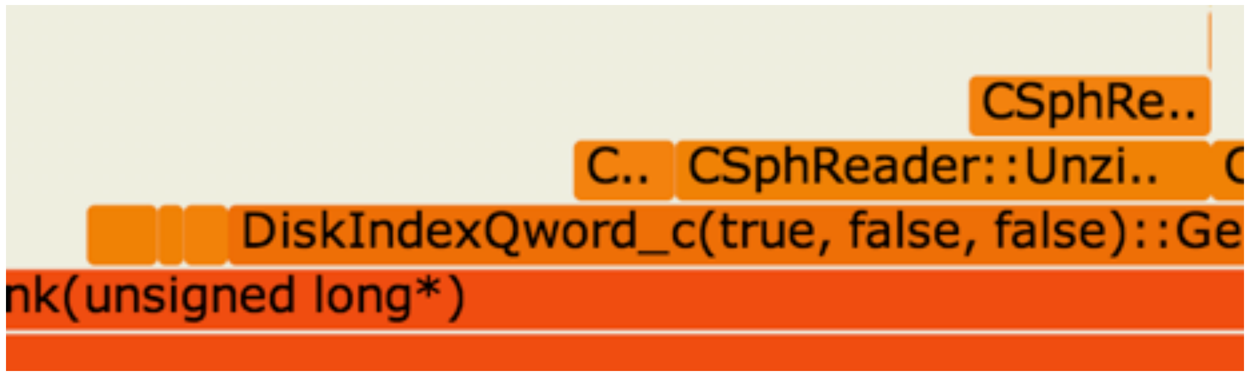
- Linux users expect to Google a question and find an answer on stackoverflow
- Either foster a community to share content on tuning, tools, configuration, or, have staff to create such content.
- Hire a good community manager!

Compiler Options

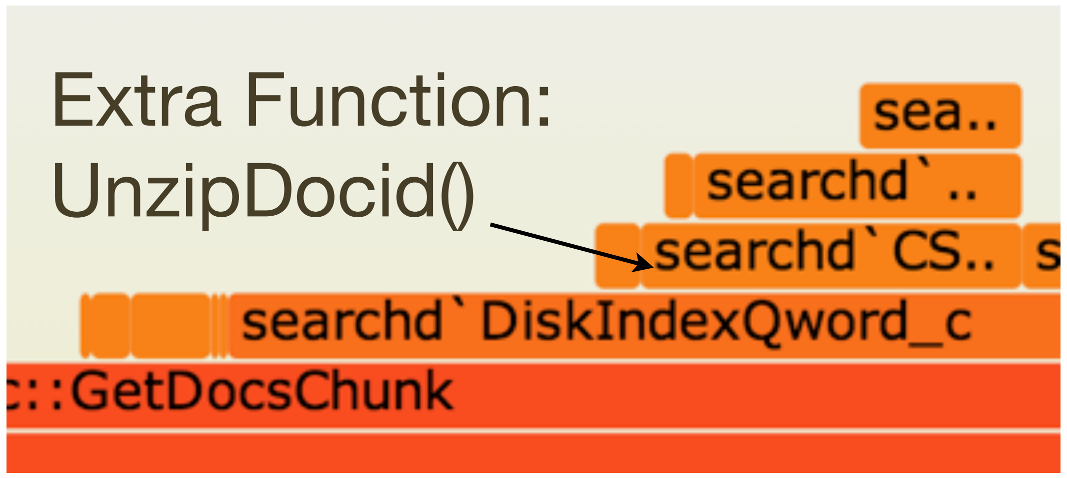
- Apps may compile with optimizations for Linux only. eg:
  - #ifdef Linux -O3 #else -O0

Oh, ha ha ha

- Developers are often writing software on Linux, and that platform gets the most attention. (Works on my system.)
- I've also seen 64-bit vs 32-bit. #ifdef Linux USE_FUTEX would be fine, since Solaris doesn't have them yet.
- Last time I found compiler differences using Flame Graphs:



Linux



SmartOS

Compiler Options, cont.

- Can be addressed by tuning packages in the repo
- Also file bugs/patches with developers to tune Makefiles
    - Someone has to do this, eg, package repo staff/community who find and do the workarounds anyway

likely()/unlikely()

- These become compiler hints (__builtin_expect) for branch prediction, and are throughout the Linux kernel:

```
net/ipv4/tcp_output.c, tcp_transmit_skb():

[...]
        if (likely(clone_it)) {
                if (unlikely(skb_cloned(skb)))
                        skb = pskb_copy(skb, gfp_mask);
                else
                        skb = skb_clone(skb, gfp_mask);
                if (unlikely(!skb))
                        return -ENOBUFS;
        }
[...]
```

- The Solaris kernel doesn't do this yet
  - If the kernel is built using profile feedback instead – which should be even better – I don't know about it
- The actual perf difference is likely to be small

likely()/unlikely(), cont.

- Could be adopted by kernel engineering
- Might help readability, might not

Tickless Kernel

- Linux does this already (DynTicks), which reduces interrupts and improves processor power saving (good for laptops and embedded devices)
- Solaris still has a clock() routine, to perform various kernel housekeeping functions
    - Called by default at 100 Hertz
    - If hires_tick=1, at 1000 Hertz
- I've occasionally encountered perf issues involving 10 ms latencies, that don't exist on Linux
- ... which become 1 ms latencies after setting hires_tick=1

Tickless Kernel, cont.

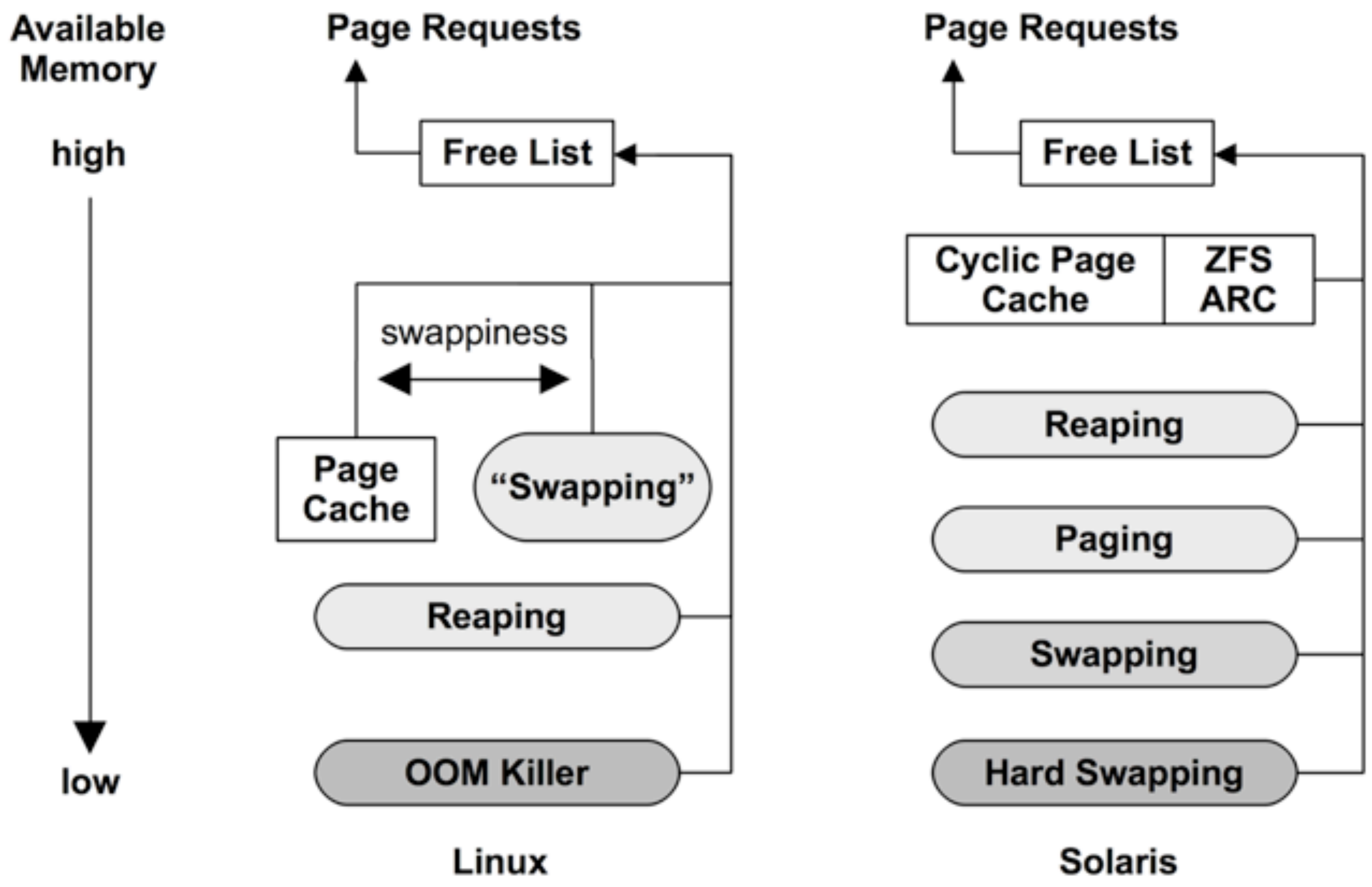
- Sun/Oracle did start work on this years ago...

Process Swapping

- Linux doesn't do it. Linux "swapping" means paging.
- Process swapping made sense on the PDP-11/20, where the maximum process size was 64 Kbytes
- Paging was added later in BSD, but the swapping code remained

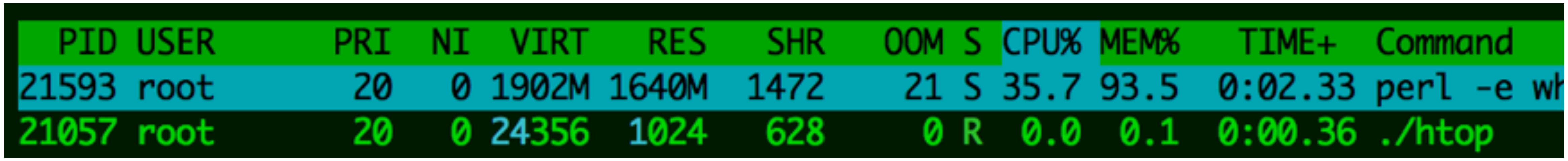
Process Swapping, cont.

