LLVM: Intermediate Representation & Optimization

Seminar *Automation, Compilers, and Code-Generation*

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Compiler Architecture

General three-phase compiler:

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Frontend Check syntax, build Abstract Syntax Tree

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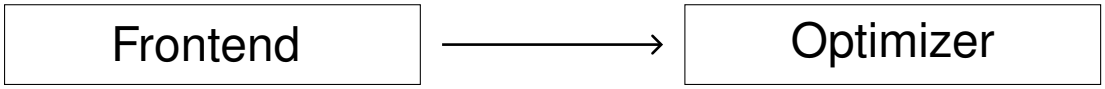

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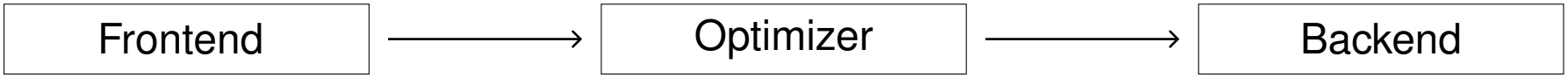

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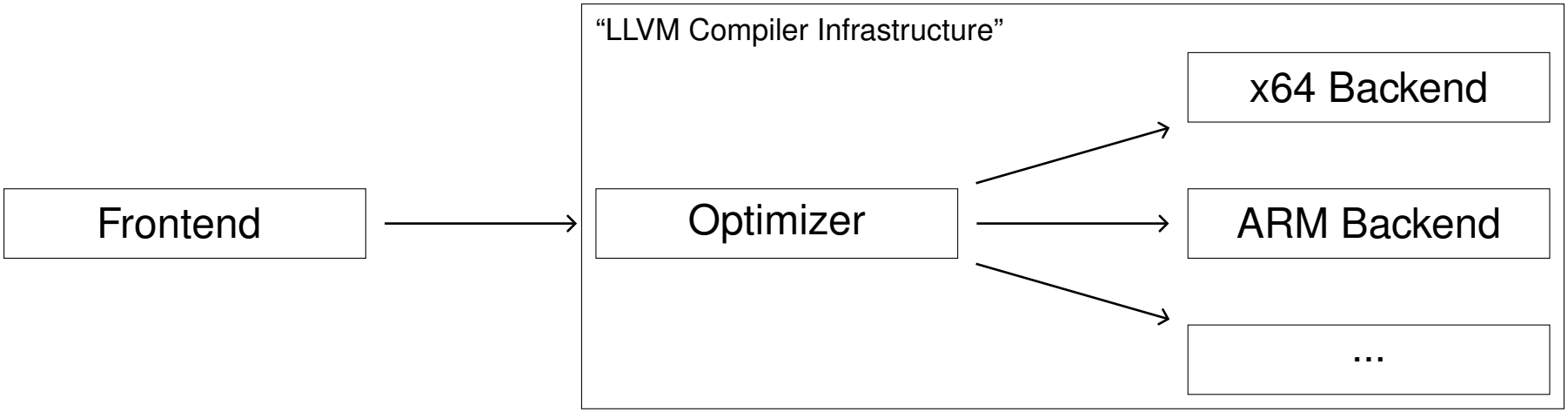

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- Reusable Design: LLVM provides the optimizer and several backends

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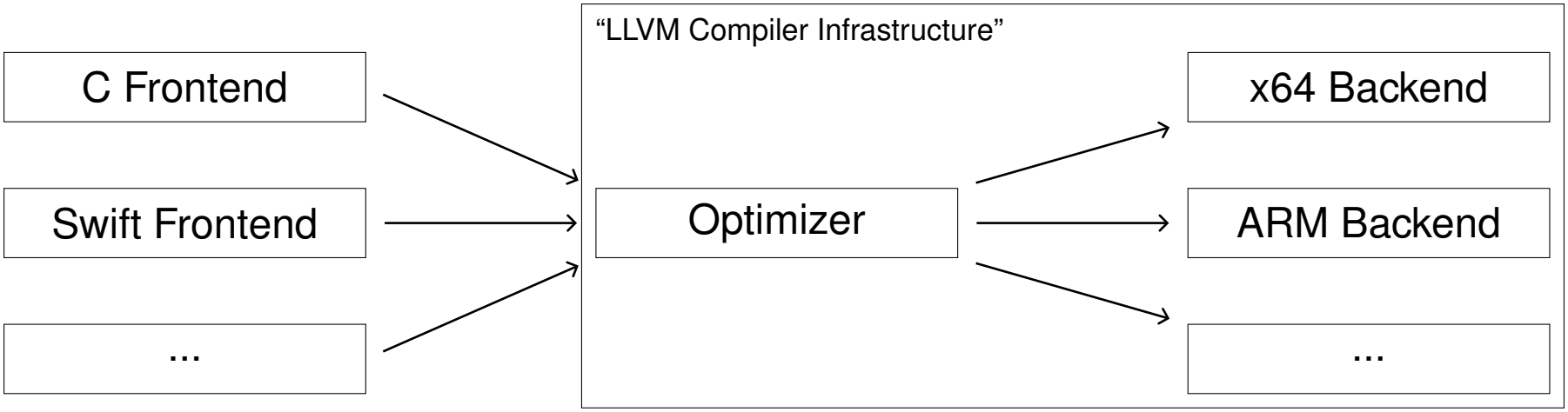

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- Reusable Design: LLVM provides the optimizer and several backends
- Language-specific frontend + LLVM yields a whole compiler, e.g `clang`

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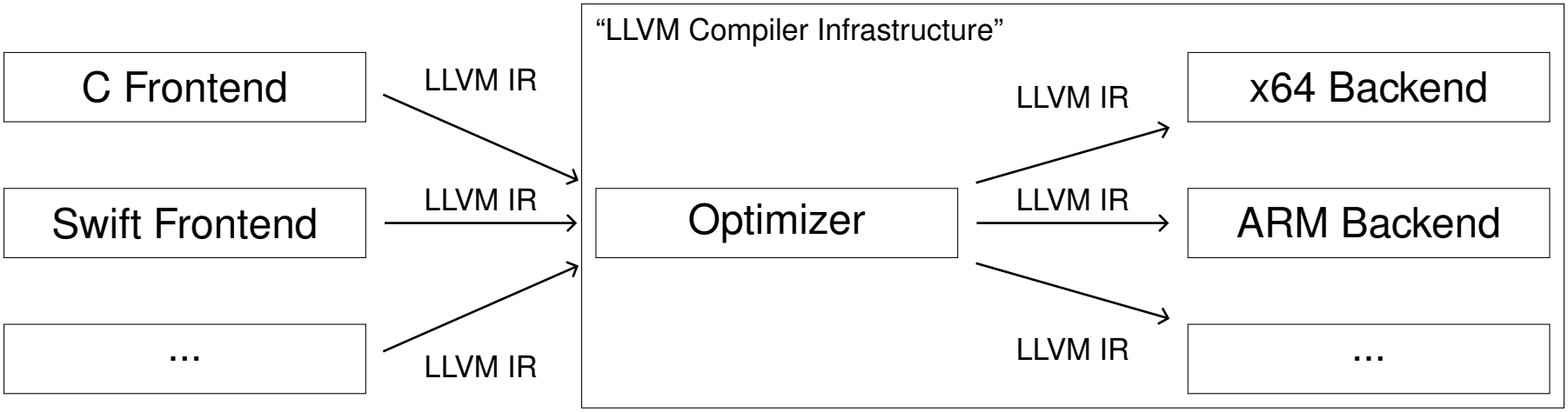

Realization by LLVM Compiler Infrastructure:

- Reusable Design: LLVM provides the optimizer and several backends
- Language-specific frontend + LLVM yields a whole compiler, e.g `clang`
- Optimizer works on the LLVM Intermediate Representation ("LLVM IR")
  - Assembly-like language
  - Complete representation of the original input program

LLVM Intermediate Representation

Example C program:

```
int example(int *arr1, int *arr2, int size, int a, int b) {
    int res = 0;
    for(int i = 0; i < size; i++) {
        int x = a + 3;
        int y = x + b;

        int cur = arr1[i];
        if(cur > 0) {
            arr1[i] = y;
        }

        res = arr2[0];
    }
    return res;
}
```

LLVM Intermediate Representation

Unoptimized Translation

`clang -S -emit-llvm -O0 example.c` yields the following:

LLVM Intermediate Representation

Unoptimized Translation

`clang -S -emit-llvm -O0 example.c` yields the following:

```
; ModuleID = 'c_example_0_hinten.c'
target datalayout = "e-m:e-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_64-pc-linux-gnu"

; Function Attrs: nounwind uwtable
define i32 @example(i32* %arr1, i32* %arr2, i32 %size, i32 %a, i32 %b) #0 {
  %1 = alloca i32*, align 8
  %2 = alloca i32*, align 8
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  %5 = alloca i32, align 4
  %res = alloca i32, align 4
  %i = alloca i32, align 4
  %x = alloca i32, align 4
  %y = alloca i32, align 4
  %cur = alloca i32, align 4
  store i32* %arr1, i32** %1, align 8
  store i32* %arr2, i32** %2, align 8
  store i32 %size, i32* %3, align 4
  store i32 %a, i32* %4, align 4
  store i32 %b, i32* %5, align 4
  store i32 0, i32* %res, align 4
  store i32 0, i32* %i, align 4
  br label %6

; <label>:6                                       ; preds = %33, %0
  %7 = load i32, i32* %i, align 4
  %8 = load i32, i32* %3, align 4
  %9 = icmp slt i32 %7, %8
  br i1 %9, label %10, label %36

; <label>:10                                      ; preds = %6
  %11 = load i32, i32* %4, align 4
  %12 = add nsw i32 %11, 3
  store i32 %12, i32* %x, align 4
  %13 = load i32, i32* %x, align 4
  %14 = load i32, i32* %5, align 4
  %15 = add nsw i32 %13, %14
  store i32 %15, i32* %y, align 4
  %16 = load i32, i32* %i, align 4
  %17 = sext i32 %16 to i64
  %18 = load i32*, i32** %1, align 8
  %19 = getelementptr inbounds i32, i32* %18, i64 %17
  %20 = load i32, i32* %19, align 4
  store i32 %20, i32* %cur, align 4
  %21 = load i32, i32* %cur, align 4
  %22 = icmp sgt i32 %21, 0
  br i1 %22, label %23, label %29

; <label>:23                                      ; preds = %10
  %24 = load i32, i32* %y, align 4
  %25 = load i32, i32* %i, align 4
  %26 = sext i32 %25 to i64
  %27 = load i32*, i32** %1, align 8
  %28 = getelementptr inbounds i32, i32* %27, i64 %26
  store i32 %24, i32* %28, align 4
  br label %29

; <label>:29                                      ; preds = %23, %10
  %30 = load i32*, i32** %2, align 8
  %31 = getelementptr inbounds i32, i32* %30, i64 0
  %32 = load i32, i32* %31, align 4
  store i32 %32, i32* %res, align 4
  br label %33

; <label>:33                                      ; preds = %29
  %34 = load i32, i32* %i, align 4
  %35 = add nsw i32 %34, 1
  store i32 %35, i32* %i, align 4
  br label %6

; <label>:36                                      ; preds = %6
  %37 = load i32, i32* %res, align 4
  ret i32 %37
}

attributes #0 = { nounwind uwtable "disable-tail-calls"="false" "less-precise-fpmad"="false" "no-frame-pointer-elim"="true" "no-frame-pointer-elim-
     non-leaf" "no-infs-fp-math"="false" "no-nans-fp-math"="false" "stack-protector-buffer-size"="8" "target-cpu"="x86-64" "target-features"="+fxsr
     ,+mmx,+sse,+sse2" "unsafe-fp-math"="false" "use-soft-float"="false" }

!llvm.ident = !{!0}

!0 = !{!"clang␣version␣3.8.0-2ubuntu3␣(tags/RELEASE_380/final)"}
```

(~80 lines)

LLVM Intermediate Representation

Manual Translation

```
define i32 @example(i32* %arr1, i32* %arr2, i32 %size, i32 %a, i32 %b)  {
entry:        %enterLoop = icmp sgt i32  %size, 0
              br i1 %enterLoop, label %loopHeader, label %return


loopHeader:   %i = phi i32 [ 0, %entry], [ %nextI, %loopLast ]
              %x = add i32 %a, 3
              %y = add i32 %x, %b

              %arr1AtI = getelementptr i32, i32* %arr1, i32 %i
              %cur = load i32, i32* %arr1AtI

              %shouldStore = icmp sgt i32 %cur, 0
              br i1 %shouldStore, label %loopStore, label %loopLast


loopStore:    store i32 %y, i32* %arr1AtI
              br label %loopLast


loopLast:     %res = load i32, i32* %arr2

              %nextI = add i32 %i, 1
              %continueLoop = icmp slt i32 %nextI, %size
              br i1 %continueLoop, label %loopHeader, label %return


return:       %finalres = phi i32 [ 0, %entry], [ %res, %loopLast ]
              ret i32 %finalres
}
```

