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Walking native stacks in BPF without frame pointers

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Agenda

- Why the need for a DWARF-based stack walker in BPF
- Design of our stack walker
- Making it production ready
- Learnings so far
- Future plans

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Native stack walker in BPF using DWARF: Why?

- Stack walking and history of frame pointers
- Current state of the world
  - How hyperscalers solve this problem
  - Recent discussions in Fedora mailing list - TL;DR: will be enabled Fedora 38 , late-april release
  - Go runtime
  - Apple ecosystem
  - Simple Frame (previously known as CTF format)
- We want to support all the runtimes and distributions

Native stack walker in BPF using DWARF

- If not frame pointers then what?
  - .eh_frame/.debug_frame and DWARF CFI
  - How ORC does it?

Motivation

- If not frame pointers then what?
- Perf and libunwind
  - Security
  - Performance

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Motivation

- If not frame pointers then what?
- Perf and libunwind
- BPF advantages
  - Higher safety
  - Lower barrier of entry

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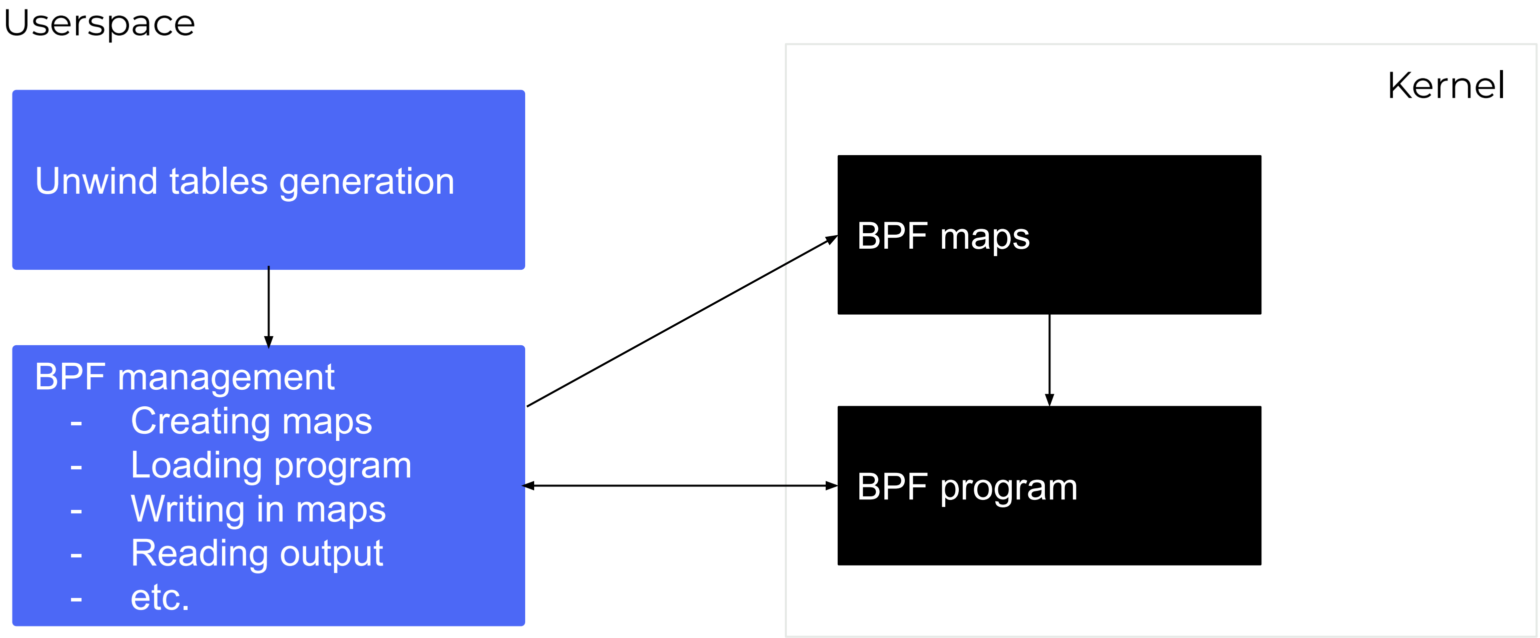
.eh_frame

