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USE IMPROVE EVANGELIZE

Solaris 10 & OpenSolaris Performance, Observability & Debugging (POD)

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About The Authors

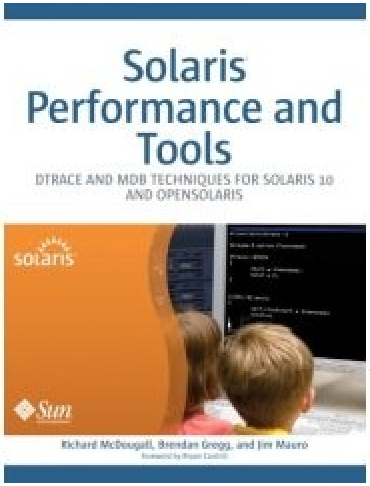
Jim Mauro is a Principle Engineer in the Systems Group Quality Office at Sun Microsystems, where he focuses on systems performance with real customer workloads. Jim also dabbles in performance for ZFS and Virtualization.

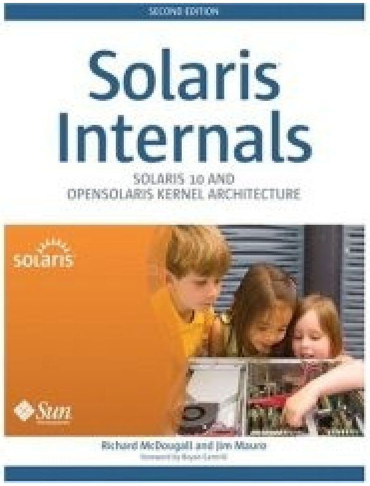
Richard McDougall is the Chief Performance Architect at VMware.

Richard and Jim authored ***Solaris Internals: Solaris 10 and Open Solaris Kernel Architecture.***
Prentice Hall, 2006. ISBN 0-13-148209-2

Richard and Jim (with Brendan Gregg) authored ***Solaris Performance and Tools: DTrace and MDB Techniques for Solaris 10 and Open Solaris***
Prentice Hall, 2006. ISBN 0-13-156819-1

Richard and Jim authored ***Solaris Internals:Core Kernel Architecture***,
Prentice Hall, 2001. ISBN 0-13-022496-0





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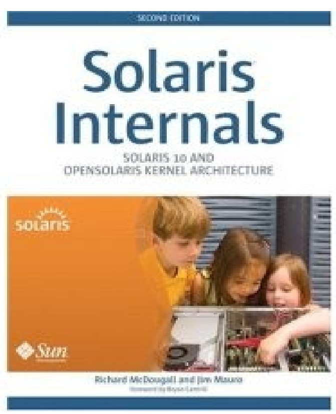
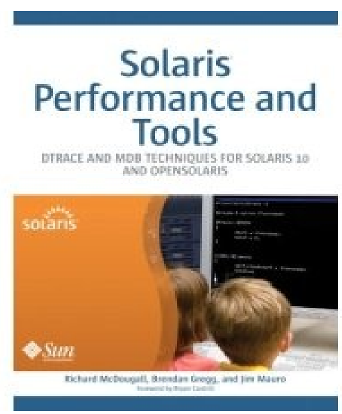
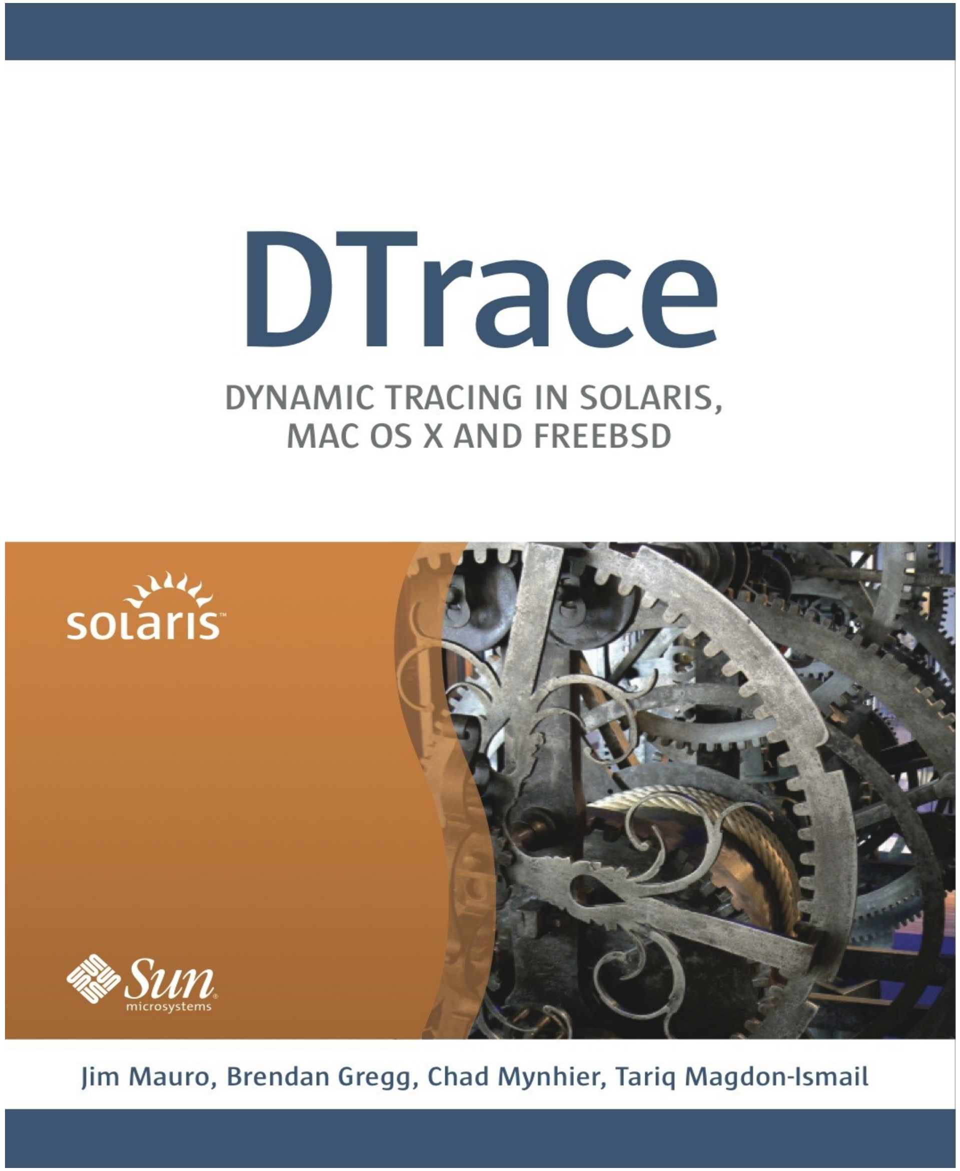
The Books (Shameless Plug)

- Solaris Internals: Solaris 10 and OpenSolaris Kernel Architecture
  - Community effort: over 35 contributing authors
  - Kernel data structures and algorithms
  - A lot of DTrace and mdb(1) examples to support the text
- Solaris Performance and Tools: DTrace and MDB Techniques for Solaris 10 and OpenSolaris
  - Guide to using the tools and utilities, methods, examples, etc





Coming Soon!


DTrace
DYNAMIC TRACING IN SOLARIS,
MAC OS X AND FREEBSD
solaris
Sun
microsystems
Jim Mauro, Brendan Gregg, Chad Mynhier, Tariq Magdon-Ismail

Before We Begin...

IT DEPENDS

What was the question...?

Batteries Not Included

Your Mileage May Vary (YMMV)

Solaris Performance

- Resources
  - www.solarisinternals.com
    - Wikipedia of Solaris Performance
  - www.opensolaris.org / www.opensolaris.com
    - Downloads, communities, documentation, discussion groups
      - DTrace, ZFS, Performance, etc
  - www.sun.com/bigadmin/collections/performance.html
    - Technical articles, tips, etc
  - www.brendangregg.com
    - DTrace Toolkit (over 230 scripts!)
    - Other Goodies
  - www.cooltools.sunsource.net
    - Development, optimized opensource software, analysis
  - blogs.sun.com
    - Too much to summarize here – search for what you're interested in
  - sunsolve.sun.com
    - Search for bugs related to what you're chasing...

Agenda

- Session 1 - 9:00AM to 10:30PM
  - Goals, non goals and assumptions
  - OpenSolaris
  - Solaris 10 Kernel Overview
  - Solaris 10 Features
  - The Tools of the Trade
- Session 2 - 11:00PM to 12:30PM
  - Memory
    - Virtual Memory
    - Physical Memory
    - Memory dynamics
    - Performance and Observability
    - Memory Resource Management

Agenda

- Session 3 - 2:00PM to 3:30PM
  - Processes, Threads & Scheduling
    - Processes, Threads, Priorities & Scheduling
    - Performance & Observability
      - Load, apps & the kernel
    - Processor Controls and Binding
    - Resource Pools, Projects & Zones
- Session 4 - 4:00PM to 5:30PM
  - File Systems and I/O
    - I/O Overview
    - UFS
    - ZFS
    - Performance & Observability
  - Network & Miscellanea

Session 1 - Intro, Tools, Stuff

Goals, Non-goals & Assumptions

- Goals
  - Architectural overview of the Solaris kernel
  - The tools – what they are, what they do, when and how to use them
  - Correlate performance & observability to key functions
  - Resource control & management framework
- Non-goals
  - Detailed look at core kernel algorithms
  - Networking internals
- Assumptions
  - General familiarity with the Solaris environment
  - General familiarity with operating systems concepts

OpenSolaris - www.opensolaris.com

- An open source operating system providing for community collaboration and development
- Source code released under the Common Development & Distribution License (CDDL – pronounced “cuddle”)
- Based on “Nevada” Solaris code-base (Solaris 10+)
- New features added to OpenSolaris, then back-ported to Solaris 10
- **OpenSolaris 2008.05**
  - First supported OpenSolaris distro with many new features
    - Live CD and easy-to-use graphical installer
    - ZFS default for root
    - Network-based package management (IPS)
    - Lots of apps
- **OpenSolaris 2009.06 – current release**
  - 2010.03 next planned release (subject to change)

Solaris 10 – Update Releases

- New features, new hardware support bug fixes
  - Check out the “What's New” Document; http://docs.sun.com/app/docs/coll/1531.1?l=en
- Solaris 10 3/05 – First release of S10
- Solaris 10 1/06 – Update 1
- Solaris 10 6/06 – Update 2
- Solaris 10 11/06 – Update 3
- Solaris 10 8/07 – Update 4
- Solaris 10 5/08 – Update 5
- Solaris 10 10/08 – Update 6
- Solaris 10 5/09 – Update 7
- Solaris 10 10/09 – Update 8

Solaris Kernel Features

- Dynamic
- Multithreaded
- Preemptive
- Multithreaded Process Model
- Multiple Scheduling Classes
  - Including realtime support, fixed priority and fair-share scheduling
- Tightly Integrated File System & Virtual Memory
- Virtual File System
- 64-bit kernel
  - 32-bit and 64-bit application support
- Resource Management
- Service Management & Fault Handling
- Integrated Networking

Solaris 10 & OpenSolaris

The Headline Grabbers

- Solaris Containers (Zones)
- Solaris Dynamic Tracing (DTrace)
- Predictive Self Healing
  - System Management Framework (SMF)
  - Fault Management Architecture (FMA)
- Process Rights Management (aka Least Privilege)
- Premier x86 support
  - Optimized 64-bit Opteron support (x64)
  - Optimized Intel support
- Zetabyte Filesystem (ZFS)
- Network Stack – TCP/IP, UDP/IP, GLDv3

... and much, much more!

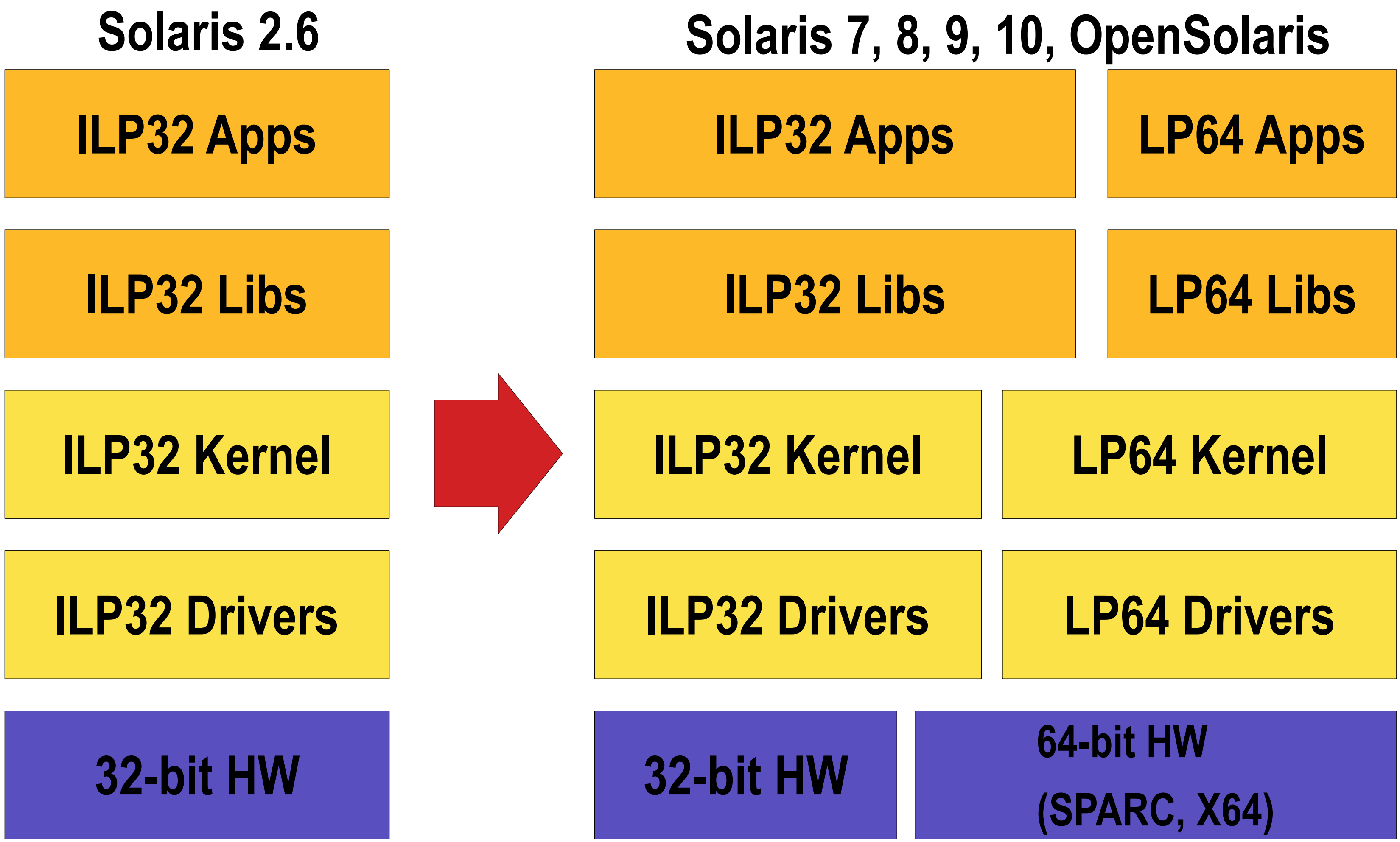
Solaris Performance Optimizations

- Threads, threads, threads...
- FULLY 64-Bit
- CPU Scalability
- UFS, NFS & ZFS File System Performance
- JVM Optimizations
- Memory Scalability
- Networking
- Resource Management
- Compiler Technology
- Observability: DTrace, Analyzer, and Perf Tools

Threads, threads, threads....

- Solaris's big-bet: large numbers of CPUs
  - SMP systems in the early days
  - Now thread-rich multicore CPUs w/hardware strands
    - 256-way T5440 (4 N2 sockets, each 8x8), 256GB RAM
    - 512-way DC3-64 (64 sockets, 256 cores, 512 strands)
- Fully preemptable kernel
- Architected around threads:
  - Kernel threads scheduled, executed
- I/O is thread-rich:
  - (Blocking) Interrupts are handled as threads
  - Worker-pools (tasks-queues) of threads avail for driving I/O
- Rich thread-development environment

The 64-bit Revolution



CPU Scalability

- Per-cpu dispatcher queues
  - Fine-grained locking on thread enqueue/dequeue
- Slab / vmem allocator in the kernel
  - Adopted by most other major kernels
  - Ported to user-land – libumem.so (scalable malloc(3C))
- CMP & CMT Optimizations
  - Chip MultiProcessing/Chip MultiThreading
    - Multi-strand, Multi-core designs
    - Optimize thread placement on cores
- NUMA Optimizations (MPO)
  - Locality groups (CPUs and Memory)

Scheduler Enhancements

- FX – Fixed Priority Scheduler
  - Integrated into Solaris 9
  - Provides fixed quantum scheduling
  - Fixed priorities
  - Eliminates uncessary context switches for server-style apps
  - Recommend setting as the default for Databases/Oracle
- FSS – Fair Share Schedule
  - Integrated into Solaris 9
  - Replaces SRM 1.X
  - Shares of CPU allocated
  - Adds Projects and Tasks for administration / management

File System Performance

- UFS & Databases
  - Direct I/O enables scalable database performance
  - Enhanced Logging Support introduced in S9
- NFS
  - Fireengine + RPC optimizations provide high throughput:
    - 108MB/s on GBE, 910MB/s on 10GBE, Solaris 10, x64
  - NFS for Databases Optimizations
    - 50,000+ Database I/O's per second via Direct I/O
- ZFS
  - Adaptive Replacement Cache (ARC)
  - Dynamic space management for metadata and data
  - Copy-On-Write (COW) – in-place data is never overwritten
  - Still evolving - new features and performance enhancements

Java VM Performance

- Java SE 6
  - Lock enhancements
  - GC improvements
  - A lot more;
  - http://java.sun.com/performance/reference/whitepapers/6_performance.html
- DTrace & Java
  - jstack() (Java 5)
    - jstackstrsize for more buffer space
  - dvm provider
    - Java 1.4.2 (libdvmpi.so)
    - Java 1.5 (libdvmti.so)
    - https://solaris10-dtrace-vm-agents.dev.java..net
  - Integrated HotSpot provider in Java 6
    - All DVM probes, plus extensions
  - Additional DTrace probes coming in Java 7

Memory Scalability

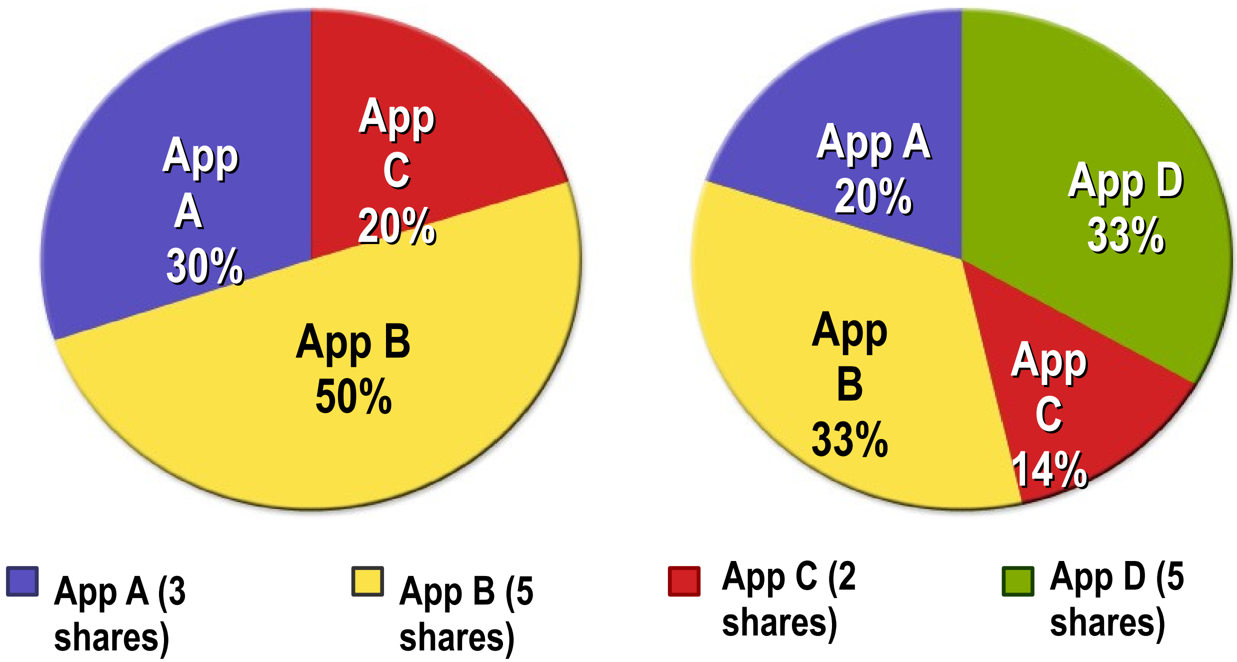
- Large Memory Optimizations
  - Solaris 9 & 10
  - 1TB shipping today. 4TB coming soon
  - 64GB hardly considered large anymore...
- Large Page Support
  - Evolved since Solaris 2.6
    - Large (4MB) pages with ISM/DISM for shared memory
  - Solaris 9/10
    - Multiple Page Size Support (MPSS)
      - Optional large pages for heap/stack
      - Programmatically via madvise()
      - Shared library for existing binaries (LD_PRELOAD)
      - Tool to observe potential gains
        - `# trapstat -t`
  - Solaris 10 Updates and OpenSolaris
    - Large Pages Out-Of-The-Box (LPOOB)

Networking

- Fire-engine in Solaris 10
  - New “vertical permiter” scaling model
  - 9Gbits/s on 10GBE, @50% of a 2-way x64 system
- Application to application round trip latency close to 40usec
- Nemo: High performance drivers in Solaris 1 Update 2
  - GLDv3 NIC Driver Interface
  - Enables multiple-ring support
  - Generic VLan and Trunking Support
- Yosemite: High performance UDP
  - Enabled in Solaris 10 Update 2
- IP Instances
  - Unique per-Zone TCP/IP stack
- Crossbow
  - Virtualization – VNICs
  - Resource management

Resource Management

- CPU & Network Resource Control Framework
  - Often used to control resource allocation to a container/zone.
- Processor Sets/Pools
  - Partition the machine into sets of processor resources
- Fair-Share Scheduler



Compiler Technology

- Studio Compilers performance optimizations
  - Highest level of optimized code for SPARC & x64
  - Studio 11 and Studio 12 **available free**
    - Outstanding profiler/performance analysis tool
    - collect(1) for collecting experiments
    - analyzer GUI, er_print(1) for command line
  - sgcc – gcc front-end, with an optimized SPARC code generator
    - Use cc(1) or gcc(1) to build apps
  - Analyzer Tool

Observability

- Performance Observability is the primary means to optimization
  - “That which is not measured, gets worse”
- Key Observability Features:
  - DTrace
  - Thread Microstate Measurements
  - *stat tools, ptools, kstats, truss, prstat
  - Lock Analysis Tools: lockstat, plockstat
  - System Statistics: sar, mpstat, vmstat etc...

Why Performance, Observability & Debugging?

- Reality, what a concept
  - Chasing performance problems
    - Sometimes they are even well defined
  - Chasing pathological behaviour
    - My app should be doing X, but it's doing Y
      - It's only doing it sometimes
  - Understand utilization
    - Resource consumption
      - CPU, Memory, IO (Disk and Network)
    - Capacity planning
  - In general, attaining a good understanding of the system, the workload, and how they interact
- 90% of system activity falls into one of the above categories, for a variety of roles
  - Admins, DBA's, Developers, etc...

Before You Begin...

“Would you tell me, please, which way I ought to go from here?” asked Alice

“*That depends a good deal on where you want to get to*” said the Cat

“*I don't much care where...*” said Alice

“*Then it doesn't matter which way you go*” said the Cat

Lewis Carroll

Alice's Adventures in Wonderland

General Methods & Approaches

- Define the problem
  - In terms of a business metric
  - Something measurable
- System View
  - Resource usage/utilization
    - CPU, Memory, Network, IO
- Process View
  - Execution profile
    - Where's the time being spent
  - May lead to a thread view
- Drill down depends on observations & goals
  - The path to root-cause has many forks
  - “bottlenecks” move
    - Moving to the next knee-in-the-curve

The Utilization Conundrum

- What is utilization?
  - The most popular metric on the planet for determining if something on your system is potentially a bottleneck or out of capacity
  - Properly defined as the amount of time something is busy relative to wall clock (elapsed) time
    - N is busy for .3 seconds over 1 second sampling periods, it's ((0.30 / 1) * 100) 30% utilized
- So... What's the problem?
  - Basic utilization metrics assume simple devices capable of only doing 1 thing at a time
    - Old disks, old networks (NICs), old CPUs
  - Bottom Line – 100% utilized is NOT necessarily a pain point

The Utilization Conundrum (cont)

- Modern Times
  - Disks, CPUs, NICs are all very sophisticated, with concurrency built-in at the lowest levels
    - Disks – integrated controllers with deep queues and NCQ
    - NICs – multiple ports, multiple IO channels per port
- Case in point, iostat “%b”
  - We've been ignoring it for years – it's meaningless because it simply means that an IO thread is in the disks queue every time it looks
  - “100% busy” Disks, or NICs, may be able to do more work with acceptable latency
  - It's all about meeting business requirements

The Utilization Conundrum (cont)

- CPUs
  - Multicore. Multiple execution cores on a chip
  - Multithread (hyperthreads) – multiple threads-per-core
  - CMT – Chip Multithreading
    - Combining multicore and multithread.
- CPU Utilization
  - Each thread (or strand) appears as a CPU to Solaris
  - Each CPU maintains its own set of utilization metrics
    - Derived from CPU microstates – sys, usr, idle
    - Multiple threads sharing the same core can each appear 100% utilized
- A CPU that shows 100% utilization (0% idle) has about as much meaning as a disk or NIC that shows 100% utilization
  - More to the point, a CPU that is observed to be 100% utilized may be capable of doing more work without a tradeoff in latency
    - e.g. a multi-execution unit pipeline running 1 thread all the time is 100% utilized, but capable of running another thread while maintaining the same service level

Google "*Utilization is Virtually Useless as a Metric*"

CPU Utilization

- Traditional “stat” tools
  - threads are CPUs
  - CPU microstates
- corestat
  - Unbundled script that uses cpustat(1)
    - cpustat(1) programs hardware counters (PICs) to gather chip statistics
      - Very hardware-specific
- corestat reports and vmstat/mpstat reports may vary due to the very different methods of data gathering

vmstat

```
 kthr      memory            page            disk          faults      cpu
 r b w   swap  free  re  mf pi po fr de sr m1 m1 m2 m2   in   sy   cs us sy id
 0 11 0 83283928 30844904 10682 15143 42254 121 106 0 0 59 0 60 0 18928 145389 24371 52 21 27
 0 16 0 83250248 30829608 9300 13420 37344 27797 27789 0 0 170 0 168 0 20669 149382 26695 49 22 29
 0 11 0 83237872 30848544 10700 13440 28631 76 76 0 0 170 0 169 0 20531 158387 27474 42 21 37
 0 13 0 83248120 30840824 11433 14640 42167 23755 23755 0 0 24 0 25 0 20447 139348 26573 47 27 26
 0 21 0 83207744 30843816 11944 15716 50408 19854 19854 0 0 47 0 46 0 20261 148615 25345 51 26 23
 0 11 0 83231536 30861544 10106 15260 90549 811 811 0 0 43 0 43 0 17916 170772 23022 50 25 26
 0 14 0 83241696 30866376 7904 12898 27841 100 100 0 0 36 0 36 0 16016 168074 20462 45 20 35
 0 15 0 83257208 30888504 9293 15014 28643 10077 10077 0 0 41 0 41 0 15377 120768 19819 32 17 51
 0 12 0 83219888 30894256 8621 16163 28433 27427 27419 0 0 30 0 30 0 14892 144676 17142 44 28 28
 0 14 0 83225824 30911520 8931 15740 26061 7036 7036 0 0 48 0 48 0 17729 143259 23048 37 20 43
 0 14 0 83241384 30914304 9709 14068 32892 177 177 0 0 42 0 42 0 16522 144625 21967 36 19 45
 0 12 0 83239696 30931664 9197 16691 31077 13915 13892 0 0 34 0 34 0 15312 141997 19194 42 19 39
 4 9 0 83255376 30947384 8979 15789 31323 54 54 0 0 34 0 34 0 15345 147188 19970 44 28 29
 2 12 0 83280600 30962944 9593 11575 27278 162 162 0 0 54 0 54 0 14589 129520 18370 37 16 47
 0 10 0 83279888 30960968 10216 11699 36746 1385 1385 0 0 35 0 35 0 13142 135268 16318 31 18 51
 0 13 0 83289392 30969488 11409 13129 44079 0 0 0 0 32 0 32 0 13245 130531 16526 24 19 56
 0 6 0 83304648 30977048 10653 10764 38600 162 162 0 0 30 0 29 0 12565 113020 15400 23 13 64
 0 12 0 83293552 30967384 10505 14347 33439 8 8 0 0 42 0 43 0 13933 116965 17959 27 15 57
 0 9 0 83316160 30977416 9349 11402 28741 447 447 0 0 35 0 35 0 13688 91570 17723 29 16 55
```

avg idle – 40.42%

avg sys - 20.53%

avg usr - 39.05%

corestat

```
CPU Utilization Mon May 11 11:00:58 2009
CPU             (Thd)          %Usr          %Sys       %Usr+Sys
---------------------    -----------   -----------   -----------
0               (0,1)          28.56         30.77         59.33
1               (2,3)          28.59         23.12         51.71
4               (8,9)          45.72         21.97         67.68
5             (10,11)          18.43         31.62         50.05
8             (16,17)          13.51         32.17         45.69
9             (18,19)          17.99         16.03         34.02
12            (24,25)          25.04         27.74         52.78
13            (26,27)          13.48         18.45         31.93
16            (32,33)          54.45         33.69         88.13
17            (34,35)          47.48         24.56         72.05
20            (40,41)          42.69         43.48         86.17
21            (42,43)          25.89         39.09         64.98
24            (48,49)          63.57         35.05         98.62
25            (50,51)          23.27         29.89         53.17
28            (56,57)          71.71         43.87        100.00
29            (58,59)          33.65         19.33         52.98
                  Avg          34.63         29.43         64.05
```

	vmstat	corestat
%sys	20.53	29.43
%usr	39.05	34.63
%idle	40.42	35.95

vmstat

```
 kthr      memory            page            disk          faults      cpu
 r b w   swap  free  re  mf pi po fr de sr m1 m1 m2 m2   in   sy   cs us sy id
 0 8 0 83293328 30951456 8724 12802 30608 4000 4000 0 0 25 0 25 0 13271 87958 17034 28 14 58
 0 6 0 83298144 30966096 9688 10972 30122 25454 25438 0 0 47 0 47 0 15283 115241 19714 28 17 55
 0 8 0 83307976 30980096 8732 11147 30765 2521 2444 0 0 39 0 39 0 13151 96896 17352 26 13 61
 0 10 0 83301456 30967616 8312 9286 29132 255 255 0 0 27 0 27 0 12856 89560 15560 27 20 53
 0 12 0 83295096 30956080 8820 8621 29532 14728 14728 0 0 50 0 51 0 13639 123786 16865 32 13 55
 0 13 0 83255472 30956744 8936 10414 28178 23928 23920 0 0 32 0 31 0 15620 142711 20481 31 20 49
 0 15 0 83215552 30959632 9234 9270 37623 21136 21128 0 0 31 0 31 0 17276 140842 22307 35 20 45
 0 14 0 83191296 30951064 9249 12303 40026 185 185 0 0 28 0 28 0 16325 143003 20585 40 16 43
 0 13 0 83184352 30937424 8859 9732 37956 1182 1182 0 0 30 0 30 0 15235 151314 17797 34 26 39
 0 16 0 83208648 30960648 9249 10079 35849 23026 23026 0 0 29 0 29 0 16332 128670 20900 32 17 51
 0 15 0 83185728 30980040 9866 6413 39944 11595 11580 0 0 17 0 17 0 17262 103816 22081 25 14 60
 0 17 0 83180464 30968800 11455 6607 115326 15 15 0 0 22 0 22 0 15087 92050 19142 25 15 60
 0 13 0 83186320 30963096 12146 6460 63788 46 46 0 0 20 0 20 0 15810 82579 20030 25 17 58
 0 15 0 83184984 30942064 12559 11172 60716 23 23 0 0 31 0 32 0 15018 82876 17789 24 15 61
 0 16 0 83192240 30920472 10457 7314 48095 2990 2990 0 0 39 0 38 0 14787 97524 18930 21 15 64
 0 18 0 83190632 30917808 9801 9156 44190 529 529 0 0 30 0 30 0 15252 110036 19890 19 18 63
 0 10 0 83178232 30890776 9107 7755 46624 272 272 0 0 23 0 23 0 15567 84655 17958 25 14 61
 0 11 0 83197376 30911640 9985 13448 42818 12116 12110 0 0 40 0 40 0 15324 101347 18084 29 23 48
 0 9 0 83187208 30916064 9256 12272 30049 13563 13555 0 0 34 0 34 0 12918 99437 15620 26 15 58
```

avg idle – 54.84%

avg sys - 16.95%

avg usr - 28.00%

corestat

```
 CPU Utilization Mon May 11 11:02:58 2009
 CPU                (Thd)           %Usr           %Sys       %Usr+Sys
 --------------------   -----------   -----------   -----------
 0                  (0,1)          22.85          19.04          41.89
 1                  (2,3)           8.76          15.82          24.58
 4                  (8,9)           6.68          24.22          30.91
 5                (10,11)          88.10          12.89         100.00
 8                (16,17)          61.92          20.17          82.10
 9                (18,19)           4.17          18.45          22.61
 12               (24,25)          60.86          14.97          75.84
 13               (26,27)           2.79          14.66          17.45
 16               (32,33)          62.64          17.38          80.02
 17               (34,35)          11.88          18.07          29.95
 20               (40,41)          24.16          29.25          53.41
 21               (42,43)          19.97          21.51          41.48
 24               (48,49)          38.06          26.48          64.54
 25               (50,51)          12.46          31.90          44.36
 28               (56,57)          40.40          26.78          67.18
 29               (58,59)          33.50          35.24          68.75
                    Avg            31.20          21.68          52.88
```

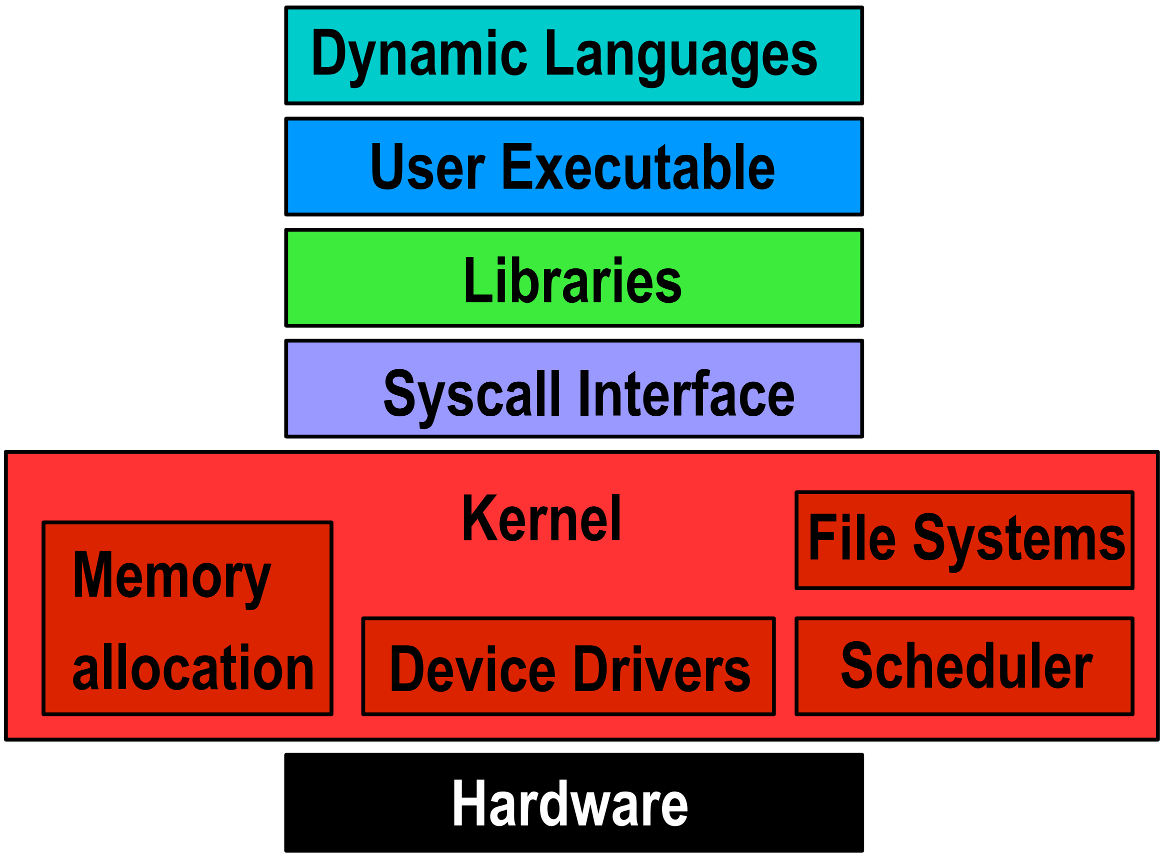
	vmstat	corestat
%sys	16.95	21.68
%usr	28.00	31.20
%idle	54.84	47.12

CPU Utilization/Capacity

- vmstat/mpstat and corestat will vary depending on the load
  - corestat will generally be more accurate
- Use “prstat -m” LAT category, in conjunction with utilization measurements, delivered workload throughput and run queue depth (vmstat “r” column) to determine for CPU capacity planning
-

The Workload Stack

- All stack layers are observable



Little's Law

- A relatively simple queueing theory theorem that relates response time to throughput
  - The throughput of a system (Q) is a factor of the rate of incoming work (N), and the average amount of time required to complete the work (R – response time)
  - Independent of any underlying probability distribution for the arrival of work or the performance of work

throughput = arrival rate / avg processing time ... or

$$Q = N / R$$

e.g

if N = 100 and R = 1 second, Q = 100 TPS

More compelling, it makes it easy to see how these critical performance metrics relate to each other....

Amdahl's Law

- In general terms, defines the expected speedup of a system when part of the system is improved
- As applied to multiprocessor systems, describes the expected speedup when a unit of work is parallelized
  - Factors in degree of parallelization

$$S = \frac{1}{(F + \frac{(1-F)}{N})}$$

S is the speedup

F is the fraction of the work that is serialized

N is the number of processors

$$S = \frac{1}{(0.5 + \frac{(1-0.5)}{4})}$$

S = 1.6 4 processors, ½ of the work is serialized

$$S = \frac{1}{(0.25 + \frac{(1-0.25)}{4})}$$

S = 2.3 4 processors, ¼ of the work is serialized

Performance & Observability Tools

Solaris Performance and Tracing Tools

Process stats

- cputrack / cpustat - processor hw counters
- plockstat – process locks
- pargs – process arguments
- pflags – process flags
- pcred – process credentials
- pldd – process's library dependencies
- psig – process signal disposition
- pstack – process stack dump
- pmap – process memory map
- pfiles – open files and names
- prstat – process statistics
- ptree – process tree
- ptime – process microstate times
- pwdx – process working directory

Process Tracing/ debugging

- abitrace – trace ABI interfaces
- dtrace – trace the world
- mdb – debug/control processes
- truss – trace functions and system calls

System Stats

- acctcom – process accounting
- busstat – Bus hardware counters
- cpustat – CPU hardware counters
- iostat – IO & NFS statistics
- kstat – display kernel statistics
- mpstat – processor statistics
- netstat – network statistics
- nfsstat – nfs server stats
- sar – kitchen sink utility
- vmstat – virtual memory stats

Process control

- pgrep – grep for processes
- pkill – kill processes list
- pstop – stop processes
- prun – start processes
- prctl – view/set process resources
- pwait – wait for process
- preap* – reap a zombie process

Kernel Tracing/ debugging

- dtrace – trace and monitor kernel
- lockstat – monitor locking statistics
- lockstat -k – profile kernel
- mdb – debug live and kernel cores

**why did Harry Cooper & Ben wish they had preap?*

Solaris Dynamic Tracing - DTrace

“ [expletive deleted] It's like they saw inside my head and gave me The One True Tool.”

- A Slashdotter, in a post referring to DTrace

“ With DTrace, I can walk into a room of hardened technologists and get them giggling”

- Bryan Cantrill, Inventor of DTrace

DTrace

Solaris Dynamic Tracing – An Observability Revolution

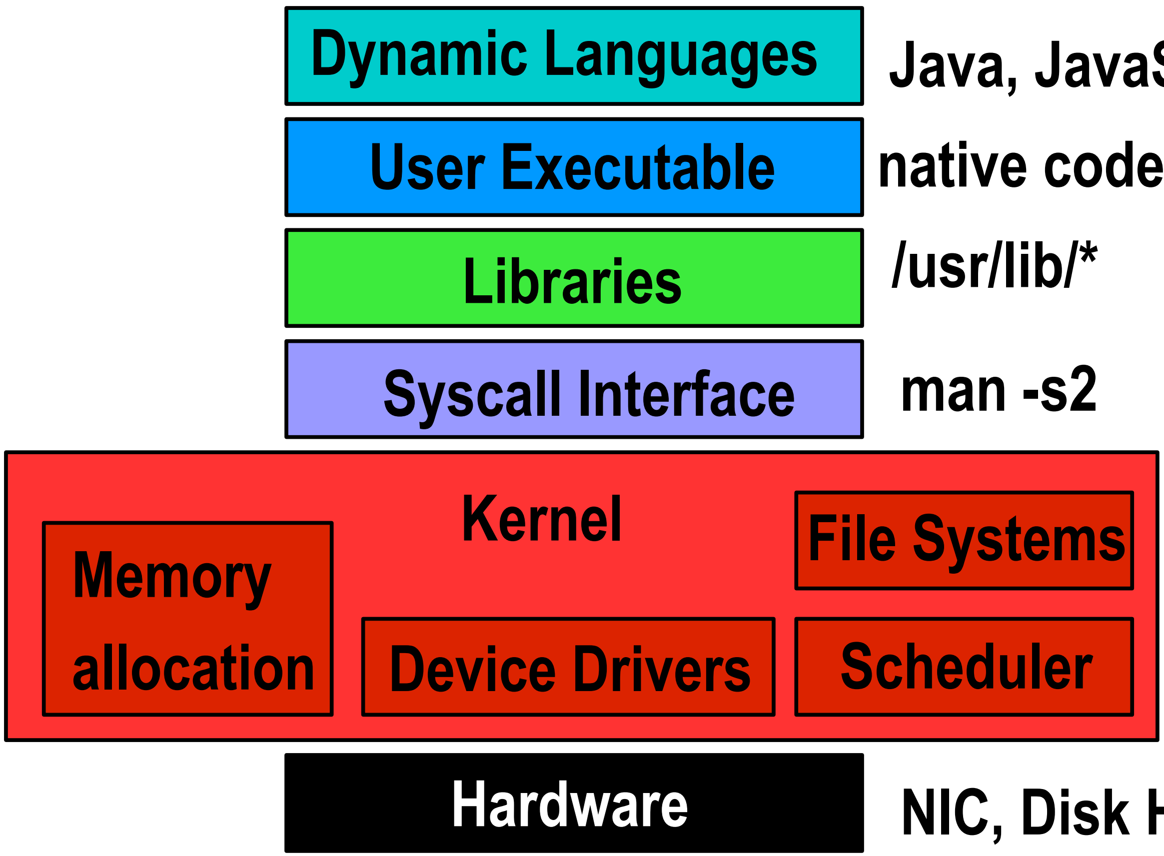
- Ease-of-use and instant gratification engenders serious hypothesis testing
- Instrumentation directed by high-level control language (not unlike AWK or C) for easy scripting and command line use
- Comprehensive probe coverage and powerful data management allow for concise answers to arbitrary questions

What is DTrace

- DTrace is a dynamic troubleshooting and analysis tool first introduced in the Solaris 10 and OpenSolaris operating systems.
- DTrace is many things, in particular:
  - A tool
  - A programming language interpreter
  - An instrumentation framework
- DTrace provides observability across the entire software stack from one tool. This allows you to examine software execution like never before.

The Entire Software Stack

- How did you analyze these?



Examples:

Java, JavaScript, ...

native code, /usr/bin/*

/usr/lib/*

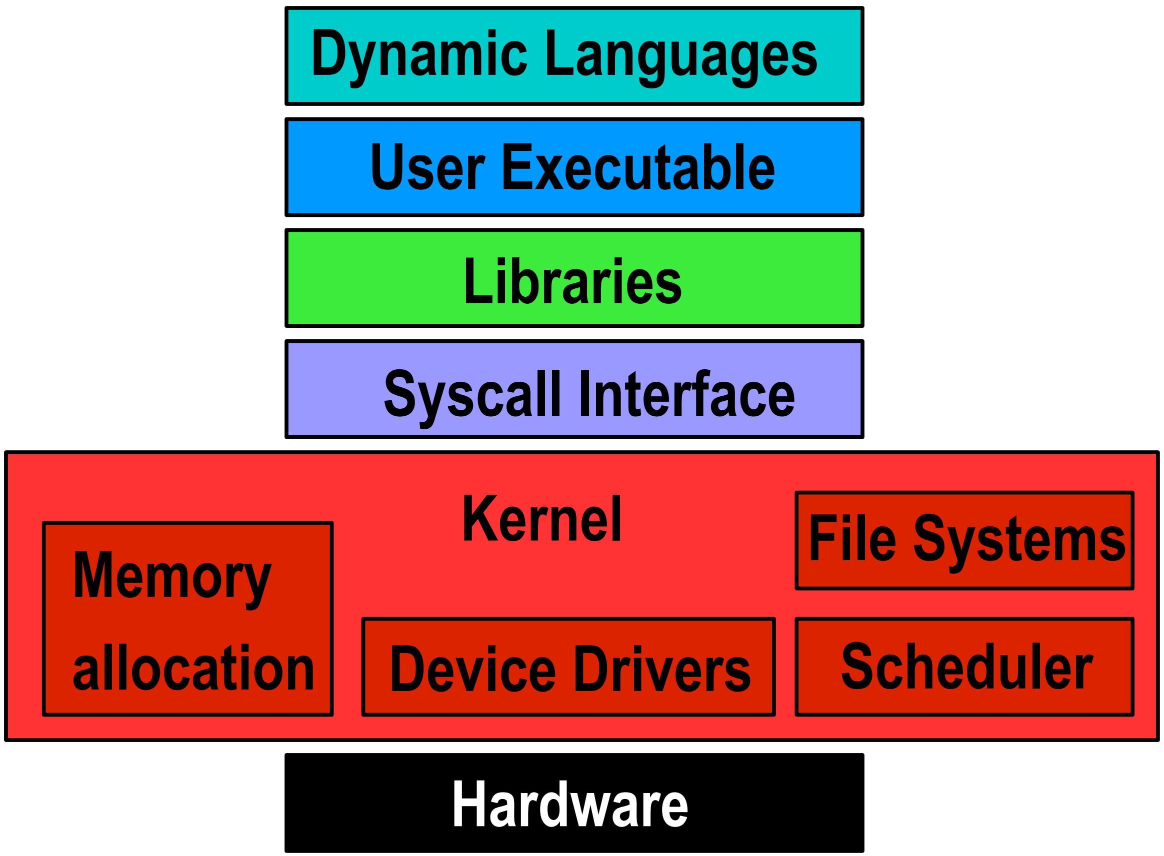
man -s2

VFS, DNLC, UFS,
ZFS, TCP, IP, ...
sd, st, hme, eri, ...

NIC, Disk HBA, Processors, etc

The Entire Software Stack

- It was possible, but difficult.



