Compiler Optimization with Retrofitting Transformations: Is there a Semantic Mismatch?

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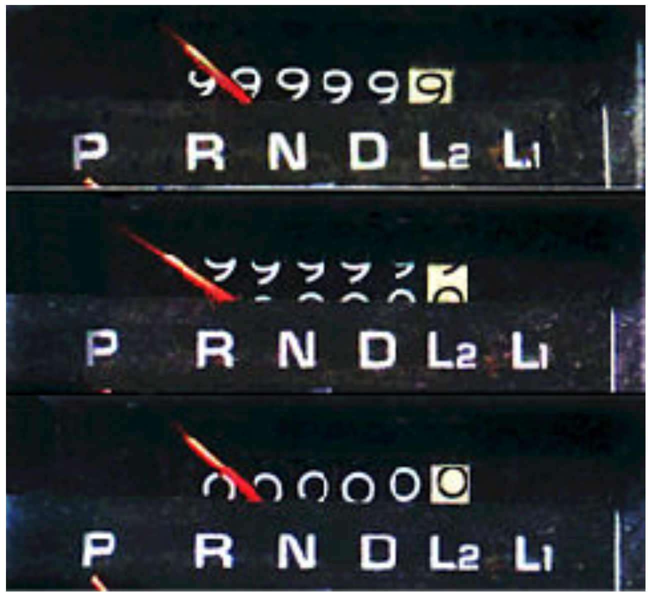
Retrofitting Transformation

Source

Retrofitting Transformation

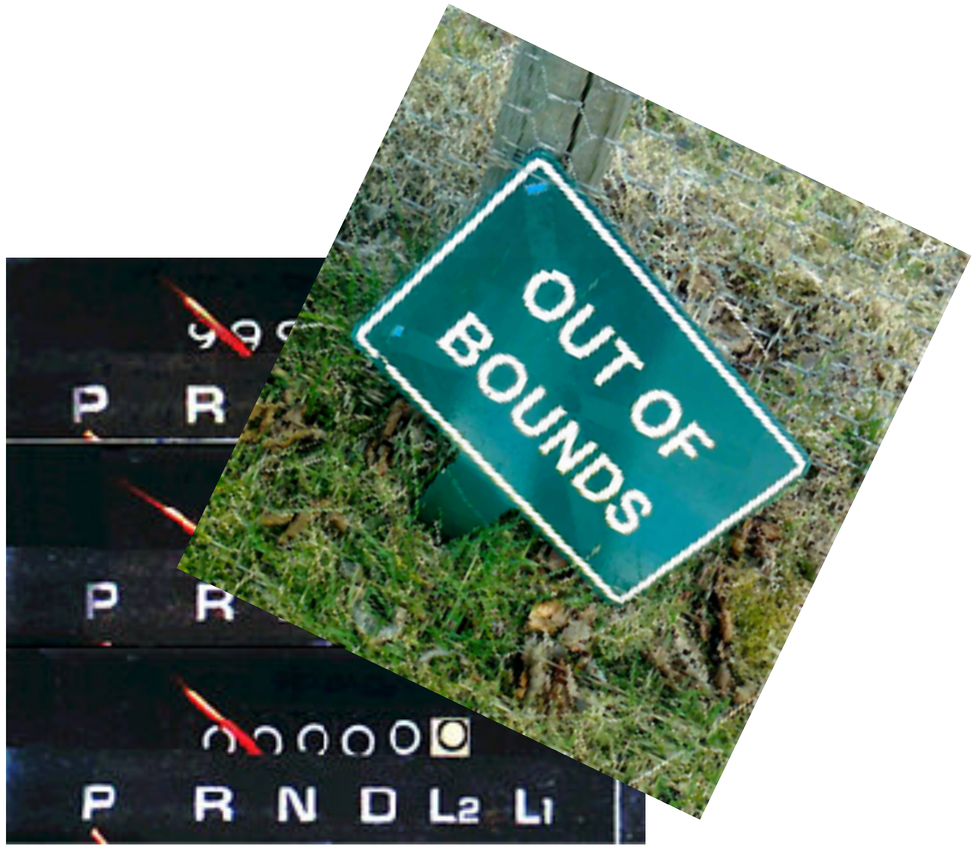
Source



Undefined Behavior

Retrofitting Transformation

Source



Bounds Safety

Retrofitting Transformation

Source

Control Flow Integrity

Retrofitting Transformation

Source

LLVM

```
  .globl  "_$add_forty_two<Int32>:Int32"
  .align  4, 0x90
"_$add_forty_two<Int32>:Int32":
  .cfi_startproc
  pushq %rbp
Ltmp3552:
  .cfi_def_cfa_offset 16
Ltmp3553:
  .cfi_offset %rbp, -16
  movq  %rsp, %rbp
Ltmp3554:
  .cfi_def_cfa_register %rbp
  addl  $42, %edi
  movl  %edi, %eax
  popq  %rbp
  retq
  .cfi_endproc
```

Assembly

Instrumentation

Retrofitting Transformation

LLVM : Optimize $\longrightarrow$ Instrument $\longrightarrow$ Optimize

Motivating Example

```
int foo(int a, int b) {
  int c = a + b;
  return c;
}
```

LLVM : Optimize → Instrument → Optimize

Motivating Example

```
int foo(int a, int b) {
  int c = a + b;
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```

signed integer overflow
= undefined behavior

LLVM : Optimize → Instrument → Optimize

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Motivating Example

Integer overflow checker

```
int foo(int a, int b) {
  int c = a + b;
  return c;
}
```

signed integer overflow
= undefined behavior

Instrumentation

```
int foo(int a, int b) {
  if (a > 0 && b > 0 && a > a + b)
    exit(1);
  if (a < 0 && b < 0 && a < a + b)
    exit(1);
  int c = a + b;
  return c;
}
```

LLVM : Optimize → Instrument → Optimize

Motivating Example

```
int foo(int a, int b) {
  int c = a + b;
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signed integer overflow
= undefined behavior

Integer overflow checker

Optimize (Linux LLVM)

Instrumentation removed

```
int foo(int a, int b) {
 if (a > 0 && b > 0 && a > a + b)
   exit(1);
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LLVM : Optimize → Instrument → Optimize

Motivating Example

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    exit(1);
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    exit(1);
  int c = a + b;
  return c;
}
```

Optimize
(MacOSX LLVM)

```
int foo(int a, int b) {
  if (b > 0 && (a & b) > 0)
    exit(0)
  int c = a + b;
  return c;
}
```

Instrumentation
modified

LLVM : Optimize → Instrument → Optimize

Motivating Example

n removed

a > a + b)

a < a + b)

int foo(int

int c = a

return c;

}

signed integ

= undefined

ptimize

OSX LLVM)

0)

LLVM : Optim

return c;

}

Instrumentation
modified

Problem Statement

Can we detect erroneously removed/modified instrumentation due to compiler optimizations?

Challenges:

1. Checks may be completely removed.
2. Checks may be partially removed.
3. Checks may be moved.
4. Some checks are indeed redundant.

Solution:

Can we frame this as a reachability problem?

P_{retro}: retrofitted program

```
int foo(int a, int b) {
  if (a > 0 && b > 0 && a > a + b)
    exit(1);
  if (a < 0 && b < 0 && a < a + b)
    exit(1);
  int c = a + b;
  return c;
}
```

P_{opt}: optimized P_{retro}

```
int foo(int a, int b) {
  if (b > 0 && (a & b) > 0)
    exit(0)
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}
```

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Reachability

P_{retro}: retrofitted program

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```

Event of Interest

P_{opt}: optimized P_{retro}

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Event of Interest

Direct unsafe execution to exit path.

P_{opt}: optimized P_{retro}

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Semantics same as P_{retro}

Reachability

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Semantics same as P_{retro}

Given same inputs,

Reachability

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Event of Interest

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Semantics same as P_{retro}

Given same inputs,

1. P_{retro} and P_{opt} reaches Event of Interest

Reachability

P_{retro}: retrofitted program

```
int foo(int a, int b) {
  if (a > 0 && b > 0 && a > a + b)
    exit(1);
  if (a < 0 && b < 0 && a < a + b)
    exit(1);
  int c = a + b;
  return c;
}
```

Event of Interest

Direct unsafe execution to exit path.

P_{opt}: optimized P_{retro}

```
int foo(int a, int b) {
  if (b > 0 && (a & b) > 0)
    exit(0)
  int c = a + b;
  return c;
}
```

Semantics same as P_{retro}

Given same inputs,

1. P_{retro} and P_{opt} reaches Event of Interest
2. P_{retro} and P_{opt} reaches exit(0)

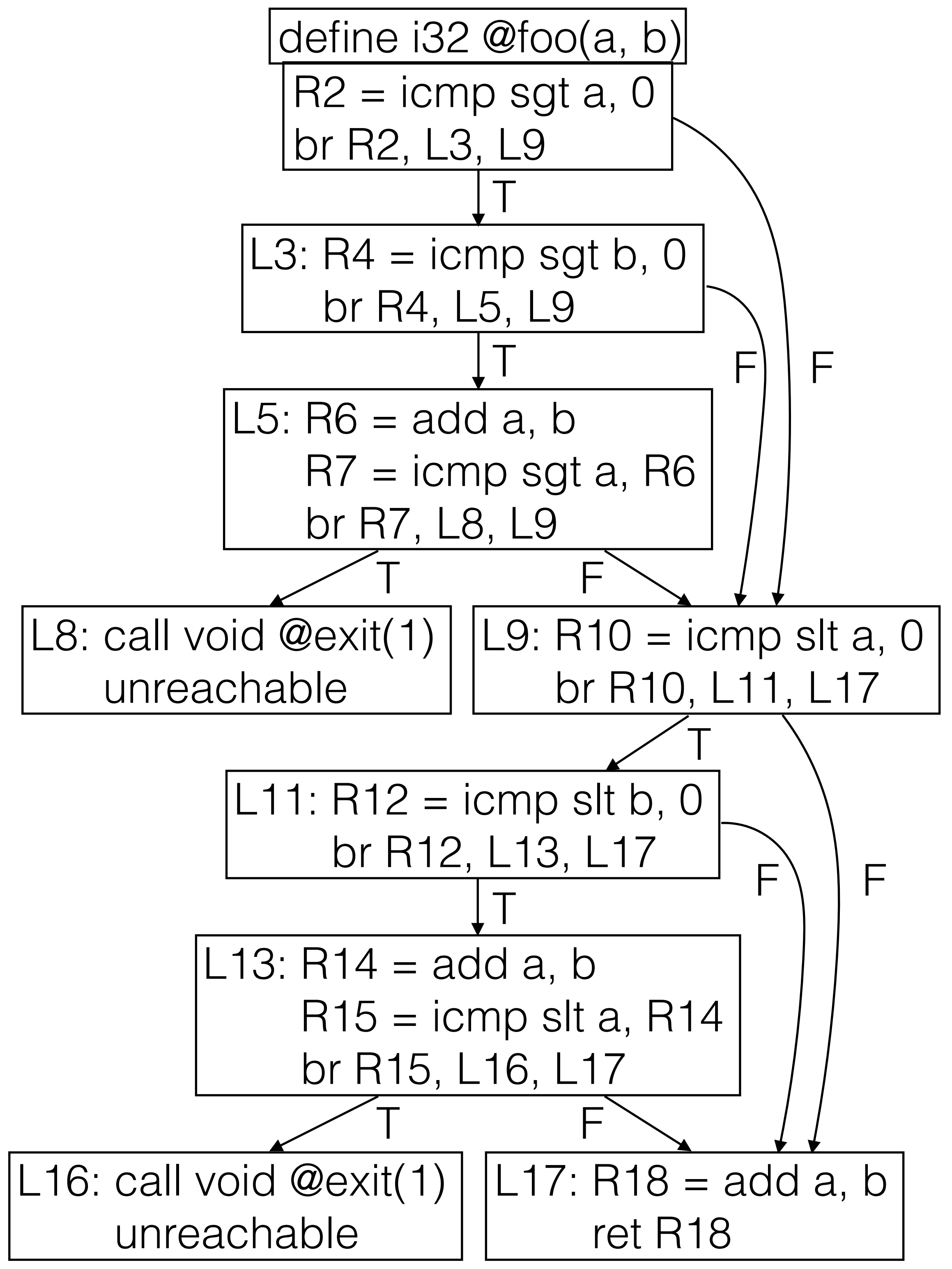
Reachability

P_{retro}: retrofitted program

```
int foo(int a, int b) {
  if (a > 0 && b > 0 && a > a + b)
    exit(1);
  if (a < 0 && b < 0 && a < a + b)
    exit(1);
  int c = a + b;
  return c;
}
```