- Consider ditching it
- All that time learning what swapping is could be spent learning more useful features



Overcommit & OOM Killer

- On Linux, malloc() may never fail
  - No virtual memory limit (main memory + swap) like Solaris by default. Tunable using vm.overcommit_memory
  - More user memory can be allocated than can be stored. May be great for small devices, running applications that sparsely use the memory they allocate
- Don't worry, if Linux runs very low on available main memory, **a sacrificial process is identified by the kernel and killed** by the Out Of Memory (OOM) Killer, based on an OOM score
- OOM score was just added to htop (1.0.2, Jan 2014):



```
  PID USER      PRI  NI  VIRT   RES   SHR   OOM S CPU% MEM%   TIME+  Command
21593 root       20   0 1902M 1640M  1472    21 S 35.7 93.5  0:02.33 perl -e wh
21057 root       20   0 24356  1024   628     0 R  0.0  0.1  0:00.36 ./htop
```

Overcommit & OOM Killer, cont.

- Solaris can learn why not to do this (cautionary tale)
- If an important app depended on this, and couldn't be fixed, the kernel could have an overcommit option that wasn't default
- ... this is why so much new code doesn't check for ENOMEM

SLUB

- Linux integrated the Solaris kernel SLAB allocator, then later simplified it: The SLUB allocator
- Removed object queues and per-CPU caches, leaving NUMA optimization to the page allocator's free lists
- Worth considering?

Lazy TLB

- Lazy TLB mode: a way to delay TLB updates (shootdowns)
- munmap() heavy workloads on Solaris can experience heavy HAT CPU cross calls. Linux doesn't seem to have this problem.

	TLB	Lazy TLB
As seen by Solaris	Correct	Reckless
As seen by Linux	Paranoid	Fast

Lazy TLB, cont.

- This difference needs to be investigated, quantified, and possibly fixed (tunable?)

TIME_WAIT Recycling

- A localhost HTTP benchmark on Solaris:

```
# netstat -s 1 | grep ActiveOpen
    tcpActiveOpens      =728004     tcpPassiveOpens     =726547
    tcpActiveOpens      =     0     tcpPassiveOpens     =     0
    tcpActiveOpens      =  4939     tcpPassiveOpens     =  4939
    tcpActiveOpens      =  5849     tcpPassiveOpens     =  5798  ← Fast
    tcpActiveOpens      =  1341     tcpPassiveOpens     =  1292
    tcpActiveOpens      =  1006     tcpPassiveOpens     =  1008
    tcpActiveOpens      =   872     tcpPassiveOpens     =   870
    tcpActiveOpens      =   932     tcpPassiveOpens     =   932  ← Slow
    tcpActiveOpens      =   879     tcpPassiveOpens     =   879
    tcpActiveOpens      =   562     tcpPassiveOpens     =   586
    tcpActiveOpens      =   613     tcpPassiveOpens     =   594
```

- Connection rate drops by 5x due to sessions in TIME_WAIT
- Linux avoids this by recycling better (tcp_tw_reuse/recycle)
- Usually doesn't hurt production workloads, as it must be a flood of connections from a single host to a single port. It comes up in benchmarks/evaluations.

TIME_WAIT Recycling, cont.

- Improve tcp_time_wait_processing()
- This is being fixed for illumos/SmartOS

sar

- Linux sar is awesome, and has extra options:

```
$ sar -n DEV -n TCP -n ETCP 1
11:16:34 PM     IFACE   rxpck/s   txpck/s    rxkB/s    txkB/s   rxcmp/s   txcmp/s  rxmcst/s
11:16:35 PM      eth0    104.00    675.00      7.35    984.72      0.00      0.00      0.00
11:16:35 PM      eth1      7.00      0.00      0.38      0.00      0.00      0.00      0.00
11:16:35 PM   ip6tnl0      0.00      0.00      0.00      0.00      0.00      0.00      0.00
11:16:35 PM        lo      0.00      0.00      0.00      0.00      0.00      0.00      0.00
11:16:35 PM   ip_vti0      0.00      0.00      0.00      0.00      0.00      0.00      0.00
11:16:35 PM      sit0      0.00      0.00      0.00      0.00      0.00      0.00      0.00
11:16:35 PM     tunl0      0.00      0.00      0.00      0.00      0.00      0.00      0.00

11:16:34 PM  active/s passive/s    iseg/s    oseg/s
11:16:35 PM      0.00      0.00     99.00    681.00

11:16:34 PM  atmptf/s  estres/s retrans/s isegerr/s   orsts/s
11:16:35 PM      0.00      0.00      0.00      0.00      0.00
```

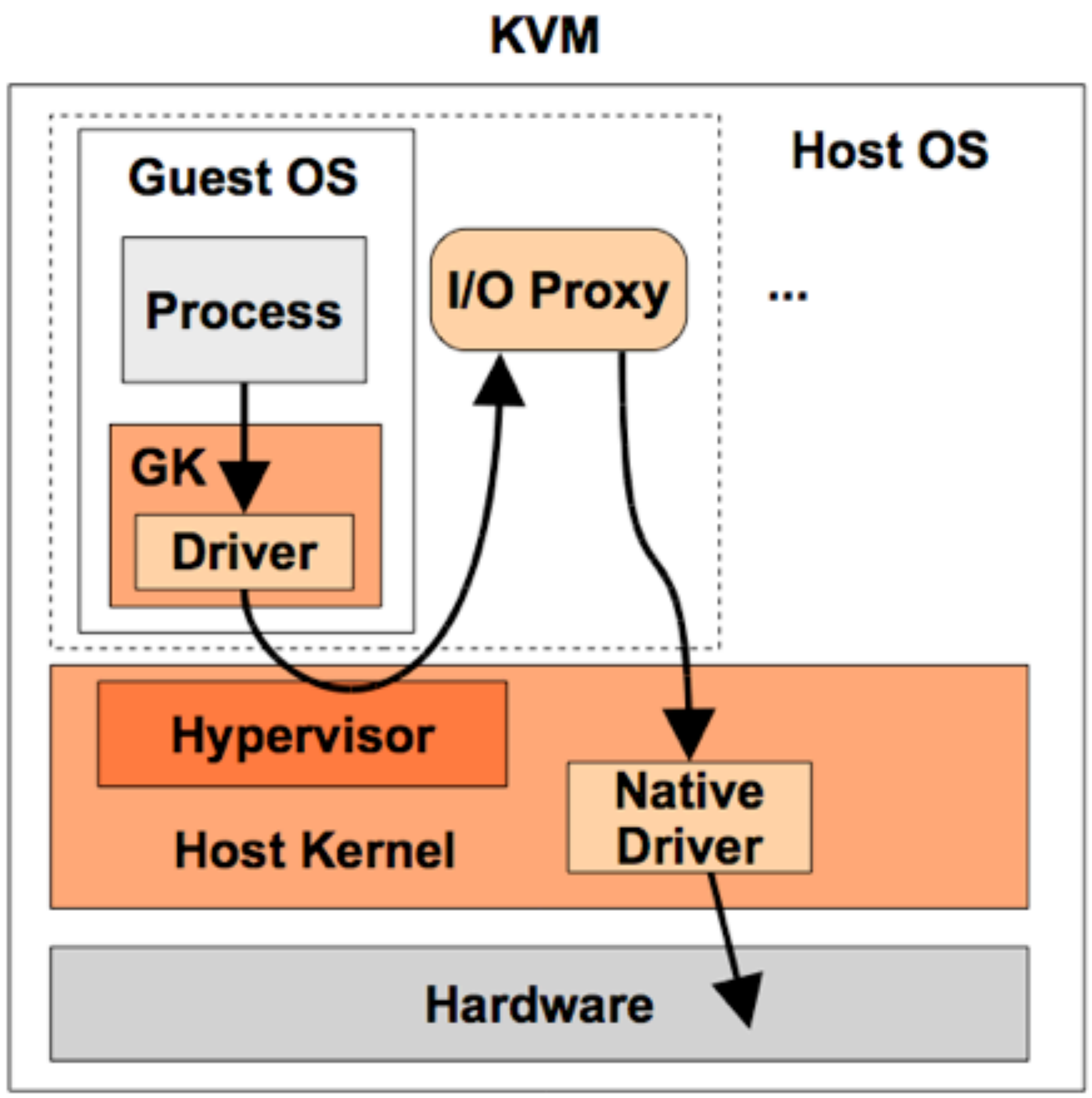
  - -n DEV: network interface statistics
  - -n TCP: TCP statistics
  - -n ETCP: TCP error statistics
- Linux sar's other metrics are also far less buggy

sar, cont.

- Sar must be fixed for the 21st century
- Use the Linux sar options and column names, which follow a neat convention

KVM

- The KVM type 2 hypervisor originated for Linux
- While Zones are faster, KVM can run different kernels (Linux)
- vs Type 1 hypervisors (Xen):
    - KVM has better perf observability, as it can use the regular OS tools
    - KVM can use OS resource controls, just like any other process



KVM, cont.

- illumos/SmartOS learned this, Joyent ported KVM!
- Oracle Solaris doesn't have it yet

What Linux can learn from Solaris performance

What Linux can learn from Solaris performance

- ZFS
- Zones
- STREAMS
- Symbols
- prstat -mLc
- vfsstat
- DTrace
- Culture

- Either learning what to do, or learning what not to do...

