Contents of Lecture 5

- Constant Folding
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Constant Folding

```
#define KB (1024)
#define MB (KB * KB)

char buffer[8 * MB]

double f(void)
{
   double         a = 1.0/3.0;
   static double b = 1.0/3.0;
   double         pi = 4 * atan(1);

}
```

- C/C++ compilers are required to perform a simple form of constant propagation called **constant folding**.
- Floating point expressions must be evaluated as if the rounding mode is taken into account (which can be set at runtime).
- In static initializers, the default rounding mode may be used.
- Many compilers exploit the C rule that the identifiers of the standard library functions are reserved — we know $\pi = 4 \times atan(1)$

Constant Propagation with Iterative Dataflow Analysis

```
a = 1;
b = 2;
if (a < b)
        c = 3;
else
        c = 4;
put(c);
```

- Invented Gary Kildall 1973.
- Every variable can be either
  - Undef
  - Constant
  - Non-constant
- Iterative dataflow analysis is performed to determine whether a variable is constant and in that case which constant.
- All branches (i.e. paths in a function) are assumed to be executable.
- Since c cannot be both 3 and 4 it's assumed to be nonconstant.

Constant Propagation with Conditional Branches

```
a = 1;
b = 2;
if (a < b)
        c1 = 3;
else
        c2 = 4;
c3 = phi(c1, c2);
put(c3);
```

- Based on SSA Form.
- Invented at IBM Research and published 1991.
- Recall Kildall's algorithm assumed every branch was executable.
- This algorithm assumes that nothing is executable except the start vertex.
- The function is interpreted and the constant expressions are propagated.
- The interpretation proceeds until no new knowledge about constants can be found.

Key Idea with ϕ-functions

```
a = 1;
b = 2;
if (a < b)
        c1 = 3;
else
        c2 = 4;
c3 = phi(c1, c2);
put(c3);
```

- Thanks to SSA Form, one statement and variable is analyzed at a time.
- At a ϕ-function, if any operand is nonconstant the result is nonconstant, and if any two constants have different values the result also is nonconstant.
- However, operands corresponding to branches which we don't think will be executed can be ignored for the moment.
- While interpreting the program we may later realize that the branch in fact might be executed and then the ϕ-function will be re-evaluated.
- We can ignore c_2 and let c_3 be 3.

Result from Two ϕ-operands

x	y	$x \wedge y$
nonconst	–	*nonconst*
–	*nonconst*	*nonconst*
undef	*undef*	*undef*
undef	$m \in \mathbb{Z}$	m
$m \in \mathbb{Z}$	*undef*	m
$m \in \mathbb{Z}$	$n \in \mathbb{Z}, n \neq m$	*nonconst*
$m \in \mathbb{Z}$	$n \in \mathbb{Z}, n = m$	m

Interpreting Unconditional Branches

```
a = 1;
b = 2;
goto L;
/* ... */
L:
```

- In the vcc compiler, an unconditional branch is called a branch-always and has mnemonic `BA`.
- The name branch-always comes from the SPARC instruction.
- A branch-always should simply tell the interpreter that the target basic block should be interpreted in the future.
- Actually we don't have a list of basic blocks waiting for interpretation but rather a list of edges.

Interpreting Conditional Branches 1(2)

```
label   U
mov     1,a
mov     2,b
bgt     a,b,V
ba      W
```

- When the branch condition can be evaluated only one of the successors should be put on the list of edges to be interpreted.
- In this case it is the edge (u, w) that is put on the list.

Interpreting Conditional Branches 2(2)

```
label   U
mov     x,a
mov     2,b
bgt     a,b,V
ba      W
```

- Assume `x` is nonconstant.
- Both edges (u, v) and (u, w) are put on the list.

Uses of a Variable on SSA Form

- Every variable has a list of instructions (three-address statements) in which it is used.
- This list is called the **uselist** of a variable and some compilers maintain it while others don't.
- With it, algorithms can be somewhat simpler but they obviously need some memory.
- For example SGI's compiler doesn't use it, while lmpcc and vcc do.
- When we have determined that the value of a variable has been lowered from Undef or Constant we must re-evaluate all instructions in which the variable is used.

Two Worklists are Maintained during Interpretation

- The **edge-worklist** of new edges to interpret.
- The **ssa-worklist** of uses which need to be re-evaluated.
- The algorithm can take an object from the lists in any order and perform interpretation. The result will always be the same.
- The algorithm terminates when both lists are empty.
- The statements are modified **after** the interpretation is complete.

Visiting a Basic Block

- Only the first time a basic block is processed are all its statements interpreted.
- On subsequent processing of v due to an edge (u, v) only the ϕ-functions in v must be re-evaluated.
- They have to be re-evaluated since the previous times v was processed we can have ignored the operand corresponding to the edge (u, v).
- The other statements will be re-evaluated if they enter the **ssa-worklist**.

