Kernel analysis using eBPF

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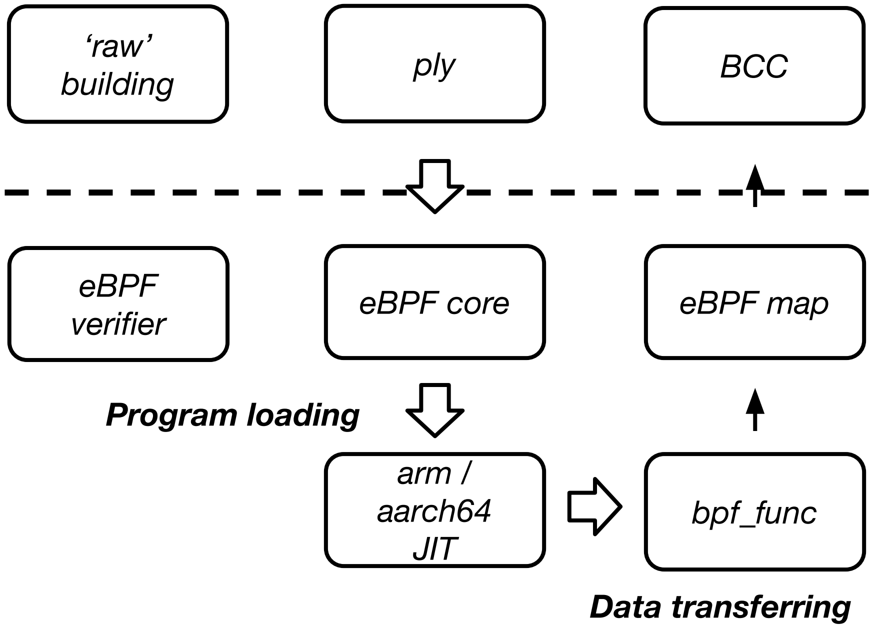
LEADING COLLABORATION IN THE ARM ECOSYSTEM

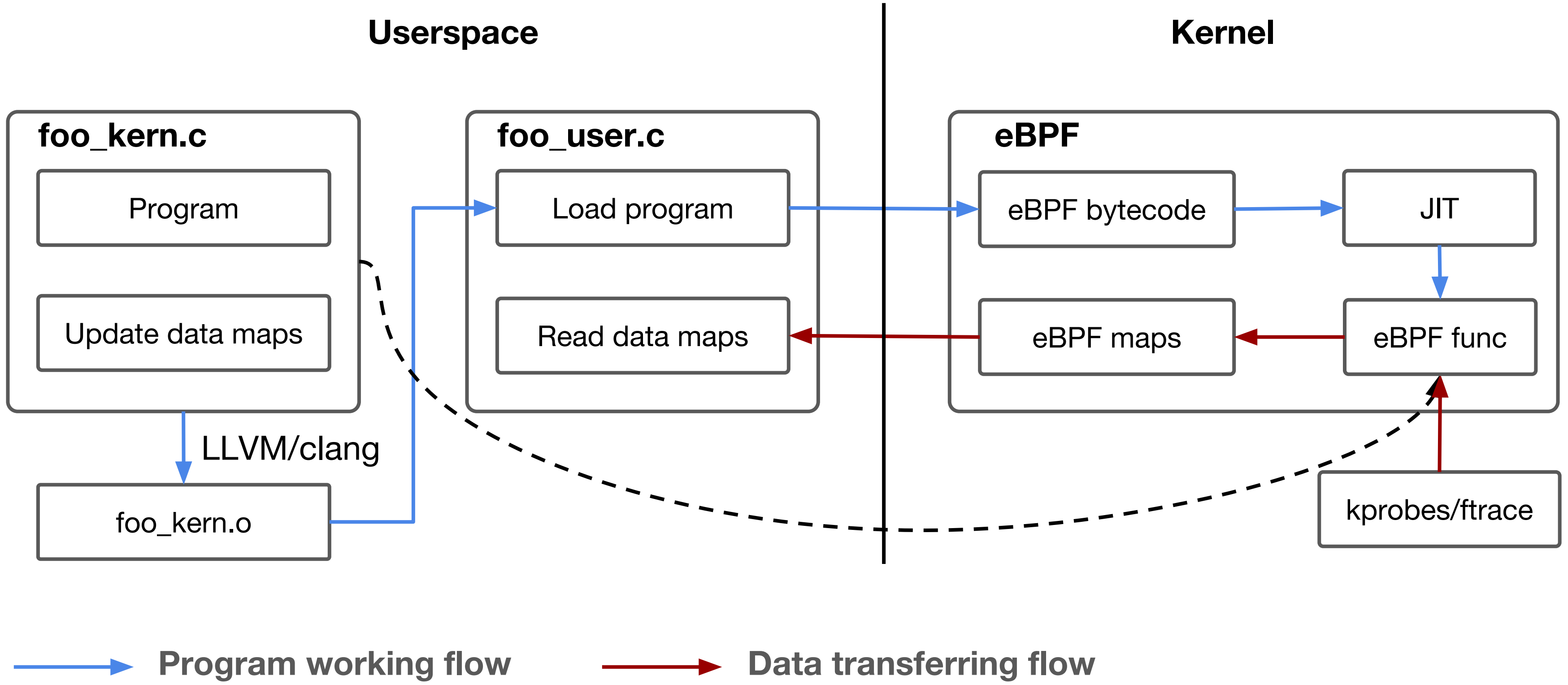
Extending the Berkeley Packet Filter

- Historically Berkeley Packet Filter provided a means to filter network packets
  - If you ever used tcpdump you've probably already used it
  - `tcpdump host helios and \( hot or ace \)`
- eBPF has extended BPF hugely:
  - Re-encoded and more expressive opcodes
  - Multiple new hook points within the kernel to attach eBPF programs to
  - Rich data structures to pass information to/from kernel
  - C functional call interface (an eBPF program can call kernel function)

Framework of eBPF



Using eBPF for debugging



Using eBPF for debugging - cont.

