Linux Plumbers Conference | Richmond, VA | Nov. 13-15, 2023

Developing a Continuous eBPF Profiler

Looking Beneath the Kernel to Beyond the Clouds

by Sumera | @sylfrena | @SumoOfShinovar

Polar Signals

Agenda

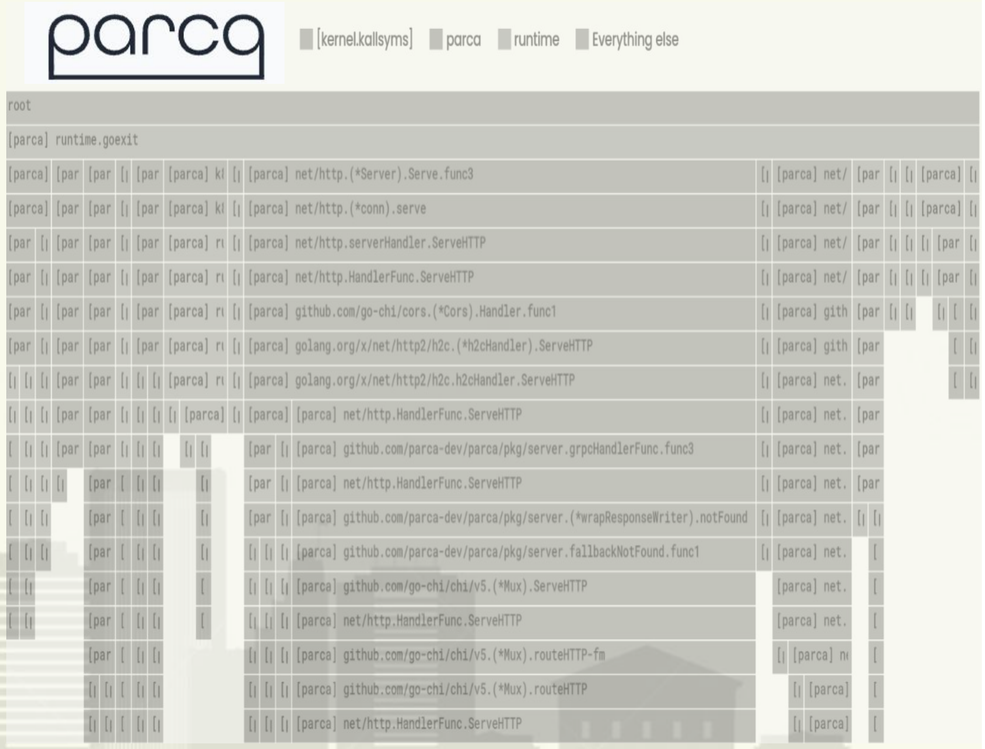
- High Resolution Continuous Profiling
- Userspace and Kernelspace
- Compilers and Runtimes
- Clouds and Kernels
- Low effort Debugging
- Future work

STORY TIME

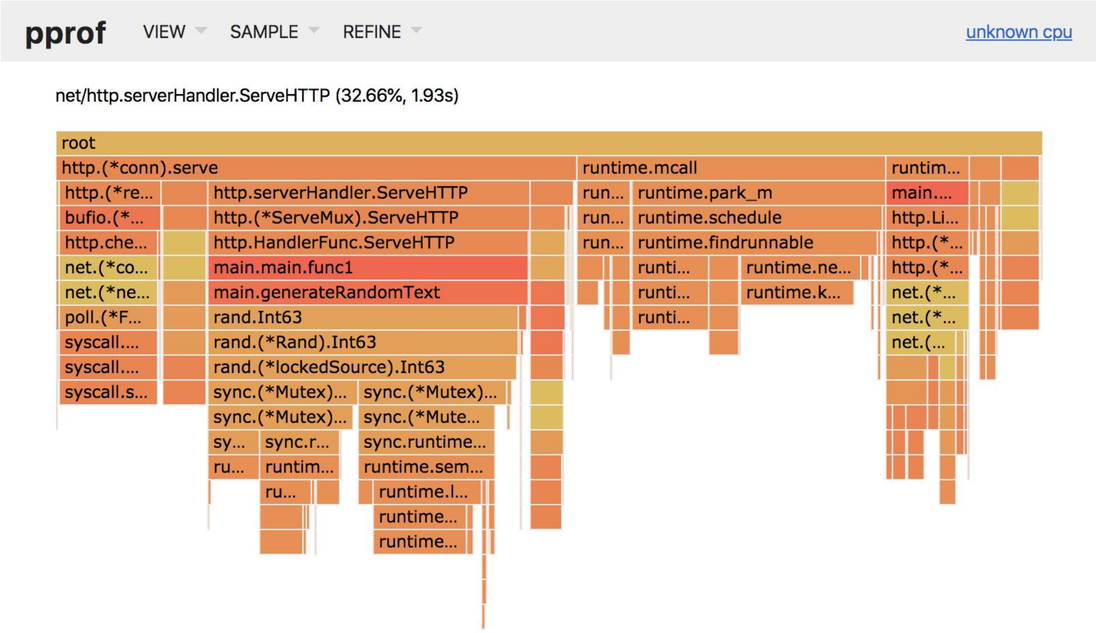
newbie kernel contributor

TO

newbie profiler maintainer



- **ftrace**: dynamic tracing
- **dmesg**: dynamic logging
- **flamegraphs**: static, infrawide profile snapshots



Debugging tools

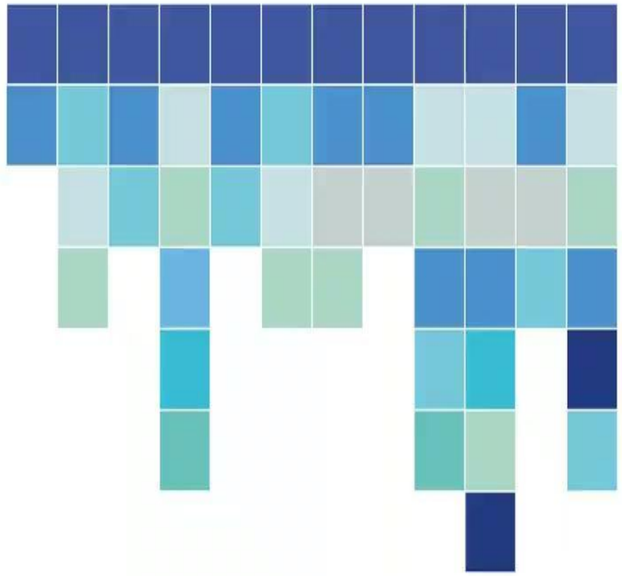
Polar Signals

About Me

- Junior Software Engineer at Polar Signals
- Open Source Maintainer
  - Parca and Parca-Agent

