Latency Distributions + Micro-benchmarks = Insights into Kernel Hotspots

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Biography

- UNIX performance engineer since 1980
- Worked on UNIX SVR3 and SVR4 virtual memory and demand paging
- Co-developed the first general purpose UNIX kernel tracing package
- Participated in the Performance Management Working Group - an industry-wide performance management standards effort
- Low latency market data
- Messaging and distributed transactions management
- Enterprise systems monitoring and capacity planning
- Working to get more “engineering” back in performance engineering
  - Visibility into Loggers… (SREcon19)
  - Pardon the Interposition… (LISA19)
  - Page Reference Sampling… (SREcon20)

Why Large Bare Metal Boxes?

- Faster local communication
  - UNIX Domain Sockets
  - Shared Memory
- Shared local state
- Assured durability of filesystem writes
- Control over resource allocation
  - High Volume and Low Latency Market Data
  - Real-time and near real-time requirements

The Scale in our Department

- >400K processes across hundreds of physical machines
    - 3 different platforms/operating systems (Linux, Solaris, AIX)
- 5-8K processes on busier hosts
- >250K threads on busier hosts

Case #1: SysV semaphore bottleneck (AIX)

- General system slowness on one of our production machines
  - Migrating services between machines did not help
    - Start-up scripts timed out
- Narrowing down the problem
  - Many services and utilities were slow
  - Using “trace” on one utility pointed to sporadic slow sem_init and sem_destroy times

Case #1: SysV semaphore bottleneck (AIX)

The micro-benchmark

```
/* sema_load.c */
for (i = 0; i < n; i++) {
        sem_init(&sem[i], 0, 10);
        sem_destroy(&sem[i]);
}
```

```
$ time ./sema_load 3000000

real    0m8.274s
user    0m0.261s
sys     0m4.738s
```

Timings

#	Avg. Wall	Avg. System	Avg. User
1	8.274	4.738	0.261
2	14.264	8.575	0.269
3	16.527	9.634	0.271
4	22.363	13.472	0.275

Case #1: Observations and Findings

- AIX CPU measurement when hyper-threading is very misleading
- No “out of the box” metrics on SysV IPC operations
  - Sporadic slowness (depending on concurrency/contention)
  - Took days to isolate the problem down to sem_init() and sem_destroy() operations
- sem_init() and sem_destroy() have critical regions that are protected by spin locks
  - Good for low contention
  - Bad during high contention

Case #2: SysV shared memory bottleneck (Linux)

- Low-level application infrastructure code dropping messages
  - Messaging leverages a form of “zero copy” IPC using SysV shared memory + message queues
  - What was causing “slow consumers”?
    - Application code?
    - Slow message queues?
    - Slow shared memory?
- Zeroing in on the problem
  - The “zero copy” mechanism puts out warnings when shmat() latency exceeds a threshold

Case #2: SysV shared memory bottleneck (Linux RHEL 6)

The micro-benchmark

```
for (i = 0; i < numloops; i++) {
   void *vaddr = shmat(shmid, NULL, 0);
   shmdt(vaddr);
}
```

```
$ time ./shm_load 3000000

real    0m3.235s
user    0m0.061s
sys     0m2.344s
```

Timings

#	Avg. Wall	Avg. System	Avg. User
1	3.235	2.344	0.061
4	98.809	33.587	1.580

Case #2: Observations and Findings

- No “out of the box” metrics on SysV IPC operations
  - Fortunately, the sub-system has measurements of the shmat/shdt system calls
  - With logs upon crossing some threshold
- shmat() and shmdt() have critical regions that are protected by spin locks
  - Good for low contention
  - Bad during high contention
- Different in RHEL 7
  - Worse in 7.4
  - Much better in 7.6