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define i32 @example(i32* %arr1, i32* %arr2, i32 %size, i32 %a, i32 %b)  {
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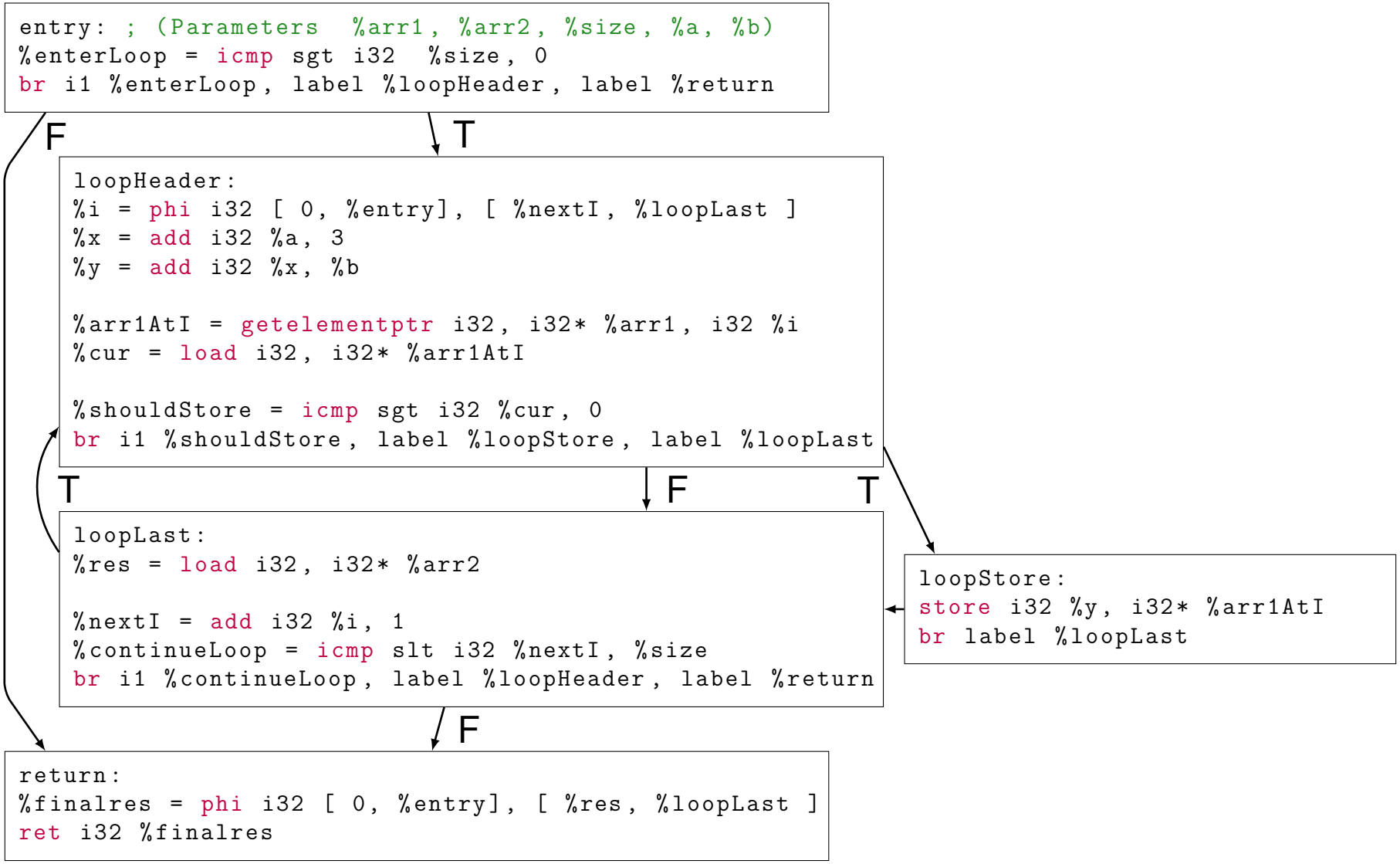
              ret i32 %finalres
}
```

First Observations:

- Functions
- Strongly typed
- Global vs. function scope
- Basic Blocks
- Conditional vs. unconditional branching

LLVM Intermediate Representation

Semantics (1)



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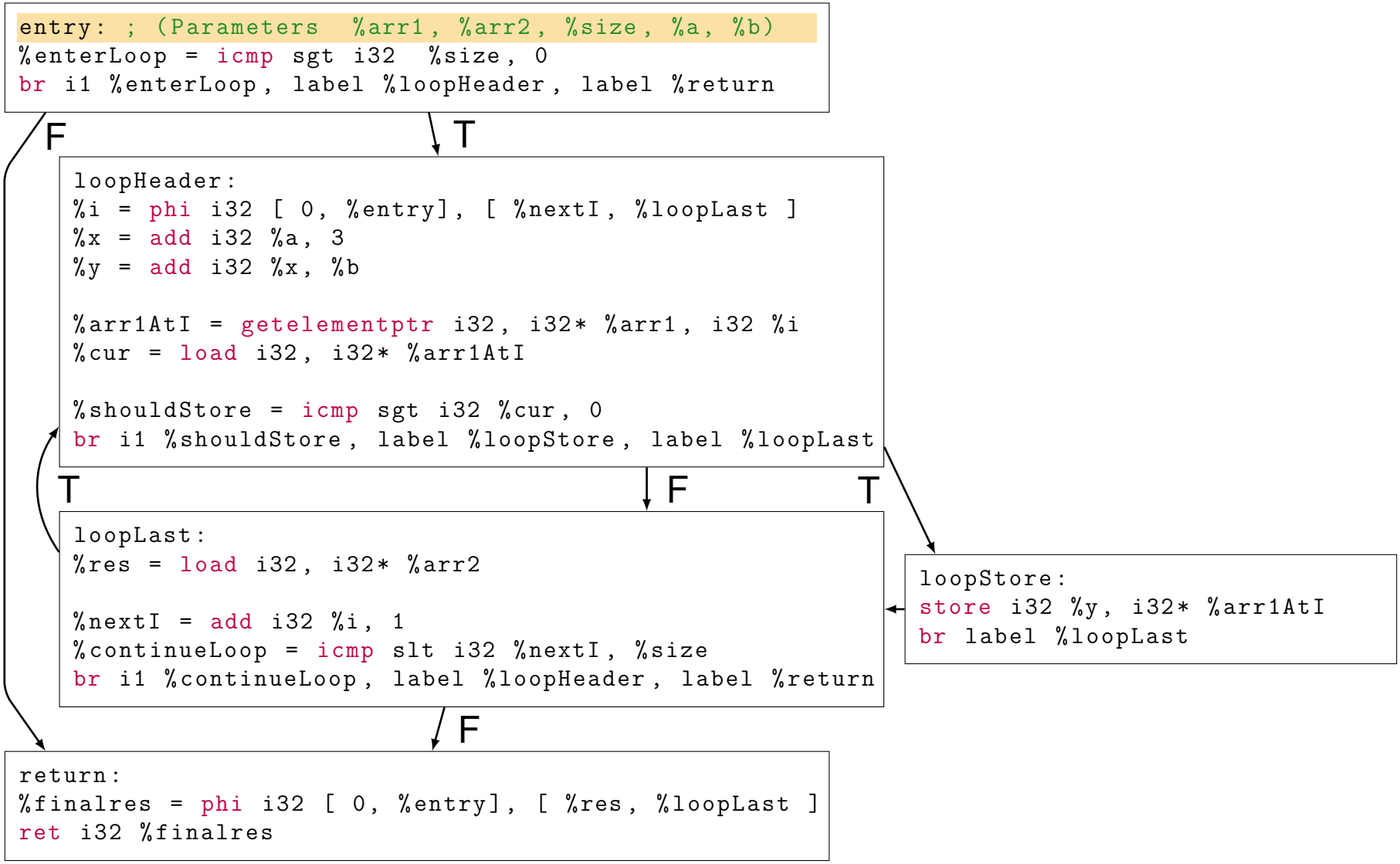

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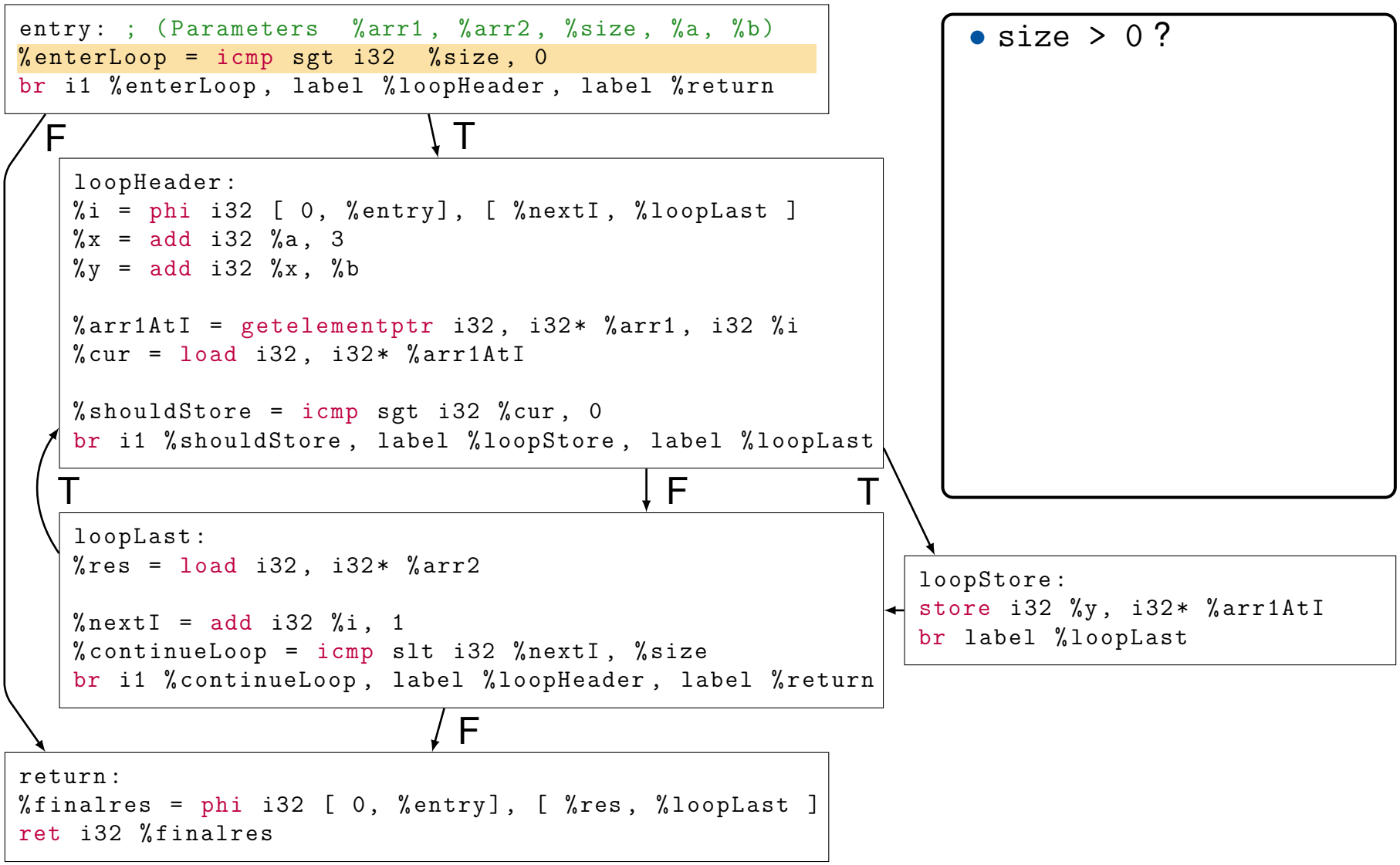

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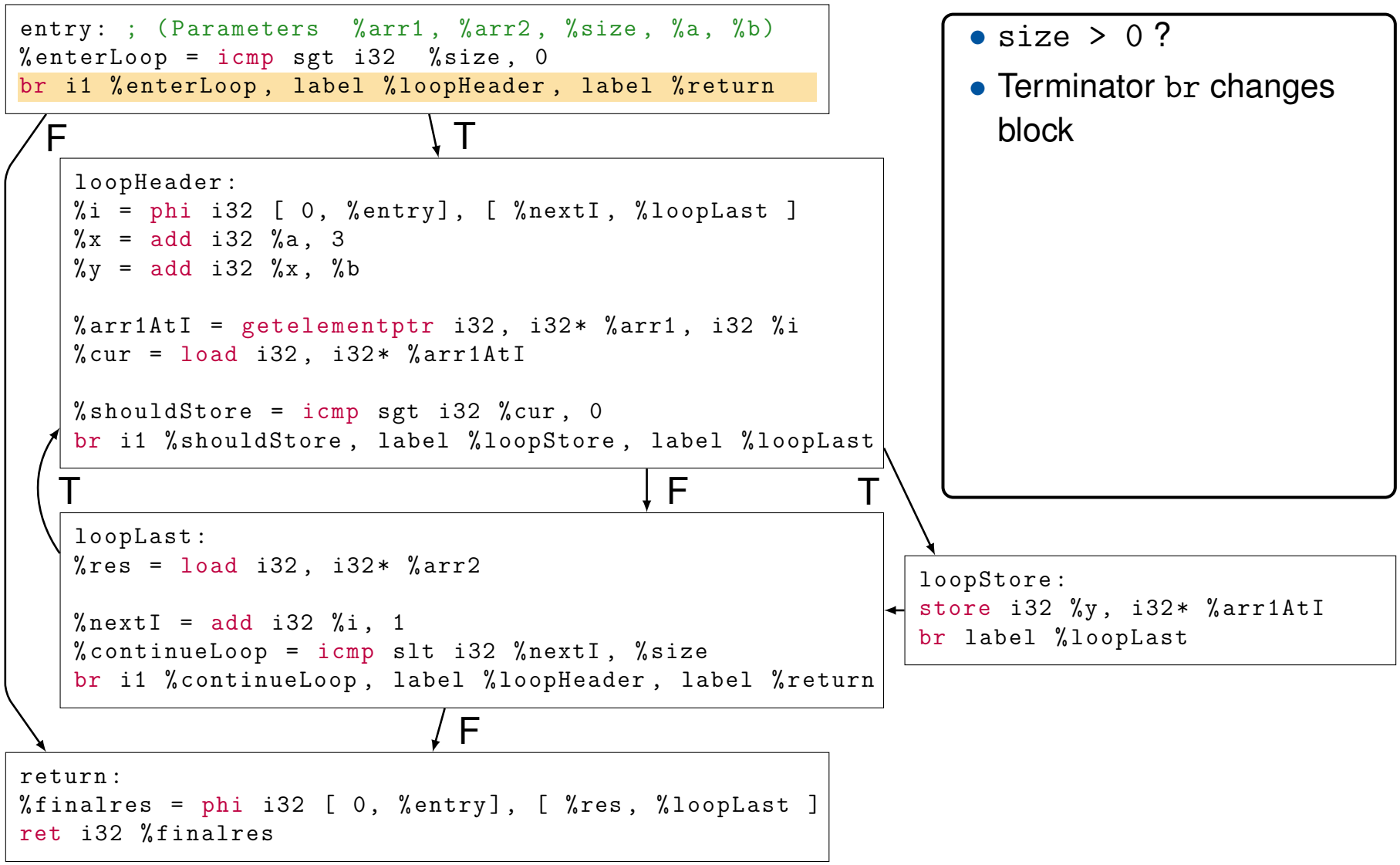

- `size > 0` ?
- Terminator `br` changes block

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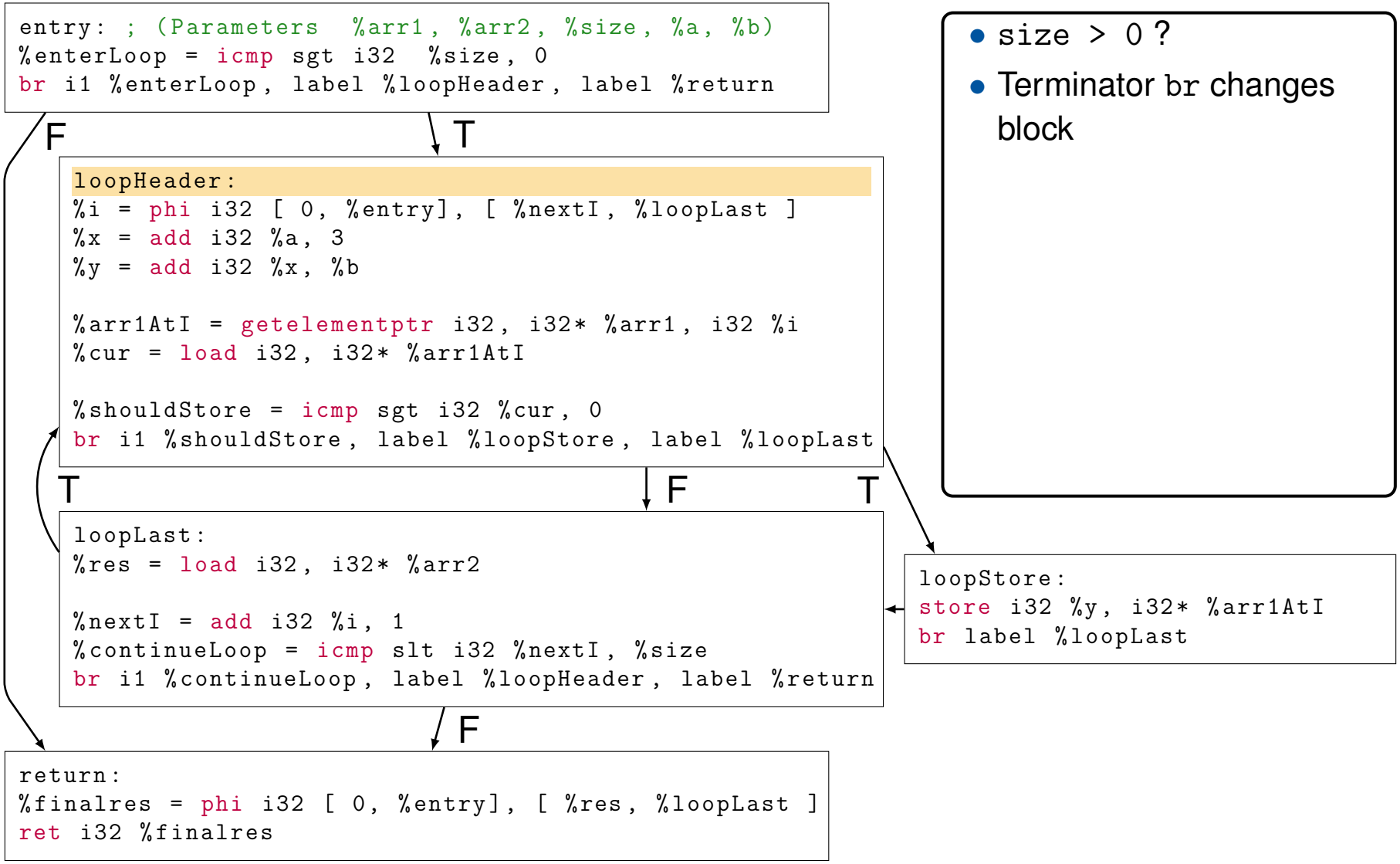

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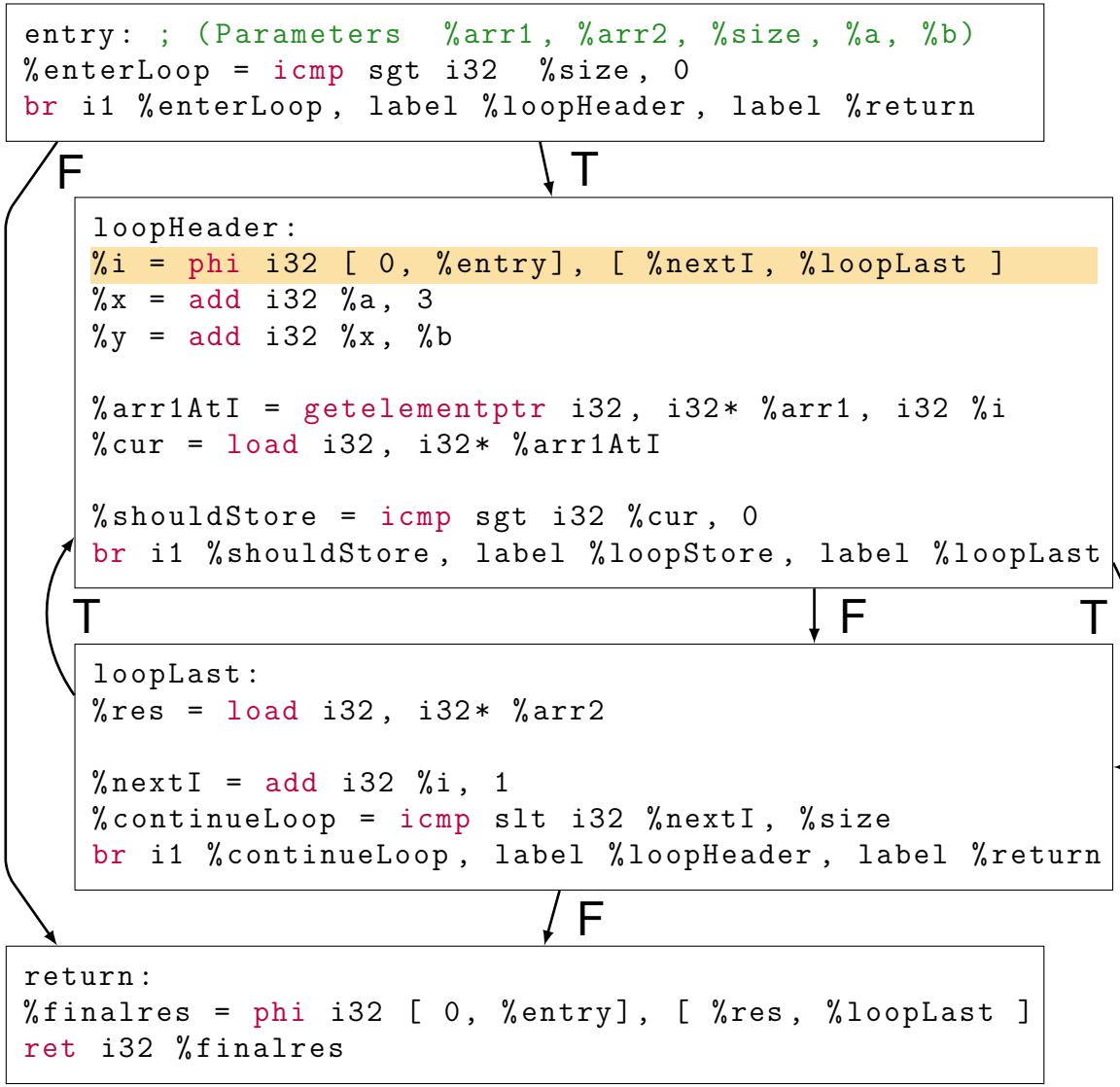