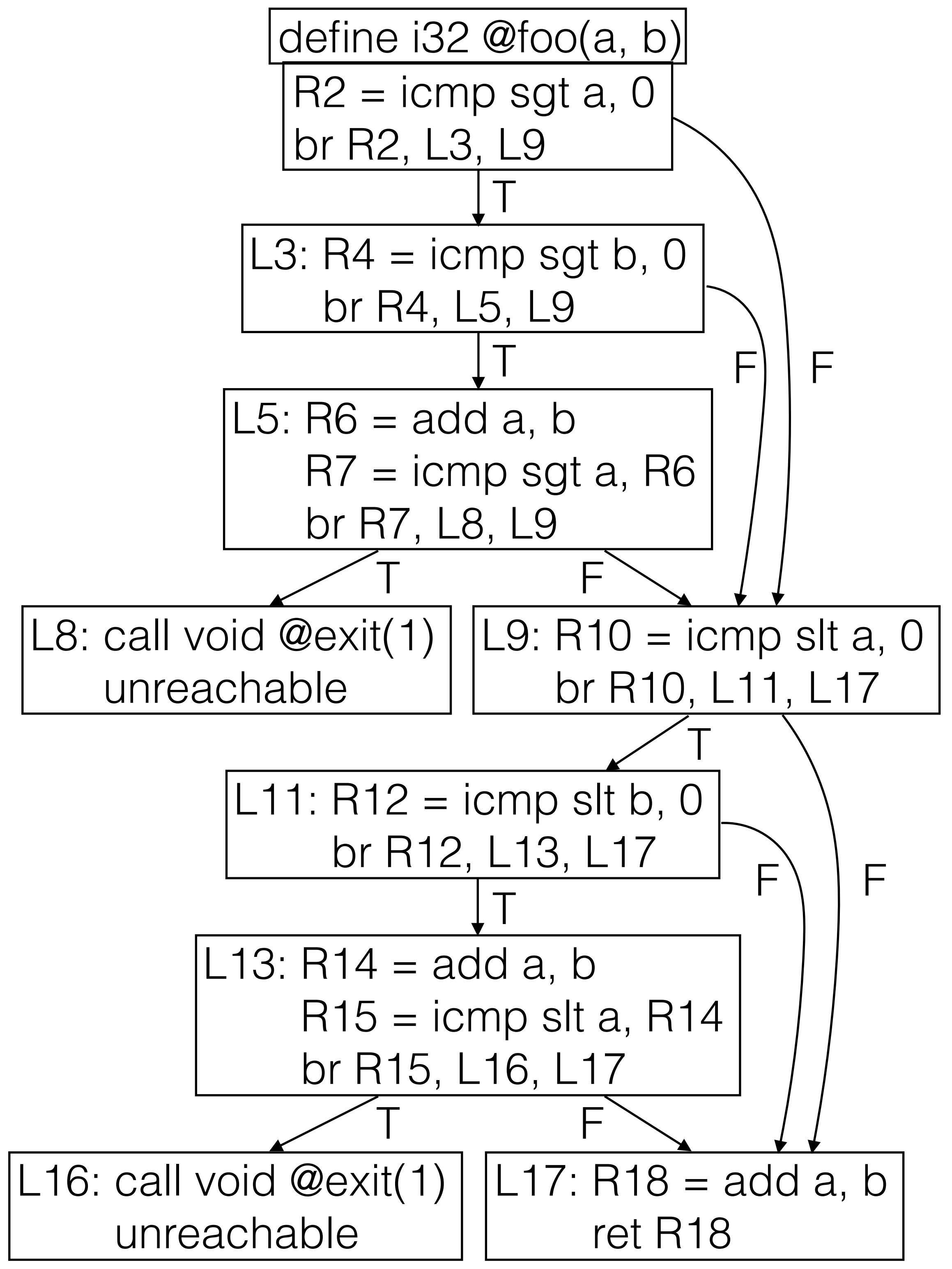
Reachability

P$_{retro}$: retrofitted program



Reachability

P_{retro}: retrofitted program



```
define i32 @foo(a, b)
R2 = icmp sgt a, 0
br R2, L3, L9

L3: R4 = icmp sgt b, 0
    br R4, L5, L9

L5: R6 = add a, b
    R7 = icmp sgt a, R6
    br R7, L8, L9

L8: call void @exit(1)
    unreachable

L9: R10 = icmp slt a, 0
    br R10, L11, L17

L11: R12 = icmp slt b, 0
     br R12, L13, L17

L13: R14 = add a, b
     R15 = icmp slt a, R14
     br R15, L16, L17

L16: call void @exit(1)
     unreachable

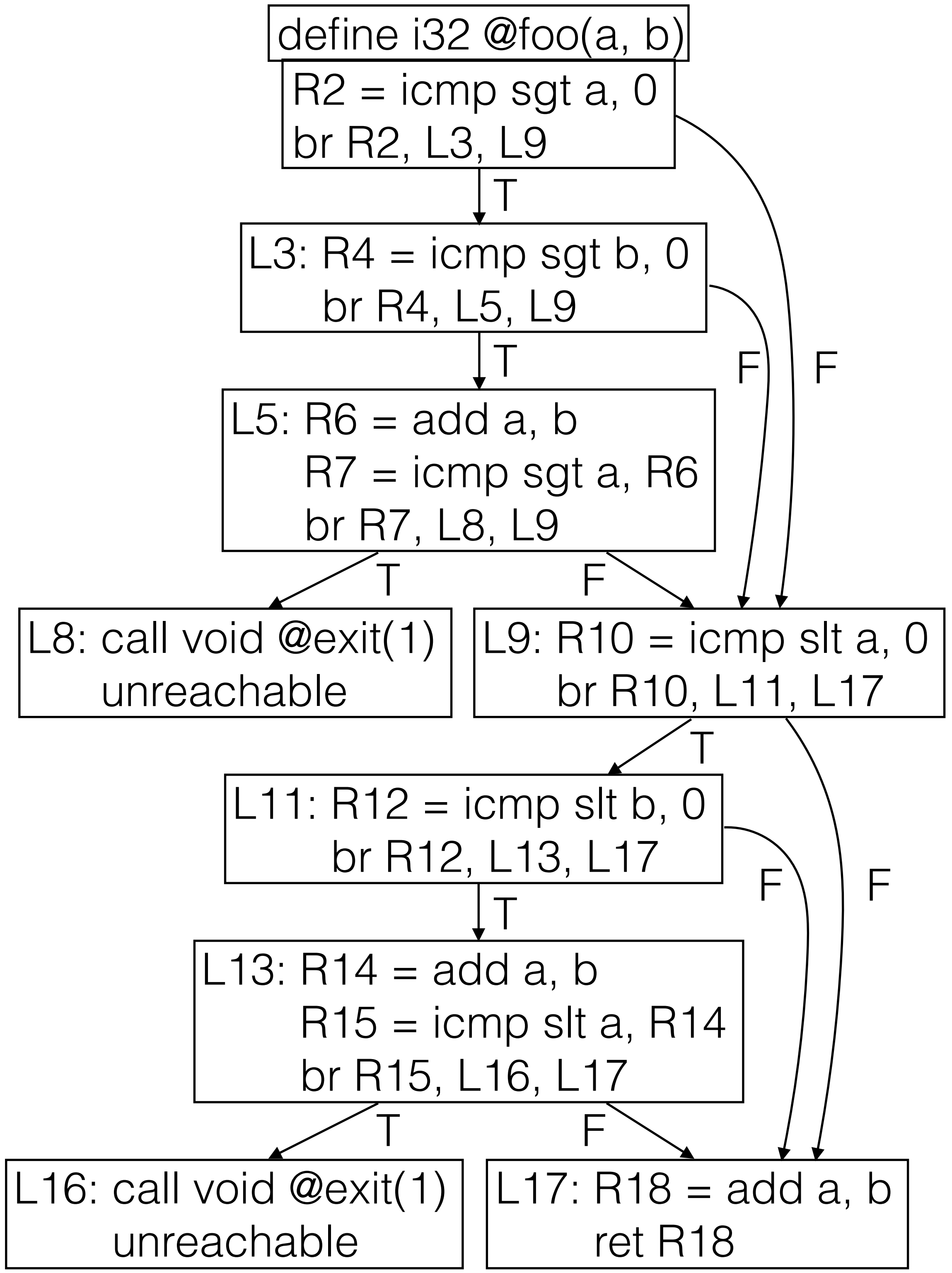
L17: R18 = add a, b
     ret R18
```

P_{opt}: optimized P_{retro}

```
int foo(int a, int b) {
  if (b > 0 && (a & b) > 0)
    exit(0)
  int c = a + b;
  return c;
}
```

Reachability

P$_{retro}$: retrofitted program



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    R7 = icmp sgt a, R6
    br R7, L8, L9

L8: call void @exit(1)
    unreachable

L9: R10 = icmp slt a, 0
    br R10, L11, L17

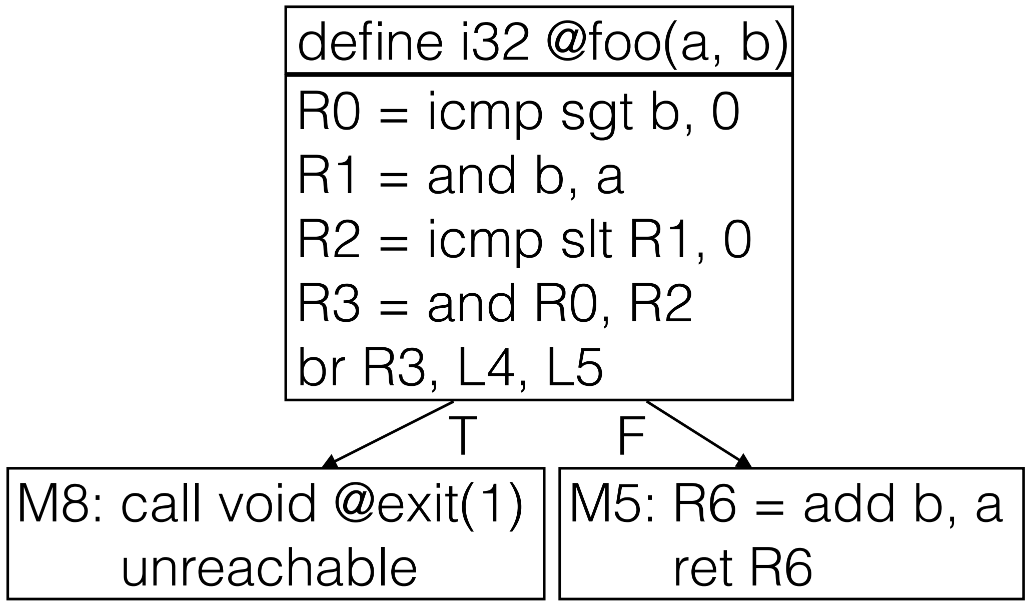
L11: R12 = icmp slt b, 0
     br R12, L13, L17

L13: R14 = add a, b
     R15 = icmp slt a, R14
     br R15, L16, L17

L16: call void @exit(1)
     unreachable

L17: R18 = add a, b
     ret R18
```

P$_{opt}$: optimized P$_{retro}$



```
define i32 @foo(a, b)
R0 = icmp sgt b, 0
R1 = and b, a
R2 = icmp slt R1, 0
R3 = and R0, R2
br R3, L4, L5

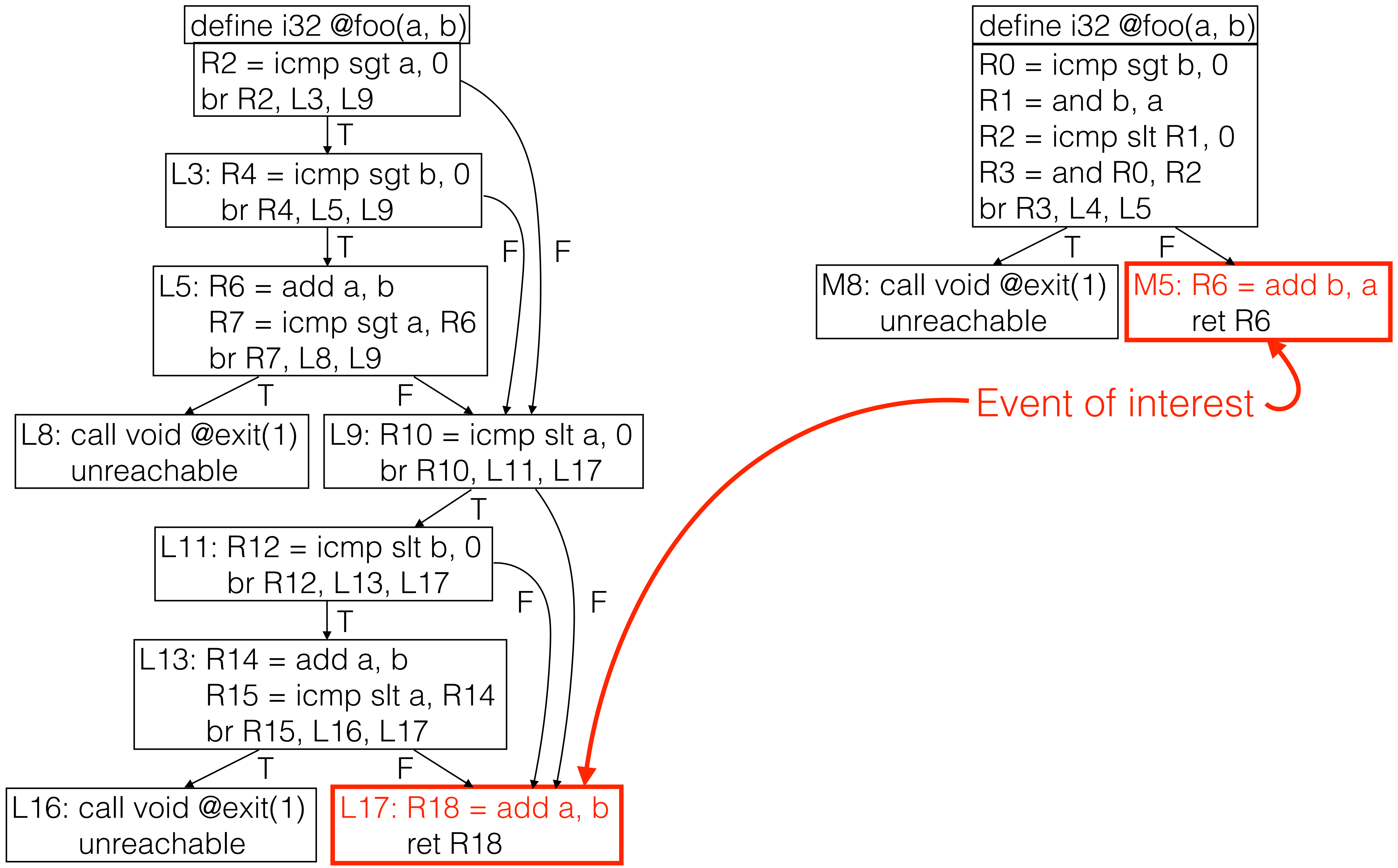
M8: call void @exit(1)
    unreachable

M5: R6 = add b, a
    ret R6
```

Reachability

P$_{retro}$: retrofitted program

P$_{opt}$: optimized P$_{retro}$



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    br R4, L5, L9

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    R7 = icmp sgt a, R6
    br R7, L8, L9

L8: call void @exit(1)
    unreachable

L9: R10 = icmp slt a, 0
    br R10, L11, L17

L11: R12 = icmp slt b, 0
     br R12, L13, L17

L13: R14 = add a, b
     R15 = icmp slt a, R14
     br R15, L16, L17

L16: call void @exit(1)
     unreachable

L17: R18 = add a, b
     ret R18
```

