Verified Static Analyzers for Kernel Extensions

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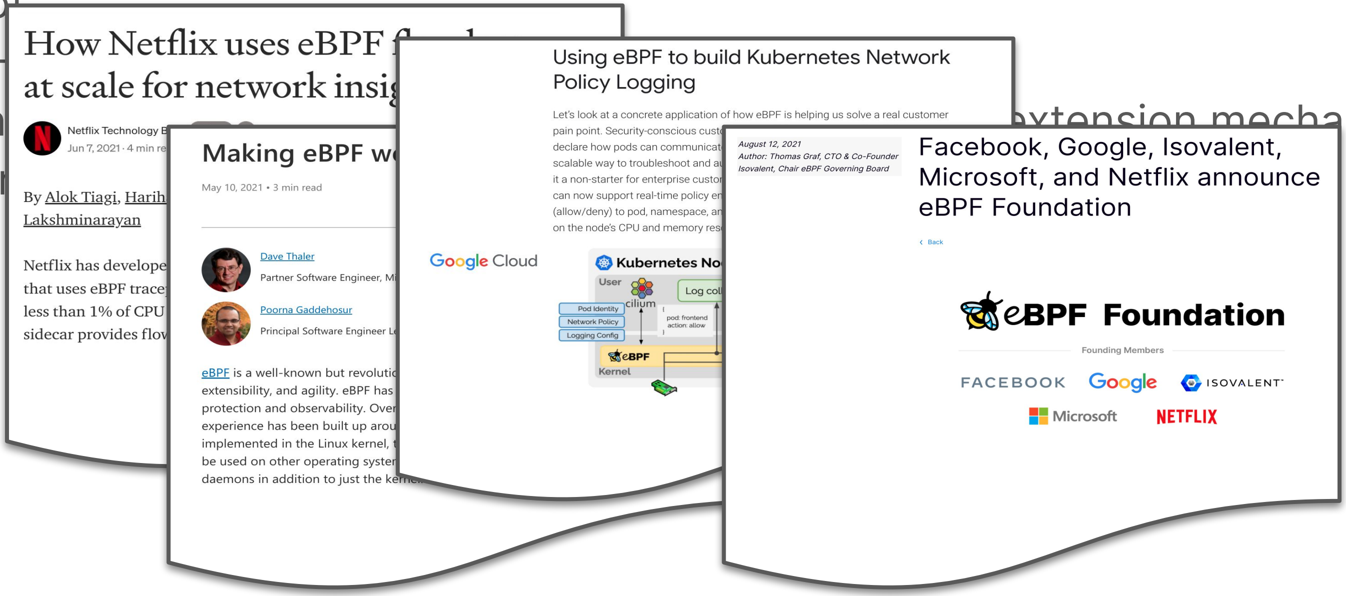
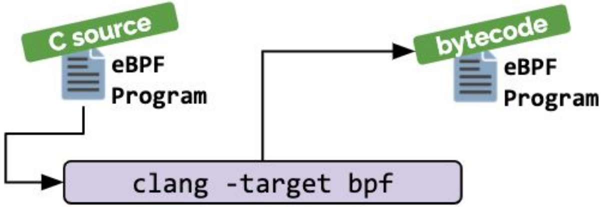
Kernel extensions

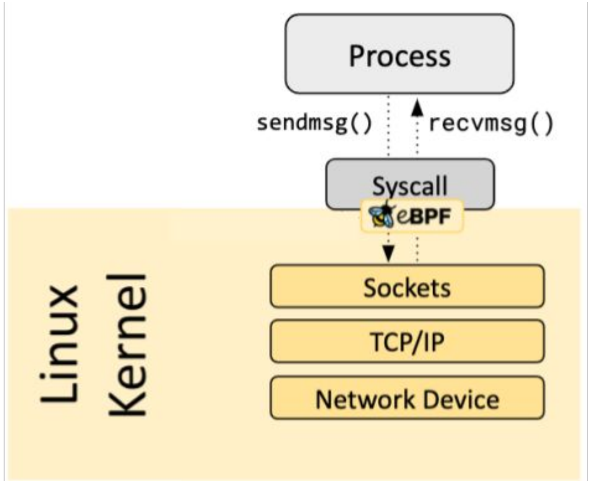
- Ability to extend the operating system kernel without having to recompile or reboot
  - H
- Exten … extension mechanism that is gai



eBPF (Extended Berkeley Packet Filter)

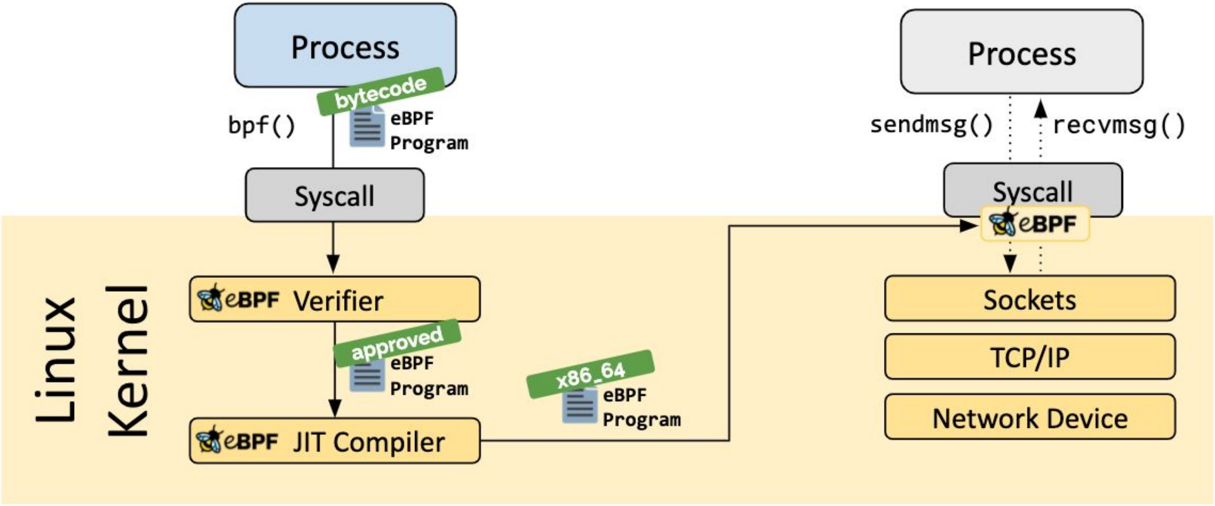


BPF_LD	Non-standard load operations
BPF_LDX	Load into register operations
BPF_ST	Store from immediate operations
BPF_STX	Store from register operations
BPF_ALU	32-bit arithmetic operations
BPF_JMP	64-bit jump operations
BPF_JMP32	32-bit jump operations
BPF_ALU64	64-bit arithmetic operations



eBPF Verifier

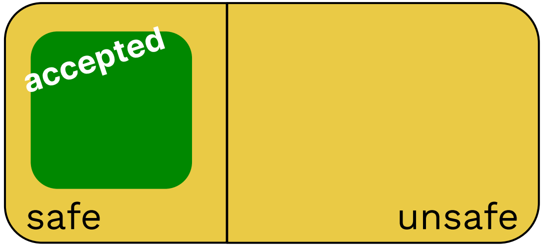
- Issue: running arbitrary user code in the kernel
- Solution: statically prove safety of the program
- Safety checks
  - Termination
  - Illegal operations
  - Memory access



Verification Must be Sound and Precise and Fast

- **Soundness** : Unsafe programs should be rejected
- **Precision** : Safe programs shouldn't be rejected
- **Speed**: Minimal load times + Prompt feedback on rejection

Can we formally verify the soundness and precision of the static analysis in the eBPF verifier?



