L41: Advanced Operating Systems

Through tracing, analysis, and experimentation

L41 Lecture 1

Dr Graeme Jenkinson

21 January 2019

Getting started

- What is an operating system?
- Operating systems research
- About the L41 module
- Laboratory reports
- Kernel tracing with DTrace
- The **probe effect**
- The kernel: Just a C program?
- A little on kernel dynamics: How work happens

What is an operating system?

(Whiteboarding exercise)

What is an operating system?

[An OS is] low-level software that supports a computer's basic functions, such as scheduling tasks and controlling peripherals.

- Google hive mind

General-purpose operating systems

… are for **general-purpose computers:**

- Servers, workstations, mobile devices
- Run **applications** – i.e., software unknown at design time
- Abstract the hardware, provide ‘class libraries’
- E.g., Windows, Mac OS X, Android, iOS, Linux, BSD, …

Userspace	Local and remote shells, management tools, daemons Run-time linker, system libraries, logging and tracing facilities
– system-call layer –	
Kernel	System calls, hypercalls, remote procedure call (RPC)* Processes, filesystems, IPC, sockets, management Drivers, packets/blocks, protocols, tracing, virtualisation VM, malloc, linker, scheduler, threads, timers, tasks, locks

* Continuing disagreement on whether distributed-filesystem servers and window systems ‘belong’ in userspace or the kernel

Other kinds of operating systems

Specialise the OS for a specific application or environment:

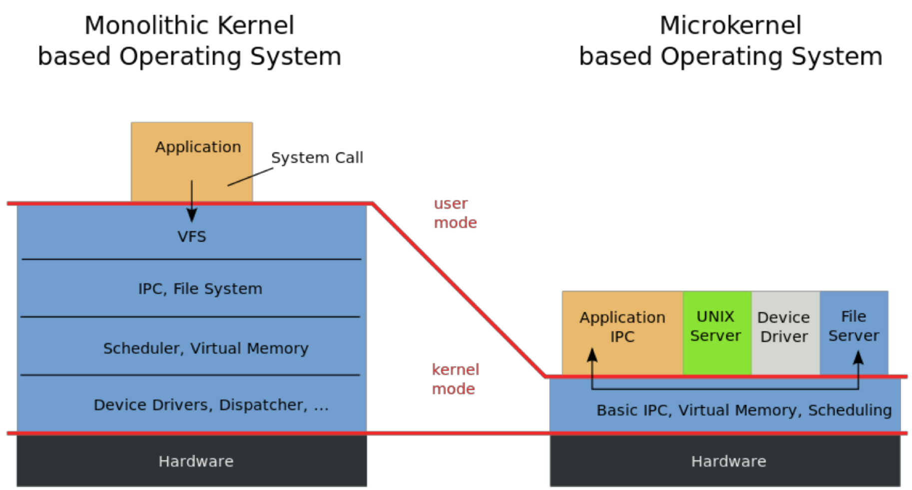
- **Embedded, real-time operating systems**
  - Serve a single application in a specific context
  - E.g., WiFi access points, medical devices, washing machines, cars
  - Small code footprint, real-time scheduling
  - Might have virtual memory / process model
  - Microkernels or single-address space: VxWorks, RTEMS, L4
  - Now also: Linux, BSD (sometimes over a real-time kernel), etc.
- **Appliance operating systems**
  - Apply embedded model to higher-level devices/applications
  - File storage appliances, routers, firewalls, ...
  - E.g., Juniper JunOS, Cisco IOS, NetApp OnTap, EMC/Isilon
  - Under the hood, almost always Linux, BSD, etc.

Key concept: **Operating system as a reusable component**

Other kinds of operating systems?

What if we rearrange the boxes?