Main Algorithm

```
procedure cprop
    for each definition d do
        value(d) ← ⊤
    for each vertex w do
        visited(w) ← false
    visit_vertex(s)
    while (not empty(edge_worklist) or not empty(ssa_worklist)) do
        if (not empty(edge_worklist))
            edge ←take edge from edge_worklist
            if (not executable(edge))
                set_executable(edge)
                visit_vertex(head(edge))
        if (not empty(ssa_worklist))
            t ←take statement from ssa_worklist
            visit_stmt(t)
```

Visiting a Basic Block

```
procedure visit_vertex(w)
    bool    onlyphi

    onlyphi ← visited(w)
    set_visited(w)
    for each statement t in w do
        if (onlyphi  and t is not φ)
            return
        visit_stmt(t)
```

Visiting a Statement 1(3)

```
procedure visit_stmt(t)
    w ← vertex(t)
    switch (stmt_type(t)) {
    case unconditional_branch:
        add_edge(w, succ(w))
        break

    case conditional_branch:
        add appropriate edges depending on what is known
        about the operands
        break
```

Visiting a Statement 2(3)

case add:
    left $\leftarrow$ value of first source operand
    right $\leftarrow$ value of second source operand
    result $\leftarrow$ what can be determined from *left* and *right*
    if (*result* $<$ *value*(t))
        add uses of destination of t to *ssa_worklist*
        value(t) $\leftarrow$ *result*
    break

Visiting a Statement 3(3)

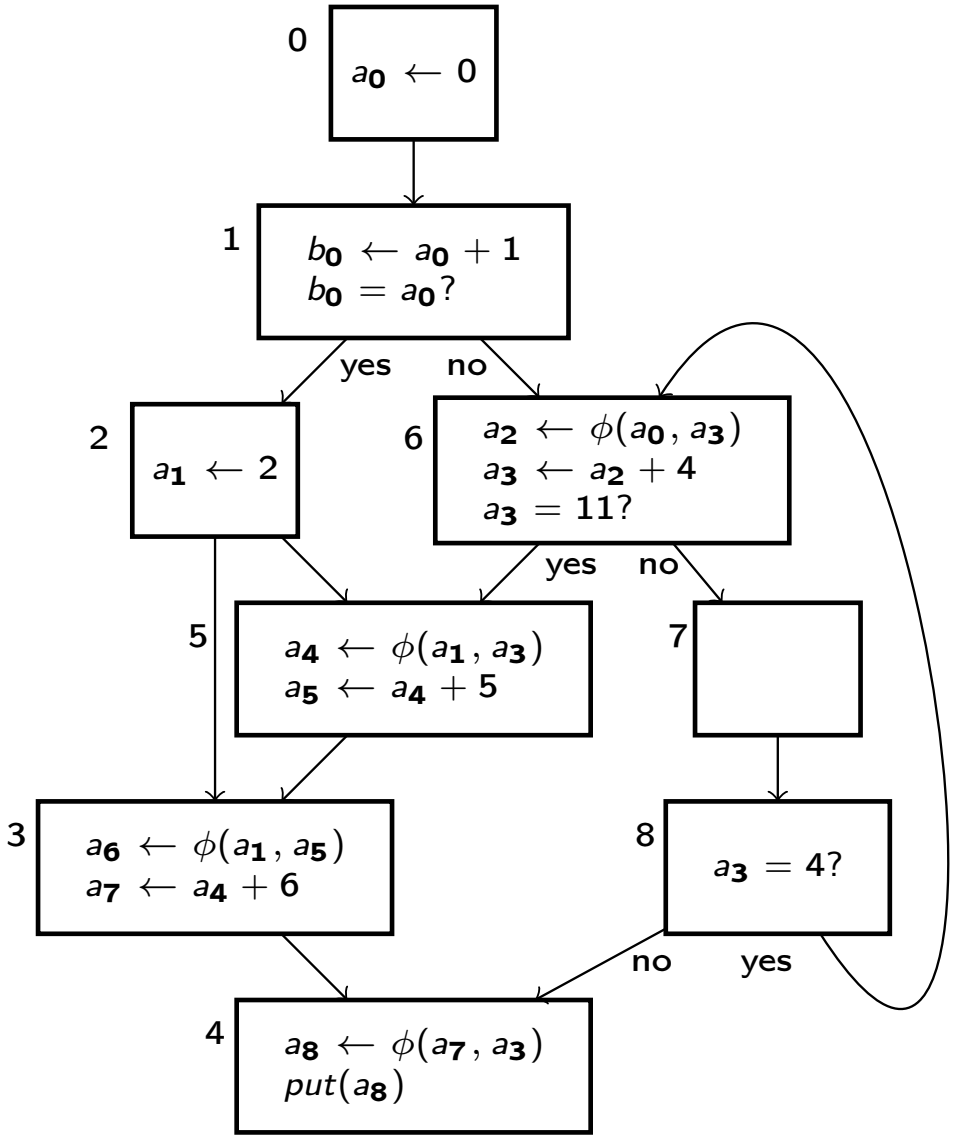
case ϕ:

    $result \leftarrow \top$
    for each $p \in pred(w)$ **do**
        if (the edge (p, w) is marked *executable*)
            $value \leftarrow$ value of ϕ-function operand for p
            $result \leftarrow result \wedge value$
    if $(result < value(t))$
        add uses of destination of t to *ssa_worklist*
        $value(t) \leftarrow result$
    break