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Static Analyses in the eBPF verifier

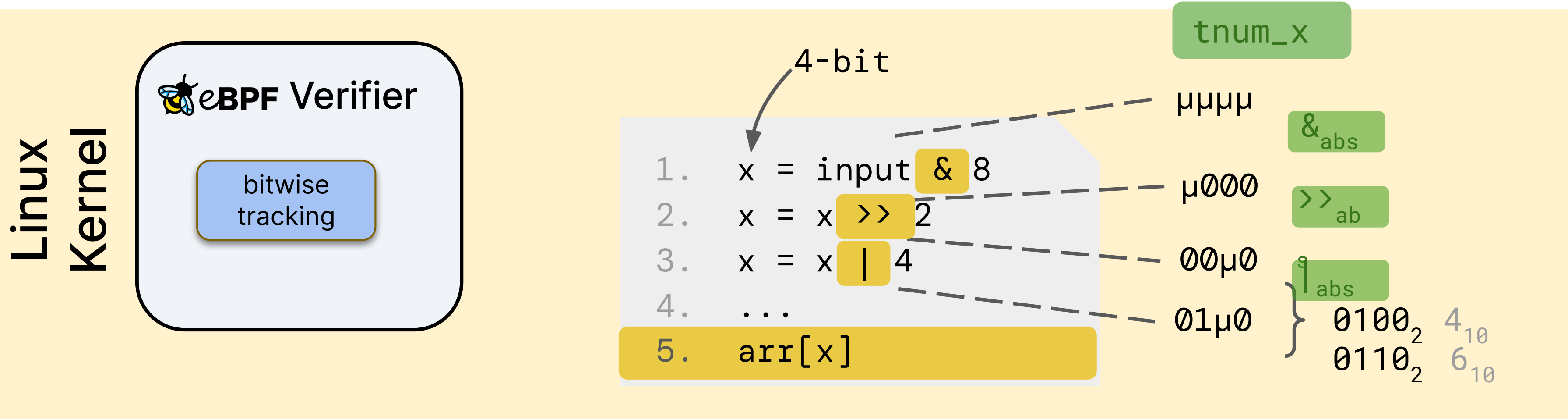
- Tnums [CGO '22]: Reasoning about the soundness and precision of bitwise tracking
- Agni [CAV '23]: Reasoning about the soundness and precision of the range analysis + bitwise tracking + their combination

Tnums

Proving the soundness and precision of bitwise tracking

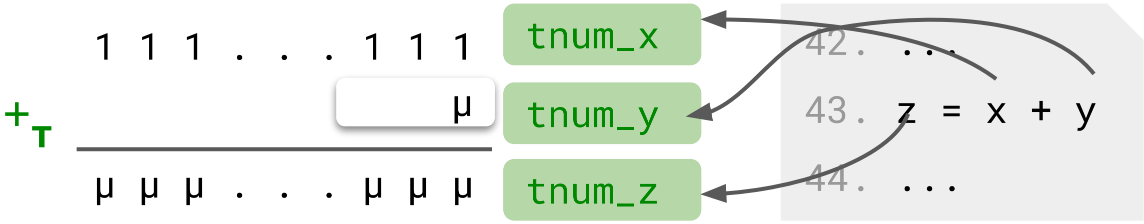
Static Analysis in the eBPF Verifier

- Sub-task: track the **values** of program variables across ***all*** executions
  - Using abstract values from an abstract domain – ***Abstract Interpretation***
- Bitwise domain: track individual bits of a program variable .
  - Kernel term: tristate numbers (tnums) `{0, 1, μ}`



Challenges

- Developing abstract operators is not trivial




```
def tnum_add(tnum P, tnum Q):
   u6
   u6
   u6
   u6
   u6                                   sk
   return tnum(value=sv & ~mu,mask=mu)
```

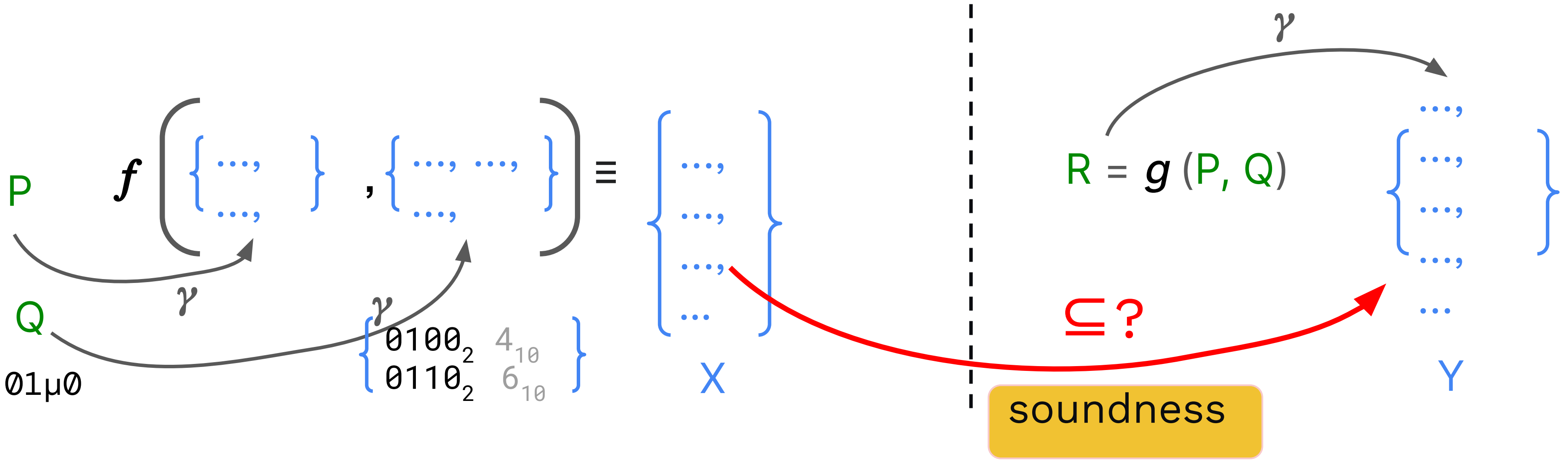
Is tnum_add sound for all tnums P & Q?

Is tnum_add precise?