ZFS

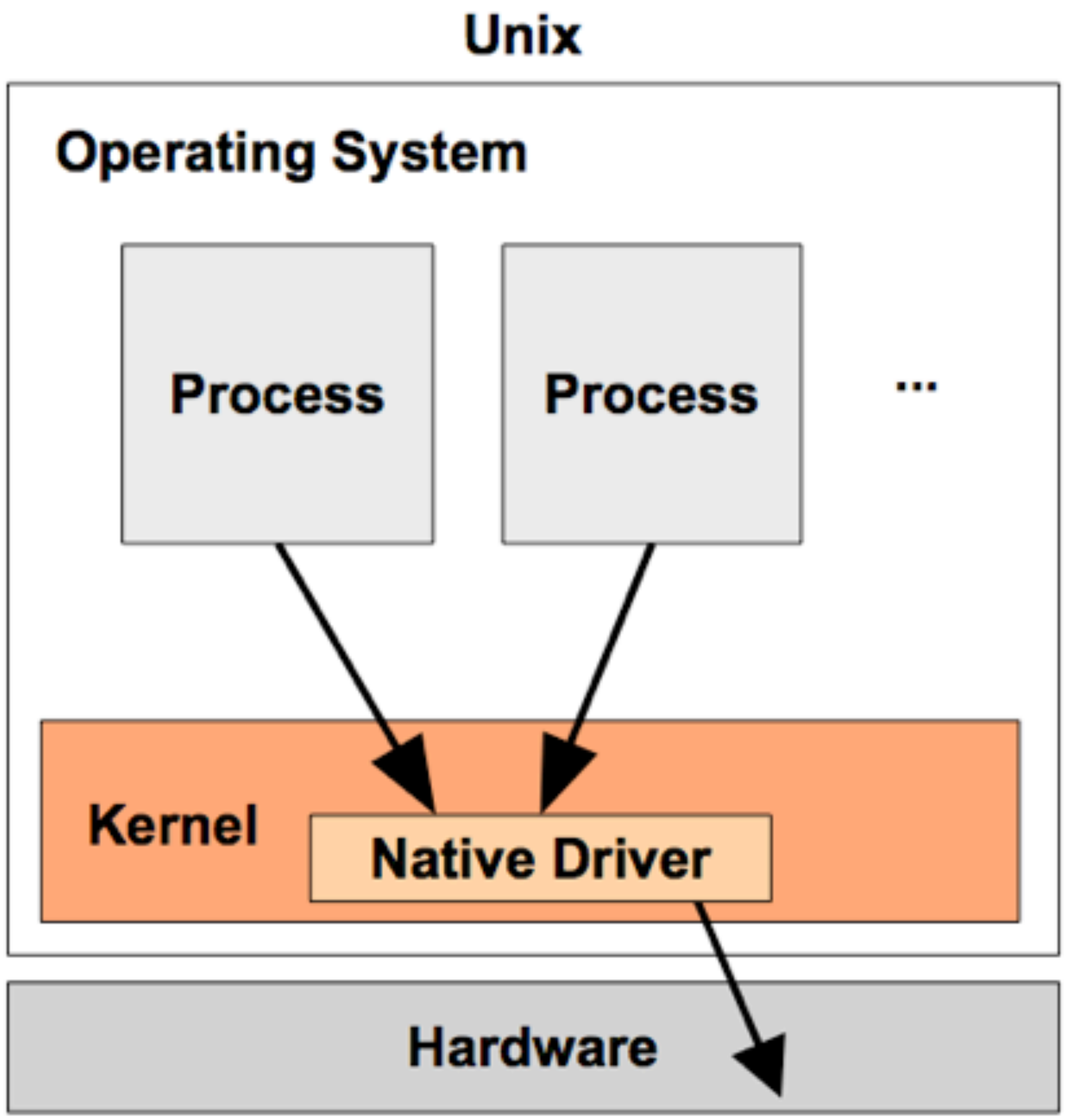
- More performance features than you can shake a stick at:
  - Pooled storage, COW, logging (batching writes), ARC, variable block sizes, dynamic striping, intelligent prefetch, multiple prefetch streams, snapshots, ZIO pipeline, compression (lzjb can improve perf by reducing I/O load), SLOG, L2ARC, vdev cache, data deduplication (possibly better cache reach)
- The Adaptive Replacement Cache (ARC) can make a big difference: it can resist perturbations (backups) and stay warm
- ZFS I/O throttling (in illumos/SmartOS) throttles disk I/O at the VFS layer, to solve cloud noisy neighbor issues
- ZFS is Mature. Widespread use in criticial environments

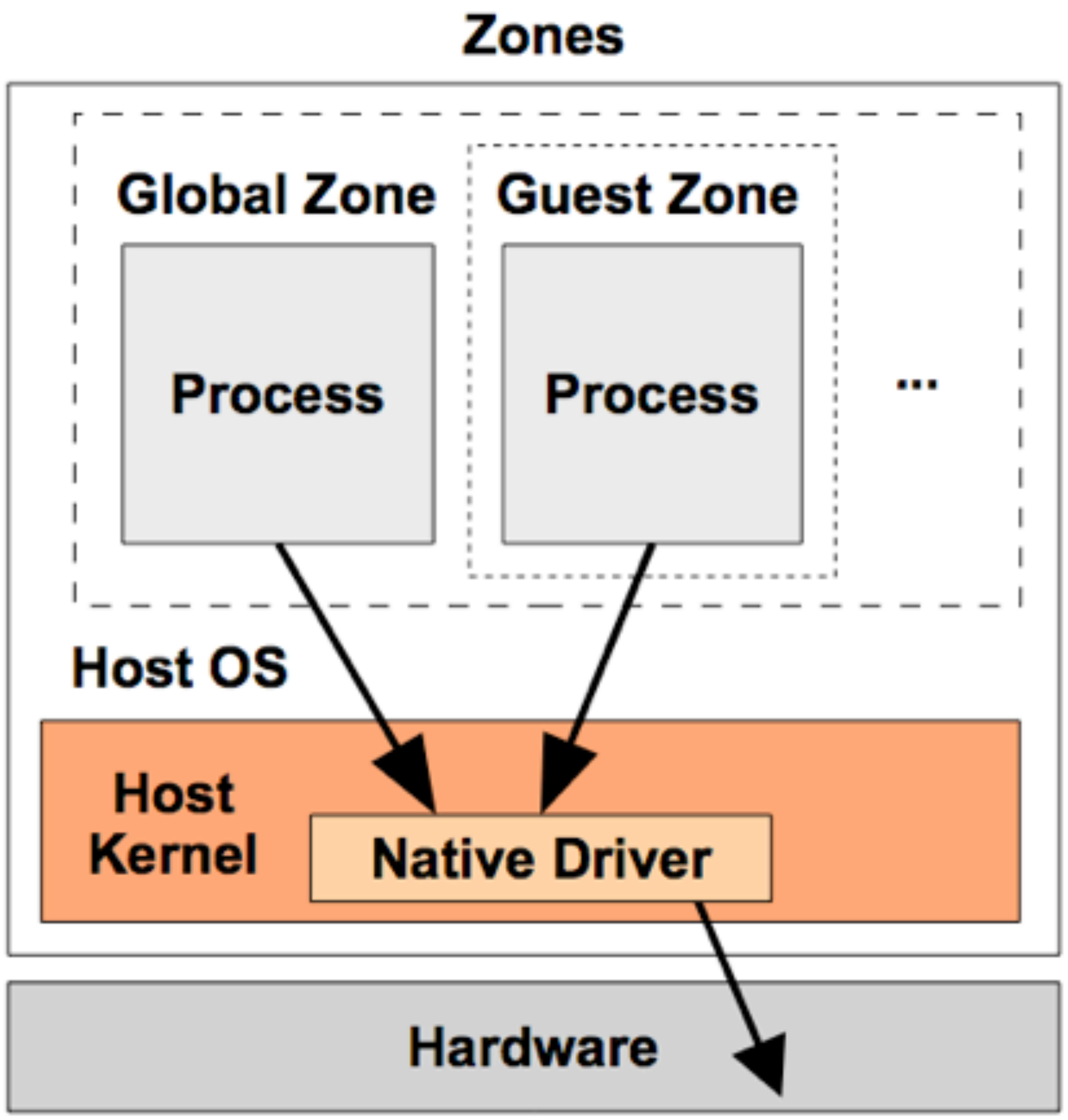
ZFS, cont.

- Linux has been learning about ZFS for a while
  - http://zfsonlinux.org/
  - btrfs

Zones

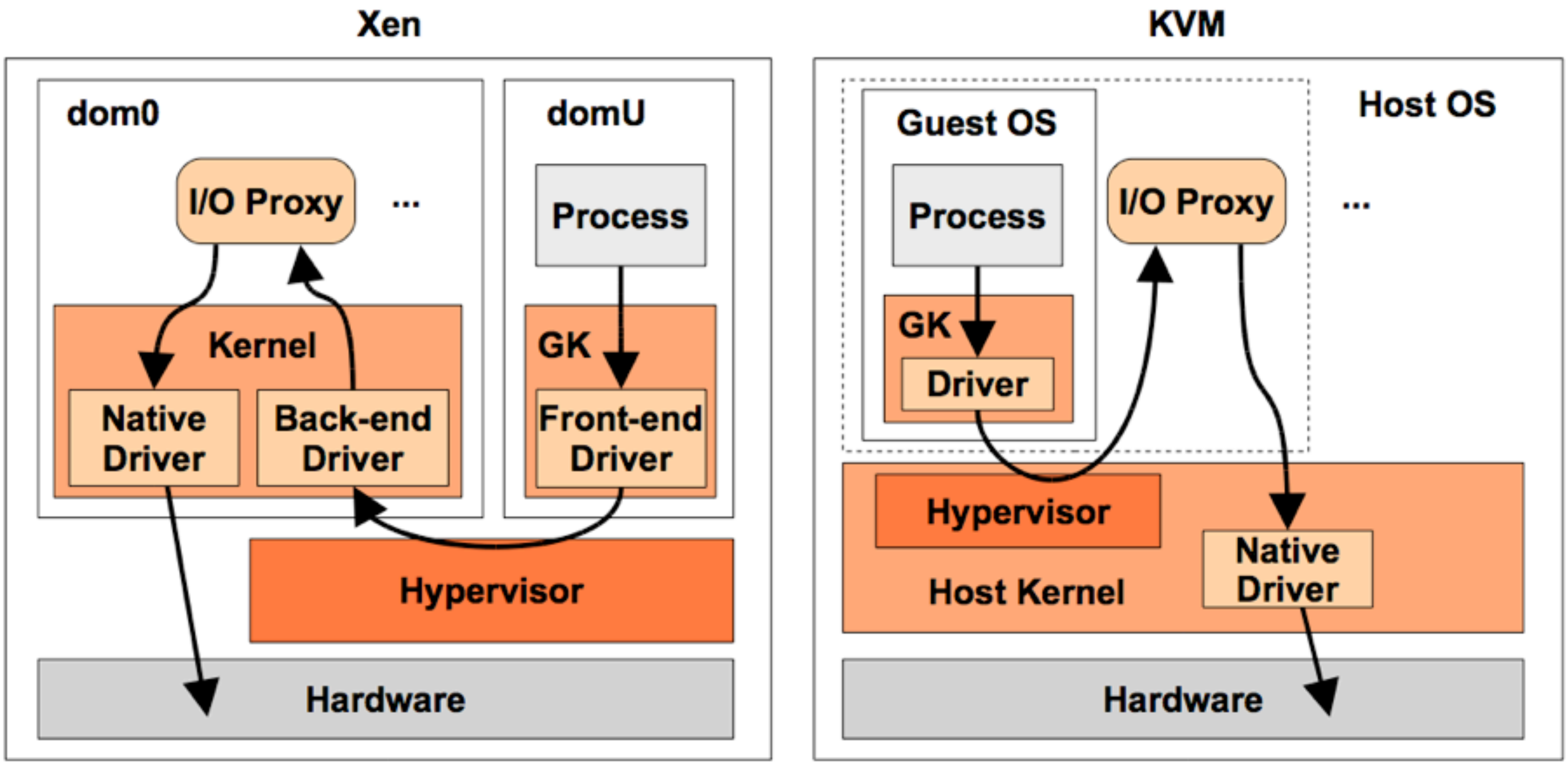
- Ancestry: chroot → FreeBSD jails → Solaris Zones
- OS Virtualization. Zero I/O path overheads.