Previously:

debuggers

truss -ua.out

apptrace, sotruss

truss

prex; tnf*

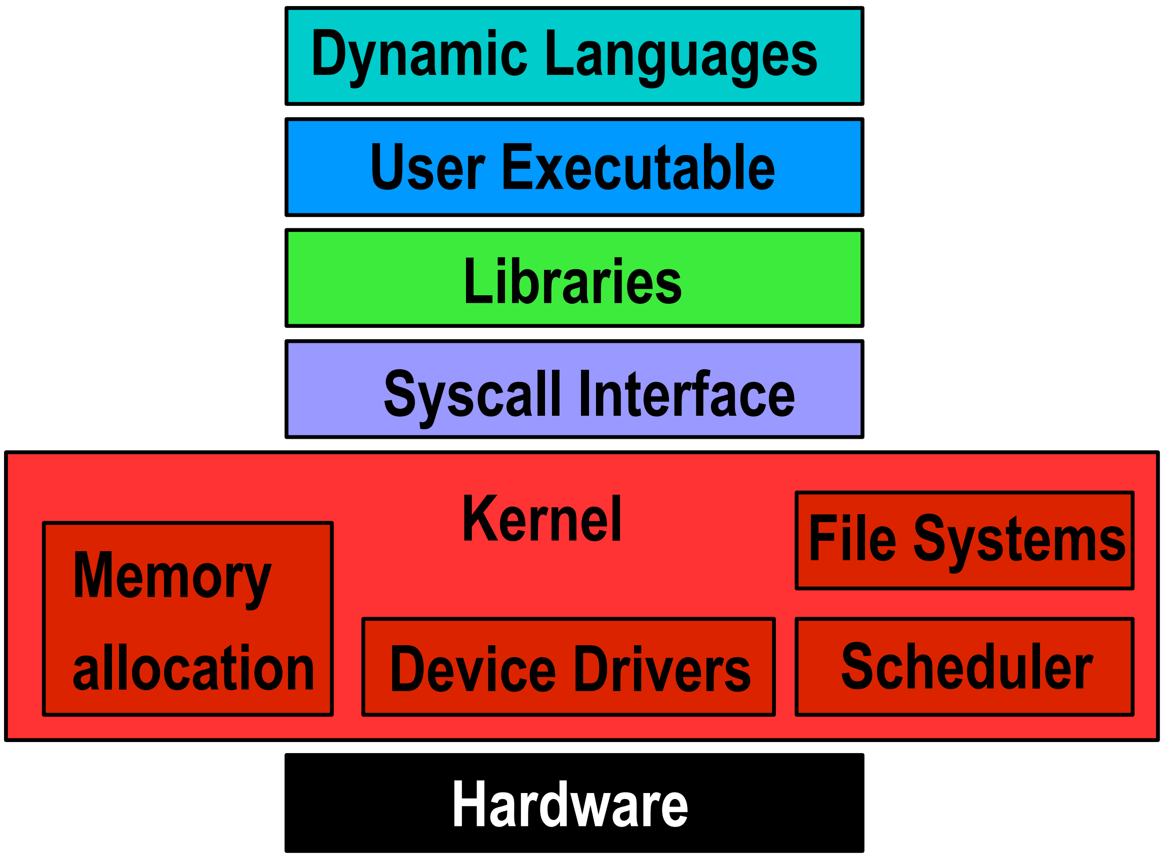
lockstat

mdb

kstat, PICs, guesswork

The Entire Software Stack

- DTrace is all seeing:



DTrace visibility:

Yes, with providers

Yes

Yes

Yes

Yes

No. Indirectly, yes

What DTrace is like

- DTrace has the combined capabilities of numerous previous tools and more,

Tool	Capability
truss -u a.out	tracing user functions
apptrace	tracing library calls
truss	tracing system calls
prex; tnf*	tracing some kernel functions
lockstat	profiling the kernel
mdb -k	accessing kernel VM
mdb -p	accessing process VM

Plus a programming language similar to C and awk.

Syscall Example

- Using truss,

Only examine 1 process

```
$ truss date
execve("/usr/bin/date", 0x08047C9C, 0x08047CA4)  argc = 1
resolvepath("/usr/lib/ld.so.1", "/lib/ld.so.1", 1023) = 12
resolvepath("/usr/bin/date", "/usr/bin/date", 1023) = 13
xstat(2, "/usr/bin/date", 0x08047A58)            = 0
open("/var/ld/ld.config", O_RDONLY)              = 3
fxstat(2, 3, 0x08047988)                         = 0
mmap(0x00000000, 152, PROT_READ, MAP_SHARED, 3, 0) = 0xFEFB0000
close(3)                                         = 0
mmap(0x00000000, 4096, PROT_READ|PROT_WRITE|PROT_EXEC, MAP_PRIVATE|MAP_ANON, -1
sysconfig(_CONFIG_PAGESIZE)                      = 4096
[...]
```

Output is limited to provided options

truss *slows down* the target

Syscall Example

- Using DTrace,

You choose the output

```
# dtrace -n 'syscall::entry { printf("%16s %x %x", execname, arg0, arg1); }'
dtrace: description 'syscall::entry ' matched 233 probes
CPU     ID                    FUNCTION:NAME
  1  75943                   read:entry            Xorg f 8047130
  1  76211              setitimer:entry            Xorg 0 8047610
  1  76143                 writev:entry            Xorg 22 80477f8
  1  76255                pollsys:entry            Xorg 8046da0 1a
  1  75943                   read:entry            Xorg 22 85121b0
  1  76035                  ioctl:entry      soffice.bin 6 5301
  1  76035                  ioctl:entry      soffice.bin 6 5301
  1  76255                pollsys:entry      soffice.bin 8047530 2
[...]
```

Minimum performance cost

Watch every process

What is DTrace for

- Troubleshooting software bugs
  - Proving what the problem is, and isn't.
  - Measuring the magnitude of the problem.
- Detailed observability
  - Observing devices, such as disk or network activity.
  - Observing applications, whether they are from Sun, 3rd party, or in-house.
- Capturing profiling data for performance analysis
  - If there is latency somewhere, DTrace can find it

Terminology

- Example #1

consumer probe action

```
# dtrace -n 'syscall::exece:return { trace(execname); }'
dtrace: description 'syscall::exece:return ' matched 1 probe
CPU     ID                    FUNCTION:NAME
  0  76044                     exece:return   man
  0  76044                     exece:return   sh
  0  76044                     exece:return   neqn
  0  76044                     exece:return   tbl
  0  76044                     exece:return   nroff
 [...]
```

Consumer

- Consumers of libdtrace(3LIB),

`dtrace`	command line and scripting interface
`lockstat`	kernel lock statistics
`plockstat`	user-level lock statistics
`intrstat`	run-time interrupt statistics

- libdtrace is currently a private interface and not to be used directly (nor is there any great reason to); the supported interface is dtrace(1M).
  - NOTE: You are still encouraged to use libkstat(3LIB) and proc(4) directly, rather than wrapping /usr/bin consumers.

Privileges

```
$ id
uid=1001(user1) gid=1(other)
$ /usr/sbin/dtrace -n 'syscall::exece:return'
dtrace: failed to initialize dtrace: DTrace requires additional privileges
```

- Non-root users need certain DTrace privileges to be able to use DTrace.
- These privileges are from the Solaris 10 “Least Privilege” feature.

root::::auths=solaris.*,solaris.grant;profiles=Web Console Management,All;lock_after_retries=no

mauroj::::defaultpriv=basic,dtrace_user,dtrace_proc,dtrace_kernel,proc_priocntl,

proc_clock_highres;project=laptop

Probes

- Data is generated from instrumentation points called “probes”.
- DTrace provides thousands of probes.
- Probe examples:

Probe Name	**Description**
`syscall::read:entry`	A read() syscall began
`proc:::exec-success`	A process created successfully
`io:::start`	An I/O was issued (disk)
`io:::done`	An I/O completed

Probe Names

- Probe names are a four-tuple,

Provider Module Function Name

```
syscall::exece:return
```

  - Provider — A library of related probes.
  - Module — The module the function belongs to, either a kernel module or user segment.
  - Function — The function name that contains the probe.
  - Name — The name of the probe.

Listing Probes

- `dtrace -l` lists all currently available probes that you have privilege to see, with one probe per line,
- Here the root user sees 69,879 available probes.
- The probe count changes – it is dynamic (DTrace).

```
# dtrace -l
   ID   PROVIDER            MODULE                          FUNCTION NAME
    1     dtrace                                                     BEGIN
    2     dtrace                                                     END
    3     dtrace                                                     ERROR
    4      sched                FX                          fx_yield schedctl-yi
[...]
# dtrace -l | wc -l
   69880
```

Tracing Probes

- `dtrace -n` takes a probe name and enables tracing,

```
# dtrace -n syscall::exece:return
dtrace: description 'syscall::exece:return' matched 1 probe
CPU     ID                    FUNCTION:NAME
  0  76044                     exece:return
  0  76044                     exece:return
^C
```

- The default output contains,
  - `CPU` CPU id that event occurred on (if this changes, the output may be shuffled)
  - `ID` DTrace numeric probe id
  - `FUNCTION:NAME` Part of the probe name

Providers

- Examples of providers,

Provider	Description
`syscall`	system call entries and returns
`proc`	process and thread events
`sched`	kernel scheduling events
`sysinfo`	system statistic events
`vminfo`	virtual memory events
`io`	system I/O events
`profile`	fixed rate sampling
`pid`	user-level tracing
`fbt`	raw kernel tracing

Providers

- Example of probes,

Provider	Example probe
`syscall`	`syscall::read:entry`
`proc`	`proc:::exec-success`
`sched`	`sched:::on-cpu`
`sysinfo`	`sysinfo:::readch`
`vminfo`	`vminfo:::maj_fault`
`io`	`io:::start`
`profile`	`profile:::profile-1000hz`
`pid`	`pid172:libc:fopen:entry`
	`pid172:a.out:main:entry`
`fbt`	`fbt::bdev_strategy:entry`

Providers

- Providers are documented in the DTrace Guide as separate chapters.
- Providers are dynamic; the number of available probes can vary.
- Some providers are "unstable interface", such as `fbt` and `sdt`.
  - This means that their probes, while useful, may vary in name and arguments between Solaris versions.
  - Try to use stable providers instead (if possible).
  - Test D scripts that use unstable providers across target Solaris releases

Provider Documentation

- Some providers assume a little background knowledge, other providers assume a lot. Knowing where to find supporting documentation is important.
- Where do you find documentation on -
  - Syscalls?
  - User Libraries?
  - Application Code?
  - Kernel functions?

Provider Documentation

- Additional documentation may be found here,

Target	Provider	Additional Docs
syscalls	**`syscall`**	man(2)
libraries	**`pid:lib*`**	man(3C)
app code	**`pid:a.out`**	source code, ISV, developers
raw kernel	**`fbt`**	Solaris Internals 2nd Ed, http://cvs.opensolaris.org

Actions

- When a probe fires, an action executes.
- Actions are written in the D programming language.
- Actions can,
  - print output
  - save data to variables, and perform calculations
  - walk kernel or process memory
- With destruction actions allowed, actions can,
  - raise signals on processes
  - execute shell commands
  - write to some areas of memory

trace() Example

The `trace()` action accepts one argument and prints it when the probe fired.

```
# dtrace -n 'syscall::exece:return { trace(execname); }'
dtrace: description 'syscall::exece:return ' matched 1 probe
CPU     ID                    FUNCTION:NAME
  0  76044                     exece:return   man
  0  76044                     exece:return   sh
  0  76044                     exece:return   neqn
  0  76044                     exece:return   tbl
  0  76044                     exece:return   nroff
  0  76044                     exece:return   col
[...]
```

printf() Example

DTrace ships with a powerful printf(), to print formatted output.

```
# dtrace -n 'syscall::exece:return { printf("%6d %s\n", pid, execname); }'
dtrace: description 'syscall::exece:return ' matched 1 probe
CPU     ID                    FUNCTION:NAME
  0  74415                     exece:return   4301 sh
  0  74415                     exece:return   4304 neqn
  0  74415                     exece:return   4305 nroff
  0  74415                     exece:return   4306 sh
  0  74415                     exece:return   4308 sh
[...]
```

DTrace Built-In Variables

- Numerous predefined variables can be used, e.g.,
  - `pid`, `tid` Process ID, Thread ID
  - `timestamp` Nanosecond timestamp since boot
  - `probefunc` Probe function name (3rd field)
  - `execname` Process name
  - `arg0`, ... Function arguments and return value
  - `errno` Last syscall failure error code
  - `curpsinfo` Struct containing current process info, e.g.,

    `curpsinfo->pr_psargs` – process + args
- Pointers and structs! DTrace can walk memory using C syntax, and has kernel types predefined.

User-Defined Variable Types

- DTrace supports the following variable types
  - Integers
  - Structs
  - Pointers
  - Strings
  - Associative arrays
  - Aggregates
- Including types from /usr/include/sys
  - e.g. uint32_t.

Predicates

- DTrace predicates are used to filter probes, so that the action fires when a conditional is true.

  `probename /predicate/ { action }`

- E.g., syscalls for processes called “bash”,

```
# dtrace -n 'syscall::entry /execname == "bash"/ { @num[probefunc] =
count(); }'
dtrace: description 'syscall::entry ' matched 233 probes
^C


  exece                                                              2
[...]
  read                                                              29
  write                                                             31
  lwp_sigmask                                                       42
  sigaction                                                         62
```

DTrace – command line

```
usenix> dtrace -n 'syscall:::entry { @scalls[probefunc] = count() }'
dtrace: description 'syscall:::entry ' matched 228 probes
^C

  lwp_self                                                         1
  fork1                                                            1
  fdsync                                                           1
  sigpending                                                       1
  rexit                                                            1
  fxstat                                                           1
  ...
  write                                                          205
  writev                                                         234
  brk                                                            272
  munmap                                                         357
  mmap                                                           394
  read                                                           652
  pollsys                                                        834
  ioctl                                                         1116
usenix>
```

The D language

- D is a C-like language specific to DTrace, with some constructs similar to awk(1)
- Complete access to kernel C types
- Complete access to statics and globals
- Complete support for ANSI-C operators
- Support for strings as first-class citizen
- We'll introduce D features as we need them...

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

probe descriptions
/ predicate /
{
   action statements
}
```

DTrace – D scripts

```
usenix> cat syscalls_pid.d

#!/usr/sbin/dtrace -s

dtrace:::BEGIN
{
        vtotal = 0;
}

syscall:::entry
/pid == $target/
{
        self->vtime = vtimestamp;
}

syscall:::return
/self->vtime/
{
        @vtime[probefunc] = sum(vtimestamp - self->vtime);
        vtotal += (vtimestamp - self->vtime);
        self->vtime = 0;
}

dtrace:::END
{
        normalize(@vtime, vtotal / 100);
        printa(@vtime);
}
```

a complete dtrace script block, including probename, a predicate, and an action in the probe clause, which sets a thread-local variable

DTrace – Running syscalls_pid.d

```
usenix> ./syscalls_pid.d -c date
dtrace: script './sc.d' matched 458 probes
Sun Feb 20 17:01:28 PST 2005
dtrace: pid 2471 has exited
CPU     ID                    FUNCTION:NAME
  0      2                             :END
  getpid                                                            0
  gtime                                                             0
  sysi86                                                            1
  close                                                             1
  getrlimit                                                         2
  setcontext                                                        2
  fstat64                                                           4
  brk                                                               8
  open                                                              8
  read                                                              9
  munmap                                                            9
  mmap                                                             11
  write                                                            15
  ioctl                                                            24
```

DTrace time-based probes

- profile – interval time based probes
  - profile-97hz – profile fires on all CPUs
  - tick-97hz – tick fires on 1 CPU
  - Interval can be specified with various suffixes
    - ns, us, ms, s, min (m), hour (h), day (d), hz
  - arg0 – kernel PC
  - arg1 – user PC
- Use arg0 or arg1 in a predicate for user or kernel profile

```
#dtrace -n 'profile-97hz / arg0 != 0 / { action } /* Am I in the kernel? */
#dtrace -n 'profile-97hz / arg1 != 0 / { action } /* Am I in user mode? */
```

Using Providers

Using the syscall provider to track bytes passed to write(2)

```
# dtrace -n 'syscall::write:entry { trace(arg2) }'
dtrace: description 'write:entry ' matched 2 probes
CPU     ID                    FUNCTION:NAME
  0   1026                   write:entry          1
  1   1026                   write:entry         53
  1   9290                   write:entry          2
  1   1026                   write:entry         25
  1   9290                   write:entry         17
  1   1026                   write:entry          2
  1   9290                   write:entry          2
  1   1026                   write:entry        450
  1   9290                   write:entry        450
```

Using the fbt provider to instrument the kernel ufs_write() function, and track the filename in the probe action

```
# dtrace -n 'fbt:ufs:ufs_write:entry { printf("%s\n",stringof(args[0]->v_path)); }'
dtrace: description 'ufs_write:entry ' matched 1 probe
CPU     ID                    FUNCTION:NAME
 13  16779                  ufs_write:entry /etc/svc/repository.db-journal
 13  16779                  ufs_write:entry /etc/svc/repository.db-journal
 13  16779                  ufs_write:entry /etc/svc/repository.db-journal
 13  16779                  ufs_write:entry /etc/svc/repository.db-journal
 13  16779                  ufs_write:entry /etc/svc/repository.db-journal
 13  16779                  ufs_write:entry /etc/svc/repository.db-journal
 13  16779                  ufs_write:entry /etc/svc/repository.db-journal
```

DTrace PID Provider

```
# dtrace -n 'pid221:libc::entry'
dtrace: description 'pid221:libc::entry' matched 2474 probes
CPU     ID                    FUNCTION:NAME
  0  41705           set_parking_flag:entry
  0  41762             setup_schedctl:entry
  0  42128                 __schedctl:entry
  0  41752                 queue_lock:entry
  0  41749              spin_lock_set:entry
  0  41765                 no_preempt:entry
  0  41753               queue_unlock:entry
  0  41750            spin_lock_clear:entry
  0  41766                    preempt:entry
  0  41791                 mutex_held:entry
  0  42160               gettimeofday:entry
  0  41807            _cond_timedwait:entry
  0  41508         abstime_to_reltime:entry
  0  42145            __clock_gettime:entry
  0  41803           cond_wait_common:entry
  0  41800            cond_wait_queue:entry
  0  41799           cond_sleep_queue:entry
  0  41949              _save_nv_regs:entry
  0  41752                 queue_lock:entry
  0  41749              spin_lock_set:entry
  0  41765                 no_preempt:entry
```

Using the PID provider to instrument all the function entry points the process calls in libc

Aggregations

- When trying to understand suboptimal performance, one often looks for patterns that point to bottlenecks
- When looking for patterns, one often doesn't want to study each datum – one wishes to aggregate the data and look for larger trends
- Traditionally, one has had to use conventional tools (e.g. awk(1), perl(1)) to post-process reams of data
- DTrace supports aggregation of data as a first class operation

Aggregations, cont.

- An aggregation is the result of an aggregating function keyed by an arbitrary tuple
- For example, to count all system calls on a system by system call name:

```
dtrace -n 'syscall:::entry \
  { @syscalls[probefunc] = count(); }'
```

- By default, aggregation results are printed when `dtrace`(1M) exits

Aggregations, cont.

- Aggregations need not be named
- Aggregations can be keyed by more than one expression
- For example, to count all ioctl system calls by both executable name and file descriptor:

```
dtrace -n 'syscall::ioctl:entry \
  { @[execname, arg0] = count(); }'
```

Aggregations, cont.

- Functions:
  - avg() - the average of specified expressions
  - min() - the minimum of specified expressions
  - max() - the maximum of specified expressions
  - count() - number of times the probe fired
  - sum() - running sum
  - quantize() - power-of-two exponential distribution
  - lquantize() - linear frequency distribution
- For example, distribution of write(2) sizes by executable name:

```
dtrace -n 'syscall::write:entry \
  { @[execname] = quantize(arg2); }'
```

count() aggregation

- Frequency counting syscalls,

```
# dtrace -n 'syscall:::entry { @num[probefunc] = count(); }'
dtrace: description 'syscall:::entry ' matched 233 probes
^C
[...]
  writev                                                    170
  write                                                     257
  read                                                      896
  pollsys                                                   959
  ioctl                                                    1253
```

Quantize

- Very cool function, here we quantize writech sizes:
  - Here we see that `ls` processes usually write between 32 and 127 bytes.
    - Makes sense?

```
# dtrace -n 'sysinfo:::writech { @dist[execname] = quantize(arg0); }'
dtrace: description 'sysinfo:::writech ' matched 4 probes
^C
[...]
  ls
           value  ------------- Distribution ------------- count
               4 |                                         0
               8 |                                         2
              16 |                                         0
              32 |@@@@@@@@@@@@@@@@@@@                      118
              64 |@@@@@@@@@@@@@@@@@@@@@                    127
             128 |                                         0
[...]
```

ls -l

```
# ls -l /etc
dttotal 793
lrwxrwxrwx   1 root     root          12 Mar 21 03:28 TIMEZONE -> default/init
drwxr-xr-x   4 root     sys            6 Apr 16 06:59 X11
drwxr-xr-x   2 adm      adm            3 Mar 20 09:25 acct
drwxr-xr-x   3 root     root           3 Apr 16 23:11 ak
lrwxrwxrwx   1 root     root          12 Mar 21 03:28 aliases -> mail/aliases
drwxr-xr-x   5 root     sys            5 Feb 20 23:29 amd64
drwxr-xr-x   7 root     bin           18 Mar 20 09:20 apache
drwxr-xr-x   4 root     bin            7 Feb 20 23:12 apache2
drwxr-xr-x   2 root     sys            5 Feb 20 23:27 apoc
-rw-r--r--   1 root     bin         1012 Mar 20 09:33 auto_home
-rw-r--r--   1 root     bin         1066 Mar 20 09:33 auto_master
lrwxrwxrwx   1 root     root          16 Mar 21 03:28 autopush -> ../sbin/autopu
[...]
```

`ls` writes one line at a time, each around 80 chars long.

Quantize aggregations – write(2) bytes by process

```
# dtrace -n 'syscall::write:entry { @[execname] = quantize(arg2); }'
dtrace: description 'syscall::write:entry ' matched 1 probe
^C
  in.rshd
           value  ------------- Distribution ------------- count
               0 |                                         0
               1 |@@@@@@@@@@                               16
               2 |@@@@                                     6
               4 |@@@                                      4
               8 |                                         0
              16 |@@@@@                                    7
              32 |@@@                                      4
              64 |@@@@@@@@@@@@@@@                          23
             128 |@                                        1
             256 |                                         0

  cat
           value  ------------- Distribution ------------- count
             128 |                                         0
             256 |@@@@@@@@@@@@@@@@@@@@@@@@@@@              2
             512 |                                         0
            1024 |                                         0
            2048 |@@@@@@@@@@@@@                            1
            4096 |                                         0
```

DTrace Enhancements post S10 FCS

- Multiple aggregations with printa()
- Aggregation key sort options
- (u)func(%pc), (u)mod(%pc), (u)sym(%pc) dtrace functions
  - Get symbolic name from address
- ucaller function
  - Track function callers
- String parsing routines
- fds[]
  - array of fileinfo_t's indexed by fd
- Providers
  - fsinfo
  - sysevent
  - Xserver
  - iscsi

Multiple aggregation printa()
Release: 08/07-30

- multiple aggregations in single printa()
- aggregations must have same type signature
- output is effectively joined by key
- 0 printed when no value present for a key
- default behavior is to sort by first aggregation value (ties broken by key order)

Multiple aggregation printa()

```
/* multagg.d */
syscall::write:entry
{
        @wbytes[execname, pid] = sum(arg2);
}

syscall::read:entry
{
        @rbytes[execname, pid] = sum(arg2);
}

END
{
        normalize(@rbytes, 1024);
        normalize(@wbytes, 1024);

        printf("%20s %10s %10s %10s\n", "PROGRAM", "PID",
            "READS", "WRITES");
        printa("%20s %10d %10@d %10@d\n", @rbytes, @wbytes);
}
```

Multiple aggregation printa()

```
# dtrace -q -s ./multagg.d
^C
           PROGRAM         PID       READS      WRITES
            dtrace      101605           0           0
          nautilus      101606           0           0
   battstat-applet-     100854           0          15
   gnome-settings-d     100781           0           0
      gnome-session     100728           0           0
              dsdm      100712           6           0
     gnome-terminal     101342           8          15
       xscreensaver     100946           9           0
        soffice.bin     101325          10          48
              init           1          32           0
        gnome-panel     100792          39           4
           gconfd-2     100767          47           5
          nautilus      100794         265         170
        wnck-applet     100822         714         262
          metacity      100789         726         263
             gedit      101607        3986          64
              Xorg      100535       12374           0
```

Aggregation sorting options Release: 08/07-30

- aggregations sorted by value by default
- options allow change of behaviour
  - aggsortkey - sort by key order, ties broken by value
  - aggsortrev - reverse sort
  - aggsortpos - position of the aggregation to use as sort primary sort key with mutiple aggs
  - aggsortkeypos- position of key to use as primary sort key when with multiple aggs
- Use the above in combination

Aggregation sorting options

```
/* aggsort.d */
syscall::read:entry
{
        @avg[execname, pid] = avg(arg2);
        @max[execname, pid] = max(arg2);
        @min[execname, pid] = min(arg2);
        @cnt[execname, pid] = count();
}

END
{
        printf("%20s %10s %10s %10s %10s %10s\n", "EXECNAME", "PID",
            "COUNT", "MIN", "MAX", "AVG");
        printa("%20s %10d %@10d %@10d %@10d %@10d\n", @cnt, @min,
            @max, @avg);
}
```

Aggregation sorting options

```
# dtrace -q -s ./aggsort.d
^C
          EXECNAME        PID       COUNT        MIN        MAX        AVG
   battstat-applet-    100981           2         32         32         32
   gnome-settings-d    100853           3         32         64         53
        soffice.bin    101382          10         32         32         32
               dsdm    100708          10         32        160         54
        xscreensaver    101082          14         32         32         32
         gnome-panel    100896          24         12        168         51
         firefox-bin    101363          31          1       1024         35
      gnome-terminal    101029          40         32       4096        163
            nautilus    100906         119         32        480         48
         wnck-applet    100961         161          8        128         32
            metacity    100893         447          4         96         33
                Xorg    100534         926         64       5104       3263
```

Sort by value of first aggregation (default)

aggregation sorting options

```
# dtrace -q -s ./aggsort.d  -x aggsortrev
^C
         EXECNAME        PID      COUNT        MIN        MAX        AVG
             Xorg     100534        875         64       5104       3433
         metacity     100893        434          4         96         33
      wnck-applet     100961        145          8         64         32
      xscreensaver    101082         71          4         32         28
   gnome-terminal     101029         54         32       4096        125
         nautilus     100906         51         32        608         74
      firefox-bin     101363         23          1          1          1
             dsdm     100708         19         32         32         32
      gnome-panel     100896         18         12        168         51
 gnome-settings-d     100853          7         32         32         32
      soffice.bin     101382          6         32         32         32
```

Reverse sort using value of first aggregation

Aggregation sorting options

```
# dtrace -q -s ./aggsort.d  -x aggsortkey -x aggsortkeypos=1 -x aggsortrev
^C
          EXECNAME        PID      COUNT         MIN         MAX         AVG
        soffice.bin     101382       525           4        1440          33
        firefox-bin     101363        29           1        1024          36
    thunderbird-bin     101337         2           1        1024         512
        xscreensaver    101082        11          32          64          34
     gnome-terminal     101029        27          32        4096         220
        wnck-applet     100961       161           8          96          32
           nautilus     100906        79          32         320          40
        gnome-panel     100896        26          12         168          49
           metacity     100893       196           4         128          34
  gnome-settings-d     100853         4          32          64          40
               dsdm     100708        23          32         128          40
               Xorg     100534       885          64        4940        3688
```

Reverse sort by key in second position

Aggregation sorting options

```
# dtrace -q -s ./aggsort.d  -x aggsortpos=2 -x aggsortrev
^C
         EXECNAME        PID      COUNT        MIN        MAX        AVG
             Xorg     100534       1655         64       5104       3756
   gnome-terminal     101029        137         32       4096         69
      wnck-applet     100961        453          4       1152         34
     xscreensaver     101082         23         32       1024        115
         nautilus     100906         43          8        736         69
      soffice.bin     101382        637          4        288         30
      gnome-panel     100896        122          8        168         39
         metacity     100893        421          4        128         34
 notification-are     100983          2         64         64         64
    mixer_applet2     100985          2         64         64         64
 gnome-settings-d     100853          7         32         32         32
             dsdm     100708        103          4         32         31
  thunderbird-bin     101337          7          4         32         24
      firefox-bin     101363         39          1         32          5
```

Reverse sorted by value of third aggregation

(u)mod/(u)func/(u)sym
Release: 08/07-23

- Profiling often requires post-processing when using %a/%A to print arg0/arg1 symbolically
- Samples in format [module]'[func]+[offset]
- Want to first get high level view and then drill down
- (u)mod(%pc) - module name
- (u)func(%pc) - function name
- (u)sym(%pc) - symbol name

(u)mod/(u)func/(u)sym

```
#pragma D option aggsortkey

cpc:::dtlbm-u-5000
{
        @[execname, umod(arg1)] = count();
}

END
{
        printf("%20s %30s %10s\n", "EXECUTABLE", "MODULE",
          "COUNT");
        printa("%20s %30A %10@d\n", @);
}
```

Example uses prototype cpc provider to show TLB misses on a global basis broken down by module.

(u)mod/(u)func/(u)sym

```
# ./tlbmissbymod.d
^C
           EXECUTABLE                              MODULE      COUNT
                 Xorg                                Xorg         17
                 Xorg                         libramdac.so         1
                 Xorg                             libfb.so         1
                 Xorg                        radeon_drv.so         1
                 Xorg                           libc.so.1         3
     battstat-applet-             libglib-2.0.so.0.1200.4         1
     battstat-applet-          libgobject-2.0.so.0.1200.4         1
             gconfd-2                libORBit-2.so.0.1.0         1
             gconfd-2               libgconf-2.so.4.1.0         1
             metacity      libpangocairo-1.0.so.0.1400.7         1
             metacity      libgdk_pixbuf-2.0.so.0.1000.6         1
             metacity         libgobject-2.0.so.0.1200.4         1
             metacity            libglib-2.0.so.0.1200.4         2
             metacity         libgdk-x11-2.0.so.0.1000.6         1
             metacity                          libc.so.1         2
```

ucaller variable
Release: 08/07-23

```
# dtrace -n 'pid$target::malloc:entry{@[ufunc(ucaller)] = count();}' -
p 101384
dtrace: description 'pid$target::malloc:entry' matched 2 probes
^C

  sax.uno.so`0xf97b2fe7                                              2
  sax.uno.so`0xf97b30e7                                              2
  sax.uno.so`0xf97b3104                                              2
  sax.uno.so`0xf97b44ba                                              2
  sax.uno.so`0xf97b44cf                                              2
  sax.uno.so`0xf97b8a18                                              4
  libX11.so.4`_XAllocScratch                                         5
  libX11.so.4`miRegionOp                                             6
  libX11.so.4`XQueryTree                                             8
  libX11.so.4`XGetWindowProperty                                    13
  libX11.so.4`XSetClassHint                                         13
  libX11.so.4`XGetImage                                            179
  libuno_sal.so.3`osl_createMutex                                  322
  libX11.so.4`XCreateRegion                                        844
  libX11.so.4`XCreateGC                                            959
  libc.so.1`calloc                                                1074
  libglib-2.0.so.0.1200.4`standard_malloc                         3533
  libCrun.so.1`__1c2n6FI_pv_                                     28668
```

The fds[] variable
Release: 01/06-16

- array of fileinfo_t's indexed by integer (fd)
- inlines expanded to accommodate associative arrays for this.
- Definition in /usr/lib/dtrace/io.d
- fileinfo_t gets new fi_oflags member

The fds[] variable

```
#pragma D option quiet

syscall::write:entry
/fds[arg0].fi_oflags & O_APPEND/
{
        printf("%s appending file %s at offset %d\n",
           execname, fds[arg0].fi_pathname, fds[0].fi_offset);
}
```

```
# ./fds.d
ksh appending file /.sh_history at offset 349345
ksh appending file /.sh_history at offset 349378
```

Allowing dtrace for non-root users

- Setting dtrace privileges
- Add a line for the user in `/etc/user_attr`

```
mauroj::::defaultpriv=basic,dtrace_user,dtrace_kernel,dtrace_proc,
proc_owner
```

from privileges(5)

PRIV_DTRACE_KERNEL
Allow DTrace kernel-level tracing.

PRIV_DTRACE_PROC
Allow DTrace process-level tracing. Allow process-level tracing probes to be placed and enabled in processes to which the user has permissions.

PRIV_DTRACE_USER
Allow DTrace user-level tracing. Allow use of the syscall and profile DTrace providers to examine processes to which the user has permissions.

Modular Debugger - mdb(1)

- Solaris 8 mdb(1) replaces adb(1) and crash(1M)
- Allows for examining a live, running system, as well as post-mortem (dump) analysis
- Solaris 9 mdb(1) adds...
  - Extensive support for debugging of processes
  - /etc/crash and adb removed
  - Symbol information via compressed typed data
  - Documentation
- MDB Developers Guide
  - mdb implements a rich API set for writing custom dcmds
  - Provides a framework for kernel code developers to integrate with mdb(1)

Modular Debugger - mdb(1)

- mdb(1) basics
  - 'd' commands (dcmd)
    - ::dcmds -l for a list
    - expression::dcmd
    - e.g. 0x300acde123::ps
  - walkers
    - ::walkers for a list
    - expression::walk <walker_name>
    - e.g. ::walk cpu
  - macros
    - !ls /usr/lib/adb for a list
    - expression$<macro
    - e.g. cpu0$<cpu

Modular Debugger – mdb(1)

- Symbols and typed data
  - address::print (for symbol)
  - address::print <type>
  - e.g. cpu0::print cpu_t
  - cpu_t::sizeof
- Pipelines
  - expression, dcmd or walk can be piped
  - ::walk <walk_name> | ::dcmd
  - e.g. ::walk cpu | ::print cpu_t
  - Link Lists
  - address::list <type> <member>
  - e.g. 0x70002400000::list page_t p_vpnext
- Modules
  - Modules in /usr/lib/mdb, /usr/platform/lib/mdb etc
  - mdb can use adb macros
  - Developer Interface - write your own dcmds and walkers

```
> ::cpuinfo
 ID ADDR        FLG NRUN BSPL PRI RNRN KRNRN SWITCH THREAD      PROC
  0 0000180c000  1b    0    0  37   no    no t-0    30002ec8ca0 threads
  1 30001b78000  1b    0    0  27   no    no t-0    31122698960 threads
  4 30001b7a000  1b    0    0  59   no    no t-0    30ab913cd00 find
  5 30001c18000  1b    0    0  59   no    no t-0    31132397620 sshd
  8 30001c16000  1b    0    0  37   no    no t-0    3112280f020 threads
  9 30001c0e000  1b    0    0  59   no    no t-1    311227632e0 mdb
 12 30001c06000  1b    0    0  -1   no    no t-0    2a100609cc0 (idle)
 13 30001c02000  1b    0    0  27   no    no t-1    300132c5900 threads
> 30001b78000::cpuinfo -v
 ID ADDR        FLG NRUN BSPL PRI RNRN KRNRN SWITCH THREAD      PROC
  1 30001b78000  1b    0    0  -1   no    no t-3    2a100307cc0 (idle)
                  |
       RUNNING <--+
         READY
        EXISTS
        ENABLE

> 30001b78000::cpuinfo -v
 ID ADDR        FLG NRUN BSPL PRI RNRN KRNRN SWITCH THREAD      PROC
  1 30001b78000  1b    0    0  27   no    no t-1    300132c5900 threads
                  |
       RUNNING <--+
         READY
        EXISTS
        ENABLE

> 300132c5900::findstack
stack pointer for thread 300132c5900: 2a1016dd1a1
  000002a1016dd2f1 user_rtt+0x20()
```

mdb(1) & dtrace(1) – Perfect Together

```
# mdb -k
Loading modules: [ unix krtld genunix specfs dtrace ufs sd ip sctp usba fcp fctl nca nfs random sppp
lofs crypto ptm logindmux md isp cpc fcip ipc ]
> ufs_read::nm -f ctype
C Type
int (*)(struct vnode *, struct uio *, int, struct cred *, struct caller_context *)
> ::print -t struct vnode
{
    kmutex_t v_lock {
        void * [1] _opaque
    }
    uint_t v_flag
    uint_t v_count
    void *v_data
    struct vfs *v_vfsp
    struct stdata *v_stream
    enum vtype v_type
    dev_t v_rdev
    struct vfs *v_vfsmountedhere
    struct vnodeops *v_op
    struct page *v_pages
    pgcnt_t v_npages
    ...
    char *v_path
    ...
}
```

```
# dtrace -n 'ufs_read:entry { printf("%s\n",stringof(args[0]->v_path));}'
dtrace: description 'ufs_read:entry ' matched 1 probe
CPU     ID                    FUNCTION:NAME
  1  16777                  ufs_read:entry /usr/bin/cut

  1  16777                  ufs_read:entry /usr/bin/cut

  1  16777                  ufs_read:entry /usr/bin/cut

  1  16777                  ufs_read:entry /usr/bin/cut

  1  16777                  ufs_read:entry /lib/ld.so.1

  1  16777                  ufs_read:entry /lib/ld.so.1
....
```

Kernel Statistics

- Solaris uses a central mechanism for kernel statistics
  - "kstat"
  - Kernel providers
    - raw statistics (c structure)
    - typed data
    - classed statistics
  - Perl and C API
  - `kstat(1M)` command

```
# kstat -n system_misc
module: unix                            instance: 0
name:   system_misc                     class:    misc

        avenrun_15min                   90
        avenrun_1min                    86
        avenrun_5min                    87
        boot_time                       1020713737
        clk_intr                        2999968
        crtime                          64.1117776
        deficit                         0
        lbolt                           2999968
        ncpus                           2
```

kstat

```
zeeroh> kstat -n e1000g0
module: e1000g                          instance: 0
name:   e1000g0                         class:    net
        brdcstrcv                       31397806
        brdcstxmt                       104402
        collisions                      0
        crtime                          142.615878752
        ierrors                         0
        ifspeed                         1000000000
        ipackets                        33545701
        ipackets64                      33545701
        multircv                        796061
        multixmt                        0
        norcvbuf                        0
        noxmtbuf                        0
        obytes                          169913542
        obytes64                        169913542
        oerrors                         0
        opackets                        1141181
        opackets64                      1141181
        rbytes                          1559052386
        rbytes64                        5854019682
        snaptime                        15146011.0147421
        unknowns                        819041
```

kstat

```
zeeroh> kstat e1000g:0:e1000g0:opackets 1 10
module: e1000g                          instance: 0
name:   e1000g0                         class:    net
        opackets                        1141265


module: e1000g                          instance: 0
name:   e1000g0                         class:    net
        opackets                        1141268


module: e1000g                          instance: 0
name:   e1000g0                         class:    net
        opackets                        1141273


module: e1000g                          instance: 0
name:   e1000g0                         class:    net
        opackets                        1141279
```

Procfs Tools

- Observability (and control) for active processes through a pseudo file system (/proc)
- Extract interesting bits of information on running processes
- Some commands work on core files as well

```
pargs      pfiles
pflags     pstop
pcred      prun
pldd       pwait
psig       ptree
pstack     ptime
pmap       preap
```

pflags, pcred, pldd, pkill

```
nv70b> pflags 3645
3645:    ./loader 2 0 /zp/space
         data model = _ILP32  flags = MSACCT|MSFORK
 /1:     flags = ASLEEP  lwp_wait(0x2,0x80471f0)
 /2:     flags = 0
 /3:     flags = 0

nv70b> pcred 3645
3645:    e/r/suid=20821  e/r/sgid=3

nv70b> pldd 3645
3645:    ./loader 2 0 /zp/space
/lib/libc.so.1

nv70b> pkill loader
nv70b>
[1]+  Terminated              ./loader 2 0 /zp/space
```

psig

```
nv70b> psig 3654
3654:   ./loader 2 0 /zp/space
HUP     default
INT     default
QUIT    default
ILL     default
TRAP    default
ABRT    default
EMT     default
FPE     default
KILL    default
BUS     default
SEGV    default
SYS     default
PIPE    default
ALRM    default
TERM    default
USR1    caught  timer           0
USR2    default
CLD     default                 NOCLDSTOP
PWR     default

. . .
```

pstack

```
nv70b> pstack 3602
3602:   /usr/lib/firefox/firefox-bin -UILocale C -contentLocale C
-----------------  lwp# 1 / thread# 1  --------------------
 d117ec45 pollsys  (82d5910, 8, 0, 0)
 d1134212 poll     (82d5910, 8, ffffffff) + 52
 d0c06653 g_main_context_iterate (80c3260, 1, 1, 815f1f0) + 397
 d0c06c8c g_main_loop_run (82f45f8) + 1b8
 d0964fae gtk_main (8047028, 808578c, 8189718, 8046d88, cd694803, 818ed20) + b2
 cdbc4bb4 __1cKnsAppShellDRun6M_I_ (818ed20) + 34
 cd694803 __1cMnsAppStartupDRun6M_I_ (8189718) + 2b
 08061824 XRE_main (5, 8047098, 8085760) + 25f4
 0805a61d main     (5, 8047098, 80470b0) + 25
 0805a56a _start   (5, 8047210, 804722d, 8047237, 8047239, 8047248) + 7a
-----------------  lwp# 2 / thread# 2  --------------------
 d117ec45 pollsys  (cdeabc70, 1, 0, 0)
 d1134212 poll     (cdeabc70, 1, ffffffff) + 52
 d0f48bfa _pr_poll_with_poll (80f00a8, 1, ffffffff) + 39a
 d0f48dc6 PR_Poll  (80f00a8, 1, ffffffff) + 16
 ce15657a __1cYnsSocketTransportServiceEPoll6MpI_i_ (80efbc0, cdeabf74) + 11e
 ce157118 __1cYnsSocketTransportServiceDRun6M_I_ (80efbc0) + 68c
 d103fff4 __1cInsThreadEMain6Fpv_v_ (80f0298) + 74
 d0f4ab0d _pt_root (80f2720) + d1
 d117d952 _thr_setup (cdd90200) + 52
 d117dbb0 _lwp_start (cdd90200, 0, 0, 0, 0, 0)
-----------------  lwp# 3 / thread# 3  --------------------
 d117dc09 lwp_park (0, cd58de58, 0)
. . .
```

pfiles

```
nv70b> pfiles 3602
3602:   /usr/lib/firefox/firefox-bin -UILocale C -contentLocale C
  Current rlimit: 512 file descriptors
   0: S_IFCHR mode:0666 dev:279,0 ino:6815752 uid:0 gid:3 rdev:13,2
      O_RDONLY|O_LARGEFILE
      /devices/pseudo/mm@0:null
   1: S_IFCHR mode:0666 dev:279,0 ino:6815752 uid:0 gid:3 rdev:13,2
      O_WRONLY|O_APPEND|O_CREAT|O_LARGEFILE
      /devices/pseudo/mm@0:null
   2: S_IFCHR mode:0666 dev:279,0 ino:6815752 uid:0 gid:3 rdev:13,2
      O_WRONLY|O_APPEND|O_CREAT|O_LARGEFILE
      /devices/pseudo/mm@0:null
   3: S_IFDOOR mode:0444 dev:290,0 ino:43 uid:0 gid:0 size:0
      O_RDONLY|O_LARGEFILE FD_CLOEXEC  door to nscd[3545]
      /var/run/name_service_door
   4: S_IFIFO mode:0666 dev:290,0 ino:40 uid:0 gid:0 size:0
      O_RDWR|O_NONBLOCK FD_CLOEXEC
. . .
  19: S_IFSOCK mode:0666 dev:287,0 ino:28594 uid:0 gid:0 size:0
      O_RDWR|O_NONBLOCK FD_CLOEXEC
        SOCK_STREAM
        SO_REUSEADDR,SO_SNDBUF(49152),SO_RCVBUF(49152)
        sockname: AF_INET 127.0.0.1  port: 59686
. . .
```

pfiles

```
solaris10> pfiles 26337
26337:  /usr/lib/ssh/sshd
  Current rlimit: 256 file descriptors
   0: S_IFCHR mode:0666 dev:270,0 ino:6815752 uid:0 gid:3 rdev:13,2
      O_RDWR|O_LARGEFILE
      /devices/pseudo/mm@0:null
   1: S_IFCHR mode:0666 dev:270,0 ino:6815752 uid:0 gid:3 rdev:13,2
      O_RDWR|O_LARGEFILE
      /devices/pseudo/mm@0:null
   2: S_IFCHR mode:0666 dev:270,0 ino:6815752 uid:0 gid:3 rdev:13,2
      O_RDWR|O_LARGEFILE
      /devices/pseudo/mm@0:null
   3: S_IFDOOR mode:0444 dev:279,0 ino:59 uid:0 gid:0 size:0
      O_RDONLY|O_LARGEFILE FD_CLOEXEC  door to nscd[93]
      /var/run/name_service_door
   4: S_IFSOCK mode:0666 dev:276,0 ino:36024 uid:0 gid:0 size:0
      O_RDWR|O_NONBLOCK
        SOCK_STREAM
        SO_REUSEADDR,SO_KEEPALIVE,SO_SNDBUF(49152),SO_RCVBUF(49880)
        sockname: AF_INET6 ::ffff:129.154.54.9  port: 22
        peername: AF_INET6 ::ffff:129.150.32.45  port: 52002
   5: S_IFDOOR mode:0644 dev:279,0 ino:55 uid:0 gid:0 size:0
      O_RDONLY FD_CLOEXEC  door to keyserv[179]
      /var/run/rpc_door/rpc_100029.1

....
```

pwdx, pstop, prun

```
nv70b> pwdx 3666
3666:   /zp/home/mauroj/Programs
nv70b> pflags 3666
3666:   ./loader 2 0 /zp/space
        data model = _ILP32  flags = MSACCT|MSFORK
 /1:    flags = ASLEEP  lwp_wait(0x2,0x80471f0)
 /2:    flags = 0
 /3:    flags = 0

nv70b> pstop 3666
nv70b> pflags 3666
3666:   ./loader 2 0 /zp/space
        data model = _ILP32  flags = MSACCT|MSFORK
        sigpend = 0x00008000,0x00000000
 /1:    flags = STOPPED|ISTOP|ASLEEP  lwp_wait(0x2,0x80471f0)
        why = PR_REQUESTED
 /2:    flags = STOPPED|ISTOP
        why = PR_REQUESTED
 /3:    flags = STOPPED|ISTOP
        why = PR_REQUESTED

nv70b> prun 3666
nv70b> pflags 3666
3666:   ./loader 2 0 /zp/space
        data model = _ILP32  flags = MSACCT|MSFORK
 /1:    flags = ASLEEP  lwp_wait(0x2,0x80471f0)
 /2:    flags = 0
 /3:    flags = 0
```

prstat(1)

- top-like utility to monitor running processes
- Sort on various thresholds (cpu time, RSS, etc)
- Enable system-wide microstate accounting
  - Monitor time spent in each microstate
- Solaris 9 - “projects” and “tasks” aware

```
  PID USERNAME  SIZE   RSS STATE  PRI NICE      TIME  CPU PROCESS/NLWP
 2597 ks130310 4280K 2304K cpu1     0    0   0:01:25  22% imapd/1
29195 bc21502  4808K 4160K sleep   59    0   0:05:26 1.9% imapd/1
 3469 tjobson  6304K 5688K sleep   53    0   0:00:03 1.0% imapd/1
 3988 tja      8480K 7864K sleep   59    0   0:01:53 0.5% imapd/1
 5173 root     2624K 2200K sleep   59    0  11:07:17 0.4% nfsd/18
 2528 root     5328K 3240K sleep   59    0  19:06:20 0.4% automountd/2
  175 root     4152K 3608K sleep   59    0   5:38:27 0.2% ypserv/1
 4795 snoqueen 5288K 4664K sleep   59    0   0:00:19 0.2% imapd/1
 3580 mauroj   4888K 4624K cpu3    49    0   0:00:00 0.2% prstat/1
 1365 bf117072 3448K 2784K sleep   59    0   0:00:01 0.1% imapd/1
 8002 root       23M   23M sleep   59    0   2:07:21 0.1% esd/1
 3598 wabbott  3512K 2840K sleep   59    0   0:00:00 0.1% imapd/1
25937 pdanner  4872K 4232K sleep   59    0   0:00:03 0.1% imapd/1
11130 smalm    5336K 4720K sleep   59    0   0:00:08 0.1% imapd/1
```

truss(1)

- “trace” the system calls of a process/command
- Extended to support user-level APIs (-u, -U)
- Can also be used for profile-like functions (-D, -E)
- Is thread-aware as of Solaris 9 (pid/lwp_id)

```
usenix> truss -c -p 2556
^C
syscall               seconds   calls  errors
read                     .013    1691
pread                    .015    1691
pread64                  .056     846
                     --------  ------   ----
sys totals:              .085    4228      0
usr time:                .014
elapsed:                7.030
usenix> truss -D -p 2556
/2:      0.0304 pread(11, "02\0\0\001\0\0\0\n c\0\0".., 256, 0) = 256
/2:      0.0008 read(8, "1ED0C2 I", 4)                          = 4
/2:      0.0005 read(8, " @C9 b @FDD4 EC6", 8)                  = 8
/2:      0.0006 pread(11, "02\0\0\001\0\0\0\n c\0\0".., 256, 0) = 256
/2:      0.0134 pread64(10, "\0\0\0\0\0\0\0\0\0\0\0\0".., 8192, 0x18C8A000) = 8192
/2:      0.0006 pread(11, "02\0\0\001\0\0\0\n c\0\0".., 256, 0) = 256
/2:      0.0005 read(8, "D6 vE5 @", 4)                          = 4
/2:      0.0005 read(8, "E4CA9A -01D7AAA1", 8)                  = 8
/2:      0.0006 pread(11, "02\0\0\001\0\0\0\n c\0\0".., 256, 0) = 256
```

lockstat(1M)

- Provides for kernel lock statistics (mutex locks, reader/writer locks)
- Also serves as a kernel profiling tool
- Use “-i 971” for the interval to avoid collisions with the clock interrupt, and gather fine-grained data

```
#lockstat -i 971 sleep 300 > lockstat.out
```

```
#lockstat -i 971 -I sleep 300 > lockstatI.out
```

Examining Kernel Activity - Kernel Profiling

```
# lockstat -kIi997 sleep 10
Profiling interrupt: 10596 events in 5.314 seconds (1994 events/sec)
Count indv cuml rcnt     nsec CPU+PIL                 Caller
-------------------------------------------------------------------------------
 5122  48%  48% 1.00     1419 cpu[0]                  default_copyout
 1292  12%  61% 1.00     1177 cpu[1]                  splx
 1288  12%  73% 1.00     1118 cpu[1]                  idle
  911   9%  81% 1.00     1169 cpu[1]                  disp_getwork
  695   7%  88% 1.00     1170 cpu[1]                  i_ddi_splhigh
  440   4%  92% 1.00     1163 cpu[1]+11               splx
  414   4%  96% 1.00     1163 cpu[1]+11               i_ddi_splhigh
  254   2%  98% 1.00     1176 cpu[1]+11               disp_getwork
   27   0%  99% 1.00     1349 cpu[0]                  uiomove
   27   0%  99% 1.00     1624 cpu[0]                  bzero
   24   0%  99% 1.00     1205 cpu[0]                  mmrw
   21   0%  99% 1.00     1870 cpu[0]                  (usermode)
    9   0%  99% 1.00     1174 cpu[0]                  xcopyout
    8   0%  99% 1.00      650 cpu[0]                  ktl0
    6   0%  99% 1.00     1220 cpu[0]                  mutex_enter
    5   0%  99% 1.00     1236 cpu[0]                  default_xcopyout
    3   0% 100% 1.00     1383 cpu[0]                  write
    3   0% 100% 1.00     1330 cpu[0]                  getminor
    3   0% 100% 1.00      333 cpu[0]                  utl0
    2   0% 100% 1.00      961 cpu[0]                  mmread
    2   0% 100% 1.00     2000 cpu[0]+10               read_rtc
```

trapstat(1)

- Solaris 9, Solaris 10 (and beyond...)
- Statistics on CPU traps
  - Very processor architecture specific
- "-t" flag details TLB/TSB miss traps
  - Extremely useful for determining if large pages will help performance
    - Solaris 9 Multiple Page Size Support (MPSS)

```
#trapstat -t
cpu m| itlb-miss %tim itsb-miss %tim | dtlb-miss %tim dtsb-miss %tim |%tim
-----+-------------------------------+-------------------------------+----
  0 u|       360  0.0         0  0.0 |       324  0.0         0  0.0 | 0.0
  0 k|        44  0.0         0  0.0 |     21517  1.1       175  0.0 | 1.1
-----+-------------------------------+-------------------------------+----
  1 u|      2680  0.1         0  0.0 |     10538  0.5        12  0.0 | 0.6
  1 k|       111  0.0         0  0.0 |     11932  0.7       196  0.1 | 0.7
-----+-------------------------------+-------------------------------+----
  4 u|      3617  0.2         2  0.0 |     28658  1.3       187  0.0 | 1.5
  4 k|        96  0.0         0  0.0 |     14462  0.8       173  0.1 | 0.8
-----+-------------------------------+-------------------------------+----
  5 u|      2157  0.1         7  0.0 |     16055  0.7      1023  0.2 | 1.0
  5 k|        91  0.0         0  0.0 |     12987  0.7       142  0.0 | 0.7
-----+-------------------------------+-------------------------------+----
  8 u|      1030  0.1         0  0.0 |      2102  0.1         0  0.0 | 0.2
  8 k|       124  0.0         1  0.0 |     11452  0.6        76  0.0 | 0.6
-----+-------------------------------+-------------------------------+----
  9 u|      7739  0.3        15  0.0 |    112351  4.9       664  0.1 | 5.3
  9 k|        78  0.0         3  0.0 |     65578  3.2      2440  0.6 | 3.8
-----+-------------------------------+-------------------------------+----
 12 u|      1398  0.1         5  0.0 |      8603  0.4       146  0.0 | 0.5
 12 k|       156  0.0         4  0.0 |     13471  0.7       216  0.1 | 0.8
-----+-------------------------------+-------------------------------+----
 13 u|       303  0.0         0  0.0 |       346  0.0         0  0.0 | 0.0
 13 k|        10  0.0         0  0.0 |     27234  1.4       153  0.0 | 1.4
=====+===============================+===============================+====
 ttl |     19994  0.1        37  0.0 |    357610  2.1      5603  0.2 | 2.4
```

The *stat Utilities

- `mpstat(1)`
  - System-wide view of CPU activity
- `vmstat(1)`
  - Memory statistics
  - Don't forget “vmstat -p” for per-page type statistics
- `netstat(1)`
  - Network packet rates
  - Use with care – it does induce probe effect
- `iostat(1)`
  - Disk I/O statistics
  - Rates (IOPS), bandwidth, service times
- `sar(1)`
  - The kitchen sink

cputrack(1)

- Gather CPU hardware counters, per process

```
solaris>  cputrack -N 20 -c pic0=DC_access,pic1=DC_miss -p 19849
   time lwp      event       pic0       pic1
  1.007   1       tick   34543793     824363
  1.007   2       tick          0          0
  1.007   3       tick 1001797338    5153245
  1.015   4       tick 976864106    5536858
  1.007   5       tick 1002880440    5217810
  1.017   6       tick 948543113    3731144
  2.007   1       tick   15425817     745468
  2.007   2       tick          0          0
  2.014   3       tick 1002035102    5110169
  2.017   4       tick 976879154    5542155
  2.030   5       tick 1018802136    5283137
  2.033   6       tick 1013933228    4072636
......

solaris> bc -l
824363/34543793
.02386428728310177171
((100-(824363/34543793)))
99.97613571271689822829
```

cpustat(1)

```
# cpustat -h
Usage:
        cpustat [-c events] [-p period] [-nstD] [interval [count]]

        -c events specify processor events to be monitored
        -n        suppress titles
        -p period cycle through event list periodically
        -s        run user soaker thread for system-only events
        -t        include %tick register
        -D        enable debug mode
        -h        print extended usage information

        Use cputrack(1) to monitor per-process statistics.

