

BPF Internals

(eBPF)

Tracing Examples

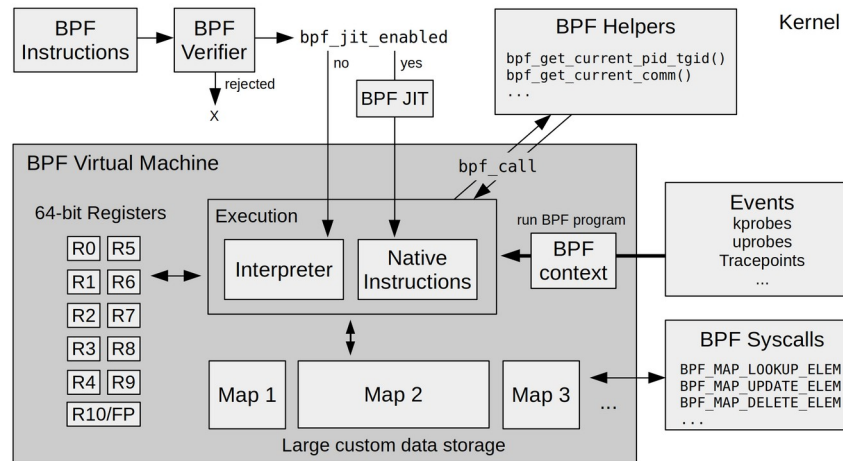
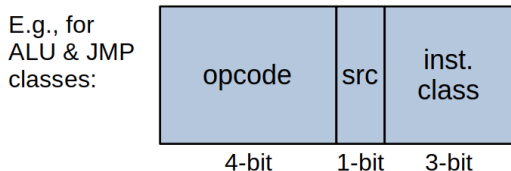
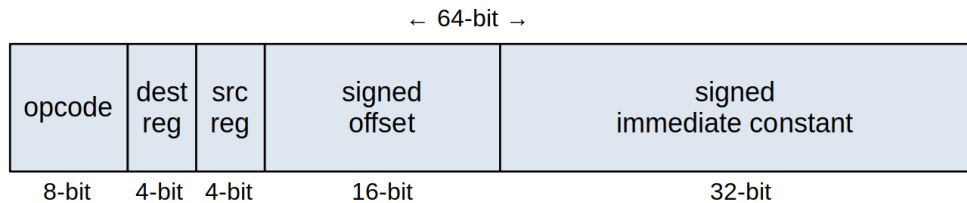
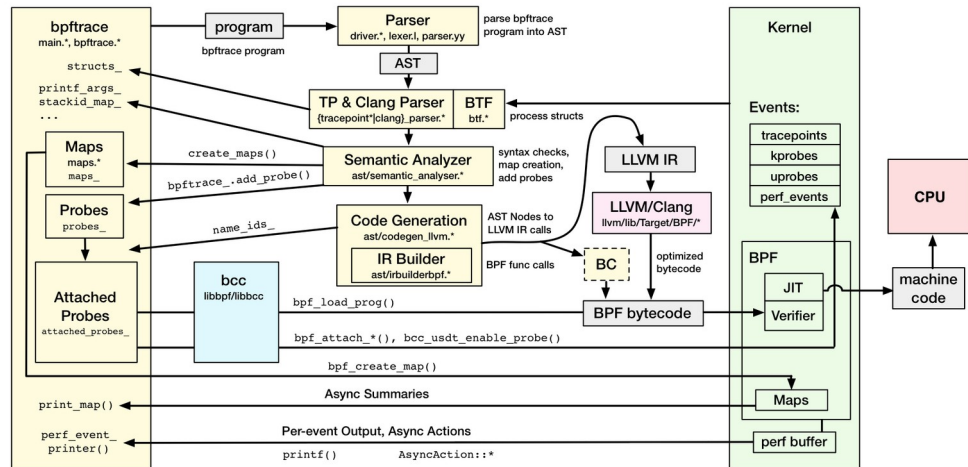
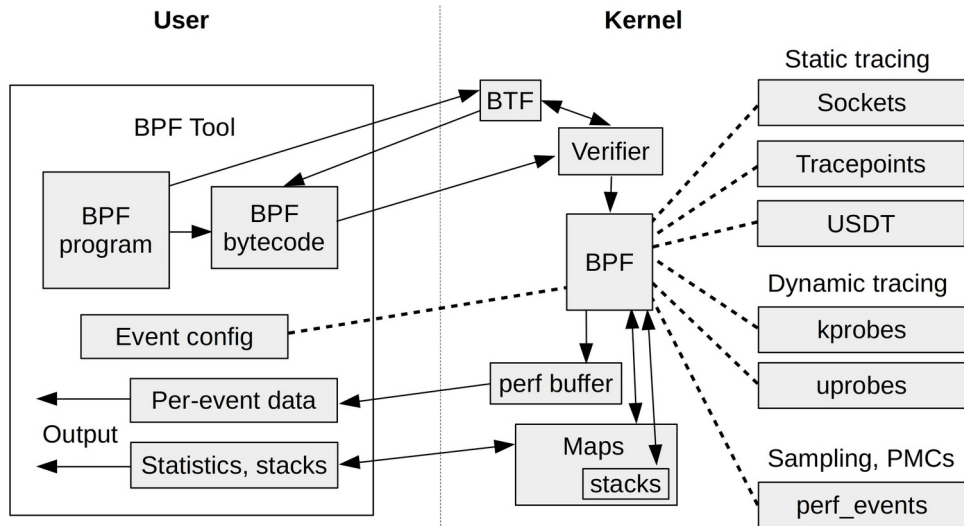
Brendan Gregg

USENIX

LISA21

Jun, 2021

NETFLIX



(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

Learning objectives

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

Slides are online

Slides: http://www.brendangregg.com/Slides/LISA2021_BPF_Internals.pdf

Video: <https://www.usenix.org/conference/lisa21/presentation/gregg-bpf>

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

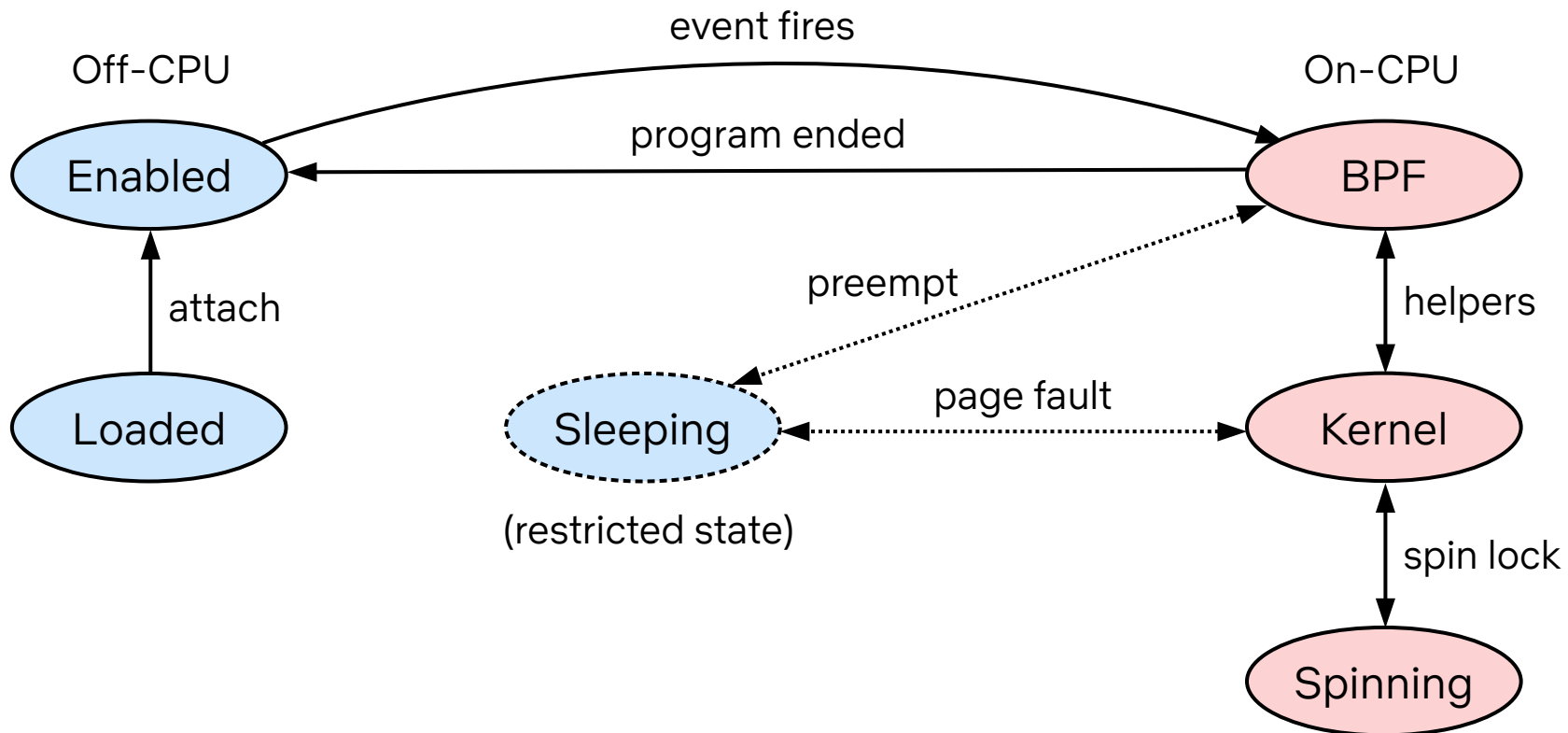
A generic in-kernel execution environment

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

A New Type of Software

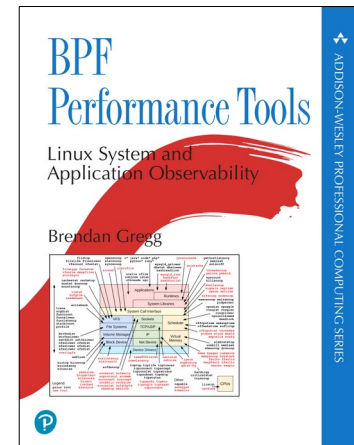
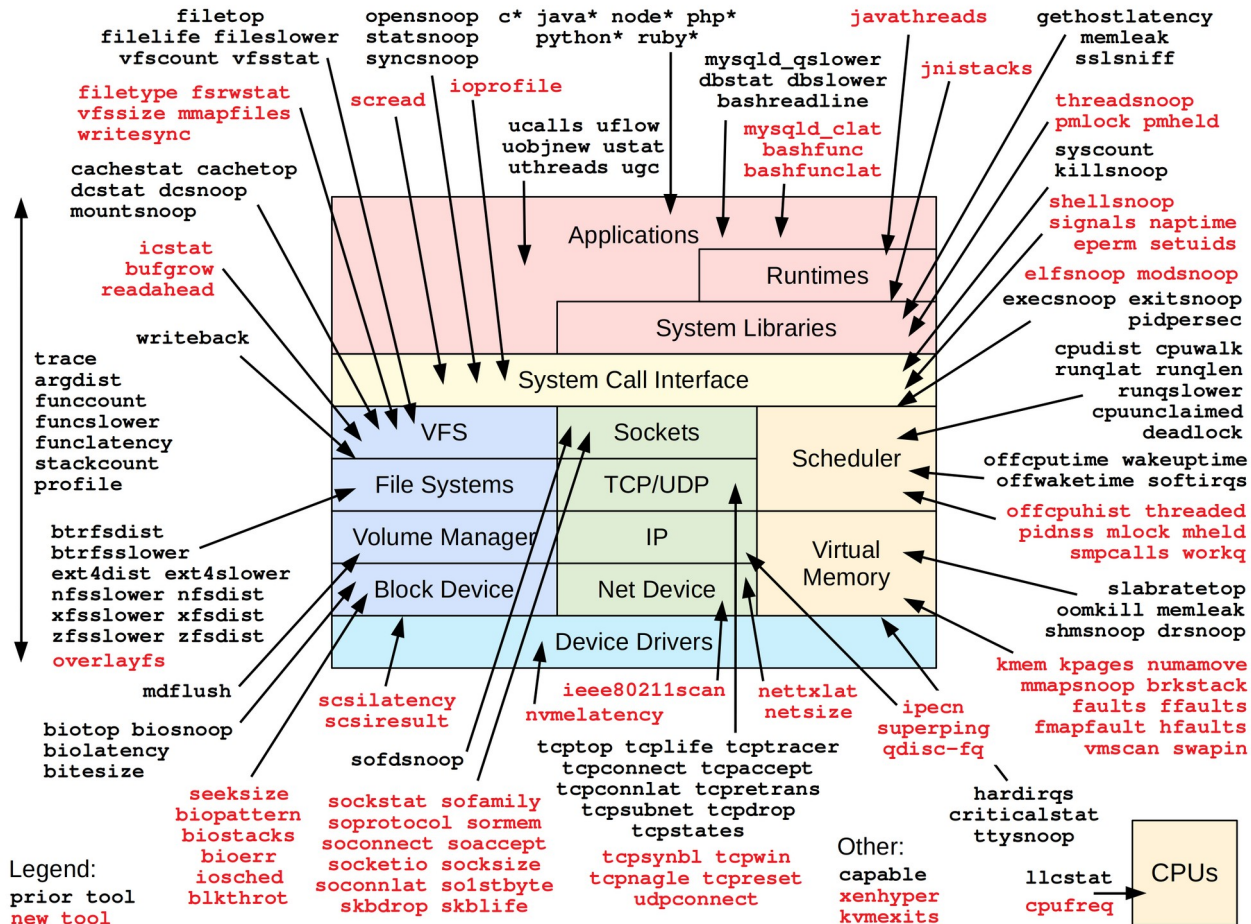
	Execution model	User defined	Compilation	Security	Failure mode	Resource access
User	task	yes	any	user based	abort	syscall, fault
Kernel	task	no	static	none	panic	direct
BPF	event	yes	JIT, CO-RE	verified, JIT	error message	restricted helpers

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, libbpf-rs**

C, C++

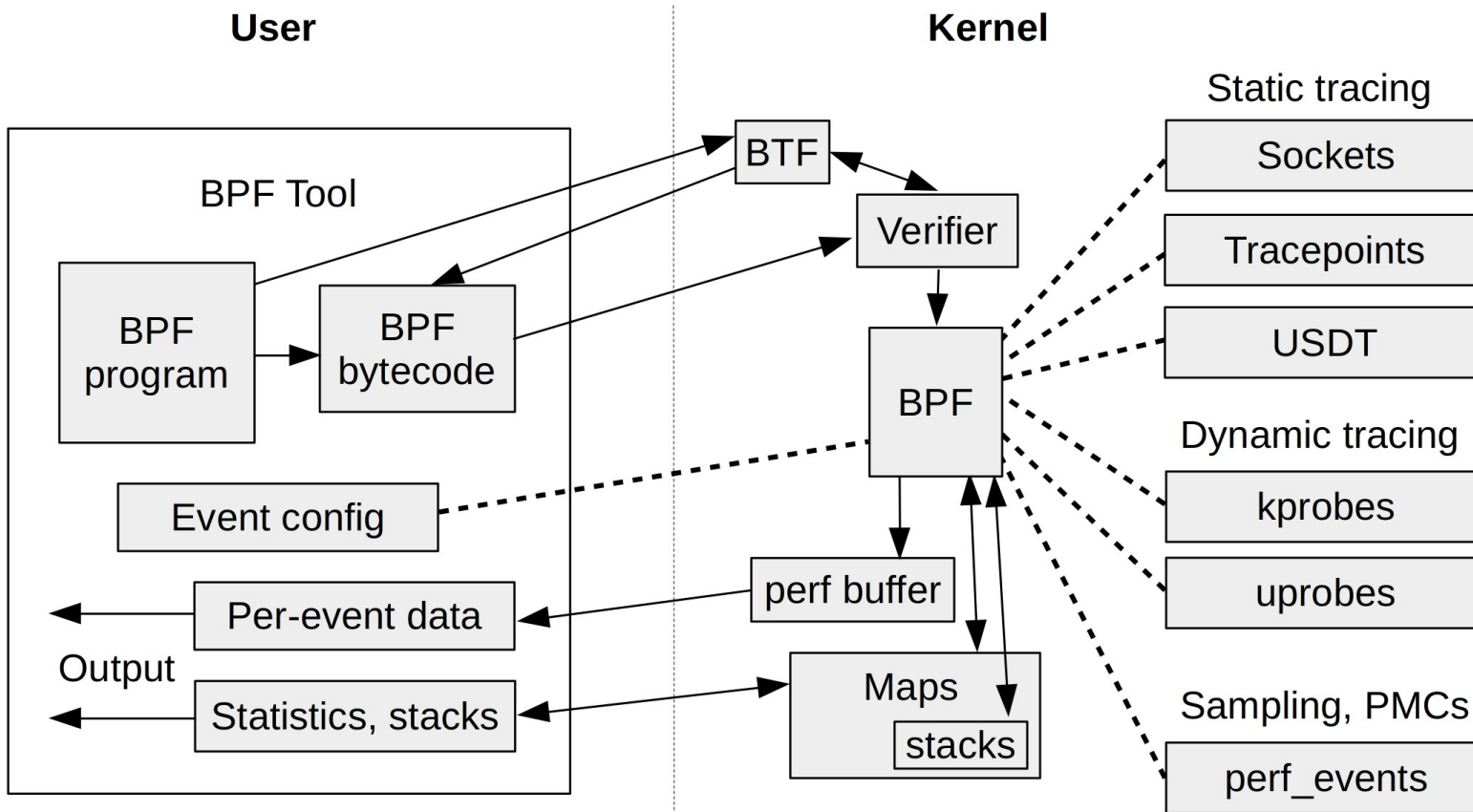
↙
New, lightweight,
CO-RE & BTF based

↘
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:

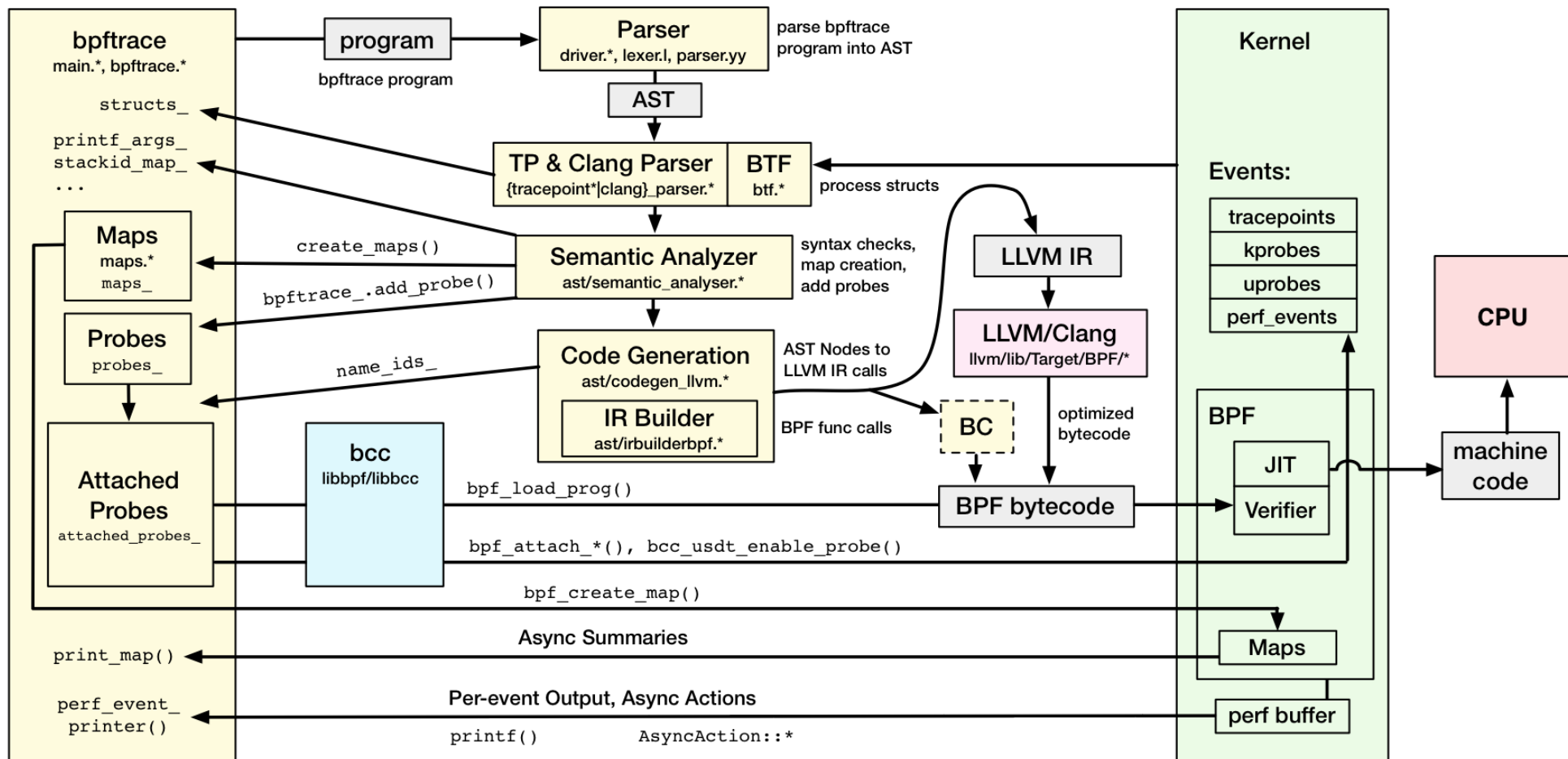
```
bpftrace -e 'kprobe:do_nanosleep {  
    printf("PID %d sleeping...\n", pid);  
}'
```

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.

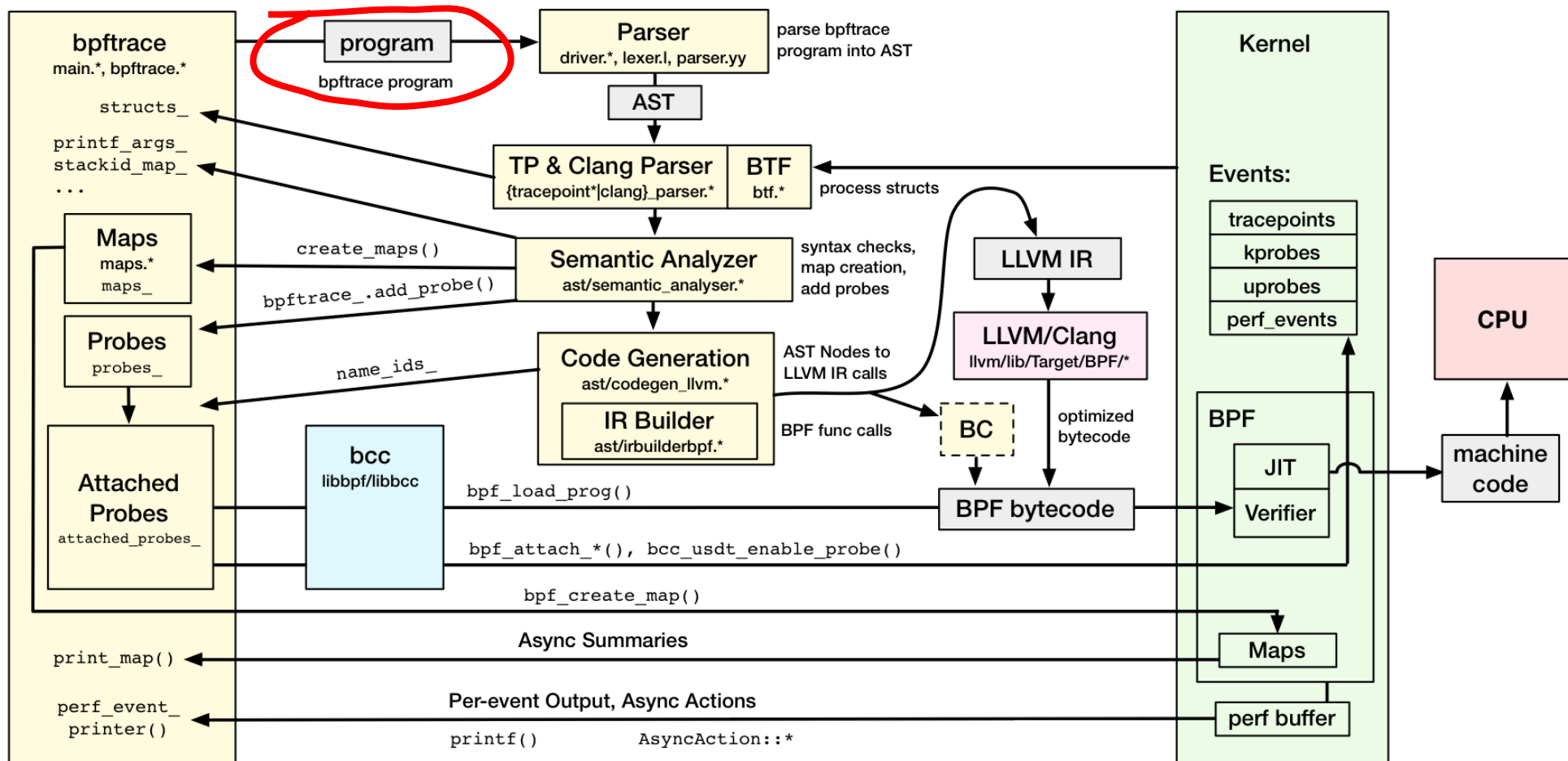
bpftrace mid-level internals



Program transformations



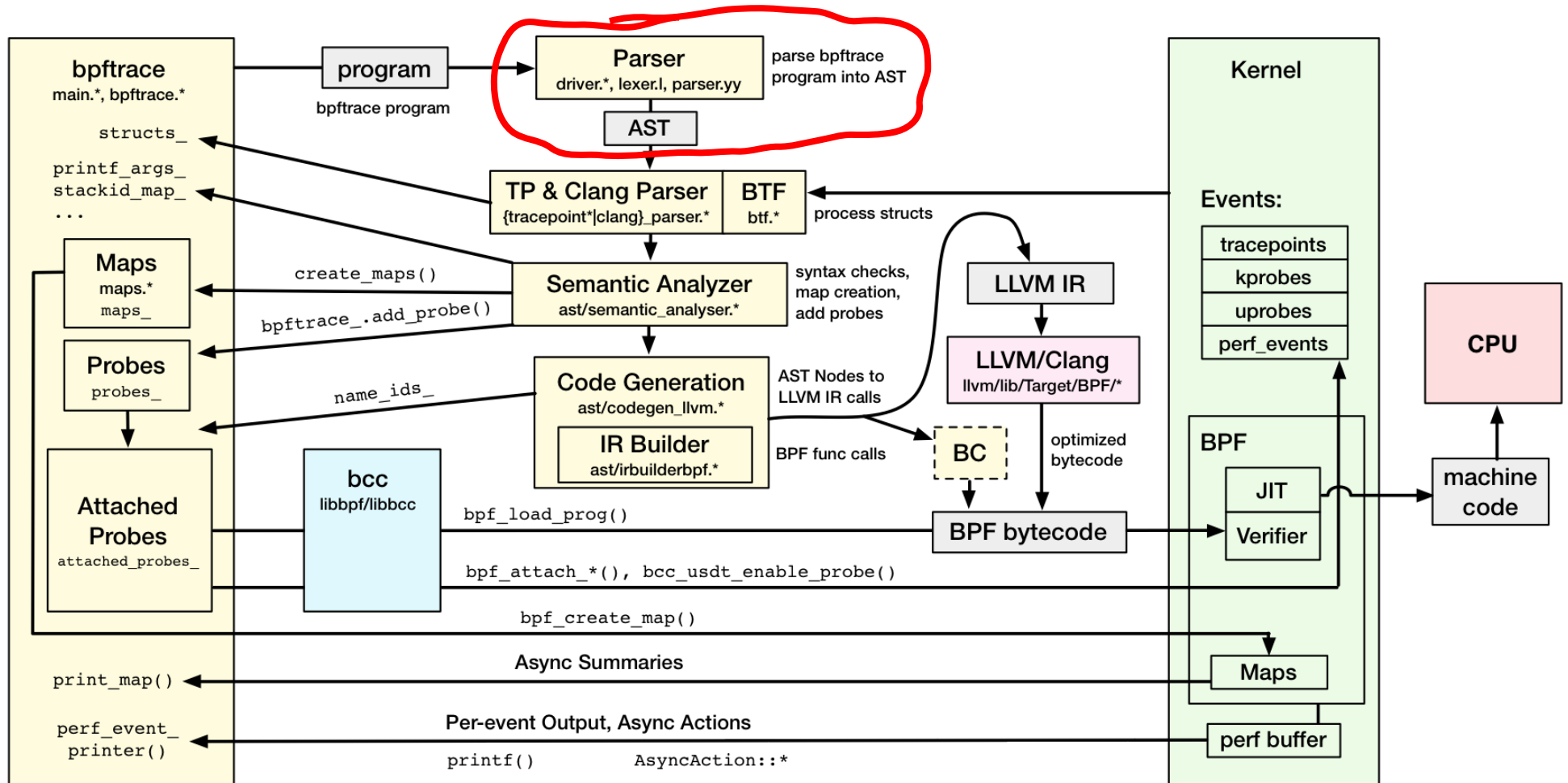
bpftrace mid-level internals 1/13



bpfttrace program

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

bpftrace mid-level internals 2/13



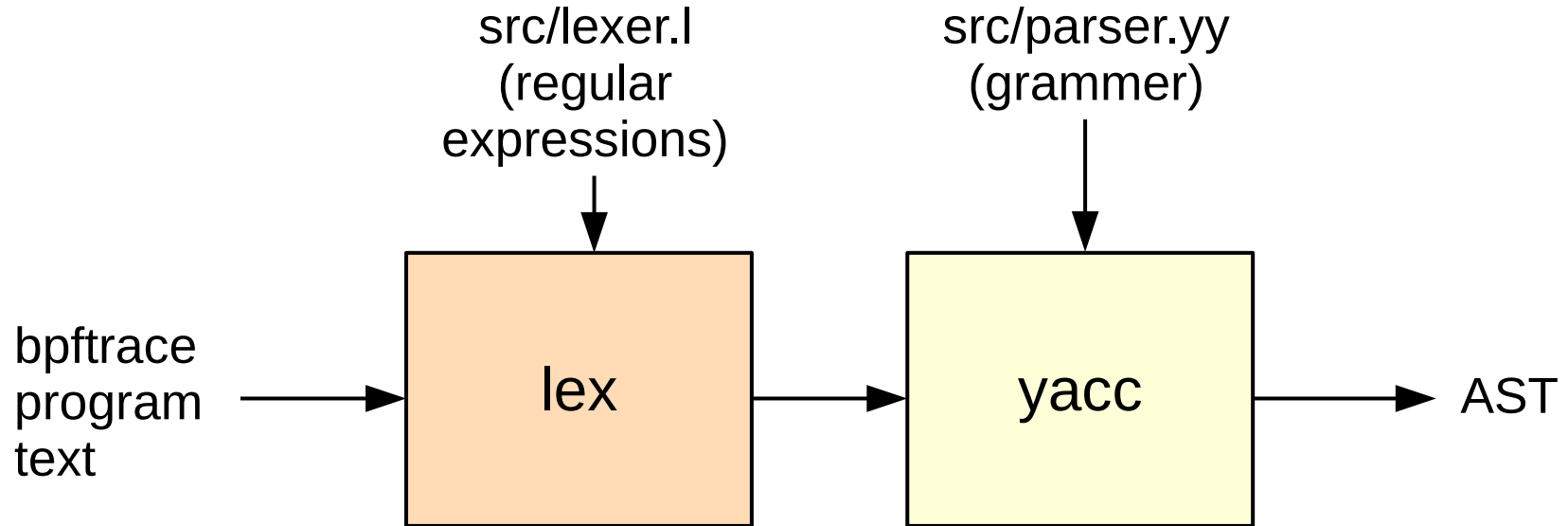
Converting to AST

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



```
probe(kprobe:do_nanosleep)  
  call(printf)  
    string("PID %d sleeping...\n")  
    builtin(pid)
```

Parsing bpftrace



(very easy)

Lexer

pid

Regular expressions

bpfttrace 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

builtin(pid)

Grammar rules

bpfttrace 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, $3, @$); }
```

Lexer (2)

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

bpfttrace 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}
[...]
```

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(...));`

bpfftrace 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, $3, @$); }
```

Lexer (3)

"PID %d sleeping... \n"

bpfttrace src/lexer.l

```
\n                { yy_push_state(STR, yyscanner); buffer.clear(); }
<STR>{
  \n                { 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")`

bpfftrace src/parser.yy

```
%token <std::string> STRING "string"
[...]
```

<code>expr :</code>	<code>int</code>	<code>{ \$\$ = \$1; }</code>
	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

bpfftrace src/lexer.l

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

bpfftrace 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.

bpfttrace src/lexer.l

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

4.

