Profiling the FreeBSD kernel boot

From hammer_time to start_init

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Why profile the FreeBSD kernel boot?

Why *did I* profile the FreeBSD kernel boot?

- In June 2017 I bought a new laptop.
- Unlike many FreeBSD developers, I insist on running FreeBSD on my laptops.
- Video driver support in laptops has traditionally been problematic.
  1. Load the `i915kms.ko` kernel module.
  2. Read the panic message.
  3. Reboot.
  4. Try changing some code.
  5. Recompile the kernel module.
  6. GOTO 1
- Hundreds and hundreds of attempts.

Why *did I* profile the FreeBSD kernel boot?

- Around reboot number 100 I started to notice things.
- Text scrolls by as the kernel initializes itself and probes devices, but sometimes the scrolling stops for a while.
- I started wondering what the kernel was doing during these "pauses".
- Make educated guesses and sprinkle `printf("%llu\n", rdtsc());`
  - Initializing the `vm_page` array. (15 ms / GB RAM)
  - Calibrating the CPU clock frequency. (1.0 s)
  - Calibrating the local APIC timer. (1.0 s)
  - Probing and initializing `psm0`. (2.0 s)
- I realized that having a systematic way of measuring everything would be much better than annotating functions only when I became suspicious.

FreeBSD boot process

- BIOS / EFI
- FreeBSD boot loader(s)
- FreeBSD kernel initialization
  - Machine-dependent initialization (e.g., `hammer_time`)
  - `mi_startup`
  - `start_init` (including `vfs_mountroot`).
- FreeBSD userland initialization
  - `rc.d` scripts

FreeBSD boot process

- BIOS / EFI
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- FreeBSD userland initialization
  - rc.d scripts

Linux boot profiling

- Linux prints a timestamp at the start of each line of kernel output.

```
[    2.082829] ACPI: Power Button [PWRF]
[    2.085704] input: Sleep Button as /devices/LNX...
[    2.092002] ACPI: Sleep Button [SLPF]
[    2.166920] input: ImExPS/2 Generic Explorer Mo...
[    2.302339] mousedev: PS/2 mouse device common ...
```

- This can make it very easy for users to notice if part of the kernel boot is taking a long time.
- Timestamping kernel log messages means that you only get timestamps when the kernel is printing log messages — not always the most useful moments.
- At the beginning of the Linux boot, all the timestamps logged are `0.000000` because the clocks aren't initialized yet — better to record raw CPU cycle count numbers and then translate them later.

DTrace

- DTrace is *the* way to profile anything and everything in FreeBSD!
- However, DTrace needs:
  - Traps
  - Memory allocation
  - Thread scheduling
  - probably lots more...
- A large part of what we want to profile happens before any of these basic kernel subroutines are available.
- We need to use something which is simpler and with fewer dependencies.

KTR

- KTR is a mechanism for logging "kernel events".
- You call a function; it logs whatever you give it into a buffer.
- Almost exactly what I needed, but...
  - It uses a circular buffer — good for answering "what happened just before we crashed" but bad for answering "what happened at the start of the boot process".
  - Its default buffer size is only 1024 records — we will need far more than this.
  - It can't *quite* run at the start of the boot process.
- All of these limitations could be worked around with a few lines of changes, but it was simpler to add a new subroutine for logging timestamped events which was designed for boot profiling.

TSLOG

- sys/tslog.h and kern/kern_tslog.c implement the TSLOG framework.
- Buffer fixed at compile time (default 256k records).
- To log an record, we atomically reserve a slot, then populate it with the appropriate data.
- When the buffer is full, future records are silently discarded.
- Each record consists of a cycle count, a thread ID, a record type, and one or two strings.
- Records are logged via TS* macros, which compile to nothing for kernels compiled without the TSLOG option.
- The buffer is dumped to userland via the debug.tslog sysctl.

Function tracing

- We can figure out most of what we want to know by knowing when we entered and exited functions.
- TSENTER() records that we have entered a function.
- TSEXIT() records that we are about to exit a function.
- Scatter these through the tree in potentially useful places!
- Top level of the boot process: hammer_time, mi_startup, start_init.
- Functions which get called a lot: DELAY(), _vprintf.
- SYSINIT routines.
- DEVICE_PROBE and DEVICE_ATTACH functions.
- VFS_MOUNT calls.

