Jitk: A trustworthy in-kernel interpreter infrastructure

Xi Wang, David Lazar, Nickolai Zeldovich, Adam Chlipala, Zachary Tatlock
MIT and University of Washington

Modern OSes run untrusted user code in kernel

- In-kernel interpreters
  - Seccomp: sandboxing (Linux)
  - BPF: packet filtering
  - INET_DIAG: socket monitoring
  - Dtrace: instrumentation
- (RAR, Bitcoin, ClamAV, Python re, ...)
- Critical to overall system security
  - Any interpreter bugs are serious!

Many bugs have been found in interpreters

- Kernel space bugs
  - Control flow errors: incorrect jump offset, ...
  - Arithmetic errors: incorrect result, ...
  - Memory errors: buffer overflow, ...
  - Information leak: uninitialized read
- Kernel-user interface bugs
  - Incorrect encoding/decoding
- User space bugs
  - Incorrect input generated by tools/libraries
- Some have security consequences: CVE-2014-2889, ...

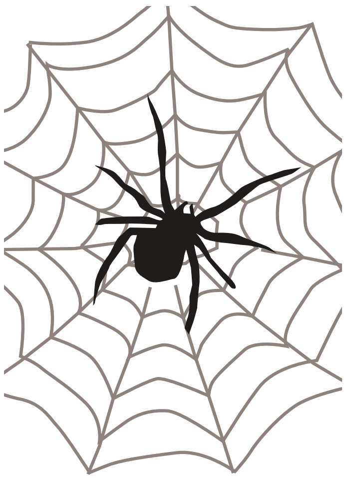
See our paper for a case study of bugs

How to get rid of all these bugs at once?

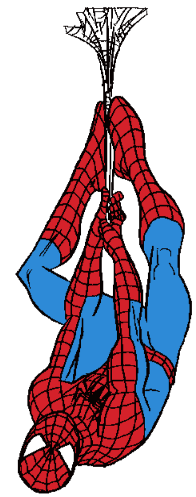
Theorem proving can help kill all these bugs

- seL4: provably correct microkernel [SOSP'09]
- CompCert: provably correct C compiler [CACM'09]
- This talk: Jitk
  - Provably correct interpreter for running untrusted user code
  - Drop-in replacement for Linux's seccomp
  - Built using Coq proof assistant + CompCert

Theorem proving: overview



$$\approx$$



specification | proof | implementation

- Proof is machine-checkable: Coq proof assistant
- Proof: correct specification ⇒ correct implementation
- Specification should be much simpler than implementation

Challenges

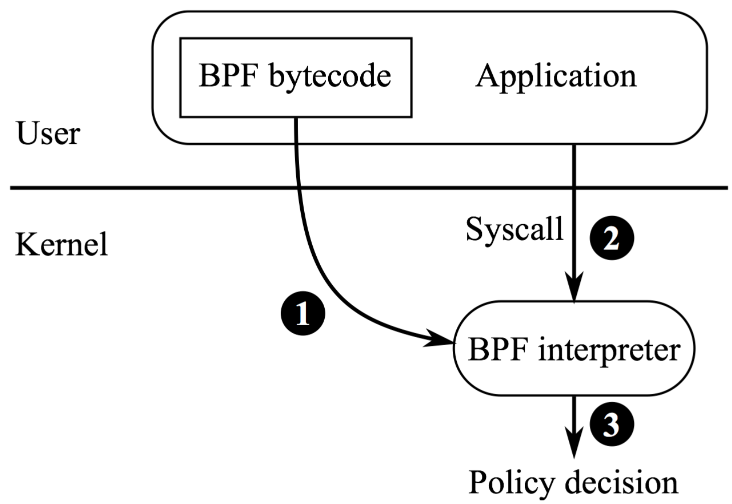
- What is the specification?
- How to translate systems properties into proofs?
- How to extract a running system?

