LTTng's Trace Filtering
and beyond

(with some eBPF goodness, of course!)

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whoami

Suchakra

- PhD student, Computer Engineering

  (Prof Michel Dagenais)

  DORSAL Lab, École Polytechnique de Montréal - UdeM
- Works on debugging, tracing and trace analysis (LTTng), bytecode interpreters, JIT compilation, dynamic instrumentation
- Loves poutine

Agenda

LTTng's Trace Filter

- Filtering primer
- LTTng's trace filters

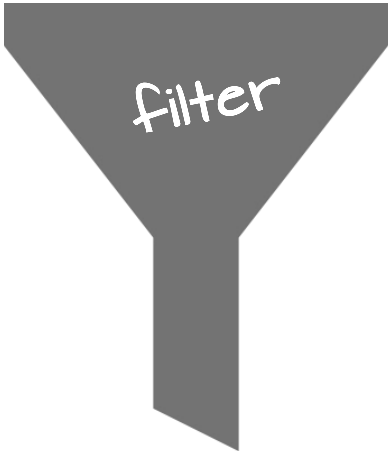
eBPF

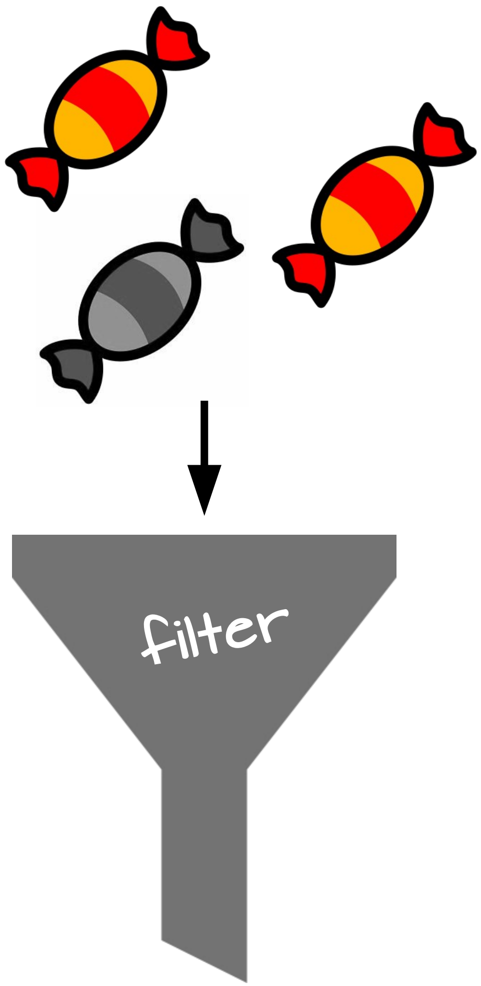
- Mechanism, current status
  - BCC
- A small eBPF trial with LTTng
- Filtering performance with experimental userspace eBPF

Beyond

- KeBPF/UeBPF?

Filters


filter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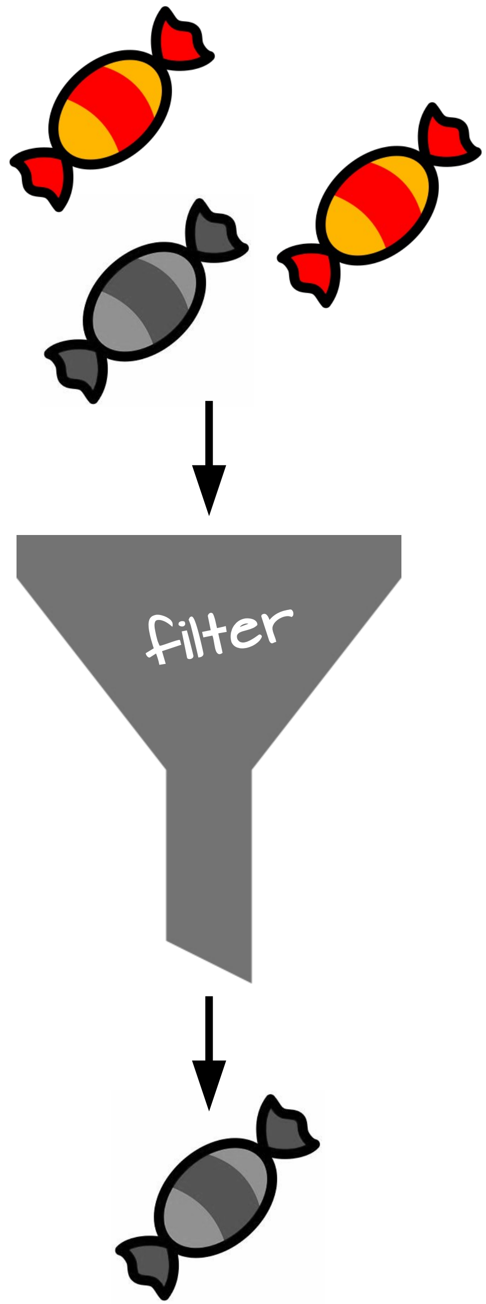
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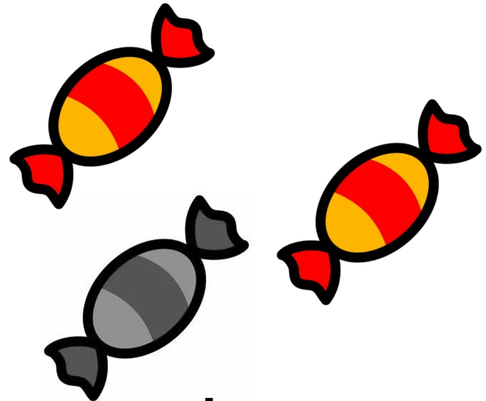
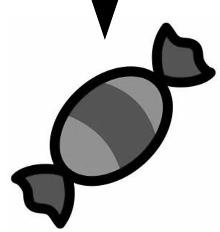
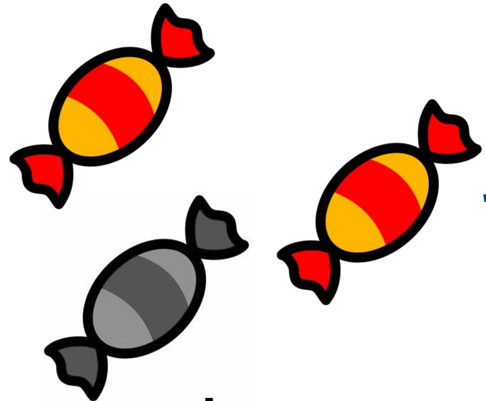


$$(\underbrace{(type = ARP)}_{P1}\ \mathbf{OR}\ \underbrace{(type = IP)}_{P2})\ \mathbf{AND}\ \underbrace{(origin = SRC)}_{P3}\ \mathbf{AND}\ \underbrace{(size < 1024)}_{P4}$$





Packets

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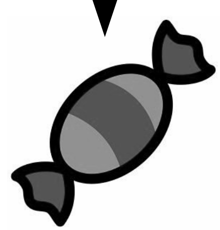
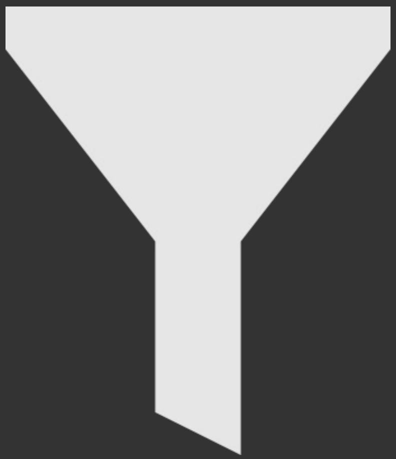
Predicates



Evaluating

Filters



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Foo Evaluator

Take whole string expression and start parsing and evaluating by hand

TRUE / FALSE

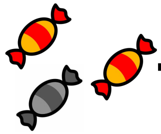
$$\underbrace{((type = ARP)}_{P1}\ \mathbf{OR}\ \underbrace{(type = IP)}_{P2})\,\mathbf{AND}\ \underbrace{(origin = SRC)}_{P3}\ \mathbf{AND}\ \underbrace{(size < 1024)}_{P4}$$

Foo Evaluator

Take whole string expression and start parsing and evaluating by hand

TRUE / FALSE

42 billion runs



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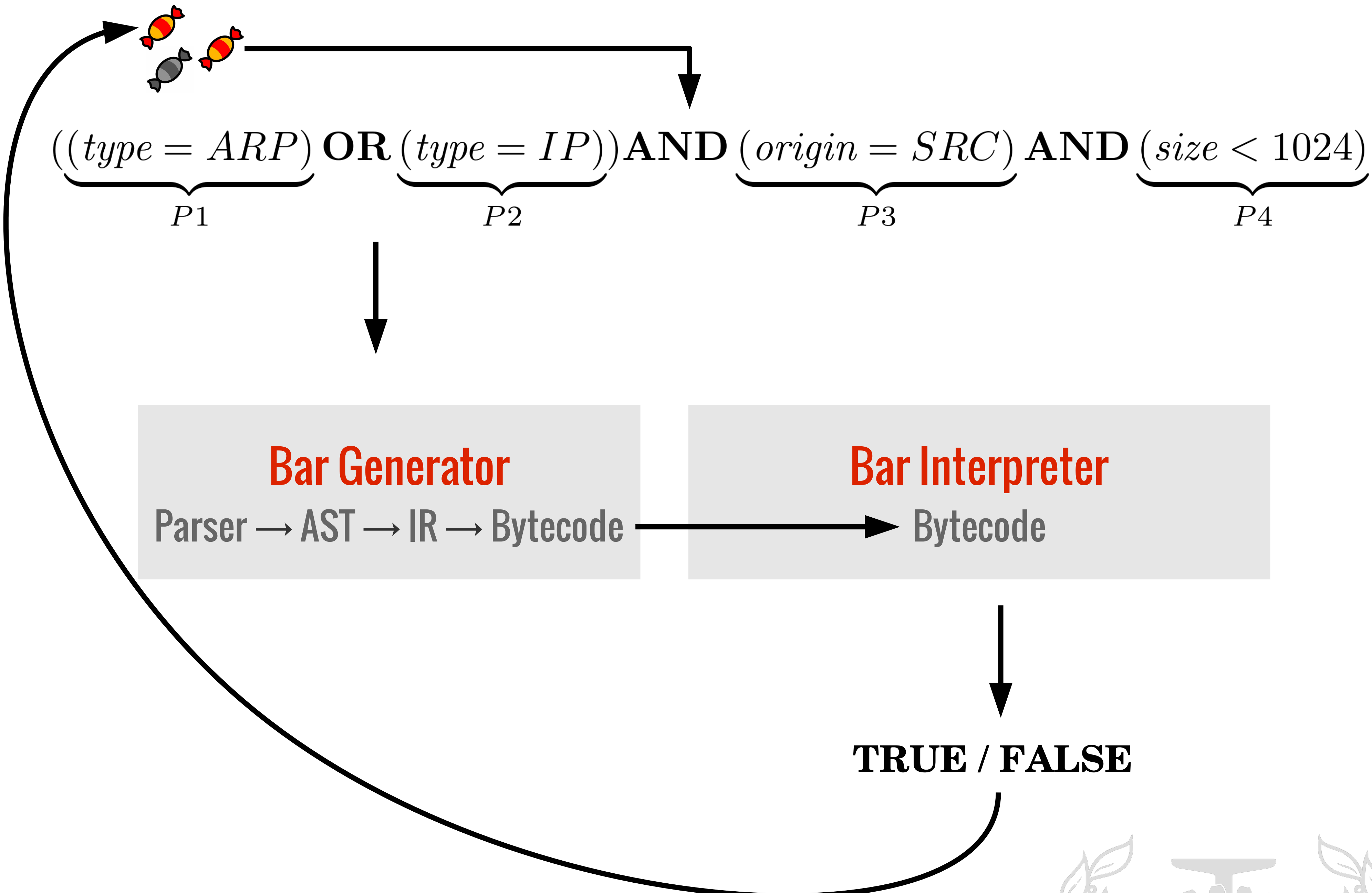
Bar Generator

