BPF Internals

(eBPF)

Tracing Examples

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LISA21
Jun, 2021

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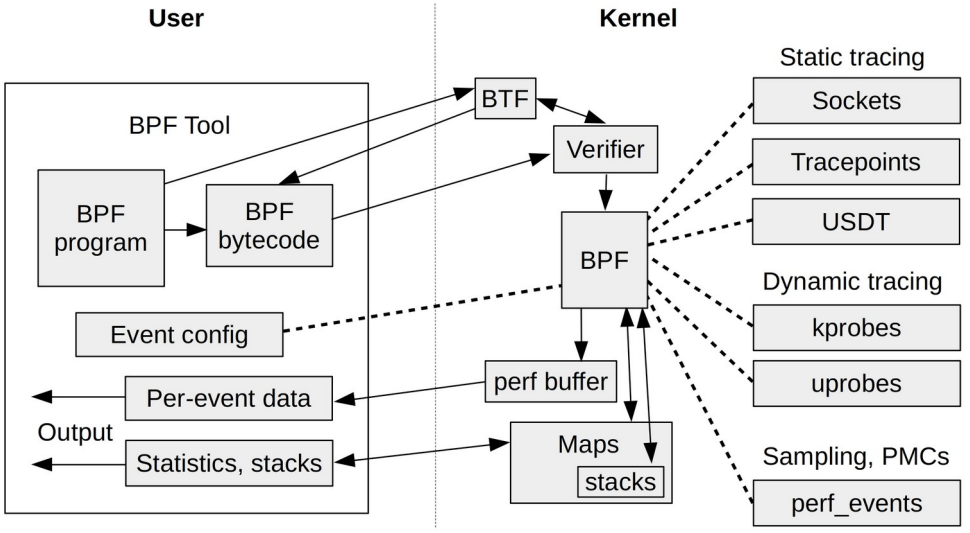
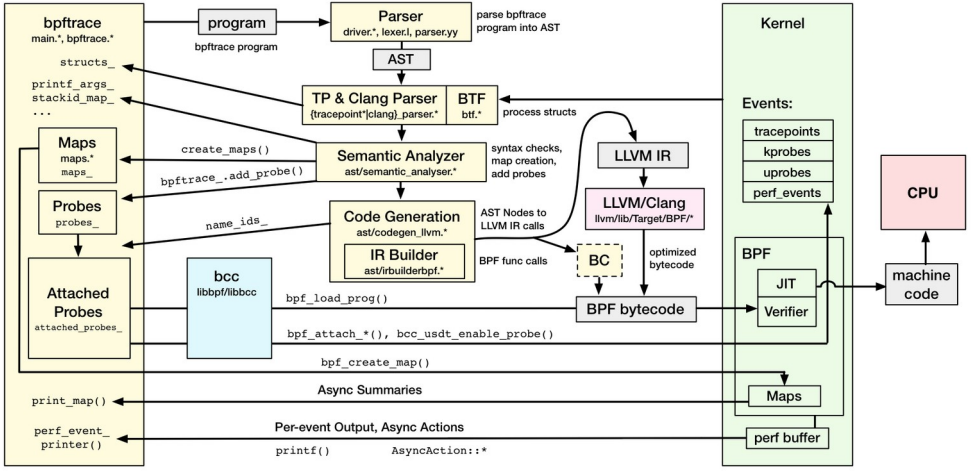
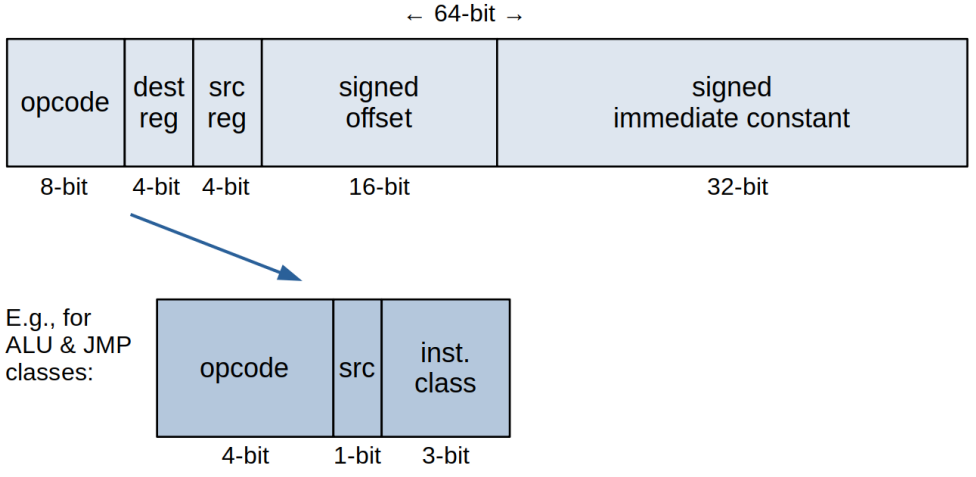
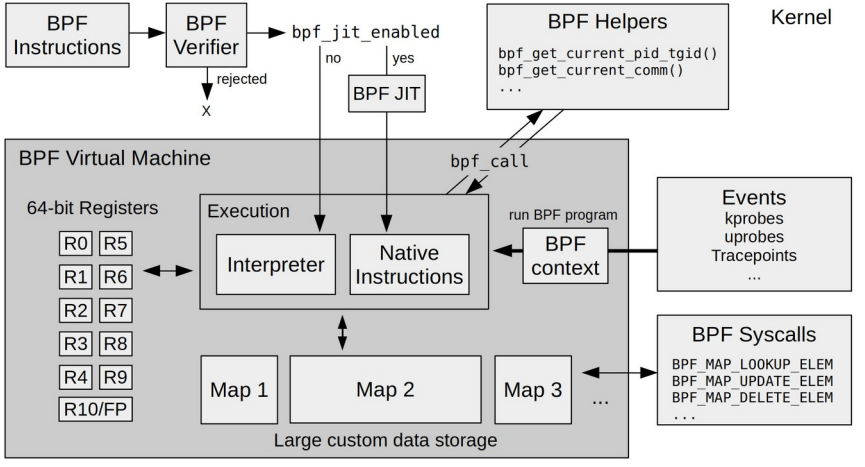




https://github.com/iovisor/bpftrace 2021, diagram by Brendan Gregg





(it's actually quite easy)

Agenda

Intro & Tracing

By Example

1. Dynamic tracing and per-event output
2. Static tracing and map summaries

For BPF internals by reference, see the References slide

Slides are online
Slides: http://www.brendangregg.com/Slides/LISA2021_BPF_Internals.pdf
Video: https://www.usenix.org/conference/lisa21/presentation/gregg-bpf

Learning objectives

- Gain a working knowledge of some BPF internals
- Evaluate ideas for BPF suitability

BPF Intro

BPF 1992: Berkeley Packet Filter

```
# tcpdump -d host 127.0.0.1 and port 80
(000) ldh      [12]
(001) jeq      #0x800           jt 2   jf 18
(002) ld       [26]
(003) jeq      #0x7f000001      jt 6   jf 4
(004) ld       [30]
(005) jeq      #0x7f000001      jt 6   jf 18
(006) ldb      [23]
(007) jeq      #0x84            jt 10  jf 8
(008) jeq      #0x6             jt 10  jf 9
(009) jeq      #0x11            jt 10  jf 18
(010) ldh      [20]
(011) jset     #0x1fff          jt 18  jf 12
(012) ldxb     4*([14]&0xf)
(013) ldh      [x + 14]
(014) jeq      #0x50            jt 17  jf 15
(015) ldh      [x + 16]
(016) jeq      #0x50            jt 17  jf 18
(017) ret      #262144
(018) ret      #0
```

A runtime for efficient packet filters

Also a narrow and arcane kernel technology that few knew existed

eBPF 2013+

Extended BPF (eBPF) modernized BPF

	Classic BPF	Extended BPF
Word size	32-bit	64-bit
Registers	2	10+1
Storage	16 slots	512 byte stack + infinite map storage
Events	packets	many event sources

Maintainers/creators: Alexei Starovoitov & Daniel Borkmann

Old BPF is now “Classic BPF,” and eBPF is usually just “BPF”

BPF 2021

BPF is now a technology name (like LLVM)

- Some still call it eBPF

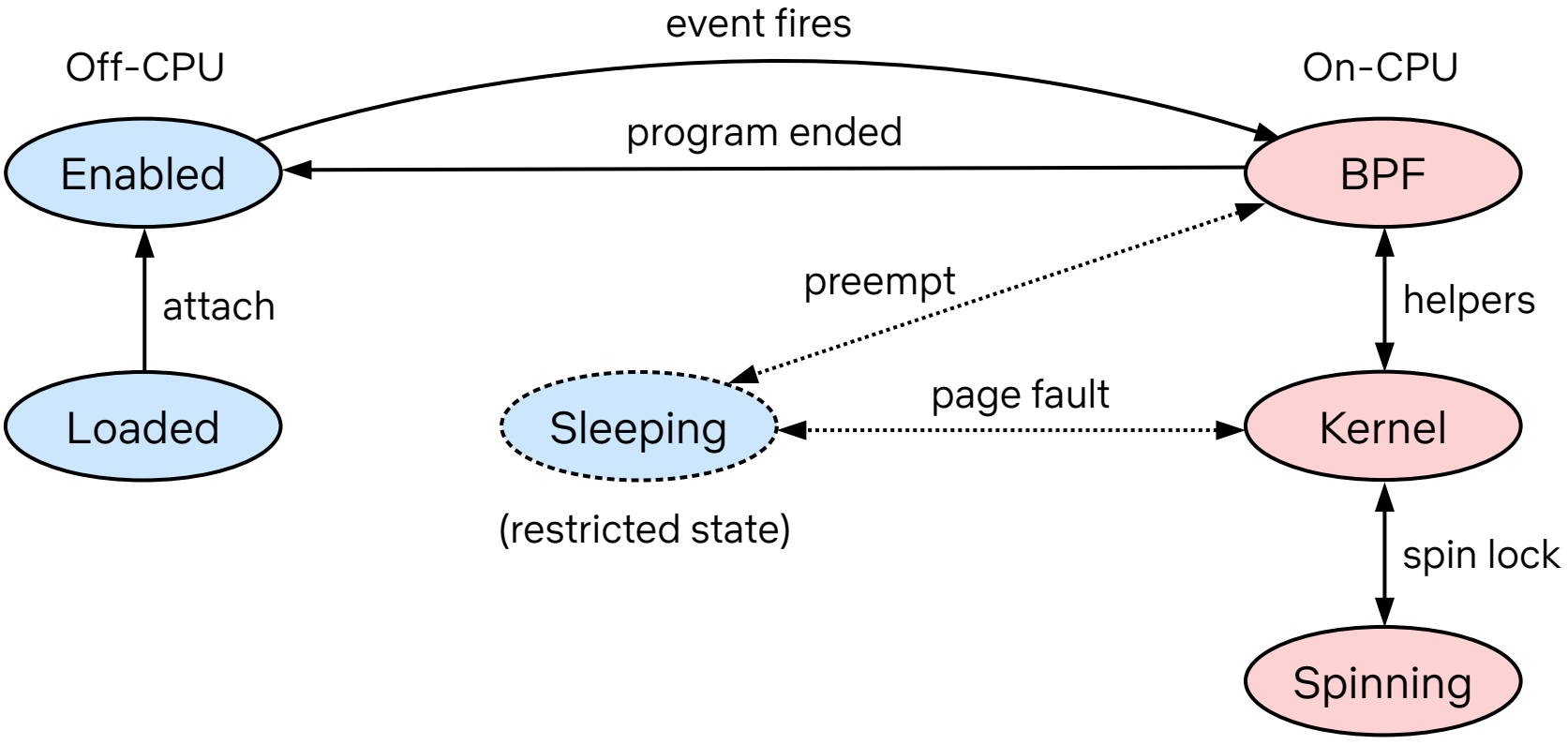
A generic in-kernel execution environment

- User-defined programs
- Limited & secure kernel access
- A new type of software

A New Type of Software

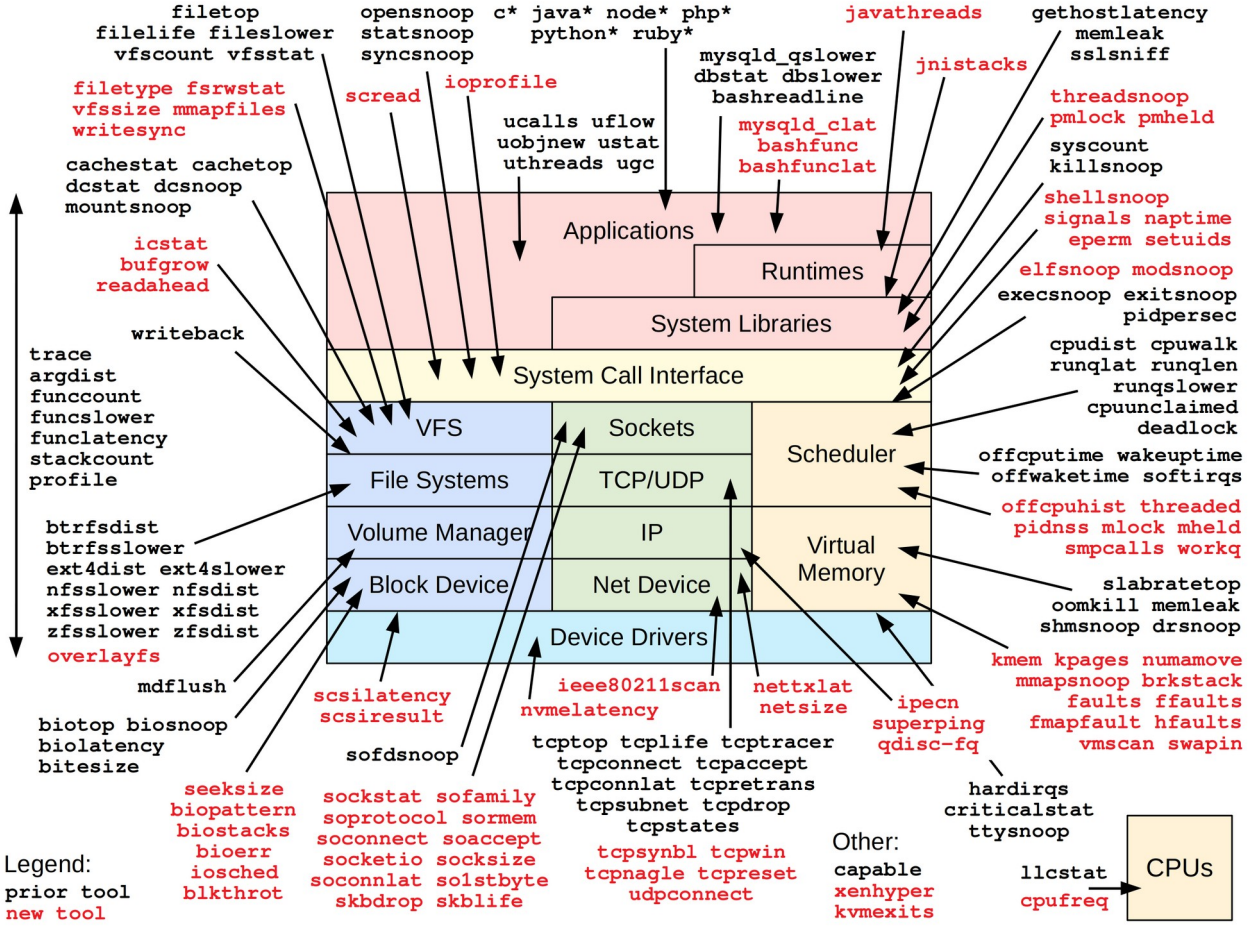
	Execution model	User defined	Compil-ation	Security	Failure mode	Resource access
User	task	yes	any	user based	abort	syscall, fault
Kernel	task	no	static	none	panic	direct
BPF	event	yes	JIT, CO-RE	verified, JIT	error message	restricted helpers

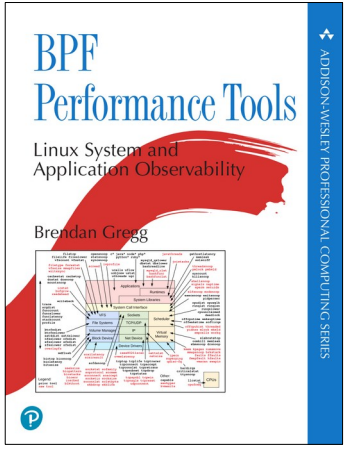
BPF program state model



BPF Tracing

BPF tracing (observability) tools





Recommended BPF tracing front-ends

I want to run some tools — Unix analogies

- **bcc, bpftrace** — /usr/bin/*

I want to hack up some *new* tools

- **bpftrace** — bash, awk

I want to spend weeks developing a BPF product

- **bcc libbpf C, bcc Python (maybe), gobpf, libbbpf-rs** — C, C++

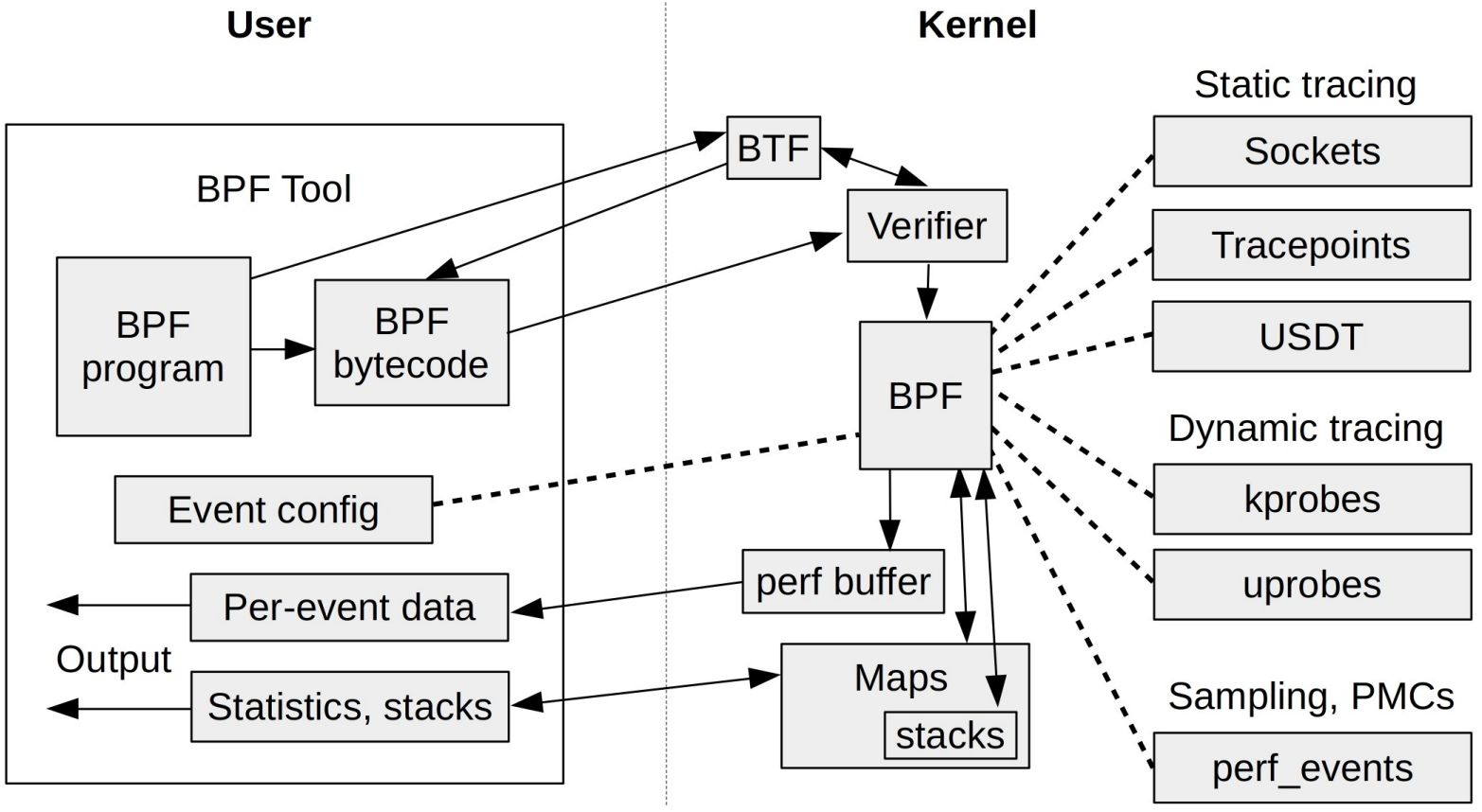
New, lightweight, CO-RE & BTF based

Requires LLVM; becoming obsolete / special-use only

BPF Internals

(developing BPF was hard;
understanding it is easy)

BPF tracing/observability high-level



From: BPF Performance Tools, Figure 2-1

Terminology

AST: Abstract Syntax Tree

LLVM: A compiler

IR: Intermediate Representation

JIT: Just-in-time compilation

kprobes: Kernel dynamic instrumentation

uprobes: User-level dynamic instrumentation

tracepoints: Kernel static instrumentation

1. Dynamic tracing and per-event output

1. Dynamic tracing and per-event output

```
bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}'
```

Example output

```
# bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}'
Attaching 1 probe...
PID 10287 sleeping...
PID 10297 sleeping...
PID 10287 sleeping…
PID 10297 sleeping...
PID 10287 sleeping...
PID 2218 sleeping...
PID 10297 sleeping...
[...]
```

Objective

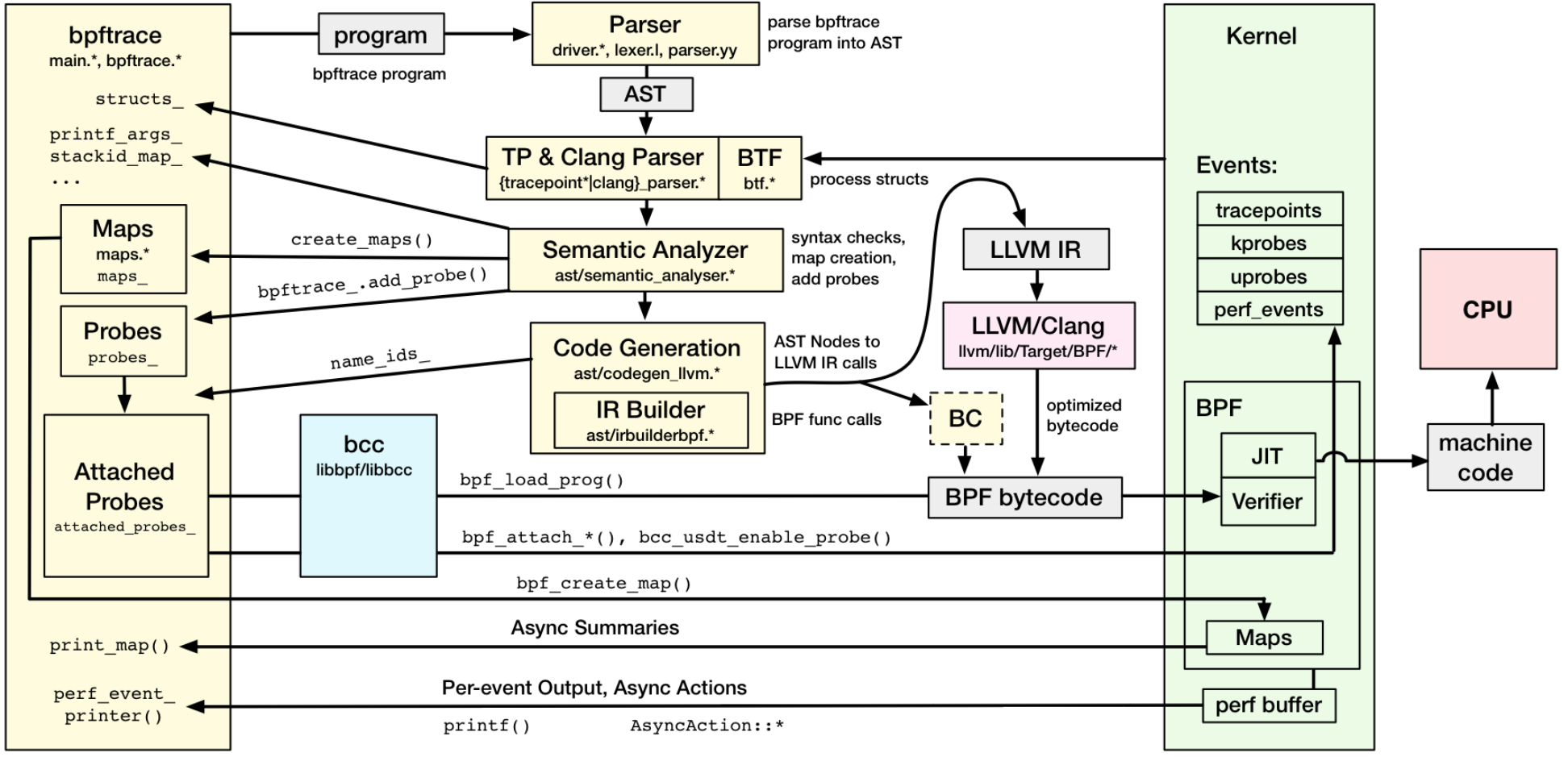
We have this:

```
bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}'
```

We want:
- BPF bytecode
- Kernel events mapped to the bytecode
- User space printing events

This is learning internals by example, including bpftrace internals.
For a complete internals see the References slide at end.