Contributions & outline

- Specifications: capture systems properties
- Theorems: ensure correctness of implementation
- Integrate Jitk with Linux kernel

Seccomp: reduce allowed syscalls

- 1: app submits a Berkeley Packet Filter (BPF) to kernel at start-up
  - Example: if syscall is `open`, return some errno
  - App cannot open new files, even if it's compromised later
- 2: kernel BPF interpreter executes the filter against every syscall
- 3: kernel decides whether to allow/deny the syscall based on result



Seccomp/BPF example: OpenSSH

```
    ld  [0]                                ; load syscall number
    jeq #SYS_open, L1, L2
L1: ret #RET_ERRNO|#EACCES                 ; deny open() with errno = EACCES
L2: jeq #SYS_gettimeofday, L3, L4
L3: ret #RET_ALLOW                         ; allow gettimeofday()
L4: ...
    ret #RET_KILL                          ; default: kill current process
```

- Deny `open()` with errno `EACCES`
- Allow `gettimeofday()`, ...
- Kill the current process if seeing other syscalls

Summary of seccomp

- Security critical: sandboxing mechanism
- Widely used: by Chrome, OpenSSH, QEMU, Tor, ...
- Performance critical: invoked for each syscall
- Non-trivial to do right: many bugs have been found
- General: similar design found in multiple OS kernels

Specification: what seccomp should do

Goal: enforce user-specified syscall policies in kernel

- What kernel executes is what user specifies
  - Kernel: BPF-to-x86 for execution
  - BPF transferred from user space to kernel
  - User space: write down policies as BPF
- Non-interference with kernel
  - Termination: no crash nor infinite loop
  - Bounded stack usage: no kernel stack overflow

Jitk 1/3: BPF-to-x86 for execution

JIT: translate BPF to x86 for in-kernel execution

- JIT is error-prone: CVE-2014-2889

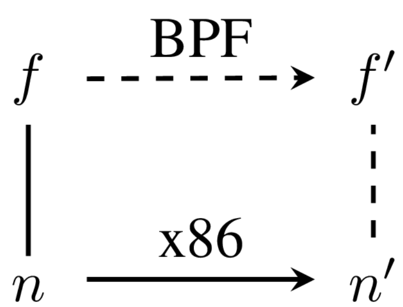
```
jcc = ...; /* conditional jump opcode */
if (filter[i].jf)
    true_offset += is_near(false_offset) ? 2 : 6;
EMIT_COND_JMP(jcc, true_offset);
if (filter[i].jf)
    EMIT_JMP(false_offset);
```

- Goal: Jitk's output x86 code preserves the behavior of input BPF
- x86 code cannot have buffer overflow, control-flow bugs, ...

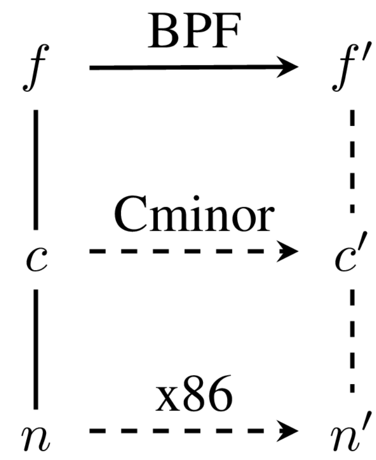
BPF-to-x86 correctness: state machine simulation

- Model BPF and x86 as two state machines: by reading manuals
  - BPF state: 2 regs, fixed-size memory, input, program counter
  - BPF instruction: state transition
  - x86: [...] - reused from CompCert
- Theorem (backward simulation):

  If JIT succeeds, every state transition in output x86 corresponds to some state transition(s) in input BPF.



Jitk's approach for BPF-to-x86



- Strawman: write & prove BPF-to-x86 translator
  - Backward simulation is hard to prove
  - Big semantic gap between BPF and x86
- Prove forward simulation and convert
  - Every state transition in BPF corresponds to some state transition(s) in output x86
  - Conversion possible if lower level (x86) is deterministic
- Add intermediate languages between BPF and x86
  - Choose Cminor ("simpler" C) from CompCert as detour
  - BPF-to-x86: BPF-to-Cminor + CompCert's Cminor-to-x86

Jitk 2/3: user-kernel interface correctness

- App submits BPF in bytecode from user space to kernel
- Kernel decodes bytecode back to BPF - bugs happened!

Goal: BPF is correctly decoded in kernel

- Alternative approach: state machine simulation
  - Spec: state machine for bytecode representation
  - Simulation: bytecode BPF $\leftrightarrow$ BPF
  - Challenge: spec is as complex as implementation

Jitk's approach: user-kernel BPF equivalence

- Two functions: `encode()` and `decode()`
- Choose a much simpler spec: equivalence

```
∀f : encode(f) = b ⇒ decode(b) = f
```

- Trade-off: can have "consistent" bugs
  - `encode()` and `decode()` could make the same mistake
  - `decode()` could behave differently from existing BPF

Jitk 3/3: input BPF correctness

Goal: input BPF is "correct"

