Fifth Project: Data flow Analysis & Optimizations

In this fifth project, you will do some analysis and optimizations of the MJIR. After building the CFG for each function in the program, you should perform some basic optimizations, such as constant propagation, constant folding and elimination of dead code, as described in the following sections.

After performing these optimizations, you can simplify the CFG by:

- merging consecutive blocks in which the father has one child, the child one parent and both have compatible instructional leaders;
- finding all immediate dead blocks and remove them, and finally
- removing unused allocations.

This simplification of the CFG is optional, but recommended. We will try to give you a hand by giving you some of the pieces prewritten and littered your code with helpful statements. By the time you are done, you will have a pretty thorough understanding of the analyses and optimizations realized by real compilers.

DataFlow Analysis

Reaching Definitions

Reaching definitions is one of the most common and useful dataflow analysis. By knowing where in a program each variable `x` may have been defined when control reaches each point `p`, we can determine many things about `x`. For just one example, a compiler then knows whether `x` is a `constant` at point `p`.

We say a definition `d` reaches a point `p` if there is a path from the point immediately following `d` to `p`, such that `d` is not "killed" along that path. We kill a definition of a variable `x` if there is any other definition of `x` anywhere along the path. Intuitively, if a definition `d` of some variable `x` reaches point `p`, then `d` might be the place at which the value of `x` used at `p` was last defined.

A definition of a variable `x` is a statement that assigns a value to `x`. For the sake of simplicity, assume that we are dealing only with variables without any aliases.

Iterative Algorithm for Reaching Definitions

For a generic instruction, we define the GEN and KILL sets as follows:

- GEN $[d : y \leftarrow f(x_1, \cdots, x_n)] = \{d\}$, a set of locally available definitions in a basic block

- KILL $[d : y \leftarrow f(x_1, \cdots, x_n)] = \text{DEFS}[y] - \{d\}$, a set of definitions (not locally available, but in the rest of the program) killed by definitions in the basic block.

where DEFS[y] is the set of all definitions that assign to the variable y. Here d is a unique label attached to the assigning instruction; thus, the domain of values in reaching definitions are these instruction labels.

We assume that every control-flow graph has an ENTRY node, which represents the starting point of the graph, and an EXIT node to which all exits out of the graph go. Since no definitions reach the beginning of the graph, the transfer function for the ENTRY block is a simple constant function that returns ϕ as an answer.

The reaching definitions problem is defined by the following equations:

OUT[ENTRY] = ϕ

and for all basic blocks B other than ENTRY,

$$OUT[B] = gen_B \bigcup (IN[B] - kill_B)$$

$$IN[B] = \bigcup_{p \ a \ predecessor \ of \ B} OUT[P]$$

These equations can be solved using the following algorithm:

```
// Initialize
for all CFG block b in B,
  OUT[b] = emptyset;

// put all blocks into the changed set
// B is all blocks in graph,
Changed = B;

//Iterate
while (Changed != emptyset)
{
  choose a block b in Changed;
  // remove it from the changed set
  Changed = Changed - { b };

  // init IN[b] to be empty
  IN[b] = emptyset;

  // calculate IN[b] from predecessors' OUT[p]
  for all blocks p in predecessors(b)
     IN[b] = IN[b] Union OUT[p];

  oldout = OUT[b]; // save old OUT[b]
```

```
    // update OUT[b] using transfer function f_b ()
    OUT[b] = GEN[b] Union (IN[b] - KILL[b]);

    // any change to OUT[b] compared to previous value?
    if (OUT[b] changed) // compare oldout vs. OUT[b]
    {
      // if yes, put all successors of b into the changed set
      for all blocks s in successors(b)
         Changed = Changed U { s };
    }
  }
```

Liveness Analysis

Liveness analysis is a data flow analysis that finds what variables are live after any statement. It is an any-path, backward flow analysis. We will perform intra-procedural liveness analysis (i.e., we will compute liveness at the function granularity, but not across functions).

Once you have built the CFG, liveness analysis is easy. Compute the GEN and KILL sets for each block. GEN represents all the temporaries and variables that are used in an instruction, and KILL represents all the temporaries and variables that are defined in an instruction. For most instructions, this should be pretty straightforward. A few tricky cases:

- `store_type` this instruction use source (GEN) & define target (KILL) while `store_type_*` use both source & target. Note that this strategy means that you do not touch the `alloc_type` instructions. An extra pass can be made at final to remove unused allocs.
- `call` instructions require special care. Because we do not analyze liveness across functions, we must make conservative assumptions about what happens in function calls. In particular, we GEN all the temporaries in `param_type`. The `call` itself kills the return var. The GEN set for any `call` instruction therefore contains all global variables, while the KILL set is their return var.