Sumera Priyadarsini

@sylfrena
@SumoOfShinovar



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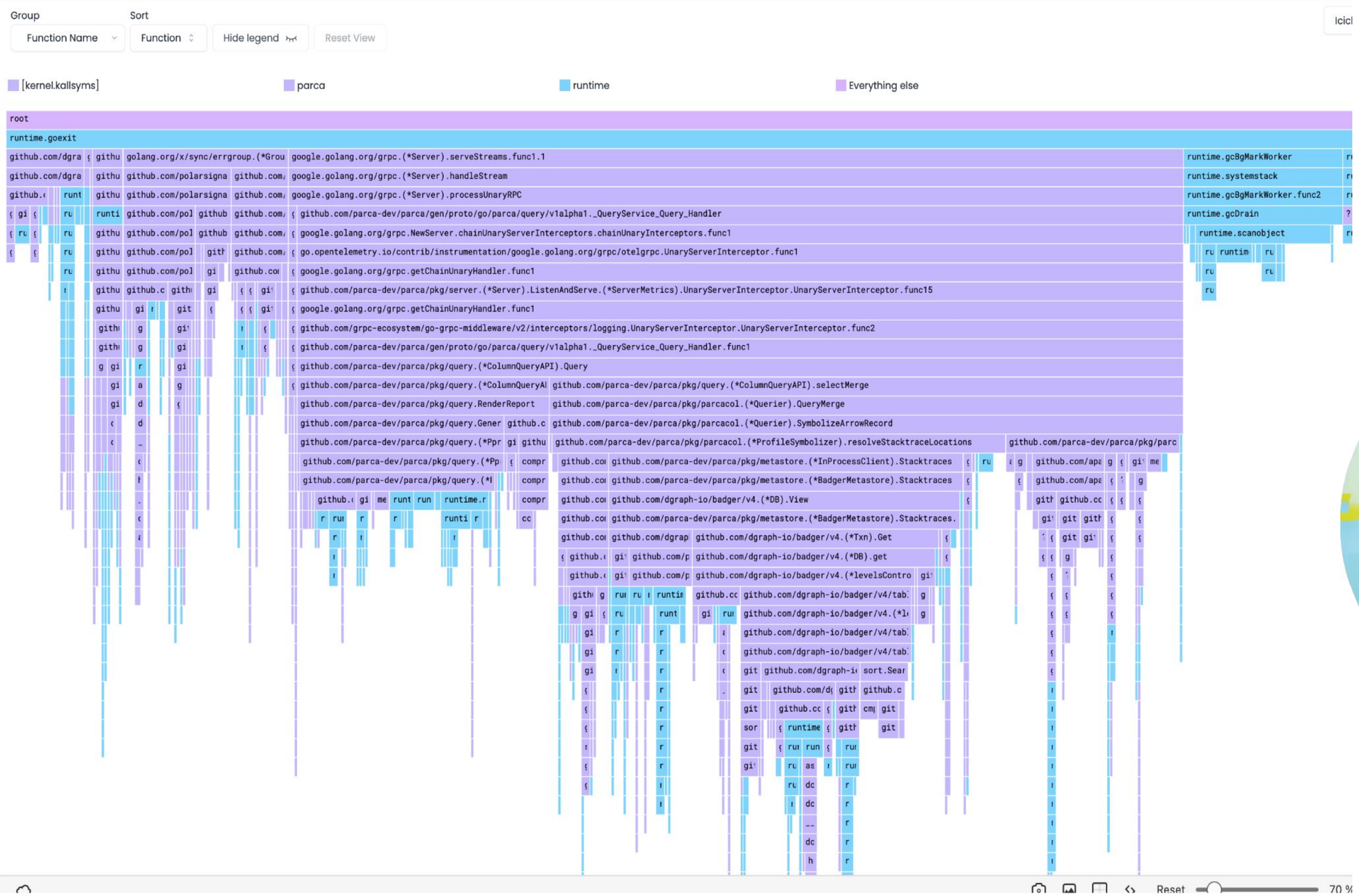

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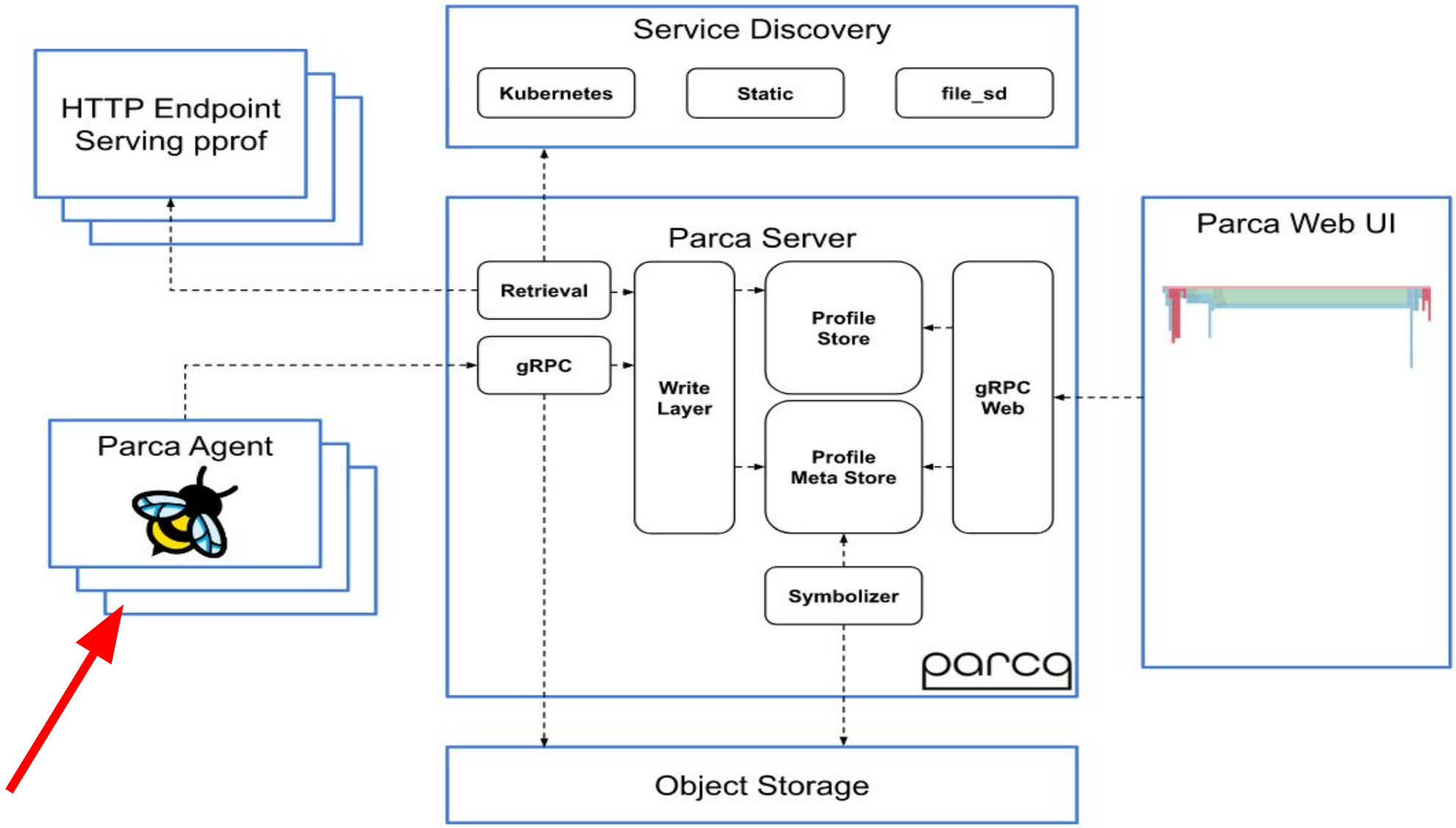

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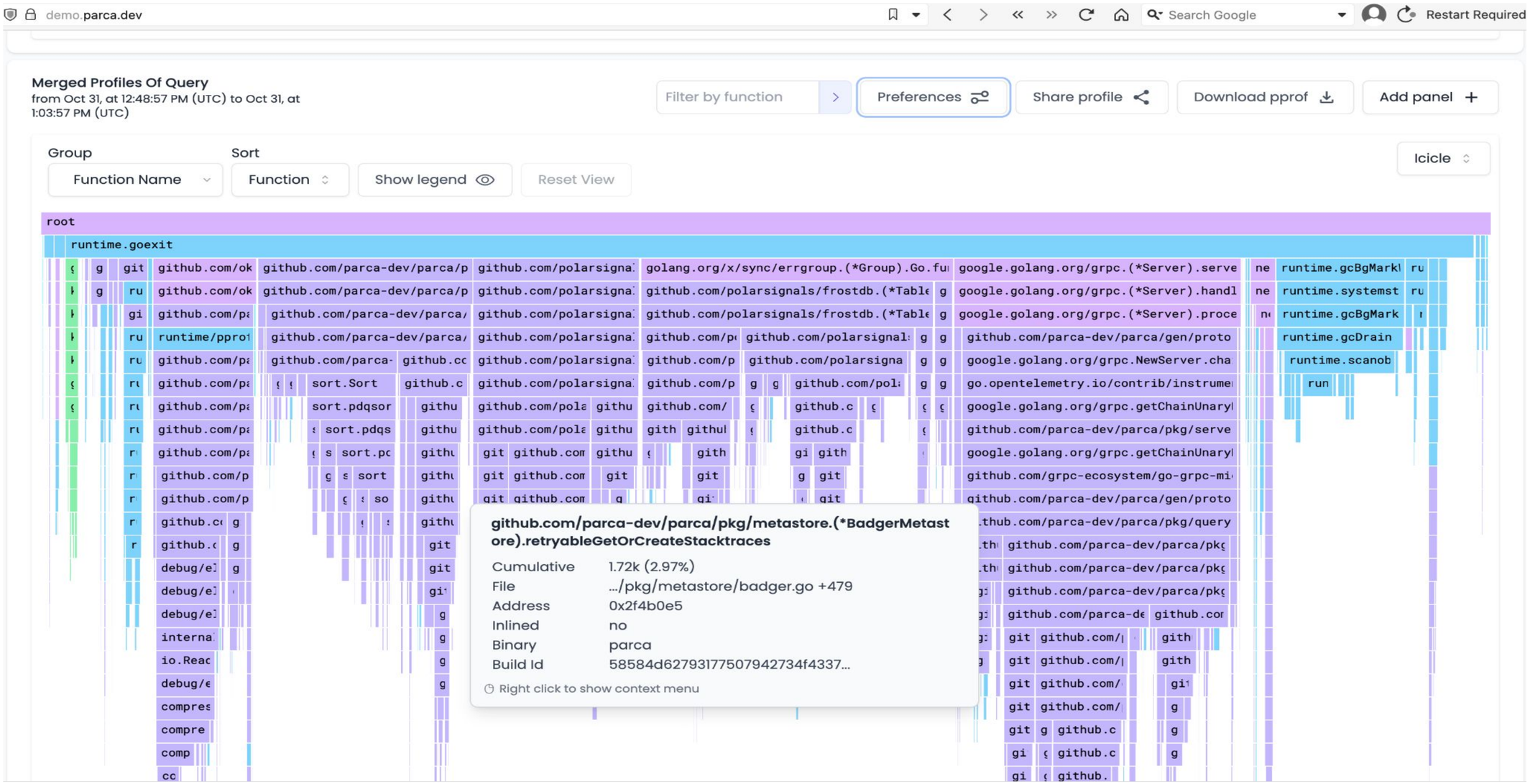
High Resolution Dynamic Continuous Profiling