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- Single Static Assignment: Only one assignment per variable

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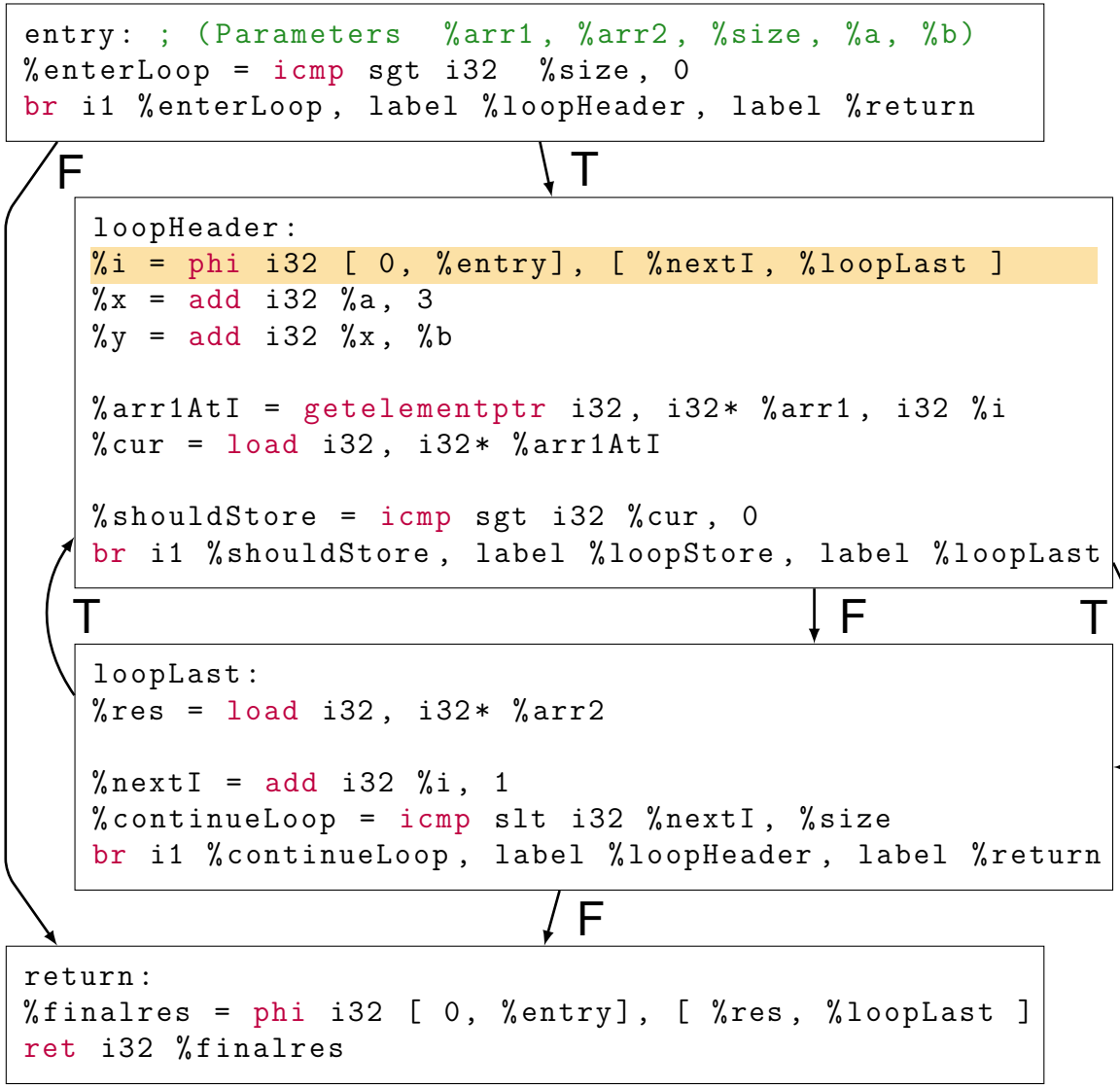

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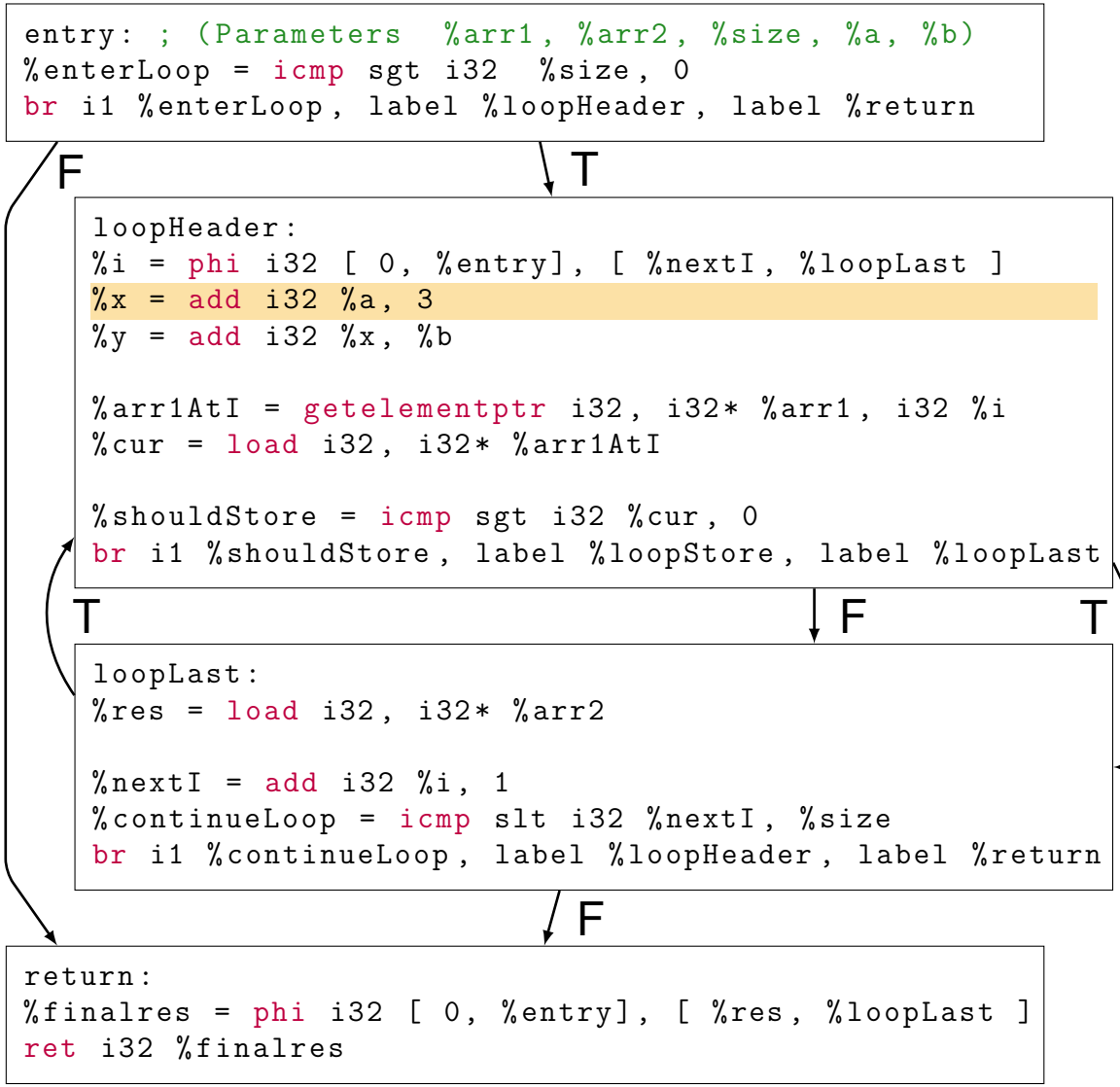

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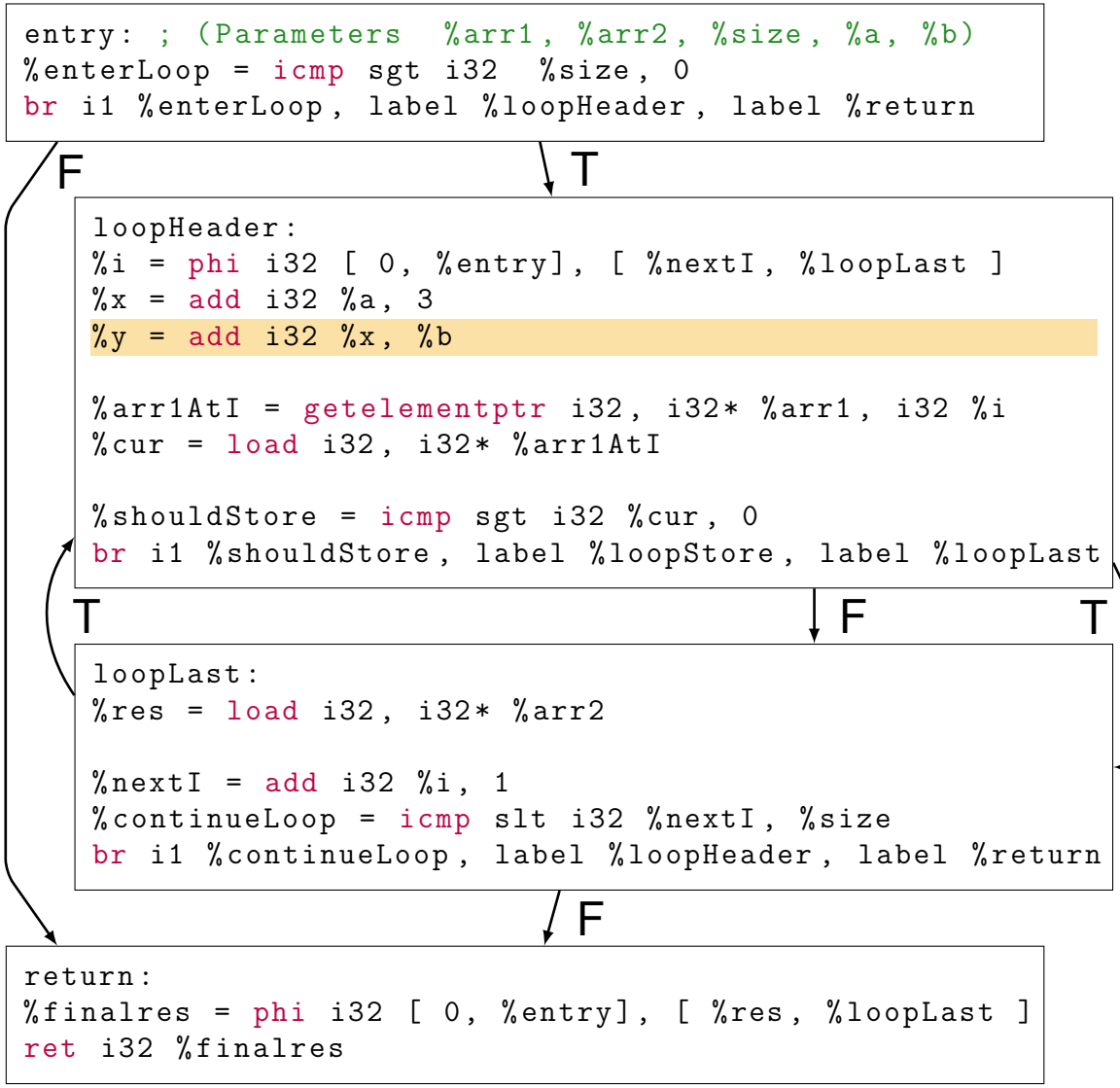

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LLVM Intermediate Representation

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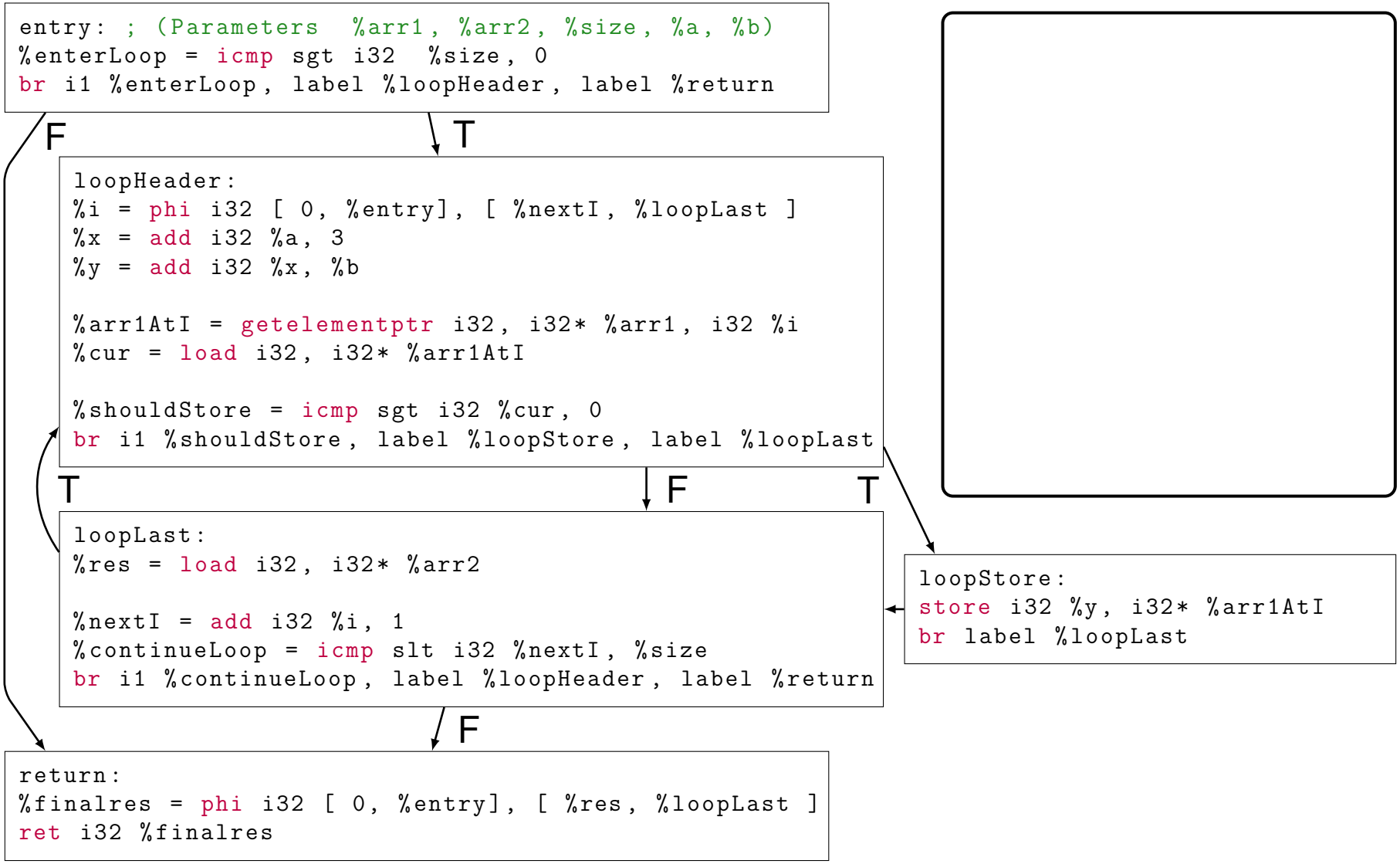

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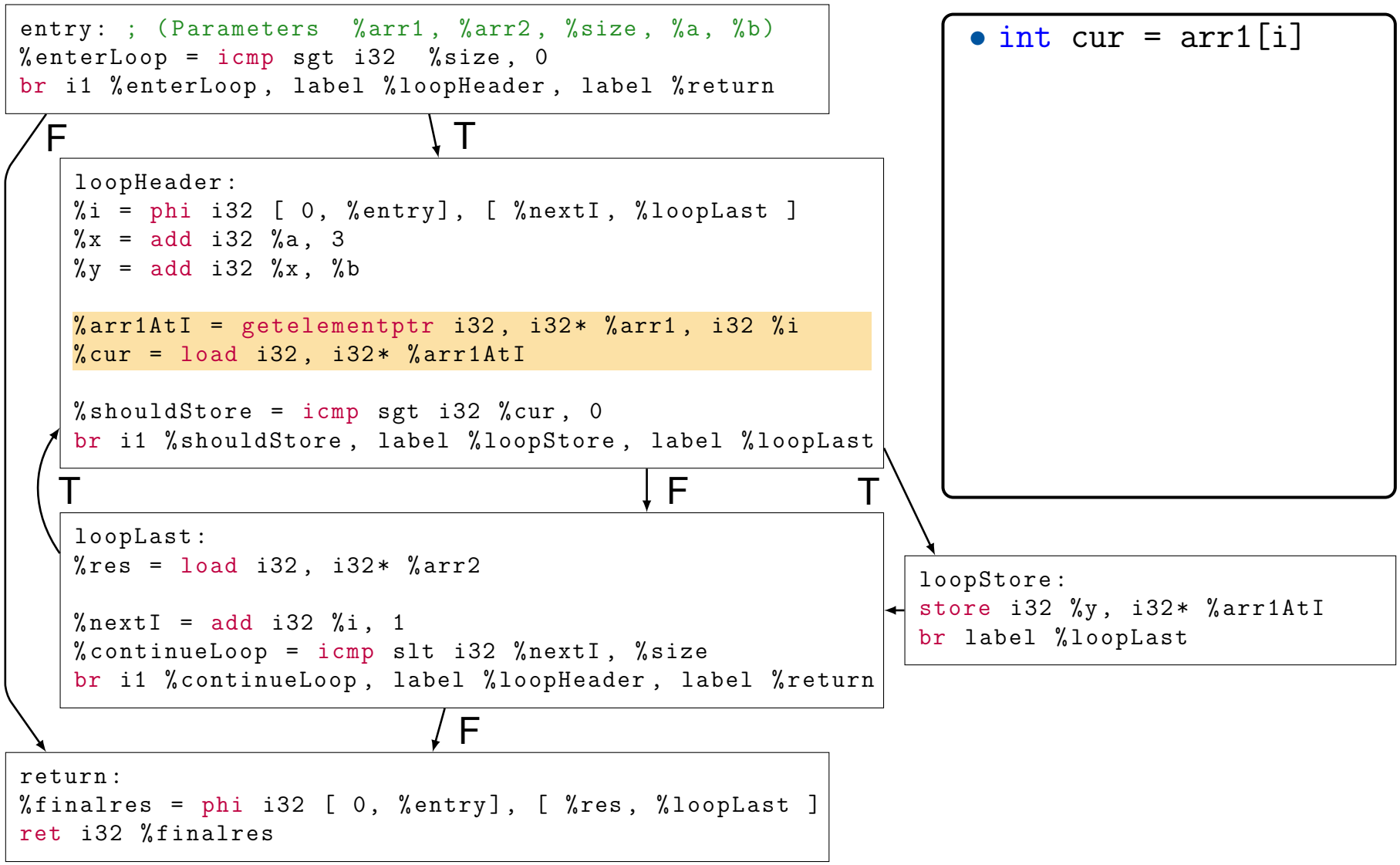

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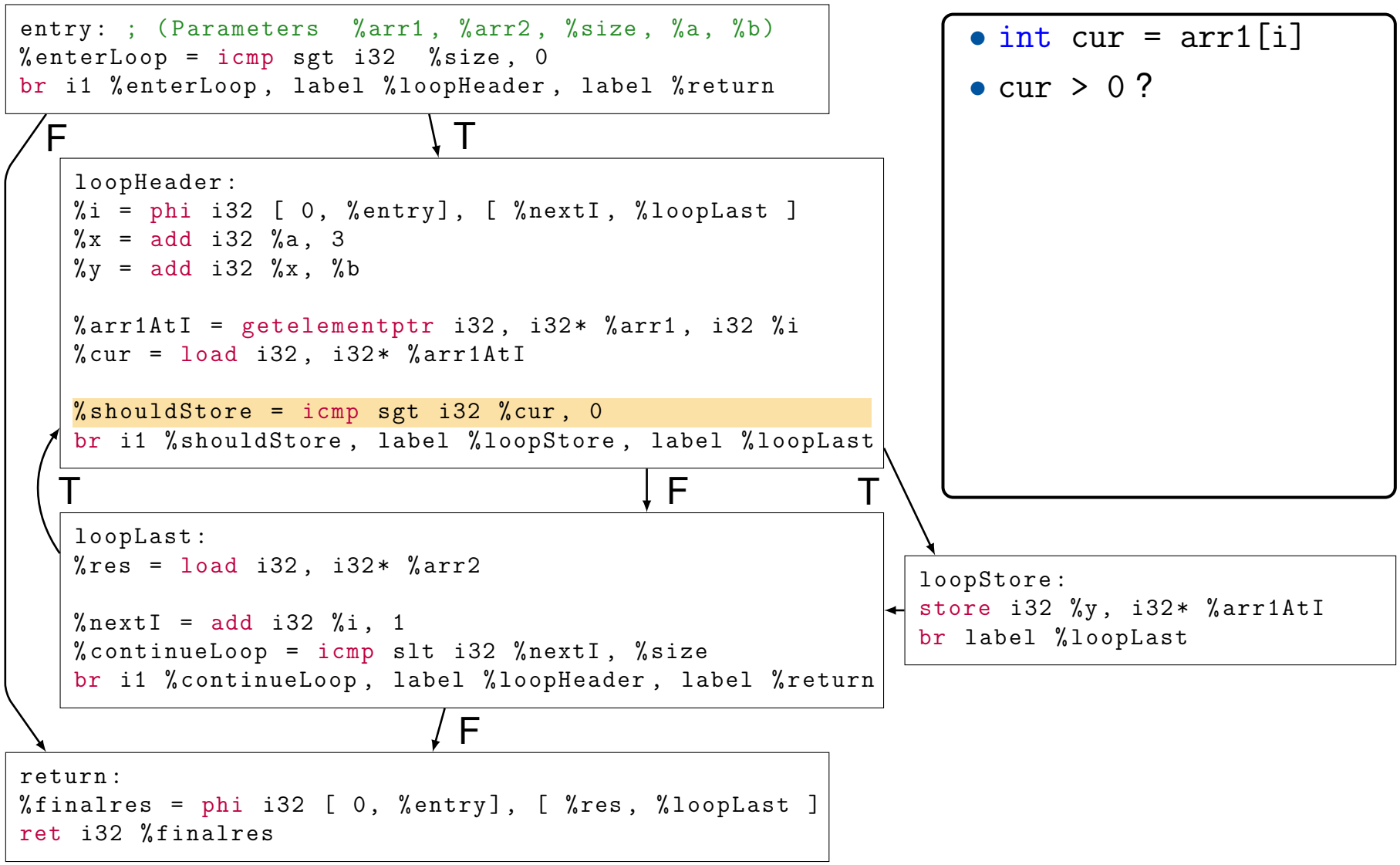

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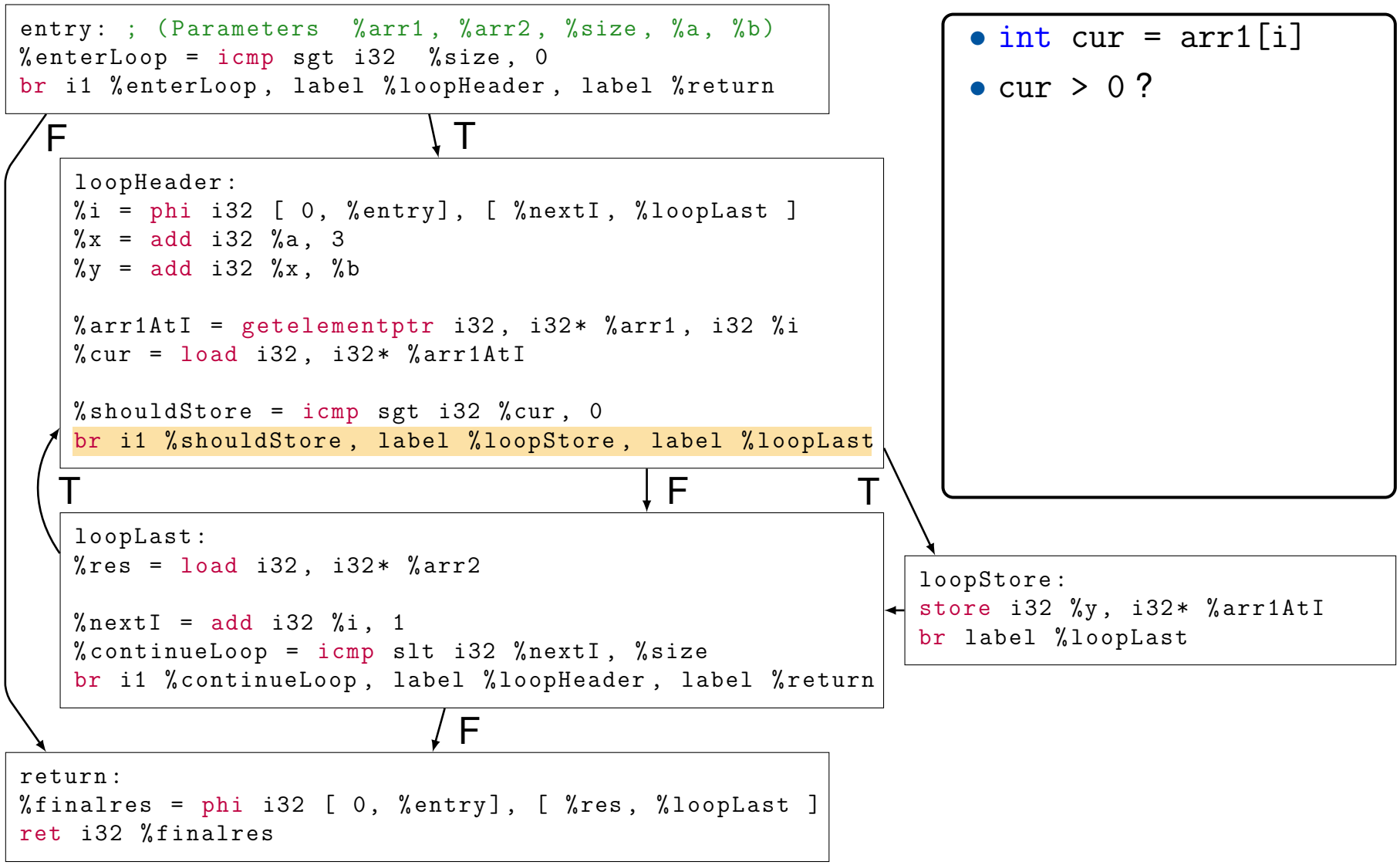

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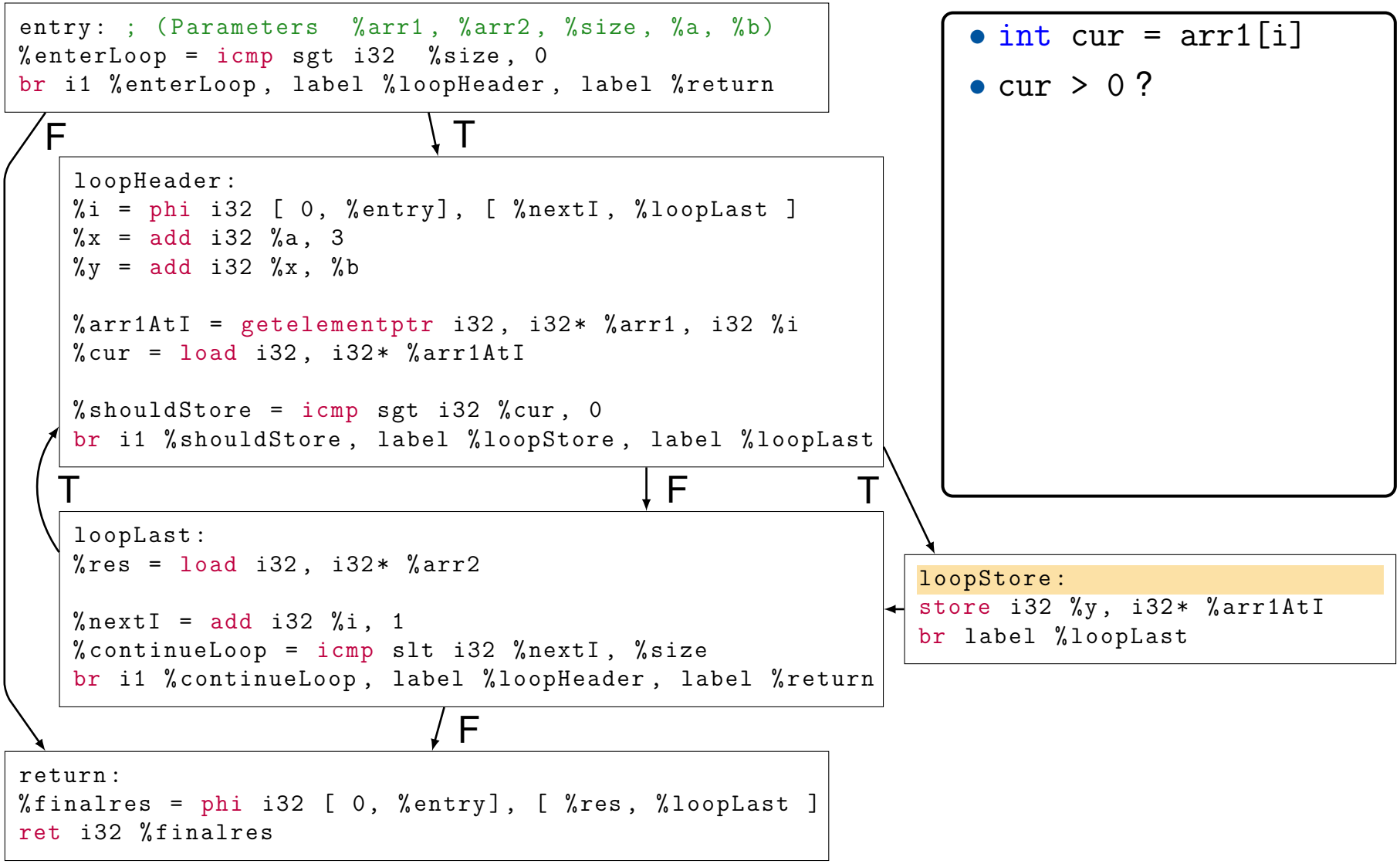

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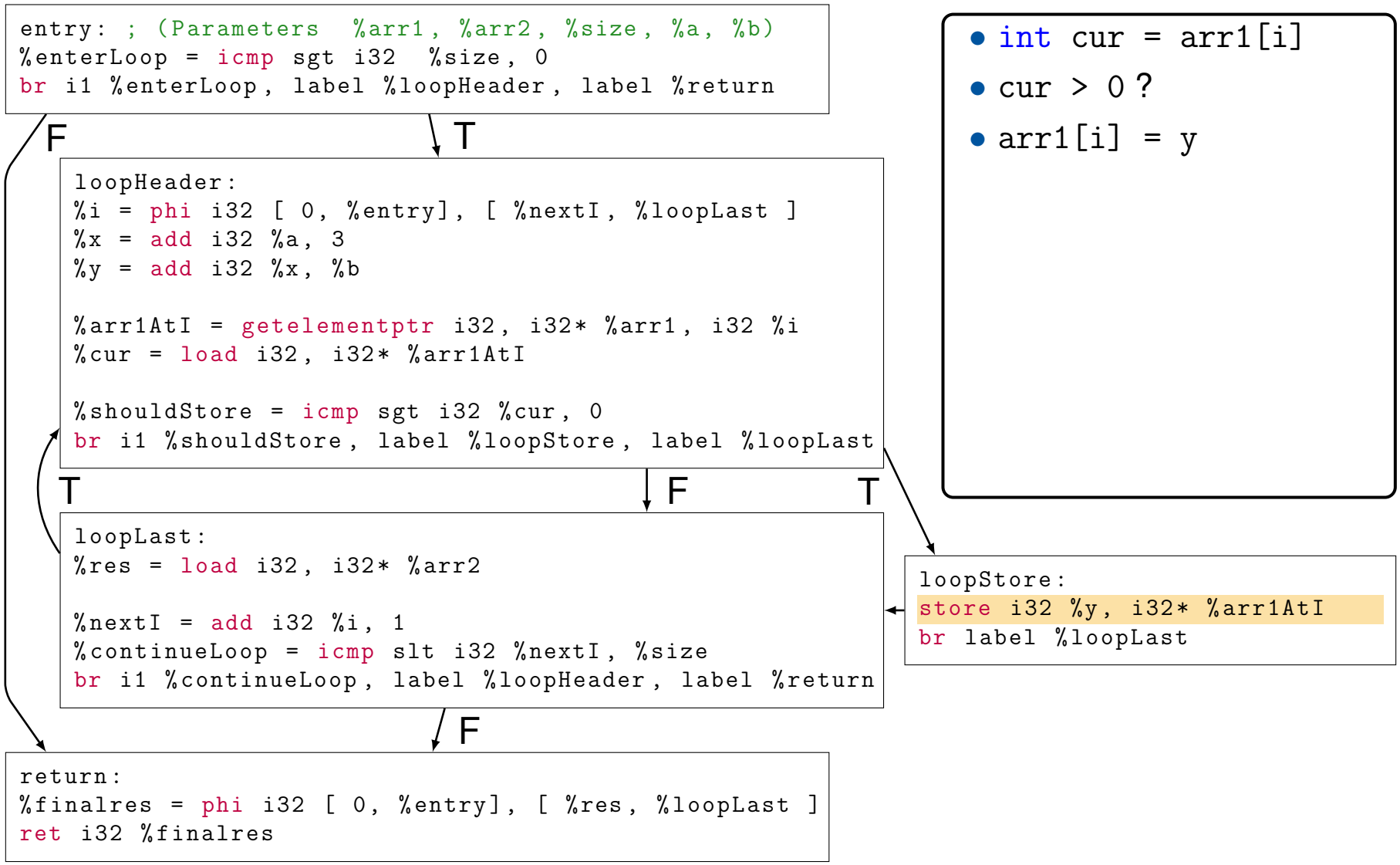