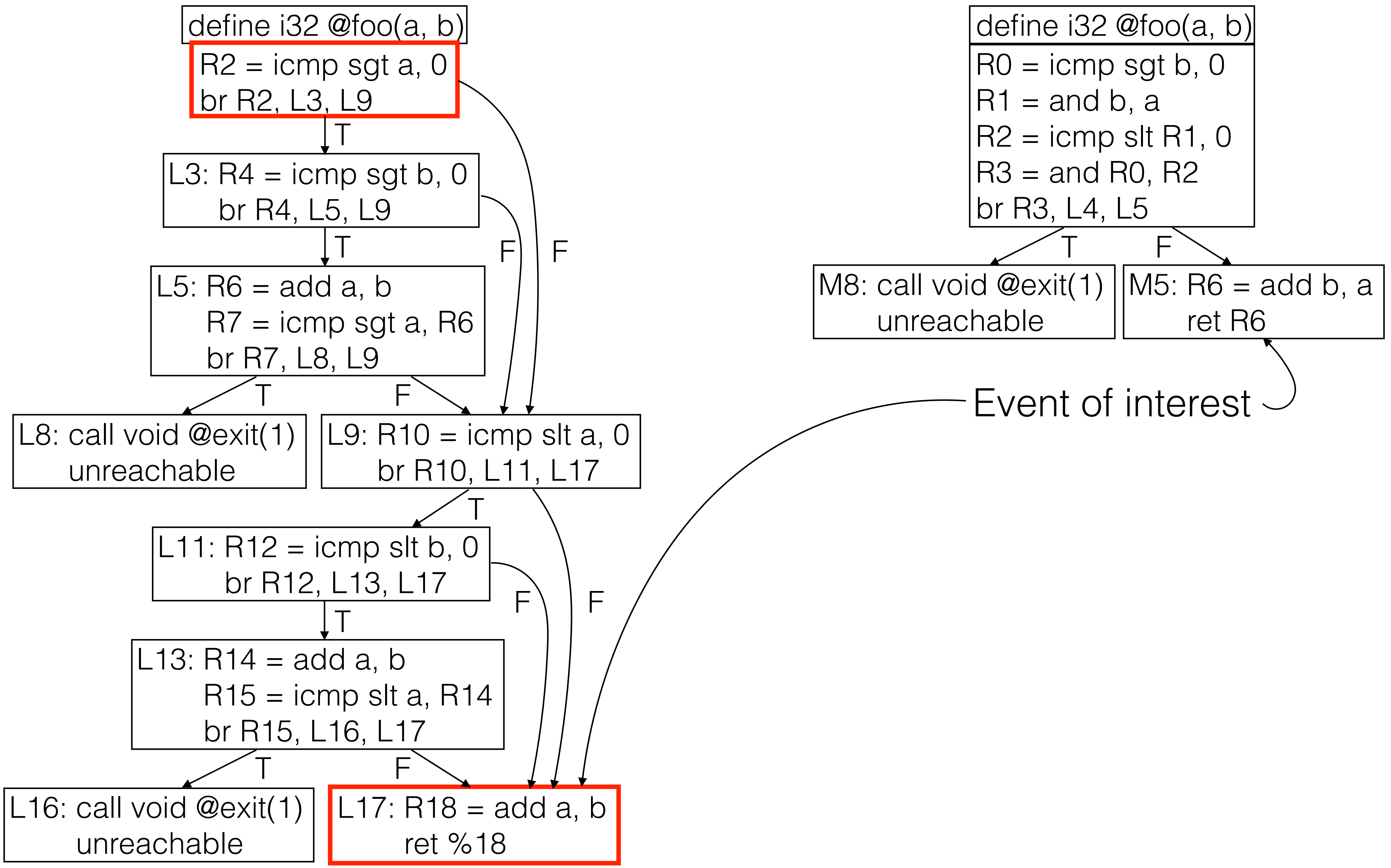
```
define i32 @foo(a, b)
R0 = icmp sgt b, 0
R1 = and b, a
R2 = icmp slt R1, 0
R3 = and R0, R2
br R3, L4, L5

M8: call void @exit(1)
    unreachable

M5: R6 = add b, a
    ret R6
```

Reachability

P_{retro}: retrofitted program $\quad$ P_{opt}: optimized P_{retro}



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L5: R6 = add a, b
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L8: call void @exit(1)
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```
L9: R10 = icmp slt a, 0
    br R10, L11, L17
```

```
L11: R12 = icmp slt b, 0
     br R12, L13, L17
```

```
L13: R14 = add a, b
     R15 = icmp slt a, R14
     br R15, L16, L17
```

```
L16: call void @exit(1)
     unreachable
```

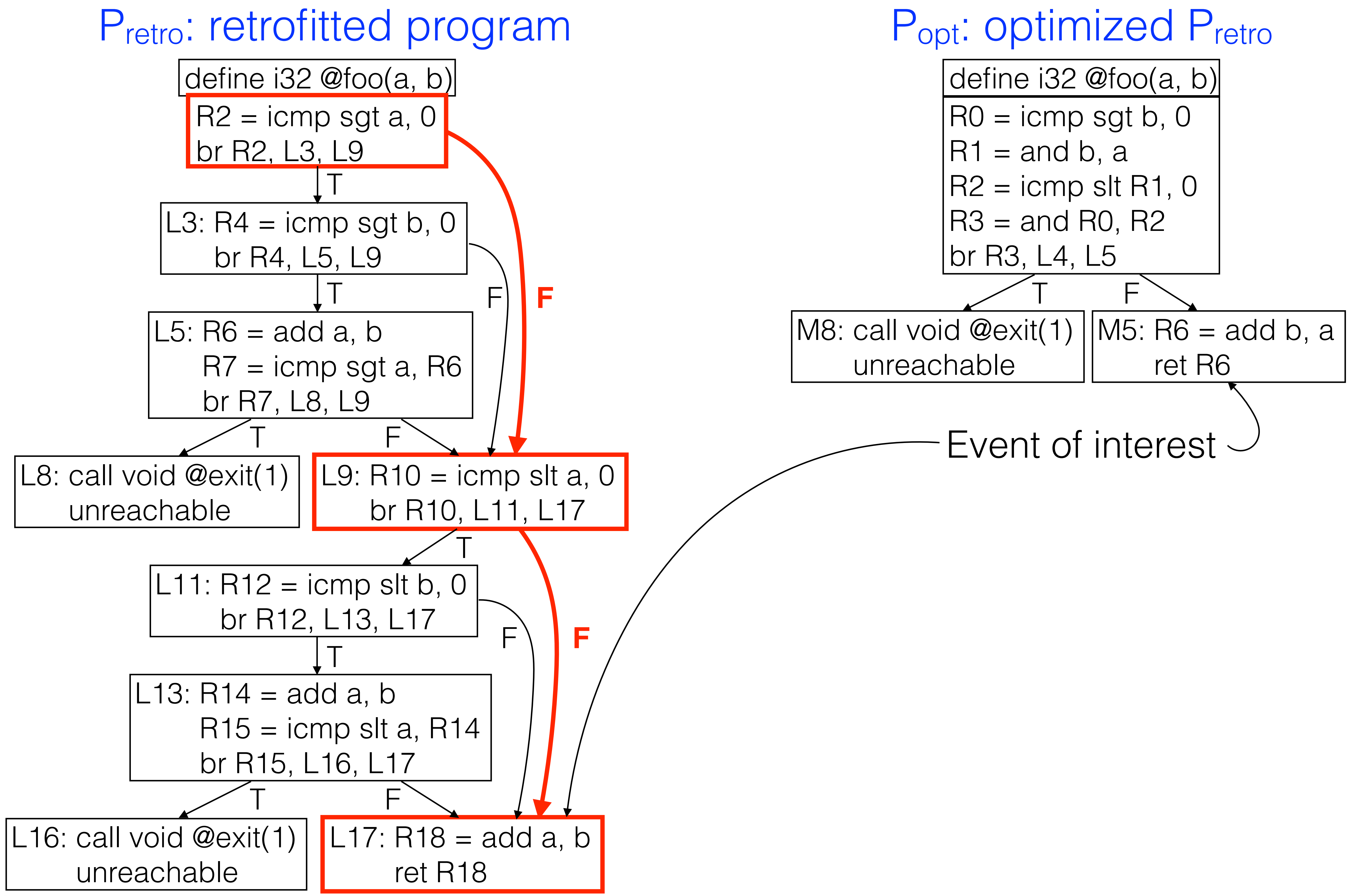
```
L17: R18 = add a, b
     ret %18
```

```
define i32 @foo(a, b)
R0 = icmp sgt b, 0
R1 = and b, a
R2 = icmp slt R1, 0
R3 = and R0, R2
br R3, L4, L5
```

```
M8: call void @exit(1)
    unreachable
```

```
M5: R6 = add b, a
    ret R6
```

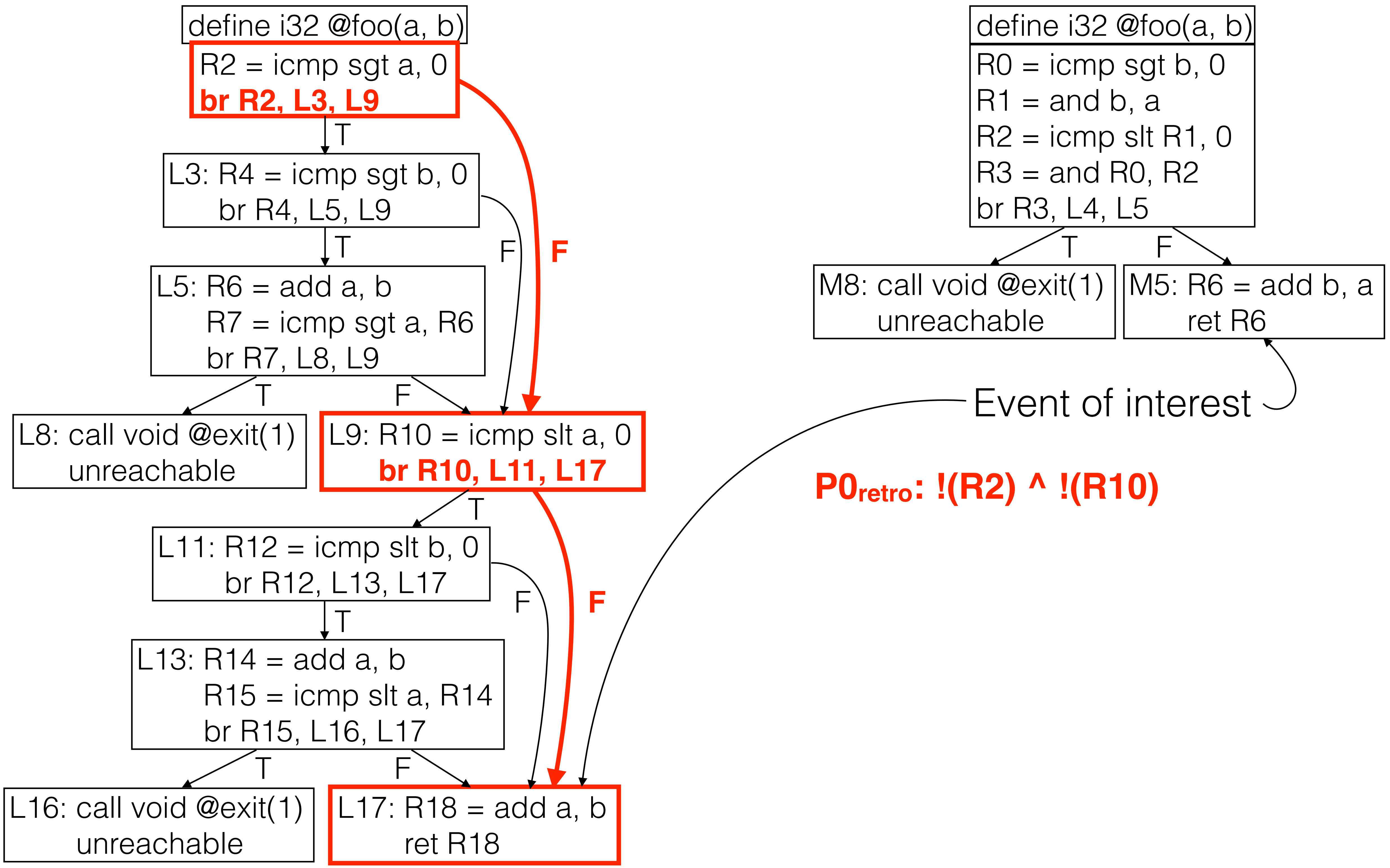
Reachability



Reachability

P_{retro}: retrofitted program

P_{opt}: optimized P_{retro}



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L3: R4 = icmp sgt b, 0
    br R4, L5, L9

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L11: R12 = icmp slt b, 0
     br R12, L13, L17

L13: R14 = add a, b
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L17: R18 = add a, b
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```

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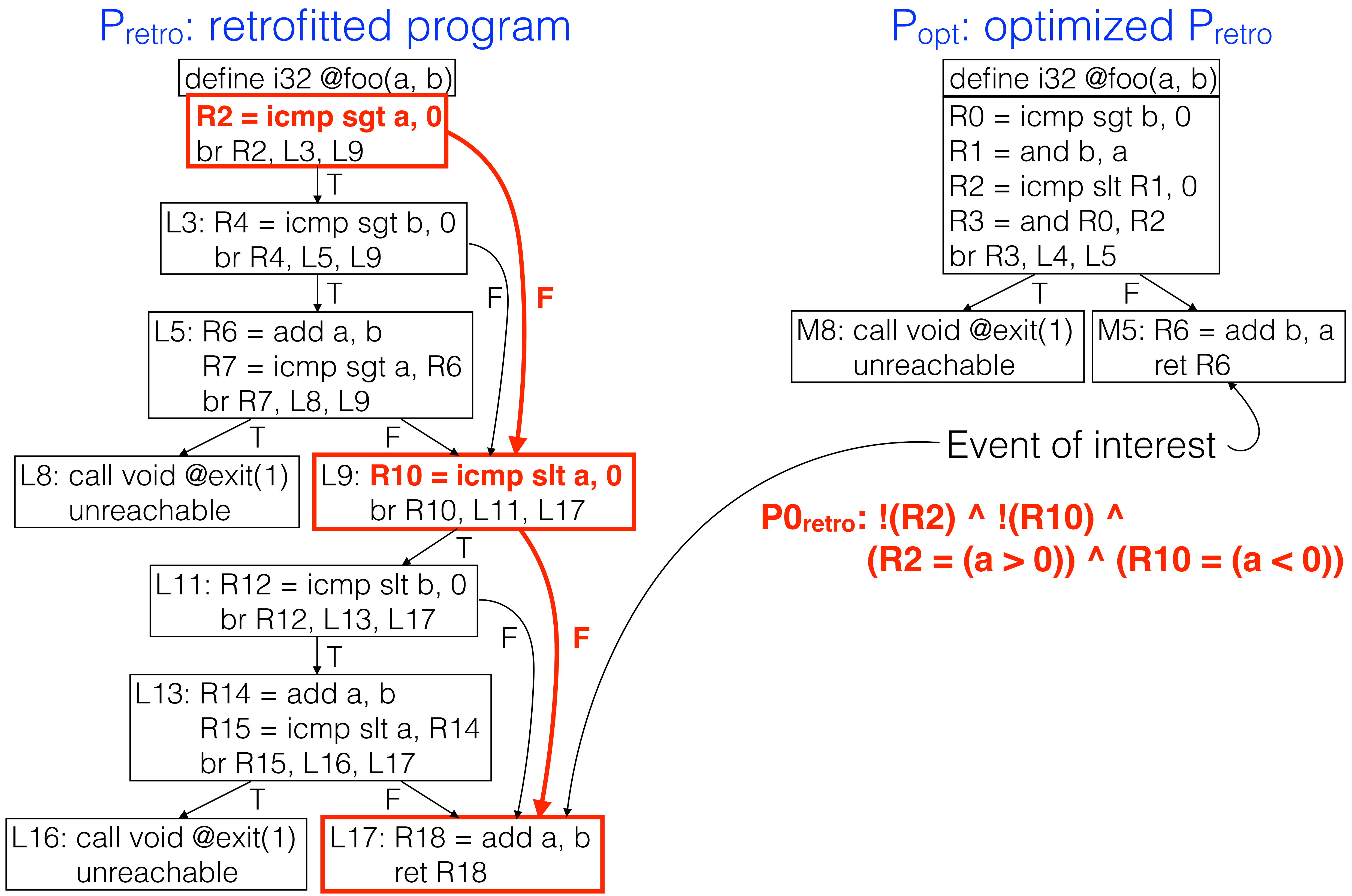
R0 = icmp sgt b, 0
R1 = and b, a
R2 = icmp slt R1, 0
R3 = and R0, R2
br R3, L4, L5

M8: call void @exit(1)
    unreachable

M5: R6 = add b, a
    ret R6
```