    ⋮

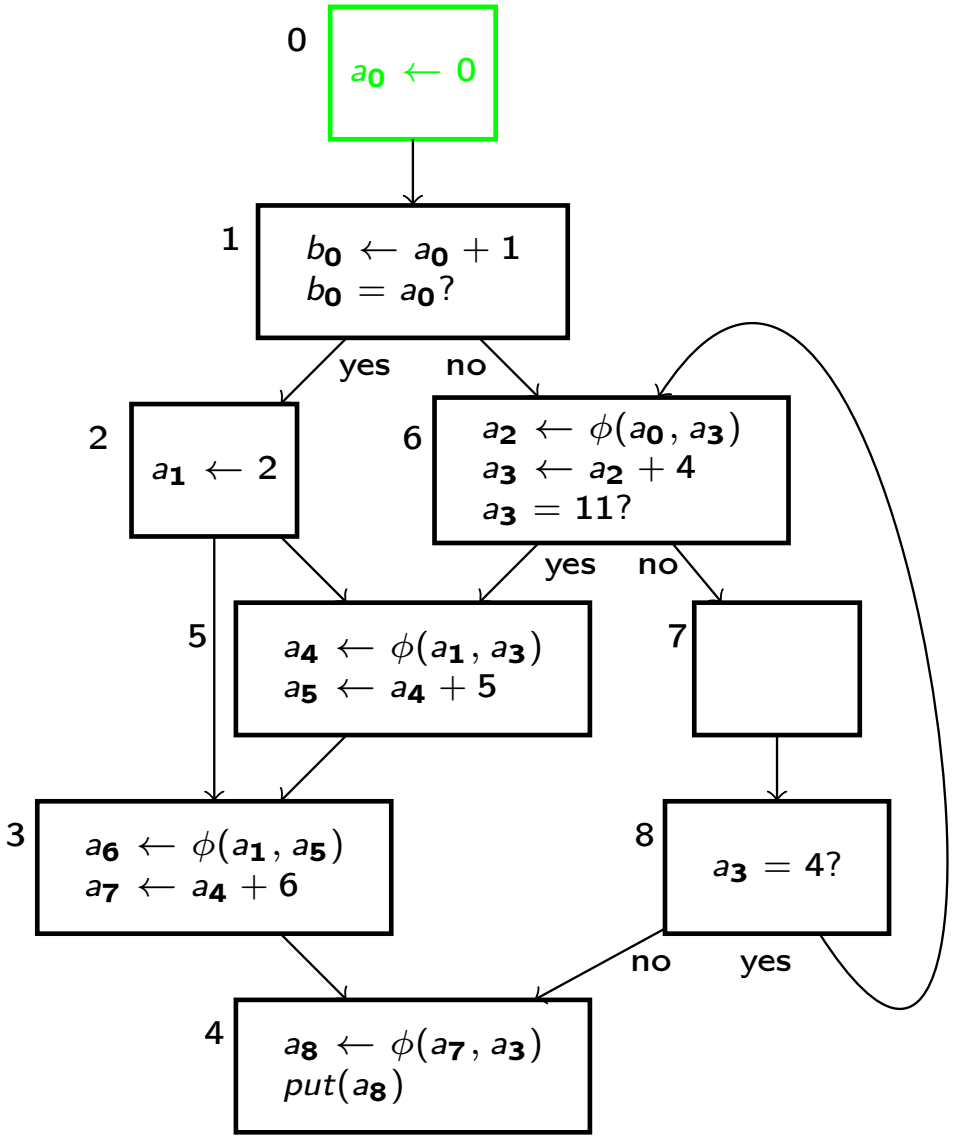
}

An Example 1(10)



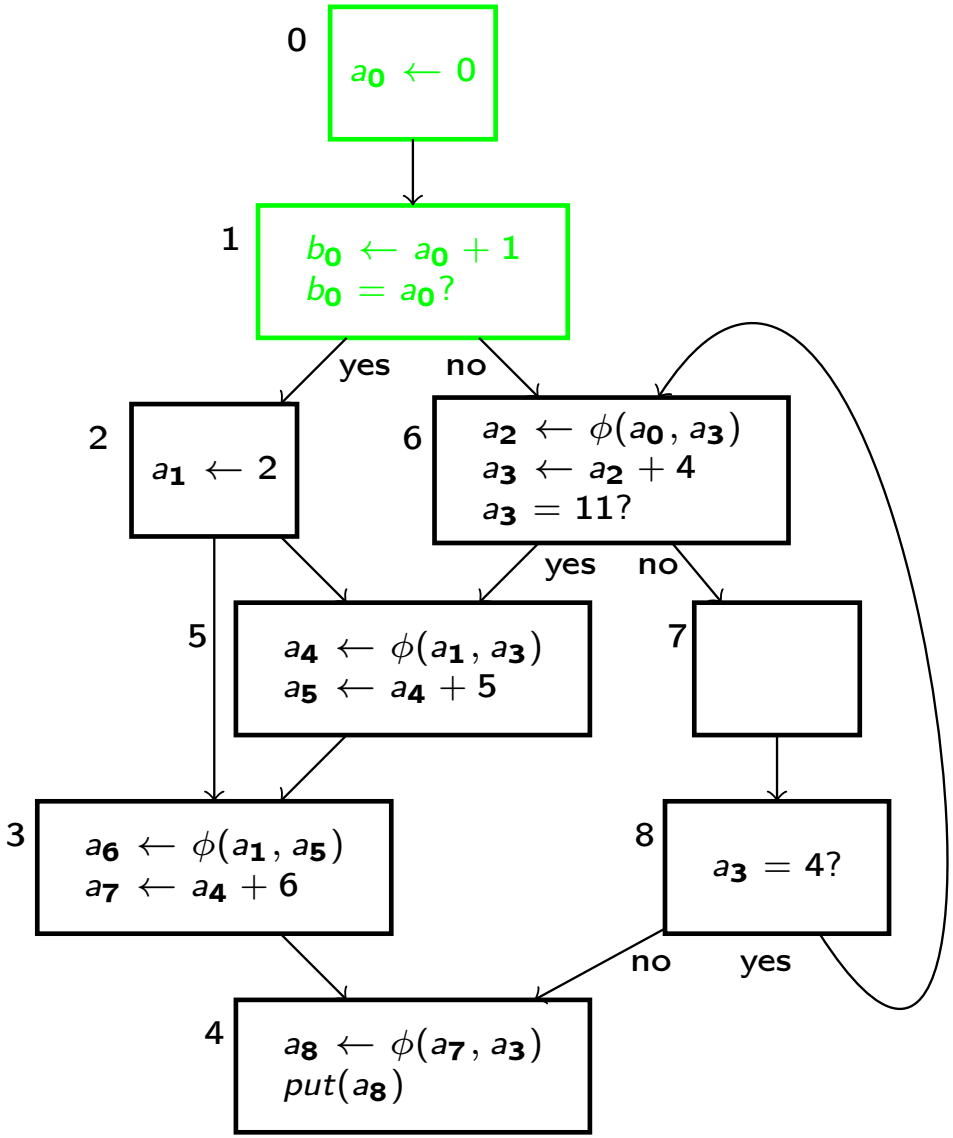
- $edge\_worklist = \emptyset$
- $ssa\_worklist = \emptyset$