Parser → AST → IR → Bytecode

Bar Interpreter

Bytecode

TRUE / FALSE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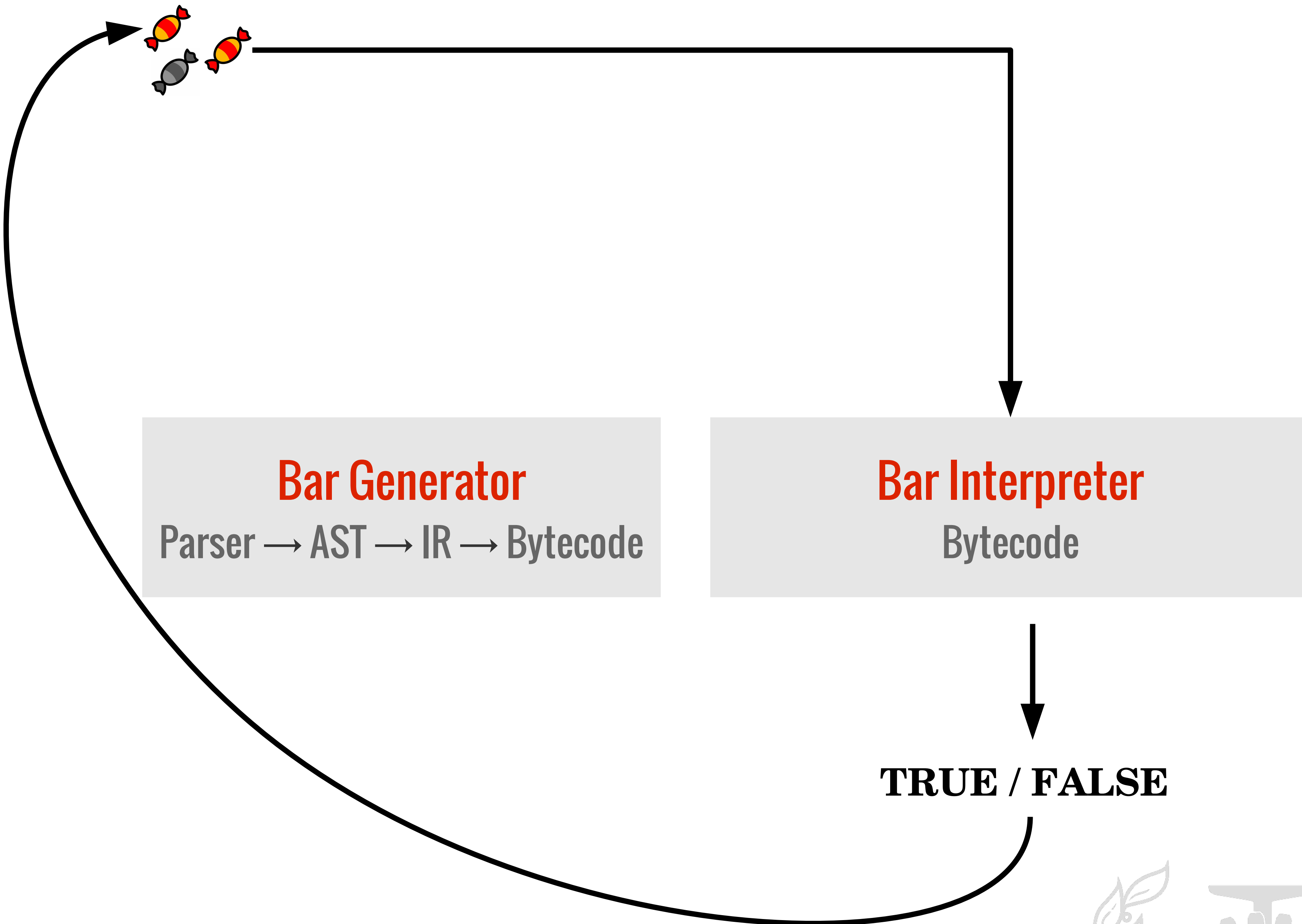
TRUE / FALSE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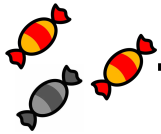

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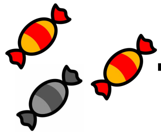

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Bar Generator

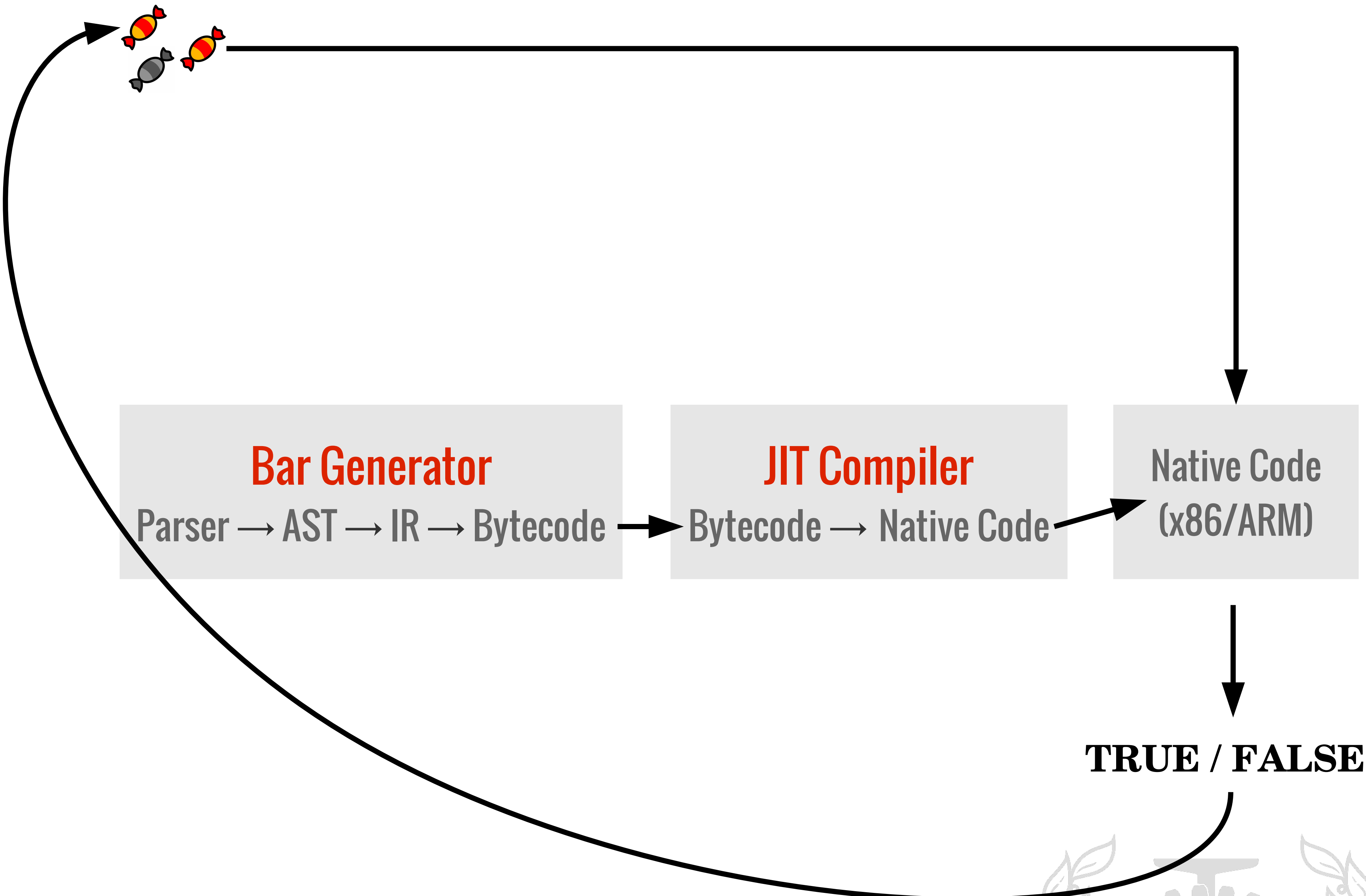
Parser → AST → IR → Bytecode

JIT Compiler

Bytecode → Native Code

Native Code (x86/ARM)

TRUE / FALSE


Bar Generator
Parser → AST → IR → Bytecode
JIT Compiler
Bytecode → Native Code
Native Code
(x86/ARM)
TRUE / FALSE

Why do we need these blazingly

FAST

filters?

Network

- Sustain network throughput
- Effect is visible on embedded devices which work uninterrupted

Tracing

- Filtering huge event flood at runtime reliably
- High frequency events long-running trace events in production systems with limited resources to defer analysis

$$\underbrace{((type = ARP)}_{P1}\ \mathbf{OR}\ \underbrace{(type = IP)}_{P2})\mathbf{AND}\ \underbrace{(origin = SRC)}_{P3}\ \mathbf{AND}\ \underbrace{(size < 1024)}_{P4}$$

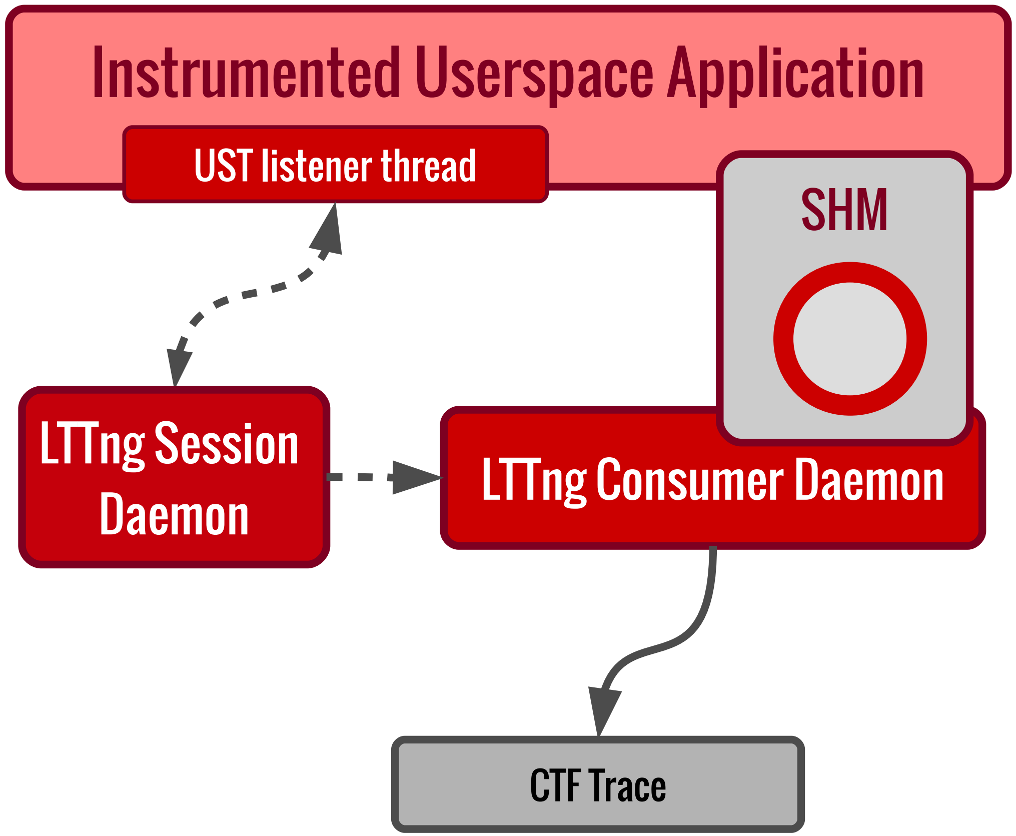
$$\downarrow$$

?