3.

bpfttrace 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 { $$ = $1 + "."; }
          | { $$ = ""; }
;
```

Yacc (5)

```
{ statements; ... }
```

Plus more grammar for program structure...

bpfftrace 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

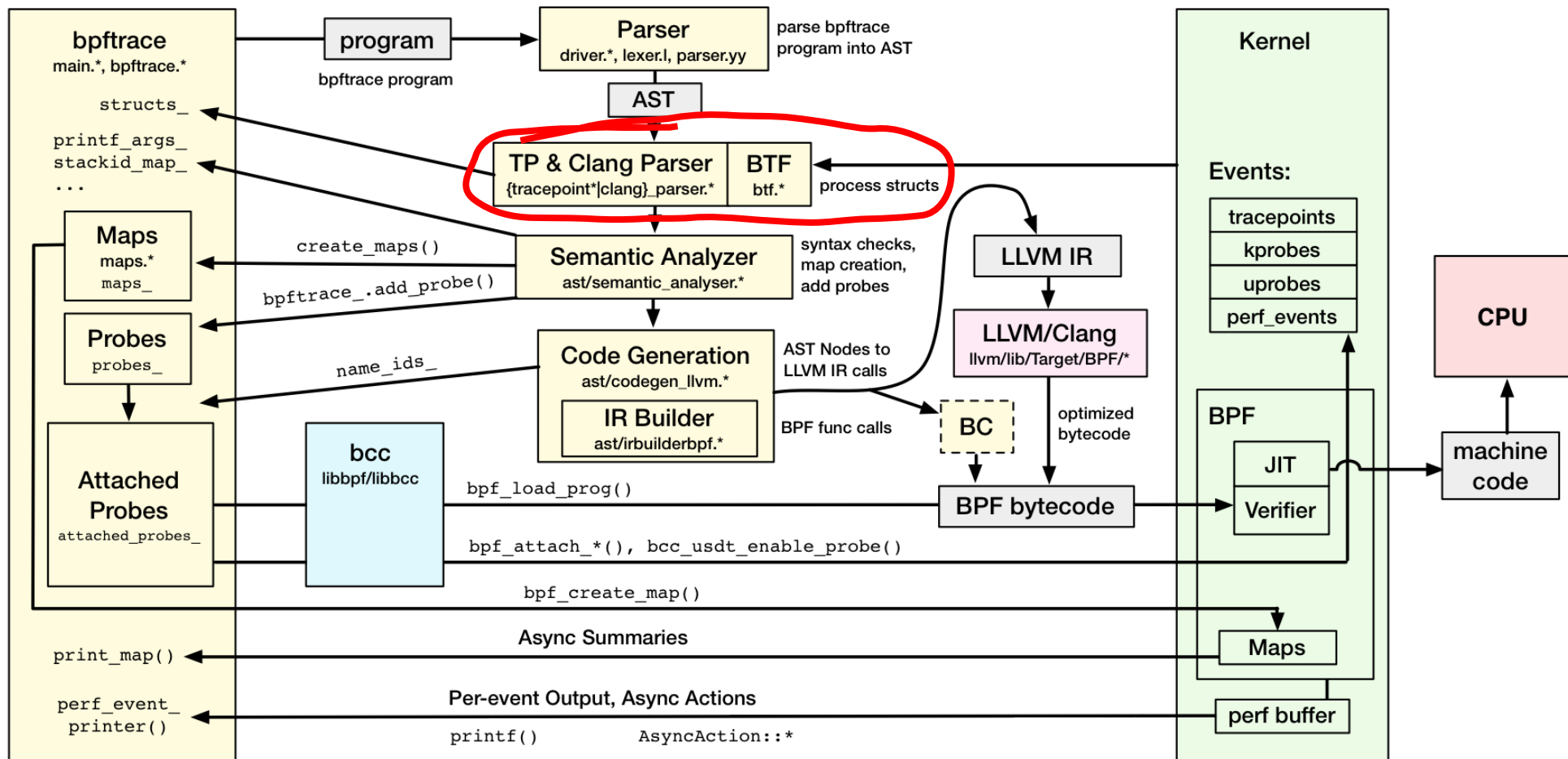
call: printf

string: PID %d sleeping...\n

builtin: pid

[...]

bpftrace mid-level internals 3/13

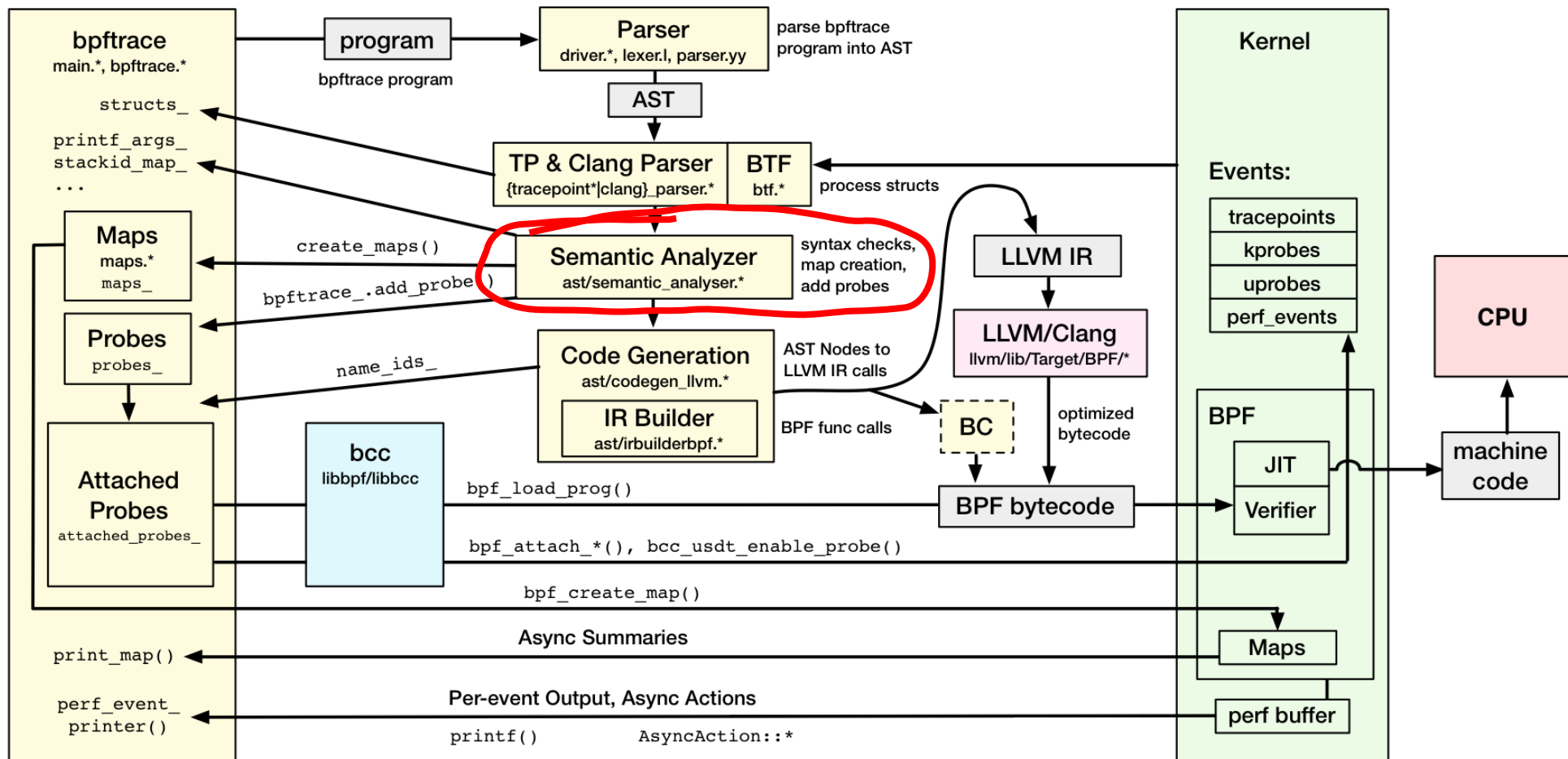


Tracepoint & Clang struct parsers

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

Not needed for this example
(no struct member dereferencing)

bpftrace mid-level internals 4/13



Semantic analyzer

Catches many program errors; E.g.:

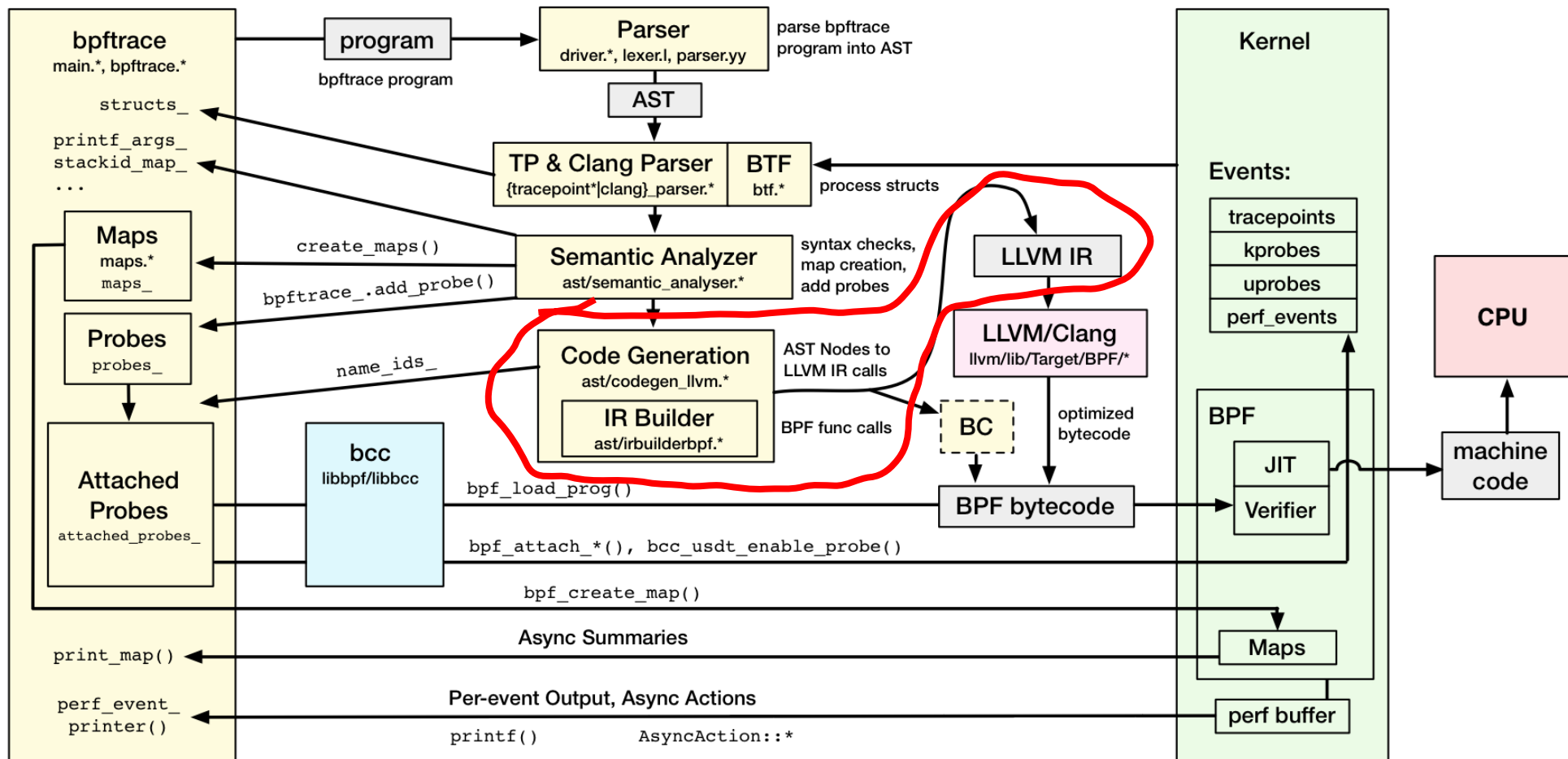
```
# bpftrace -e 'kprobe:do_nanosleep {  
    printf("PID %d sleeping...\n", pidd); }'  
stdin:2:36-38: ERROR: Unknown identifier: 'pidd'  
    printf("PID %d sleeping...\n", pidd);
```

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

bpfftrace 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), \
    [...]

→ #14
```

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  
}
```

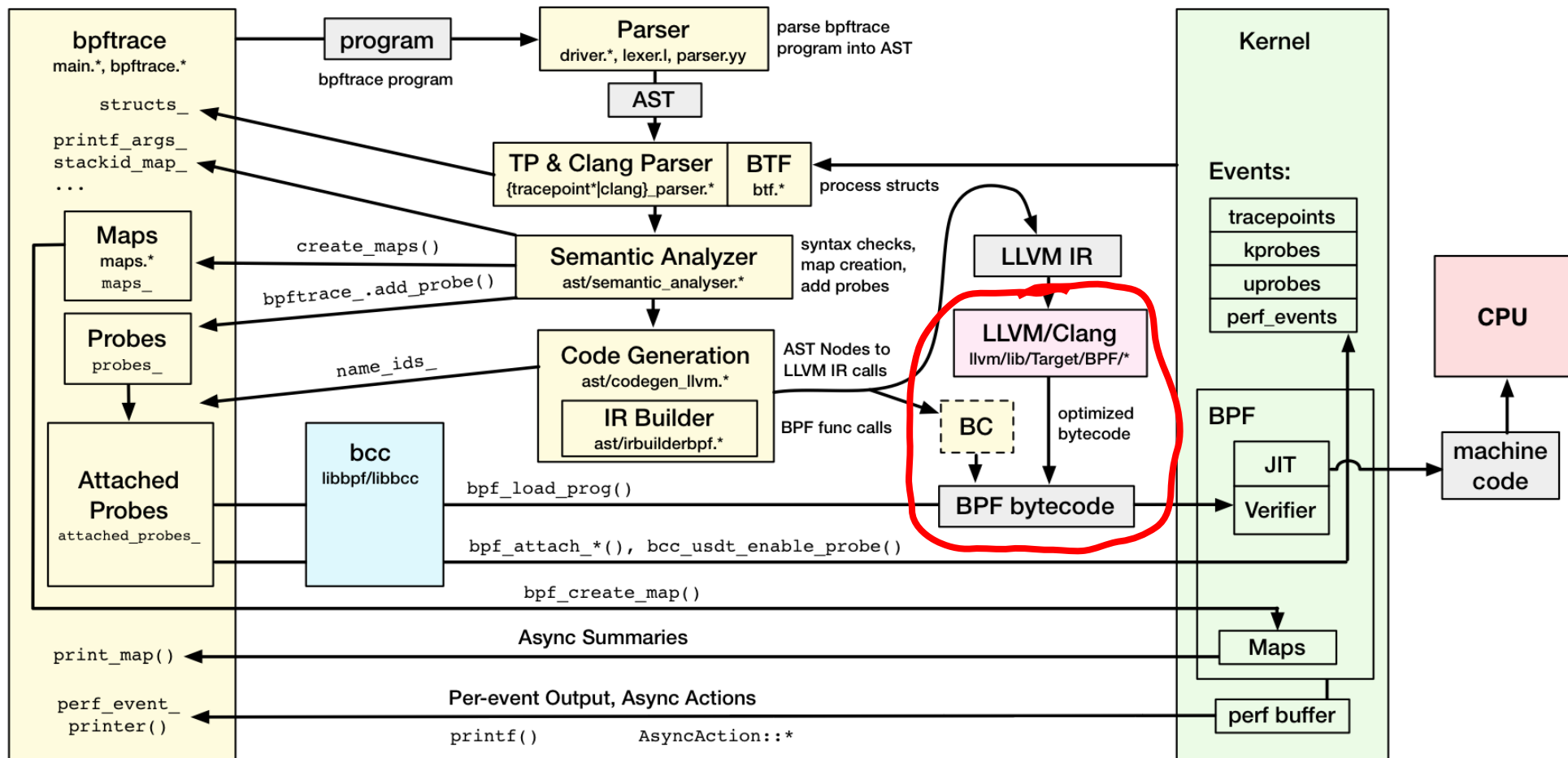
Now you have LLVM IR! (3)

```
# 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/*

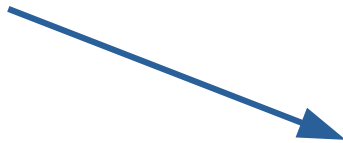
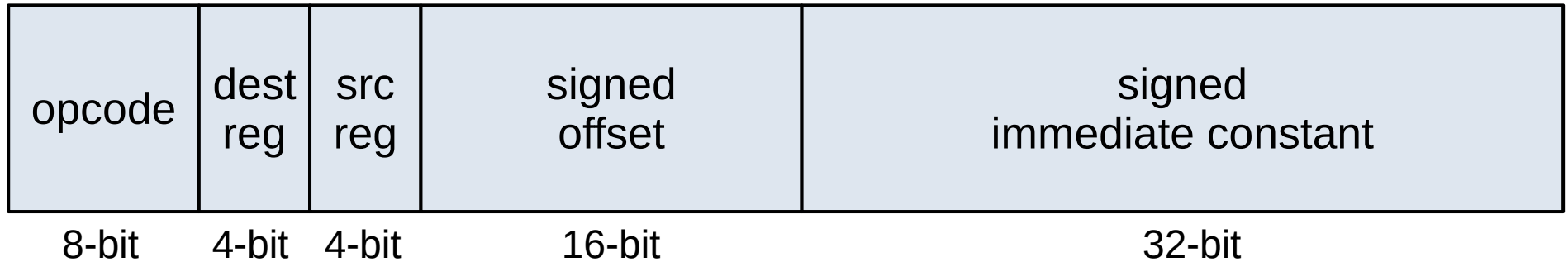
Lots of CreateAllocaBPF(), CreateGEP(), etc. (this gets verbose)

bpftrace mid-level internals 6/13

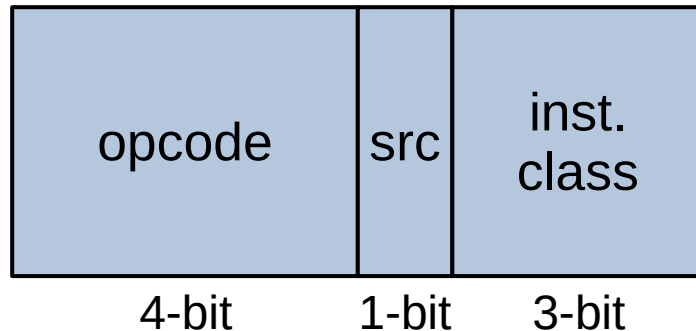


Extended BPF instruction (bytecode) format

← 64-bit →

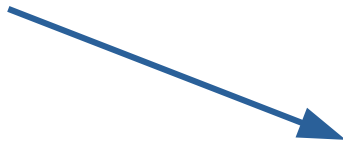
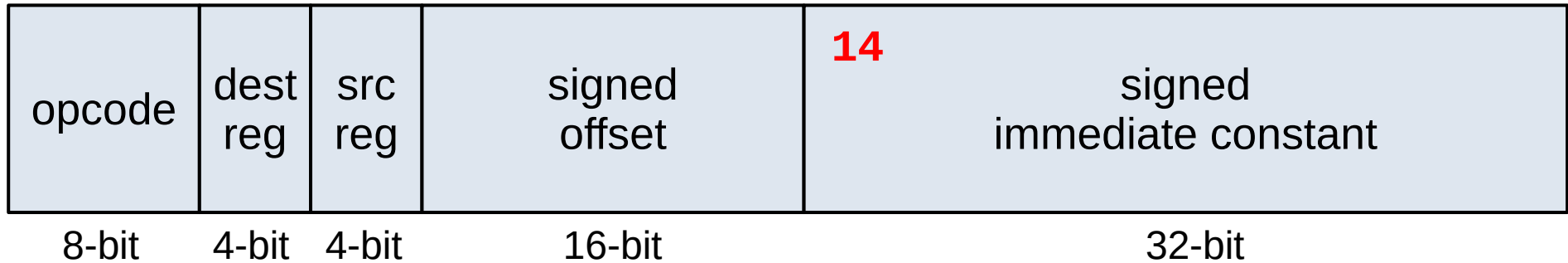