High Resolution Profiling

ignals

High Resolution Profiling



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High Resolution Profiling

Merged Profiles Of Query
from Oct 11, at 11:11:32 PM (UTC) to Oct 11, at 11:26:32 PM (UTC)

Filter by function | Preferences | Share profile | Download pprof | Add panel +

Columns | Table

Flat	Cumulative	Cumulative (%)	Name
0	13.52k	106.27%	google.golang.org/grpc.getChainUnaryHandler.func1
0	12.7k	99.83%	runtime.goexit
0	6.77k	53.18%	google.golang.org/grpc.(*Server).processUnaryRPC
0	6.77k	53.18%	google.golang.org/grpc.(*Server).handleStream
0	6.77k	53.18%	google.golang.org/grpc.(*Server).serveStreams.func1.1
0	6.76k	53.16%	go.opentelemetry.io/contrib/instrumentation/google.golang.org/grpc/otelgrpc.UnaryServerInterceptor.func1
0	6.76k	53.16%	google.golang.org/grpc.NewServer.chainUnaryServerInterceptors.chainUnaryInterceptors.func1
0	6.76k	53.14%	github.com/parca-dev/parca/pkg/server.(*Server).ListenAndServe.(*ServerMetrics).UnaryServerInterceptor.UnaryServerInterceptor.func15
0	6.76k	53.13%	github.com/grpc-ecosystem/go-grpc-middleware/v2/interceptors/logging.UnaryServerInterceptor.UnaryServerInterceptor.func2
0	6.52k	51.23%	github.com/parca-dev/parca/pkg/query.(*ColumnQueryAPI).Query
0	6.52k	51.23%	github.com/parca-dev/parca/gen/proto/go/parca/query/v1alpha1._QueryService_Query_Handler.func1
0	6.52k	51.23%	github.com/parca-dev/parca/gen/proto/go/parca/query/v1alpha1._QueryService_Query_Handler
0	5.42k	42.59%	github.com/parca-dev/parca/pkg/parcacol.(*Querier).QueryMerge
0	5.42k	42.59%	github.com/parca-dev/parca/pkg/query.(*ColumnQueryAPI).selectMerge
1	5.41k	42.52%	github.com/parca-dev/parca/pkg/parcacol.(*Querier).SymbolizeArrowRecord
44	3.28k	25.79%	github.com/parca-dev/parca/pkg/parcacol.(*ProfileSymbolizer).resolveStacktraceLocations
5	2.99k	23.51%	runtime.systemstack
0	2.95k	23.19%	github.com/dgraph-io/badger/v4.(*DB).View
0	2.52k	19.82%	github.com/parca-dev/parca/pkg/metastore.(*BadgerMetastore).Stacktraces
0	2.52k	19.82%	github.com/parca-dev/parca/pkg/metastore.(*InProcessClient).Stacktraces
4	2.49k	19.59%	github.com/parca-dev/parca/pkg/metastore.(*BadgerMetastore).Stacktraces.func1
10	2.33k	18.33%	github.com/dgraph-io/badger/v4.(*Txn).Get
0	2.22k	17.44%	runtime.gcBgMarkWorker
0	2.21k	17.36%	runtime.gcBgMarkWorker.func2
94	2.21k	17.34%	runtime.gcDrain
13	2.15k	16.86%	github.com/dgraph-io/badger/v4.(*DB).get
808	2.13k	16.74%	runtime.scanobject
148	2.11k	16.58%	github.com/parca-dev/parca/pkg/parcacol.BuildArrowLocations
0	1.98k	15.55%	golang.org/x/sync/errgroup.(*Group).Go.func1

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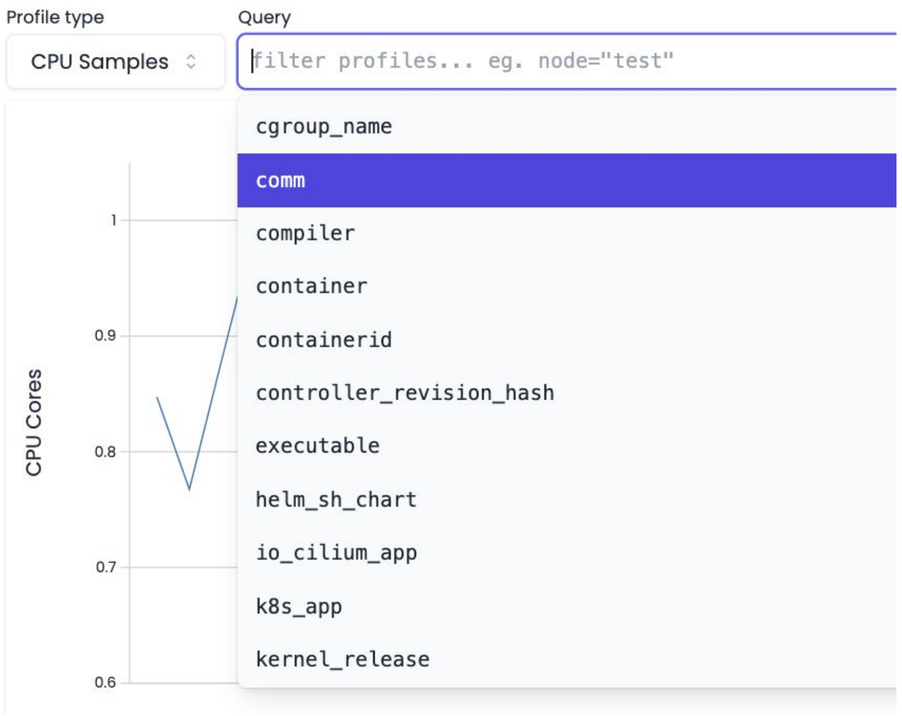
parca



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eBPF Profilers: Userspace and Kernelspace

Profilers for the cloud native environment

Discovery mechanism for the targets

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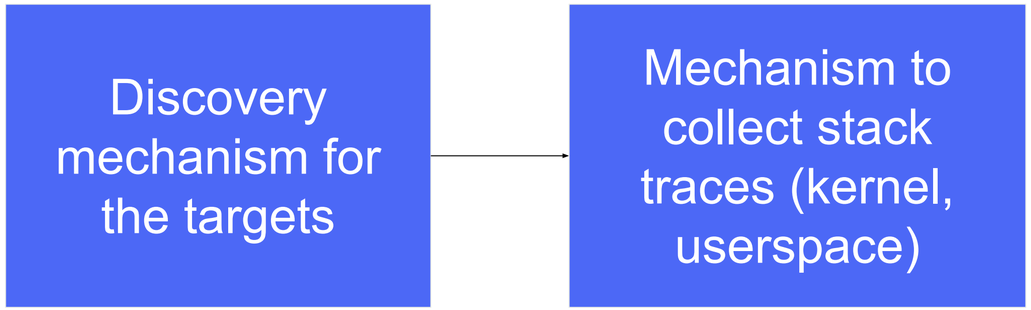
Profilers for the cloud native environment