- Call Frame Information (CFI)
- Space efficient and versatile
- Encoded unwind tables
- CFI opcodes
- Two main layers
  - State machine encoded in a VM - only need DW_CFA_remember_state and DW_CFA_restore_state
  - A special opcode that contains another set of opcode

Design


Userspace
Kernel
Unwind tables generation
BPF maps
BPF management
- Creating maps
- Loading program
- Writing in maps
- Reading output
- etc.
BPF program

Design

- Read the initial registers
    - Instruction pointer $rip

Design

- Read the initial registers
    - Instruction pointer $rip
    - Stack pointer $rsp

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- Read the initial registers
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  - Frame pointer $rbp
- While **unwind_frame_count <= MAX_STACK_DEPTH**
  - Find the unwind table row for the PC

Design

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  - Update the registers with the calculated values for the previous frame

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  - Frame pointer $rbp
- While **unwind_frame_count <= MAX_STACK_DEPTH**
  - Find the unwind table row for the PC
  - Add instruction pointer to the stack
  - Calculate the previous frame's stack pointer
  - Updates the registers with the calculated values for the previous frame
  - Continue with the next frame - go back to adding instruction pointer

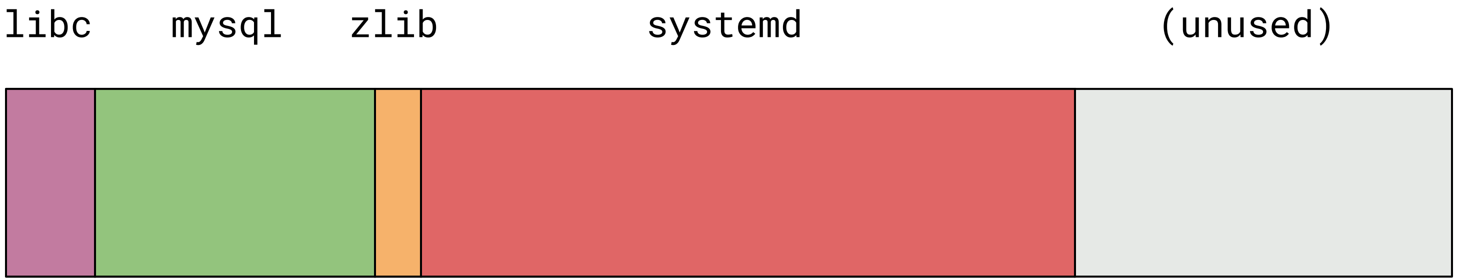
Storing the unwind information

- 🙅🏻‍♂️ In-process, hijacking the process using `ptrace(2)` + `mmap(2)` + `mlock(2)`
    - Altering the execution flow of the program is a no-go
    - We must lock this memory
    - When to clean up?
    - Sharing of memory is harder, accounting for our overhead is also harder

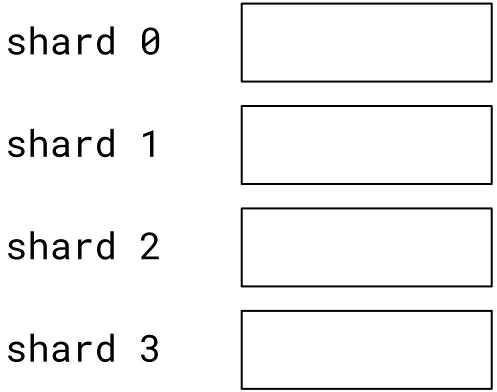
Storing the unwind information

- BPF maps
  - A `<bytes,bytes>` hash-table
  - Always locked in memory, `BPF_F_NO_PREALLOC` is forbidden in tracing programs
  - We can reuse the same tables for multiple processes that share the same mappings