LTTng's

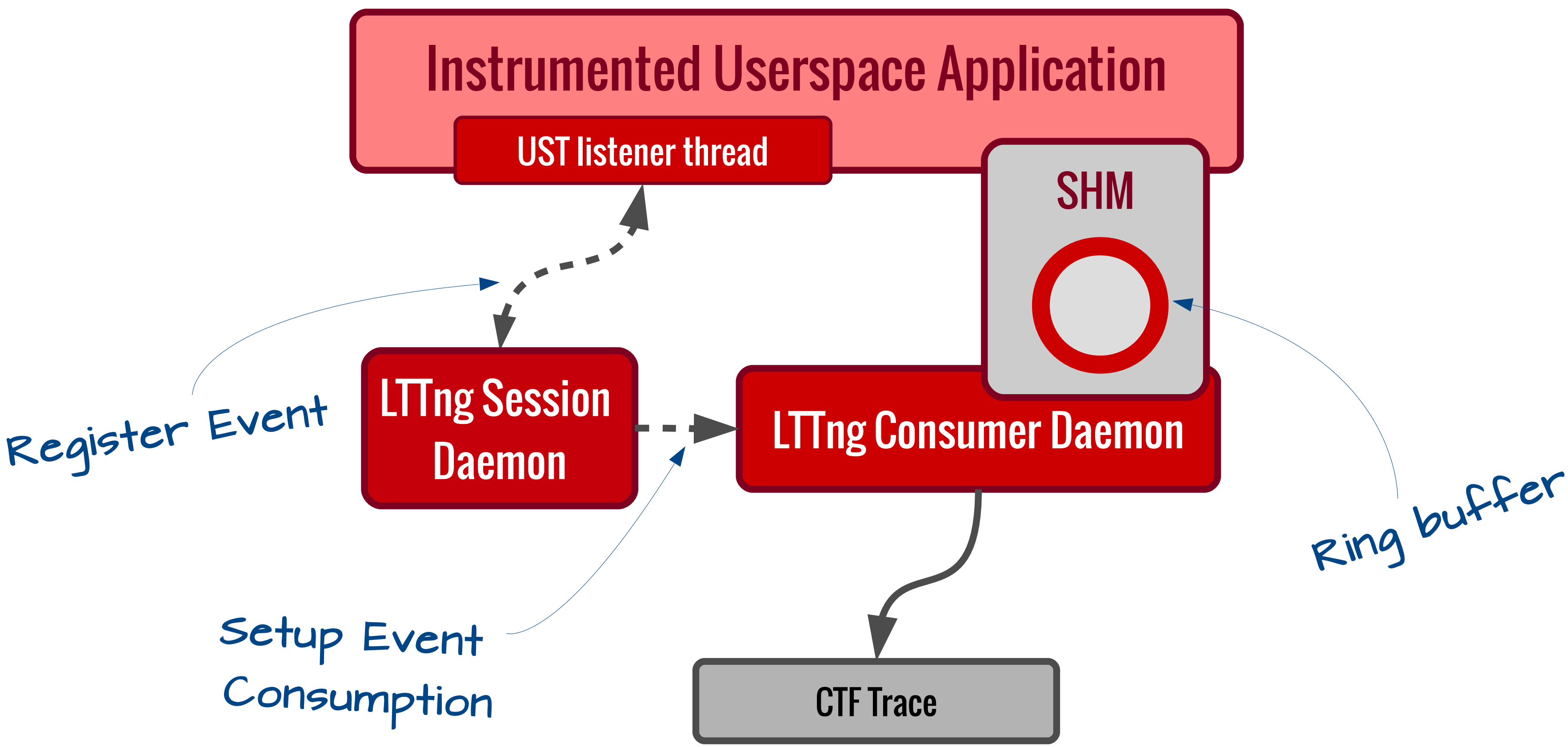
Trace Filtering

LTTng-UST

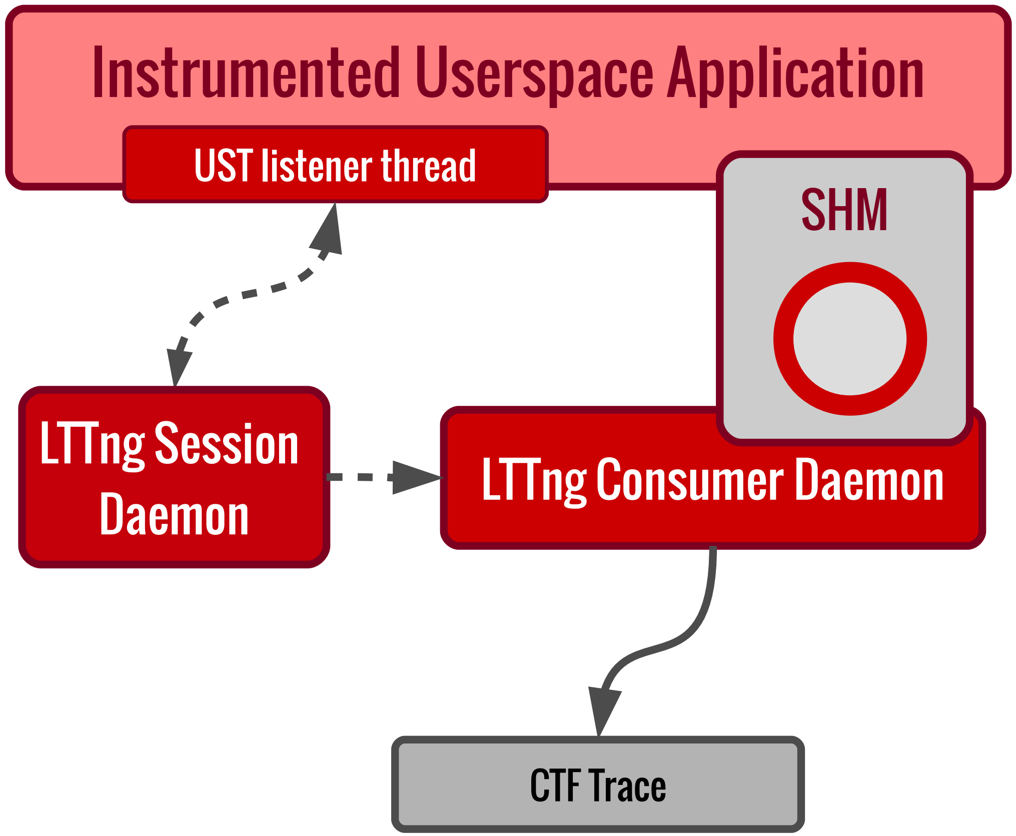


Instrumented Userspace Application
UST listener thread
SHM
LTTng Session Daemon
LTTng Consumer Daemon
CTF Trace

LTTng-UST


Instrumented Userspace Application
UST listener thread
SHM
Register Event
LTTng Session Daemon
LTTng Consumer Daemon
Ring buffer
Setup Event Consumption
CTF Trace

LTTng-UST



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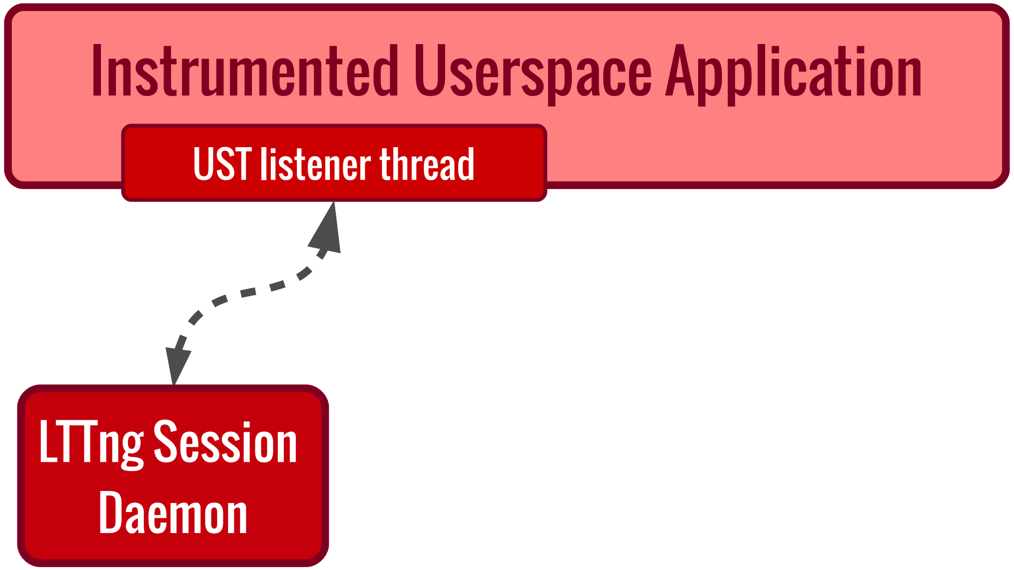
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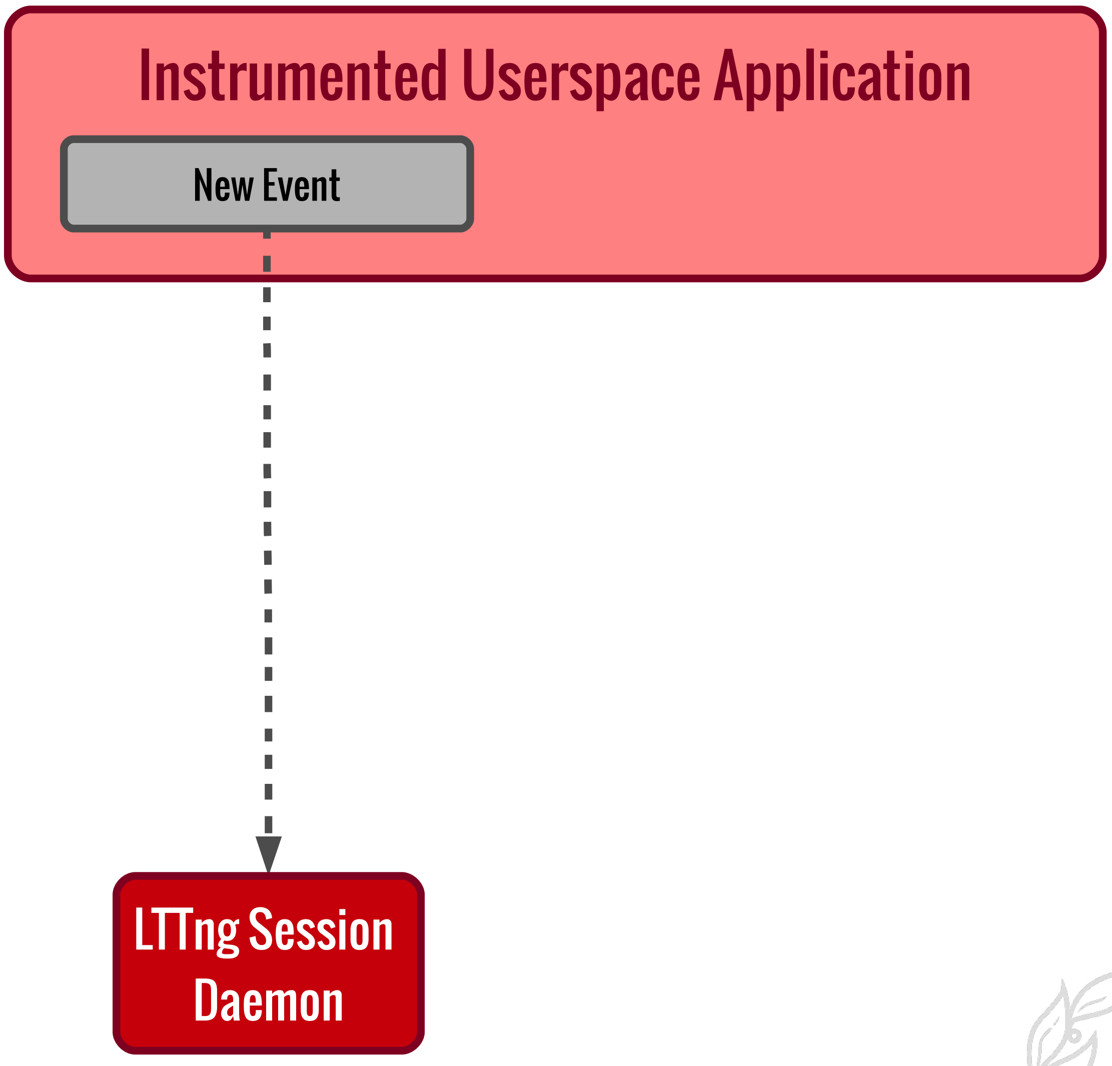
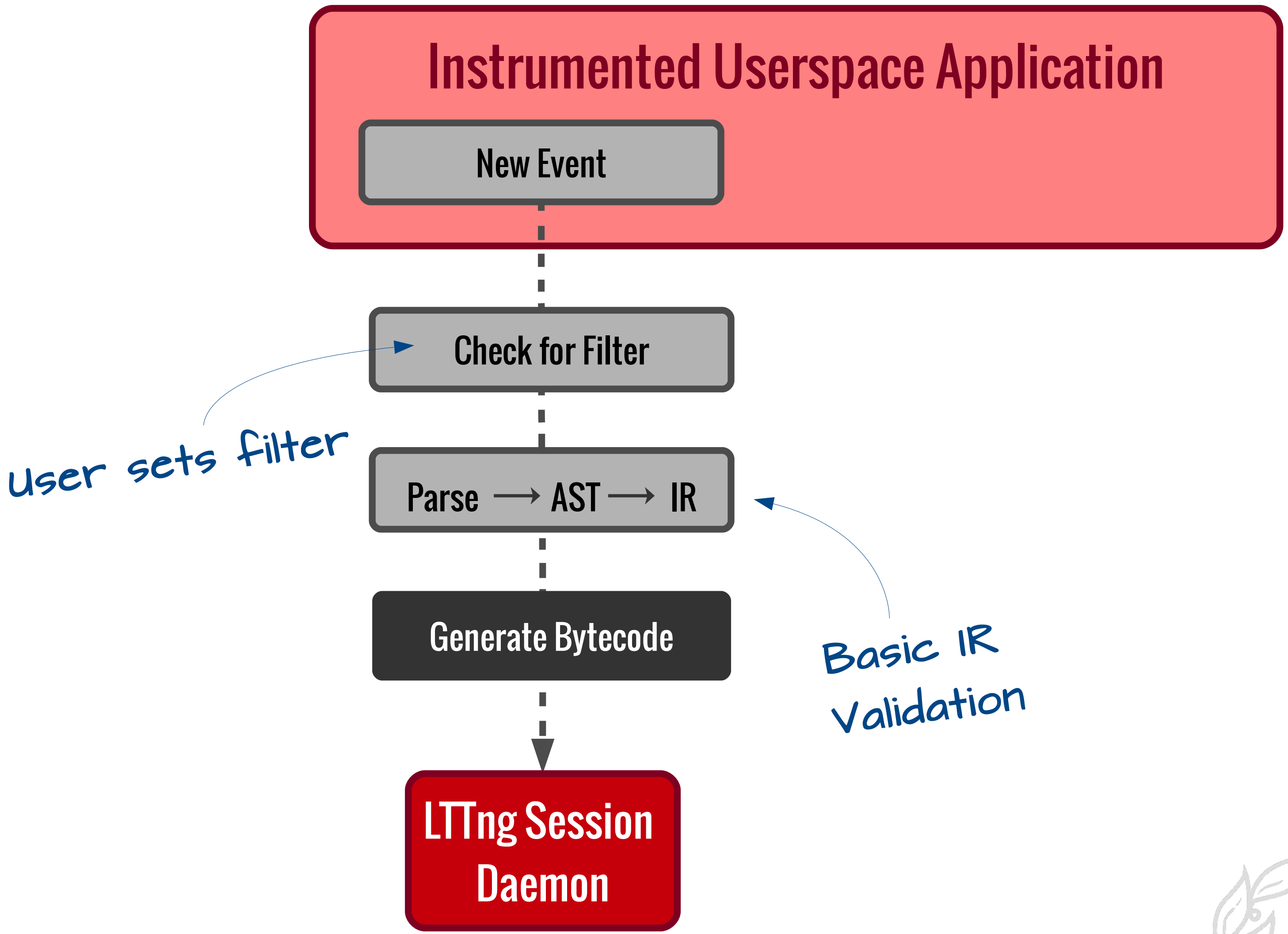
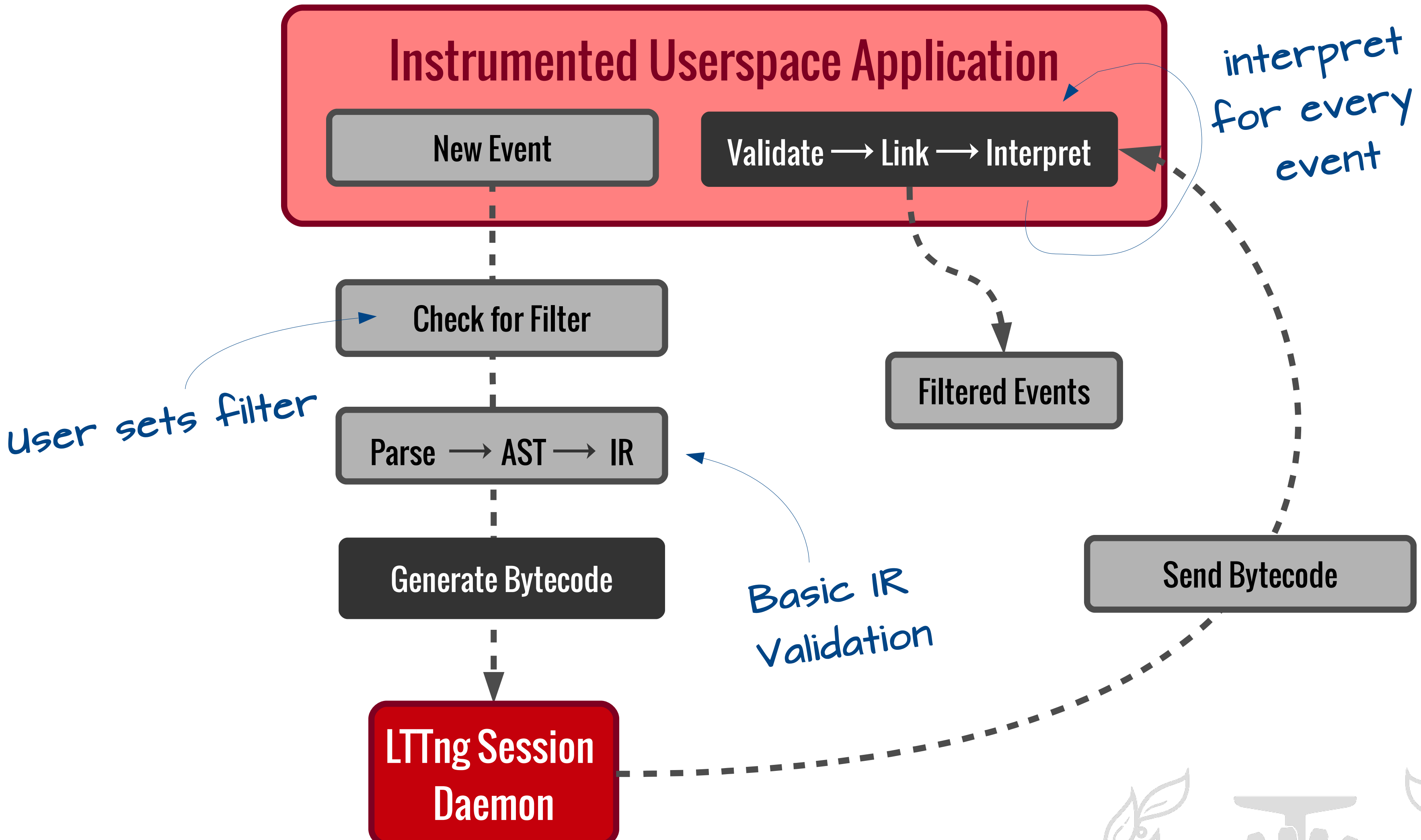
LTTng-UST Filtering