        CPU performance counter interface: SPARC64 VI

        event specification syntax:
        [picn=]<eventn>[,attr[n][=<val>]][,[picn=]<eventn>[,attr[n][=<val>]],...]

        event0:  cycle_counts instruction_counts op_stv_wait
                 load_store_instructions branch_instructions
                 floating_instructions impdep2_instructions
                 prefetch_instructions flush_rs 2iid_use toq_rsbr_phantom
                 trap_int_vector ts_by_sxmiss active_cycle_count
                 op_stv_wait_sxmiss eu_comp_wait swpf_fail_all
                 sx_miss_wait_pf jbus_cpi_count jbus_reqbus1_busy

        event1:  cycle_counts instruction_counts instruction_flow_counts
                 iwr_empty op_stv_wait load_store_instructions
                 branch_instructions floating_instructions
           . . . .
```

cpustat(1)

```
# cpustat -c pic0=cycle_counts,pic1=instruction_counts,sys
   time cpu event      pic0       pic1
  5.011   8  tick 11411962932 5348741180
  5.011 131  tick 11400819057 5249797028
  5.011 130  tick 11400858896 5244266999
  5.011  16  tick 11407356349 5303050712
  5.011  10  tick 11409702171 5344586657
  5.011  18  tick 11407295550 5306963656
  5.011  19  tick 11406349340 5292477138
  5.011   0  tick 11412859729 5222752733
  5.011  17  tick 11408093975 5307307043
  5.011  26  tick 11403459560 5254359643
  5.011 144  tick 11394770612 5325801245
  5.011  24  tick 11403518595 5256957295
  5.011 128  tick 11397600354 5234695931
  5.012   1  tick 11414392475 5284187266
  5.011 137  tick 11397641918 5313760153
  5.011  11  tick 11410206642 5347201300
  5.011  27  tick 11402593843 5285054790
. . .
# bc -l
11394446629/5320324508
2.14168263831774526036
```

Applying The Tools - Example

Start with a System View

```
# mpstat 1
CPU minf mjf xcal  intr ithr  csw icsw migr smtx  srw syscl  usr sys  wt idl
  0    0   0  294   329  227  117   60   12 40597    0 245787   10  90   0   0
  1   11   0    0   141    4   73   41   12 37736    0 244729   11  89   0   0
  2    0   0    0   140    2   64   37    1 34046    0 243383   10  90   0   0
  3    0   0    0   130    0   49   32    2 31666    0 243440   10  90   0   0
CPU minf mjf xcal  intr ithr  csw icsw migr smtx  srw syscl  usr sys  wt idl
  0    0   0   16   432  230  149   68   25 42514   25 250163   10  90   0   0
  1    0   0  100   122    5  117   55   26 38418    8 247621   10  90   0   0
  2    0   0  129   103    2  124   53   12 34029   12 244908    9  91   0   0
  3    0   0   24   123    0  110   45    6 30893   18 242016   10  90   0   0
```

- What jumps out at us...
  - Processors a fully utilized, 90% sys
    - Question: Where is the kernel spending time?
  - syscalls-per-second are high
    - Question: What are these system calls, and where are they coming from
  - mutex's per second are high
    - Question: Which mutex locks, and why?

Processor – kernel profile

```
# lockstat -i997 -Ikw sleep 30

Profiling interrupt: 119780 events in 30.034 seconds (3988 events/sec)

Count indv cuml rcnt     nsec CPU+PIL                  Hottest Caller
-------------------------------------------------------------------------------
29912  25%  25% 0.00     5461 cpu[2]                   kcopy
29894  25%  50% 0.00     5470 cpu[1]                   kcopy
29876  25%  75% 0.00     5401 cpu[3]                   kcopy
29752  25% 100% 0.00     5020 cpu[0]                   kcopy
  119   0% 100% 0.00     1689 cpu[0]+10                dosoftint
   71   0% 100% 0.00     1730 cpu[0]+11                sleepq_wakeone_chan
   45   0% 100% 0.00     5209 cpu[1]+11                lock_try
   39   0% 100% 0.00     4024 cpu[3]+11                lock_set_spl
   33   0% 100% 0.00     5156 cpu[2]+11                setbackdq
   30   0% 100% 0.00     3790 cpu[3]+2                 dosoftint
    6   0% 100% 0.00     5600 cpu[1]+5                 ddi_io_getb
    3   0% 100% 0.00     1072 cpu[0]+2                 apic_redistribute_compute
-------------------------------------------------------------------------------
# dtrace -n 'profile-997ms / arg0 != 0 / { @ks[stack()]=count() }'
dtrace: description 'profile-997ms ' matched 1 probe
^C


              genunix`syscall_mstate+0x1c7
              unix`sys_syscall32+0xbd
                1

              unix`bzero+0x3
              procfs`pr_read_lwpusage_32+0x2f
              procfs`prread+0x5d
              genunix`fop_read+0x29
              genunix`pread+0x217
              genunix`pread32+0x26
              unix`sys_syscall32+0x101
                1
```

[Continue from previous slide – dtrace stack() aggregation output...]

```
  .....
unix`kcopy+0x38
genunix`copyin_nowatch+0x48
genunix`copyin_args32+0x45
genunix`syscall_entry+0xcb
unix`sys_syscall32+0xe1
  1

unix`sys_syscall32+0xae
  1

unix`mutex_exit+0x19
ufs`rdip+0x368
ufs`ufs_read+0x1a6
genunix`fop_read+0x29
genunix`pread64+0x1d7
unix`sys_syscall32+0x101
  2

unix`kcopy+0x2c
genunix`uiomove+0x17f
ufs`rdip+0x382
ufs`ufs_read+0x1a6
genunix`fop_read+0x29
genunix`pread64+0x1d7
unix`sys_syscall32+0x101
 13
```

Another Kernel Stack View

```
# lockstat -i997 -Ikws 10 sleep 30

Profiling interrupt: 119800 events in 30.038 seconds (3988 events/sec)

-------------------------------------------------------------------------------
Count indv cuml rcnt     nsec CPU+PIL                 Hottest Caller
29919  25%  25% 0.00     5403 cpu[2]                  kcopy

      nsec ------ Time Distribution ------ count     Stack
      1024 |                               2         uiomove
      2048 |                               18        rdip
      4096 |                               25        ufs_read
      8192 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@  29853     fop_read
     16384 |                               21        pread64
                                                     sys_syscall32
-------------------------------------------------------------------------------
Count indv cuml rcnt     nsec CPU+PIL                 Hottest Caller
29918  25%  50% 0.00     5386 cpu[1]                  kcopy

      nsec ------ Time Distribution ------ count     Stack
      4096 |                               38        uiomove
      8192 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@  29870     rdip
     16384 |                               10        ufs_read
                                                     fop_read
                                                     pread64
                                                     sys_syscall32
-------------------------------------------------------------------------------
Count indv cuml rcnt     nsec CPU+PIL                 Hottest Caller
29893  25%  75% 0.00     5283 cpu[3]                  kcopy

      nsec ------ Time Distribution ------ count     Stack
      1024 |                               140       uiomove
      2048 |                               761       rdip
      4096 |@                              1443      ufs_read
      8192 |@@@@@@@@@@@@@@@@@@@@@@@@@@@    27532     fop_read
     16384 |                               17        pread64
                                                     sys_syscall32
-------------------------------------------------------------------------------
```

Who's Doing What...

```
#prstat -Lmc 10 10 > prstat.out
#cat prstat.out
PID USERNAME USR SYS TRP TFL DFL LCK SLP LAT VCX ICX SCL SIG PROCESS/LWPID
  4448 root      12  44 0.0 0.0 0.0 0.0  43 0.5  2K 460 .1M   0 prstat/1
  4447 root     1.2  11 0.0 0.0 0.0 0.1  14  73  54  65 .2M   0 filebench/27
  4447 root     1.1  10 0.0 0.0 0.0 0.1  15  74  57  52 .2M   0 filebench/29
  4447 root     1.1  10 0.0 0.0 0.1 0.0  15  74  64  53 .2M   0 filebench/19
  4447 root     1.1  10 0.0 0.0 0.0 0.4  14  74  49  55 .2M   0 filebench/7
  4447 root     1.1  10 0.0 0.0 0.0 0.2  14  74  51  44 .2M   0 filebench/17
  4447 root     1.1 9.9 0.0 0.0 0.0 0.3  14  74  48  57 .2M   0 filebench/14
  4447 root     1.1 9.9 0.0 0.0 0.0 0.3  14  74  42  61 .2M   0 filebench/9
  4447 root     1.1 9.8 0.0 0.0 0.0 0.1  15  74  51  49 .2M   0 filebench/25
  4447 root     1.1 9.8 0.0 0.0 0.0 0.0  15  74  60  38 .2M   0 filebench/4
  4447 root     1.1 9.7 0.0 0.0 0.0 0.2  14  75  25  69 .2M   0 filebench/26
  4447 root     1.0 9.7 0.0 0.0 0.1 0.0  15  75  54  46 .2M   0 filebench/12
  4447 root     1.1 9.6 0.0 0.0 0.0 0.3  14  75  40  46 .2M   0 filebench/21
  4447 root     1.1 9.6 0.0 0.0 0.0 0.1  15  75  39  70 .2M   0 filebench/31
  4447 root     1.1 9.6 0.0 0.0 0.1 0.0  15  75  38  75 .2M   0 filebench/22
Total: 59 processes, 218 lwps, load averages: 9.02, 14.30, 10.36
   PID USERNAME USR SYS TRP TFL DFL LCK SLP LAT VCX ICX SCL SIG PROCESS/LWPID
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  86  43  41 .3M   0 filebench/16
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  35  46 .3M   0 filebench/14
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  36  60 .3M   0 filebench/7
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  27  44 .3M   0 filebench/24
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  41  61 .3M   0 filebench/3
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  38  49 .3M   0 filebench/13
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  14  71 .3M   0 filebench/2
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  32  57 .3M   0 filebench/19
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  31  57 .3M   0 filebench/27
  4447 root     1.3  12 0.0 0.0 0.0 0.0 0.0  87  34  47 .3M   0 filebench/4
  4447 root     1.3  11 0.0 0.0 0.0 0.0 0.0  87  21  74 .3M   0 filebench/26
  4447 root     1.2  11 0.0 0.0 0.0 0.0 0.0  87  42  51 .3M   0 filebench/9
  4447 root     1.3  11 0.0 0.0 0.0 0.0 0.0  87  16  83 .3M   0 filebench/18
  4447 root     1.2  11 0.0 0.0 0.0 0.0 0.0  87  42  47 .3M   0 filebench/33
  4447 root     1.2  11 0.0 0.0 0.0 0.0 0.0  87  15  76 .3M   0 filebench/15
Total: 59 processes, 218 lwps, load averages: 12.54, 14.88, 10.59
```

System Calls – What & Who

```
# dtrace -n 'syscall:::entry { @sc[probefunc]=count() }'
dtrace: description 'syscall:::entry ' matched 228 probes
^C

  fstat                                                         1
  mmap                                                          1
  schedctl                                                      1
  waitsys                                                       1
  recvmsg                                                       2
  sigaction                                                     2
  sysconfig                                                     3
  brk                                                           6
  pset                                                          9
  gtime                                                        16
  lwp_park                                                     20
  p_online                                                     21
  setcontext                                                   29
  write                                                        30
  nanosleep                                                    32
  lwp_sigmask                                                  45
  setitimer                                                    54
  pollsys                                                     118
  ioctl                                                       427
  pread64                                                 1583439
  pread                                                   3166885
  read                                                    3166955
# dtrace -n 'syscall::read:entry { @[execname,pid]=count()}'
dtrace: description 'syscall::read:entry ' matched 1 probe
^C

  sshd                                              4342                3
  Xorg                                               536               36
  filebench                                         4376          2727656
```

smtx – Lock Operations

```
# lockstat sleep 30 > lockstat.locks1
# more lockstat.locks1

Adaptive mutex spin: 3486197 events in 30.031 seconds (116088 events/sec)

Count indv cuml rcnt     spin Lock                   Caller
-------------------------------------------------------------------------------
1499963  43%  43% 0.00       84 pr_pidlock              pr_p_lock+0x29
1101187  32%  75% 0.00       24 0xffffffff810cdec0      pr_p_lock+0x50
285012    8%  83% 0.00       27 0xffffffff827a9858      rdip+0x506
212621    6%  89% 0.00       29 0xffffffff827a9858      rdip+0x134
98531     3%  92% 0.00      103 0xffffffff9321d480     releasef+0x55
92486     3%  94% 0.00       19 0xffffffff8d5c4990     ufs_lockfs_end+0x81
89404     3%  97% 0.00       27 0xffffffff8d5c4990     ufs_lockfs_begin+0x9f
83186     2%  99% 0.00       96 0xffffffff9321d480     getf+0x5d
 6356     0%  99% 0.00      186 0xffffffff810cdec0     clock+0x4e9
 1164     0% 100% 0.00      141 0xffffffff810cdec0     post_syscall+0x352
  294     0% 100% 0.00       11 0xffffffff801a4008     segmap_smapadd+0x77
  279     0% 100% 0.00       11 0xffffffff801a41d0     segmap_getmapflt+0x275
  278     0% 100% 0.00       11 0xffffffff801a48f0     segmap_smapadd+0x77
  276     0% 100% 0.00       11 0xffffffff801a5010     segmap_getmapflt+0x275
  276     0% 100% 0.00       11 0xffffffff801a4008     segmap_getmapflt+0x275
...
Adaptive mutex block: 3328 events in 30.031 seconds (111 events/sec)

Count indv cuml rcnt     nsec Lock                   Caller
-------------------------------------------------------------------------------
 1929  58%  58% 0.00 48944759 pr_pidlock             pr_p_lock+0x29
  263   8%  66% 0.00    47017 0xffffffff810cdec0     pr_p_lock+0x50
  255   8%  74% 0.00 53392369 0xffffffff9321d480     getf+0x5d
  217   7%  80% 0.00    26133 0xffffffff810cdec0     clock+0x4e9
  207   6%  86% 0.00   227146 0xffffffff827a9858     rdip+0x134
  197   6%  92% 0.00    64467 0xffffffff8d5c4990     ufs_lockfs_begin+0x9f
  122   4%  96% 0.00    64664 0xffffffff8d5c4990     ufs_lockfs_end+0x81
  112   3%  99% 0.00   164559 0xffffffff827a9858     rdip+0x506
```

smtx – Lock Operations (cont)

```
Spin lock spin: 3491 events in 30.031 seconds (116 events/sec)

Count indv cuml rcnt     spin Lock                   Caller
-------------------------------------------------------------------------------
 2197  63%  63% 0.00     2151 turnstile_table+0xbd8  disp_lock_enter+0x35
  314   9%  72% 0.00     3129 turnstile_table+0xe28  disp_lock_enter+0x35
  296   8%  80% 0.00     3162 turnstile_table+0x888  disp_lock_enter+0x35
  211   6%  86% 0.00     2032 turnstile_table+0x8a8  disp_lock_enter+0x35
  127   4%  90% 0.00      856 turnstile_table+0x9f8  turnstile_interlock+0x171
  114   3%  93% 0.00      269 turnstile_table+0x9f8  disp_lock_enter+0x35
   44   1%  95% 0.00       90 0xffffffff827f4de0     disp_lock_enter_high+0x13
   37   1%  96% 0.00      581 0xffffffff827f4de0     disp_lock_enter+0x35
...
Thread lock spin: 1104 events in 30.031 seconds (37 events/sec)

Count indv cuml rcnt     spin Lock                   Caller
-------------------------------------------------------------------------------
  487  44%  44% 0.00     1671 turnstile_table+0xbd8  ts_tick+0x26
  219  20%  64% 0.00     1510 turnstile_table+0xbd8  turnstile_block+0x387
   92   8%  72% 0.00     1941 turnstile_table+0x8a8  ts_tick+0x26
   77   7%  79% 0.00     2037 turnstile_table+0xe28  ts_tick+0x26
   74   7%  86% 0.00     2296 turnstile_table+0x888  ts_tick+0x26
   36   3%  89% 0.00      292 cpu[0]+0xf8            ts_tick+0x26
   27   2%  92% 0.00       55 cpu[1]+0xf8            ts_tick+0x26
   11   1%  93% 0.00       26 cpu[3]+0xf8            ts_tick+0x26
   10   1%  94% 0.00       11 cpu[2]+0xf8            post_syscall+0x556
...
```

```
R/W writer blocked by writer: 17 events in 30.031 seconds (1 events/sec)

Count indv cuml rcnt     nsec Lock                   Caller
-------------------------------------------------------------------------------

Count indv cuml rcnt     nsec Lock                   Caller
-------------------------------------------------------------------------------
   17 100% 100% 0.00   465308 0xffffffff831f3be0     ufs_getpage+0x369
-------------------------------------------------------------------------------

R/W writer blocked by readers: 55 events in 30.031 seconds (2 events/sec)

Count indv cuml rcnt     nsec Lock                   Caller
-------------------------------------------------------------------------------
   55 100% 100% 0.00  1232132 0xffffffff831f3be0     ufs_getpage+0x369
-------------------------------------------------------------------------------

R/W reader blocked by writer: 22 events in 30.031 seconds (1 events/sec)

Count indv cuml rcnt     nsec Lock                   Caller
-------------------------------------------------------------------------------
   18  82%  82% 0.00    56339 0xffffffff831f3be0     ufs_getpage+0x369
    4  18% 100% 0.00    45162 0xffffffff831f3be0     ufs_putpages+0x176
-------------------------------------------------------------------------------

R/W reader blocked by write wanted: 47 events in 30.031 seconds (2 events/sec)

Count indv cuml rcnt     nsec Lock                   Caller
-------------------------------------------------------------------------------
   46  98%  98% 0.00   369379 0xffffffff831f3be0     ufs_getpage+0x369
    1   2% 100% 0.00   118455 0xffffffff831f3be0     ufs_putpages+0x176
-------------------------------------------------------------------------------
```

Chasing the hot lock caller...

```
# dtrace -n 'pr_p_lock:entry { @s[stack()]=count() }'
dtrace: description 'pr_p_lock:entry ' matched 1 probe
^C
              procfs`pr_read_lwpusage_32+0x4f
              procfs`prread+0x5d
              genunix`fop_read+0x29
              genunix`pread+0x217
              genunix`pread32+0x26
              unix`sys_syscall32+0x101
         12266066
# dtrace -n 'pr_p_lock:entry { @s[execname]=count() }'
dtrace: description 'pr_p_lock:entry ' matched 1 probe
^C

  filebench                                                   8439499
# pgrep filebench
4485
# dtrace -n 'pid4485:libc:pread:entry { @us[ustack()]=count() }'
dtrace: description 'pid4485:libc:pread:entry ' matched 1 probe
^C
              libc.so.1`pread
              filebench`flowop_endop+0x5b
              filebench`flowoplib_read+0x238
              filebench`flowop_start+0x2b1
              libc.so.1`_thr_setup+0x51
              libc.so.1`_lwp_start
          2084651

              libc.so.1`pread
              filebench`flowop_beginop+0x6a
              filebench`flowoplib_read+0x200
              filebench`flowop_start+0x2b1
              libc.so.1`_thr_setup+0x51
              libc.so.1`_lwp_start
          2084651
```

Icing on the cake...

```
# dtrace -q -n 'ufs_read:entry { printf("UFS Read: %s\n",stringof(args[0]->v_path)); }'
UFS Read: /ufs/largefile1
UFS Read: /ufs/largefile1
UFS Read: /ufs/largefile1
UFS Read: /ufs/largefile1
UFS Read: /ufs/largefile1
UFS Read: /ufs/largefile1
^c

#
#
# dtrace -q -n 'ufs_read:entry { @[execname,stringof(args[0]->v_path)]=count() }'
^C

  filebench                                           /ufs/largefile1
                        864609
```

Session 2 - Memory

Virtual Memory

- Simple programming model/abstraction
- Fault Isolation
- Security
- Management of Physical Memory
- Sharing of Memory Objects
- Caching

Solaris Virtual Memory Glossary

Address Space	Linear memory range visible to a program, that the instructions of the program can directly load and store. Each Solaris process has an address space; the Solaris kernel also has its own address space.
Virtual Memory	Illusion of real memory within an address space.
Physical Memory	Real memory (e.g. RAM)
Mapping	A memory relationship between the address space and an object managed by the virtual memory system.
Segment	A co-managed set of similar mappings within an address space.
Text Mapping	The mapping containing the program's instructions and read-only objects.
Data Mapping	The mapping containing the program's initialized data
Heap	A mapping used to contain the program's heap (malloc'd) space
Stack	A mapping used to hold the program's stack
Page	A linear chunk of memory managed by the virtual memory system
VNODE	A file-system independent file object within the Solaris kernel
Backing Store	The storage medium used to hold a page of virtual memory while it is not backed by physical memory
Paging	The action of moving a page to or from its backing store
Swapping	The action of swapping an entire address space to/from the swap device
Swap Space	A storage device used as the backing store for anonymous pages.

Solaris Virtual Memory Glossary (cont)

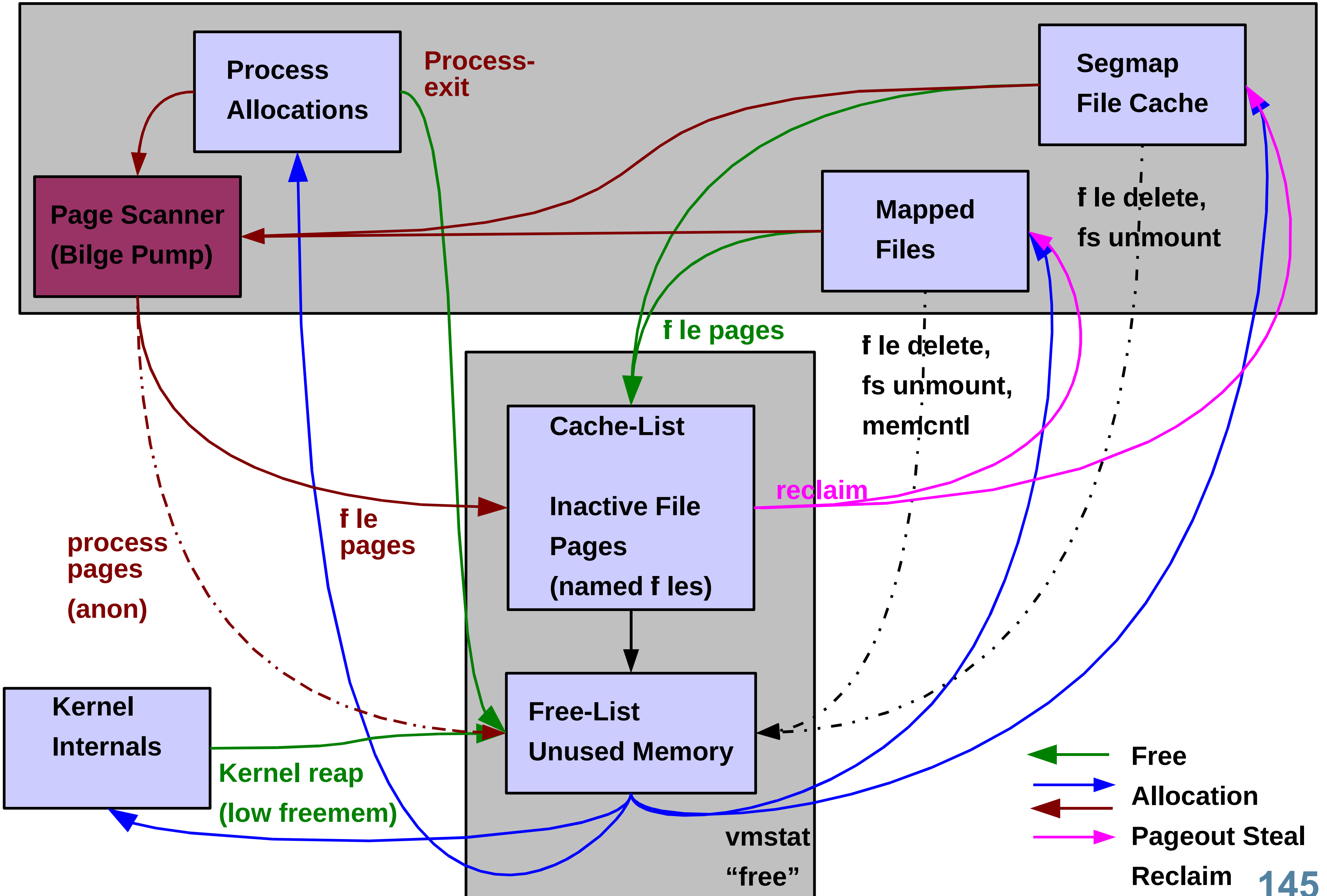
Scanning	The action of the virtual memory system takes when looking for memory which can be freed up for use by other subsystems.
Named Pages	Pages which are mappings of an object in the file system.
Anonymous Memory	Pages which do not have a named backing store
Protection	A set of booleans to describe if a program is allowed to read, write or execute instructions within a page or mapping.
ISM	Intimate Shared Memory - A type of System V shared memory optimized for sharing between many processes
DISM	Pageable ISM
NUMA	Non-uniform memory architecture - a term used to describe a machine with differing processor-memory latencies.
Lgroup	A locality group - a grouping of processors and physical memory which share similar memory latencies
MMU	The hardware functional unit in the microprocessor used to dynamically translate virtual addresses into physical addresses.
HAT	The Hardware Address Translation Layer - the Solaris layer which manages the translation of virtual addresses to physical addresses
TTE	Translation Table Entry - The UltraSPARC hardware's table entry which holds the data for virtual to physical translation
TLB	Translation Lookaside Buffer - the hardware's cache of virtual address translations
Page Size	The translation size for each entry in the TLB
TSB	Translation Software Buffer - UltraSPARC's software cache of TTEs, used for lookup when a translation is not found in the TLB

Solaris Virtual Memory

- Demand Paged, Globally Managed
- Integrated file caching
- Layered to allow virtual memory to describe multiple memory types (Physical memory, frame buffers)
- Layered to allow multiple MMU architectures

Physical Memory Management

Memory Allocation Transitions

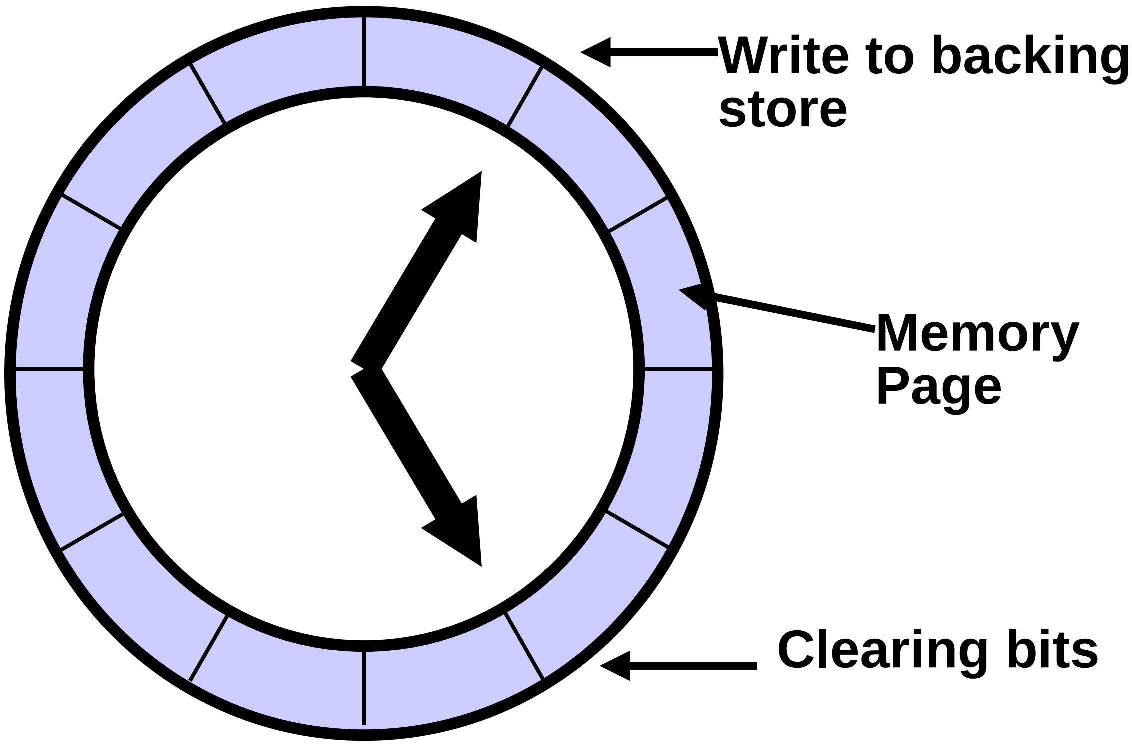


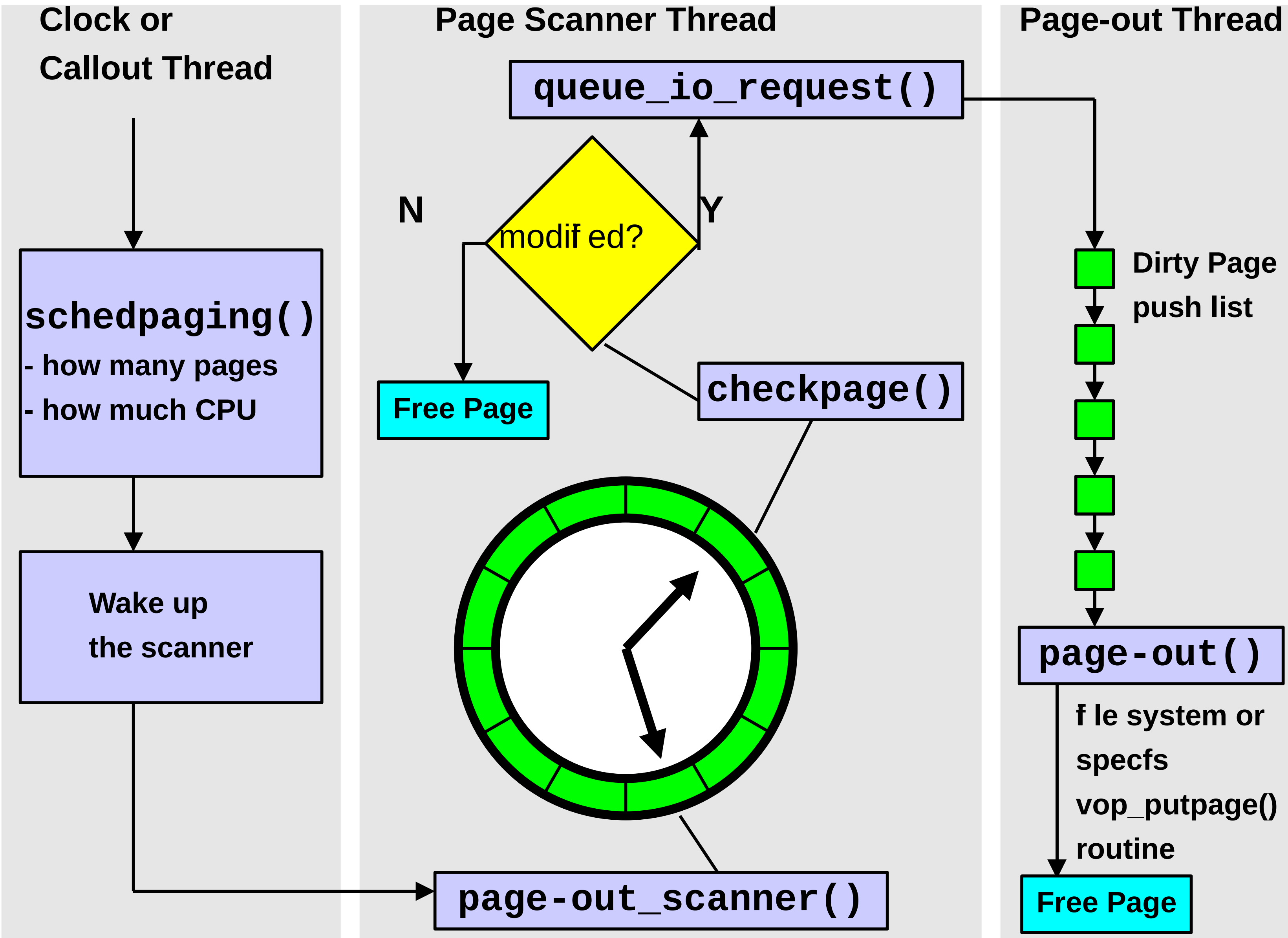
Page Lists

- Free List
  - does not have a vnode/offset associated
  - put on list at process exit.
  - may be always small (pre Solaris 8)
- Cache List
  - still have a vnode/offset
  - seg_map free-behind and seg_vn executables and libraries (for reuse)
  - reclaims are in **`vmstat`** "re"
- Sum of these two are in **`vmstat`** "free"

Page Scanning

- Steals pages when memory is low
- Uses a Least Recently Used process.
- Puts memory out to "backing store"
- Kernel thread does the scanning




Clock or
Callout Thread
schedpaging()
- how many pages
- how much CPU
Wake up
the scanner
Page Scanner Thread
queue_io_request()
N
modif ed?
Y
Free Page
checkpage()
page-out_scanner()
Page-out Thread
Dirty Page
push list
page-out()
f le system or
specfs
vop_putpage()
routine
Free Page

Scanning Algorithm

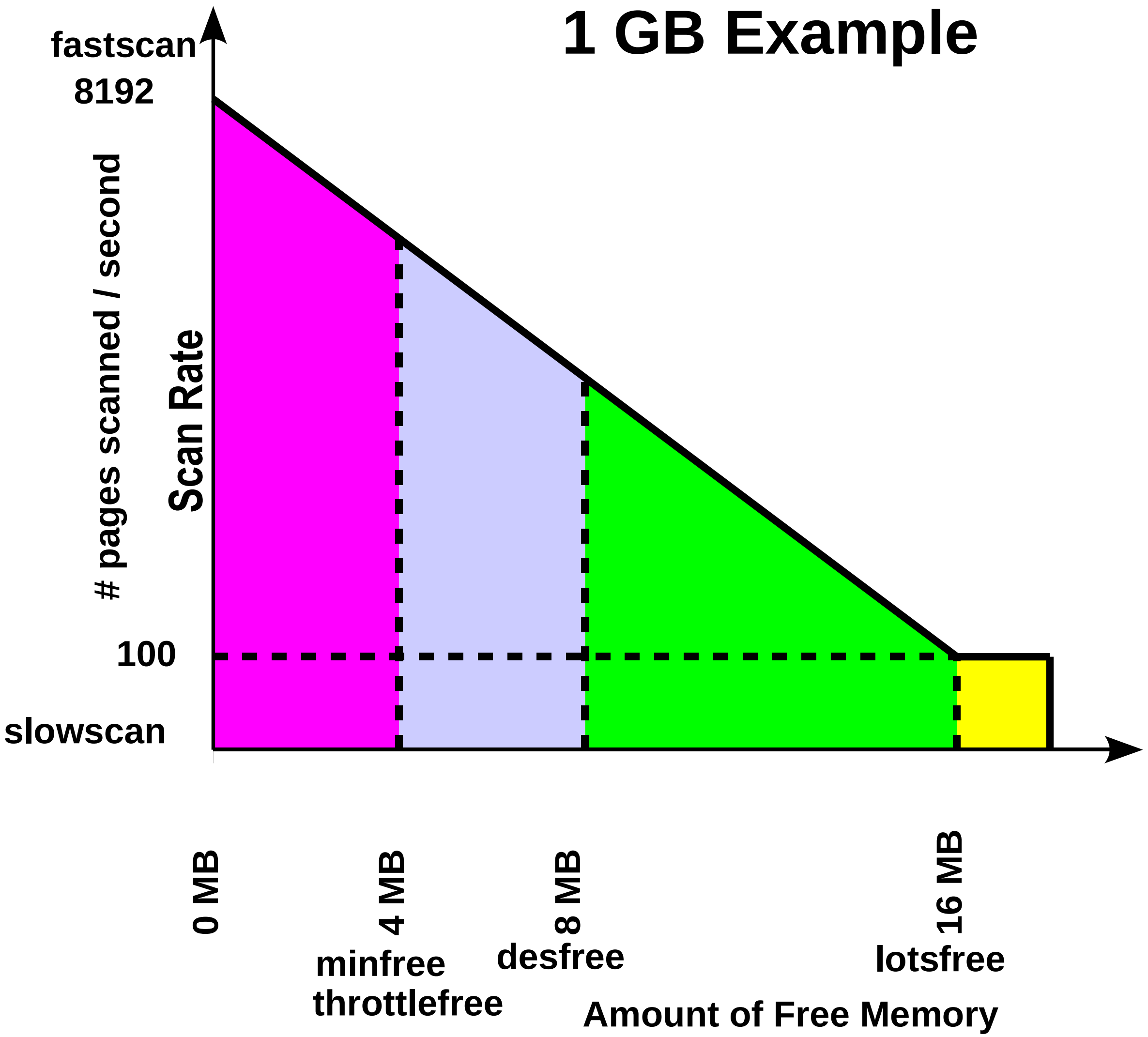
- Free memory is lower than (lotsfree)
- Starts scanning @ slowscan (pages/sec)
- Scanner Runs:
  - four times / second when memory is short
  - Awoken by page allocator if very low
- Limits:
  - Max # of pages /sec. swap device can handle
  - How much CPU should be used for scanning

$$\text{scanrate} = \left(\frac{\text{lotsfree} - \text{freemem}}{\text{lotsfree}} \times \text{fastscan} \right) + \left(\text{slowscan} \times \frac{\text{freemem}}{\text{lotsfree}} \right)$$

Scanning Parameters

Parameter	Description	Min	Default (Solaris 8)
lotsfree	starts stealing anonymous memory pages	512K	1/64 th of memory
desfree	scanner is started at 100 times/second	minfree	½ of lotsfee
minfree	start scanning every time a new page is created		½ of desfree
throttlefree	page_create routine makes the caller wait until free pages are available		minfree
fastscan	scan rate (pages per second) when free memory = minfree	slowscan	minimum of 64MB/s or ½ memory size
slowscan	scan rate (pages per second) when free memory = lotsfree		100
maxpgio	max number of pages per second that the swap device can	~60	60 or 90 pages per spindle
hand-spreadpages	number of pages between the front hand (clearing) and back hand (checking)	1	fastscan
min_percent_cpu	CPU usage when free memory is at lotsfree	4% (~1 clock tick)	of a single CPU

Scan Rate

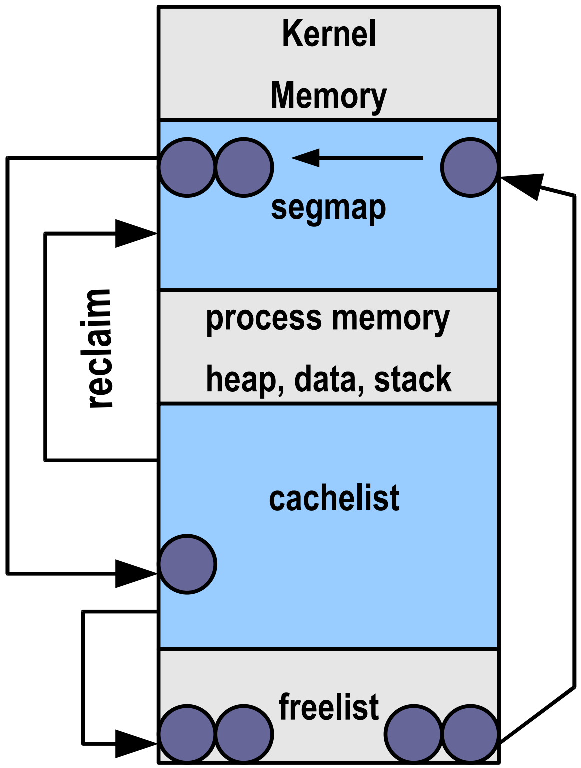

1 GB Example
fastscan
8192
pages scanned / second
Scan Rate
100
slowscan
0 MB
4 MB
8 MB
16 MB
minfree
throttlefree
desfree
lotsfree
Amount of Free Memory

The Solaris Page Cache

- Page list is broken into two:
  - Cache List: pages with a valid vnode/offset
  - Free List: pages has no vnode/offset
- Unmapped pages where just released
- Non-dirty pages, not mapped, should be on the "free list"
- Places pages on the "tail" cache/free list
- Free memory = cache + free
- UFS
  - segmap kernel address space segment
  - Starting in Solaris 10 3/05, segkpm integration (SPARC)
- ZFS
  - Uses kernel memory (kmem_alloc) for ARC cache

The Solaris UFS Cache- segmap

Sol 8 (and beyond) segmap



The Solaris Cache

- Now `vmstat` reports a useful `free`
- Throw away your old `/etc/system` pager configuration parameters
  - `lotsfree, desfree, minfree`
  - `fastscan, slowscan`
  - `priority_paging, cachefree`

Memory Summary

Physical Memory:

```
# prtconf
System Configuration:  Sun Microsystems  sun4u
Memory size: 512 Megabytes
```

Kernel Memory:

```
# sar -k 1 1
SunOS ian 5.8 Generic_108528-03 sun4u    08/28/01
13:04:58 sml_mem   alloc  fail  lg_mem   alloc  fail  ovsz_alloc  fail
13:04:59 10059904 7392775     0 133349376 92888024     0    10346496     0
```

Free Memory:

```
# vmstat 3 3
 procs     memory                  page                disk           faults      cpu
 r b w   swap  free  re  mf pi po fr de sr f0 s0 s1 s6   in   sy   cs us sy id
 0 0 0 478680 204528  0   2  0  0  0  0  0  0  0  1  0  209 1886  724 35  5 61
 0 0 0 415184 123400  0   2  0  0  0  0  0  0  0  0  0  238  825  451  2  1 98
 0 0 0 415200 123416  0   0  0  0  0  0  0  0  0  3  0  219  788  427  1  1 98
```

Memory Summary

```
nv70b> kstat unix:0:system_pages:pp_kernel
module: unix                            instance: 0
name:   system_pages                    class:    pages
        pp_kernel                       53610

nv70b> pagesize
4096
nv70b> bc -l
4096*53610
219586560
nv70b> su
Password:
# mdb -k
Loading modules: [ unix genunix specfs dtrace uppc pcplusmp scsi_vhci ufs mpt ip
> ::memstat
Page Summary                Pages                MB  %Tot
------------     ----------------  ----------------  ----
Kernel                      50377               196   19%
Anon                        63005               246   24%
Exec and libs               13689                53    5%
Page cache                   8871                34    3%
Free (cachelist)            52344               204   20%
Free (freelist)             71696               280   28%

Total                      259982              1015
Physical                   259981              1015
>
```

vmstat

- r = run queue length
- b = processes blocked waiting for I/O
- w = idle processes that have been swapped at some time
- swap = free and unreserved swap in KBytes
- free = free memory measured in pages
- re = kilobytes reclaimed from cache/free list
- mf = minor faults - the page was in memory but was not mapped
- pi = kilobytes paged-in from the f le system or swap device
- po = kilobytes paged-out to the f le system or swap device
- fr = kilobytes that have been destroyed or freed
- de = kilobytes freed after writes
- sr = pages scanned / second
- s0-s3 = disk I/Os per second for disk 0-3
- in = interrupts / second
- sy = system calls / second
- cs = context switches / second
- us = user cpu time
- sy = kernel cpu time
- id = idle + wait cpu time