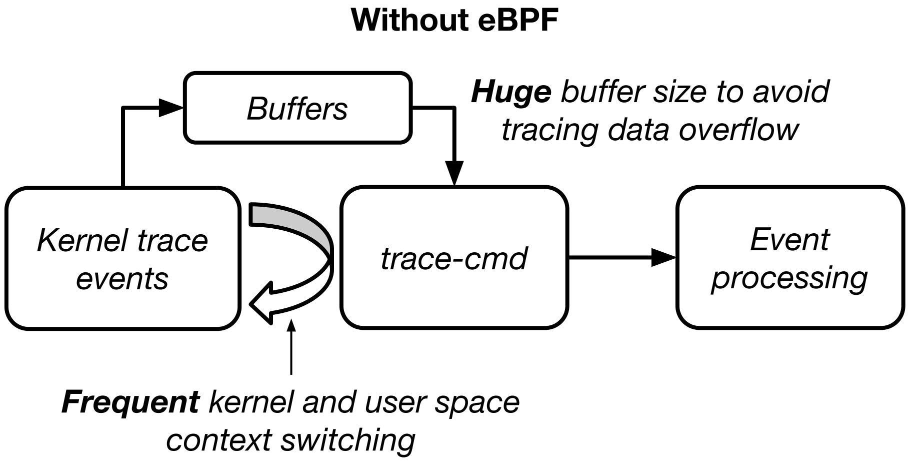
- eBPF program is written in C code and compiled to eBPF bytecode
  - LLVM/clang provides us a eBPF compiler (no support in gcc)
  - Direct code generation is also possible (or LLVM without clang)
- eBPF program is loaded inside eBPF virtual machine with sanity-checking
- eBPF program is "attached" to a designated code path in the kernel
  - eBPF in its traditional use case is attached to networking hooks allowing it to filter and classify network traffic using (almost) arbitrarily complex programs
  - Furthermore, we can attach eBPF programs to tracepoints, kprobes, and perf events for debugging the kernel and carrying out performance analysis.
- Kernel and user space typically use eBPF map; it is a generic data structure well suited to transfer data from kernel to userspace

Debugging with eBPF versus tracing

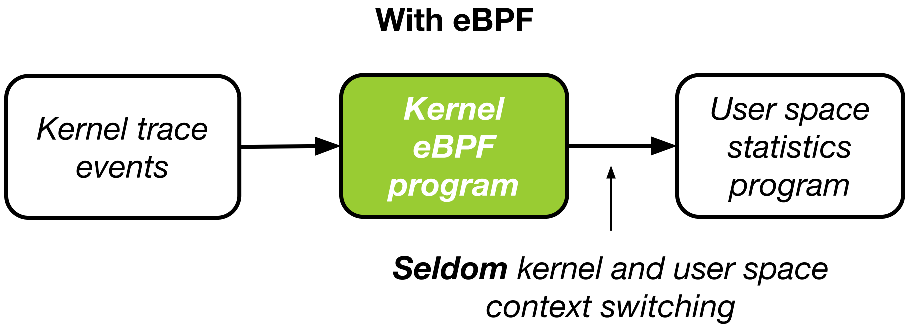
Tracing is very powerful but it can also be cumbersome for whole system analysis due to the volume of trace information generated.

Most developers end up writing programs to summarize the trace.

eBPF allows us to write program to summarize trace information without tracing.



Without eBPF
Buffers
Huge buffer size to avoid tracing data overflow
Kernel trace events
trace-cmd
Event processing
Frequent kernel and user space context switching



With eBPF
Kernel trace events
Kernel eBPF program
User space statistics program
Seldom kernel and user space context switching

Introducing the VM

- Instruction set architecture (ISA)
- Verifier
- Maps
- Just-in-time compilation

eBPF bytecode instruction set architecture (ISA)

Uses a simple RISC-like instruction set. It is intentionally easy to map eBPF program to native instructions (especially on RISC machines).

10 general purpose 64-bit registers and one register for frame pointer, maps 1:1 to registers on many 64-bit architectures.

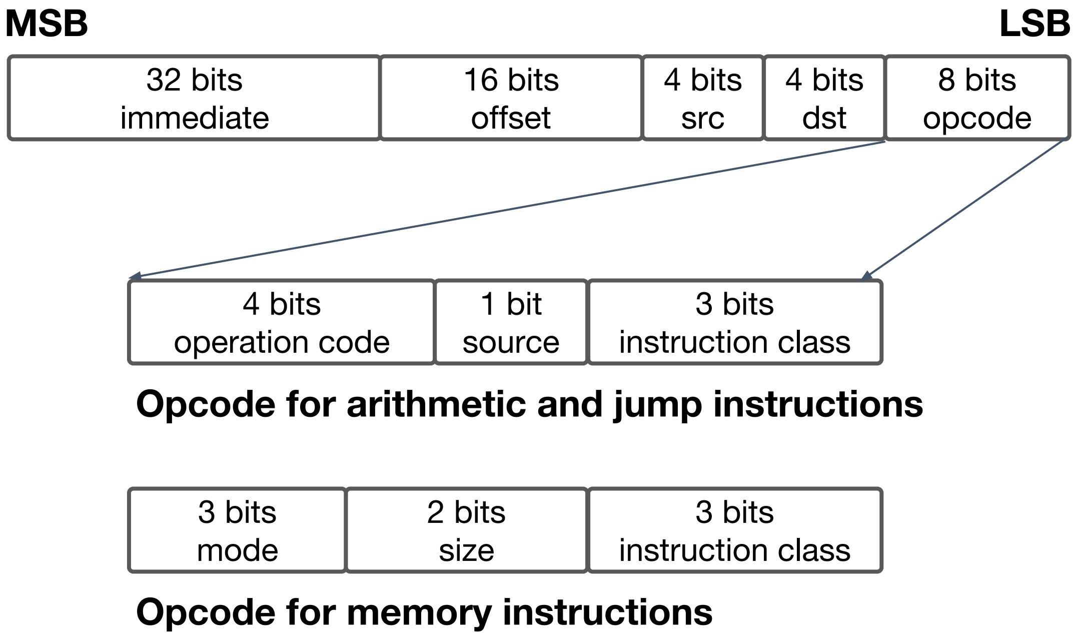
Every instruction is 64-bit, the eBPF program can contain a maximum of 4096 instructions.

eBPF Register	Description
`R0`	Return value from in-kernel function, and exit value for eBPF program
`R1 ~ R5`	Arguments from eBPF program to in-kernel function
`R6 ~ R9`	Callee saved registers that in-kernel function will preserve
`R10`	Read-only frame pointer to access stack

Instruction encoding

Three instruction types:
ALU instructions
memory instructions
branch instructions

New **BPF_CALL** instruction made it possible to call in-kernel functions cheaply.