- **Microkernels, library operating systems, unikernels**
  - Shift code out of the kernel into userspace to reduce Trusted Computing Base (TCB); improve robustness/flexibility; 'bare-metal' apps
  - Early 1990s: Microkernels are king!
  - Late 1990s: Microkernels are too slow!
  - 2000s/2010s: Microkernels are back! But now 'hypervisors'
  - Sometimes: programming-language runtime as OS



Other kinds of operating systems?

- **Hypervisors**
  - Kernels host applications; hypervisors host virtual machines
  - Virtualised hardware interface rather than POSIX
  - Paravirtualisation reintroduces OS-like interfaces for performance
  - A lot of microkernel ideas have found a home here
  - E.g., System/370, VMware, Xen, KVM, VirtualBox, bhyve, ...
- **Containers**
  - Host OS as hypervisor, but using the process model
  - Really more about code/ABI (Application Binary Interface) distribution and maintenance

What does an operating system do?

- Key hardware-software surface
- Low-level abstractions and services
  - **Operational model**: bootstrap, shutdown, watchdogs
  - **Process model, IPC**: processes, threads, IPC, program model
  - **Resource sharing**: scheduling, multiplexing, virtualisation
  - **I/O**: drivers, local/distributed filesystems, network stack
  - **Security**: authentication, encryption, ACLs, MAC, audit
  - **Local or remote access**: console, window system, SSH
  - **Libraries**: math, protocols, RPC, crypto, UI, multimedia
  - **Monitoring/debugging**: logs, profiling, tracing, debugging

Compiler? Text editor? E-mail package? Web browser?
Can an operating system be “distributed”?

Why study operating systems?

The OS plays a central role in **whole-system design** when building efficient, effective, and secure systems:

- Strong influence on whole-system performance
- Critical foundation for computer security
- Exciting programming techniques, algorithms, problems
  - Virtual memory; network stack; filesystem; run-time linker; …
- Co-evolves with platforms, applications, users
- Multiple active research communities
- Reusable techniques for building complex systems
- Boatloads of fun (best text adventure ever)

Where is the OS research?

A sub-genre of **systems research**:

- Evolving hardware-software interfaces
  - New computation models/architectures
  - New kinds of peripheral devices
- Integration with programming languages and runtimes
- Concurrent/parallel programming models; scheduling
- Security and virtualisation
- Networking, storage, and distributed systems
- Tracing and debugging techniques
- Formal modeling and verification
- As a platform for other research – e.g., mobile systems

Venues: SOSP, OSDI; ATC; EuroSys; HotOS; FAST; NSDI; HotNets; ASPLOS; USENIX Sec.; ACM CCS; IEEE SSP; …

What are the research questions?

Just a few examples: By changing the OS, can I…

- Create new abstractions for new hardware?
- Make my application run faster by…
  - Better masking latency?
  - Using parallelism more effectively?
  - Exploiting new storage mediums?
  - Adopting distributed-system ideas in local systems?
- Make my application more {reliable, energy efficient}
- Limit {security, privacy} impact of exploited programs?
- Use new language/analysis techniques in new ways?

Systems research focuses on **evaluation** with respect to **applications** or **workloads**: How can we measure whether it is {faster, better, ...}?

Teaching operating systems

- Two common teaching tropes:
  - **Trial by fire**: in micro, recreate classic elements of operating systems: microkernels with processes, filesystems, etc.
  - **Research readings course**: read, present, discuss, and write about classic works in systems research
- This module adopts elements of both styles while:
  - mitigating the risk of OS kernel hacking in a short course
  - working on real-world systems rather than toys; and
  - targeting research skills not just operating-system design
- Trace and analyse real systems driven by specially crafted benchmarks
- Possible only because of recent developments in tracing and hardware-based performance analysis tools

Aims of the module (1/2)

Teaching **methodology**, **skills**, and **knowledge** required to understand and perform research on contemporary operating systems by…

- Employing systems methodology and practice
- Exploring real-world systems artefacts through performance and functional evaluation/analysis
- Developing scientific writing skills
- Reading selected original systems research papers

Aims of the module (2/2)

On completion of this module, students should:

- Have an understanding of high-level OS kernel structure.
- Gained insight into hardware-software interactions for compute and I/O.
- Have practical skills in system tracing and performance analysis.
- Have been exposed to research ideas in system structure and behaviour.
- Have learned how to write systems-style performance evaluations.