```
# vmstat 5 5
 procs     memory            page                     disk          faults           cpu
 r b w   swap  free     re  mf pi po  fr  de  sr f0 s0  s1 s2   in     sy    cs     us sy id
 ...
 0 0 0 46580232 337472 18 194 30 0   0   0   0  0  0   0  0  5862   81260 28143   19  7 74
 0 0 0 45311368 336280 32 249 48 0   0   0   0  0  0   0  0  6047   93562 29039   21 10 69
 0 0 0 46579816 337048 12 216 60 0   0   0   0  0 10   0  7  5742 100944 27032   20  7 73
 0 0 0 46580128 337176  3 111 3  0   0   0   0  0  0   0  0  5569   93338 26204   21  6 73
```

vmstat -p

swap = free and unreserved swap in KBytes

free = free memory measured in pages

re = kilobytes reclaimed from cache/free list

mf = minor faults - the page was in memory but was not mapped

fr = kilobytes that have been destroyed or freed

de = kilobytes freed after writes

sr = kilobytes scanned / second

executable pages: kilobytes in - out - freed

anonymous pages: kilobytes in - out – freed

f le system pages:

kilobytes in - out - freed

```
# vmstat -p 5 5
     memory           page          executable      anonymous      filesystem
   swap    free  re  mf  fr  de  sr  epi  epo  epf  api  apo  apf  fpi  fpo  fpf
 46715224 891296 24  350 0   0   0    0    0    0    4    0    0   27    0    0
 46304792 897312 151 761 25  0   0   17    0    0    1    0    0  280   25   25
 45886168 899808 118 339 1   0   0    3    0    0    1    0    0  641    1    1
 46723376 899440 29  197 0   0   0    0    0    0   40    0    0   60    0    0
```

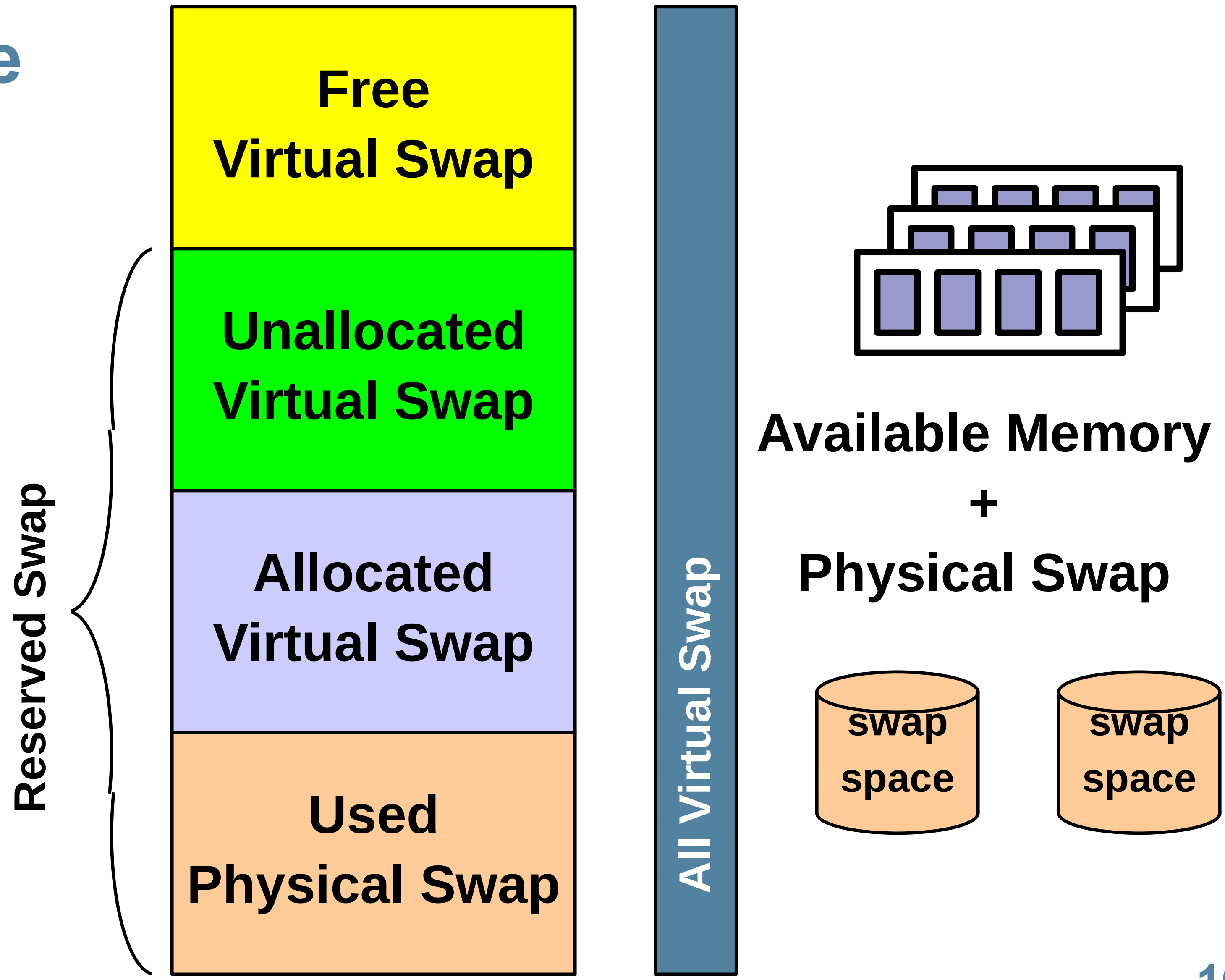
Swapping

- Scheduler/Dispatcher:
  - Dramatically affects process performance
  - Used when demand paging is not enough
- Soft swapping:
  - Avg. freemem below desfree for 30 sec.
  - Look for inactive processes, at least **`maxslp`**
- Hard swapping:
  - Run queue >= 2 (waiting for CPU)
  - Avg. freemem below desfree for 30 sec.
  - Excessive paging, **`(pageout + pagein ) > maxpgio`**
  - Aggressive; unload kernel mods & free cache

Swap space states

- Reserved:
  - Virtual space is reserved for the segment
  - Represents the virtual size being created
- Allocated:
  - Virtual space is allocated when the first physical page is assigned
  - A swapfs vnode / offset are assigned
- Swapped out:
  - When a shortage occurs
  - Page is swapped out by the scanner, migrated to swap storage

Swap Space


Free
Virtual Swap
Unallocated
Virtual Swap
Allocated
Virtual Swap
Used
Physical Swap
Reserved Swap
All Virtual Swap
Available Memory
+
Physical Swap
swap
space
swap
space

Swap Usage

- Virtual Swap:
  - reserved: unallocated + allocated
  - available = bytes

```
# swap -s
total: 175224k bytes unallocated + 24464k allocated = 199688k reserved, 416336k
available
```

- Physical Swap:
  - space available for physical page-outs
  - free = blocks (512 bytes)

```
# swap -l
swapfile             dev   swaplo blocks   free
/dev/dsk/c0t1d0s1   32,9       16 524864 524864
```

- Ensure both are non-zero
  - swap -s "available"
  - swap -l "free"

A Quick Guide to Analyzing Memory

- Quick Memory Health Check
  - Check free memory and scanning with vmstat
  - Check memory usage with ::memstat in mdb
- Paging Activity
  - Use vmstat -p to check if there are anonymous page-ins
- Attribution
  - Use DTrace to see which processes/files are causing paging
- Time based analysis
  - Use DTrace to estimate the impact of paging on application performance
- Process Memory Usage
  - Use pmap to inspect process memory usage and sharing
- MMU/Page Size Performance
  - Use trapstat to observe time spent in TLB misses

Memory Kstats – via kstat(1m)

```
sol8# kstat -n system_pages
module: unix                            instance: 0
name:   system_pages                    class:    pages
        availrmem                       343567
        crtime                          0
        desfree                         4001
        desscan                         25
        econtig                         4278190080
        fastscan                        256068
        freemem                         248309
        kernelbase                      3556769792
        lotsfree                        8002
        minfree                         2000
        nalloc                          11957763
        nalloc_calls                    9981
        nfree                           11856636
        nfree_calls                     6689
        nscan                           0
        pagesfree                       248309
        pageslocked                     168569
        pagestotal                      512136
        physmem                         522272
        pp_kernel                       64102
        slowscan                        100
        snaptime                        6573953.83957897
```

Memory Kstats – via kstat Perl API

```
%{$now} = %{$kstats->{0}{system_pages}};
print "$now->{pagesfree}\n";

sol8# wget http://www.solarisinternals.com/si/downloads/prtmem.pl
sol8# prtmem.pl 10
prtmem started on 04/01/2005 15:46:13 on devnull, sample interval 5
seconds
                   Total      Kernel        Delta        Free       Delta
15:46:18            2040         250            0         972         -12
15:46:23            2040         250            0         968          -3
15:46:28            2040         250            0         968           0
15:46:33            2040         250            0         970           1
```

Checking Paging Activity

- Good Paging
  - Plenty of memory free
  - Only file system page-in/page-outs (vmstat: fpi, fpo > 0)

```
%sol8# vmstat -p 3
     memory           page          executable      anonymous      filesystem
   swap  free  re  mf  fr  de  sr  epi  epo  epf  api  apo  apf  fpi  fpo  fpf
 1512488 837792 160 20 12   0   0    0    0    0    0    0    0   12   12   12
 1715812 985116 7  82   0   0   0    0    0    0    0    0    0   45    0    0
 1715784 983984 0   2   0   0   0    0    0    0    0    0    0   53    0    0
 1715780 987644 0   0   0   0   0    0    0    0    0    0    0   33    0    0
```

Checking Paging Activity

- Bad Paging
  - Non zero Scan rate (vmstat: sr >0)
  - Low free memory (vmstat: free < 1/16th physical)
  - Anonymous page-in/page-outs (vmstat: api, apo > 0)

```
sol8# vmstat -p 3
     memory           page          executable      anonymous      filesystem
   swap  free  re  mf  fr  de  sr  epi  epo  epf  api  apo  apf  fpi  fpo  fpf
 2276000 1589424 2128 19969 1 0 0    0    0    0    0    0    0    0    1    1
 1087652 388768 12 129675 13879 0 85590 0 0   12    0 3238 3238   10 9391 10630
 608036 51464  20 8853 37303 0 65871 38    0  781   12 19934 19930 95 16548 16591
  94448  8000  17 23674 30169 0 238522 16 0  810   23 28739 28804 56  547  556
```

Using prstat to estimate paging slow-downs

- Microstates show breakdown of elapsed time
  - prstat -m
  - USR through LAT columns summed show 100% of wallclock execution time for target thread/process
  - DFL shows time spent waiting in major faults in anon:

```
sol8$ prstat -mL
   PID USERNAME USR SYS TRP TFL DFL LCK SLP LAT VCX ICX SCL SIG PROCESS/LWPID
 15625 rmc      0.1 0.7 0.0 0.0  95 0.0 0.9 3.2  1K 726  88   0 filebench/2
 15652 rmc      0.1 0.7 0.0 0.0  94 0.0 1.8 3.6  1K  1K  10   0 filebench/2
 15635 rmc      0.1 0.7 0.0 0.0  96 0.0 0.5 3.2  1K  1K   8   0 filebench/2
 15626 rmc      0.1 0.6 0.0 0.0  95 0.0 1.4 2.6  1K 813  10   0 filebench/2
 15712 rmc      0.1 0.5 0.0 0.0  47 0.0  49 3.8  1K 831 104   0 filebench/2
 15628 rmc      0.1 0.5 0.0 0.0  96 0.0 0.0 3.1  1K 735   4   0 filebench/2
 15725 rmc      0.0 0.4 0.0 0.0  92 0.0 1.7 5.7 996 736   8   0 filebench/2
 15719 rmc      0.0 0.4 0.0 0.0  40  40  17 2.9  1K 708 107   0 filebench/2
 15614 rmc      0.0 0.3 0.0 0.0  92 0.0 4.7 2.4 874 576  40   0 filebench/2
```

Using DTrace for memory Analysis

- The “vminfo” provider has probes at the all the places memory statistics are gathered.
- Everything visible via vmstat -p and kstat are defined as probes
  - arg0: the value by which the statistic is to be incremented. For most probes, this argument is always 1, but for some it may take other values; these probes are noted in Table 5-4.
  - arg1: a pointer to the current value of the statistic to be incremented. This value is a 64 bit quantity that is incremented by the value in arg0. Dereferencing this pointer allows consumers to determine the current count of the statistic corresponding to the probe.

Using DTrace for Memory Analysis

- For example, if you should see the following paging activity with vmstat, indicating page-in from the swap device, you could drill down to investigate.

```
sol8# vmstat -p 3
     memory           page            executable      anonymous      filesystem
   swap  free  re  mf  fr   de   sr  epi  epo  epf  api  apo  apf  fpi  fpo  fpf
 1512488 837792 160 20 12    0    0    0    0    0 8102    0    0   12   12   12
 1715812 985116 7  82   0    0    0    0    0    0 7501    0    0   45    0    0
 1715784 983984 0   2   0    0    0    0    0    0 1231    0    0   53    0    0
 1715780 987644 0   0   0    0    0    0    0    0 2451    0    0   33    0    0

sol10$ dtrace -n anonpgin '{@[execname] = count()}'
dtrace: description anonpgin matched 1 probe
  svc.startd                                                       1
  sshd                                                             2
  ssh                                                              3
  dtrace                                                           6
  vmstat                                                          28
  filebench                                                      913
```

dtrace pagefaults

```
# cat pf.d
#!/usr/sbin/dtrace -s

#pragma D option quiet

fbt:unix:pagefault:entry
{
        @st[execname] = count();
        self->pfst[execname] = timestamp
}
fbt:unix:pagefault:return
/ self->pfst[execname] /
{
        @pft[execname] = sum(timestamp - self->pfst[execname]);
        self->pfst[execname] = 0;
}
tick-10s
{
        printf("Pagefault counts by execname ...\n");
        printa(@st);

        printf("\nPagefault times (in nano's) by execname...\n");
        printa(@pft);

        clear(@st);
        clear(@pft);
}
```

tracking pagefault entry and returns for counts and times

dtrace pagefaults

```
# ./pf.d
Pagefault counts by execname ...

  dtrace                                                        93
  java                                                        1257
  kstat                                                       1588

Pagefault times (in nano's) by execname...

  dtrace                                                    798535
  kstat                                                   17576367
  java                                                    85760822
Pagefault counts by execname ...

  dtrace                                                         2
  java                                                        1272
  kstat                                                       1588

Pagefault times (in nano's) by execname...

  dtrace                                                     80192
  kstat                                                   18227212
  java                                                    75422709
^C
```

Large Memory

- Large Memory in Perspective
- 64-bit Solaris
- 64-bit Hardware
- Solaris enhancements for Large Memory
- Large Memory Databases
- Configuring Solaris for Large Memory
- Using larger page sizes

64-bit Solaris

- LP64 Data Model
- 32-bit or 64-bit kernel, with 32-bit & 64-bit application support
  - 64-bit kernel only on SPARC
    - 32-bit apps no problem
  - Solaris 10 64-bit on AMD64 and Intel
- Comprehensive 32-bit application compatibility

Why 64-bit for large memory?

- Extends the existing programming model to large memory
  - Beyond 4GB limit imposed by 32 bits
- Existing POSIX APIs extend to large data types (e.g. file offsets. file handle limits eliminated)
- Simple transition of existing source to 64-bits

Developer Perspective

- Virtually unlimited address space
  - Data objects, files, large hardware devices can be mapped into virtual address space
  - 64-bit data types, parameter passing
  - Caching can be implemented in application, yielding much higher performance
- Small Overhead
- 64-bit on AMD64
  - Native 64-bit integer arithmetic
  - 16 general purpose registers (instead of 8)
  - optimized function call interface – register based arg passing
  - other instruction set optimizations

Large Memory Configs
Configuring Solaris

- fsflush uses too much CPU on Solaris 8
  - Set “autoup” in /etc/system
  - Symptom is one CPU using 100%sys
- Corrective Action
  - Default is 30s, recommend setting larger
  - e.g. 10x nGB of memory

Large Dump Performance

- Configure “kernel only”
  - dumpadm(1m)
- Estimate dump as 20% of memory size
- Configure separate dump device
  - Reliable dumps
  - Asynchronous saves during boot (savecore)
- Configure a fast dump device
  - If possible, a HW RAID stripe dump device

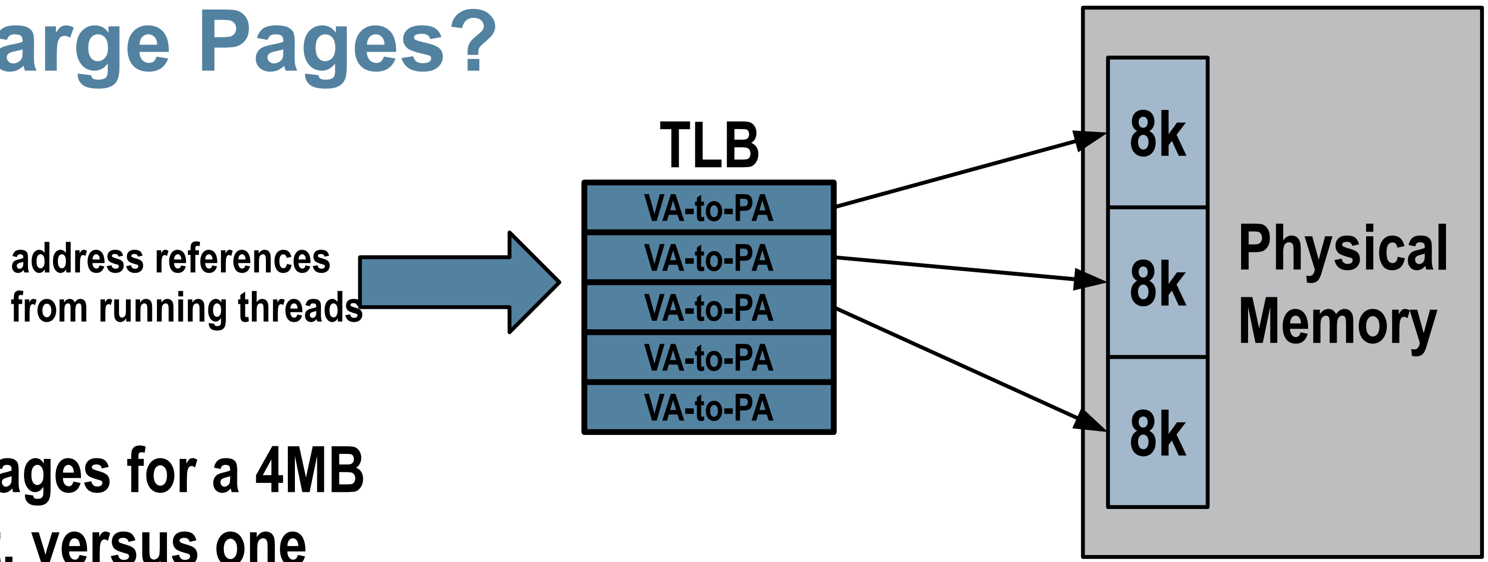
Databases

- Exploit memory to reduce/eliminate I/O!
- Eliminating I/O is the easiest way to tune it...
- Increase cache hit rates:
  - 95% means 1 out 20 accesses result in I/O
    - For every 1000 IOs, 50 are going to disk
  - 99% means 1 out of 100
    - For every 1000 IOs, 10 are going to disk
  - **That's a 5X (500%) reduction is physical disk IOs!**
- Use memory for caching
- Write-mostly I/O pattern results
  - Reads satistfied from cache

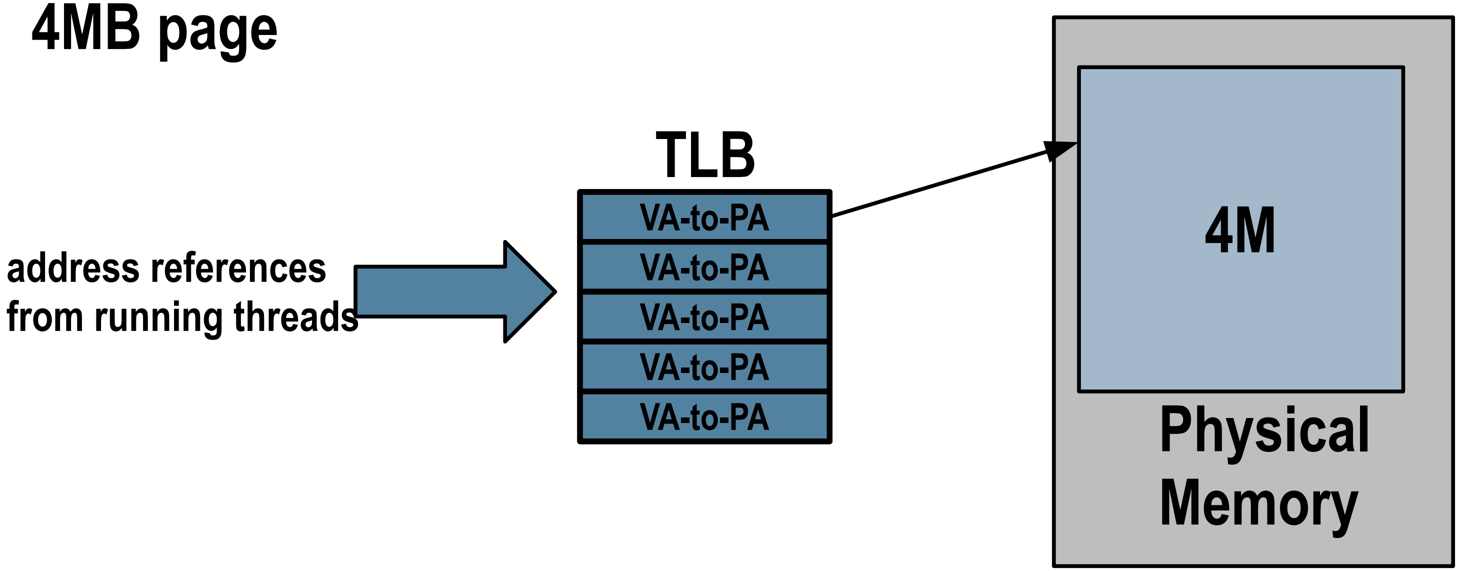
Multiple Pagesize Support (MPSS)
aka Large Pages

- Leverage hardware MMU support for multiple page sizes
- Supported page sizes will vary across different processors
  - pagesize(1)
- Functionality has been an ongoing effort, evolving over time
- Intended to improve performance through more efficient use of hardware TLB
- Be aware of cache effects of large pages (page coloring)
- For DR-capable systems, an interesting dynamic between kernel cage and large pages
  - cage-on: good for LP, may be not good for performance
  - cage-off: more memory fragmentation, not good for LP, but sometimes helps performance

Why Large Pages?



512 8k pages for a 4MB segment, versus one 4MB page



Large Pages – A Brief History

- Solaris 2.6 – Solaris 8
  - SPARC: 4MB pages for ISM
  - SPARC: 4MB pages for initial kernel text and data segments
- Solaris 9
  - SPARC: 8k, 64k, 512k, 4M for user process anon, heap and stack via ppgsz(1), memcntl(2), mpss.so
  - SPARC: 4M for ISM / DISM
- Solaris 10 1/05
  - SPARC: Same as above
  - AMD64: 4k, 2M pages - same constraints as Solaris 9 SPARC
- Solaris 10 1/06 (Update 1)
  - SPARC: Added MPSS for regular file mappings (VMPSS) – enabled by default, 8k & 4M for sun4u, 8k, 64, 4M for sun4v
  - SPARC: Added Large Pages Out-Of-The-Box (LPOOB) for user process anon, stack and heap
  - SPARC: KPR integrated
  - AMD64: 2M for text can be enabled via /etc/system

Large Pages – A Brief History (continued)

- Solaris 10 6/06 (Update 2)
  - SPARC: Large page support for kernel heap
  - SPARC: sun4v 8k, 64k, 512k, 4M, **32M, 256M**
- Solaris 10 11/06 (Update 3)
  - SPARCV9 (OPL): 8k, 64k, 512k, 4M, **32M, 256M**
- Solaris 10 8/07 (Update 4)
  - SPARC: MPSS Extended to MAP_SHARED anon mappings and non-ISM/DISM SysV Shared Segments. 8k and 4M defaults on all sun4u
  - SPARC: LPOOB changed to use smaller page sizes on N1
  - SPARC: Now have large page support for all types of user segments
  - AMD64: 4k, 2M
  - X64:

Do I need Large Pages?

- Is the application memory intensive?
- How large is the address space?
- How much time is being wasted in MMU traps?
  - MMU traps are not visible with %usr/%sys
  - MMU traps are counted in the current context
  - e.g. User-bound process reports as %usr

Trapstat Introduction

```
sol9# trapstat -t 1 111
cpu m| itlb-miss %tim itsb-miss %tim | dtlb-miss %tim dtsb-miss %tim |%tim
-----+-------------------------------+-------------------------------+----
  0 u|         1  0.0         0  0.0 |   2171237 45.7         0  0.0 |45.7
  0 k|         2  0.0         0  0.0 |      3751  0.1         7  0.0 | 0.1
=====+===============================+===============================+====
 ttl |         3  0.0         0  0.0 |   2192238 46.2         7  0.0 |46.2
```

- This application *might* run almost 2x faster!

Observing MMU traps

```
sol9# trapstat -T 1 111
cpu m size| itlb-miss %tim itsb-miss %tim | dtlb-miss %tim dtsb-miss %tim |%tim
----------+-------------------------------+-------------------------------+----
  0 u   8k|        30  0.0         0  0.0 |   2170236 46.1         0  0.0 |46.1
  0 u  64k|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
  0 u 512k|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
  0 u   4m|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
- - - - - + - - - - - - - - - - - - - - - + - - - - - - - - - - - - - - - + - -
  0 k   8k|         1  0.0         0  0.0 |      4174  0.1        10  0.0 | 0.1
  0 k  64k|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
  0 k 512k|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
  0 k   4m|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
==========+===============================+===============================+====
      ttl |        31  0.0         0  0.0 |   2174410 46.2        10  0.0 |46.2
 sol9# trapstat -t 1 111
 cpu m| itlb-miss %tim itsb-miss %tim | dtlb-miss %tim dtsb-miss %tim |%tim
 -----+-------------------------------+-------------------------------+----
   0 u|         1  0.0         0  0.0 |   2171237 45.7         0  0.0 |45.7
   0 k|         2  0.0         0  0.0 |      3751  0.1         7  0.0 | 0.1
 =====+===============================+===============================+====
  ttl |         3  0.0         0  0.0 |   2192238 46.2         7  0.0 |46.2
```

Setting Page Sizes

- Solution: ppgsize(1), or mpss.so.1
  - Sets page size preference
  - Doesn't persist across exec()
  - Beginning with Solaris 10 1/06, Large Pages Out Of the Box (LPOOB) is enabled, so you don't need to do this...
    - You really want to be at Solaris 10 Update 4...

```
sol9# ppgsz -o heap=4M ./testprog
sol9# LD_PRELOAD=$LD_PRELOAD:mpss.so.1
sol9# export LD_PRELOAD=$LD_PRELOAD:mpss.so.1
sol9# export MPSSHEAP=4M
sol9# ./testprog
MPSSHEAP=size
MPSSSTACK=size
MPSSHEAP and MPSSSTACK specify the preferred page
sizes for the heap and stack, respectively. The speci-
fied page size(s) are applied to all created
processes.
MPSSCFGFILE=config-file
config-file is a text file which contains one or more
mpss configuration entries of the form:
exec-name:heap-size:stack-size
```

Checking Allocated Page Sizes

```
Sol9# pmap -sx `pgrep testprog`
2953:   ./testprog
 Address  Kbytes     RSS    Anon  Locked Pgsz Mode   Mapped File
00010000       8       8       -       -   8K r-x--  dev:277,83 ino:114875
00020000       8       8       8       -   8K rwx--  dev:277,83 ino:114875
00022000    3960    3960    3960       -   8K rwx--    [ heap ]
00400000  131072  131072  131072       -   4M rwx--    [ heap ]
FF280000     120     120       -       -   8K r-x--  libc.so.1
FF340000       8       8       8       -   8K rwx--  libc.so.1
FF390000       8       8       -       -   8K r-x--  libc_psr.so.1
FF3A0000       8       8       -       -   8K r-x--  libdl.so.1
FF3B0000       8       8       8       -   8K rwx--    [ anon ]
FF3C0000     152     152       -       -   8K r-x--  ld.so.1
FF3F6000       8       8       8       -   8K rwx--  ld.so.1
FFBFA000      24      24      24       -   8K rwx--    [ stack ]
-------- ------- ------- ------- -------
total Kb  135968  135944  135112       -
```

TLB traps eliminated

```
sol9# trapstat -T 1 111
cpu m size| itlb-miss %tim itsb-miss %tim | dtlb-miss %tim dtsb-miss %tim |%tim
----------+-------------------------------+-------------------------------+----
  0 u   8k|        30  0.0         0  0.0 |        36  0.1         0  0.0 | 0.1
  0 u  64k|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
  0 u 512k|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
  0 u   4m|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
- - - - - + - - - - - - - - - - - - - - - + - - - - - - - - - - - - - - - + - -
  0 k   8k|         1  0.0         0  0.0 |      4174  0.1        10  0.0 | 0.1
  0 k  64k|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
  0 k 512k|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
  0 k   4m|         0  0.0         0  0.0 |         0  0.0         0  0.0 | 0.0
==========+===============================+===============================+====
      ttl |        31  0.0         0  0.0 |      4200  0.2        10  0.0 | 0.2
```

Address Spaces: A Deeper Dive

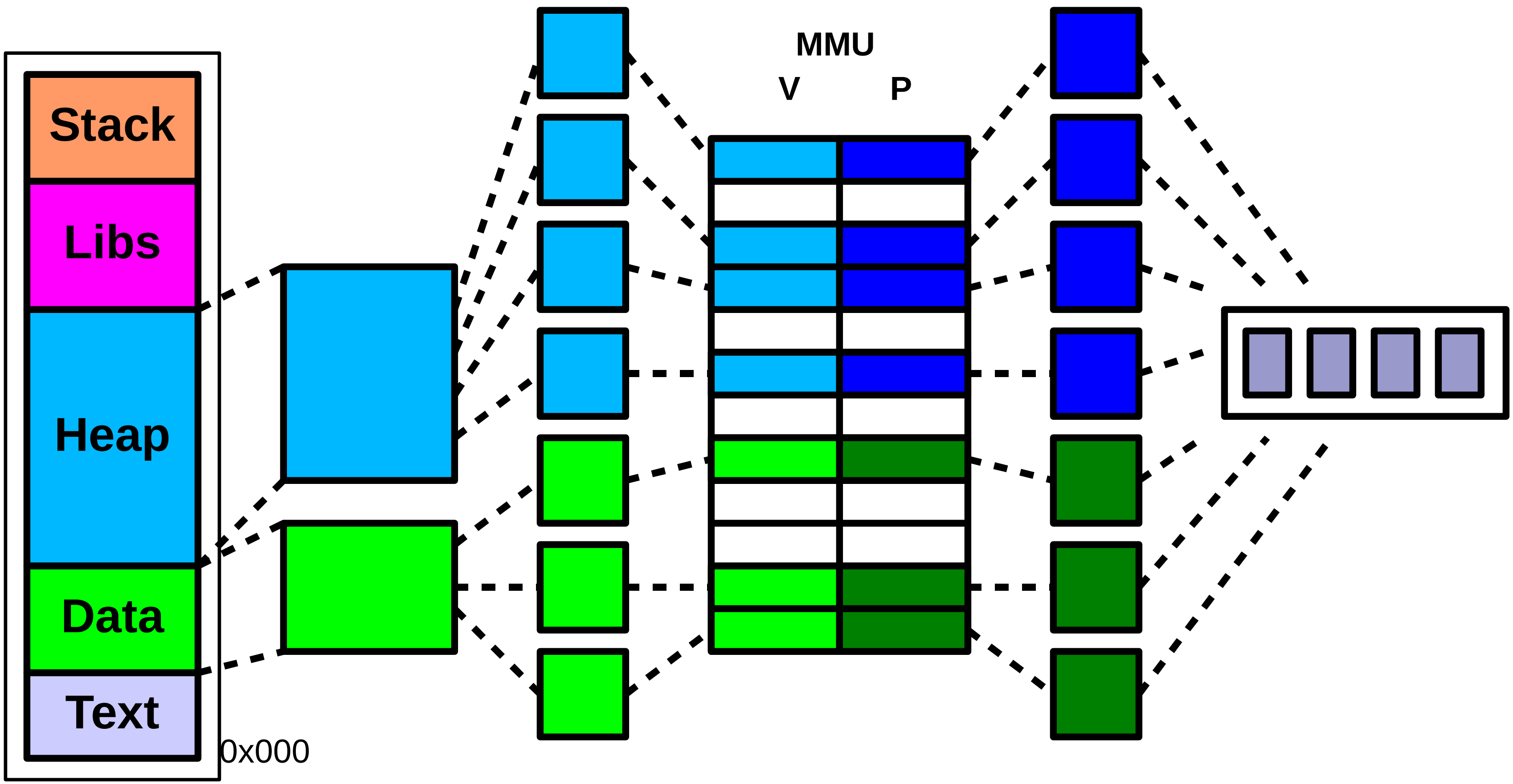
Example Program

```
#include <sys/types.h>
const char * const_str = "My const string";
char * global_str = "My global string";
int    global_int = 42;
int
main(int argc, char * argv[])
{
        int local_int = 123;
        char * s;
        int i;
        char command[1024];


        global_int = 5;
        s = (char *)malloc(14000);
        s[0] = 'a';
        s[100] = 'b';
        s[8192] = 'c';

}
```

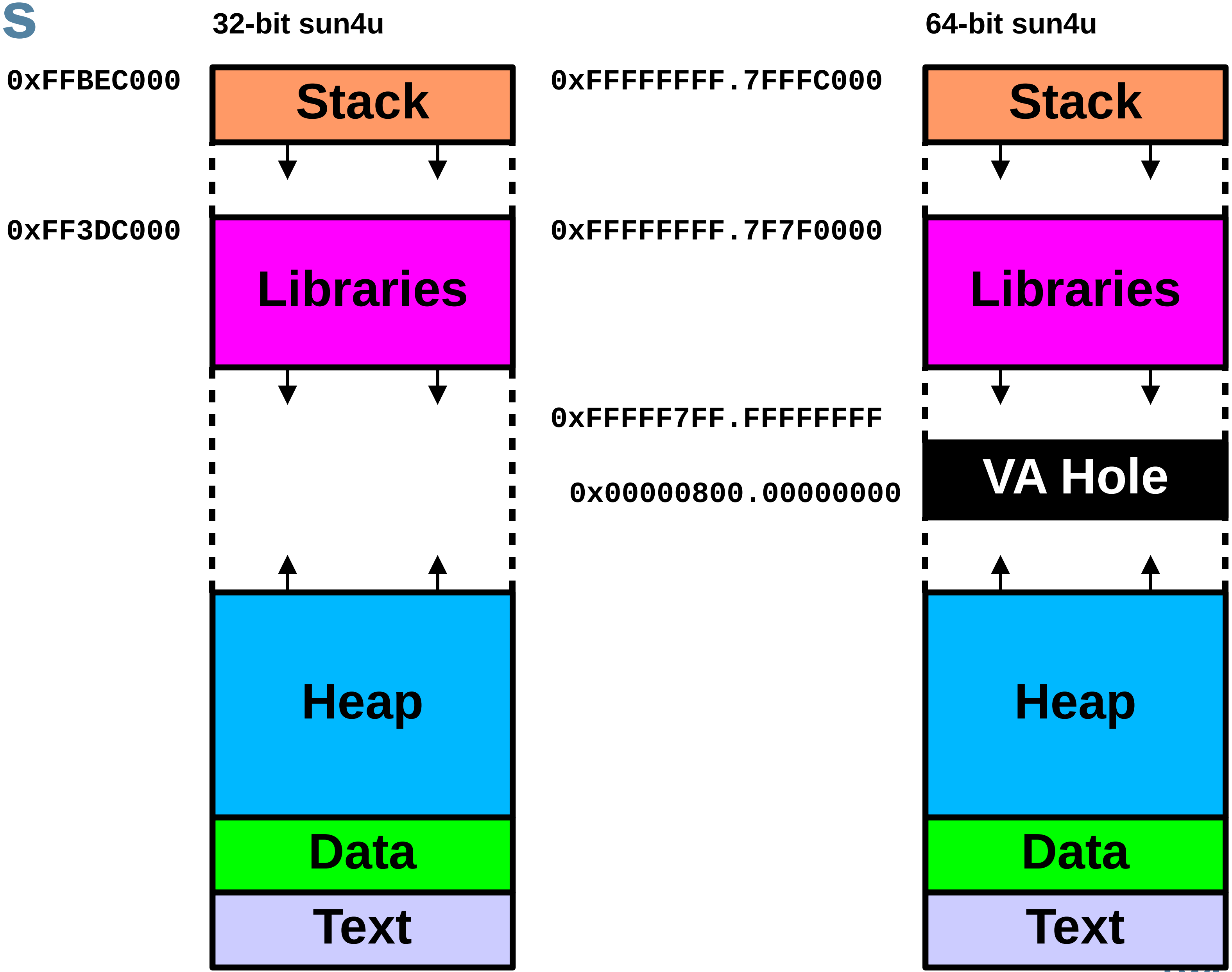
Virtual to Physical

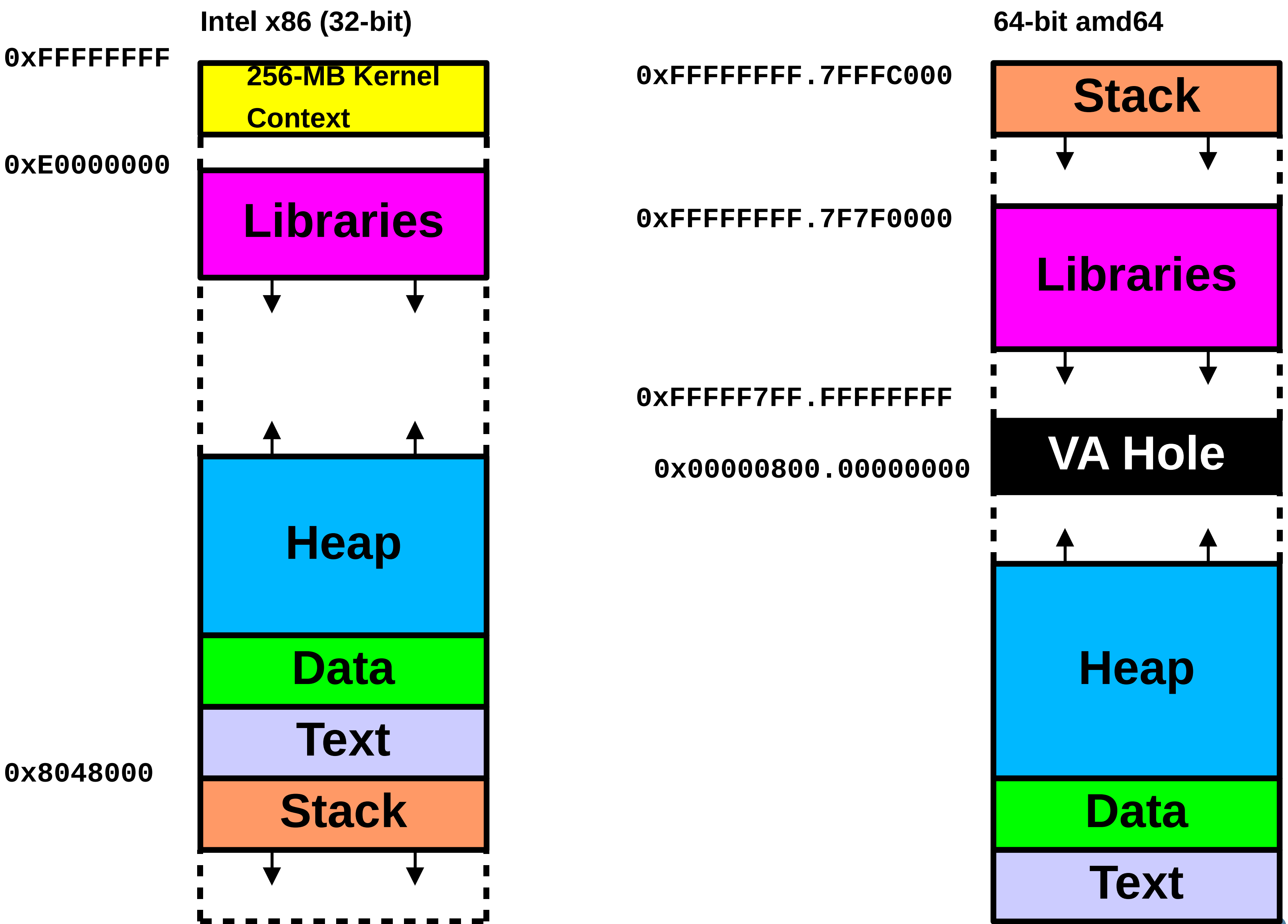


Address Space

- Process Address Space
  - Process Text and Data
  - Stack (anon memory) and Libraries
  - Heap (anon memory)
- Kernel Address Space
  - Kernel Text and Data
  - Kernel Map Space (data structs, caches)
  - 32-bit Kernel map (64-bit Kernels only)
  - Trap table
  - Critical virtual memory data structures
  - Mapping File System Cache
    - ARC for ZFS mapped to kernel heap

Address Space




Intel x86 (32-bit)
0xFFFFFFFF
256-MB Kernel Context
0xE0000000
Libraries
Heap
Data
Text
0x8048000
Stack
64-bit amd64
0xFFFFFFFF.7FFFC000
Stack
0xFFFFFFFF.7F7F0000
Libraries
0xFFFFF7FF.FFFFFFFF
VA Hole
0x00000800.00000000
Heap
Data
Text

pmap -x

```
Sol8# /usr/proc/bin/pmap -x $$
18084:   csh
 Address   Kbytes Resident Shared Private Permissions       Mapped File
00010000      144      144    136       8 read/exec         csh
00044000       16       16      -      16 read/write/exec   csh
00048000      120      104      -     104 read/write/exec     [ heap ]
FF200000      672      624    600      24 read/exec         libc.so.1
FF2B8000       24       24      -      24 read/write/exec   libc.so.1
FF2BE000        8        8      -       8 read/write/exec   libc.so.1
FF300000       16       16      8       8 read/exec         libc_psr.so.1
FF320000        8        8      -       8 read/exec
libmapmalloc.so.1
FF332000        8        8      -       8 read/write/exec
libmapmalloc.so.1
FF340000        8        8      -       8 read/write/exec     [ anon ]
FF350000      168      112     88      24 read/exec         libcurses.so.1
FF38A000       32       32      -      32 read/write/exec   libcurses.so.1
FF392000        8        8      -       8 read/write/exec   libcurses.so.1
FF3A0000        8        8      -       8 read/exec         libdl.so.1
FF3B0000      136      136    128       8 read/exec         ld.so.1
FF3E2000        8        8      -       8 read/write/exec   ld.so.1
FFBE6000       40       40      -      40 read/write/exec     [ stack ]
--------  ------  ------  ------  ------
total Kb     1424     1304    960     344
```

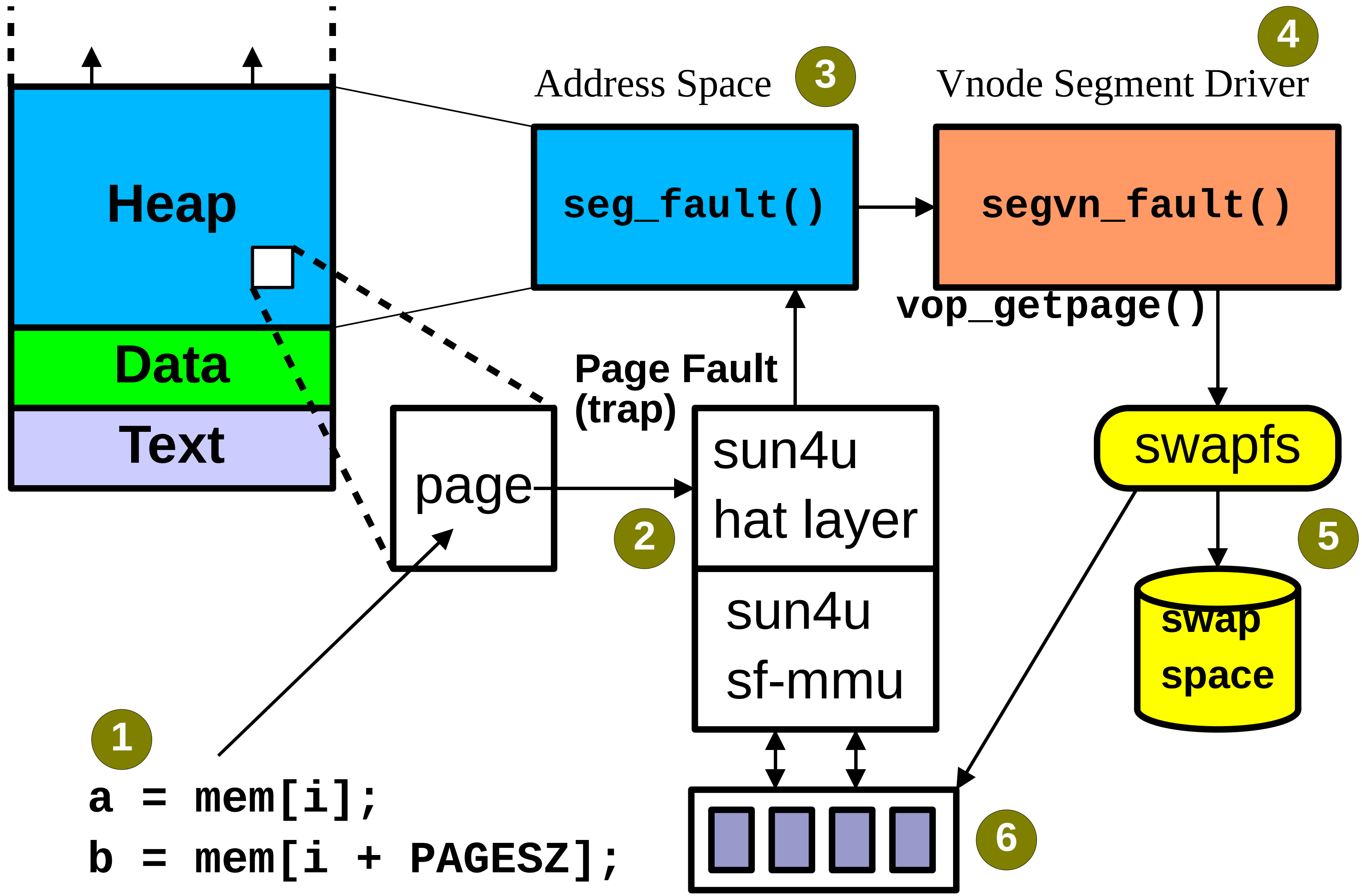
Address Space Management

- Duplication; **`fork() -> as_dup()`**
- Destruction; **`exit()`**
- Creation of new segments
- Removal of segments
- Page protection (read, write, executable)
- Page Fault routing
- Page Locking
- Watchpoints

Page Faults

- MMU-generated exception:
- Major Page Fault:
  - Failed access to VM location, in a segment
  - Page does not exist in physical memory
  - New page is created or copied from swap
  - If addr not in a valid segment (SIG-SEGV)
- Minor Page Fault:
  - Failed access to VM location, in a segment
  - Page is in memory, but no MMU translation
- Page Protection Fault:
  - An access that violates segment protection

Page Fault Example:




```
a = mem[i];
b = mem[i + PAGESZ];
```

vmstat -p

swap = free and unreserved swap in KBytes

free = free memory measured in pages

re = kilobytes reclaimed from cache/free list

mf = minor faults - the page was in memory but was not mapped

fr = kilobytes that have been destroyed or freed

de = kilobytes freed after writes

sr = kilobytes scanned / second

executable pages: kilobytes in - out - freed

anonymous pages: kilobytes in - out – freed

f le system pages:

kilobytes in - out - freed

```
# vmstat -p 5 5
```

memory		page					executable			anonymous			filesystem		
swap	free	re	mf	fr	de	sr	epi	epo	epf	api	apo	apf	fpi	fpo	fpf
46715224	891296	24	350	0	0	0	0	0	0	4	0	0	27	0	0
46304792	897312	151	761	25	0	0	17	0	0	1	0	0	280	25	25
45886168	899808	118	339	1	0	0	3	0	0	1	0	0	641	1	1
46723376	899440	29	197	0	0	0	0	0	0	40	0	0	60	0	0

Examining paging with dtrace VM Provider

- The dtrace VM provider provides a probe for each VM statistic
- We can observe all VM statistics via kstat:

```
$ kstat -n vm
module: cpu                                 instance: 0
name:   vm                                  class:    misc
        anonfree                            0
        anonpgin                            0
        anonpgout                           0
        as_fault                            3180528
        cow_fault                           37280
        crtime                              463.343064
        dfree                               0
        execfree                            0
        execpgin                            442
        execpgout                           0
        fsfree                              0
        fspgin                              2103
        fspgout                             0
        hat_fault                           0
        kernel_asflt                        0
        maj_fault                           912
```

Examining paging with dtrace

- Suppose one were to see the following output from vmstat(1M):