Soundness of Abstract Operators

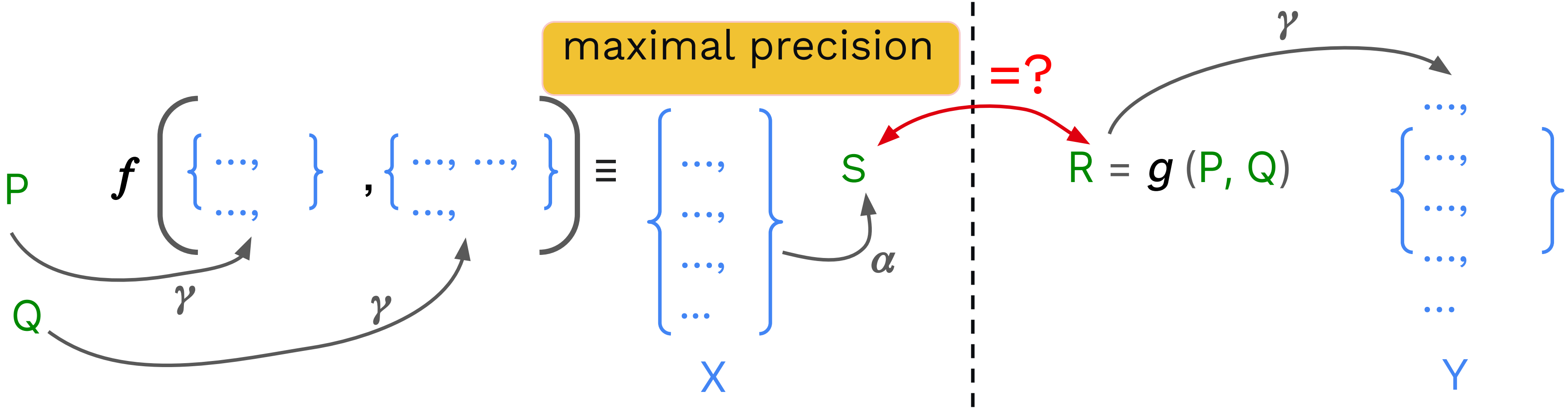
- BPF instruction set:

  `add, sub, mul, div, or, and, lsh, rsh, neg, mod, xor, arsh`
- Concrete operator (eg. integer addition) $f : \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z}$
- Abstract operator (eg. tnum addition) $g : \mathbb{A}_{\text{tnum}} \times \mathbb{A}_{\text{tnum}} \rightarrow \mathbb{A}_{\text{tnum}}$



Maximal Precision of Abstract Operators

- BPF instruction set:
  `add, sub, mul, div, or, and, lsh, rsh, neg, mod, xor, arsh`
- Concrete operator (eg. integer addition) $f : \mathbb{Z} \times \mathbb{Z} \to \mathbb{Z}$
- Abstract operator (eg. tnum addition) $g : \mathbb{A}_{\text{tnum}} \times \mathbb{A}_{\text{tnum}} \to \mathbb{A}_{\text{tnum}}$



SMT Verification (A quick aside)

- The Boolean SATisfiability problem
  - Boolean variables A, B, C
  - Boolean expressions $\psi_1 = (A \lor \neg B) \land C$
    $\psi_2 = (\neg A \lor B) \land (A \lor C) \land (B \lor \neg C)$
  - Ask a SAT Solver: is the set of constraints satisfiable? $\{\psi_1, \psi_2\}$

- Outcomes:
  - SAT
    - `+ model [A = true, B = true, C = true]`
  - UNSAT
  - UNKNOWN

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SATisfiability Modulo Theories

- Satisfiability taking into account theories
- Binary variables are replaced by predicates over a set of non-binary variables
  - e.g A ⇒ 3x + 2y -z >= 4 (linear inequalities)
- Predicates are classified according to theories used
  - Theory defines rules on the (non-binary) variables: operations, and how to combine them
    - if x, y, z are real numbers, we use the theory of linear real arithmetic
- Generally, program analysis relies on the theory of bitvectors

Building A Soundness Specification in First Order Logic

- Membership predicate

$$member_{\texttt{tnum}}(x, P)$$

- Semantics of concrete operator f

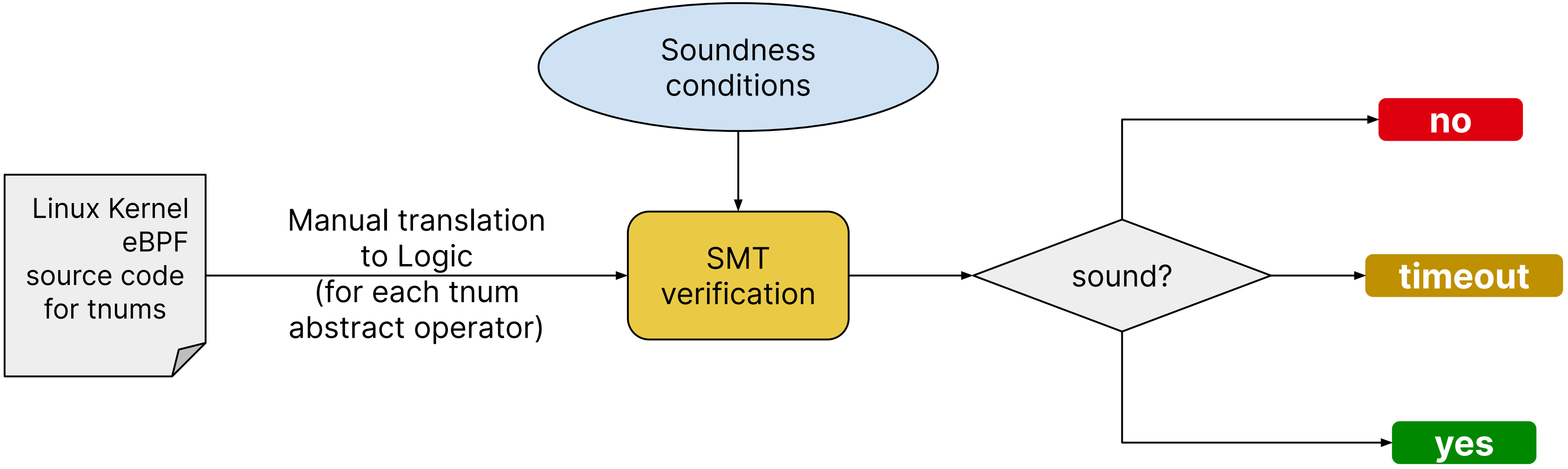
$$z = f(x, y)$$

- Semantics of abstract operator g
  - Manually translate from C to SMT

$$R = g(P, Q)$$

Soundness Specification in First Order Logic

Overview (Verification of Tnum Abstract Operators)



Results from Automated Verification

- Proved the soundness of the following kernel's tnum abstract operators: `add`, `sub`, `mul`, `div`, `or`, `and`, `lsh`, `rsh`, `neg`, `mod`, `xor`, `arsh`
- What about `mul`, `div`, `mod`?
  - `div`, `mod`: The kernel implements these abstract operators by setting the result to completely unknown: μμμμ…μ
  - These operators are trivially sound
  - `mul`?