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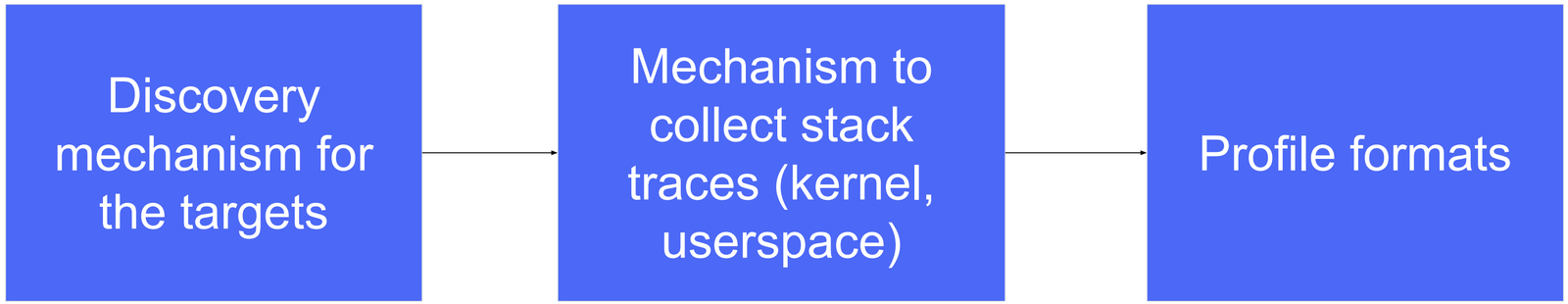
Profilers for the cloud native environment



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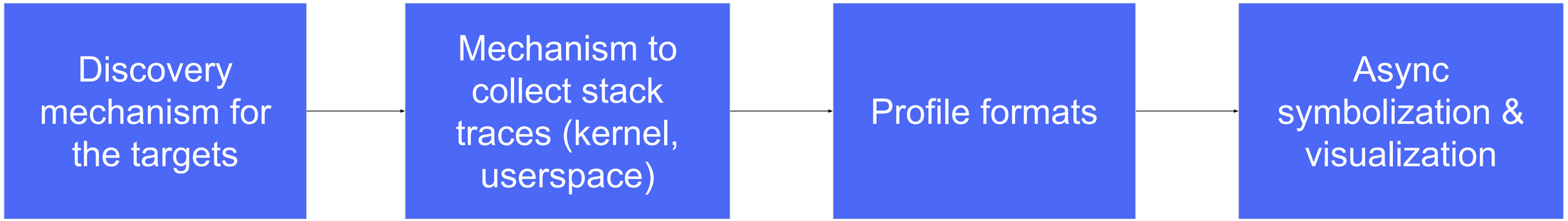
Profilers for the cloud native environment



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Profilers for the cloud native environment

Discovery mechanism for the targets

→

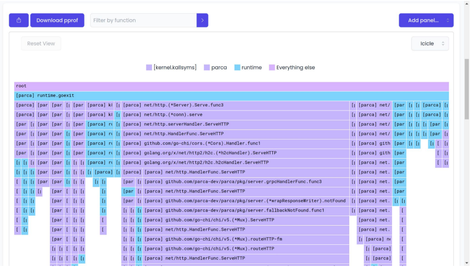
Mechanism to collect stack traces (kernel, userspace)