LTTng-UST Filtering



LTTng-UST Filtering



LTTng's Trace Filtering

A filtered session

```
$ lttng create mysession
$ lttng enable-event --filter '(foo == 42) && (bar == "baz")' -a -u
```

```
Filter '(foo == 42) && (bar == "baz")' successfully set
```

```
$ lttng start

<do some science>

$ lttng stop
$ lttng view
```

LTTng's Trace Filtering

A filtered session

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$ lttng create mysession
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```

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Filter '(foo == 42) && (bar == "baz")' successfully set
```

```
$ lttng start

<do some science>

$ lttng stop
$ lttng view
```

Generating Bytecode

Filter Bytecode Generation

`generate_filter()`

- Flex-Bison generated lexer-parser
- Custom tokens and grammar

```
ctx = filter_parser_ctx_alloc(fmem);
```

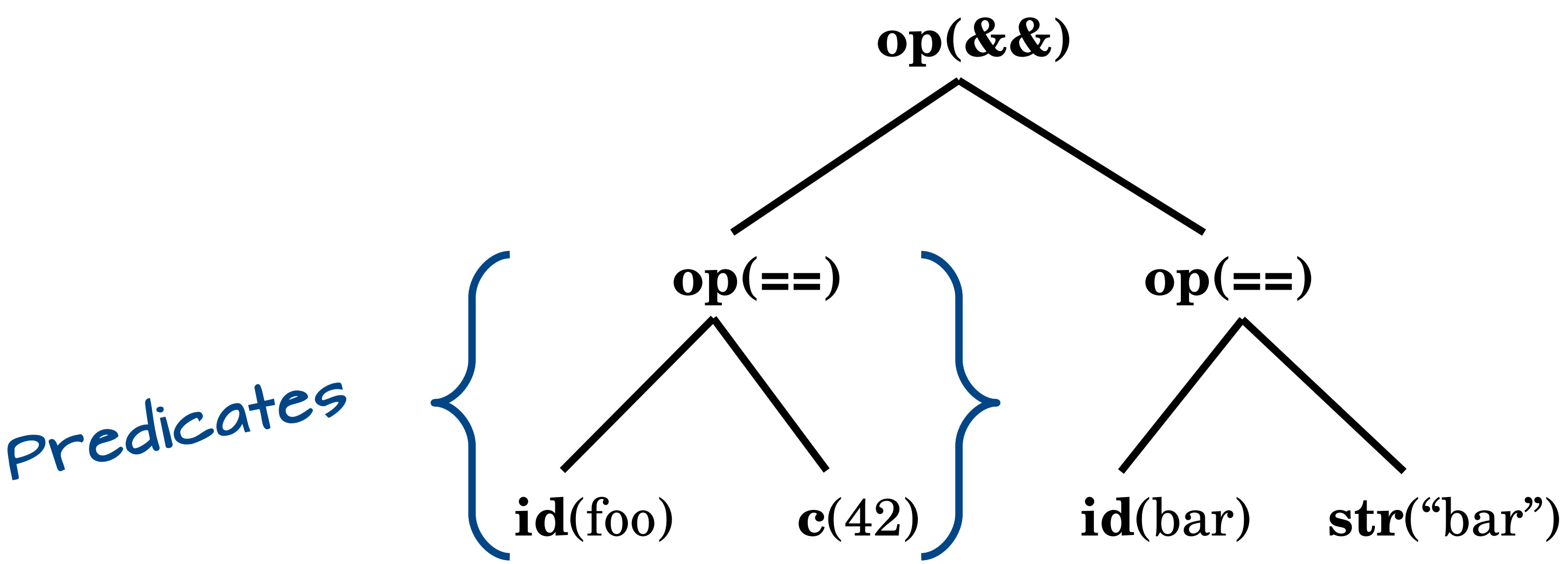
- Allocate/initialize parser, AST, create root node

```
filter_parser_ctx_append_ast(ctx);
filter_visitor_set_parent(ctx);
```

- Run `yyparse()`, `yylex()`
- Generate syntax tree

Filter Bytecode Generation

Syntax Tree



Filter Bytecode Generation

```
filter_visitor_ir_generate(ctx);
```

- Hand written IR generator
- Go through each node recursively, classify them
- **No binary arithmetic** supported for now. Only logic and comparisons

```
filter_visitor_ir_check_binary_op_nesting(ctx);
filter_visitor_ir_validate_string(ctx);
```

- Basic IR Validation
  - Except logical operators, operator nesting not allowed
  - Validate string as literal part - No wildcard in between strings, no unsupported characters

Filter Bytecode Generation

```
filter_visitor_bytecode_generate(ctx);
```

- Traverse tree post-order
- Based on node type, start emitting instructions
- Save the bytecode in ctx
- Add symbol table data to bytecode.
- We are done, lets send it to lttng-sessiond!

Interpreting Bytecode

Filter Bytecode Interpretation

`lttng_filter_event_link_bytecode()`

- Link bytecode to the event and create bytecode runtime
  - Copy original bytecode to runtime
  - Apply field and context relocations

```
lttng_filter_validate_bytecode(runtime);
```

- Check unsupported bytecodes (eg. arithmetic)
- Check range overflow for different insn classes
- Validate current context and merge points for all insn

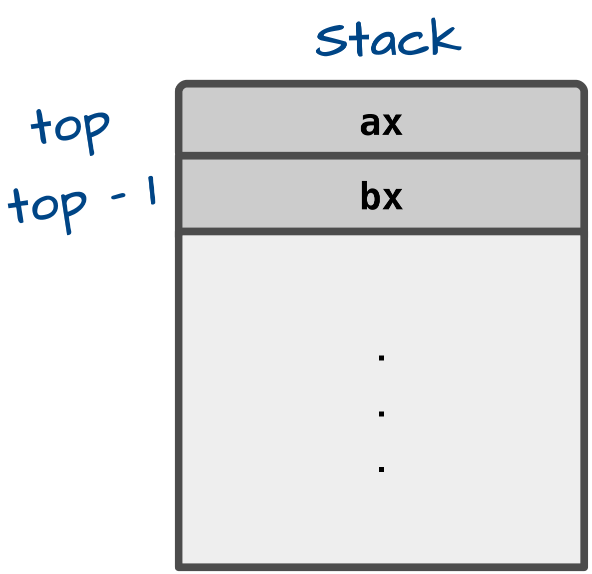
```
lttng_filter_specialize_bytecode(runtime);
```

- We know event field types now
- Lets specialize operations based on that

Filter Bytecode Interpretation

`lttng_filter_interpret_bytecode()`

- Hybrid virtual machine
  - 2 registers (ax & bx) aliased to top of stack
  - Functions like register machine - flexible like stack
- Threaded instruction dispatch/normal dispatch (fallback)




```
OP(FILTER_OP_NE_S64):
{
	int res;