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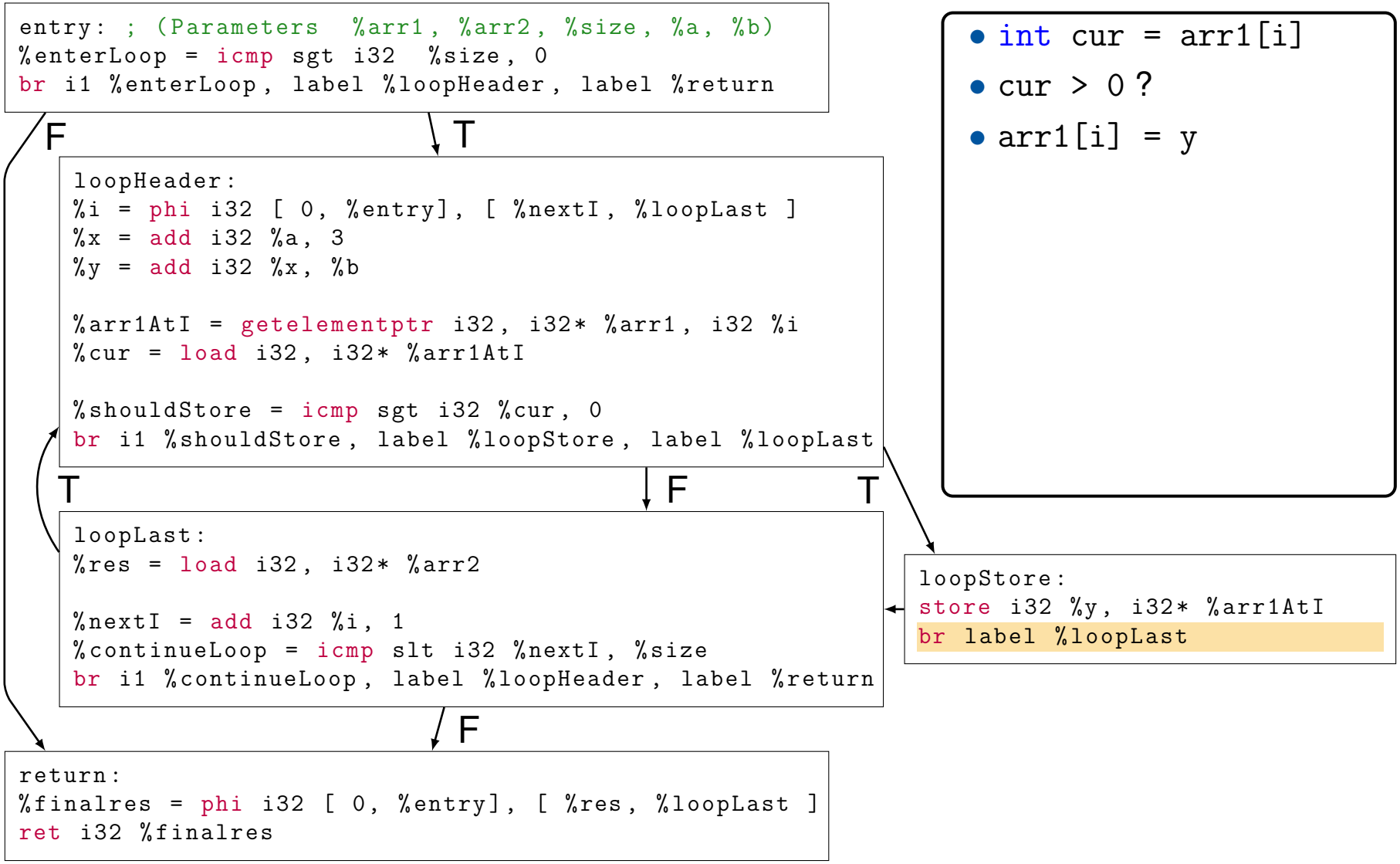

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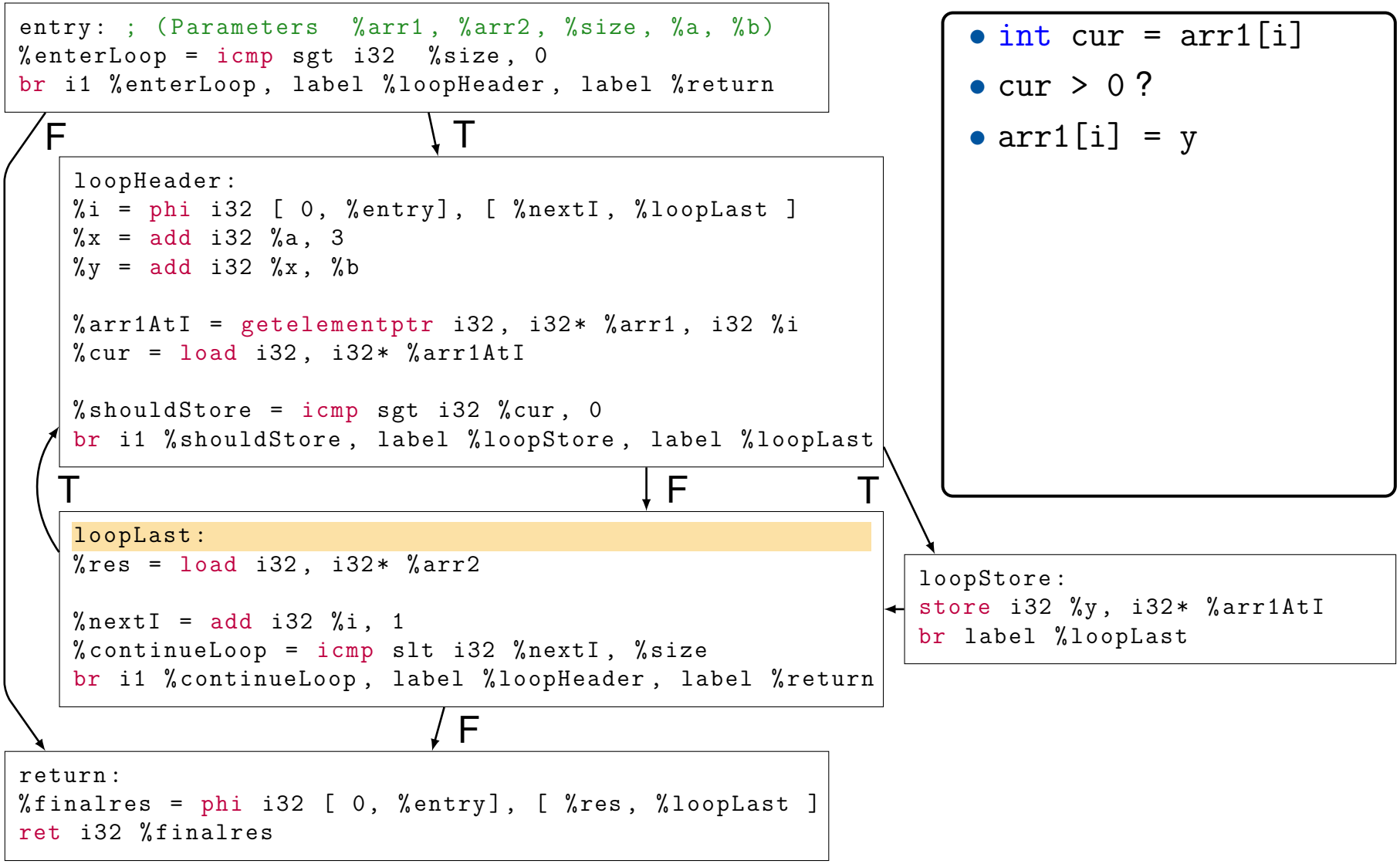

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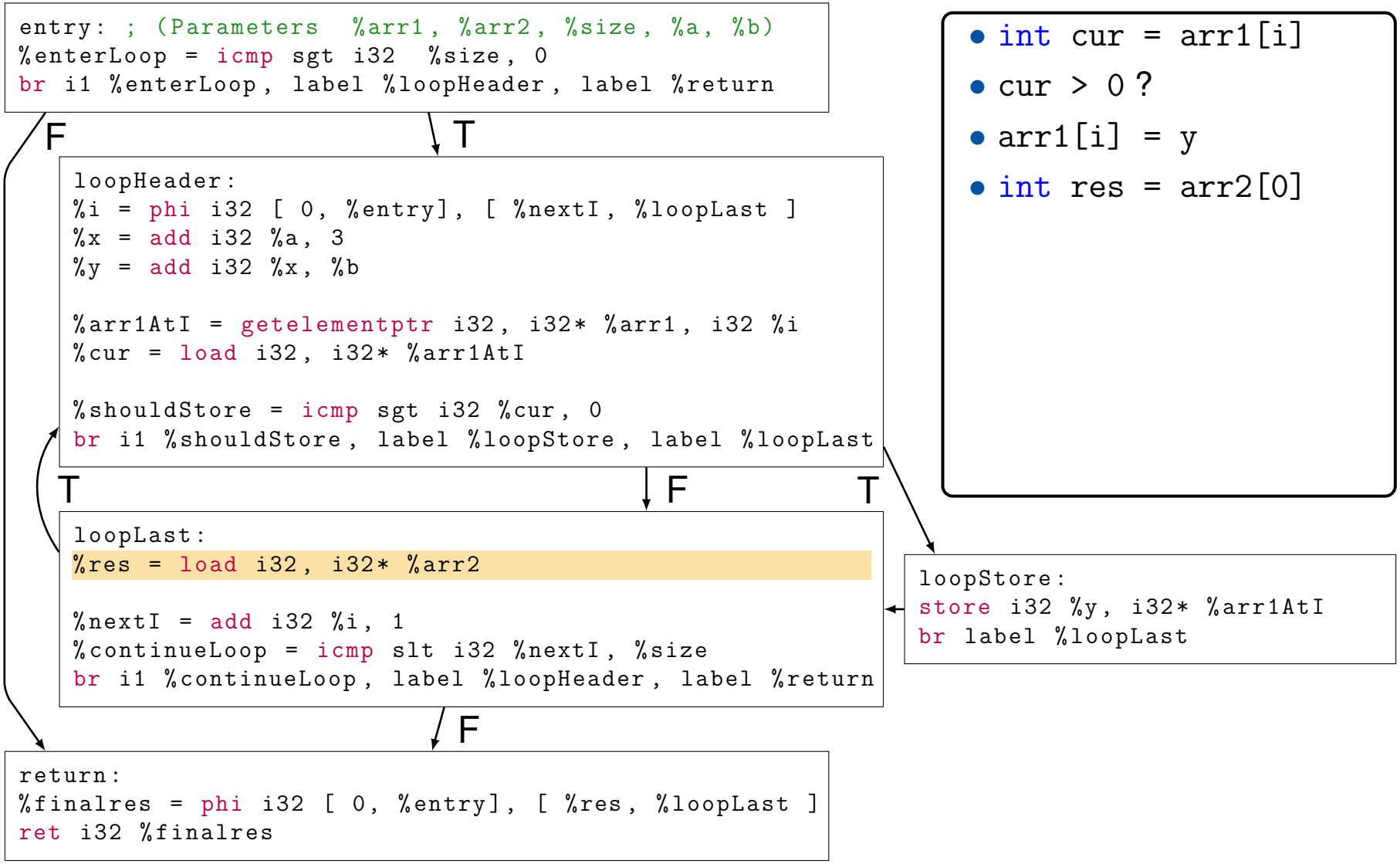

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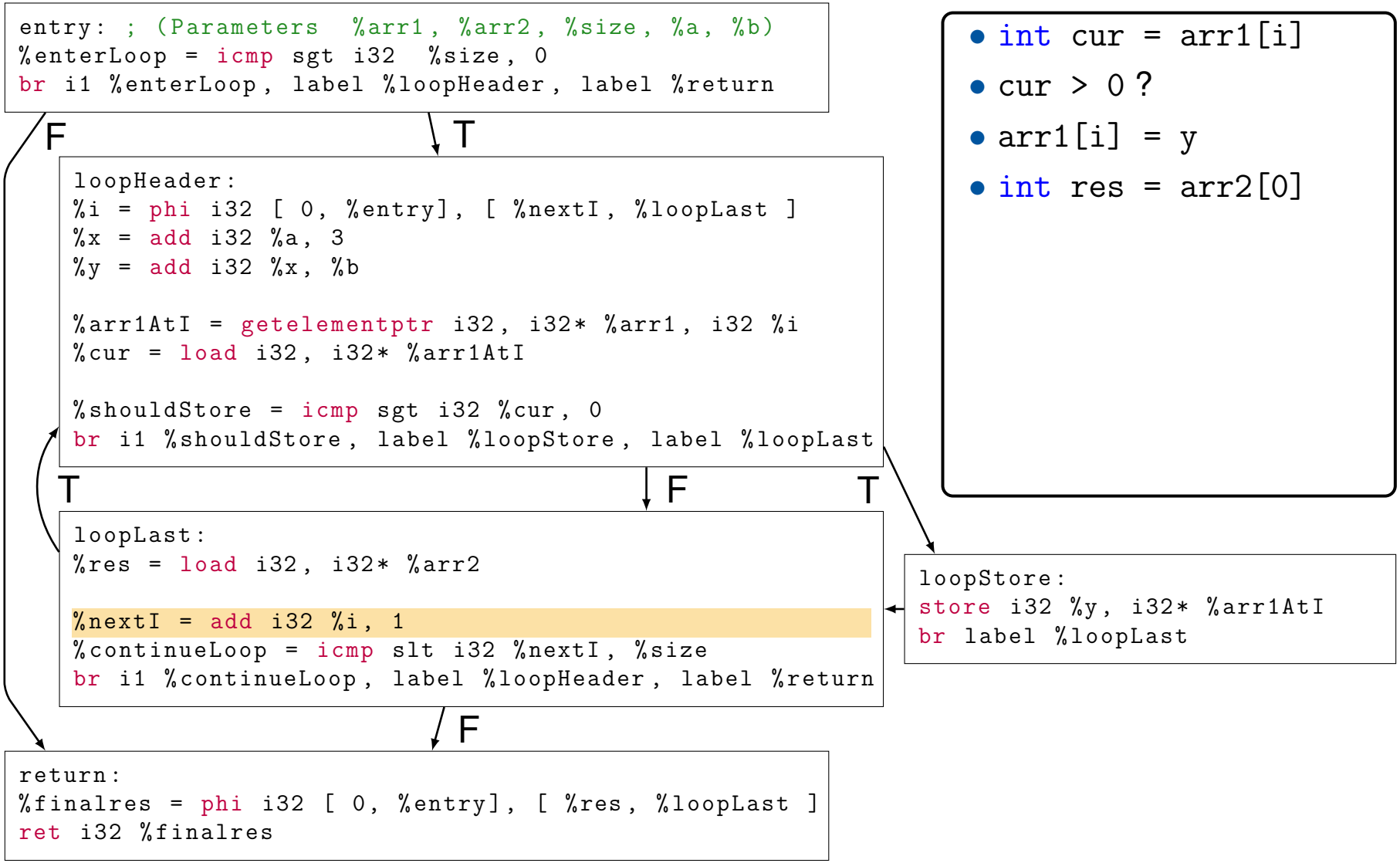

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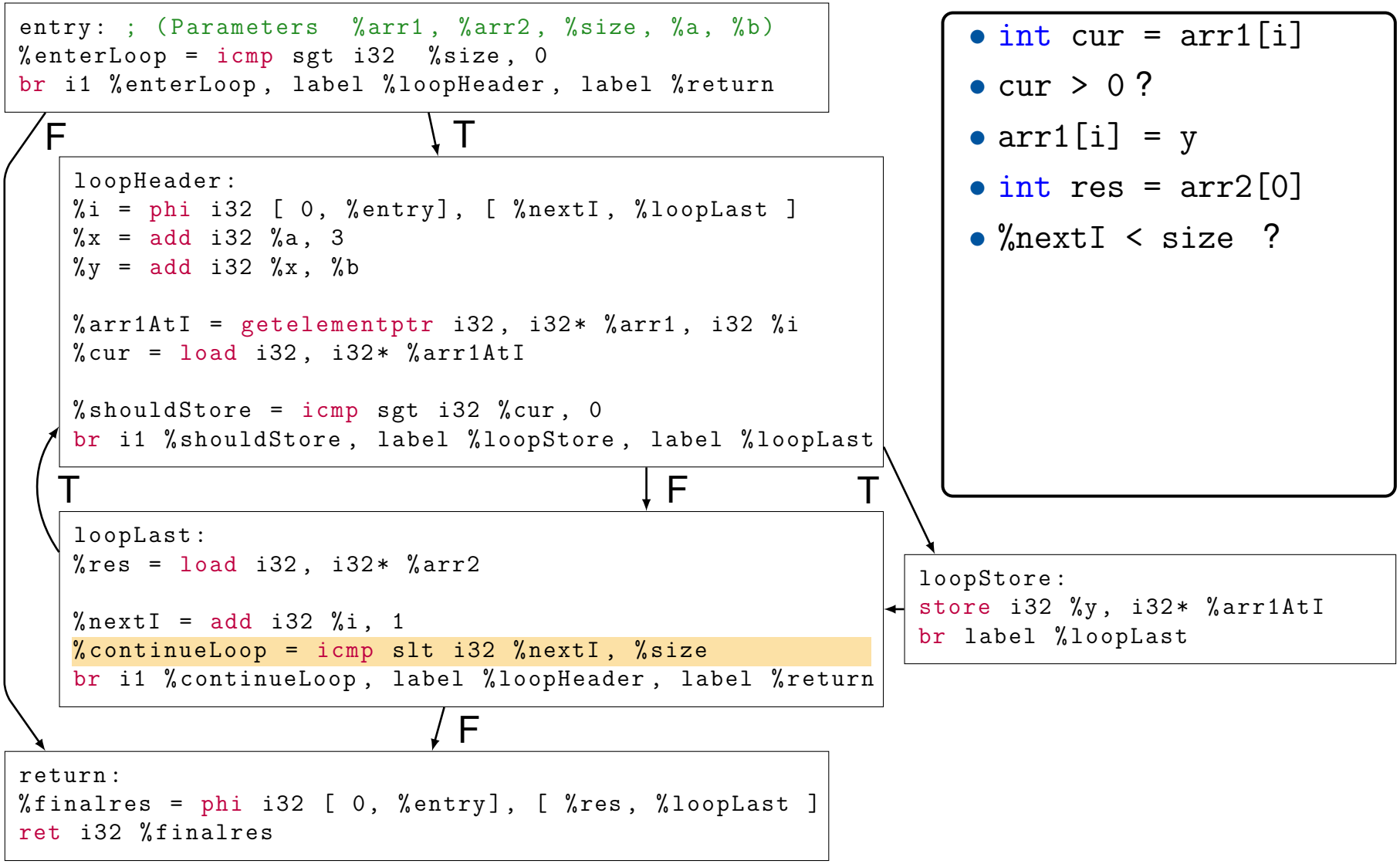

- int cur = arr1[i]
- cur > 0 ?
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- %nextI < size ?

LLVM Intermediate Representation

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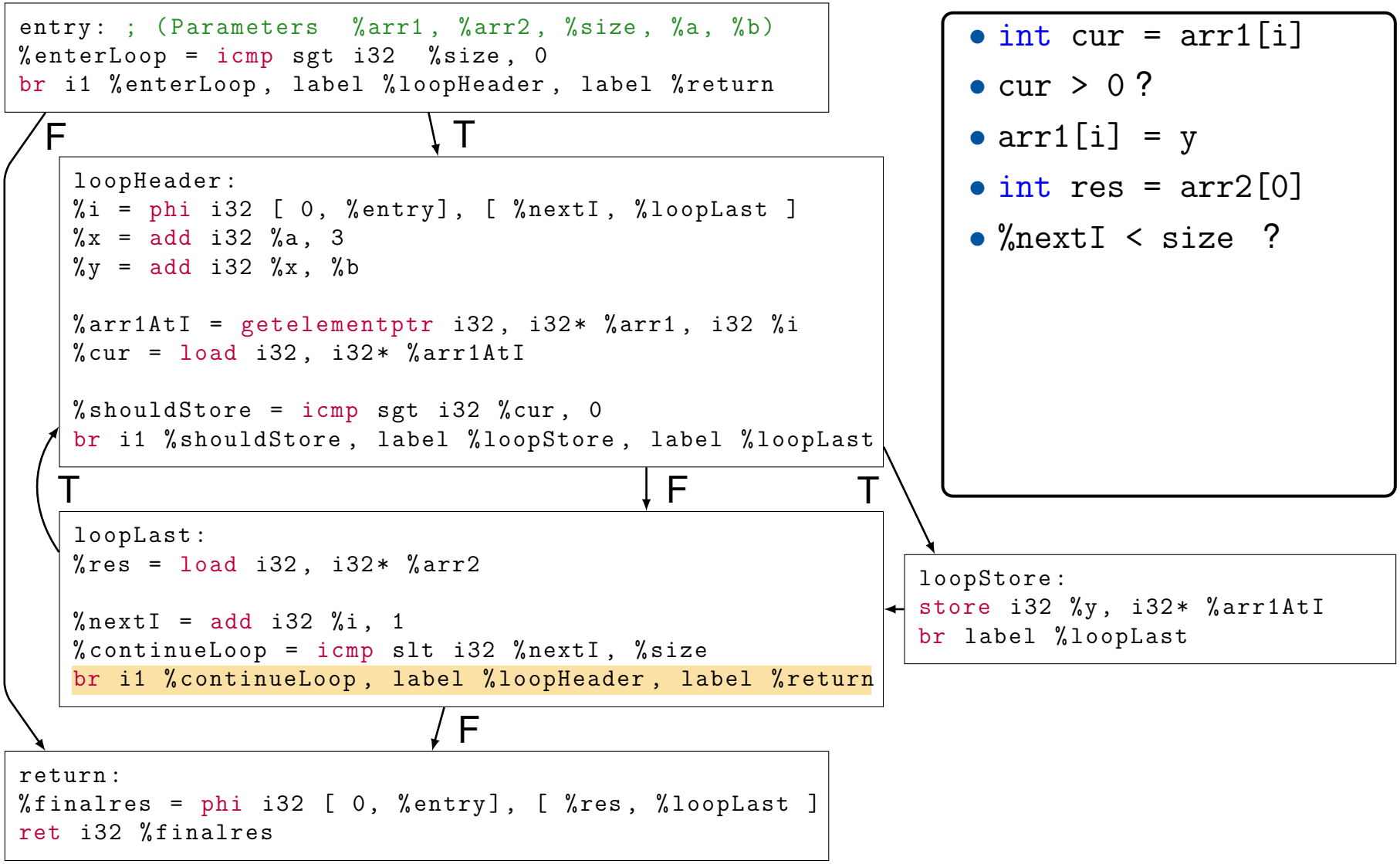

LLVM Intermediate Representation

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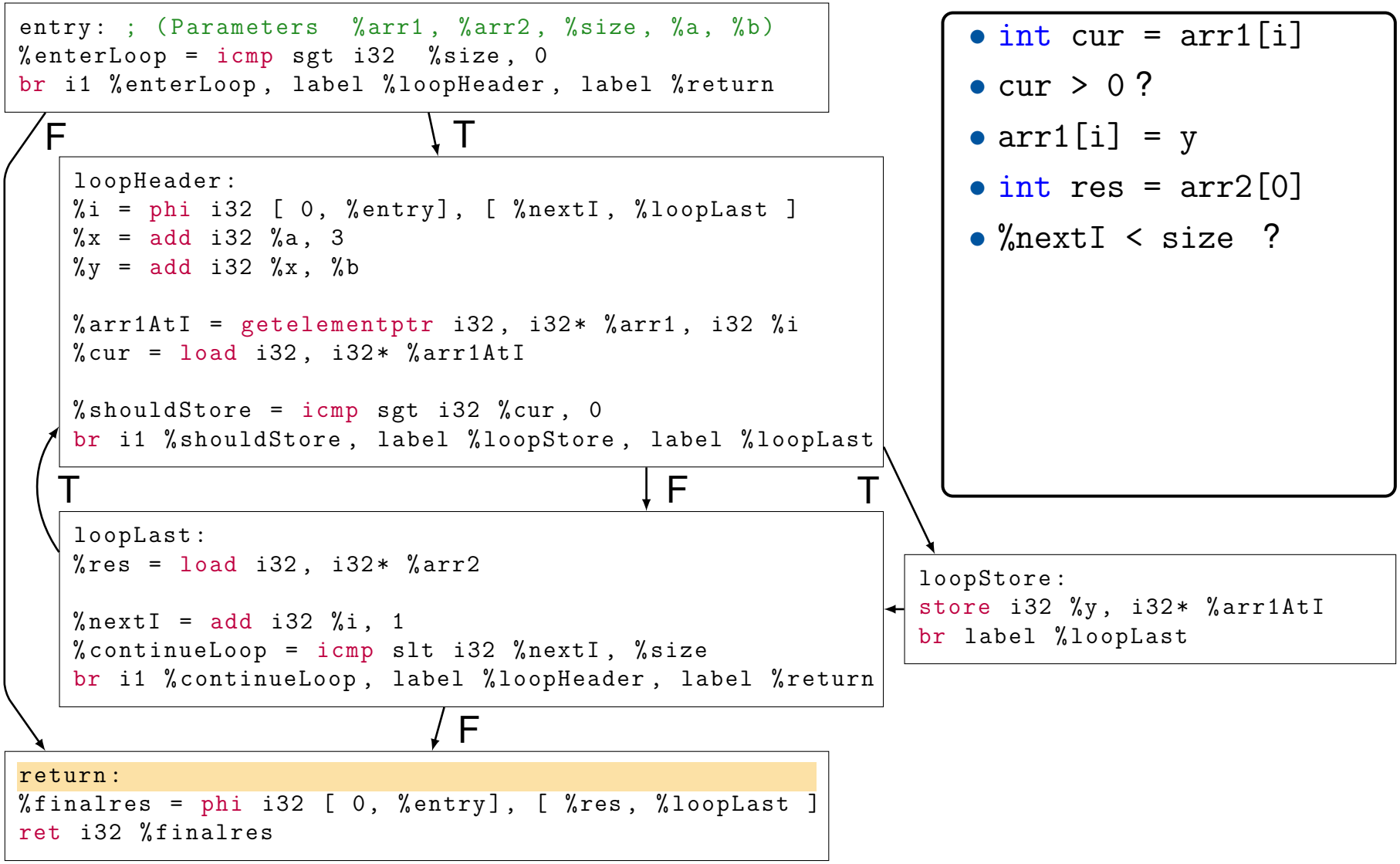

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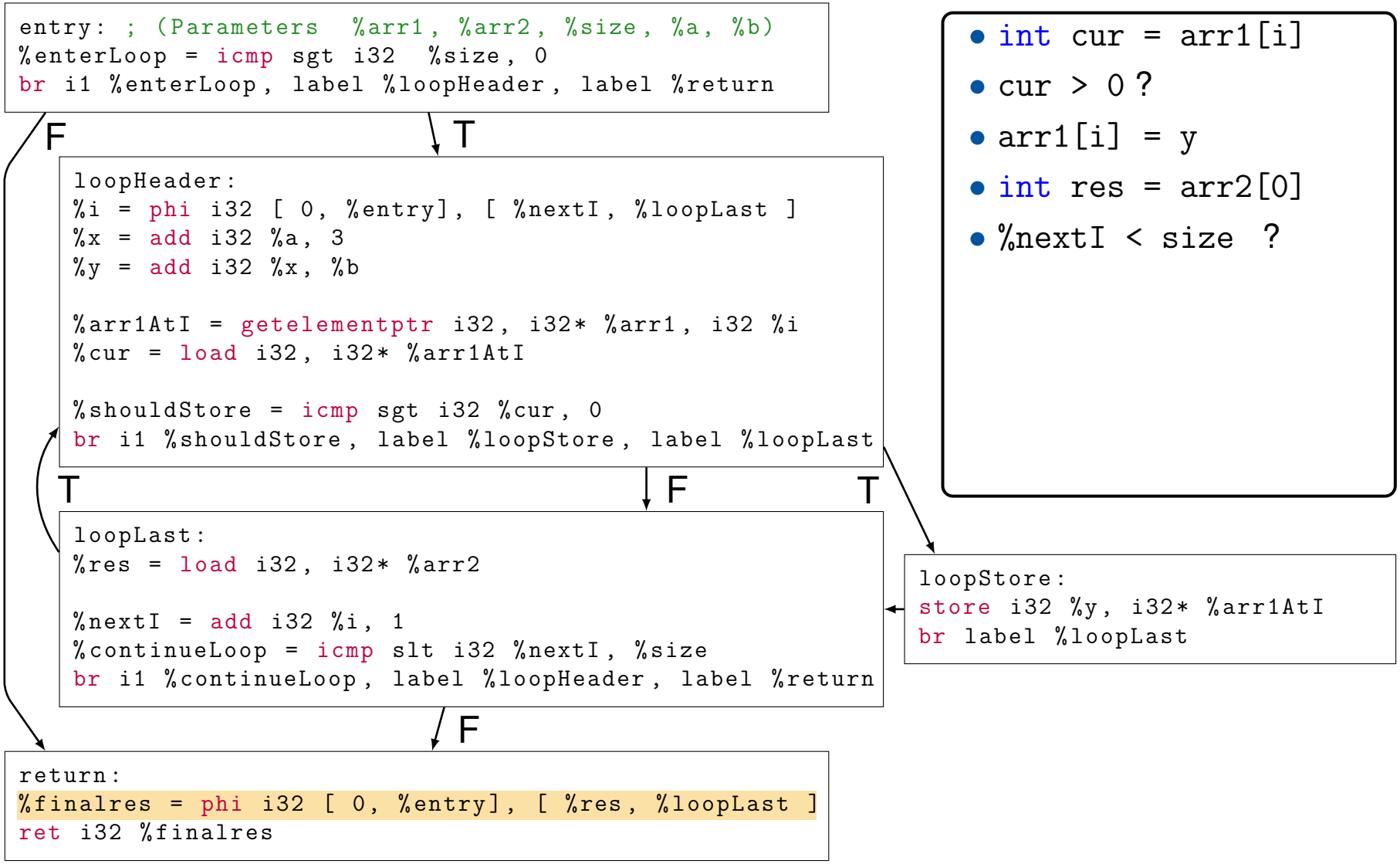

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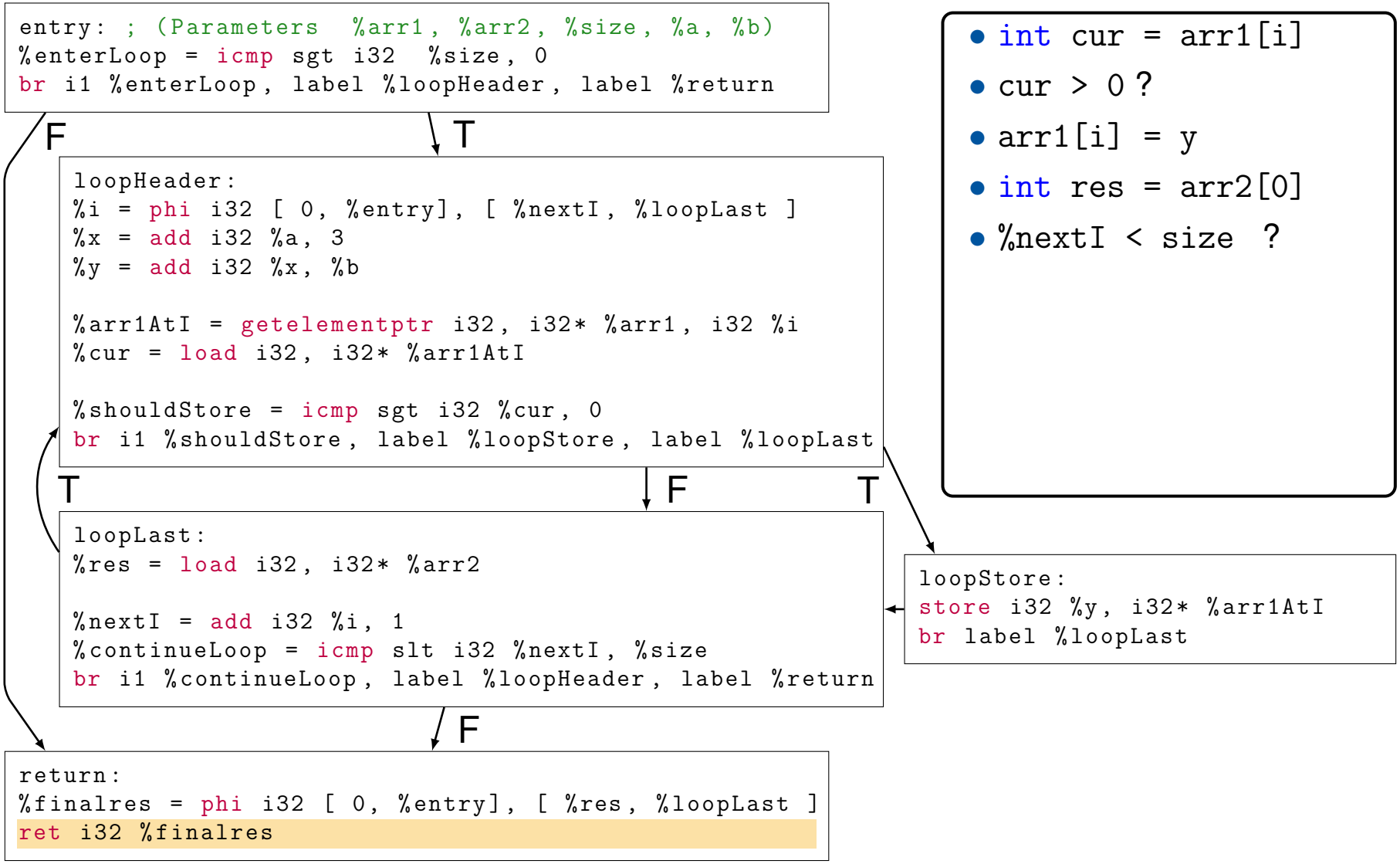
