Running Python in the Linux Kernel with bpf

Alex Gartrell

Software Engineer @ Facebook

Agenda

1. Who am I?
2. bpf Overview?
3. Python Virtual Machine
4. Transpiling from python to bpf bytecode
5. Woo, we made it!

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Who am I?

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- Alex Gartrell
- Software Engineer @ Facebook
- Work in Infrastructure for ~6 years
  - Caching Infrastructure
  - Content Distribution Network
  - Linux Kernel Networking Stack
  - Linux Containers
  - Network Block Devices

Who am I?

- Alex Gartrell
- Software Engineer @ Facebook
- Work in Infrastructure for ~6 years
  - Caching Infrastructure
  - Content Distribution Network
  - Linux Kernel Networking Stack
  - Linux Containers
  - Network Block Devices
- I am **not** a compilers expert

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Let's watch programs start

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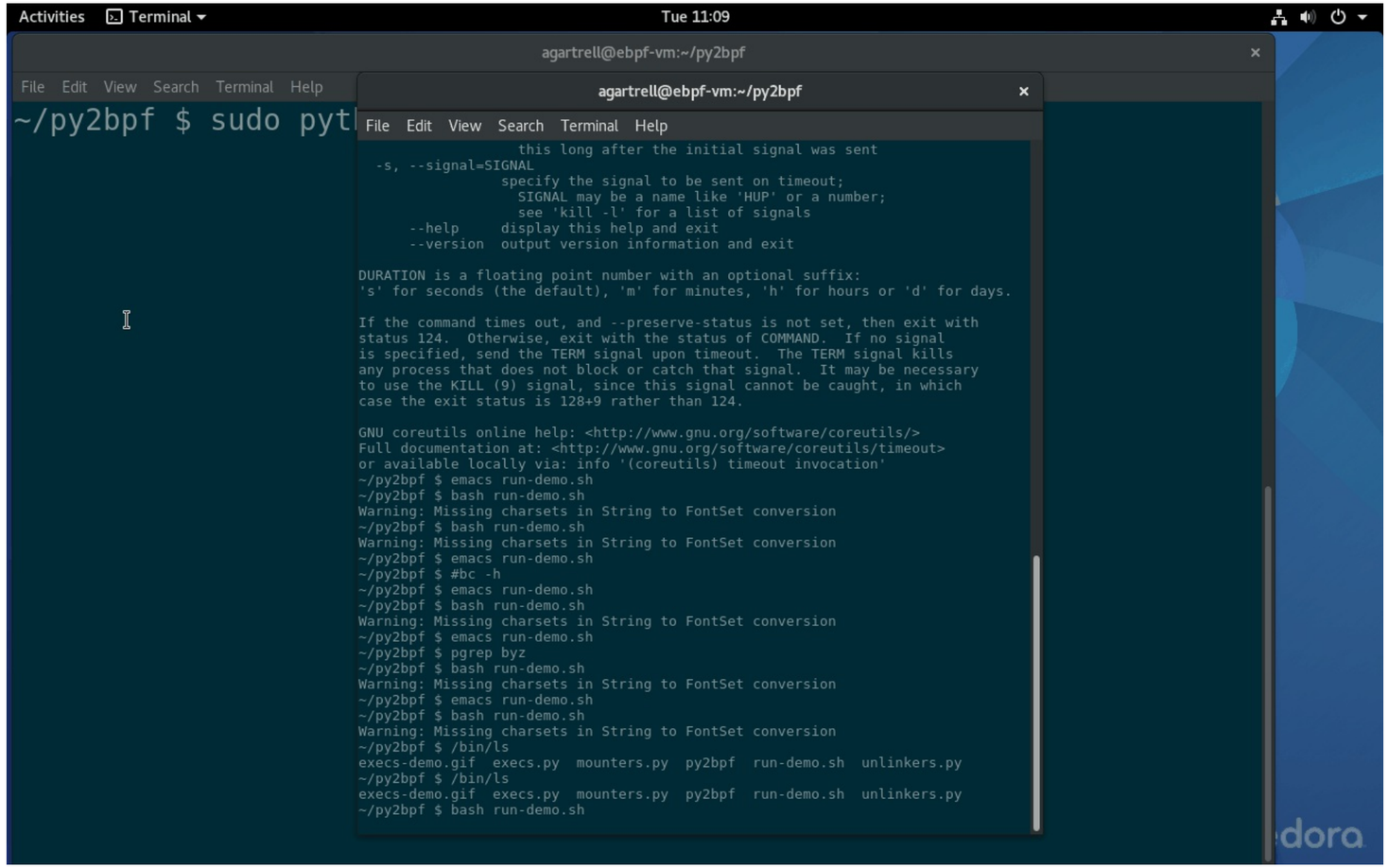

How are we doing that?

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```
int sys_execve(filename, argv) {
   // Execute a program!
   ...
}
```

How are we doing that?

```
int sys_execve(filename, argv) {
   goto my_new_tracepoint;
   // Execute a program!
   ...
}
```

How are we doing that?

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```
with ExecveProbe() as probe:
    for call in probe.queue:
        print(
            call.pid,
            call.comm.decode(),
            call.arg0.decode(),
            call.arg1.decode(),
            call.arg2.decode(),
            call.arg3.decode())
```

But what does the probe look like?

But what does the probe look like?

```
def fn(pt_regs):
    call = Call()
    call.pid = funcs.get_current_pid_tgid() & 0xffffffff
    funcs.get_current_comm(call.comm)

    arg = ctypes.c_int64()
    addrof_arg = funcs.addrof(arg)

    funcs.probe_read(addrof_arg, pt_regs.rsi)
    if arg != 0: # Read argv[0]
        funcs.probe_read(call.arg1, arg)
        funcs.probe_read(addrof_arg, pt_regs.rsi + 8)

    ...

    funcs.perf_event_output(pt_regs, q, 0, call)

    return 0
```

What is the kernel?

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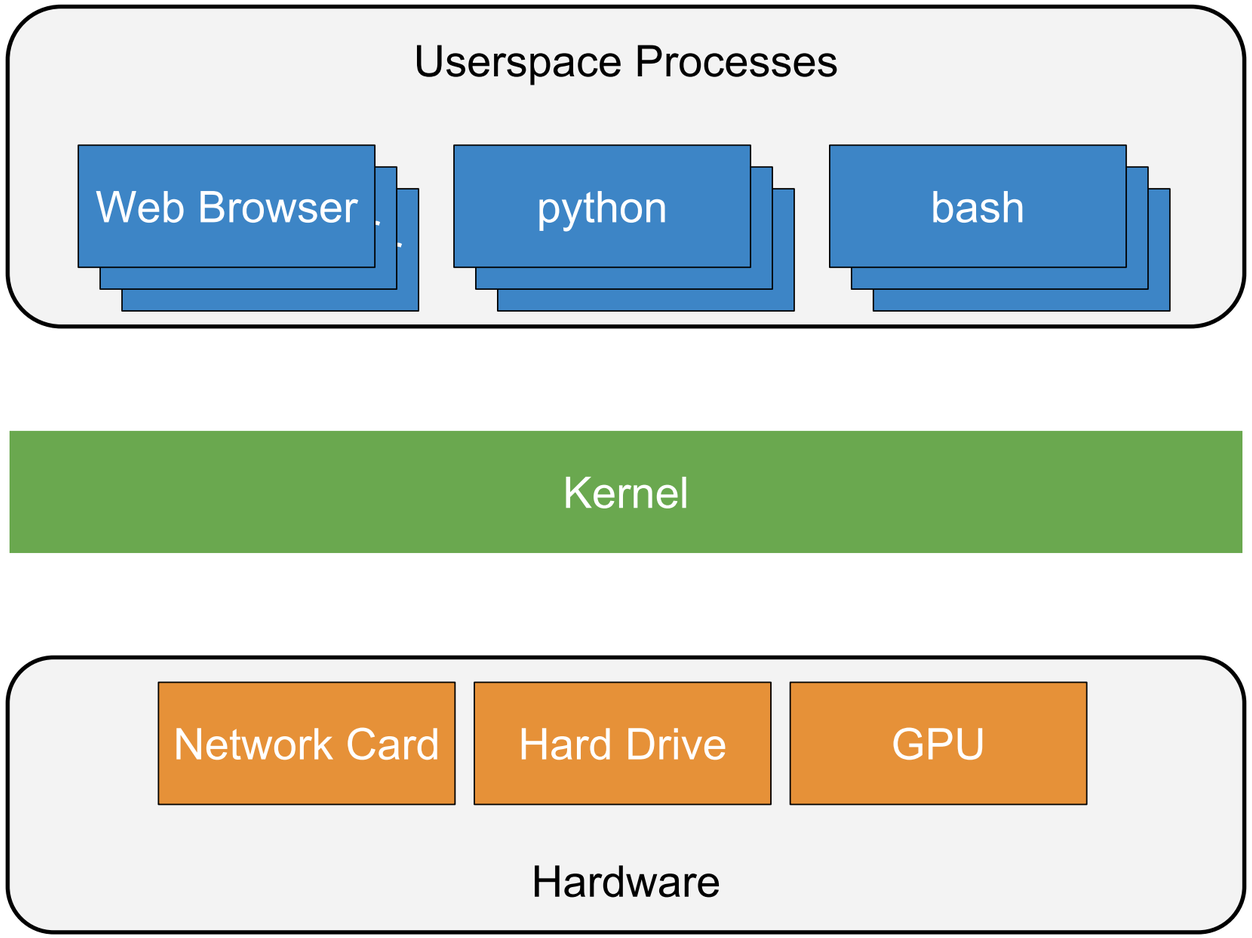