Prerequisites

We will take for granted:

- **High-level knowledge of OS terminology** from an undergraduate course (or equivalent); e.g.,:
  - What **schedulers** do
  - What **processes** are … and how they differ from threads
  - What **Inter-Process Communication (IPC**) does
  - How might a simple **filesystem** might work
- Reasonable fluency in reading multithreaded C
- Working knowledge of Python (or R)
- Comfort with the UNIX command-line environment
- Undergraduate skills with statistics
  (mean/median/mode/stddev/*t*-tests/linear regression/boxplots/scatterplots ...)

You can pick up some of this as you go (e.g., IPC, Python, *t*-tests), but will struggle if you are missing several

Module structure – four complementary strands

- **3x two-hour lectures** in FS09
  - Theory, methodology, architecture, and practice
- **5x two-hour labs** in SW02
  - Start with 10-20-minute *lecturelets* on artefacts, practical skills
  - Remainder on hands-on measurement and experimentation – learn skills required to write assigned lab reports, start on experiments
  - Lab **experimental questions** must be answered in your lab reports
- **Assigned research and applied readings**
  - Selected portions of module texts – learn skills, methodology
  - Historic and contemporary research papers – research exposure
- **Marked lab reports**
  - Based on experiments done in (and out) of scheduled labs
  - Refine scientific writing style suitable for systems research
  - One 'practice run' marked but not assessed ← **not optional!**
  - Two assessed; 50% of final mark each

Outline of module schedule

- Submodule 1: **Introduction to kernels and tracing/analysis**
  - 1 lecture, 1 lab (I/O)
  - **Introduction**: OSes, Systems Research, and L41
  - **The Kernel**: Kernel and Tracing
  - First lab report due - 2019-02-11
- Submodule 2: **The Process Model**
  - 1 lecture, 2 labs (IPC, PMC)
  - **The Process Model** (1) – Binaries and Processes
  - **The Process Model** (2) – Traps, System Calls, and Virtual Memory
  - Second lab report due - 2019-03-19
- Submodule 3: **The Network Stack (TCP/IP)**
  - 1 lecture, 2 labs (TCP state machine, congestion control)
  - **The Network Stack** (1) – Sockets, NICs, and Work Distribution
  - **The Network Stack** (2) – TCP protocol
  - Final lab report due - 2019-04-24

The platform

TI BeagleBone Black

- 1GHz ARM Cortex-A8 32-bit CPU
- Superscalar pipeline, MMU, L1/L2 caches
- FreeBSD operating system (13-CURRENT) + DTrace
- Bespoke “potted benchmarks”
- Jupyter notebook measurement and analysis environment

Labs and lab reports

Lab reports document an experiment and analyse its results – typically using **one or more hypotheses**.

Our lab reports will contain the following sections (see notes, template):

1. Title + abstract (1 page)	5. Conclusion (1-2 para)
2. Introduction (1-2 para)	6. References
3. Experimental setup and methodology (1-2 pages)	7. Appendices
4. Results and discussion (3-4 pages)	

Some formats break out (e.g.) experimental setup vs. methodology, and results vs. discussion. The combined format seems to work better for systems experimentation as compared to (e.g.) biology.

- The target length is **10 pages excluding appendices, references**
- **Over-length reports** will be assessed within page limit
- **Appendices** may not be read if too long, and should not be essential to understanding the core content of the report

Module texts – core material

You will need to make frequent reference to these books both in the labs and outside of the classroom:

Operating systems: Marshall Kirk McKusick, George V. Neville-Neil, and Robert N. M. Watson, ***The Design and Implementation of the FreeBSD Operating System, 2nd Edition***, Pearson Education, Boston, MA, USA, September 2014.