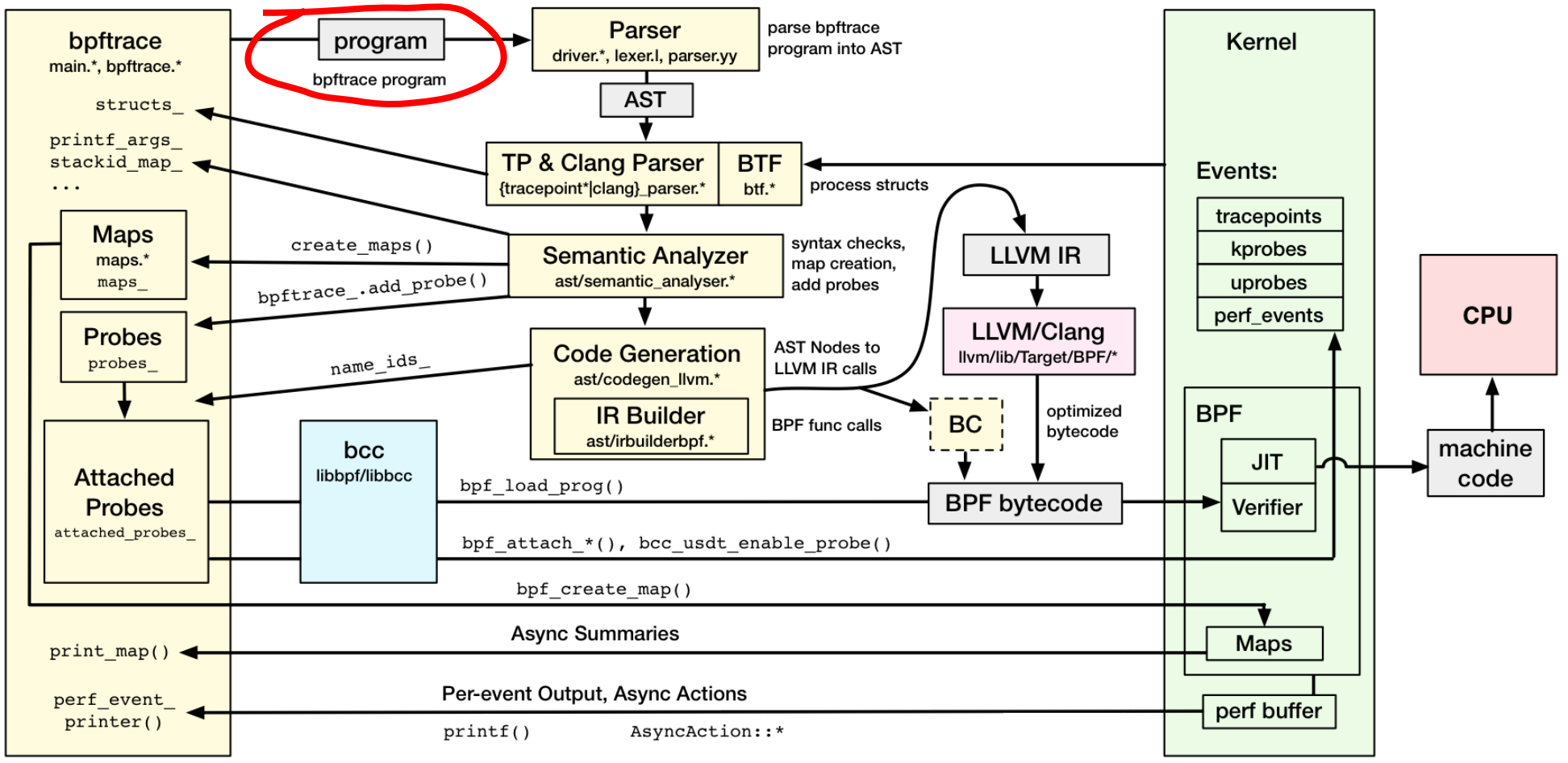
bpftrace mid-level internals



https://github.com/iovisor/bpftrace 2021, diagram by Brendan Gregg

Program transformations

bpftrace mid-level internals 1/13

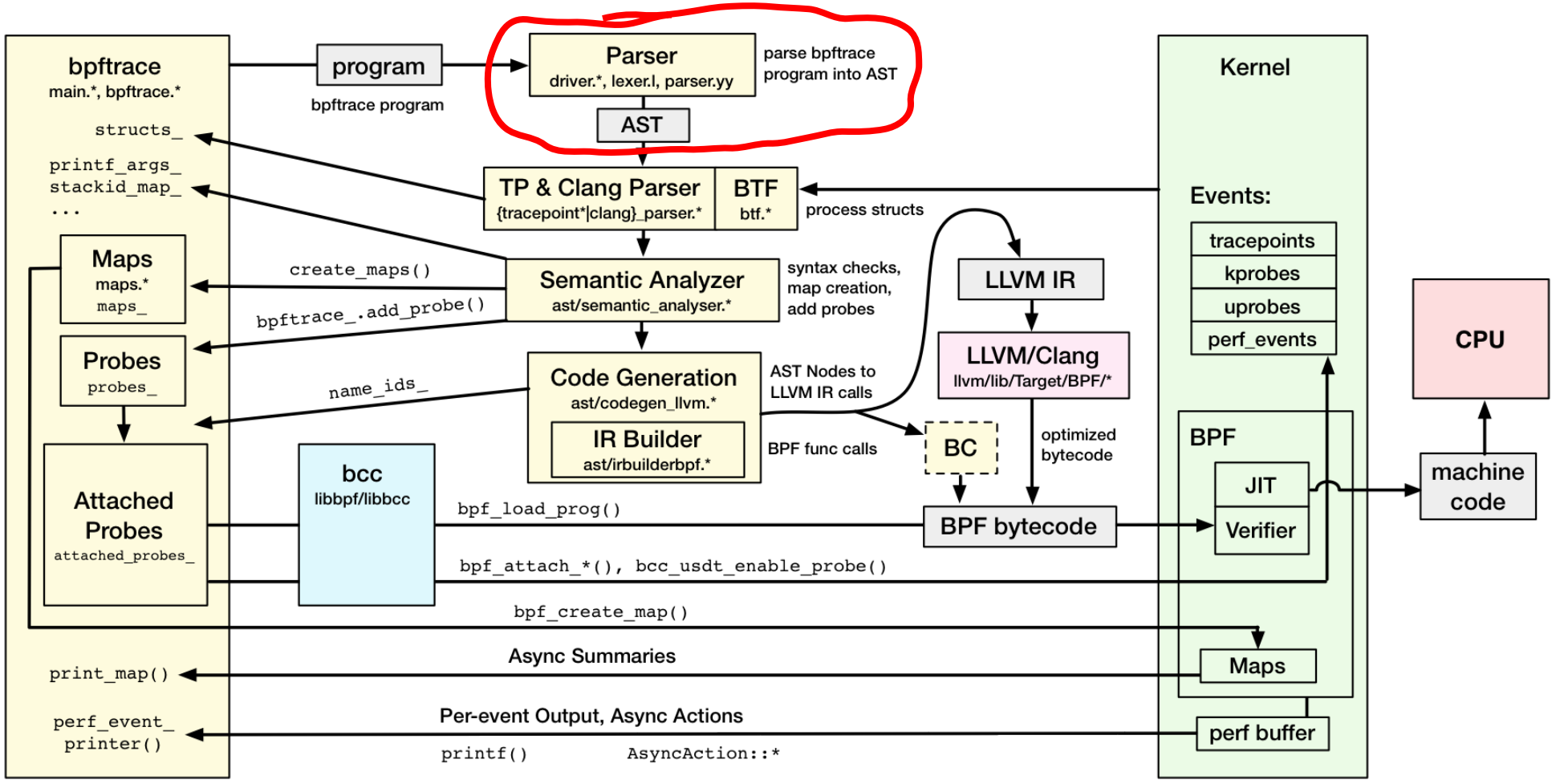


https://github.com/iovisor/bpftrace 2021, diagram by Brendan Gregg

bpftrace program

```
kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}
```

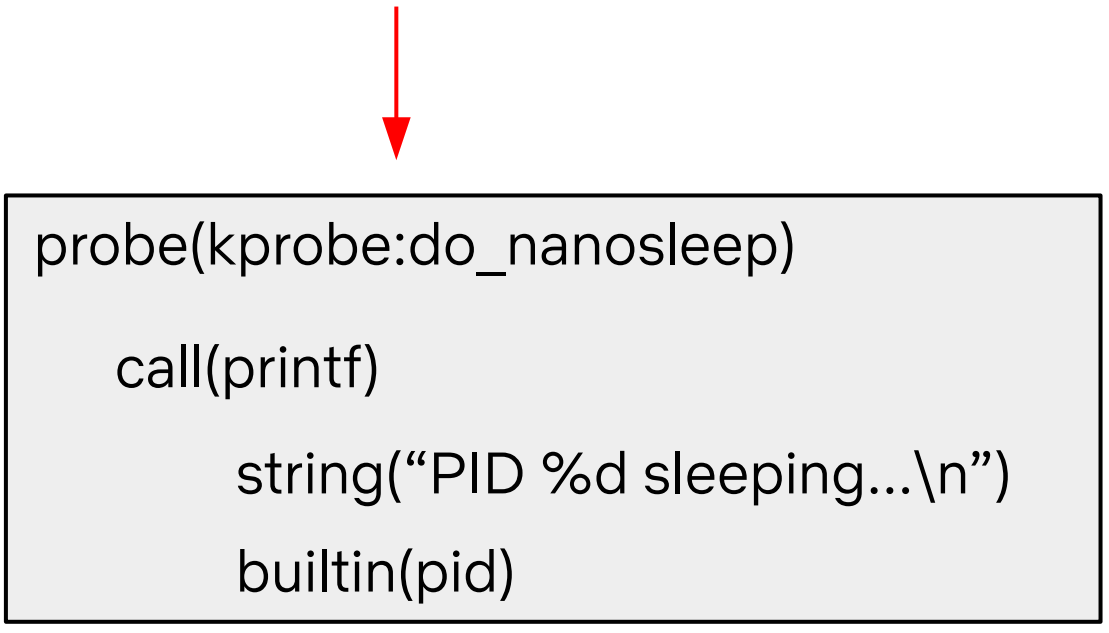
bpftrace mid-level internals 2/13



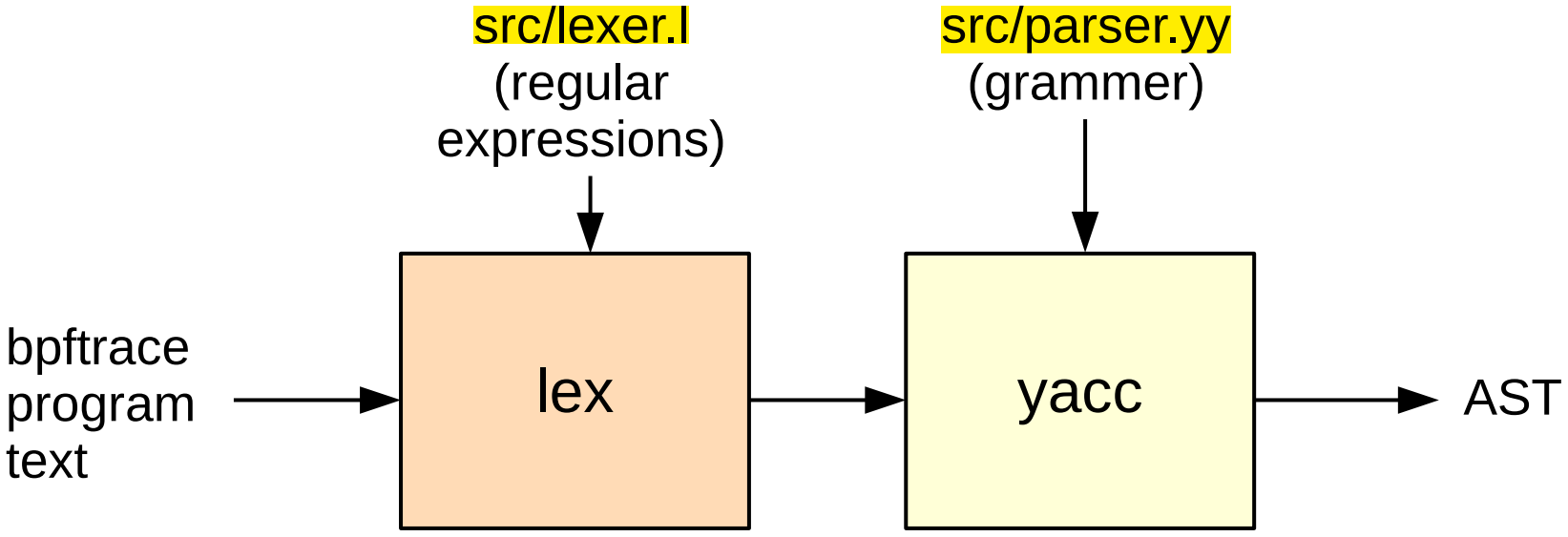
https://github.com/iovisor/bpftrace 2021, diagram by Brendan Gregg

Converting to AST

```
kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}
```



Parsing bpftrace



(very easy)

Lexer

如何翻译pid?

pid

Regular expressions

bpftrace src/lexer.l

```
ident    [_a-zA-Z][_a-zA-Z0-9]*
map      @{ident}|@
var      ${ident}
int      [0-9]+|0[xX][0-9a-fA-F]+
cint     :{int}:
hex      (x|X)[0-9a-fA-F]{1,2}
[...]
builtin arg[0-9]|args|cgroup|comm|cpid|cpu|ctx|curtask|elapsed|func|
gid|nsecs|pid|probe|rand|retval|sarg[0-9]|tid|uid|username
call     avg|cat|cgroupid|clear|count|delete|exit|hist|join|kaddr|ksym|
lhist|max|min|ntop|override_return|print|printf|reg|signal|stats|str|
strncmp|sum|sym|system|time|uaddr|usym|zero
```

pid gets matched and identified as a builtin

Yacc

builtin(pid)

Grammar rules

bpftrace src/parser.yy

```
%token <std::string> BUILTIN "builtin"
%token <std::string> CALL "call"
[...]
expr : int                                  { $$ = $1; }
     | STRING                               { $$ = new ast::String($1, @$); }
     | BUILTIN                              { $$ = new ast::Builtin($1, @$); }
     | CALL_BUILTIN                         { $$ = new ast::Builtin($1, @$); }
     | IDENT                                { $$ = new ast::Identifier($1, @$); }
     | STACK_MODE                           { $$ = new ast::StackMode($1, @$); }
     | ternary                              { $$ = $1; }
     | param                                { $$ = $1; }
     | map_or_var                           { $$ = $1; }
     | call                                 { $$ = $1; }
[...]
call : CALL "(" ")"                   { $$ = new ast::Call($1, @$); }
     | CALL "(" vargs ")"             { $$ = new ast::Call($1, $3, @$); }
```

这样就识别到pid并给pid创建了一个ast builtin node

Lexer (2)

如何翻译printf?

```
printf("PID %d sleeping...\n", pid);
```

bpftrace src/lexer.l

```
ident   [_a-zA-Z][_a-zA-Z0-9]*
map     @{ident}|@
var     ${ident}
int     [0-9]+|0[xX][0-9a-fA-F]+
cint    :{int}:
hex     (x|X)[0-9a-fA-F]{1,2}
[...]
builtin arg[0-9]|args|cgroup|comm|cpid|cpu|ctx|curtask|elapsed|func|
gid|nsecs|pid|probe|rand|retval|sarg[0-9]|tid|uid|username
call    avg|cat|cgroupid|clear|count|delete|exit|hist|join|kaddr|ksym|
lhist|max|min|ntop|override_return|print|printf|reg|signal|stats|str|
strncmp|sum|sym|system|time|uaddr|usym|zero
```

Yacc (2)

`call(printf(...));`

bpftrace src/parser.yy

```
%token <std::string> BUILTIN "builtin"
%token <std::string> CALL "call"
[...]
expr : int                                  { $$ = $1; }
     | STRING                               { $$ = new ast::String($1, @$); }
     | BUILTIN                              { $$ = new ast::Builtin($1, @$); }
     | CALL_BUILTIN                         { $$ = new ast::Builtin($1, @$); }
     | IDENT                                { $$ = new ast::Identifier($1, @$); }
     | STACK_MODE                           { $$ = new ast::StackMode($1, @$); }
     | ternary                              { $$ = $1; }
     | param                                { $$ = $1; }
     | map_or_var                           { $$ = $1; }
     | call                                 { $$ = $1; }
[...]
call : CALL "(" ")"                    { $$ = new ast::Call($1, @$); }
     | CALL "(" vargs ")"              { $$ = new ast::Call($1, $3, @$); }
```

识别为一个带有多个参数的函数调用

Lexer (3)

"PID %d sleeping...\n"

bpftrace src/lexer.l

```
\"                    { yy_push_state(STR, yyscanner); buffer.clear(); }
<STR>{
  \"                  { yy_pop_state(yyscanner); return Parser::make_STRING(buffer, loc); }
  [^\\\n\"]+          buffer += yytext;
  \\n                 buffer += '\n';
  \\t                 buffer += '\t';
  \\r                 buffer += '\r';
  \\\"                buffer += '\"';
  \\\\                buffer += '\\';
  \\{oct}             {
                          long value = strtol(yytext+1, NULL, 8);
                          if (value > UCHAR_MAX)
                            driver.error(loc, std::string("octal escape sequence out of range '") +
                                                yytext + "'");
                          buffer += value;
                      }
  \\{hex}             buffer += strtol(yytext+2, NULL, 16);
  \n                  driver.error(loc, "unterminated string"); yy_pop_state(yyscanner);
loc.lines(1); loc.step();
  <<EOF>>             driver.error(loc, "unterminated string"); yy_pop_state(yyscanner);
  \\.                 { driver.error(loc, std::string("invalid escape character '") +
                                          yytext + "'"); }
  .                   driver.error(loc, "invalid character"); yy_pop_state(yyscanner);
}
```

Yacc (3)

`string("PID %d sleeping...\n")`

bpftrace src/parser.yy

```
%token <std::string> STRING "string"
[...]
expr : int                                  { $$ = $1; }
     | STRING                               { $$ = new ast::String($1, @$); }
     | BUILTIN                              { $$ = new ast::Builtin($1, @$); }
     | CALL_BUILTIN                         { $$ = new ast::Builtin($1, @$); }
     | IDENT                                { $$ = new ast::Identifier($1, @$); }
     | STACK_MODE                           { $$ = new ast::StackMode($1, @$); }
     | ternary                              { $$ = $1; }
     | param                                { $$ = $1; }
     | map_or_var                           { $$ = $1; }
     | call                                 { $$ = $1; }
[...]
```

Lexer & Yacc (4)

kprobe:do_nanosleep

bpftrace src/lexer.l

```
ident   [_a-zA-Z][_a-zA-Z0-9]*
map     @{ident}|@
[...]
```

bpftrace src/parser.yy

```
attach_point : ident                              { $$ = new ast::AttachPoint($1, @$); }
             | ident ":" wildcard                 { $$ = new ast::AttachPoint($1, $3, @$); }
             | ident ":" wildcard PLUS INT        { $$ = new ast::AttachPoint($1, $3, $5, @$); }
             | ident PATH STRING                  { $$ = new ast::AttachPoint($1, $2.substr(1, $2.si...
[...]

wildcard : wildcard ident    { $$ = $1 + $2; }
         | wildcard MUL      { $$ = $1 + "*"; }
         | wildcard LBRACKET { $$ = $1 + "["; }
         | wildcard RBRACKET { $$ = $1 + "]"; }
         | wildcard DOT      { $$ = $1 + "."; }
         |                   { $$ = ""; }
         ;
```

Lexer & Yacc (4)

kprobe:do_nanosleep

1. 2.

bpftrace src/lexer.l

```
ident   [_a-zA-Z][_a-zA-Z0-9]*
map     @{ident}|@
[...]
```

4. 3.

bpftrace src/parser.yy

```
attach_point : ident                      { $$ = new ast::AttachPoint($1, @$); }
             | ident ":" wildcard         { $$ = new ast::AttachPoint($1, $3, @$); }
             | ident ":" wildcard PLUS INT { $$ = new ast::AttachPoint($1, $3, $5, @$); }
             | ident PATH STRING          { $$ = new ast::AttachPoint($1, $2.substr(1, $2.si...
[...]

wildcard : wildcard ident    { $$ = $1 + $2; }
         | wildcard MUL      { $$ = $1 + "*"; }
         | wildcard LBRACKET { $$ = $1 + "["; }
         | wildcard RBRACKET { $$ = $1 + "]"; }
         | wildcard DOT      { $$ = $1 + "."; }
         |                   { $$ = ""; }
         ;
```

6.

5.