Once you know the GEN and KILL sets for each CFG node, you can compute liveness. To do this, define IN (live-in) and OUT (live-out) sets for each CFG Node. Initialize the OUT sets for Exit nodes to all global variables (because global variables may be used after the function returns), and initialize all other sets to empty. Then compute the live-in and live-out sets for node as follows:

- The set of variables that are live out of a node is the union of all the variables that are live in to the node's successors.
- The set of variables that are live in to a node is the set of variables that are live out for the node, minus any variables that are killed by the node, plus any variables that are gen-ed by the node.

Note that these definitions are recursive: the live-out set of a node is defined in terms of the live-in sets of its successors, which are in turn defined in terms of the live-in sets of their successors, and so on. If there is a loop in the code, then the definition seems circular.

The trick to computing liveness is to compute a fixpoint: assignments to each of the live-in and live-out sets so that if you try to compute any node's live-in or live-out set again, you will get the same result you already have. To do this, we will use a worklist algorithm:

1. Put all the IR nodes on the worklist
2. Pull an IR node off the worklist, and compute its live-out and live-in sets according to the definitions above.
3. If the live-in set of the node gets updated by the previous step, put all of the node's predecessors on the worklist (because they may need to update their live-out sets).
4. Repeat steps 2 and 3 until the worklist is empty. The live-out sets of each node now represent a fixpoint.

Constant Propagation

Constants assigned to a variable can be propagated through the flow graph and substituted at the use of the variable.

Example: In the code fragment below, the value of x can be propagated to the use of x.

```
int x = 14;
int y = 7 - x / 2;
return y * (28 / x + 2);
```

Below is the code fragment after `constant propagation` and `constant folding` (which would likely be further optimized by `dead code elimination` of both x and y).

```
int x = 14;
int y = 0;
return 0;
```

Constant propagation is implemented in compilers using `reaching definition` analysis results. If all variable's reaching definitions are the same assignment which assigns a same constant to the variable, then the variable has a constant value and can be replaced with the constant.

Constant propagation can also cause conditional branches to simplify to one or more unconditional statements, when the conditional expression can be evaluated to true or false at compile time to determine the only possible outcome.

Dead Code Elimination

Code that is unreachable or that does not affect the program (e.g. dead stores) can be eliminated.

Example: In the example below, the value assigned to it is never used, and the dead store can be eliminated. The first assignment to global is dead, and the third assignment to global is unreachable; both can be eliminated.

```
class Program {
    int global;
    public void f ()
    {
        int i;
        i = 1;               /* dead store */
        this.global = 1;     /* dead store */
        this.global = 2;
        return;
        this.global = 3;     /* unreachable */
    }
}
```

Below is the code fragment after dead code elimination.