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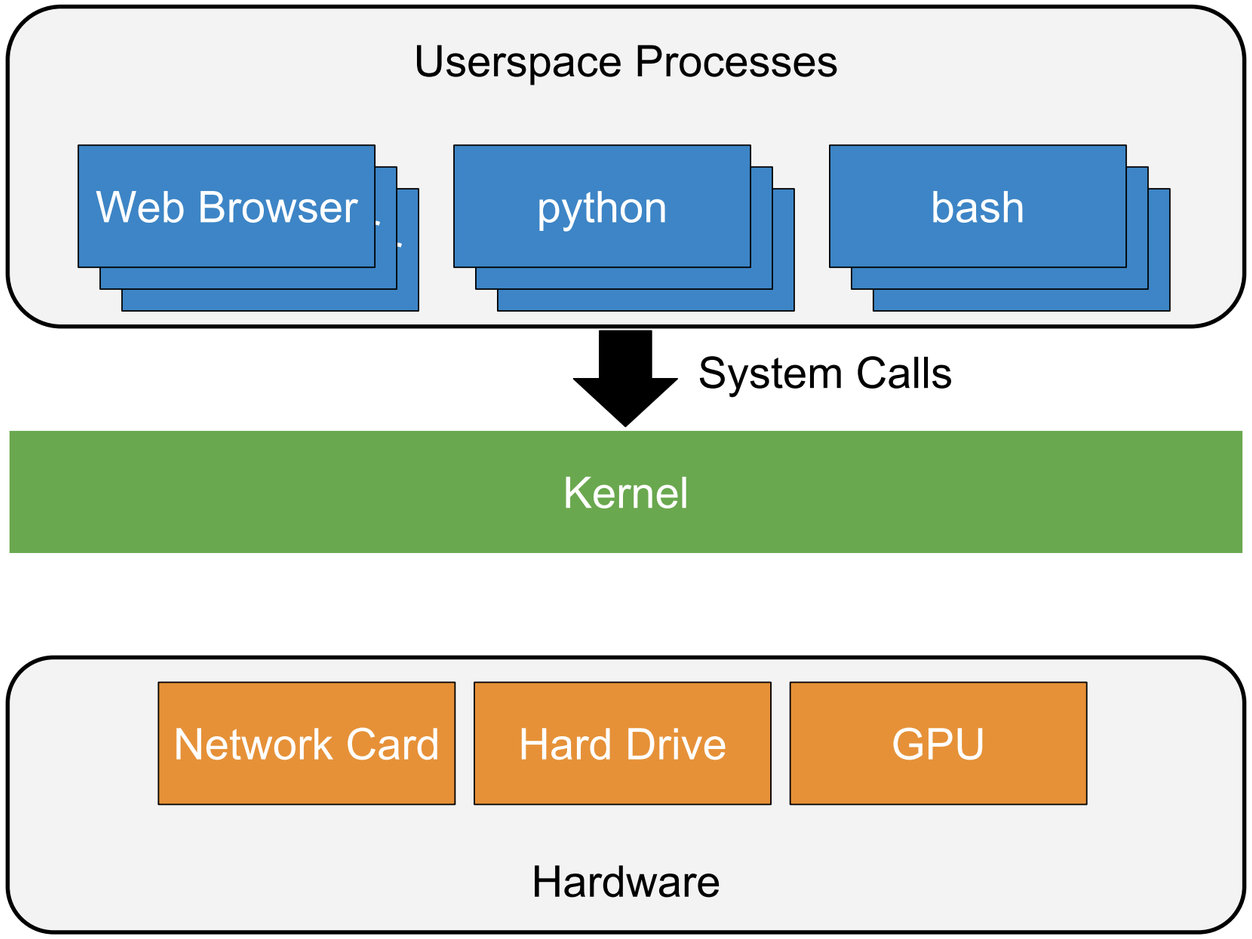
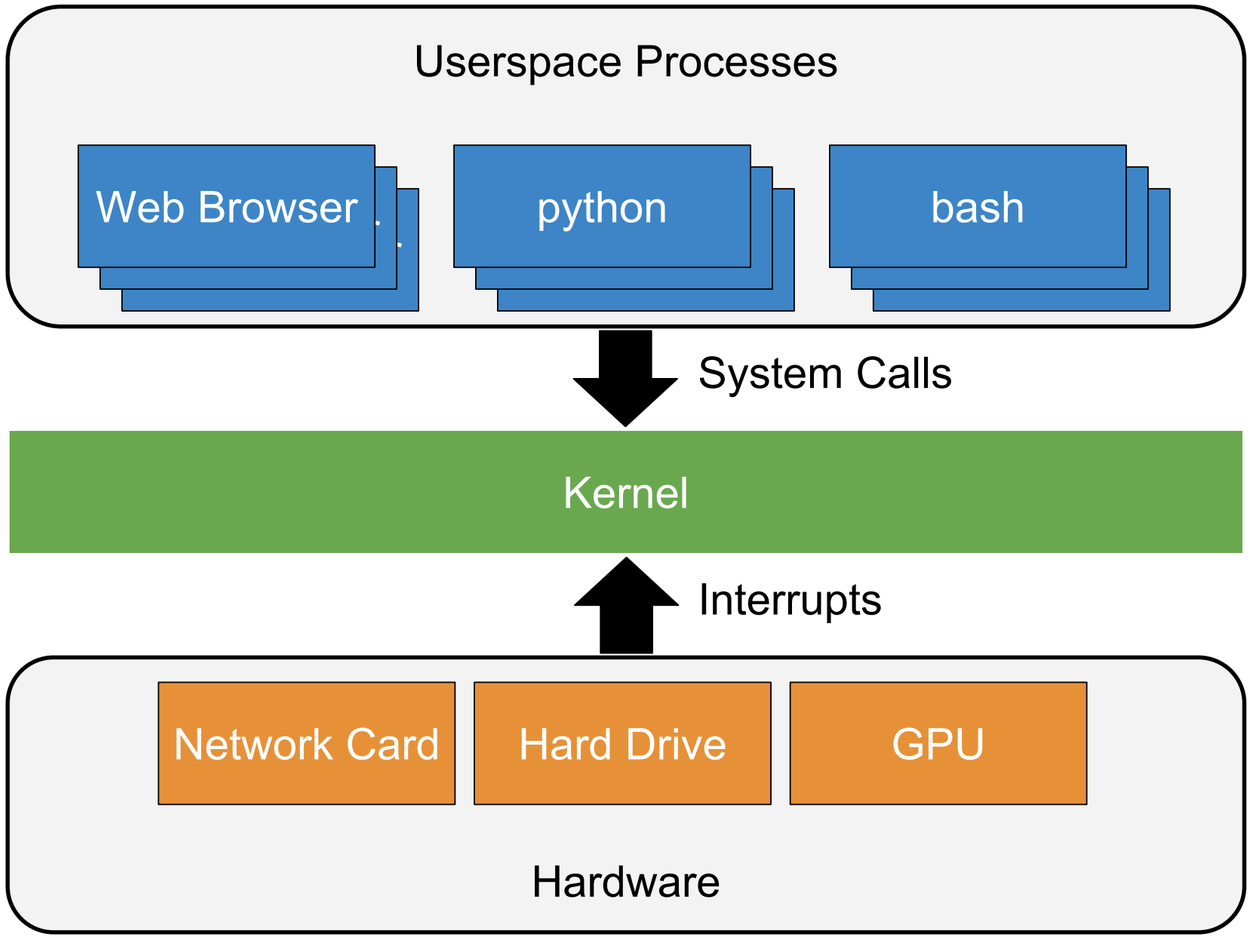


What is the kernel?



Constraints of the kernel environment

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- Giant, complicated async app

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Constraints of the kernel environment

- Giant, complicated async app
- Full access to everything
- Bugs can:
  - Cause a system crash
  - Totally break security

So how can we probe the state of the kernel without breaking stuff?

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- **Problem:** www.facebook.com isn't loading

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- **Problem:** www.facebook.com isn't loading
- Is it a network problem?

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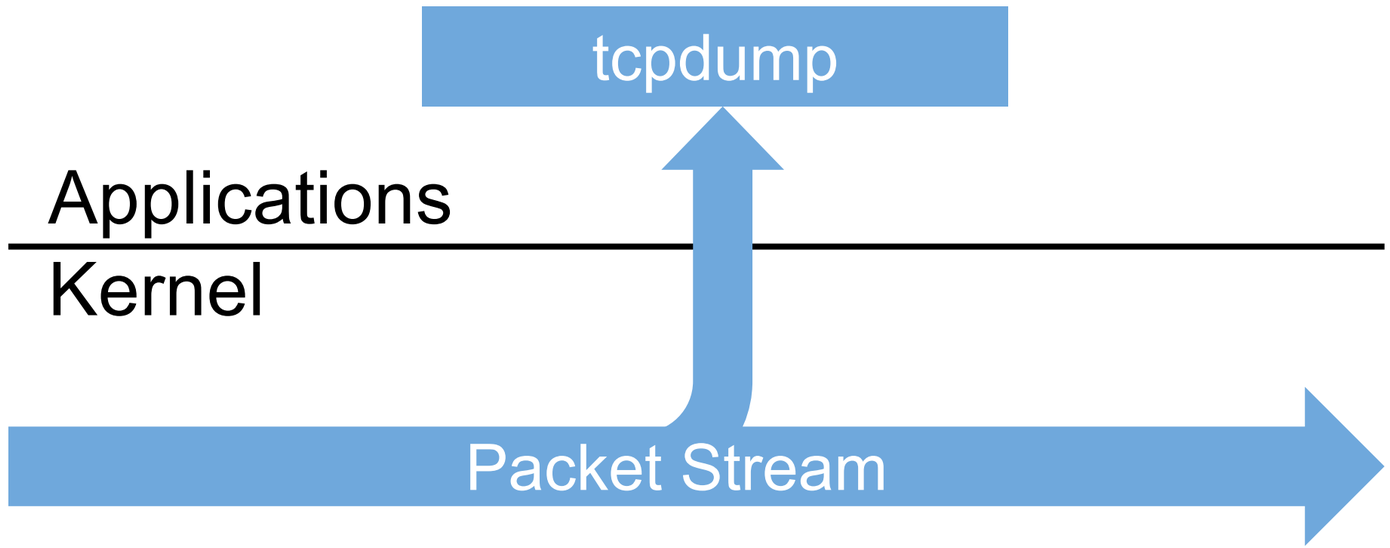
- Check by examining the network!