	res = (estack_bx_v != estack_ax_v);
	estack_pop(stack, top, ax, bx);
	estack_ax_v = res;
	next_pc += sizeof(struct binary_op);
	PO;
}
```

eBPF

Filters & More

eBPF

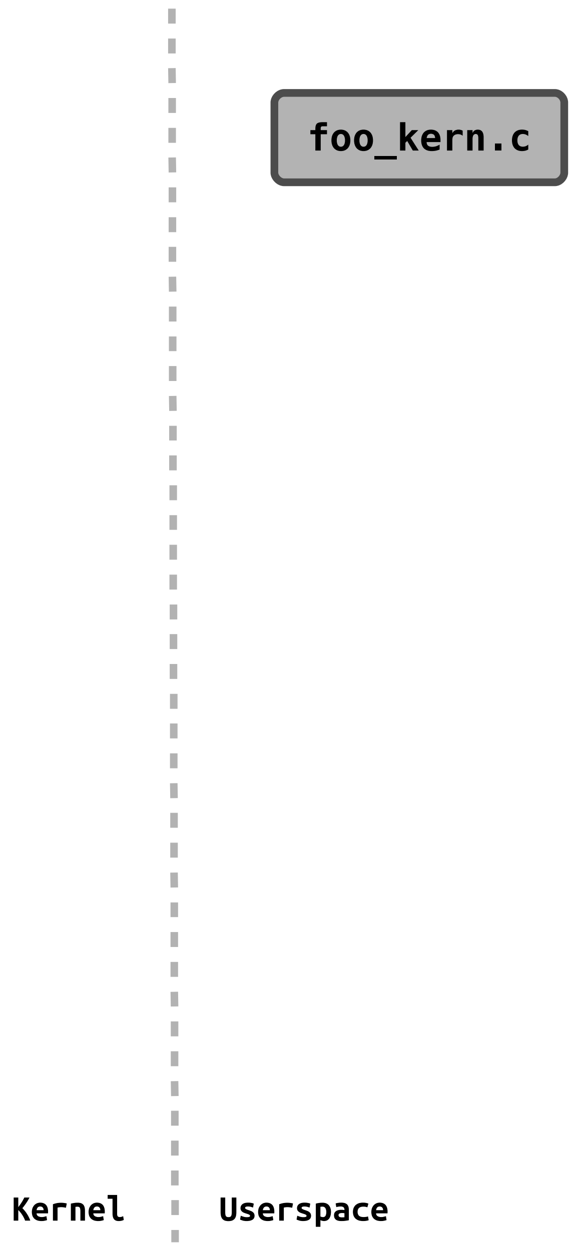
Berkeley Packet Filter (BPF)

- Filter expressions → Bytecode → Interpret
- Fast, small, in-kernel packet & syscall filtering
- Register based, switch-dispatch interpreter

Current Status of BPF

- Extensions for trace filtering (Kprobes!! Kprobes!!)
- More than just filtering. JITed programs - FAST!
- Evolved to *extended* BPF (eBPF)
  - BPF maps, *bpf* syscall - aggregation and userspace access
  - More registers (64 bit), back jumps, tail-calls, safety

Example eBPF Session



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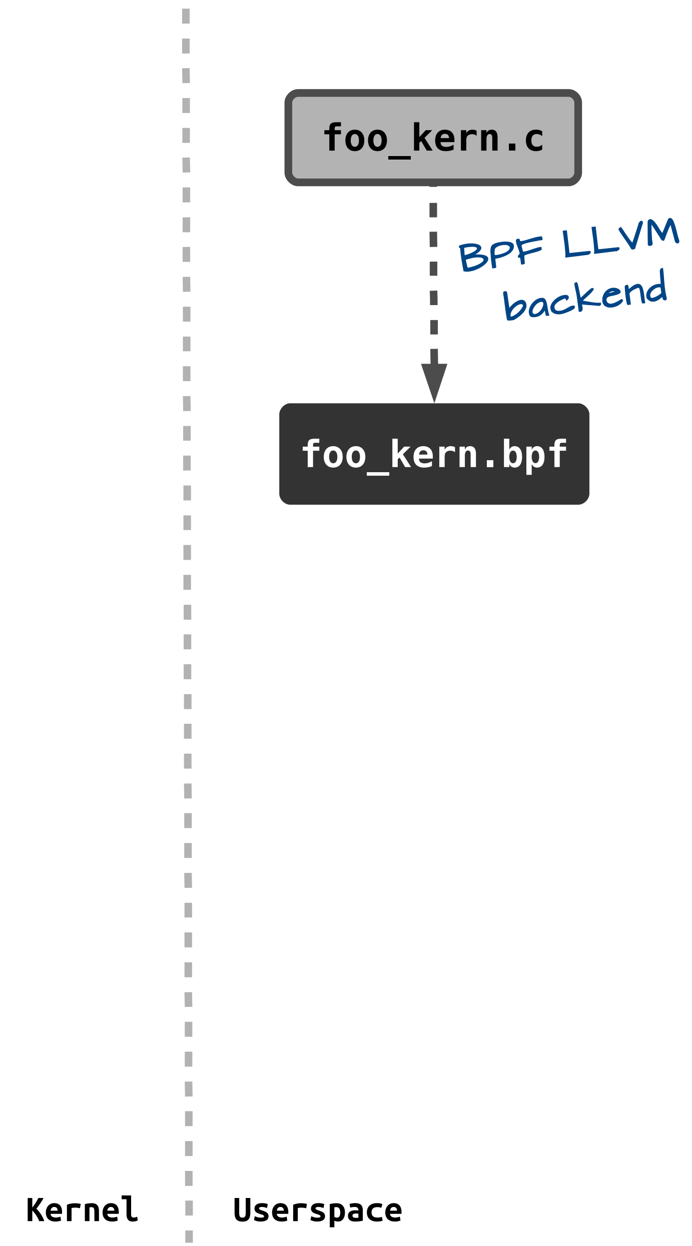

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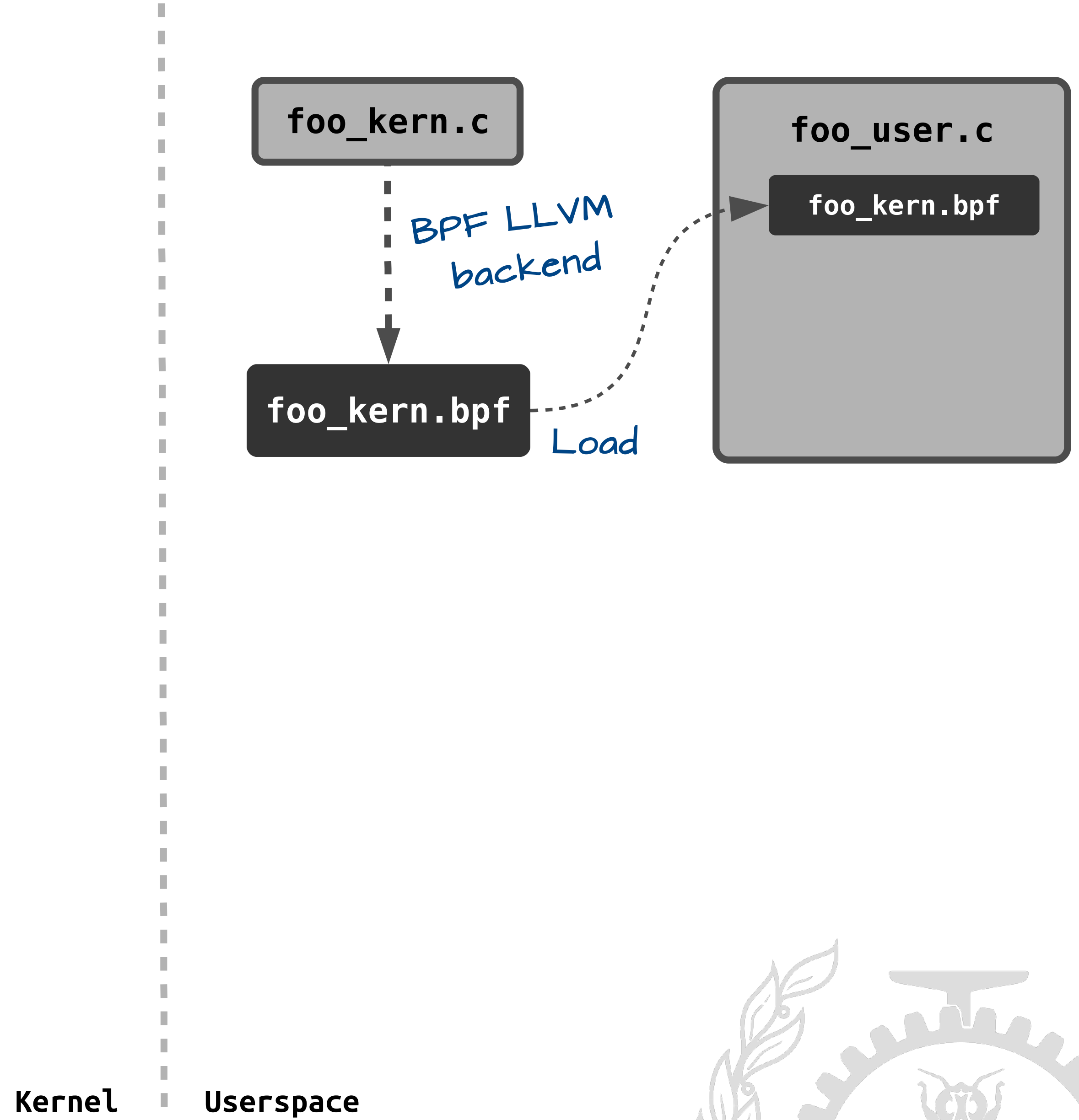

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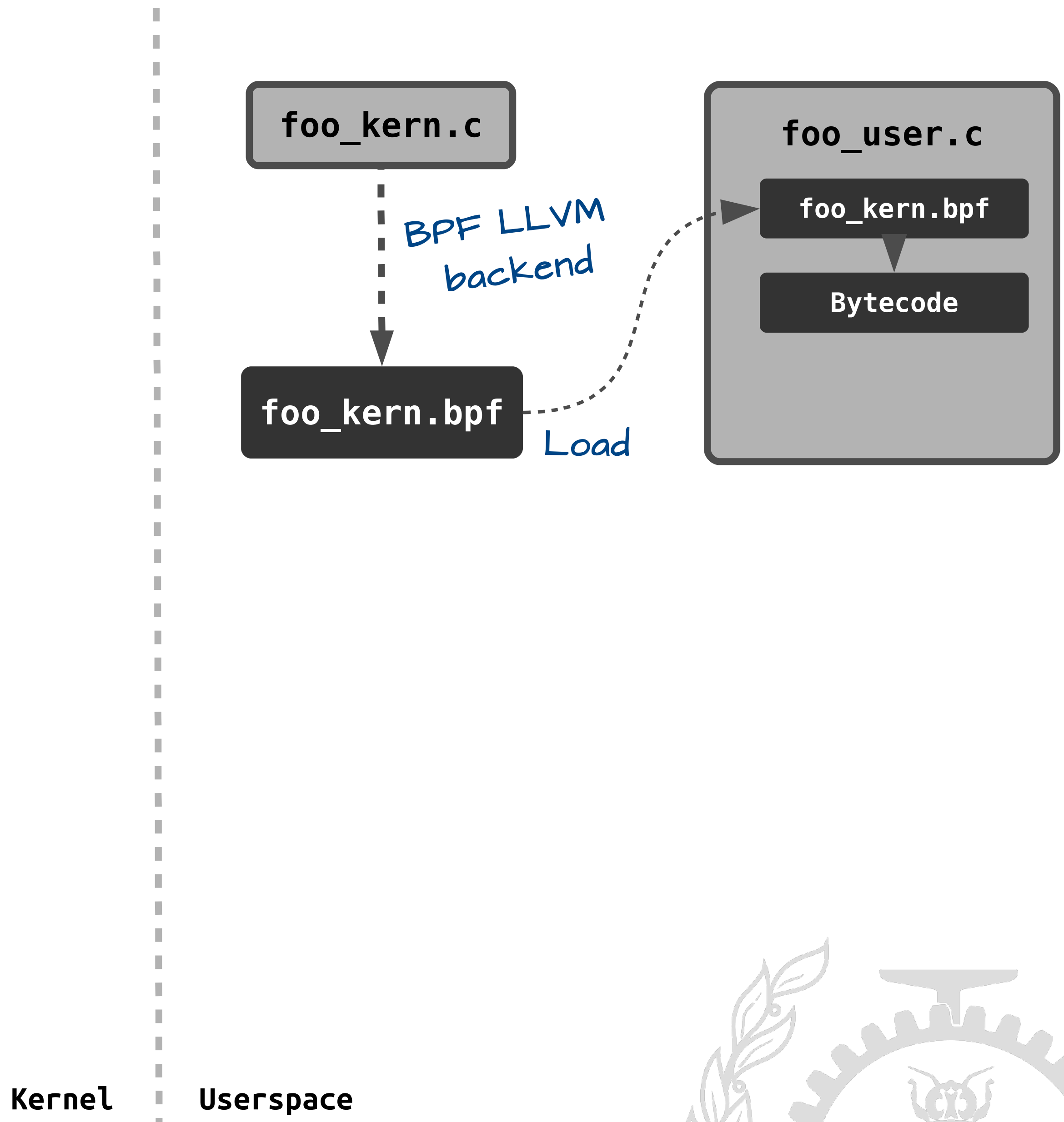

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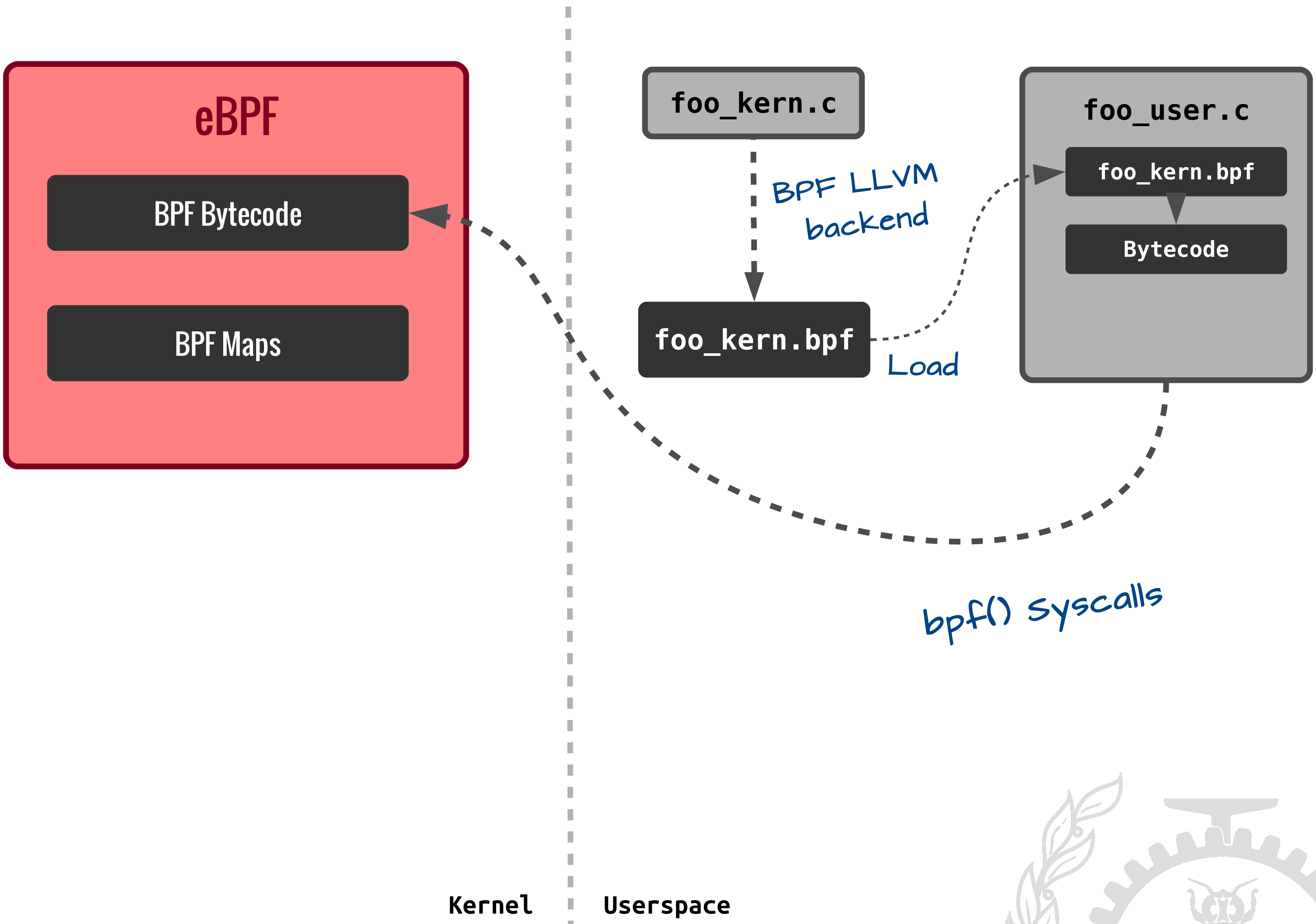

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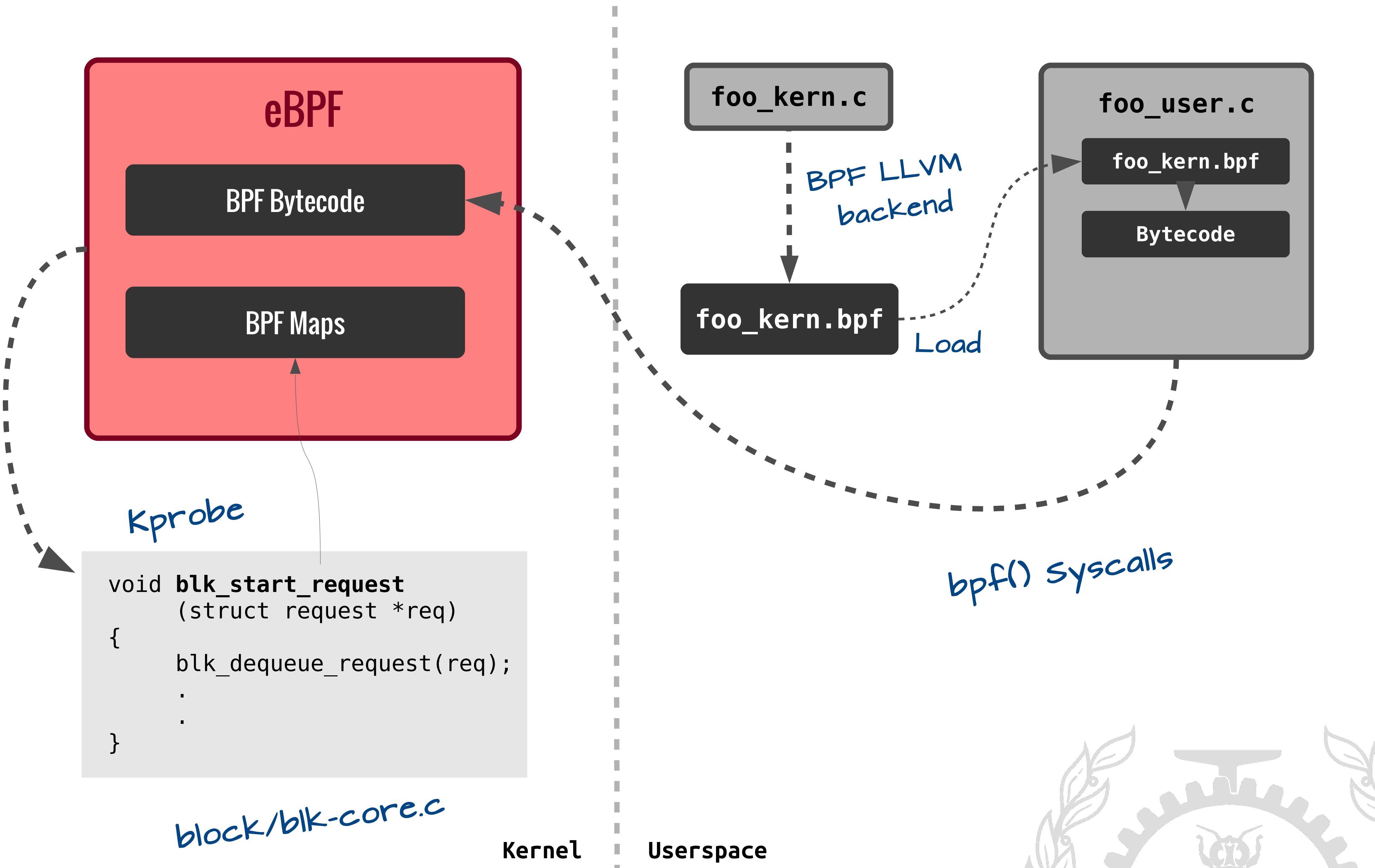

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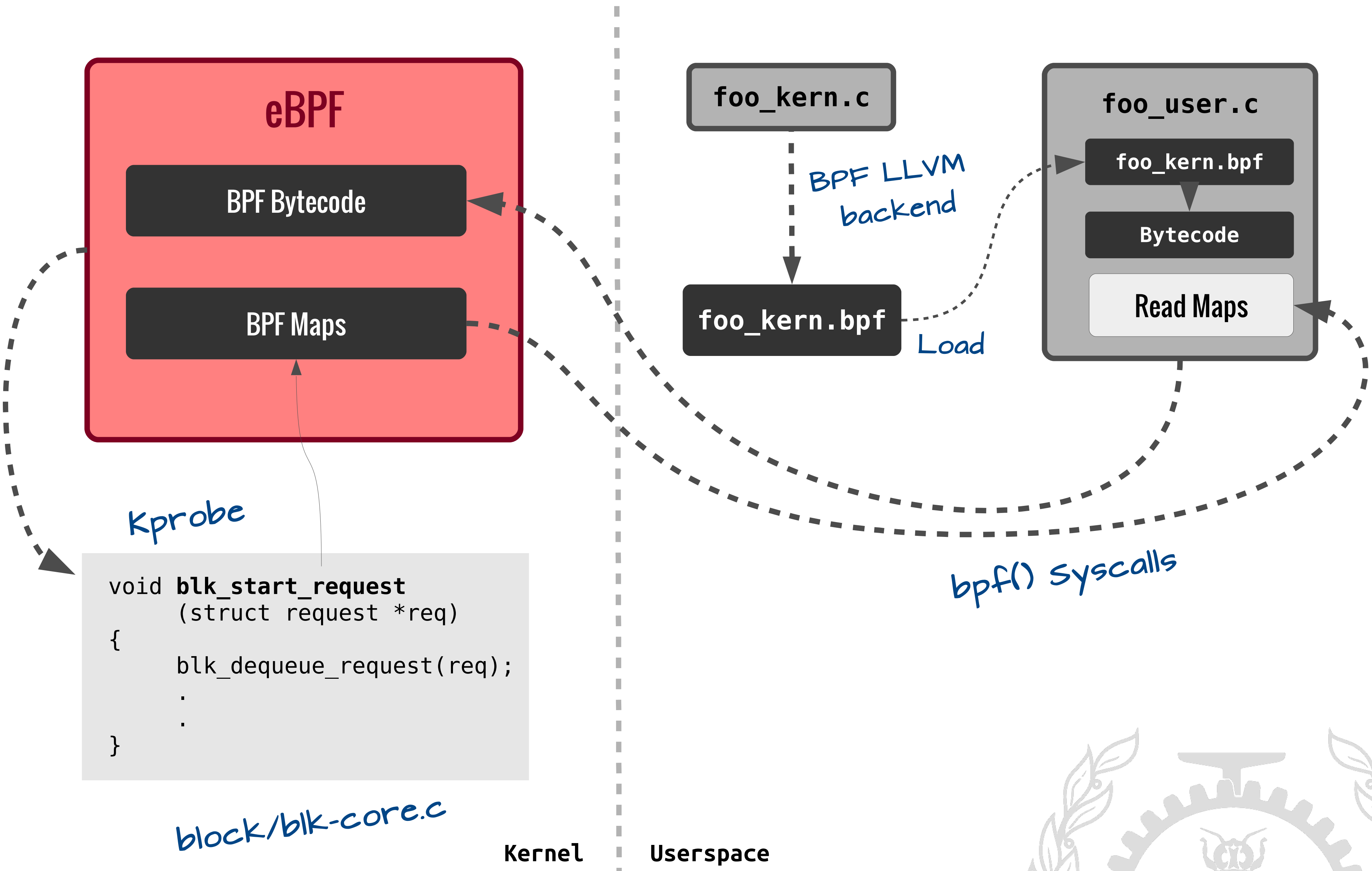


Sample eBPF Filter

eBPF Filter on LTTng Kernel Event