Annotating a function

```
void
DELAY(int n)
{

        TSENTER();
        if (delay_tc(n)) {
                TSEXIT();
                return;
        }

        init_ops.early_delay(n);
        TSEXIT();
}
```

SYSINIT

- SYSINITs are a mechanism used by FreeBSD to specify that code should be run during the kernel startup process.

  `SYSINIT(name, order1, order2, function, cookie);`
- Similar to Linux `initcalls`.
- A record is created in a special ELF section, and linker magic makes it possible to get a list of all the SYSINITs declared all over the kernel.
- `mi_startup` sorts the SYSINIT functions and calls them in the appropriate order.
- With the `TSLOG` kernel option, we redefine the SYSINIT macro to call a shim function which logs the entry/exit.

SYSINIT

```
#ifdef TSLOG
struct sysinit_tslog {
        sysinit_cfunc_t func;
        const void * data;
        const char * name;
};
static inline void
sysinit_tslog_shim(const void * data)
{
        const struct sysinit_tslog * x = data;

        TSRAW(curthread, TS_ENTER, "SYSINIT", x->name);
        (x->func)(x->data);
        TSRAW(curthread, TS_EXIT, "SYSINIT", x->name);
}
...
```

DEVICE_PROBE and DEVICE_ATTACH

- The configure2 SYSINIT function recurses through the attached buses looking for devices.
- As the names suggest, DEVICE_PROBE is used to probe devices, and DEVICE_ATTACH is used to attach devices once they are found.
- Drivers declare their probe and attach methods via the DEVMETHOD macro.
  - Yes, the FreeBSD kernel is object-oriented! See kobj(9).
- DEVICE_* are inline functions defined in device_if.h, which is generated at build-time from device_if.m.
  - Generic object method dispatch code: Look up the function pointer, then call it.
- I taught makeobjops.awk to add prologues and epilogues to the generated code, then annotated device_if.m.

VFS_MOUNT

```
#define VFS_MOUNT(MP) ({                                    \
        int _rc;                                            \
                                                            \
        TSRAW(curthread, TS_ENTER, "VFS_MOUNT",             \
            (MP)->mnt_vfc->vfc_name);                       \
        VFS_PROLOGUE(MP);                                   \
        _rc = (*(MP)->mnt_op->vfs_mount)(MP);               \
        VFS_EPILOGUE(MP);                                   \
        TSRAW(curthread, TS_EXIT, "VFS_MOUNT",              \
            (MP)->mnt_vfc->vfc_name);                       \
        _rc; })
```

Boot holds

- Tracing function entry/exit points tells us what each kernel *thread* is doing at any given time.
- Once the kernel is running multiple threads, we need a bit more than this — sometimes one thread will wait for another.
- The `intr_config_hooks` `SYSINIT` waits for hooks which were established via `config_intrhook_establish`.
- The `g_waitidle` function waits for the GEOM event queue to be empty.
- The `vfs_mountroot_wait` function waits for holds registered via `root_mount_hold`.
- Extracting information from the kernel scheduler might help here, but that gets complicated fast.

Boot holds

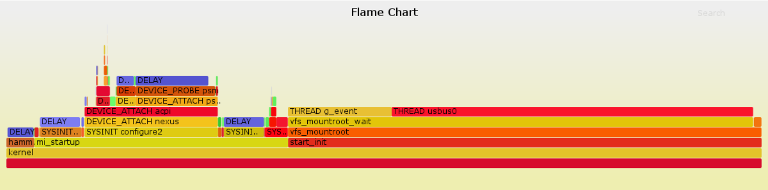
- Much simpler: Annotate the places where the “main thread” is blocked waiting for other threads to finish something.
- Record the start and end of “waits”, and when “holds” are acquired and released.
- Record the identity of newly created kernel threads.
- Heuristic: Blame “blocked” time on whatever thread was the last one to release a hold, for as long as that thread held it.
- Heuristic: Assume the thread was blocking the boot process starting at the latest of when it picked up a hold and when the thread was created.

