THE BPF TARGET IN LLVM

ABOUT ME

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- Interests: Linux kernel, Rust, ZK cryptography

BPF

- "Berkeley Packet Filter"
- ...but that's not what it is, really.
- It's a virtual machine for running minimal, sandboxed programs.
- Restricted environment (instruction limit, verifier).
- Rules: execute fast, don't sleep*, don't allocate too much memory.

USE CASES

- **Linux kernel** - BPF originates from there
  - Network filtering
  - Tracing and profiling
  - Security policies
  - Extending scheduler
  - HID-BPF

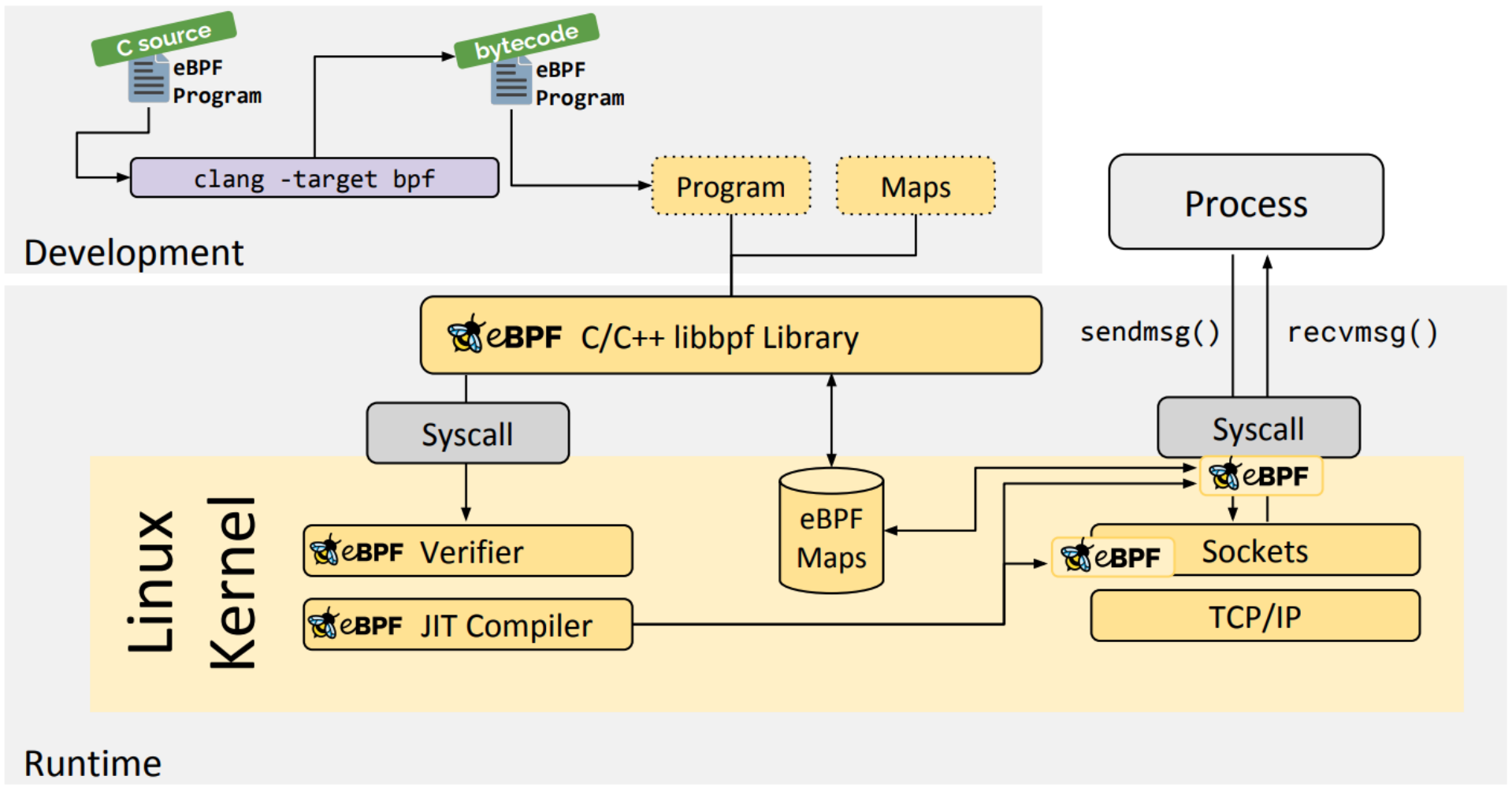
USE CASES

- **Solana**
  - Smart contracts
- **IoT / microcontrollers**

STORING DATA

- Stack memory is limited (512 bytes).
- Linux kernel BPF
  - BPF maps (stored in memory)
- Solana BPF
  - Accounts (stored in memory of validator nodes)

OVERVIEW (FOR LINUX KERNEL)



PROJECTS

- **Cilium** - Container Network Interface for Kubernetes.
- **Falco** - Security alert engine.
- Pretty much every Solana project. Orca, Mango, Audius, Metaplex, Light Protocol etc.
- **Good stuff from Deepfence coming soon!** Security, but with focus on enforcement.

BPF AND LLVM

- First and main compiler providing BPF support.
- BPF has a backend in LLVM.
- Supported by Clang (C) and Rust.

ENABLING BPF BACKEND

```
-DLLVM_TARGETS_TO_BUILD="host;BPF"
```

e.g.

```
CC=clang CXX=clang++ cmake -DCMAKE_BUILD_TYPE=Debug \
  -DLLVM_PARALLEL_LINK_JOBS=1 -DLLVM_BUILD_LLVM_DYLIB=1 \
  -DLLVM_ENABLE_LLD=1 -DLLVM_ENABLE_PROJECTS="clang" \
  -DLLVM_TARGETS_TO_BUILD="host;BPF"
```

LINKING

- BPF target is **not** supported by lld.
- Instead, BPF has its own linkers:
  - **bpftool-link** - creted by libbpf community