Just-in-time compilation (JIT)

Just-in-time (JIT) compiler translates eBPF bytecode into a host system's assembly code and speed up program execution. For most opcodes there is a 1:1 mapping between eBPF and AArch64 instructions.

ARM/ARM64 JIT is enabled by kernel config: `CONFIG_BPF_JIT`.

ARM/ARM64 JIT complies with *Procedure Call Standard for the ARM® Architecture* (AAPCS) to map eBPF registers to machine registers and build prologue/epilogue for function entry and exit.

eBPF Register	Aarch64 Register	Description
`R0`	`X7`	Return value from in-kernel function, and exit value for eBPF program
`R1 ~ R5`	`X0 ~ X4`	Arguments from eBPF program to in-kernel function
`R6 ~ R9`	`X19 ~ X22`	Callee saved registers that in-kernel function will preserve
`R10`	`X25`	Read-only frame pointer to access stack

Verifier

- eBPF programs are loaded from user space but will run in kernel space; the eBPF verifier checks that the program is safe to run before invoking it
- Checks that the program license is GNU GPL and, for kprobes, also the kernel version
- Function call verification
  - Allows function calls from one bpf function to another
  - Only calls to known functions are allowed
  - Unresolved function calls and dynamic linking are **not** permitted
- Check that control flow graph of eBPF program is a directed acyclic graph
  - Used to disallow loops to ensure the program don't cause the kernel to lock up
  - Detect unreachable instructions
  - Program terminates with **BPF_EXIT** instruction
  - All branch instructions except for **BPF_EXIT** or **BPF_CALL** instructions are within program boundary
- Simulates execution of every instructions and observes the state change of registers and stack

Control flow graph (CFG) to detect loop

Example 1: detect back edge for loop.

```
BPF_MOV64_REG(BPF_REG_1, BPF_REG_0)
BPF_MOV64_REG(BPF_REG_2, BPF_REG_0)
BPF_MOV64_REG(BPF_REG_3, BPF_REG_0)
BPF_JMP_IMM(BPF_JA, 0, 0, -4)
BPF_EXIT_INSN()
```

✗

Example 2: detect back edge for conditional loop.

```
BPF_MOV64_REG(BPF_REG_1, BPF_REG_0)
BPF_MOV64_REG(BPF_REG_2, BPF_REG_0)
BPF_MOV64_REG(BPF_REG_3, BPF_REG_0)
BPF_JMP_IMM(BPF_JEQ, BPF_REG_1, 0, -3)
BPF_EXIT_INSN()
```

✗

The state change of registers and stack

The verifier tracks register state and monitors the usage for stack:

- Registers with uninitialized contents cannot be read.
- After a kernel function call, R1-R5 are reset to unreadable and R0 has a return type of the function.
- Since R6-R9 are callee saved, their state is preserved across the call.
- load/store instructions are allowed only with registers of valid types, which are PTR_TO_CTX, PTR_TO_MAP, PTR_TO_STACK and verify if out of bound.
- Allow eBPF program to read data from stack only if it wrote into it.

Example 1: Registers with uninitialized contents cannot be read.

```
BPF_MOV64_REG(BPF_REG_0, BPF_REG_2)
BPF_EXIT_INSN()
```

✗

Example 2: Allow eBPF program to read data from stack only after it wrote into it.

```
BPF_MOV64_REG(BPF_REG_2, BPF_REG_10)
BPF_LDX_MEM(BPF_DW, BPF_REG_0,
BPF_REG_2, -8)
BPF_EXIT_INSN()
```

✗

Maps

- eBPF uses map as generic key/value data structure for data transfer between Kernel and user space
- The maps are managed by using file descriptor and they are accessed from user space via BPF syscall:
  - `bpf(BPF_MAP_CREATE, attr, size):` create a map with given type and attributes
  - `bpf(BPF_MAP_LOOKUP_ELEM, attr, size):` lookup key in a given map
  - `bpf(BPF_MAP_UPDATE_ELEM, attr, size):` create or update key/value pair in a given map
  - `bpf(BPF_MAP_DELETE_ELEM, attr, size):` find and delete element by key in a given map
  - `close(fd):` delete map
- eBPF programs can use map file descriptors of the process that loaded the program.
- When the userspace generates an eBPF program the file descriptors will embedded into immediate values of the appropriate opcode.

Access map in Kernel space

imm	off	src	dst	opcode
fd	0	P	DST	BPF_LD | BPF_DW | BPF_IMM
0	0	0	0	0

imm	off	src	dst	opcode
map	0	0	DST	BPF_LD | BPF_DW | BPF_IMM
map >> 32	0	0	0	0

Map accessing instruction opcode is ‘`BPF_LD | BPF_DW | BPF_IMM`’, which means "load 64-bit (Double Word) immediate"; the instruction is to combine the two ‘`imm`’ fields of this instruction and the subsequent one for ‘`DST`’ register.

The ‘`imm`’ field is set to file descriptor and ‘`src`’ field = `BPF_PSEUDO_MAP_FD` to indicate this is a pseudo instruction for loading map data. `BPF_LD_MAP_FD()` macro is used for instruction assembly. Because ‘`src`’ is non-zero so the opcode is invalid at this stage.

The invalid opcode is fixed up during programing loading `bpf_prog_load()`. At this stage the ‘fd’ will be replaced with a map pointer that can be used as an argument during a BPF_CALL.

Coding for eBPF in assembler

- Before introducing the high level tools let's look at a simple userspace program (in C) that runs an eBPF program
- It is not very common to write eBPF programs in assembler
  - Writing in assembler allows us to explore the syscalls that hold everything together
  - We'll look at the higher level tools in a moment

libbpf: helper functions for eBPF

`libbpf` library makes easier to write eBPF programs, which includes helper functions for loading eBPF programs from kernel space to user space and creating and manipulating eBPF maps:

- User program reads the eBPF bytecode into a buffer and pass it to `bpf_load_program()` for program loading and verification.
- The eBPF program includes the libbpf header for the function definition for building, when run by the kernel, will call `bpf_map_lookup_elem()` to find an element in a map and store a new value in it.
- The user application calls `bpf_map_lookup_elem()` to read out the value stored by the eBPF program in the kernel.

```
int bpf_map_lookup_elem(int fd, const void *key,
                        void *value)
{
        union bpf_attr attr;

        bzero(&attr, sizeof(attr));
        attr.map_fd = fd;
        attr.key = ptr_to_u64(key);
        attr.value = ptr_to_u64(value);

        return sys_bpf(BPF_MAP_LOOKUP_ELEM, &attr,
                       sizeof(attr));
}
```