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Existing Tnum multiplication

- Implementation has a loop, when unrolled leads to a large formula
- Performs multiplication on integers which is expensive to solve when encoded in bitvector theory.
- Verification times out

```
def hma(tnum ACC, u64 x, u64 y):
  for y in range(0...64):
    if (LSB of y is 1):
      ACC := ACC +_T tnum(value=0,
                           mask=x)
    y := y >> 1
    x := x << 1
  return ACC

def tnum_mul(tnum P, tnum Q):
  tnum π := tnum(P.v * Q.v, 0)
  tnum ACC := hma(π, P.m, Q.m|Q.v)
  tnum R := hma(ACC, Q.m, P.v)
  return R
```

Existing algorithm

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A new algorithm for tnum multiplication

- Faster and more precise than the existing implementation
- Analytical proof of soundness

sound

```
def our_mul(tnum P, tnum Q):
    ACCv := tnum(0, 0)
    ...
    ...th):
    ... (P.m[0] == 0):
    ...(ACCv, tnum(Q.v, 0))
    ...(ACCm, tnum(0, Q.m))
    ...):
    ...(ACCm,
    ...m(0, Q.v|Q.m))
    ...1)
    ...1)
    tnum R := tnum_add(ACCv, ACCm)
    return R
```

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* **[PATCH bpf-next] bpf: tnums: Provably sound, faster, and more precise algorithm for tnum_mul**
@ 2021-05-28 3:55 hv90
2021-05-30 5:59 ` Andrii Nakryiko
0 siblings, 1 reply; 5+ messages in thread

From: hv90 @ 2021-05-28 3:55 UTC (permalink / raw)
To: ast
Cc: bpf, Harishankar Vishwanathan, Matan Shachnai, Srinivas Narayana, Santosh Nagarakatte

From: Harishankar Vishwanathan <harishankar.vishwanathan@rutgers.edu>

This patch introduces a new algorithm for multiplication of tristate numbers (tnums) that is provably sound. It is faster and more precise when compared to the existing method.

Our new algorithm

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Analytical proofs of maximal precision for addition and subtraction

maximally precise

```
def tnum_add(tnum P, tnum Q):
  u64 sm = P.mask + Q.mask
  u64 sv = P.value + Q.value
  u64 sigma = sm + sv
  u64 chi = sigma ^ sv
  u64 mu = chi | a.mask | b.mask
  return tnum(value=sv & ~mu,mask=mu)
```

Existing algorithm for tnum addition

maximally precise

```
def tnum_sub(tnum P, tnum Q):
  u64 dv = P.value - Q.value
  u64 alpha = dv + P.mask
  u64 beta = dv - Q.mask
  u64 chi = alpha ^ beta
  u64 mu = chi | P.mask | Q.mask
  return tnum(value=dv & ~mu, mask=mu)
```

Existing algorithm for tnum subtraction

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Summary of Contributions to the Domain of Tristate Numbers

- Proved the soundness of all the kernel existing algorithms for tristate numbers
- A faster, more precise version of tnum multiplication
- Analytical proof of soundness
- Analytical proof that tnum addition and subtraction are maximally precise

Agni

Proving the soundness of the entire value tracking analysis

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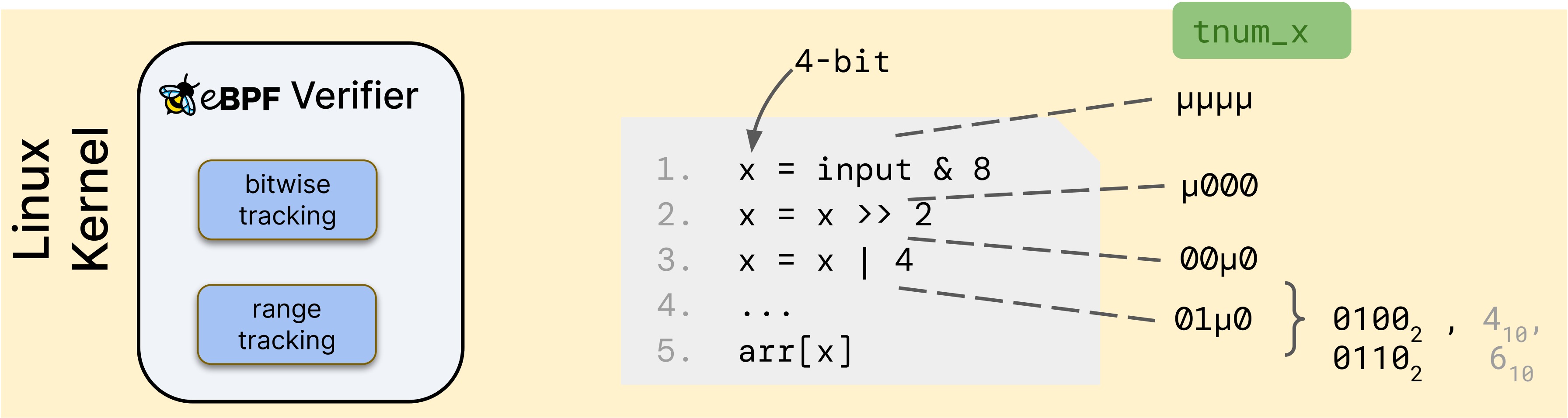
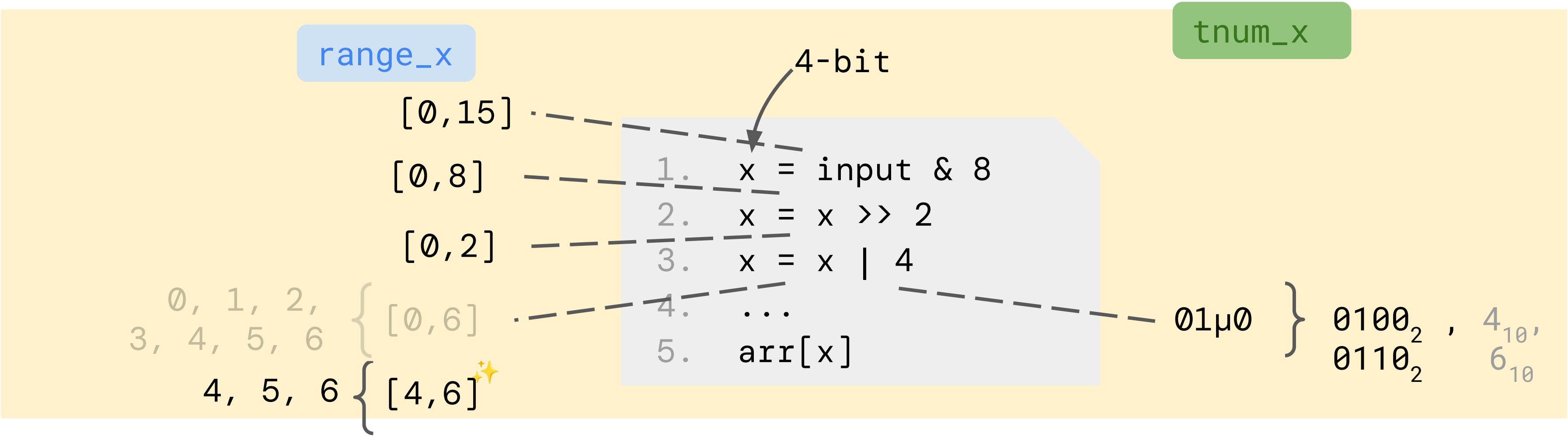
Range Analysis



