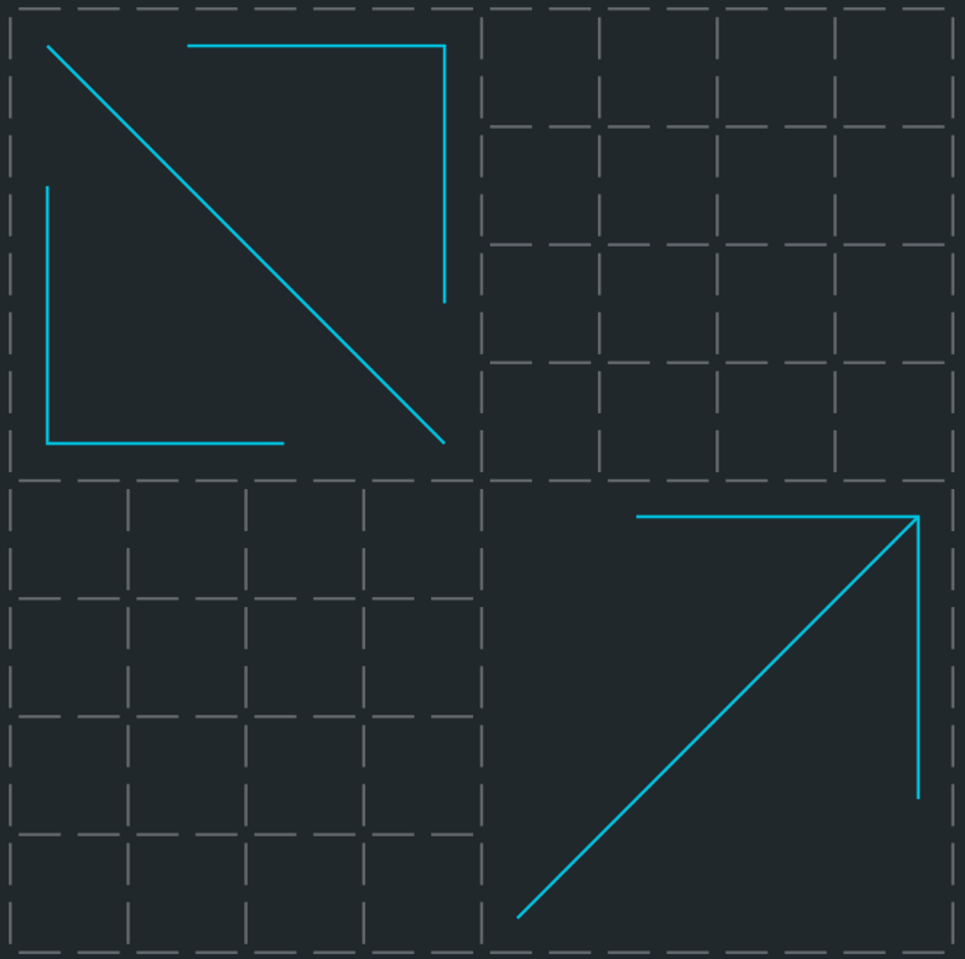
arm
DEVSUMMIT

Automated Failure Analysis of Remote Edge Devices at Scale

Tyler Hoffman



Speaker

Tyler Hoffman, Co-founder @ Memfault

Previously a Firmware Engineer @ Pebble & Fitbit

Split time between writing & debugging firmware and building internal services to help monitor millions of devices.

Can find my thoughts and content on Memfault's Interrupt blog: interrupt.memfault.com

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What are we trying to do today?

- Talk about firmware on embedded MCU systems
- Speed from **development** to **testing** to **mass production** and **scaling**
- Find and fix (quickly) 1 in 10,000 hour bugs in production
- Prevent issues from being released to 100% of users
- Establish measurable stats to track progress on goals

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One of my favorite quotes

“These techniques are not necessary because experienced firmware engineers do not introduce bugs in their code”

- A (real) Firmware Engineer

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Agenda

1. **State of the union**
2. Quantifying current issues
3. Analyzing the issues
4. Preventing future issues
5. Best Practices

5

State of the union for firmware

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Firmware is *pervasive*, but difficult

- In Q4 2020, 4.4 billion Cortex M's shipped
- Tons and tons of firmware running on these devices
- Very few tools to help debug these devices
- Software is becoming more complex - leads to bugs
- Software issues lead to:
  - Bricked devices, RMA's, and security exploits