→

Profile formats

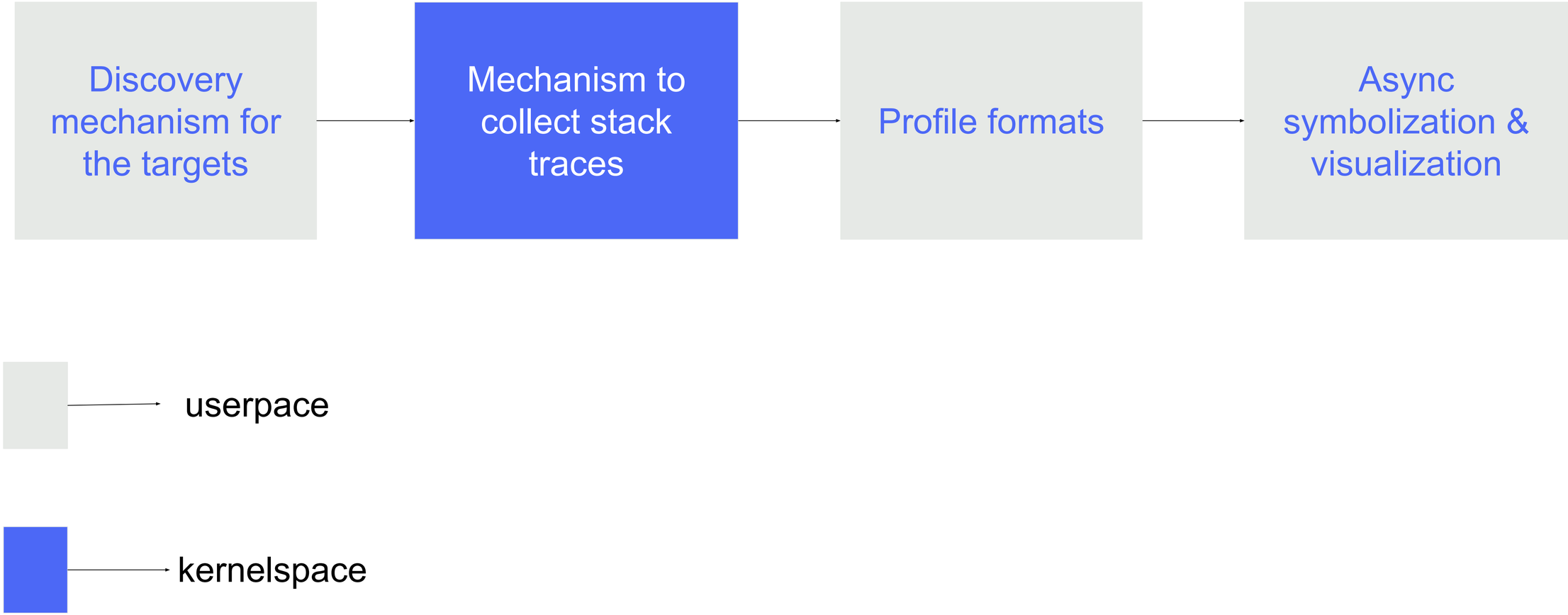
→

Async symbolization & visualization

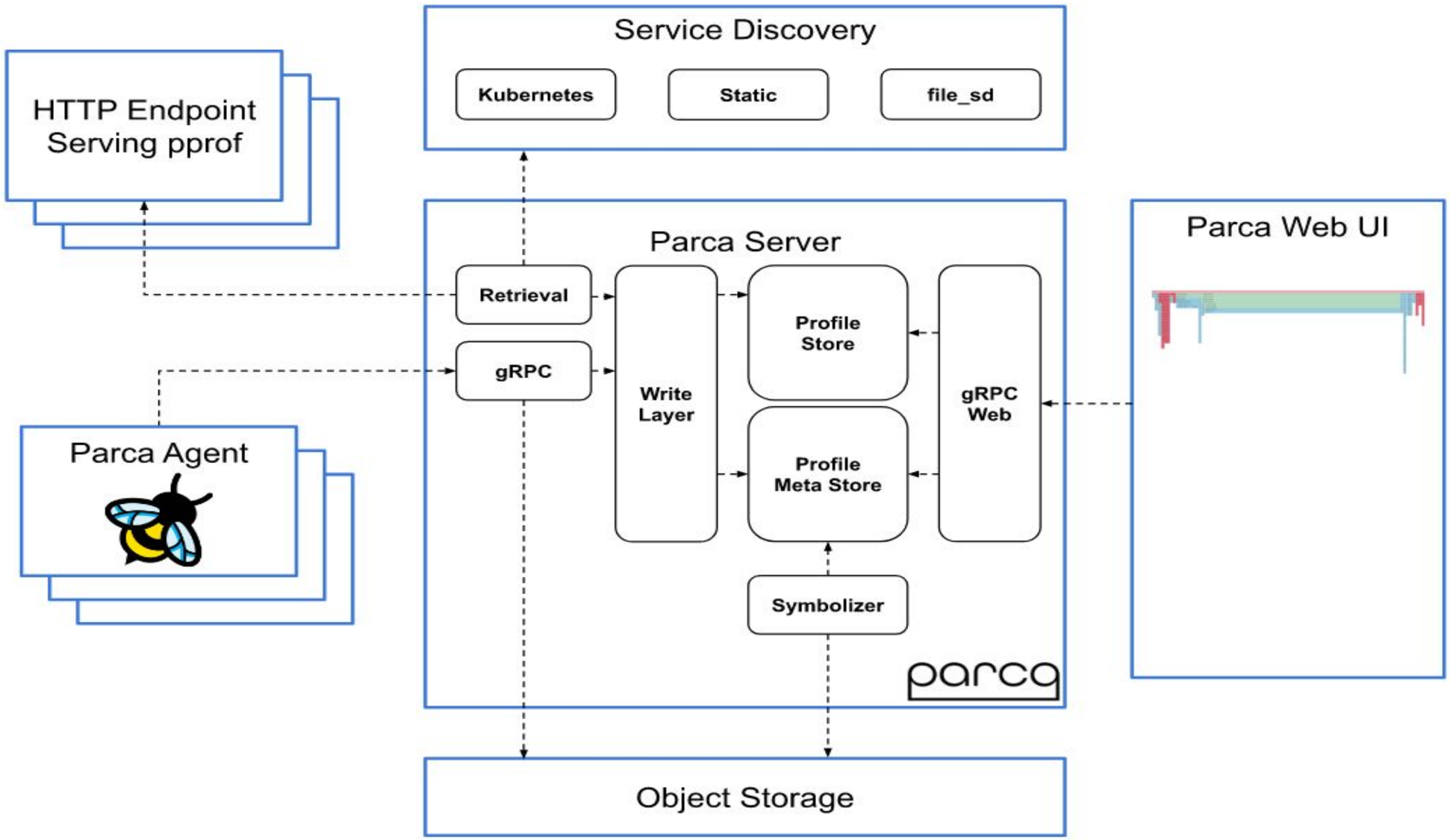


Polar Signals

Profilers for the cloud native environment



Polar Signals



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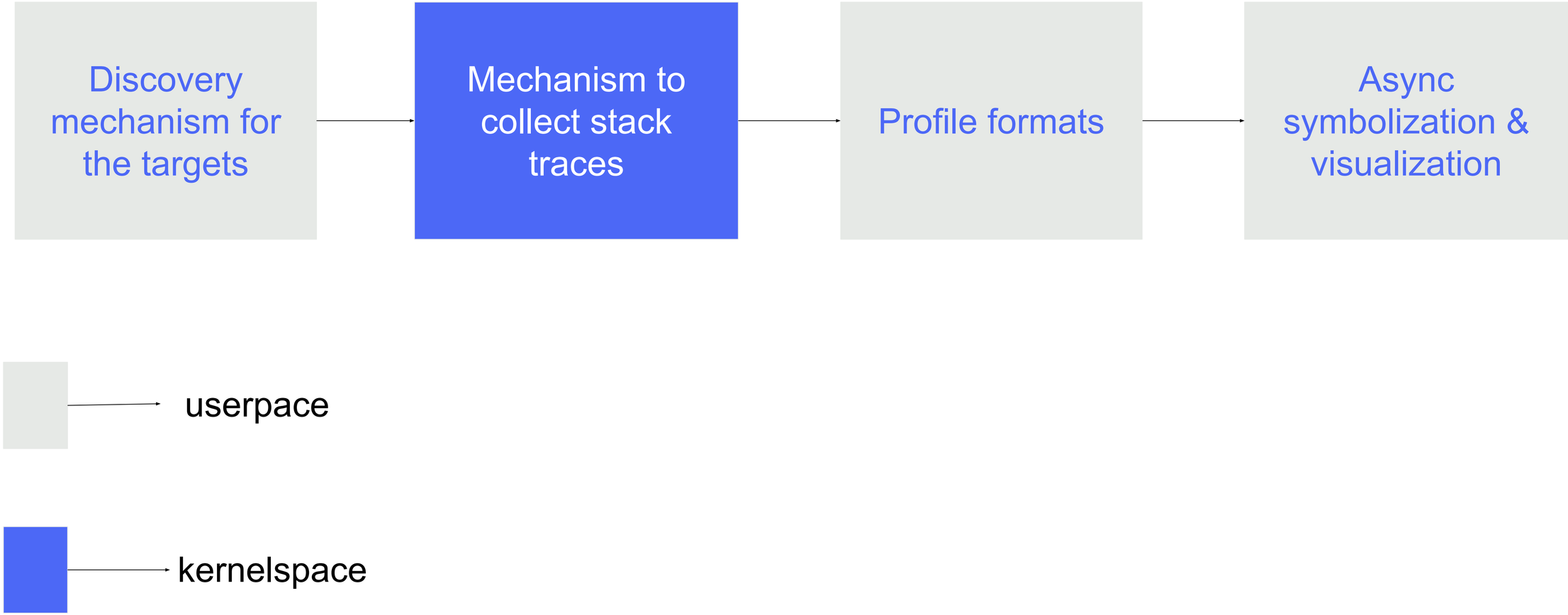
Userspace

Profilers for the cloud native environment



Polar Signals

Userspace

- Discovery of targets
  - pods
  - binaries
- Debuginfo extraction
  - can be uploaded separately

Userspace

- Discovery of targets
- Debuginfo extraction
- Extract Unwind information from DWARF
  - **Executable Linkable format - ELF**: For obj file, executable program, shared object etc
  - **DWARF - widely used debugging format**: CIE - Common Information Entry
  - **Tools to read ELF and/or DWARF information**: readelf, objdump, elfutils, llvm-dwarfdump

```
// UnwindTableRow represents a single row in the unwind table.
// x86_64: rip (instruction pointer register), rsp (stack pointer register), rbp (base pointer/frame pointer register)
// aarch64: lr(link register), sp(stack pointer register), fp(frame pointer register)
Francisco Javier Honduvilla Coto, 13 months ago | 2 authors (Francisco Javier Honduvilla Coto and others)
type UnwindTableRow struct {
    // The address of the machine instruction.
    // Each row covers a range of machine instruction, from its address (Loc) to that of the row below.
    Loc uint64
    // CFA, the value of the stack pointer in the previous frame.
    CFA frame.DWRule
    // The value of the RBP register.
    RBP frame.DWRule
    // The value of the saved return address. This is not needed in x86_64 as it's part of the ABI but is necessary
    // in arm64.
    RA frame.DWRule
}
```

Polar Signals

Userspace: DWARF Unwind Tables

```go
// UnwindTableRow represents a single row in the unwind table.
// x86_64: rip (instruction pointer register), rsp (stack pointer register), rbp (base pointer/frame pointer register)
// aarch64: lr(link register), sp(stack pointer register), fp(frame pointer register)
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    RBP frame.DWRule
    // The value of the saved return address. This is not needed in x86_64 as it's part of the ABI but is necessary
    // in arm64.
    RA frame.DWRule
}
```

```go
// CompactUnwindTableRows encodes unwind information using 2x 64 bit words.
// `lrOffset` is the link register for arm64; it is initialized to 0 for x86.
You, 3 months ago | 2 authors (You and others)
type CompactUnwindTableRow struct {
    pc        uint64
    lrOffset  int16
    cfaType   uint8
    rbpType   uint8
    cfaOffset int16
    rbpOffset int16
}
```

compact unwind table

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Userspace

- DWARF information is included in (ELF) binaries
- Extract Unwind tables from DWARF info

```
=> Function start: 293c0, Function end: 29427
    pc: 293c0 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
    pc: 293c5 cfa_type: 2  rbp_type: 0  cfa_offset: 16   rbp_offset: 0
    pc: 293cb cfa_type: 2  rbp_type: 0  cfa_offset: 32   rbp_offset: 0
    pc: 29408 cfa_type: 2  rbp_type: 0  cfa_offset: 16   rbp_offset: 0
    pc: 29409 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
    pc: 2940e cfa_type: 2  rbp_type: 0  cfa_offset: 32   rbp_offset: 0
```

compact unwind table snippet for `libc` on x86

Polar Signals

```
=> Function start: 293c0, Function end: 29427
    pc: 293c0 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
    pc: 293c5 cfa_type: 2  rbp_type: 0  cfa_offset: 16   rbp_offset: 0
    pc: 293cb cfa_type: 2  rbp_type: 0  cfa_offset: 32   rbp_offset: 0
    pc: 29408 cfa_type: 2  rbp_type: 0  cfa_offset: 16   rbp_offset: 0
    pc: 29409 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
    pc: 2940e cfa_type: 2  rbp_type: 0  cfa_offset: 32   rbp_offset: 0
```