Performance measurement: Raj Jain, ***The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modeling***, Wiley - Interscience, New York, NY, USA, April 1991.

Tracing and profiling: Brendan Gregg and Jim Mauro, ***DTrace: Dynamic Tracing in Oracle Solaris***, Mac OS X and FreeBSD, Prentice Hall Press, Upper Saddle River, NJ, USA, April 2011.

Module texts – additional material

If your OS recollections feel a bit hazy:

Operating systems: Abraham Silberschatz, Peter Baer Galvin, and Greg Gagne

Operating System Concepts, Eighth Edition, John Wiley & Sons, Inc., New York, NY, USA, July 2008.

If you want to learn a bit more about architecture and measurement:

Performance measurement and diagnosis: Brendan Gregg, ***Systems Performance: Enterprise and the Cloud***, Prentice Hall Press, Upper Saddle River, NJ, USA, October 2013.

Dynamic tracing with DTrace

- Bryan M. Cantrill, Michael W. Shapiro, and Adam H. Leventhal. *Dynamic Instrumentation of Production Systems*, USENIX ATC 2004.
  - "Facility for dynamic instrumentation of production systems"
  - Unified and safe **instrumentation** of kernel and user space
  - Zero **probe effect** when not enabled
  - Dozens of **providers** representing different trace mechanisms
  - Tens (hundreds?) of thousands of **instrumentation probes**
  - **D language**: C-like scripting language with **predicates**, **actions**
  - Scalar variables, thread-local variables, associative arrays
  - **Data aggregation** and **speculative tracing**
- Solaris, Mac OS X, FreeBSD; Linux + Windows modules
- Wide influence – e.g., on Linux SystemTap, eBPF
- **Our tool of choice in this course**

DTrace scripts

- Human-facing, C-like **D Programming Language**
- One or more {**probe name**, **predicate**, **action**} tuples
- Expression limited to control side effects (e.g., no loops)
- Specified on command line or via a `.d` file

Probe name	Identifies the probe(s) to instrument; wildcards allowed; identifies the provider and provider-specific probe name
Predicate	Filters cases where action will execute
Action	Describes tracing operations

```
fbt::malloc:entry /execname == "csh"/ { trace(arg0); }
```

Probe name **Predicate** **Action**

Some FreeBSD DTrace providers

- Providers represent data sources – instrumentation types:

Provider	Description
callout_execute	Timer-driven "callout" event probes
dtmalloc	Kernel `malloc()/free()`
dtrace	DTrace script events (`BEGIN`, `END`)
fbt	Function Boundary Tracing (function prologues, epilogues)
io	Block I/O read/write
ip,udp,tcp,sctp	TCP/IP events
lockstat	Kernel locking primitives
proc,sched	Kernel process, scheduling primitives
profile	Profiling timers
syscall	System-call entry/return
vfs	Virtual File System operations

- Apparent duplication: FBT vs. event-class providers?
  - Efficiency, expressivity, interface stability, portability

Tracing kernel malloc() calls

- Trace first argument to kernel `malloc()` for `csh`
- NB: Captures both successful and failed allocations

```
# dtrace -n
  'fbt::malloc:entry /execname=="csh"/ { trace(arg0); }'
```

Probe	Use FBT to instrument `malloc()` function prologue
Predicate	Limit actions to processes executing `csh`
Action	Trace the first argument (`arg0`)

```
CPU     ID          FUNCTION:NAME
  0   8408           malloc:entry        64
  0   8408           malloc:entry      2748
  0   8408           malloc:entry        48
  0   8408           malloc:entry       392
^C
```

Aggregations – summarising traces

- **Aggregations** allow early, efficient reduction
  - Scalable multicore implementations (i.e., commutative)

```
@variable = function(.. args ..);
printa(@variable)
```