Yacc (5)

`{ statements; ... }`

Plus more grammar for program structure...

bpftrace src/parser.yy

```
probe : attach_points pred block { $$ = new ast::Probe($1, $2, $3); }

attach_points : attach_points "," attach_point { $$ = $1; $1->push_back($3); }
              | attach_point                   { $$ = new ast::AttachPointList; $$->push_back($1); }

[...]

block : "{" stmts "}"     { $$ = $2; }
      ;

semicolon_ended_stmt: stmt ";"  { $$ = $1; }
                    ;

stmts : semicolon_ended_stmt stmts { $$ = $2; $2->insert($2->begin(), $1); }
      | block_stmt stmts           { $$ = $2; $2->insert($2->begin(), $1); }
      | stmt                       { $$ = new ast::StatementList; $$->push_back($1); }
      |                            { $$ = new ast::StatementList; }
      ;
```

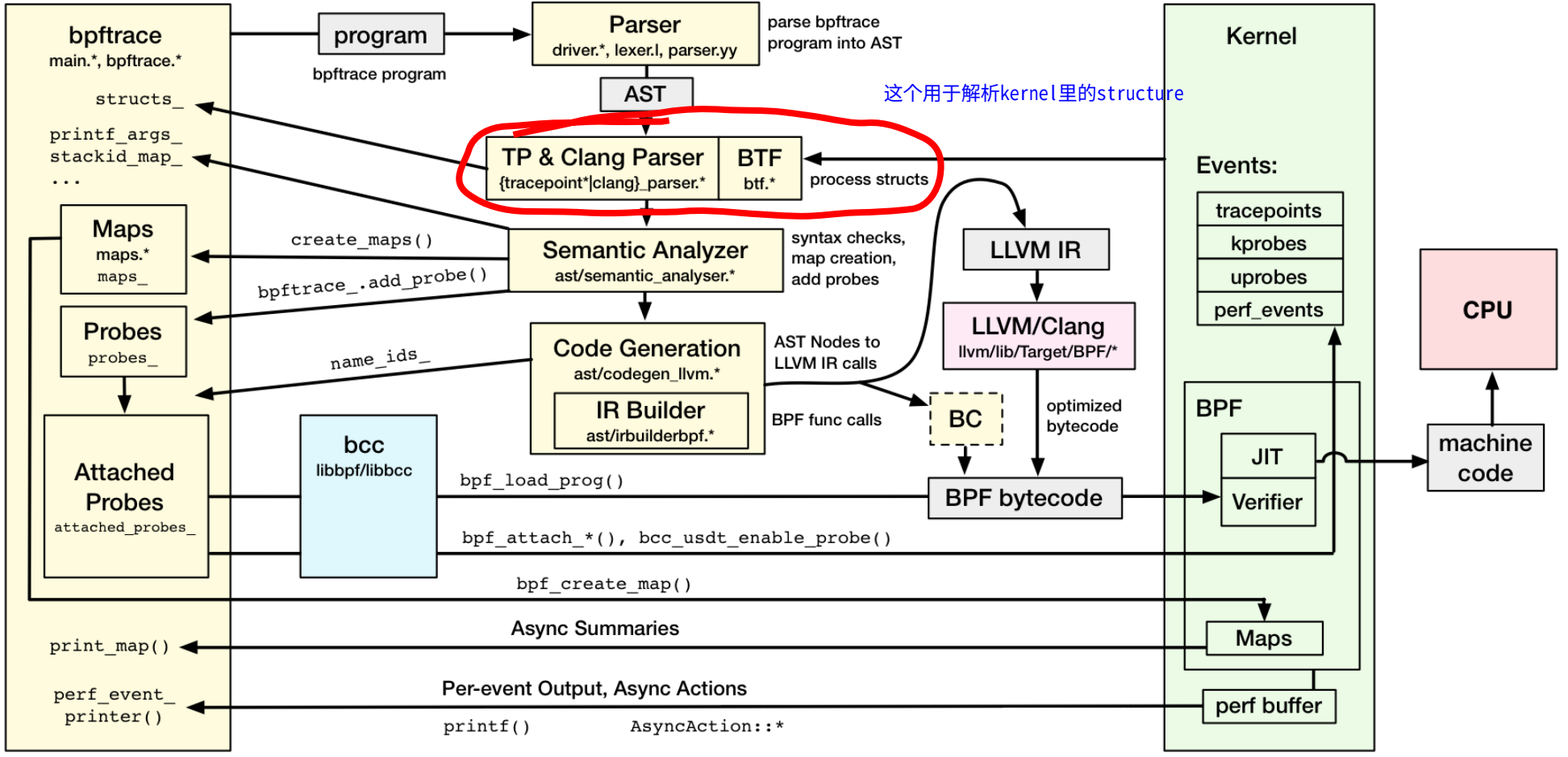
Now you have AST nodes!

```
# bpftrace -d -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}'

AST
--------------------
Program
 kprobe:do_nanosleep
  call: printf
   string: PID %d sleeping...\n
   builtin: pid

[...]
```

bpftrace mid-level internals 3/13

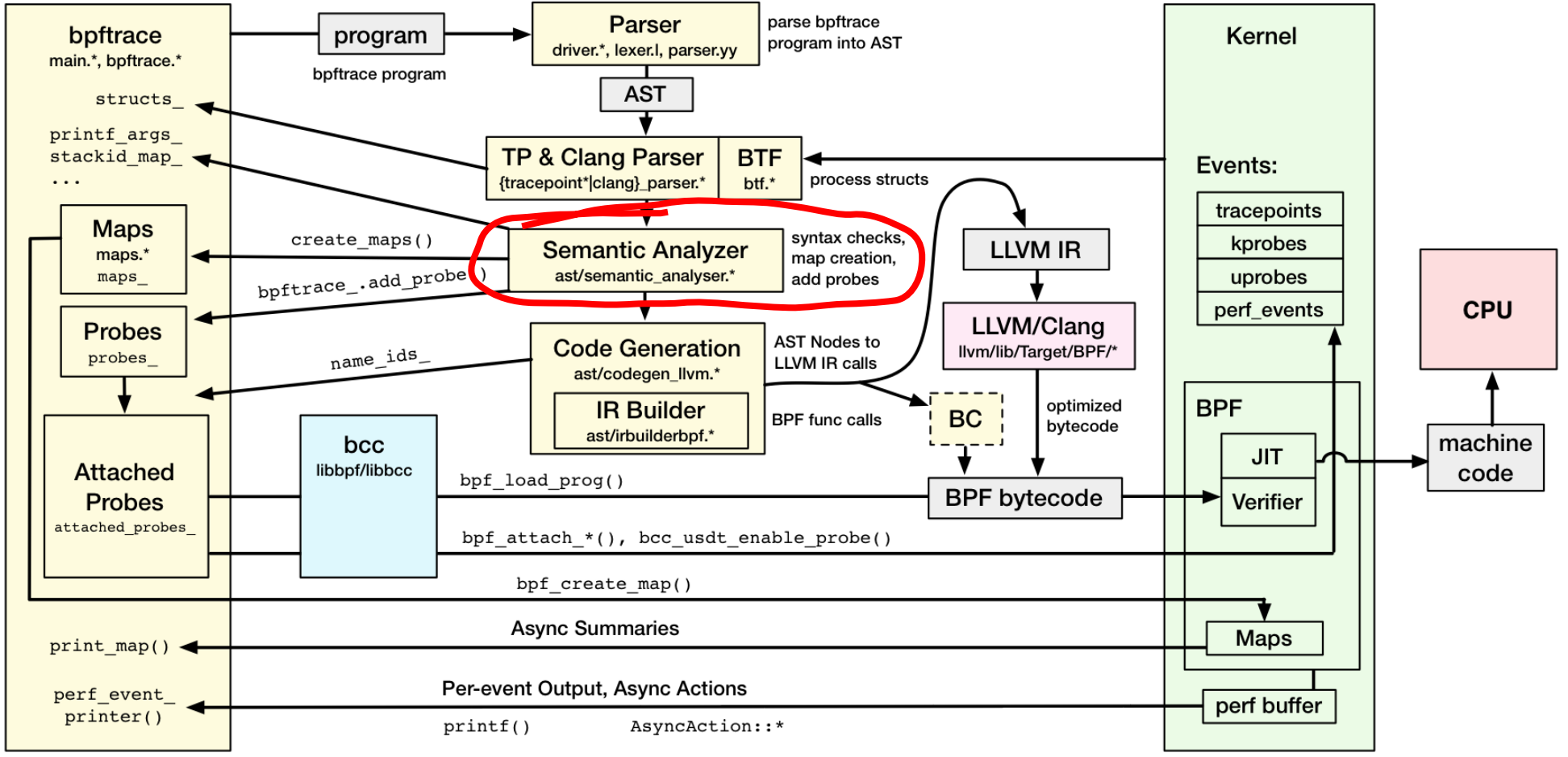


Tracepoint & Clang struct parsers

```
kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}
```

Not needed for this example
(no struct member dereferencing)

bpftrace mid-level internals 4/13



https://github.com/iovisor/bpftrace 2021, diagram by Brendan Gregg

Semantic analyzer

Catches many program errors; E.g.:

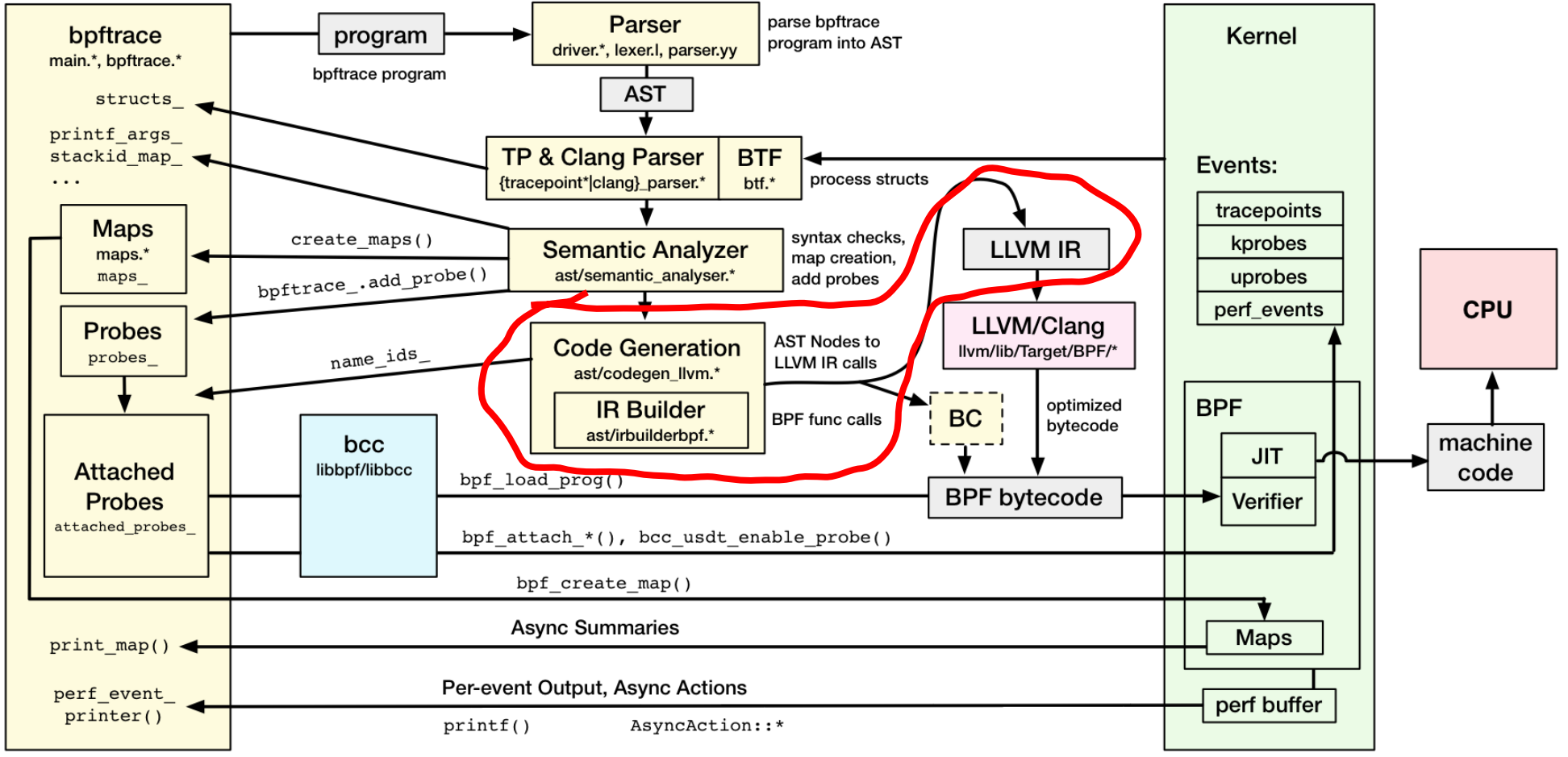
```
# bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pidd); }'
stdin:2:36-38: ERROR: Unknown identifier: 'pidd'
    printf("PID %d sleeping...\n", pidd);
```

bpftrace src/ast/semantic_analyser.cpp

```
void SemanticAnalyser::visit(Identifier &identifier)
{
  if (bpftrace_.enums_.count(identifier.ident) != 0) {
    identifier.type = SizedType(Type::integer, 8);
  }
  else {
    identifier.type = SizedType(Type::none, 0);
    error("Unknown identifier: '" + identifier.ident + "'", identifier.loc);
  }
}
```

>2000 lines of code

bpftrace mid-level internals 5/13



AST → LLVM IR

bpftrace src/ast/codegen_llvm.cpp

```
void CodegenLLVM::visit(Builtin &builtin)
{
[…]
  else if (builtin.ident == "pid" || builtin.ident == "tid")
  {
    Value *pidtgid = b_.CreateGetPidTgid();
    if (builtin.ident == "pid")
    {
      expr_ = b_.CreateLShr(pidtgid, 32);
[…]
```

BPF logical shift right instruction

AST → LLVM IR (2)

bpftrace src/ast/irbuilderbpf.cpp

```
CallInst *IRBuilderBPF::CreateGetPidTgid()
{
  // u64 bpf_get_current_pid_tgid(void)
  // Return: current->tgid << 32 | current->pid
  FunctionType *getpidtgid_func_type = FunctionType::get(getInt64Ty(),
false);
  PointerType *getpidtgid_func_ptr_type =
PointerType::get(getpidtgid_func_type, 0);
  Constant *getpidtgid_func = ConstantExpr::getCast(
      Instruction::IntToPtr,
      getInt64(libbpf::BPF_FUNC_get_current_pid_tgid),
      getpidtgid_func_ptr_type);
  return CreateCall(getpidtgid_func, {}, "get_pid_tgid");
}
```

BPF helper call number

BPF helper calls

Linux include/uapi/linux/bpf.h

```
#define __BPF_FUNC_MAPPER(FN)           \
        FN(unspec),                     \
        FN(map_lookup_elem),            \
        FN(map_update_elem),            \
        FN(map_delete_elem),            \
        FN(probe_read),                 \
        FN(ktime_get_ns),               \
        FN(trace_printk),               \
        FN(get_prandom_u32),            \
        FN(get_smp_processor_id),       \
        FN(skb_store_bytes),            \
        FN(l3_csum_replace),            \
        FN(l4_csum_replace),            \
        FN(tail_call),                  \
        FN(clone_redirect),             \
        FN(get_current_pid_tgid),       \
        FN(get_current_uid_gid),        \
[...]
```

Now you have LLVM IR!

```
# bpftrace -d -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid); }'
[…]
define i64 @"kprobe:do_nanosleep"(i8*) local_unnamed_addr section
"s_kprobe:do_nanosleep_1" {
entry:
  %printf_args = alloca %printf_t, align 8
  %1 = bitcast %printf_t* %printf_args to i8*
  call void @llvm.lifetime.start.p0i8(i64 -1, i8* nonnull %1)
  %2 = getelementptr inbounds %printf_t, %printf_t* %printf_args, i64 0, i32 0
  store i64 0, i64* %2, align 8
  %get_pid_tgid = tail call i64 inttoptr (i64 14 to i64 ()*)()
  %3 = lshr i64 %get_pid_tgid, 32
  %4 = getelementptr inbounds %printf_t, %printf_t* %printf_args, i64 0, i32 1
  store i64 %3, i64* %4, align 8
  %pseudo = tail call i64 @llvm.bpf.pseudo(i64 1, i64 1)
  %get_cpu_id = tail call i64 inttoptr (i64 8 to i64 ()*)()
  %perf_event_output = call i64 inttoptr (i64 25 to i64 (i8*, i64, i64, %printf_t*,
i64)*)(i8* %0, i64 %pseudo, i64 %get_cpu_id, %printf_t* nonnull %printf_args, i64 16)
  call void @llvm.lifetime.end.p0i8(i64 -1, i8* nonnull %1)
  ret i64 0
}
```

Now you have LLVM IR! (2)

```
# bpftrace -d -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid); }'
[…]
define i64 @"kprobe:do_nanosleep"(i8*) local_unnamed_addr section
"s_kprobe:do_nanosleep_1" {
entry:
  %printf_args = alloca %printf_t, align 8
  %1 = bitcast %printf_t* %printf_args to i8*
  call void @llvm.lifetime.start.p0i8(i64 -1, i8* nonnull %1)
  %2 = getelementptr inbounds %printf_t, %printf_t* %printf_args, i64 0, i32 0
  store i64 0, i64* %2, align 8
  %get_pid_tgid = tail call i64 inttoptr (i64 14 to i64 ()*)()
  %3 = lshr i64 %get_pid_tgid, 32
  %4 = getelementptr inbounds %printf_t, %printf_t* %printf_args, i64 0, i32 1
  store i64 %3, i64* %4, align 8
  %pseudo = tail call i64 @llvm.bpf.pseudo(i64 1, i64 1)
  %get_cpu_id = tail call i64 inttoptr (i64 8 to i64 ()*)()
  %perf_event_output = call i64 inttoptr (i64 25 to i64 (i8*, i64, i64, %printf_t*,
i64)*)(i8* %0, i64 %pseudo, i64 %get_cpu_id, %printf_t* nonnull %printf_args, i64 16)
  call void @llvm.lifetime.end.p0i8(i64 -1, i8* nonnull %1)
  ret i64 0
}
```

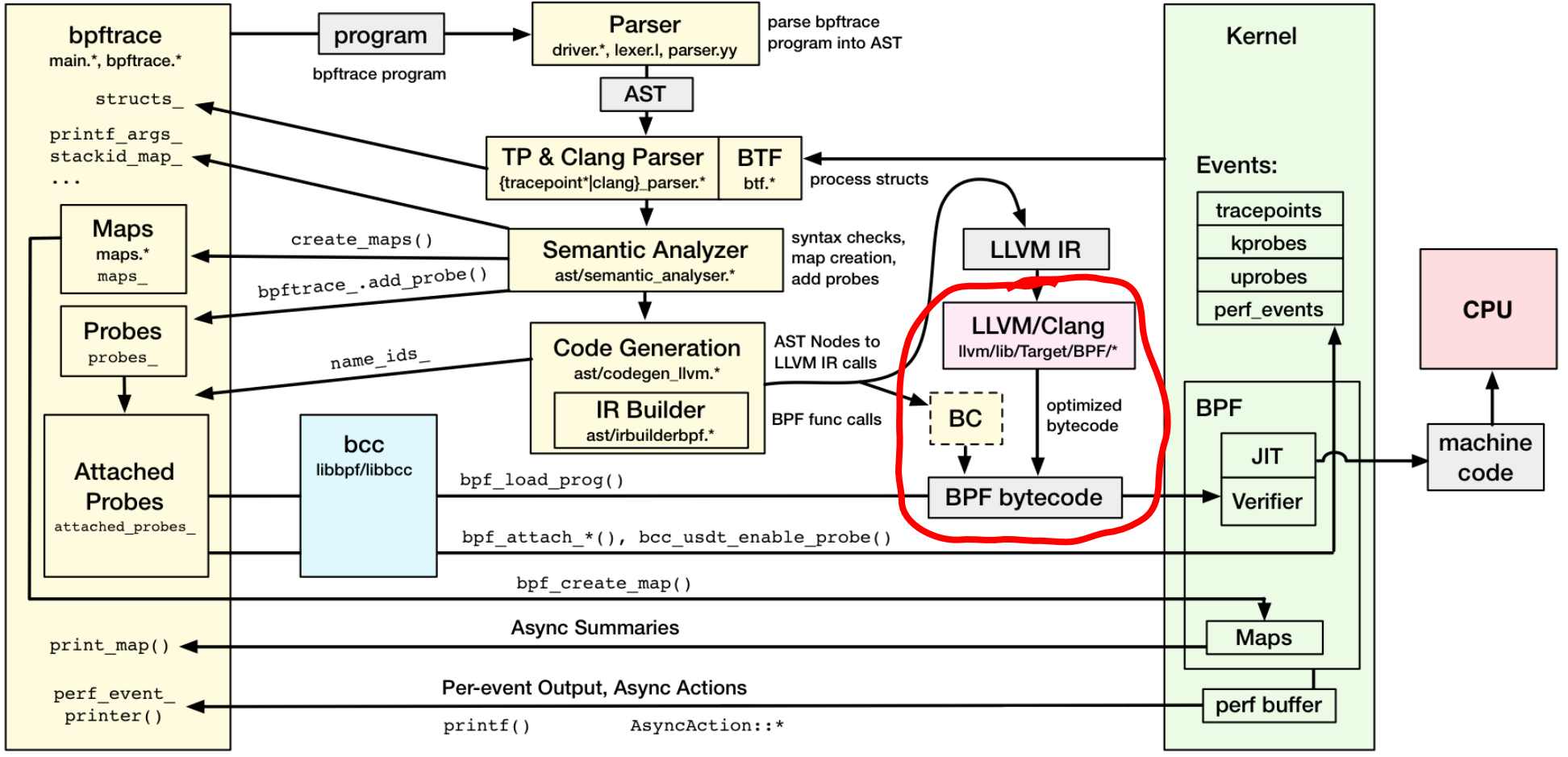
Now you have LLVM IR! (3)

```
# bpftrace -d -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid); }'
[…]
define i64 @"kprobe:do_nanosleep"(i8*) local_unnamed_addr section
"s_kprobe:do_nanosleep_1" {
entry:
  %printf_args = alloca %printf_t, align 8
  %1 = bitcast %printf_t* %printf_args to i8*
  call void @llvm.lifetime.start.p0i8(i64 -1, i8* nonnull %1)
  %2 = getelementptr inbounds %printf_t, %printf_t* %printf_args, i64 0, i32 0
  store i64 0, i64* %2, align 8
[...]
```

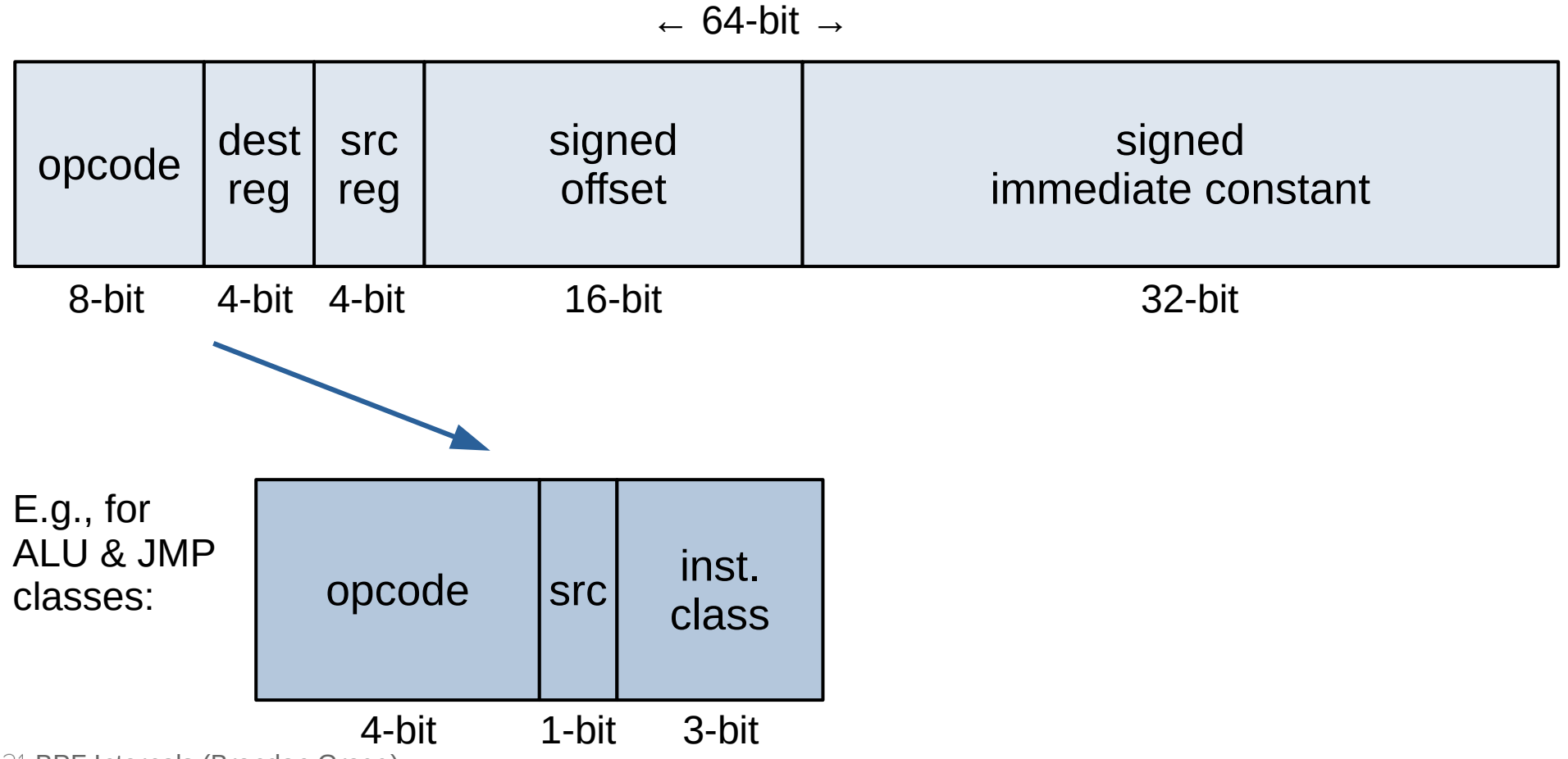
This is all generated from LLVM IR calls in bpftrace src/ast/*

Lots of CreateAllocaBPF(), CreateGEP(), etc. (this gets verbose)

bpftrace mid-level internals 6/13

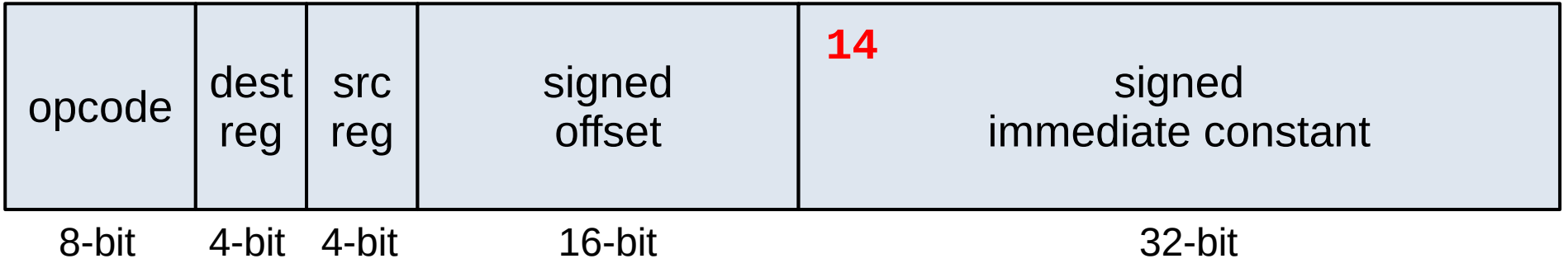


Extended BPF instruction (bytecode) format

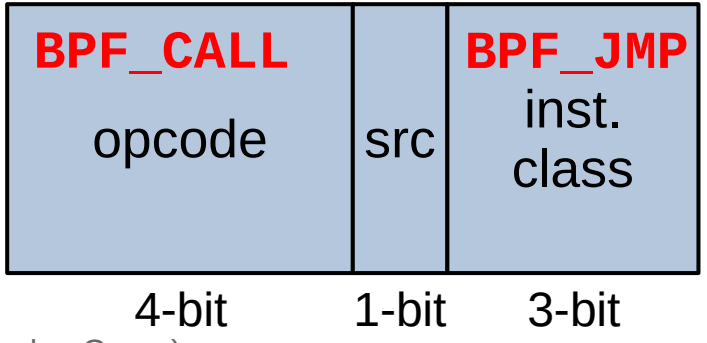


Extended BPF instruction (bytecode) format (2)