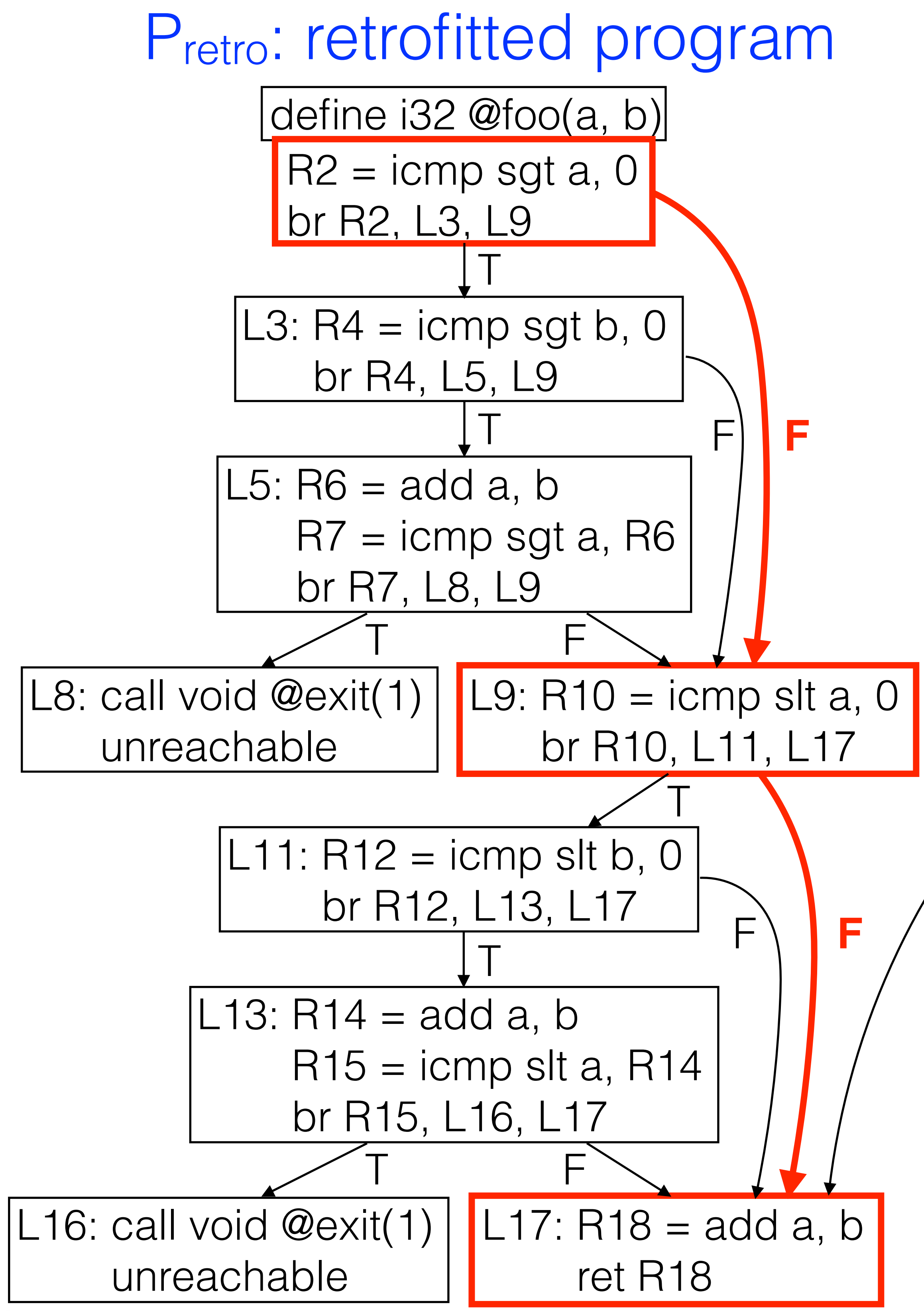
$P0_{retro}$: !(R2) ^ !(R10)

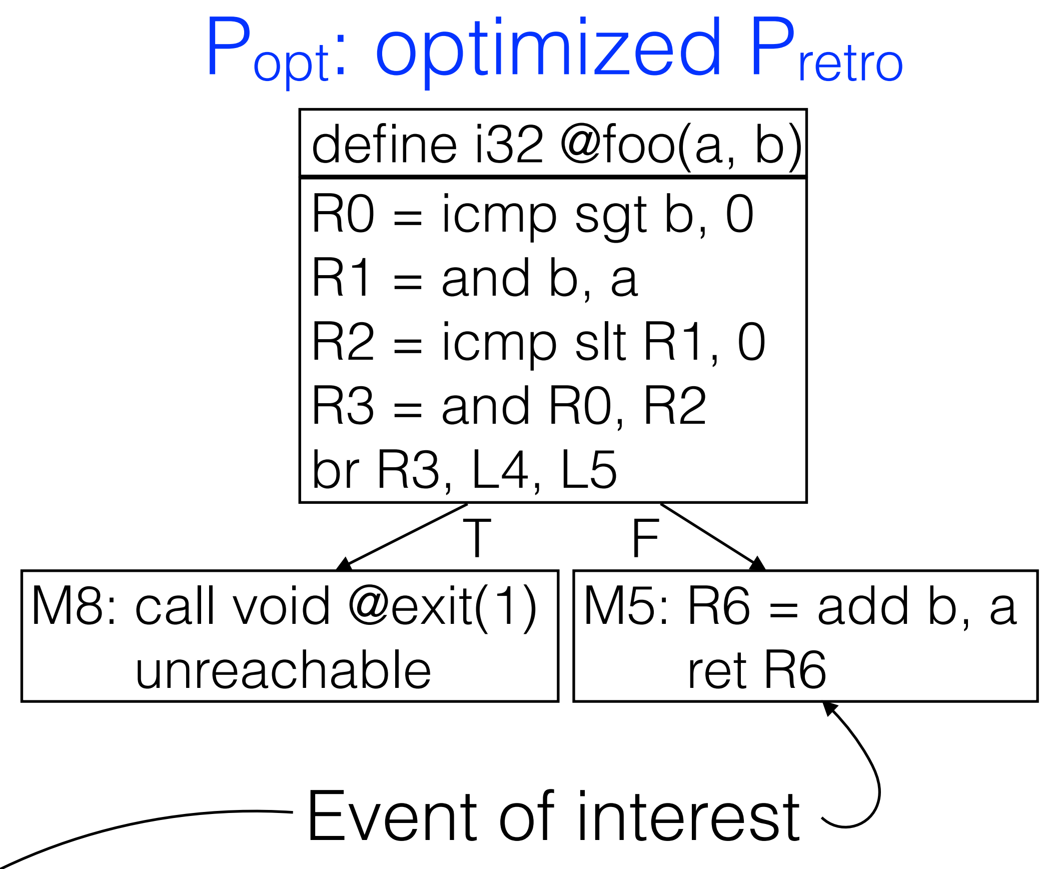
Reachability



$P0_{retro}$: !(R2) ^ !(R10) ^ (R2 = (a > 0)) ^ (R10 = (a < 0))

Reachability

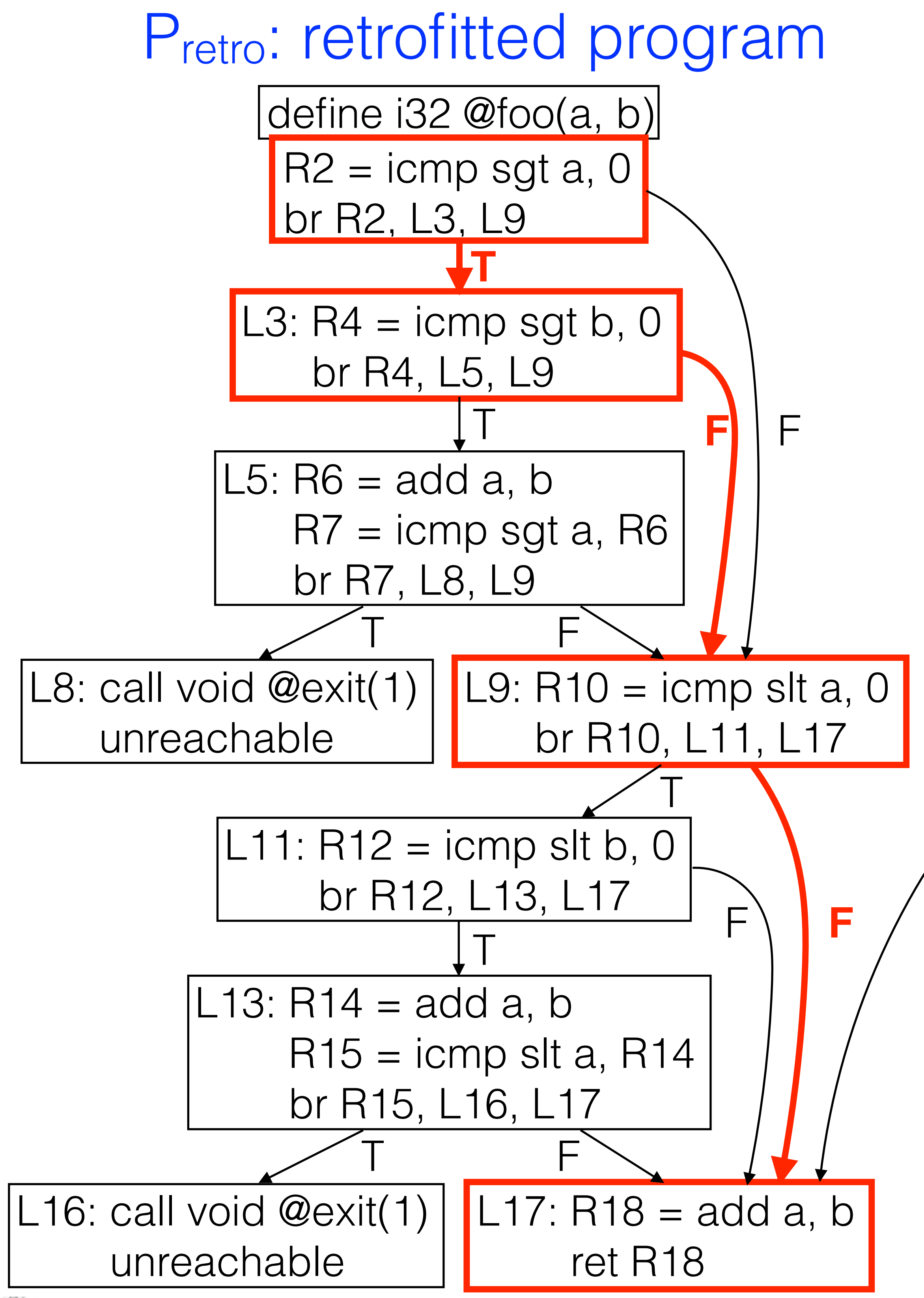


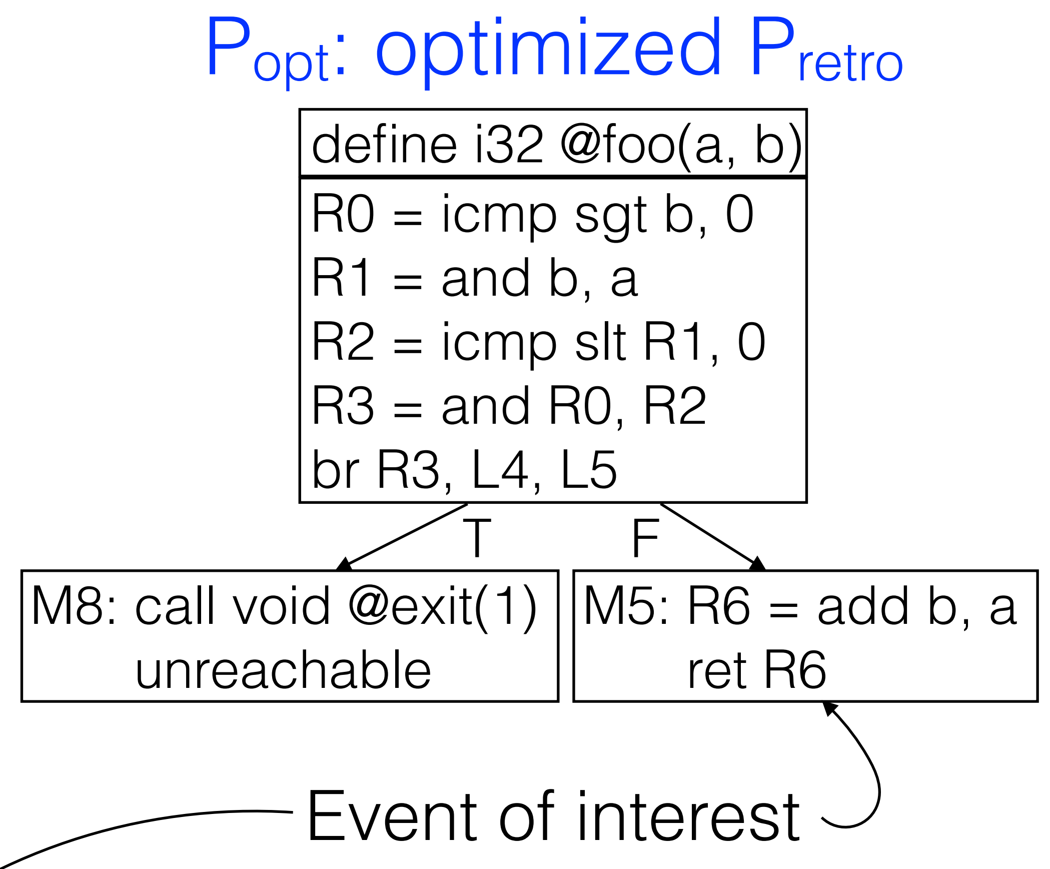


$P0_{retro}$: !(R2) ^ !(R10) ^
(R2 = (a > 0)) ^ (R10 = (a < 0))