Visualization

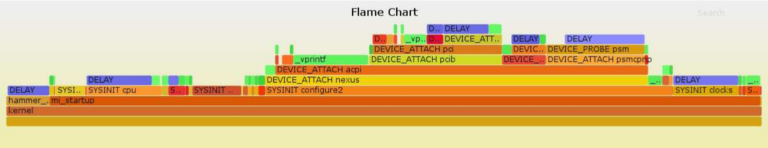
- After booting, dump all of the logged records.
- Organize them into threads and use entry/exit records to construct timestamped stacks.
- The "kernel boot process" is `thread0` (aka. `swapper`) plus `init` prior to when it enters userland.
- Where a boot hold occurs, identify the thread which we're waiting for and splice its stacks on top.
- Now we have a series of stacks covering the kernel boot process.
- Obvious visualization tool: Flame Graphs.
- Unfortunately Flame Graphs sort stacks in alphabetical order...
- Flame *Charts* are like Flame Graphs but keep the stacks in chronological order.

Flame Charts

My laptop:



Amazon EC2 c5.4xlarge:



Where's the time going? (my laptop)

- THREAD usbus0: 9000 ms — root mount waiting for usbus0.
- THREAD g_event: 2600 ms — GELI key derivation.
- DEVICE_PROBE psm: 2000 ms.
- SYSINIT cpu DELAY: 1000 ms.
- SYSINIT clocks DELAY: 1000 ms.
- _vprintf: 720 ms.
- hammer_time DELAY: 640 ms.
- SYSINIT vm_mem: 640 ms.
- DEVICE_ATTACH atkbd DELAY: 430 ms.
- VFS_MOUNT zfs: 190 ms.
- SYSINIT cpu_mp DELAY: 60 ms.
- Everything else: 1080 ms.
- TOTAL: 19360 ms.

Where's the time going? (EC2)

- _vprintf: 3240 ms.
- DEVICE_PROBE psm: 1570 ms.
- SYSINIT cpu DELAY: 1000 ms.
- SYSINIT clocks DELAY: 1000 ms.
- DEVICE_ATTACH ena DELAY: 800 ms.
- hammer_time DELAY: 640 ms.
- SYSINIT start_aps: 620 ms.
- SYSINIT vm_mem: 460 ms.
- DEVICE_ATTACH atkbd DELAY: 430 ms.
- DEVICE_PROBE hpt*: 330 ms.
- DEVICE_ATTACH nvme DELAY: 250 ms.
- SYSINIT cpu_mp DELAY: 156 ms.
- Everything else: 470 ms.
- TOTAL: 10970 ms.

Where's the time going? (EC2)

- _vprintf: 3240 ms $= 2680 + 35$ ms per CPU.
- DEVICE_PROBE psm: 1570 ms.
- SYSINIT cpu DELAY: 1000 ms.
- SYSINIT clocks DELAY: 1000 ms.
- DEVICE_ATTACH ena DELAY: 800 ms.
- hammer_time DELAY: 640 ms.
- SYSINIT start_aps: 620 ms = 41 ms per AP.
- SYSINIT vm_mem: 460 ms = 15 ms per GB RAM.
- DEVICE_ATTACH atkbd DELAY: 430 ms.
- DEVICE_PROBE hpt*: 330 ms.
- DEVICE_ATTACH nvme DELAY: 250 ms.
- SYSINIT cpu_mp DELAY: 156 ms = 10.4 ms per AP.
- Everything else: 470 ms.
- TOTAL: 10970 ms.

Making things faster (done)

- SYSINIT vm_mem: 460 ms = 15 ms per GB RAM.
  - We were making three passes over the vm_page array to initialize it. Doing everything in a single pass is faster!
  - r323290 by markj: Reduced to 3.5 ms per GB RAM.
- DEVICE_PROBE hpt*: 330 ms.
  - Some initialization work which belonged in the DEVICE_ATTACH routine was in DEVICE_PROBE instead.
  - HighPoint provided new drivers within a week of me reporting the performance problem.
  - r325383 by delphij: Reduced to < 0.1 ms.
- SYSINIT start_aps: 620 ms = 41 ms per AP.
  - SMP: AP CPU #%d Launched!
  - Having every CPU announce itself takes a while...
  - This is actually _vprintf but shows up as start_aps because that function is waiting for all the other CPUs.
  - r33333[345] by imp: Reduced to 3 ms per AP.
- EC2 c5.4xlarge reduced from 10970 ms to 8990 ms.