An Example 2(10): Visit 0



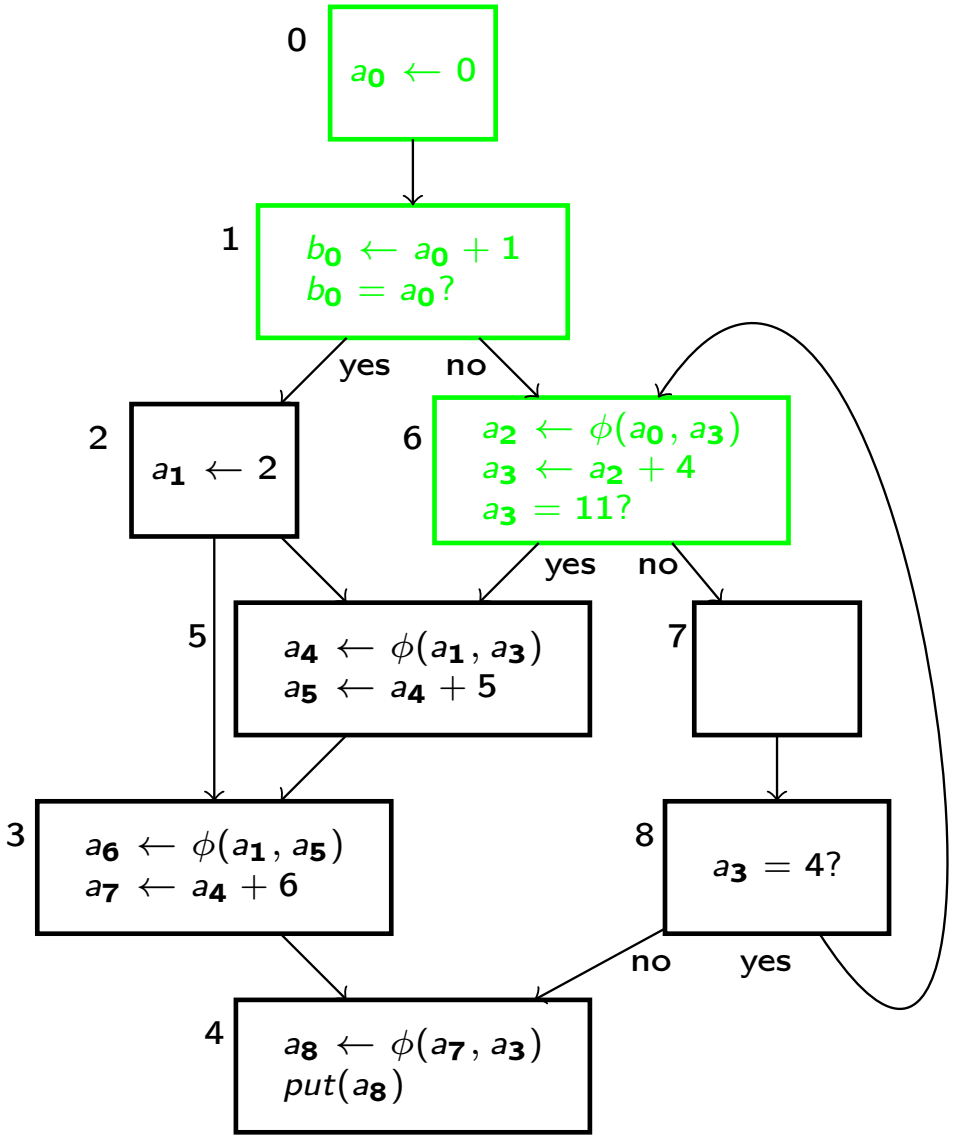
- $edge\_worklist = \{(0, 1)\}$

An Example 3(10): Visit 1



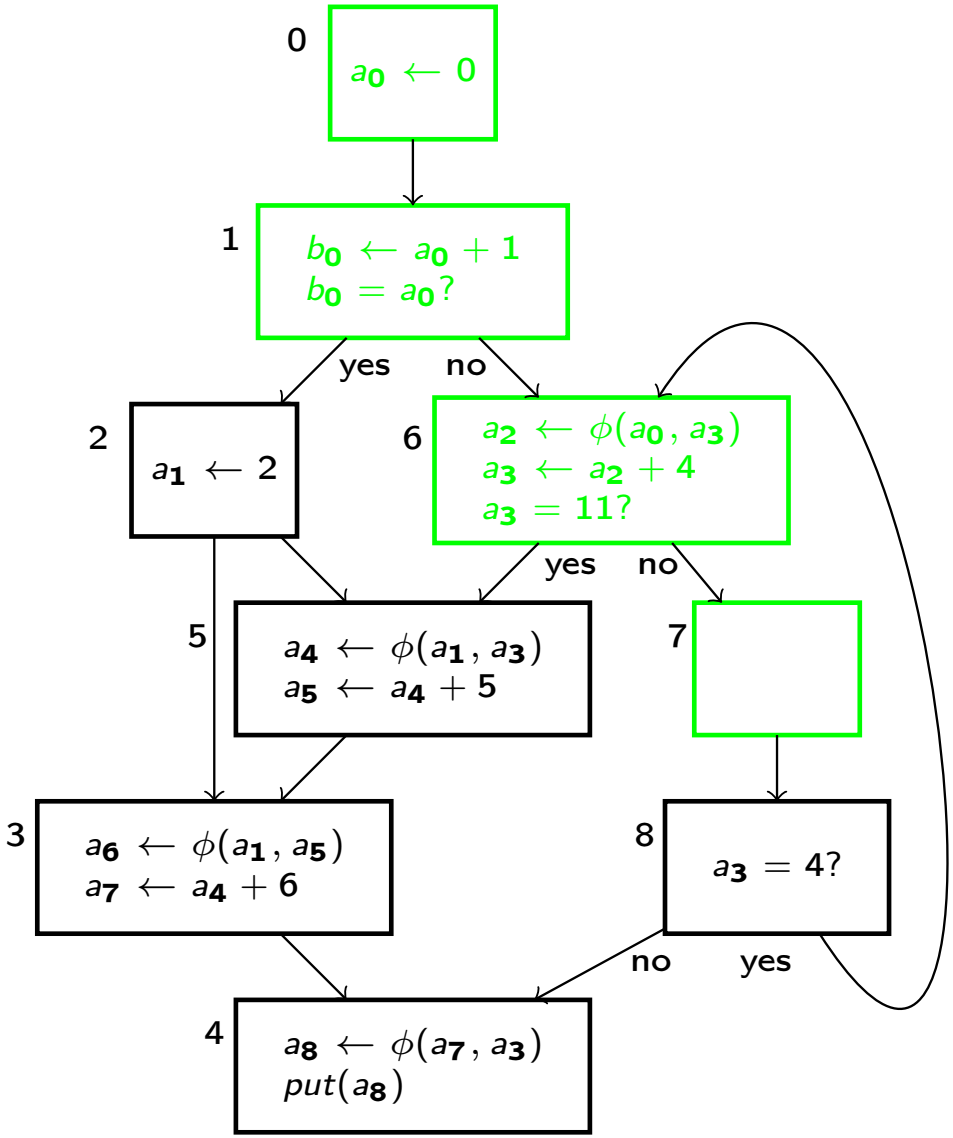