compact unwind table snippet for `libc` on x86

x86

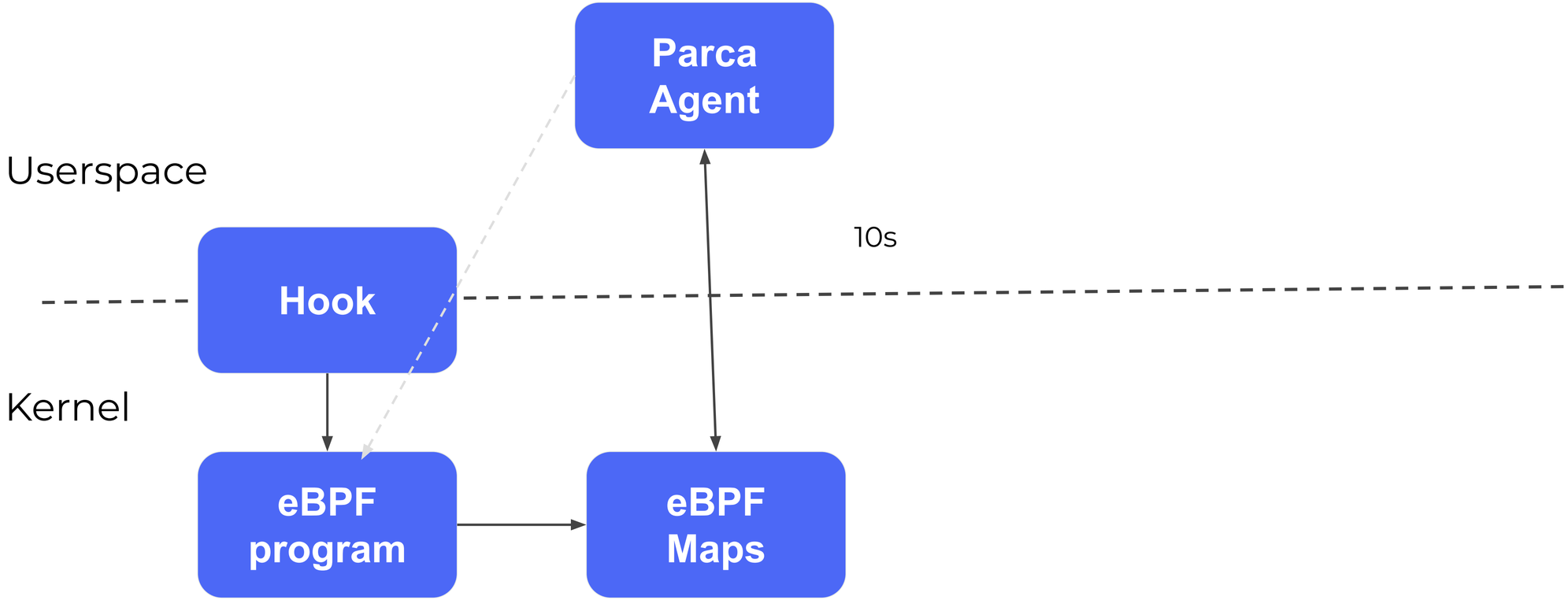
Aarch64

```
=> Function start: 26c00, Function end: 26c80
    pc: 26c00 cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26c04 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
    pc: 26c14 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
    pc: 26c6c cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26c70 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
=> Function start: 26a00, Function end: 26a0c
    pc: 26a00 cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26a04 cfa_type: 2  rbp_type: 1  cfa_offset: 16   rbp_offset: -16 lr_offset: -
```

compact unwind table snippet for `libc` on Arm64

Kernelspace

Communicating with Userspace



Polar Signals

Communicating with Userspace

```
        }
        r
    }

    mapsH
    if er
        r
    }
    m.pro
    retur
}

// writeU
    You
```

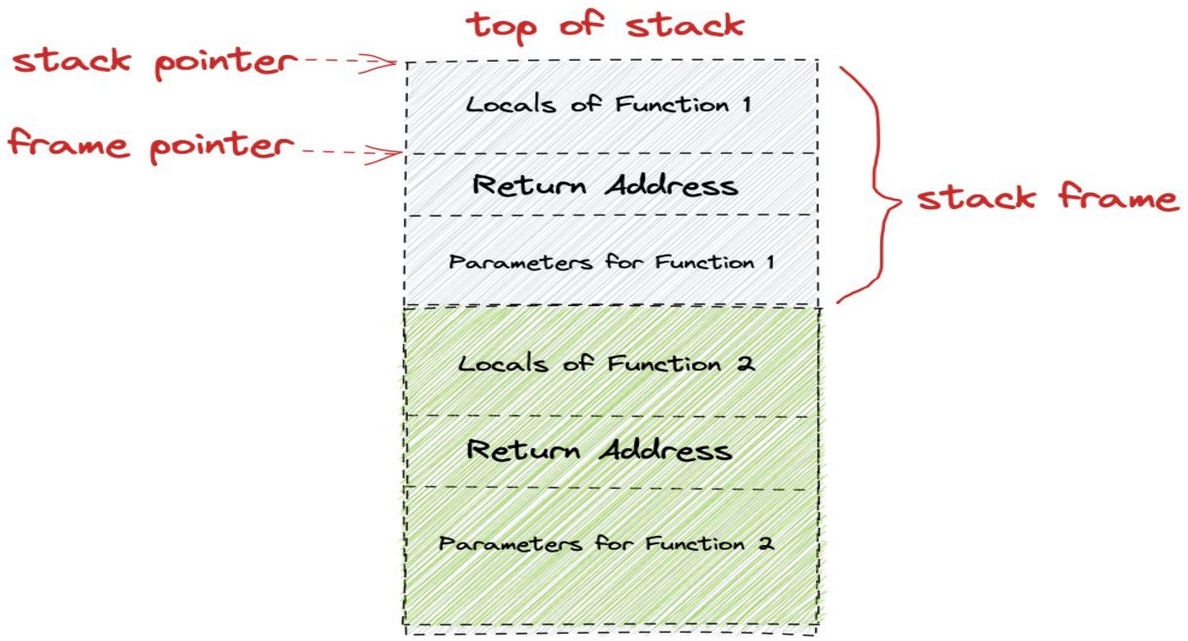
```
    pythonPIDToProcessInfo       *libbpf.BPFMap
    pythonVersionSpecificOffsets *libbpf.BPFMap
    pythonVersionToOffsetIndex   map[string]uint32

    unwindShards *libbpf.BPFMap
    unwindTables *libbpf.BPFMap
    programs     *libbpf.BPFMap
    processInfo  *libbpf.BPFMap

    // Unwind stuff 🔬
    processCache      *processCache
    mappingInfoMemory profiler.EfficientBuffer
```

```go
func (m *Maps) writeUnwindTableRow(rowSlice *profiler.EfficientBuffer, row unwind.CompactUnwindTableRow, arch elf.Machine) {
    // .pc
    rowSlice.PutUint64(row.Pc())
    if arch == elf.EM_AARCH64 {
        // .lr_offset
        rowSlice.PutInt16(row.LrOffset())
    }
    // .cfa_type
    rowSlice.PutUint8(row.CfaType())
    // .rbp_type
    rowSlice.PutUint8(row.RbpType())
    // .cfa_offset
    rowSlice.PutInt16(row.CfaOffset())
    // .rbp_offset
    rowSlice.PutInt16(row.RbpOffset())
}
```

Polar Signals



Kernelspace:

Walking the Stacks

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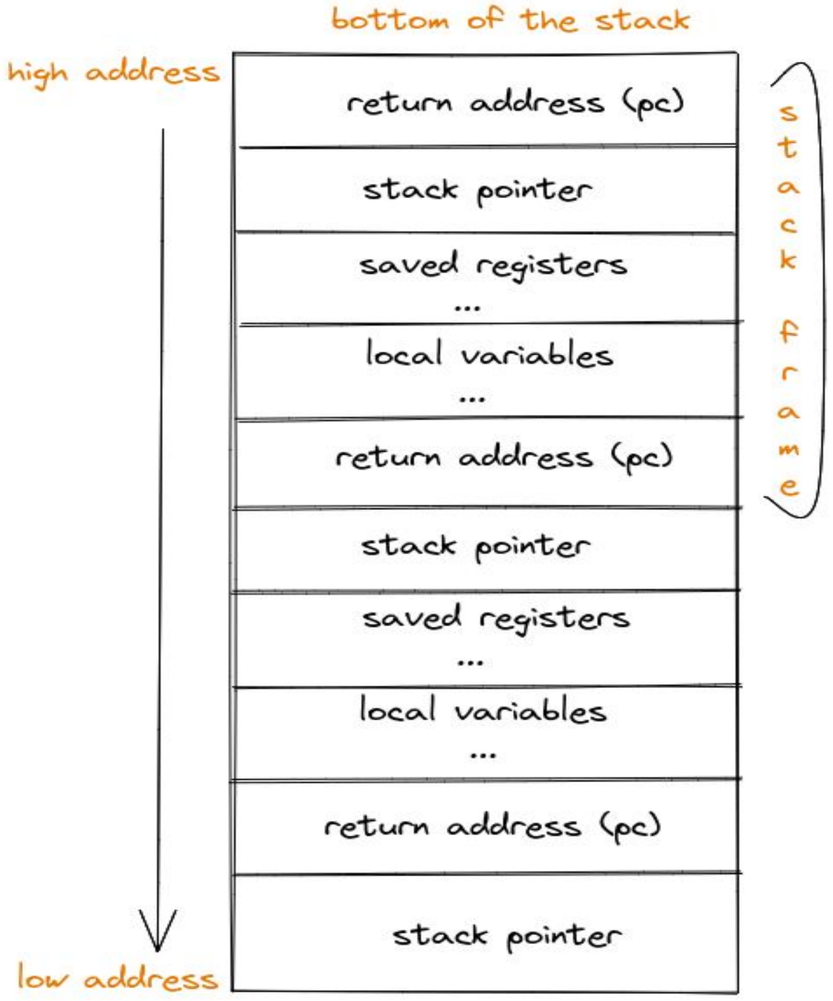
Stacktraces