- Range Analysis: tracks range of possible values – [min, max]
  - Interval domain

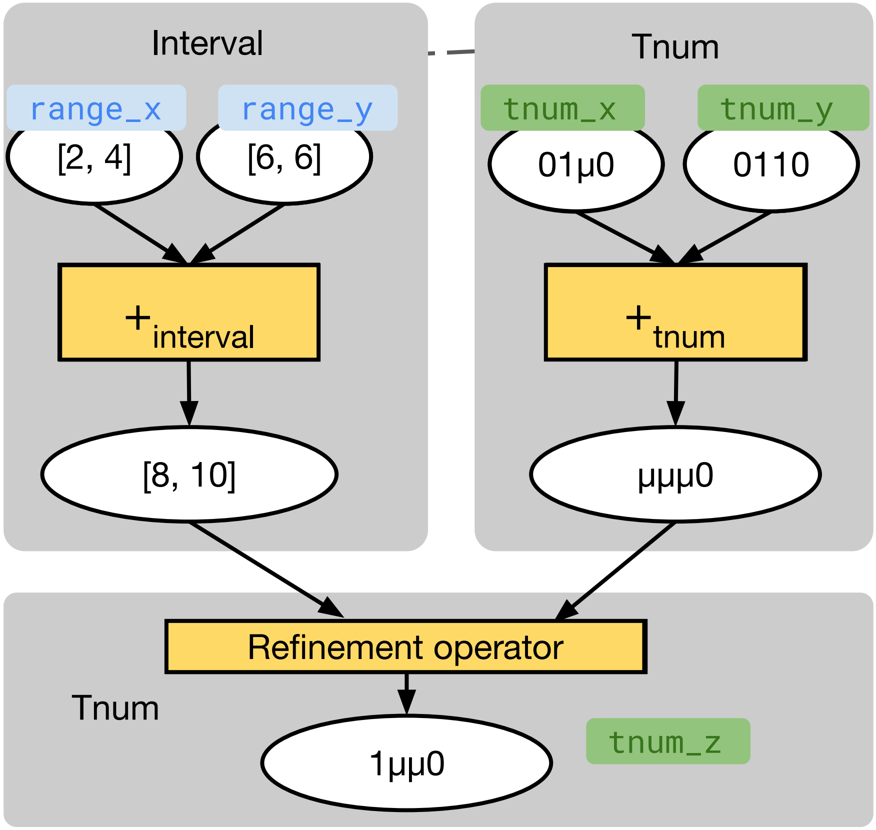
Range Analysis: Refinement



- Range Analysis: tracks range of possible values – [min, max]
    - Interval domain
- Refinement: Abstract values in one domain can be used to refine abstract values in another domain

Typical Refinement in Abstract Interpretation

```
41.   ...
42.   z = x + y
43.   ...
```

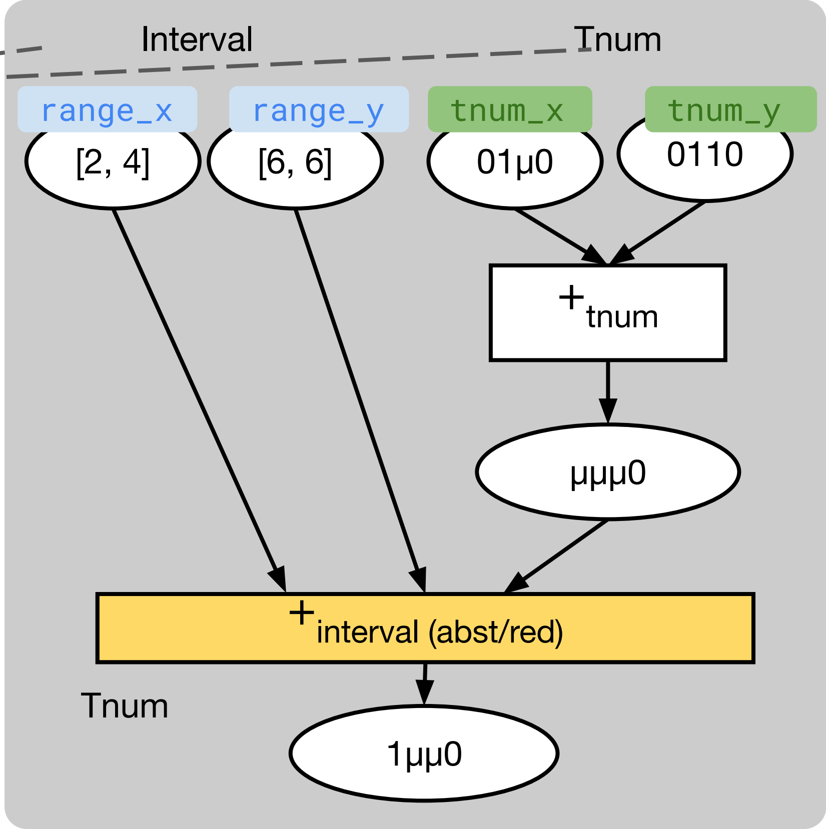


Soundness?