- $edge\_worklist = \{(1, 6)\}$

An Example 4(10): Visit 6



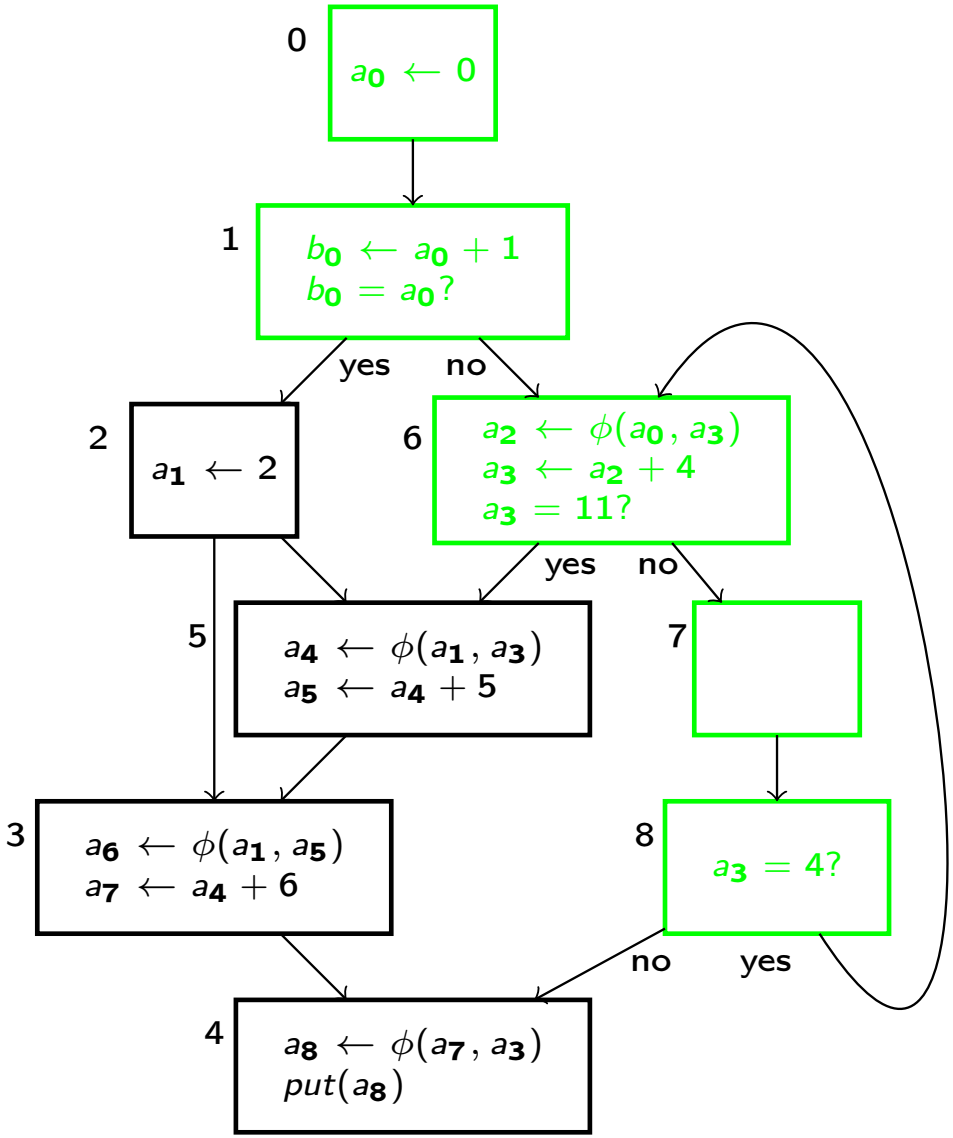
- Ignore a_3 in ϕ-function in vertex 6.
- $edge\_worklist = \{(6, 7)\}$