E.g., for
ALU & JMP
classes:

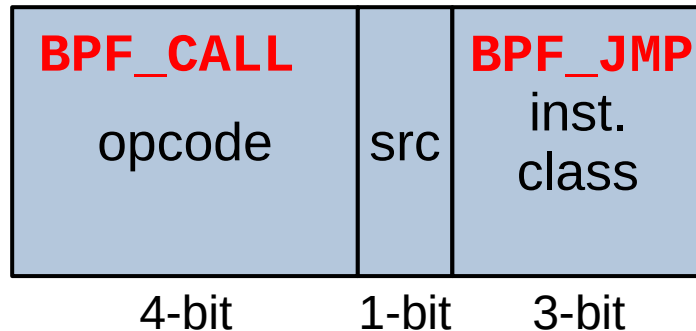


Extended BPF instruction (bytecode) format (2)

E.g., call get_current_pid_tgid

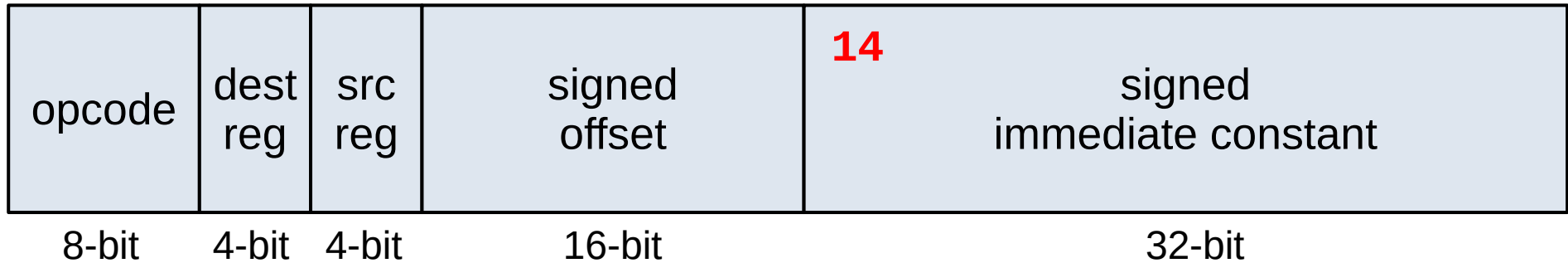


E.g., for
ALU & JMP
classes:

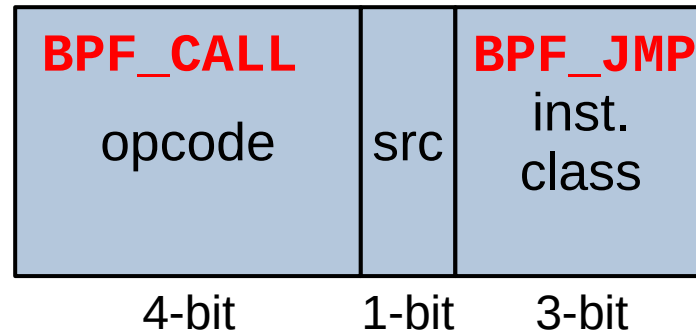


Extended BPF instruction (bytecode) format (3)

E.g., call get_current_pid_tgid



E.g., for ALU & JMP classes:



Linux include/uapi/linux/bpf.h

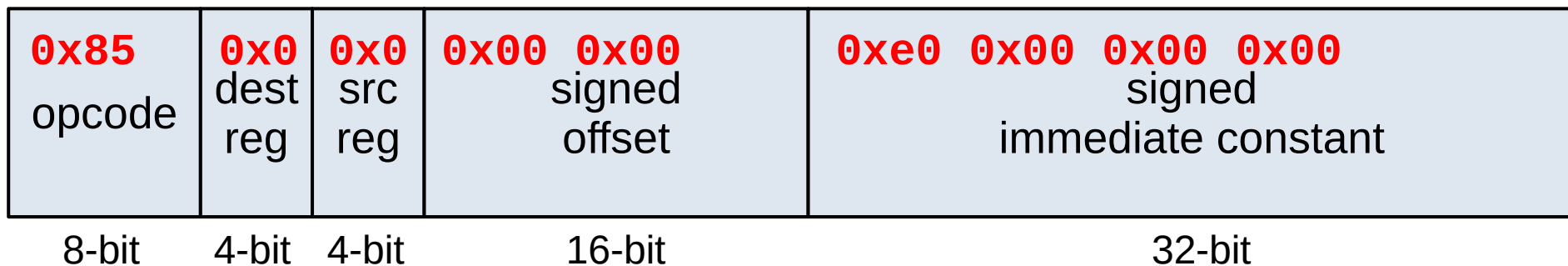
```
#define BPF_JMP 0x05
```

Linux include/uapi/linux/bpf_common.h

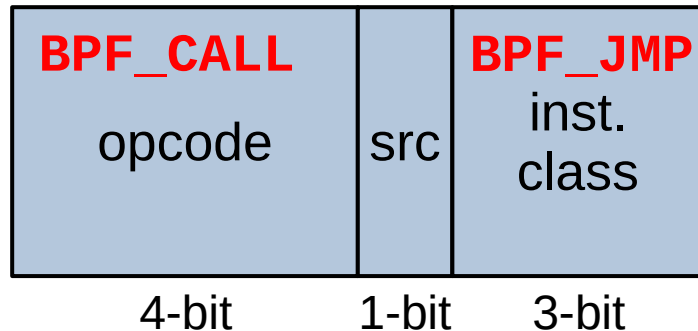
```
#define BPF_CALL 0x80
```

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)

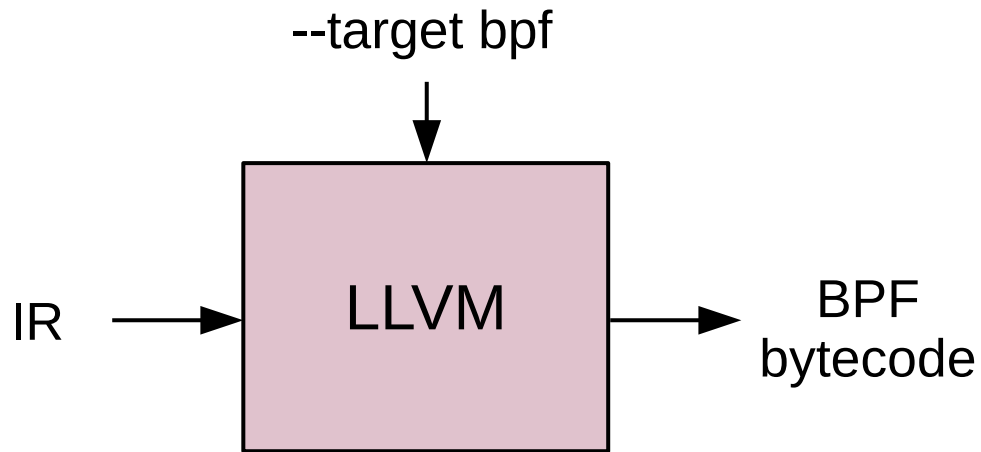
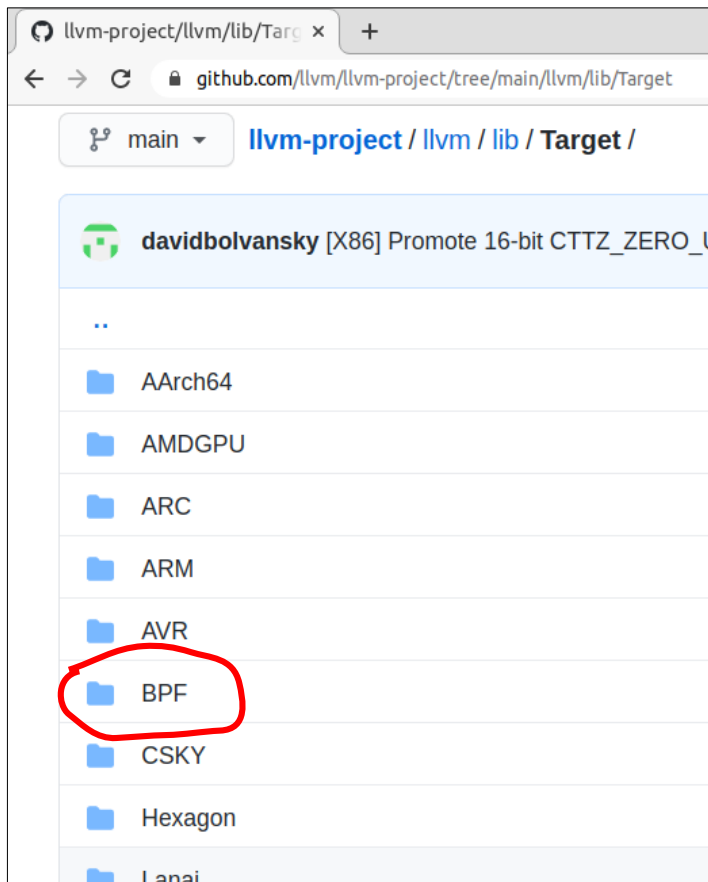
E.g., call get_current_pid_tgid



(hex) 85 00 00 e0 00 00 00

As per the BPF specification (currently Linux headers)

LLVM/Clang has a BPF target

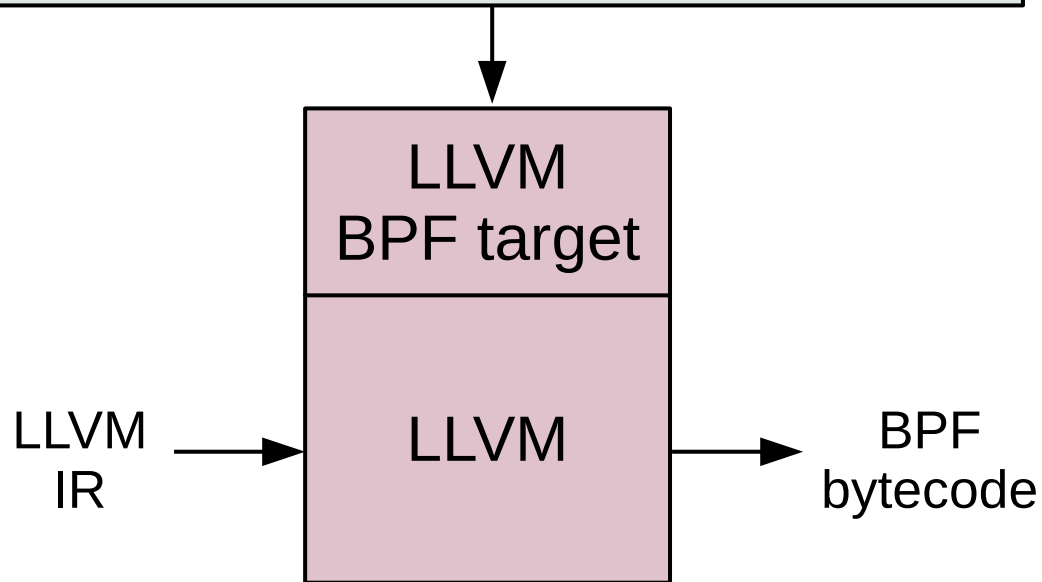


Future: bpfftrace may include its own lightweight bpfftrace compiler (BC) as an *option* (pros: no dependencies; cons: less optimal code)

LLVM/Clang has a BPF target (2)

BPF
specification
(#defines)

Linux include/uapi/linux/bpf_common.h
Linux include/uapi/linux/bpf.h
Linux include/uapi/linux/filter.h



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; → 14
  let BPFClass = BPF_JMP;
}
```

↓ 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
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
```