Modular reasoning

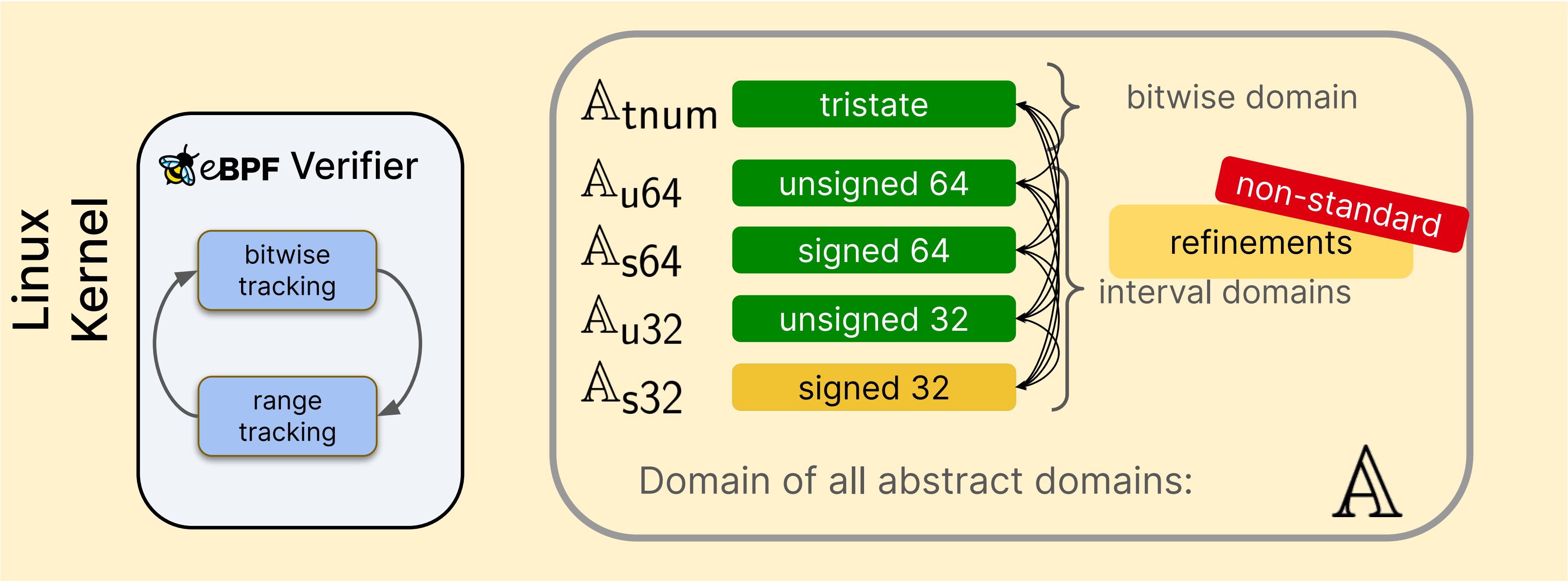
The Linux Kernel's Non-modular Refinement

```
41.   ...
42.   z = x + y
43.   ...
```



"One-shot" reasoning

Value Tracking Abstract Domains in the Linux Kernel



$$\mathbb{A} \triangleq \mathbb{A}_{tnum} \times \mathbb{A}_{u64} \times \mathbb{A}_{s64} \times \mathbb{A}_{u32} \times \mathbb{A}_{s32}$$

Soundness Specification in First Order Logic for Multiple Domains

$$\forall P, Q \in \mathbb{A} : \ {}_{n} :$$

$$\forall x, y \in \mathbb{Z} :$$

$$member(x, P) \wedge member(y, Q) \wedge \ ) \wedge$$

$$z = f(x, y) \ \wedge R = g(P, Q) \wedge$$

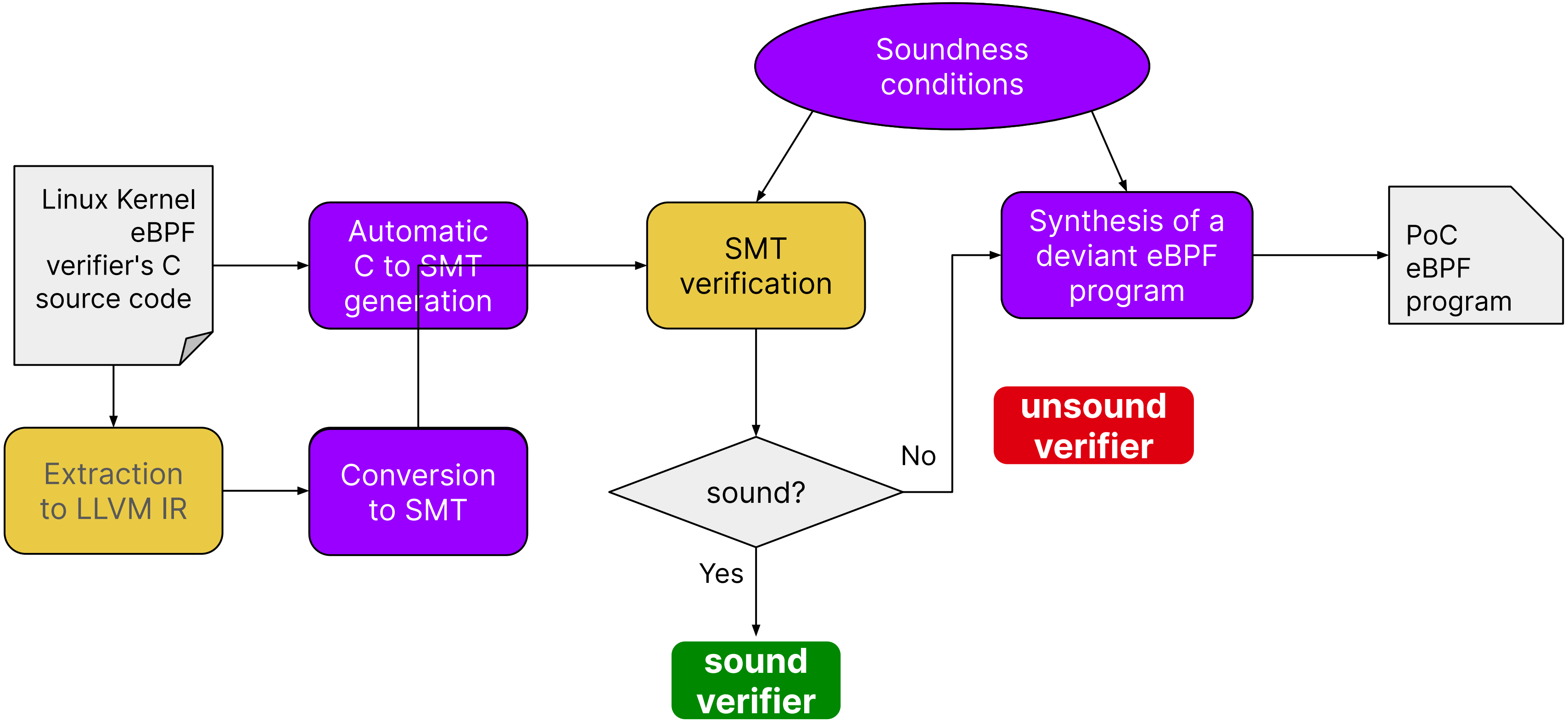
$$\implies$$

$$member(z, R)$$

$$member_{tnum}(z, R)$$

- Tedious and error-prone to write down manually
- Changing across kernel versions - which one to write and verify?
- 🤖 Automate 🤖

Agni: Overview



LLVM To SMT

```c
int foo(int a, int b) {
    int retval;
    if (a <= b)
        retval = b - 10;
    else
        retval = a + 10;
    return retval;
}
```

```llvm
define i32 @max(i32 %a, i32 %b)

entry:
    %x0 = icmp sgt i32 %a, %b
    br i1 %x0, label %btrue, label %bfalse
```

```llvm
btrue:
    %x1 = add i32 %a, 10
    br label %end
```

```llvm
bfalse:
    %x2 = sub i32 %b, 10
    br label %end
```

```llvm
end:
    %retval = phi i32 [%x1, %btrue], [%x2, %bfalse]
    ret i32 %retval
```