History: The Berkeley Packet Filter

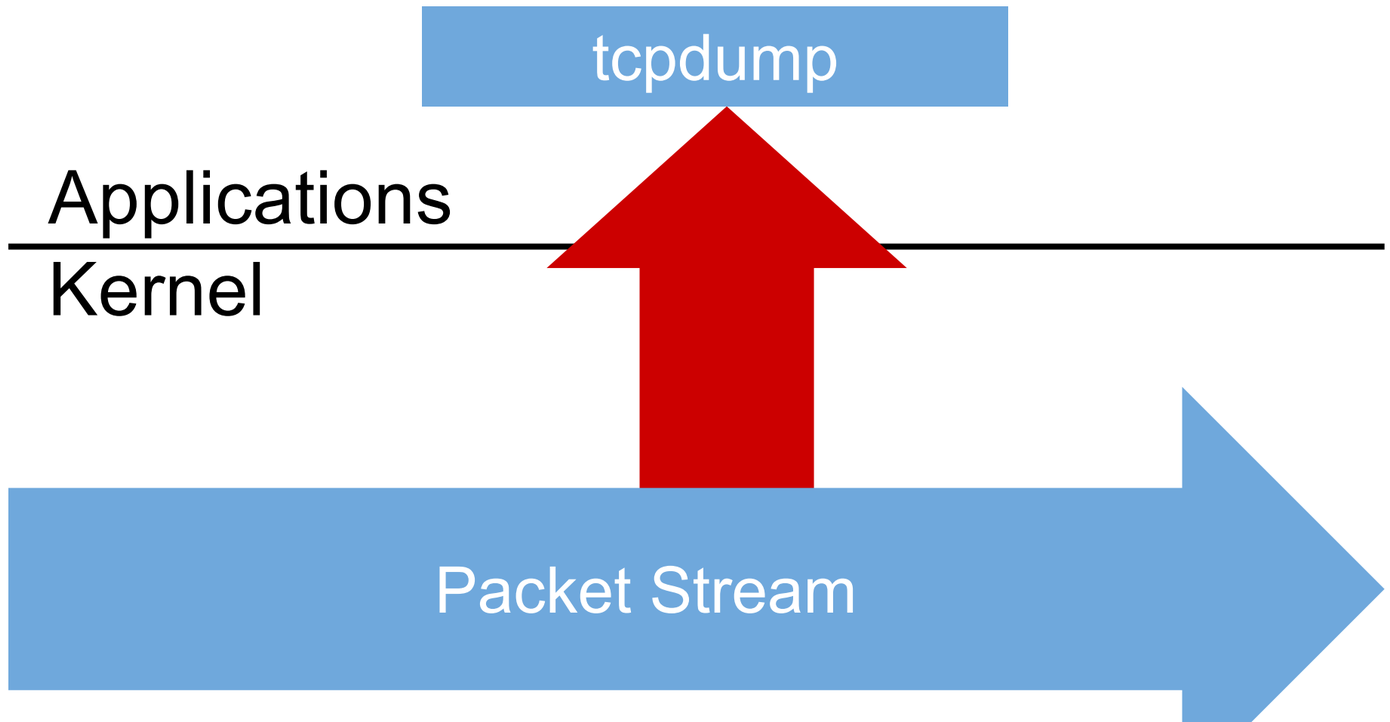
- **Problem:** www.facebook.com isn't loading
- Is it a network problem?
- Check by examining the network!

```
 $ sudo tcpdump -t -niany -c 10 port 80
IP 10.232.0.24.http > 192.168.124.179.52178: \
    Flags [S.], ... options [mss 1460], length 0
IP 192.168.124.179.52178 > 10.232.0.24.http: \
    Flags [.], ack 1, win 29200, length 0
IP 192.168.124.179.52178 > 10.232.0.24.http: \
     Flags [P.], seq 1:81, ack 1, win 29200, \
     length 80: HTTP: GET / HTTP/1.1
```

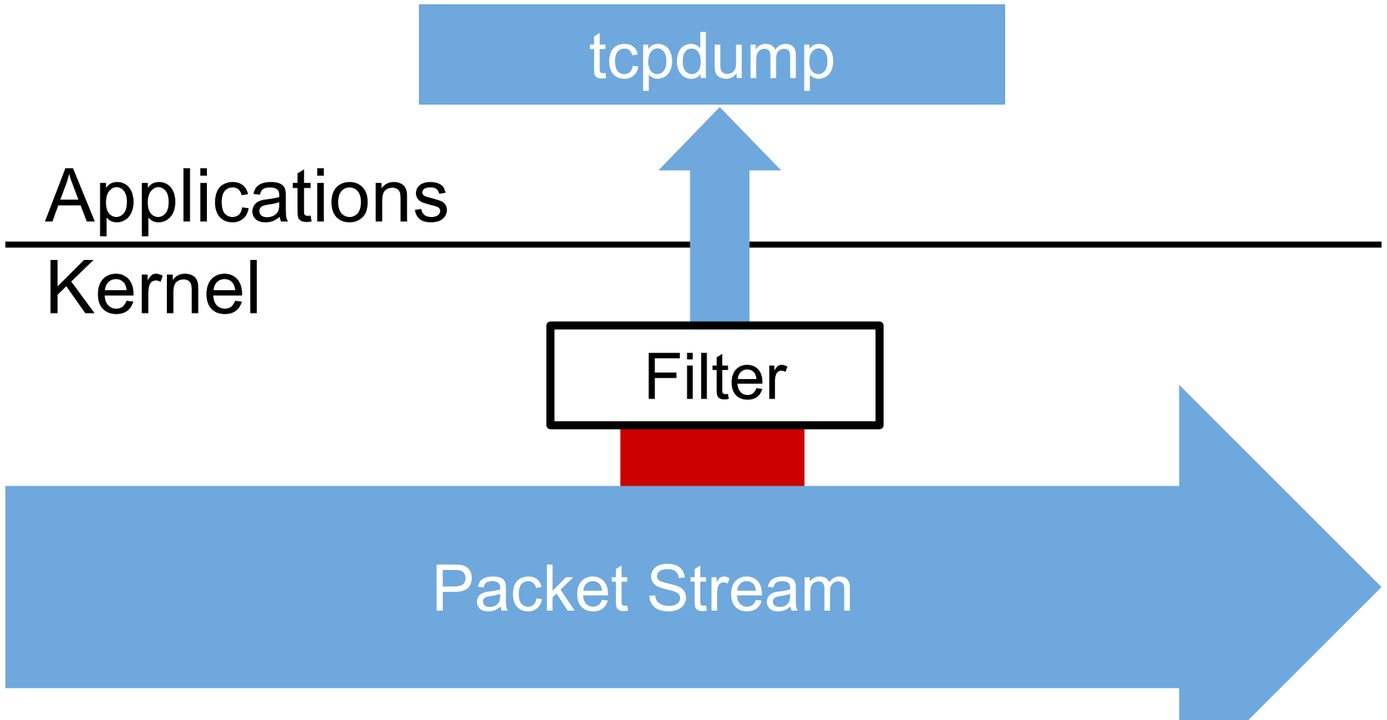
Getting packets from the kernel



It gets expensive fast



Answer: filter in the kernel



Building packet filters is hard

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- Infinite network protocols to match on
  - TCP, UDP, DNS, ICMP, HTTP, ...

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- Infinite network protocols to match on
  - TCP, UDP, DNS, ICMP, HTTP, ...
- Need to dynamically match on range of bytes (or bits!)

```
# Match tcp FIN packets
tcpdump 'tcp[13] & 1 != 0'

# Match packets with low (< 10 hop) time to live
tcpdump 'ip[8] < 10'
```

One option: run arbitary code

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One option: run arbitary code

- Fast - perfectly optimized machine code
- Flexible - do anything you want
- Dangerous - A buggy filter crashes the system
- Dangerous - Evil users are "above the law"

The Berkeley Packet Filter

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- Provide a minimal set of instructions

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- Statically verify that the code is valid

The Berkeley Packet Filter

- Provide a minimal set of instructions
- Statically verify that the code is valid
- (Optionally) translate it to native machine code

The Berkeley Packet Filter Operations

http://www.tcpdump.org/papers/bpf-usenix93.pdf

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- Data access
  - Load/store data

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- Data access
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The Berkeley Packet Filter Operations

- Data access
  - Load/store data
- Jumps
  - Unconditionally, >=, >, ==
- Math
  - +, -, *, /, &, |, <<, >>
- Return

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Scope creep

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- Turns out an in-kernel VM is useful

Scope creep

- Turns out an in-kernel VM is useful
- In 2014, Alexei begins making code changes to extend/generalize bpf
  - New bytecode that looks more like x86_64
  - General purpose bpf system call
  - Shared datastructures with applications (maps, arrays, etc.)

https://lwn.net/Articles/603983/

Extending bpf

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- Local memory

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- More registers
  - From 2 to 10

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Extending bpf

- Local memory
- More registers
  - From 2 to 10
- Function calls
  - Built-in kernel helpers like getpid
- Shared datastructures
  - Maps/Arrays that can be accessed from applications

Where can we use it today?

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- Software Tracepoints

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- Traffic Control

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- Software Tracepoints
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- In the network card with XDP

bpf Toolchain

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- C function is compiled to bpf using new clang backend

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- Primary interface is bcc
- C function is compiled to bpf using new clang backend
- Python script loads and inserts compiled C function
- ctypes enables datastructure sharing

simple_tc.py example

```
# Copyright (c) PLUMgrid, Inc.
# Licensed under the Apache License, Version 2.0 ...

...

text = """
int hello(struct __sk_buff *skb) {
  return 1;
}
"""

b = BPF(text=text, debug=0)
fn = b.load_func("hello", BPF.SCHED_CLS)
IPRoute().tc("add-filter", "bpf", fd=fn.fd, ...)
```

https://github.com/iovisor/bcc/blob/master/examples/networking/simple_tc.py

Why not just translate python bytecode to bpf bytecode? — Me (naïve)

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Python bytecode overview

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- Single magical, infinite stack of python objects
- Each python bytecode operates on the magical stack
- No real concept of the physical machine

Wait, python bytecode?