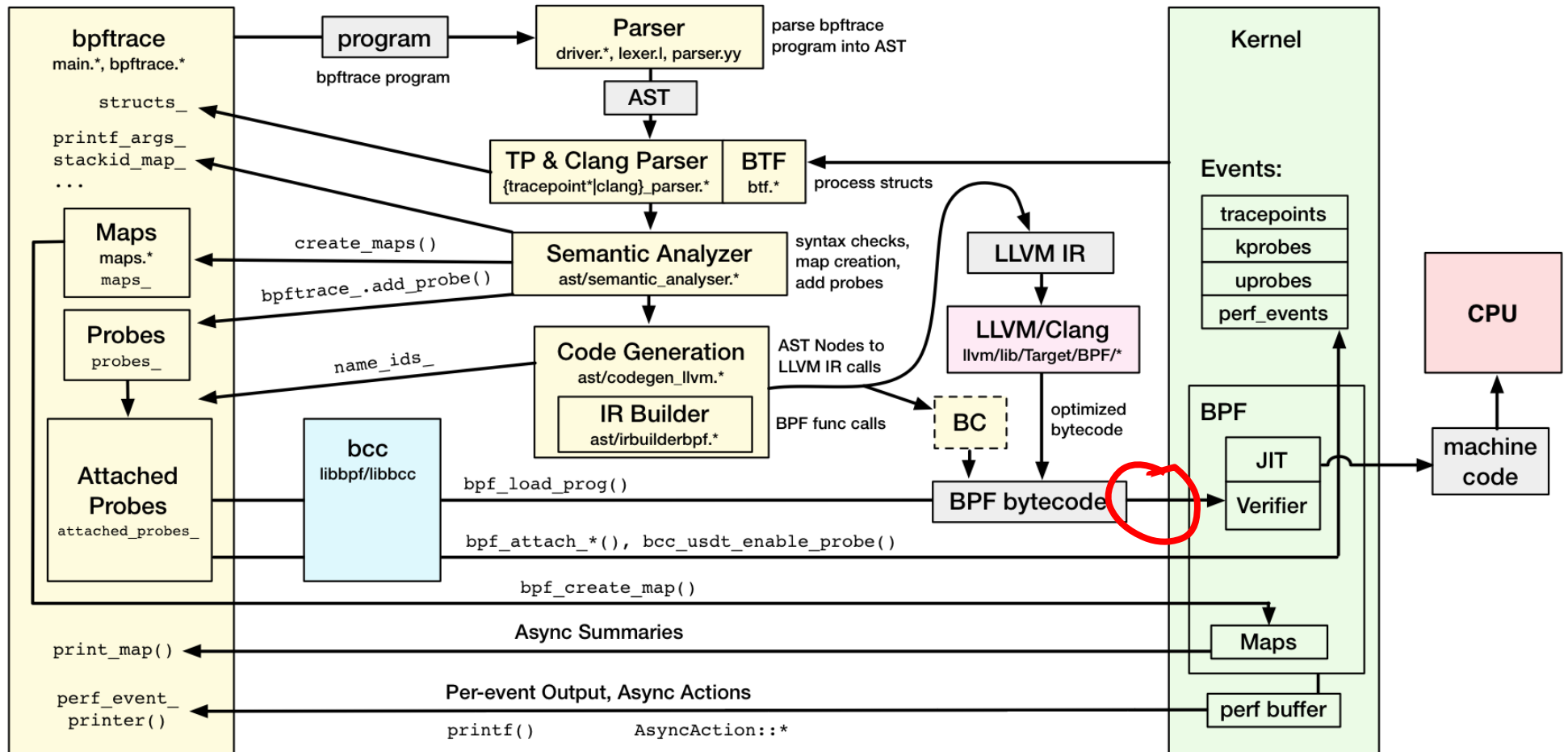
Now you have BPF bytecode! (2)

```
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

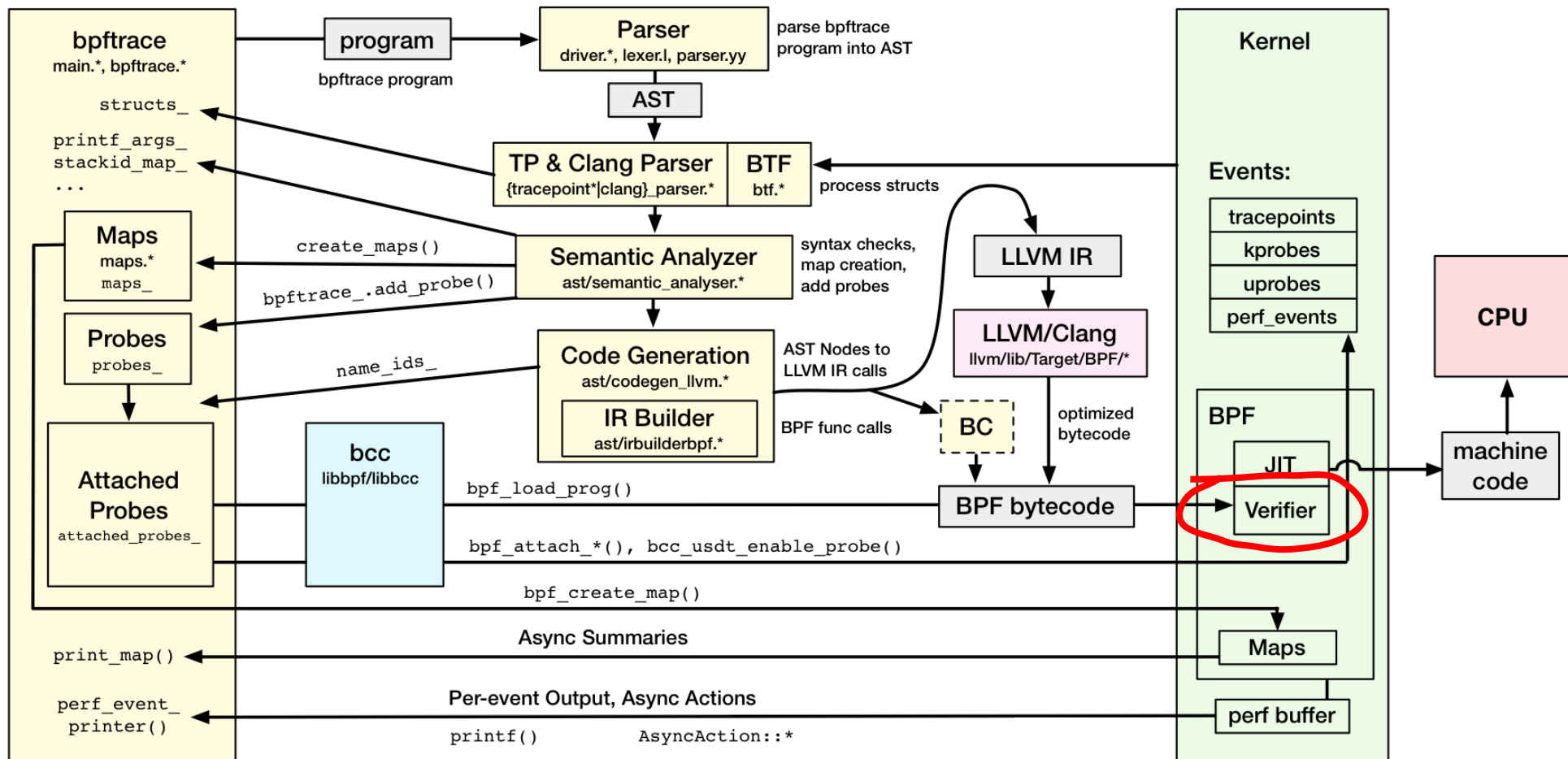


Sending BPF bytecode to the kernel

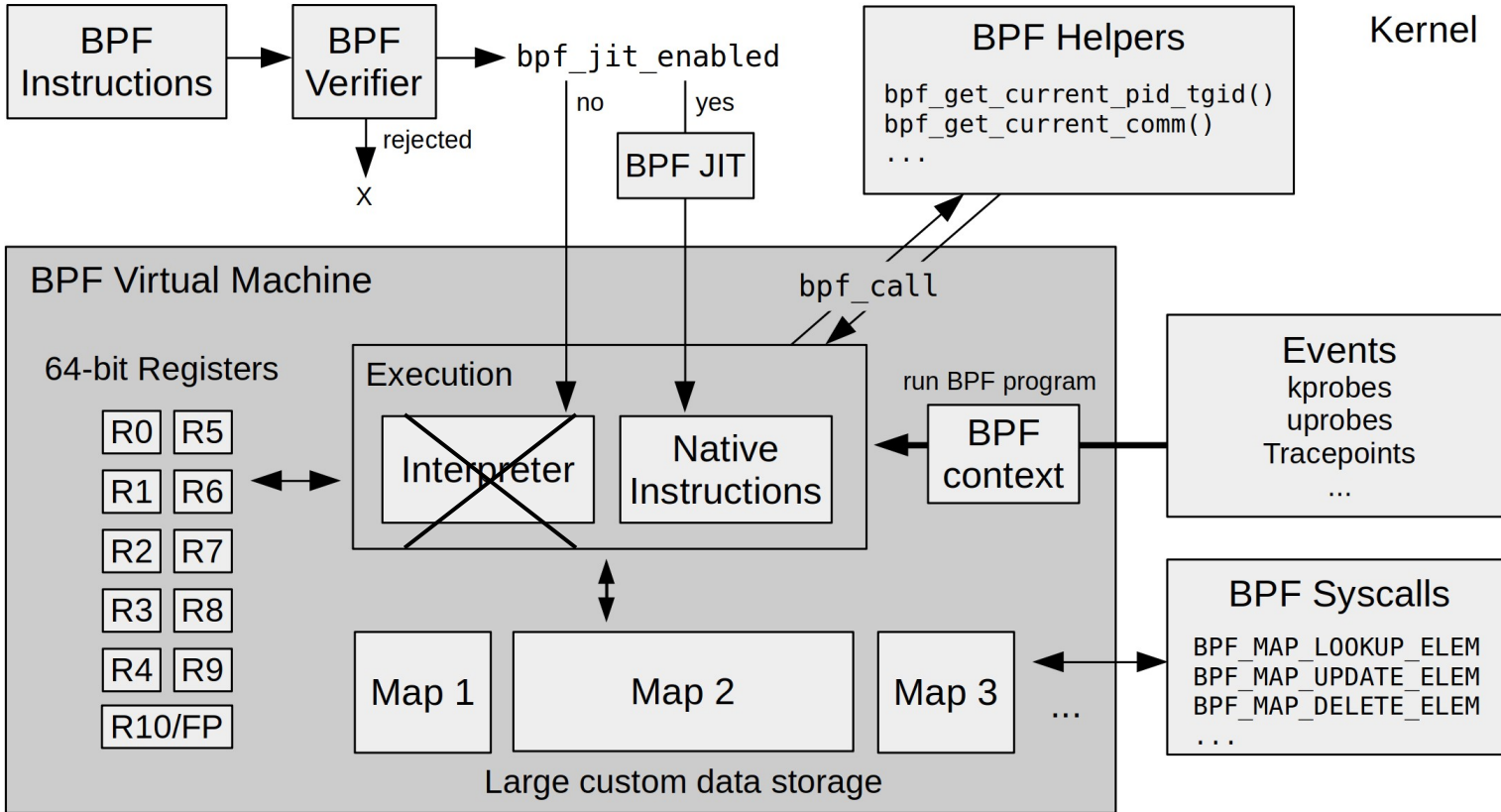
```
# strace -fe bpf bpftrace -e 'kprobe:do_nanosleep {  
    printf("PID %d sleeping...\n", pid);  
}'  
[...]  
bpf(BPF_PROG_LOAD, {prog_type=BPF_PROG_TYPE_KPROBE, insn_cnt=18, insns=0x7fdde5305000,  
license="GPL", log_level=0, log_size=0, log_buf=NULL, kern_version=KERNEL_VERSION(5, 8,  
18), prog_flags=0, 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

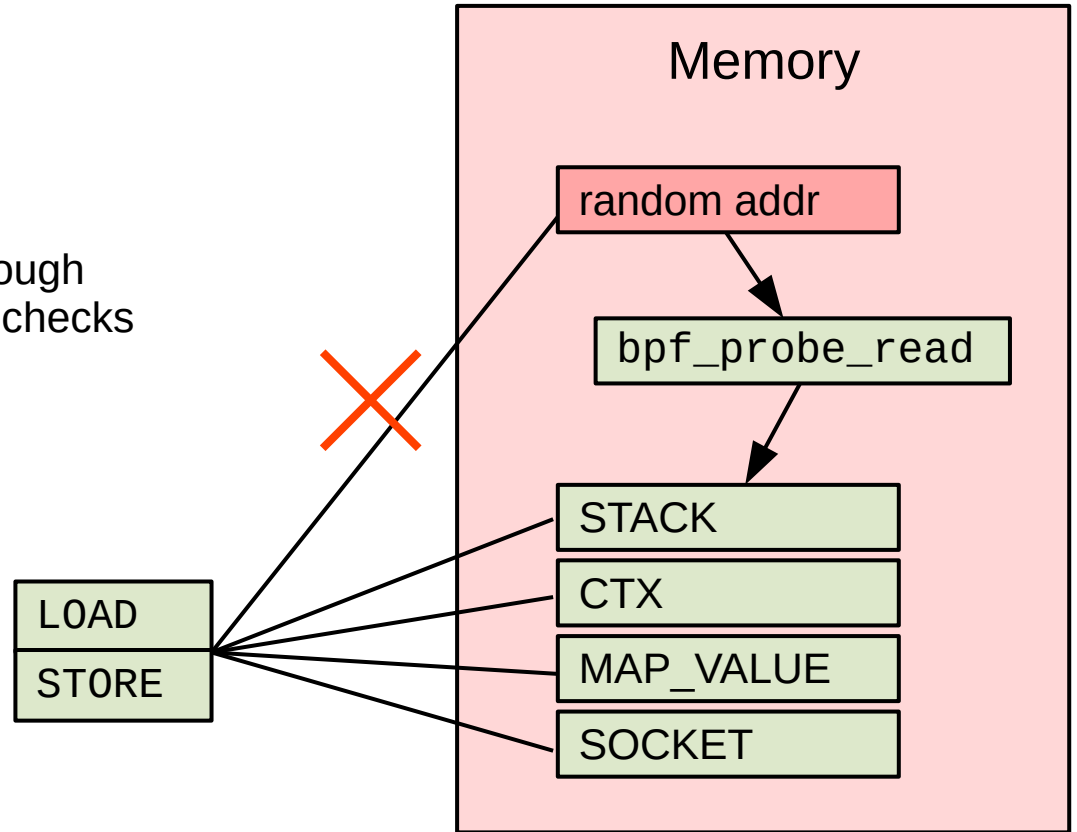
Rewrites some bytecode

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

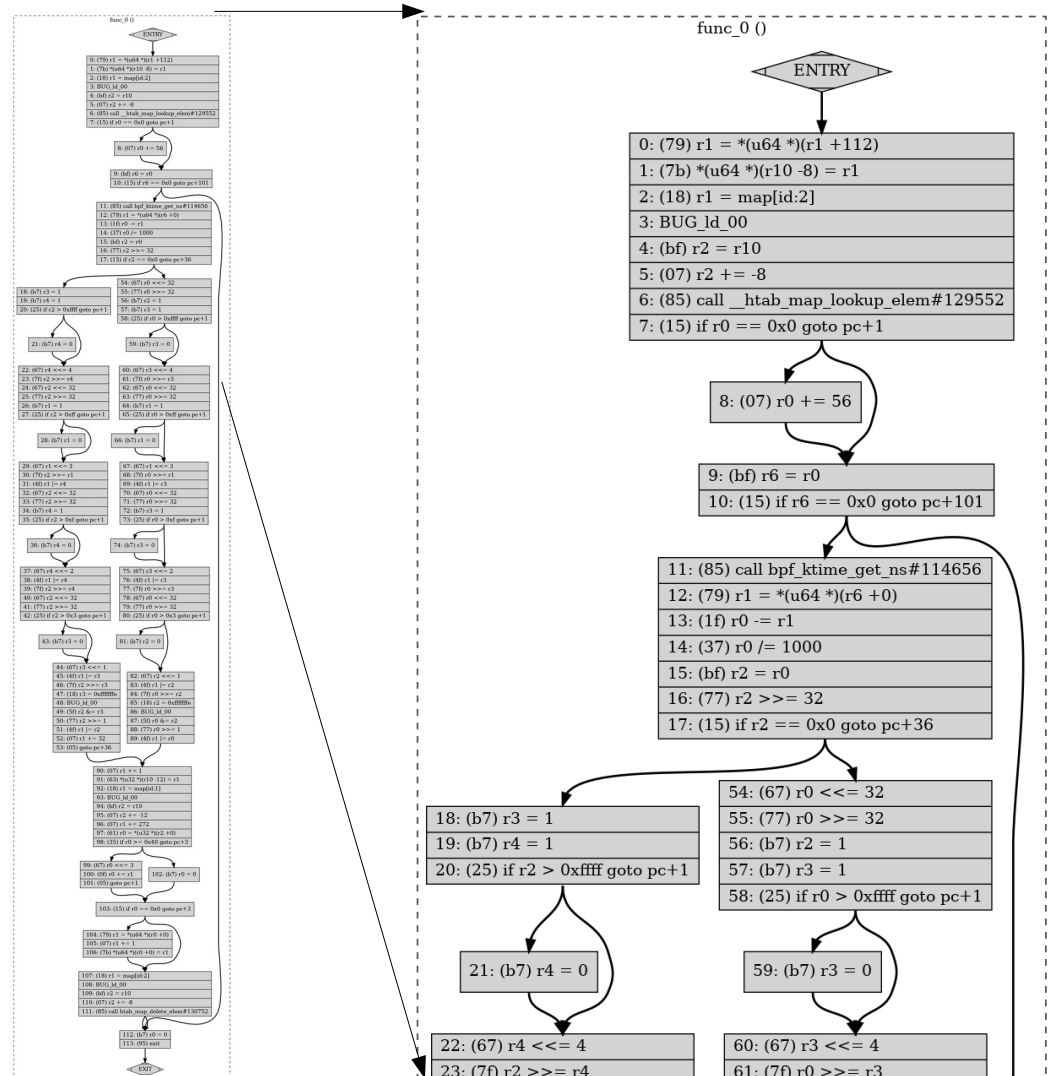
- Memory access
 - Direct access extremely restricted
 - Can only read initialized memory
 - Other kernel memory must pass through the `bpf_probe_read()` helper and its checks
- Arguments are the correct type
- Register usage allowed
 - E.g., no frame pointer writes
- No write overflows
- No addr leaks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



Verifying Code Paths

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

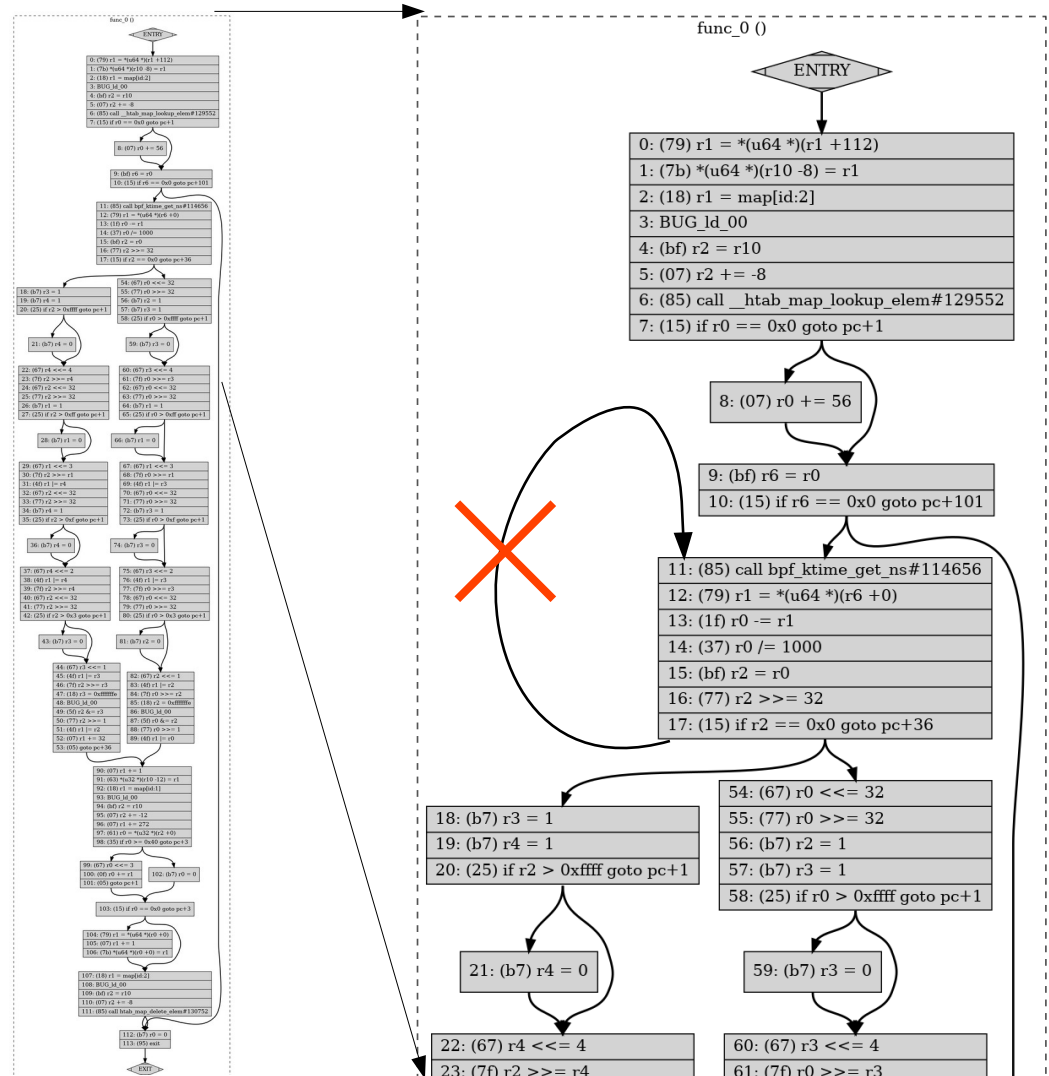
biolateny as GraphViz dot:



Verifying Code Paths

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

biolateny 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
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
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
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
[...]
```

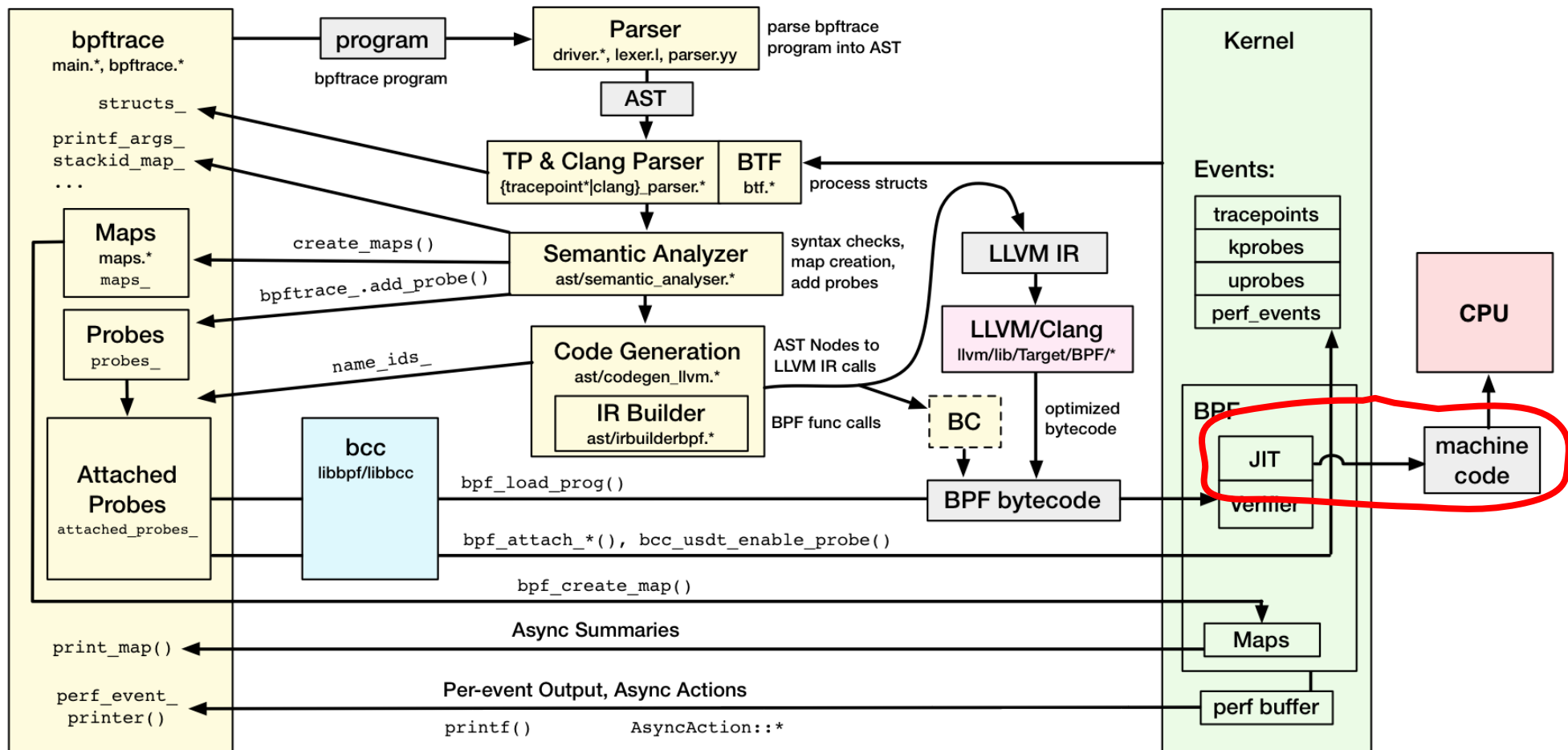
Using bpftool
on a running
instance of the
program

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



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;
[...]
```

E.g., call get_current_pid_tgid

```
static int emit_call(u8 **pprog, void *func, void *ip)
{
    return emit_patch(pprog, func, ip, 0xE8);
}
```

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   $0xffffffffffffffff,%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 → get_current_pid_tgid
 22:  shr   $0x20,%rax
 26:  mov   %rax,-0x8(%rbp)
 2a:  movabs $0xffff9d3ab87bb600,%r13
 34:  callq 0xffffffffc2448ae2
 39:  mov   %rbp,%rcx
 3c:  add   $0xffffffffffffffff,%rcx
[...]
```

BPF prologue

BPF program

→ get_current_pid_tgid

Plus you have BPF helper code

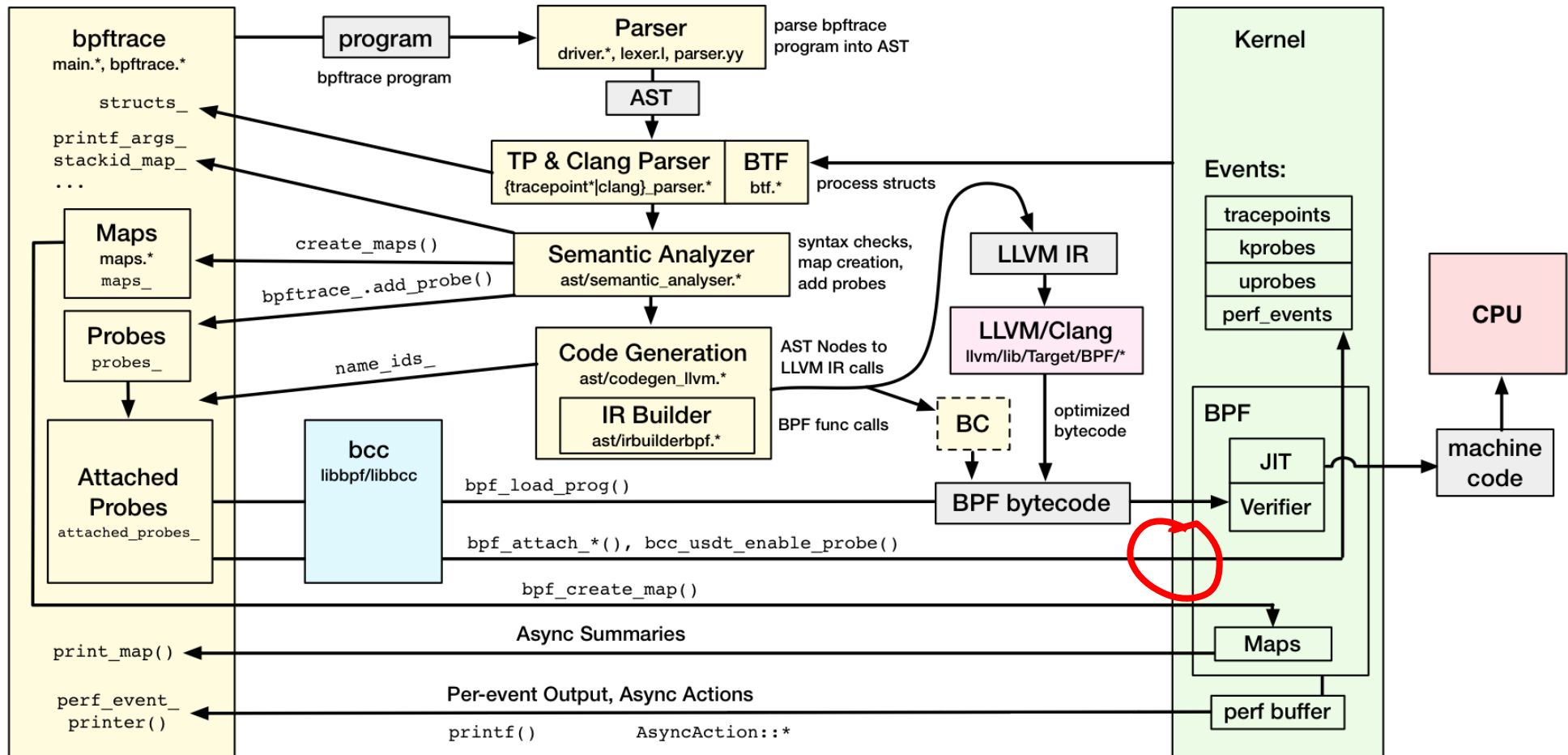
Linux kernel/bpf/helpers.c

```
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

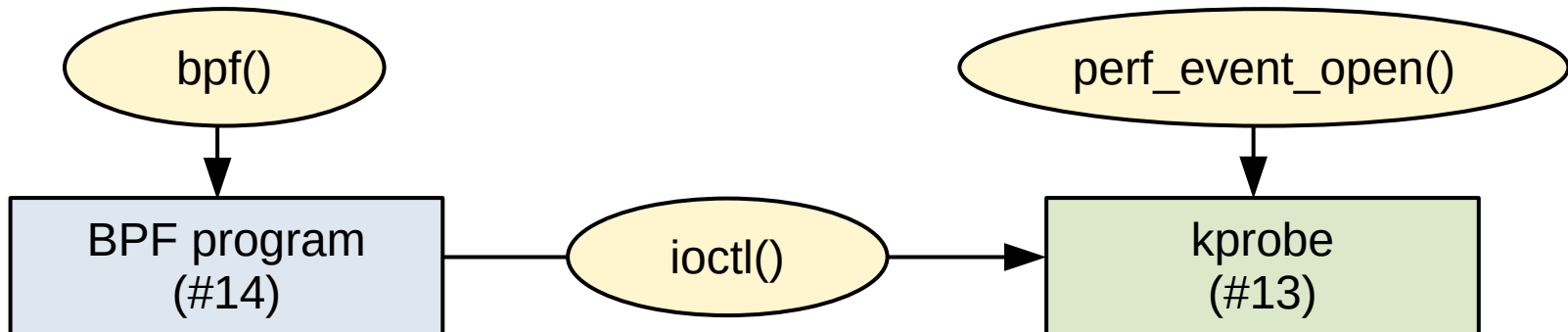
```
# strace -fe perf_event_open,bpf,ioctl bpftrace -e 'kprobe:do_nanosleep {
    printf("PID %d sleeping...\n", pid); }'
[...]
```

```
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
```

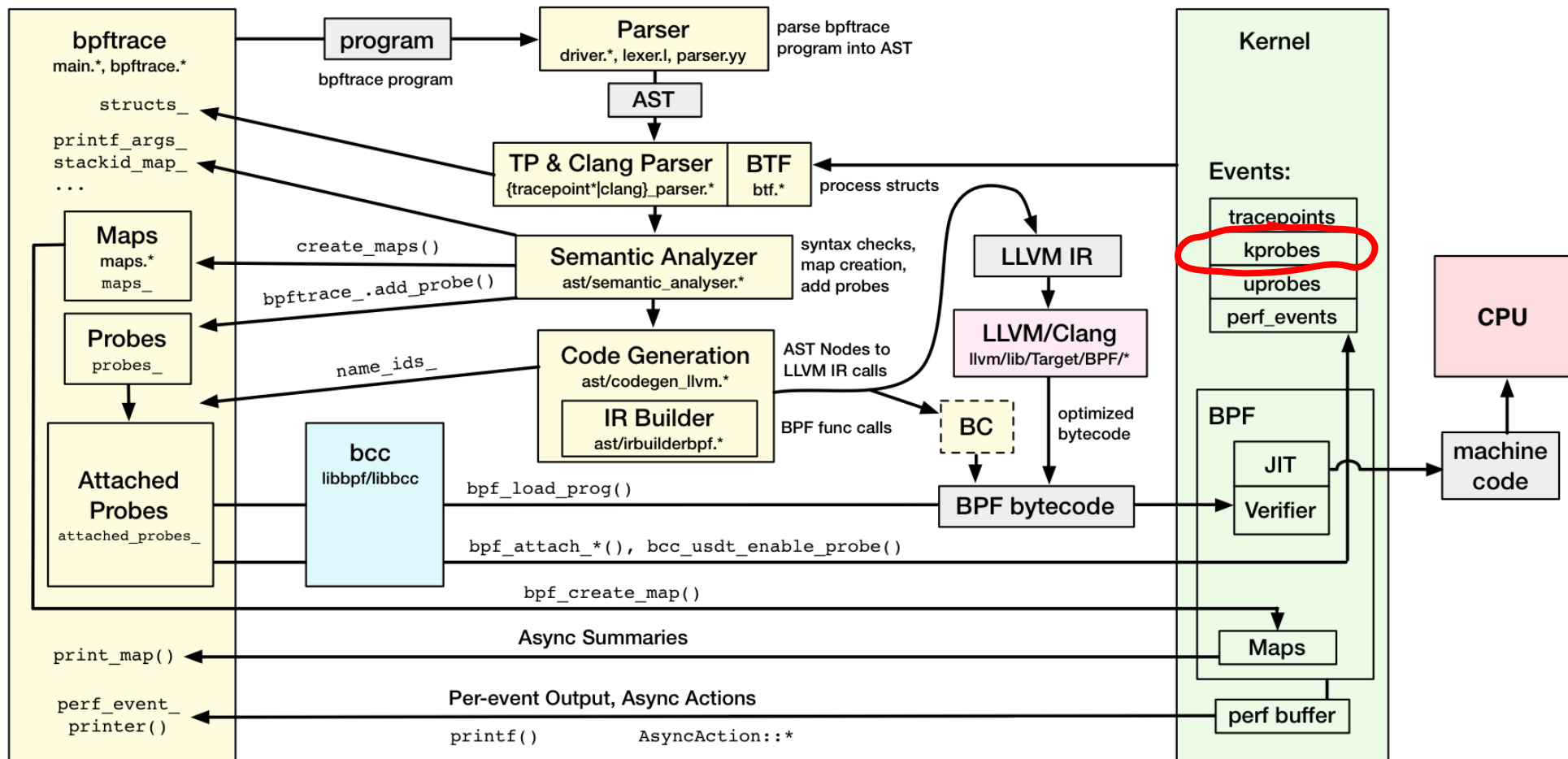
Attaching BPF to a kprobe (2)

```
# 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  
ioctl(13, PERF_EVENT_IOC_SET_BPF, 14) = 0  
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))
            schedule_timeout(&t->timer.expires);
    } while (!t->timer.expires);

    restart = restart_block_get(t);
    restart_block_put(restart);

    return 0;
}
[...]
```

(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)