E_{retro} = $P0_{retro}$

Reachability

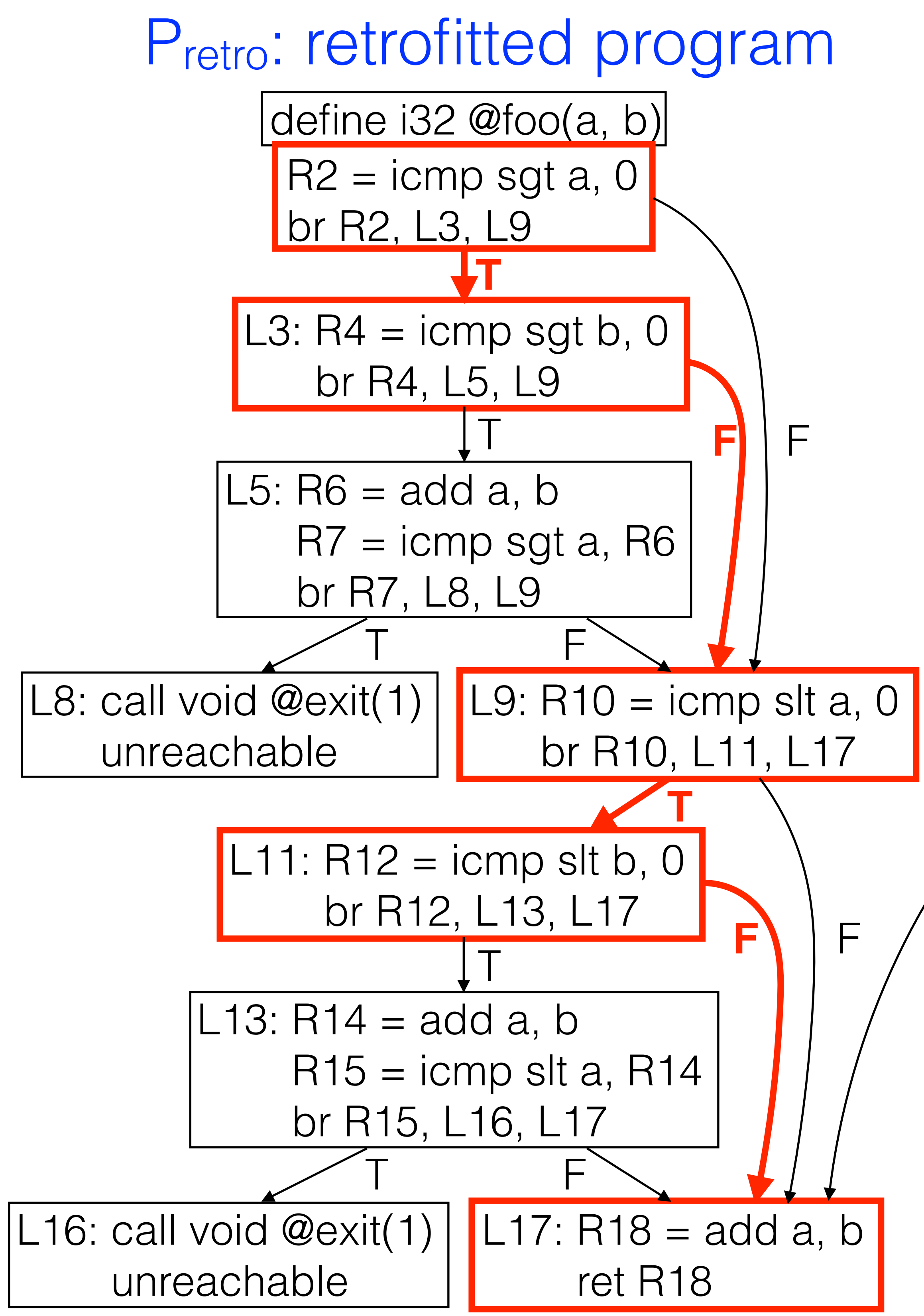


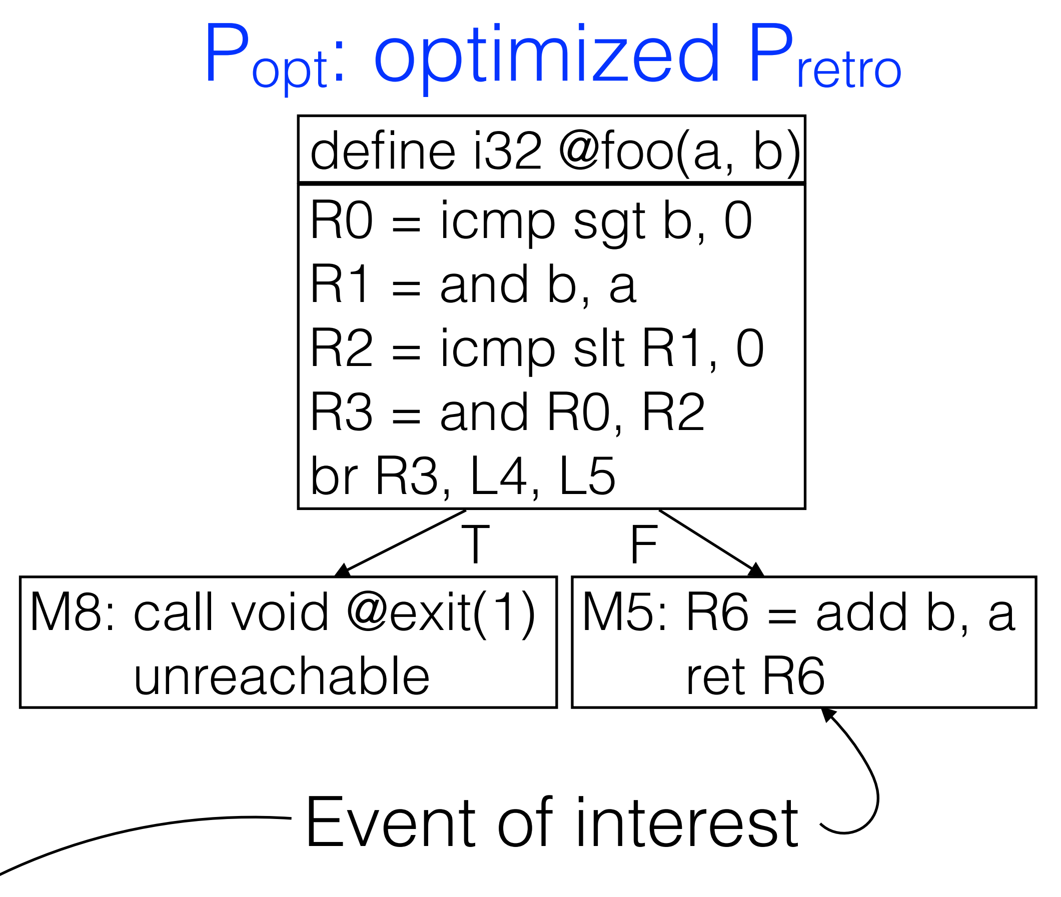


$P0_{retro}$: $!(R2) \wedge !(R10) \wedge$
$(R2 = (a > 0)) \wedge (R10 = (a < 0))$

$E_{retro} = P0_{retro} \vee \ldots \vee Pi_{retro}$

Reachability





$P0_{retro}$: $!(R2) \wedge !(R10) \wedge$
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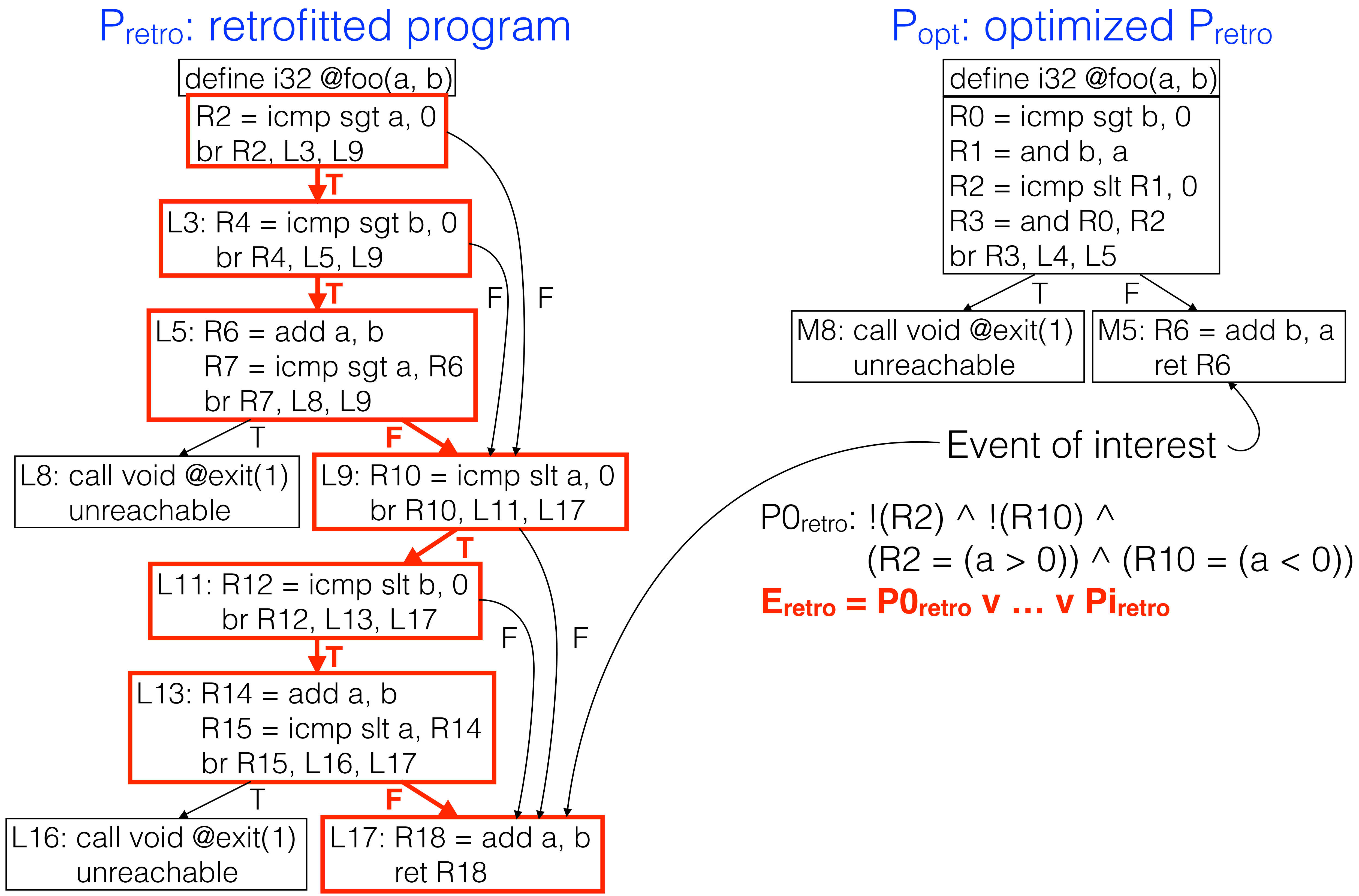
Reachability



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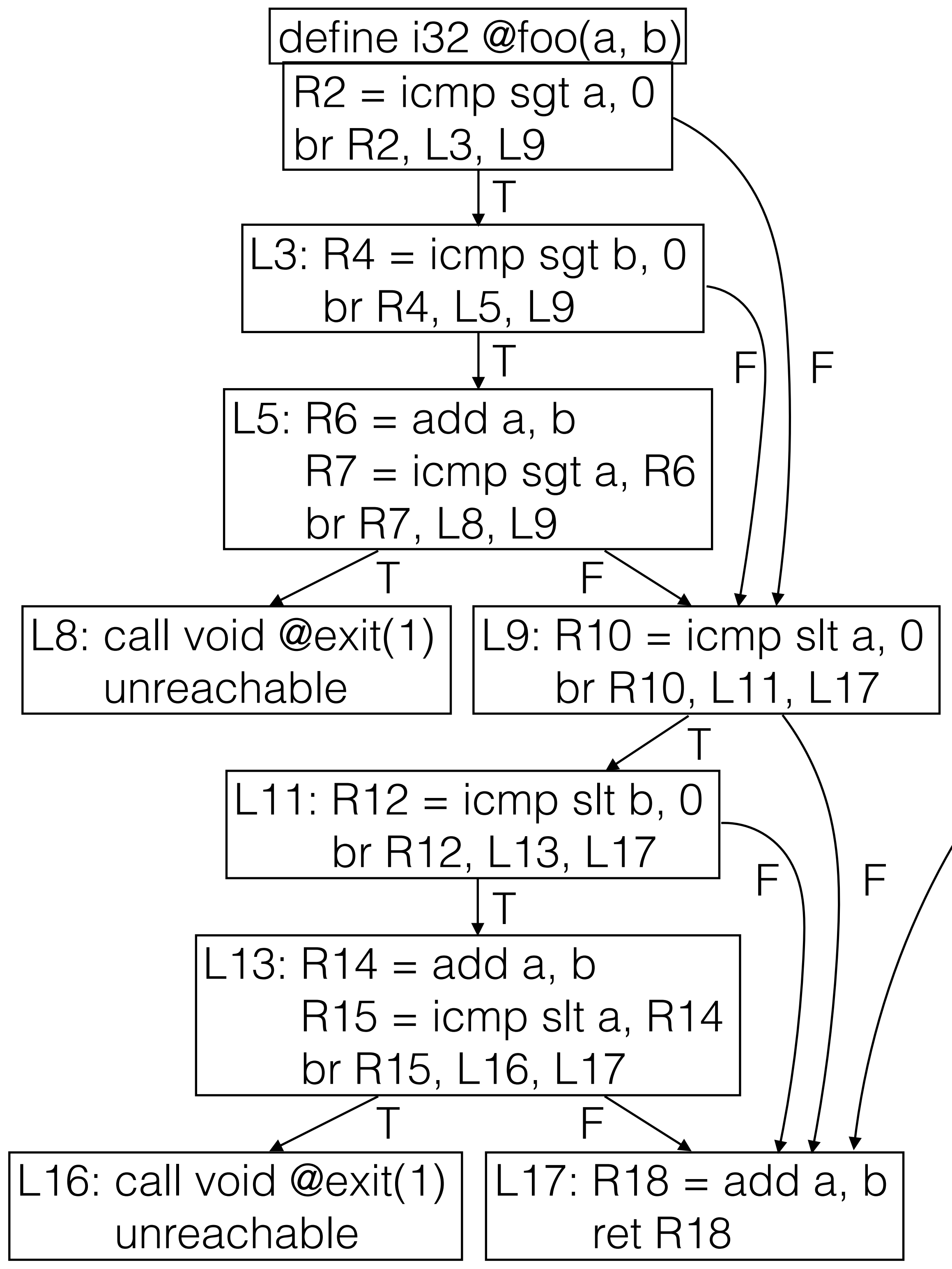
(R2 = (a > 0)) ^ (R10 = (a < 0))