Zones, cont.

- Compare to HW Virtualization:



- This shows the initial I/O control flow. There are optimizations/ variants for improving the HW Virt I/O path, esp for Xen.

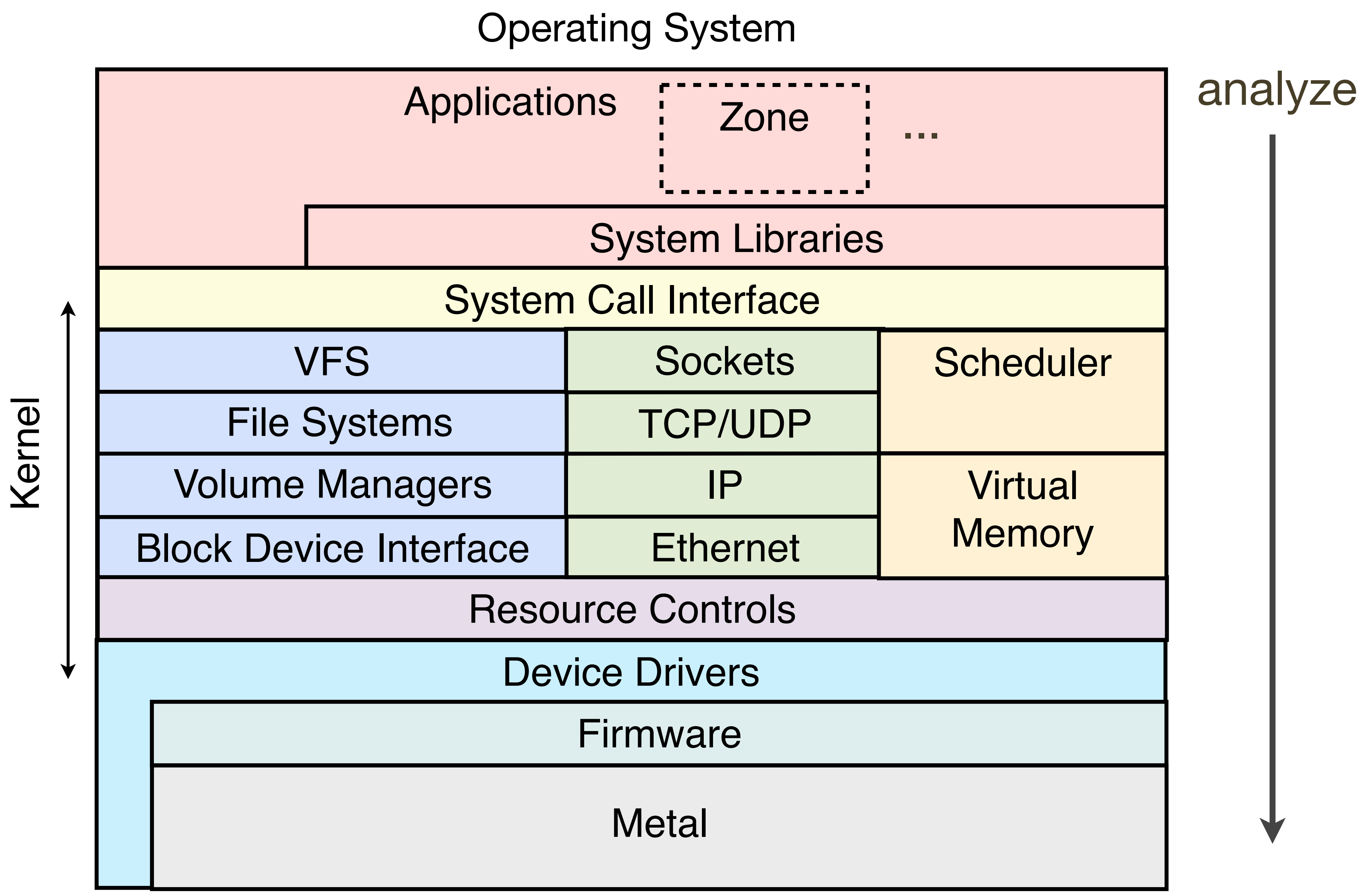
Zones, cont.

- Comparing 1 GB instances on Joyent
- Max network throughput:
  - KVM: 400 Mbits/sec
  - Zones: 4.54 Gbits/sec (over 10x)
- Max network IOPS:
  - KVM: 18,000 packets/sec
  - Zones: 78,000 packets/sec (over 4x)
- Numbers go much higher for larger instances

- http://dtrace.org/blogs/brendan/2013/01/11/virtualization-performance-zones-kvm-xen

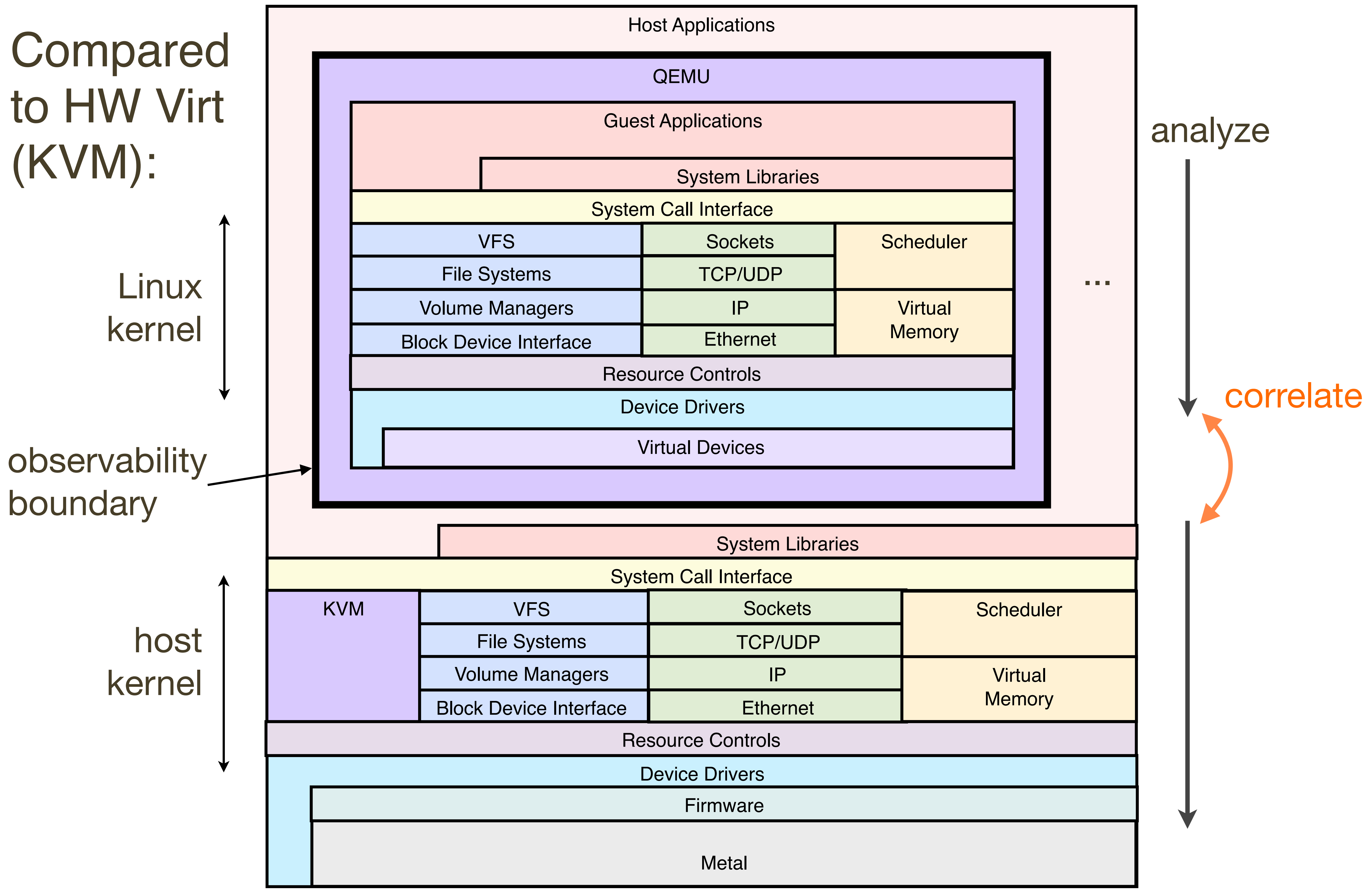
Zones, cont.

- Performance analysis for Zones is also easy. Analyze the applications as usual:



Zones, cont.

- Compared to HW Virt (KVM):



Zones, cont.

- Linux has been learning: LXC & cgroups, but not widespread adoption yet. Docker will likely drive adoption.

STREAMS

- AT&T modular I/O subsystem
- Like Unix shell pipes, but for kernel messages. Can push modules into the stream to customize processing
- Introduced (fully) in Unix **8th** Ed Research Unix, became SVr4 STREAMS, and was used by Solaris for network TCP/IP stack
- With greater demands for TCP/IP performance, the overheads of STREAMS reduced scalability
- Sun switched high-performing paths to be direct function calls

STREAMS, cont.