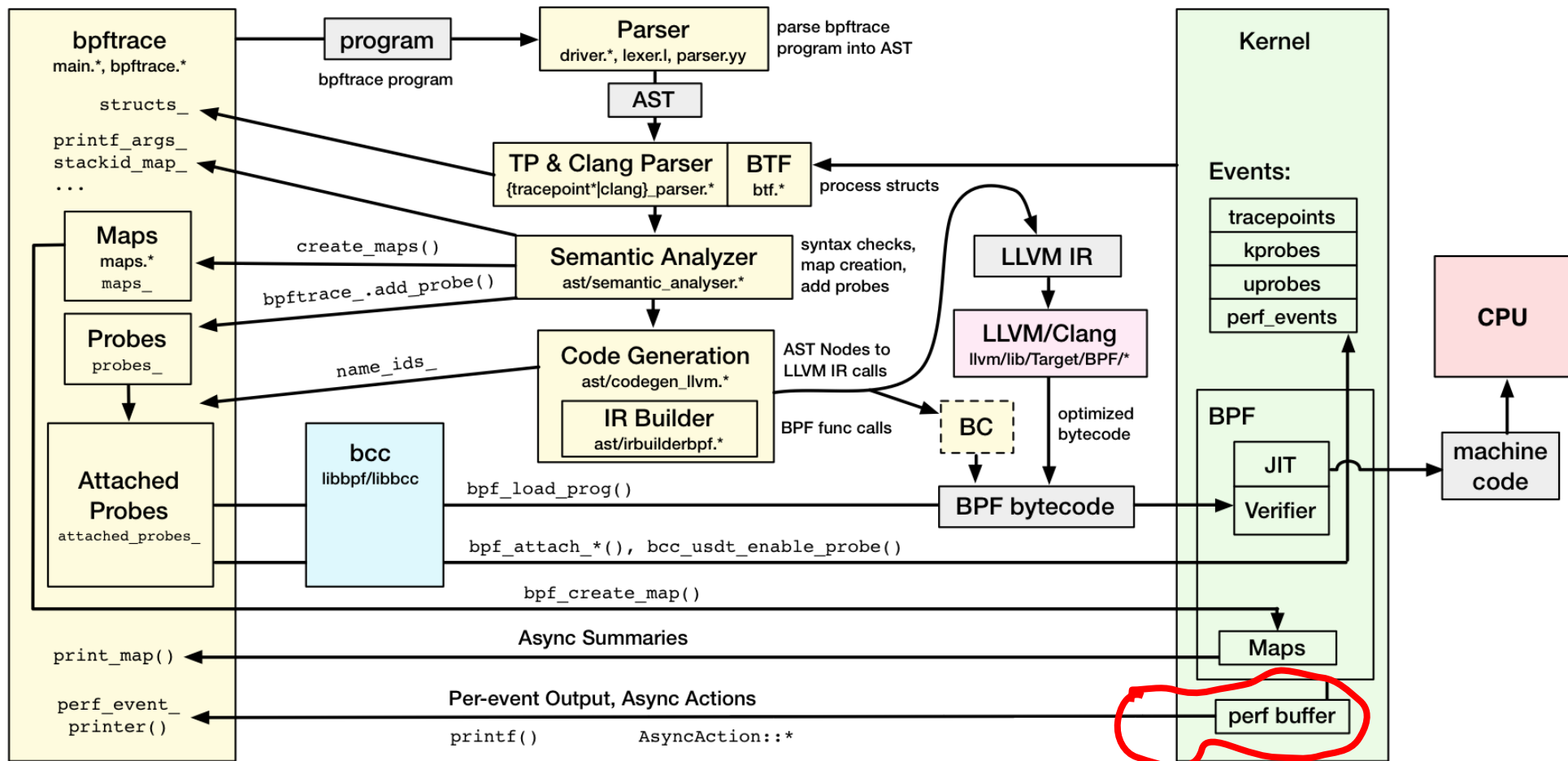
```
(gdb) disas/r do_nanosleep
Dump of assembler code for function do_nanosleep:
0xffffffff81b7d810 <+0>:  e8 1b 00 4f ff    callq 0xffffffff8106d830 <__fentry__>
0xffffffff81b7d815 <+5>:  55               push  %rbp
0xffffffff81b7d816 <+6>:  89 f1           mov   %esi,%ecx
0xffffffff81b7d818 <+8>:  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



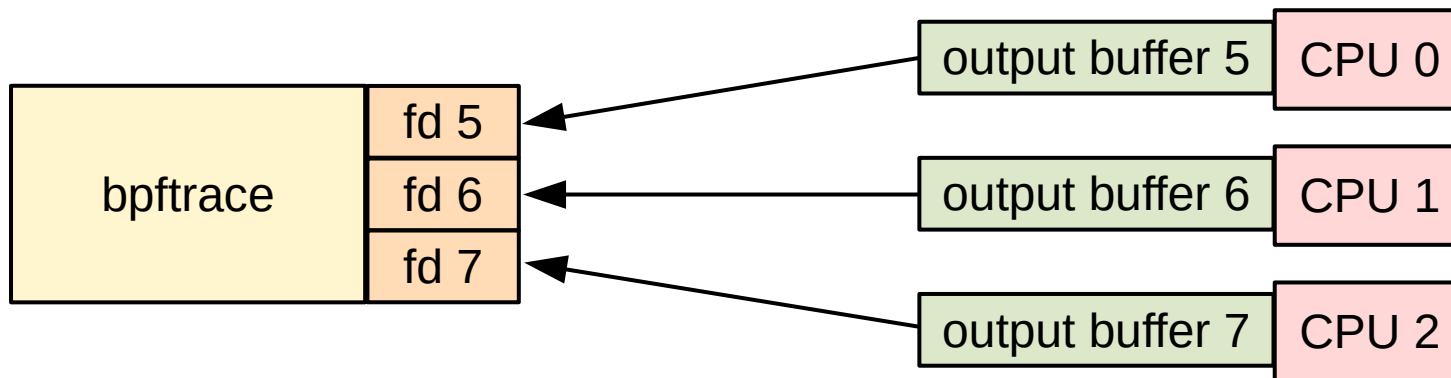
Perf output buffers

```
# 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 bpfttrace -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  
[...]
```

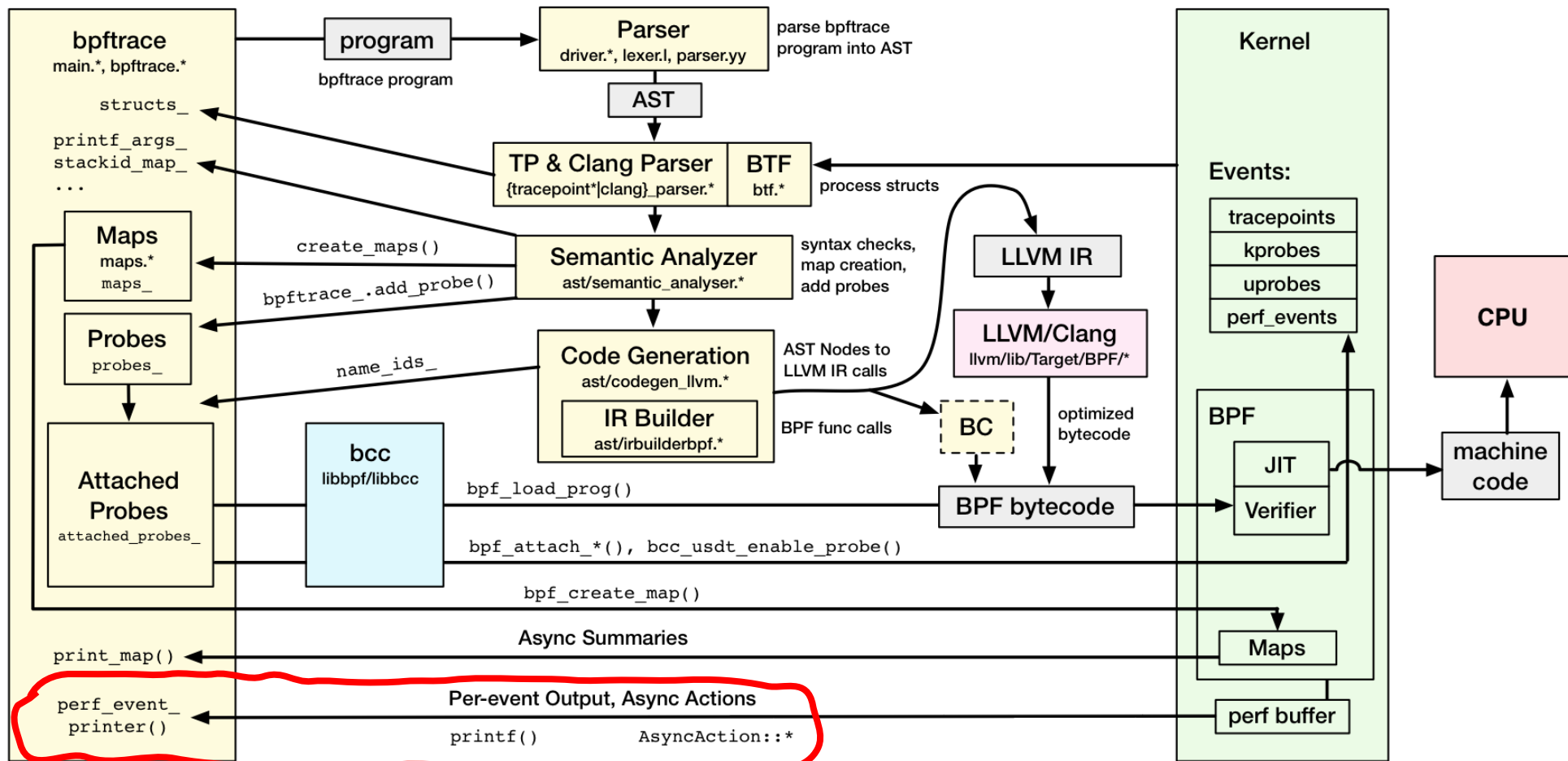
CPU ID



bpfttrace waits for events using `epoll_wait(2)`

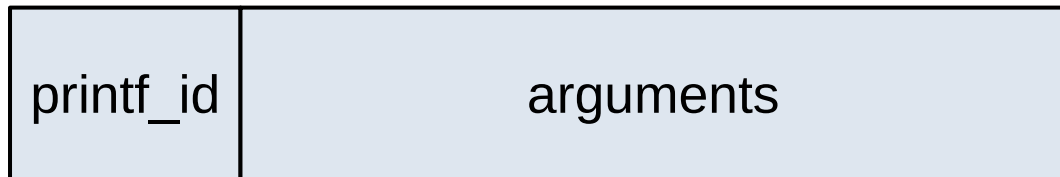
...

bpftrace mid-level internals 13/13



bpftrace printf & async actions

bpftrace perf output message format:



64-bit

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

bpftrace src/types.h

High numbers are used
for other async actions:

```
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,
    [...]
}
```

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

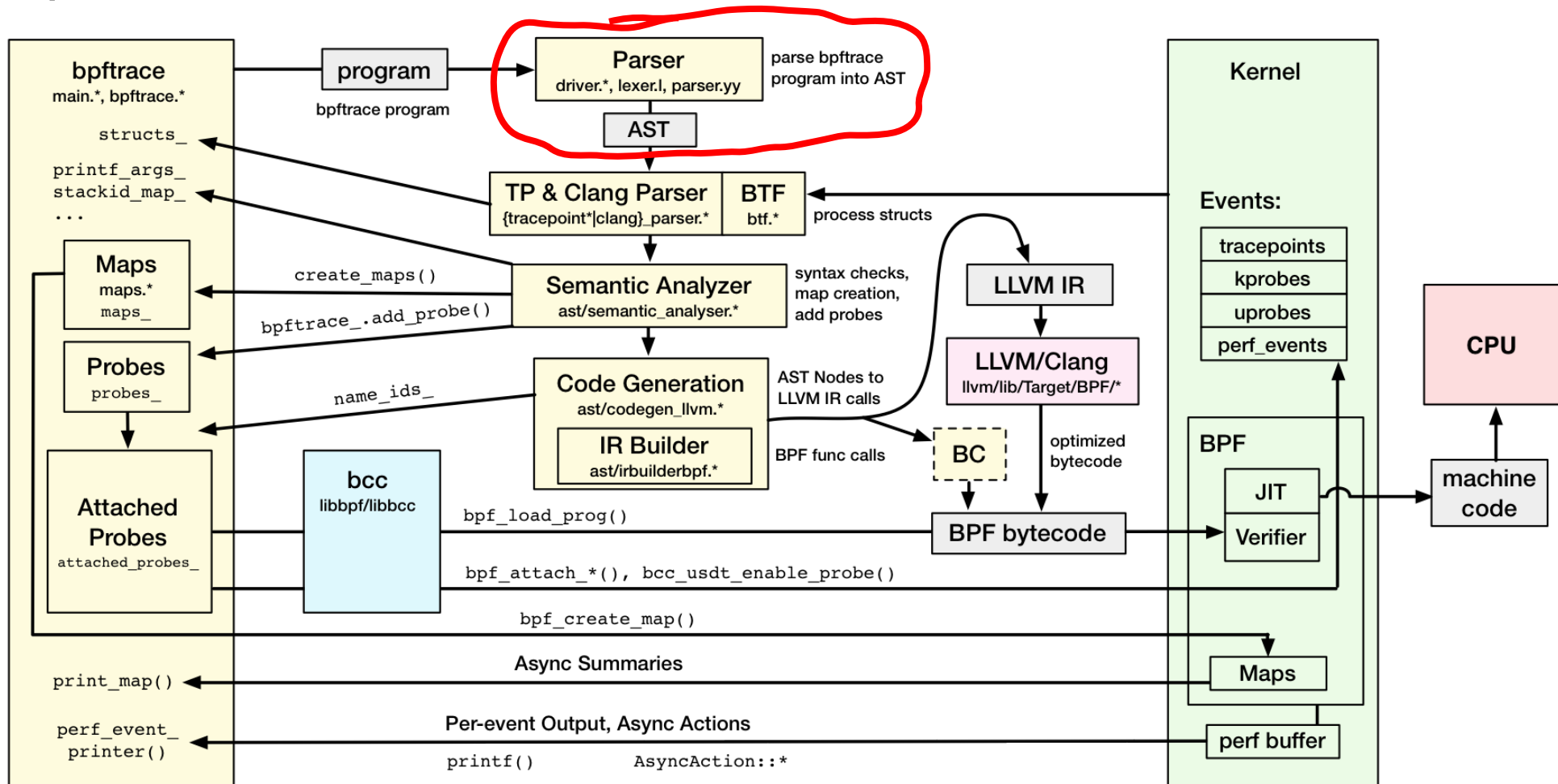
2. Static tracing and map summaries

```
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  
@[dmccrypt_write/2]: 1993
```

bpftrace mid-level internals 1/4



Lexer & Yacc

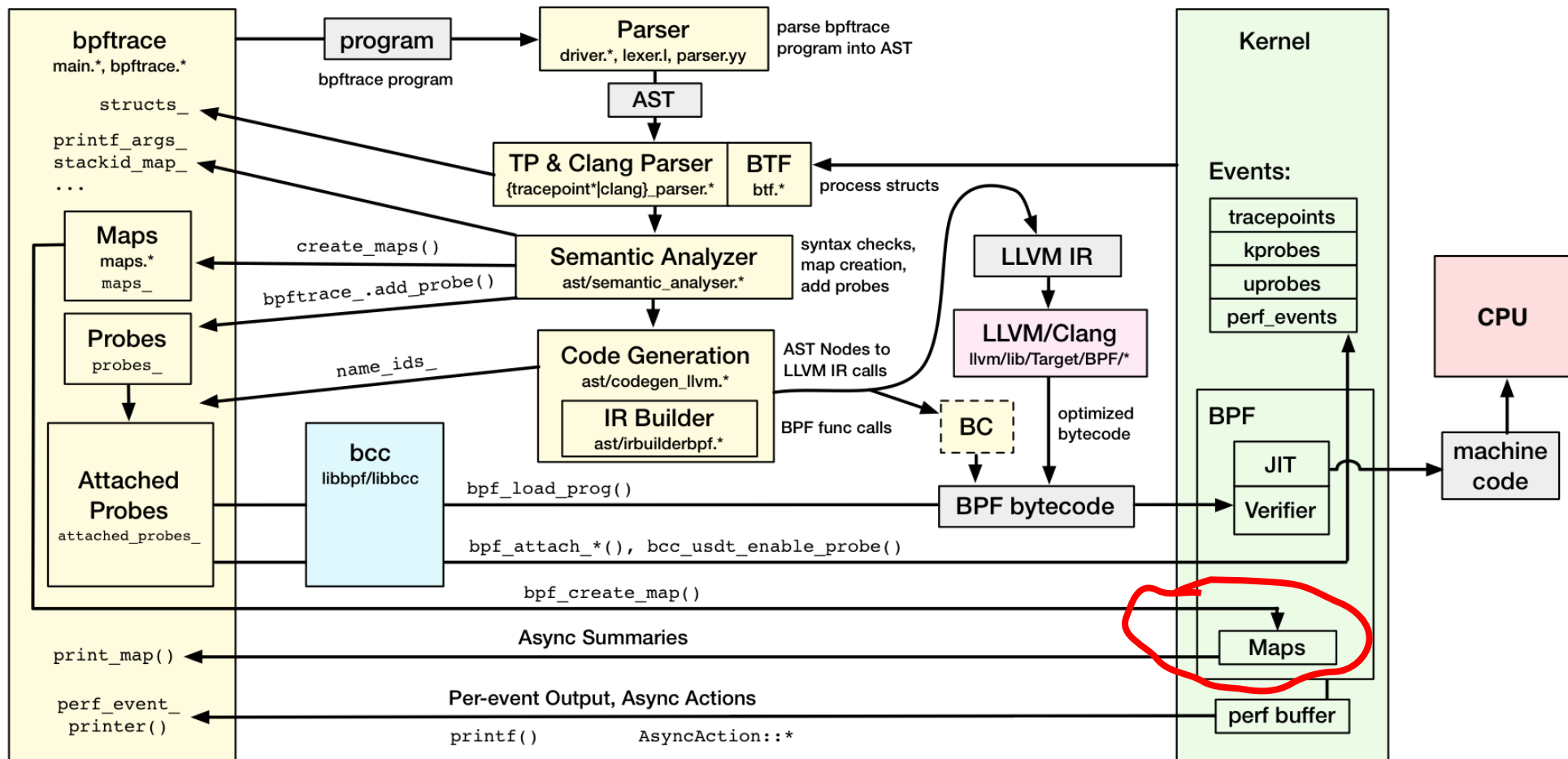
bpffrace src/lexer.l

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

bpffrace 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, $3, @$); }
```