Aggregation	Description
`count()`	Number of times called
`sum()`	Sum of arguments
`avg()`	Average of arguments
`min()`	Minimum of arguments
`max()`	Maximum of arguments
`stddev()`	Standard deviation of arguments
`lquantize()`	Linear frequency distribution (histogram)
`quantize()`	Log frequency distribution (histogram)

Profiling kernel malloc() calls by csh

```
fbt::malloc:entry
/execname=="csh"/
{ @traces[stack()] = count(); }
```

Probe	Use FBT to instrument `malloc()` function prologue
Predicate	Limit actions to processes executing `csh`
Action	Keys of associative array are stack traces (`stack()`); values are aggregated counters (`count()`)

```
^C
              kernel`malloc
              kernel`fork1+0x14b4
              kernel`sys_vfork+0x2c
              kernel`swi_handler+0x6a8
              kernel`swi_exit
              kernel`swi_exit
                3
...
```

D Intermediate Format (DIF)

```
# dtrace -Sn
  'fbt::malloc:entry /execname == "csh"/ { trace(arg0); }'
```

Predicate

```
DIFO 0x0x8047d2320 returns D type (integer) (size 4)
OFF OPCODE      INSTRUCTION
00: 29011801    ldgs DT_VAR(280), %r1         ! DT_VAR(280) = "execname"
01: 26000102    sets DT_STRING[1], %r2        ! "csh"
02: 27010200    scmp %r1, %r2
03: 12000006    be   6
04: 0e000001    mov  %r0, %r1
05: 11000007    ba   7
06: 25000001    setx DT_INTEGER[0], %r1       ! 0x1
07: 23000001    ret  %r1

NAME                ID   KND SCP FLAG TYPE
execname            118  scl glb r    string (unknown) by ref (size 256)
```

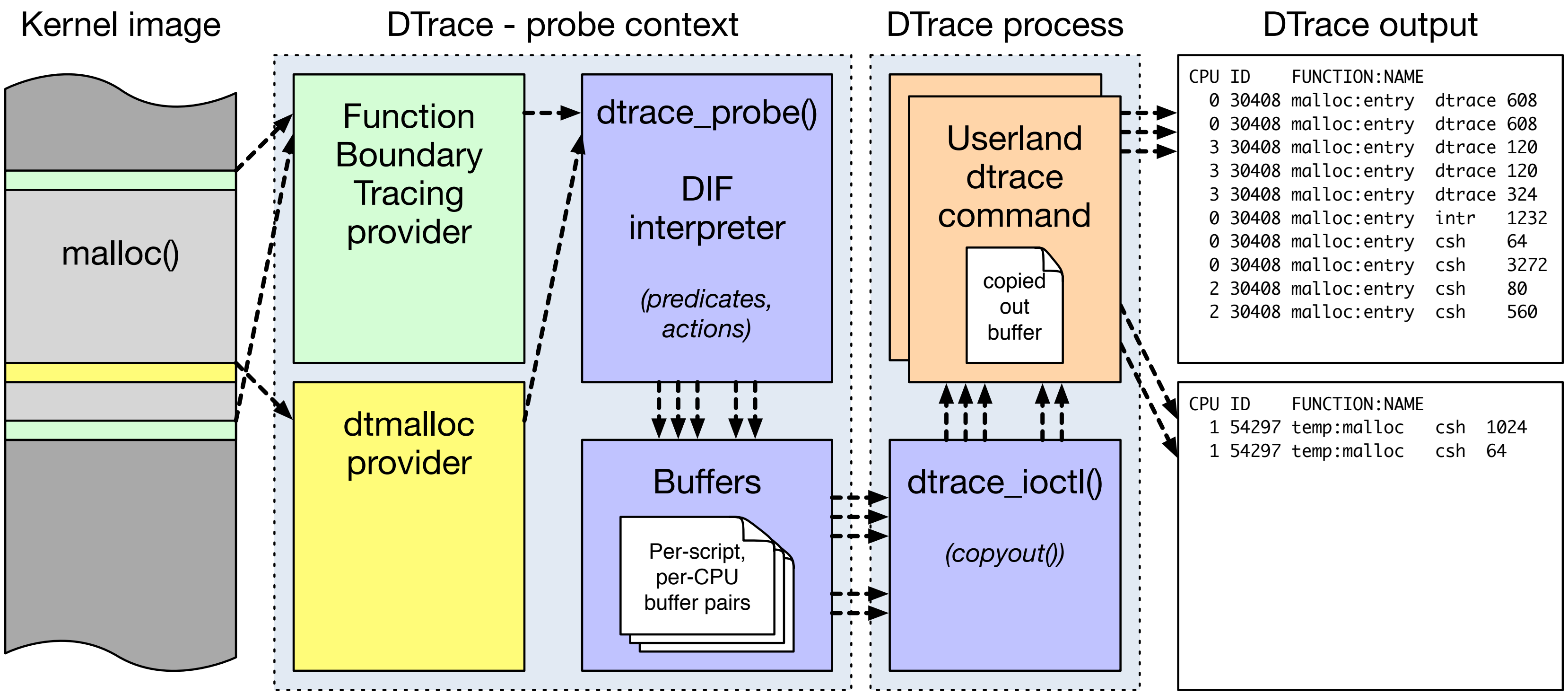
Action

```
DIFO 0x0x8047d2390 returns D type (integer) (size 8)
OFF OPCODE      INSTRUCTION
00: 29010601    ldgs DT_VAR(262), %r1         ! DT_VAR(262) = "arg0"
01: 23000001    ret  %r1

NAME                ID   KND SCP FLAG TYPE
arg0                106  scl glb r    D type (integer) (size 8)
```