An Example 5(10): Visit 7



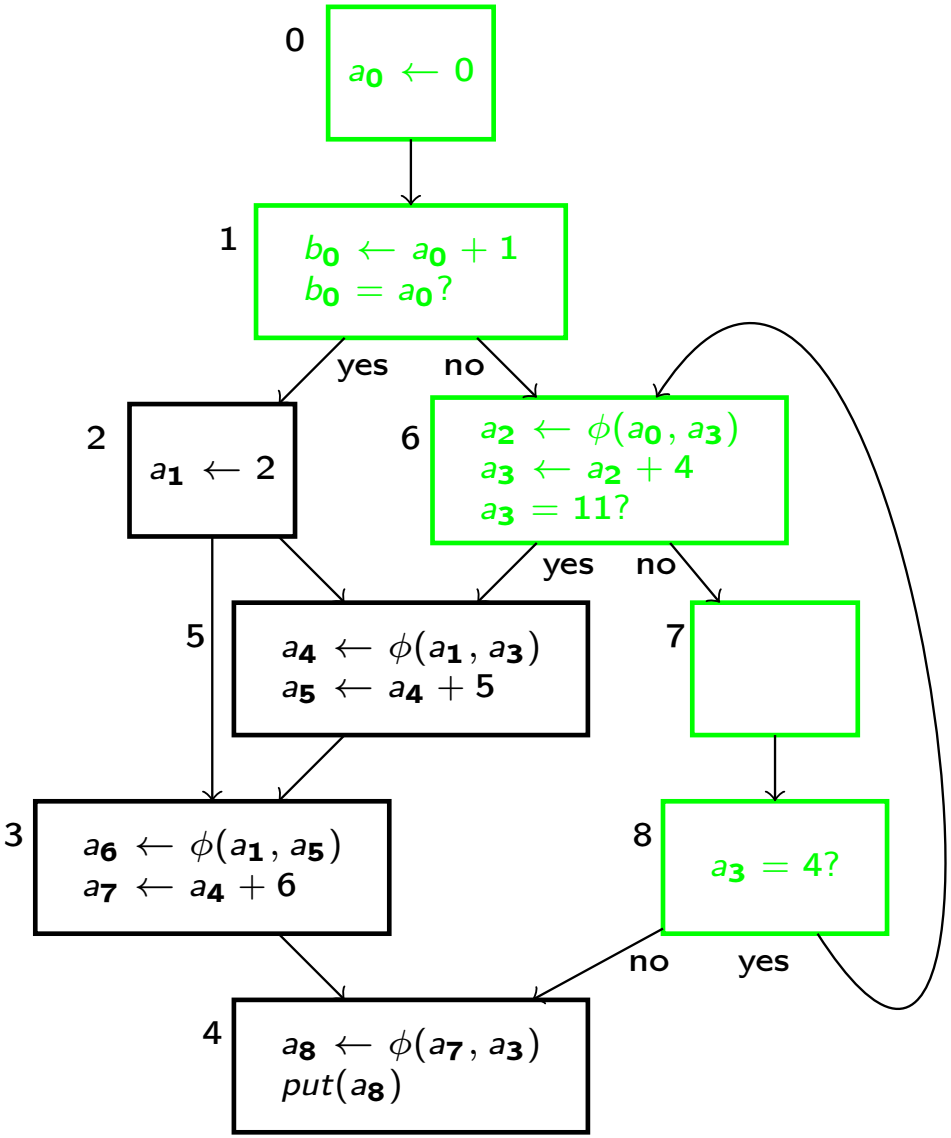
- Ignore a_3 in ϕ-function in vertex 6.
- $edge\_worklist = \{(7, 8)\}$