Storing the unwind information



Storing the unwind information – sharding



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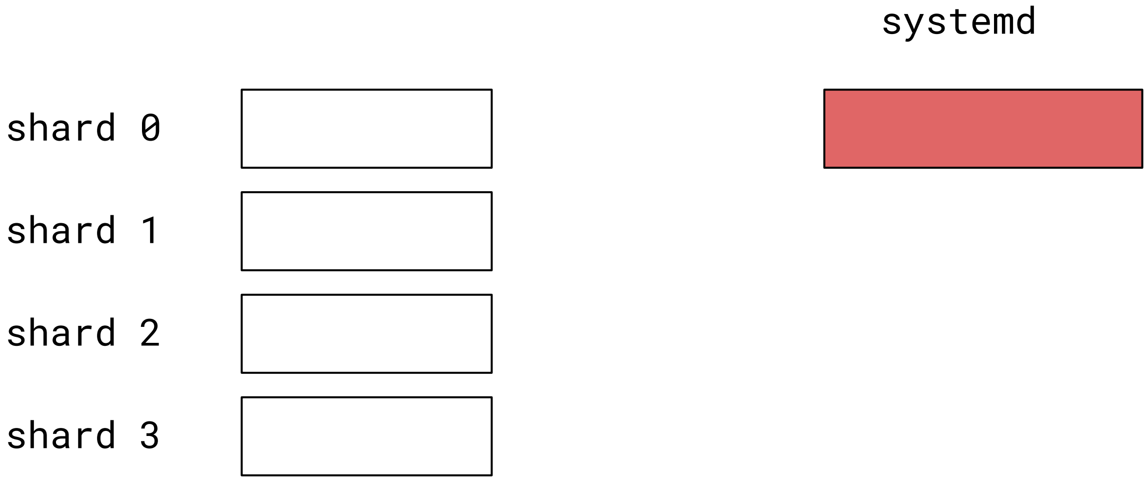

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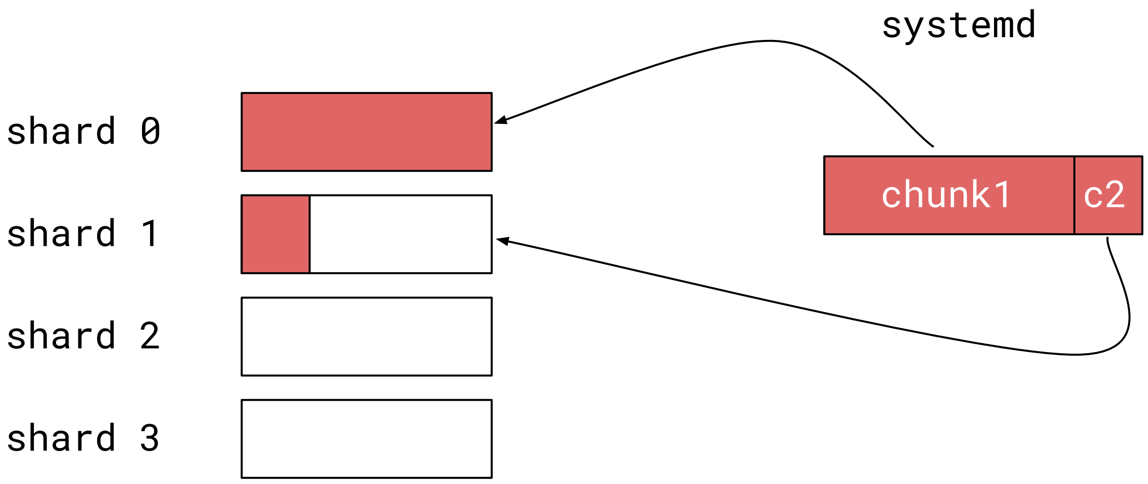