DTrace: Implementation

```
dtrace -n 'fbt::malloc:entry { trace(execname); trace(arg0); }'
```




```
dtrace -n 'dtmalloc::temp:malloc /execname="csh"/ { trace(execname); trace(arg3); }'
```

The *Probe Effect*

- The **probe effect** is the unintended alteration of system behaviour that arises from measurement
  - Software instrumentation is **active**: execution is changed
- DTrace minimises probe effect when not being used…
  - ... but has a very significant impact when it is used
  - Disproportionate effect on probed events
- Potential perturbations:
  - Speed relative to other cores (e.g., lock hold times)
  - Speed relative to external events (e.g., timer ticks)
  - Microarchitectural effects (e.g., cache, branch predictor)
- What does this mean for us?
  - Don't benchmark while running DTrace ...
  - ... unless **measuring probe effect**
  - Be aware that traced applications may behave differently
  - E.g., more timer ticks will fire, I/O will "seem faster"

Probe effect example: dd(1) execution time

- Simple (naïve) microbenchmark – `dd(1)`
  - dd copies blocks from input to output
  - Copy 10M buffer from `/dev/zero` to `/dev/null`
  - Execution time measured with `/usr/bin/time`

```
# dd if=/dev/zero of=/dev/null bs=10m count=1 status=none
```

- Simultaneously, run various DTrace scripts
  - Compare resulting execution times using `ministat`
  - Difference is probe effect (+/- measurement error)

Probe effect 1: memory allocation

- Using the `dtmalloc` provider, count kernel memory allocations:

```
dtmalloc:::
{ @count = count(); }
```

```
x no-dtrace
+ dtmalloc-count
+------------------------------------------------------------------------------+
|                                      *                                       |
|                                      *                                       |
|                                      *                                     + |
|x                                    *                                     + |
|x                                    *                                     + |
|*                                    *                                     * |
|        |_______________|______A______M__________A_____|__________________|   |
+------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  11           0.2          0.22          0.21    0.20818182  0.0060302269
+  11           0.2          0.22          0.21    0.21272727  0.0064666979
No difference proven at 95.0% confidence
```