```
kthr memory page disk faults cpu
r b w swap    free    re    mf    pi  po fr de sr   cd s0s1 s2  in    sy    cs us sy id
0 1 0 1341844 836720 26   311 1644  0  0  0  0 216 0   0   0 797   817   697 9  10 81
0 1 0 1341344 835300 238 934 1576  0  0  0  0 194 0   0   0 750 2795   791 7  14 79
0 1 0 1340764 833668 24   165 1149  0  0  0  0 133 0   0   0 637   813   547 5  4  91
0 1 0 1340420 833024 24   394 1002  0  0  0  0 130 0   0   0 621 2284   653 14 7  79
0 1 0 1340068 831520 14   202   380  0  0  0  0  59 0   0   0 482 5688 1434 25 7  68
```

- The pi column in the above output denotes the number of pages paged in. The vminfo provider makes it easy to learn more about the source of these page-ins:

```
dtrace -n pgin {@[execname] = count()}
dtrace: description ÕpginÕ matched 1 probe
^C
xterm 1
ksh 1
ls 2
lpstat 7
sh 17
soffice 39
javaldx 103
soffice.bin 3065
```

Examining paging with dtrace

- From the above, we can see that a process associated with the StarOffice Office Suite, soffice.bin, is reponsible for most of the page-ins.
- To get a better picture of soffice.bin in terms of VM behavior, we may wish to enable all vminfo probes.
- In the following example, we run dtrace(1M) while launching StarOffice:

```
dtrace -P vminfo/execname == "soffice.bin"/{@[probename] = count()}
dtrace: description vminfo matched 42 probes
^C
pgout 16
anonfree 16
anonpgout 16
pgpgout 16
dfree 16
execpgin 80
prot_fault 85
maj_fault 88
pgin 90
pgpgin 90
cow_fault 859
zfod 1619
pgfrec 8811
pgrec 8827
as_fault 9495
```

Examining paging with dtrace

- To further drill down on some of the VM behavior of StarOffice during startup, we could write the following D script:

```
vminfo:::maj_fault, vminfo:::zfod, vminfo:::as_fault
/execname == "soffice.bin" && start == 0/
{
  /*
   * This is the first time that a vminfo probe has been hit; record
   * our initial timestamp.
   */
  start = timestamp;
}
vminfo:::maj_fault, vminfo:::zfod,vminfo:::as_fault
/execname == "soffice.bin"/
{
  /*
   * Aggregate on the probename, and lquantize() the number of seconds
   * since our initial timestamp. (There are 1,000,000,000 nanoseconds
   * in a second.) We assume that the script will be terminated before
   * 60 seconds elapses.
   */
  @[probename] = lquantize((timestamp - start) / 1000000000, 0, 60);
}
```

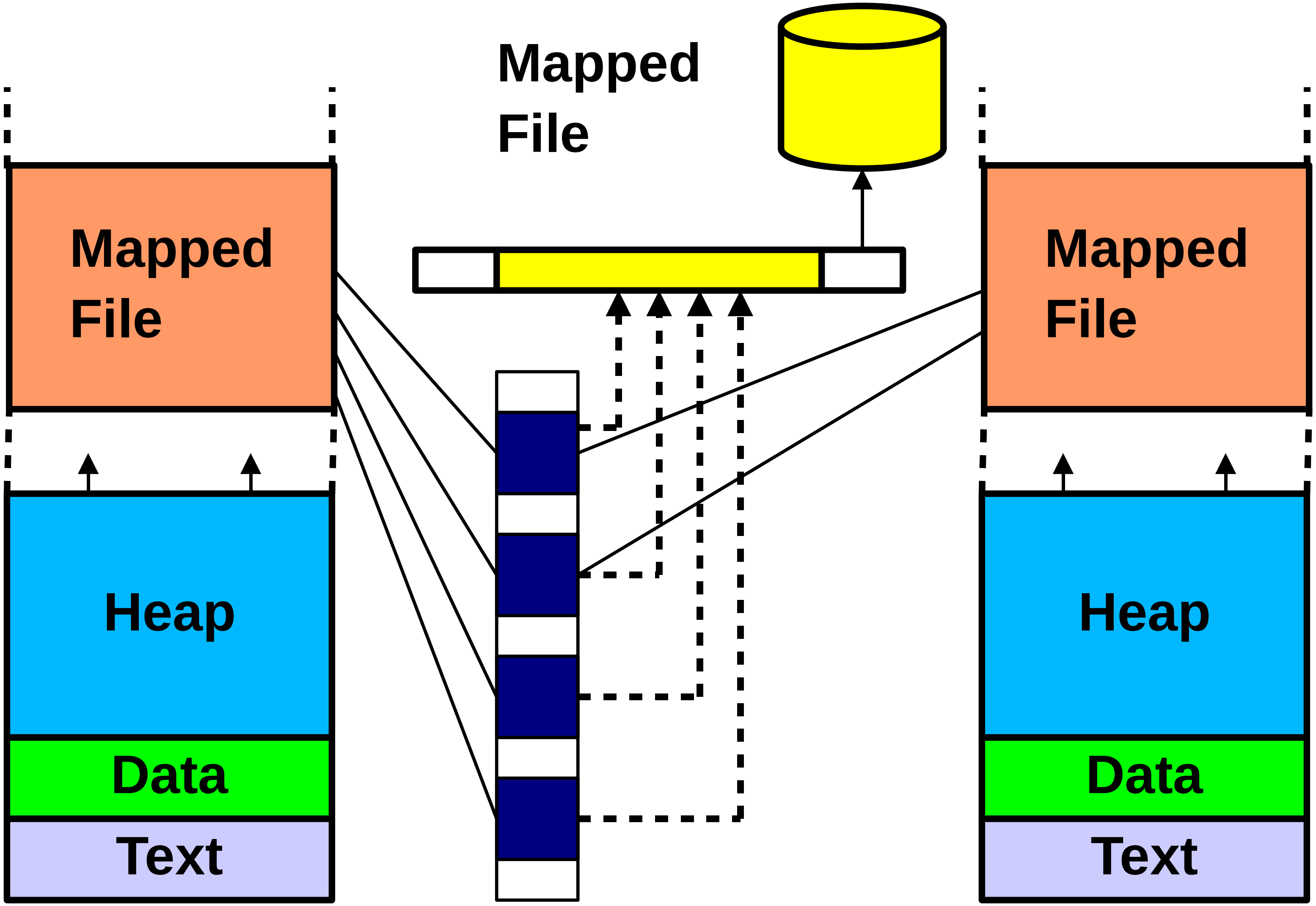
Examining paging with dtrace

```
# dtrace -s ./soffice.d
dtrace: script Õ./soffice.dÕ matched 10 probes
^C
maj_fault
value ------------- Distribution ------------- count
7    |                                         0
8    | @@@@@@@@@                               88
9    | @@@@@@@@@@@@@@@@@@@@                    194
10   | @                                       18
11   |                                         0
12   |                                         0
13   |                                         2
14   |                                         0
15   |                                         1
16   | @@@@@@@@                                82
17   |                                         0
18   |                                         0
19   |                                         2
20   |                                         0
```

Examining paging with dtrace

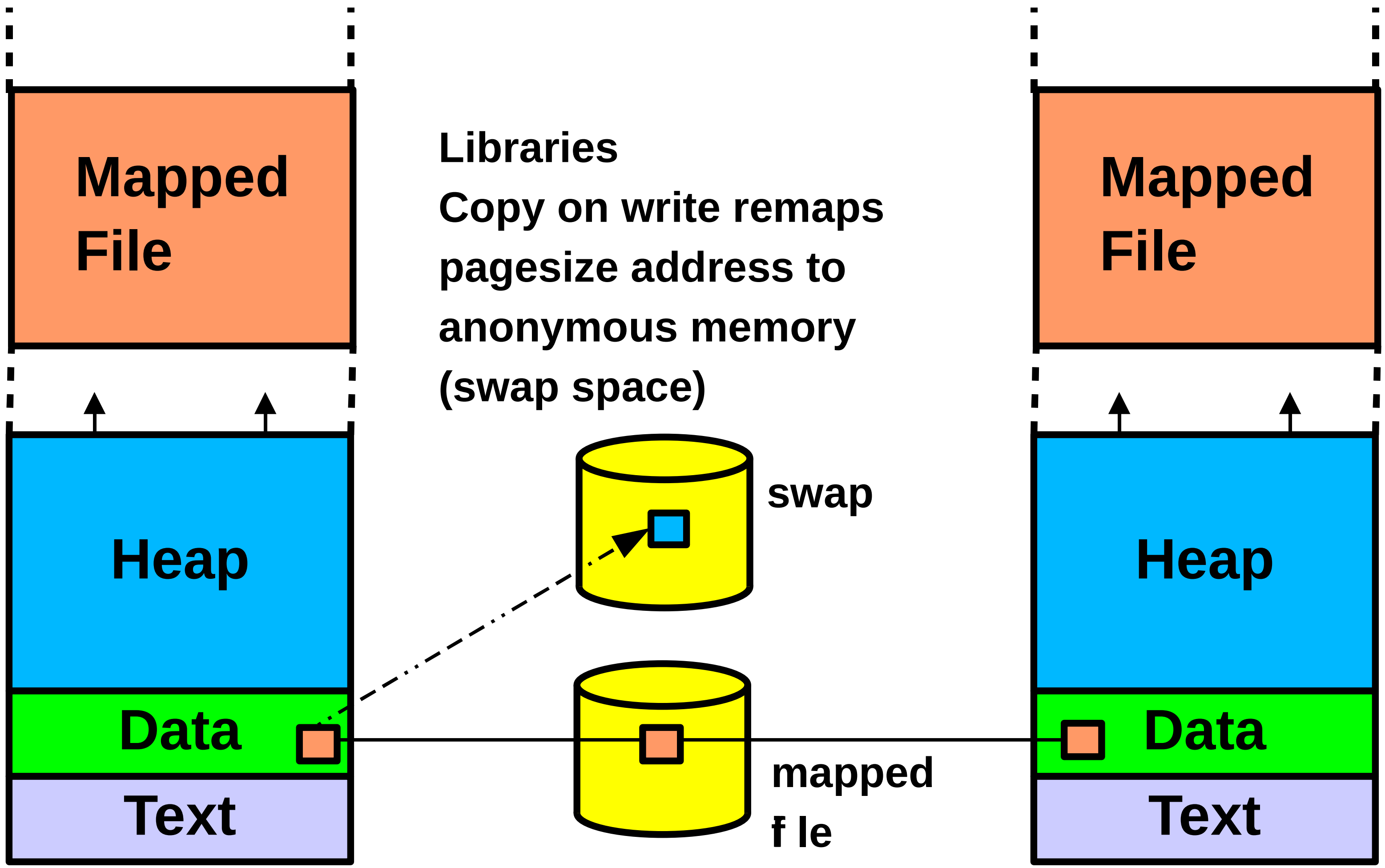
```
Zfod
value ------------- Distribution ------------- count
< 0 |                                           0
0    |@@@@@@@                                   525
1    |@@@@@@@@                                  605
2    |@@                                        208
3    |@@@                                       280
4    |                                          4
5    |                                          0
6    |                                          0
7    |                                          0
8    |                                          44
9    |@@                                        161
10   |                                          2
11   |                                          0
12   |                                          0
13   |                                          4
14   |                                          0
15   |                                          29
16   |@@@@@@@@@@@@@@                            1048
17   |                                          24
18   |                                          0
19   |                                          0
20   |                                          1
21   |                                          0
22   |                                          3
23   |                                          0
```

Shared Mapped File



Copy-on-write

Libraries
Copy on write remaps pagesize address to anonymous memory (swap space)



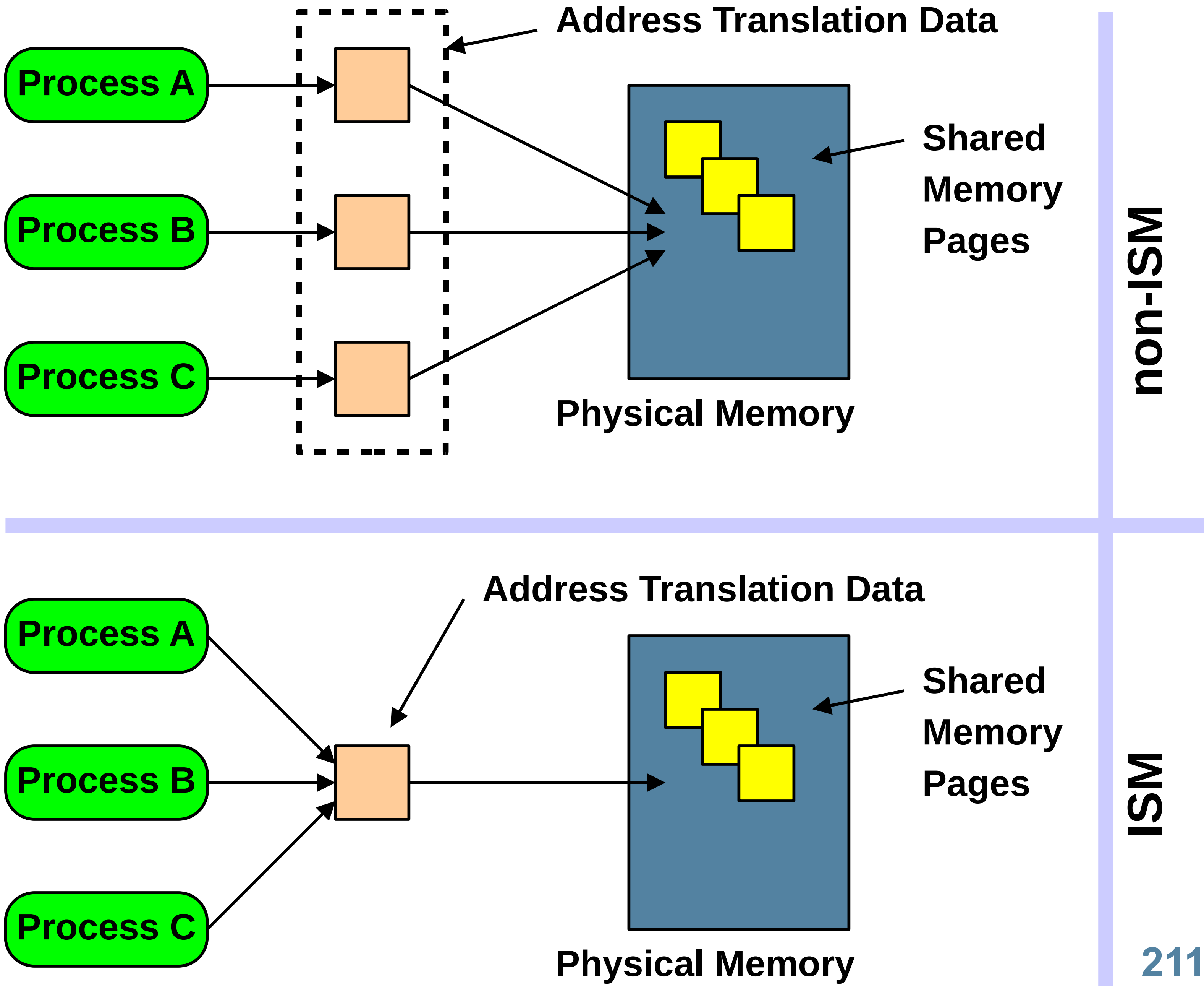
Anonymous Memory

- Pages not "directly" backed by a vnode
- Heap, Stack and Copy-On-Write pages
- Pages are reserved when "requested"
- Pages allocated when "touched"
- Anon layer:
  - creates slot array for pages
  - Slots point to Anon structs
- Swapfs layer:
  - Pseudo file system for anon layer
  - Provides the backing store

Intimate Shared Memory

- System V shared memory (ipc) option
- Shared Memory optimization:
  - Additionally share low-level kernel data
  - Reduce redundant mapping info (V-to-P)
- Shared Memory is locked, never paged
  - No swap space is allocated
- Use **`SHM_SHARE_MMU`** flag in **`shmat()`**

ISM


Process A
Process B
Process C
Address Translation Data
Shared
Memory
Pages
Physical Memory
non-ISM
Process A
Process B
Process C
Address Translation Data
Shared
Memory
Pages
Physical Memory
ISM

Session 3 Processes, Threads, Scheduling Classes & The Dispatcher

Process/Threads Glossary

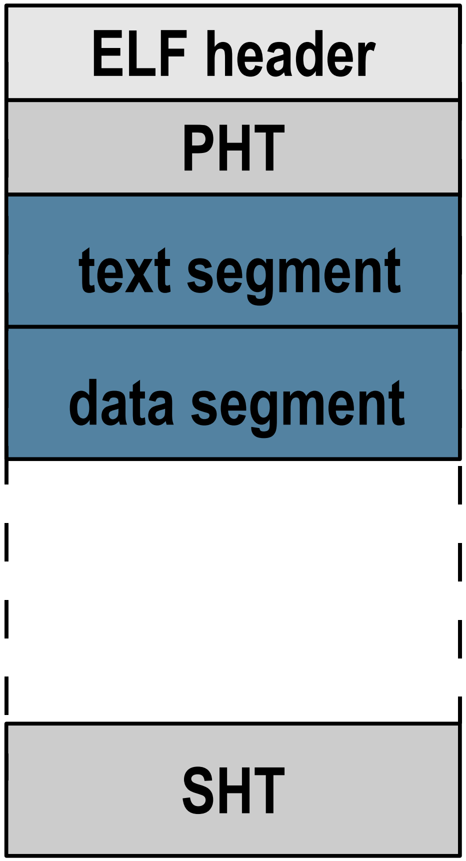
Process	The executable form of a program. An Operating System abstraction that encapulates the execution context of a program
Thread	An executable entity
User Thread	A thread within the address space of a process
Kernel Thread	A thread in the address space of the kernel
Lightweight Process	LWP – An execution context for a kernel thread
Dispatcher	The kernel subsystem that manages queues of runnable kernel threads
Scheduling Class	Kernel classes that define the scheduling parameters (e.g. priorities) and algorithms used to multiplex threads onto processors
Dispatch Queues	Per-processor sets of queues of runnable threads (run queues)
Sleep Queues	Queues of sleeping threads
Turnstiles	A special implementation of sleep queues that provide priority inheritance.

Executable Files

- Processes originate as executable programs that are exec'd
- Executable & Linking Format (ELF)
  - Standard executable binary file Application Binary Interface (ABI) format
  - Two standards components
    - Platform independent
    - Platform dependent (SPARC, x86)
  - Defines both the on-disk image format, and the in-memory image
  - ELF files components defined by
    - ELF header
    - Program Header Table (PHT)
    - Section Header Table (SHT)

Executable & Linking Format (ELF)

- ELF header
  - Roadmap to the file
- PHT
  - Array of Elf_Phdr structures, each defines a segment for the loader (exec)
- SHT
  - Array of Elf_Shdr structures, each defines a section for the linker (ld)



ELF Files

- ELF on-disk object created by the link-editor at the tail-end of the compilation process (although we still call it an a.out by default...)
- ELF objects can be statically linked or dynamically linked
  - Compiler "-B static" flag, default is dynamic
  - Statically linked objects have all references resolved and bound in the binary (libc.a)
  - Dynamically linked objects rely on the run-time linker, ld.so.1, to resolve references to shared objects at run time (libc.so.1)
  - Static linking is discouraged, and not possible for 64-bit binaries

Examing ELF Files

- Use `elfdump(1)` to decompose ELF files

```
borntorun> elfdump -e /bin/ls

ELF Header
  ei_magic:   { 0x7f, E, L, F }
  ei_class:   ELFCLASS32          ei_data:       ELFDATA2MSB
  e_machine:  EM_SPARC            e_version:     EV_CURRENT
  e_type:     ET_EXEC
  e_flags:                     0
  e_entry:               0x10f00  e_ehsize:      52  e_shstrndx:    26
  e_shoff:                0x4654  e_shentsize:   40  e_shnum:       27
  e_phoff:                  0x34  e_phentsize:   32  e_phnum:        6
borntorun>
```

Examining ELF Files

- `elfdump` -c dumps section headers

```
borntorun> elfdump -c /bin/ls
Section Header[11]:  sh_name: .text
    sh_addr:      0x10f00          sh_flags:   [ SHF_ALLOC  SHF_EXECINSTR ]
    sh_size:      0x2ec4           sh_type:    [ SHT_PROGBITS ]
    sh_offset:    0xf00            sh_entsize: 0
    sh_link:      0                sh_info:    0
    sh_addralign: 0x8

Section Header[17]:  sh_name: .got
    sh_addr:      0x24000          sh_flags:   [ SHF_WRITE  SHF_ALLOC ]
    sh_size:      0x4              sh_type:    [ SHT_PROGBITS ]
    sh_offset:    0x4000           sh_entsize: 0x4
    sh_link:      0                sh_info:    0
    sh_addralign: 0x2000

Section Header[18]:  sh_name: .plt
    sh_addr:      0x24004          sh_flags:   [ SHF_WRITE  SHF_ALLOC  SHF_EXECINSTR ]
    sh_size:      0x28c            sh_type:    [ SHT_PROGBITS ]
    sh_offset:    0x4004           sh_entsize: 0xc
    sh_link:      0                sh_info:    0
    sh_addralign: 0x4

Section Header[22]:  sh_name: .data
    sh_addr:      0x24380          sh_flags:   [ SHF_WRITE  SHF_ALLOC ]
    sh_size:      0x154            sh_type:    [ SHT_PROGBITS ]
    sh_offset:    0x4380           sh_entsize: 0
    sh_link:      0                sh_info:    0
    sh_addralign: 0x8
```

Examing ELF Linker Dependencies

- Use `ldd(1)` to invoke the runtime linker (ld.so) on a binary file, and `pldd(1)` on a running process

```
borntorun> ldd netstat
     libdhcpagent.so.1 =>   /usr/lib/libdhcpagent.so.1
     libcmd.so.1 =>     /usr/lib/libcmd.so.1
     libsocket.so.1 => /usr/lib/libsocket.so.1
     libnsl.so.1 =>     /usr/lib/libnsl.so.1
     libkstat.so.1 =>  /usr/lib/libkstat.so.1
     libc.so.1 =>  /usr/lib/libc.so.1
     libdl.so.1 =>      /usr/lib/libdl.so.1
     libmp.so.2 =>      /usr/lib/libmp.so.2
     /usr/platform/SUNW,Ultra-60/lib/libc_psr.so.1
```

```
borntorun> pldd $$
495: ksh
/usr/lib/libsocket.so.1
/usr/lib/libnsl.so.1
/usr/lib/libc.so.1
/usr/lib/libdl.so.1
/usr/lib/libmp.so.2
/usr/platform/sun4u/lib/libc_psr.so.1
/usr/lib/locale/en_US.ISO8859-1/en_US.ISO8859-1.so.2
borntorun>
```

Runtime Linker Debug

```
solaris> LD_DEBUG=help date
00000:
...
00000: args       display input argument processing (ld only)
00000: audit      display runtime link-audit processing (ld.so.1 only)
00000: basic      provide basic trace information/warnings
00000: bindings   display symbol binding; detail flag shows absolute:relative
00000:              addresses (ld.so.1 only)
00000: cap        display hardware/software capability processing
00000: detail     provide more information in conjunction with other options
00000: demangle   display C++ symbol names in their demangled form
00000: entry      display entrance criteria descriptors (ld only)
00000: files      display input file processing (files and libraries)
00000: got        display GOT symbol information (ld only)
00000: help       display this help message
00000: libs       display library search paths; detail flag shows actual
00000:              library lookup (-l) processing
00000: long       display long object names without truncation
00000: map        display map file processing (ld only)
00000: move       display move section processing
00000: reloc      display relocation processing
00000: sections   display input section processing (ld only)
00000: segments   display available output segments and address/offset
00000:              processing; detail flag shows associated sections (ld only)
00000: statistics display processing statistics (ld only)
00000: strtab     display information about string table compression; detail
00000:              shows layout of string tables (ld only)
. . . .
```

Runtime Linker Debug - Libs

```
solaris> LD_DEBUG=libs /opt/filebench/bin/filebench
13686:
13686: hardware capabilities - 0x2b  [ VIS  V8PLUS  DIV32  MUL32 ]
...
13686: find object=libc.so.1; searching
13686:  search path=/lib  (default)
13686:  search path=/usr/lib  (default)
13686:  trying path=/lib/libc.so.1
13686: 1: calling .init (from sorted order): /lib/libc.so.1
13686: 1: calling .init (done): /lib/libc.so.1
13686: 1: transferring control: /opt/filebench/bin/filebench
13686: 1:  trying path=/platform/SUNW,Ultra-Enterprise/lib/libc_psr.so.1
...
13686: find object=libm.so.2; searching
13686:  search path=/usr/lib/lwp/sparcv9  (RPATH from file /opt/filebench/bin/sparcv9/
filebench)
13686:  trying path=/usr/lib/lwp/sparcv9/libm.so.2
13686:  search path=/lib/64  (default)
13686:  search path=/usr/lib/64  (default)
13686:  trying path=/lib/64/libm.so.2
13686:
13686: find object=libl.so.1; searching
13686:  search path=/usr/lib/lwp/sparcv9  (RPATH from file /opt/filebench/bin/sparcv9/
filebench)
13686:  trying path=/usr/lib/lwp/sparcv9/libl.so.1
13686:  search path=/lib/64  (default)
13686:  search path=/usr/lib/64  (default)
13686:  trying path=/lib/64/libl.so.1
13686:  trying path=/usr/lib/64/libl.so.1
```

Runtime Linker Debug - Bindings

```
solaris> LD_DEBUG=bindings /opt/filebench/bin/filebench
15151:
15151: hardware capabilities - 0x2b  [ VIS  V8PLUS  DIV32  MUL32 ]
15151: configuration file=/var/ld/ld.config: unable to process file
15151: binding file=/opt/filebench/bin/filebench to 0x0 (undefined weak): symbol
`__1cG__CrunMdo_exit_code6F_v_'
15151: binding file=/opt/filebench/bin/filebench to file=/lib/libc.so.1: symbol `__iob'
15151: binding file=/lib/libc.so.1 to 0x0 (undefined weak): symbol `__tnf_probe_notify'
15151: binding file=/lib/libc.so.1 to file=/opt/filebench/bin/filebench: symbol `_end'
15151: binding file=/lib/libc.so.1 to 0x0 (undefined weak): symbol `_ex_unwind'
15151: binding file=/lib/libc.so.1 to file=/lib/libc.so.1: symbol `__fnmatch_C'
15151: binding file=/lib/libc.so.1 to file=/lib/libc.so.1: symbol `__getdate_std'
...
15151: binding file=/opt/filebench/bin/sparcv9/filebench to file=/lib/64/libc.so.1: symbol
`__iob'
15151: binding file=/opt/filebench/bin/sparcv9/filebench to file=/lib/64/libc.so.1: symbol
`optarg'
15151: binding file=/lib/64/libm.so.2 to file=/opt/filebench/bin/sparcv9/filebench: symbol
`free'
15151: binding file=/lib/64/libm.so.2 to file=/lib/64/libm.so.2: symbol `__signgamf'
15151: binding file=/lib/64/libm.so.2 to file=/lib/64/libm.so.2: symbol `__signgaml'
15151: binding file=/lib/64/libm.so.2 to file=/lib/64/libm.so.2: symbol `__xpg6'
...
15151: 1: binding file=/lib/64/libc.so.1 to file=/lib/64/libc.so.1: symbol `_sigemptyset'
15151: 1: binding file=/lib/64/libc.so.1 to file=/lib/64/libc.so.1: symbol `_sigaction'
```

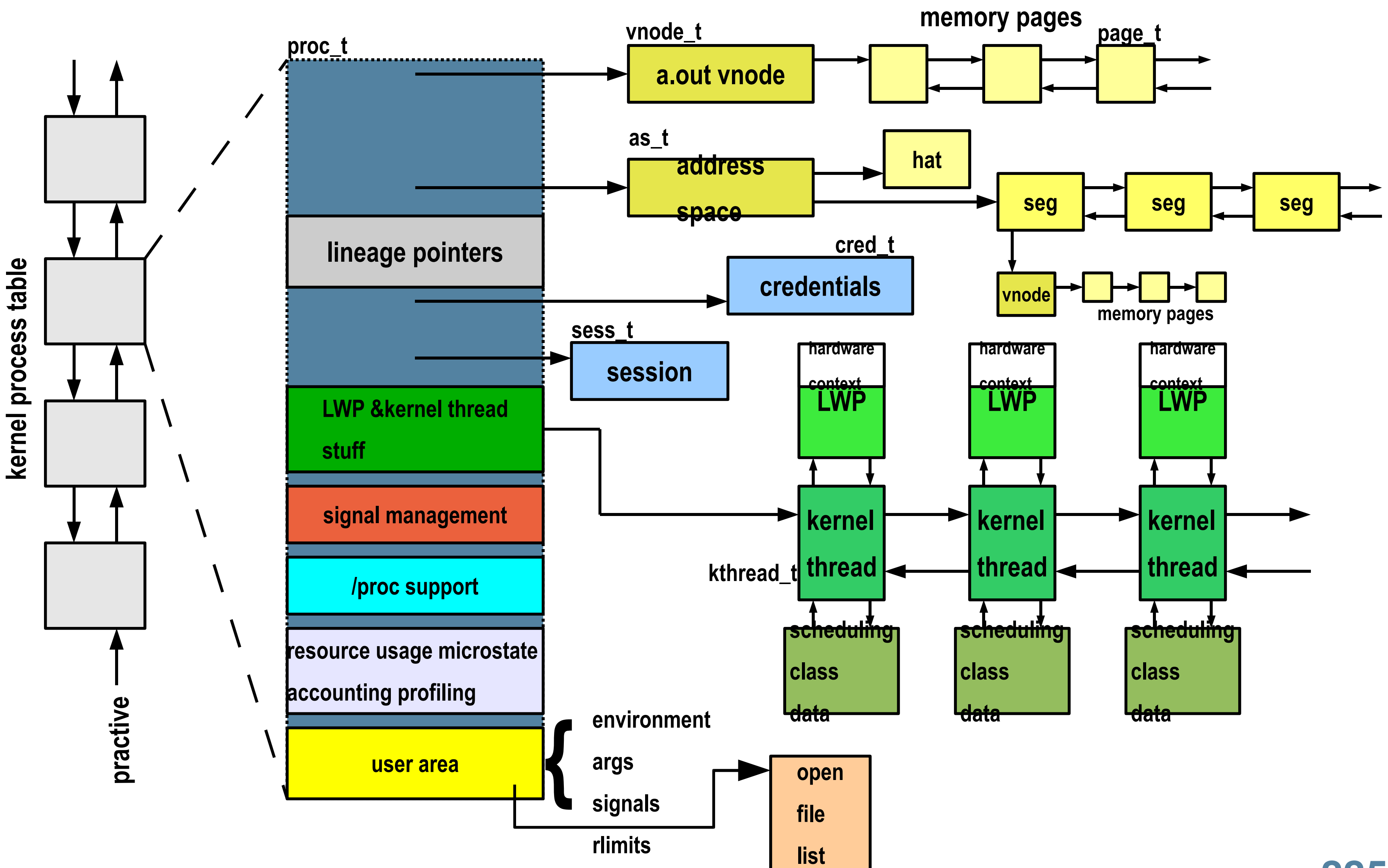
Runtime Linker – Debug

- Explore the options in **The Linker and Libraries Guide**

Solaris Process Model

- Solaris implements a multithreaded process model
  - Kernel threads are scheduled/executed
  - LWPs allow for each thread to execute system calls
  - Every kernel thread has an associated LWP
  - A non-threaded process has 1 kernel thread/LWP
  - A threaded process will have multiple kernel threads
  - All the threads in a process share all of the process context
    - Address space
    - Open files
    - Credentials
    - Signal dispositions
  - Each thread has its own stack

Solaris Process



Process Structure

```
# mdb -k
Loading modules: [ unix krtld genunix specfs dtrace ufs ip sctp usba fctl nca lofs nfs random
sppp crypto ptm logindmux cpc ]
> ::ps
S    PID   PPID   PGID    SID    UID      FLAGS             ADDR NAME
R      0      0      0      0      0 0x00000001 fffffffffbc1ce80 sched
R      3      0      0      0      0 0x00020001 ffffffff880838f8 fsflush
R      2      0      0      0      0 0x00020001 ffffffff88084520 pageout
R      1      0      0      0      0 0x42004000 ffffffff88085148 init
R  21344      1  21343  21280   2234 0x42004000 ffffffff95549938 tcpPerfServer
...
> ffffffff95549938::print proc_t
{
    p_exec = 0xffffffff9285dc40
    p_as = 0xffffffff87c776c8
    p_cred = 0xffffffff8fdeb448
    p_lwpcnt = 0x6
    p_zombcnt = 0
    p_tlist = 0xffffffff8826bc20
        .....
        u_ticks = 0x16c6f425
        u_comm = [ "tcpPerfServer" ]
        u_psargs = [ "/export/home/morgan/work/solaris_studio9/bin/tcpPerfServer 9551 9552" ]
        u_argc = 0x3
        u_argv = 0x8047380
        u_envp = 0x8047390
        u_cdir = 0xffffffff8bf3d7c0
        u_saved_rlimit = [
            {
                rlim_cur = 0xfffffffffffffffd
                rlim_max = 0xfffffffffffffffd
            }
        ......
            fi_nfiles = 0x3f
            fi_list = 0xffffffff8dc44000
            fi_rlist = 0
        }
    p_model = 0x100000
    p_rctls = 0xffffffffa7cbb4c8
    p_dtrace_probes = 0
    p_dtrace_count = 0
    p_dtrace_helpers = 0
    p_zone = zone0
```

Kernel Process Table

- Linked list of all processes (proc structures)
- kmem_cache allocator dynamically allocates space needed for new proc structures
  - Up to v.v_proc

```
borntorun> kstat -n var
module: unix                            instance: 0
name:   var                             class:    misc
      crtime                          61.041156087
      snaptime                        113918.894449089
      v_autoup                        30
      v_buf                           100
      v_bufhwm                        20312
      [snip]
      v_maxsyspri                     99
      v_maxup                         15877
      v_maxupttl                      15877
      v_nglobpris                     110
      v_pbuf                          0
      v_proc                          15882
      v_sptmap                        0
```

```
# mdb -k
Loading modules: [ unix krtld genunix ... ptm ipc ]
> max_nprocs/D
max_nprocs:
max_nprocs:     15882
>
```

System-wide Process View - ps(1)

```
F S      UID   PID  PPID   C PRI NI     ADDR     SZ     WCHAN    STIME TTY         TIME CMD
0 S     root   824   386   0  40 020        ?    252         ?   Sep 06 console  0:00 /usr/lib/saf/ttymon -g -h
-p mcdoug
0 S     root   823   386   0  40 20        ?    242         ?   Sep 06 ?           0:00 /usr/lib/saf/sac -t 300
0 S   nobody  1718   716   0  40 20        ?    834         ?   Sep 07 ?           0:35 /usr/apache/bin/httpd
0 S     root   591   374   0  40 20        ?    478         ?   Sep 06 ?           0:00
/usr/lib/autofs/automountd
0 S     root   386   374   0  40 20        ?    262         ?   Sep 06 ?           0:01 init
1 S     root   374   374   0   0 SY        ?      0         ?   Sep 06 ?           0:00 zsched
0 S   daemon   490   374   0  40 20        ?    291         ?   Sep 06 ?           0:00 /usr/sbin/rpcbind
0 S   daemon   435   374   0  40 20        ?    450         ?   Sep 06 ?           0:00 /usr/lib/crypto/kcfd
0 S     root   603   374   0  40 20        ?    475         ?   Sep 06 ?           0:12 /usr/sbin/nscd
0 S     root   580   374   0  40 20        ?    448         ?   Sep 06 ?           0:02 /usr/sbin/syslogd
0 S     root   601   374   0  40 20        ?    313         ?   Sep 06 ?           0:00 /usr/sbin/cron
0 S   daemon   548   374   0  40 20        ?    319         ?   Sep 06 ?           0:00 /usr/lib/nfs/statd
0 S   daemon   550   374   0  40 20        ?    280         ?   Sep 06 ?           0:00 /usr/lib/nfs/lockd
0 S     root   611   374   0  40 20        ?    329         ?   Sep 06 ?           0:00 /usr/sbin/inetd -s
0 S     root   649   374   0  40 20        ?    152         ?   Sep 06 ?           0:00 /usr/lib/utmpd
0 S   nobody   778   716   0  40 20        ?    835         ?   Sep 06 ?           0:26 /usr/apache/bin/httpd
0 S     root   678   374   0  40 20        ?    612         ?   Sep 06 ?           0:00 /usr/dt/bin/dtlogin
-daemon
```

System-wide Process View - prstat(1)

```
  PID USERNAME  SIZE   RSS STATE  PRI NICE      TIME  CPU PROCESS/NLWP
26292 root     5368K 3080K run     24    0   0:00:00 1.5% pkginstall/1
26188 rmc      4880K 4512K cpu0    49    0   0:00:00 0.6% prstat/1
  202 root     3304K 1800K sleep   59    0   0:00:07 0.3% nscd/24
23078 root       20M   14M sleep   59    0   0:00:56 0.2% lupi_zones/1
23860 root     5104K 2328K sleep   59    0   0:00:01 0.1% sshd/1
...
  365 root     4760K  128K sleep   59    0   0:00:00 0.0% zoneadmd/4
  364 root     4776K  128K sleep   59    0   0:00:00 0.0% zoneadmd/4
  374 root        0K    0K sleep   60    -   0:00:00 0.0% zsched/1
  361 root     2016K    8K sleep   59    0   0:00:00 0.0% ttymon/1
  349 root     8600K  616K sleep   59    0   0:00:20 0.0% snmpd/1
  386 root     2096K  360K sleep   59    0   0:00:00 0.0% init/1
  345 root     3160K  496K sleep   59    0   0:00:00 0.0% sshd/1
  591 root     3824K  184K sleep   59    0   0:00:00 0.0% automountd/2
  ....
  242 root     1896K    8K sleep   59    0   0:00:00 0.0% smcboot/1
  248 smmsp    4736K  696K sleep   59    0   0:00:08 0.0% sendmail/1
  245 root     1888K    0K sleep   59    0   0:00:00 0.0% smcboot/1
  824 root     2016K    8K sleep   59    0   0:00:00 0.0% ttymon/1
  204 root     2752K  536K sleep   59    0   0:00:00 0.0% inetd/1
  220 root     1568K    8K sleep   59    0   0:00:00 0.0% powerd/3
  313 root     2336K  216K sleep   59    0   0:00:00 0.0% snmpdx/1
  184 root     4312K  872K sleep   59    0   0:00:01 0.0% syslogd/13
  162 daemon   2240K   16K sleep   60  -20   0:00:00 0.0% lockd/2
Total: 126 processes, 311 lwps, load averages: 0.48, 0.48, 0.41
```

The Life Of A Process

- Process creation
  - fork(2) system call creates all processes
    - SIDL state
  - exec(2) overlays newly created process with executable image
- State Transitions
  - Typically runnable (SRUN), running (SONPROC) or sleeping (aka blocked, SSLEEP)
  - Maybe stopped (debugger) SSTOP
- Termination
  - SZOMB state
  - implicit or explicit exit(), signal (kill), fatal error

Process Creation

- Traditional UNIX fork/exec model
  - fork(2) - replicate the entire process, including all threads
  - fork1(2) - replicate the process, only the calling thread
  - vfork(2) - replicate the process, but do not dup the address space
    - The new child borrows the parent's address space, until exec()

```
main(int argc, char *argv[])
{
        pid_t pid;
        pid = fork();
        if (pid == 0)   /* in the child */
                exec();
        else if (pid > 0)    /* in the parent */
                wait();
        else
                fork failed
}
```

fork(2) in Solaris 10

- Solaris 10 unified the process model
  - libthread merged with libc
  - threaded and non-threaded processes look the same
- fork(2) now replicates only the calling thread
  - Previously, fork1(2) needed to be called to do this
  - Linking with -lpthread in previous releases also resulted in fork1(2) behaviour
- forkall(2) added for applications that require a fork to replicate all the threads in the process

Process create example

C code calling fork()

```
#include <sys/types.h>
#include <unistd.h>

int main(int argc, char *argv[])
{
        pid_t   ret, cpid, ppid;

        ppid = getpid();
        ret = fork();
        if (ret == -1) {
                perror("fork");
                exit(0);
        } else if (ret == 0) {
                printf("In child...\n");
        } else {
                printf("Child PID: %d\n",ret);
        }
        exit(0);
}
```

D script to generate kernel trace

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

syscall::fork1:entry
/ pid == $target /
{
        self->trace = 1;
}
fbt:::
/ self->trace /
{
}
syscall::fork1:return
/ pid == $target /
{
        self->trace = 0;
        exit(0);
}
```

Fork Kernel Trace

```
CPU FUNCTION
  0  -> fork1
  0  <- fork1
  0  -> cfork
  0    -> secpolicy_basic_fork
  0    <- secpolicy_basic_fork
  0    -> priv_policy
  0    <- priv_policy
  0    -> holdlwps
  0      -> schedctl_finish_sigblock
  0      <- schedctl_finish_sigblock
  0      -> pokelwps
  0      <- pokelwps
  0    <- holdlwps
  0    -> flush_user_windows_to_stack
  0    -> getproc
  0      -> page_mem_avail
  0      <- page_mem_avail
  0      -> zone_status_get
  0      <- zone_status_get
  0      -> kmem_cache_alloc
  0        -> kmem_cpu_reload
  0        <- kmem_cpu_reload
  0      <- kmem_cache_alloc
  0      -> pid_assign
  0        -> kmem_zalloc
  0          <- kmem_cache_alloc
  0        <- kmem_zalloc
  0        -> pid_lookup
  0        -> pid_getlockslot
  0      -> crgetruid
  0      -> crgetzoneid
  0      -> upcount_inc
  0        -> rctl_set_dup
                ...
  0          -> project_cpu_shares_set
  0          -> project_lwps_set
  0          -> project_ntasks_set
                ...
  0        <- rctl_set_dup
```

Fork Kernel Trace (cont)

```
  0    -> as_dup
                 ...
  0        <- hat_alloc
  0      <- as_alloc
  0      -> seg_alloc
  0      -> rctl_set_fill_alloc_gp
  0    <- rctl_set_dup_ready
  0    -> rctl_set_dup
                 ...
  0    -> forklwp
  0      <- flush_user_windows_to_stack
  0      -> save_syscall_args
  0      -> lwp_create
  0        <- thread_create
  0        -> lwp_stk_init
  0        -> kmem_zalloc
  0      <- lwp_create
  0      -> init_mstate
  0      -> lwp_forkregs
  0      -> forkctx
  0      -> ts_alloc
  0      -> ts_fork
  0    <- forklwp
  0    -> contract_process_fork
  0    -> ts_forkret
  0      -> continuelwps
  0      -> ts_setrun
  0      -> setbackdq
  0      -> generic_enq_thread
  0    <- ts_forkret
  0    -> swtch
  0      -> disp
  0    <- swtch
  0    -> resume
  0      -> savectx
  0      <- savectx
  0      -> restorectx
  0    <- resume
  0  <- cfork
  0  <= fork1
```

Watching Forks

D script for watching fork(2)

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

syscall::forkall:entry
{
        @fall[execname] = count();
}
syscall::fork1:entry
{
        @f1[execname] = count();
}
syscall::vfork:entry
{
        @vf[execname] = count();
}

dtrace:::END
{
        printf("forkall\n");
        printa(@fall);
        printf("fork1\n");
        printa(@f1);
        printf("vfork\n");
        printa(@vf);
}
```

Example run

```
# ./watchfork.d
^C
forkall

fork1

  start-srvr            1
  bash                  3
  4cli                  6
vfork
```

exec(2) – Load a new process image

- Most fork(2) calls are followed by an exec(2)
- exec – execute a new file
- exec overlays the process image with a new process constructed from the binary file passed as an arg to exec(2)
- The exec'd process inherits much of the caller's state:
  - nice value, scheduling class, priority, PID, PPID, GID, task ID, project ID, session membership, real UID & GID, current working directory, resource limits, processor binding, times, etc, ...

Watching exec(2) with DTrace

- The D script...