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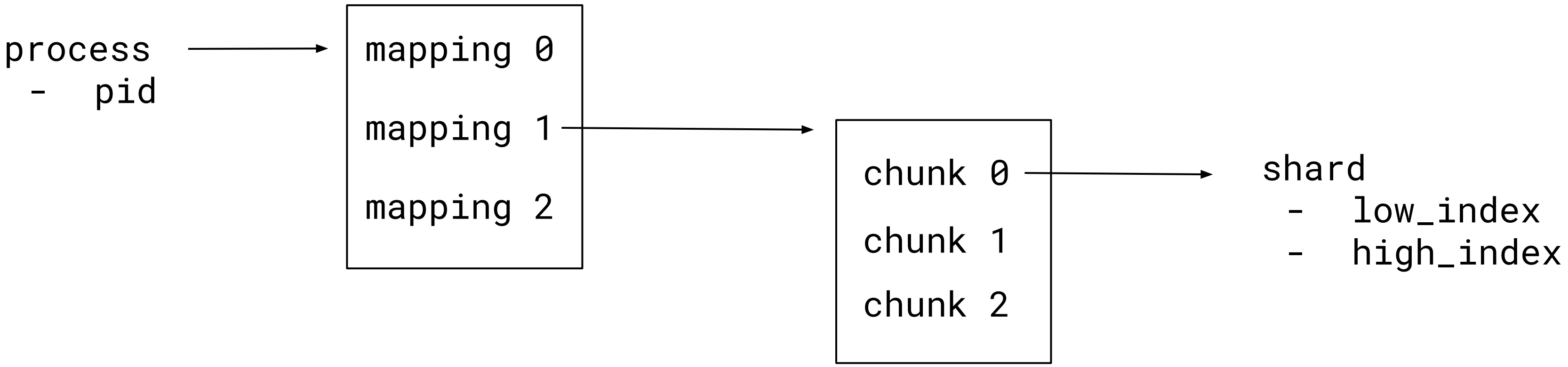

(The above are stored in BPF maps)

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Making our unwinder scale

- Unwind table for each executable mapping
  - Skip table generation most of the time (~0.9% of our CPU cycles in prod)
- This is suspiciously similar to a bump allocator

The unwinding process – in-depth

- pid

The unwinding process – in-depth

- pid
  - Do we have unwind information?

The unwinding process – in-depth

- pid
    - Do we have unwind information?
    - Find mapping with our current instruction pointer

The unwinding process – in-depth

- pid
  - Do we have unwind information?
  - Find mapping with our current instruction pointer
  - Find chunk

The unwinding process – in-depth

- pid
  - Do we have unwind information?
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  - We have the shard information

The unwinding process – in-depth

- pid
    - Do we have unwind information?
    - Find mapping with our current instruction pointer
    - Find chunk
    - We have the shard information
    - Let’s find the unwind info

The unwinding process – in-depth

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  - Do we have unwind information?
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  - Let’s find the unwind info
  - Binary search in the table of up to 250k entries (~8 iterations)

The unwinding process – in-depth

- pid
    - Do we have unwind information?
    - Find mapping with our current instruction pointer
    - Find chunk
    - We have the shard information
    - Let's find the unwind info
    - Binary search in the table of up to 250k entries (~8 iterations)
    - Apply unwind action, add frame to stack-trace, continue with next frame

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The unwinding process – in-depth

- If the stack is “correct”
  - We hash the addresses
  - Add the hash to a map
  - Bump a counter

BPF challenges

- Memlock, being aware of memory usage
- BPF verifier woes
    - Stack size: we rely on BPF maps to store state
    - Program size:
        - BPF tail calls to have bigger programs
        - Bounded loops (and `bpf_loop`) if you don't need to support older kernels 🥲

Performance in userspace

- Many Go APIs aren't designed with performance in mind
  - DWARF and ELF library in the stdlib
  - `binary.Read` & `binary.Write` allocate in the fast path (!!!)
- Profiling our profiler
  - Lots of found opportunities
  - But there's more work to do!

Testing

- Thorough unit testing coverage for most of the core functions
- Snapshot testing for unwind tables ❤️

Testing – snapshot testing

testdata @ c0d23d5

```
=> Function start: 2b450, Function end: 2b809
        pc: 2b450 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
        pc: 2b451 cfa_type: 2  rbp_type: 1  cfa_offset: 16   rbp_offset: -16
        pc: 2b454 cfa_type: 1  rbp_type: 1  cfa_offset: 16   rbp_offset: -16
        pc: 2b461 cfa_type: 1  rbp_type: 1  cfa_offset: 16   rbp_offset: -16
        pc: 2b6f2 cfa_type: 2  rbp_type: 1  cfa_offset: 8    rbp_offset: -16
        pc: 2b6f8 cfa_type: 1  rbp_type: 1  cfa_offset: 16   rbp_offset: -16
```

Testing – snapshot testing

```
write-dwarf-unwind-tables: build
	make -C testdata validate EH_FRAME_BIN=../dist/eh-frame
	make -C testdata validate-compact EH_FRAME_BIN=../dist/eh-frame

test-dwarf-unwind-tables: write-dwarf-unwind-tables
	$(CMD_GIT) diff --exit-code testdata/
```

Takeaways

- De-risking the project
- Invest early and often in automated testing
- BPF programs **must** have kernel tests
- Measure, profile, test…
    - but make sure to do it in prod do it in prod, too!