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- You can see this bytecode with the dis module

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- You can see this bytecode with the dis module

```
>>> def func(a, b):
...     return a.x + max(b)
...
>>> dis.dis(func)
  2           0 LOAD_FAST                0 (a)
              2 LOAD_ATTR                0 (x)
              4 LOAD_GLOBAL              1 (max)
              6 LOAD_FAST                1 (b)
              8 CALL_FUNCTION            1
             10 BINARY_ADD
             12 RETURN_VALUE
```

Stack-based virtual machine??

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- All operations occur with the stack

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- All operations occur with the stack
- Take the expression: x + y * z

Stack-based virtual machine??

- All operations occur with the stack
- Take the expression: x + y * z
- In a stack-based representation:

```
push x
push y
push z
multiply
add
return
```

Stack-Based Example

x + y * z

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push x
push y
push z
multiply
add
return
```

Stack-Based Example

x + y * z

```
push x    - stack.append(x)
push y    - stack.append(y)
push z    - stack.append(z)
multiply
add
return
```

Stack-Based Example

x + y * z

```
push x     - stack.append(x)
push y     - stack.append(y)
push z     - stack.append(z)
multiply   - stack.append(stack.pop() * stack.pop())
add
return
```

Stack-Based Example

x + y * z

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push x     - stack.append(x)
push y     - stack.append(y)
push z     - stack.append(z)
multiply   - stack.append(stack.pop() * stack.pop())
add        - stack.append(stack.pop() + stack.pop())
return
```

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push z     - stack.append(z)
multiply   - stack.append(stack.pop() * stack.pop())
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return     - return stack.pop()
```

Stack-Based Example

x + y * z (x=2, y=3, z=5)

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push x    - stack.append(x)
push y    - stack.append(y)
push z    - stack.append(z)
multiply  - stack.append(stack.pop() * stack.pop())
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return    - return stack.pop()
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push x     - stack.append(x)
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push z     - stack.append(z)
multiply   - stack.append(stack.pop() * stack.pop())
add        - stack.append(stack.pop() + stack.pop())
return     - return stack.pop()
```

```
stack = [2]
```

Stack-Based Example

x + y * z (x=2, y=3, z=5)

```
push x    - stack.append(x)
push y    - stack.append(y)
push z    - stack.append(z)
multiply  - stack.append(stack.pop() * stack.pop())
add       - stack.append(stack.pop() + stack.pop())
return    - return stack.pop()
```

```
stack = [2, 3]
```

Stack-Based Example

x + y * z (x=2, y=3, z=5)

```
push x     - stack.append(x)
push y     - stack.append(y)
push z     - stack.append(z)
multiply   - stack.append(stack.pop() * stack.pop())
add        - stack.append(stack.pop() + stack.pop())
return     - return stack.pop()
```

```
stack = [2, 3, 5]
```

Stack-Based Example

x + y * z (x=2, y=3, z=5)

```
push x     - stack.append(x)
push y     - stack.append(y)
push z     - stack.append(z)
multiply   - stack.append(stack.pop() * stack.pop())
add        - stack.append(stack.pop() + stack.pop())
return     - return stack.pop()
```

```
stack = [2, 15]
```

Stack-Based Example

x + y * z (x=2, y=3, z=5)

```
push x     - stack.append(x)
push y     - stack.append(y)
push z     - stack.append(z)
multiply   - stack.append(stack.pop() * stack.pop())
add        - stack.append(stack.pop() + stack.pop())
return     - return stack.pop()
```

```
stack = [17]
```

Stack-Based Example

x + y * z (x=2, y=3, z=5)

```
push x     - stack.append(x)
push y     - stack.append(y)
push z     - stack.append(z)
multiply   - stack.append(stack.pop() * stack.pop())
add        - stack.append(stack.pop() + stack.pop())
return     - return stack.pop()
```

```
stack = []
```

Generating stack-based bytecode

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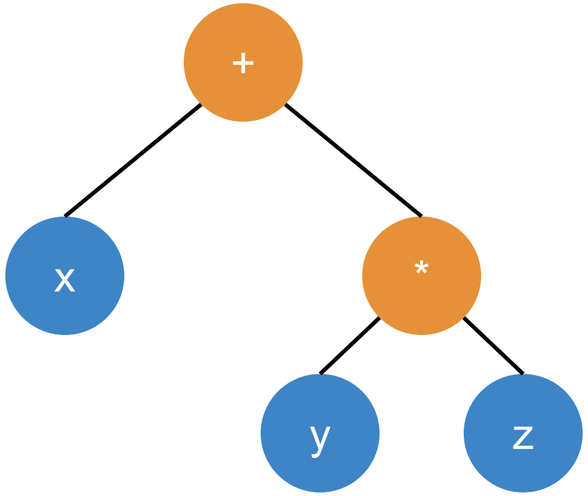

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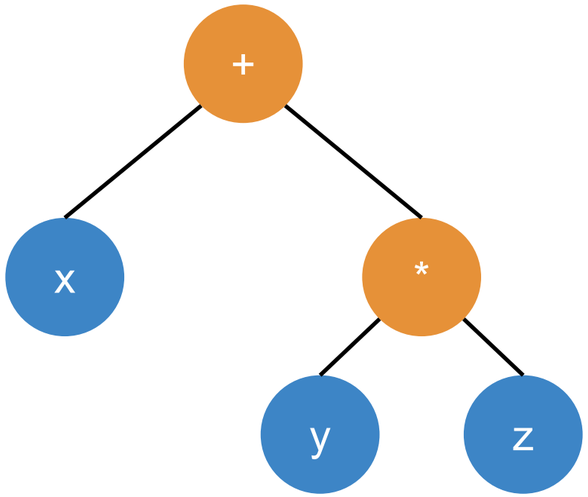

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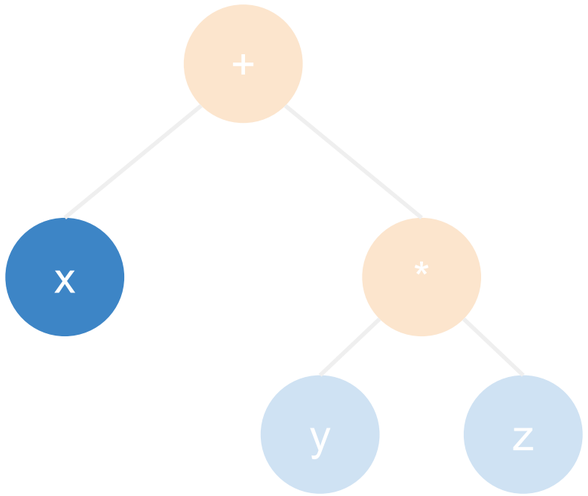
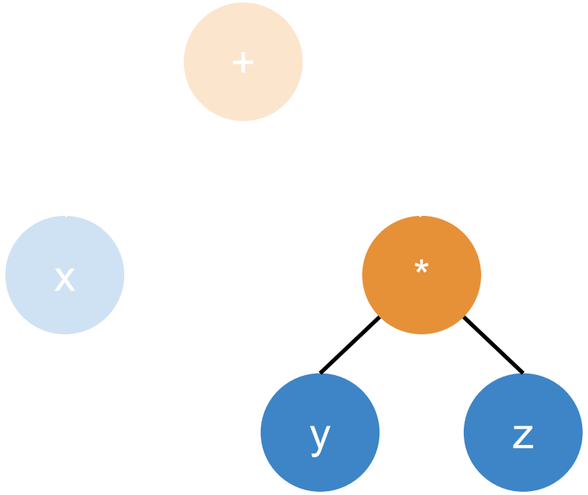



```
push x
```

Generating stack-based bytecode

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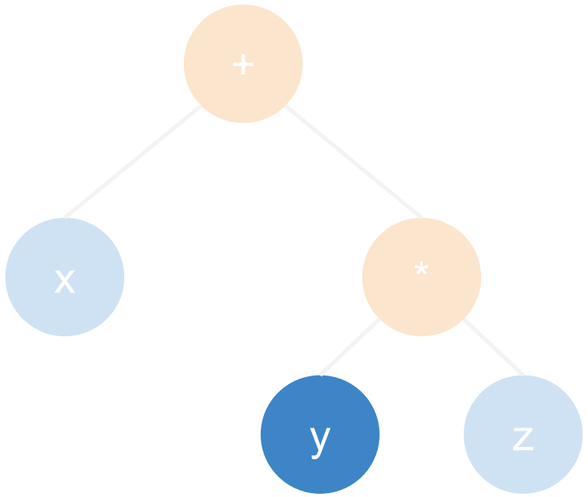
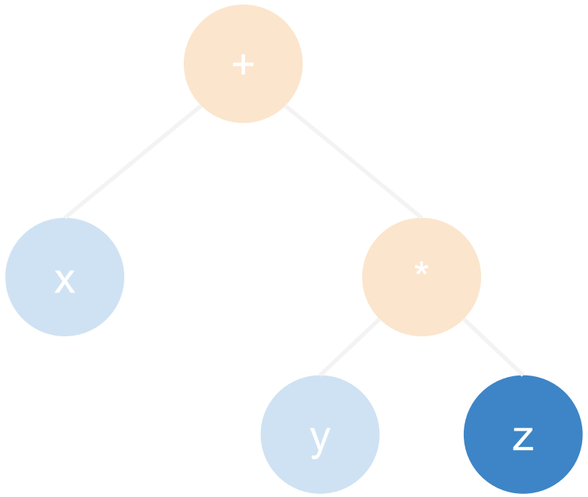