Coding for eBPF in assembler

```
int main(void)
{
        int map_fd, i, key;
        long long value = 0, cnt;

        map_fd = bpf_create_map(BPF_MAP_TYPE_ARRAY, sizeof(key), sizeof(value), 5000, 0);
        struct bpf_insn prog[] = {
                BPF_MOV64_REG(BPF_REG_6, BPF_REG_1),
                BPF_MOV64_IMM(BPF_REG_0, 0), /* r0 = 0 */
                BPF_STX_MEM(BPF_W, BPF_REG_10, BPF_REG_0, -4), /* *(u32 *)(fp - 4) = r0 */
                BPF_MOV64_REG(BPF_REG_2, BPF_REG_10),
                BPF_ALU64_IMM(BPF_ADD, BPF_REG_2, -4), /* r2 = fp - 4 */
                BPF_LD_MAP_FD(BPF_REG_1, map_fd),
                BPF_RAW_INSN(BPF_JMP | BPF_CALL, 0, 0, 0, BPF_FUNC_map_lookup_elem),
                BPF_JMP_IMM(BPF_JEQ, BPF_REG_0, 0, 2),
                BPF_MOV64_IMM(BPF_REG_1, 1), /* r1 = 1 */
                BPF_RAW_INSN(BPF_STX | BPF_XADD | BPF_DW, BPF_REG_0, BPF_REG_1, 0, 0), /* xadd r0 += r1 */
                BPF_MOV64_IMM(BPF_REG_0, 0), /* r0 = 0 */
                BPF_EXIT_INSN(),
        };
        size_t insns_cnt = sizeof(prog) / sizeof(struct bpf_insn);
        pfd = bpf_load_program(BPF_PROG_TYPE_KPROBE, prog, insns_cnt, "GPL",
                               LINUX_VERSION_CODE, bpf_log_buf, BPF_LOG_BUF_SIZE);

        attach_kprobe();

        sleep(1);
        key = 0;
        assert(bpf_map_lookup_elem(map_fd, &key, &cnt) == 0);
        printf("sys_read counts %lld\n", cnt);
        return 0;
}
```

The example is ~50 lines of code for eBPF in assembler; it demonstrates the eBPF code have components: eBPF bytecode, syscalls, maps.

`attach_kprobe()` is used to enable kprobe event and attach the event with eBPF program.

```
void attach_kprobe(void)
{
    system("echo 'p:sys_read sys_read' >> \
                /sys/kernel/debug/tracing/kprobe_events")

    efd = open("/sys/kernel/debug/tracing/events/kprobes/sys_read/id”,
               O_RDONLY, 0);
    read(efd, buf, sizeof(buf));
    close(efd);

    buf[err] = 0;
    id = atoi(buf);
    attr.config = id;

    efd = sys_perf_event_open(&attr, -1/*pid*/, 0/*cpu*/, -1, 0);
    ioctl(efd, PERF_EVENT_IOC_ENABLE, 0);
    ioctl(efd, PERF_EVENT_IOC_SET_BPF, pfd);
}
```

eBPF tooling

- Kernel examples
- Ply
- bcc
- SystemTap (stapbpf)
- ...

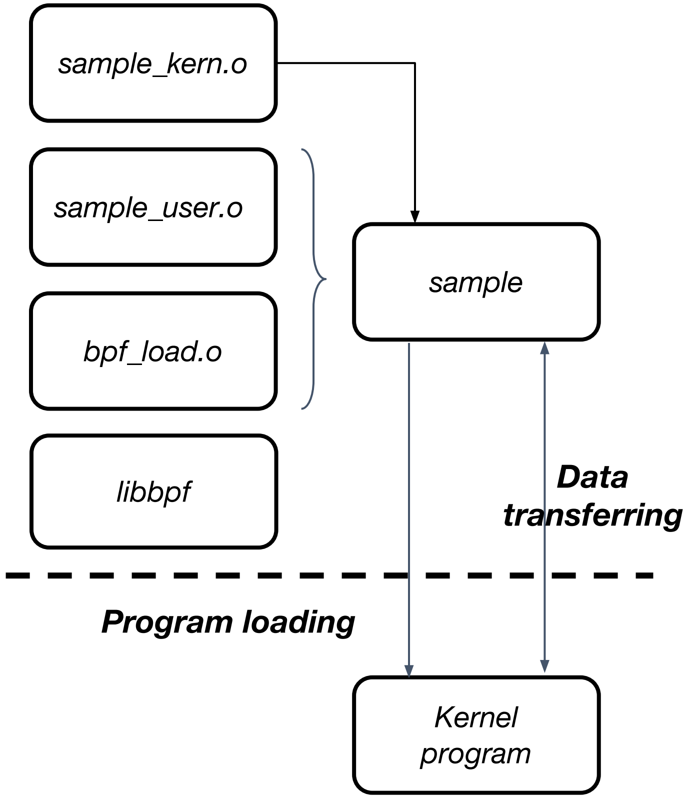
Kernel samples

It's good to start from eBPF kernel samples; Linux kernel tree provides eBPF system call wrapper functions in lib `libbpf`; the samples use `bpf_load.c` to create map and load kernel program, **attach trace point**.

Kernel and user space programs use the naming convention `xxx_user.c` and `xxx_kern.c`, and the user space program to use file name `xxx_kern.o` to search kernel program.

The user space program is compiled by GCC for executable file and it reacts for '`CROSS_COMPILE=aarch64-linux-gnu-`' for cross compiling. Kernel program is compiled by LLVM/Clang, by default it uses LLVM/Clang in distro and can specify path for new built LLVM/Clang. Build commands:

```
make headers_install   # creates "usr/include" directory in the build top directory
make samples/bpf/ LLC=xxx/llc CLANG=xxx/clang
```



Sample code: trace kmem_cache_alloc_node

tracex4_kern.c

```
struct bpf_map_def SEC("maps") my_map = {
        .type = BPF_MAP_TYPE_HASH,
        .key_size = sizeof(long),
        .value_size = sizeof(struct pair),
        .max_entries = 1000000,
};

SEC("kretprobe/kmem_cache_alloc_node")
int bpf_prog2(struct pt_regs *ctx)
{
        long ptr = PT_REGS_RC(ctx);
        long ip = 0;

        /* get ip address of kmem_cache_alloc_node() caller */
        BPF_KRETPROBE_READ_RET_IP(ip, ctx);

        struct pair v = {
                .val = bpf_ktime_get_ns(),
                .ip = ip,
        };

        bpf_map_update_elem(&my_map, &ptr, &v, BPF_ANY);
        return 0;
}
char _license[] SEC("license") = "GPL";
u32 _version SEC("version") = LINUX_VERSION_CODE;
```