An Example 6(10): Visit 8



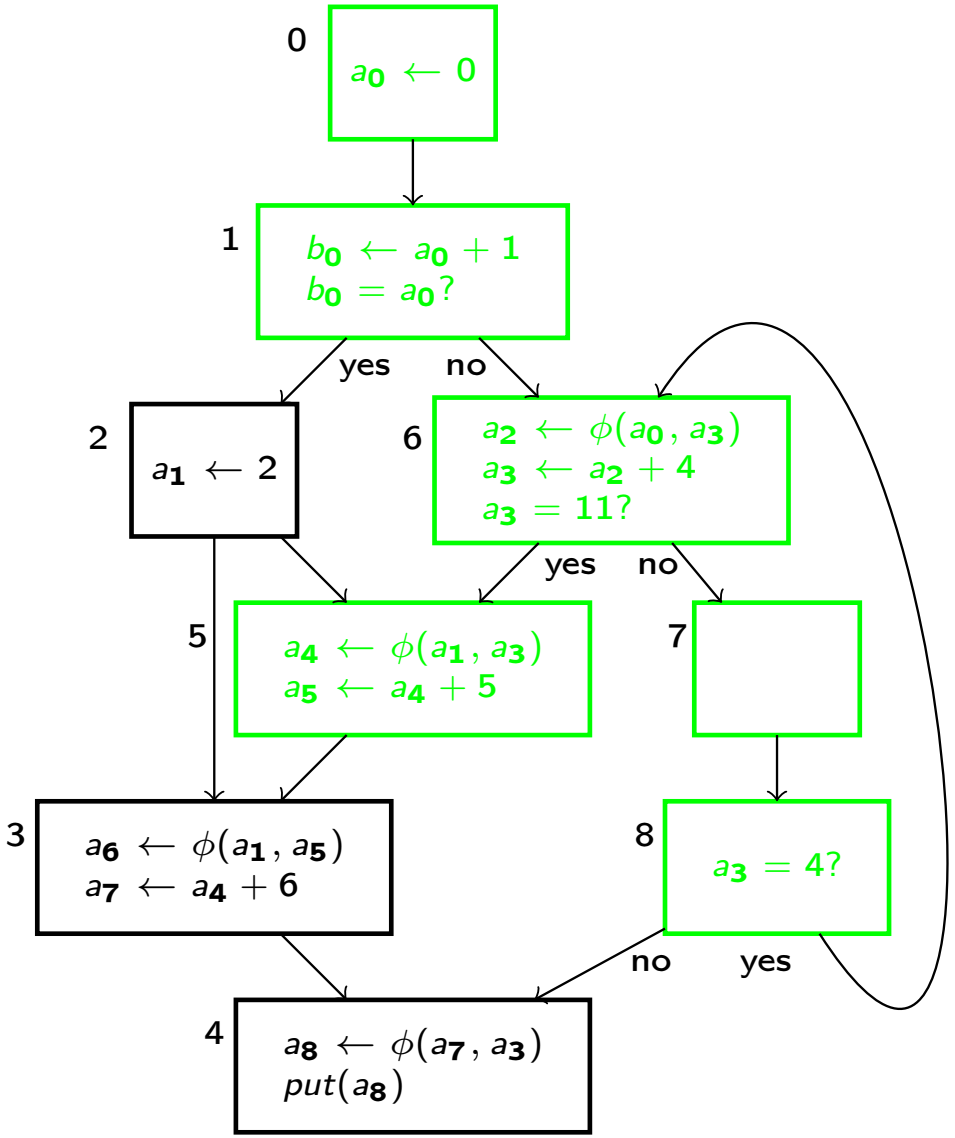
- $edge\_worklist = \{(8, 6)\}$

An Example 7(10): Revisit 6



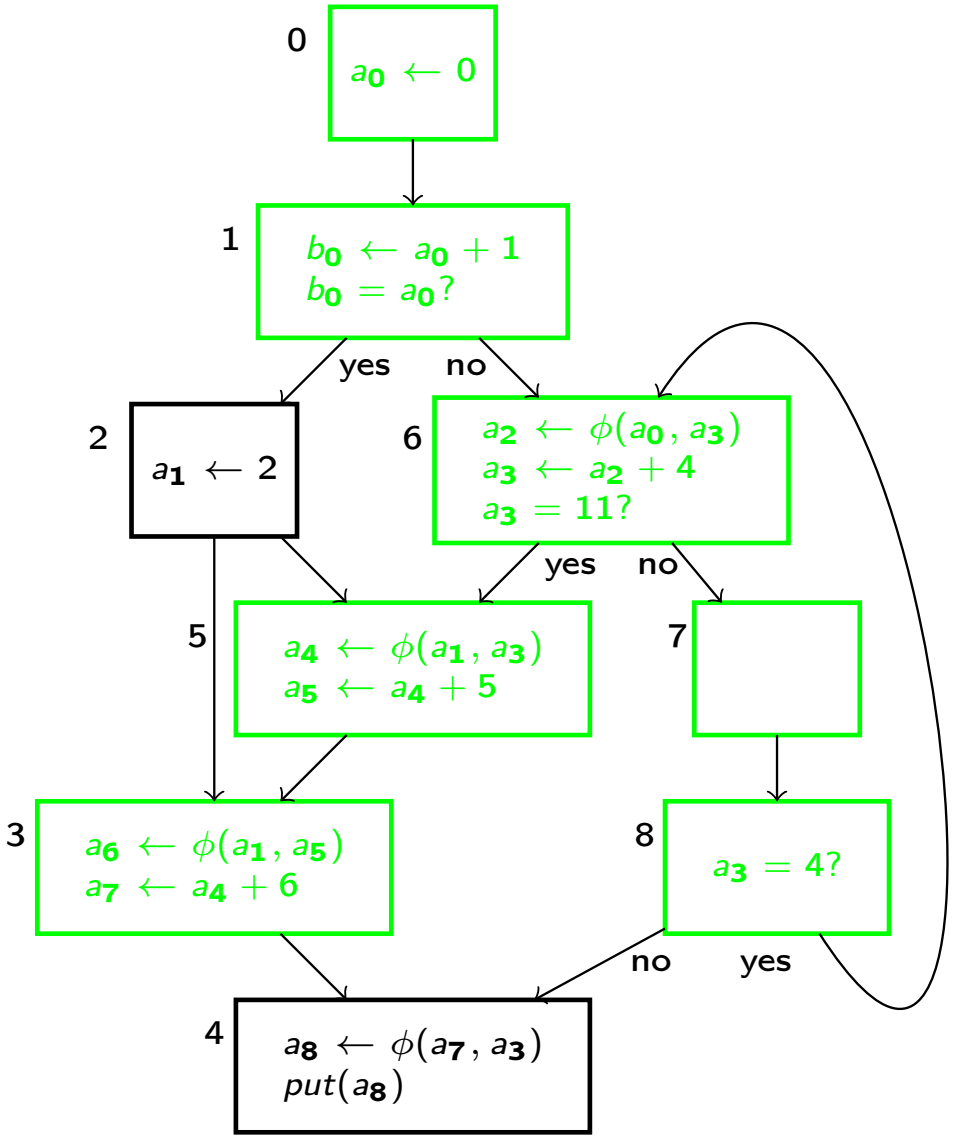
- Now only the ϕ-function is re-evaluated at first.
- This time a_2 is classified as a nonconstant.
- Then use of a_2 is put in the ssa-worklist.
- Then use of a_3 in the branch is put in the ssa-worklist.
- Since a_3 is nonconstant also $(6, 5)$ will be interpreted.
- $edge\_worklist = \{(6, 5)\}$