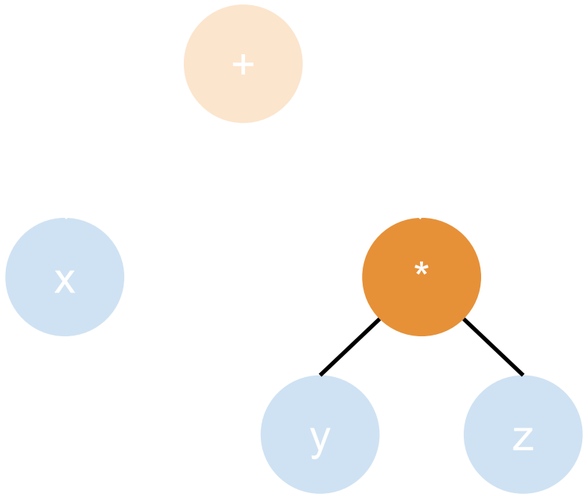

```
push x
push y
```

Generating stack-based bytecode



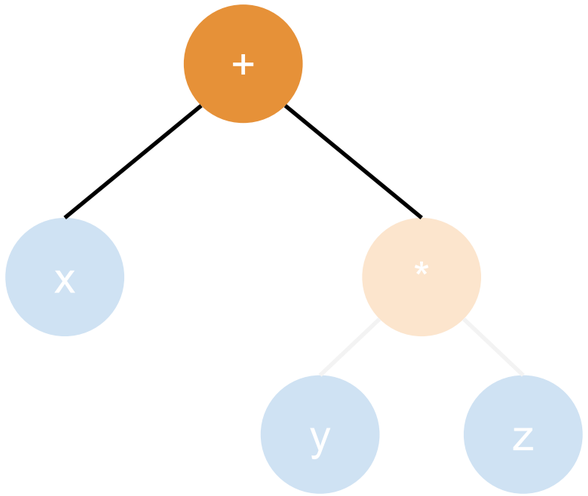

```
push x
push y
push z
```

Generating stack-based bytecode



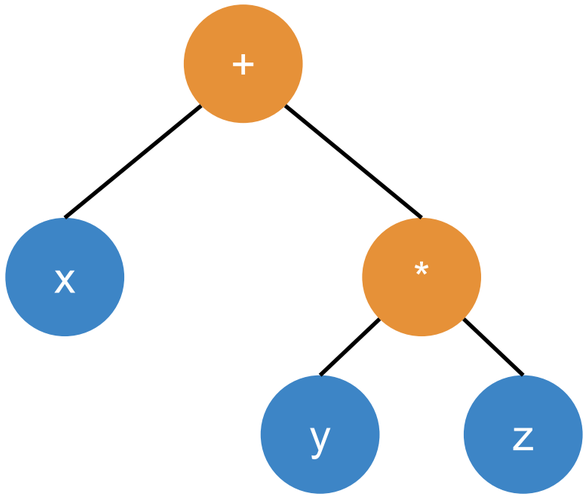

```
push x
push y
push z
multiply
```

Generating stack-based bytecode




```
push x
push y
push z
multiply
add
```

Generating stack-based bytecode




```
push x
push y
push z
multiply
add
return
```

The python virtual machine (in python!)

```
def run(instructions):



    while True:
        pass
```

Program Counter

```
def run(instructions):
    pc = 0



    while True:
        ins = instructions[pc]
        pc += 1
```

The Stack - Write Ops

```
def run(instructions):
    pc = 0
    stack = []


    while True:
        ins = instructions[pc]
        pc += 1
        if ins.opcode == LOAD_CONST:
            stack.append(ins.argval)
        ...
```

The Stack - Read Ops

```
def run(instructions):
    pc = 0
    stack = []


    while True:
        ins = instructions[pc]
        pc += 1
        ...
        elif ins.opcode == RETURN_VALUE:
            return stack.pop()
        ...
```

The Stack - Read/Write Ops

```
def run(instructions):
    pc = 0
    stack = []


    while True:
        ins = instructions[pc]
        pc += 1
        ...
        elif ins.opcode == BINARY_MULTIPLY:
            arg1 = stack.pop()
            arg2 = stack.pop()
            stack.append(arg1 * arg2)
        ...
```

Control Flow - Absolute

```
def run(instructions):
    pc = 0
    stack = []


    while True:
        ins = instructions[pc]
        pc += 1
        ...
        elif ins.opcode == JUMP_ABSOLUTE:
            pc = ins.argval
        ...
```

Control Flow - Conditional

```
def run(instructions):
    pc = 0
    stack = []


    while True:
        ins = instructions[pc]
        pc += 1
        ...
        elif ins.opcode == POP_JUMP_IF_TRUE:
            if stack.pop():
                pc = ins.argval
        ...
```

Fast Vars - Reading

```
def run(instructions):
    pc = 0
    stack = []
    vars = {}

    while True:
        ins = instructions[pc]
        pc += 1
        ...
        elif ins.opcode == LOAD_FAST:
            stack.append(vars[ins.argval])
        ...
```

Fast Vars - Writing

```
def run(instructions):
    pc = 0
    stack = []
    vars = {}

    while True:
        ins = instructions[pc]
        pc += 1
        ...
        elif ins.opcode == STORE_FAST:
            var[ins.argval] = stack.pop()
        ...
```

Global Vars

```
def run(instructions, globals):
    pc = 0
    stack = []
    vars = {}

    while True:
        ins = instructions[pc]
        pc += 1
        ...
        elif ins.opcode == LOAD_GLOBAL:
            stack.append(globals[ins.argval])
        elif ins.opcode == STORE_GLOBAL:
             globals[ins.argval] = stack.pop()
        ...
```

Many more python opcodes

POP_TOP	ROT_TWO	ROT_THREE	DUP_TOP
DUP_TOP_TWO	NOP	UNARY_POSITIVE	UNARY_NEGATIVE
UNARY_NOT	UNARY_INVERT	BINARY_MATRIX_MULTIPLY	INPLACE_MATRIX_MULTIPLY
BINARY_POWER	BINARY_MULTIPLY	BINARY_MODULO	BINARY_ADD
BINARY_SUBTRACT	BINARY_SUBSCR	BINARY_FLOOR_DIVIDE	BINARY_TRUE_DIVIDE
INPLACE_FLOOR_DIVIDE	INPLACE_TRUE_DIVIDE	GET_AITER	GET_ANEXT
BEFORE_ASYNC_WITH	INPLACE_ADD	INPLACE_SUBTRACT	INPLACE_MULTIPLY
INPLACE_MODULO	STORE_SUBSCR	DELETE_SUBSCR	BINARY_LSHIFT
BINARY_RSHIFT	BINARY_AND	BINARY_XOR	BINARY_OR
INPLACE_POWER	GET_ITER	GET_YIELD_FROM_ITER	PRINT_EXPR
LOAD_BUILD_CLASS	YIELD_FROM	GET_AWAITABLE	INPLACE_LSHIFT
INPLACE_RSHIFT	INPLACE_AND	INPLACE_XOR	INPLACE_OR
BREAK_LOOP	WITH_CLEANUP_START	WITH_CLEANUP_FINISH	RETURN_VALUE
IMPORT_STAR	SETUP_ANNOTATIONS	YIELD_VALUE	POP_BLOCK
END_FINALLY	POP_EXCEPT	STORE_NAME	DELETE_NAME
UNPACK_SEQUENCE	FOR_ITER	UNPACK_EX	STORE_ATTR
DELETE_ATTR	STORE_GLOBAL	DELETE_GLOBAL	LOAD_CONST
LOAD_NAME	BUILD_TUPLE	BUILD_LIST	BUILD_SET
BUILD_MAP	LOAD_ATTR	COMPARE_OP	IMPORT_NAME
IMPORT_FROM	JUMP_FORWARD	JUMP_IF_FALSE_OR_POP	JUMP_IF_TRUE_OR_POP
JUMP_ABSOLUTE	POP_JUMP_IF_FALSE	POP_JUMP_IF_TRUE	LOAD_GLOBAL
CONTINUE_LOOP	SETUP_LOOP	SETUP_EXCEPT	SETUP_FINALLY
LOAD_FAST	STORE_FAST	DELETE_FAST	STORE_ANNOTATION
RAISE_VARARGS	CALL_FUNCTION	MAKE_FUNCTION	BUILD_SLICE
LOAD_CLOSURE	LOAD_DEREF	STORE_DEREF	DELETE_DEREF
CALL_FUNCTION_KW	CALL_FUNCTION_EX	SETUP_WITH	LIST_APPEND
SET_ADD	MAP_ADD	LOAD_CLASSDEREF	EXTENDED_ARG
BUILD_LIST_UNPACK	BUILD_MAP_UNPACK	BUILD_MAP_UNPACK_WITH_CALL	BUILD_TUPLE_UNPACK
BUILD_SET_UNPACK	SETUP_ASYNC_WITH	FORMAT_VALUE	BUILD_CONST_KEY_MAP
	BUILD_STRING	BUILD_TUPLE_UNPACK_WITH_CALL	

https://docs.python.org/3.6/library/dis.html

Agenda

1. Who am I?
2. Overview
3. Python Virtual Machine
4. **Transpiling from python to bpf bytecode**
5. Woo, we made it!

bpf bytecode overview

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- Small stack is just array of bytes

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- Everything has a fixed size and type
  - 32-bit int, 8-bit character, etc.

bpf bytecode overview

- Small stack is just array of bytes
- Most opcodes operate on registers only
- Need to store/load from/to memory
- Everything has a fixed size and type
  - 32-bit int, 8-bit character, etc.
- No backward or absolute jumping allowed

Essential Steps

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1. Freeze python-isms in place with constant folding

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2. Normalize stack-based VM to variable-based VM

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1. Freeze python-isms in place with constant folding

2. Normalize stack-based VM to variable-based VM

3. Deduce type and allocate space for each variable

4. Translate bytecodes

Constant folding

Constant folding

- Freeze all globals in place

Constant folding

- Freeze all globals in place
- Perform as many operations as we can
  - Attribute loads
  - Arithmetic
  - Function calls

Constant folding

```
>>> def filter(skb):
...     return socket.htons(ETH_P_IP)
...
```

Constant folding

```
>>> def filter(skb):
...     return socket.htons(ETH_P_IP)
...
```

```
>>> dis.dis(filter)
  2           0 LOAD_GLOBAL              0 (socket)
              2 LOAD_ATTR                1 (htons)
              4 LOAD_GLOBAL              2 (ETH_P_IP)
              6 CALL_FUNCTION            1
              8 RETURN_VALUE
```