- A cautionary tale: not good for high performance code paths

Symbols

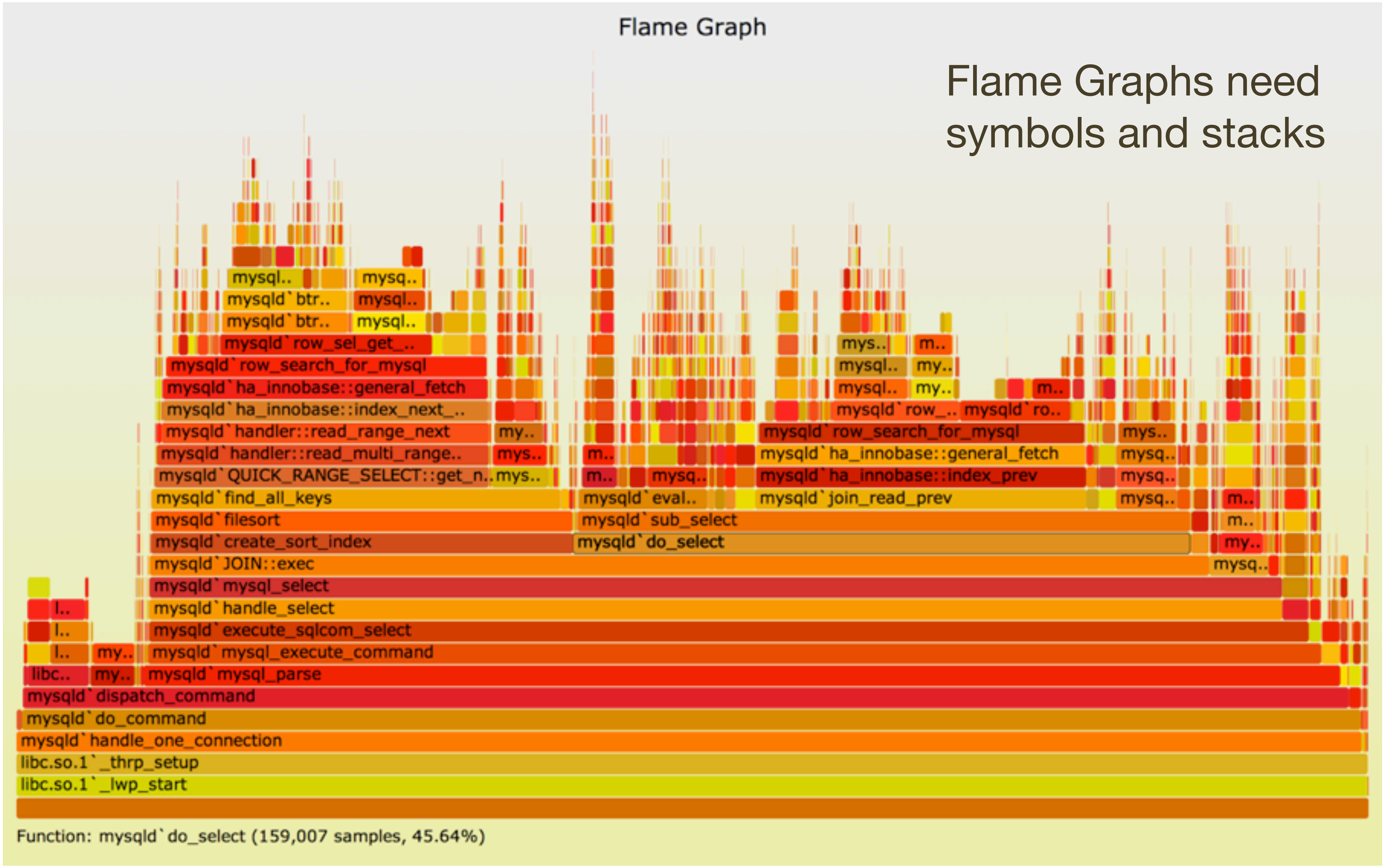
- Compilers on Linux strip symbols by default, making perf profiler output inscrutable without the dbgsym packages

```
    57.14%     sshd  libc-2.15.so        [.] connect
               |
               --- connect
                  |
                  |--25.00%-- 0x7ff3c1cddf29
                  |
                  |--25.00%-- 0x7ff3bfe82761
                  |           0x7ff3bfe82b7c
                  |
                  |--25.00%-- 0x7ff3bfe82dfc
                   --25.00%-- [...]
```

What??

- Linux compilers also drop frame pointers, making stacks hard to profile. Please use **-fno-omit-frame-pointer** to stop this.
    - as a workaround, perf_events has "-g dwarf" for libunwind
- Solaris keeps symbols and stacks, and often has CTF too, making Mean Time To Flame Graph very fast

Symbols, cont.



Flame Graphs need symbols and stacks

Symbols, cont.

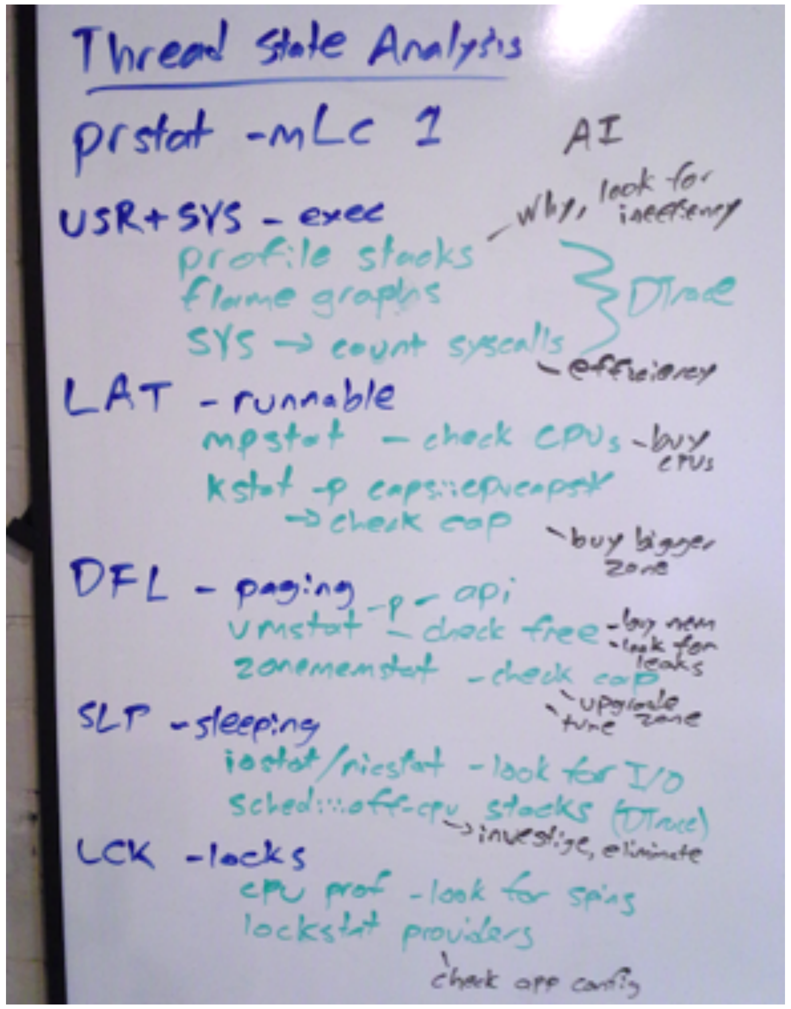
- Keep symbols and frame pointers. Faster resolution for performance analysis and troubleshooting.

prstat -mLc

- Per-thread time broken down into states, from a top-like tool:

```
$ prstat -mLc 1
   PID USERNAME  USR SYS  TRP TFL DFL LCK SLP LAT  VCX ICX SCL SIG PROCESS/LWPID
 63037 root       83  16  0.1 0.0 0.0 0.0 0.0 0.5   30 243 45K   0 node/1
 12927 root       14  49  0.0 0.0 0.0 0.0  34 2.9   6K 365 .1M   0 ab/1
 63037 root      0.5 0.6  0.0 0.0 0.0 3.7  95 0.4   1K   0  1K   0 node/2
[...]
```

- These columns narrow an investigation immediately, and have been critical for solving countless issues. Unsung hero of Solaris performance analysis
- Well suited for the Thread State Analysis (TSA) methodology, which I've taught in class, and has helped students get started and fix unknown perf issues
- http://www.brendangregg.com/tsamethod.html



Thread State Analysis

prstat -mLc 1 AI

USR+SYS - exec - why, look for inefficiency
 profile stacks
 flame graphs } DTrace
 SYS → count syscalls - efficiency

LAT - runnable
 mpstat - check CPUs - buy CPUs
 kstat -p caps::cpucaps:*
 → check cap - buy bigger zone

DFL - paging
 vmstat -p - api - check free - buy mem - look for leaks
 zonememstat - check cap - upgrade zone - tune

SLP - sleeping
 iostat/nicstat - look for I/O
 sched:::off-cpu stacks (DTrace) → investige, eliminate

LCK - locks
 cpu prof - look for spins
 lockstat providers
 check app config

prstat -mLc, cont.

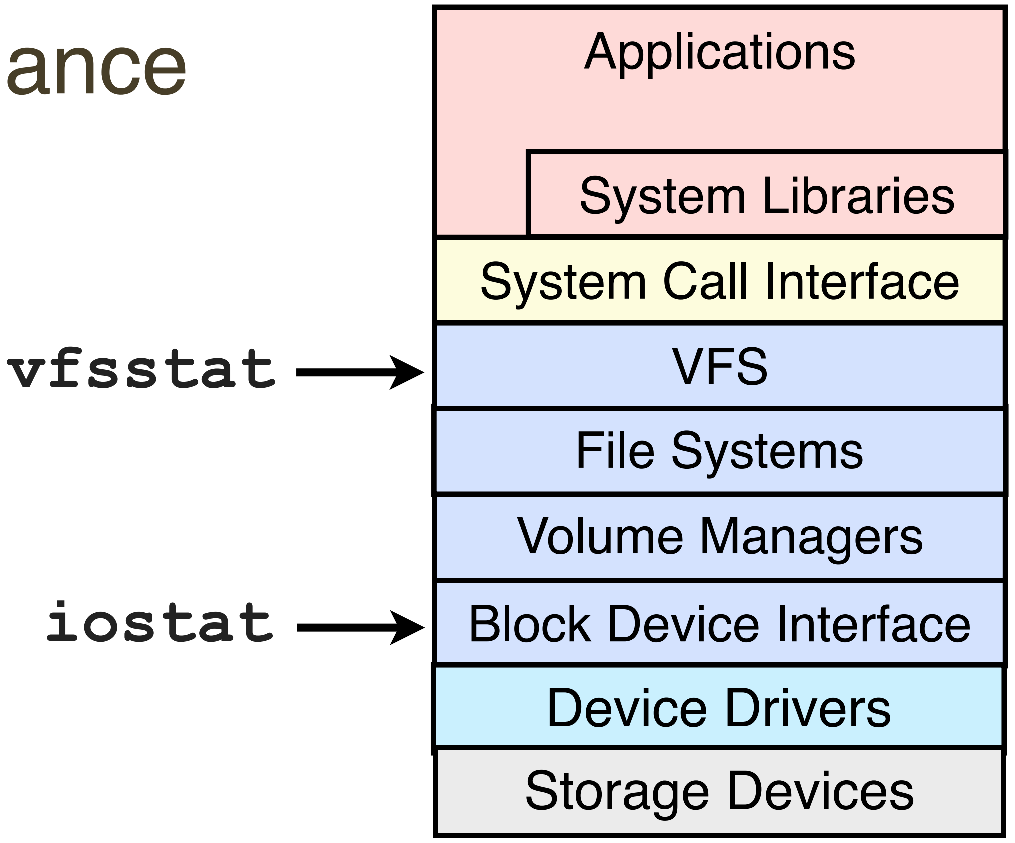
- Linux has various thread states: delay accounting, I/O accounting, schedstats. Can they be added to htop? See TSA Method for use case and desired metrics.