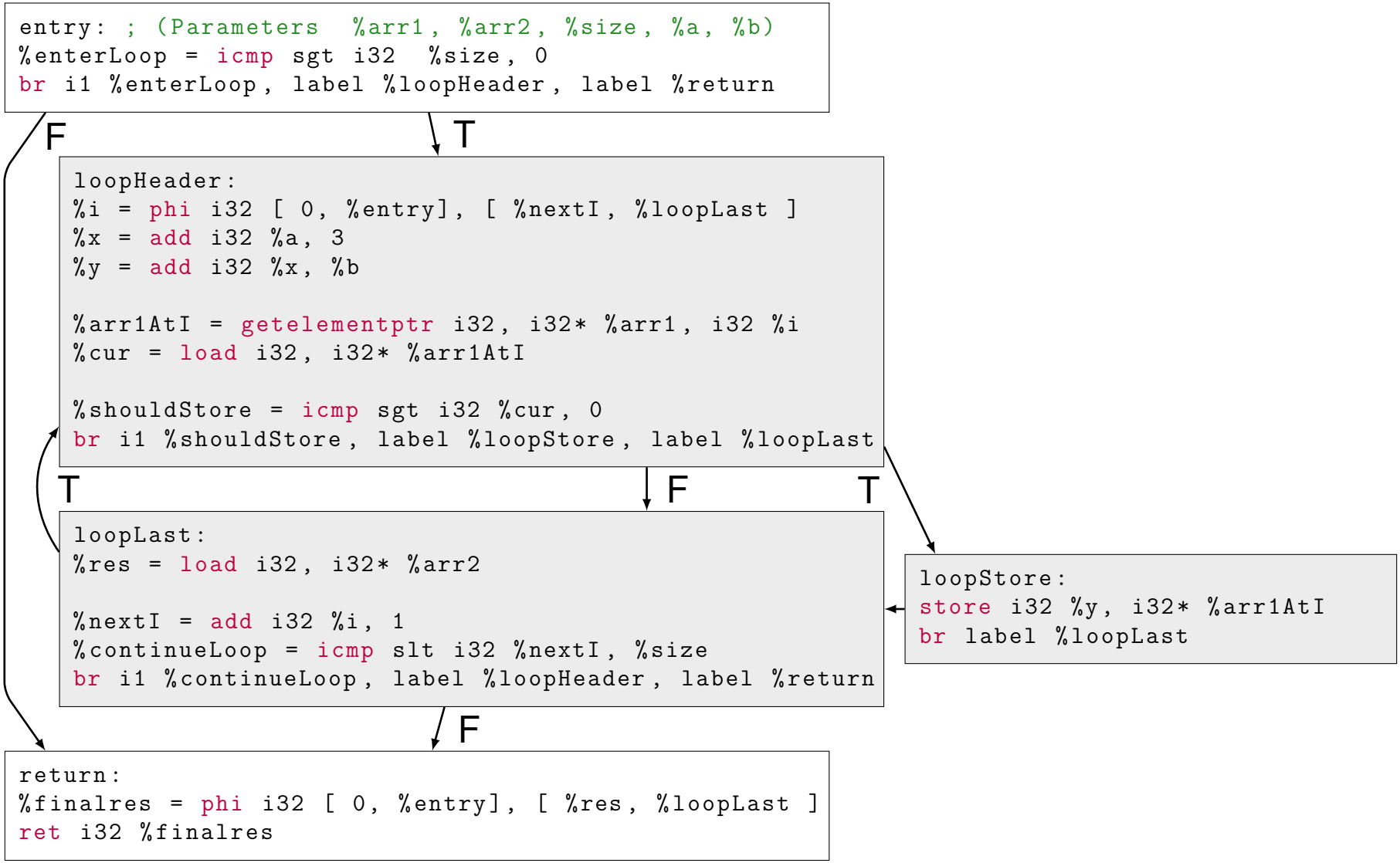
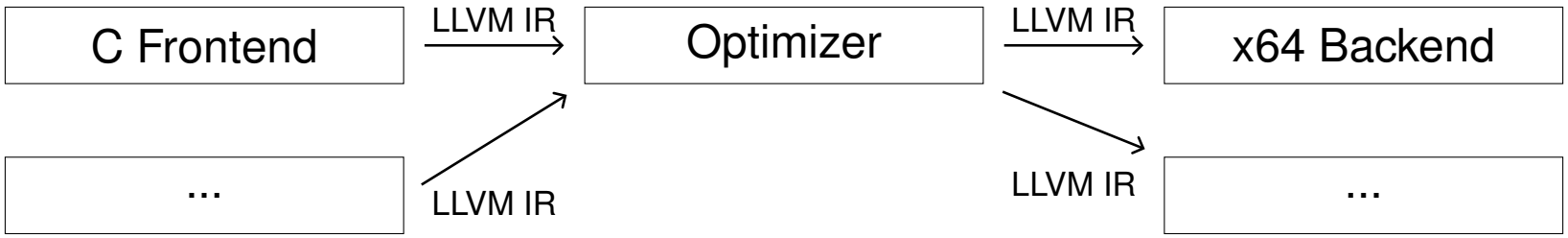


LLVM Intermediate Representation

Semantics (3)



LLVM's Optimizer Design



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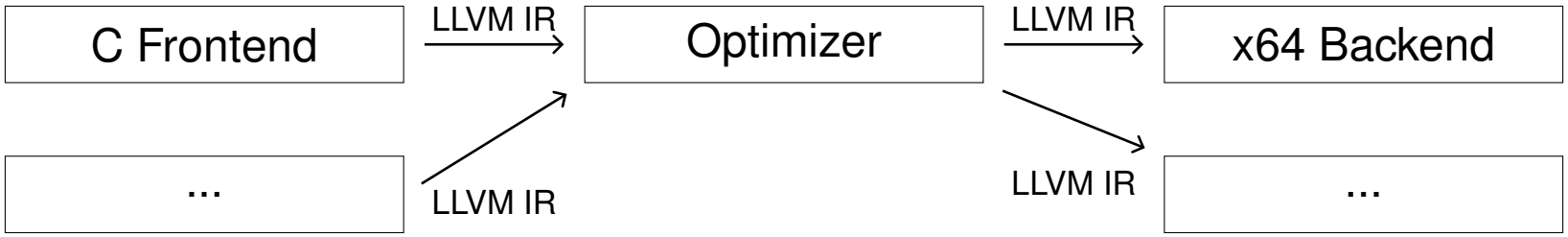
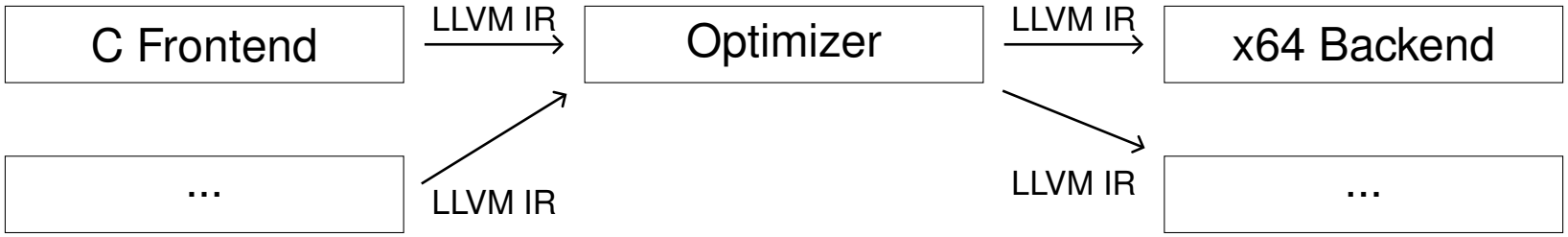


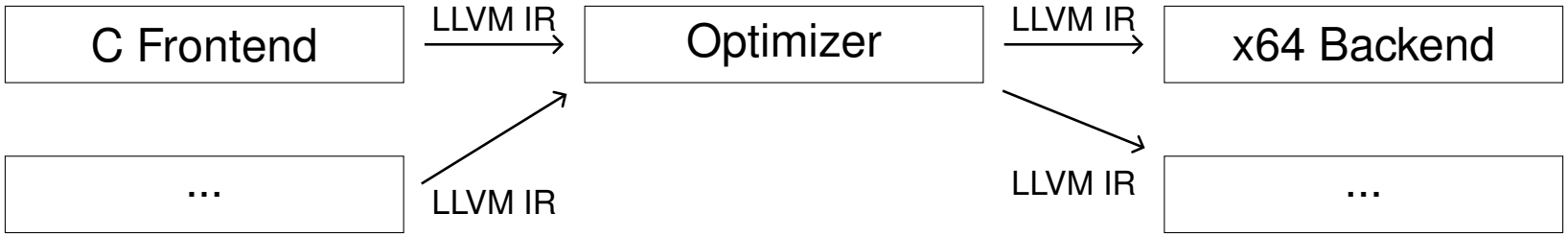
- Variety of optimizations offered:
  (Inline functions, find dead code, pre-compute arithmetic operations on constants, ...)

LLVM's Optimizer Design



- Variety of optimizations offered:
  (Inline functions, find dead code, pre-compute arithmetic operations on constants, ...)
- Modular organization as *passes*

LLVM's Optimizer Design



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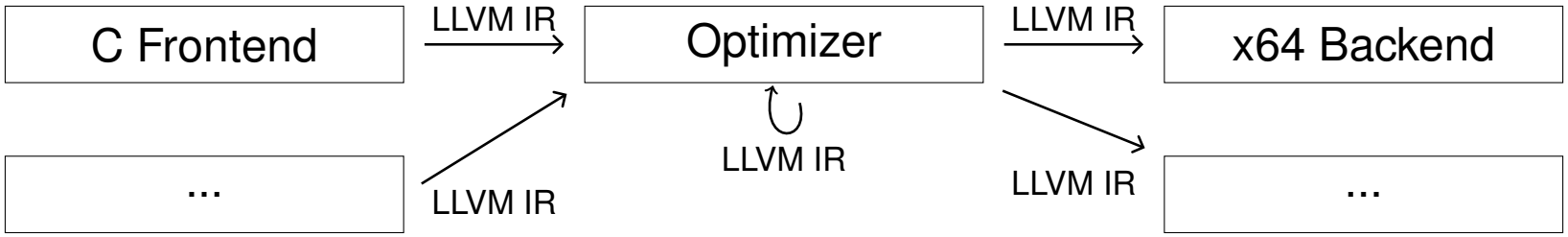

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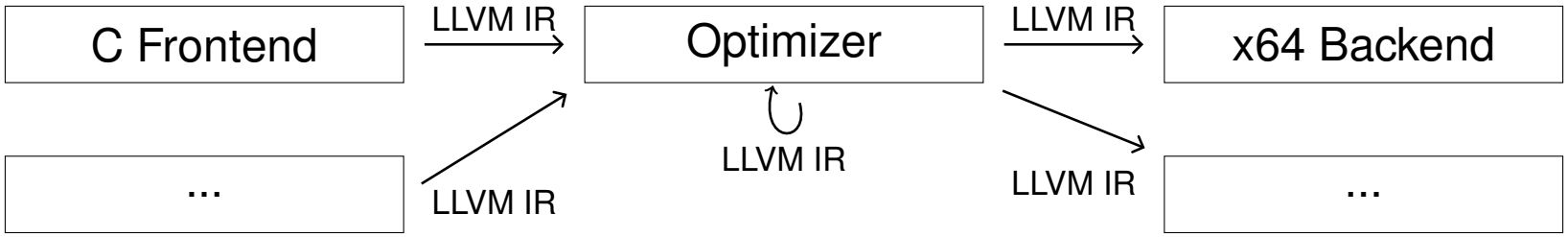

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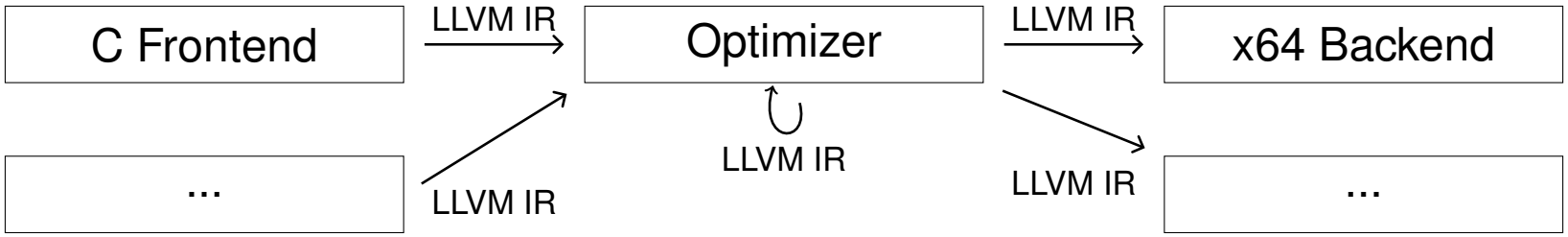