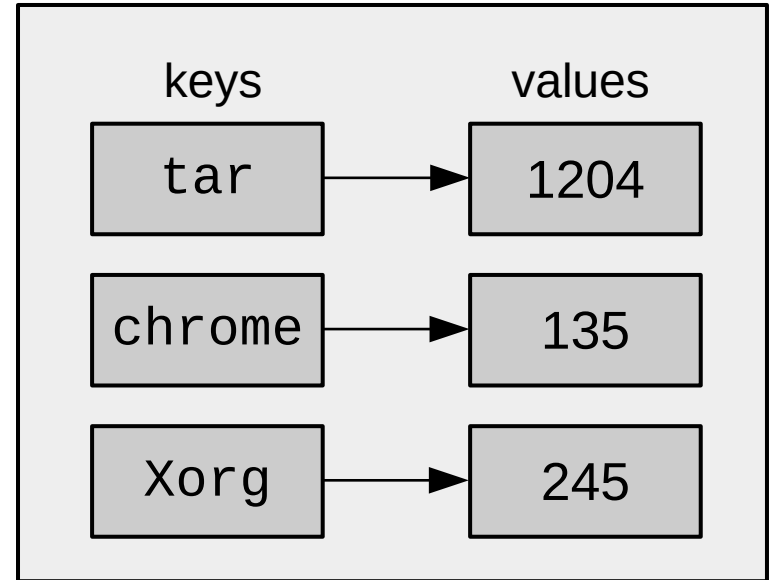
bpftrace mid-level internals 2/4



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()  
[...]
```

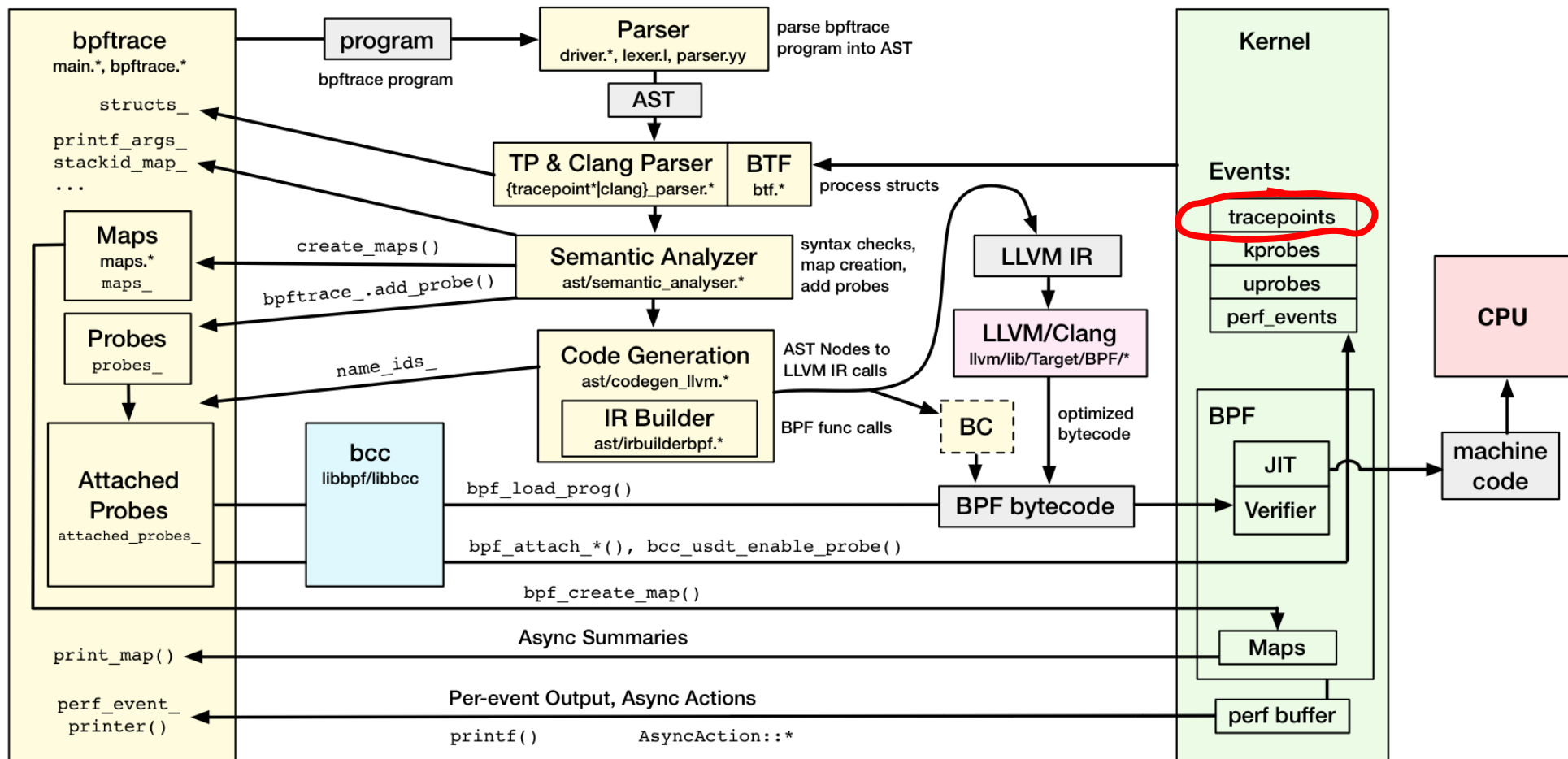
Creating BPF maps

```
# 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 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?

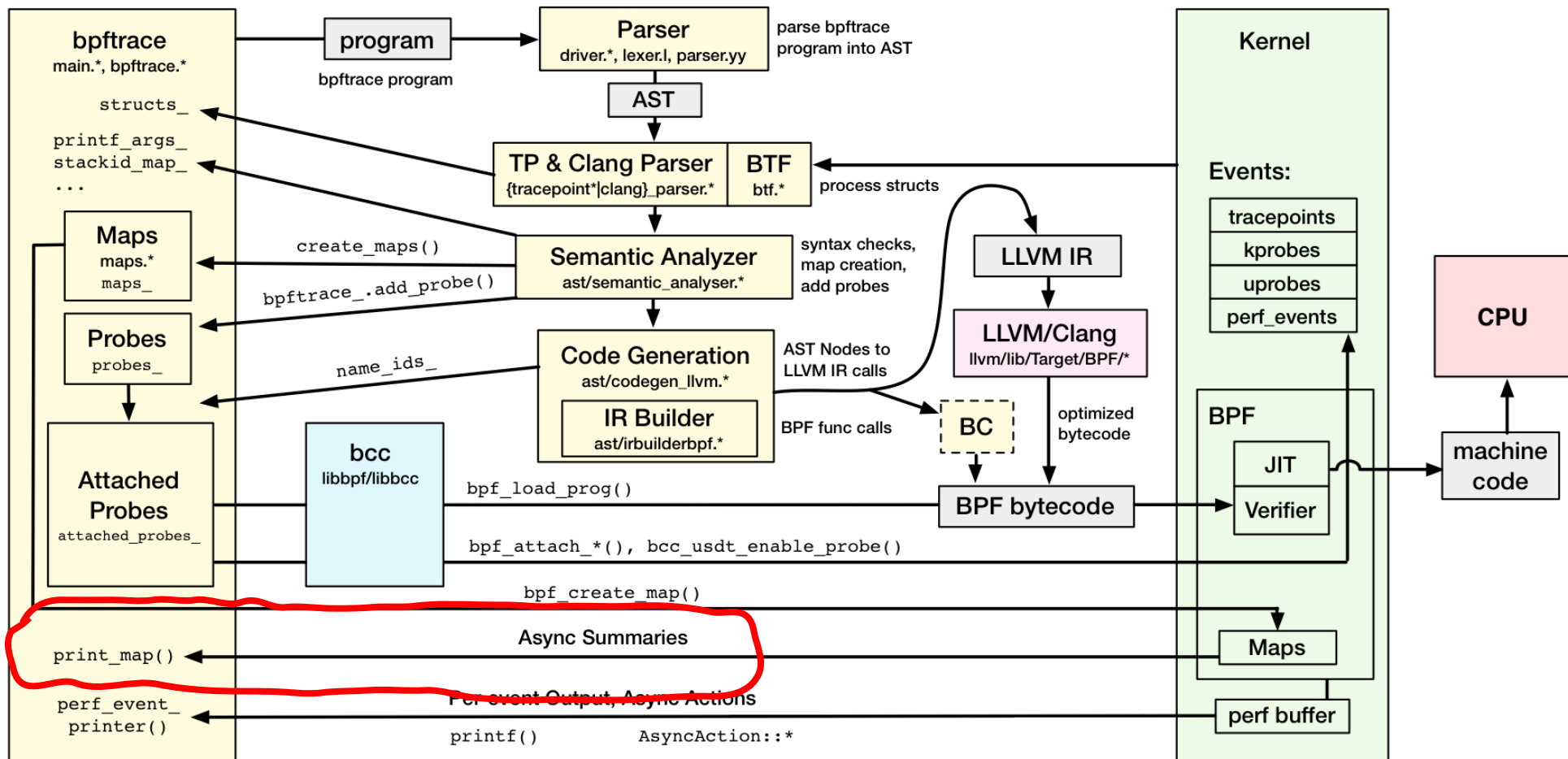
```
(gdb) disas/r blk_mq_start_request
Dump of assembler code for function blk_mq_start_request:
0xffffffff815118e0 <+0>:  e8 4b bf b5 ff    callq 0xffffffff8106d830 <__fentry__>
0xffffffff815118e5 <+5>:  55                push  %rbp
0xffffffff815118e6 <+6>:  48 89 e5          mov   %rsp,%rbp
0xffffffff815118e9 <+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 5-byte nop is a placeholder. Does nothing quickly.

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

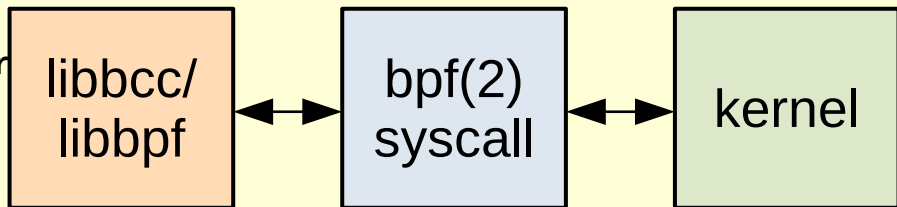
bpftrace mid-level internals 4/4



User-space map iteration

bpfftrace src/bpfftrace.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: " << err;  
        return -1;  
    }  
    values_by_key.push_back({key, value});  
    old_key = key;  
}
```



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  
@[dmccrypt_write/2]: 1993
```

Discussion of other internals

Stack walking

BTF

CO-RE

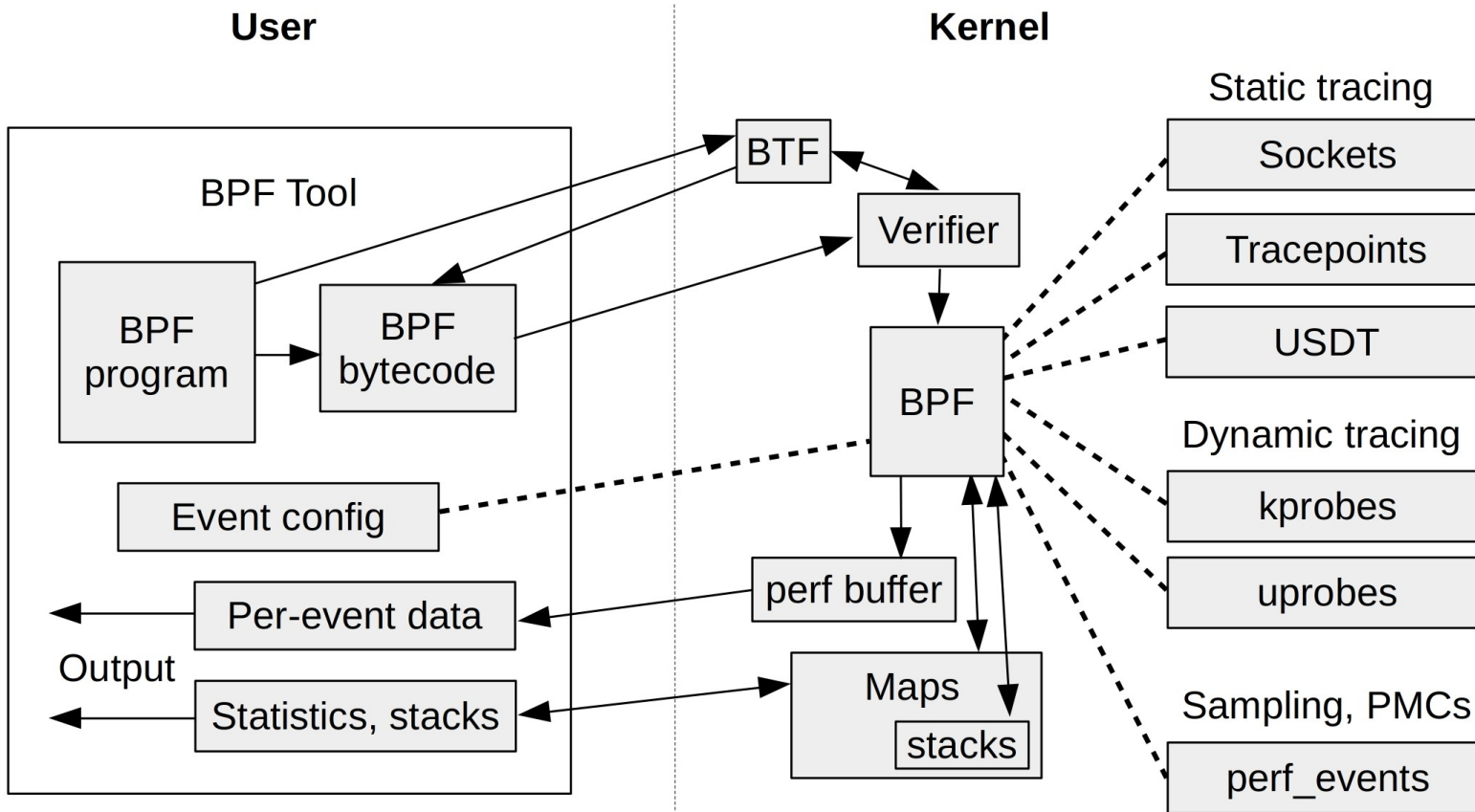
Tests

raw_tracepoints & fentry

Networking & XDP

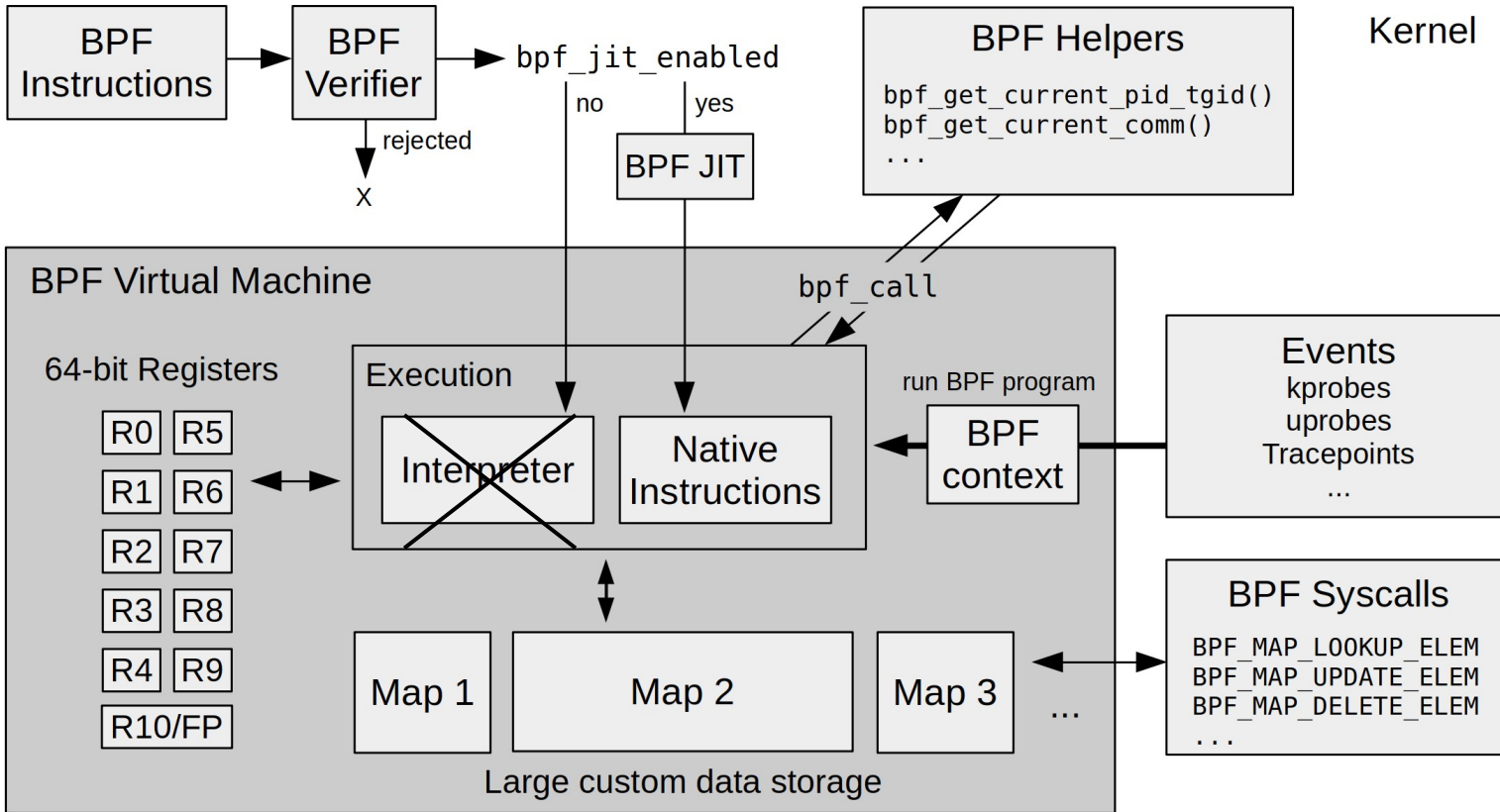
Security & Cgroups

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

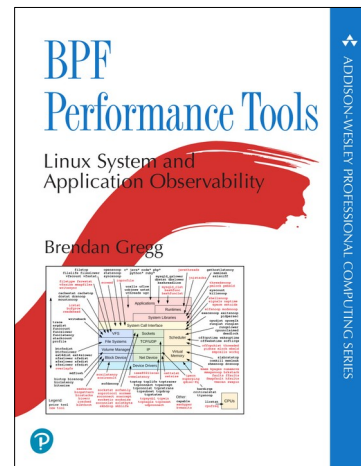
CONFIG_DEBUG_INFO_BTF=y

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

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

USENIX

LISA21

Jun, 2021

<https://ebpf.io>

NETFLIX