We need proper tools to help us build quality products

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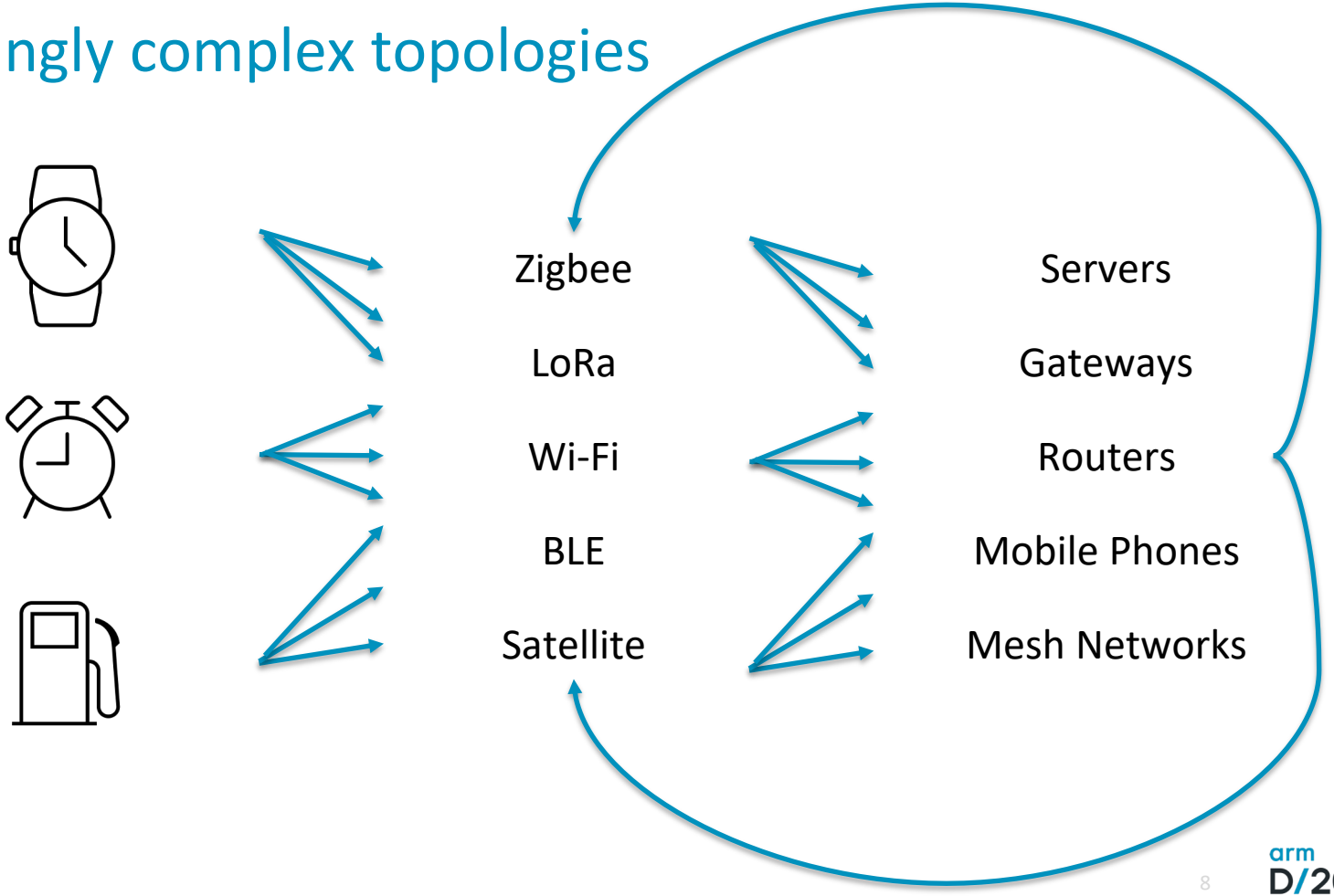
Increasingly complex topologies



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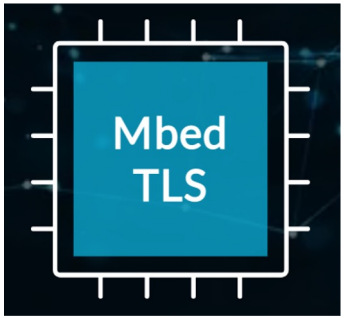
Increasingly complex software

- Firmware no longer is complete isolated
  - Must communicate to mobile phones & gateways
  - Protocols, devices, and security issues constantly changing
  - Libraries are *massively complicated* (e.g. mbedTLS)
- Expectations are growing
  - Everything connects to Internet
  - Must enable firmware updates
  - Competition is growing