  - **bpf-linker** - for Rust, created by Aya community
- Only static linking.

LLD

- There is a patch for lld to support BPF target, but it's not accepted.
  - https://reviews.llvm.org/D101336

REGISTERS

- **R0** - return value from functions, exit values for programs.
- **R1 - R5** - function arguments.
- **R6 - R9** - callee saved registers that function calls will preserve.
- **R10** - read-only frame pointer to access stack.

R0 - R5: scratch registers, programs need to spill them if necessary across calls.

BASIC INSTRUCTION ENCODING

32 bits (MSB)	16 bits	4 bits	4 bits	8 bits (LSB)
Integer Immediate Value	Offset	Source register	Destination register	Opcode

WIDE INSTRUCTION ENCODING

64 bits (MSB)	64 bits (LSB)
basic instruction	pseudo instruction

ARITHMETIC INSTRUCTIONS

Code	Description
BPF_ADD	dst += src
BPF_SUB	dst -= src
BPF_MUL	dst *= src
BPF_DIV	dst = (src != 0) ? (dst / src) : 0
BPF_OR	dst
BPF_AND	dst &= src

ARITHMETIC INSTRUCTIONS

Code	Description
BPF_LSH	dst <<= src
BPF_RSH	dst >>= src
BPF_NEG	dst = ~src
BPF_MOD	dst = (src != 0) ? (dst % src) : dst
BPF_XOR	dst ^= src

ARITHMETIC INSTRUCTIONS

Code	Description
BPF_MOV	dst = src
BPF_ARSH	sign extending shift right
BPF_END	byte swap operations

BYTE SWAP INSTRUCTIONS

Code	Description
BPF_TO_LE	host byte order -> little endian
BPF_TO_BE	host byte order -> big endian

JUMP INSTRUCTIONS

Code	Description
BPF_JA	PC += off
BPF_JEQ	PC += off if dst == src
BPF_JGT	PC += off if dst > src
BPF_JGE	PC += off if dst >= src

JUMP INSTRUCTIONS

Code	Description
BPF_JSET	PC += off if dst & src
BPF_JNE	PC += off if dst != src
BPF_JSGT	PC += off if dst > src
BPF_JSGE	PC += off if dst >= src