```
if ((dev->name[0] == “l”) && (dev->name[1] == “o”))
{
    trace_netif_receive_skb_filter(skb);
}
```

eBPF Bytecode :

R2 = ctx

R3 = *(dev->name)
R4 = 0x6f6c

```
static struct bpf_insn insn_prog[] = {
    BPF_LDX_MEM(BPF_DW, BPF_REG_2, BPF_REG_1, 0),
    BPF_LDX_MEM(BPF_DW, BPF_REG_3, BPF_REG_2, 0), /* ctx->arg1 */
    BPF_LDX_MEM(BPF_DW, BPF_REG_4, BPF_REG_1, 8), /* ctx->arg2 */
    BPF_JMP_REG(BPF_JEQ, BPF_REG_3, BPF_REG_4, 3), /* compare arg1 & arg2 */
    BPF_LD_IMM64(BPF_REG_0, 0), /* FALSE */
    BPF_EXIT_INSN(),
    BPF_LD_IMM64(BPF_REG_0, 1), /* TRUE */
    BPF_EXIT_INSN(),
};
```

Sample eBPF Filter

eBPF JITed :

```
  0:    push   %rbp
  1:    mov    %rsp,%rbp
  4:    sub    $0x228,%rsp
  b:    mov    %rbx,-0x228(%rbp)
 12:    mov    %r13,-0x220(%rbp)
        mov    %r14,-0x218(%rbp)
        mov    %r15,-0x210(%rbp)
 27:    xor    %eax,%eax
 29:    xor    %r13,%r13
        mov    0x0(%rdi),%rsi
        mov    0x0(%rsi),%rdx
        mov    0x8(%rdi),%rcx
 38:    cmp    %rcx,%rdx
```