Constant folding

```
LOAD_GLOBAL('socket')
LOAD_ATTR('htons')
LOAD_GLOBAL('ETH_P_IP')
CALL_FUNCTION(1)
RETURN_VALUE
```

Constant folding - pin globals

```
    LOAD_CONST(socket) # socket module
    LOAD_ATTR('htons')
    LOAD_CONST(0x0800) # ETH_P_IP
    CALL_FUNCTION(1)
    RETURN_VALUE
```

Constant folding - fold constants

```
LOAD_CONST(socket.htons) # socket.htons
LOAD_CONST(0x0800) # ETH_P_IP
CALL_FUNCTION(1)
RETURN_VALUE
```

Constant folding - fold constants

```
LOAD_CONST(0x0008) # socket.htons(ETH_P_IP)
RETURN_VALUE
```

Eliminating the stack

Eliminating the stack

- Trace every execution path

Eliminating the stack

- Trace every execution path
- Identify source instructions for each operation

Eliminating the stack

- Trace every execution path
- Identify source instructions for each operation
- Normalize all destinations into "variables"

Eliminating the stack

```
>>> def func(a, b):
...     return a * (b if b > 0 else 7)
...
```

Eliminating the stack

```
>>> def func(a, b):
...     return a * (b if b > 0 else 7)
...
```

```
>>> dis.dis(func)
  2           0 LOAD_FAST                0 (a)
              2 LOAD_FAST                1 (b)
              4 LOAD_CONST               1 (0)
              6 COMPARE_OP               4 (>)
              8 POP_JUMP_IF_FALSE       14
             10 LOAD_FAST                1 (b)
             12 JUMP_FORWARD             2 (to 16)
        >>   14 LOAD_CONST               2 (7)
        >>   16 BINARY_MULTIPLY
             18 RETURN_VALUE
```

Tracing execution paths

```
  0:   LOAD_FAST('a')
  1:   LOAD_FAST('b')
  2:   LOAD_CONST(0)
  3:   COMPARE_OP(>)
  4:   POP_JUMP_IF_FALSE(14)

  5:   LOAD_FAST('b')
  6:   JUMP_FORWARD(16)

  7: LABEL(14)
  8:   LOAD_CONST(7)

  9: LABEL(16)
 10:   BINARY_MULTIPLY()
 11:   RETURN_VALUE
`
```

Tracing execution paths - b <= 0

```
  0:   LOAD_FAST('a')
  1:   LOAD_FAST('b')
  2:   LOAD_CONST(0)
  3:   COMPARE_OP(>)
  4:   POP_JUMP_IF_FALSE(14)

  5:   LOAD_FAST('b')
  6:   JUMP_FORWARD(16)

  7: LABEL(14)
  8:   LOAD_CONST(7)

  9: LABEL(16)
 10:   BINARY_MULTIPLY()
 11:   RETURN_VALUE
```

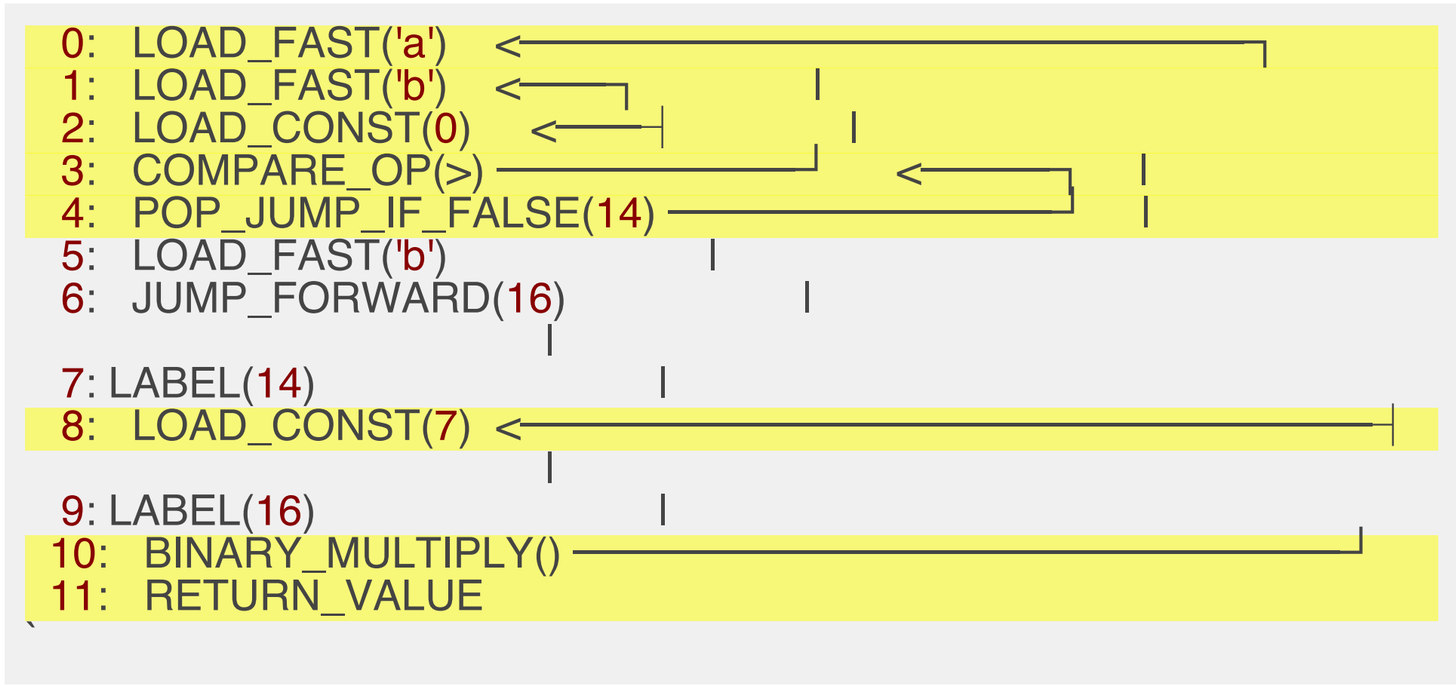
Tracing execution paths - b <= 0

```
  0:   LOAD_FAST('a')
  1:   LOAD_FAST('b')    <----,
  2:   LOAD_CONST(0)     <----|
  3:   COMPARE_OP(>) ---------'
  4:   POP_JUMP_IF_FALSE(14)
  5:   LOAD_FAST('b')
  6:   JUMP_FORWARD(16)

  7: LABEL(14)
  8:   LOAD_CONST(7)

  9: LABEL(16)
 10:   BINARY_MULTIPLY()
 11:   RETURN_VALUE
```

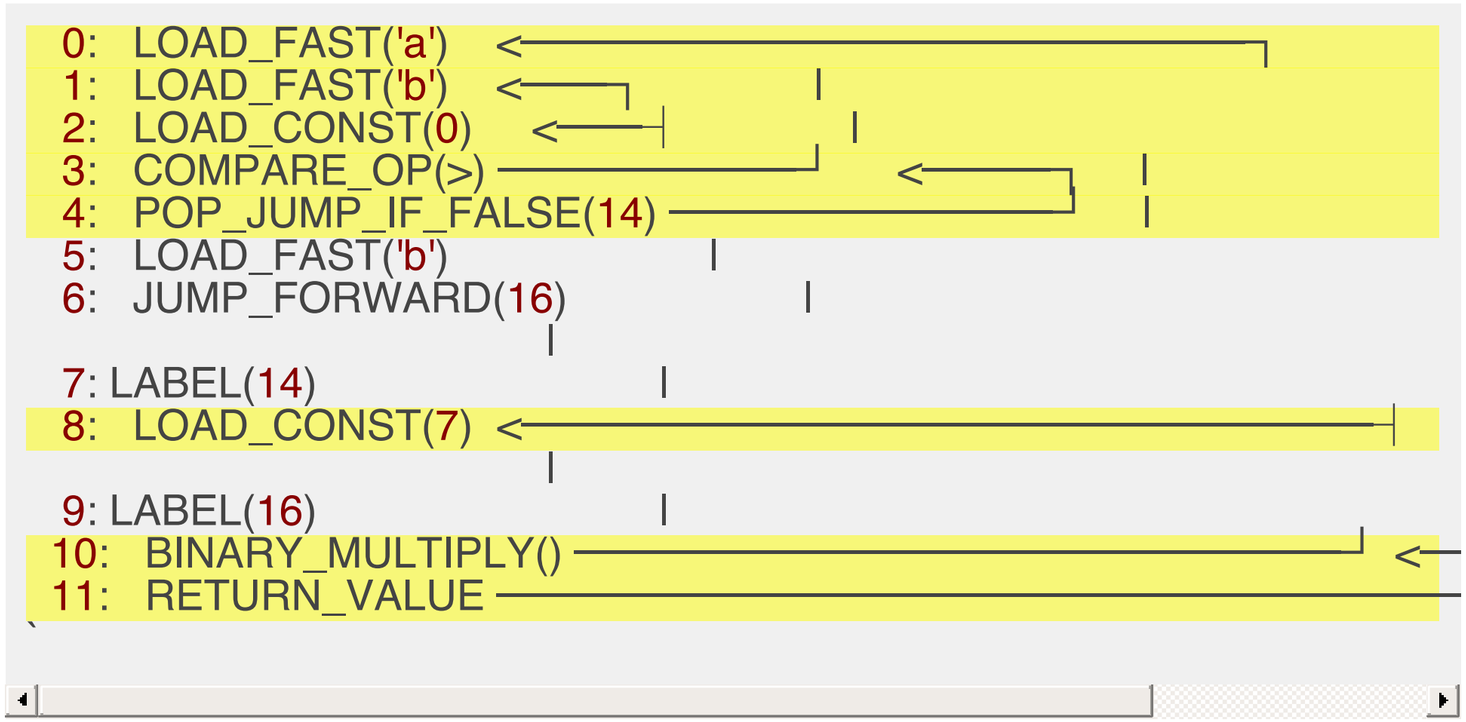
Tracing execution paths - b <= 0

```
  0:   LOAD_FAST('a')
  1:   LOAD_FAST('b')    <----,
  2:   LOAD_CONST(0)     <----|
  3:   COMPARE_OP(>)     -----|----,
  4:   POP_JUMP_IF_FALSE(14) -|----|----,
  5:   LOAD_FAST('b')         |    |    |
  6:   JUMP_FORWARD(16)       |    |    |
                              |    |    |
  7: LABEL(14)                |    |    |
  8:   LOAD_CONST(7)          |    |    |
                              |    |    |
  9: LABEL(16)                |    |    |
 10:   BINARY_MULTIPLY()      |    |    |
 11:   RETURN_VALUE           |    |    |
`                             |    |    |
```