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Testing in multiple kernels

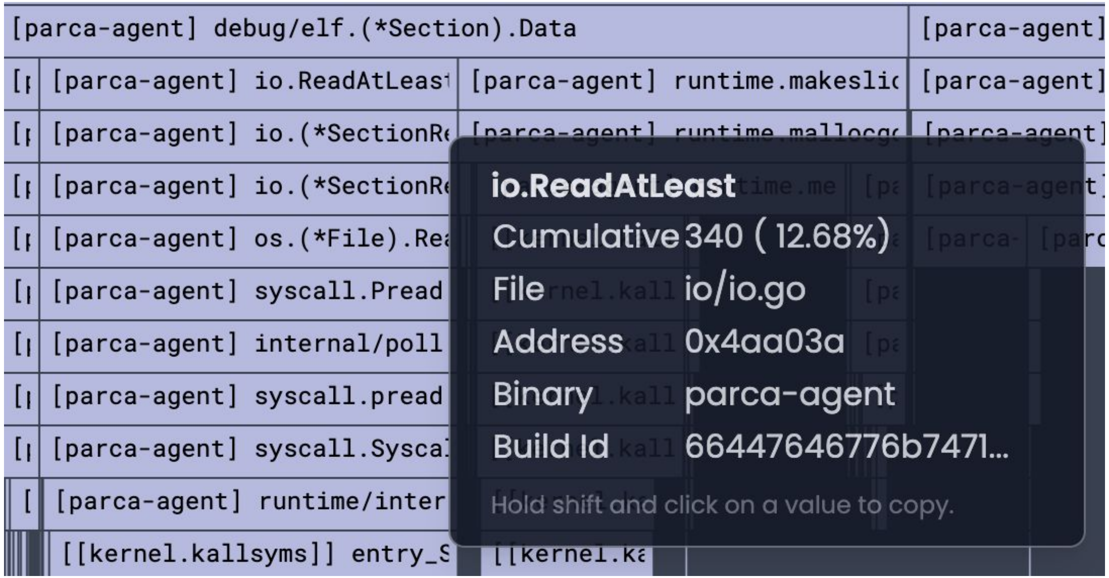
```
===============
Test results:
===============
- ✅ 5.4
- ✅ 5.10
- ✅ 5.18
- ✅ 5.19

Test summary: 4 passed, 0 failed
```

Takeaways – different environments

- Different environments can radically change the performance profile
  - Different hardware
  - Different configuration (pprof…)

Different hardware – slow disks



Different configuration – signals in prod

Do not enable pprof profiling until BPF program is loaded #1276

Merged javierhonduco merged 1 commit into `main` from `fix-sigprofs-interrupting-bpf-loading` 2 days ago

Different configuration – signals in prod

- Go's signal-based profiler uses `SIGPROF`
- Which interrupts our process' execution
- Our BPF program is loaded and verified by the kernel
- Gets interrupted
- Libbpf retries up to 5 times
- And then we crash!

Other considerations

- Short-lived processes
- DWARF CFI vs our format
- Benchmarking the BPF code

Other considerations – DWARF CFI vs our format

```
typedef struct {
  u64 pc;
  u16 _reserved_do_not_use;
  u8 cfa_type;
  u8 rbp_type;
  s16 cfa_offset;
  s16 rbp_offset;
} stack_unwind_row_t;
```