```
3b:    je     0x0000000000000049
3d:    movabs $0x0,%rax       ;FALSE
47:    jmp    0x0000000000000053
49:    movabs $0x1,%rax       ;TRUE
53:    mov    -0x228(%rbp),%rbx
       mov    -0x220(%rbp),%r13
       mov    -0x218(%rbp),%r14
68:    mov    -0x210(%rbp),%r15
6f:    leaveq
70:    retq
```

Make some space on stack

Save callee saved regs

Clear A and X

Compare R3, R4

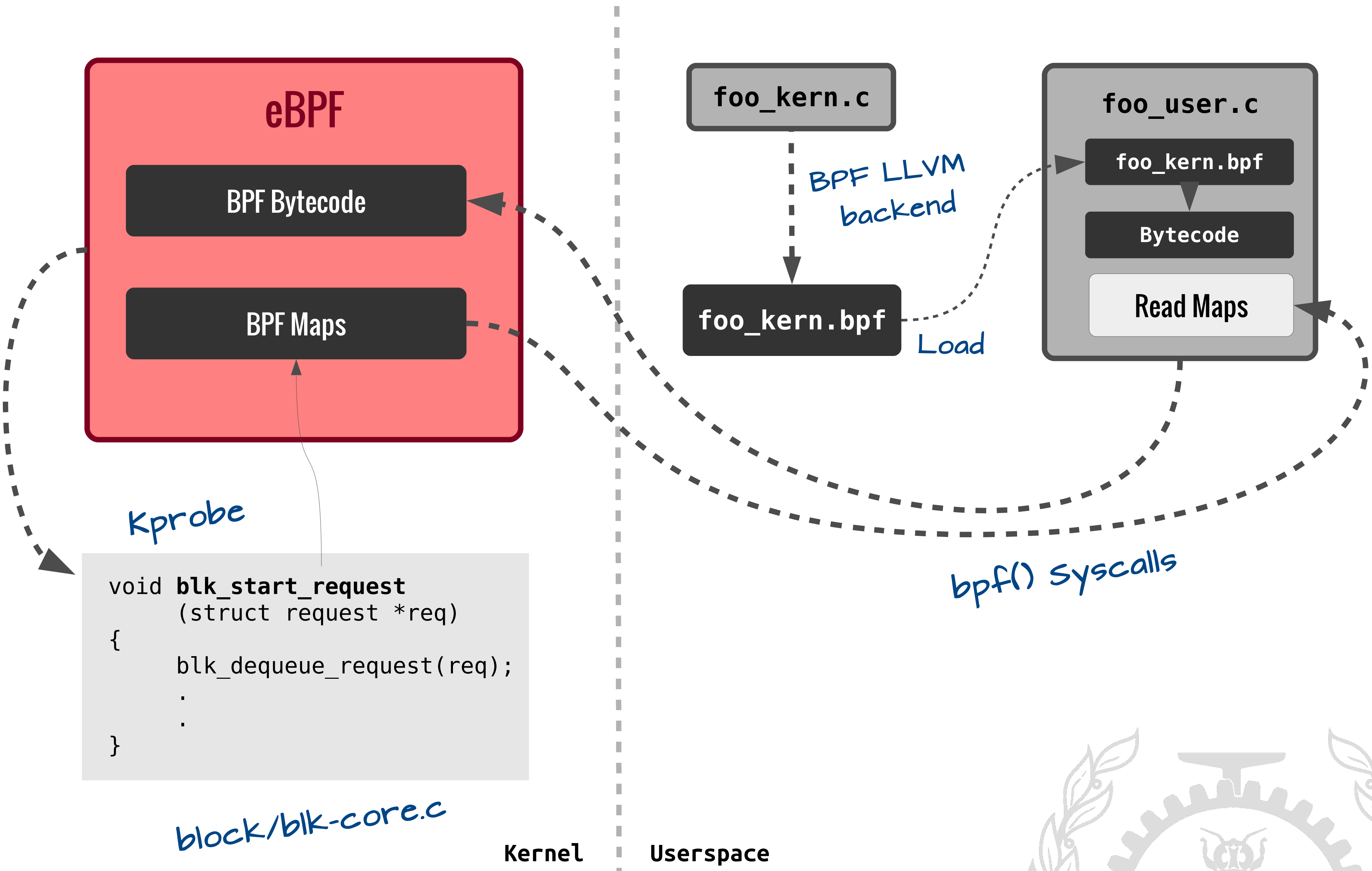
Load ctx args to R3 and R4

Jump to **TRUE**

Restore regs

One-to-one direct *method* JIT. eBPF is close to modern architectures

Example eBPF Session

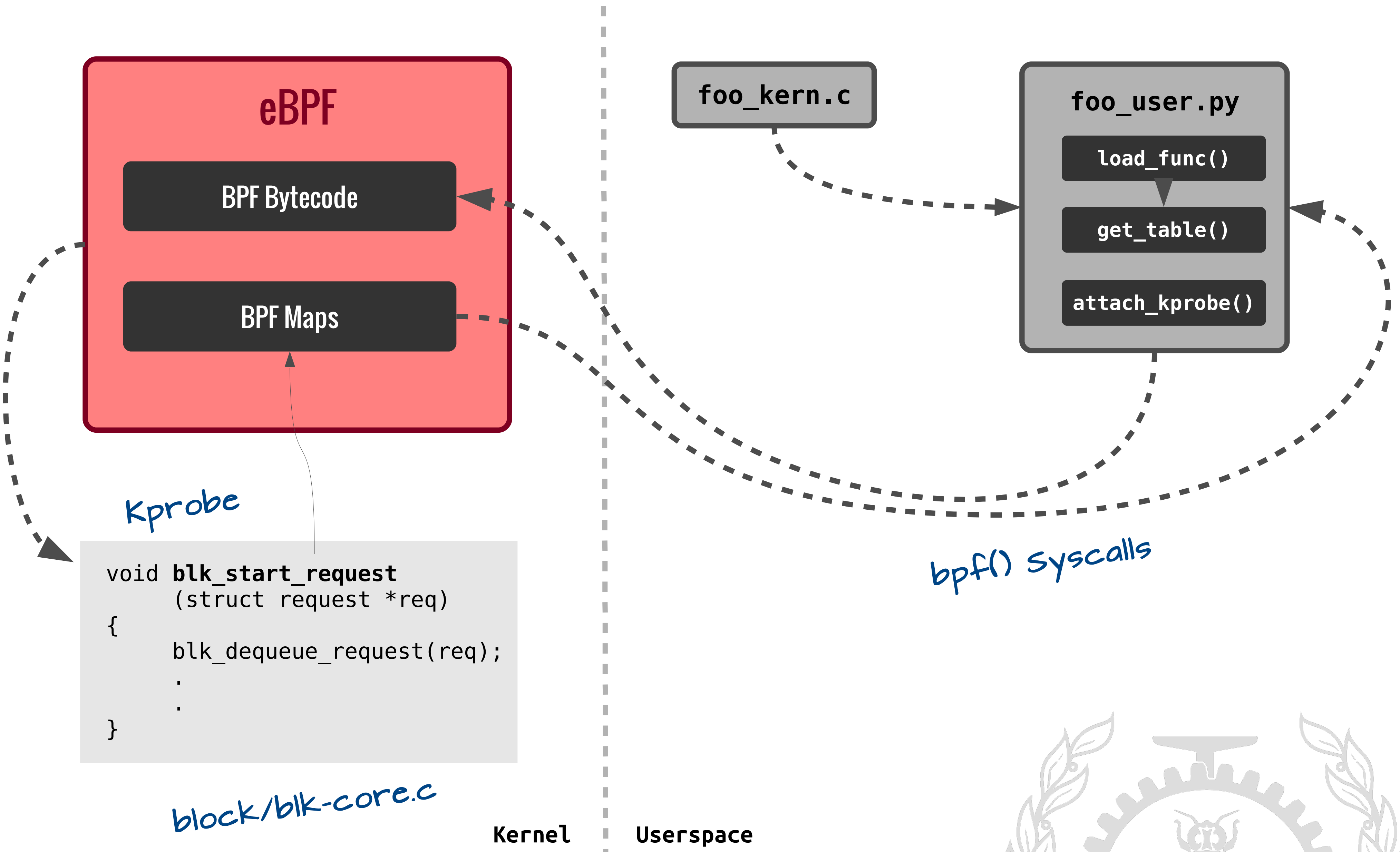


BPF COMPILER COLLECTION

Yes, `'bcc'` **exists!**

https://github.com/iovisor/bcc

Example bcc Session



Example bcc Session

task_switch.c

```
#include <uapi/linux/ptrace.h>
#include <linux/sched.h>

struct key_t {
  u32 prev_pid;
  u32 curr_pid;
};

BPF_TABLE("hash", struct key_t, u64, stats, 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;
}
```

Kernel side BPF program

task_switch.py

```
from bpf import BPF
from time import sleep

b = BPF(src_file="task_switch.c")
fn = b.load_func("count_sched", BPF.KPROBE)
stats = b.get_table("stats")
BPF.attach_kprobe(fn, "finish_task_switch")

# generate many schedule events
for i in range(0, 100): sleep(0.01)

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

eBPF

Why eBPF in Tracing

- Primarily for filters & script driven tracing - FAST, very FAST!
- Add sophisticated features to tracing, at low cost
  - Fast stateful kernel event filtering/data aggregation
    - Record system wide sched_wakeup only when target process is blocked to reduce overhead
    - Utilize *side-effects* for assisted-tracing
- A more uniform way of filtering events across userspace and kernel

Experiments

Userspace eBPF (UeBPF)

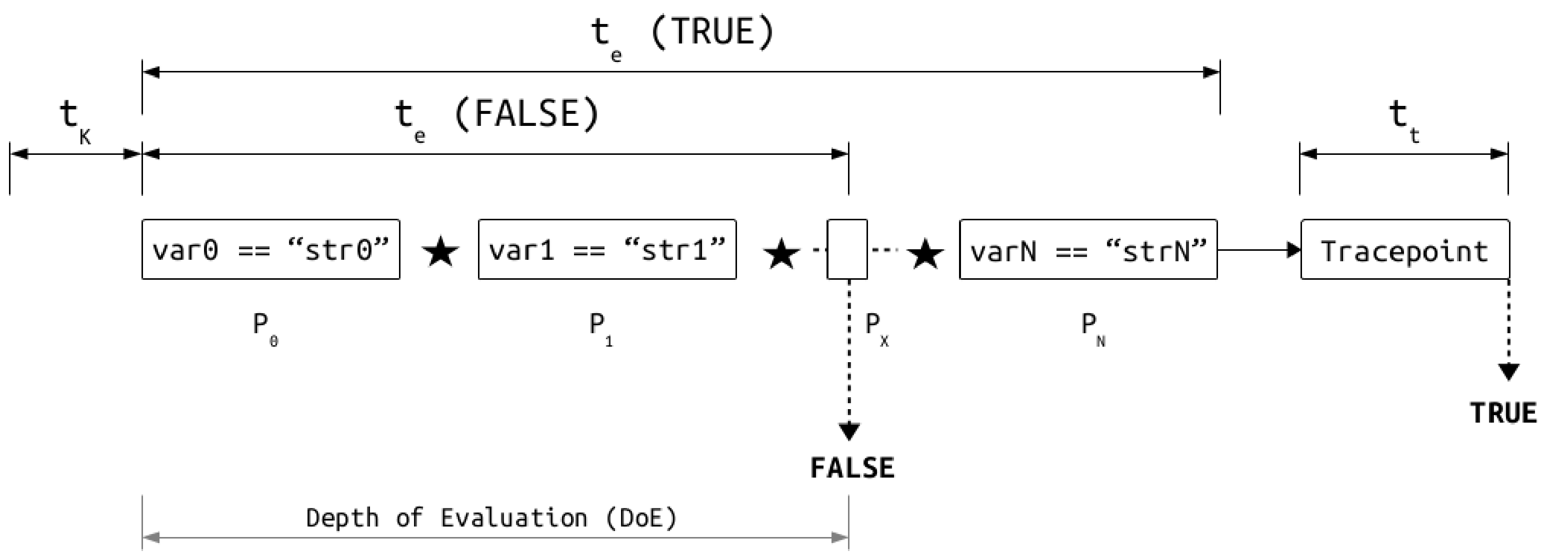
- Experimental *libebpf* to provide filtering in userspace tracing
- Includes side-effects through communication with modified KeBPF
- Easy switch between JIT/interpret for performance analysis
- Includes LLVM BPF backend.
- Load bytecode from eBPF binaries

Performance Analysis

- Apply LTTng, eBPF, eBPF+JIT, hardcoded filters
- Measure $t_{execution} + t_{tracepoint}$

Experiments

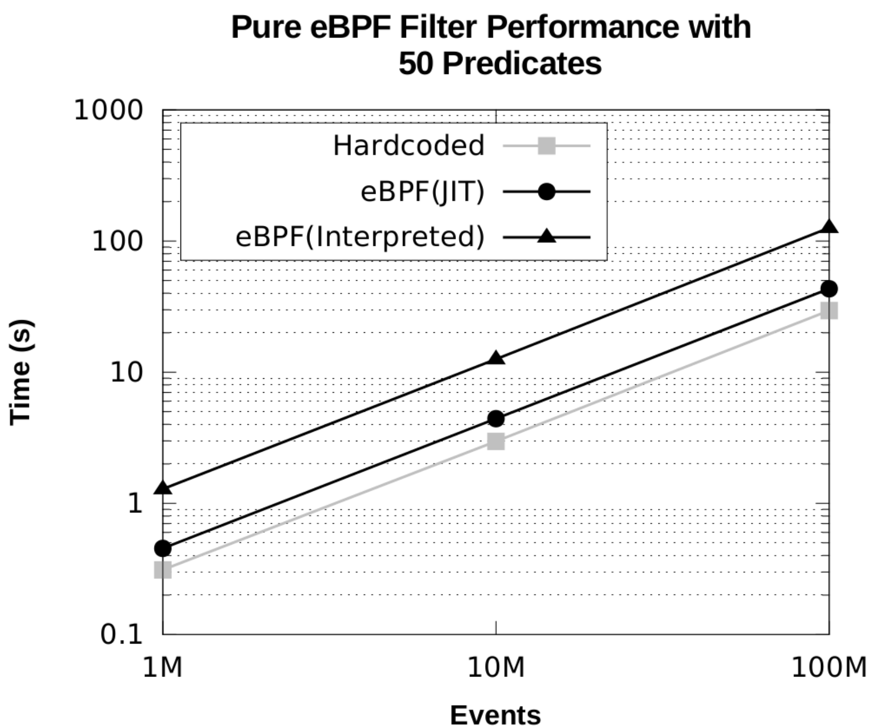
Performance Analysis

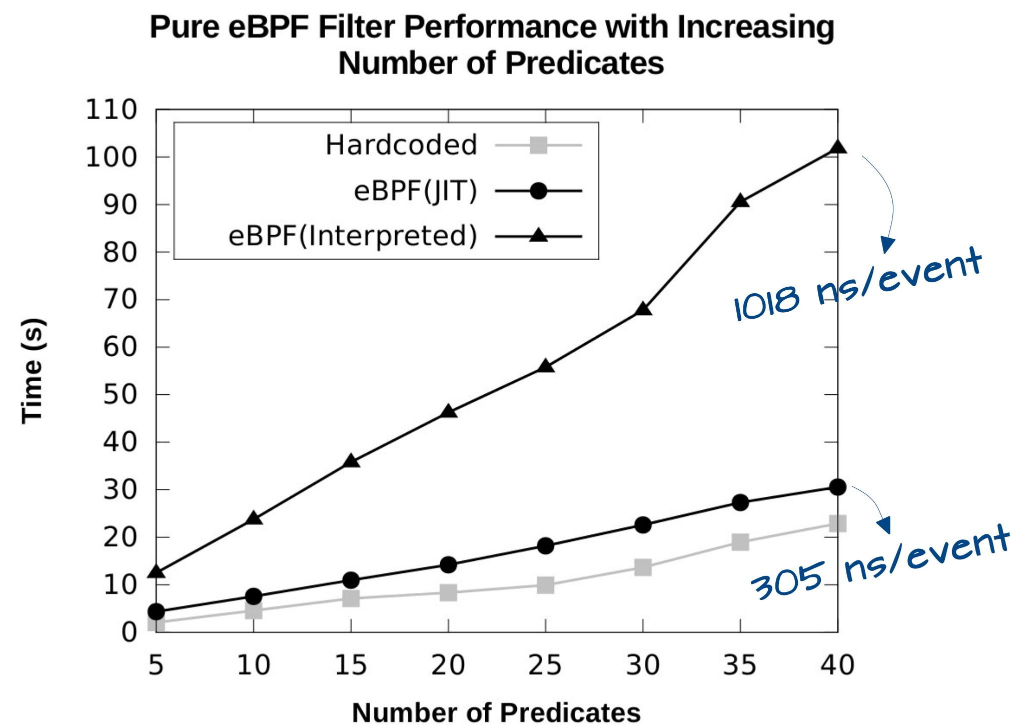


- Pure filter evaluation.
  - TRUE/FALSE biased AND chain with varying predicates
- Measure $t_e + t_t$ with varying *DoE* (Biased TRUE)