E.g., call get_current_pid_tgid

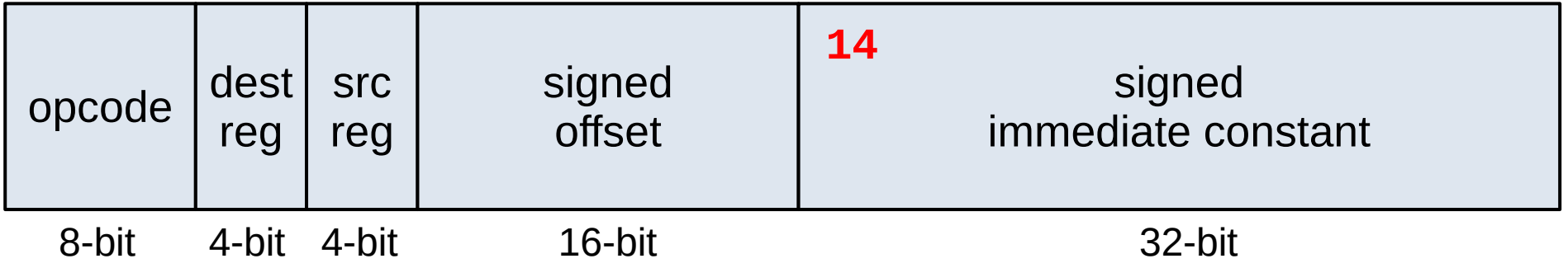


E.g., for ALU & JMP classes:

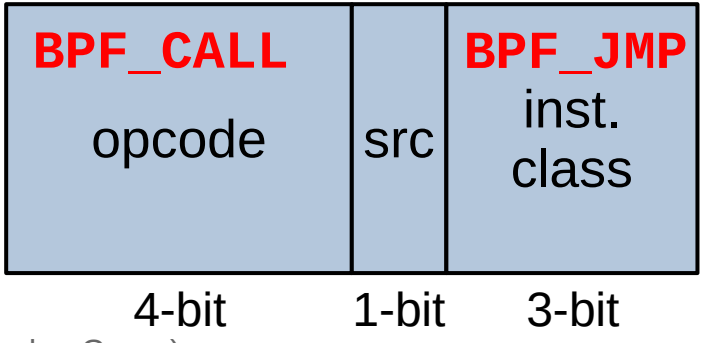


Extended BPF instruction (bytecode) format (3)

E.g., call get_current_pid_tgid



E.g., for ALU & JMP classes:



Linux include/uapi/linux/bpf.h

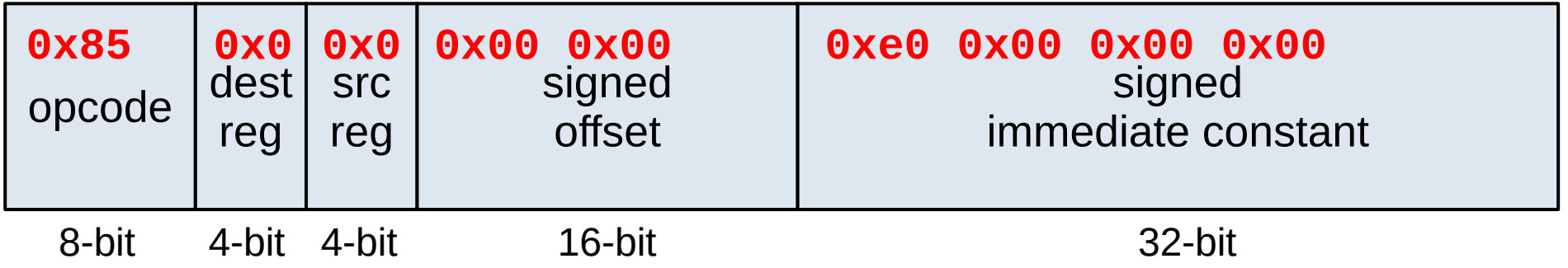
```
#define     BPF_JMP      0x05
```

Linux include/uapi/linux/bpf_common.h

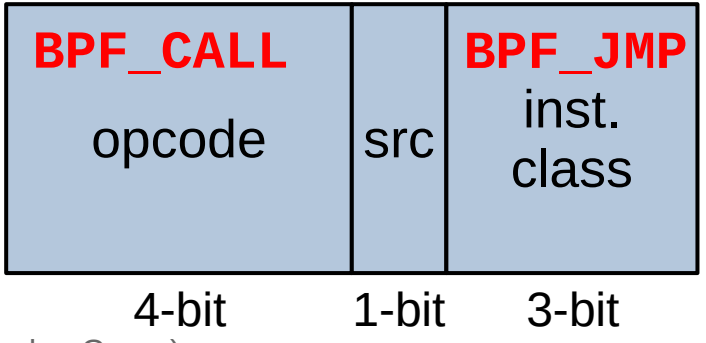
```
#define     BPF_CALL     0x80
```

Extended BPF instruction (bytecode) format (4)

E.g., call get_current_pid_tgid



E.g., for ALU & JMP classes:



Linux include/uapi/linux/bpf.h

```
#define     BPF_JMP      0x05
```

Linux include/uapi/linux/bpf_common.h

```
#define     BPF_CALL     0x80
```

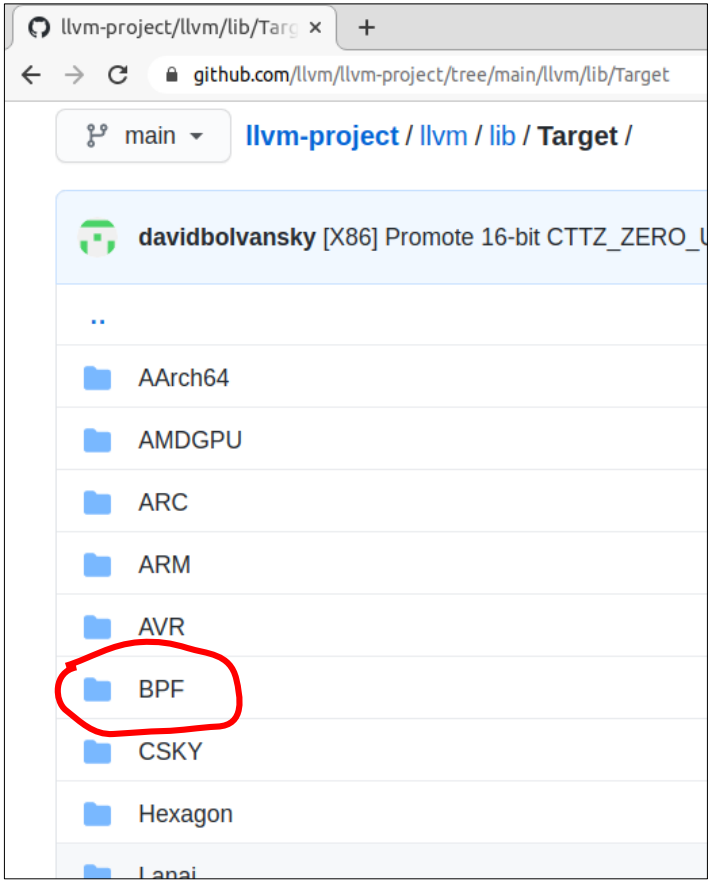
Extended BPF instruction (bytecode) format (5)

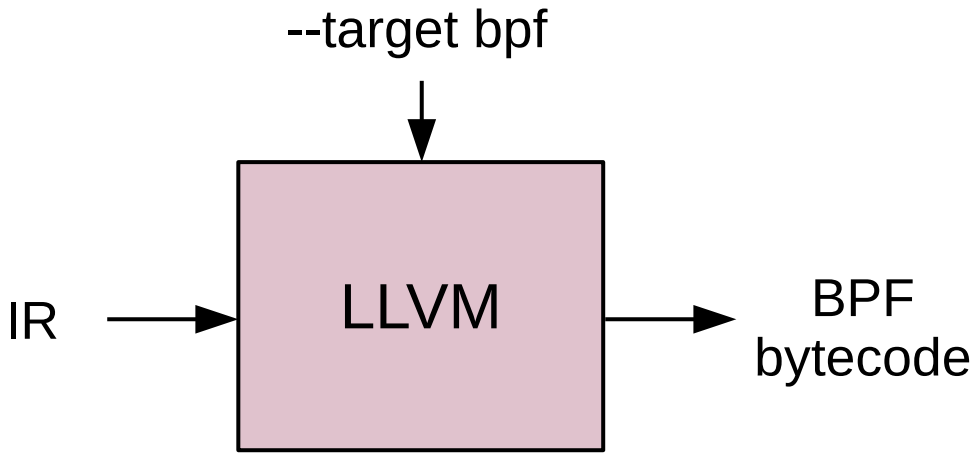
E.g., call get_current_pid_tgid

(hex) 85 00 00 e0 00 00 00

As per the BPF specification (currently Linux headers)

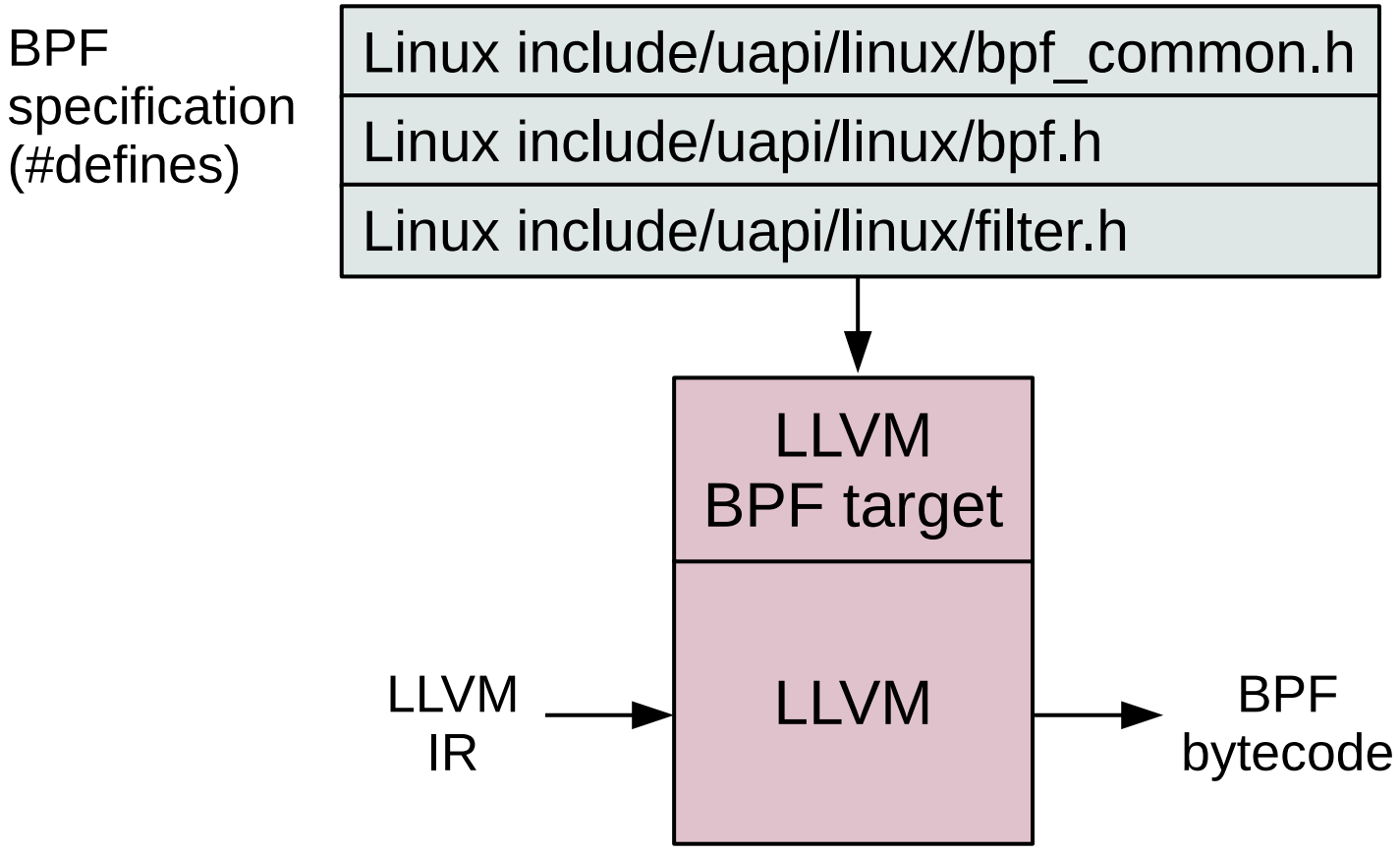
LLVM/Clang has a BPF target





Future: bpftrace may include its own lightweight bpftrace compiler (BC) as an *option*
(pros: no dependencies; cons: less optimal code)

LLVM/Clang has a BPF target (2)



LLVM IR → BPF

E.g., tail call i64 inttoptr (i64 14 to i64 ()*)()

LLVM llvm/lib/Target/BPF/BPFInstrInfo.td

```
class CALL<string OpcodeStr>
    : TYPE_ALU_JMP<BPF_CALL.Value, BPF_K.Value,
                   (outs),
                   (ins calltarget:$BrDst),
                   !strconcat(OpcodeStr, " $BrDst"),
                   []> {
  bits<32> BrDst;

  let Inst{31-0} = BrDst;
  let BPFClass = BPF_JMP;
}
```

→ 14

Plus more llvm boilerplate & BPF headers shown earlier

```
85 00 00 e0 00 00 00
```

Now you have BPF bytecode!

```
bf 16 00 00 00 00 00 00
b7 01 00 00 00 00 00 00
7b 1a f0 ff 00 00 00 00
85 00 00 00 0e 00 00 00
77 00 00 00 20 00 00 00
7b 0a f8 ff 00 00 00 00
18 17 00 00 30 00 00 00 00 00 00 00 00 00 00 00 00
85 00 00 00 08 00 00 00
bf a4 00 00 00 00 00 00
07 04 00 00 f0 ff ff ff
bf 61 00 00 00 00 00 00
bf 72 00 00 00 00 00 00
bf 03 00 00 00 00 00 00
b7 05 00 00 10 00 00 00
85 00 00 00 19 00 00 00
b7 00 00 00 00 00 00 00
95 00 00 00 00 00 00 00
```

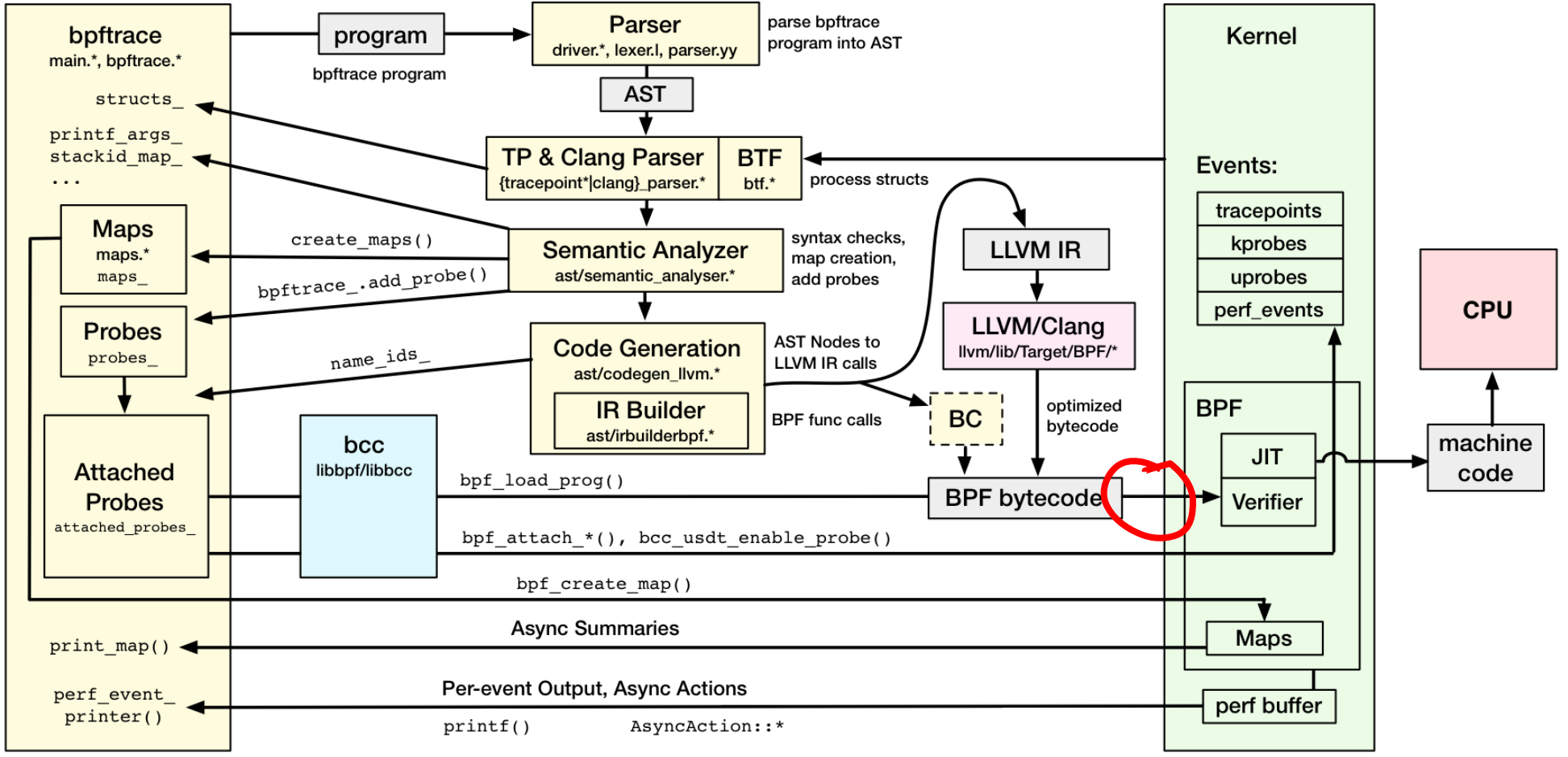
Now you have BPF bytecode! (2)

```
bf 16 00 00 00 00 00 00
b7 01 00 00 00 00 00 00
7b 1a f0 ff 00 00 00 00
85 00 00 00 0e 00 00 00
77 00 00 00 20 00 00 00
7b 0a f8 ff 00 00 00 00
18 17 00 00 30 00 00 00 00 00 00 00 00 00 00 00
85 00 00 00 08 00 00 00
bf a4 00 00 00 00 00 00
07 04 00 00 f0 ff ff ff
bf 61 00 00 00 00 00 00
bf 72 00 00 00 00 00 00
bf 03 00 00 00 00 00 00
b7 05 00 00 10 00 00 00
85 00 00 00 19 00 00 00
b7 00 00 00 00 00 00 00
95 00 00 00 00 00 00 00
```

0x05 (BPF_JMP) | 0x80 (BPF_CALL)

14 (BPF_FUNC_get_current_pid_tgid)

bpftrace mid-level internals 7/13

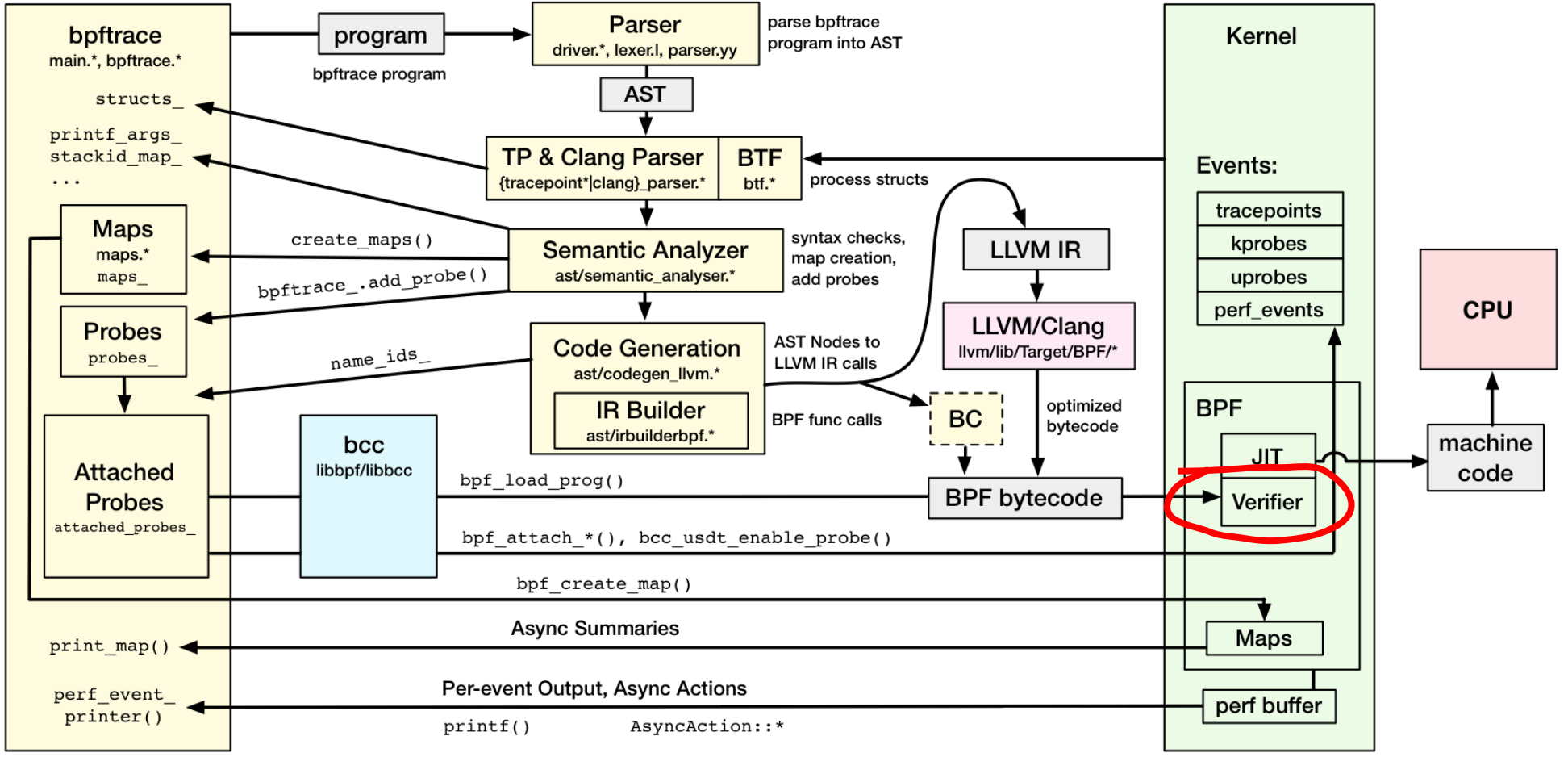


Sending BPF bytecode to the kernel

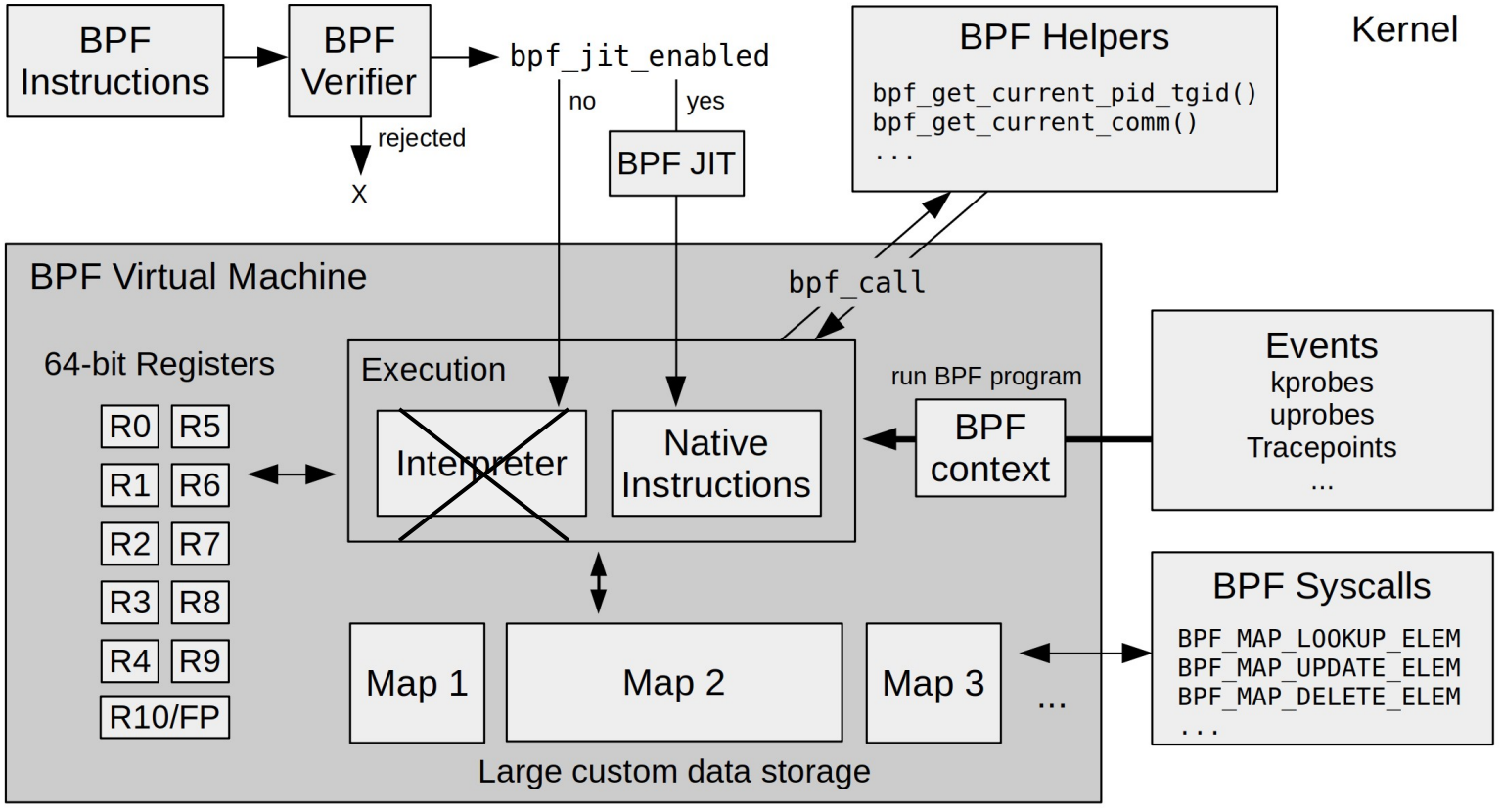
```
# strace -fe bpf bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}'
[...]
bpf(BPF_PROG_LOAD, {prog_type=BPF_PROG_TYPE_KPROBE, insn_cnt=18, insns=0x7fdde5305000,
license="GPL", log_level=0, log_size=0, log_buf=NULL, kern_version=KERNEL_VERSION(5, 8,
18), prog_flags=0, prog_name="do_nanosleep", prog_ifindex=0,
expected_attach_type=BPF_CGROUP_INET_INGRESS, prog_btf_fd=0, func_info_rec_size=0,
func_info=NULL, func_info_cnt=0, line_info_rec_size=0, line_info=NULL, line_info_cnt=0,
attach_btf_id=0, attach_prog_fd=0}, 120) = 14
```

Success! Passed the verifier...

bpftrace mid-level internals 8/13



BPF mid-level internals



From: BPF Performance Tools, Figure 2-3

Verifying BPF instructions

```
85 00 00 00 12 34 56 78
```

Imagine we call a bogus function...