JUMP INSTRUCTIONS

Code	Description
BPF_CALL	function call
BPF_EXIT	program return

JUMP INSTRUCTIONS

Code	Description
BPF_JLT	PC += off if dst < src
BPF_JLE	PC += off if dst <= src
BPF_JSLT	PC += off if dst < src
BPF_JSLE	PC += off if dst <= src

ATOMIC OPERATIONS

Code	Description
BPF_ADD	atomic add
BPF_OR	atomic or
BPF_AND	atomic and
BPF_XOR	atomic xor

ATOMIC OPERATIONS

These atomic operations work only on 64 and 32 bit types.

Atomic CAS is **not** supported.

EXAMPLE (C CODE)

```
#include <linux/bpf.h>
#include <bpf/bpf_helpers.h>

SEC("xdp")
int  xdp_prog_simple(struct xdp_md *ctx)
{
    return XDP_PASS;
}

char _license[] SEC("license") = "GPL";
```

BUILDING (CLANG)

```
clang -O2 -target bpf -c -g xdp_pass_kern.c \
  -o xdp_pass_kern.o
```

LLVM-READELF

```
$ llvm-readelf -S xdp_pass_kern.o
Section Headers:
  [Nr] Name              Type            Address          Off    S
  [ 0]                   NULL            0000000000000000 000000
  [ 1] .strtab           STRTAB          0000000000000000 000b5a
  [ 2] .text             PROGBITS        0000000000000000 000040
  [ 3] xdp               PROGBITS        0000000000000000 000040
  [ 4] license           PROGBITS        0000000000000000 000050
  [ 5] .debug_abbrev     PROGBITS        0000000000000000 000054
  [ 6] .debug_info       PROGBITS        0000000000000000 000111
  [ 7] .rel.debug_info   REL             0000000000000000 0008b8
  [ 8] .debug_str_offsets PROGBITS       0000000000000000 0001de 0
  [ 9] .rel.debug_str_offsets REL        0000000000000000 0008f8 0
  [10] .debug_str        PROGBITS        0000000000000000 000246
  [11] .debug_addr       PROGBITS        0000000000000000 0003cd
```

LLVM-OBJDUMP

```
$ llvm-objdump -S xdp_pass_kern.o

xdp_pass_kern.o:        file format elf64-bpf

Disassembly of section xdp:

0000000000000000 <xdp_prog_simple>:
;       return XDP_PASS;
       0:       b7 00 00 00 02 00 00 00 r0 = 0x2
       1:       95 00 00 00 00 00 00 00 exit
```

EMITTING IR

```
clang -O2 -target bpf -c -g xdp.c -S -emit-llvm -o xdp.ll
```

IR

```
define dso_local i32 @xdp_prog_simple(ptr nocapture readnone
  %ctx) #0 section "xdp" !dbg !24 {
entry:
  call void @llvm.dbg.value(metadata ptr poison, metadata !40,
    metadata !DIExpression()), !dbg !41
  ret i32 2, !dbg !42
}
```

EXAMPLE (RUST CODE)

```
#![no_std]
#![no_main]

use aya_bpf::{bindings::xdp_action, cty::c_long, macros::xdp, pro

#[xdp(name = "xdp")]
pub fn xdp(ctx: XdpContext) -> u32 {
    match try_xdp_hello(ctx) {
        Ok(ret) => ret,
        Err(_) => xdp_action::XDP_ABORTED,
    }
}

fn try_xdp_hello(_ctx: XdpContext) -> Result<u32, c_long> {
    Ok(xdp_action::XDP_PASS)
}
```

BUILDING (RUST)

```
cargo +nightly build --target=bpfel-unknown-none \
  -Z build-std=core
```

LLVM-READELF

```
$ llvm-readelf -S target/bpfel-unknown-none/debug/xdp
There are 5 section headers, starting at offset 0x220:

Section Headers:
  [Nr] Name              Type            Address          Off    S
  [ 0]                   NULL            0000000000000000 000000
  [ 1] .strtab           STRTAB          0000000000000000 0001c0
  [ 2] .text             PROGBITS        0000000000000000 000040
  [ 3] xdp/xdp           PROGBITS        0000000000000000 0000d8
  [ 4] .symtab           SYMTAB          0000000000000000 0000e8
```