Tracing execution paths - b <= 0



Tracing execution paths - b <= 0



Tracing execution paths - b > 0

```
  0:   LOAD_FAST('a')
  1:   LOAD_FAST('b')
  2:   LOAD_CONST(0)
  3:   COMPARE_OP(>)
  4:   POP_JUMP_IF_FALSE(14)
  5:   LOAD_FAST('b')
  6:   JUMP_FORWARD(16)

  7: LABEL(14)
  8:   LOAD_CONST(7)

  9: LABEL(16)
 10:   BINARY_MULTIPLY()
 11:   RETURN_VALUE
```

Tracing execution paths - b > 0

```
  0:   LOAD_FAST('a')
  1:   LOAD_FAST('b')    <┐
  2:   LOAD_CONST(0)     <┤
  3:   COMPARE_OP(>) ─────┘
  4:   POP_JUMP_IF_FALSE(14)
  5:   LOAD_FAST('b')
  6:   JUMP_FORWARD(16)

  7: LABEL(14)
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  9: LABEL(16)
 10:   BINARY_MULTIPLY()
 11:   RETURN_VALUE
`
```

Tracing execution paths - b > 0

```
  0:   LOAD_FAST('a')
  1:   LOAD_FAST('b')    <----┐
  2:   LOAD_CONST(0)     <----|
  3:   COMPARE_OP(>)     ---------┘      <----┐
  4:   POP_JUMP_IF_FALSE(14) ---------------------┘
  5:   LOAD_FAST('b')
  6:   JUMP_FORWARD(16)

  7: LABEL(14)
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  9: LABEL(16)
 10:   BINARY_MULTIPLY()
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```
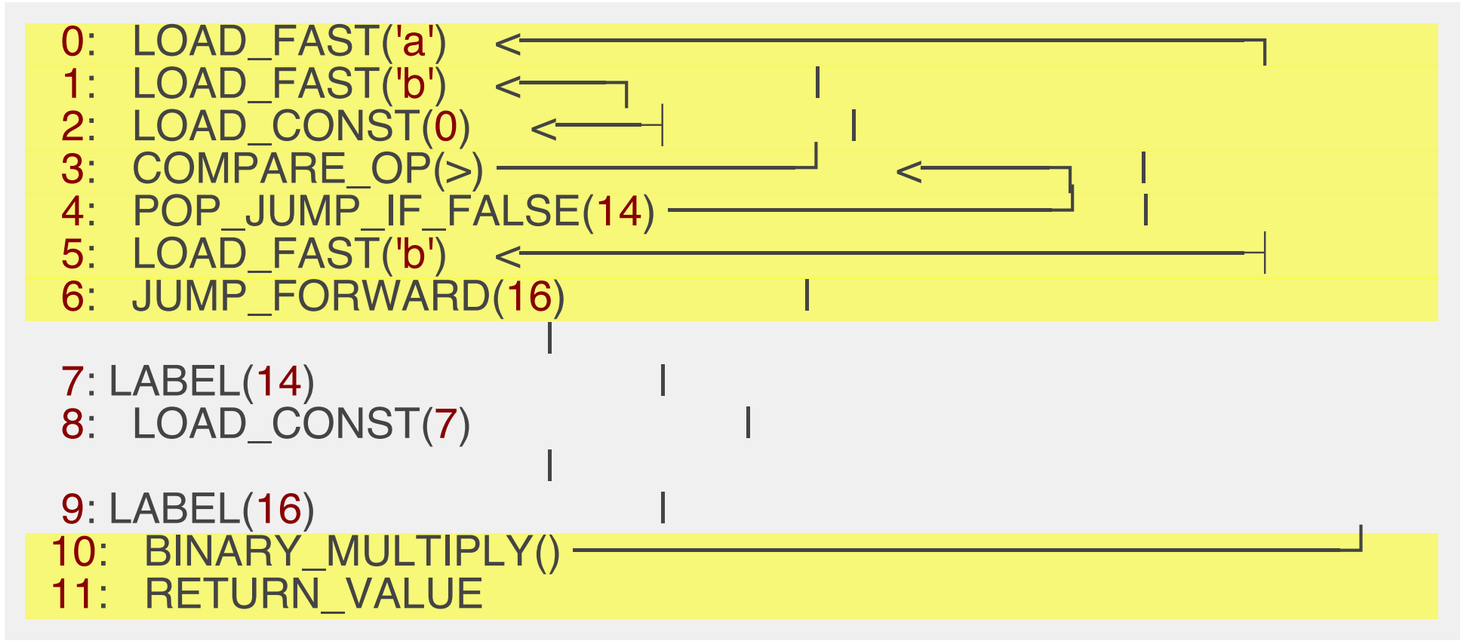
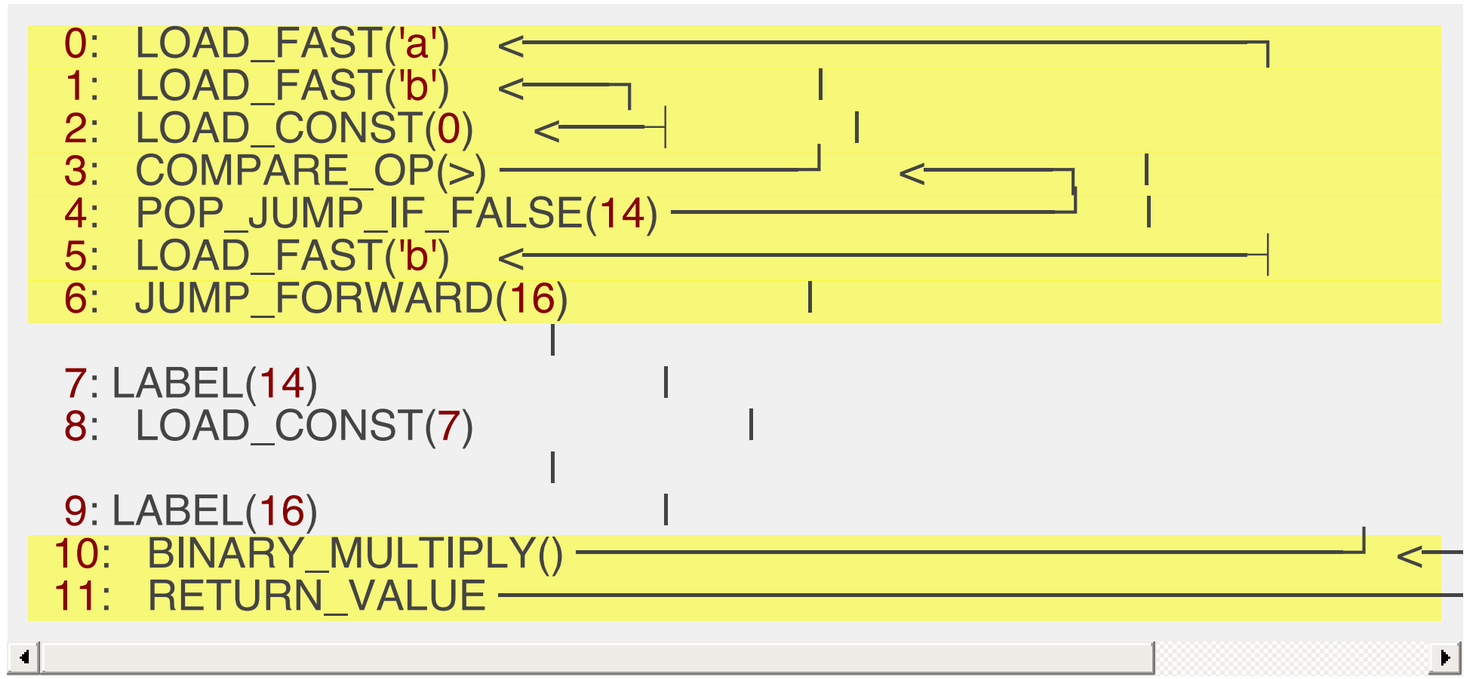

Tracing execution paths - b > 0



Tracing execution paths - b > 0



Normalizing to variables

Normalizing to variables

- Most of these were uninteresting
  - 3 always reads 1 and 2
  - 4 always reads 3
  - etc.

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- Most of these were uninteresting
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  - 4 always reads 3
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- 10 is interesting
  - If b <= 0, it reads 0 and 8
  - If b > 0, it reads 0 and 5

Normalizing to variables

- Most of these were uninteresting
  - 3 always reads 1 and 2
  - 4 always reads 3
  - etc.

- 10 is interesting
  - If b <= 0, it reads 0 and 8
  - If b > 0, it reads 0 and 5

- So we know that 5 and 8 output to the same variable

Now, with variables

```
  var1 = LOAD_FAST('a')
  var2 = LOAD_FAST('b')
  var3 = LOAD_CONST(0)
  var4 = COMPARE_OP(>, var1, var2)
  POP_JUMP_IF_FALSE(14, var4)

  var6 = LOAD_FAST('b')
  JUMP_FORWARD(16)

LABEL(14)
  var6 = LOAD_CONST(7)

LABEL(16)
  var7 = BINARY_MULTIPLY(va1, var6)
  RETURN_VALUE(var7)
```

Observed the shared variable!