Linux kernel/bpf/verifier.c

```
static int do_check(struct bpf_verifier_env *env)
[...]
                } else if (class == BPF_JMP || class == BPF_JMP32) {
                        u8 opcode = BPF_OP(insn->code);
                        env->jmps_processed++;
                        if (opcode == BPF_CALL) {
[...]
                                        err = check_helper_call(env, insn->imm, env->insn_idx);
[...]
static int check_helper_call(struct bpf_verifier_env *env, int func_id, int insn_idx)
{
        const struct bpf_func_proto *fn = NULL;
        struct bpf_reg_state *regs;
        struct bpf_call_arg_meta meta;
        bool changes_data;
        int i, err;

        /* find function prototype */
        if (func_id < 0 || func_id >= __BPF_FUNC_MAX_ID) {
                verbose(env, "invalid func %s#%d\n", func_id_name(func_id),
                        func_id);
                return -EINVAL;
```

>9000 lines of code

BPF verifier

>9000 lines of code

>260 error returns

Checks every instruction

Checks every code path

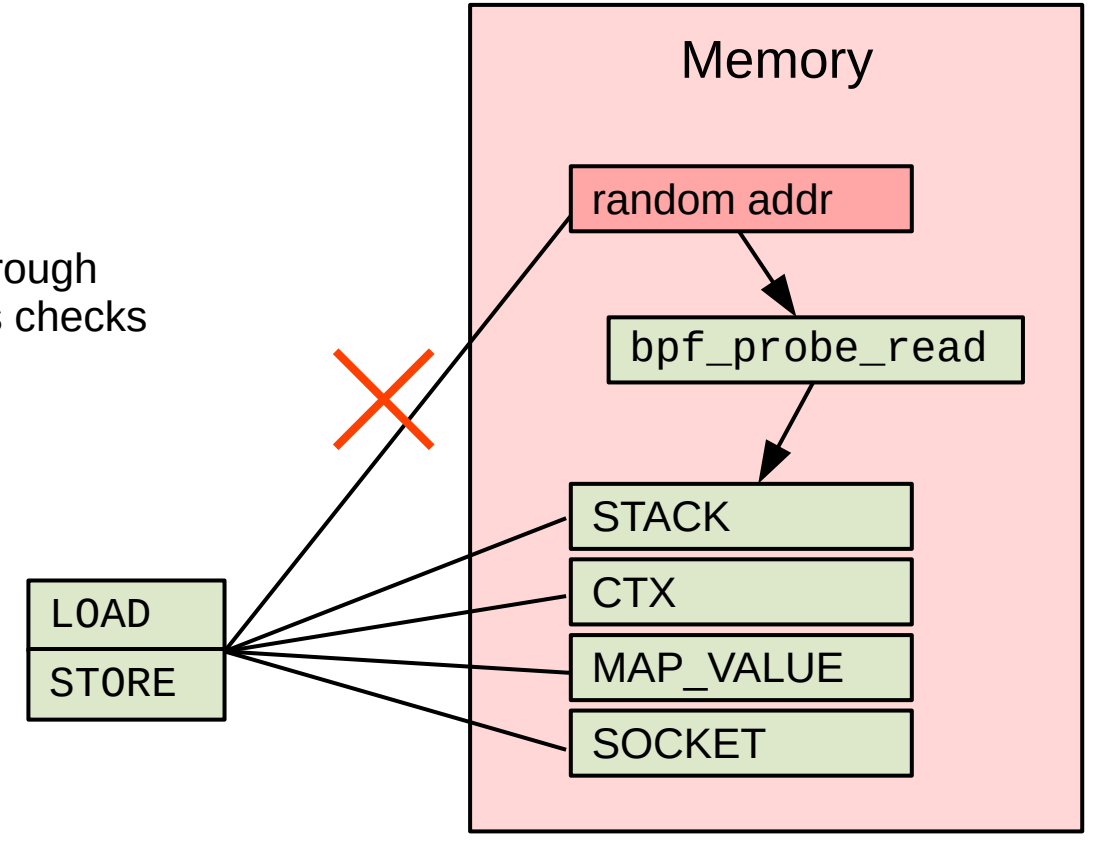
Rewrites some bytecode

Verifier functions:

```
check_subprogs                  check_helper_mem_access
check_reg_arg                   check_func_arg
check_stack_write               check_map_func_compatibility
check_stack_read                check_func_proto
check_stack_access              check_func_call
check_map_access_type           check_reference_leak
check_mem_region_access         check_helper_call
check_map_access                check_alu_op
check_packet_access             check_cond_jmp_op
check_ctx_access                check_ld_imm
check_flow_keys_access          check_ld_abs
check_sock_access               check_return_code
check_pkt_ptr_alignment         check_cfg
check_generic_ptr_alignment     check_btf_func
check_ptr_alignment             check_btf_line
check_max_stack_depth           check_btf_info
check_tp_buffer_access          check_map_prealloc
check_ptr_to_btf_access         check_map_prog_compatibility
check_mem_access                check_struct_ops_btf_id
check_xadd                      check_attach_modify_return
check_stack_boundary            check_attach_btf_id
```

Verifying Instructions

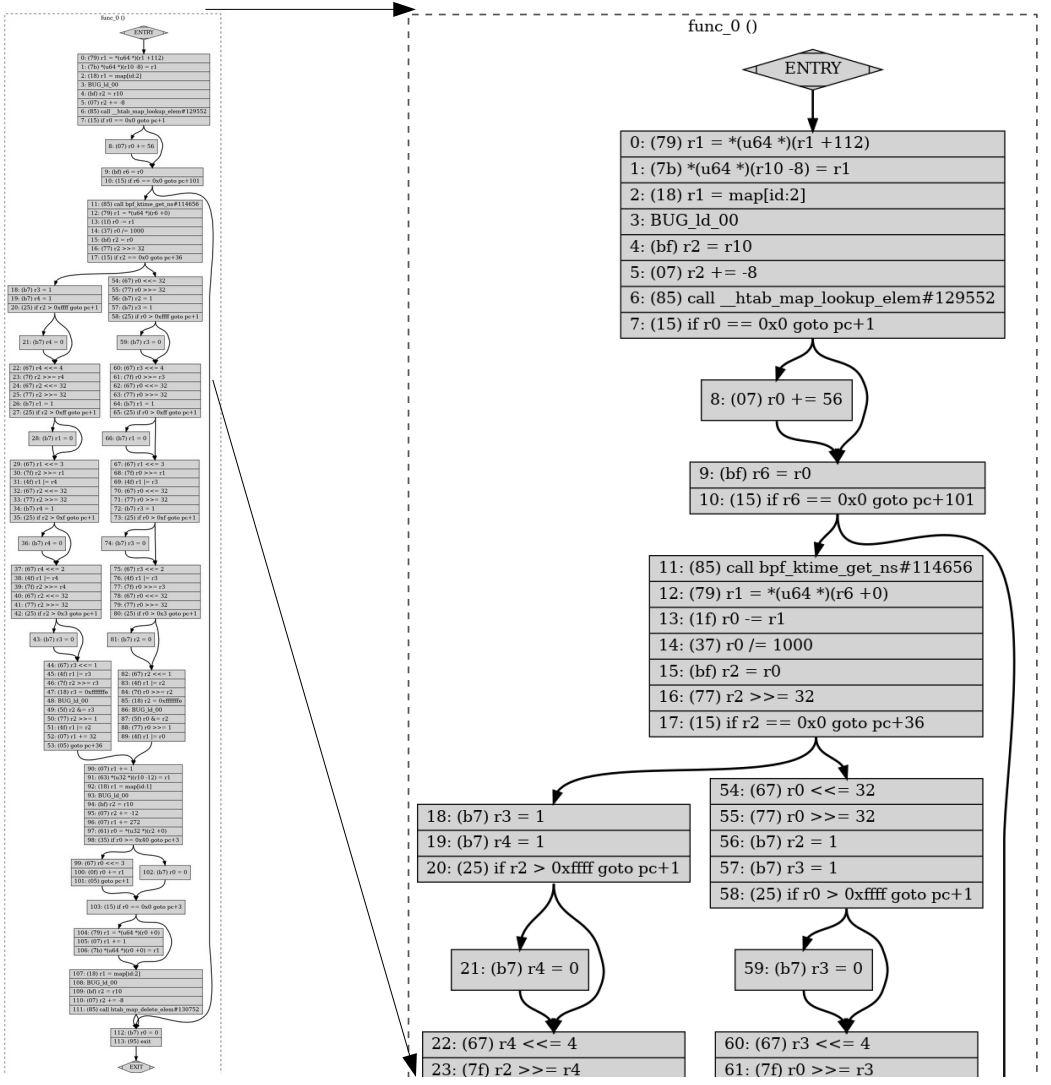
- Memory access
  - Direct access extremely restricted
  - Can only read initialized memory
  - Other kernel memory must pass through the bpf_probe_read() helper and its checks
- Arguments are the correct type
- Register usage allowed
  - E.g., no frame pointer writes
- No write overflows
- No addr leaks
- Etc.



Verifying Code Paths

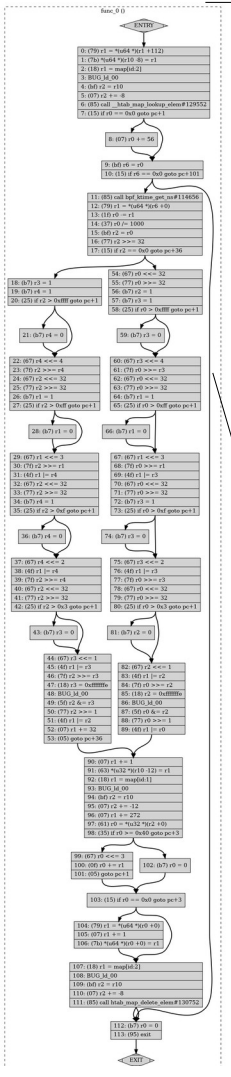
- All instruction must lead to exit
- No unreachable instructions
- No backwards branches (loops) except BPF bounded loops

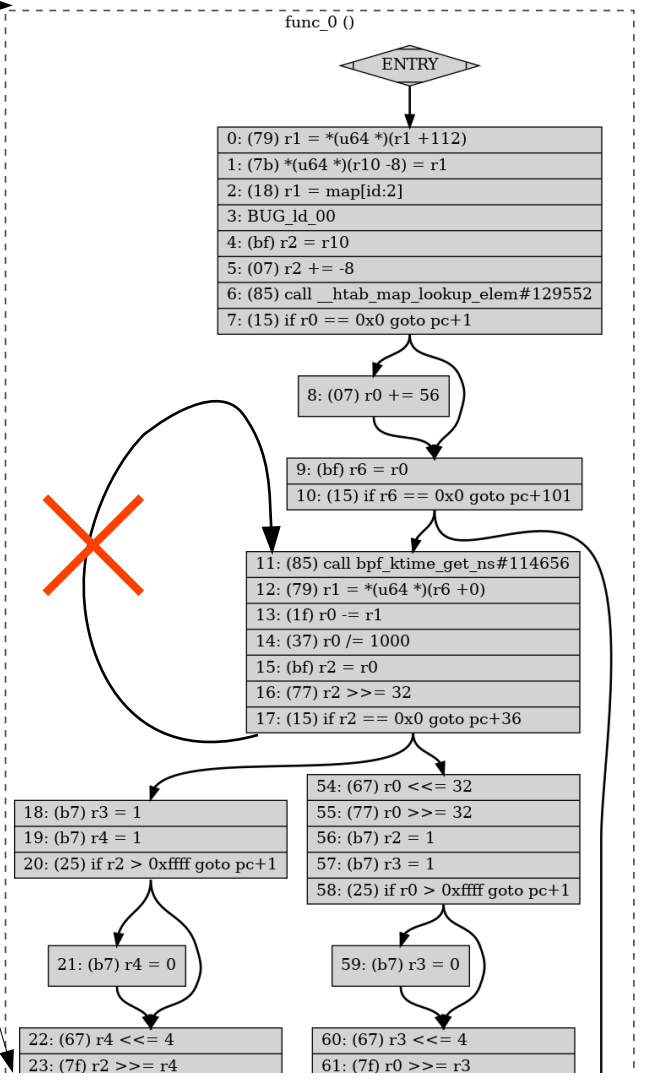
biolatency as GraphViz dot:



Verifying Code Paths

- All instruction must lead to exit
- No unreachable instructions
- No backwards branches (loops) except BPF bounded loops





biolatency as GraphViz dot:

Pre-verifier BPF bytecode

```
bf 16 00 00 00 00 00 00
b7 01 00 00 00 00 00 00
7b 1a f0 ff 00 00 00 00
85 00 00 00 0e 00 00 00
77 00 00 00 20 00 00 00
7b 0a f8 ff 00 00 00 00
18 17 00 00 30 00 00 00 00 00 00 00 00 00 00 00 00
85 00 00 00 08 00 00 00
bf a4 00 00 00 00 00 00
07 04 00 00 f0 ff ff ff
bf 61 00 00 00 00 00 00
bf 72 00 00 00 00 00 00
bf 03 00 00 00 00 00 00
b7 05 00 00 10 00 00 00
85 00 00 00 19 00 00 00
b7 00 00 00 00 00 00 00
95 00 00 00 00 00 00 00
```

Post-verifier BPF bytecode

```
bf 16 00 00 00 00 00 00
b7 01 00 00 00 00 00 00
7b 1a f0 ff 00 00 00 00
85 00 00 00 d0 81 01 00
77 00 00 00 20 00 00 00
7b 0a f8 ff 00 00 00 00
18 17 00 00 18 00 00 00 00 00 00 00 00 00 00 00 00
85 00 00 00 f0 80 01 00
bf a4 00 00 00 00 00 00
07 04 00 00 f0 ff ff ff
bf 61 00 00 00 00 00 00
bf 72 00 00 00 00 00 00
bf 03 00 00 00 00 00 00
b7 05 00 00 10 00 00 00
85 00 00 00 30 2c ff ff
b7 00 00 00 00 00 00 00
95 00 00 00 00 00 00 00
```

Post-verifier BPF bytecode (2)

```
bf 16 00 00 00 00 00 00
b7 01 00 00 00 00 00 00
7b 1a f0 ff 00 00 00 00
85 00 00 00 d0 81 01 00
77 00 00 00 20 00 00 00
7b 0a f8 ff 00 00 00 00
18 17 00 00 18 00 00 00 00 00 00 00 00 00 00 00 00
85 00 00 00 f0 80 01 00
bf a4 00 00 00 00 00 00
07 04 00 00 f0 ff ff ff
bf 61 00 00 00 00 00 00
bf 72 00 00 00 00 00 00
bf 03 00 00 00 00 00 00
b7 05 00 00 10 00 00 00
85 00 00 00 30 2c ff ff
b7 00 00 00 00 00 00 00
95 00 00 00 00 00 00 00
```

E.g., call get_current_pid_tgid

helper index value has become an instruction offset addresses from __bpf_call_base

BPF bytecode with human words

```
# bpftool prog show
[…]
70: kprobe  name do_nanosleep  tag 8dc93a3b6a21ef3b  gpl
    loaded_at 2021-05-02T00:44:26+0000  uid 0
    xlated 144B  jited 96B  memlock 4096B  map_ids 24

# bpftool prog dump xlated id 70 opcodes
   0: (bf) r6 = r1
       bf 16 00 00 00 00 00 00
   1: (b7) r1 = 0
       b7 01 00 00 00 00 00 00
   2: (7b) *(u64 *)(r10 -16) = r1
       7b 1a f0 ff 00 00 00 00
   3: (85) call bpf_get_current_pid_tgid#98768
       85 00 00 00 d0 81 01 00
   4: (77) r0 >>= 32
       77 00 00 00 20 00 00 00
   5: (7b) *(u64 *)(r10 -8) = r0
       7b 0a f8 ff 00 00 00 00
   6: (18) r7 = map[id:24]
       18 17 00 00 18 00 00 00 00 00 00 00 00 00 00 00
[...]
```

Using bpftool on a running instance of the program

BPF bytecode with human words (2)

```
# bpftool prog show
[…]
70: kprobe  name do_nanosleep  tag 8dc93a3b6a21ef3b  gpl
    loaded_at 2021-05-02T00:44:26+0000  uid 0
    xlated 144B  jited 96B  memlock 4096B  map_ids 24

# bpftool prog dump xlated id 70 opcodes
   0: (bf) r6 = r1
       bf 16 00 00 00 00 00 00
   1: (b7) r1 = 0
       b7 01 00 00 00 00 00 00
   2: (7b) *(u64 *)(r10 -16) = r1
       7b 1a f0 ff 00 00 00 00
   3: (85) call bpf_get_current_pid_tgid#98768
       85 00 00 00 d0 81 01 00
   4: (77) r0 >>= 32
       77 00 00 00 20 00 00 00
   5: (7b) *(u64 *)(r10 -8) = r0
       7b 0a f8 ff 00 00 00 00
   6: (18) r7 = map[id:24]
       18 17 00 00 18 00 00 00 00 00 00 00 00 00 00 00
[...]
```

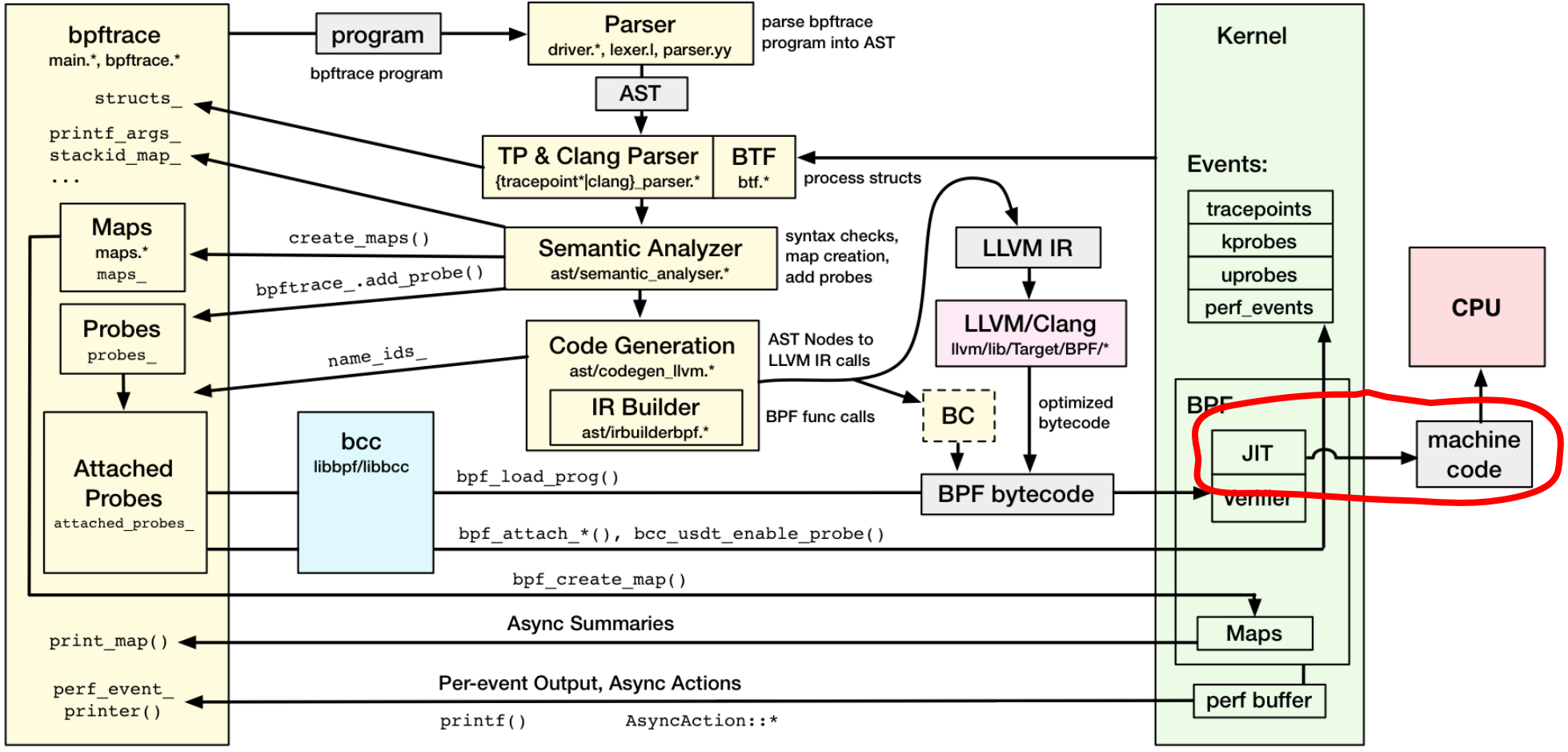
Using bpftool on a running instance of the program

BPF bytecode, opcodes only

```
# bpftool prog dump xlated id 70
   0: (bf) r6 = r1
   1: (b7) r1 = 0
   2: (7b) *(u64 *)(r10 -16) = r1
   3: (85) call bpf_get_current_pid_tgid#98768
   4: (77) r0 >>= 32
   5: (7b) *(u64 *)(r10 -8) = r0
   6: (18) r7 = map[id:24]
   8: (85) call bpf_get_smp_processor_id#98544
   9: (bf) r4 = r10
  10: (07) r4 += -16
  11: (bf) r1 = r6
  12: (bf) r2 = r7
  13: (bf) r3 = r0
  14: (b7) r5 = 16
  15: (85) call bpf_perf_event_output#-54224
  16: (b7) r0 = 0
  17: (95) exit
```