Step 2: kernel program update map data

tracex4_user.c

Step 3: user space program reads map data

```
static void print_old_objects(int fd)
{
        long long val = time_get_ns();
        __u64 key, next_key;
        struct pair v;

        /* Based on current ‘key’ value, we can get next key value
         * and iterate all bpf map elements. */
        key = -1;
        while (bpf_map_get_next_key(map_fd[0], &key, &next_key) == 0) {
                bpf_map_lookup_elem(map_fd[0], &next_key, &v);
                key = next_key;
                printf("obj 0x%llx is %2lldsec old was allocated at ip %llx\n",
                       next_key, (val - v.val) / 1000000000ll, v.ip);
        }
}

int main(int ac, char **argv)
{
        char filename[256];
        int i;

        snprintf(filename, sizeof(filename), "%s_kern.o", argv[0]);

        if (load_bpf_file(filename)) {
                printf("%s", bpf_log_buf);
                return 1;
        }

        for (i = 0; ; i++) {
                print_old_objects(map_fd[1]);
                sleep(1);
        }

        return 0;
}
```

Step 1: load kernel program & enable kretprobe trace point

Ply: light dynamic tracer for eBPF

https://wkz.github.io/ply/

Ply uses an awk-like mini language describing how to attach eBPF programs to tracepoints and kprobes. It has a built-in compiler and can perform compilation and execution with a single command.

Ply can extract arbitrary data, i.e register values, function arguments, stack/heap data, stack traces.

Ply keeps dependencies to a minimum, leaving libc as the only runtime dependency. Thus, ply is well suited for **embedded targets**.

```
trace:raw_syscalls/sys_exit / (ret() < 0) /
{
        @[comm()].count()
}
```

```
^Cde-activating probes

@:
dbus-daemon                     2
ply                             3
irqbalance                      4
```

System call (sys_exit) failure statistics in ply

provider: selects which probe interface to use

probe definition: the point(s) of instrumentation

predicate: filter events to match criteria

```
trace:raw_syscalls/sys_exit / (ret() < 0) /
{
        @[comm()].count()
}
```

method: common way is to aggregate data using methods, have two functions: .count() and .quantize()

Key value

@: sign of map

```
^Cde-activating probes

@:
dbus-daemon                    2
ply                            3
irqbalance                     4
```

Tracing result: task name + counts

Build ply

https://github.com/iovisor/ply

If applicable, please check build: Fix kernel header installation on ARM64 is in your repository before building.

Method 1: Native compilation

```
./autogen.sh
./configure --with-kerneldir=/path/to/linux
make
make install
```

```
$ ldd src/ply
linux-vdso.so.1 (0x0000ffff9320d000)
libc.so.6 =>
/lib/aarch64-linux-gnu/libc.so.6
(0x0000ffff93028000)
/lib/ld-linux-aarch64.so.1
(0x0000ffff931e2000)
```

Method 2: Cross-Compilation for arm64

```
./autogen.sh
./configure --host=aarch64 --with-kerneldir=/path/to/linux
make CC=aarch64-linux-gnu-gcc
# copy src/ply to target board
```

BPF Compiler Collection (BCC)

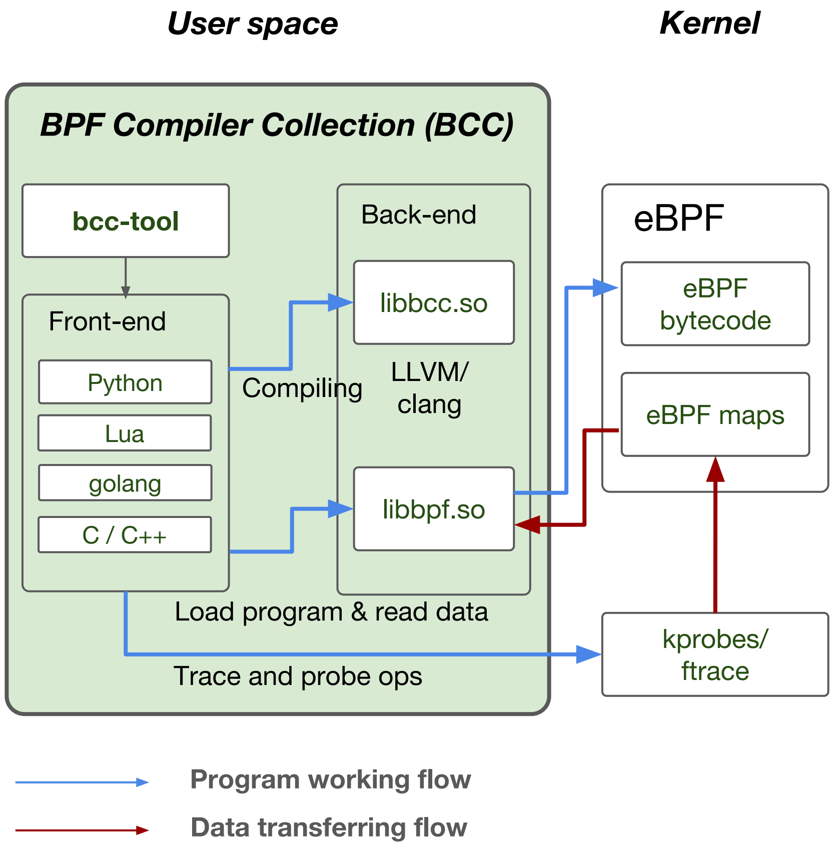
BPF compiler collection (BCC) project is a **toolchain** which reduces the difficulty for writing, compiling (invokes LLVM/Clang) and loading eBPF programs.

BCC **reports errors for mistake** for compiling, loading program, etc; this reduces difficulty for eBPF programming.

For writing short and expressive programs, **high-level languages** are available in BCC (python, Lua, go, etc).

BCC provides scripts that use **User Statically-Defined Tracing** (USDT) probes to place tracepoints in user-space code; these are probes that are inserted into user applications statically at compile-time.

BCC includes an impressive **collection** of examples and ready-to-use tracing tools.