wolfSSL

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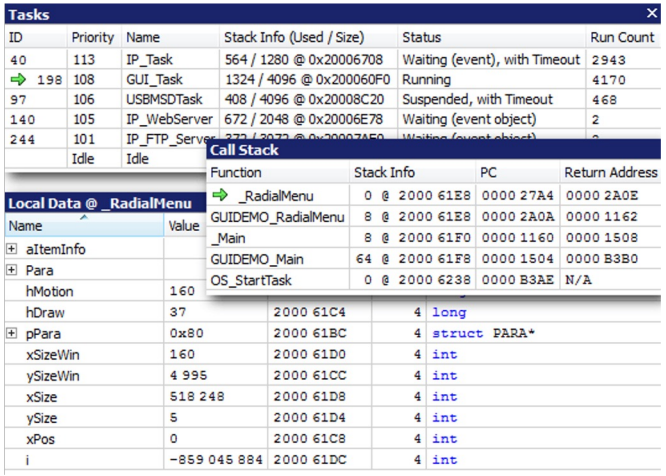
Rudimentary Debugging Tools

```
***** MPU FAULT *****
  Instruction Access Violation
***** Hardware exception *****
Current thread ID = 0x20000074
Faulting instruction address = 0xe0000000
Fatal fault in thread 0x20000074! Aborting.
```

```
[I][1605794400] Wi-Fi connected
[W][1605796200] Wi-Fi disconnected, reason: -2
[I][1605796500] Wi-Fi connected
[W][1605797100] Wi-Fi disconnected, reason: -2
[I][1605798000] Battery status: 67%, 3574 mV
```



The existing tools are decent, **but only when connected using JTAG**

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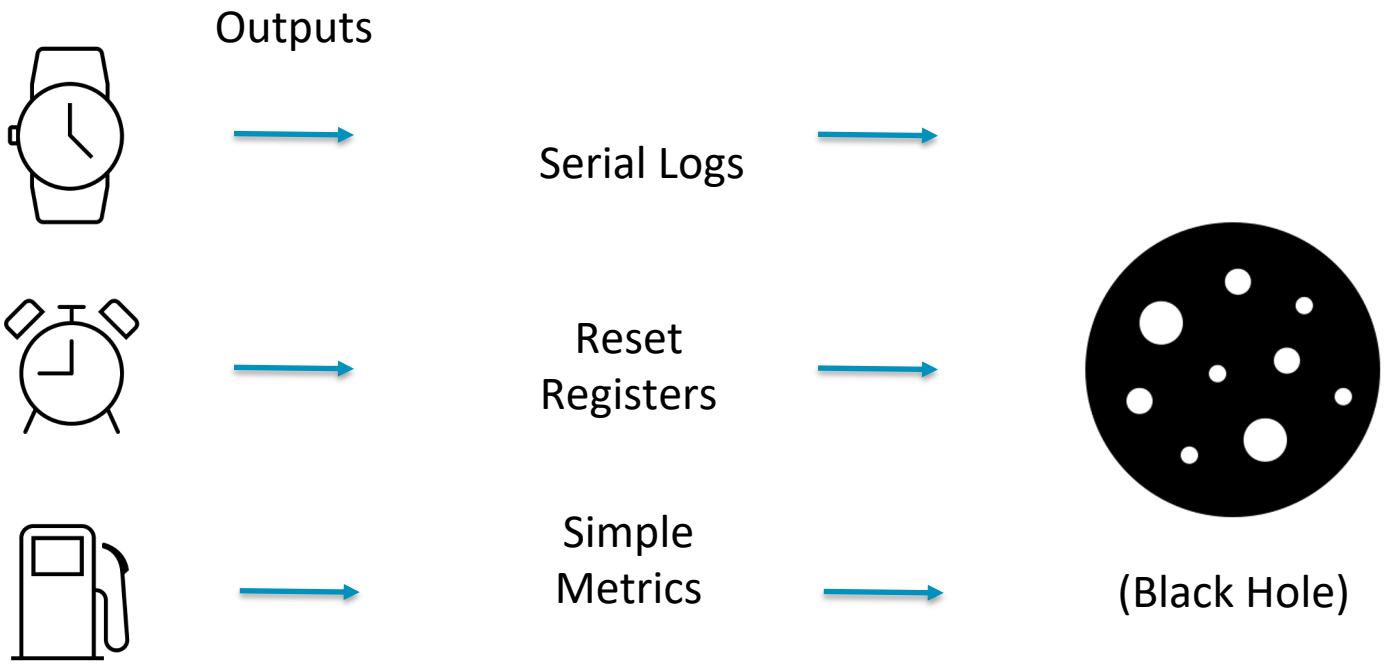
Debugging Data Exported to ???



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Not much exists to help us

- Existing software solutions won't work
  - We aren't monitoring 10-100 servers, rather **10k – 1m+ devices**
  - We don't have MB's and GB's of RAM lying around, **we have KB's**
  - Assembly, C, C++, Rust (?)
  - Symbol files (.elf's) required for typical debugging experiences
  - AWS IoT,
- Few existing solutions that can help embedded devices
- Firmware is not an open-source ecosystem or sharing community

Whatever we need, we have to build ourselves

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Some issues will only happen in the field

“a third of all software faults take more than 5000 execution-years to manifest themselves.”