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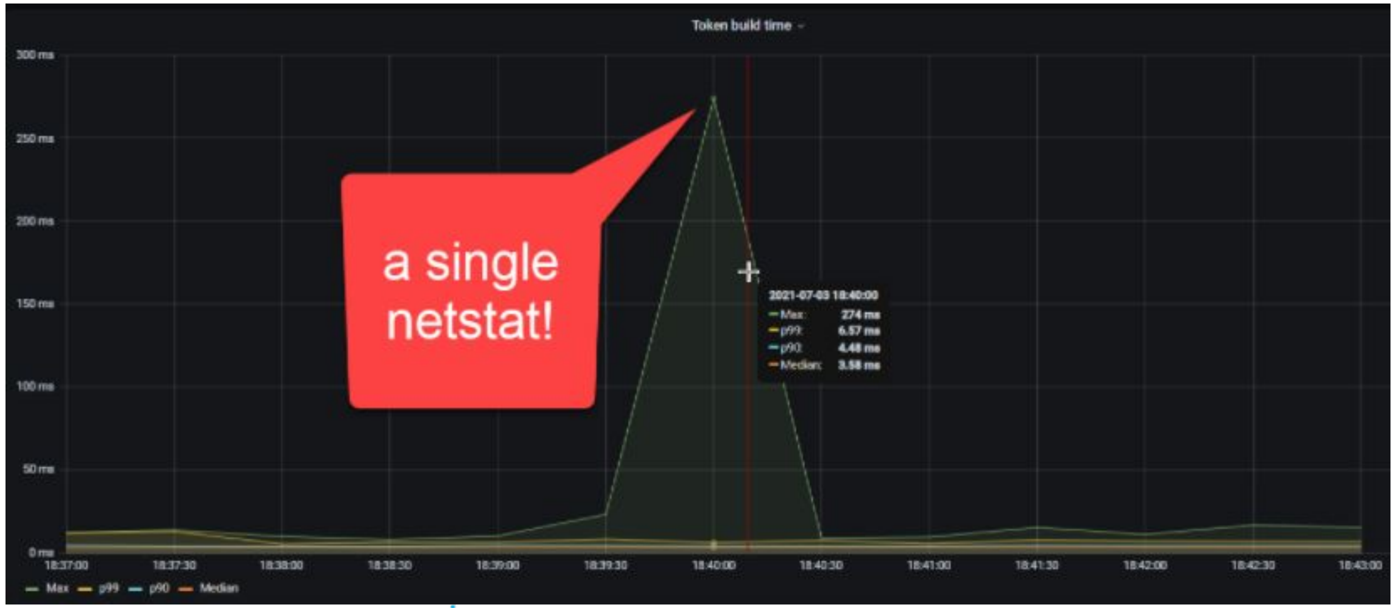
Case #3: UNIX domain socket bottleneck (Solaris)

- Critical software infrastructure experiencing timeouts on load
  - Identity management with very strict SLOs
- Narrowing down the problem
  - A key SLI for the service is token generation latency