- **No statistically significant overhead** at 95% confidence level

Probe effect 2: locking

- Using the `lockstat` provider, track kernel lock acquire, release:

```
lockstat:::
{ @count = count(); }
```

```
x no-dtrace
+ lockstat-count
+--------------------------------------------------------------------------------+
|   x                                                                           +|
|   x                                                                           +|
|   x                                                                       +   +|
|x  x                                                                       +   +|
|x  x                                                                       +   +|
|x  x  x                                                                 +  +   +|
| |_A_|                                                                     |_A_M|
+--------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  11           0.2          0.22          0.21    0.20818182  0.0060302269
+  11          0.42          0.44          0.44    0.43454545  0.0068755165
Difference at 95.0% confidence
        0.226364 +/- 0.00575196
        108.734% +/- 2.76295%
        (Student's t, pooled s = 0.0064667)
```

- **109% overhead** – 170K locking operations vs. 6 `malloc()` calls!

Probe effect 3: limiting to dd(1)?

- Limit the `action` to processes with the name dd:

```
lockstat::: /execname == "dd"/
{ @count = count(); }
```

```
x no-dtrace
+ lockstat-count-dd
+------------------------------------------------------------------------------+
|                                                                          +   |
|  x                                                                       +   |
|  x                                                                       +   |
|  x                                                                       +   |
|  x                                                                       +   |
|x x                                                                       +   |
|x x                                                                       +   |
|x x x                                                                 + + + +|
||_A|                                                                    |_A|  |
+------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  11           0.2          0.22          0.21    0.20818182  0.0060302269
+  11          0.54          0.57          0.56    0.55818182  0.0075075719
Difference at 95.0% confidence
        0.35 +/- 0.0060565
        168.122% +/- 2.90924%
        (Student's t, pooled s = 0.00680908)
```

- Well, crumbs. Now **168% overhead**!

Probe effect 4: stack traces

- Gather more locking information in `action` – capture call stacks:

```
lockstat::: { @stacks[stack()] = count(); }
lockstat::: /execname == "dd"/ { @stacks[stack()] =  count(); }
```

```
x no-dtrace
+ lockstat-stack
* lockstat-stack-dd
+--------------------------------------------------------------------------------+
|                                                                           *    |
|                                                                           *    |
|                                                                           *    |
|                                                                           *    |
|xx                                                                   ++  **    |
|xx                                                                   ++  **    |
|xx                                                                +  +++ ** *+|
|AM                                                                  |_MA_|A|   |
+--------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  11           0.2          0.22          0.21    0.20818182  0.0060302269
+  11          1.38          1.57          1.44     1.4618182   0.058449668
        1.25364 +/- 0.0369572
        602.183% +/- 17.7524%
*  11           1.5          1.55          1.51     1.5127273   0.014206273
        1.30455 +/- 0.00970671
        626.638% +/- 4.66261%
```

The kernel: "Just a C program"?

- I claimed that the kernel was mostly "just a C program"
- This is indeed mostly true, especially in higher-level subsystems

Userspace	Kernel
`crt/csu`	`locore`
`rtld`	Kernel linker
Shared objects	Kernel modules
`main()`	`main()`, `platform_start()`
`libc`	`libkern`
POSIX threads API	`kthread` KPI
POSIX filesystem API	VFS KPI
POSIX sockets API	`socket` KPI
DTrace	DTrace
…	…