```
#pragma D option quiet
proc:::exec
{
     self->parent = execname;
}
proc:::exec-success
/self->parent != NULL/
{
     @[self->parent, execname] = count();
     self->parent = NULL;
}
proc:::exec-failure
/self->parent != NULL/
{
     self->parent = NULL;
}
END
{
     printf("%-20s %-20s %s\n", "WHO", "WHAT", "COUNT");
     printa("%-20s %-20s %@d\n", @);
}
```

Watching exec(2) with DTrace

- Example output:

```
# dtrace -s ./whoexec.d
^C
WHO         WHAT        COUNT
make.bin    yacc        1
tcsh        make        1
make.bin    spec2map    1
sh          grep        1
lint        lint2       1
sh          lint        1
sh          ln          1
cc          ld          1
make.bin    cc          1
lint        lint1       1
```

DTraceToolkit - execsnoop

In this example the command "man gzip" was executed. The output lets us see what the man command is actually doing,

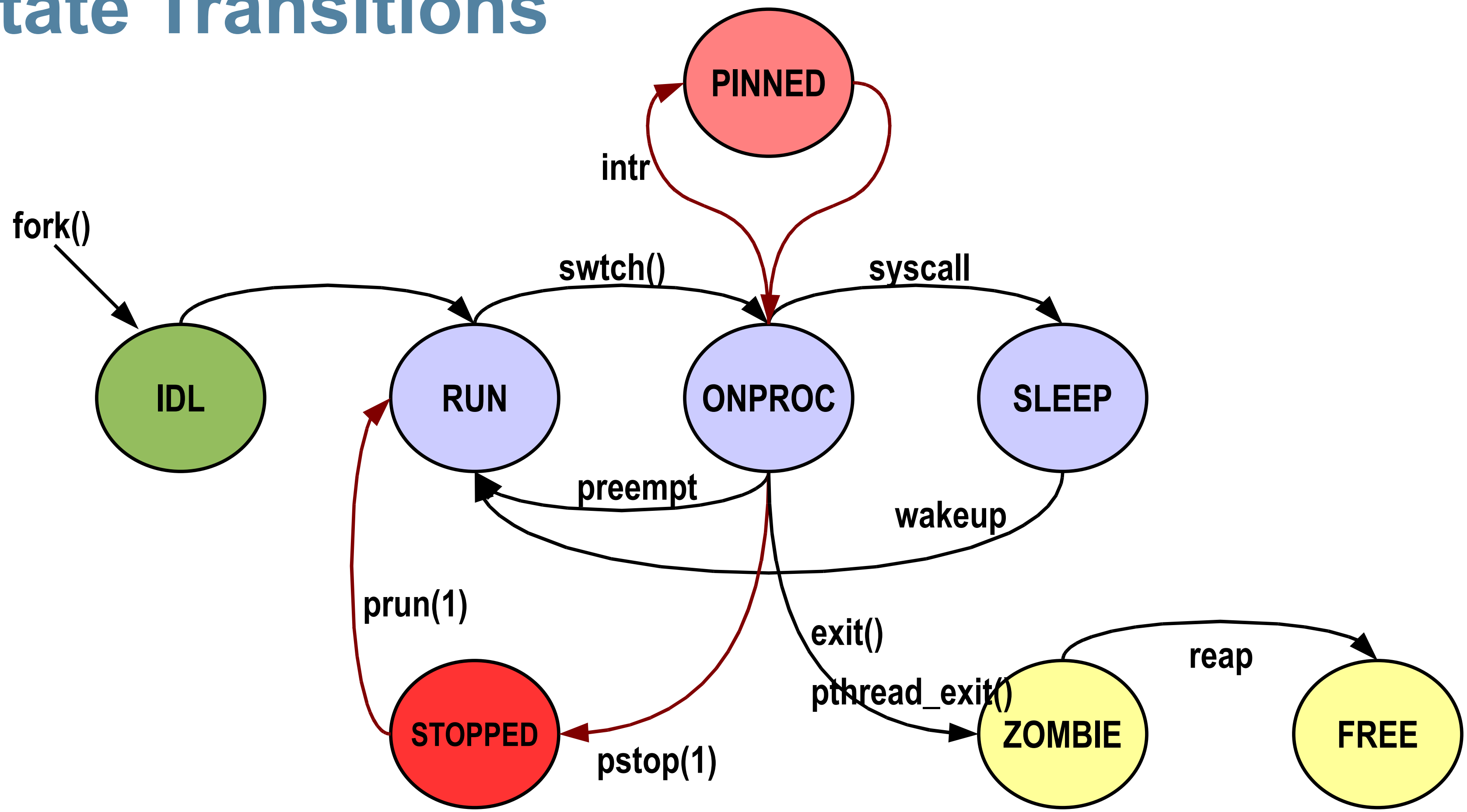
```
# ./execsnoop
  UID   PID  PPID ARGS
  100  3064  2656 man gzip
  100  3065  3064 sh -c cd /usr/share/man; tbl /usr/share/man/man1/gzip.1 |nroff -u0 -Tlp -man -
  100  3067  3066 tbl /usr/share/man/man1/gzip.1
  100  3068  3066 nroff -u0 -Tlp -man -
  100  3066  3065 col -x
  100  3069  3064 sh -c trap '' 1 15; /usr/bin/mv -f /tmp/mpoMaa_f /usr/share/man/cat1/gzip.1 2>
  100  3070  3069 /usr/bin/mv -f /tmp/mpoMaa_f /usr/share/man/cat1/gzip.1
  100  3071  3064 sh -c more -s /tmp/mpoMaa_f
  100  3072  3071 more -s /tmp/mpoMaa_f
^C
```

Process / Thread States

- It's really kernel threads that change state
- Kernel thread creation is not flagged as a distinct state
  - Initial state is TS_RUN
- Kernel threads are TS_FREE when the process, or LWP/kthread, terminates

Process State	Kernel Thread State
SIDL	
SRUN	TS_RUN
SONPROC	TS_ONPROC
SSLEEP	TS_SLEEP
SSTOP	TS_STOPPED
SZOMB	TS_ZOMB
	TS_FREE

State Transitions



Watching Process States

```
   PID USERNAME  SIZE   RSS STATE  PRI NICE      TIME  CPU PROCESS/NLWP
 27946 root     4880K 4520K cpu0    59    0   0:00:00 0.7% prstat/1
 28010 root     4928K 2584K run     29    0   0:00:00 0.7% pkginstall/1
 23078 root       20M   14M sleep   59    0   0:00:57 0.3% lupi_zones/1
 25947 root     5160K 2976K sleep   59    0   0:00:04 0.3% sshd/1
 24866 root     5136K 2136K sleep   59    0   0:00:01 0.2% sshd/1
   202 root     3304K 1800K sleep   59    0   0:00:09 0.2% nscd/24
 23001 root     5136K 2176K sleep   59    0   0:00:04 0.1% sshd/1
 23860 root     5248K 2392K sleep   59    0   0:00:05 0.1% sshd/1
 25946 rmc      3008K 2184K sleep   59    0   0:00:02 0.1% ssh/1
 25690 root     1240K  928K sleep   59    0   0:00:00 0.1% sh/1
  ...
   312 root     4912K   24K sleep   59    0   0:00:00 0.0% dtlogin/1
   250 root     4760K  696K sleep   59    0   0:00:16 0.0% sendmail/1
   246 root     1888K    0K sleep   59    0   0:00:00 0.0% smcboot/1
   823 root     1936K  224K sleep   59    0   0:00:00 0.0% sac/1
   242 root     1896K    8K sleep   59    0   0:00:00 0.0% smcboot/1
   248 smmsp    4736K  680K sleep   59    0   0:00:08 0.0% sendmail/1
   245 root     1888K    0K sleep   59    0   0:00:00 0.0% smcboot/1
   824 root     2016K    8K sleep   59    0   0:00:00 0.0% ttymon/1
   204 root     2752K  520K sleep   59    0   0:00:00 0.0% inetd/1
   220 root     1568K    8K sleep   59    0   0:00:00 0.0% powerd/3
   313 root     2336K  216K sleep   59    0   0:00:00 0.0% snmpdx/1
Total: 127 processes, 312 lwps, load averages: 0.62, 0.62, 0.53
```

Microstates

- Fine-grained state tracking for processes/threads
  - Off by default in Solaris 8 and Solaris 9
  - On by default in Solaris 10
- Can be enabled per-process via /proc
- prstat -m reports microstates
  - As a percentage of time for the sampling period
    - USR – user mode
    - SYS - kernel mode
    - TRP – trap handling
    - TFL – text page faults
    - DFL – data page faults
    - LCK – user lock wait
    - SLP - sleep
    - LAT – waiting for a processor (sitting on a run queue)

prstat – process microstates

```
# prstat -m
   PID USERNAME USR SYS TRP TFL DFL LCK SLP LAT VCX ICX SCL SIG PROCESS/NLWP
   739 root     0.3 0.3 0.0 0.0 0.0 0.0  99 0.0 126   3 345   5 Xsun/1
 15611 root     0.1 0.3 0.0 0.0 0.0 0.0 100 0.0  23   0 381   0 prstat/1
  1125 tlc      0.3 0.0 0.0 0.0 0.0 0.0 100 0.0  29   0 116   0 gnome-panel/1
 15553 rmc      0.1 0.2 0.0 0.0 0.0 0.0 100 0.0  24   0 381   0 prstat/1
  5591 tlc      0.1 0.0 0.0 0.0 0.0  33  66 0.0 206   0  1K   0 mozilla-bin/6
  1121 tlc      0.0 0.0 0.0 0.0 0.0 0.0 100 0.1  50   0 230   0 metacity/1
  2107 rmc      0.0 0.0 0.0 0.0 0.0 0.0 100 0.0  25   0  36   0 gnome-termin/1
   478 root     0.0 0.0 0.0 0.0 0.0 0.0 100 0.0  17   0  14   0 squid/1
   798 root     0.0 0.0 0.0 0.0 0.0 0.0 100 0.0  11   0  23   0 Xsun/1
  1145 tlc      0.0 0.0 0.0 0.0 0.0 0.0 100 0.0  25   1  34   0 mixer_applet/1
  1141 rmc      0.0 0.0 0.0 0.0 0.0 0.0 100 0.0  25   0  32   0 mixer_applet/1
  1119 tlc      0.0 0.0 0.0 0.0 0.0 0.0 100 0.0   5   0  40   0 gnome-smprox/1
  1127 tlc      0.0 0.0 0.0 0.0 0.0 0.0 100 0.0   7   0  29   0 nautilus/3
  1105 rmc      0.0 0.0 0.0 0.0 0.0 0.0 100 0.0   7   0  27   0 nautilus/3
   713 root     0.0 0.0 0.0 0.0 0.0  85  15 0.0   2   0 100   0 mibiisa/7
   174 root     0.0 0.0 0.0 0.0 0.0 0.0 100 0.0   5   0  50   5 ipmon/1
  1055 tlc      0.0 0.0 0.0 0.0 0.0 0.0 100 0.0   5   0  30   0 dsdm/1
Total: 163 processes, 275 lwps, load averages: 0.07, 0.07, 0.07
```

prstat – user summary

```
# prstat -t
NPROC USERNAME  SIZE   RSS MEMORY      TIME  CPU
   128 root      446M  333M   1.4%  47:14:23  11%
     2 measter  6600K 5016K   0.0%   0:00:07 0.2%
     1 clamb    9152K 8344K   0.0%   0:02:14 0.1%
     2 rmc      7192K 6440K   0.0%   0:00:00 0.1%
     1 bricker  5776K 4952K   0.0%   0:00:20 0.1%
     2 asd        10M 8696K   0.0%   0:00:01 0.1%
     1 fredz    7760K 6944K   0.0%   0:00:05 0.1%
     2 jenks    8576K 6904K   0.0%   0:00:01 0.1%
     1 muffin     15M   14M   0.1%   0:01:26 0.1%
     1 dte      3800K 3016K   0.0%   0:00:04 0.0%
     2 adjg     8672K 7040K   0.0%   0:00:03 0.0%
     3 msw        14M   10M   0.0%   0:00:00 0.0%
     1 welza    4032K 3248K   0.0%   0:00:29 0.0%
     2 kimc     7848K 6344K   0.0%   0:00:25 0.0%
     4 jcmartin   13M 9904K   0.0%   0:00:03 0.0%
     1 rascal     17M   16M   0.1%   0:02:11 0.0%
     1 rab      3288K 2632K   0.0%   0:02:11 0.0%
     1 gjmurphy 3232K 2392K   0.0%   0:00:00 0.0%
     1 ktheisen   15M   14M   0.1%   0:01:16 0.0%
     1 nagendra 3232K 2400K   0.0%   0:00:00 0.0%
     2 ayong    8320K 6832K   0.0%   0:00:02 0.0%
Total: 711 processes, 902 lwps, load averages: 3.84, 4.30, 4.37
```

Solaris 9 / 10 ptools

```
/usr/bin/pflags [-r] [pid | core] ...
/usr/bin/pcred [pid | core] ...
/usr/bin/pldd [-F] [pid | core] ...
/usr/bin/psig [-n] pid...
/usr/bin/pstack [-F] [pid | core] ...
/usr/bin/pfiles [-F] pid...
/usr/bin/pwdx [-F] pid...
/usr/bin/pstop pid...
/usr/bin/prun pid...
/usr/bin/pwait [-v] pid...
/usr/bin/ptree [-a] [pid | user] ...
/usr/bin/ptime command [arg...]
/usr/bin/pmap -[xS] [-rslF] [pid | core] ...
/usr/bin/pgrep  [-flvx]  [-n  |  -o]  [-d delim][-P ppidlist]  [-
g pgrplist]   [-s sidlist]    [-u euidlist]   [-U uidlist]  [-
G gidlist]  [-J projidlist]  [-t termlist]   [-T taskidlist]
[pattern]
/usr/bin/pkill  [-signal][-fvx][-n  |  -o][-P ppidlist]  [-
g pgrplist]   [-s sidlist]    [-u euidlist]   [-U uidlist]  [-
G gidlist]  [-J projidlist]  [-t termlist]   [-T taskidlist]
[pattern]
/usr/bin/plimit [-km] pid...
{-cdfnstv} soft,hard... pid...
/usr/bin/ppgsz  [-F] -o option[,option]  cmd | -p pid...
/usr/bin/prctl [-t [basic | privileged | system] ] [ -e | -d  action]
[-rx] [ -n name [-v value]] [-i idtype] [id...]
/usr/bin/preap [-F] pid
/usr/bin/pargs [-aceFx] [pid | core] ...
```

Tracing

- Trace user signals and system calls - truss
  - Traces by stopping and starting the process
  - Can trace system calls, inline or as a summary
  - Can also trace shared libraries and a.out
- Linker/library interposing/profiling/tracing
  - LD_ environment variables enable link debugging
  - man ld.so.1
  - using the LD_PRELOAD env variable
- Trace Normal Formal (TNF)
  - Kernel and Process Tracing
  - Lock Tracing
- Kernel Tracing
  - lockstat, tnf, kgmon

Process Tracing – Truss

```
# truss -d dd if=500m of=/dev/null bs=16k count=2k 2>&1 |more
Base time stamp:  925931550.0927  [ Wed May  5 12:12:30 PDT 1999 ]
 0.0000 execve("/usr/bin/dd", 0xFFBEF68C, 0xFFBEF6A4)  argc = 5
 0.0034 open("/dev/zero", O_RDONLY)                    = 3
 0.0039 mmap(0x00000000, 8192, PROT_READ|PROT_WRITE|PROT_EXEC, MAP_PRIVATE, 3, 0) = 0xFF3A0000
 0.0043 open("/usr/lib/libc.so.1", O_RDONLY)           = 4
 0.0047 fstat(4, 0xFFBEF224)                           = 0
 0.0049 mmap(0x00000000, 8192, PROT_READ|PROT_EXEC, MAP_PRIVATE, 4, 0) = 0xFF390000
 0.0051 mmap(0x00000000, 761856, PROT_READ|PROT_EXEC, MAP_PRIVATE, 4, 0) = 0xFF280000
 0.0054 munmap(0xFF324000, 57344)                      = 0
 0.0057 mmap(0xFF332000, 25284, PROT_READ|PROT_WRITE|PROT_EXEC, MAP_PRIVATE|MAP_FIXED, 4, 663552) = 0xFF332000
 0.0062 close(4)                                       = 0
 0.0065 open("/usr/lib/libdl.so.1", O_RDONLY)          = 4
 0.0068 fstat(4, 0xFFBEF224)                           = 0
 0.0070 mmap(0xFF390000, 8192, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_FIXED, 4, 0) = 0xFF390000
 0.0073 close(4)                                       = 0
 0.0076 open("/usr/platform/SUNW,Ultra-2/lib/libc_psr.so.1", O_RDONLY) = 4
 0.0079 fstat(4, 0xFFBEF004)                           = 0
 0.0082 mmap(0x00000000, 8192, PROT_READ|PROT_EXEC, MAP_PRIVATE, 4, 0) = 0xFF380000
 0.0084 mmap(0x00000000, 16384, PROT_READ|PROT_EXEC, MAP_PRIVATE, 4, 0) = 0xFF370000
 0.0087 close(4)                                       = 0
 0.0100 close(3)                                       = 0
 0.0103 munmap(0xFF380000, 8192)                       = 0
 0.0110 open64("500m", O_RDONLY)                       = 3
 0.0115 creat64("/dev/null", 0666)                     = 4
 0.0119 sysconfig(_CONFIG_PAGESIZE)                    = 8192
 0.0121 brk(0x00023F40)                                = 0
 0.0123 brk(0x0002BF40)                                = 0
 0.0127 sigaction(SIGINT, 0xFFBEF470, 0xFFBEF4F0)      = 0
 0.0129 sigaction(SIGINT, 0xFFBEF470, 0xFFBEF4F0)      = 0
 0.0134 read(3, "\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0"..., 16384)   = 16384
 0.0137 write(4, "\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0"..., 16384)  = 16384
 0.0140 read(3, "\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0"..., 16384)   = 16384
 0.0143 write(4, "\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0"..., 16384)  = 16384
 0.0146 read(3, "\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0"..., 16384)   = 16384
 0.0149 write(4, "\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0"..., 16384)  = 16384
 0.0152 read(3, "\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0"..., 16384)   = 16384
 0.0154 write(4, "\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0"..., 16384)  = 16384
```

Process Tracing – System Call Summary

- Counts total cpu seconds per system call and calls

```
# truss -c dd if=500m of=/dev/null bs=16k count=2k
syscall          seconds   calls  errors
_exit                .00       1
read                 .34    2048
write                .03    2056
open                 .00       4
close                .00       6
brk                  .00       2
fstat                .00       3
execve               .00       1
sigaction            .00       2
mmap                 .00       7
munmap               .00       2
sysconfig            .00       1
llseek               .00       1
creat64              .00       1
open64               .00       1
                    ----     ---    ---
sys totals:          .37    4136      0
usr time:            .00
elapsed:             .89
```

Library Tracing - truss -u

```
# truss -d -u a.out,libc dd if=500m of=/dev/null bs=16k count=2k
Base time stamp:  925932005.2498  [ Wed May  5 12:20:05 PDT 1999 ]
 0.0000 execve("/usr/bin/dd", 0xFFBEF68C, 0xFFBEF6A4)  argc = 5
 0.0073 open("/dev/zero", O_RDONLY)                  = 3
 0.0077 mmap(0x00000000, 8192, PROT_READ|PROT_WRITE|PROT_EXEC, MAP_PRIVATE, 3, 0) = 0xFF3A0000
 0.0094 open("/usr/lib/libc.so.1", O_RDONLY)         = 4
 0.0097 fstat(4, 0xFFBEF224)                         = 0
 0.0100 mmap(0x00000000, 8192, PROT_READ|PROT_EXEC, MAP_PRIVATE, 4, 0) = 0xFF390000
 0.0102 mmap(0x00000000, 761856, PROT_READ|PROT_EXEC, MAP_PRIVATE, 4, 0) = 0xFF280000
 0.0105 munmap(0xFF324000, 57344)                    = 0
 0.0107 mmap(0xFF332000, 25284, PROT_READ|PROT_WRITE|PROT_EXEC, MAP_PRIVATE|MAP_FIXED, 4, 663552) = 0xFF332000
 0.0113 close(4)                                     = 0
 0.0116 open("/usr/lib/libdl.so.1", O_RDONLY)        = 4
 0.0119 fstat(4, 0xFFBEF224)                         = 0
 0.0121 mmap(0xFF390000, 8192, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_FIXED, 4, 0) = 0xFF390000
 0.0124 close(4)                                     = 0
 0.0127 open("/usr/platform/SUNW,Ultra-2/lib/libc_psr.so.1", O_RDONLY) = 4
 0.0131 fstat(4, 0xFFBEF004)                         = 0
 0.0133 mmap(0x00000000, 8192, PROT_READ|PROT_EXEC, MAP_PRIVATE, 4, 0) = 0xFF380000
 0.0135 mmap(0x00000000, 16384, PROT_READ|PROT_EXEC, MAP_PRIVATE, 4, 0) = 0xFF370000
 0.0138 close(4)                                     = 0
 0.2369 close(3)                                     = 0
 0.2372 munmap(0xFF380000, 8192)                     = 0
 0.2380 -> libc:atexit(0xff3b9e8c, 0x23400, 0x0, 0x0)
 0.2398 <- libc:atexit() = 0
 0.2403 -> libc:atexit(0x12ed4, 0xff3b9e8c, 0xff334518, 0xff332018)
 0.2419 <- libc:atexit() = 0
 0.2424 -> _init(0x0, 0x12ed4, 0xff334518, 0xff332018)
 0.2431 <- _init() = 0
 0.2436 -> main(0x5, 0xffbef68c, 0xffbef6a4, 0x23400)
 0.2443   -> libc:setlocale(0x6, 0x12f14, 0x0, 0x0)
 0.2585   <- libc:setlocale() = 0xff31f316
```

Library Tracing – apptrace(1)

```
sunsys> apptrace ls
ls         -> libc.so.1:atexit(func = 0xff3caa24) = 0x0
ls         -> libc.so.1:atexit(func = 0x13ad4) = 0x0
ls         -> libc.so.1:setlocale(category = 0x6, locale = "") = "/en_US.ISO8859-1/en_"
ls         -> libc.so.1:textdomain(domainname = "SUNW_OST_OSCMD") = "SUNW_OST_OSCMD"
ls         -> libc.so.1:time(tloc = 0x0) = 0x3aee2678
ls         -> libc.so.1:isatty(fildes = 0x1) = 0x1
ls         -> libc.so.1:getopt(argc = 0x1, argv = 0xffbeeff4, optstring =
                                   "RaAdC1xmnlogrtucpFbq") = 0xffffffff errno = 0 (Error 0)
ls         -> libc.so.1:getenv(name = "COLUMNS") = "<nil>"
ls         -> libc.so.1:ioctl(0x1, 0x5468, 0x2472a)
ls         -> libc.so.1:malloc(size = 0x100) = 0x25d10
ls         -> libc.so.1:malloc(size = 0x9000) = 0x25e18
ls         -> libc.so.1:lstat64(path = ".", buf = 0xffbeee98) = 0x0
ls         -> libc.so.1:qsort(base = 0x25d10, nel = 0x1, width = 0x4, compar = 0x134bc)
ls         -> libc.so.1:.div(0x50, 0x3, 0x50)
ls         -> libc.so.1:.div(0xffffffff, 0x1a, 0x0)
ls         -> libc.so.1:.mul(0x1, 0x0, 0xffffffff)
ls         -> libc.so.1:.mul(0x1, 0x1, 0x0)
```

User Threads

- The programming abstraction for creating multithreaded programs
  - Parallelism
  - POSIX and UI thread APIs
    - thr_create(3THR)
    - pthread_create(3THR)
  - Synchronization
    - Mutex locks, reader/writer locks, semaphores, condition variables
- Solaris 2 originally implemented an MxN threads model (T1)
  - “unbound” threads
- Solaris 8 introduced the 1 level model (T2)
  - /usr/lib/lwp/libthread.so
- T2 is the default in Solaris 9 and Solaris 10

Threads Primer Example:

```
#include <pthread.h>
#include <stdio.h>
mutex_t mem_lock;
void childthread(void *argument)
{
     int i;
     for(i = 1; i <= 100; ++i) {
          print("Child Count - %d\n", i);
     }
     pthread_exit(0);
}
int main(void)
{
     pthread_t thread, thread2;
     int ret;

     if ((pthread_create(&thread, NULL, (void *)childthread, NULL)) < 0) {
          printf ("Thread Creation Failed\n");
          return (1);
     }
     pthread_join(thread,NULL);
     print("Parent is continuing....\n");
     return (0);
}
```

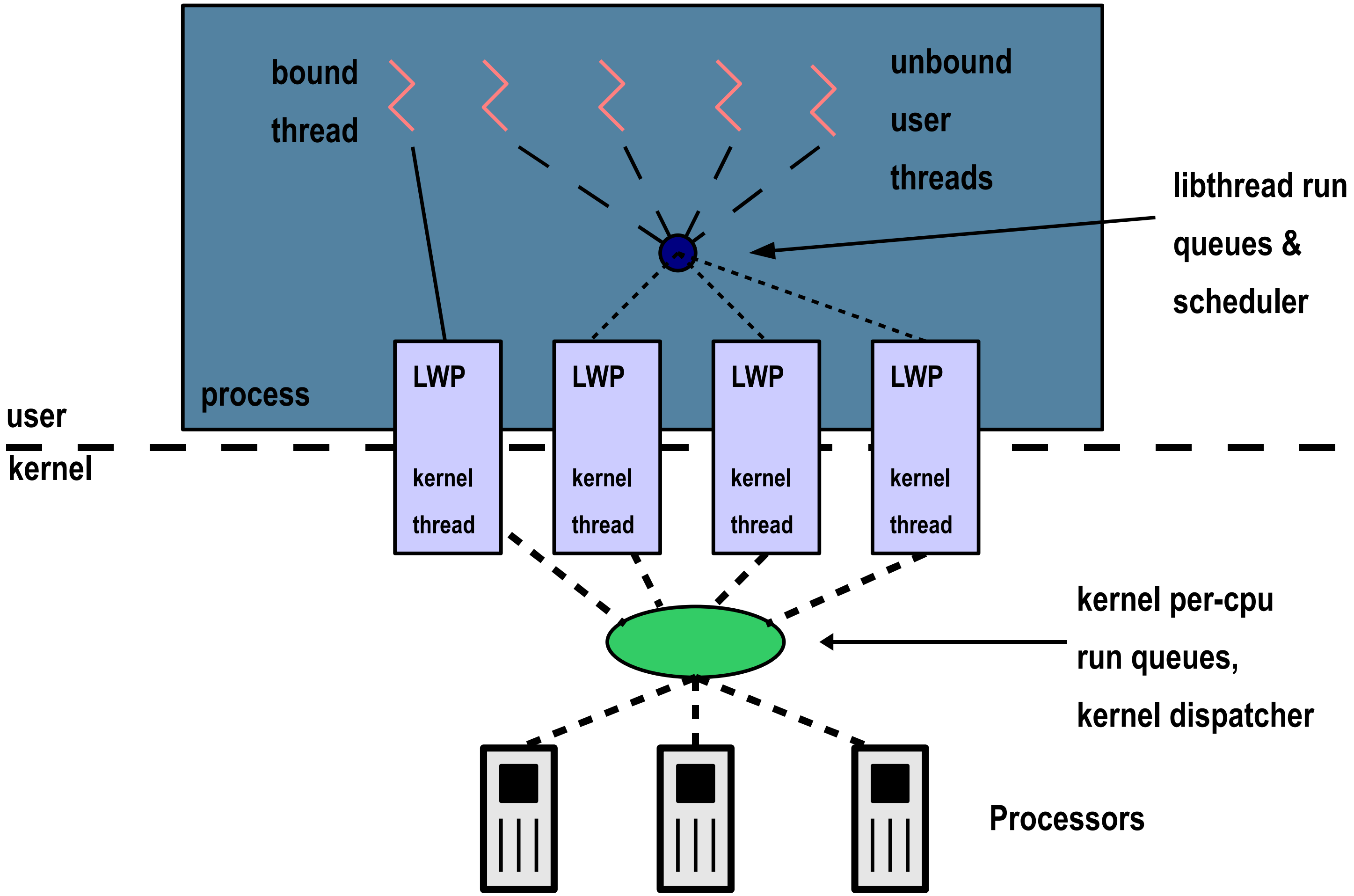
T1 – Multilevel MxN Model

- /usr/lib/libthread.so.1
- Based on the assumption that kernel threads are expensive, user threads are cheap.
- User threads are virtualized, and may be multiplexed onto one or more kernel threads
  - LWP pool
- User level thread synchronization - threads sleep at user level. (Process private only)
- Concurrency via set_concurrency() and bound LWPs

T1 – Multilevel Model

- Unbound Thread Implementation
  - User Level scheduling
  - Unbound threads switched onto available lwps
  - Threads switched when blocked on sync object
  - Thread temporary bound when blocked in system call
  - Daemon lwp to create new lwps
  - Signal direction handled by Daemon lwp
  - Reaper thread to manage cleanup
  - Callout lwp for timers

T1- Multilevel Model (default in Solaris 8)



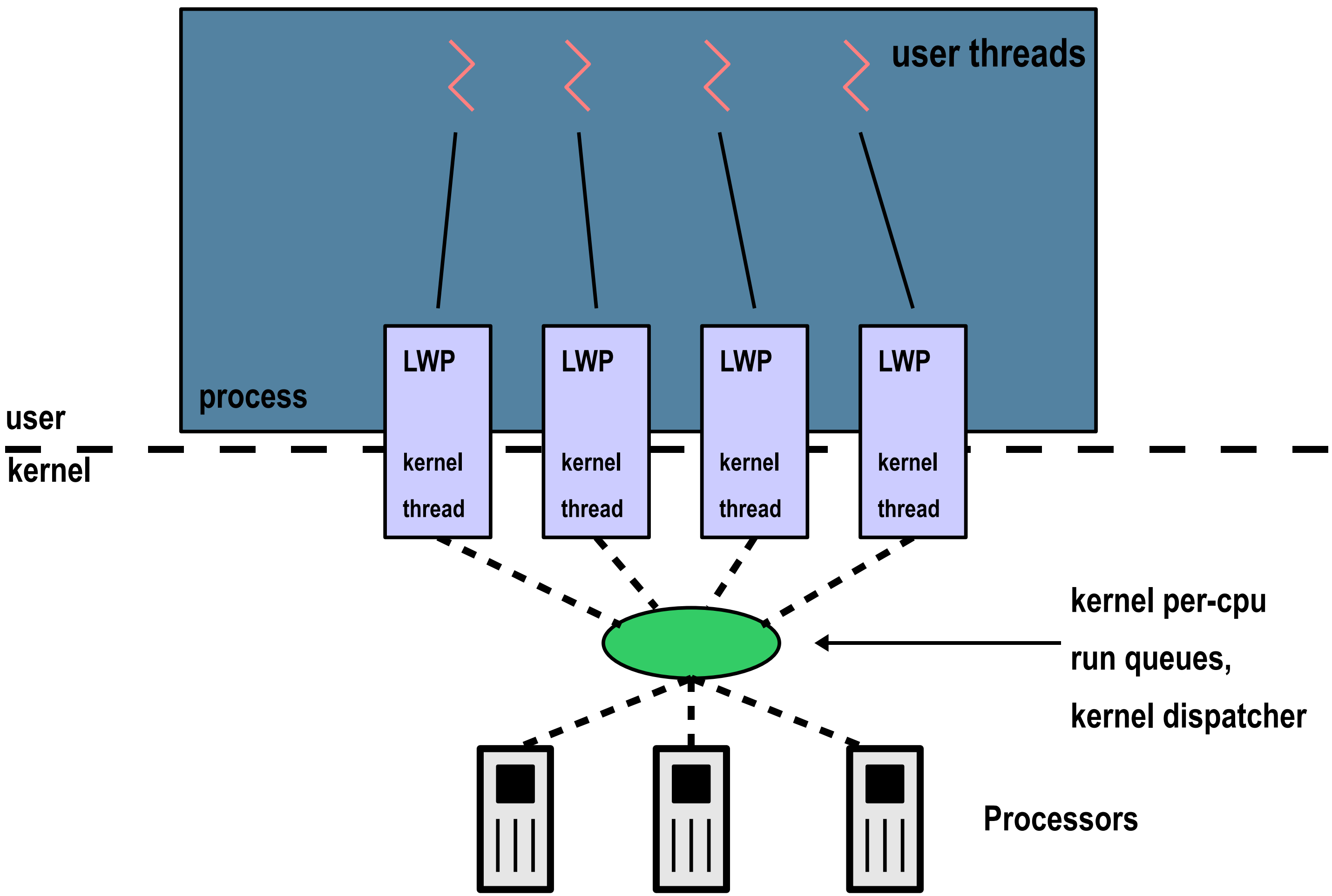
T1 – Multilevel Model

- Pros:
  - Fast user thread create and destroy
  - Allows many-to-few thread model, to mimimize the number of kernel threads and LWPs
  - Uses minimal kernel memory
  - No system call required for synchronization
  - Process Private Synchronization only
  - Can have thousands of threads
  - Fast context-switching
- Cons:
  - Complex, and tricky programming model wrt achieving good scalability - need to bind or use set_concurrency()
  - Signal delivery
  - Compute bound threads do not surrender, leading to excessive CPU consumption and potential starving
  - Complex to maintain (for Sun)

T2 – Single Level Threads Model

- All user threads bound to LWPs
  - All bound threads
- Kernel level scheduling
  - No more libthread.so scheduler
- Simplified Implementation
- Uses kernel's synchronization objects
  - Slightly different behaviour LIFO vs. FIFO
  - Allows adaptive lock behaviour
- More expensive thread create/destroy, synchronization
- More responsive scheduling, synchronization

T2 – Single Level Threads Model



T2 - Single Level Thread Model

- Scheduling wrt Synchronization (S8U7/S9/S10)
  - Adaptive locks give preference to a thread that is running, potentially at the expense of a thread that is sleeping
  - Threads that rely on fairness of scheduling/CPU could end up ping-ponging, at the expense of another thread which has work to do.
- Default S8U7/S9/S10 Behavior
  - Adaptive Spin
    - 1000 of iterations (spin count) for adaptive mutex locking before giving up and going to sleep.
  - Maximum number of spinners
    - The number of simultaneously spinning threads
    - attempting to do adaptive locking on one mutex is limited to 100.
  - One out of every 16 queuing operations will put a thread at the end of the queue, to prevent starvation.
  - Stack Cache
    - The maximum number of stacks the library retains after threads exit for re-use when more threads are created is 10.

Thread Semantics Added to pstack, truss

```
# pstack 909/2
909:    dbwr -a dbwr -i 2 -s b0000000 -m /var/tmp/fbencAAAmxaqxb
-----------------  lwp# 2  --------------------------------
 ceab1809 lwp_park (0, afffde50, 0)
 ceaabf93 cond_wait_queue (ce9f8378, ce9f83a0, afffde50, 0) + 3b
 ceaac33f cond_wait_common (ce9f8378, ce9f83a0, afffde50) + 1df
 ceaac686 _cond_reltimedwait (ce9f8378, ce9f83a0, afffdea0) + 36
 ceaac6b4 cond_reltimedwait (ce9f8378, ce9f83a0, afffdea0) + 24
 ce9e5902 __aio_waitn (82d1f08, 1000, afffdf2c, afffdf18, 1) + 529
 ceaf2a84 aio_waitn64 (82d1f08, 1000, afffdf2c, afffdf18) + 24
 08063065 flowoplib_aiowait (b4eb475c, c40f4d54) + 97
 08061de1 flowop_start (b4eb475c) + 257
 ceab15c0 _thr_setup (ce9a8400) + 50
 ceab1780 _lwp_start (ce9a8400, 0, 0, afffdff8, ceab1780, ce9a8400)
 pae1> truss -p 2975/3
 /3:   close(5)                              = 0
 /3:   open("/space1/3", O_RDWR|O_CREAT, 0666)       = 5
 /3:   lseek(5, 0, SEEK_SET)                         = 0
 /3:   write(5, " U U U U U U U U U U U U".., 1056768)    = 1056768
 /3:   lseek(5, 0, SEEK_SET)                         = 0
 /3:   read(5, " U U U U U U U U U U U U".., 1056768)     = 1056768
 /3:   close(5)                              = 0
 /3:   open("/space1/3", O_RDWR|O_CREAT, 0666)       = 5
 /3:   lseek(5, 0, SEEK_SET)                         = 0
 /3:   write(5, " U U U U U U U U U U U U".., 1056768)    = 1056768
```

Thread Microstates

```
   PID USERNAME USR SYS TRP TFL DFL LCK SLP LAT VCX ICX SCL SIG PROCESS/LWPID
   918 rmc      0.2 0.4 0.0 0.0 0.0 0.0  99 0.0  27   2  1K   0 prstat/1
   919 mauroj   0.1 0.4 0.0 0.0 0.0 0.0  99 0.1  44  12  1K   0 prstat/1
   907 root     0.0 0.1 0.0 0.0 0.0 0.0  97 3.1 121   2  20   0 filebench/2
   913 root     0.1 0.0 0.0 0.0 0.0 100 0.0 0.0  15   2 420   0 filebench/2
   866 root     0.0 0.0 0.0 0.0 0.0 0.0  96 4.1  44  41 398   0 filebench/2
   820 root     0.0 0.0 0.0 0.0 0.0 0.0  95 5.0  43  42 424   0 filebench/2
   814 root     0.0 0.0 0.0 0.0 0.0 0.0  95 5.0  43  41 424   0 filebench/2
   772 root     0.0 0.0 0.0 0.0 0.0 0.0  96 3.6  46  39 398   0 filebench/2
   749 root     0.0 0.0 0.0 0.0 0.0 0.0  96 3.7  45  41 398   0 filebench/2
   744 root     0.0 0.0 0.0 0.0 0.0 0.0  95 4.7  47  39 398   0 filebench/2
   859 root     0.0 0.0 0.0 0.0 0.0 0.0  95 4.9  44  41 424   0 filebench/2
   837 root     0.0 0.0 0.0 0.0 0.0 0.0  96 4.0  43  43 405   0 filebench/2
  [snip]
   787 root     0.0 0.0 0.0 0.0 0.0 0.0  95 4.5  43  41 424   0 filebench/2
   776 root     0.0 0.0 0.0 0.0 0.0 0.0  95 4.8  43  42 398   0 filebench/2
   774 root     0.0 0.0 0.0 0.0 0.0 0.0  96 4.2  43  40 398   0 filebench/2
   756 root     0.0 0.0 0.0 0.0 0.0 0.0  96 3.8  44  41 398   0 filebench/2
   738 root     0.0 0.0 0.0 0.0 0.0 0.0  96 4.4  43  42 398   0 filebench/2
   735 root     0.0 0.0 0.0 0.0 0.0 0.0  96 3.9  47  39 405   0 filebench/2
   734 root     0.0 0.0 0.0 0.0 0.0 0.0  96 4.3  44  41 398   0 filebench/2
   727 root     0.0 0.0 0.0 0.0 0.0 0.0  96 4.4  43  43 398   0 filebench/2
   725 root     0.0 0.0 0.0 0.0 0.0 0.0  96 4.4  43  43 398   0 filebench/2
 Total: 257 processes, 3139 lwps, load averages: 7.71, 2.39, 0.97
```

Watching Threads

```
   PID USERNAME  SIZE   RSS STATE  PRI NICE      TIME  CPU PROCESS/LWPID
 29105 root     5400K 3032K sleep   60    0   0:00:00 1.3% pkginstall/1
 29051 root     5072K 4768K cpu0    49    0   0:00:00 0.8% prstat/1
   202 root     3304K 1256K sleep   59    0   0:00:07 0.3% nscd/23
 25947 root     5160K  608K sleep   59    0   0:00:05 0.2% sshd/1
 23078 root       20M 1880K sleep   59    0   0:00:58 0.2% lupi_zones/1
 25946 rmc      3008K  624K sleep   59    0   0:00:02 0.2% ssh/1
 23860 root     5248K  688K sleep   59    0   0:00:06 0.2% sshd/1
 29100 root     1272K  976K sleep   59    0   0:00:00 0.1% mpstat/1
 24866 root     5136K  600K sleep   59    0   0:00:02 0.0% sshd/1
   340 root     2504K  672K sleep   59    0   0:11:14 0.0% mibiisa/2
 23001 root     5136K  584K sleep   59    0   0:00:04 0.0% sshd/1
   830 root     2472K  600K sleep   59    0   0:11:01 0.0% mibiisa/2
   829 root     2488K  648K sleep   59    0   0:11:01 0.0% mibiisa/2
     1 root     2184K  400K sleep   59    0   0:00:01 0.0% init/1
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/13
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/12
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/11
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/10
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/9
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/8
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/7
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/6
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/5
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/4
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/3
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/2
   202 root     3304K 1256K sleep   59    0   0:00:00 0.0% nscd/1
   126 daemon   2360K    8K sleep   59    0   0:00:00 0.0% rpcbind/1
   814 root     1936K  280K sleep   59    0   0:00:00 0.0% sac/1
    64 root     2952K    8K sleep   59    0   0:00:00 0.0% picld/5
    64 root     2952K    8K sleep   59    0   0:00:00 0.0% picld/4
    64 root     2952K    8K sleep   59    0   0:00:00 0.0% picld/3
    64 root     2952K    8K sleep   59    0   0:00:00 0.0% picld/2
    64 root     2952K    8K sleep   59    0   0:00:00 0.0% picld/1
    61 daemon   3640K    8K sleep   59    0   0:00:00 0.0% kcfd/3
    61 daemon   3640K    8K sleep   59    0   0:00:00 0.0% kcfd/2
    61 daemon   3640K    8K sleep   59    0   0:00:00 0.0% kcfd/1
    55 root     2416K    8K sleep   59    0   0:00:00 0.0% syseventd/14
    55 root     2416K    8K sleep   59    0   0:00:00 0.0% syseventd/13
    55 root     2416K    8K sleep   59    0   0:00:00 0.0% syseventd/12
    55 root     2416K    8K sleep   59    0   0:00:00 0.0% syseventd/11
 Total: 125 processes, 310 lwps, load averages: 0.50, 0.38, 0.40
```

Who's Creating Threads?

```
# dtrace -n 'thread_create:entry { @[execname]=count()}'
dtrace: description 'thread_create:entry ' matched 1 probe
^C

  sh                                                       1
  sched                                                    1
  do1.6499                                                 2
  do1.6494                                                 2
  do1.6497                                                 2
  do1.6508                                                 2
  in.rshd                                                 12
  do1.6498                                                14
  do1.6505                                                16
  do1.6495                                                16
  do1.6504                                                16
  do1.6502                                                16
  automountd                                              17
  inetd                                                   19
  filebench                                               34
  find                                                   130
  csh                                                    177
```

Scheduling Classes & The Kernel Dispatcher

Solaris Scheduling

- Solaris implements a central dispatcher, with multiple scheduling classes
  - Scheduling classes determine the priority range of the kernel threads on the system-wide (global) scale, and the scheduling algorithms applied
  - Each scheduling class references a dispatch table
    - Values used to determine time quantums and priorities
    - Admin interface to “tune” thread scheduling
  - Solaris provides command line interfaces for
    - Loading new dispatch tables
    - Changing the scheduling class and priority and threads
  - Observability through
    - `ps(1)`
    - `prstat(1)`
    - `dtrace(1)`

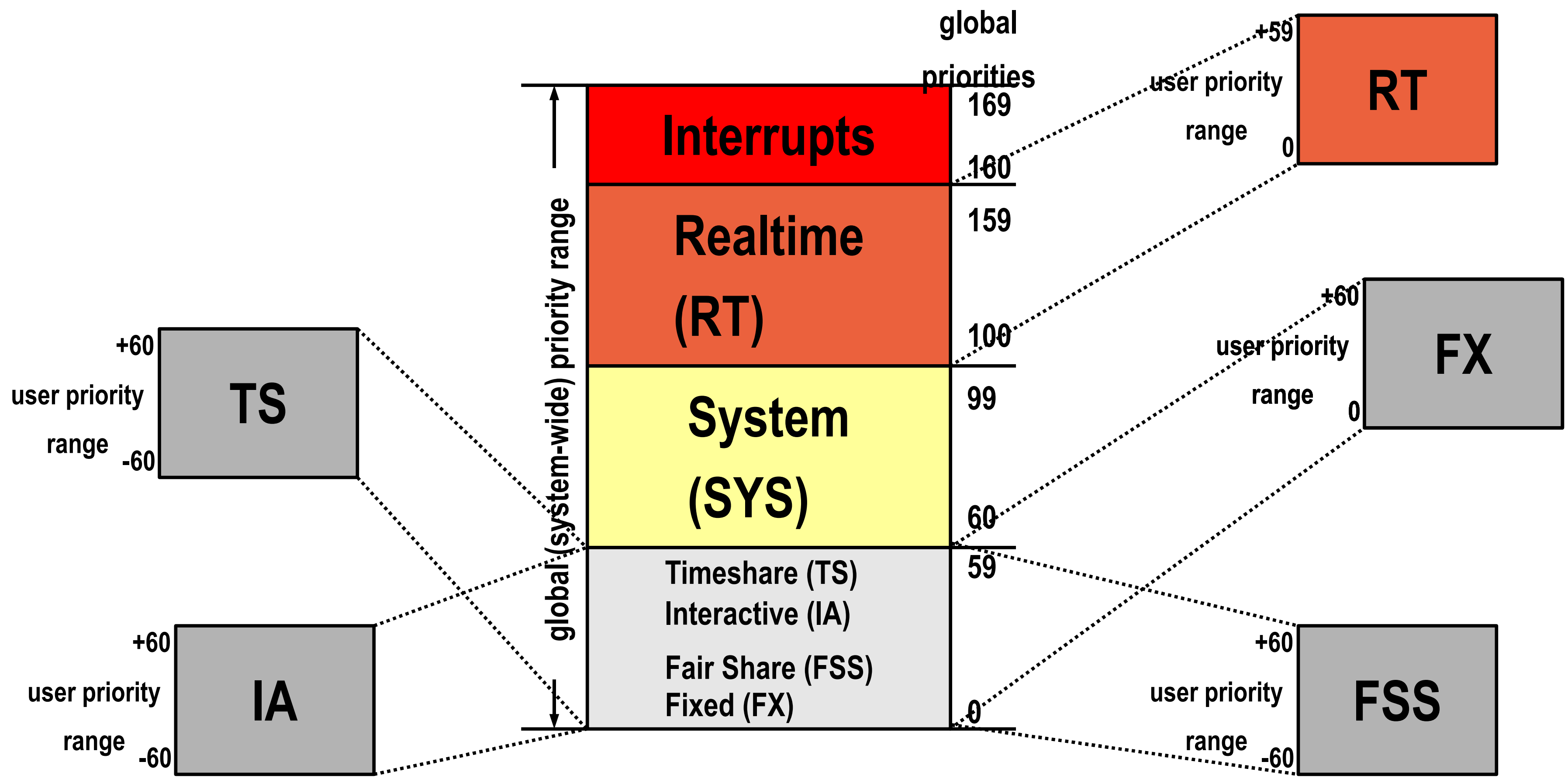
Scheduling Classes

- Traditional Timeshare (TS) class
  - attempt to give every thread a fair shot at execution time
- Interactive (IA) class
  - Desktop only
  - Boost priority of active (current focus) window
  - Same dispatch table as TS
- System (SYS)
  - Only available to the kernel, for OS kernel threads
- Realtime (RT)
  - Highest priority scheduling class
  - Will preempt kernel (SYS) class threads
  - Intended for realtime applications
    - Bounded, consistent scheduling latency

Scheduling Classes – Solaris 9 & 10

- Fair Share Scheduler (FSS) Class
  - Same priority range as TS/IA class
  - CPU resources are divided into shares
  - Shares are allocated (projects/tasks) by administrator
  - Scheduling decisions made based on shares allocated and used, not dynamic priority changes
- Fixed Priority (FX) Class
  - The kernel will not change the thread's priority
  - A “batch” scheduling class
- Same set of commands for administration and management
  - `dispadmin`(1M), `priocntl`(1)
  - Resource management framework
    - `rctladm`(1M), `prctl`(1)

Scheduling Classes and Priorities



Scheduling Classes

- Use `dispadmin`(1M) and `priocntl`(1)

```
# dispadmin -l
CONFIGURED CLASSES
==================

SYS   (System Class)
TS    (Time Sharing)
FX    (Fixed Priority)
IA    (Interactive)
FSS   (Fair Share)
RT    (Real Time)
# priocntl -l
CONFIGURED CLASSES
==================

SYS (System Class)

TS (Time Sharing)
      Configured TS User Priority Range: -60 through 60

FX (Fixed priority)
      Configured FX User Priority Range: 0 through 60

IA (Interactive)
      Configured IA User Priority Range: -60 through 60

FSS (Fair Share)
      Configured FSS User Priority Range: -60 through 60

RT (Real Time)
      Maximum Configured RT Priority: 59
#
```

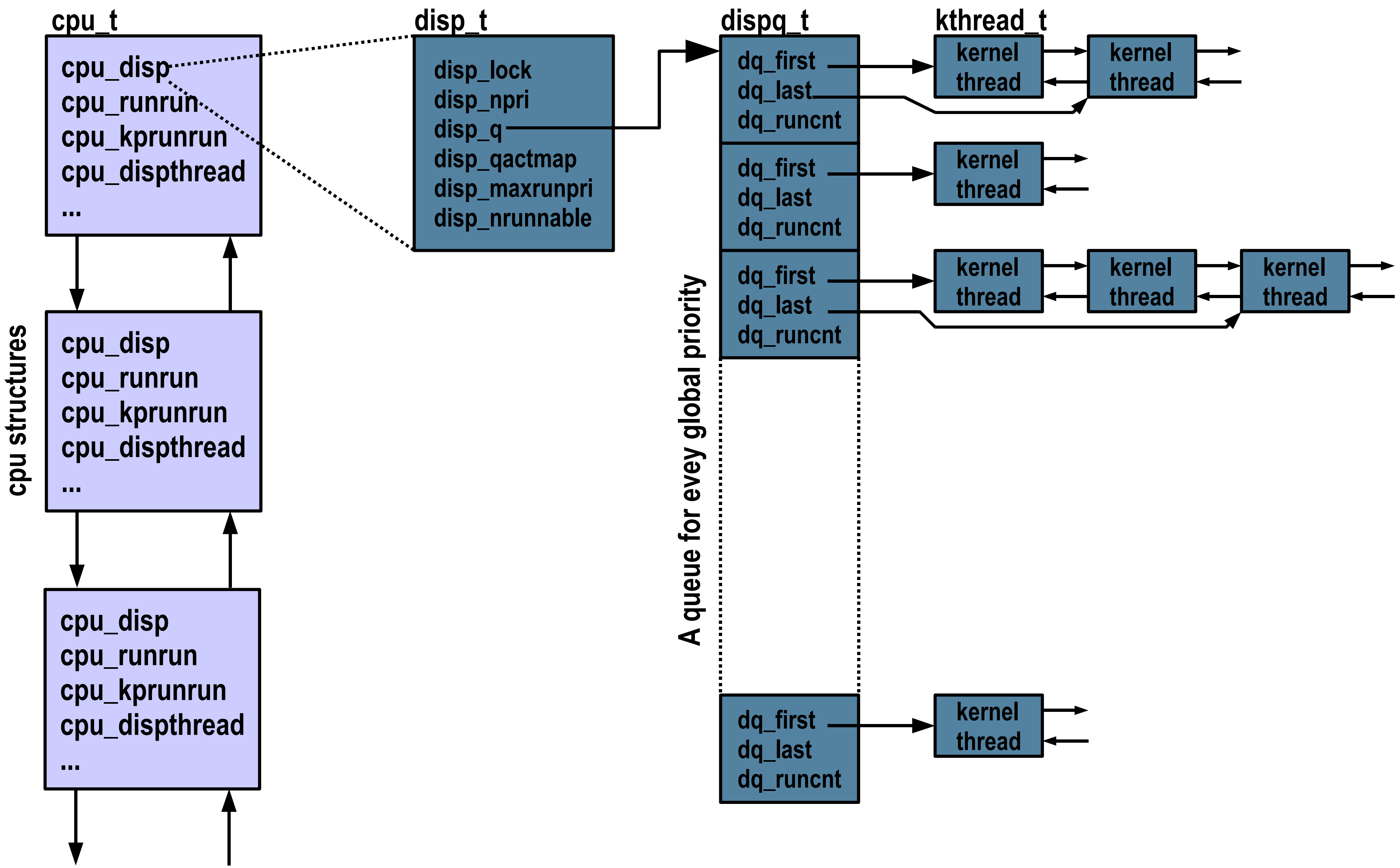
Scheduling Class & Priority of Threads

```
solaris10> ps -eLc
   PID   LWP  CLS PRI TTY        LTIME CMD
     0     1  SYS  96 ?           0:00 sched
     1     1   TS  59 ?           0:00 init
     2     1  SYS  98 ?           0:00 pageout
     3     1  SYS  60 ?           5:08 fsflush
   402     1   TS  59 ?           0:00 sac
   269     1   TS  59 ?           0:00 utmpd
   225     1   TS  59 ?           0:00 automoun
   225     2   TS  59 ?           0:00 automoun
   225     4   TS  59 ?           0:00 automoun
    54     1   TS  59 ?           0:00 sysevent
    54     2   TS  59 ?           0:00 sysevent
    54     3   TS  59 ?           0:00 sysevent
    [snip]
   426     1   IA  59 ?           0:00 dtgreet
   343     1   TS  59 ?           0:00 mountd
   345     1   FX  60 ?           0:00 nfsd
   345     3   FX  60 ?           0:00 nfsd
   350     1   TS  59 ?           0:00 dtlogin
   375     1   TS  59 ?           0:00 snmpdx
   411     1   IA  59 ?           0:00 dtlogin
   412     1   IA  59 ??          0:00 fbconsol
   403     1   TS  59 console     0:00 ttymon
   405     1   TS  59 ?           0:00 ttymon
   406     1   IA  59 ?           0:03 Xsun
   410     1   TS  59 ?           0:00 sshd
   409     1   TS  59 ?           0:00 snmpd
  1040     1   TS  59 ?           0:00 in.rlogi
  1059     1   TS  49 pts/2       0:00 ps
solaris10>
```

Dispatch Queues & Dispatch Tables

- Dispatch queues
  - Per-CPU run queues
    - Actually, a queue of queues
  - Ordered by thread priority
  - Queue occupation represented via a bitmap
  - For Realtime threads, a system-wide kernel preempt queue is maintained
    - Realtime threads are placed on this queue, not the per-CPU queues
    - If processor sets are configured, a kernel preempt queue exists for each processor set
- Dispatch tables
  - Per-scheduling class parameter tables
  - Time quantums and priorities
  - tuneable via `dispadmin`(1M)

Per-CPU Dispatch Queues



Timeshare Dispatch Table

- TS and IA class share the same dispatch table
  - *RES*. Defines the granularity of ts_quantum
  - *ts_quantum*. CPU time for next ONPROC state
  - *ts_tqexp*. New priority if time quantum expires
  - *ts_slpret*. New priority when state change from TS_SLEEP to TS_RUN
  - *ts_maxwait*. “waited too long” ticks
  - *ts_lwait.* New priority if “waited too long”