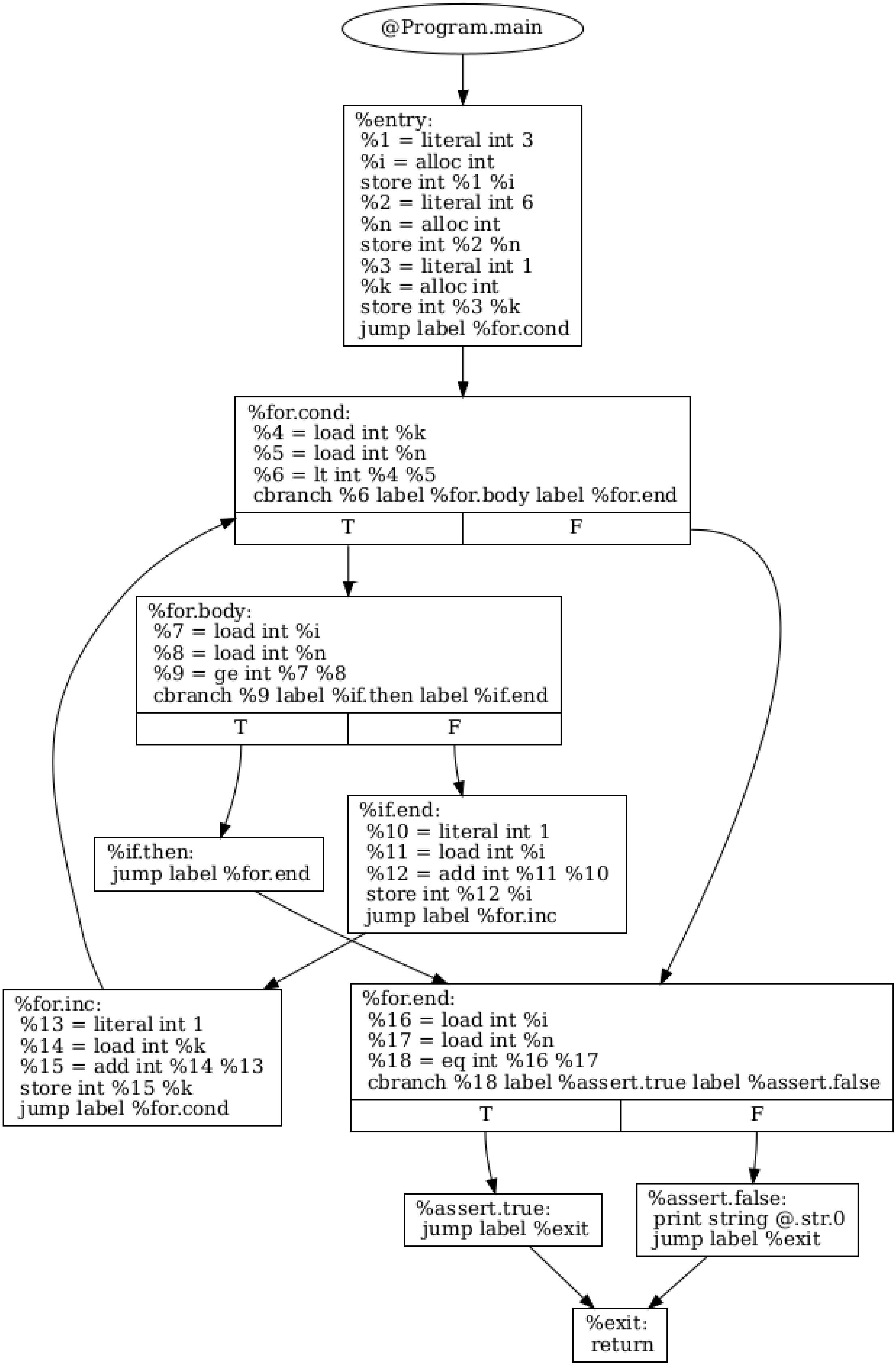
```
class Program {
    int global;
    void f ()
    {
        this.global = 2;
        return;
    }
}
```