BCC example code

https://github.com/iovisor/bcc/blob/master/examples/tracing/task_switch.py

```
b = BPF(text="""

struct key_t {
  u32 prev_pid, curr_pid;
};

BPF_HASH(stats, struct key_t, u64, 1024);
int count_sched(struct pt_regs *ctx, struct task_struct *prev) {
  struct key_t key = {};
  u64 zero = 0, *val;

  key.curr_pid = bpf_get_current_pid_tgid();
  key.prev_pid = prev->pid;

  val = stats.lookup_or_init(&key, &zero);
  (*val)++;
  return 0;
}
""")

b.attach_kprobe(event="finish_task_switch", fn_name="count_sched")

# generate many schedule events

for i in range(0, 100): sleep(0.01)


for k, v in b["stats"].items():
    print("task_switch[%5d->%5d]=%u" % (k.prev_pid, k.curr_pid, v.value))
```

Kernel program

Enable kprobe event

Read map data “stats”

https://github.com/iovisor/bcc/blob/master/INSTALL.md

Build BCC

BCC runs on the target but cannot be easily cross-compiled. These instructions show how to perform a native build (and work on an AArch64 platform)

Install build dependencies

```
sudo apt-get install debhelper cmake libelf-dev bison
flex libedit-dev python python-netaddr python-pyroute2
arping iperf netperf ethtool devscripts zlib1g-dev
libfl-dev
```

Build luajit lib

```
git clone http://luajit.org/git/luajit-2.0.git
cd luajit-2.0
git checkout -b v2.1 origin/v2.1
make
sudo make install
```

Build LLVM/Clang

```
cd where-llvm-live
svn co http://llvm.org/svn/llvm-project/llvm/trunk llvm
cd where-llvm-live
cd llvm/tools
svn co http://llvm.org/svn/llvm-project/cfe/trunk clang
cd where-llvm-live
mkdir build (in-tree build is not supported)
cd build
cmake -G "Unix Makefiles" \
      -DCMAKE_INSTALL_PREFIX=$PWD/install ../llvm
make; make install
```

Build BCC

```
# Use self built LLVM/clang binaries
export PATH=where-llvm-live/build/install/bin:$PATH

git clone https://github.com/iovisor/bcc.git
mkdir bcc/build; cd bcc/build
cmake .. -DCMAKE_INSTALL_PREFIX=/usr
make
sudo make install
```

BCC and embedded systems

- BCC native build has many dependencies
  - Dependency with libs and binaries, e.g. cmake, luajit lib, etc
  - Most dependencies can be resolved for Debian/Ubuntu by using ‘apt-get’ command
  - BCC depends on LLVM/Clang to compile for eBPF bytecode, but LLVM/Clang itself also introduces many dependencies
- BCC and LLVM building requires powerful hardware
  - Have big pressure for both memory and filesystem space
  - Building is impossible or, with swap, extremely slow on systems without sufficient memory
  - Consumes lots of disk space. For AArch64: BCC needs **12GB**, additionally LLVM needs **42GB**
  - Even with strong hardware, the compilation process takes a long time
  - Save LLVM and BCC binaries on PC and use them by mounting NFS node :)
- Difficult to deploy BCC on Android system
  - No package manager means almost all library dependencies must be compiled from scratch
  - Android uses bionic C library, which makes it difficult to build libraries that use GNU extensions
  - androdeb: https://github.com/joelagnel/adeb

SystemTap - eBPF backend

- SystemTap introduced, stapbpf, an eBPF backend in Oct, 2017
  - Joins existing backends: kernel module and Dyninst

- SystemTap is both the tool and the scripting language
  - Language is inspired by awk, and predecessor tracers such as DTrace…
  - Uses the familar awk-like structure: probe.point { action(s) }
  - Extracts symbolic information based on DWARF parsing

```
# stap --runtime=bpf -v - <<EOF
> probe kernel.function("ksys_read") {
>   printf("ksys_read(%d): %d, %d\n",
>              pid(), $fd, $count);
>   exit();
> }
> EOF
Pass 1: parsed user script and 61 library
scripts using
410728virt/101984res/8796shr/93148data kb, in
260usr/20sys/272real ms.
Pass 2: analyzed script: 1 probe, 2 functions,
0 embeds, 0 globals using
468796virt/161004res/9684shr/151216data kb, in
820usr/10sys/843real ms.
Pass 4: compiled BPF into "stap_10960.bo" in
10usr/0sys/33real ms.
Pass 5: starting run.
ksys_read(18719): 0, 8191
Pass 5: run completed in 0usr/0sys/30real ms.
```

SystemTap - Revenge of the verifier

- eBPF verifier is more aggressive than the SystemTap language
    - Language permits looping but verifier prohibits loops (3.2 did not implement loop unrolling to compensate)
    - The 4096 opcode limit restriction also looms
    - `$$vars` and `$$locals` cause verification failure if used (likely depends on traced function)
    - *This runtime is in an early stage of development and it currently lacks support for a number of features available in the default runtime.* -- STAPBPF(8)

- SystemTap has a rich library of useful tested examples and war stories
    - Almost all are tested and developed using the kernel module backend
    - Thus it common to find canned examples that only work with the kernel module backend
    - This quickly grows frustrating… so one tends to end up using the default backend

BPFtrace - high level tracing language for eBPF

HOLD THE PRESS… HOLD THE PRESS…

BPFtrace language is inspired by awk and C, and predecessor tracers such as DTrace and SystemTap. Brendan Gregg's blogged about it: bpftrace (DTrace 2.0) for Linux 2018 (and most of this slide comes from that blog post). I picked up from lwn.net (many thanks) three days before my slides were due in ;-)