*Source: http://www.ganssle.com/tem/tem417.html

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Detecting Current Issues

Do we have issues in the field…

They’re likely having issues

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Detecting current issues

Fundamentally, we need to know if and how many times devices are experiencing issues.

Once we have this information

- Can assess whether further work is needed.
- Can make assumptions about whether a firmware update improved stability
- Can guide business & product decisions
- Leaders know whether it’s time to fix bugs and tech debt or build new features

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Detecting current issues

```
void buggy_function(void) {
  *(uint32_t *)0xbadcafe = 0x0;
}
```

```
void HardFault_Handler(void) {
   // … fault handling code ...
   NVIC_SystemReset();
}
```


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Detecting current issues

```
::::::: LOGS ::::::::
ERROR: Connection lost - reason -7
```


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Detecting current issues

- Sending & Parsing logs
  - Log important device events
  - Log resets and registers
  - **Hard and doesn't scale well**

- Tracking simple metrics
  - # device resets
  - # devices alive and well
  - Average uptime of devices
  - **Scalable, but less information**

Requirements:

1. Path to the Internet
2. Central repository for device data

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Detecting current issues

Aggregate!

Reset

```
{
    “reason”: “watchdog”,
}
```

Watchdogs: 67
Hardfaults: 23
Shutdowns: 17

```
“uptime”: 86345
```

Number devices: 890
Average Uptime: 90,234 seconds

Hourly Heartbeat

```
“ble_connected_s”: 3212
```

Average BLE Connected per hour: 3212 seconds
% Connected per hour: 89%

```
“main_stack_min”: 16
```

Stack low watermark is 16 bytes on some devices. Yikes!

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Analyzing the Issues

We have issues. How do we fix them?

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Debugging in Production

- We don’t have access to our normal toolset.
  - No UART & serial logs
  - No JTAG and quick re-flashing
  - No IDE, GDB, or step-through debugging
  - RMA’s take weeks. Devices must persist the data.
- We need tools specifically for debugging in production
  - Build these tools **as early as possible**
  - Having them early will pay off **10x** (Speaking from experience)
  - If you have no interest in building them, check out **Memfault**

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Using Logs to Analyze Issues

```
[I][1605794400] Wi-Fi connected
[W][1605796200] Wi-Fi disconnected, reason: -2
[I][1605796500] Wi-Fi connected
[W][1605797100] Wi-Fi disconnected, reason: -2
[I][1605798000] Battery status: 67%, 3574 mV
```

2 Wi-Fi disconnect events

1 Battery level event

```
***** MPU FAULT *****
  Instruction Access Violation
***** Hardware exception *****
Current thread ID = 0x20000074
Faulting instruction address = 0xe0000000
Fatal fault in thread 0x20000074! Aborting.
```

1 crash due to MPU violation

Program Counter:
0xe0000000

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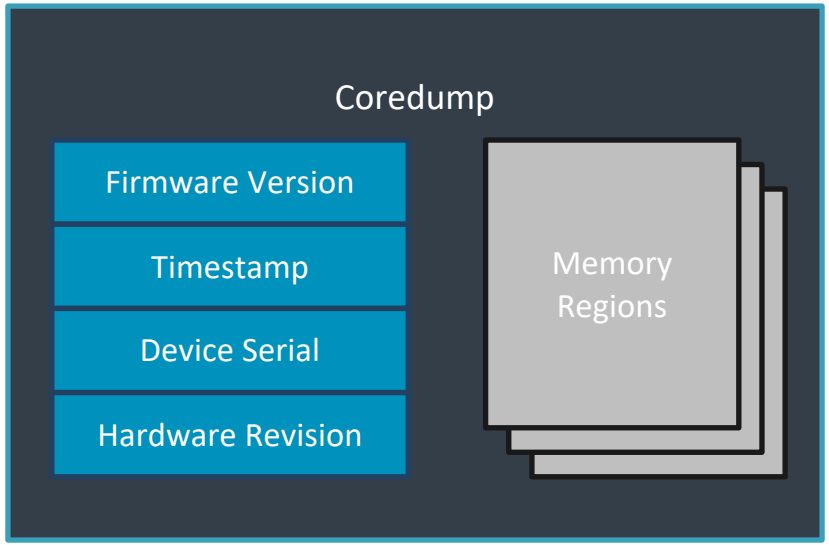
Using Coredumps to Analyze Issues

- What is a coredump
  - A snapshot of RAM regions at a specific moment in time.
  - Can be captured on command, or at time of a fault, such as a hardfault or ASSERT.
  - Helps with post-mortem debugging
  - Requires symbol file & clever parsing
- What RTOS's support coredumps natively?
  - ESP32, Zephyr RTOS, MyNewt RTOS
  - Any RTOS with Memfault