BPF

```
    ld  [0]                          ; load syscall number
    jeq #SYS_open, L1, L2
L1: ret #RET_ERRNO|#EACCES           ; deny open() with errno = EACCES
L2: jeq #SYS_gettimeofday, L3, L4
L3: ret #RET_ALLOW                   ; allow gettimeofday()
L4: ...
    ret #RET_KILL                    ; default: kill current process
```

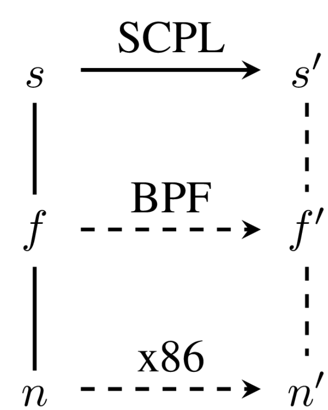
- Does this BPF correctly implement policies?
- Is the BPF spec correct?

Jitk's approach: add a higher level

SCPL: domain-specific language for writing syscall policies

```
{ default_action = Kill;
  rules = [
    { action = Errno EACCES; syscall = SYS_open };
    { action = Allow; syscall = SYS_gettimeofday };
    ...
  ] }
```

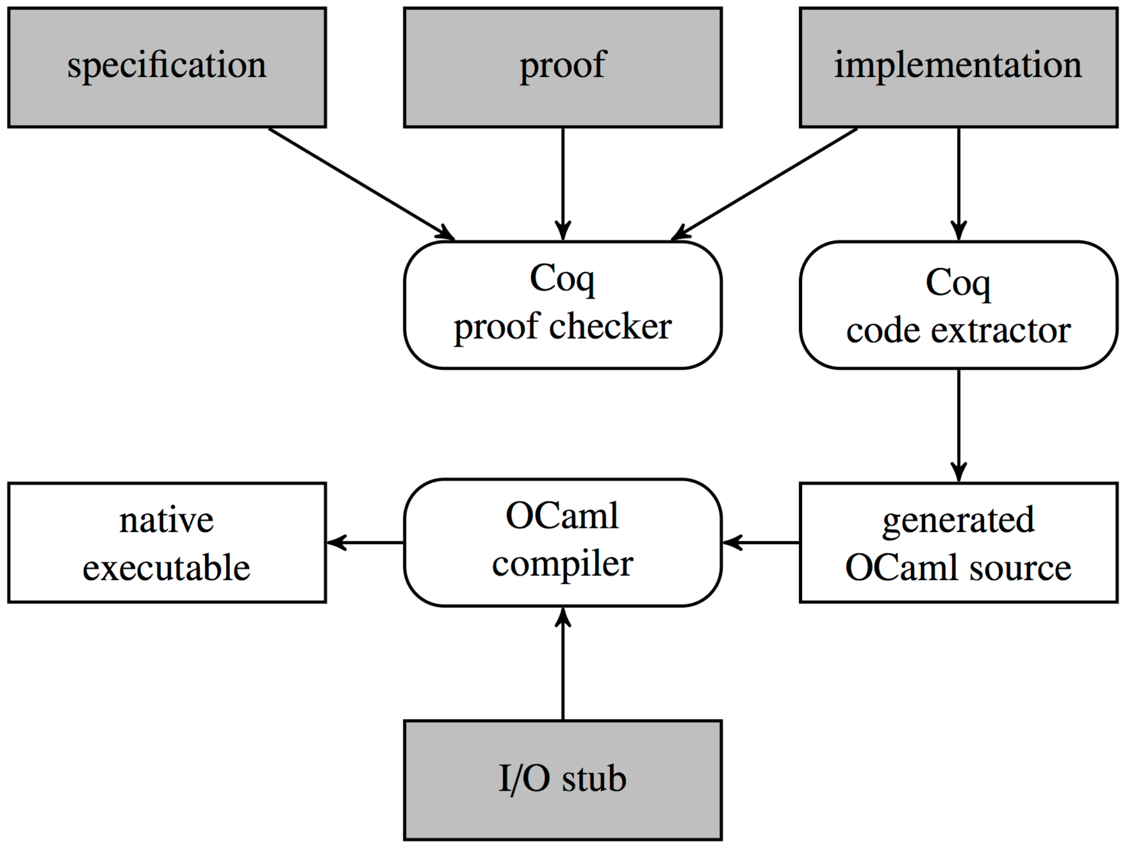
- Much simpler than BPF → unlikely to make mistakes
- SCPL-to-x86 = SCPL-to-BPF + BPF-to-x86
  - Proof: state machine simulation
  - Use SCPL: don't need to trust BPF spec
  - Improve confidence in BPF spec