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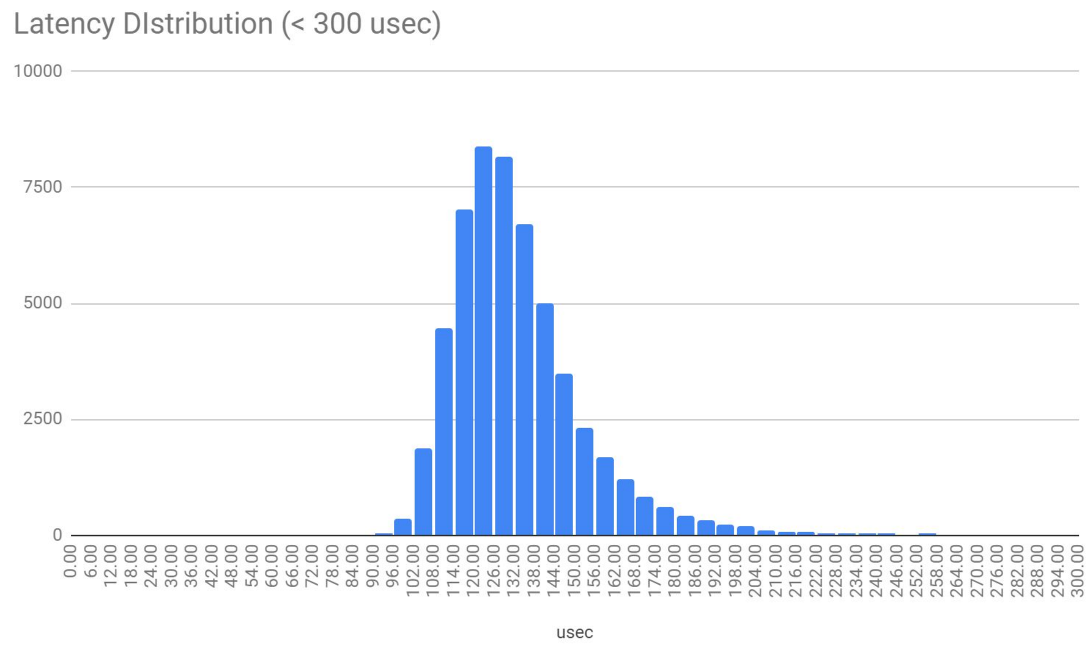
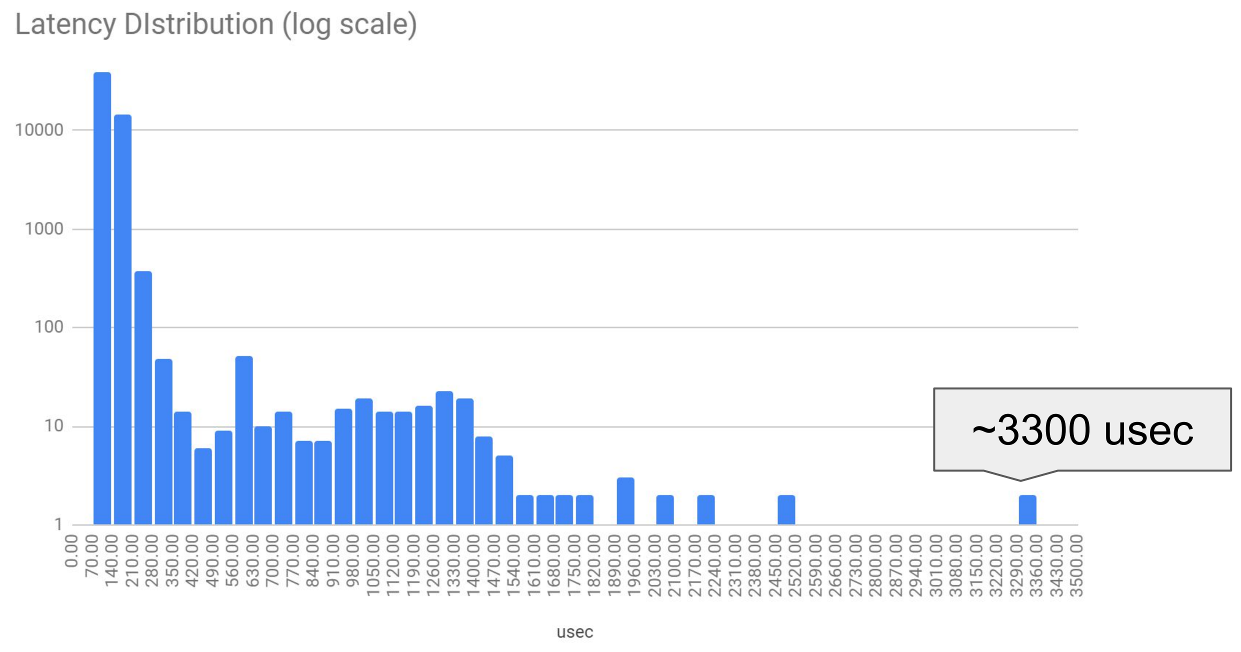
An Aside: Histograms and Distributions are Useful!

- More representative of the data set
  - Most data is not "normally distributed" -> means and std dev are not meaningful (and worse, misleading)
  - Is data bi-modal (or multi-modal)?
  - Long tails are meaningful
    - Sensitive detection of *performance hiccups*
  - Relatively compact storage requirements
  - Many SLAs and SLOs are stated in terms of distributions

An Aside: A Histogram Example





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Case #3: Early Observations

- No “out of the box” metrics on socket operations
  - Fortunately, the sub-system kept distribution metrics on key latencies
  - This allowed an exact correlation between latency blips and execution of the netstat command
- The maximum netstat impact on latency varied widely from system to system
  - Conjecture: the level of impact was related to the number of UDS sockets on a system
    - Netstat holds a lock for the duration of its “read-only” operation when extracting the list of active UDS sockets

Case #3: UNIX domain socket bottleneck (Solaris)