```
# dispadmin -g -c TS
# Time Sharing Dispatcher Configuration
RES=1000

# ts_quantum             ts_tqexp ts_slpret  ts_maxwait     ts_lwait            PRIORITY LEVEL
      200             0         50            0         50                #        0
      200             0         50            0         50                #        1
        .........
      160             0         51            0         51                #       10
      160             1         51            0         51                #       11
        ..........
      120             10        52            0         52                #       20
      120             11        52            0         52                #       21
        .........
      80              20        53            0         53                #       30
      80              21        53            0         53                #       31
        ..........
      40              30        55            0         55                #       40
      40              31        55            0         55                #       41
        ...........
      20              49        59            32000     59                #       59
```

RT, FX & FSS Dispatch Tables

- RT
  - Time quantum only
  - For each possible priority
- FX
  - Time quantum only
  - For each possible priority
- FSS
  - Time quantum only
  - Just one, not defined for each priority level
    - Because FSS is share based, not priority based
- SYS
  - No dispatch table
  - Not needed, no rules apply
- INT
  - Not really a scheduling class

Dispatch Queue Placement

- Queue placement is based a few simple parameters
  - The thread priority
  - Processor binding/Processor set
  - Processor thread last ran on
    - Warm affinity
  - Depth and priority of existing runnable threads
  - Solaris 9 added Memory Placement Optimization (MPO) enabled will keep thread in defined locality group (lgroup)

```
if (thread is bound to CPU-n) && (pri < kpreemptpri)
        CPU-n dispatch queue
if (thread is bound to CPU-n) && (pri >= kpreemptpri)
        CPU-n dispatch queue
if (thread is not bound) && (pri < kpreemptpri)
    place thread on a CPU dispatch queue
if (thread is not bound) && (pri >= kpreemptpri)
    place thread on cp_kp_queue
```

Thread Preemption

- Two classes of preemption
  - User preemption
    - A higher priority thread became runnable, but it's not a realtime thread
    - Flagged via cpu_runrun in CPU structure
    - Next clock tick, you're outta here
  - Kernel preemption
    - A realtime thread became runnable. Even OS kernel threads will get preempted
    - Poke the CPU (cross-call) and preempt the running thread now
  - *Note that threads that use-up their time quantum are evicted via the preempt mechanism*
  - Monitor via “icsw” column in `mpstat`(1)

Thread Execution

- Run until
  - A preemption occurs
    - Transition from S_ONPROC to S_RUN
    - placed back on a run queue
  - A blocking system call is issued
    - e.g. read(2)
    - Transition from S_ONPROC to S_SLEEP
    - Placed on a sleep queue
  - Done and exit
    - Clean up
  - Interrupt to the CPU you're running on
    - pinned for interrupt thread to run
    - unpinned to continue

Context Switching

```
CPU minf mjf xcal  intr ithr  csw icsw migr smtx  srw syscl  usr sys  wt idl
  0   74   2  998   417  302  450   18   45  114    0  1501   56   7   0  37
  1  125   3  797   120  102 1107   16   58  494    0  1631   41  16   0  44
  4  209   2  253   114  100  489   12   45   90    0  1877   56  11   0  33
  5  503   7 2448   122  100  913   21   53  225    0  2626   32  21   0  48
  8  287   3   60   120  100  771   20   35  122    0  1569   50  12   0  38
  9   46   1   51   115   99  671   16   20  787    0   846   81  16   0   3
 12  127   2  177   117  101  674   14   27  481    0   881   74  12   0  14
 13  375   7  658  1325 1302  671   23   49  289    0  1869   48  16   0  37
CPU minf mjf xcal  intr ithr  csw icsw migr smtx  srw syscl  usr sys  wt idl
  0    0   0  733   399  297  548   10    8  653    0   518   80  11   0   9
  1  182   4   45   117  100  412   16   34   49    0   904   54   8   0  38
  4  156   4  179   108  102 1029    6   46  223    0  1860   15  16   0  70
  5   98   1   53   110  100  568    9   19  338    0   741   60   9   0  31
  8   47   1   96   111  101  630    6   22  712    0   615   56  13   0  31
  9  143   4  127   116  102 1144   11   42  439    0  2443   33  15   0  52
 12  318   0  268   111  100  734    9   30   96    0  1455   19  12   0  69
 13   39   2   16   938  929  374    8    9  103    0   756   69   6   0  25
```

```
#!/usr/sbin/dtrace -Zqs
long inv_cnt;   /* all invountary context switches */
long tqe_cnt;   /* time quantum expiration count   */
long hpp_cnt;   /* higher-priority preempt count   */
long csw_cnt;   /* total number context switches   */

dtrace:::BEGIN
{
        inv_cnt = 0; tqe_cnt = 0; hpp_cnt = 0; csw_cnt = 0;

        printf("%-16s %-16s %-16s %-16s\n","TOTAL CSW","ALL INV","TQE_INV","HPP_INV");
        printf("==========================================================\n");
}

sysinfo:unix:preempt:inv_swtch
{
        inv_cnt += arg0;
}
sysinfo:unix::pswitch
{
        csw_cnt += arg0;
}

fbt:TS:ts_preempt:entry
/ ((tsproc_t *)args[0]->t_cldata)->ts_timeleft <= 1 /
{
        tqe_cnt++;
}

fbt:TS:ts_preempt:entry
/ ((tsproc_t *)args[0]->t_cldata)->ts_timeleft > 1 /
{
        hpp_cnt++;
}

fbt:RT:rt_preempt:entry
/ ((rtproc_t *)args[0]->t_cldata)->rt_timeleft <= 1 /
{
        tqe_cnt++;
}
fbt:RT:rt_preempt:entry
/ ((rtproc_t *)args[0]->t_cldata)->rt_timeleft > 1 /
{
        hpp_cnt++;
}
tick-1sec
{
        printf("%-16d %-16d %-16d %-16d\n",csw_cnt,inv_cnt,tqe_cnt,hpp_cnt);

        inv_cnt = 0; tqe_cnt = 0; hpp_cnt = 0; csw_cnt = 0;
}
```

```
solaris10> ./csw.d
TOTAL CSW         ALL INV          TQE_INV          HPP_INV
==========================================================
1544              63               24               40
3667              49               35               14
4163              59               34               26
3760              55               29               26
3839              71               39               32
3931              48               33               15
^C

solaris10> ./threads &
[2]     19913
solaris10>
solaris10> ./csw.d
TOTAL CSW         ALL INV          TQE_INV          HPP_INV
==========================================================
3985              1271             125              1149
5681              1842             199              1648
5025              1227             151              1080
9170              520              108              412
4100              390              84               307
2487              174              74               99
1841              113              64               50
6239              170              74               96
^C
1440              155              68               88
```

Observability and Performance

- Use `prstat`(1) and `ps`(1) to monitor running processes and threads
- Use `mpstat`(1) to monitor CPU utilization, context switch rates and thread migrations
- Use `dispadmin`(1M) to examine and change dispatch table parameters
- User `priocntl`(1) to change scheduling classes and priorities
  - `nice`(1) is obsolete (but there for compatibility)
  - User priorities also set via `priocntl`(1)
  - Must be root to use RT class

Dtrace sched provider probes:

- change-pri – change pri
- dequeue – exit run q
- enqueue – enter run q
- off-cpu – start running
- on-cpu – stop running
- preempt - preempted
- remain-cpu
- schedctl-nopreempt – hint that it is not ok to preempt
- schedctl-preempt – hint that it is ok to preempt
- schedctl-yield - hint to give up runnable state
- sleep – go to sleep
- surrender – preempt from another cpu
- tick – tick-based accounting
- wakeup – wakeup from sleep

Processors, Processor Controls & Binding

Processor Controls

- Processor controls provide for segregation of workload(s) and resources
- Processor status, state, management and control
  - Kernel linked list of CPU structs, one for each CPU
  - Bundled utilities
    - `psradm(1)`
    - `psrinfo(1)`
  - Processors can be taken offline
    - Kernel will not schedule threads on an offline CPU
  - The kernel can be instructed not to bind device interrupts to processor(s)
    - Or move them if bindings exist

Processor Control Commands

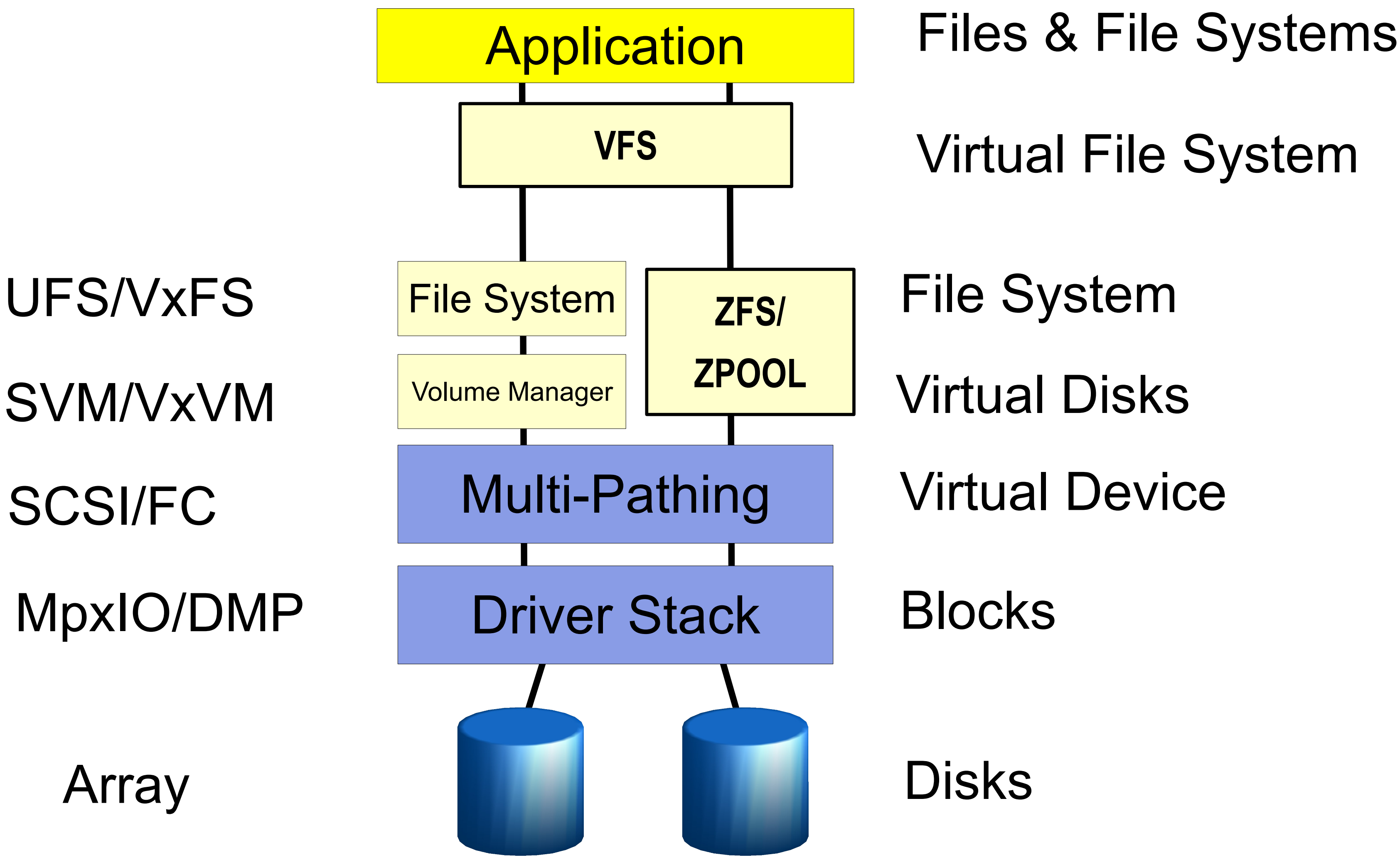
- psrinfo(1M) - provides information about the processors on the system. Use "-v" for verbose
- psradm(1M) - online/offline processors. Pre Sol 7, offline processors still handled interrupts. In Sol 7, you can disable interrupt participation as well
- psrset(1M) - creation and management of processor sets
- pbind(1M) - original processor bind command. Does not provide exclusive binding
- processor_bind(2), processor_info(2), pset_bind(2), pset_info(2), pset_creat(2), p_online(2)
  - system calls to do things programmatically

Processor Sets

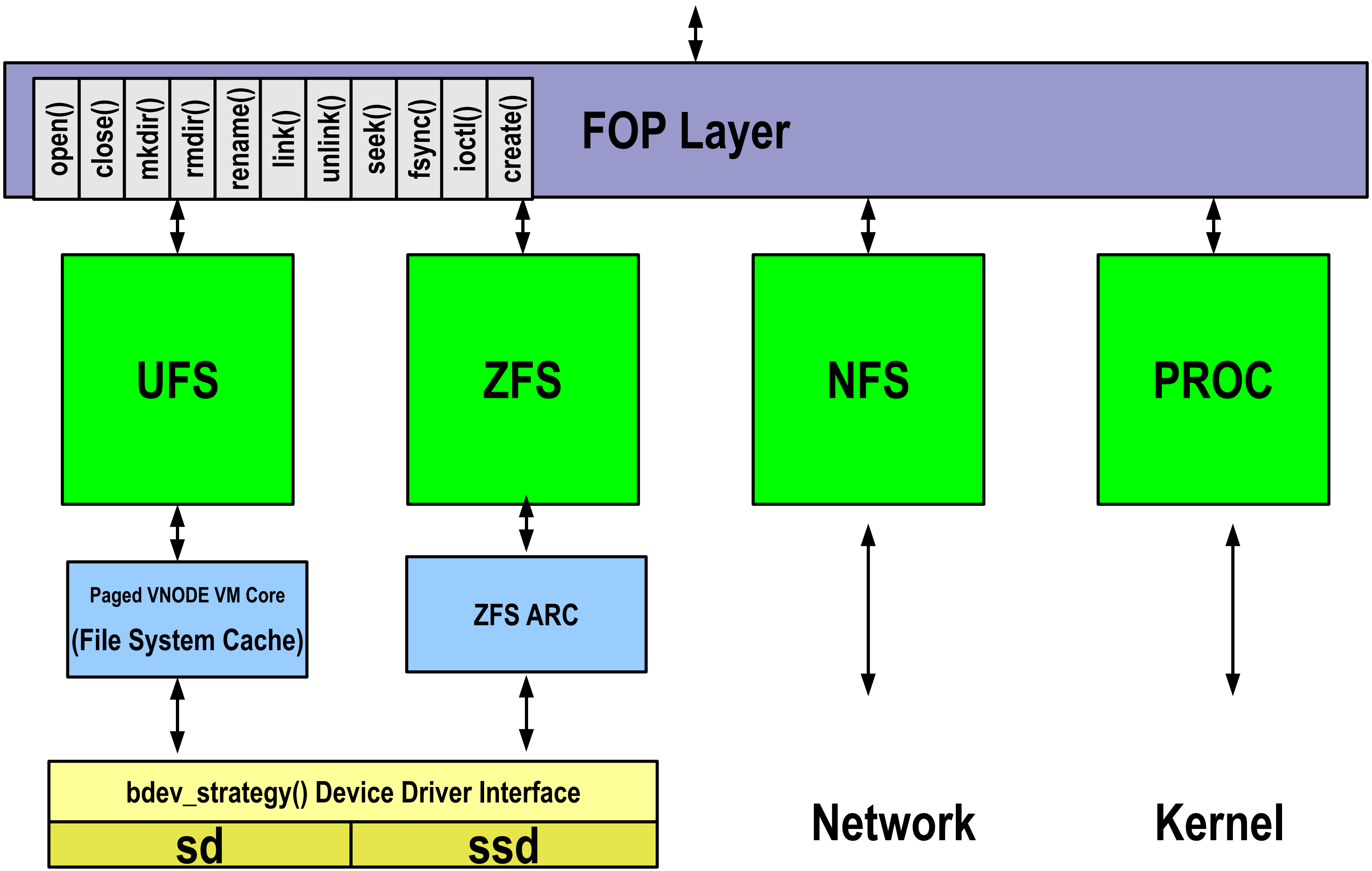
- Partition CPU resources for segregating workloads, applications and/or interrupt handling
- Dynamic
  - Create, bind, add, remove, etc, without reboots
- Once a set is created, the kernel will only schedule threads onto the set that have been explicitly bound to the set
  - And those threads will only ever be scheduled on CPUs in the set they've been bound to
- Interrupt disabling can be done on a set
  - Dedicate the set, through binding, to running application threads
  - Interrupt segregation can be effective if interrupt load is heavy
    - e.g. high network traffic

Session 4
File Systems &
Disk I/O
Performance

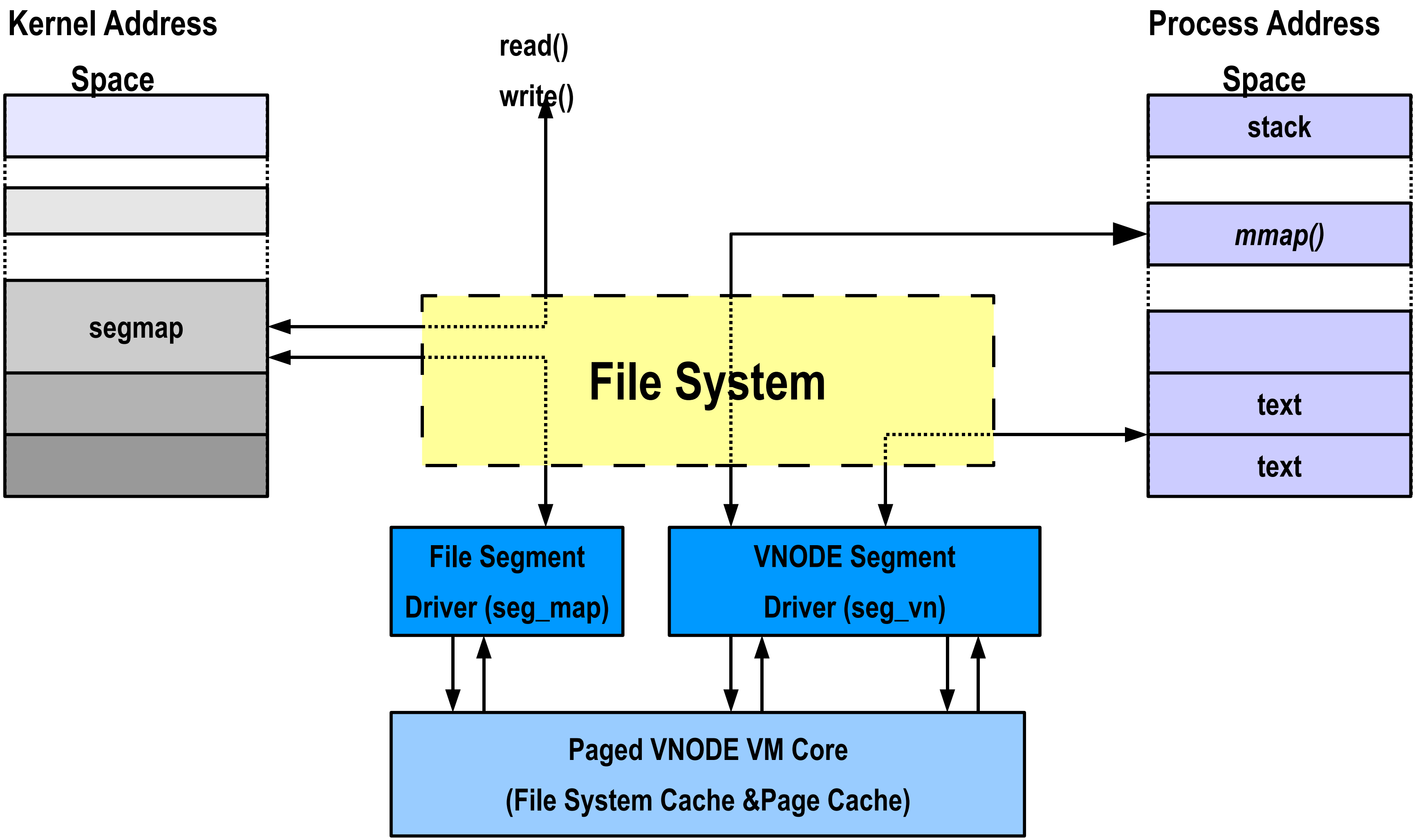
The Solaris File System/IO Stack



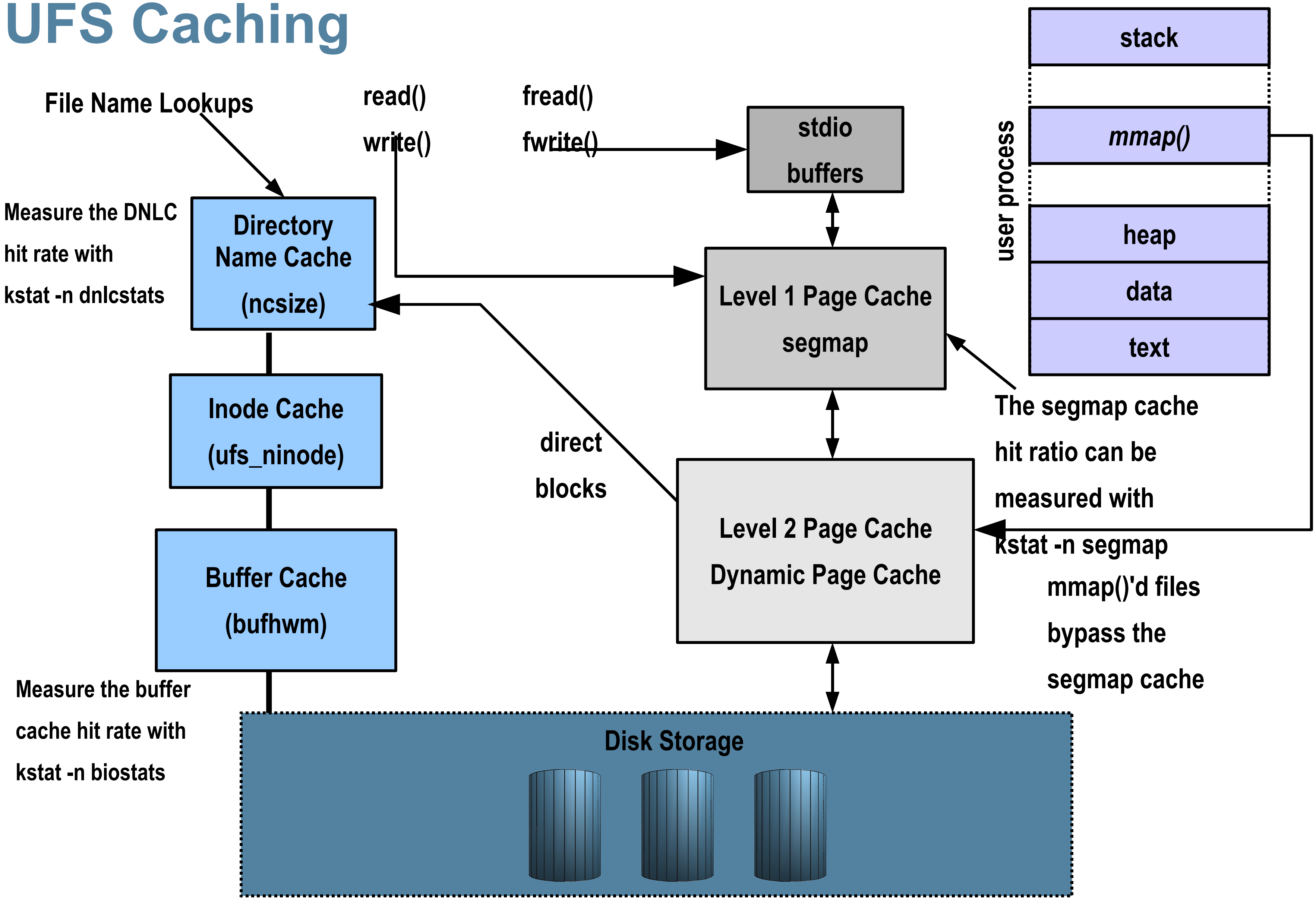
File System Architecture



UFS I/O


Kernel Address Space
read()
write()
Process Address Space
stack
mmap()
segmap
File System
text
text
File Segment Driver (seg_map)
VNODE Segment Driver (seg_vn)
Paged VNODE VM Core
(File System Cache &Page Cache)

UFS Caching


File Name Lookups
read()
write()
fread()
fwrite()
stdio
buffers
stack
mmap()
heap
data
text
user process
Measure the DNLC
hit rate with
kstat -n dnlcstats
Directory
Name Cache
(ncsize)
Level 1 Page Cache
segmap
Inode Cache
(ufs_ninode)
direct
blocks
The segmap cache
hit ratio can be
measured with
kstat -n segmap
Level 2 Page Cache
Dynamic Page Cache
mmap()'d files
bypass the
segmap cache
Buffer Cache
(bufhwm)
Measure the buffer
cache hit rate with
kstat -n biostats
Disk Storage

Filesystem performance

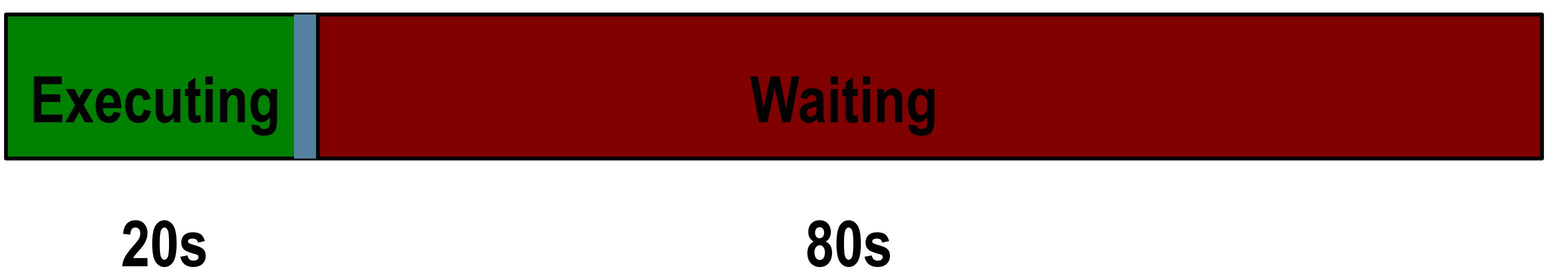
- Attribution
  - How much is my application being slowed by I/O?
  - i.e. How much faster would my app run if I optimized I/O?
- Accountability
  - What is causing I/O device utilization?
  - i.e. What user is causing this disk to be hot?
- Tuning/Optimizing
  - Tuning for sequential, random I/O and/or meta-data intensive applications

Solaris FS Perf Tools

- iostat: raw disk statistics
- sar -b: meta-data buffer cachestat
- vmstat -s: monitor dnlc
- Filebench: emulate and measure various FS workloads
- DTrace: trace physical I/O – IO provider
- DTrace: fsinfo provider
- DTrace: top for files – logical and physical per file
- DTrace: top for fs – logical and physical per filesystem
- DTraceToolkit – iosnoop and iotop

Simple performance model

- Single-threaded processes are simpler to estimate
  - Calculate elapsed vs. waiting for I/O time, express as a percentage
  - i.e. My app spent 80% of its execution time waiting for I/O
  - Inverse is potential speed up – e.g. 80% of time waiting equates to a potential 5x speedup
  - The key is to estimate the time spent waiting



Estimating wait time

- Elapsed vs. cpu seconds
  - Time <cmd>, estimate wait as real – user - sys
- Etruss
  - Uses microstates to estimate I/O as wait time
  - http://www.solarisinternals.com
- Measure explicitly with dtrace
  - Measure and total I/O wait per thread

Examining IO wait with dtrace

- Measuring on-cpu vs io-wait time:

```
sol10$ ./iowait.d 639
^C
Time breakdown (milliseconds):
 <on cpu>                                                   2478
 <I/O wait>                                                 6326

I/O wait breakdown (milliseconds):
 file1                                                       236
 file2                                                       241
 file4                                                       244
 file3                                                       264
 file5                                                       277
 file7                                                       330
 .
 .
 .
```

Solaris iostat

```
# iostat -xnz
                    extended device statistics
    r/s    w/s   kr/s   kw/s wait actv wsvc_t asvc_t  %w  %b device
  687.8    0.0 38015.3    0.0  0.0  1.9    0.0    2.7   0 100 c0d0
```

- Wait: number of threads queued for I/O
- Actv: number of threads performing I/O
- wsvc_t: Average time spend waiting on queue
- asvc_t: Average time performing I/O
- %w: Only useful if one thread is running on the entire machine – time spent waiting for I/O
- %b: Device utilization – only useful if device can do just 1 I/O at a time (invalid for arrays etc...)

Thread I/O example

```
sol$ cd labs/disks
sol$ ./1thread
 1079: 0.007: Random Read Version 1.8 05/02/17 IO personality successfully loaded
 1079: 0.008: Creating/pre-allocating files
 1079: 0.238: Waiting for preallocation threads to complete...
 1079: 0.238: Re-using file /filebench/bigfile0
 1079: 0.347: Starting 1 rand-read instances
 1080: 1.353: Starting 1 rand-thread threads
 1079: 4.363: Running for 600 seconds...
sol$ iostat -xncz 5
      cpu
 us sy wt id
 22  3  0 75
                    extended device statistics
    r/s    w/s   kr/s   kw/s wait actv wsvc_t asvc_t  %w  %b device
   62.7    0.3  501.4    2.7  0.0  0.9    0.0   14.1   0  89 c1d0
```

64 Thread I/O example

```
sol$ cd labs/disks
sol$ ./64thread
 1089: 0.095: Random Read Version 1.8 05/02/17 IO personality successfully loaded
 1089: 0.096: Creating/pre-allocating files
 1089: 0.279: Waiting for preallocation threads to complete...
 1089: 0.279: Re-using file /filebench/bigfile0
 1089: 0.385: Starting 1 rand-read instances
 1090: 1.389: Starting 64 rand-thread threads
 1089: 4.399: Running for 600 seconds...

sol$ iostat -xncz 5
      cpu
 us sy wt id
 15  1  0 83
                    extended device statistics
    r/s    w/s   kr/s   kw/s wait actv wsvc_t asvc_t  %w  %b device
   71.0    0.3  568.0   17.3 61.8  2.0  866.5   28.0 100 100 c1d0
```

Solaris iostat

- New Formatting flags -C, -l, -m, -r, -s, -z, -T
  - -C: report disk statistics by controller
  - -l n: Limit the number of disks to n
  - -m: Display mount points (most useful with -p)
  - -r: Display data n comma separated format
  - -s: Suppress state change messages
  - -z: Suppress entries with all zero values
  - -T d|u Display a timestamp in date (d) or unix time_t (u)

Examining Physical IO by file with dtrace

```
#pragma D option quiet

BEGIN
{
        printf("%10s %58s %2s %8s\n", "DEVICE", "FILE", "RW", "Size");
}

io:::start
{
        printf("%10s %58s %2s %8d\n", args[1]->dev_statname,
            args[2]->fi_pathname, args[0]->b_flags & B_READ ? "R" : "W",
            args[0]->b_bcount);
}

# dtrace -s ./iotrace

    DEVICE                                                       FILE RW     SIZE
     cmdk0                                /export/home/rmc/.sh_history  W     4096
     cmdk0                                  /opt/Acrobat4/bin/acroread  R     8192
     cmdk0                                  /opt/Acrobat4/bin/acroread  R     1024
     cmdk0                                  /var/tmp/wscon-:0.0-gLaW9a  W     3072
     cmdk0                            /opt/Acrobat4/Reader/AcroVersion  R     1024
     cmdk0              /opt/Acrobat4/Reader/intelsolaris/bin/acroread  R     8192
     cmdk0              /opt/Acrobat4/Reader/intelsolaris/bin/acroread  R     8192
     cmdk0              /opt/Acrobat4/Reader/intelsolaris/bin/acroread  R     4096
     cmdk0              /opt/Acrobat4/Reader/intelsolaris/bin/acroread  R     8192
     cmdk0              /opt/Acrobat4/Reader/intelsolaris/bin/acroread  R     8192
```

Physical Trace Example

```
sol8$ cd labs/disks
sol8$ ./64thread
 1089: 0.095: Random Read Version 1.8 05/02/17 IO personality successfully loaded
 1089: 0.096: Creating/pre-allocating files
 1089: 0.279: Waiting for preallocation threads to complete...
 1089: 0.279: Re-using file /filebench/bigfile0
 1089: 0.385: Starting 1 rand-read instances
 1090: 1.389: Starting 64 rand-thread threads
 1089: 4.399: Running for 600 seconds...

sol8$ iotrace.d
    DEVICE                                          FILE RW     Size
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
     cmdk0                            /filebench/bigfile0  R     8192
```

DTraceToolkit - iotop

```
# iotop -C
  Sampling... Please wait.
  2005 Jul 16 00:34:40,  load: 1.21,  disk_r:  12891 Kb,  disk_w:   1087 Kb

    UID    PID   PPID CMD              DEVICE  MAJ MIN D            BYTES
      0      3      0 fsflush          cmdk0   102   4 W              512
      0      3      0 fsflush          cmdk0   102   0 W            11776
      0  27751  20320 tar              cmdk0   102  16 W            23040
      0      3      0 fsflush          cmdk0   102   0 R            73728
      0      0      0 sched            cmdk0   102   0 R           548864
      0      0      0 sched            cmdk0   102   0 W          1078272
      0  27751  20320 tar              cmdk0   102  16 R          1514496
      0  27751  20320 tar              cmdk0   102   3 R         11767808
```

DTraceToolkit - iosnoop

```
# iosnoop
  UID   PID D     BLOCK   SIZE       COMM PATHNAME
  100 15795 R      3808   8192        tar /usr/bin/eject
  100 15795 R     35904   6144        tar /usr/bin/eject
  100 15795 R     39828   6144        tar /usr/bin/env
  100 15795 R      3872   8192        tar /usr/bin/expr
  100 15795 R     21120   7168        tar /usr/bin/expr
  100 15795 R     43680   6144        tar /usr/bin/false
  100 15795 R     44176   6144        tar /usr/bin/fdetach
  100 15795 R      3920   8192        tar /usr/bin/fdformat
  100 15795 R      3936   8192        tar /usr/bin/fdformat
  100 15795 R      4080   8192        tar /usr/bin/fdformat
  100 15795 R      9680   3072        tar /usr/bin/fdformat
  100 15795 R      4096   8192        tar /usr/bin/fgrep
  100 15795 R     46896   6144        tar /usr/bin/fgrep
  100 15795 R      4112   8192        tar /usr/bin/file
[...]
```

File system I/O via Virtual Memory

- File system I/O is performed by the VM system
  - Reads are performed by page-in
  - Write are performed by page-out
- Practical Implications
  - Virtual memory caches files, cache is dynamic
  - Minimum I/O size is the page size
  - Read/modify/write may occur on sub page-size writes
- Memory Allocation Policy:
  - File system cache is lower priority than app, kernel etc
  - File system cache grows when there is free memory available
  - File system cache shrinks when there is demand elsewhere.

File System Reads: A UFS Read

- Application calls read()
- Read system call calls fop_read()
- FOP layer redirector calls underlying filesystem
- FOP jumps into ufs_read
- UFS locates a mapping for the corresponding pages in the file system page cache using vnode/offset
- UFS asks segmap for a mapping to the pages
- If the page exists in the fs, data is copied to App.
  - We're done.
- If the page doesn't exist, a Major fault occurs
  - VM system invokes ufs_getpage()
  - UFS schedules a page size I/O for the page
  - When I/O is complete, data is copied to App.

vmstat -p

swap = free and unreserved swap in KBytes

free = free memory measured in pages

re = kilobytes reclaimed from cache/free list

mf = minor faults - the page was in memory but was not mapped

fr = kilobytes that have been destroyed or freed

de = kilobytes freed after writes

sr = kilobytes scanned / second

executable pages: kilobytes in - out - freed

anonymous pages: kilobytes in - out – freed

f le system pages:

kilobytes in - out - freed

```
# vmstat -p 5 5
     memory                  page                 executable      anonymous      filesystem
   swap    free     re  mf  fr   de   sr   epi  epo  epf    api  apo  apf   fpi  fpo  fpf
 ...
 46715224 891296 24   350 0    0    0     0    0    0      4    0    0    27    0    0
 46304792 897312 151  761 25   0    0    17    0    0      1    0    0   280   25   25
 45886168 899808 118  339 1    0    0     3    0    0      1    0    0   641    1    1
 46723376 899440 29   197 0    0    0     0    0    0     40    0    0    60    0    0
```

Observing the File System I/O Path

```
Sol10# cd labs/fs_paging
sol10# ./fsread
 2055: 0.004: Random Read Version 1.8 05/02/17 IO personality successfully loaded
 2055: 0.004: Creating/pre-allocating files
 2055: 0.008: Waiting for preallocation threads to complete...
 2055: 28.949: Pre-allocated file /filebench/bigfile0
 2055: 30.417: Starting 1 rand-read instances
 2056: 31.425: Starting 1 rand-thread threads
 2055: 34.435: Running for 600 seconds...

sol10# vmstat -p 3
     memory           page          executable      anonymous      filesystem
   swap  free  re  mf  fr  de  sr  epi  epo  epf  api  apo  apf  fpi  fpo  fpf
 1057528 523080 22 105  0   0   8    5    0    0    0    0    0   63    0    0
 776904 197472  0  12   0   0   0    0    0    0    0    0    0  559    0    0
 776904 195752  0   0   0   0   0    0    0    0    0    0    0  555    0    0
 776904 194100  0   0   0   0   0    0    0    0    0    0    0  573    0    0

sol10# ./pagingflow.d
  0  => pread64                                               0
  0    | pageio_setup:pgin                                   40
  0    | pageio_setup:pgpgin                                 42
  0    | pageio_setup:maj_fault                              43
  0    | pageio_setup:fspgin                                 45
  0    | bdev_strategy:start                                 52
  0    | biodone:done                                     11599
  0  <= pread64                                          11626
```

Observing File System I/O

```
Sol10# cd labs/fs_paging
sol10# ./fsread
 2055: 0.004: Random Read Version 1.8 05/02/17 IO personality successfully loaded
 2055: 0.004: Creating/pre-allocating files
 2055: 0.008: Waiting for preallocation threads to complete...
 2055: 28.949: Pre-allocated file /filebench/bigfile0
 2055: 30.417: Starting 1 rand-read instances
 2056: 31.425: Starting 1 rand-thread threads
 2055: 34.435: Running for 600 seconds...

sol10# ./fspaging.d
Event          Device                                                   Path RW     Size
get-page                                             /filebench/bigfile0            8192
getpage-io      cmdk0                                /filebench/bigfile0  R         8192
get-page                                             /filebench/bigfile0            8192
getpage-io      cmdk0                                /filebench/bigfile0  R         8192
get-page                                             /filebench/bigfile0            8192
getpage-io      cmdk0                                /filebench/bigfile0  R         8192
get-page                                             /filebench/bigfile0            8192
```

Observing File System I/O: Sync Writes

```
Sol10# cd labs/fs_paging
sol10# ./fswritesync
 2276: 0.008: Random Write Version 1.8 05/02/17 IO personality successfully loaded
 2276: 0.009: Creating/pre-allocating files
 2276: 0.464: Waiting for preallocation threads to complete...
 2276: 0.464: Re-using file /filebench/bigfile0
 2276: 0.738: Starting 1 rand-write instances
 2277: 1.742: Starting 1 rand-thread threads
 2276: 4.743: Running for 600 seconds...

sol10# ./fspaging.d
Event          Device                                                  Path RW     Size   Offset
put-page                                                 /filebench/bigfile0       8192
putpage-io       cmdk0                                   /filebench/bigfile0  W    8192 18702224
other-io         cmdk0                                                <none>  W     512    69219
put-page                                                 /filebench/bigfile0       8192
putpage-io       cmdk0                                   /filebench/bigfile0  W    8192 11562912
other-io         cmdk0                                                <none>  W     512    69220
put-page                                                 /filebench/bigfile0       8192
putpage-io       cmdk0                                   /filebench/bigfile0  W    8192 10847040
other-io         cmdk0                                                <none>  W     512    69221
put-page                                                 /filebench/bigfile0       8192
putpage-io       cmdk0                                   /filebench/bigfile0  W    8192 22170752
other-io         cmdk0                                                <none>  W     512    69222
put-page                                                 /filebench/bigfile0       8192
putpage-io       cmdk0                                   /filebench/bigfile0  W    8192 25189616
other-io         cmdk0                                                <none>  W     512    69223
put-page                                                 /filebench/bigfile0       8192
```

fsinfo(1)

```
# fsstat ufs 1
 new  name   name  attr  attr lookup rddir  read read  write write
 file remov  chng   get   set    ops   ops   ops bytes   ops bytes
96.0K 91.7K    48 10.6M 46.0K  40.6M  429K  362K 57.2G 8.46M 67.3G ufs
    0     0     0     0     0      0     0     0     0     3   352 ufs
    0     0     0     0     0      0     0     0     0     2   176 ufs
    0     0     0     0     0      0     0     0     0     2   176 ufs
    0     0     0     0     0      0     0     0     0     2   176 ufs
    0     0     0     5     0      4     0     1 2.47K     3   240 ufs
    0     0     0     0     0      0     0     0     0     2   176 ufs
    0     0     0     0     0      9     0     0     0     2   176 ufs
    0     0     0    58     0    505     4     0     0     2   176 ufs
```

Memory Mapped I/O

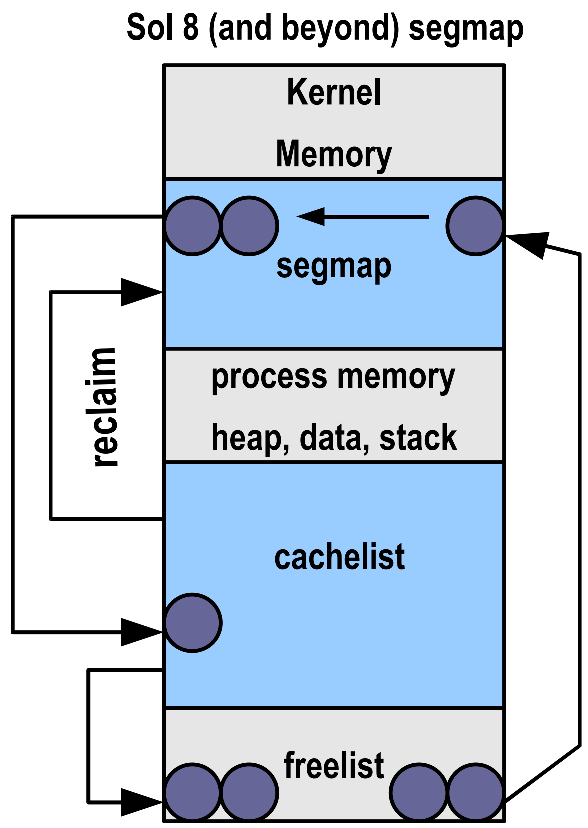
- Application maps file into process with mmap()
- Application references memory mapping
- If the page exists in the cache, we're done.
- If the page doesn't exist, a Major fault occurs
  - VM system invokes ufs_getpage()
  - UFS schedules a page size I/O for the page
  - When I/O is complete, data is copied to App.

Optimizing Random I/O File System Performance

Random I/O

- Attempt to cache as much as possible
  - The best I/O is the one you don't have to do
  - Eliminate physical I/O
  - Add more RAM to expand caches
  - Cache at the highest level
    - Cache in app if we can
    - In Oracle if possible
- Match common I/O size to FS block size
  - e.g. Write 2k on 8k FS = Read 8k, Write 8k

The Solaris UFS Cache



Tuning segmap (UFS L1 cache)

- By default, on SPARC, segmap is sized at 12% of physical memory
  - Effectively sets the minimum amount of file system cache on the system by caching in segmap over and above the dynamically-sized cachelist
- On Solaris 8/9
  - If the system memory is used primarily as a cache, cross calls (mpstat xcall) can be reduced by increasing the size of segmap via the system parameter segmap_percent (12 by default)
  - segmap_percent = 100 is like Solaris 7 without priority paging, and will cause a paging storm
  - Must keep segmap_percent at a reasonable value to prevent paging pressure on applications e.g. 50%
  - segkpm in Solaris 10 and OpenSolaris
- On Solaris 10 on X64, segmap is 64MB by default
  - Tune with segmapsize in /etc/system or eeprom
    - set segmapsize = `1073741824` (1 GB)
  - On 32-bit X64, max segmapsize is 128MB

Tuning segmap_percent

- There are kstat statistics for segmap hit rates
  - Estimate hit rate as (get_reclaim+get_use) / getmap

```
# kstat -n segmap
module: unix                            instance: 0
name:   segmap                          class:    vm

        crtime                          17.299814595
        fault                           17361
        faulta                          0
        free                            0
        free_dirty                      0
        free_notfree                    0
        get_nofree                      0
        get_reclaim                     67404
        get_reuse                       0
        get_unused                      0
        get_use                         83
        getmap                          71177
        pagecreate                      757
        rel_abort                       0
        rel_async                       3073
        rel_dontneed                    3072
        rel_free                        616
        rel_write                       2904
        release                         67658
        snaptime                        583596.778903492
```

UFS Access times

- Access times are updated when file is accessed or modified
  - e.g. A web server reading files will storm the disk with atime writes!
- Options allow atimes to be eliminated or deferred
  - dfratime: defer atime write until write
  - noatime: do not update access times, great for web servers and databases

Asynchronous I/O

- An API for single-threaded process to launch multiple outstanding I/Os
  - Multi-threaded programs could just just multiple threads
  - Oracle databases use this extensively
  - See aio_read(), aio_write() etc...
- Slightly different variants for RAW disk vs file system
  - UFS, NFS etc: libaio creates lwp's to handle requests via standard pread/pwrite system calls
  - RAW disk: I/Os are passed into kernel via kaio(), and then managed via task queues in the kernel
    - Moderately faster than user-level LWP emulation

Key UFS Features

- Direct I/O
  - Solaris 2.6+
- Logging
  - Solaris 7+
- Async I/O
  - Oracle 7.x, -> 8.1.5 - Yes
  - 8.1.7, 9i - New Option
- Concurrent Write Direct I/O
  - Solaris 8, 2/01

Database big rules...

- Always put re-do logs on Direct I/O
- Cache as much as possible in the SGA
- Use 64-Bit RDBMS
- Always use Asynch I/O
- Use Solaris 8 Concurrent Direct I/O
- Place as many tables as possible on Direct I/O, assuming SGA sized correct
- Place write-intensive tables on Direct I/O

Sequential I/O

- Disk performance fundamentals
  - Disk seek latency will dominate for random I/O
    - ~5ms per seek
  - A typical disk will do ~200 I/Os per second random I/O
  - 200 x 8k = 1.6MB/s
  - Seekless transfers are typically capable of ~50MB/s
    - Requires I/O sizes of 64k+
- Optimizing for sequential I/O
  - Maximizing I/O sizes
  - Eliminating seeks
  - Minimizing OS copies

Sequential I/O – Looking at disks via iostat

- Use iostat to determine average I/O size
  - I/O size = kbytes/s divided by I/Os per second
- What is the I/O size in our example?
  - 38015 / 687 = 56k
  - Too small for best sequential performance

```
# iostat -xnz
                    extended device statistics
    r/s    w/s   kr/s   kw/s wait actv wsvc_t asvc_t  %w  %b device
  687.8    0.0 38015.3    0.0  0.0  1.9    0.0    2.7   0 100 c0d0
```

Sequential I/O – Maximizing I/O Sizes

- Application
  - Ensure application is issuing large writes
    - 1MB is a good starting point
  - truss or dtrace app
- File System
  - Ensure file system groups I/Os and does read ahead
  - A well tuned fs will group small app I/Os into large Physical I/Os
  - e.g. UFS cluster size
- IO Framework
  - Ensure large I/O's can pass though
  - System param *maxphys* set largest I/O size
- Volume Manager
  - md_maxphys for SVM, or equiv for Veritas
- SCSI or ATA drivers often set defaults to upper layers

Sequential on UFS

- Sequential mode is detected by 2 adjacent operations
  - e.g read 8k, read8k
- UFS uses “clusters” to group reads/write
  - UFS “maxcontig” param, units are 8k
  - Maxcontig becomes the I/O size for sequential
  - Cluster size defaults to 1MB on Sun FCAL
    - 56k on x86, 128k on SCSI
    - Auto-detected from SCSI driver's default
    - Set by default at newfs time (can be overridden)
  - e.g. Set cluster to 1MB for optimal sequential perf...
  - Check size with “mkfs -m”, set with “tunefs -a”

```
# mkfs -m /dev/dsk/c0d0s0
mkfs -F ufs -o nsect=63,ntrack=32,bsize=8192,fragsize=1024,cgsize=49,free=1,rps=60,
nbpi=8143,opt=t,apc=0,gap=0,nrpos=8,maxcontig=7,mtb=n /dev/dsk/c0d0s0 14680512