$E_{retro} = P0_{retro} \vee \ldots \vee Pi_{retro}$

Reachability

P_{retro}: retrofitted program



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L3: R4 = icmp sgt b, 0
    br R4, L5, L9

L5: R6 = add a, b
    R7 = icmp sgt a, R6
    br R7, L8, L9

L8: call void @exit(1)
    unreachable

L9: R10 = icmp slt a, 0
    br R10, L11, L17

L11: R12 = icmp slt b, 0
     br R12, L13, L17

L13: R14 = add a, b
     R15 = icmp slt a, R14
     br R15, L16, L17

L16: call void @exit(1)
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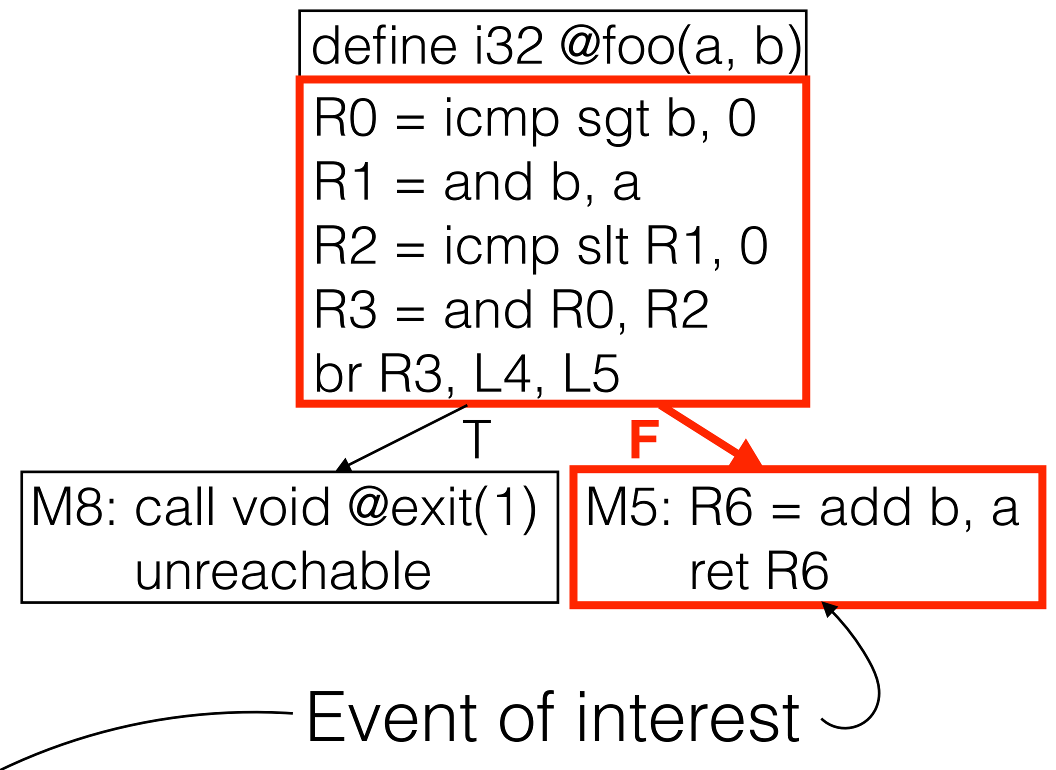
L17: R18 = add a, b
     ret R18
```

P_{opt}: optimized P_{retro}



```
define i32 @foo(a, b)
R0 = icmp sgt b, 0
R1 = and b, a
R2 = icmp slt R1, 0
R3 = and R0, R2
br R3, L4, L5

M8: call void @exit(1)
    unreachable

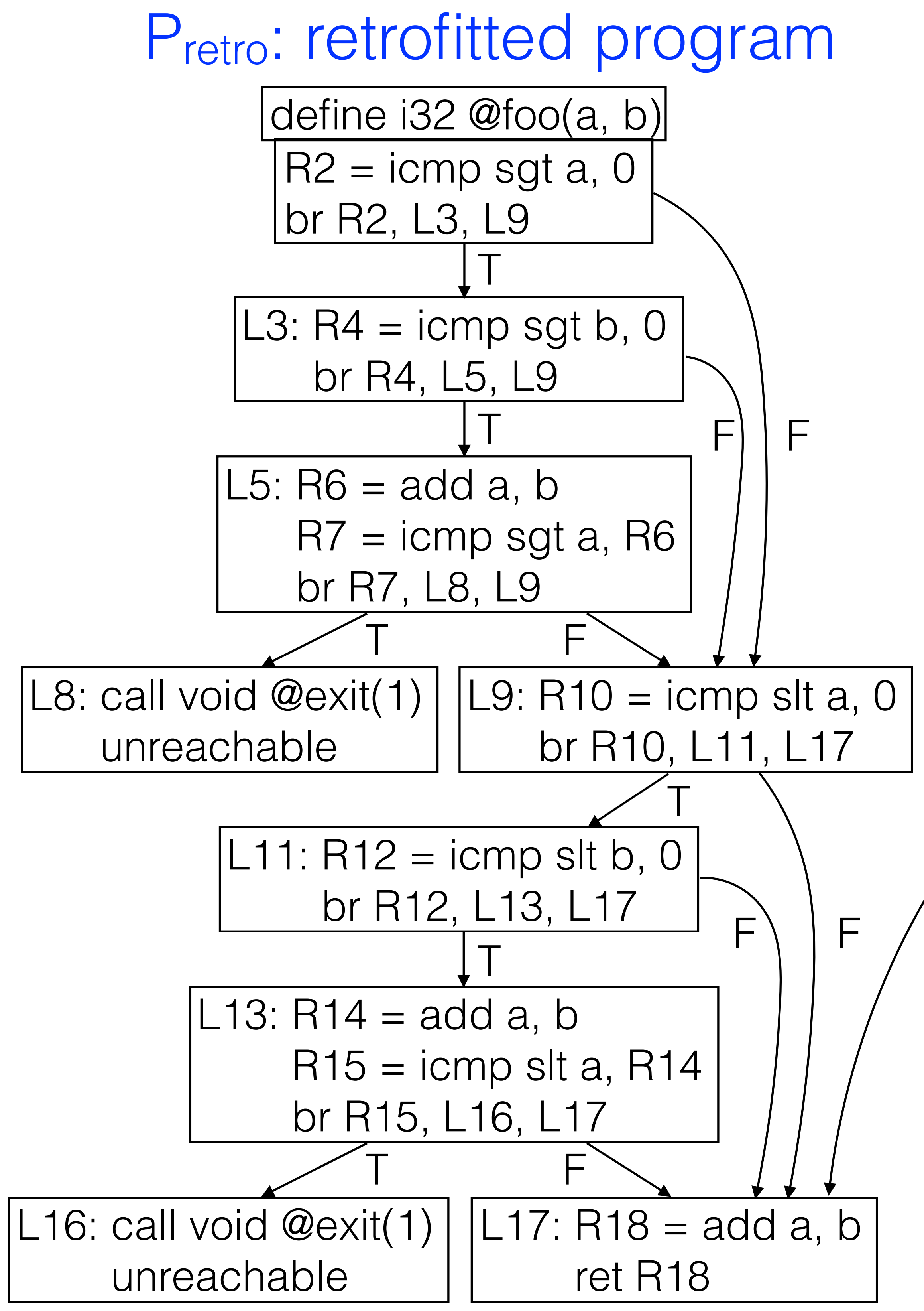
M5: R6 = add b, a
    ret R6
```

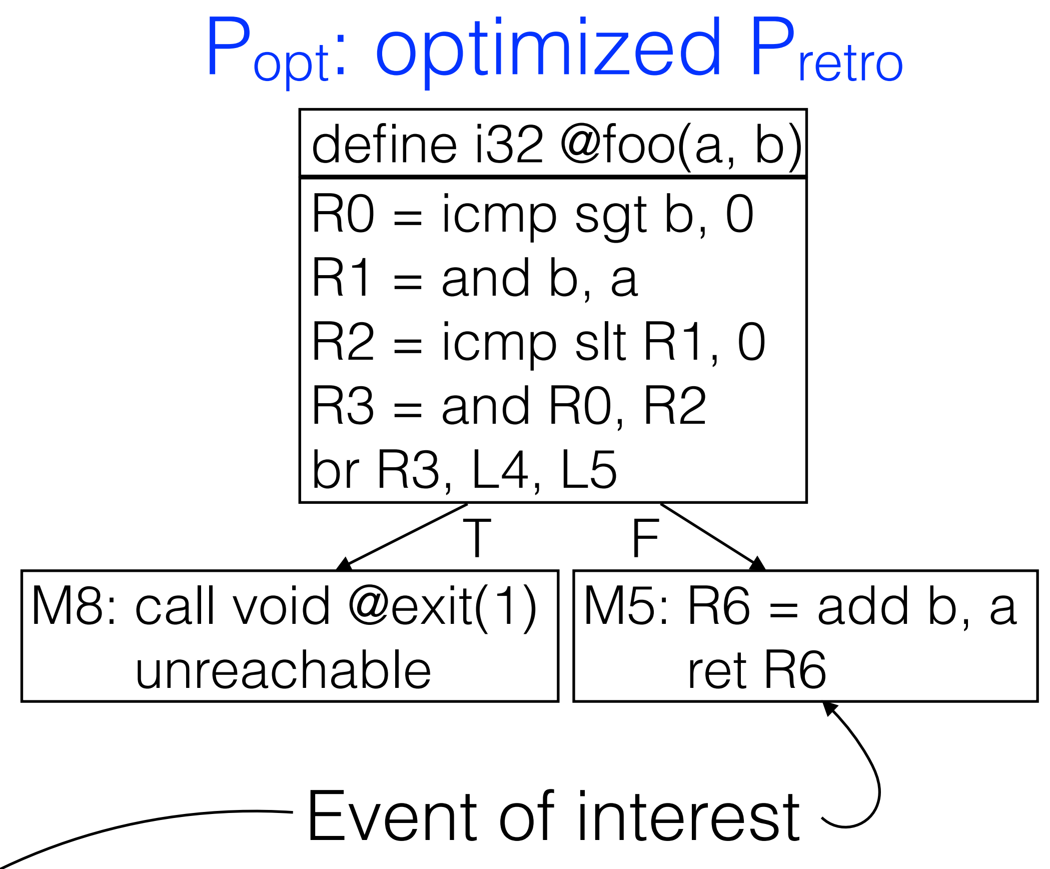
$P0_{retro}$: $!(R2) \wedge !(R10) \wedge$
$(R2 = (a > 0)) \wedge (R10 = (a < 0))$

$E_{retro} = P0_{retro} \vee \ldots \vee Pi_{retro}$

$\mathbf{E_{opt} = P0_{opt} \vee \ldots \vee Pj_{opt}}$

Reachability





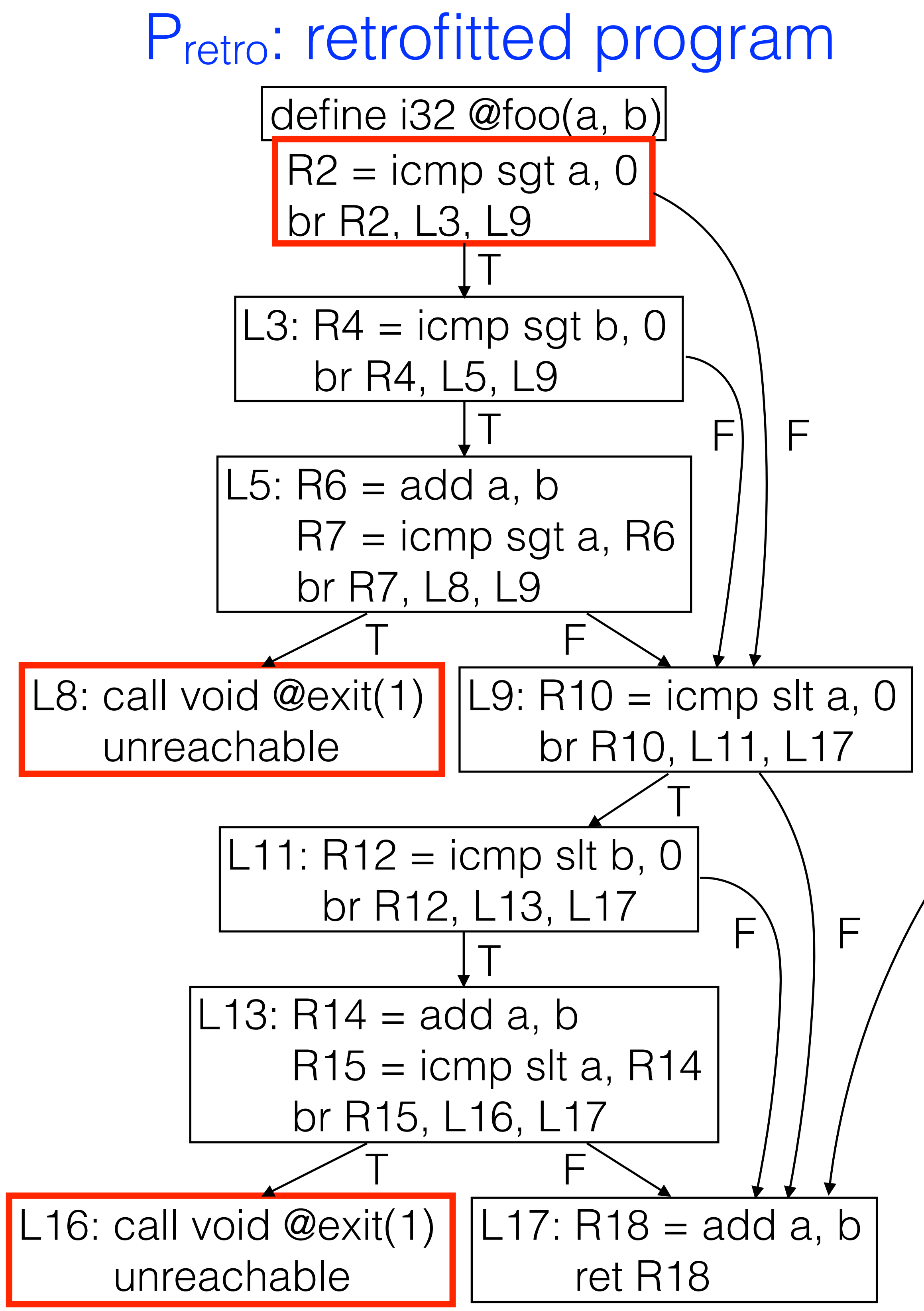
$P0_{retro}$: !(R2) ^ !(R10) ^
(R2 = (a > 0)) ^ (R10 = (a < 0))

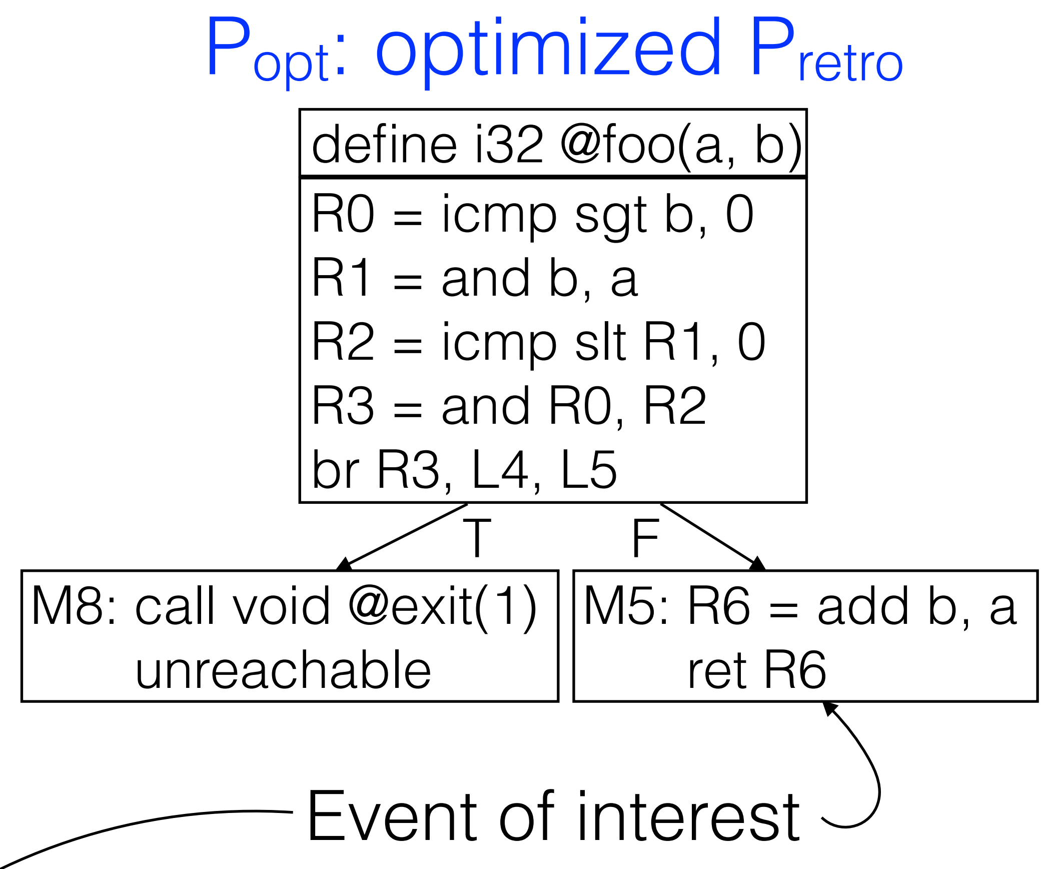
$E_{retro} = P0_{retro} \vee \ldots \vee Pi_{retro}$

$E_{opt} = P0_{opt} \vee \ldots \vee Pj_{opt}$

If P_{retro} reaches event of interest, then P_{opt} reaches event of interest (E_{retro}=>E_{opt})

Reachability





$P0_{retro}$: !(R2) ^ !(R10) ^
(R2 = (a > 0)) ^ (R10 = (a < 0))

$E_{retro} = P0_{retro} \vee \ldots \vee Pi_{retro}$

$E_{opt} = P0_{opt} \vee \ldots \vee Pj_{opt}$

If P_{retro} reaches event of interest, then P_{opt} reaches event of interest ($E_{retro} \Rightarrow E_{opt}$)

$\sim E_{retro}$

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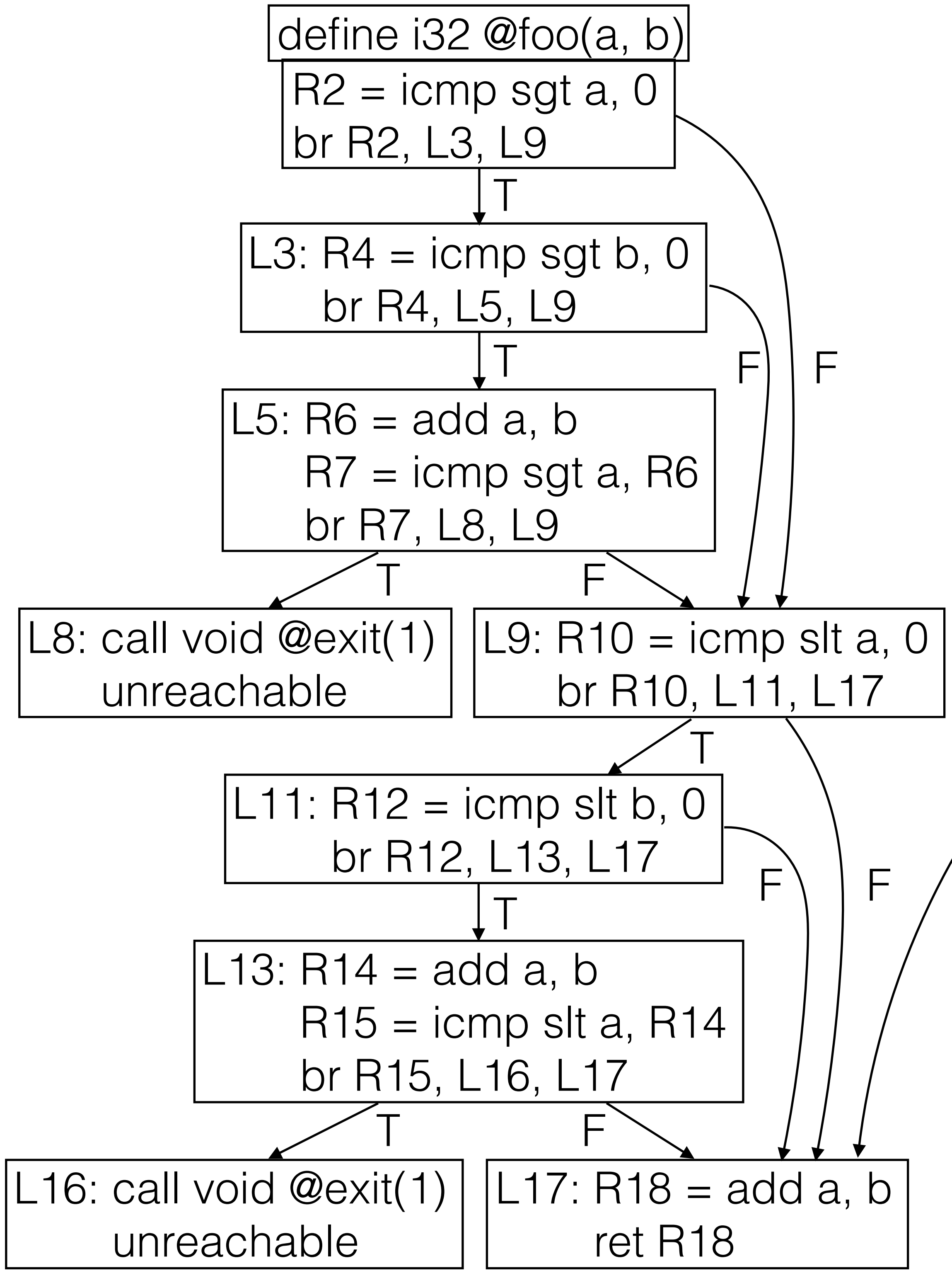
Reachability

P_{retro}: retrofitted program