Examples

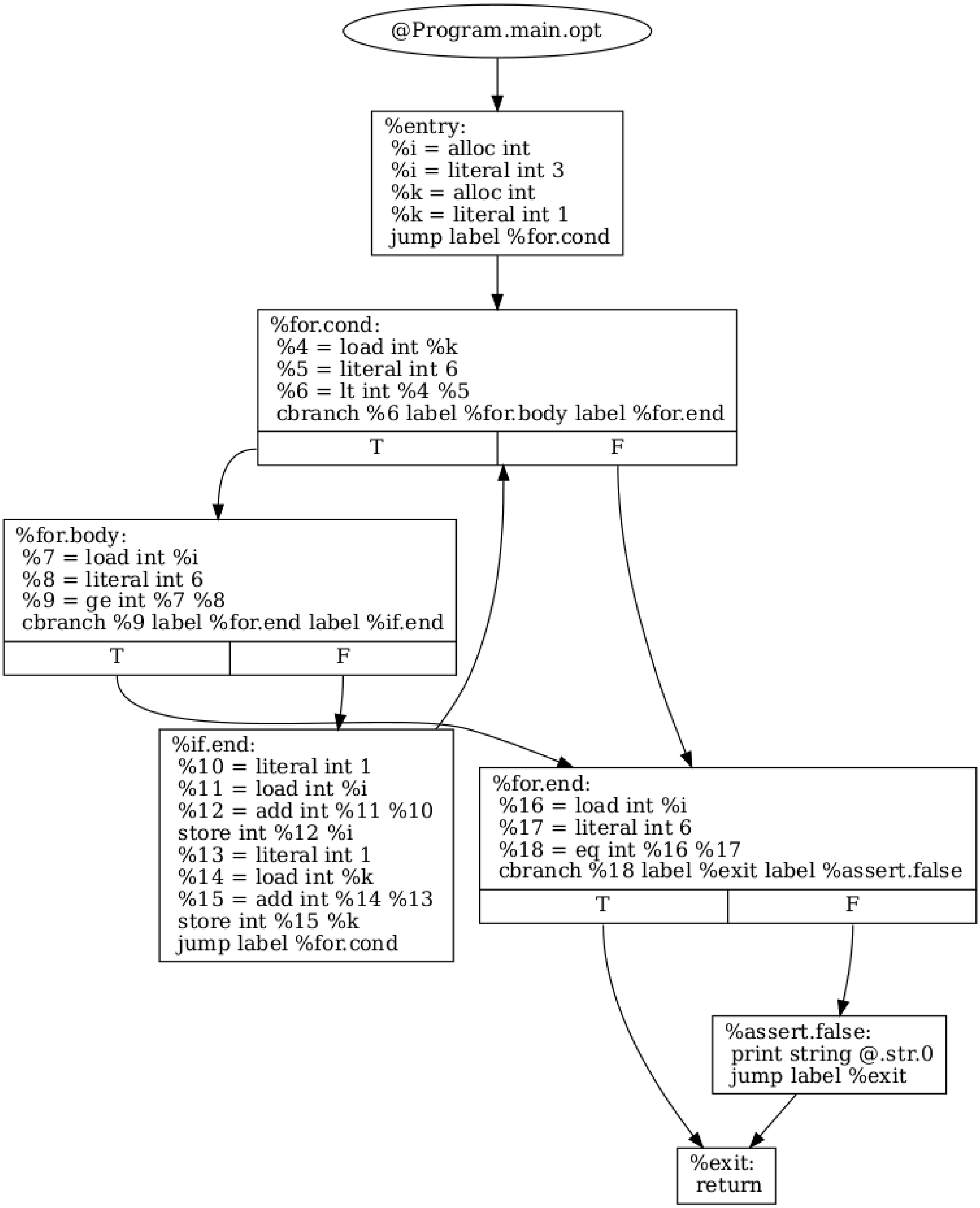
```
class Program {
    public static void main(String[] args) {
        int i = 3, n = 6;
        for (int k = 1; k < n; k=k+1) {
            if (i >= n) {
                break;
            }
            else {
```

```
                i=i+1;
            }
        }
        assert i == n;
    }
}
```

CFG before optimization:



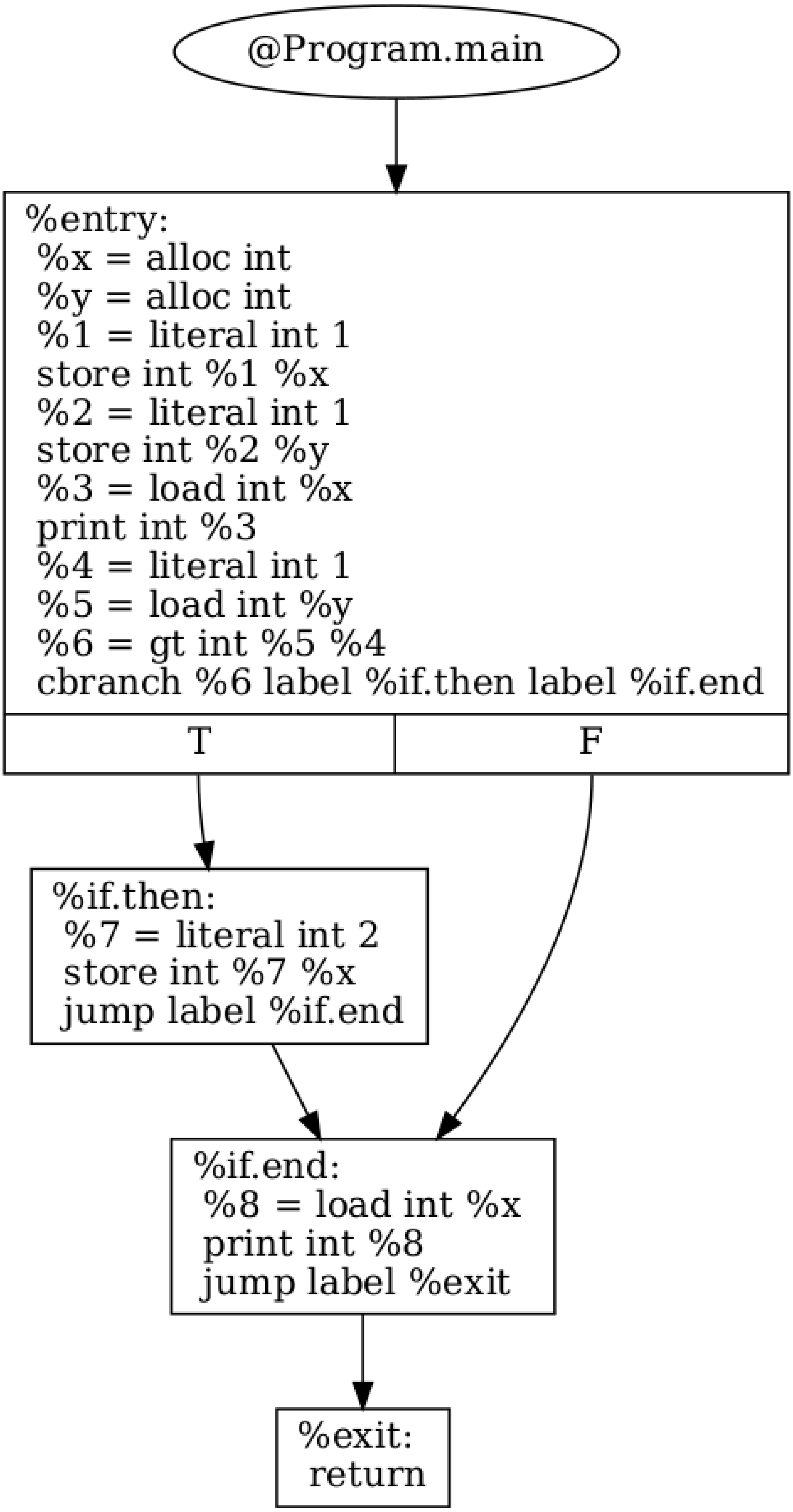
CFG after optimization:



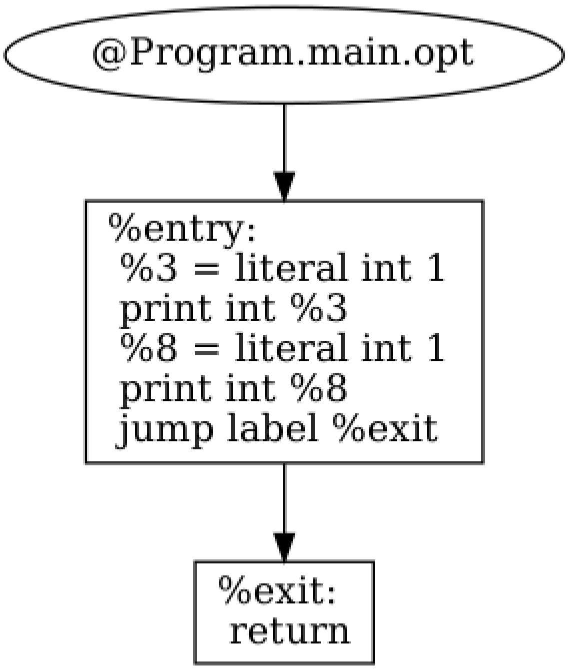

```
class Program {
    public static void main(String[] args) {
        int x, y;
        x = 1;
        y = 1;
        print(x);
```

```
        if (y > 1) {
            x = 2;
        }
        print(x);
    }
}
```

CFG before optimization:



CFG after optimization:



Performing Analysis & Optimizations

As you may have noted, we kept the CFG built for each method as an attribute of the `MethodDecl` node in the AST. This is not the traditional approach: we could have built a new object which would represent the IR of the whole program apart from AST, since we no longer depend on it. But we decided to reuse the AST to avoid creating yet another data-structure. As a result, the method below visit the `method_decls` nodes from the `class_decls` in the root node (`Program`) to have access to the CFGs of the functions in order to perform the analyzes and apply the optimizations.

```
class DataFlow(NodeVisitor):
    def __init__(self, viewcfg):
        # flag to show the optimized control flow graph
        self.viewcfg = viewcfg
        # list of code instructions after optimizations
        self.code = []
        ...

    def show(self):
        _str = ""
        for _code in self.code:
            _str += format_instruction(_code) + "\n"
        rich.print(_str.strip())
```