Experiments

Performance Analysis

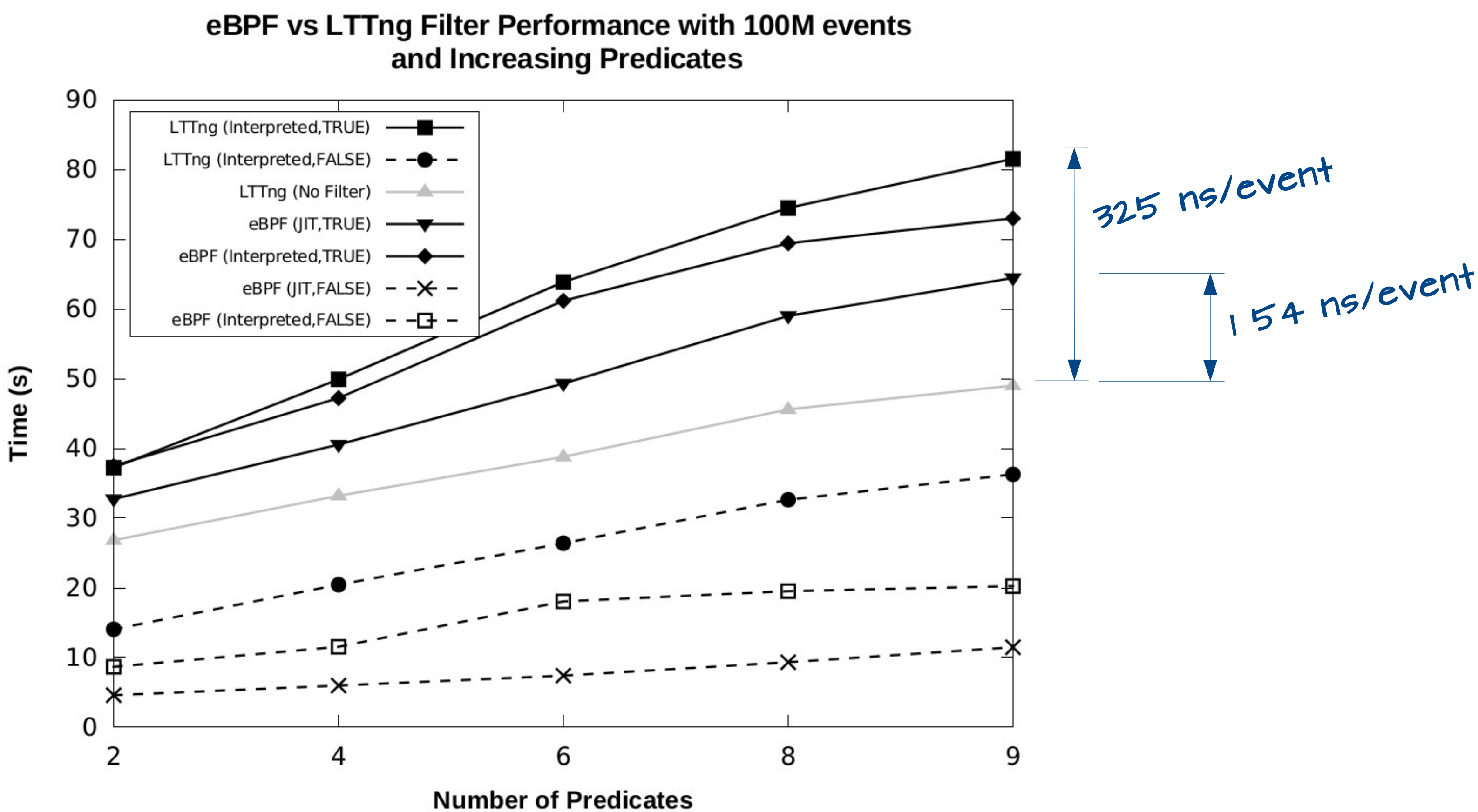




- Steady gain in **3x** range for JIT vs Interpreted with increasing events (**3.1x** to **3.3x**)

Experiments

Performance Analysis



- eBPF JIT*ed* filter is **3.1x** faster than LTTng's interpreted bytecode and eBPF's interpreted filter is **1.8x** faster than LTTng's interpreted version

Learnings

Inferences from Experiments

- JIT is so fast it makes everything slow
  - Next thing after “throw some cores” and “add some cache”
- Small specialized interpreters can be quite fast too (LTTng)
- For the tracing use-case, LTTng's filter works remarkably well
- Integrate with LTTng and real life benchmarks on specialized hardware

Beyond

KeBPF ↔ UeBPF Extensions

- Syscall latency tracking use-case.
- Latency threshold is defined statically and manually
  - In real life, it may need to be set dynamically - different machines can have different *normal levels* for syscalls
  - We may need to adaptively set thresholds per syscall based on user's criteria as well as tracking the *normal* behaviour.
  - We can use eBPF *side-effects* to provide dynamic and adaptive thresholds

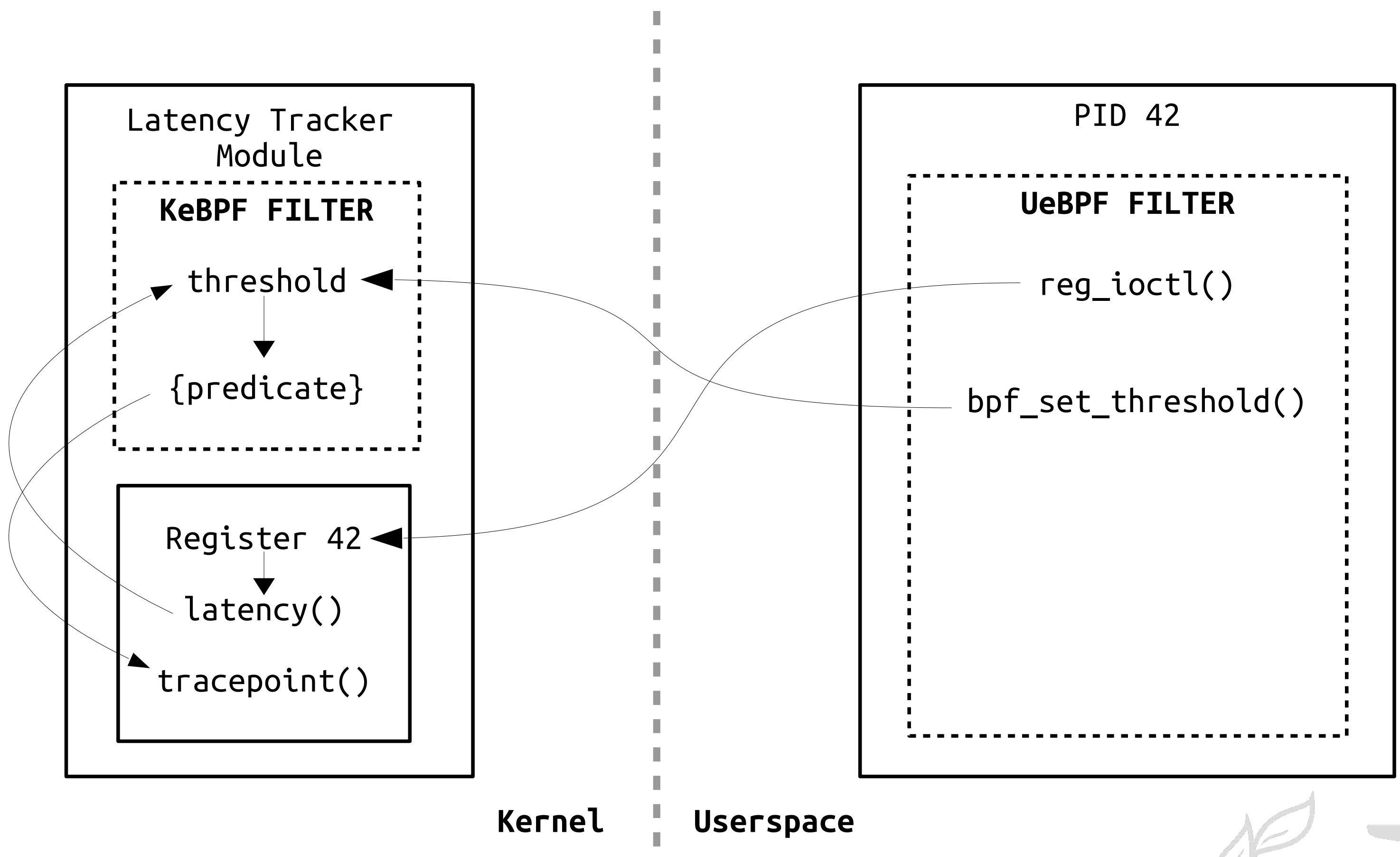
Beyond

KeBPF ↔ UeBPF Extensions

- *Side-effects?*
  - eBPF can do more complex things like perform internal actions in addition to decisions
  - Use it to make decisions in kernel BPF based on userspace BPF inputs
  - Access shared data from KeBPF/UeBPF

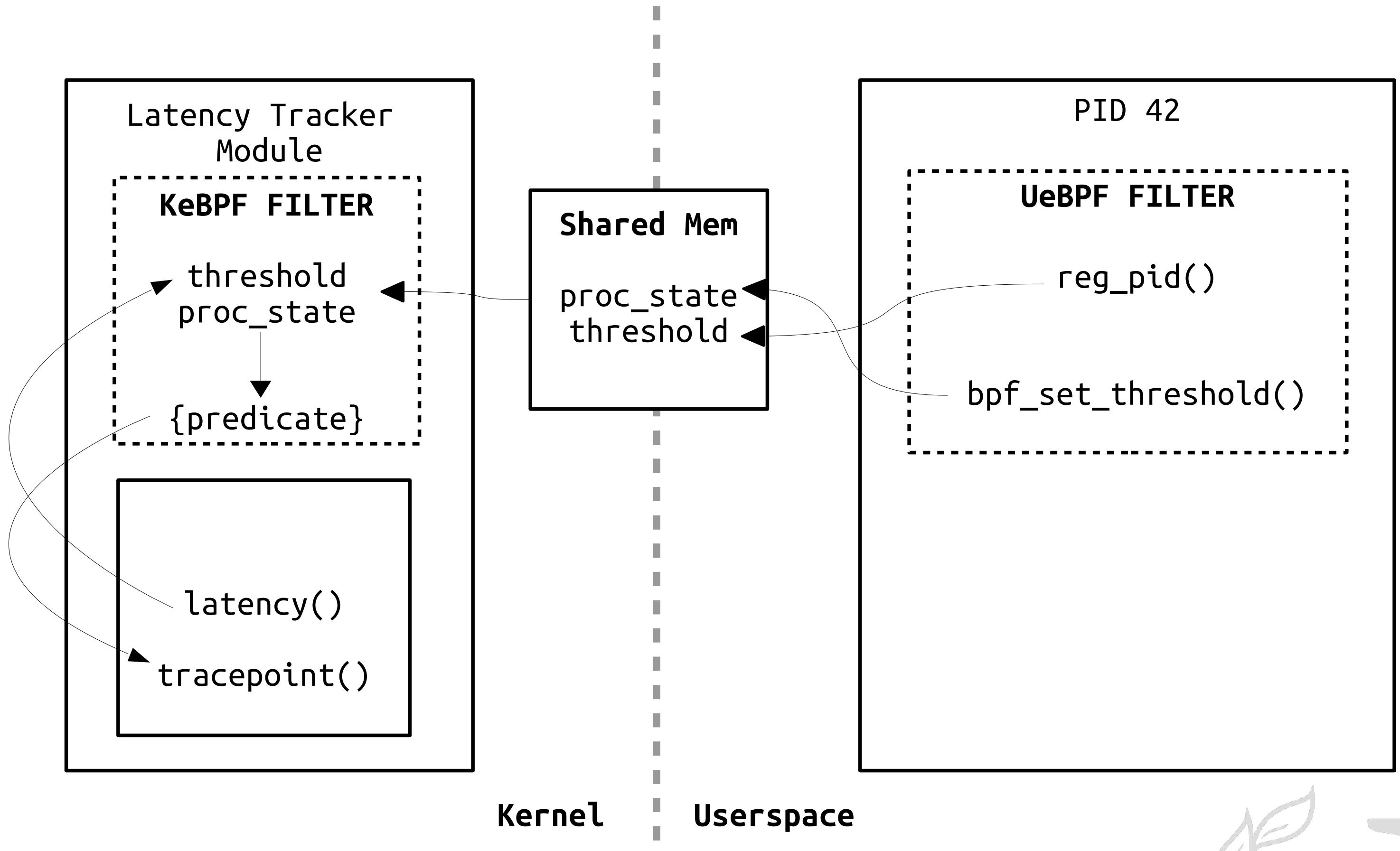
Beyond

KeBPF ↔ UeBPF Syscall Latency Tracking



Beyond

KeBPF ↔ UeBPF Syscall Latency Tracking



References

- Graphics and text on slide 24-26 have been adapted from David Goulet's talk at FOSDEM '14.
- Example for 'bcc' on slide 54 : https://github.com/iovisor/bcc
- Experimental libebpf : https://github.com/tuxology/libebpf
- BPF Internals
  - Part - I : http://ur1.ca/nheth
  - Part - II : http://ur1.ca/nheto

Acknowledgments

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Questions?

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