# tunefs -a 128 /dev/rdsk/...
```

Sequential on UFS

- Cluster Read
  - When sequential detected, read ahead entire cluster
  - Subsequent reads will hit in cache
  - Sequential blocks will not pollute cache by default
    - i.e. Sequential reads will be freed sooner
    - Sequential reads go to head of cachelist by default
    - Set system param *cache_read_ahead*=1 if all reads should be cached
- Cluster Write
  - When sequential detected, writes are deferred until cluster is full

UFS write throttle

- UFS will block when there are too many pending dirty pages
  - Application writes by default go to memory, and are written asynchronously
  - Throttle blocks to prevent filling memory with async. Writes
- Solaris 8 Defaults
  - Block when 384k of unwritten cache
    - Set *ufs_HW*=<bytes>
  - Resume when 256k of unwritten cache
    - Set *ufs_LW*=<bytes>
- Solaris 9+ Defaults
  - Block when >16MB of unwritten cache
  - Resume when <8MB of unwritten cache

Direct I/O

- Introduced in Solaris 2.6
- Bypasses page cache
  - Zero copy: DMA from controller to user buffer
- Eliminate any paging interaction
  - No 8k block size I/O restriction
  - I/Os can be any multiple of 512 bytes
  - Avoids write breakup of O_SYNC writes
- But
  - No caching! Avoid unless application caches
  - No read ahead – application must do it's own
- Works on multiple file systems
  - UFS, NFS, VxFS, QFS

Direct I/O

- Enabling direct I/O
  - Direct I/O is a global setting, per file or filesystem
  - Mount option

```
# mount -o forcedirectio /dev/dsk... /mnt
```

  - Library call

```
directio(fd, DIRECTIO_ON | DIRECTIO_OFF)
```

- Some applications can call directio(3c)
  - e.g. Oracle – see later slides

Enabling Direct I/O

- Monitoring Direct I/O via directiostat
  - See http://www.solarisinternals.com/tools

```
# directiostat 3
  lreads lwrites  preads pwrites     Krd      Kwr holdrds  nflush
       0       0       0       0       0        0       0       0
       0       0       0       0       0        0       0       0
       0       0       0       0       0        0       0       0

lreads = logical reads to the UFS via directio

lwrites = logical writes to the UFS via directio

preads = physical reads to media

pwrites = physical writes to media

Krd = kilobytes read

Kwr = kilobytes written

nflush = number of cached pages flushed

holdrds = number of times the read was a "hole" in the file.
```

Using Direct I/O

- Enable per-mount point is the simplest option
- Remember, it's a system-wide setting
- Use sparingly, only applications which don't want caching will benefit
  - It disables caching, read ahead, write behind
  - e.g. Databases that have their own cache
  - e.g. Streaming high bandwidth in/out
- Check the side effects
  - Even though some applications can benefit, it may have side affects for others using the same files
    - e.g. Broken backup utils doing small I/O's will hurt due to lack of prefetch

ZFS

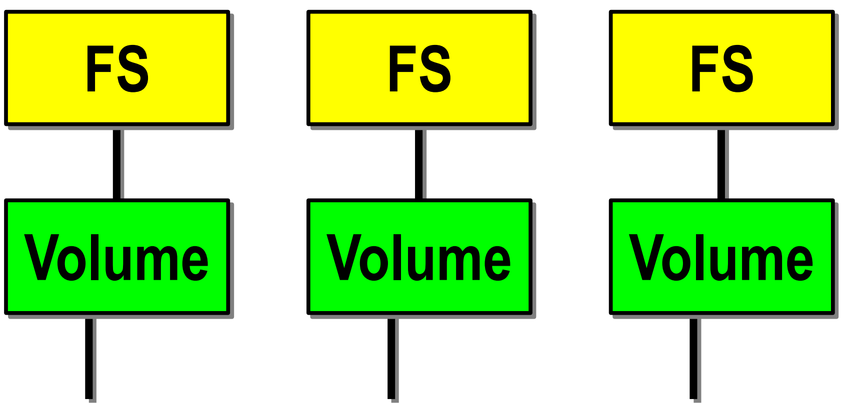
ZFS

- Started from scratch with today's problems in mind
- Pooled Storage
  - Do for storage what VM does for RAM
- End-to-End Data integrity
  - Block-level checksum
  - Self-correcting when redundant data available
  - No more silent data corruption
- Transaction Model
  - COW updates – no changes to on-disk data
  - FS on-disk integrity maintained
  - Many opportunities for performance optimizations (IO scheduler and transaction reordering)
- Massive Scale – 128 bits

FS/Volume Model vs. Pooled Storage

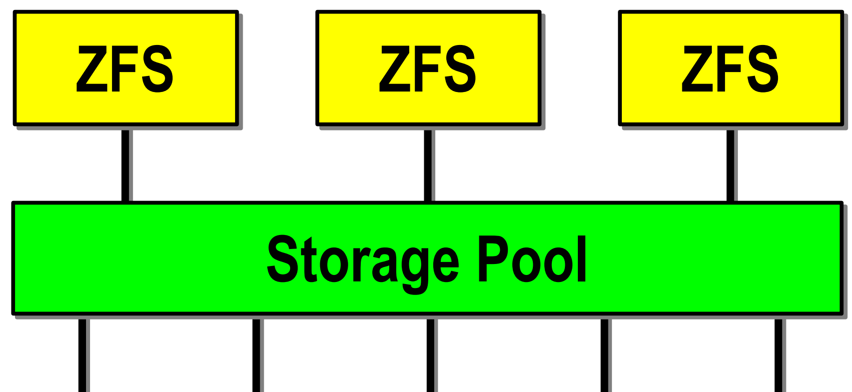
Traditional Volumes

- Abstraction: virtual disk
- Partition/volume for each FS
- Grow/shrink by hand
- Each FS has limited bandwidth
- Storage is fragmented, stranded



ZFS Pooled Storage

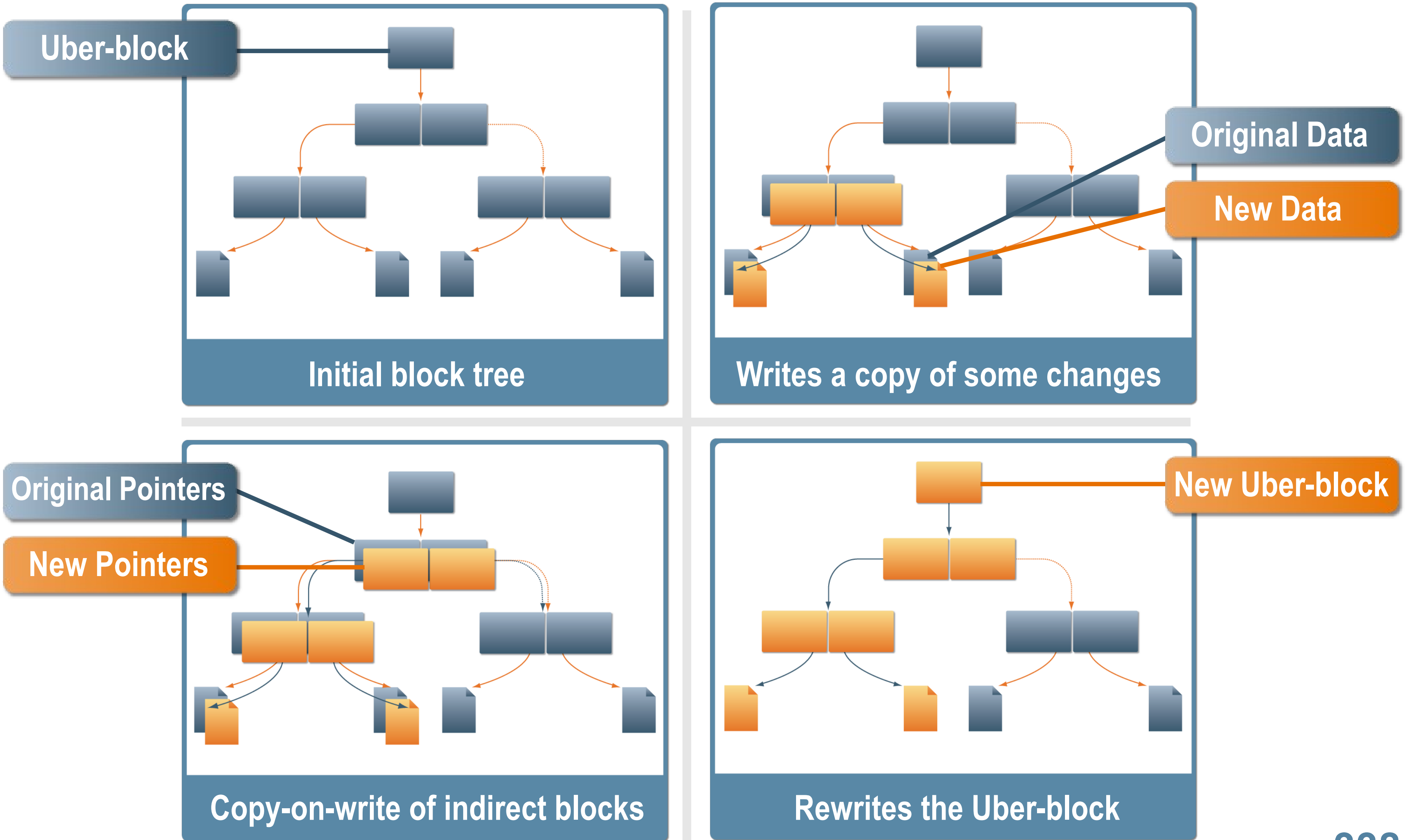
- Abstraction: malloc/free
- No partitions to manage
- Grow/shrink automatically
- All bandwidth always available
- All storage in the pool is shared



ZFS Data Integrity Model

- Copy-on-write, transactional design
- Everything is checksummed
- RAID-Z/Mirroring protection
- Ditto Blocks
- Disk Scrubbing
- Write Failure Handling

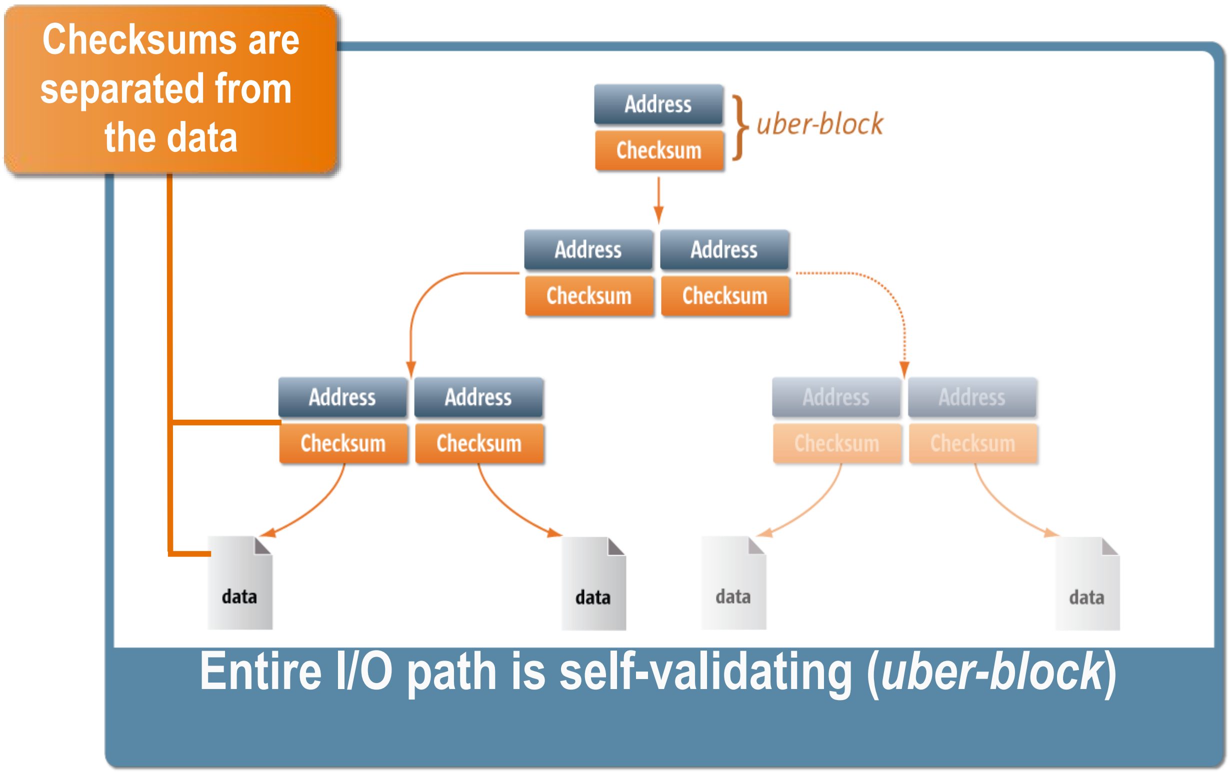
Copy-on-Write and Transactional



Measurements at CERN

- Wrote a simple application to write/verify 1GB file
  - Write 1MB, sleep 1 second, etc. until 1GB has been written
  - Read 1MB, verify, sleep 1 second, etc.
- Ran on 3000 rack servers with HW RAID card
- After 3 weeks, found <u>152</u> instances of <u>silent</u> data corruption
  - Previously thought “everything was fine”
- HW RAID only detected “noisy” data errors
- Need end-to-end verification to catch silent data corruption

End-to-End Checksums



Prevents:

- Silent data corruption
- Panics from corrupted metadata
- Phantom writes
- Misdirected reads and writes
- DMA parity errors
- Errors from driver bugs
- Accidental overwrites

Disk Scrubbing

- Uses checksums to verify the integrity of all the data
- Traverses metadata to read every copy of every block
- Finds latent errors while they're still correctable
- It's like ECC memory scrubbing – but for disks
- Provides fast and reliable re-silvering of mirrors

- Copy-on-Write Design
- Multiple Block Sizes
- Pipelined I/O
- Dynamic Striping
- Intelligent Pre-Fetch
- Separate Intent Log
- Dedicated cache device

Architected for Speed

Variable Block Size

- No single block size is optimal for everything
  - Large blocks: less metadata, higher bandwidth
  - Small blocks: more space-efficient for small objects
  - Record-structured files (e.g. databases) have natural granularity;
    filesystem must match it to avoid read/modify/write
- Why not arbitrary extents?
  - Extents don't COW or checksum nicely (too big)
  - Large blocks suffice to run disks at platter speed
- Per-object granularity
  - A 37k file consumes 37k – no wasted space
- Enables transparent block-based compression

ZFS Intent Log (ZIL)

- Satisfies synchronous writes semantics
  - O_SYNC/O_DSYNC
- Blocks are allocated from the main pool
  - Guaranteed to be written to stable storage before system call returns
- Examples:
  - Database often utilize synchronous writes to ensure transactions are on stable storage
  - NFS and other applications can issue fsync() to commit prior to writes

Separate Intent Log (slog)

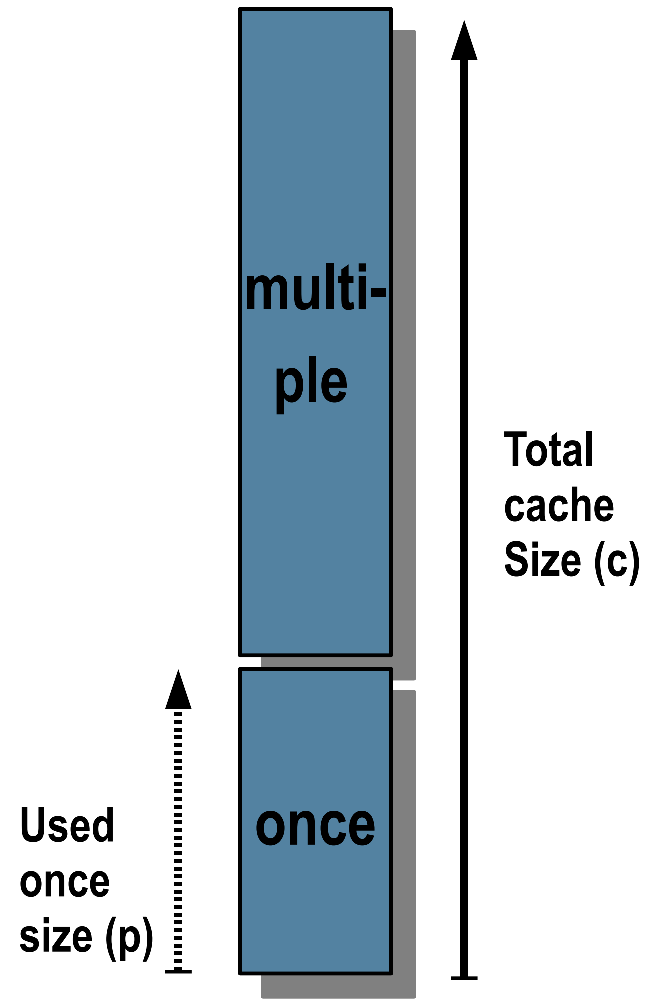
- Leverages high speed devices for dedicated intent log processing
  - Low latency devices such as SSDs (aka Logzilla)
- Can be mirrored and striped
- Blocks are allocated from dedicated log device
  - Failure reverts back to general pool

Example: Create a pool with a dedicated log device

```
# zpool create tank mirror c0d0 c1d0 log c2d0
```

Adaptive Replacement Cache (ARC)

- Scan-resistant LRU (least recently used)
- Cache size divided into two:
  - Used once
  - Used multiple times
- Automatically adjust to memory pressure and workload
  - Data which is not being referenced is evicted
  - Ratio of once/multiple adjust dynamically based on workload



L2ARC – cache device

Only on opensolaris

- Provides a level of caching between main memory and disk
  - Utilizes specialized read-biased SSDs to extend the cache (aka "Readzilla")
- Asynchronously populates the cache
  - Moves blocks from the ARC to L2ARC cache device

Example: Create a pool with a cache device

```
# zpool create tank mirror c0d0 c1d0 cache c2d0
```

Typical way to Improve Performance

- Buy lots of RAM
  - Cache as much as possible
  - Use DRAM to compensate for slower disks
- Use lots of spindles
  - Spread the load across as many devices as possible
  - Use the outer most cylinders of the disk (make sure the disks don't seek)
  - Use NVRAM
- Throw $$$ at the problem

How to get terrible performance

- Run against storage array that flush caches
- Run simple benchmarks without decoding the numbers
  - compare write to cache vs write to disk
- Run the pool at 95% disk full
- Do random reads from widest raid-z
- Run a very large DB without tuning the recordsize
- Don't provision enough CPU
- Don't configure swap space
- Don't read the ZFS Best Practices

How to get Great performance

- small files (<128K)
  - ufs allocates 1 inode per MB
  - netapps 1 / 32K
  - ZFS uses 1.2K to store 1K files !!!
  - Create 10s of files per single I/Os
  - $ miss reads == single disk I/O
- ZFS does constant time snapshot
  - it's basically a noop to take a snapshot
  - snap deletions proportional to changes
  - snapshots helps simplify your business

How to get Great performance

- Run ZFS in the storage back end (7000 Storage)
- Or provision for CPU usage.
- Configure enough RPM
  - 2 Mirrored 7.2 K RPM vs 1 x 15 K RPM in Raid-5
- Move Spindle Constrained setup to ZFS
  - write streaming + I/O aggregation
    - efficient use of spindles on writes,
    - 100% full stripes in storage
  - free spindles for reads
  - use a separate intent log (NVRAM or SSD or just N separate spindles) for an extra boost

Solaris 10 Update 6

- Finally got write throttling, ZFS won't eat all of memory
  - Grows and shrink dance now as designed
  - Capping the ARC seems commonly done
  - ZFS reports accurate freemem, others cache data in freemem
- Cache flushes to SAN array partially solved
  - HDS, EMC with recent firmware are ok.
  - Can be tuned per array
  - Others ? set zfs_nocacheflush (cf evil tuning guide)
- Vdev level prefetching is auto tuning
  - no problems there

Solaris 10 Update 6

- We have the separate intent log
  - one or a few disks, but preferably SSD or NVRAM/DRAM device

Upcoming

- L2 ARC
  - on/off per dataset
- ARC
  - on/off per dataset, ~directio
- Storage 7000
  - Tracks Nevada

Tuning is Evil

- Leave a trace, explain motivation
  - zfs_nocacheflush (on storage arrays that do)
  - capping the ARC (to preserve large pages)
  - zfs_prefetch_disable (zfetch consuming cpus)
  - zfs_vdev_max_pending (default 35, 10-16 for DB)
  - zil_disable (NO!!! don't or face application corruptions)
- No tuning required
  - vdev prefetch (issue now fixed)

ZFS Best Practices

- Tune recordsize only on fixed records DB files
- Mirror for performance
- 64-bit kernel (allows greater ZFS caches)
- configure swap (don't be scared by low memory)
- Don't slice up devices (confuses I/O scheduler)
- For raid-z[2] : don't go two wide (for random reads)
- Isolate DB log writer if that is critical (use few devices)
- Separate Root pool (system's identify) and data pools (system's function)

ZFS Best Practices

- Don't mix legacy and non legacy shares (it's confusing)
- 1 FS per user (1 quota/reserv; user quota are coming)
- Rolling Snapshots (smf service)
- Instruct backup tool to skip .zfs
- Keep pool below 80% full (helps COW)

MySQL Best Practices

- Match Recordsize with DB (16K)
- Use a separate intent log device within main zpool
- Find creative use of Snapshot/Clones send/recv
  - backups
  - master & slave architecture
- Use the ARC and L2ARC instead of disk RPM
  - a caching 7000 series serving masters & slaves
- NFS Directio and Jumbo Frames
  - save CPU cycles and memory for application
- Set innodb_doublewrite=0
- `Linux`
  - `innodb_flush_method = O_DIRECT`
  - `echo noop > /sys/block/sde/queue/scheduler`

Tuning & Best Practices

- Tuning and BP wikis
  - http://www.solarisinternals.com/wiki/index.php/ZFS_Best_Practices_Guide
  - http://www.solarisinternals.com/wiki/index.php/ZFS_Evil_Tuning_Guide
  - http://www.solarisinternals.com/wiki/index.php/ZFS_for_Databases
  - http://en.wikipedia.org/wiki/Zfs
- ZFS Dynamics : In-Depth view
  - http://blogs.sun.com/roch/entry/the_dynamics_of_zfs
- Blue Prints
  - http://wikis.sun.com/display/BluePrints/Main
- Performance Savvy Bloggers
  - joyent (Ben Rockwood), Smugmug (Don Mcaskill), Neel (Oracle and MySQL), Media Temple

Networks

Some Useful Numbers

- 1Gbit – theoretical 134MB/sec (megaBYTES)
- 10Gbit – theoretical 1.3GB/sec (gigaBYTES)

Bus	Technology	Bandwidth
PCI	32bit/33Mhz	133MB/sec
PCI	32bit/66Mhz	266MB/sec
PCI	64bit/66Mhz	530MB/sec
PCI-X	64bit/133Mhz	1GB/sec
PCI Express	1 lane, v1.X	250MB/sec
PCI Express	2 lanes, v1.X	500MB/sec
PCI Express	4 lanes, v1.X	1GB/sec
PCI Express	8 lanes, v1.x	2GB/sec (1.7GB/sec)

Networks...

- Network performance and tuning is probably the most difficult to setup and measure
  - Hardware choices (NICs, PCI-Express attributes, platform-specific (SPARC versus X64) attributes), network switches
  - Software layers – TCP/IP stack, platform-specific device stack, platform-independent device stack...
  - OS releases (Solaris 10 updates versus NV)
    - software churn
  - Resource allocation – CPU to support load
  - Tuning methods - /etc/system and ndd(1M)
- Bandwidth is often the quoted performance metric
  - And it's important, but...
  - Many workloads care more about packets-per-second and latency

NICs and Drivers

- The device name (ifconfig -a) is the driver
  - It's possible for multiple drivers to be available for the same hardware, i.e. configuring T2000 NICs with either e1000g or ipge (note: e1000g is better)

NICs and Drivers

NIC Tuneables

Networks

- Key Observables
  - Link Utilization
  - Transmission, framing, checksum errors
  - Upstream software congestion
  - Routing
  - Over the wire latency
- What to measure
  - Link Bandwidth: nicstat
  - Link Speed: checkcable
  - Dropped upstream packets (nocanput)

Networking - Tools

- netstat – kstat based, packet rates, errors, etc
- kstat – raw counters for NICs and TCP/UDP/IP
- nx.se – SE toolkit utility for bandwidth
- nicstat – NIC utilization
- snmpnetstat – network stats from SNMP
- checkcable – NIC status
- ping – host status
- traceroute – path to host, latency and hops
- snoop – network packets
- TTCP – workload generator
- pathchar – path to host analysis
- ntop – network traffic sniffer
- tcptop – DTrace tool, per process network usage
- tcpsnoop – DTrace tool, network packets by process
- dtrace – TCP, UDP, IP, ICMP, NIC drivers, etc....

netstat(1)

```
# netstat -i 1
    input    bge0       output          input   (Total)    output
packets errs  packets errs  colls  packets errs  packets errs  colls
15381402 0     1280618 0      0      15384170 0     1283386 0      0
160      0     177      0     0     160      0     177      0     0
213      0     205      0     0     213      0     205      0     0
138      0     159      0     0     138      0     159      0     0
159      0     172      0     0     159      0     172      0     0
215      0     213      0     0     215      0     213      0     0
```

kstat(1)

```
# kstat -p bge:0:bge0:*bytes64
bge:0:bge0:obytes64     969276250
bge:0:bge0:rbytes64     1917373531
#
```

TCP

```
# netstat -s | grep Bytes
        tcpOutDataSegs      =862707     tcpOutDataBytes     =879539866
        tcpRetransSegs      =  1189     tcpRetransBytes     =1159401
        tcpInAckSegs        =473250     tcpInAckBytes       =879385959
        tcpInInorderSegs    =694607     tcpInInorderBytes   =623233594
        tcpInUnorderSegs    =  3926     tcpInUnorderBytes   =4877730
        tcpInDupSegs        =   187     tcpInDupBytes       = 75281
        tcpInPartDupSegs    =     6     tcpInPartDupBytes   =  7320
        tcpInPastWinSegs    =     0     tcpInPastWinBytes   =     0
# kstat -n tcp
module: tcp                              instance: 0
name:   tcp                              class:    mib2
        activeOpens                      4809
        attemptFails                     22
        connTableSize                    56
        connTableSize6                   84
        crtime                           237.364807266
        . . .
```

nicstat

```
$ nicstat 1
    Time    Int   rKb/s   wKb/s   rPk/s   wPk/s    rAvs    wAvs   %Util     Sat
12:33:04   hme0    1.51    4.84    7.26   10.32  213.03  480.04    0.05    0.00
12:33:05   hme0    0.20    0.26    3.00    3.00   68.67   90.00    0.00    0.00
12:33:06   hme0    0.14    0.26    2.00    3.00   73.00   90.00    0.00    0.00
12:33:07   hme0    0.14    0.52    2.00    6.00   73.00   88.00    0.01    0.00
12:33:08   hme0    0.24    0.36    3.00    4.00   81.33   92.00    0.00    0.00
12:33:09   hme0    2.20    1.77   16.00   18.00  140.62  100.72    0.03    0.00
12:33:10   hme0    0.49    0.58    8.00    9.00   63.25   66.00    0.01    0.00
12:33:11   hme0   12.16 1830.38  185.06 1326.42   67.26 1413.06   15.09    0.00
12:33:12   hme0   19.03 3094.19  292.88 2229.11   66.53 1421.40   25.50    0.00
12:33:13   hme0   19.55 3151.87  301.00 2270.98   66.50 1421.20   25.98    0.00
12:33:14   hme0   11.99 1471.67  161.07 1081.45   76.25 1393.49   12.15    0.00
12:33:15   hme0    0.14    0.26    2.00    3.00   73.00   90.00    0.00    0.00
12:33:16   hme0    0.14    0.26    2.00    3.00   73.00   90.00    0.00    0.00
12:33:17   hme0    0.14    0.26    2.00    3.00   73.00   90.00    0.00    0.00
[...]
```

http://blogs.sun.com/timc

http://www.brendangregg.com

tcptop

http://www.brendangregg.com/dtrace.html#DTraceToolkit

```
# tcptop -C 10
   Sampling... Please wait.
   2005 Jul  5 04:55:25,  load: 1.11,  TCPin:      2 Kb,  TCPout:    110 Kb

    UID    PID LADDR           LPORT FADDR           FPORT      SIZE NAME
    100  20876 192.168.1.5     36396 192.168.1.1        79      1160 finger
    100  20875 192.168.1.5     36395 192.168.1.1        79      1160 finger
    100  20878 192.168.1.5     36397 192.168.1.1        23      1303 telnet
    100  20877 192.168.1.5       859 192.168.1.1       514    115712 rcp

   2005 Jul  5 04:55:35,  load: 1.10,  TCPin:      0 Kb,  TCPout:      0 Kb

    UID    PID LADDR           LPORT FADDR           FPORT      SIZE NAME
      0    242 192.168.1.5        79 192.168.1.1     54220       272 inetd
      0  20879 192.168.1.5        79 192.168.1.1     54220       714
in.fingerd

   [...]
```

tcpsnoop

```
# tcpsnoop.d
  UID    PID LADDR           LPORT DR RADDR           RPORT  SIZE CMD
  100  20892 192.168.1.5     36398 -> 192.168.1.1        79    54 finger
  100  20892 192.168.1.5     36398 <- 192.168.1.1        79    66 finger
  100  20892 192.168.1.5     36398 -> 192.168.1.1        79    54 finger
  100  20892 192.168.1.5     36398 -> 192.168.1.1        79    56 finger
  100  20892 192.168.1.5     36398 <- 192.168.1.1        79    54 finger
  100  20892 192.168.1.5     36398 <- 192.168.1.1        79   606 finger
  100  20892 192.168.1.5     36398 -> 192.168.1.1        79    54 finger
  100  20892 192.168.1.5     36398 <- 192.168.1.1        79    54 finger
  100  20892 192.168.1.5     36398 -> 192.168.1.1        79    54 finger
  100  20892 192.168.1.5     36398 -> 192.168.1.1        79    54 finger
  100  20892 192.168.1.5     36398 <- 192.168.1.1        79    54 finger
    0    242 192.168.1.5        23 <- 192.168.1.1     54224    54 inetd
    0    242 192.168.1.5        23 -> 192.168.1.1     54224    54 inetd
...
```

dtrace

```
# dtrace -n 'fbt:ip::entry { @[probefunc] = count(); }'
dtrace: description 'fbt:ip::entry ' matched 1875 probes
^C
. . .
  tcp_set_rto                                                   2
  tcp_timeout_cancel                                            2
  tcp_timer_free                                                2
  tcp_wput_data                                                 2
  ip_input                                                      3
  ip_loopback_src_or_dst                                        3
  ip_tcp_input                                                  3
  ipcl_classify_v4                                              3
  ire_cache_lookup                                              3
  squeue_enter_chain                                            3
  tcp_find_pktinfo                                              3
  tcp_input                                                     3
```

dtrace

```
# dtrace -n 'fbt:bge::entry { @[probefunc] = count(); }'
dtrace: description 'fbt:bge::entry ' matched 164 probes
^C
  bge_atomic_renounce                                             1
  bge_atomic_claim                                                2
  bge_atomic_reserve                                              2
  bge_send                                                        2
  bge_m_tx                                                        3
  bge_atomic_shl32                                                6
  bge_chip_factotum                                               6
  bge_factotum_link_check                                         6
  bge_factotum_stall_check                                        6
  bge_mbx_put                                                    10
  bge_intr                                                       11
  bge_receive                                                    11
  bge_recycle                                                    11
  bge_chip_cyclic                                                12
...
```

Summary

- Systems (hardware + software) are extremely complex
  - Understanding behavior requires a variety of skills
- Experience is your friend
  - Dive in!
- The Good News
  - Solaris/OpenSolaris is SECOND TO NONE when it comes to tools, utilities and observability
    - ...and some other things to
  - With few exceptions, typing the wrong thing won't hurt
    - exceptions include truss(1), dtrace with thousands of probes, dtrace PID provider with tens-of-thousands of probes
- With Solaris 10 and OpenSolaris, All questions can and will be answered
  - The Dark Ages are behind us...
  - Come to the light...

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வெளிப்படை

open

USE IMPROVE EVANGELIZE

Solaris 10 & OpenSolaris Performance, Observability & Debugging (POD)

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Supplemental Material

Memory Corruption & Memory Leak Detection

The Problem

- Memory leaks
  - allocated memory is not freed when the program no longer needs it
  - Process address space size continues to grow
    - 32-bit processes can run out of address space
    - 64-bit processes can consume a LOT of memory
- Memory corruption
  - Overwriting a segment boundary
  - Unsynchronized writes into a mapped segment

Memory Leak/Corruption Tools

- DTrace
  - Not the best tool for this job
  - pid provider can instrument malloc/free calls
    - track addresses and call stacks
- dbx
  - Has facilities for memory access errors and memory leak detection
- watchmalloc(3MALLOC)
  - binary replacement for libc malloc, free, etc
  - Environmental variable settings for debugging
- libumem(3LIB)
  - Extended feature set for debugging memory leaks and corruption
  - Used in conjunction with mdb(1)

Memory Leak - DTrace

- Use the pid provider to instrument malloc/free calls
  - Post process to align mallocs & frees
- Grab a stack frame

```
#!/usr/sbin/dtrace -s
pid$target:$1:malloc:entry
{
        ustack();
}
pid$target:$1:malloc:return
{
        printf("%s: %x\n", probefunc, arg1);
}
pid$target:$1:free:entry
{
        printf("%s: %x\n", probefunc, arg0);
}
```

dbx

```
    which is 184 bytes above the current stack pointer
Variable is 'j'
stopped in access_error at line 26 in file "hello.c"
   26       i = j;
(dbx) cont
hello world
Checking for memory leaks...

Actual leaks report    (actual leaks:  1  total size:    32 bytes)

Memory Leak (mel):
Found leaked block of size 32 bytes at address 0x100101768
At time of allocation, the call stack was:
    [1] memory_leak() at line 19 in "hello.c"
    [2] main() at line 31 in "hello.c"

Possible leaks report  (possible leaks: 0  total size:     0 bytes)

Checking for memory use...

Blocks in use report   (blocks in use:  1 total size:    12 bytes)

Block in use (biu):
Found block of size 12 bytes at address 0x100103778 (100.00% of

At time of allocation, the call stack was:
    [1] memory_use() at line 11 in "hello.c"
    [2] main() at line 32 in "hello.c"

 execution completed, exit code is 0
```

watchmalloc(3MALLOC)

- Binary replacement for malloc, etc
  - Access via LD_PRELOAD=watchmalloc.so.1
- Uses watchpoint facility of procfs (/proc)
- Imposes some constraints
  - See the man page
- Enabled via environmental variables
  - MALLOC_DEBUG=WATCH,RW,STOP

    WATCH – WA_WRITE SIGTRAP

    RW – enables WA_READ & WA_WRITE

    STOP – Stop process instead of SIGTRAP

watchmalloc(3MALLOC)

```
     buf[8]  8060df0
     buf[9]  8060df1
     buf[10] 8060df2
     buf[11] 8060df3
     buf[12] 8060df4
     buf[13] 8060df5
     buf[14] 8060df6
     buf[15] 8060df7
     buf[16] 8060df8
Trace/Breakpoint Trap (core dumped)
opensolaris> pstack core
core 'core' of 841:   ./mover 8
 08050b25 main     (2, 80479c8, 80479d4, 80479bc) + c5
 080509cd _start   (2, 8047ae8, 8047af0, 0, 8047af2, 8047b08) + 7d
opensolaris> dbx mover core
For information about new features see `help changes'
To remove this message, put `dbxenv suppress_startup_message 7.7' in your .dbxrc
Reading mover
core file header read successfully
Reading ld.so.1
Reading watchmalloc.so.1
Reading libc.so.1
program terminated by signal TRAP (write access watchpoint trap)
0x08050b25: main+0x00c5:  movb     %al,0x00000000(%edx)
(dbx)
```

libumem.so

- Binary replacement for malloc, etc
  - enable via LD_PRELOAD
- Designed after the kernel heap allocator
  - Scalable. Less lock contention with threaded apps
- Also enables debug features for memory leak/access issues
  - special buffer management scheme for detecting memory issues

metadata section	memory available to the application	0xbb	memory not available to the application	redzone	debug metadata section

http://developers.sun.com/solaris/articles/libumem_library.html

libumem.so

- Enable with LD_PRELOAD
- Set UMEM_DEBUG & UMEM_LOGGING
  - UMEM_DEBUG=default UMEM_LOGGING=transaction
- Records Thread ID, Timestamp and stack trace for every memory transaction
- Fills allocated & freed segments within the buffer with special patterns
  - Detect use of uninitialized data and previously freed buffers
- Check redzone
- Debug metadata for buffer audit information

libumem.so

- Detects
  - Buffer overruns
  - Multiple frees
  - Use of uninitialized data
  - Use of freed buffers
- Leak detection
  - Most useful when **UMEM_DEBUG** is set to at least **default**
  - Can use **mdb(1)**'s ::findleaks dcmd to search for memory leaks in core files and running processes
  - Get leaked memory summary, breakdown by stack trace

SunStudio

SunStudio 12

- Compilers
  - C, C++, FORTRAN
- Thread Analyzer
- Performance Analyzer
- NetBeans IDE
- Add-on performance libraries
- Misc Tools
  - dbx
  - lint
  - cscope
  - etc...

Thread Analyzer

- Detects data races and deadlocks in a multithreaded application
  - Points to non-deterministic or incorrect execution
  - Bugs are notoriously difficult to detect by examination
  - Points out actual and potential deadlock situations
- Process
  - Instrument the code with `-xinstrument=datarace`
  - Detect runtime condition with `collect -r` all [or race, detection]
  - Use graphical analyzer to identify conflicts and critical regions

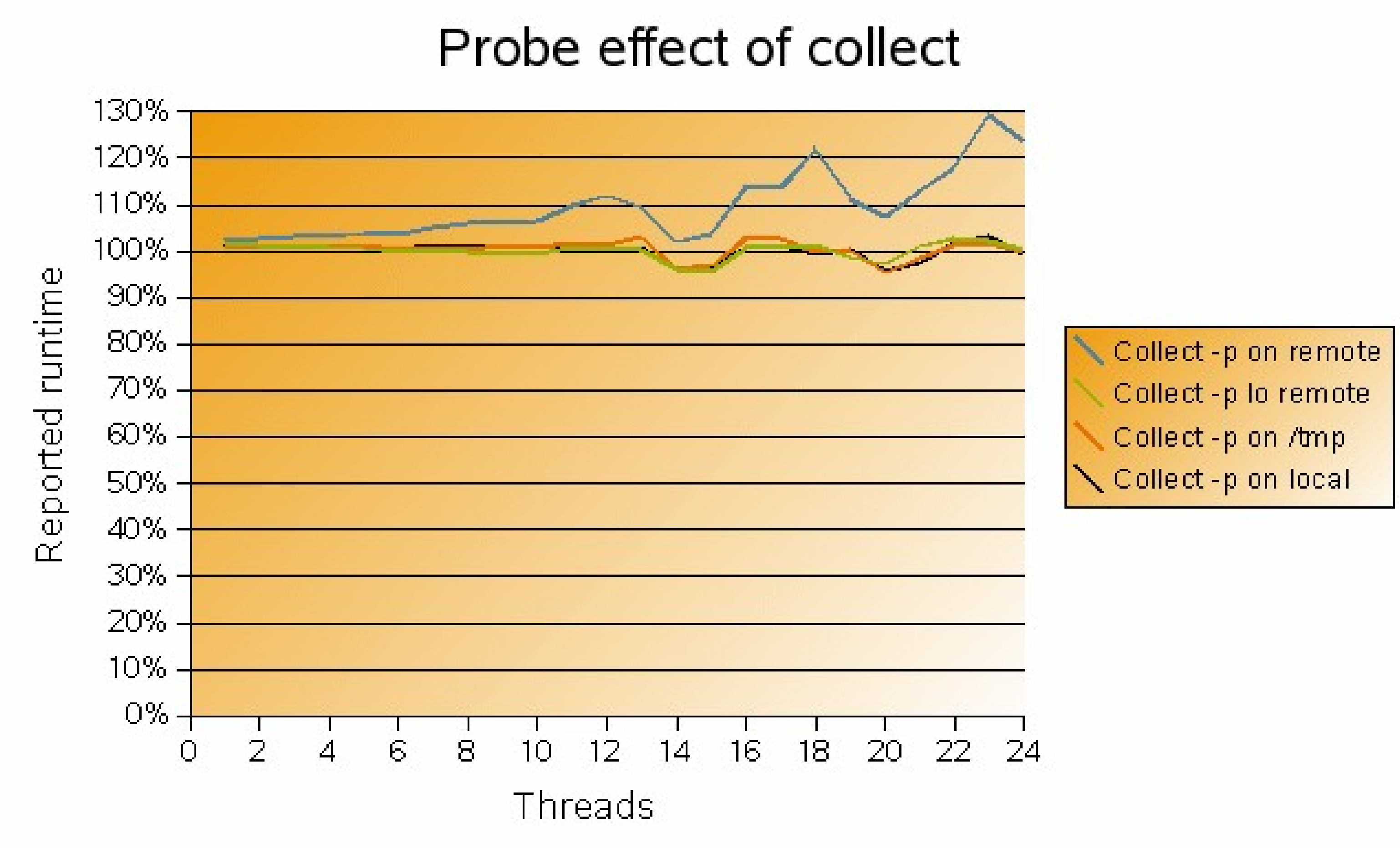
Performance Analyzer

- Thread analyzer integrated into performance analyzer
  - Extentions to the .er files to accommodate THA data
  - collect command extensions
  - er_print command extensions
- More extensive data collection
  - function, instruction count, dataspace profiling
  - attach to PID and collect data
- Probe effect can be mitigated
  - Reduce sampling rates when a lot of threads, or long-running collection

http://blogs.sun.com/d/entry/analyzer_probe_effect

http://blogs.sun.com/d/entry/analyzer_probe_effects_part_2

Performance Analyzer Probe Effect



Graph courtesy of Darryl Gove, from http://blogs.sun.com/d/entry/analyzer_probe_effect

Performance Analyzer

- Collector Tool
  - collect(1)
  - profiles code and traces function calls
  - call stacks, microstates, hardware counters, memory allocation data, summary information
- Analyzer Tool
  - er_print(1), analyzer(1)
  - Clock profiling metrics
  - Hardware counter metrics
  - Synchronization delay metrics
  - Memory allocation metrics
  - MPI tracing metrics

Performance Analyzer

- Clock-based profiling
  - Thread state sampled/stored at regular intervals (SIGPROF)
  - Default resolution of 10milliseconds
  - High-res of 1ms possible
  - Low-res of 100ms for longer collections

User CPU time	**LWP time spent running in user mode on the CPU.**
Wall time LWP	**time spent in LWP 1. This is usually the "wall clock time"**
Total LWP time	**Sum of all LWP times.**
System CPU time	**LWP time spent running in kernel mode on the CPU or in a trap state.**
Wait CPU time	**LWP time spent waiting for a CPU.**
User lock time	**LWP time spent waiting for a lock.**
Text page fault time	**LWP time spent waiting for a text page.**
Data page fault time	**LWP time spent waiting for a data page.**
Other wait time	**LWP time spent waiting for a kernel page, or time spent sleeping or stopped.**

Performance Analyzer

- Hardware Counter Overflow Profiling Data
  -

Hardware Counters

- PIC – Programmable Interval Counters
- Can be programmed to count hardware events (e.g. L2 cache miss, TLB miss, etc)
  - VERY processor-specific
  - Need to reference processor's PRM
- cpustat, cputrack
  - Solaris commands to setting PICs and tracking events
- Perf Analyzer & DTrace cpc provider
  - Use overflow profiling

-D enable debug mode

-h print extended usage information

cpustat from a X4600

Use cputrack(1) to monitor per-process statistics.

CPU performance counter interface: AMD Opteron & Athlon64

event specification syntax:

[picn=]<eventn>[,attr[n][=<val>]][,[picn=]<eventn>[,attr[n][=<val>]],...]

Generic Events:

event[0-3]: PAPI_br_ins PAPI_br_msp PAPI_br_tkn PAPI_fp_ops
PAPI_fad_ins PAPI_fml_ins PAPI_fpu_idl PAPI_tot_cyc
PAPI_tot_ins PAPI_l1_dca PAPI_l1_dcm PAPI_l1_ldm
PAPI_l1_stm PAPI_l1_ica PAPI_l1_icm PAPI_l1_icr
PAPI_l2_dch PAPI_l2_dcm PAPI_l2_dcr PAPI_l2_dcw
PAPI_l2_ich PAPI_l2_icm PAPI_l2_ldm PAPI_l2_stm
PAPI_res_stl PAPI_stl_icy PAPI_hw_int PAPI_tlb_dm
PAPI_tlb_im PAPI_fp_ins PAPI_vec_ins

See generic_events(3CPC) for descriptions of these events

DC_uarch_early_cancel_access DC_dispatched_prefetch_instr

DC_dcache_accesses_by_locks BU_memory_requests

BU_data_prefetch BU_cpu_clk_unhalted IC_fetch IC_miss

IC_refill_from_L2 IC_refill_from_system

IC_itlb_L1_miss_L2_hit IC_uarch_resync_snoop

IC_instr_fetch_stall IC_return_stack_hit

IC_return_stack_overflow FR_retired_x86_instr_w_excp_intr

. . . . . .

DC_copyback DC_dtlb_L1_miss_L2_hit DC_dtlb_L1_miss_L2_miss

DC_1bit_ecc_error_found BU_system_read_responses

BU_quadwords_written_to_system BU_internal_L2_req

BU_fill_req_missed_L2 BU_fill_into_L2

IC_itlb_L1_miss_L2_miss FR_retired_fpu_instr

NB_mem_ctrlr_page_access NB_mem_ctrlr_page_table_overflow

NB_mem_ctrlr_turnaround NB_ECC_errors NB_sized_commands

NB_probe_result NB_gart_events NB_ht_bus0_bandwidth

NB_ht_bus1_bandwidth NB_ht_bus2_bandwidth NB_sized_blocks

NB_cpu_io_to_mem_io NB_cache_block_commands

attributes: edge pc inv cmask umask nouser sys

See Chapter 10 of the "BIOS and Kernel Developer's Guide for the AMD Athlon 64 and AMD Opteron Processors," AMD publication #26094 insts[/{0|1|2|3}],9999991 (`Instructions Executed', alias for FR_retired_x86_instr_w_excp_intr; events)

ic[/{0|1|2|3}],100003 (`I$ Refs', alias for IC_fetch; events)

icm[/{0|1|2|3}],100003 (`I$ Misses', alias for IC_miss; events)

itlbh[/{0|1|2|3}],100003 (`ITLB Hits', alias for IC_itlb_L1_miss_L2_hit; events)

itlbm[/{0|1|2|3}],100003 (`ITLB Misses', alias for IC_itlb_L1_miss_L2_miss; events)

eci[/{0|1|2|3}],1000003 (`E$ Instr. Refs', alias for BU_internal_L2_req~umask=0x1; events)

ecim[/{0|1|2|3}],10007 (`E$ Instr. Misses', alias for BU_fill_req_missed_L2~umask=0x1; events)

dc[/{0|1|2|3}],1000003 (`D$ Refs', alias for DC_access; load events)

dcm[/{0|1|2|3}],100003 (`D$ Misses', alias for DC_miss; load events)

dtlbh[/{0|1|2|3}],100003 (`DTLB Hits', alias for DC_dtlb_L1_miss_L2_hit; load-store events)

dtlbm[/{0|1|2|3}],100003 (`DTLB Misses', alias for DC_dtlb_L1_miss_L2_miss; load-store events)

ecd[/{0|1|2|3}],1000003 (`E$ Data Refs', alias for BU_internal_L2_req~umask=0x2; load-store events)

ecdm[/{0|1|2|3}],10007 (`E$ Data Misses', alias for BU_fill_req_missed_L2~umask=0x2; load-store events)

fpadd[/{0|1|2|3}],1000003 (`FP Adds', alias for FP_dispatched_fpu_ops~umask=0x1; events)

fpmul[/{0|1|2|3}],1000003 (`FP Muls', alias for FP_dispatched_fpu_ops~umask=0x2; events)

fpustall[/{0|1|2|3}],1000003 (`FPU Stall Cycles', alias for FR_dispatch_stall_fpu_full; CPU-cycles)

memstall[/{0|1|2|3}],1000003 (`Memory Unit Stall Cycles', alias for FR_dispatch_stall_ls_full; CPU-cycles)

Function Metrics

- Exclusive metrics – events inside the function itself, excluding calls to other functions
  - Use exclusive metrics to locate functions with high metric values
- Inclusive metrics – events inside the function and any functions it calls
  - Use inclusive metrics to determine which call sequence in your program was responsible for high metric values
- Attributed metrics – how much of an inclusive metric came from calls from/to another function; they attribute metrics to another function

Using the Performance Analyzer...

```
# collect -p lo -d exper ./ldr 8 1 /zp/space

# collect -p lo -s all -d exper ./ldr 8 1 /zp/space

#collect -p lo -s all -t 10 -o synct.er -d exper ./ldr 8 1 /zp/space
```

Run Time Checking (RTC)

- Detects memory access errors
- Detects memory leaks
- Collects data on memory use
- Works with all languages
- Works with multithreaded code
- Requires no recompiling, relinking or makefile changes