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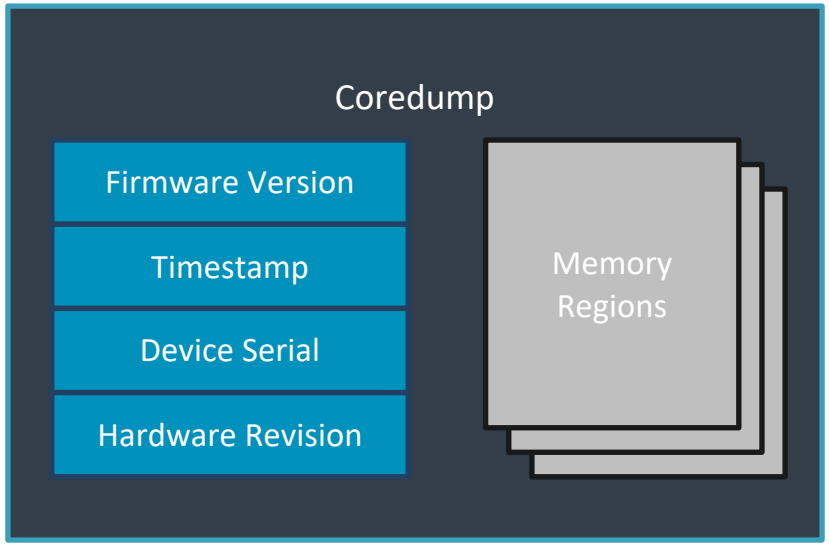
Using Coredumps to Analyze Issues

```
void HardFault_Handler(void) {
   // … fault handling code ...
   NVIC_SystemReset();

   // Don’t just crash…
   capture_coredump();
}
```



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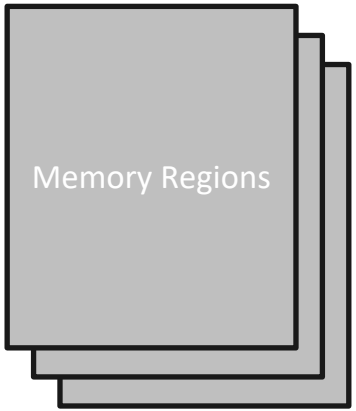
Using Coredumps to Analyze Issues

A coredump is comprised of raw memory regions

- From coredumps, one can recover:
  - Threads and stacktraces
  - Heap allocations and statistics
  - Global variables
  - Local variables and function arguments
  - System and peripheral registers
  - Anything else you want to collect (and parse)



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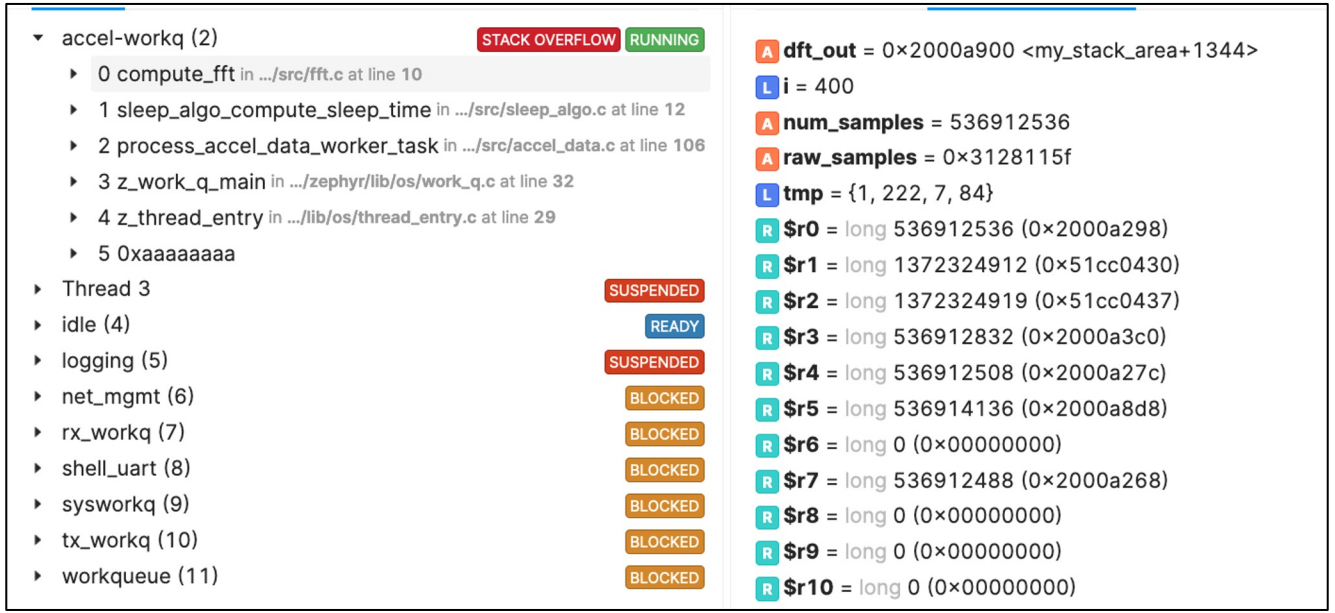
Using Coredumps to Analyze Issues