The micro-benchmark #1 - testing against size

```
#define MAX_TESTFDS 32*1024
for (i = 0; i < MAX_TESTFDS; i++) {
      fd[i] = socket(AF_UNIX, SOCK_STREAM, 0);
} pause();
```

Timings (sequential)

#	Avg. Wall (sec)	Avg. System (sec)	Avg. User (sec)
1	.240	.230	.011
2	.308	.298	.011
3	.371	.360	.011
4	.445	.443	.011
5	.552	.512	.011
6	.585	.573	.011

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Case #3: Conclusions

- Solaris 11.3 is limited to a max of 256K UDS sockets
- The more UDS sockets there are, the longer it takes to create new, unbound UDS sockets

Case #4: Task clone and exit bottleneck (Linux)

- Preliminary: Does task creation/deletion take longer with more threads?
    - On hosts with >250K threads, we start to see timeouts in start-up and shutdown

Case #4: Task clone and exit bottleneck (Linux)

The micro-benchmark

```
void *hangaround(void *args) {
  pause();
  return NULL;
}

int main(int argc, char *argv[]) {
  for (i = 0; i < nthreads; i++) {
    pthread_create(&tid, &attr, hangaround, NULL);
  }
  pause();
}
```

Case #4: Task clone and exit bottleneck (Linux)

```
$ time (ps auxww | wc)
   2967   42706  500273

real    0m0.174s
user    0m0.038s
sys     0m0.137s

$ ./lotsathreads 125000 &

$ time (ps auxww | wc)
   2984   42896  487592

real    0m0.482s
user    0m0.032s
sys     0m0.450s

$ ./lotsathreads 125000 &

$ time (ps auxww | wc)
   3032   43784  500467

real    0m1.892s
user    0m0.026s
sys     0m1.212s
```

- Note the growth in system time with threads
- Similar growth in system time if we **ls /proc**
- Answer: processes and threads are *tasks* to the Linux kernel

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Case #4: Task clone and exit bottleneck (Linux)

```
$ for i in {1..1}; do time (ps > /dev/null) & done
real    0m1.175s
user    0m0.015s
sys     0m1.058s

$ for i in {1..2}; do time (ps > /dev/null) & done
real    0m3.139s
user    0m0.014s
sys     0m1.360s

real    0m3.449s
user    0m0.015s
sys     0m1.753s
```

```
$ for i in {1..4}; do time (ps > /dev/null) & done
real    0m2.641s
user    0m0.011s
sys     0m1.630s

real    0m3.479s
user    0m0.014s
sys     0m1.531s

real    0m4.299s
user    0m0.015s
sys     0m1.817s

real    0m4.424s
user    0m0.011s
sys     0m1.112s
```

- Note the serialization around concurrent ps instances
- There doesn't appear to be a huge spin lock that ps (/proc access) encounters
- But ps is only reading data. Why the serialization around concurrent reads?
  - Is it possible that /proc access might impact task create/destroy?
  - Can task create/destroy also impact one another?

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Summary

- Systems are not infinitely scalable
  - No OS has a monopoly on scale problems
- Latency histograms provide key visibility into spotting problems early
- Think of the kernel and the system call interface as a privileged library
  - Micro-benchmarks can help zero in on kernel hotspots
    - Complementary with kernel lock/tracing tools
    - Small, compact tests are easy to re-run
    - Be aware of “designing to the benchmark”
      - Latency histograms can help compare “before and after” behavior

More Summary (Plea to Kernel Folks)

- The Prime Directive of Monitoring: Non-interference
  - Design monitoring interfaces and utilities to interact as minimally as possible with the system being monitored
  - Design the kernel to facilitate passive monitoring
- More visibility!
  - Latency histograms (as full fledged, full-time metrics) are crucially important
    - System calls
    - Key lock acquisition and hold
      - Take care in use of spin locks

References

- Jon Bentley's “Performance Bugs”: https://youtu.be/89qiHoDjeDg
- The case for histograms:
  - How NOT to Measure Latency (Gil Tene): https://www.youtube.com/watch?v=lJ8ydIuPFeU
  - Latency SLOs Done Right (Fred Moyer): https://www.usenix.org/conference/srecon19americas/presentation/moyer

Thank you!

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