LLVM To SMT: Aggregating Basic Blocks' Logic

```
(declare-const a (_ BitVec 32))
(declare-const b (_ BitVec 32))
(declare-const x0 Bool)
(declare-const x1 (_ BitVec 32))
(declare-const x2 (_ BitVec 32))
```

bfalse

```
(= x2 (bvsub b 10)
```

```
define i32 @max(i32 %a, i32 %b)
```

```
entry:
    %x0 = icmp sgt i32 %a, %b
    br i1 %x0, label %btrue, label %bfalse
```

```
btrue:
    %x1 = add i32 %a, 10
    br label %end
```

```
bfalse:
    %x2 = sub i32 %b, 10
    br label %end
```

```
end:
    %retval = phi i32 [%x1, %btrue], [%x2, %bfalse]
    ret i32 %retval
```

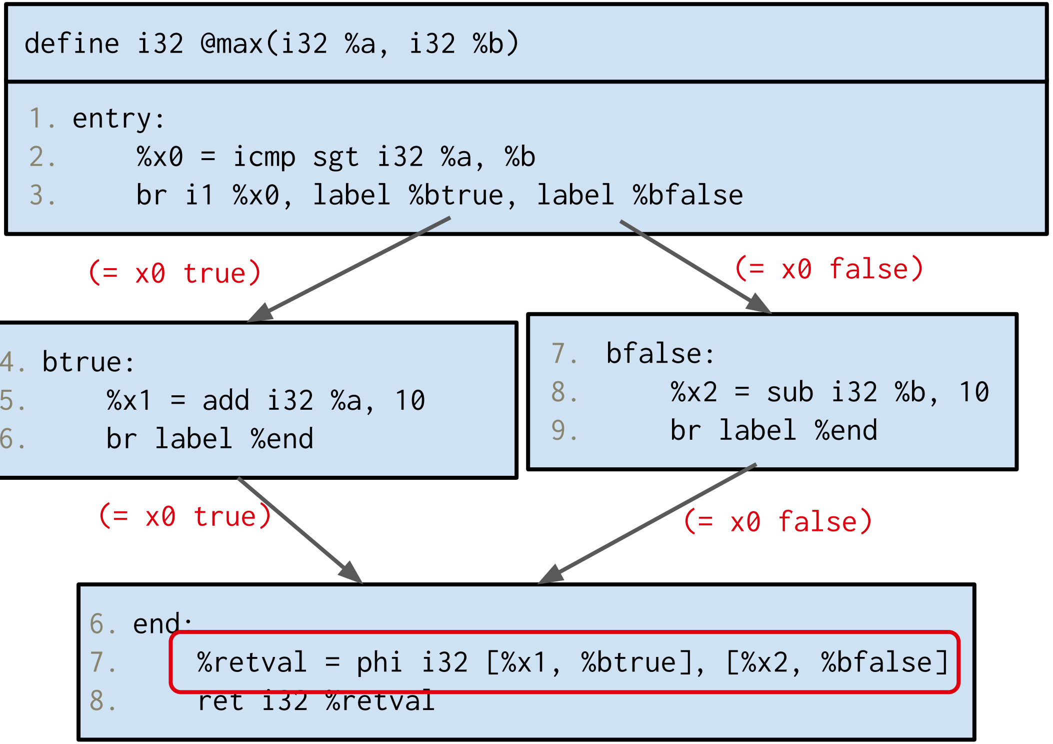
Handling LLVM code: Resolving Phi nodes

```
(declare-const a (_ BitVec 32))
(declare-const b (_ BitVec 32))
(declare-const x0 Bool)
(declare-const x1 (_ BitVec 32))
(declare-const x2 (_ BitVec 32))
(declare-const retval (_ BitVec 32))
```

end

```
(=> (= x0 true) (= retval x1))

(=> (= x0 false) (= retval x2))
```



Handling LLVM code: Path Conditions

```
define i32 @max(i32 %a, i32 %b)
```

(true)

```
entry:
    %x0 = icmp sgt i32 %a, %b
    br i1 %x0, label %btrue, label %bfalse
```

(= x0 true)

```
btrue:
    %x1 = add i32 %a, 10
    br label %end
```

(= x0 false)

```
bfalse:
    %x2 = sub i32 %b, 10
    br label %end
```

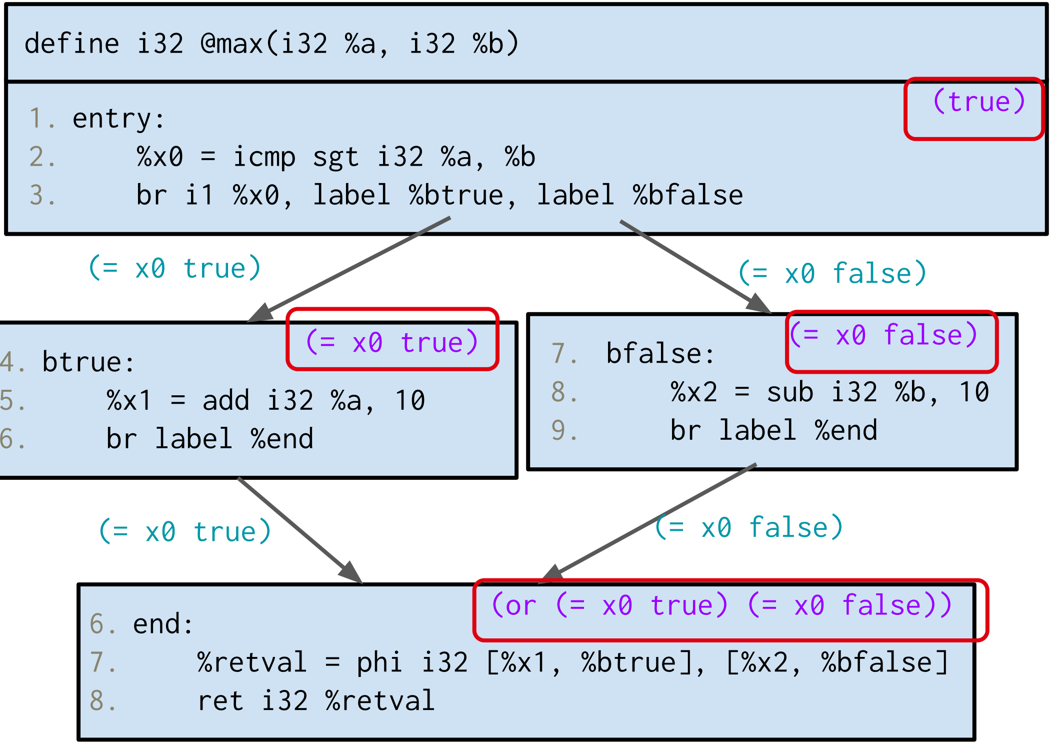
(or (= x0 true) (= x0 false))

```
end:
    %retval = phi i32 [%x1, %btrue], [%x2, %bfalse]
    ret i32 %retval
```