Threads, backtraces, local variables, and registers

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Using Coredumps to Analyze Issues

Analysis

Memory management fault detected at 0×2000a3c0

Memory management fault on a data access

Fault Register	Value	Hex Value
CFSR	130	0×00000082
HFSR	0	0×00000000
SHCSR	458753	0×00070001

Parse and interpret system registers

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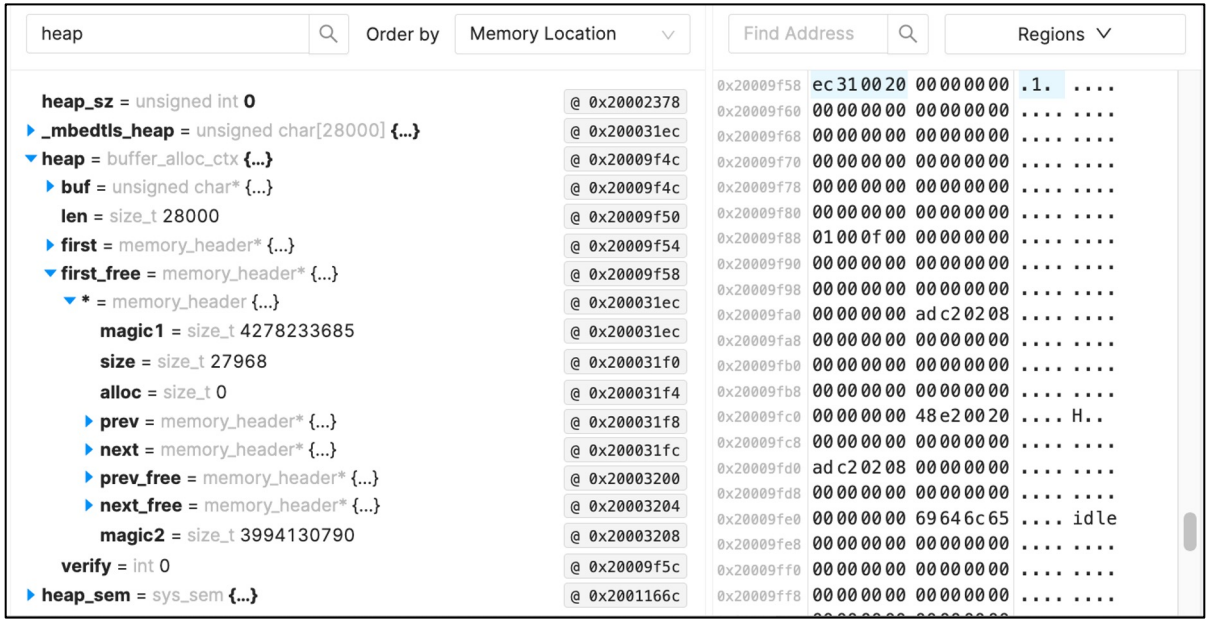
Using Coredumps to Analyze Issues



View all global variables at time of coredump

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Coredumps – What can I debug?

- Crashes and other items worth extra investigation
  - Hardfaults, Memfaults, Asserts, etc.
  - Deadlocks, system stalls
  - Memory corruption issues
  - Heap out-of-memory
  - Stack overflows
  - Undefined behavior
    (”SHOULD NEVER HAPPEN” 😉)

```
static void prv_handle_new_state(eWifiState state) {
    switch (state) {
        case kWifiState_Off:
            do_something();
            break;
        case kWifiState_Connecting:
            do_something();
            break;
        case kWifiState_Connected:
            do_something();
            break;
        // !! Should never get here. !!
        case kWifiState_UNDEFINED:
            TRIGGER_COREDUMP();
    }
}
```

https://embeddedartistry.com/blog/2021/01/11/hard-fault-debugging/

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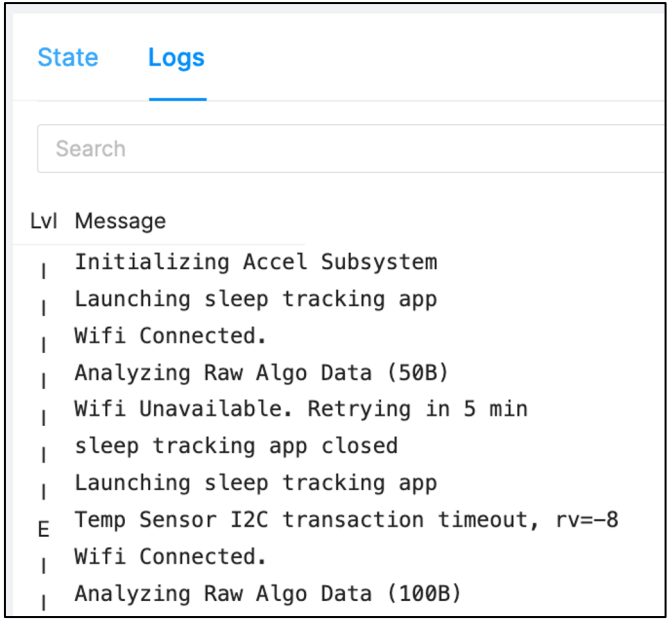
When Coredumps Aren’t Enough