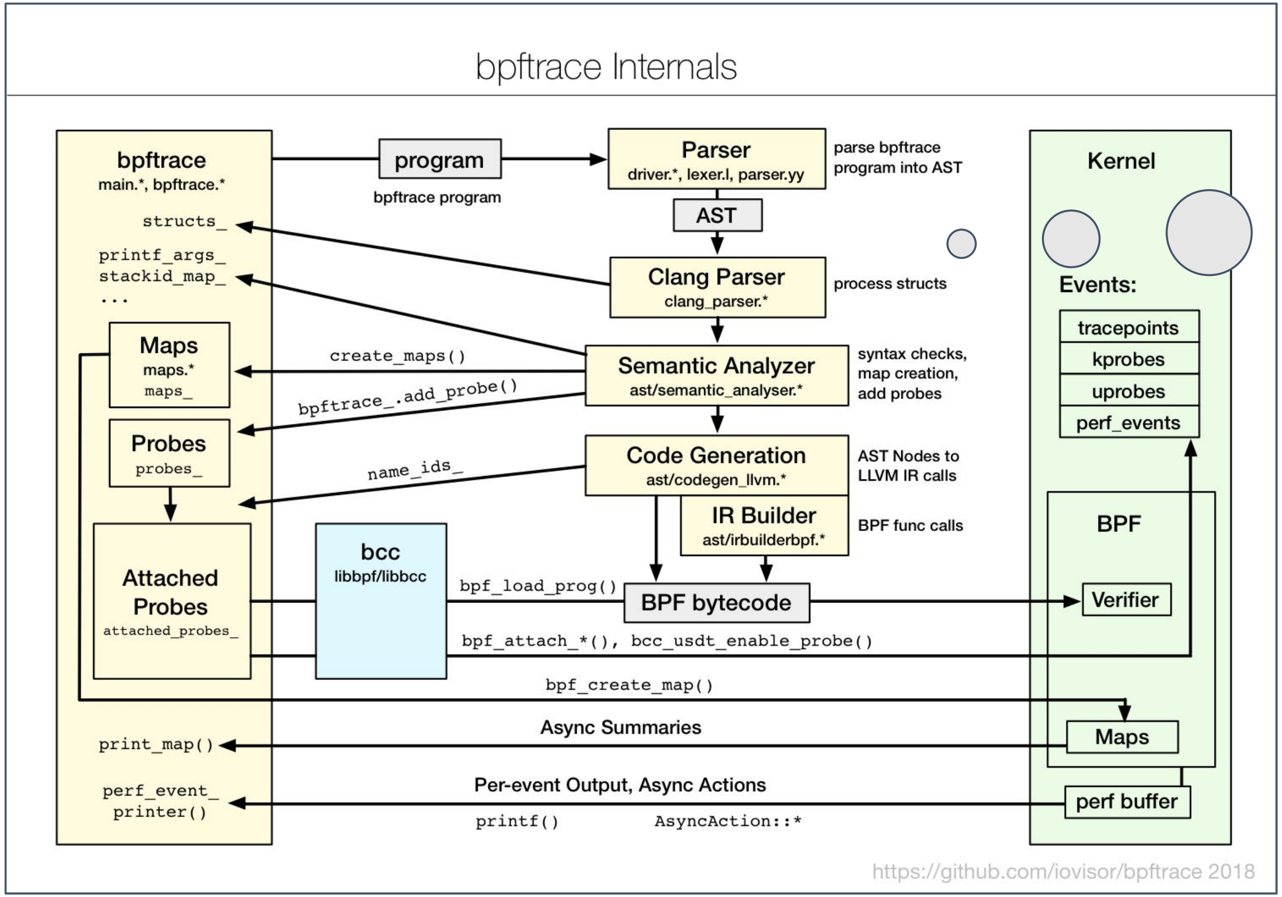
```
# cat > path.bt <<EOF
#include <linux/path.h>
#include <linux/dcache.h>

kprobe:vfs_open
{
    printf("open path: %s\n",
      str(((path *)arg0)->dentry->d_name.name));
}
EOF
# bpftrace path.bt
Attaching 1 probe...
open path: dev
open path: if_inet6
open path: retrans_time_ms
```

"Created by Alastair Robertson, bpftrace is an open source high-level tracing front-end that lets you analyze systems in custom ways. It's shaping up to be a DTrace version 2.0: more capable, and built from the ground up for the modern era of the eBPF virtual machine."

-- Brendan Gregg

BPFtrace - Internals



Good news:
bpftrace has superpowers

Bad news:
Dependencies are inconsistently packaged

Examples

- Report CPU power state
- Who is hammering a library function?
- Hunting leaks
- Debug kernel functions at the runtime

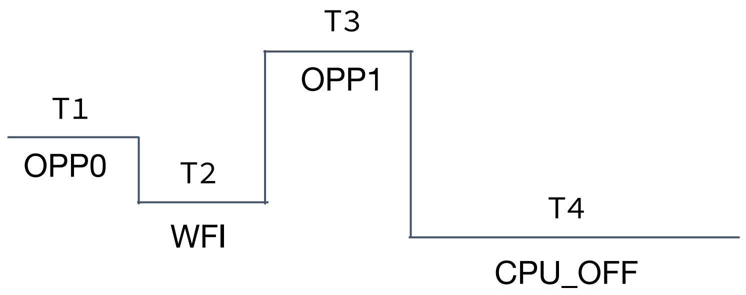
The story - Report CPU power state

When I run one test case, I want to quickly do statistics for CPU frequency so I can get to know if CPU frequency can meet the performance requirement or not.

We can do this with ‘offline’ mode like idlestat tool, but is there any method that can display live info?

- The target is to use high efficient method to count CPU frequency duration time.
- Kernel has existing trace points to record CPU frequency, eBPF kernel program can finish simple computation for CPU frequency state duration based on these trace points.
- Need to get rid of CPU idle duration from CPU frequency time.
- In this example we use tools from the kernel `samples/bpf/` directory.

CPU power state statistics with eBPF



Kernel program

```
T(pstate-0)    += T1
T(pstate-1)    += T3
T(cstate-0)    += T2
T(cstate-1)    += T4
```

User space program

```
CPU states statistics:
state(ms)  cstate-0   cstate-1   cstate-2   pstate-0   pstate-1   pstate-2   pstate-3   pstate-4
CPU-0      767        6111       111863     561        31         756        853        190
CPU-1      241        10606      107956     484        125        646        990        85
CPU-2      413        19721      98735      636        84         696        757        89
CPU-3      84         11711      79989      17516      909        4811       5773       341
CPU-4      152        19610      98229      444        53         649        708        1283
CPU-5      185        8781       108697     666        91         671        677        1365
CPU-6      157        21964      95825      581        67         566        684        1284
CPU-7      125        15238      102704     398        20         665        786        1197
```

LEADING COLLABORATION
IN THE ARM ECOSYSTEM

The story - Who is hammering a library function?

I did a quick profile and its showing a library function dominating one of the cores.