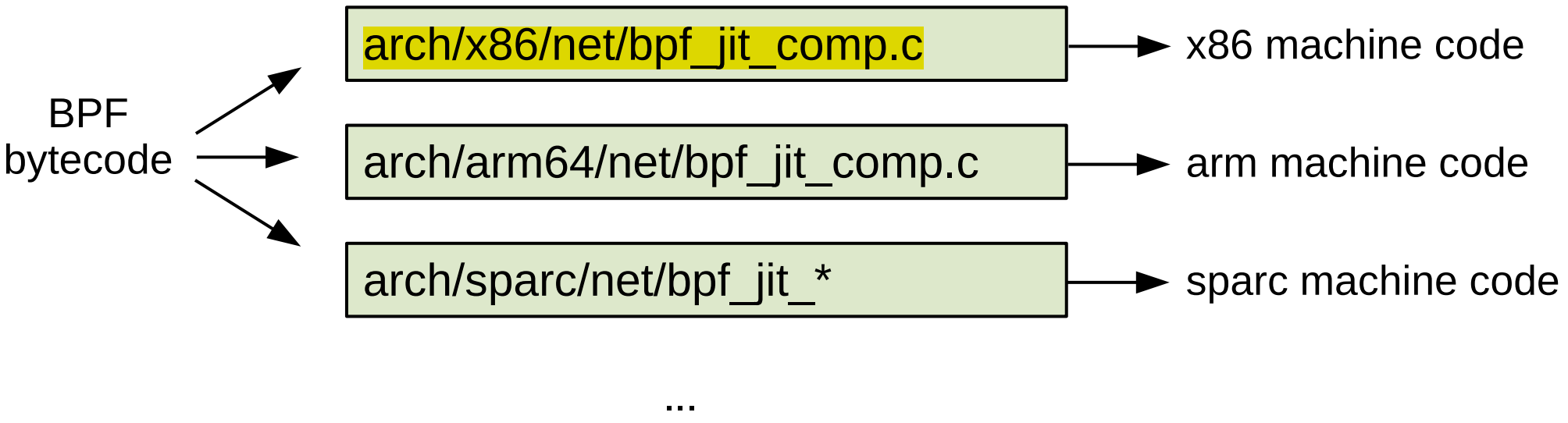
just the opcode 8 bits

bpftrace mid-level internals 9/13



https://github.com/iovisor/bpftrace 2021, diagram by Brendan Gregg

BPF bytecode → native machine code



BPF bytecode → x86 machine code

Linux arch/x86/net/bpf_jit_comp.c

```
static int do_jit(struct bpf_prog *bpf_prog, int *addrs, u8 *image,
                  int oldproglen, struct jit_context *ctx)
{
[…]
        for (i = 1; i <= insn_cnt; i++, insn++) {
[…]
                switch (insn->code) {
[…]
                case BPF_JMP | BPF_CALL:
                        func = (u8 *) __bpf_call_base + imm32;
                        if (!imm32 || emit_call(&prog, func, image + addrs[i - 1]))
                                return -EINVAL;
                        break;
[…]
static int emit_call(u8 **pprog, void *func, void *ip)
{
        return emit_patch(pprog, func, ip, 0xE8);
}
```

BPF bytecode → x86 machine code

Linux arch/x86/net/bpf_jit_comp.c

```
static int do_jit(struct bpf_prog *bpf_prog, int *addrs, u8 *image,
                  int oldproglen, struct jit_context *ctx)
{
[…]
        for (i = 1; i <= insn_cnt; i++, insn++) {
[…]
                switch (insn->code) {
[…]
                case BPF_JMP | BPF_CALL:
                        func = (u8 *) __bpf_call_base + imm32;
                        if (!imm32 || emit_call(&prog, func, image + addrs[i - 1]))
                                return -EINVAL;
                        break;
[…]
static int emit_call(u8 **pprog, void *func, void *ip)
{
        return emit_patch(pprog, func, ip, 0xE8);
}
```

E.g., call get_current_pid_tgid

0xe8 is x86 CALL

Now you have x86 machine code!

```
# bpftool prog dump jited id 80 opcodes | grep -v :
    55
    48 89 e5
    48 81 ec 10 00 00 00
    53
    41 55
    41 56
    41 57
    6a 00
    48 89 fb
    31 ff
    48 89 7d f0
    e8 a0 8b 44 c2
    48 c1 e8 20
    48 89 45 f8
    49 bd 00 b6 7b b8 3a 9d ff ff
    e8 a9 8a 44 c2
    48 89 e9
    48 83 c1 f0
    48 89 df
[...]
```

31 instructions

Now you have x86 machine code!

```
# bpftool prog dump jited id 80 opcodes | grep -v :
    55
    48 89 e5
    48 81 ec 10 00 00 00
    53
    41 55
    41 56
    41 57
    6a 00
    48 89 fb
    31 ff
    48 89 7d f0
    e8 a0 8b 44 c2 ──────► CALL get_current_pid_tgid
    48 c1 e8 20
    48 89 45 f8
    49 bd 00 b6 7b b8 3a 9d ff ff
    e8 a9 8a 44 c2
    48 89 e9
    48 83 c1 f0
    48 89 df
[...]
```

31 instructions

... or you have ARM machine code!

```
# bpftool prog dump jited id 71 opcodes | grep -v :
    fd 7b bf a9
    fd 03 00 91
    f3 53 bf a9
    f5 5b bf a9
    f9 6b bf a9
    f9 03 00 91
    1a 00 80 d2
    ff 43 00 d1
    13 00 00 91
    00 00 80 d2
    ea 01 80 92
    20 6b 2a f8
    ea 48 9e 92
    0a 05 a2 f2
    0a 00 d0 f2
    40 01 3f d6
    07 00 00 91
    e7 fc 60 d3
    ea 00 80 92
[...]
```

48 instructions

x86 instruction disassembly

```
# bpftool prog dump jited id 80
0xffffffffc0192b2e:
   0:    push   %rbp
   1:    mov    %rsp,%rbp
   4:    sub    $0x10,%rsp
   b:    push   %rbx
   c:    push   %r13
   e:    push   %r14
  10:    push   %r15
  12:    pushq  $0x0
  14:    mov    %rdi,%rbx
  17:    xor    %edi,%edi
  19:    mov    %rdi,-0x10(%rbp)
  1d:    callq  0xffffffffc2448bc2
  22:    shr    $0x20,%rax
  26:    mov    %rax,-0x8(%rbp)
  2a:    movabs $0xffff9d3ab87bb600,%r13
  34:    callq  0xffffffffc2448ae2
  39:    mov    %rbp,%rcx
  3c:    add    $0xfffffffffffffff0,%rcx
[...]
```

x86 instruction disassembly (2)

```
# bpftool prog dump jited id 80
0xffffffffc0192b2e:
   0:    push   %rbp
   1:    mov    %rsp,%rbp
   4:    sub    $0x10,%rsp
   b:    push   %rbx
   c:    push   %r13
   e:    push   %r14
  10:    push   %r15
  12:    pushq  $0x0
  14:    mov    %rdi,%rbx
  17:    xor    %edi,%edi
  19:    mov    %rdi,-0x10(%rbp)
  1d:    callq  0xffffffffc2448bc2
  22:    shr    $0x20,%rax
  26:    mov    %rax,-0x8(%rbp)
  2a:    movabs $0xffff9d3ab87bb600,%r13
  34:    callq  0xffffffffc2448ae2
  39:    mov    %rbp,%rcx
  3c:    add    $0xfffffffffffffff0,%rcx
[...]
```

BPF prologue

BPF program

get_current_pid_tgid

Plus you have BPF helper code

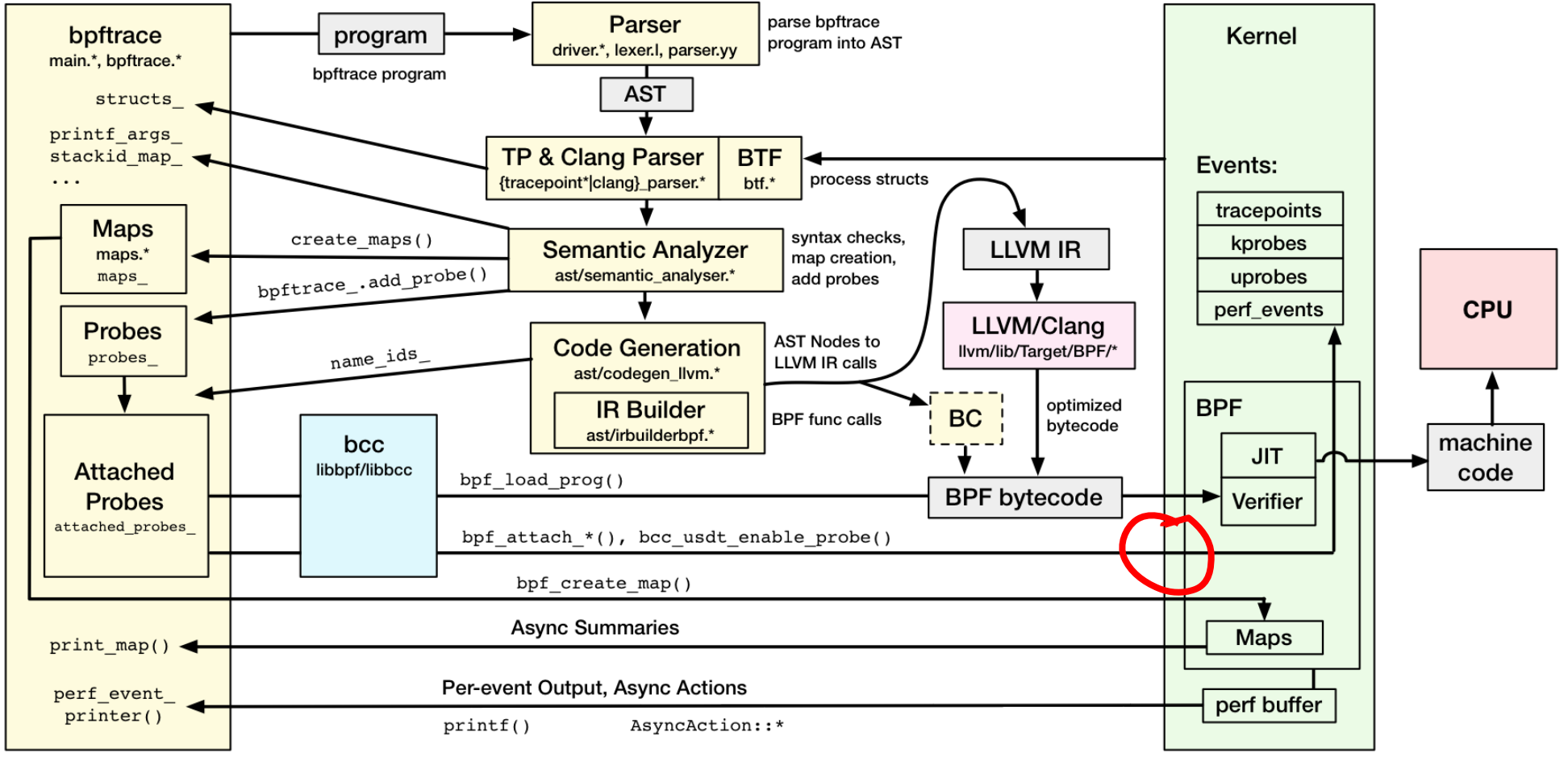
Linux kernel/bpf/helpers.c

```
BPF_CALL_0(bpf_get_current_pid_tgid)
{
        struct task_struct *task = current;

        if (unlikely(!task))
                return -EINVAL;

        return (u64) task->tgid << 32 | task->pid;
}
[...]
```

bpftrace mid-level internals 10/13



Attaching BPF to a kprobe

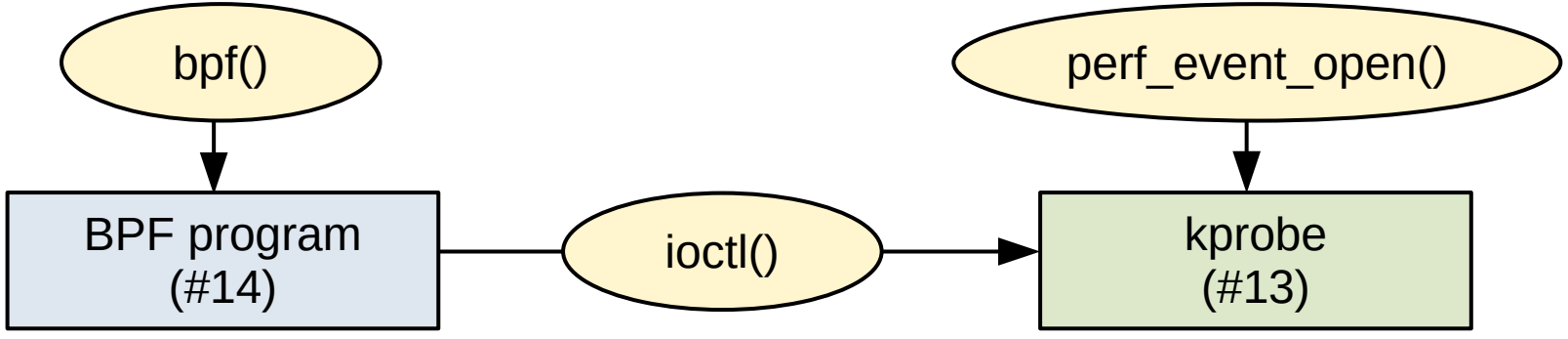
```
# strace -fe perf_event_open,bpf,ioctl bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid); }'
[...]
bpf(BPF_PROG_LOAD, {prog_type=BPF_PROG_TYPE_KPROBE, insn_cnt=18, insns=0x7f6e826cf000,
license="GPL", log_level=0, log_size=0, log_buf=NULL, kern_version=KERNEL_VERSION(5, 8,
18), prog_flags=0, prog_name="do_nanosleep", prog_ifindex=0,
expected_attach_type=BPF_CGROUP_INET_INGRESS, prog_btf_fd=0, func_info_rec_size=0,
func_info=NULL, func_info_cnt=0, line_info_rec_size=0, line_info=NULL, line_info_cnt=0,
attach_btf_id=0, attach_prog_fd=0}, 120) = 14
perf_event_open({type=0x6 /* PERF_TYPE_??? */, size=PERF_ATTR_SIZE_VER5, config=0, ...},
-1, 0, -1, PERF_FLAG_FD_CLOEXEC) = 13
ioctl(13, PERF_EVENT_IOC_SET_BPF, 14)   = 0
ioctl(13, PERF_EVENT_IOC_ENABLE, 0)     = 0
```

Attaching BPF to a kprobe (2)

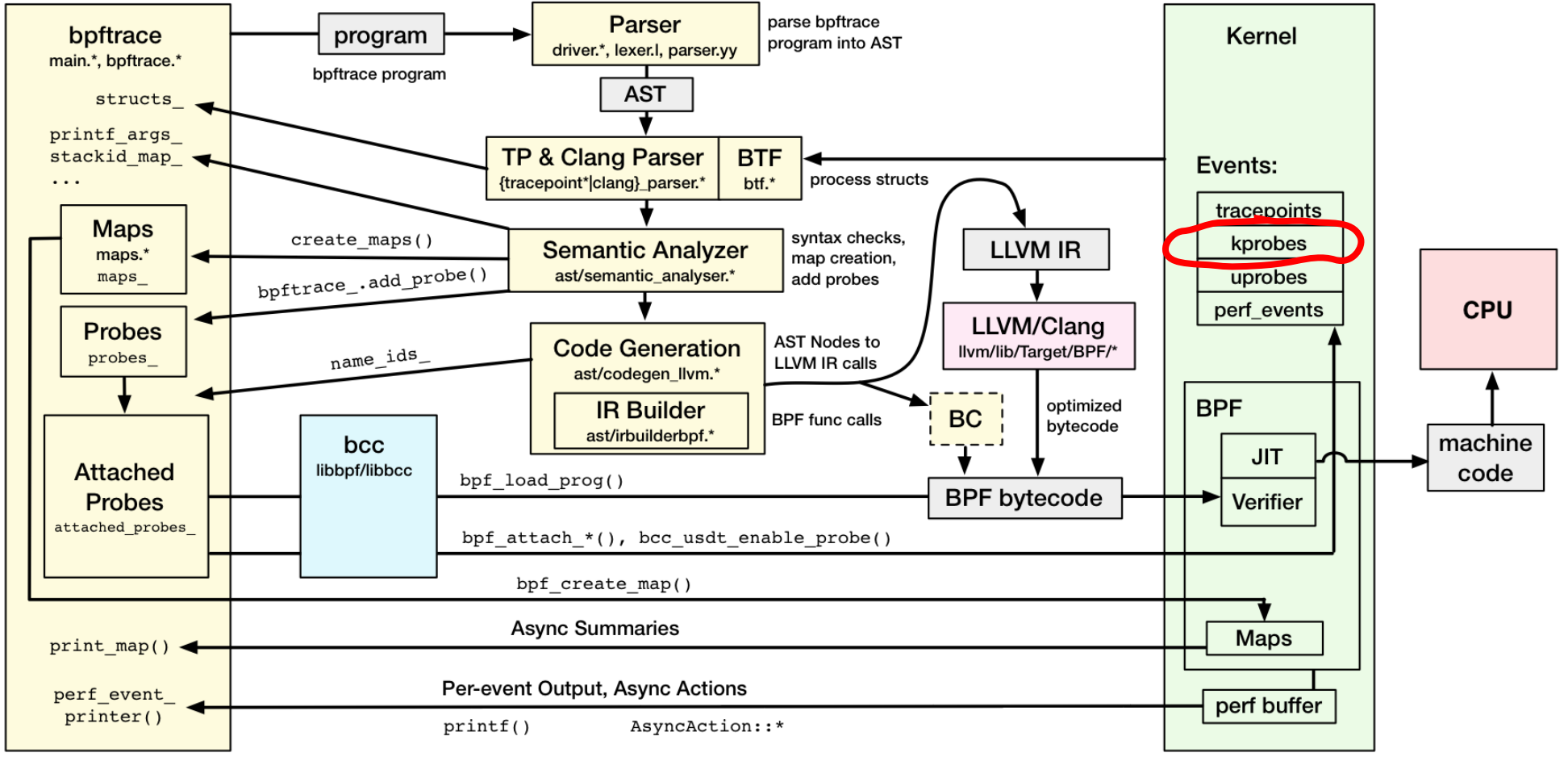
```
# strace -fe perf_event_open,bpf,ioctl bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid); }'
[...]
bpf(BPF_PROG_LOAD, {prog_type=BPF_PROG_TYPE_KPROBE, insn_cnt=18, insns=0x7f6e826cf000,
license="GPL", log_level=0, log_size=0, log_buf=NULL, kern_version=KERNEL_VERSION(5, 8,
18), prog_flags=0, prog_name="do_nanosleep", prog_ifindex=0,
expected_attach_type=BPF_CGROUP_INET_INGRESS, prog_btf_fd=0, func_info_rec_size=0,
func_info=NULL, func_info_cnt=0, line_info_rec_size=0, line_info=NULL, line_info_cnt=0,
attach_btf_id=0, attach_prog_fd=0}, 120) = 14
perf_event_open({type=0x6 /* PERF_TYPE_??? */, size=PERF_ATTR_SIZE_VER5, config=0, ...},
-1, 0, -1, PERF_FLAG_FD_CLOEXEC) = 13      initialize the kprobe
ioctl(13, PERF_EVENT_IOC_SET_BPF, 14)   = 0   attach bpf 14 to kprobe 13
ioctl(13, PERF_EVENT_IOC_ENABLE, 0)     = 0
```

creates the kprobe

strace is lacking some translation



bpftrace mid-level internals 11/13



kprobes

How do we instrument this?

Linux kernel/time/hrtimer.c

```
static int __sched do_nanosleep(struct hrtimer_sleeper *t, enum hrtimer_mode mode)
{
        struct restart_block *restart;

        do {
                set_current_state(TASK_INTERRUPTIBLE);
                hrtimer_sleeper_start_expires(t, mode);

                if (likely(t->task))
[...]
```

(it's actually quite easy)

Instrumenting live kernel functions

```
(gdb) disas/r do_nanosleep
Dump of assembler code for function do_nanosleep:
   0xffffffff81b7d810 <+0>:   e8 1b 00 4f ff   callq  0xffffffff8106d830 <__fentry__>
   0xffffffff81b7d815 <+5>:   55               push   %rbp
   0xffffffff81b7d816 <+6>:   89 f1            mov    %esi,%ecx
   0xffffffff81b7d818 <+8>:   48 89 e5         mov    %rsp,%rbp
   0xffffffff81b7d81b <+11>:  41 55            push   %r13
   0xffffffff81b7d81d <+13>:  41 54            push   %r12
   0xffffffff81b7d81f <+15>:  53               push   %rbx
[...]
```

Instrumenting live kernel functions (2)

```
(gdb) disas/r do_nanosleep
Dump of assembler code for function do_nanosleep:
   0xffffffff81b7d810 <+0>:   e8 1b 00 4f ff   callq  0xffffffff8106d830 <__fentry__>
   0xffffffff81b7d815 <+5>:   55               push   %rbp
   0xffffffff81b7d816 <+6>:   89 f1            mov    %esi,%ecx
   0xffffffff81b7d818 <+8>:   48 89 e5         mov    %rsp,%rbp
   0xffffffff81b7d81b <+11>:  41 55            push   %r13
   0xffffffff81b7d81d <+13>:  41 54            push   %r12
   0xffffffff81b7d81f <+15>:  53               push   %rbx
[...]
```

this is usually nop'd out

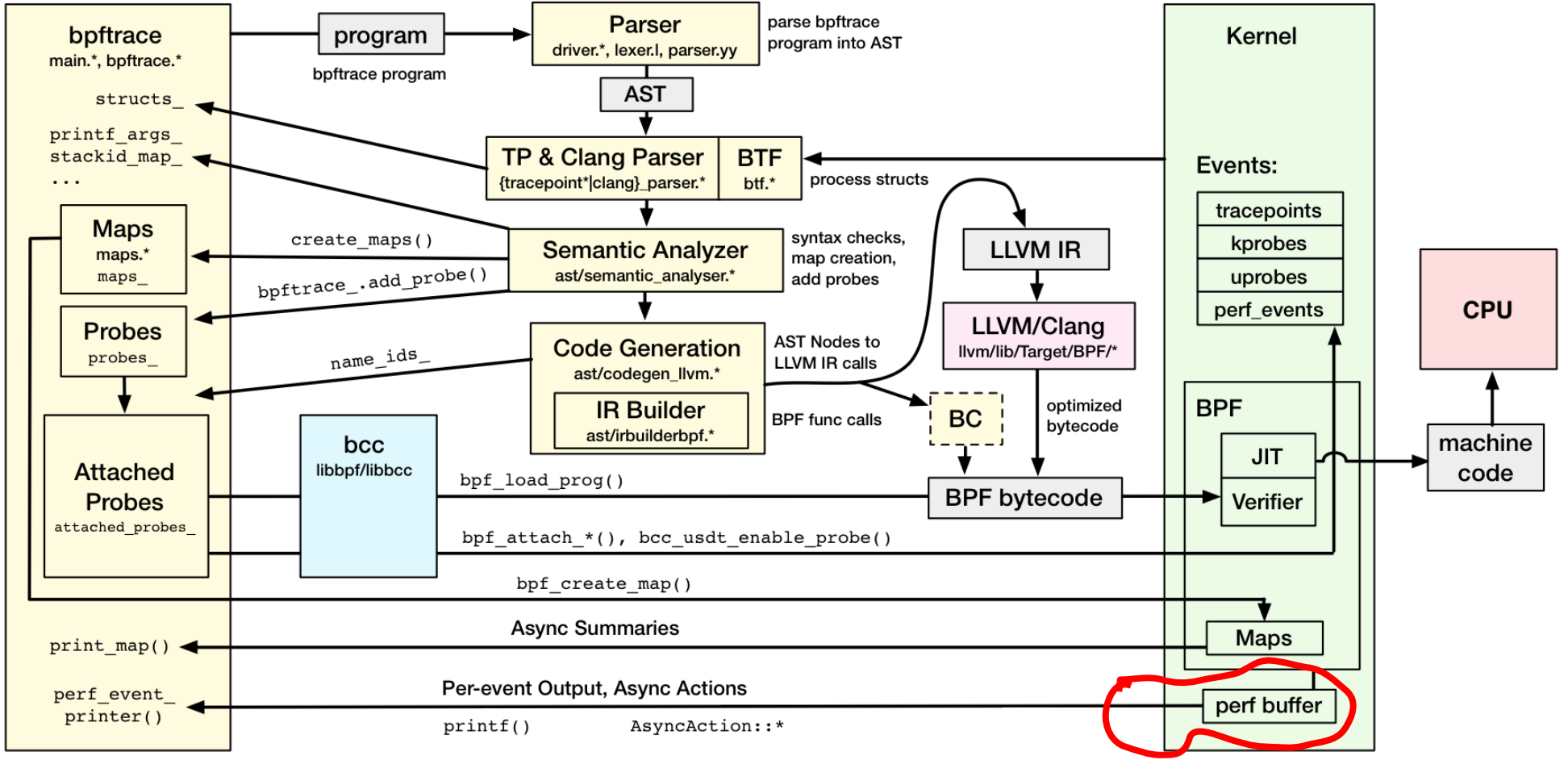
A) Ftrace is already there. Kprobes can add a handler.