- Coredumps aren’t the perfect solution for all issues
  - Behavioral bugs require more of a timeline than a snapshot (if this & this, then that)
  - Devices with storage or bandwidth constraints
  - Issues in interpreted languages (MicroPython, JerryScript)
  - Determining trends
- When you need context before a crash…
  - Use logging or simple tracing
  - Store log lines in a RAM buffer, send it with coredump!



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Preventing Issues

We fixed the issues. How do we don’t introduce more?

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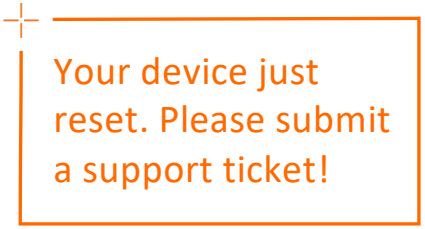
Internal Testing

- You must be testing the devices internally
  - Catch and fix as many bugs before production as possible
  - Firmware team, QA, engineers, and other employees
  - Ask biggest fans of your product to be beta testers
  - Encourage users to report bugs
  - Less concerns around privacy & data collection
- Build and deploy nightly or regular firmware updates to devices
  - Constantly be fixing and verifying fixes
  - Perform experiments!



Unfortunately, some bugs will only be caught in production.

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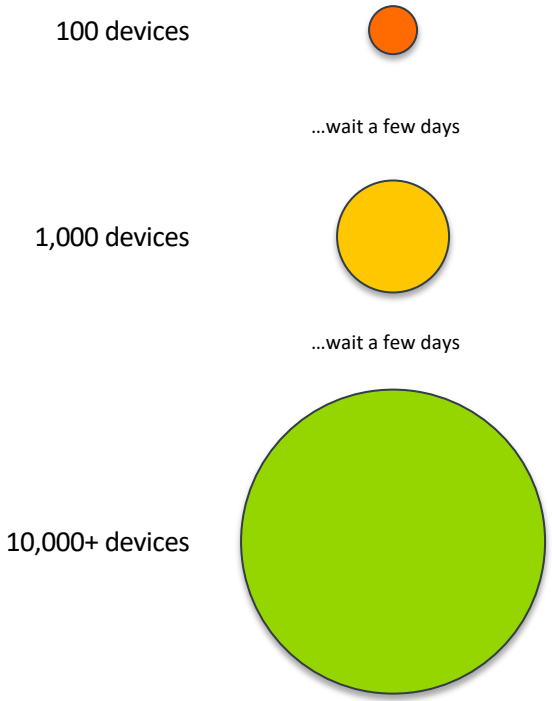
Staged Rollouts

- Send out firmware updates in a controlled manner
  - Send it out to 5%, then 10%, then 20%, etc.
  - At each step, assess quality and performance
  - New issues? – pull the firmware update!
- How to implement staged rollouts?
  - Hosted firmware update solutions have this feature
  - At the very least, can set up devices to poll once every 24 hours (random interval) for new firmware update



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Metrics

Uncover trends on anything that is numerical

- Common metrics are:
  - Task runtimes
  - Heap information
  - Connectivity statistics
  - Frequency of errors
  - Peripheral utilization and power states

```
Example App Booting
Metric ID: 1 -- Value: 15000  # elapsed ticks
Metric ID: 2 -- Value: 8531   # Main Task ticks
Metric ID: 3 -- Value: 8223   # Timer Task ticks
Metric ID: 4 -- Value: 14     # Timer Task count
Metric ID: 5 -- Value: 3593   # "sensor on" ticks
Metric ID: 6 -- Value: 4696   # heap-free low watermark
```

Pinpoint power, connectivity, and performance issues and regressions

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Metrics

```
void flash_sector_erase(uint16_t sector) {
    ...
    device_metrics_incr(kDeviceMetric_FlashSectorErases);
}

void flash_write_bytes(uint32_t addr, void *buf, size_t n) {
    ...
    device_metrics_incr_by(kDeviceMetric_FlashWriteBytes, n);
}
```

https://interrupt.memfault.com/blog/device-heartbeat-metrics

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Metrics

Per Device

Counts
Averages
Min/Max

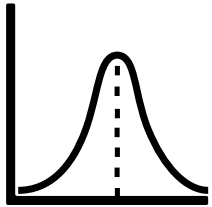
0110...

