Constant Folding
Earlier Constant Propagation Algorithms
Constant Propagation with Conditional Branches
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.

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.
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 $\phi$-functions

Thanks to SSA Form, one statement and variable is analyzed at a time.

At a $\phi$-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 $\phi$-function will be re-evaluated.

We can ignore $c_2$ and let $c_3$ be 3.
## Result from Two $\phi$-operands

<table>
<thead>
<tr>
<th>$x$</th>
<th>$y$</th>
<th>$x \land y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>nonconst</td>
<td>$-$</td>
<td>nonconst</td>
</tr>
<tr>
<td>$-$</td>
<td>nonconst</td>
<td>nonconst</td>
</tr>
<tr>
<td>$\text{undef}$</td>
<td>$\text{undef}$</td>
<td>$\text{undef}$</td>
</tr>
<tr>
<td>$\text{undef}$</td>
<td>$m \in \mathbb{Z}$</td>
<td>$m$</td>
</tr>
<tr>
<td>$m \in \mathbb{Z}$</td>
<td>$\text{undef}$</td>
<td>$m$</td>
</tr>
<tr>
<td>$m \in \mathbb{Z}$</td>
<td>$n \in \mathbb{Z}, n \neq m$</td>
<td>nonconst</td>
</tr>
<tr>
<td>$m \in \mathbb{Z}$</td>
<td>$n \in \mathbb{Z}, n = m$</td>
<td>$m$</td>
</tr>
</tbody>
</table>
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.
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.
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 executable instructions in which the variable is used.

An instruction in vertex $v$ is executable if there is an executable edge $(u, v)$ in the control flow graph.
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 $\nu$ due to an edge $(u, \nu)$ only the $\phi$-functions in $\nu$ must be re-evaluated.
- They have to be re-evaluated since the previous times $\nu$ was processed we ignored the operand corresponding to the edge $(u, \nu)$.
- The other statements will be re-evaluated if they enter the ssa-worklist and are executable.
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
            v ← vertex(t)
            if (any edge (u, v) is executable)
                visit Stmt(t)
Visiting a Basic Block

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

$\text{result} \leftarrow \top$

for each $p \in \text{pred}(w)$ do

if (the edge $(p, w)$ is marked executable)

$\text{value} \leftarrow \text{value of } \phi\text{-function operand for } p$

$\text{result} \leftarrow \text{result} \land \text{value}$

if ($\text{result} < \text{value}(t)$)

add uses of destination of $t$ to $\text{ssa\_worklist}$

$\text{value}(t) \leftarrow \text{result}$

break

::
An Example 1

\[
\begin{align*}
0 & : a_0 \leftarrow 0 \\
1 & : b_0 \leftarrow a_0 + 1 \\
& \quad b_0 = a_0? \\
2 & : a_1 \leftarrow 2 \\
6 & : a_2 \leftarrow \phi(a_0, a_3) \\
& \quad a_3 \leftarrow a_2 + 4 \\
& \quad a_3 = 11? \\
5 & : a_4 \leftarrow \phi(a_1, a_3) \\
& \quad a_5 \leftarrow a_4 + 5 \\
3 & : a_6 \leftarrow \phi(a_1, a_5) \\
& \quad a_7 \leftarrow a_4 + 6 \\
4 & : a_8 \leftarrow \phi(a_7, a_3) \\
& \quad put(a_8) \\
7 & : \\
8 & : a_3 = 4? \\
\end{align*}
\]

- \textit{edge\_worklist} = \emptyset
- \textit{ssa\_worklist} = \emptyset
An Example 2(10): Visit 0

- $a_0 \leftarrow 0$
- $b_0 \leftarrow a_0 + 1$
- $b_0 = a_0$?
- $a_2 \leftarrow \phi(a_0, a_3)$
- $a_3 \leftarrow a_2 + 4$
- $a_3 = 11$?
- $a_4 \leftarrow \phi(a_1, a_3)$
- $a_5 \leftarrow a_4 + 5$
- $a_6 \leftarrow \phi(a_1, a_5)$
- $a_7 \leftarrow a_4 + 6$
- $a_8 \leftarrow \phi(a_7, a_3)$
- put($a_8$)

- $\text{edge\_worklist} = \{(0, 1)\}$
An Example 3(10): Visit 1

$\phi(a, b) = \{a, b\}$

```
0
  \[a_0 \leftarrow 0\]

1
  \[b_0 \leftarrow a_0 + 1\]
  \[b_0 = a_0?\]
  yes
    \[a_1 \leftarrow 2\]
  no
    \[a_2 \leftarrow \phi(a_0, a_3)\]
    \[a_3 \leftarrow a_2 + 4\]
    \[a_3 = 11?\]

2
  \[a_4 \leftarrow \phi(a_1, a_3)\]
  \[a_5 \leftarrow a_4 + 5\]

3
  \[a_6 \leftarrow \phi(a_1, a_5)\]
  \[a_7 \leftarrow a_4 + 6\]

4
  \[a_8 \leftarrow \phi(a_7, a_3)\]
  \[\text{put}(a_8)\]

5

6
  \[a_2 \leftarrow \phi(a_0, a_3)\]
  \[a_3 \leftarrow a_2 + 4\]
  \[a_3 = 11?\]

7

8
  \[a_3 = 4?\]
```

- $\text{edge\_worklist} = \{(1, 6)\}$
An Example 4(10): Visit 6

- Ignore $a_3$ in $\phi$-function in vertex 6.
- $\text{edge\_worklist} = \{(6, 7)\}$
An Example 5(10): Visit 7

- Ignore $a_3$ in $\phi$-function in vertex 6.
- $edge\_worklist = \{(7, 8)\}$
An Example 6(10): Visit 8

```
\begin{align*}
0 & : a_0 \leftarrow 0 \\
1 & : b_0 \leftarrow a_0 + 1 \\
& \quad b_0 = a_0? \\
& \quad \text{yes \ no} \\
2 & : a_1 \leftarrow 2 \\
3 & : a_6 \leftarrow \phi(a_1, a_5) \\
& \quad a_7 \leftarrow a_4 + 6 \\
5 & : a_4 \leftarrow \phi(a_1, a_3) \\
& \quad a_5 \leftarrow a_4 + 5 \\
6 & : a_2 \leftarrow \phi(a_0, a_3) \\
& \quad a_3 \leftarrow a_2 + 4 \\
& \quad a_3 = 11? \\
7 & : \text{edge_worklist} = \{(8, 6)\} \\
8 & : a_3 = 4? \\
& \quad \text{no \ yes} \\
4 & : a_8 \leftarrow \phi(a_7, a_3) \\
& \quad \text{put}(a_8)
\end{align*}
```
Now only the $\phi$-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.

\[ \text{edge\_worklist} = \{(6, 5)\} \]
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.
- $\text{edge\_worklist} = \{(5, 3)\}$
Again $a_1$ is ignored but $a_5$ is nonconstant.

$a_6$ and $a_7$ become nonconstant as well.

$\text{edge\_worklist} = \{(3, 4)\}$
In this example, for simplicity, we have not included the contents of the ssa-worklist.

- \(a_8\) will be read from memory.
- Vertex 2 and the branch to it can be deleted.
if (a != 44)
    b = a + 1;
else {
    b = a + 2;
    f(b);
}

- The parameter must have the value 46.
- By inserting `a = 44` in the else-clause, the constant propagation algorithm is helped.
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.
- But see next slide!
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!