vfsstat

- VFS-level iostat (added to SmartOS, not Solaris):

```
$ vfsstat -M 1
  r/s    w/s   Mr/s   Mw/s ractv wactv read_t writ_t  %r  %w   d/s  del_t zone
761.0 267.1   15.4    1.6   0.0   0.0   12.0   24.7   0   0   1.3   23.5 5716a5b6
4076.8 2796.0  41.7   2.3   0.1   0.0   16.6    3.1   6   0   0.0    0.0 5716a5b6
4945.1 2807.4 157.1   2.3   0.1   0.0   25.2    3.4  12   0   0.0    0.0 5716a5b6
3550.9 1910.4 109.7   1.6   0.4   0.0  112.9    3.3  39   0   0.0    0.0 5716a5b6
[...]
```

- Shows what the applications request from the file system, and the *true* performance that they experience
- iostat includes asynchronous I/O
- vfsstat sees issues iostat can't:
  - lock contention
  - resource control throttling

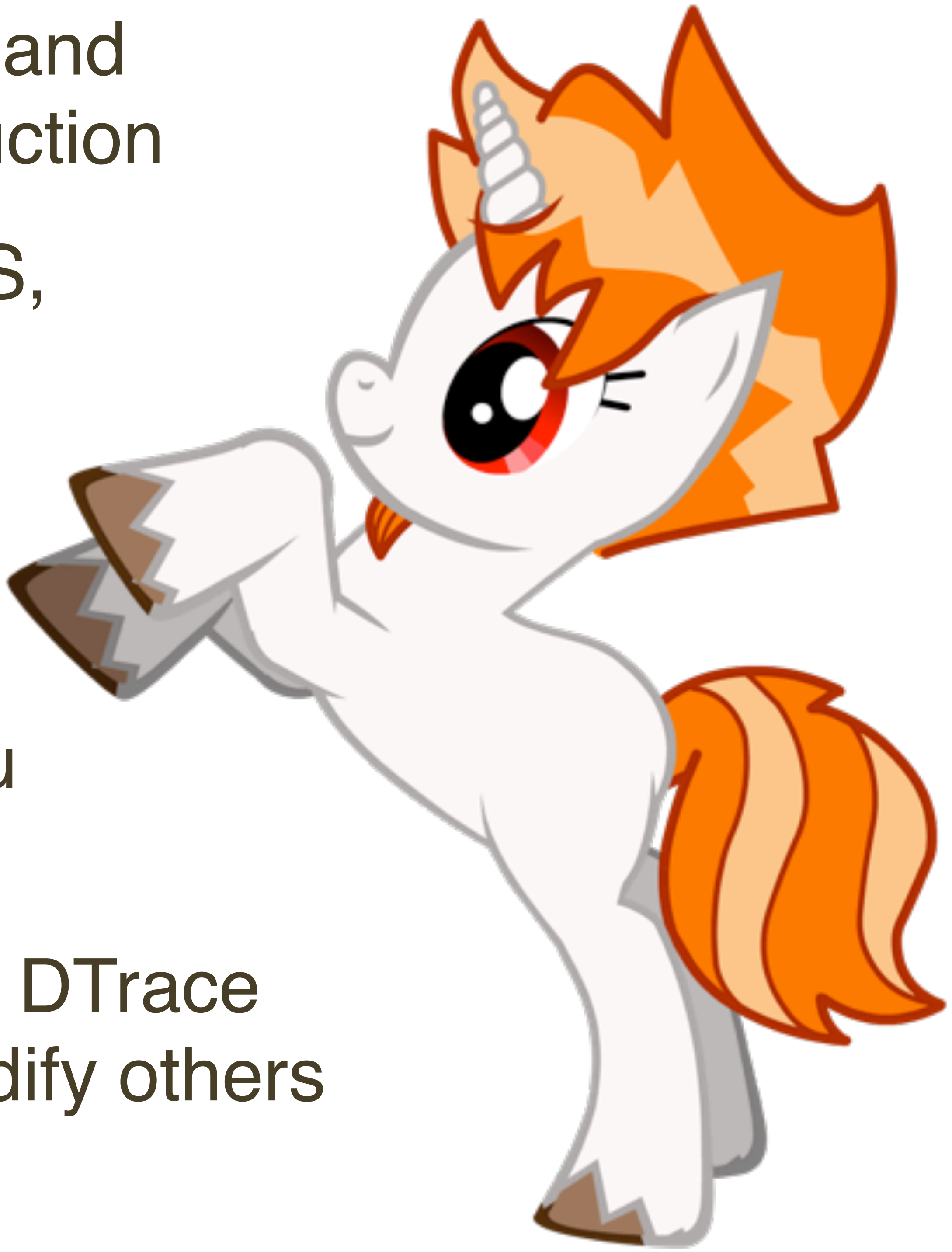


vfsstat, cont.

- Add vfsstat, or VFS metrics to sar.

DTrace

- Programmable, real-time, dynamic and static tracing, for performance analysis and troubleshooting, in dev and production
- Used on Solaris, illumos/SmartOS, Mac OS X, FreeBSD, ...
- Solve virtually any perf issue. eg, fix the earlier Perl 15% delta, no matter where the problem is. Without DTrace's capabilities, you may have to wear that 15%.
- Users can write their own custom DTrace one-liners and scripts, or use/modify others (eg, mine).



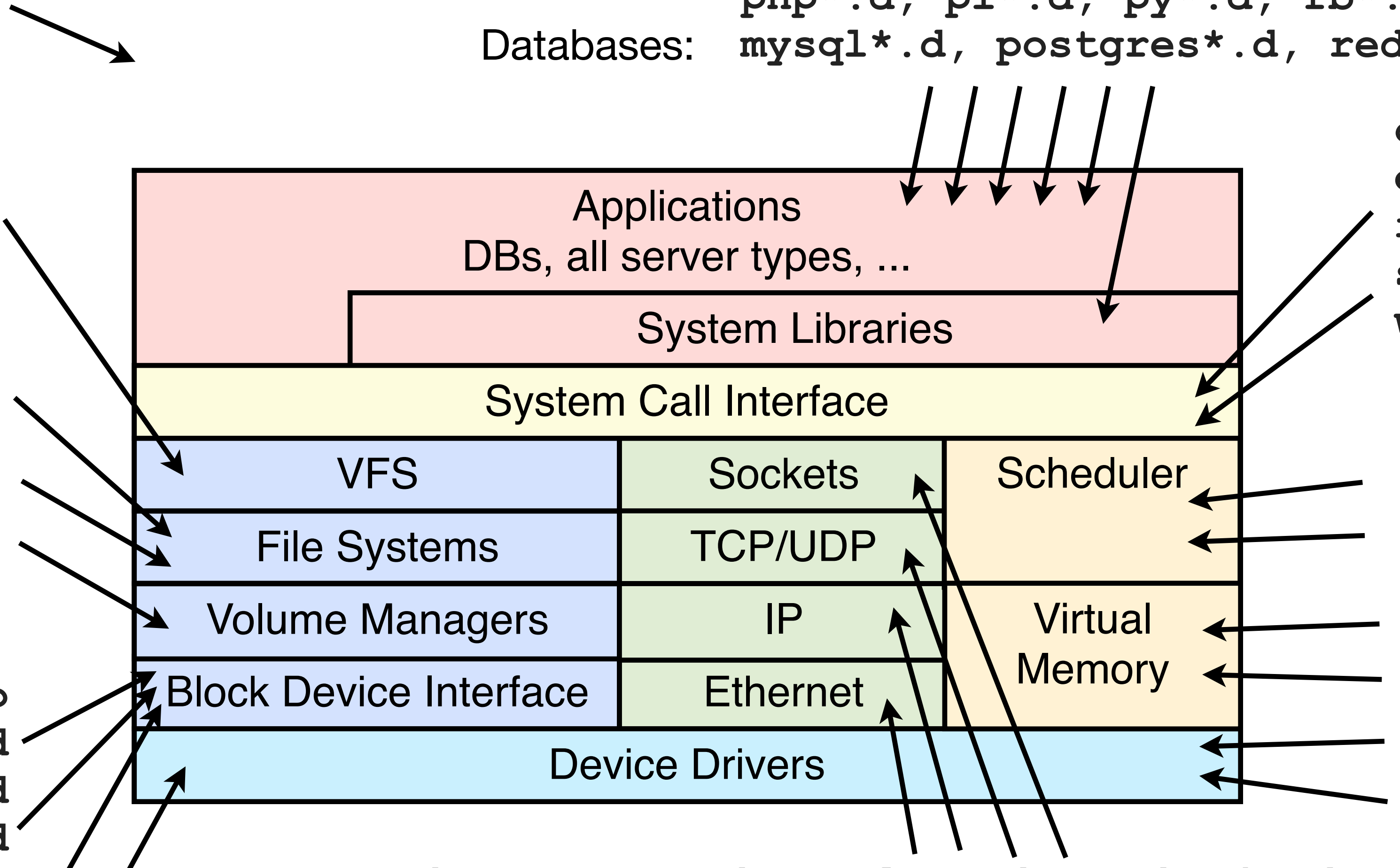
DTrace: illumos Scripts

- Some of my DTrace scripts from the DTraceToolkit, DTrace book...