0001...

1110...

Entire Fleet

Counts
Averages
Min/Max



7.2 days battery life

1.7 reboots/day

87% connected

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Metrics

We can compare metrics between firmware versions

	v1.0.0	v1.1.0	Improvement?
CPU sleep time	83%	96%	
Average Uptime	1.3 days	1.32 days	-
Stack bytes free – low water mark	150 bytes	72 bytes	

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~~Best Practices~~
My Favorite Practices

Sharing my tips & tricks monitoring millions of devices with proper tooling in place

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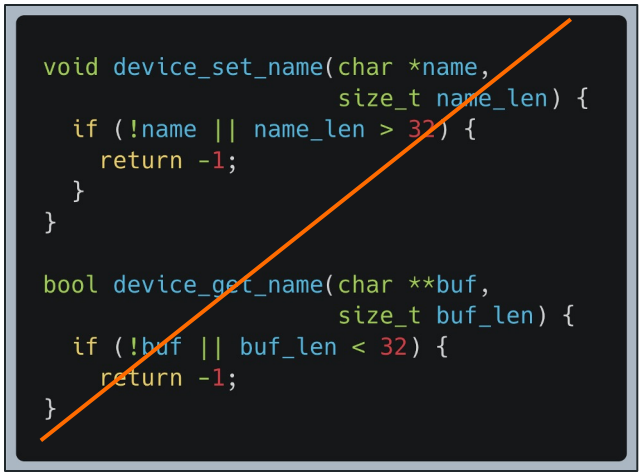
Life With Debugging Infrastructure

If you have logs & coredumps being sent from devices, you can employ what I call **offensive programming**.

This is the proper way to debug “in production”

- During runtime, **raise errors immediately**!
  - Bring bugs front and center
  - Undefined behavior – reset to a known state
  - Assume that if bugs are raised early and often, they can be fixed before shipping
  - With a handful of devices, the 1 in 10,000 hour bugs can be caught



BAD BAD BAD BAD

https://interrupt.memfault.com/blog/defensive-and-offensive-programming

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Use ASSERT() Liberally

```
void device_set_name(char *name,
                     size_t name_len) {
  ASSERT(name && name_len <= 32);
  ...
}

bool device_get_name(char **buf,
                     size_t buf_len) {
  ASSERT(buf && buf_len >= 32);
  ...
}
```

Argument validation

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Use ASSERT() Liberally

```
void *malloc_assert(size_t n) {
  void *p = malloc(n)
  ASSERT(p);
  return p;
  ...
}
```

Assert on heap exhaustion

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Use ASSERT() Liberally

```
void timing_sensitive_task(void) {
  const bool success =
      mutex_lock(&s_mutex, 1000 /* 1 second */);
  ASSERT(success);
  {
    ...
  }
}
```

Easily capture and diagnose timing issues

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Use ASSERT() Liberally

```
void on_commit(eState prev_state) {
  ASSERT(prev_state == kState_Flushing
      || prev_state == kState_Idle);
}
```

State machine transition violations

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Erase after free

```
void free_and_erase(void *ptr) {
  HeapInfo *info = heap_get_info(ptr);
  memset(info->ptr, '0', info->len);
  free(ptr);
}
```

Zero out allocations after free

*Now standard in iOS 16.1 and macOS Ventura***

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The End

- Happy to connect!
- https://www.linkedin.com/in/tyhoff/
- https://memfault.com/webinars/
- https://interrupt.memfault.com
- Email: tyler@memfault.com

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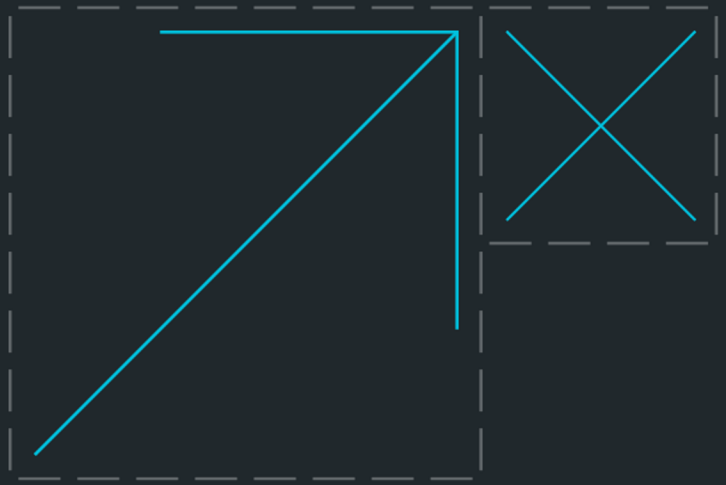

Thank You
Danke
Gracias
Grazie
谢谢
ありがとう
Asante
Merci
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Kiitos
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