Making things faster (WIP)

- _vprintf: 3240 ms.
  - Most of the time here is spent redrawing everything when a newline character is printed to the console and we scroll.
  - Particularly bad on systems with virtualized consoles (EC2) and systems with 400x112 displays (my laptop).
  - At any given time most of the screen is blank — when we scroll, we re-draw blanks on top of blanks!
  - Significant speedup by remembering what's on the screen and not re-drawing it if it hasn't changed.
  - Reduced from 3240 to 860 ms.
- SYSINIT cpu DELAY: 1000 ms.
- SYSINIT clocks DELAY: 1000 ms.
  - These SYSINITs are calibrating the CPU clock and the local APIC timer frequencies by measuring the clocks before and after a 1 second DELAY.
  - Using a statistical regression on two clocks, we can get the same accuracy in $\approx$ 20 ms.
- EC2 c5.4xlarge reduced from 10970 to 5210 ms.

Making things faster (WIP)

- DEVICE_ATTACH ena DELAY: 800 ms.
  - Initializing the Amazon ENA device involves sending "reset" commands and waiting 100 ms for responses.
  - A future version will make this faster.
  - This happens in the critical path of the kernel boot because the driver wants to have its DEVICE_ATTACH routine fail if the hardware cannot be initialized.
- DEVICE_ATTACH nvme DELAY: 250 ms.
  - As with ENA, this is slow because we wait to see if the hardware is resetting properly before returning from DEVICE_ATTACH.
  - I think imp is looking at speeding this up and/or moving it out of the critical path.
- EC2 c5.4xlarge reduced from 10970 to... maybe $\approx$ 4500 ms?

Making things faster (HELP WANTED)

- DEVICE_PROBE psm: 1570 ms.
- hammer_time DELAY: 640 ms.
- DEVICE_ATTACH atkbd DELAY: 430 ms.
  - Probing and attaching PS/2 keyboards and mice involves resetting the PS/2 keyboard controller several times.
  - Each time you reset the PS/2 keyboard controller, you have to wait 200 ms for the voltage to stabilize before reading a response.
  - We do this even if the "PS/2" keyboard is actually USB.
  - Should be easy to save $\approx$ 2500 ms here!
  - I'm hoping someone with access to lots of *physical* hardware can tackle this one.
  - If nothing else, using a loader tunable to disable these drivers in EC2 would speed things up...
- EC2 c5.4xlarge reduced from 10970 to $\approx$ 2000 ms?

Making things faster (HELP WANTED)

- `THREAD usbus0`: 9000 ms — root mount waiting for usbus0.
  - If you run UFS, this doesn't affect you: FreeBSD recognizes that it has the disks needed to mount your root filesystem.
  - We don't do this for ZFS, and I don't know why.
  - Warner Losh might be fixing this...
- `THREAD g_event`: 2600 ms — GELI key derivation.
  - This has to be slow in order to be secure.
  - I have two disks encrypted with the same passphrase — if they had been set up using the same salt when I first installed FreeBSD, we would theoretically only need to perform *one* key derivation calculation instead of two.
  - Allan Jude might be fixing this...
- My laptop reduced from 19360 to $\approx$ 3000 ms?

Making things faster (HELP WANTED)

- `SYSINIT cpu_mp DELAY`: 10.4 ms per AP.
  - Intel Multiprocessor Specification: "Send an INIT IPI, then wait 10 ms, then send a STARTUP IPI".
  - Right now we only launch one AP at a time — with 16 CPUs this only takes 156 ms, but on 128-CPU monsters this takes 1330 ms.
  - Can we launch all the APs at once instead of waiting for them to start up one by one?
  - John Baldwin might tackle this?
- `SYSINIT vm_mem`: 3.5 ms per GB RAM.
  - Only 115 ms with 32 GB of RAM — but 15 s on an EC2 instance with 4 TB of RAM.
  - Can we start booting with a modest number of pages of memory available (say, 16 GB) and initialize the rest of the `vm_page` structures later in the boot process?
  - Some developers looked terrified...

Availability

- `TSLOG` code is in FreeBSD HEAD.
- Visualization code is at `https://github.com/cperciva/freebsd-boot-profiling`.
- I've only tested with the systems I personally use — please try this out on your systems and find their performance bottlenecks!

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Questions?