- What collecting stack traces involve
  - Kernel stacks
  - Application stacks
- Direction of stack growth
- So what are stack pointers, where do they come from

Figure 3.3: Stack Frame with Base Pointer

Position	Contents	Frame
8n+16(%rbp)	argument eightbyte n	Previous
	...	
16(%rbp)	argument eightbyte 0	
8(%rbp)	return address	Current
0(%rbp)	previous %rbp value	
-8(%rbp)	unspecified	
	...	
0(%rsp)	variable size	
-128(%rsp)	red zone	



From: x86_64 ABI specification

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Userspace

```
=> Function start: 293c0, Function end: 29427
    pc: 293c0 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
    pc: 293c5 cfa_type: 2  rbp_type: 0  cfa_offset: 16   rbp_offset: 0
    pc: 293cb cfa_type: 2  rbp_type: 0  cfa_offset: 32   rbp_offset: 0
    pc: 29408 cfa_type: 2  rbp_type: 0  cfa_offset: 16   rbp_offset: 0
    pc: 29409 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
    pc: 2940e cfa_type: 2  rbp_type: 0  cfa_offset: 32   rbp_offset: 0
```

x86

compact unwind table snippet for `libc` on x86

```
=> Function start: 26c00, Function end: 26c80
    pc: 26c00 cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26c04 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
    pc: 26c14 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
    pc: 26c6c cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26c70 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
=> Function start: 26a00, Function end: 26a0c
    pc: 26a00 cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26a04 cfa_type: 2  rbp_type: 1  cfa_offset: 16   rbp_offset: -16 lr_offset: -
```

Aarch64

compact unwind table snippet for `libc` on Arm64

Polar Signals

DWARF Unwinding in x86

```
pc: 293c0 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
pc: 293c5 cfa_type: 2  rbp_type: 0  cfa_offset: 16   rbp_offset: 0
pc: 293cb cfa_type: 2  rbp_type: 0  cfa_offset: 32   rbp_offset: 0
pc: 29408 cfa_type: 2  rbp_type: 0  cfa_offset: 16   rbp_offset: 0
pc: 29409 cfa_type: 2  rbp_type: 0  cfa_offset: 8    rbp_offset: 0
pc: 2940e cfa_type: 2  rbp_type: 0  cfa_offset: 32   rbp_offset: 0
```

compact unwind table snippet for `libc` on x86

Unwind table in x86

```
// HACK(javierhonduco): This is an architectural shortcut we can take. As we
// only support x86_64 at the minute, we can assume that the return address
// is *always* 8 bytes ahead of the previous stack pointer.
#if __TARGET_ARCH_x86
    u64 previous_rip_addr = previous_rsp - 8;
    int err = bpf_probe_read_user(&previous_rip, 8, (void *)(previous_rip_addr));
    if (err < 0) {
      LOG("\n[error] Failed to read previous rip with error: %d", err);
    }
    LOG("\tprevious ip: %llx (@ %llx)", previous_rip, previous_rip_addr);
#endif
```

Polar Signals

DWARF Unwinding in Aarch64

```
=> Function start: 26c00, Function end: 26c80
    pc: 26c00 cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26c04 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
    pc: 26c14 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
    pc: 26c6c cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26c70 cfa_type: 2  rbp_type: 1  cfa_offset: 48   rbp_offset: -48 lr_offset: -
=> Function start: 26a00, Function end: 26a0c
    pc: 26a00 cfa_type: 2  rbp_type: 0  cfa_offset: 0    rbp_offset: 0   lr_offset: 0
    pc: 26a04 cfa_type: 2  rbp_type: 1  cfa_offset: 16   rbp_offset: -16 lr_offset: -
```

compact unwind table snippet for `libc` on Arm64

```
#if __TARGET_ARCH_arm64
    // For the leaf frame, the saved pc/ip is always be stored in the link register i
    if (found_lr_offset == 0) {
      previous_rip = PT_REGS_RET(&ctx->regs);
    } else {
      u64 previous_rip_addr = previous_rsp + found_lr_offset;
      int err = bpf_probe_read_user(&previous_rip, 8, (void *)(previous_rip_addr));
      if (err < 0) {
        LOG("\n[error] Failed to read previous rip with error: %d", err);
      }
      LOG("\tprevious ip: %llx (@ %llx)", previous_rip, previous_rip_addr);
    }
#endif
```

Aarch64

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Compilers and Runtimes

Parca Agent Language Support

Compiled Languages

- C
- C++
- Rust
- Go
- and more!

With or without frame pointers!

JIT (Just in Time Compiled) Languages

With Perf map or jitdump

- C#
- Erlang
- JVM(with async-profiler)
- Julia
- NodeJS

Interpreted Languages

- Python
- Ruby

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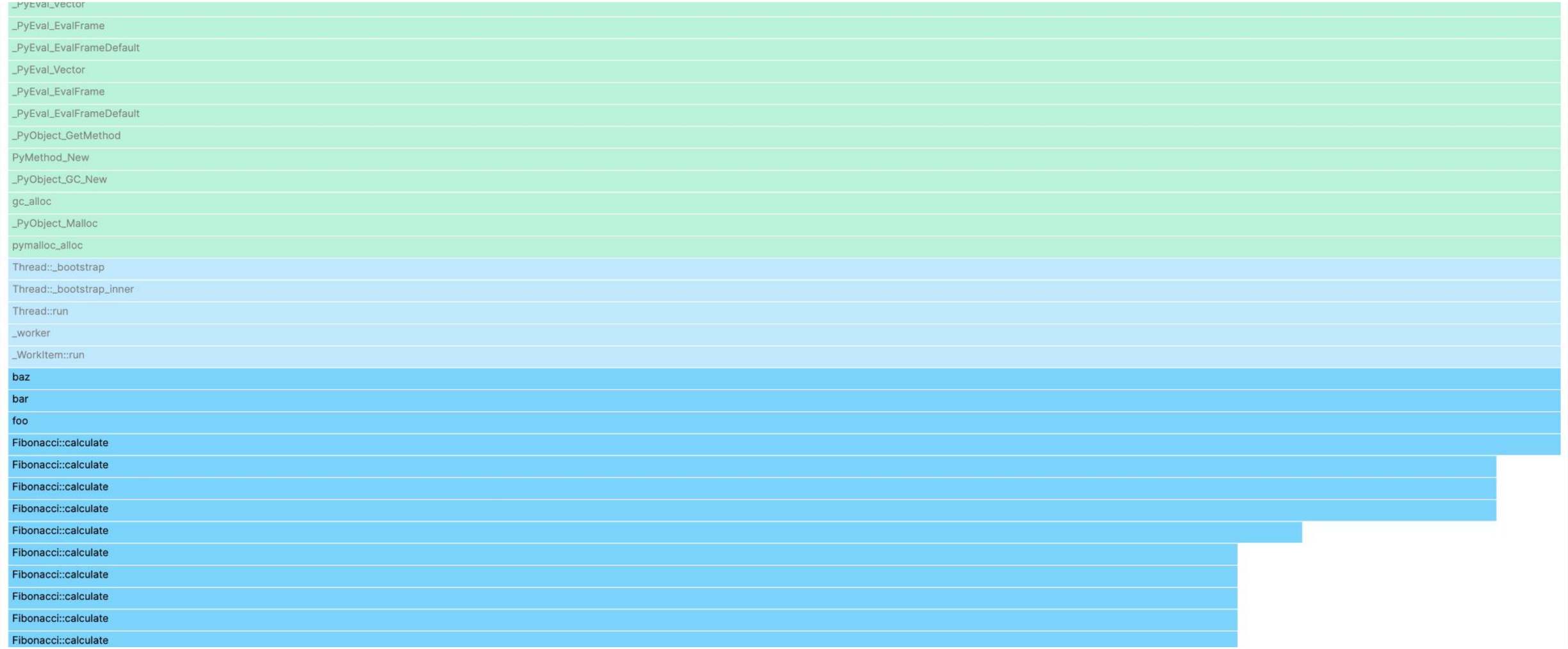
Interpreted Languages: Python