LLVM-OBJDUMP

```
$ llvm-objdump -S target/bpfel-unknown-none/debug/xdp-hello
[...]
Disassembly of section xdp/xdp:

0000000000000000 <xdp>:
       0:       b7 00 00 00 02 00 00 00 r0 = 0x2
       1:       95 00 00 00 00 00 00 00 exi
```

EMITTING IR

```
cargo +nightly rustc --target=bpfel-unknown-none \
  -Z build-std=core --  --emit=llvm-ir
```

IR

```
define dso_local noundef i32 @xdp(ptr nocapture noundef
  readnone %ctx) unnamed_addr #0 section "xdp/xdp" {
start:
  ret i32 2
}
```

BPF TYPE FORMAT (BTF)

- Debug info format for BPF, way more lightweight than DWARF.
- Used for offsets across Linux kernel versions.
- Used for stack traces in BPF verifier.
- But there is no debugger (yet).

EXAMPLE: C CODE

```
struct foo {
    __u32 a;
    __u64 b;
};
```

EXAMPLE: LLVM DEBUG INFO

```
!49 = distinct !DICompositeType(tag: DW_TAG_structure_type,
  name: "foo", file: !3, line: 21, size: 128, elements: !50)
!50 = !{!51, !54}
!51 = !DIDerivedType(tag: DW_TAG_member, name: "a", scope: !49,
  file: !3, line: 22, baseType: !52, size: 32)
!52 = !DIDerivedType(tag: DW_TAG_typedef, name: "__u32",
  file: !53, line: 27, baseType: !12)
!54 = !DIDerivedType(tag: DW_TAG_member, name: "b", scope: !49,
  file: !3, line: 23, baseType: !55, size: 64, offset: 64)
!55 = !DIDerivedType(tag: DW_TAG_typedef, name: "__u64",
  file: !53, line: 31, baseType: !56)
```

EXAMPLE: BTF

```
[8] STRUCT 'foo' size=16 vlen=2
        'a' type_id=9 bits_offset=0
        'b' type_id=10 bits_offset=64
```

EXAMPLE: RUST CODE

```
pub struct Foo {
    a: u32,
    b: u64,
}
```

EXAMPLE: LLVM DEBUG INFO

```
!42 = !DIBasicType(name: "u32", size: 32,
  encoding: DW_ATE_unsigned)
!60 = !DICompositeType(tag: DW_TAG_structure_type, name: "Foo",
  scope: !2, file: !5, size: 128, align: 64, elements: !61,
  templateParams: !65,
  identifier: "63dcf8d9f7a7a7ed6f05eaed70c4b12f")
!61 = !{!62, !63}
!62 = !DIDerivedType(tag: DW_TAG_member, name: "a", scope: !60,
  file: !5, baseType: !42, size: 32, align: 32, offset: 64)
!63 = !DIDerivedType(tag: DW_TAG_member, name: "b", scope: !60,
  file: !5, baseType: !64, size: 64, align: 64)
!64 = !DIBasicType(name: "u64", size: 64,
  encoding: DW_ATE_unsigned)
```

EXAMPLE: BTF

```
[20] STRUCT 'Foo' size=16 vlen=2
        'a' type_id=14 bits_offset=64
        'b' type_id=21 bits_offset=0
```

LOCAL BTF

Each modern Linux kernel comes with BTF info:

```
# bpftool btf dump file /sys/kernel/btf/vmlinux
[...]
[335] STRUCT 'pid' size=112 vlen=8
        'count' type_id=330 bits_offset=0
        'level' type_id=59 bits_offset=32
        'lock' type_id=324 bits_offset=64
        'tasks' type_id=336 bits_offset=128
        'inodes' type_id=134 bits_offset=384
        'wait_pidfd' type_id=328 bits_offset=448
        'rcu' type_id=139 bits_offset=640
        'numbers' type_id=337 bits_offset=768
```

BTF RELOCATIONS

- BPF programs are adjusted to read type fields at the offset specified in **local** BTF info.
- Regardless of the memory layout of the type.
- Types with BTF-based access are annotated with `llvm.preserve.*.access.index` intrinsics.