The kernel: not just *any* C program

- **Core kernel**: ≈3.4M LoC in ≈6,450 files
  - **Kernel runtime**: Run-time linker, object model, scheduler, memory allocator, threads, debugger, tracing, I/O routines, timekeeping
  - **Base kernel**: VM, process model, IPC, VFS w/20+ filesystems, network stack (IPv4/IPv6, 802.11, ATM, …), crypto framework
  - Includes roughly ≈70K lines of assembly over ≈6 architectures
- Alternative C runtime – e.g., `SYSINIT`, `curthread`
- Highly concurrent – really very, very concurrent
- Virtual memory makes pointers .. odd
- Debugging features – e.g., `WITNESS` lock-order verifier
- **Device drivers**: ≈3.0M LoC in ≈3,500 files
  - 415 device drivers (may support multiple devices)

Spelunking the kernel

```
% ls
Makefile        ddb/            mips/           nfs/            sys/
amd64/          dev/            modules/        nfsclient/      teken/
arm/            fs/             net/            nfsserver/      tools/
boot/           gdb/            net80211/       nlm/            ufs/
bsm/            geom/           netgraph/       ofed/           vm/
cam/            gnu/            netinet/        opencrypto/     x86/
cddl/           i386/           netinet6/       pc98/           xdr/
compat/         isa/            netipsec/       powerpc/        xen/
conf/           kern/           netnatm/        rpc/
contrib/        kgssapi/        netpfil/        security/
crypto/         libkern/        netsmb/         sparc64/

% ls kern
Make.tags.inc           kern_racct.c            subr_prof.c
Makefile                kern_rangelock.c        subr_rman.c
bus_if.m                kern_rctl.c             subr_rtc.c
capabilities.conf       kern_resource.c         subr_sbuf.c
clock_if.m              kern_rmlock.c           subr_scanf.c
...
```

- Kernel source lives in `/usr/src/sys`:
  - `kern/` – core kernel features
  - `sys/` – core kernel headers
- Useful resource: `http://fxr.watson.org/`

How work happens in the kernel

- Kernel code executes concurrently in multiple threads
  - User threads in the kernel (e.g., a system call)
  - Shared worker threads (e.g., callouts)
  - Subsystem worker threads (e.g., network-stack workers)
  - Interrupt threads (e.g., Ethernet interrupt handling)
  - Idle threads

```
# procstat -at
  PID    TID COMM             TDNAME           CPU  PRI STATE   WCHAN
    0 100000 kernel           swapper           -1   84 sleep   swapin
    0 100006 kernel           dtrace_taskq      -1   84 sleep   -
...
   10 100002 idle             -                 -1  255 run     -
   11 100003 intr             swi3: vm           0   36 wait    -
   11 100004 intr             swi4: clock (0)   -1   40 wait    -
   11 100005 intr             swi1: netisr 0    -1   28 wait    -
...
   11 100018 intr             intr16: ti_adc0    0   20 wait    -
   11 100019 intr             intr91: ti_wdt0    0   20 wait    -
   11 100020 intr             swi0: uart        -1   24 wait    -
...
  739 100064 login            -                 -1  108 sleep   wait
  740 100079 csh              -                 -1  140 sleep   ttyin
  751 100089 procstat         -                  0  140 run     -
```

Work processing and distribution

- Many operations begin with system calls in a user thread
- But may trigger work in many other threads; for example:
  - Triggering a callback in an interrupt thread when I/O is complete
  - Eventually writing back data to disk from the buffer cache
  - Delayed transmission if TCP isn't able to send immediately
- We will need to be careful about these things, as not all work we are analysing will be in the obvious user thread
- Multiple mechanisms provide this asynchrony; e.g.:

callout	Closure called after wall-clock delay
eventhandler	Closure called for key global events
task	Closure called .. eventually
`SYSINIT`	Function called when module loads/unloads

* Where *closure* in C means: function pointer, opaque data pointer

For next time

- McKusick, et al. – Chapter 3
- Cantrill, et al. 2004 – full article
- Read Ellard and Seltzer, *NFS Tricks and Benchmarking Traps*
- Skim the handout, *L41: DTrace Quick Start* (available from L41 module website)
- Be prepared to try out DTrace on a real system