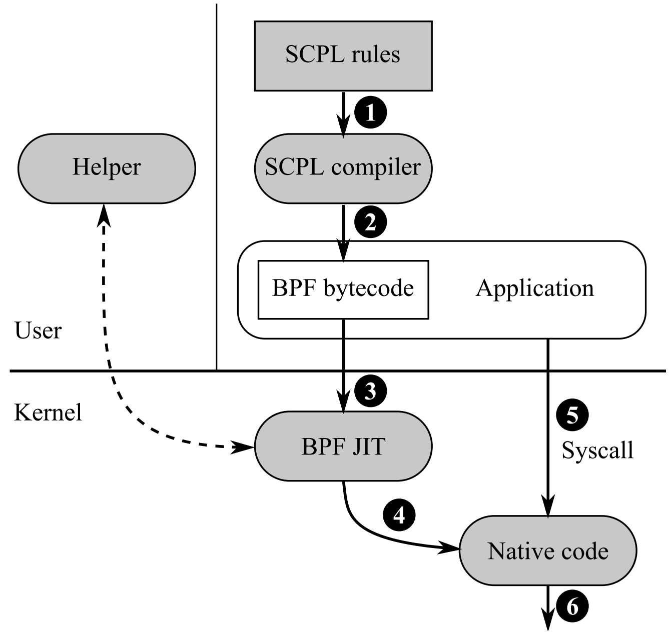
Summary of Jitk's approaches

- State machine simulation: BPF-to-x86 and SCPL-to-BPF
  - Add extra levels in-between to bridge gap
  - Forward simulation to backward simulation
  - More abstraction, more confidence
- Equivalence: user-kernel data passing
  - Trade-off: simpler spec vs. can have "consistent" bugs

Development: write shaded boxes



Integrate Jitk (shaded boxes) with Linux kernel



- Modify Linux kernel to invoke BPF-to-x86 translator
  - Run the translator as a trusted user-space process
  - The translator includes OCaml runtime & GNU assembler
- Modify Linux kernel to invoke output x86 code for each syscall

Jitk's theorems can stop a large class of bugs

Manually inspected existing bugs

- Kernel space bugs: BPF-to-x86 correctness
  - ☑ Control flow errors
  - ☑ Arithmetic errors
  - ☑ Memory errors
  - ☑ Information leak
- Kernel-user interface bugs: user-kernel BPF equivalence
  - ☑ Incorrect encoding/decoding
- User space bugs: SCPL-to-BPF correctness
  - ☑ Incorrect input generated by tools/libraries

What Jitk's theorems cannot stop

- Over-strict: Jitk could reject correct input SCPL/BPF
- Side channel: JIT spraying attacks
- Bugs in specifications: SCPL, BPF, x86
- Bugs in CompCert's TCB: Coq, OCaml runtime, GNU assembler
- Bugs in other parts of Linux kernel

Evaluation

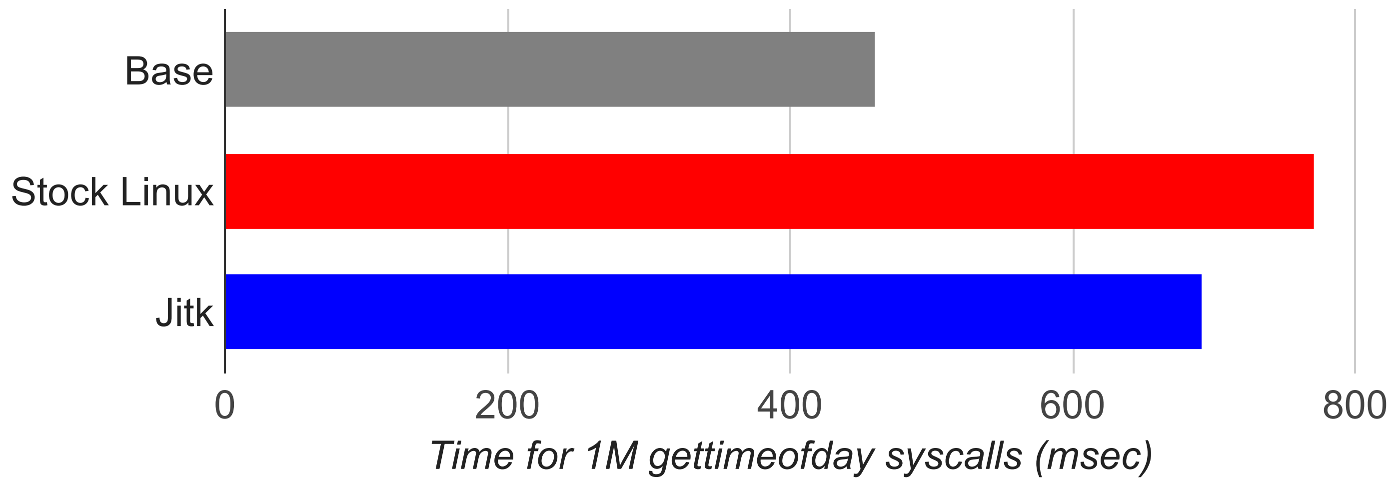
- How much effort does it take to build Jitk?
- What is the end-to-end performance?
- Does Jitk's JIT produce efficient x86 code?