(3.11)

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Interpreted Languages: Ruby

Filter by function | Preferences | Download pprof | Add panel

Group: Function Name | Sort: Function | Show legend | Reset View | Icicle

root
__libc_start_main_impl
__libc_start_call_main
main
ruby_run_node
rb_ec_exec_node
rb_vm_exec
vm_exec_core
vm_sendish
vm_call_cfunc_with_frame
range_each
range_each_fixnum_loop
rb_yield
rb_yield_0
vm_yield
invoke_block_from_c_bh
<main>

a1	a2	a3
b1	b2	b3
c1	c2	c3
cpu	hog	program

Showing 12,183 values.

(3.0.4)

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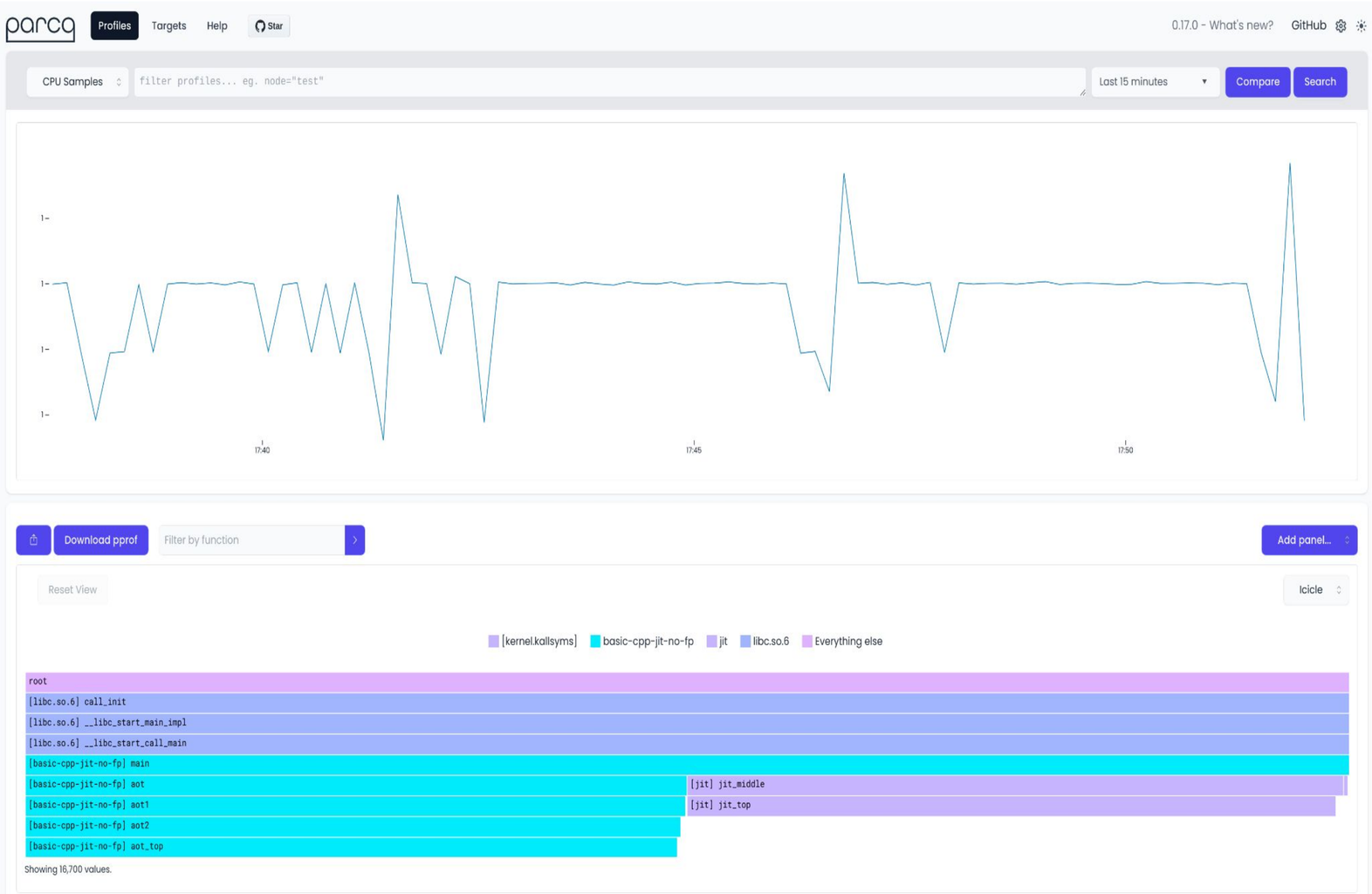
Parca Agent Language Support: JITed Runtimes and Stacks




```c
// This implements a simple JIT for x86_64 with support for symbolizatio
// with perfmap. We don't use any JIT framework or assembler for the sak
// of simplicity.

// Some tools have heuristics to unwind the stack even
// with frame pointers *and* unwind information omitted.
#define ENABLE_FRAME_POINTERS_IN_JIT true
// Amount of items to push into the stack to simulate a
// more realistic stack usage. Otherwise stack unwinding with
// frame pointers might work by accident.
#define STACK_ITEMS 30

int __attribute__((noinline)) aot_top() {
  for (int i = 0; i < 1000; i++) {
  }

  return 0;
}

// ahead of time
int __attribute__((noinline)) aot2() { return aot_top(); }

int __attribute__((noinline)) aot1() { return aot2(); }

int __attribute__((noinline)) aot() { return aot1(); }

void add_preamble(char **mem) {
  if (!ENABLE_FRAME_POINTERS_IN_JIT) {
    return;
  }

  *(*mem)++ = 0x55; // push   %rbp
  *(*mem)++ = 0x48; // mov    %rsp,%rbp
  *(*mem)++ = 0x89;
  *(*mem)++ = 0xe5; //   < difference between this and 0xec?
```

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JITed Runtimes: Symbolising VSCode

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- Bottom of the Stack in C++
- Correctly Profiling NodeJS
- Am I contained ?

How Compilers affect Icicle Graphs:

the cool edition

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Clouds and Kernels

Kernels in the Cloud

- GKE by Google Cloud
- Graviton by AWS
- Custom kernels
- Custom cloud kernels

.... and others

Linux Kernel v5.3+ with BTF

Kernels versions we support

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- Bad kernel bug causing a CPU lockup in Linux Kernel >= **v5.19** && **< v6.1**
  - https://github.com/parca-dev/parca-agent/issues/1675

- Fix backported to ~stable for 6.1 and 6.3

Kernels versions we prefer and recommend

Linux Kernel >= **v6.4**

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BUT....

- Most OS Distros don’t update as frequently as upstream
- Custom kernels don’t backport fixes
- Cloud providers largely use v5.xx and <v6.2x kernels

Future Work

Future Roadmap

- Language Support
  - JVM
  - PHP
  - LuaJIT
  - Python
- Improve Memory Usage in the Agent
- More code coverage in Testing:
  - Kernel tests with QEMU
  - Integration tests to ensure correctness
  - Using ASAN and TSAN while developing
  - Snapshot testing of the unwind tables

Resources

- https://www.polarsignals.com/blog/posts/2023/10/17/profiling-arm64-with-ebpf-in-parca-agent
- https://www.polarsignals.com/blog/posts/2023/10/04/profiling-python-and-ruby-with-ebpf
- https://www.polarsignals.com/blog/posts/2022/11/29/dwarf-based-stack-walking-using-ebpf
- https://www.polarsignals.com/blog/posts/2023/03/28/how-to-read-icicle-and-flame-graphs/
- https://www.polarsignals.com/blog/posts/2022/01/13/fantastic-symbols-and-where-to-find-them/
- https://demo.parca.dev

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Thank you for listening!

by Sumera | @sylfrena | @SumoOfShinovar

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