```
define i32 @foo(a, b)
R2 = icmp sgt a, 0
br R2, L3, L9
```

```
L3: R4 = icmp sgt b, 0
    br R4, L5, L9
```

```
L5: R6 = add a, b
    R7 = icmp sgt a, R6
    br R7, L8, L9
```

```
L8: call void @exit(1)
    unreachable
```

```
L9: R10 = icmp slt a, 0
    br R10, L11, L17
```

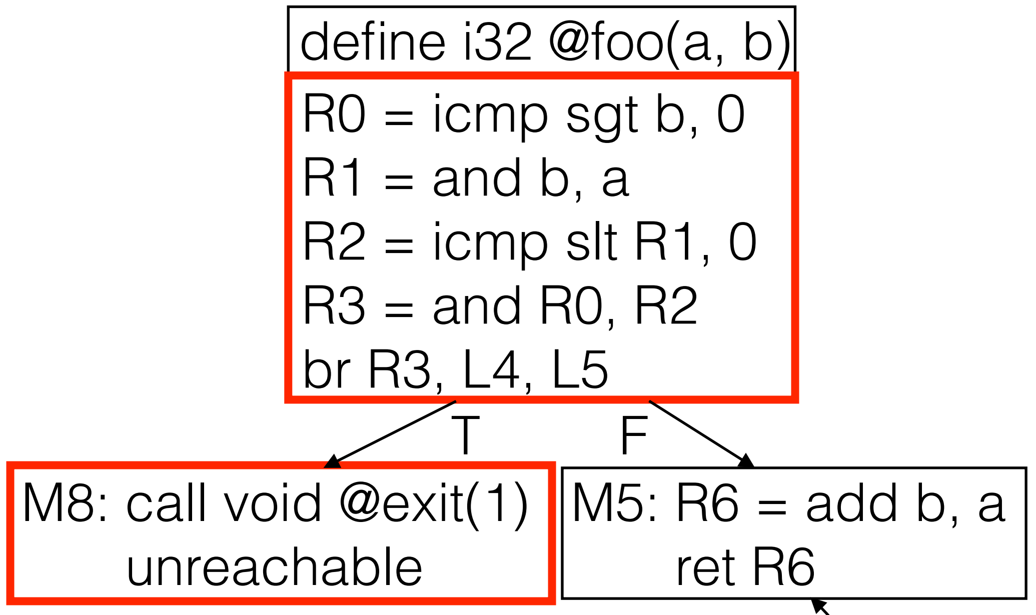
```
L11: R12 = icmp slt b, 0
     br R12, L13, L17
```

```
L13: R14 = add a, b
     R15 = icmp slt a, R14
     br R15, L16, L17
```

```
L16: call void @exit(1)
     unreachable
```

```
L17: R18 = add a, b
     ret R18
```

P_{opt}: optimized P_{retro}



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define i32 @foo(a, b)
R0 = icmp sgt b, 0
R1 = and b, a
R2 = icmp slt R1, 0
R3 = and R0, R2
br R3, L4, L5
```

```
M8: call void @exit(1)
    unreachable
```

```
M5: R6 = add b, a
    ret R6
```

Event of interest

$P0_{retro}$: $!(R2) \wedge !(R10) \wedge$
$(R2 = (a > 0)) \wedge (R10 = (a < 0))$

$E_{retro} = P0_{retro} \vee \ldots \vee Pi_{retro}$

$E_{opt} = P0_{opt} \vee \ldots \vee Pj_{opt}$

If P_{retro} reaches event of interest, then P_{opt} reaches event of interest ($E_{retro} \Rightarrow E_{opt}$)

$\sim E_{retro}$, **$\sim E_{opt}$**

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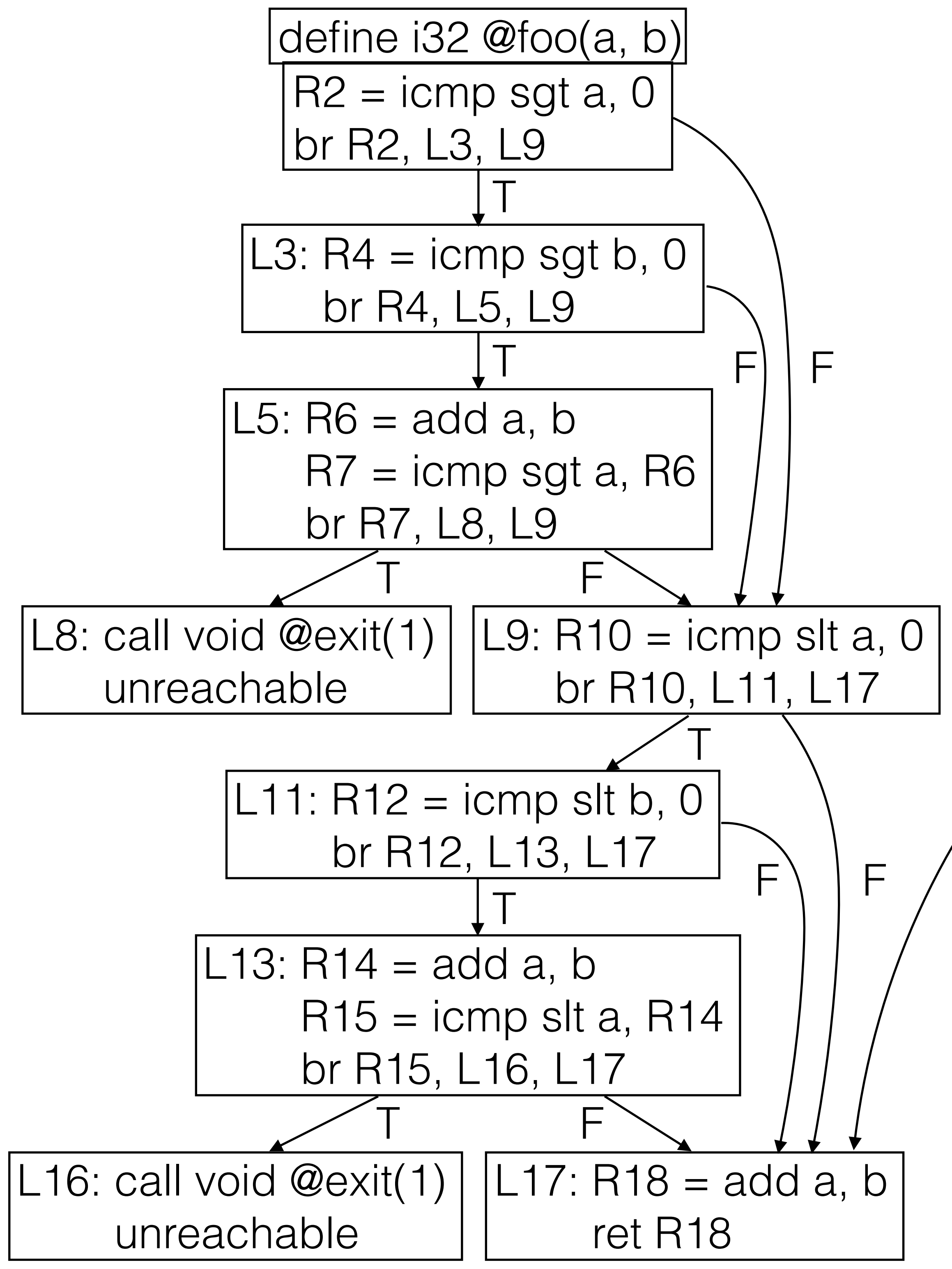
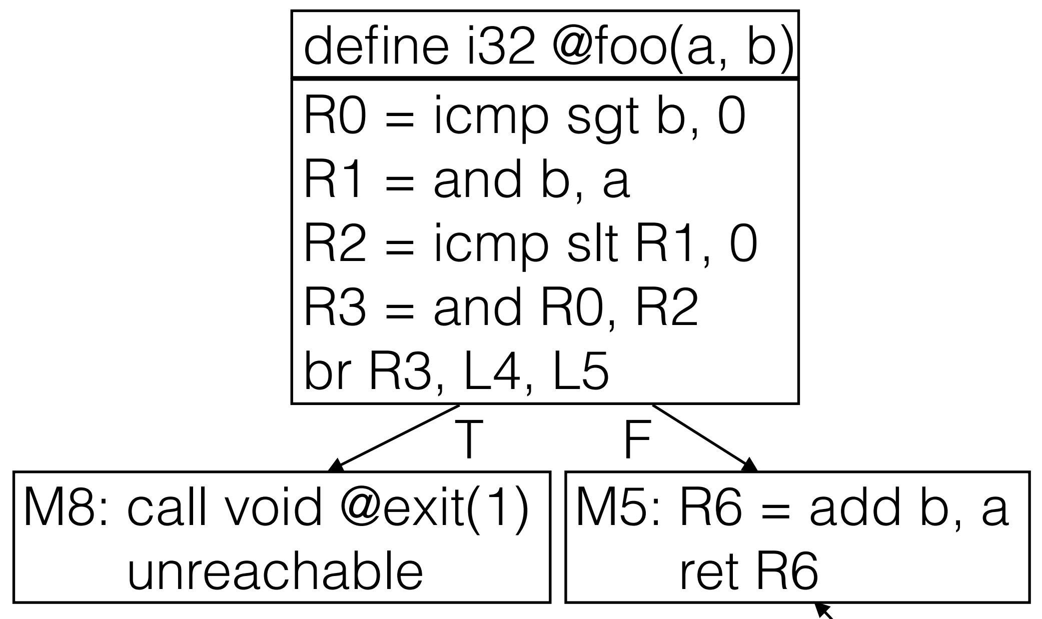
Reachability