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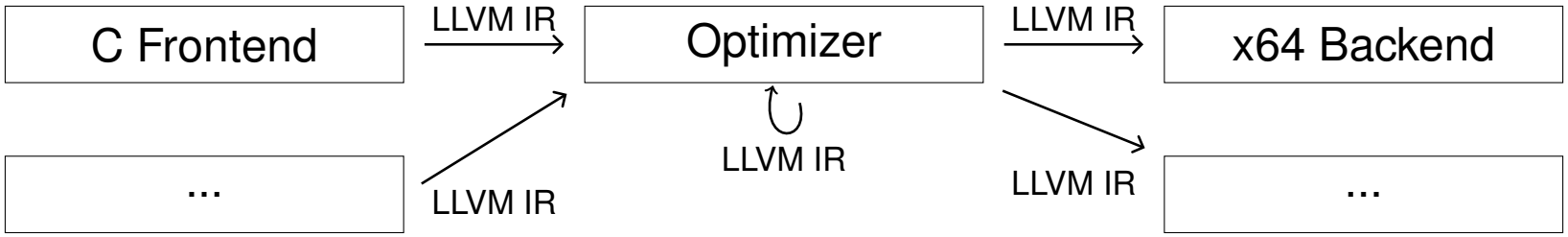

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- We look at the *Loop Invariant Code Motion* transformation pass

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- Questions:
  1. How to detect invariant code in general?
  2. Where to move such code in general?

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- These conditions are sufficient to move invariant instructions ahead of the loop (“Hoisting”)

Loop Invariant Code Motion

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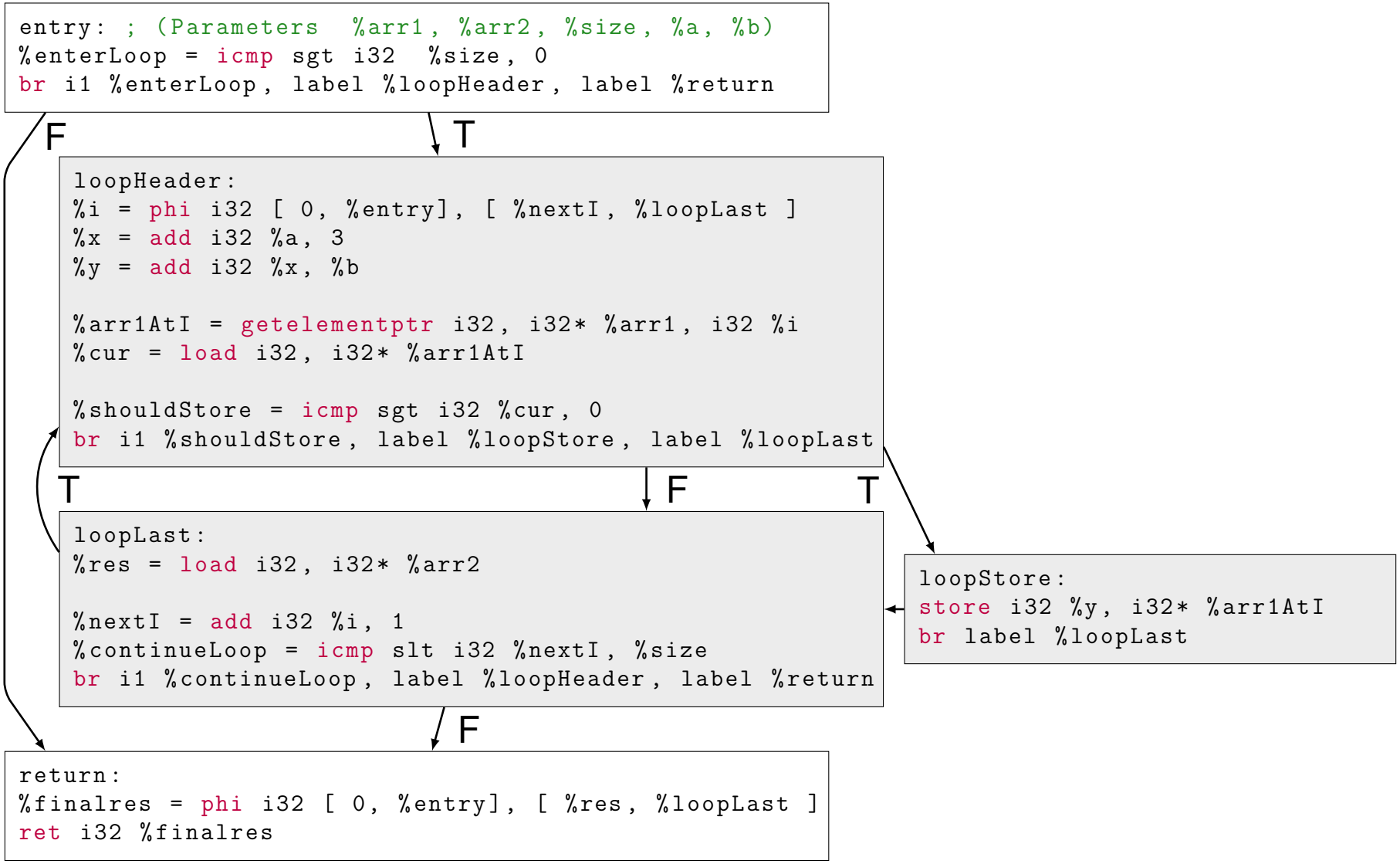

Loop Invariant Code Motion

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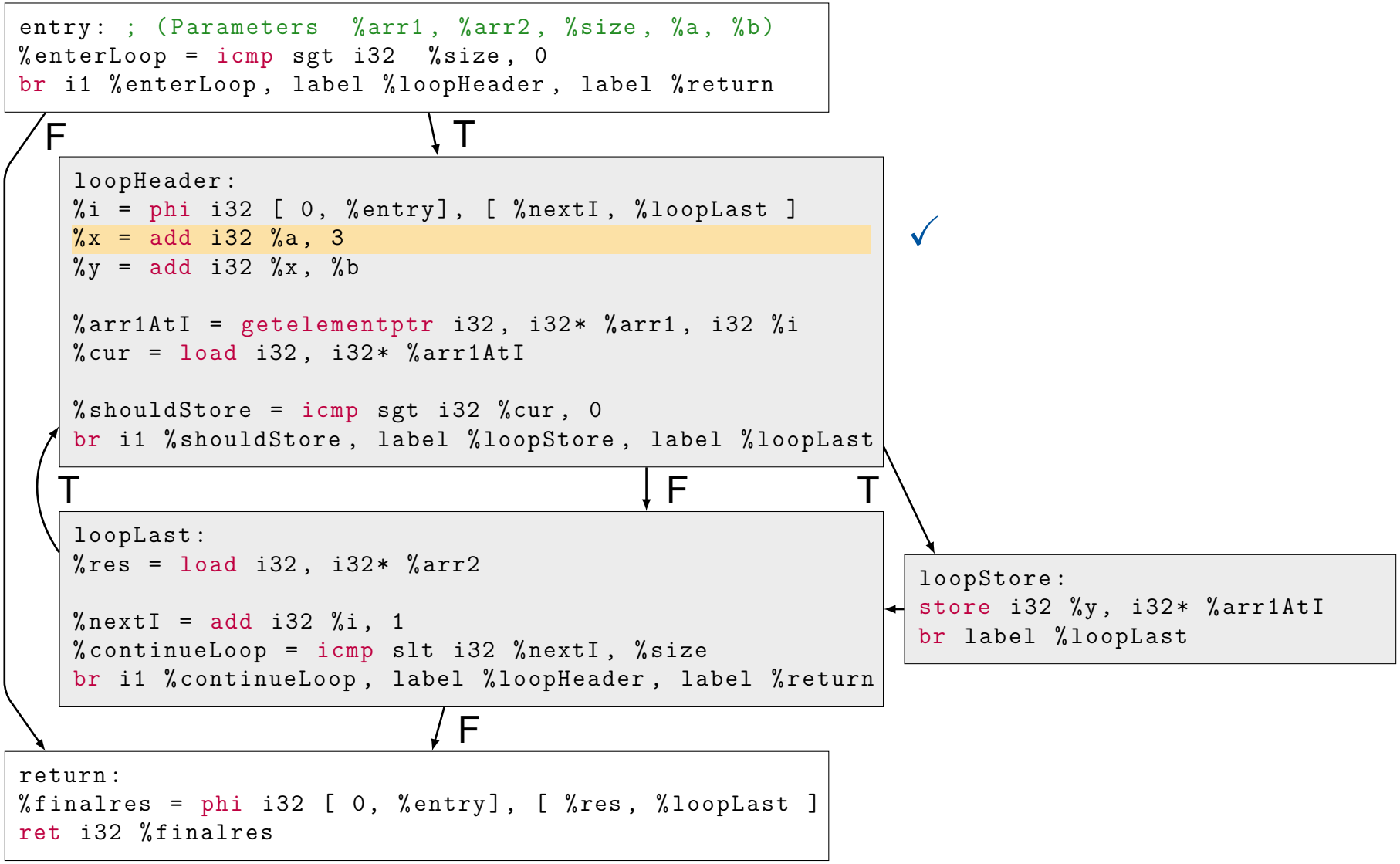

Loop Invariant Code Motion

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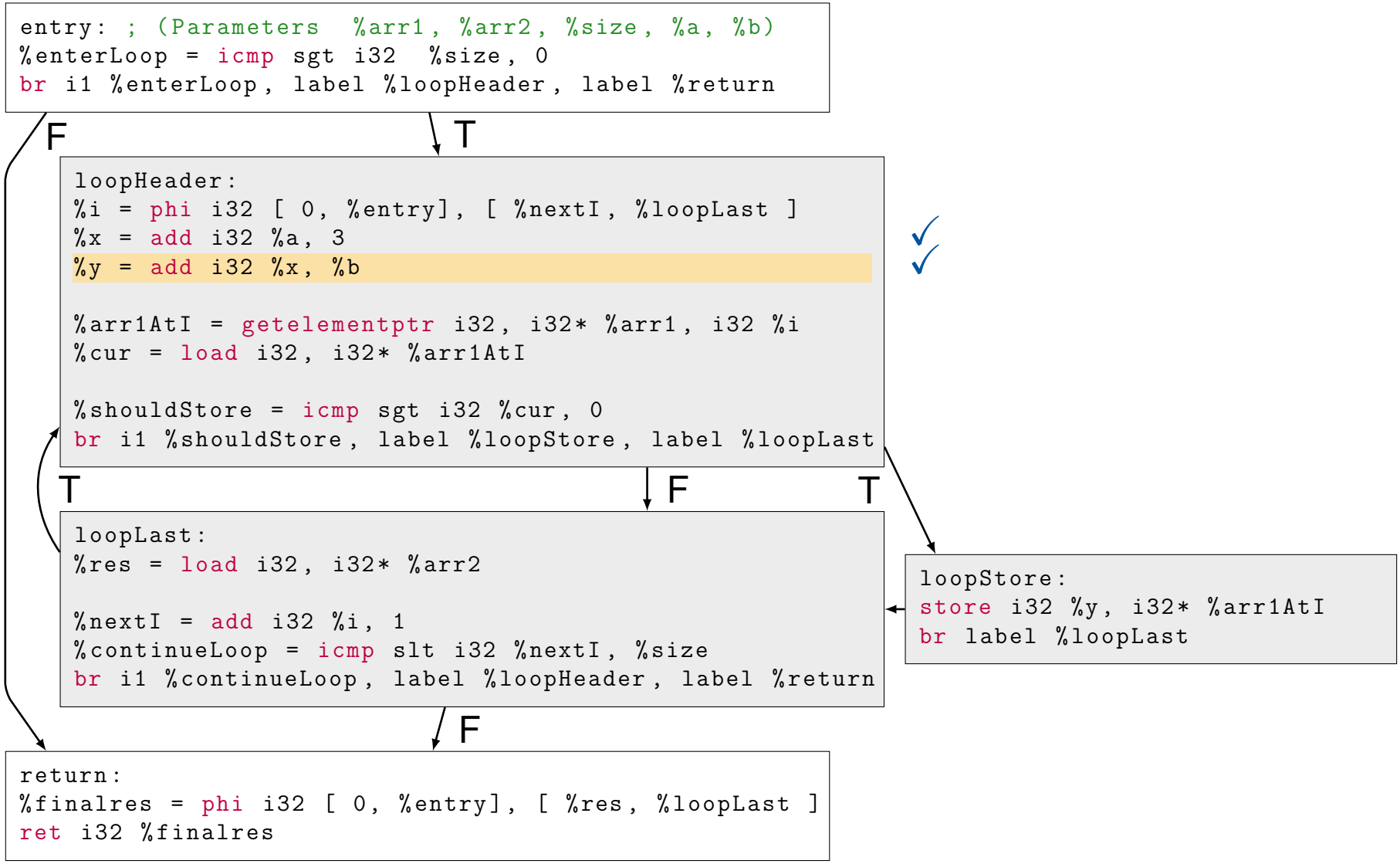

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  - All incoming edges from outside of the loop to the header point to the preheader instead