```
  var1 = LOAD_FAST('a')
  var2 = LOAD_FAST('b')
  var3 = LOAD_CONST(0)
  var4 = COMPARE_OP(>, var1, var2)
  POP_JUMP_IF_FALSE(14, var4)

  var6 = LOAD_FAST('b')
  JUMP_FORWARD(16)

LABEL(14)
  var6 = LOAD_CONST(7)

LABEL(16)
  var7 = BINARY_MULTIPLY(va1, var6)
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Deducing types

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- Each variable needs to become "real"
  - i.e. a ctype with sizeof

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- Each variable needs to become "real"
  - i.e. a ctype with sizeof
- We know the input argument types ahead of time
  - In this example, ints
- Other type clues
  - Type of constant
  - Operation type (i.e. compare, multiply)
  - We created the var (and knew it then)
  - Type of attribute

Deducing types

```
  var1 = LOAD_FAST('a')
  var2 = LOAD_FAST('b')
  var3 = LOAD_CONST(0)
  var4 = COMPARE_OP(>, var1, var2)
  POP_JUMP_IF_FALSE(14, var4)

  var6 = LOAD_FAST('b')
  JUMP_FORWARD(16)

LABEL(14)
  var6 = LOAD_CONST(7)

LABEL(16)
  var7 = BINARY_MULTIPLY(va1, var6)
  RETURN_VALUE(var7)
```

Deducing types from constants

```
  var1 = LOAD_FAST('a')
  var2 = LOAD_FAST('b')
  var3<int> = LOAD_CONST(0)
  var4 = COMPARE_OP(>, var1, var2)
  POP_JUMP_IF_FALSE(14, var4)

  var6 = LOAD_FAST('b')
  JUMP_FORWARD(16)

LABEL(14)
  var6<int> = LOAD_CONST(7)

LABEL(16)
  var7 = BINARY_MULTIPLY(va1, var6)
  RETURN_VALUE(var7)
```

Deducing types from known arguments

```
  var1<int> = LOAD_FAST('a')
  var2<int> = LOAD_FAST('b')
  var3<int> = LOAD_CONST(0)
  var4 = COMPARE_OP(>, var1, var2)
  POP_JUMP_IF_FALSE(14, var4)

  var6<int> = LOAD_FAST('b')
  JUMP_FORWARD(16)

LABEL(14)
  var6<int> = LOAD_CONST(7)

LABEL(16)
  var7 = BINARY_MULTIPLY(va1, var6)
  RETURN_VALUE(var7)
```

Deducing types from operations

```
  var1<int> = LOAD_FAST('a')
  var2<int> = LOAD_FAST('b')
  var3<int> = LOAD_CONST(0)
  var4<bool> = COMPARE_OP(>, var1, var2)
  POP_JUMP_IF_FALSE(14, var4)

  var6<int> = LOAD_FAST('b')
  JUMP_FORWARD(16)

LABEL(14)
  var6<int> = LOAD_CONST(7)

LABEL(16)
  var7<int> = BINARY_MULTIPLY(va1, var6)
  RETURN_VALUE(var7)
```

Deducing types

```
  var1<int> = LOAD_FAST('a')
  var2<int> = LOAD_FAST('b')
  var3<int> = LOAD_CONST(0)
  var4<bool> = COMPARE_OP(>, var1, var2)
  POP_JUMP_IF_FALSE(14, var4)

  var6<int> = LOAD_FAST('b')
  JUMP_FORWARD(16)

LABEL(14)
  var6<int> = LOAD_CONST(7)

LABEL(16)
  var7<int> = BINARY_MULTIPLY(va1, var6)
  RETURN_VALUE(var7)
```

Dealing with primitive types

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```
x = 1
foo(x) # (Logically) makes a copy

x = Obj()
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- Not how machine code works

Dealing with primitive types

```
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foo(x) # (Logically) makes a copy

x = Obj()
foo(x) # Passes a reference
```

- Both can be references in python, because ints are immutable
- Not how machine code works
- Some backflips to do what you'd expect, semantically
  - Not in scope for this presentation

Assigning vars to memory

Assigning vars to memory

- Variables can't just magically "exist"

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- Need to live somewhere

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  - Pointed to by arguments

Assigning vars to memory

- Variables can't just magically "exist"
- Need to live somewhere
  - Pointed to by arguments
  - Stored on the stack

Assigning vars to memory

```
>>> def func(a):
...     c = a
...     return c
```

Assigning vars to memory

```
>>> def func(a):
...     c = a
...     return c
```

```
>>> dis.dis(func)
  2           0 LOAD_FAST                0 (a)
              2 STORE_FAST               1 (c)

  3           4 LOAD_FAST                1 (c)
              6 RETURN_VALUE
```

After folding and type deduction

```
var1<int> = LOAD_FAST('a')
STORE_FAST('c', var1<int>)
var2<int> = LOAD_FAST('c', var1<int>)
RETURN_VALUE(var2)
```

Convert argument fast vars

```
var1<int> = LOAD_FAST('a')
STORE_FAST('c', var1<int>)
var2<int> = LOAD_FAST('c', var1<int>)
RETURN_VALUE(var2)
```

```
var1<int> = arg_var_0<int> # register 1
STORE_FAST('c', var1<int>)
var2<int> = LOAD_FAST('c', var1<int>)
RETURN_VALUE(var2)
```

Convert other fast vars (locals)

```
var1<int> = arg_var_0<int>
STORE_FAST('c', var1<int>)
var2<int> = LOAD_FAST('c', var1<int>)
RETURN_VALUE(var2)
```

```
var1<int> = arg_var_0<int>
fast_var_c<int> = var1
var2<int> = fast_var_c
RETURN_VALUE(var2)
```

Allocate space for local vars

```
var1<int> = arg_var_0<int>
fast_var_c<int> = var1
var2<int> = fast_var_c
RETURN_VALUE(var2)
```

```
var1<int> = arg_var_0<int>
stack_var_c<int, off=0> = var1
var2<int> = stack_var_c<int, off=0>
RETURN_VALUE(var2)
```

Allocate space for remaining vars

```
var1<int> = arg_var_0<int>
stack_var_c<int, off=0> = var1
var2<int> = stack_var_c<int, off=0>
RETURN_VALUE(var2)
```

```
stack_var1<int, off=8> = arg_var_0<int>
stack_var_c<int, off=0> = stack_var1<int, off=8>
stack_var2<int, off=16> = stack_var_c<int, off=0>
RETURN_VALUE(stack_var2<int, off=16>)
```

Template compilation

Template compilation

- At this point, representation is "close enough"

Template compilation

- At this point, representation is "close enough"
- We can simply take each op code and translate it

Translating RETURN_VALUE

Pseudo-python

```
RETURN_VALUE(stack_var1<int, off=0>)
```

Translating RETURN_VALUE

Pseudo-python

```
RETURN_VALUE(stack_var1<int, off=0>)
```

bpf

```
# Return value is in register 0
LOAD64(src=stack, off=0, dst=R0)
RET()
```

Translating BINARY_MULTIPLY

Pseudo-python

```
stack_var3<int, off=16> = BINARY_MULTIPLY(
    stack_var1<int, off=0>, stack_var2<int, off=8>)
```

Translating BINARY_MULTIPLY

Pseudo-python

```
stack_var3<int, off=16> = BINARY_MULTIPLY(
    stack_var1<int, off=0>, stack_var2<int, off=8>)
```

bpf

```
LOAD64(src=stack, off=0, dst=R1)
LOAD64(src=stack, off=8, dst=R2)
MULTIPLY(src=R2, dst=R1)
STORE64(src=R1, dst=stack, off=16)
```

Translating COMPARE_OP(==)

```
stack_var3<bool, off=16> = COMPARE_OP(
    '==', stack_var1<int, off=0>,
    stack_var2<int, off=8>)
```

Translating COMPARE_OP(==)

```
stack_var3<bool, off=16> = COMPARE_OP(
    '==', stack_var1<int, off=0>,
    stack_var2<int, off=8>)
```

```
LOAD64(src=stack, off=0, dst=R1)
LOAD64(src=stack, off=8, dst=R2)
JUMP_IF_EQUAL_TO(src=R1, dst=R2, off='tmp_true')

STORE64(imm=FALSE, dst=R1)
JUMP(off='tmp_done')

LABEL('tmp_true')
STORE64(imm=TRUE, dst=R1)

LABEL('tmp_done')
STORE64(src=R1, dst=stack, off=16)
```

Dealing with shared datastructures

Dealing with shared datastructures

- Some datastructures can be shared

Dealing with shared datastructures

- Some datastructures can be shared
  - Hash Map

Dealing with shared datastructures

- Some datastructures can be shared
  - Hash Map
  - Queue

Dealing with shared datastructures

- These are incredibly useful

```
# Create a map from protocol to packet count
my_map = create_map(
    ctypes.c_int8, ctypes.c_int32, 256)

def socket_filter(skb):
    my_map[skb.protocol] += 1 # Access in kernel
    return 0

start_filter(socket_filter)

print(my_map[ETH_P_IP]) # Access in userspace
```

Accessing shared datastructures

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- In application
  - Referenced by file descriptor
  - Accessed with bpf(...) syscall

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  - Referenced by pointer
  - Accessed with built-in functions

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- Solution: create a special datastructure class

Accessing shared datastructures

- In application
  - Referenced by file descriptor
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  - Provides __getitem__, __setitem__ for application access

Accessing shared datastructures

- In application
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  - Provides __getitem__, __setitem__ for application access
  - Looks like ctypes.c_int to variable allocator

Accessing shared datastructures

- In application
  - Referenced by file descriptor
  - Accessed with bpf(...) syscall

- In kernel
  - Referenced by pointer
  - Accessed with built-in functions

- Solution: create a special datastructure class
  - Provides __getitem__, __setitem__ for application access
  - Looks like ctypes.c_int to variable allocator
  - Supports opcode translation for BINARY_SUBSCR, et. al.

Agenda

1. Who am I?
2. Overview
3. Python Virtual Machine
4. Transpiling from python to bpf bytecode
5. **Woo, we made it!**

More things to do

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- Variable lifetime analysis
  - Keep things in register to avoid stores/loads
  - Reuse stack space

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- Variable lifetime analysis
  - Keep things in register to avoid stores/loads
  - Reuse stack space

- Higher level abstractions to simplify use
  - Currently tracing requires low-level knowledge of C

Thank You