`cifs*.d, iscsi*.d` :Services
`nfsv3*.d, nfsv4*.d`
`ssh*.d, httpd*.d`

Language Providers: `hotuser, umutexmax.d, lib*.d`
`node*.d, erlang*.d, j*.d, js*.d`
`php*.d, pl*.d, py*.d, rb*.d, sh*.d`

Databases: `mysql*.d, postgres*.d, redis*.d, riak*.d`



`fswho.d, fssnoop.d`
`sollife.d`
`solvfssnoop.d`

`dnlcsnoop.d`
`zfsslower.d`
`ziowait.d`
`ziostacks.d`
`spasync.d`
`metaslab_free.d`

`iosnoop, iotop`
`disklatency.d`
`satacmds.d`
`satalatency.d`
`scsicmds.d`
`scsilatency.d`
`sdretry.d, sdqueue.d`

`ide*.d, mpt*.d`

`opensnoop, statsnoop`
`errinfo, dtruss, rwtop`
`rwsnoop, mmap.d, kill.d`
`shellsnoop, zonecalls.d`
`weblatency.d, fddist`

`priclass.d, pridist.d`
`cv_wakeup_slow.d`
`displat.d, capslat.d`

`minfbypid.d`
`pgpginbypid.d`

`macops.d, ixgbecheck.d`
`ngesnoop.d, ngelink.d`

`soconnect.d, soaccept.d, soclose.d, socketio.d, so1stbyte.d`
`sotop.d, soerror.d, ipstat.d, ipio.d, ipproto.d, ipfbtsnoop.d`
`ipdropper.d, tcpstat.d, tcpaccept.d, tcpconnect.d, tcpioshort.d`
`tcpio.d, tcpbytes.d, tcpsize.d, tcpnmap.d, tcpconnlat.d, tcp1stbyte.d`
`tcpfbtwatch.d, tcpsnoop.d, tcpconnreqmaxq.d, tcprefused.d`
`tcpretranshosts.d, tcpretranssnoop.d, tcpsackretrans.d, tcpslowstart.d`
`tcptimewait.d, udpstat.d, udpio.d, icmpstat.d, icmpsnoop.d`

DTrace, cont.

- What Linux needs to learn about DTrace:

Feature #1 is production safety

- There should be NO risk of panics or freezes. It should be an everyday tool like top(1).
- Related to production safety is the minimization of overheads, which can be done with in-kernel summaries. Some of the Linux tools need to learn how to do this, too, as the overheads of dump & post-analysis can get too high.
- Features aren't features if users don't use them

DTrace, cont.

- Linux might get DTrace-like capabilities via:
  - dtrace4linux
  - perf_events
  - ktap
  - SystemTap
  - LTTng
- The Linux kernel has the necessary frameworks which are sourced by these tools: tracepoints, kprobes, uprobes
- ... and another thing Linux can learn:
  - DTrace has a memorable unofficial mascot (the ponycorn by Deirdré Straughan, using General Zoi's pony creator). She's created some for the Linux tools too...

dtrace4linux

- Two DTrace ports in development for Linux:
- 1. dtrace4linux
    - https://github.com/dtrace4linux/linux
    - Mostly by Paul Fox
    - Not safe for production use yet; I've used it to solve issues by first reproducing them in the lab
- 2. Oracle Enterprise Linux DTrace
    - Has been steady progress. Oracle Linux 6.5 featured "full DTrace integration" (Dec 2013)

dtrace4linux: Example

- Tracing ext4 read/write calls with size distributions (bytes):

```
#!/usr/sbin/dtrace -s

fbt::vfs_read:entry, fbt::vfs_write:entry
/stringof(((struct file *)arg0)->f_path.dentry->d_sb->s_type->name) == "ext4"/
{
        @[execname, probefunc + 4] = quantize(arg2);
}

dtrace:::END
{
        printa("\n  %s %s (bytes)%@d", @);
}
```

```
# ./ext4rwsize.d
dtrace: script './ext4rwsize.d' matched 3 probes
^C
CPU     ID                    FUNCTION:NAME
  1      2                             :END
[...]
  vi read (bytes)
           value  ------------- Distribution ------------- count
             128 |                                         0
             256 |                                         1
             512 |@@@@@@@                                  17
            1024 |@                                        2
            2048 |                                         0
            4096 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@         75
            8192 |                                         0
```

dtrace4linux: Example

- Tracing TCP retransmits (tcpretransmit.d for 3.11.0-17):

```
#!/usr/sbin/dtrace -qs

dtrace:::BEGIN { trace("Tracing TCP retransmits... Ctrl-C to end.\n"); }

fbt::tcp_retransmit_skb:entry {
        this->so = (struct sock *)arg0;
        this->d = (unsigned char *)&this->so->__sk_common; /* 1st is skc_daddr */
        printf("%Y: retransmit to %d.%d.%d.%d, by:", walltimestamp,
            this->d[0], this->d[1], this->d[2], this->d[3]);
        stack(99);
}
```

```
# ./tcpretransmit.d
Tracing TCP retransmits... Ctrl-C to end.
1970 Jan  1 12:24:45: retransmit to 50.95.220.155, by:
              kernel`tcp_retransmit_skb
              kernel`dtrace_int3_handler+0xcc
              kernel`dtrace_int3+0x3a
              kernel`tcp_retransmit_skb+0x1
              kernel`tcp_retransmit_timer+0x276
              kernel`tcp_write_timer
              kernel`tcp_write_timer_handler+0xa0
              kernel`tcp_write_timer+0x6c
              kernel`call_timer_fn+0x36
              kernel`tcp_write_timer
              kernel`run_timer_softirq+0x1fd
              kernel`__do_softirq+0xf7
              kernel`call_softirq+0x1c
[...]
```

that used to work...

perf_events

- In the Linux tree. perf-tools package. Can do sampling, static and dynamic tracing, with stack traces and local variables
- Often involves an enable→collect→dump→analyze cycle
- A powerful profiler, loaded with features (eg, libunwind stacks!)
- Isn't programmable, and so has limited ability for processing data in-kernel. Does counts.
- You can post-process in user-land, but the overheads of passing all event data incurs overhead; can be Gbytes of data

perf_events: Example

- Dynamic tracing of tcp_sendmsg() with size:

```
# perf probe --add 'tcp_sendmsg size'
[...]
# perf record -e probe:tcp_sendmsg -a
^C[ perf record: Woken up 1 times to write data ]
[ perf record: Captured and wrote 0.052 MB perf.data (~2252 samples) ]
# perf script
# ========
# captured on: Fri Jan 31 23:49:55 2014
# hostname : dev1
# os release : 3.13.1-ubuntu-12-opt
[...]
# ========
#
     sshd  1301 [001]   502.424719: probe:tcp_sendmsg: (ffffffff81505d80) size=b0
     sshd  1301 [001]   502.424814: probe:tcp_sendmsg: (ffffffff81505d80) size=40
     sshd  2371 [000]   502.952590: probe:tcp_sendmsg: (ffffffff81505d80) size=27
     sshd  2372 [000]   503.025023: probe:tcp_sendmsg: (ffffffff81505d80) size=3c0
     sshd  2372 [001]   503.203776: probe:tcp_sendmsg: (ffffffff81505d80) size=98
     sshd  2372 [001]   503.281312: probe:tcp_sendmsg: (ffffffff81505d80) size=2d0
[...]
```

ktap

- A new static/dynamic tracing tool for Linux
- Lightweight, simple, based on lua. Uses bytecode for programmable and safe tracing
- Suitable for use on embedded Linux
- http://www.ktap.org
- Features are limited (still in development), but I've been impressed so far
- In development, so I can't recommend production use yet

ktap: Example

- Summarize read() syscalls by return value (size/err):

```
# ktap -e 's = {}; trace syscalls:sys_exit_read { s[arg2] += 1 }
    trace_end { histogram(s); }'
^C
                             value ------------- Distribution ------------- count
                               -11 |@@@@@@@@@@@@@@@@@@@@@@@@                 50
                                18 |@@@@@@                                   13
                                72 |@@                                       6
                              1024 |@                                        4
                                 0 |                                         2
                                 2 |                                         2
                               446 |                                         1
                               515 |                                         1
                                48 |                                         1
```

histogram of a key/ value table →

- Write scripts (excerpt from syslatl.kp, highlighting time delta):

```
trace syscalls:sys_exit_* {
        if (self[tid()] == nil) { return }
        delta = (gettimeofday_us() - self[tid()]) / (step * 1000)
        if (delta > max) { max = delta }
        lats[delta] += 1
        self[tid()] = nil
}
```

ktap: Setup

- Installing on Ubuntu (~5 minutes):

```
# apt-get install git gcc make
# git clone https://github.com/ktap/ktap
# cd ktap
# make
# make install
# make load
```

- Example dynamic tracing of tcp_sendmsg() and stacks:

```
# ktap -e 's = ptable(); trace probe:tcp_sendmsg { s[backtrace(12, -1)] <<< 1 }
    trace_end { for (k, v in pairs(s)) { print(k, count(v), "\n"); } }'
Tracing... Hit Ctrl-C to end.
^C
ftrace_regs_call
sock_aio_write
do_sync_write
vfs_write
SyS_write
system_call_fastpath
       17
```

SystemTap

- Sampling, static and dynamic tracing, fully programmable
- The most featured of all the tools. Does some things that DTrace can't (eg, loops).
- http://sourceware.org/systemtap
- Has its own tracing language, which is compiled (gcc) into kernel modules (slow; safe?)
- I used it a lot in 2011, and had problems with panics/freezes; never felt safe to run it on my customer's production systems
- Needs vmlinux/debuginfo

SystemTap: Setup

- Setting up a SystemTap on ubuntu (2014):

```
# ./opensnoop.stp
semantic error: while resolving probe point: identifier 'syscall' at ./
opensnoop.stp:11:7
        source: probe syscall.open
                      ^
semantic error: no match
Pass 2: analysis failed.  [man error::pass2]
Tip: /usr/share/doc/systemtap/README.Debian should help you get started.

# more /usr/share/doc/systemtap/README.Debian
[...]
supported yet, see Debian bug #691167). To use systemtap you need to
manually install the linux-image-*-dbg and linux-header-* packages
that match your running kernel. To simplify this task you can use the
stap-prep command. Please always run this before reporting a bug.

# stap-prep
You need package linux-image-3.11.0-17-generic-dbgsym but it does not seem
to be available
 Ubuntu -dbgsym packages are typically in a separate repository
 Follow https://wiki.ubuntu.com/DebuggingProgramCrash to add this
repository
```

helpful tips...

SystemTap: Setup, cont.

- After following ubuntu's DebuggingProgramCrash site:

```
# apt-get install linux-image-3.11.0-17-generic-dbgsym
Reading package lists... Done
Building dependency tree
Reading state information... Done
The following NEW packages will be installed:
  linux-image-3.11.0-17-generic-dbgsym
0 upgraded, 1 newly installed, 0 to remove and 0 not upgraded.
Need to get 834 MB of archives.
After this operation, 2,712 MB of additional disk space will be used.
Get:1 http://ddebs.ubuntu.com/ saucy-updates/main linux-image-3.11.0-17-
generic-dbgsym amd64 3.11.0-17.31 [834 MB]
0% [1 linux-image-3.11.0-17-generic-dbgsym 1,581 kB/834 MB 0%]    215 kB/s
1h 4min 37s
```

but my perf issue is happening *now*...