Loop Invariant Code Motion

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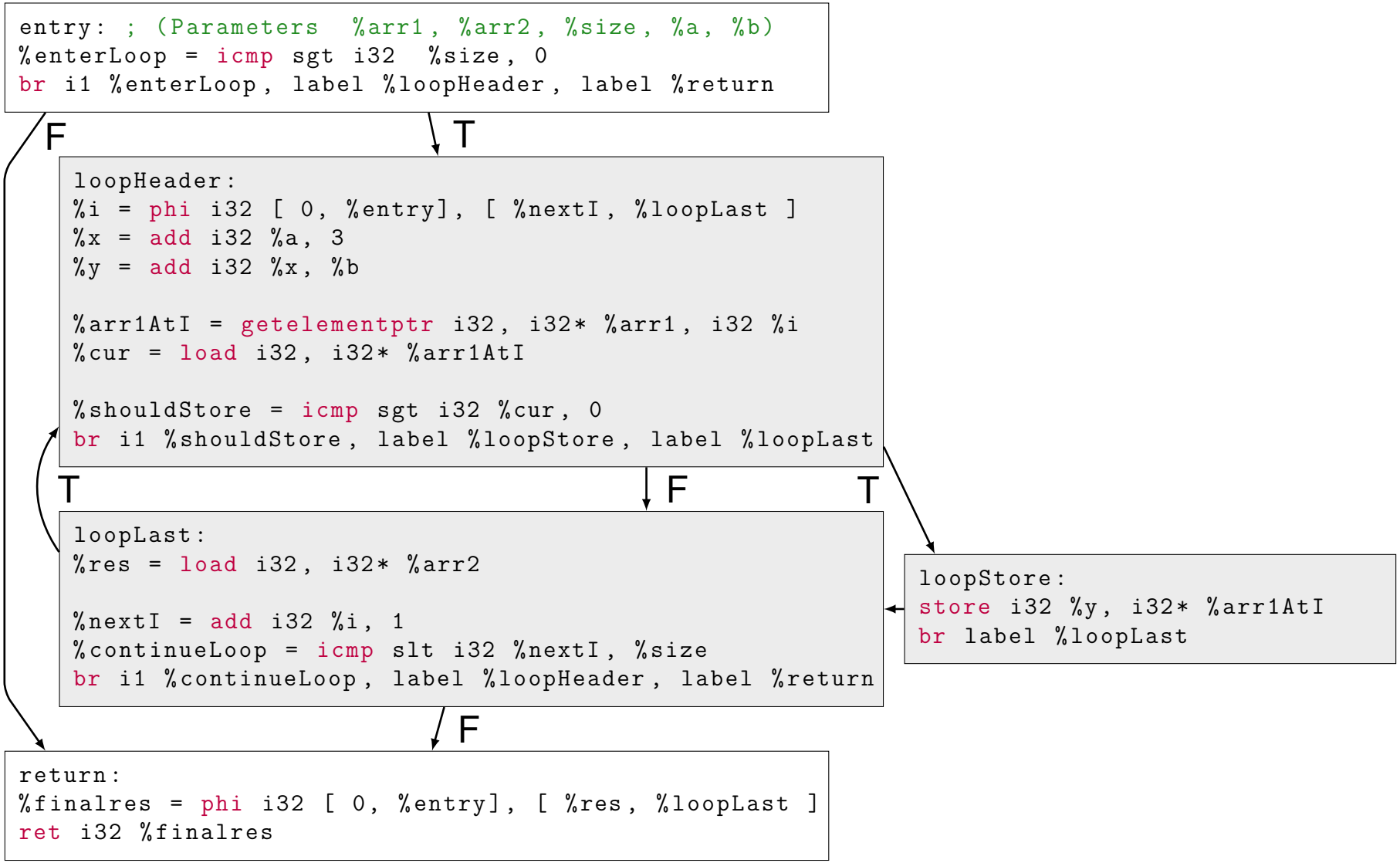

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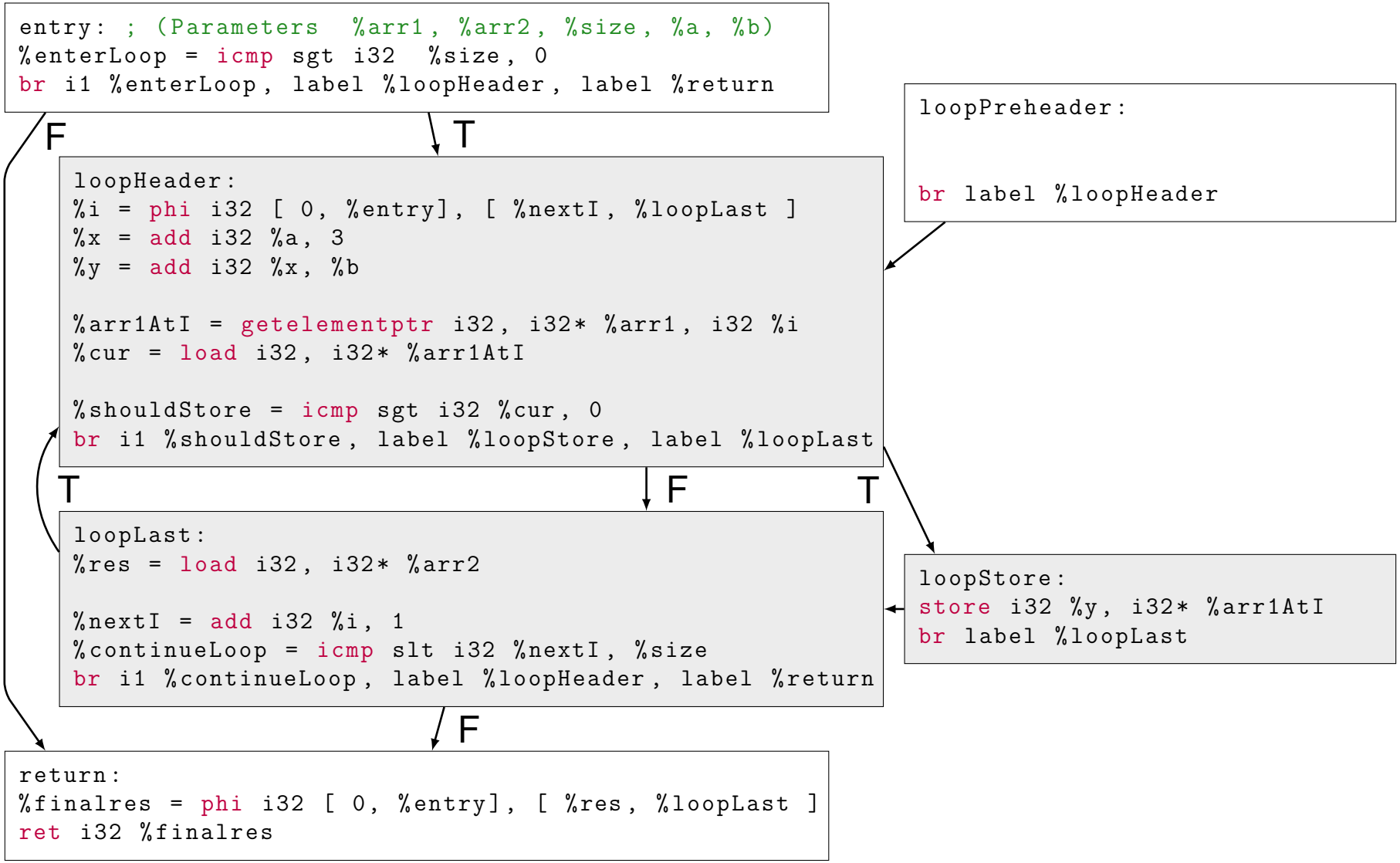

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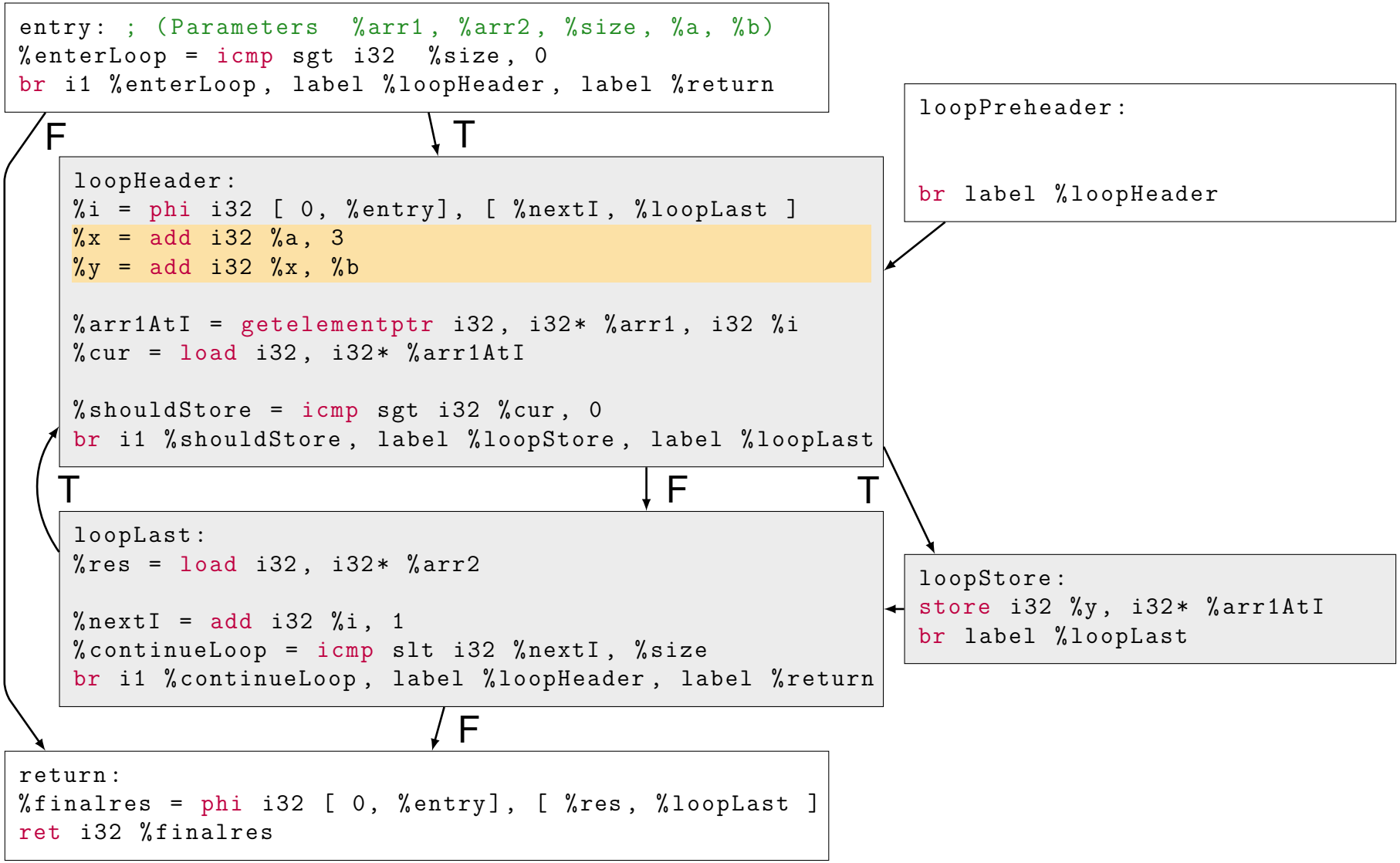

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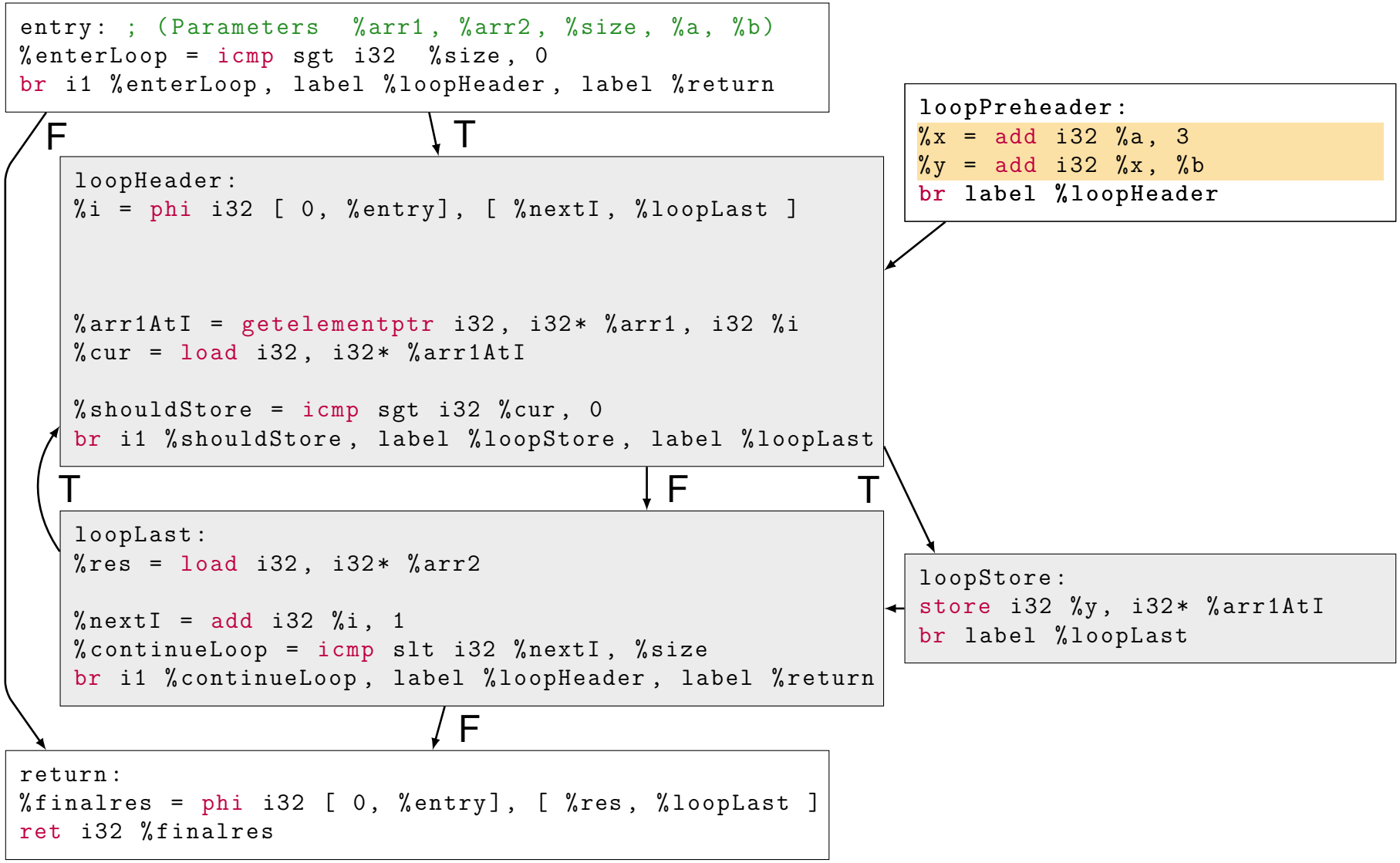

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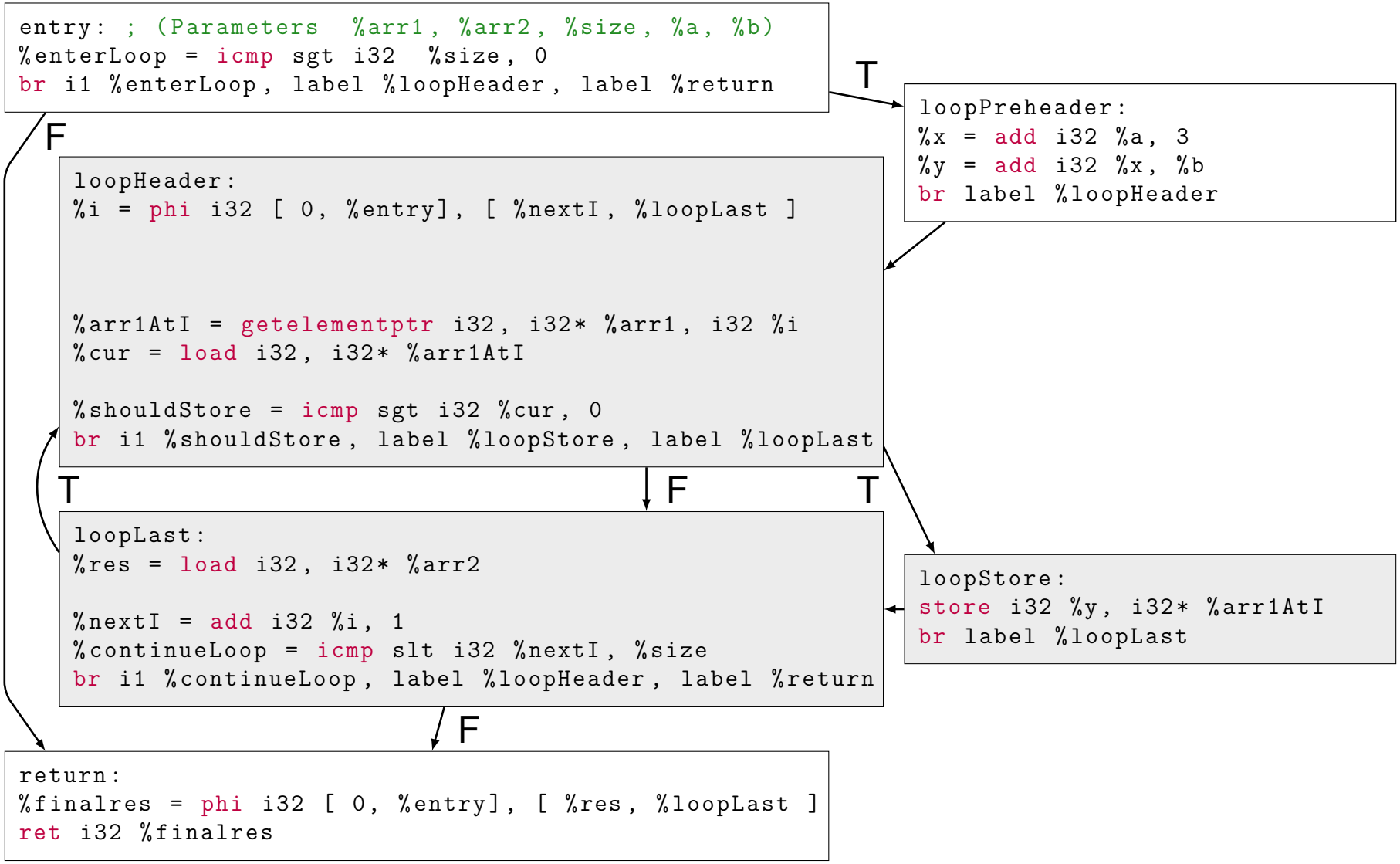

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- How to handle these memory-sensitive instructions?

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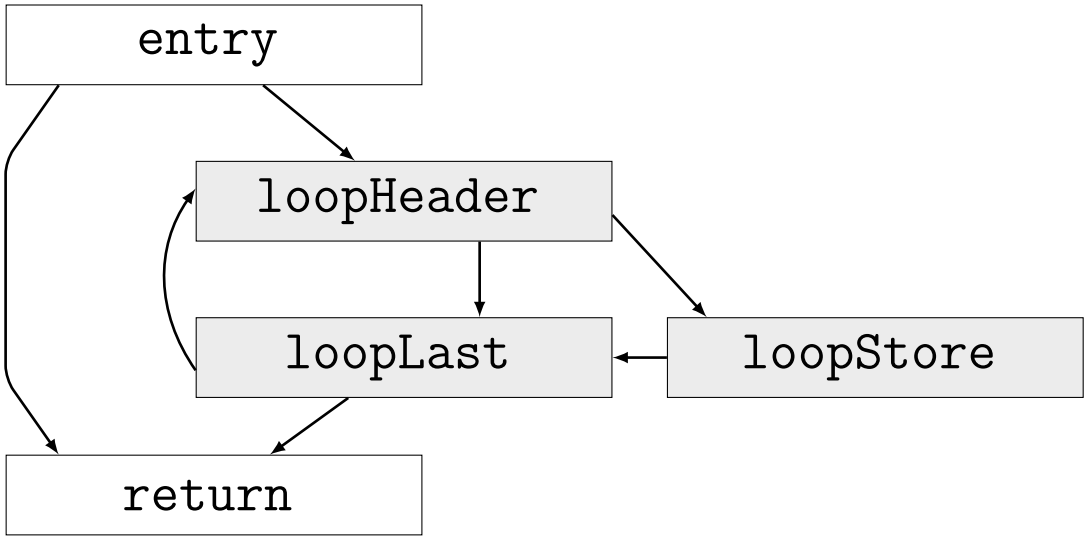
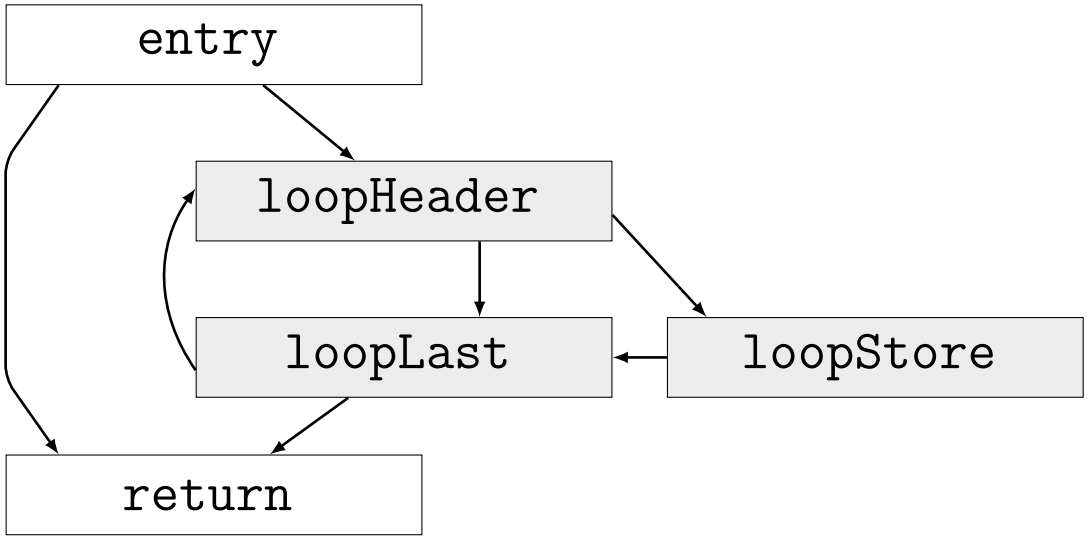
Thank you.

- Only branch at end of blocks $\Rightarrow$ Basic blocks as atomic units of control flow of function



- Block *A dominates* block *B* ("*A* dom *B*") iff in every execution, *A* is executed before *B*.
  - `entry` dominates all blocks
  - `loopHeader` dominates all blocks in the loop
  - `loopStore` and `return` dominate no blocks but themselves
- *Strict* domination ("*A* sdom *B*") iff additionally $A \neq B$

Dominator Tree



- Each block *B* but the initial block has a unique *immediate dominator I* such that
  1. *I* sdom *B* and
  2. There is no *A* with *I* sdom *A* and *A* sdom *B*
- Example:
  - `entry` sdom `loopLast`, but `entry` is not the immediate dominator of `loopLast`:
  - `entry` sdom `loopHeader` and `loopHeader` sdom `loopLast`
  - However, `loopHeader` is the immediate dominator of `loopLast`
- This yields the *dominator tree* in which the parent nodes dominate their child nodes

Natural Loops

Loop Invariant Code Motion operates on *natural loops*

- H is always executed before B and B has an edge back to H (“back edge”)
  $\Rightarrow$ H is header of the loop defined by the back edge
- All blocks A that have a path to B and H is always executed before A are part of the loop