Handling LLVM code: Putting it all together

```
(=> true entry)
(=> (= x0 true) btrue)
(=> (= x0 false) bfalse)
(=> (or (= x0 true) (= x0 false)) end)
```

```
(assert
 (=> (= x0 false) (= retval x2))
)
```



Handling LLVM code: Putting it all together

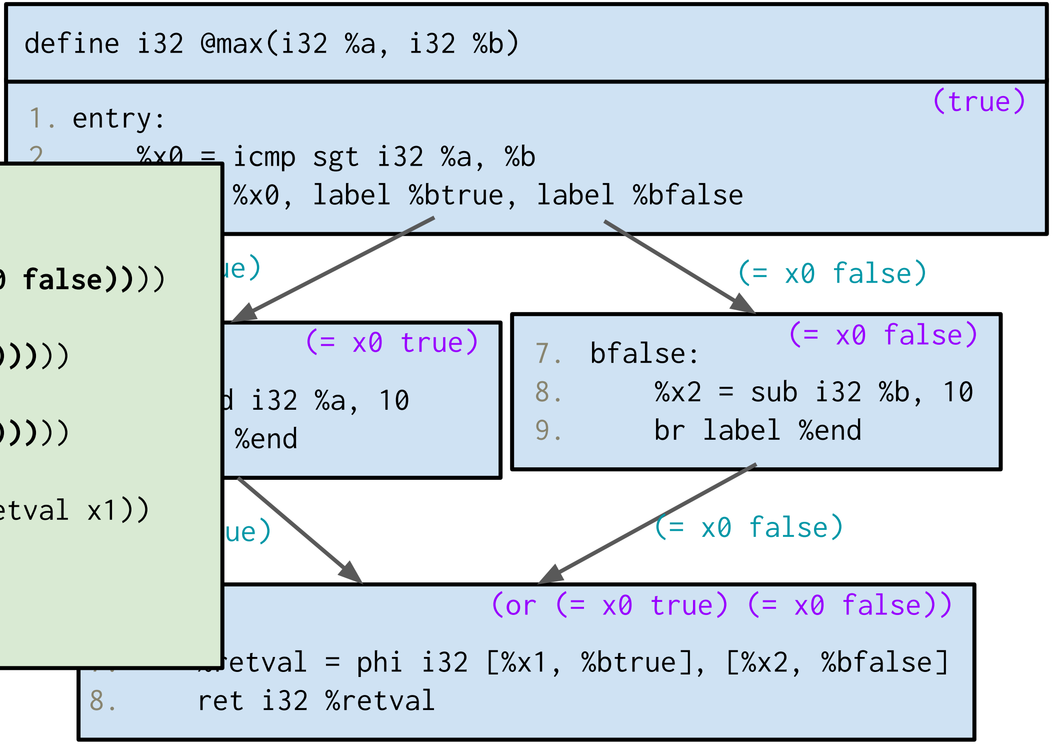
```
(assert (=> true (ite (bvsgt a b) (= x0 true) (= x0 false))))

(assert (=> (= x0 true)  (= x1 (bvadd a (_ bv10 32)))))

(assert (=> (= x0 false) (= x2 (bvsub b (_ bv10 32)))))

(assert (=> (=> (or (= x0 true) (= x0 false)) (= retval x1))
        (and (=> (= x0 true) (= retval x1))
             (=> (= x0 false) (= retval x2)))
))
```

```
(assert
 (=> (= x0 false) (= retval x2))
)
```



Handling Real-World Kernel Code

- Converting C to LLVM IR is not straightforward
  - Custom passes to eliminate dead code, and inline function calls, making it conducive to work with
- Generated IR is much larger than our toy example
  - ~600 llvm code, ~50 basic basic block (per eBPF abstract operator)
- Memory access instructions: structs and pointers, loads and stores to memory.
  - Leverage LLVM's MemorySSA analysis
    - Stores and branch merges are annotated with new versions of memory
    - Loads are annotated with existing versions of memory that they load from
- Testing harness
  - Unit testing SMT translations

Results   But Can We do More?

- Automatically test kernels 4.14 through 5.19 for soundness
- Proved that all abstract operators in kernels v5.13 to v 5.19 are sound
- What can we do about unsound versions?

Generate *actual* eBPF programs!

- Generated eBPF program that manifests the bugs in 97% of the cases

Kernel Version	Sound?
v4.14	❌
v5.5	❌
v5.7	❌
...	❌
v5.12	❌
v5.13	✅
v5.14	✅
v5.15	✅
...	✅

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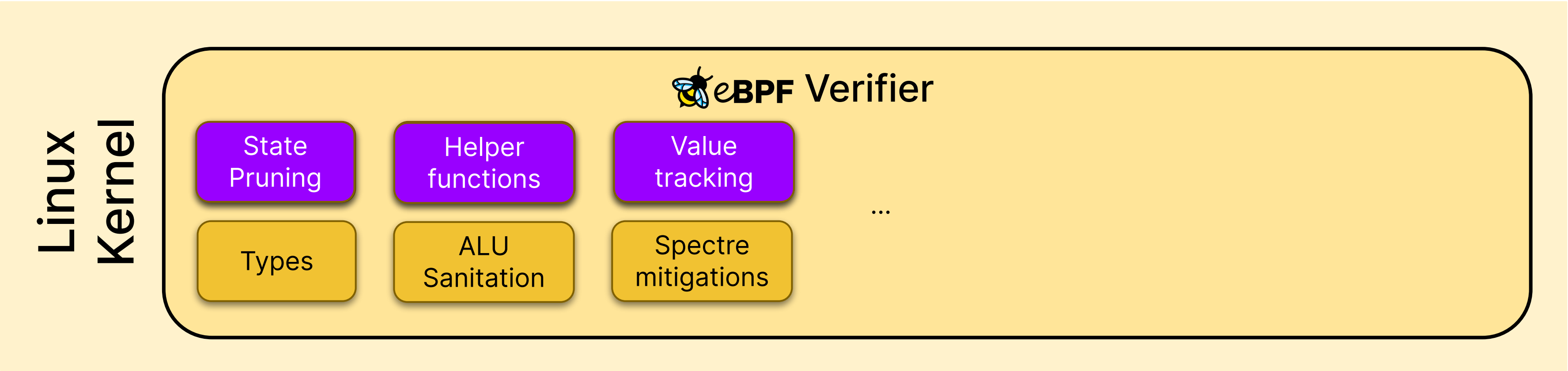
Future

Next Steps

- Agni
  - Pushing Agni to Linux's Continuous Integration
  - Reducing Verification Time
    - Using environments like Rosette with tooling for finding verification bottlenecks
    - Trying other bitvector solvers (Bitwuzla)
  - Completeness of Synthesis
  - Exploring techniques to reduce our TCB by doing conversion to SMT in Coq.

Extending Current Work

- Hardening other parts of the verifier



Long Term Vision

- Fortifying eBPF verification with formal foundations
- Exploring techniques to build a verifier that is correct-by-construction
  - Domain specific requirements: speed, low resource consumption

Questions?