- In fairness:
  - 1. The Red Hat SystemTap developer's primary focus is to get it working on Red Hat (where they say it works fine)
  - 2. Lack of CTF isn't SystemTap's fault, as said earlier

SystemTap: Example

- opensnoop.stp:

```
#!/usr/bin/stap

probe begin
{
        printf("\n%6s %6s %16s %s\n", "UID", "PID", "COMM", "PATH");
}

probe syscall.open
{
        printf("%6d %6d %16s %s\n", uid(), pid(), execname(), filename);
}
```

- Output:

```
# ./opensnoop.stp
   UID    PID             COMM PATH
     0  11108             sshd <unknown>
     0  11108             sshd <unknown>
     0  11108             sshd /lib/x86_64-linux-gnu/libwrap.so.0
     0  11108             sshd /lib/x86_64-linux-gnu/libpam.so.0
     0  11108             sshd /lib/x86_64-linux-gnu/libselinux.so.1
     0  11108             sshd /usr/lib/x86_64-linux-gnu/libck-connector.so.0
[...]
```

LTTng

- Profiling, static and dynamic tracing
- Based on Linux Trace Toolkit (LTT), which dabbled with dynamic tracing (DProbes) in 2001
- Involves an enable→start→stop→view cycle
- Designed to be highly efficient
- I haven't used it properly yet, so I don't have an informed opinion (sorry LTTng, not your fault)

LTTng, cont.

- Example sequence:

```
# lttng create session1
# lttng enable-event sched_process_exec -k
# lttng start
# lttng stop
# lttng view
# lttng destroy session1
```

DTrace, cont.

- 2014 is an exciting year for dynamic tracing and Linux – one of these may reach maturity and win!

DTrace, final word

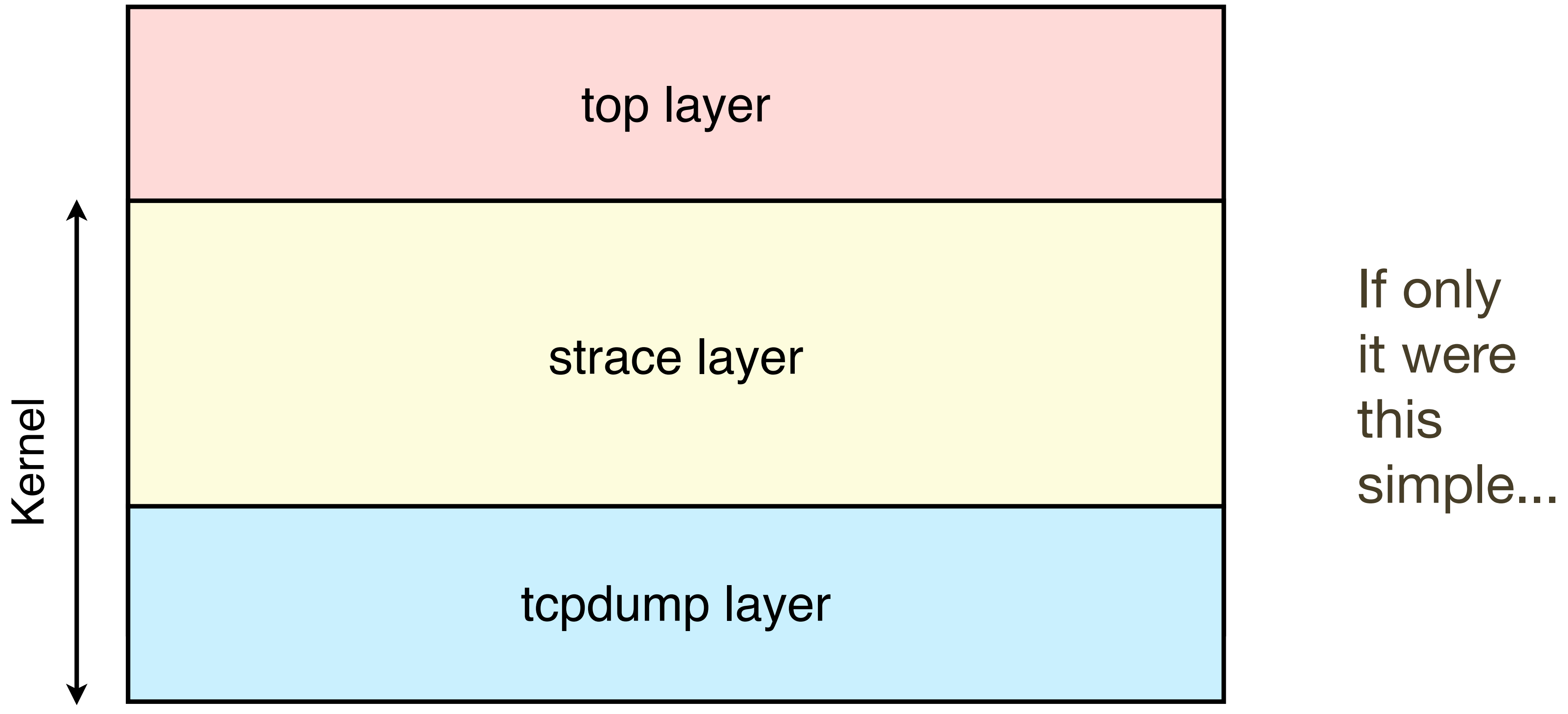
- What **Oracle Solaris** can learn from dtrace4linux:
    - Dynamic tracing is crippled without source code
    - Oracle could give customers scripts to run, but customers lose any practical chance of writing them themselves
- If the dtrace4linux port is completed, it will be more useful than Oracle Solaris DTrace (unless they open source it again)

Culture

- Sun Microsystems, out of necessity, developed a performance engineering culture that had an appetite for understanding and measuring the system: data-driven analysis
    - If your several-million-dollar Ultra Enterprise 10000 doesn't perform well and your company is losing non-trivial sums of money every minute because of it, you call Sun Service and start demanding answers.
      – System Performance Tuning [Musumeci 02]
- Includes the diagnostic cycle:
    - hypothesis → instrumentation → data → hypothesis
- Some areas of Linux are already learning this (and some areas of Solaris never did)

Culture, cont.

- Linux perf issues are often debugged using only top(1), *stat, sar(1), strace(1), and tcpdump(8). These leave many areas not measured.



- What about the other tools and metrics that are part of Linux? perf_events, tracepoints/kprobes/uprobes, schedstats, I/O accounting, blktrace, etc.

Culture, cont.

- Understand the system, and measure if at all possible
- Hypothesis → instrumentation → data → hypothesis
- Use perf_events (and others once they are stable/safe)
- strace(1) is intermediate, not advanced
- High performance doesn't just mean hardware, system, and config. It foremost means analysis of performance limiters.

What Both can Learn

What Both can Learn

- Get better at benchmarking

Benchmarking

- How Linux vs Solaris performance is often compared
- Results incorrect or misleading almost 100% of the time
- Get reliable benchmark results by **active benchmarking**:
    - Analyze performance of all components *during* the benchmark, to identify limiters
    - Takes time: benchmarks may take weeks, not days
- Opposite of passive benchmarking: fire and forget
- If SmartOS loses a benchmark, my management demands answers, and I almost always overturn the result with analysis
- Test variance as well as steady workloads. Measure jitter. These differ between systems as well.

Results

Out-of-the-Box

- Out-of-the-box, which is faster, Linux or Solaris?

Out-of-the-Box

- Out-of-the-box, which is faster, Linux or Solaris?
- There are many differences, it's basically a crapshoot.
  I've seen everything from 5% to 5x differences either way
- It really depends on workload and platform characteristics:
  - CPU usage, FS I/O, TCP I/O, TCP connect rates, default TCP tunables, synchronous writes, lock calls, library calls, multithreading, multiprocessor, network driver support, ...
- From prior Linux vs SmartOS comparisons, it's hard to pick a winner, but in general my expectations are:
  - SmartOS: for heavy file system or network I/O workloads
  - Linux: for CPU-bound workloads

Out-of-the-Box Relevance

- Out-of-the-box performance isn't that interesting: if you care about performance, why *not* do some analysis and tuning?

In Practice

- With some analysis and tuning, which is faster?

In Practice

- With some analysis and tuning, which is faster?
- Depends on the workload, and which differences matter to you
- With analysis, I can usually make SmartOS beat Linux
    - DTrace and microstate accounting give me a big advantage: I can analyze and fix all the small differences (which sometimes exist as apps are developed for Linux)
    - Although, perf/ktap/... are catching up
- I can do the same and make Linux beat SmartOS, but it's much more time-consuming without an equivalent DTrace
- On the same hardware, it's more about the performance engineer than the kernel. DTrace doesn't run itself.

At Joyent

- Joyent builds high performance SmartOS instances that frequently beat Linux, but that's due to more than just the OS. We use:
  - Config: OS virtualization (Zones), all instances on ZFS
  - Hardware: 10 GbE networks, plenty of DRAM for the ARC
  - Analysis: DTrace to quickly root-cause issues and tune
- With SmartOS (ZFS, DTrace, Zones, KVM) configured for performance, and with some analysis, I expect to win most head-to-head performance comparisons

Learning From Linux

- Joyent has also been learning from Linux to improve SmartOS.
  - Package repos: dedicated staff
  - Community: dedicated staff
  - Compiler options: dedicated repo staff
  - KVM: ported!
  - TCP TIME_WAIT: fixed localhost; more fixes to come
  - sar: fix understood
- More to do...

References

- General Zoi's Awesome Pony Creator: http://generalzoi.deviantart.com/art/Pony-Creator-v3-397808116
- More perf examples: http://www.brendangregg.com/perf.html
- More ktap examples: http://www.brendangregg.com/ktap.html
- http://www.ktap.org/doc/tutorial.html
- Flame Graphs: http://www.brendangregg.com/flamegraphs.html
- Diagnostic cycle: http://dtrace.org/resources/bmc/cec_analytics.pdf
- http://www.brendangregg.com/activebenchmarking.html
- https://blogs.oracle.com/OTNGarage/entry/doing_more_with_dtrace_on

Thank You

- More info:
  - illumos: http://illumos.org
  - SmartOS: http://smartos.org
  - DTrace: http://dtrace.org
  - Joyent: http://joyent.com
  - Systems Performance book: http://www.brendangregg.com/sysperf.html
  - Me: http://www.brendangregg.com, http://dtrace.org/blogs/brendan, @brendangregg, brendan@joyent.com