An Example 8(10): Visit 5



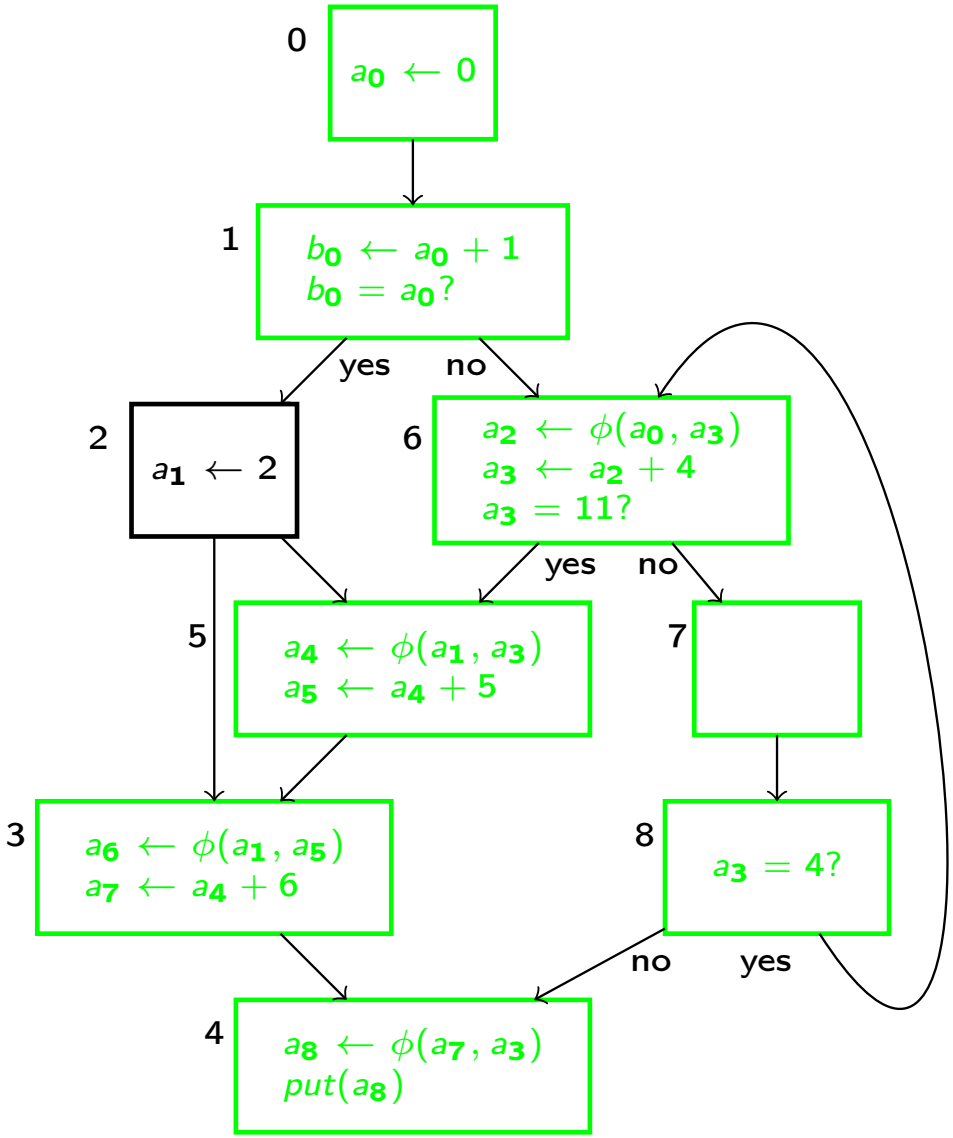
- Now a_1 is ignored but a_3 is nonconstant.
- a_4 and a_5 become nonconstant as well.
- $edge\_worklist = \{(5, 3)\}$

An Example 9(10): Visit 3



- Again a_1 is ignored but a_5 is nonconstant.
- a_6 and a_7 become nonconstant as well.
- $edge\_worklist = \{(3, 4)\}$

An Example 10(10): Visit 4



- a_8 will be read from memory.
- Vertex 2 and the branch to it can be deleted.
- In this example, for simplicity, we have not included the contents of the ssa-worklist.

Simple Extensions 1

```
if (a != 44)
        b = a + 1;
else {
        b = a + 2;
        f(b);
}
```

- The parameter must have the value 46.
- By inserting `b = 44` in the else-clause, the constant propagation algorithm is helped.

Simple Extensions 2

```
if (x != y) {
        a = 1;
        b = 2;
} else {
        a = 2;
        b = 1;
}

c = a + b;
```

- Clearly the sum is 3 but the present algorithm cannot find this.
- It's a rather trivial extension to "enhance" the algorithm to cover such codes as well.
- Is it worth it? No, only in very rare codes is it beneficial while all compilations would be somewhat slower.
- Also see next slide for an important principle!

A Remark About Rarely Used Optimizations

- And a more important point than making the compiler slightly slower: **never** include optimizations in a compiler which are rarely useful because then they are much more likely to contain obscure bugs than if they are used millions of times every day!
- There was a famous bug in a Bell Labs FORTRAN compiler which was an "optimization" which had never been useful for years.
- Once it was but it resulted in incorrect code and a lot of confusion for the programmer!
- It is said to have costed the compiler writer several days to implement for no use and then additional application debugging time!