P_{retro}: retrofitted program



P_{opt}: optimized P_{retro}



Event of interest

$P0_{retro}$: $!(R2) \wedge !(R10) \wedge$
$(R2 = (a > 0)) \wedge (R10 = (a < 0))$

$E_{retro} = P0_{retro} \vee \dots \vee Pi_{retro}$

$E_{opt} = P0_{opt} \vee \dots \vee Pj_{opt}$

If P_{retro} reaches event of interest, then P_{opt} reaches event of interest ($E_{retro} \Rightarrow E_{opt}$)

$\sim E_{retro}$, $\sim E_{opt}$

If P_{retro} does not reach event of interest, then P_{opt} does not reach event of interest ($\sim E_{retro} \Rightarrow \sim E_{opt}$)

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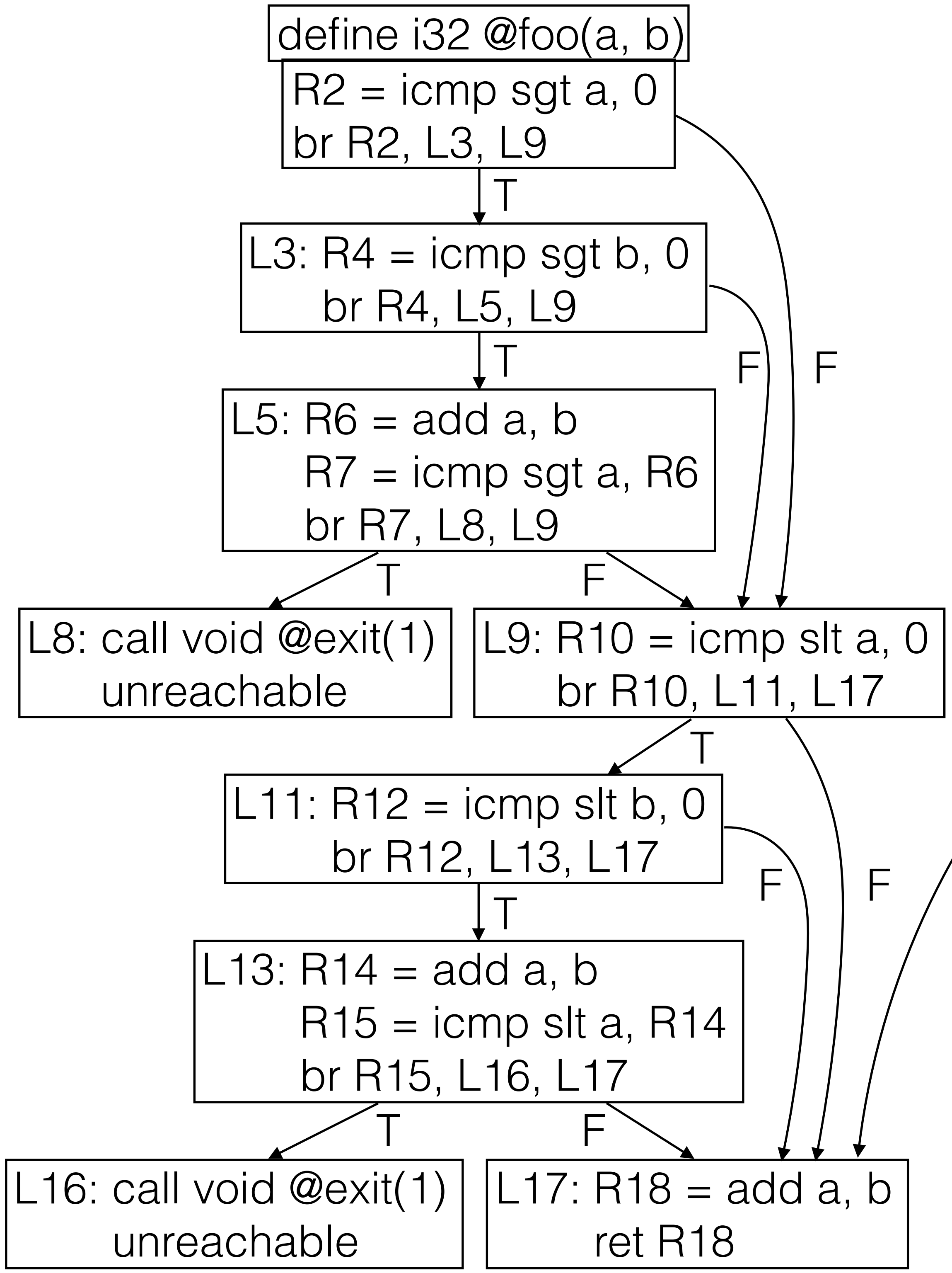
Reachability

P_{retro}: retrofitted program



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L3: R4 = icmp sgt b, 0
    br R4, L5, L9

L5: R6 = add a, b
    R7 = icmp sgt a, R6
    br R7, L8, L9

L8: call void @exit(1)
    unreachable

L9: R10 = icmp slt a, 0
    br R10, L11, L17

L11: R12 = icmp slt b, 0
     br R12, L13, L17

L13: R14 = add a, b
     R15 = icmp slt a, R14
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L16: call void @exit(1)
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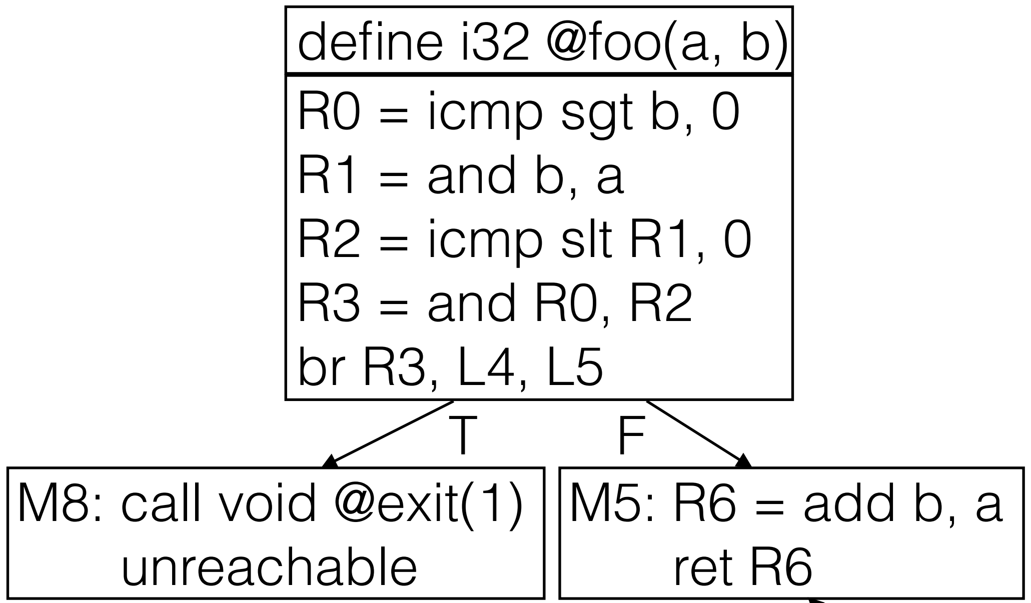
L17: R18 = add a, b
     ret R18
```

P_{opt}: optimized P_{retro}



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R1 = and b, a
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R3 = and R0, R2
br R3, L4, L5

M8: call void @exit(1)
    unreachable

M5: R6 = add b, a
    ret R6
```

Event of interest

$P0_{retro}$: $!(R2) \wedge !(R10) \wedge$
$(R2 = (a > 0)) \wedge (R10 = (a < 0))$

$E_{retro} = P0_{retro} \vee \ldots \vee Pi_{retro}$

$E_{opt} = P0_{opt} \vee \ldots \vee Pj_{opt}$

If P_{retro} reaches event of interest, then P_{opt} reaches event of interest ($E_{retro} \Rightarrow E_{opt}$)

$\sim E_{retro}$, $\sim E_{opt}$

If P_{opt} reaches event of interest, then P_{retro} reaches event of interest ($E_{opt} \Rightarrow E_{retro}$)

Evaluation

- Built prototype for LLVM IR programs.
- Modified retrofitting transformation to mark event of interests.
- Z3 for query.
- Naive integer overflow checker, Address Sanitizer, SoftboundCETS
- Scalability optimizations

Address Sanitizer

Benchmark	Functions	Total Events	Check Success	Check Failed	Time-Out
bh	38	135	121	9	5
bisort	7	20	18	1	1
em3d	9	27	21	4	2
health	13	41	37	3	1
mst	10	14	11	2	1
perimeter	6	28	27	1	0
power	13	56	48	2	6
treeadd	6	8	6	2	0
tsp	9	19	16	2	1

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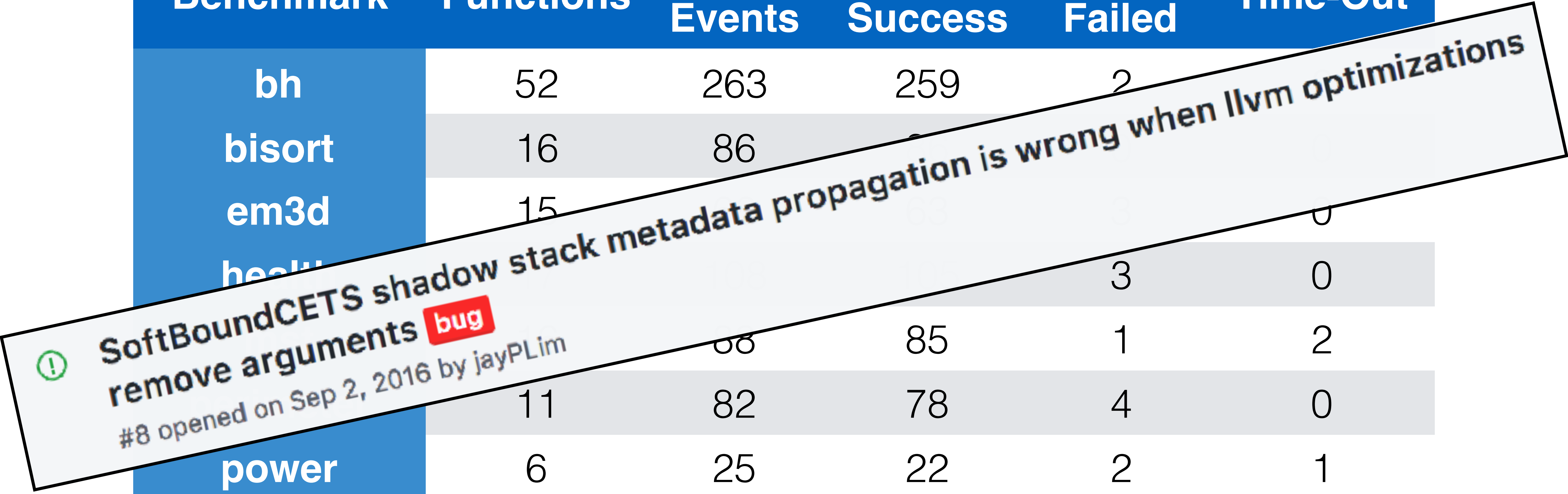
SoftBoundCETS

Benchmark	Functions	Total Events	Check Success	Check Failed	Time-Out
bh	52	263	259	2	[illegible]
bisort	16	86	[illegible]	[illegible]	[illegible]
em3d	15	[illegible]	63	3	0
health	[illegible]	105	[illegible]	3	0
mst	[illegible]	88	85	1	2
perimeter	11	82	78	4	0
power	6	25	22	2	1
treeadd	8	43	43	0	0
tsp	13	84	84	0	0


SoftBoundCETS shadow stack metadata propagation is wrong when llvm optimizations remove arguments bug

#8 opened on Sep 2, 2016 by jayPLim

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Conclusion

- Optimization do erroneously remove checks.
- Formulating as Reachability detects errors.
- Must address false positives.
  - better memory axioms.

SoftboundCETS bug

```
define void quantum_qec_get_status(i32* pwidth, i32* ptype) {
entry:
  R0 = call __softboundcets_load_base_shadow_stack(2)
  R1 = call __softboundcets_load_bound_shadow_stack(2)
  R2 = call __softboundcets_load_key_shadow_stack(2)
  R3 = call __softboundcets_load_lock_shadow_stack(2)
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  R6 = call __softboundcets_load_key_shadow_stack(1)
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  R8 = call __softboundcets_get_global_lock()
   …
  cmp = (ptype < R0)
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  or.cond.i = cmp ll cmp1
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RUTGERS

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Related Work

- Translation Validation
  - Checks for equivalence of semantics in code before and after optimization.
  - Heuristics may cause false positives.
- SymDiff
  - Checks for equivalence of two C programs using HAVOC and Boogie.
  - We are interested in LLVM IR programs.
- STACK
  - Detects instrumentations removed due to undefined behavior (unstable code).
  - Does not detect all removal of instrumentations.