B) Or a breakpoint written (e.g., int3).

C) Or a jmp is written.

May need to stop_machine() to ensure other cores don't execute changing instruction text

bpftrace mid-level internals 12/13



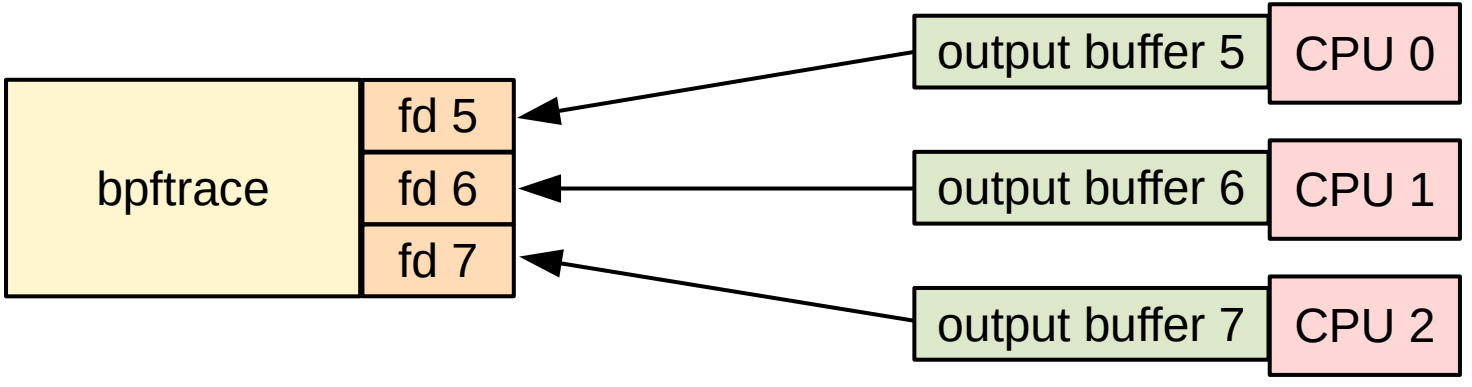
Perf output buffers

```
# strace -fe perf_event_open bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid); }'
strace: Process 3229968 attached
[pid 3229968] +++ exited with 0 +++
perf_event_open({type=PERF_TYPE_SOFTWARE, ..., config=PERF_COUNT_SW_BPF_OUTPUT, ...}, -1, 0, -1,
PERF_FLAG_FD_CLOEXEC) = 5
perf_event_open({type=PERF_TYPE_SOFTWARE, ..., config=PERF_COUNT_SW_BPF_OUTPUT, ...}, -1, 1, -1,
PERF_FLAG_FD_CLOEXEC) = 6
perf_event_open({type=PERF_TYPE_SOFTWARE, ..., config=PERF_COUNT_SW_BPF_OUTPUT, ...}, -1, 2, -1,
PERF_FLAG_FD_CLOEXEC) = 7
[...]
```

Perf output buffers

```
# strace -fe perf_event_open bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid); }'
strace: Process 3229968 attached
[pid 3229968] +++ exited with 0 +++
perf_event_open({type=PERF_TYPE_SOFTWARE, ..., config=PERF_COUNT_SW_BPF_OUTPUT, ...}, -1, 0, -1,
PERF_FLAG_FD_CLOEXEC) = 5
perf_event_open({type=PERF_TYPE_SOFTWARE, ..., config=PERF_COUNT_SW_BPF_OUTPUT, ...}, -1, 1, -1,
PERF_FLAG_FD_CLOEXEC) = 6
perf_event_open({type=PERF_TYPE_SOFTWARE, ..., config=PERF_COUNT_SW_BPF_OUTPUT, ...}, -1, 2, -1,
PERF_FLAG_FD_CLOEXEC) = 7
[...]
```

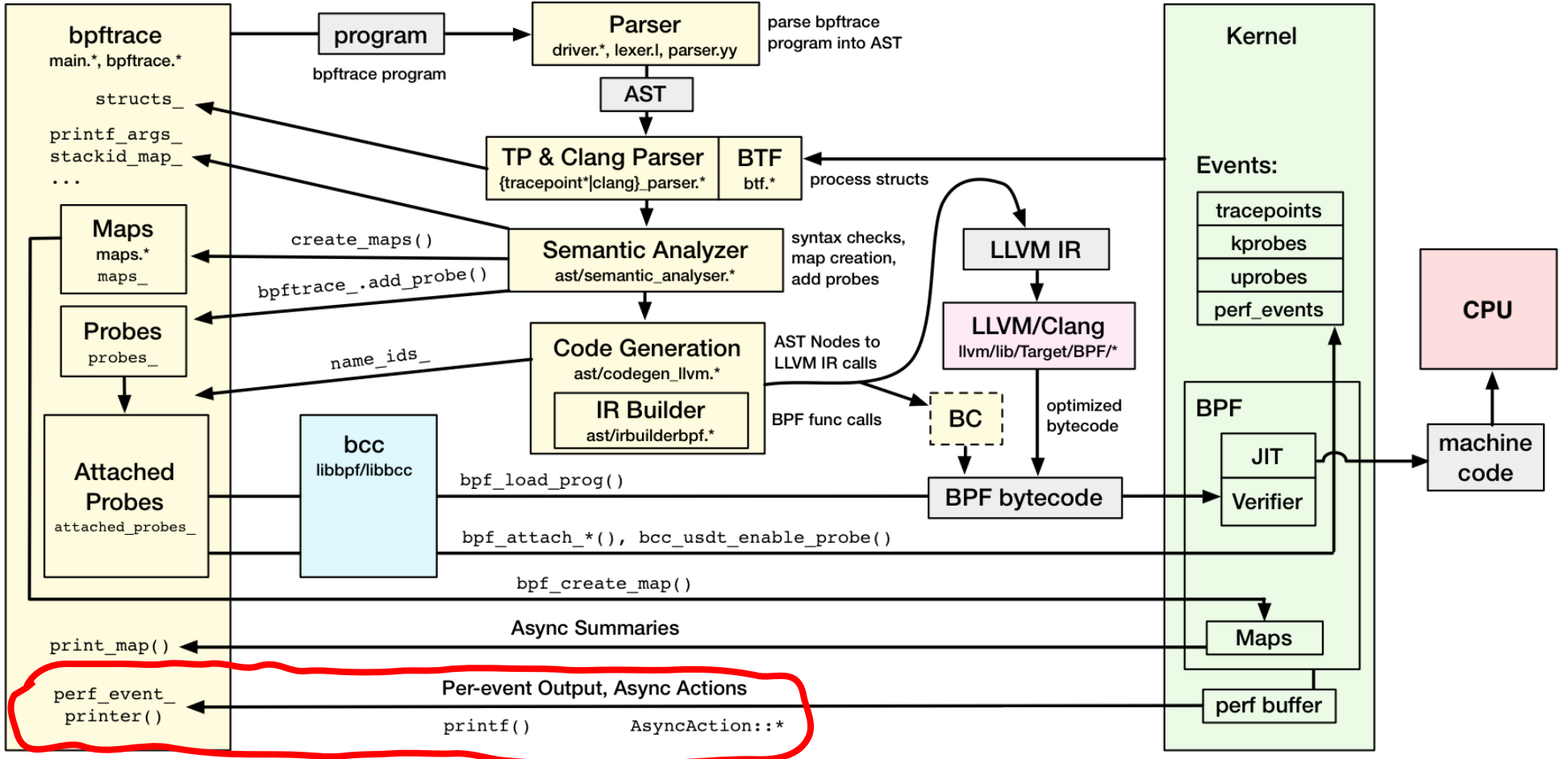
CPU ID



bpftrace waits for events using epoll_wait(2)

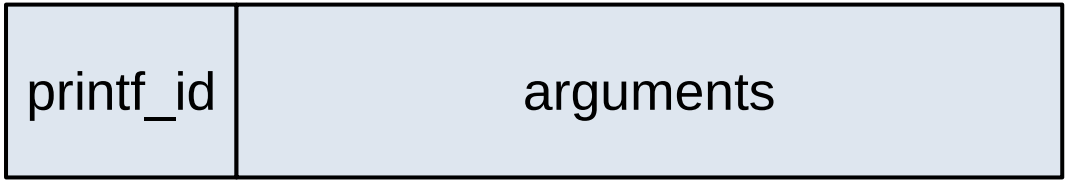
...

bpftrace mid-level internals 13/13



bpftrace printf & async actions

bpftrace perf output message format:



E.g., printf_id 0: `"PID %d sleeping...\n"`

bpftrace src/types.h

```
enum class AsyncAction
{
  // clang-format off
  printf  = 0,     // printf reserves 0-9999 for printf_ids
  syscall = 10000, // system reserves 10000-19999 for printf_ids
  cat     = 20000, // cat reserves 20000-29999 for printf_ids
  exit    = 30000,
  print,
  clear,
[...]
```

High numbers are used for other async actions:

bpftrace printf & async actions (2)

bpftrace src/bpftrace.cpp

```
void perf_event_printer(void *cb_cookie, void *data, int size)
{
[…]
  auto printf_id = *reinterpret_cast<uint64_t *>(arg_data);
[…]
  // async actions
  if (printf_id == asyncactionint(AsyncAction::exit))
  {
    bpftrace->request_finalize();
    return;
  }
[…]
  // printf
  auto fmt = std::get<0>(bpftrace->printf_args_[printf_id]);
  auto args = std::get<1>(bpftrace->printf_args_[printf_id]);
  auto arg_values = bpftrace->get_arg_values(args, arg_data);

  bpftrace->out_->message(MessageType::printf, format(fmt, arg_values), false);
```

message() just prints it out

Final output

```
# bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid);
}'
Attaching 1 probe...
PID 10287 sleeping...
PID 10297 sleeping...
PID 10287 sleeping…
PID 10297 sleeping...
PID 10287 sleeping...
PID 2218 sleeping...
PID 10297 sleeping...
[...]
```

2. Static tracing and map summaries

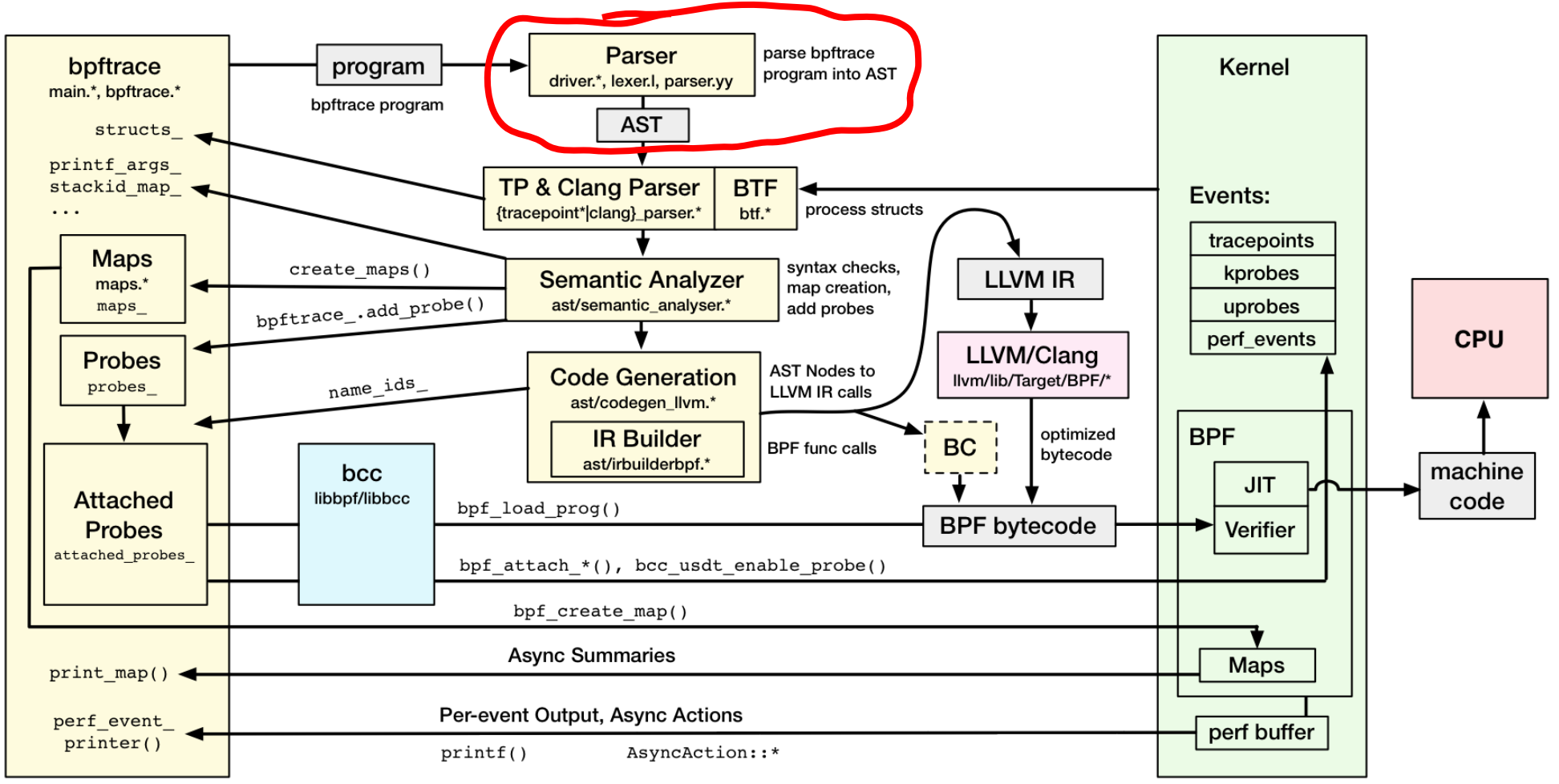
2. Static tracing and map summaries

```
bpftrace -e 'tracepoint:block:block_rq_issue {
    @[comm] = count();
}'
```

Example output

```
# bpftrace -e 'tracepoint:block:block_rq_issue {
    @[comm] = count();
}'
Attaching 1 probe…
^C
@[kworker/2:2H]: 131
@[chrome]: 135
@[kworker/7:1H]: 185
@[Xorg]: 245
@[tar]: 1204
@[dmcrypt_write/2]: 1993
```

bpftrace mid-level internals 1/4



Lexer & Yacc

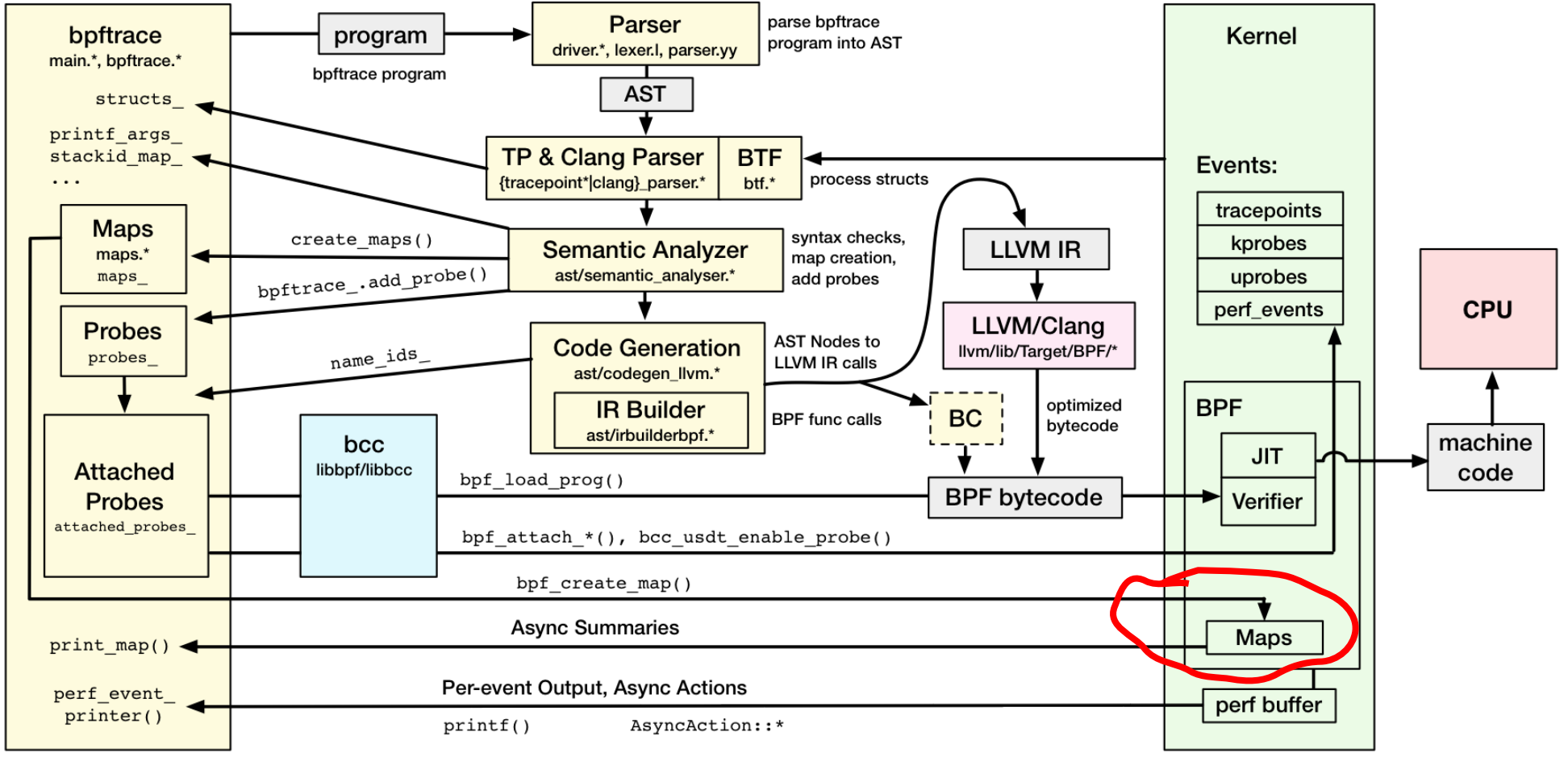
bpftrace src/lexer.l

```
map     @{ident}|@
[...]
```

bpftrace src/parser.yy

```
%token <std::string> MAP "map"
[...]
stmt : expr                 { $$ = new ast::ExprStatement($1, @1); }
     | compound_assignment  { $$ = $1; }
     | jump_stmt            { $$ = $1; }
     | map "=" expr         { $$ = new ast::AssignMapStatement($1, $3, false, @2); }
[...]
map : MAP                { $$ = new ast::Map($1, @$); }
    | MAP "[" vargs "]" { $$ = new ast::Map($1, $3, @$); }
```

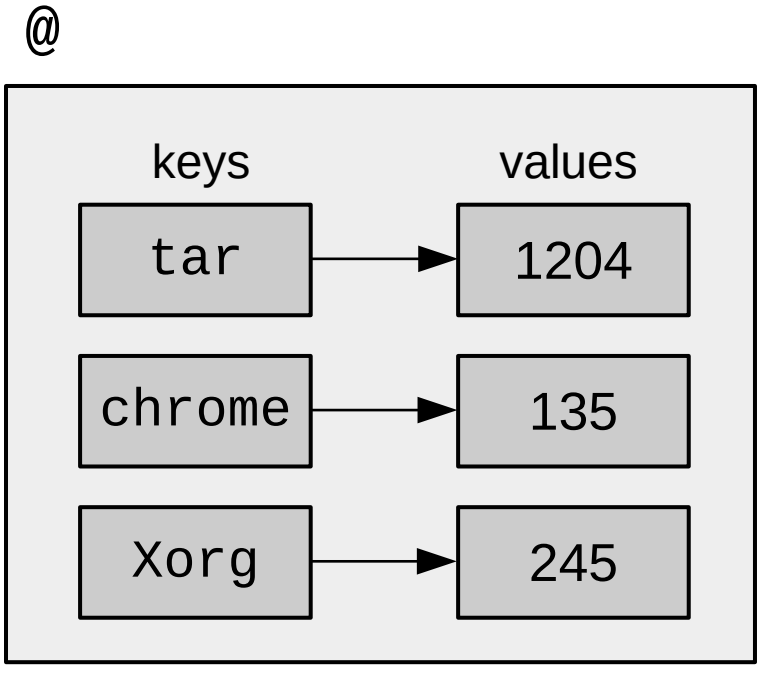
bpftrace mid-level internals 2/4



https://github.com/iovisor/bpftrace 2021, diagram by Brendan Gregg

BPF maps

- Custom data storage
- Can be a key/value store (hash)
- Also used for histogram summaries (BPF code calculates a bucket index as the key)



BPF map operations

User-space

bpf(2) syscall

BPF_MAP_CREATE
BPF_MAP_LOOKUP_ELEM
BPF_MAP_UPDATE_ELEM
BPF_MAP_DELETE_ELEM
BPF_MAP_GET_NEXT_KEY
[…]

BPF-space (kernel)

BPF helpers

bpf_map_lookup_elem()
bpf_map_update_elem()
bpf_map_delete_elem()
[…]

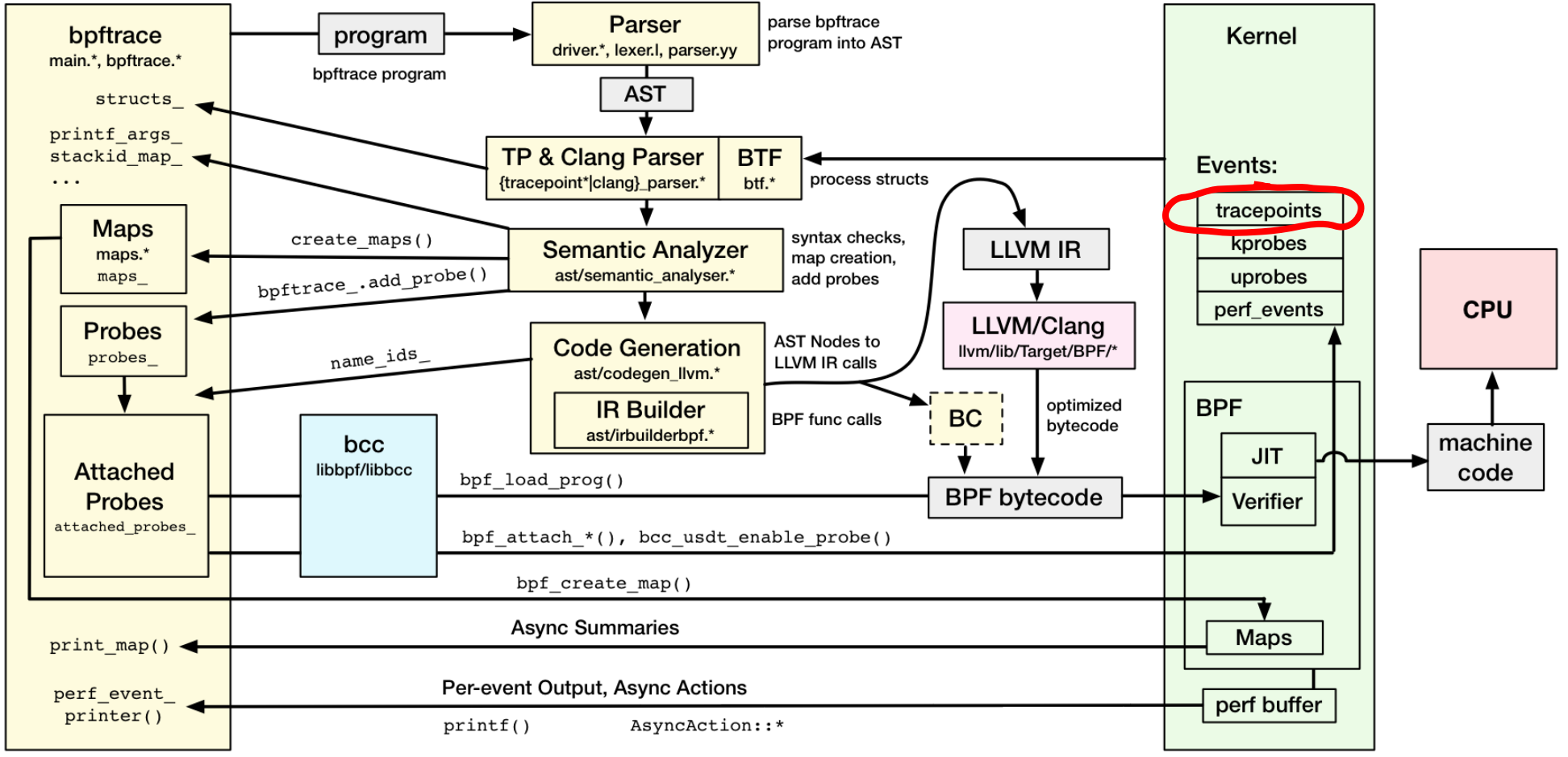
Creating BPF maps

```
# strace -febpf bpftrace -e 'block:block_rq_issue {
    @[comm] = count(); }'
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_ARRAY, key_size=4, value_size=4, max_entries=1,
map_flags=0, inner_map_fd=0, map_name="", map_ifindex=0, btf_fd=0, btf_key_type_id=0,
btf_value_type_id=0}, 120) = 3
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_PERCPU_HASH, key_size=16, value_size=8, max_entries=4096,
map_flags=0, inner_map_fd=0, map_name="@", map_ifindex=0, btf_fd=0, btf_key_type_id=0,
btf_value_type_id=0}, 120) = -1 EINVAL (Invalid argument)
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_PERCPU_HASH, key_size=16, value_size=8, max_entries=4096,
map_flags=0, inner_map_fd=0, map_name="", map_ifindex=0, btf_fd=0, btf_key_type_id=0,
btf_value_type_id=0}, 120) = 3
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_PERF_EVENT_ARRAY, key_size=4, value_size=4,
max_entries=8, map_flags=0, inner_map_fd=0, map_name="printf", map_ifindex=0, btf_fd=0,
btf_key_type_id=0, btf_value_type_id=0}, 120) = 4
[...]
```