What now?

```
# ply -t 5 -c ‘kprobe:kmem_cache_alloc_node
 { @[stack()].count() }’
     …
     kmem_cache_alloc_node
     _do_fork+0xd0
     __se_sys_clone+0x4c
     el0_svc_naked+0x30          31

     kmem_cache_alloc_node
     alloc_skb_with_frags+0x70
     sock_alloc_send_pskb+0x220
     unix_stream_sendmsg+0x1f4
     sock_sendmsg+0x60
     __sys_sendto+0xd4
     __se_sys_sendto+0x50
     __sys_trace_return         232
```

The story - Hunting leaks

I know I'm leaking memory (or some other precious resource) from a particular pool whenever I run a particular workload. Unfortunately my system is almost ready to ship and we've started disabling all the resource tracking. Is there anything I can do to get a clue about what is going on?

```
# cat track.ply
kprobe:kmem_cache_alloc_node {
        # Can't read stack from a retprobe :-(
        @[0] = stack();
}
kretprobe:kmem_cache_alloc_node {
        @[retval()] = @[0];
        @[0] = nil;
}
kprobe:kmem_cache_free {
        @[arg(1)] = nil;
}
# ply -t 1 track.ply
3 probes active
de-activating probes

@:
        <leaks show up here>
```

The story - Debug kernel functions at the runtime

Inspired by: [BPF: Tracing and More (Brendan Gregg)]

When I debug CPU frequency change flow in kernel, kernel have several different components to work together for frequency changing, including clock driver, mailbox driver, etc.

I want to confirm if the functions have been properly called and furthermore to check function arguments have expected values.

How can I dynamically debug kernel functions at the runtime with high efficiency and safe method?

- SystemTap and Kprobes can be used to debug kernel function, but eBPF is safer to deploy because the verifier will ensure kernel integrity.
- For kernel functions tracing, eBPF can avoid to change kernel code and save time for compilation.
- If it’s safe enough, we even can use it in production for customer support.
- In this example, we use tools from the bcc distribution

Debug kernel functions

```
static int hi3660_stub_clk_set_rate(struct clk_hw *hw, unsigned long rate,
                                    unsigned long parent_rate)
{
        struct hi3660_stub_clk *stub_clk = to_stub_clk(hw);

        stub_clk->msg[0] = stub_clk->cmd;
        stub_clk->msg[1] = rate / MHZ;

        mbox_send_message(stub_clk_chan.mbox, stub_clk->msg);
        mbox_client_txdone(stub_clk_chan.mbox, 0);

        stub_clk->rate = rate;
        return 0;
}
```

```
$ ./tools/trace.py 'hi3660_stub_clk_set_rate "rate: %d" arg2'
PID     TID     COMM            FUNC             -
2002    2002    kworker/3:2     hi3660_stub_clk_set_rate rate: 1421000000
2469    2469    kworker/3:1     hi3660_stub_clk_set_rate rate: 1421000000
2469    2469    kworker/3:1     hi3660_stub_clk_set_rate rate: 1421000000
84      84      kworker/0:1     hi3660_stub_clk_set_rate rate: 903000000
2469    2469    kworker/3:1     hi3660_stub_clk_set_rate rate: 903000000
84      84      kworker/0:1     hi3660_stub_clk_set_rate rate: 903000000
84      84      kworker/0:1     hi3660_stub_clk_set_rate rate: 903000000
2469    2469    kworker/3:1     hi3660_stub_clk_set_rate rate: 903000000
```

BCC `tools/trace.py` can be used to debug kernel function; this tool can trace function with infos: kernel or user space stack, timestamp, CPU ID, PID/TID.

We can use tool `trace.py` to confirm function `hi3660_stub_clk_set_rate()` has been invoked and print out the target frequency.

Debug kernel functions - cont.

```
static int hi3660_mbox_send_data(struct mbox_chan *chan, void *msg)
{
        [...]

        /* Fill message data */
        for (i = 0; i < MBOX_MSG_LEN; i++)
                writel_relaxed(buf[i], base + MBOX_DATA_REG + i * 4);

        /* Trigger data transferring */
        writel(BIT(mchan->ack_irq), base + MBOX_SEND_REG);
        return 0;
}
```

```
$ ./tools/trace.py 'hi3660_mbox_send_data(struct mbox_chan *chan, void *msg)
"msg_id: 0x%x rate: %d", *((unsigned int *)msg), *((unsigned int *)msg + 1)'

PID     TID     COMM            FUNC                -
84      84      kworker/0:1     hi3660_mbox_send_data msg_id: 0x2030a rate: 903
2413    2413    kworker/1:0     hi3660_mbox_send_data msg_id: 0x2030a rate: 903
2413    2413    kworker/1:0     hi3660_mbox_send_data msg_id: 0x2030a rate: 903
```

We can continue to check program flow from high level function to low level function for arguments, and BCC supports C style sentence to print out more complex data structure.

These data “watch points” can easily help us to locate the issue happens in which component.

For left example, we can observe the `msg_id` value to check if pass correct message ID to MCU firmware.

Statistics based on function arguments

```
static int **hi3660_stub_clk_set_rate**(struct clk_hw *hw, unsigned long **rate**,
                                        unsigned long parent_rate)
{
        struct hi3660_stub_clk *stub_clk = to_stub_clk(hw);

        stub_clk->msg[0] = stub_clk->cmd;
        stub_clk->msg[1] = rate / MHZ;

        mbox_send_message(stub_clk_chan.mbox, stub_clk->msg);
        mbox_client_txdone(stub_clk_chan.mbox, 0);

        stub_clk->rate = rate;
        return 0;
}
```

After the kernel functionality has been validated, we can continue to do simple profiling based on Kernel function argument statistics.

Using the `argdist.py` invocation below, we can observe the the CPI frequency mostly changes to 533MHz and 1844MHz.

```
$ tools/argdist.py -I 'linux-mainline/include/linux/clk-provider.h'
  -c -C 'p::hi3660_stub_clk_set_rate(struct clk_hw *hw, unsigned long rate,
unsigned long parent_rate):u64:rate'

      COUNT        EVENT
      1            rate = 903000000
      1            rate = 2362000000
      1            rate = 999000000
      27           rate = 1844000000
      31           rate = 533000000
```

Summary (and thank you)

Everything is awesome…

… and many, many thanks to all the people who have worked to make it so!

Hand-rolled

Asm	Hack value?
Pure C	No “magic”, great examples in kernel

Awk-like

Ply	Easy to deploy esp. on embedded system
SystemTap	DWARF parsing (and wait a bit?)
BPFtrace	`#include <linux/dentry.h>`

BCC	Great tool for tool makers (and running tools from tool makers)

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