Building effort is moderate

Component	Lines of code
Specifications (SCPL, BPF)	420 lines of Coq
Implementation (SCPL, BPF)	520 lines of Coq
Proof (SCPL, BPF)	2,300 lines of Coq
Extraction to OCaml	50 lines of Coq
I/O stub	70 lines of OCaml
Linux kernel changes	150 lines of C
Total	3,510 lines of code

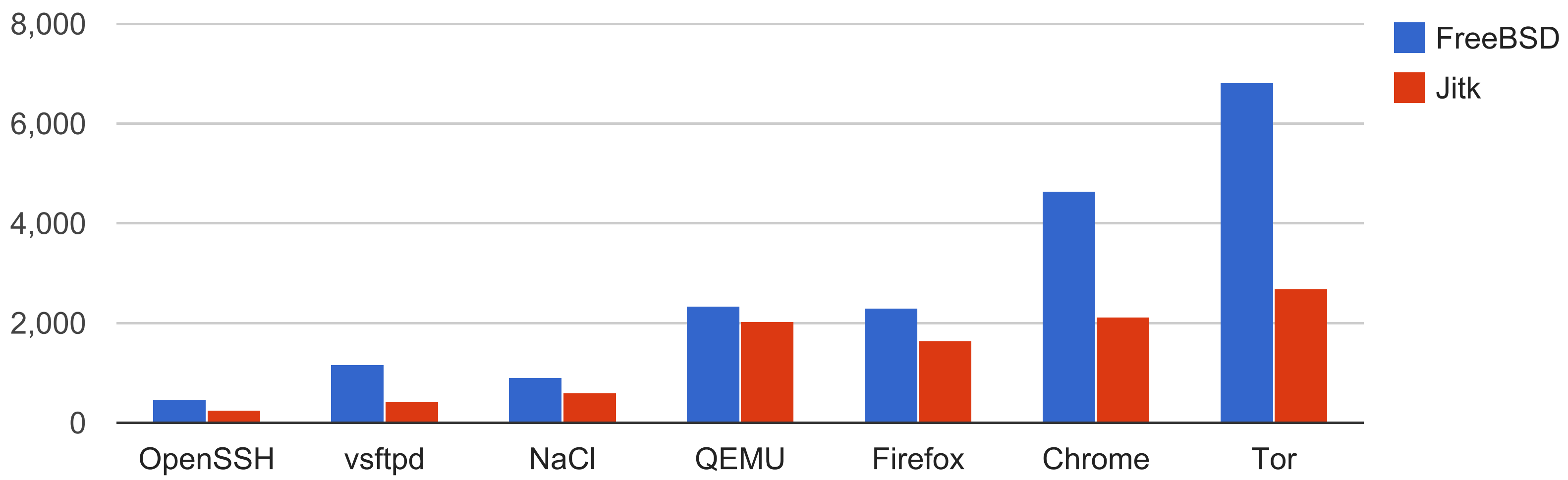
End-to-end performance overhead is low

- OpenSSH on Linux/x86
  - Stock Linux: interpreter (no x86 JIT support)
  - Jitk: JIT
- Jitk's BPF-to-x86 one-time overhead: 20 msec per session
- Time for 1M gettimeofday syscalls: smaller is better (in msec)



Jitk produces good (often better) code

Output x86 code size comparison (smaller is better)



- Existing BPF JITs have very limited optimizations
- Jitk leverages optimizations from CompCert

Related work

- Theorem proving: seL4, CompCert
- Model checking & testing: EXE, KLEE
- Microkernel, SFI, type-safe languages

Conclusion

Jitk: run untrusted user code in kernel with theorem proving

- Strong correctness guarantee
- Good performance
- Approaches for proving systems properties