Creating BPF maps

```
# strace -febpf bpftrace -e 'block:block_rq_issue {
    @[comm] = count(); }'
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_ARRAY, key_size=4, value_size=4, max_entries=1,
map_flags=0, inner_map_fd=0, map_name="", map_ifindex=0, btf_fd=0, btf_key_type_id=0,
btf_value_type_id=0}, 120) = 3
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_PERCPU_HASH, key_size=16, value_size=8, max_entries=4096,
map_flags=0, inner_map_fd=0, map_name="@", map_ifindex=0, btf_fd=0, btf_key_type_id=0,
btf_value_type_id=0}, 120) = -1 EINVAL (Invalid argument)
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_PERCPU_HASH, key_size=16, value_size=8, max_entries=4096,
map_flags=0, inner_map_fd=0, map_name="", map_ifindex=0, btf_fd=0, btf_key_type_id=0,
btf_value_type_id=0}, 120) = 3
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_PERF_EVENT_ARRAY, key_size=4, value_size=4,
max_entries=8, map_flags=0, inner_map_fd=0, map_name="printf", map_ifindex=0, btf_fd=0,
btf_key_type_id=0, btf_value_type_id=0}, 120) = 4
[...]
```

bpftrace mid-level internals 3/4



Tracepoint defined

Linux include/trace/events/block.h

```
DECLARE_EVENT_CLASS(block_rq,

        TP_PROTO(struct request_queue *q, struct request *rq),

        TP_ARGS(q, rq),

        TP_STRUCT__entry(
                __field(  dev_t,        dev                     )
                __field(  sector_t,     sector                  )
                __field(  unsigned int, nr_sector               )
                __field(  unsigned int, bytes                   )
                __array(  char,         rwbs,   RWBS_LEN        )
                __array(  char,         comm,   TASK_COMM_LEN   )
                __dynamic_array( char,  cmd,    1               )
        ),

        TP_fast_assign(
                __entry->dev       = rq->rq_disk ? disk_devt(rq->rq_disk) : 0;
                __entry->sector    = blk_rq_trace_sector(rq);
[...]
DEFINE_EVENT(block_rq, block_rq_issue,

        TP_PROTO(struct request_queue *q, struct request *rq),

        TP_ARGS(q, rq)
);
```

Tracepoints in code

Linux kernel/block/block-mq.c

```
void blk_mq_start_request(struct request *rq)
{
        struct request_queue *q = rq->q;

        trace_block_rq_issue(q, rq);

        if (test_bit(QUEUE_FLAG_STATS, &q->queue_flags)) {
                rq->io_start_time_ns = ktime_get_ns();
                rq->stats_sectors = blk_rq_sectors(rq);
[...]
```

This is a (best effort) *stable* interface

Use tracepoints instead of kprobes when possible!

Instrumenting tracepoints (2)

How do we include the tracepoint without adding overhead?

```
(gdb) disas/r blk_mq_start_request
Dump of assembler code for function blk_mq_start_request:
   0xffffffff815118e0 <+0>:   e8 4b bf b5 ff   callq  0xffffffff8106d830 <__fentry__>
   0xffffffff815118e5 <+5>:   55               push   %rbp
   0xffffffff815118e6 <+6>:   48 89 e5         mov    %rsp,%rbp
   0xffffffff815118e9 <+9>:   41 55            push   %r13
   0xffffffff815118eb <+11>:  41 54            push   %r12
   0xffffffff815118ed <+13>:  49 89 fc         mov    %rdi,%r12
   0xffffffff815118f0 <+16>:  53               push   %rbx
   0xffffffff815118f1 <+17>:  4c 8b 2f         mov    (%rdi),%r13
   0xffffffff815118f4 <+20>:  0f 1f 44 00 00   nopl   0x0(%rax,%rax,1)
   0xffffffff815118f9 <+25>:  49 8b 45 60      mov    0x60(%r13),%rax
[...]
```

(this is actually quite easy)

Instrumenting tracepoints (2)

How do we include the tracepoint without adding overhead?

```
(gdb) disas/r blk_mq_start_request
Dump of assembler code for function blk_mq_start_request:
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   0xffffffff815118e9 <+9>:   41 55            push   %r13
   0xffffffff815118eb <+11>:  41 54            push   %r12
   0xffffffff815118ed <+13>:  49 89 fc         mov    %rdi,%r12
   0xffffffff815118f0 <+16>:  53               push   %rbx
   0xffffffff815118f1 <+17>:  4c 8b 2f         mov    (%rdi),%r13
   0xffffffff815118f4 <+20>:  0f 1f 44 00 00   nopl   0x0(%rax,%rax,1)
   0xffffffff815118f9 <+25>:  49 8b 45 60      mov    0x60(%r13),%rax
[...]
```
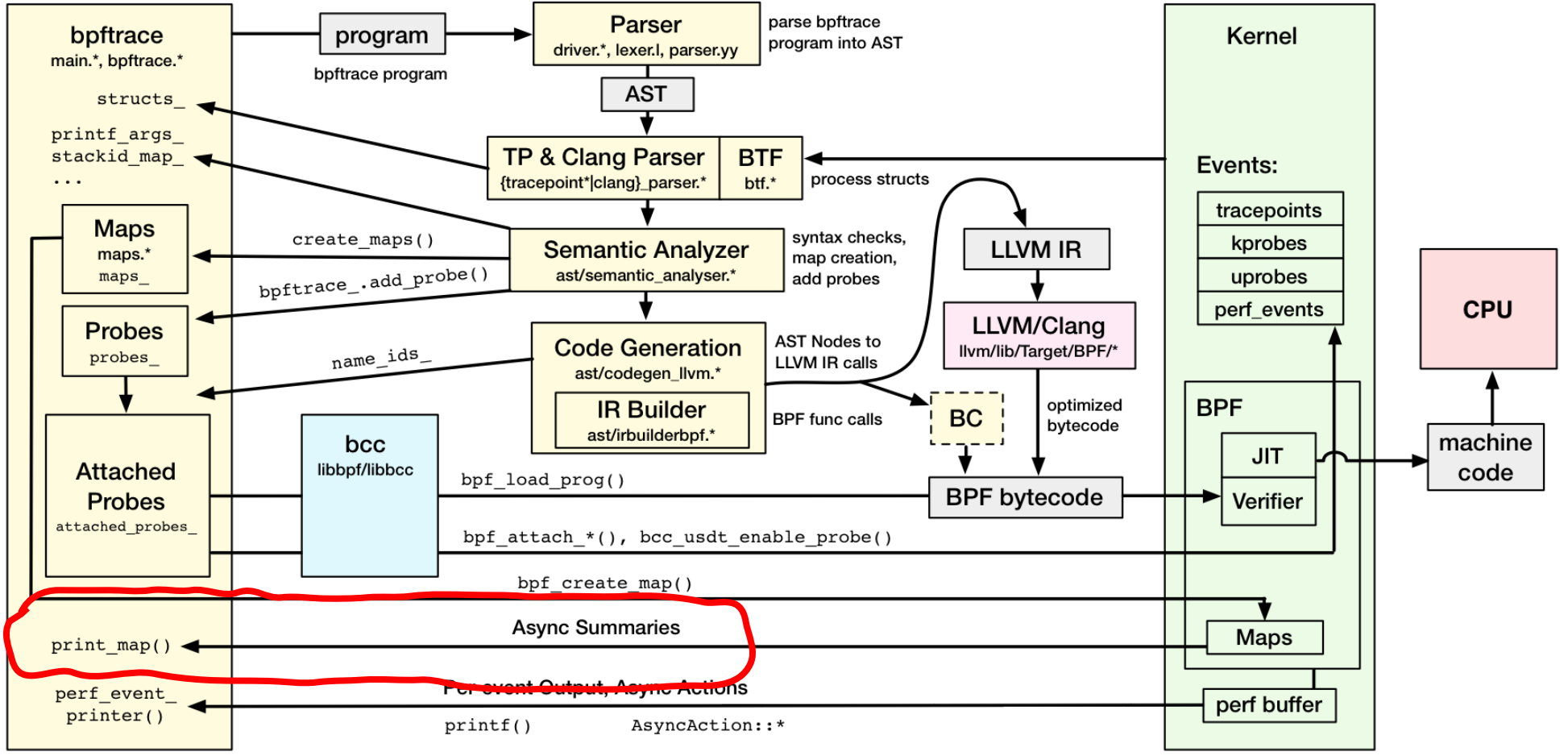

This 5-byte nop is a placeholder. Does nothing quickly.

When the tracepoint is enabled, the nop becomes a jmp to the tracepoint trampoline.

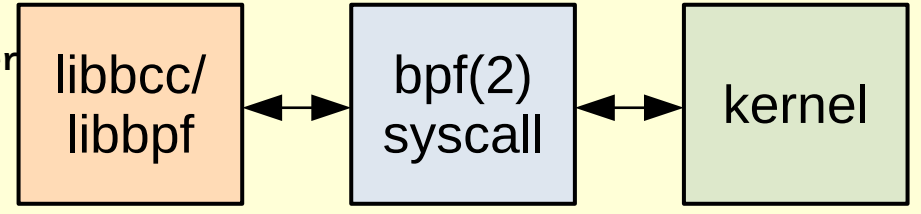
bpftrace mid-level internals 4/4



User-space map iteration

bpftrace src/bpftrace.cpp

```
int BPFtrace::print_map(IMap &map, uint32_t top, uint32_t div)
[…]
  while (bpf_get_next_key(map.mapfd_, old_key.data(), key.data()) == 0)
  {
    int value_size = map.type_.GetSize();
    value_size *= nvalues;
    auto value = std::vector<uint8_t>(value_size);
    int err = bpf_lookup_elem(map.mapfd_, key.data(), value.data());
    if (err == -1)
    {
      // key was removed by the eBPF program during bpf_get_next_key() and bpf_lookup_elem(),
      // let's skip this key
      continue;
    }
    else if (err)
    {
      LOG(ERROR) << "failed to look up elem: " << er
      return -1;
    }

    values_by_key.push_back({key, value});

    old_key = key;
  }
```



Reading entire BPF maps

```
# strace -febpf bpftrace -e 'block:block_rq_issue {
    @[comm] = count(); }'
[...]
bpf(BPF_MAP_LOOKUP_ELEM, {map_fd=3, key=0x557e422133e0, value=0x557e4221eab0, flags=BPF_ANY}, 120) = -
1 ENOENT (No such file or directory)
bpf(BPF_MAP_GET_NEXT_KEY, {map_fd=3, key=0x557e422133e0, next_key=0x557e4224d3f0}, 120) = 0
bpf(BPF_MAP_LOOKUP_ELEM, {map_fd=3, key=0x557e4224d3f0, value=0x557e4221eab0, flags=BPF_ANY}, 120) = 0
bpf(BPF_MAP_GET_NEXT_KEY, {map_fd=3, key=0x557e422133e0, next_key=0x557e4224d3f0}, 120) = 0
bpf(BPF_MAP_LOOKUP_ELEM, {map_fd=3, key=0x557e4224d3f0, value=0x557e4221eab0, flags=BPF_ANY}, 120) = 0
bpf(BPF_MAP_GET_NEXT_KEY, {map_fd=3, key=0x557e422133e0, next_key=0x557e4224d3f0}, 120) = 0
bpf(BPF_MAP_LOOKUP_ELEM, {map_fd=3, key=0x557e4224d3f0, value=0x557e4221eab0, flags=BPF_ANY}, 120) = 0
bpf(BPF_MAP_GET_NEXT_KEY, {map_fd=3, key=0x557e422133e0, next_key=0x557e4224d3f0}, 120) = 0
bpf(BPF_MAP_LOOKUP_ELEM, {map_fd=3, key=0x557e4224d3f0, value=0x557e4221eab0, flags=BPF_ANY}, 120) = 0
bpf(BPF_MAP_GET_NEXT_KEY, {map_fd=3, key=0x557e422133e0, next_key=0x557e4224d3f0}, 120) = 0
bpf(BPF_MAP_LOOKUP_ELEM, {map_fd=3, key=0x557e4224d3f0, value=0x557e4221eab0, flags=BPF_ANY}, 120) = 0
bpf(BPF_MAP_GET_NEXT_KEY, {map_fd=3, key=0x557e422133e0, next_key=0x557e4224d3f0}, 120) = 0
bpf(BPF_MAP_LOOKUP_ELEM, {map_fd=3, key=0x557e4224d3f0, value=0x557e4221eab0, flags=BPF_ANY}, 120) = 0
[...]
```

This is an infrequent activity (this program only does this once)

Final output

```
# bpftrace -e 'tracepoint:block:block_rq_issue {
    @[comm] = count();
}'
Attaching 1 probe…
^C
@[kworker/2:2H]: 131
@[chrome]: 135
@[kworker/7:1H]: 185
@[Xorg]: 245
@[tar]: 1204
@[dmcrypt_write/2]: 1993
```

Discussion of other internals

Stack walking

BTF

CO-RE

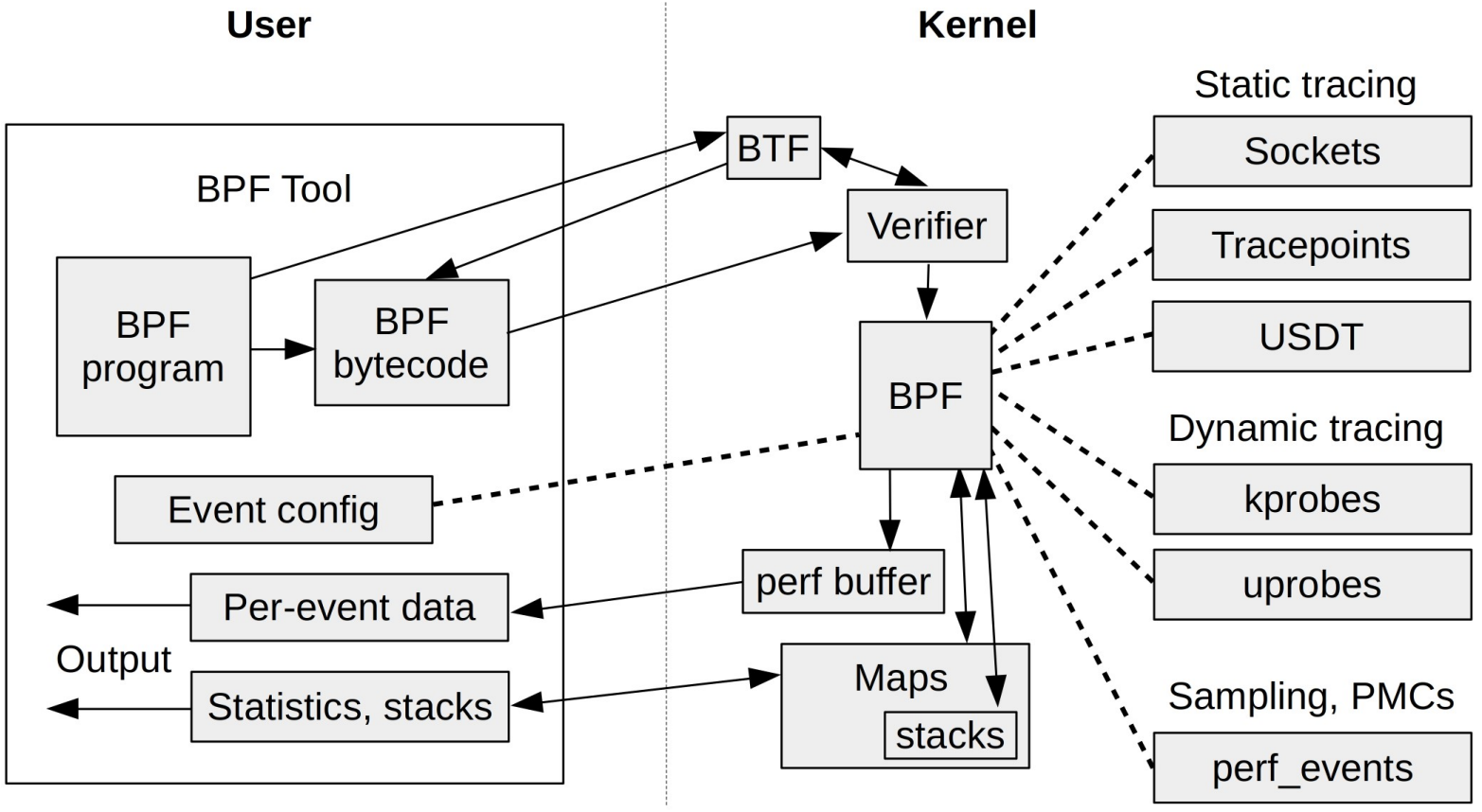
Tests

raw_tracepoints & fentry

Networking & XDP

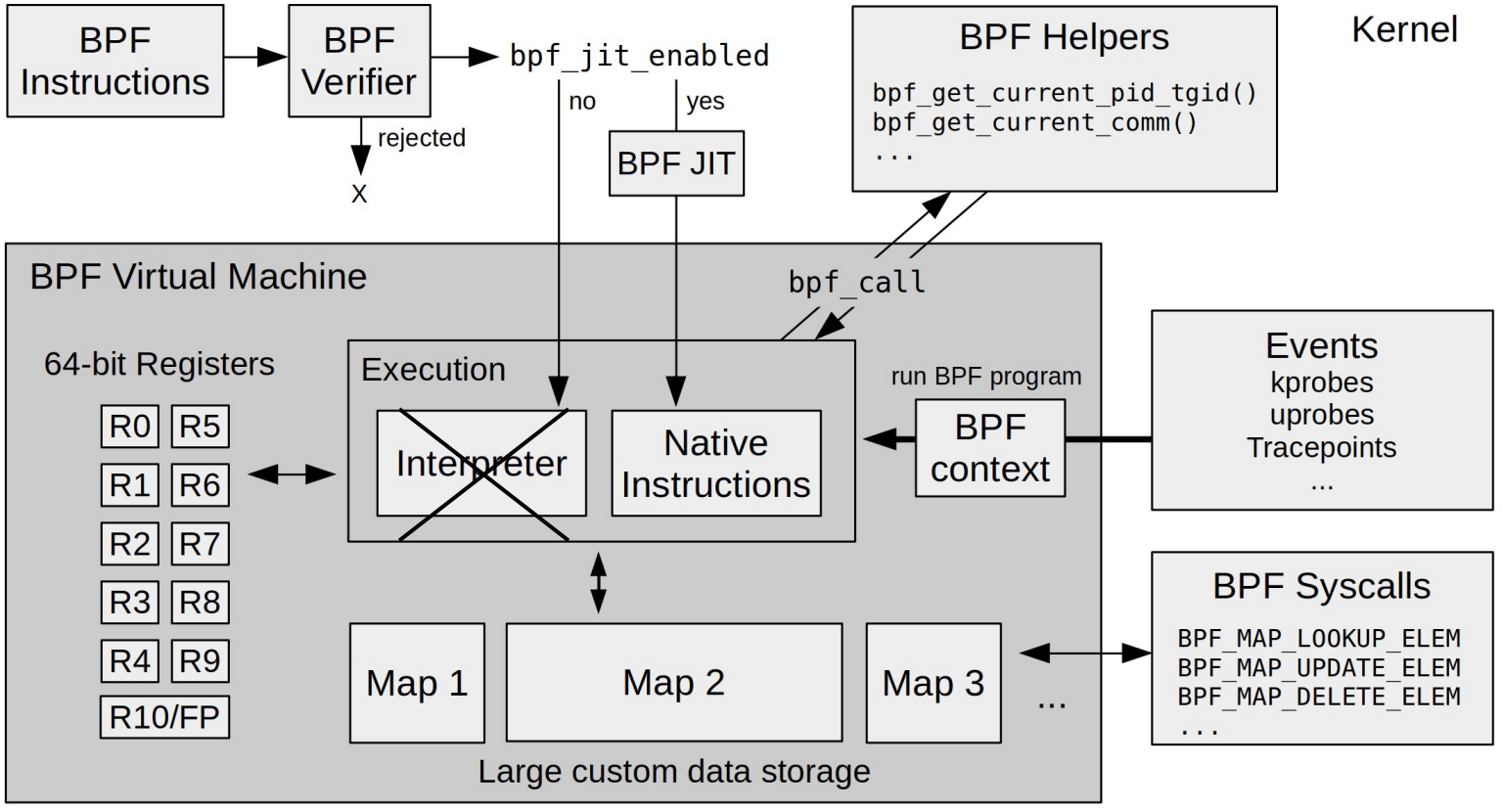
Security & Cgroups

BPF tracing/observability high-level recap



From: BPF Performance Tools, Figure 2-1

BPF mid-level internals recap



From: BPF Performance Tools, Figure 2-3

PSA

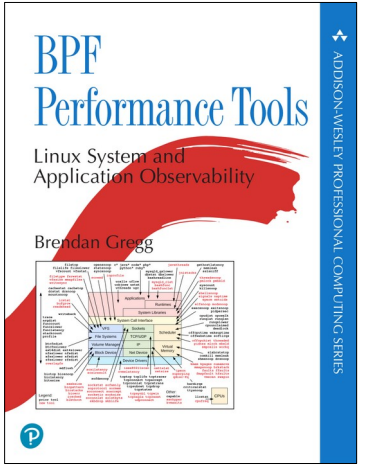
CONFIG_DEBUG_INFO_BTF=y

E.g., Ubuntu 20.10, Fedora 30, and RHEL 8.2 have it

References

This is also where I recommend you go to learn more:

- https://events.static.linuxfound.org/sites/events/files/slides/bpf_collabsummit_2015feb20.pdf
- Linux include/uapi/linux/bpf_common.h
- Linux include/uapi/linux/bpf.h
- Linux include/uapi/linux/filter.h
- https://docs.cilium.io/en/v1.9/bpf/#bpf-guide
- BPF Performance Tools, Addison-Wesley 2020
- https://ebpf.io/what-is-ebpf
- http://www.brendangregg.com/ebpf.html
- https://github.com/iovisor/bcc
- https://github.com/iovisor/bpftrace



Thanks

BPF: Alexei Starovoitov (Facebook), Daniel Borkmann (Isovalent), David S. Miller (Red Hat), Jakub Kicinski (Facebook), Yonghong Song (Facebook), Martin KaFai Lau (Facebook), John Fastabend (Isovalent), Quentin Monnet (Isovalent), Jesper Dangaard Brouer (Red Hat), Andrey Ignatov (Facebook), and Stanislav Fomichev (Google), Linus Torvalds, and many more in the BPF community

LLVM BPF: Alexei Starovoitov, Chandler Carruth (Google), Yonghong Song, and more

bpftrace: Alastair Robertson (Yellowbrick Data), Dan Xu (Facebook), Bas Smit, Mary Marchini (Netflix), Masanori Misono, Jiri Olsa, Viktor Malík, Dale Hamel, Willian Gaspar, Augusto Mecking Caringi, and many more in the bpftrace community

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Jun, 2021

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