Other considerations – DWARF CFI vs our format

```
typedef struct {
  u64 pc; // 🧐
  u16 _reserved_do_not_use; // 🧐
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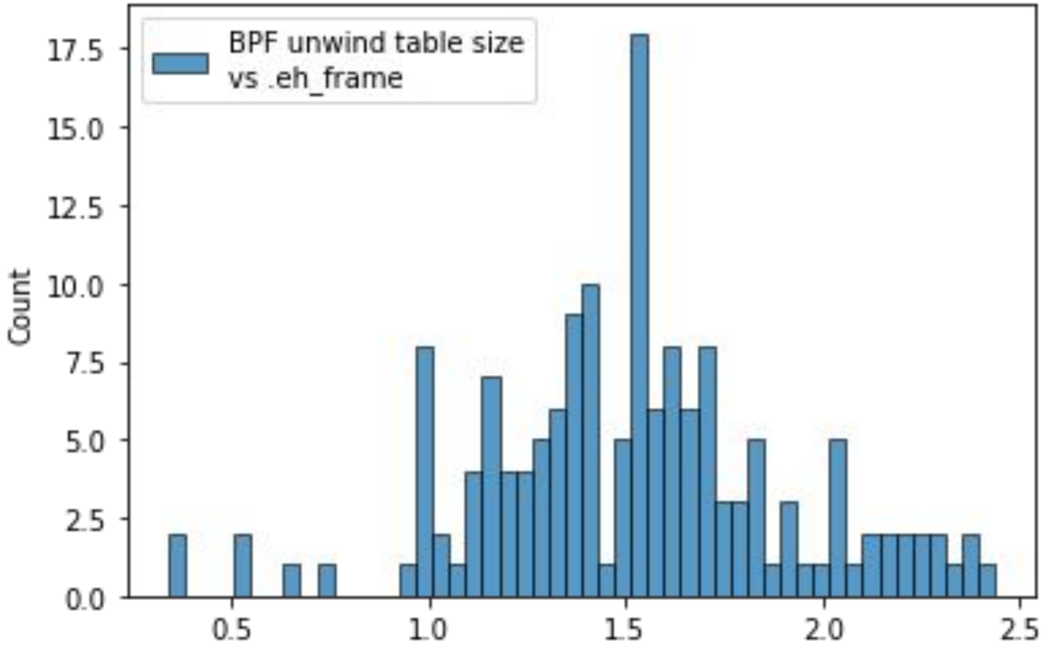

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Other considerations – DWARF CFI vs our format

- We support parsing every DWARF CFI opcode
- Only can unwind if
    - Previous frame stack pointer (CFA) is based off the current stack pointer or frame pointer + offsets
    - DWARF expressions in Procedure Linkage Tables (PLT) for CFA
    - We are working on:
        - CFA := any_register + offset
        - Frame pointer defined by an known expression

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Other considerations – DWARF CFI vs our format

- 2 DWARF expressions account for the ~50% of what we've seen in the wild (https://github.com/parca-dev/parca-agent/pull/1058)
- CFA based off not $rbp or $rsp rarely happens
- Some other instances that very rarely occur

Other considerations – BFP performance

- Walking stacks of a host running Postgres, CPython, Ruby (MRI) applications (some with >90 frames)
  - `P50: 285ns`
  - `P90: 370ns`
  - `Max: 428ns`

(kernel 6.0.18 with Intel i7-8700K (late ‘17))

Profiling Ruby with BPF – rbperf

- Knowledge of the ABI of each interpreter version
- Stack walker implemented in BPF
  - Directly extract the function names and other information off Ruby's memory

What's coming in Parca

- Mixed unwinding mode
- arm64 support
- Enabling this feature by default
- Support for other runtimes (JVM, Ruby, etc)

We ❤️ OSS – contributors welcome!

- Everything we've talked about here is fully OSS
    - Userspace: Apache 2.0
    - BPF: GPL

parca

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References

- Blogpost: https://www.polarsignals.com/blog/posts/2022/11/29/profiling-without-frame-pointers/
- Our project website: https://www.parca.dev/
  - Agent: https://github.com/parca-dev/parca-agent
  - BPF code: https://github.com/parca-dev/parca-agent/tree/main/bpf/cpu
- Previous talk at Linux Plumbers conference: https://www.youtube.com/watch?v=Gr1rrSzvqfg
- rbperf: https://github.com/javierhonduco/rbperf

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Thank you!

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