CHALLENGES WITH RUST

- BPF support introduced later than in Clang.
- BTF emission not supported, but close to be done!
- BTF relocations not supported.

WHAT'S THE PROBLEM?

- Kernel expects specific BTF layout.
- It's very C-specific.
  - BPF maps definitions have to be anonymous structs (which Rust doesn't support).
  - Complex Rust types (e.g. data carrying enums) are not supported.

SOLUTIONS

- Temporary: modify DI in bpf-linker.
- Long-term: `#[btf_export]` macro in Rust.

BPF-LINKER

Currently working PoC. Transforms DI to meet kernel expectations:

- Removes names from pointer types and BTF map structs.
- Tweaks the DI of Rust-specific types to be C-compatible.

BTF (FROM RUST) AFTER MODIFICATIONS

```
[10] STRUCT '(anon)' size=40 vlen=5
        'type' type_id=1 bits_offset=0
        'key' type_id=5 bits_offset=64
        'value' type_id=5 bits_offset=128
        'max_entries' type_id=6 bits_offset=192
        'map_flags' type_id=8 bits_offset=256
```

```
[6] PTR '(anon)' type_id=7
```

DEBUG INFO INCLUDED

```
; let parent_pid: i32 = unsafe {
    ctx.read_at(PARENT_PID_OFFSET)? };
9: 63 1a f4 ff 00 00 00 00 *(u32 *)(r10 - 0xc) = r1
[...]
; let child_pid: i32 = unsafe {
    ctx.read_at(CHILD_PID_OFFSET)? };
19: 63 1a f8 ff 00 00 00 00 *(u32 *)(r10 - 0x8) = r1
20: bf a2 00 00 00 00 00 00 r2 = r10
```

LLVM CHANGES

- Already merged, but to be released in LLVM 17:
  - `LLVMGetDINodeTag` function to get the tag of DI Node.
  - `LLVMReplaceMDNodeOperandWith` function to modify DI.

IF YOU WANT TO TRY IT OUT

- github.com/vadorovsky/aya-btf-map - structs and macros for BTF maps.
- github.com/vadorovsky/aya-btf-maps-experiments - example project using it.
- Requires LLVM and bpf-linker patches.

#[BTF_EXPORT]

- Decoupled from `-C debuginfo`.
- Generates DI, which produces correct BTF for annotated types.
- Raises a compiler error when used on BTF-incompatible type.

VERIFIER

- (So far) only in Linux kernel (Solana, rBPF and other user space implementations don't have it).
- Ensuring safe memory access - kinda, like, making C Rusty (͡° ͜ʖ ͡°).
- Descending all possible instruction paths, observing the change of registers and stack.

REGISTER STATE TYPES

- `NOT_INIT` - was never written to.
- `SCALAR_VALUE` - value not usable as a pointer.
- `PTR_TO_CTX` - program context.
- `CONST_PTR_TO_MAP` - pointer to BPF map.
- `PTR_TO_MAP_VALUE` - pointer to BPF map value.
- `PTR_TO_MAP_VALUE_OR_NULL` - pointer to BPF map value or NULL.
- `PTR_TO_STACK` - frame pointer.

REGISTER STATE TYPES

- `PTR_TO_PACKET` - pointer to network packet data.
- `PTR_TO_PACKET_END` - pointer to end of network packet data.
- `PTR_TO_SOCKET` - pointer to `bpf_sock_ops`.
- `PTR_TO_SOCKET_OR_NULL` - pointer to `bpf_sock_ops` or NULL.

WHAT DOESN'T PASS VERIFIER

- Reading from registers which were never written to.
- Instructions which are unreachable.
- Loops without bounds (to a constant).
- Memory access without bounds (to a constant).
- Direct packet access outside the end of packet.

DEMO

Let's write a simple LSM program which restricts filesystem access!

THANK YOU

- aya-rs.dev
  - github.com/aya-rs/aya
  - Discord
- lightprotocol.com