Global Optimization
Lecture Outline

• Global flow analysis

• Global constant propagation

• Liveness analysis
Local Optimization

Recall the simple basic-block optimizations

- Constant propagation
- Dead code elimination

\[
\begin{align*}
x &:= 42 \\
y &:= z \times w \\
q &:= y + x
\end{align*}
\]
Global Optimization

These optimizations can be extended to an entire control-flow graph.
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\[
x := 42 \\
b > 0 \\
y := z \times w \\
y := 0 \\
q := y + x
\]
Global Optimization

These optimizations can be extended to an entire control-flow graph
Correctness

• How do we know it is OK to globally propagate constants?
• There are situations where it is incorrect:

```
\begin{align*}
x &:= 42 \\
b &> 0 \\
y &:= z \times w \\
x &:= 54 \\
y &:= 0 \\
q &:= y + x
\end{align*}
```
Correctness (Cont.)

To replace a use of $x$ by a constant $k$ we must know that the following property ** holds:

\[
\text{On every path to the use of } x, \\
\text{the last assignment to } x \text{ is } x := k
\] **
Example 1 Revisited

\begin{align*}
x &:= 42 \\
b &> 0 \\
y &:= z \ast w \\
y &:= 0 \\
q &:= y + x
\end{align*}
Example 2 Revisited

\begin{align*}
\text{\(x := 42\)} \\
\text{\(b > 0\)} \\
y := z \times w \\
x := 54 \\
y := 0 \\
q := y + x
\end{align*}
Discussion

- The correctness condition is not trivial to check
- “All paths” includes paths around loops and through branches of conditionals
- Checking the condition requires *global analysis*
  - An analysis that determines how data flows over the entire control-flow graph
Global Analysis

Global optimization tasks share several traits:

- The optimization depends on knowing a property $P$ at a particular point in program execution.
- Proving $P$ at any point requires knowledge of the entire function body.
- It is OK to be conservative: If the optimization requires $P$ to be true, then want to know either:
  - that $P$ is definitely true, or
  - that we don’t know whether $P$ is true.

- It is always safe to say “don’t know.”
Global Analysis (Cont.)

- **Global dataflow analysis** is a standard technique for solving problems with these characteristics.

- Global constant propagation is one example of an optimization that requires global dataflow analysis.
Global Constant Propagation

• Global constant propagation can be performed at any point where property ** holds

• Consider the case of computing ** for a single variable x at all program points
Global Constant Propagation (Cont.)

- To make the problem precise, we associate one of the following values with $x$ at every program point

<table>
<thead>
<tr>
<th>value</th>
<th>interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>This statement never executes</td>
</tr>
<tr>
<td>c</td>
<td>$x = \text{constant } c$</td>
</tr>
<tr>
<td>*</td>
<td>Don’t know whether $X$ is a constant</td>
</tr>
</tbody>
</table>
Example

\[ x := 42 \]
\[ b > 0 \]
\[ y := z \times w \]
\[ x := 54 \]
\[ y := 0 \]
\[ q := y + x \]
Using the Information

• Given global constant information, it is easy to perform the optimization
  - Simply inspect the $x = ?$ associated with a statement using $x$
  - If $x$ is constant at that point replace that use of $x$ by the constant

• But how do we compute the properties $x = ?$
The Analysis Idea

The analysis of a (complicated) program can be expressed as a combination of simple rules relating the change in information between adjacent statements.
Explanation

• The idea is to “push” or “transfer” information from one statement to the next

• For each statement \( s \), we compute information about the value of \( x \) immediately before and after \( s \)

\[
C_{\text{in}}(x,s) = \text{value of } x \text{ before } s
\]
\[
C_{\text{out}}(x,s) = \text{value of } x \text{ after } s
\]
Transfer Functions

• Define a transfer function that transfers information from one statement to another

• In the following rules, let statement \( s \) have as immediate predecessors statements \( p_1, ..., p_n \)
Rule 1

if $C_{out}(x, p_i) = *$ for any $i$, then $C_{in}(x, s) = *$
Rule 2

If $C_{out}(x, p_i) = c$ and $C_{out}(x, p_j) = d$ and $d \neq c$
then $C_{in}(x, s) = *$
Rule 3

\[
\text{if } C_{\text{out}}(x, p_i) = c \text{ or } \# \text{ for all } i, \\
\text{then } C_{\text{in}}(x, s) = c
\]
Rule 4

if $C_{\text{out}}(x, p_i) = \#$ for all $i$,
then $C_{\text{in}}(x, s) = \#$
The Other Half

• Rules 1-4 relate the *out* of one statement to the *in* of the successor statement

• We also need rules relating the *in* of a statement to the *out* of the same statement
Rule 5

\[ C_{\text{out}}(x, s) = \# \quad \text{if} \quad C_{\text{in}}(x, s) = \# \]
Rule 6

\[ C_{\text{out}}(x, x := c) = c \] if \( c \) is a constant
Rule 7

\[ C_{out}(x, x := f(...)) = * \]

This rule says that we do not perform inter-procedural analysis (i.e. we do not look at other functions do)
Rule 8

\[ C_{\text{out}}(x, y := ...) = C_{\text{in}}(x, y := ...) \text{ if } x \neq y \]
An Algorithm

1. For every entry $s$ to the function, set $C_{in}(x, s) = *$

2. Set $C_{in}(x, s) = C_{out}(x, s) = \#$ everywhere else

3. Repeat until all points satisfy 1-8:
   Pick $s$ not satisfying 1-8 and update using the appropriate rule
The Value #

To understand why we need #, look at a loop

```
x := 42
b > 0
y := z * w
y := 0
q := y + x
q < b
x = *
x = 42
x = 42
```
Discussion

• Consider the statement $y := 0$
• To compute whether $x$ is constant at this point, we need to know whether $x$ is constant at the two predecessors
  - $x := 42$
  - $q := y + x$

• But information for $q := y + x$ depends on its predecessors, including $y := 0$!
The Value # (Cont.)

• Because of cycles, all points must have values at all times

• Intuitively, assigning some initial value allows the analysis to break cycles

• The initial value # means “So far as we know, control never reaches this point”
Example

\begin{align*}
x &:= 42 \\
b &> 0 \\
y &:= z \ast w \\
q &:= x + y \quad (q < b)
\end{align*}
Example

\[ x := 42 \]
\[ b > 0 \]

\[ y := z \times w \]

\[ y := 0 \]

\[ q := x + y \]
\[ q < b \]
Example

\[
\begin{align*}
  x &:= 42 \\
b &> 0 \\
y &:= z \times w \\
q &:= x + y \\
q &< b
\end{align*}
\]
Example

\[ x := 42 \]
\[ b > 0 \]
\[ y := z \times w \]
\[ y := 0 \]
\[ q := x + y \]
\[ q < b \]
Orderings

• We can simplify the presentation of the analysis by ordering the values
  \[ \# < c < * \]

• Drawing a picture with “lower” values drawn lower, we get
Orderings (Cont.)

- * is the greatest value, # is the least
  - All constants are in between and incomparable

- Let \( l\text{ub} \) be the least-upper bound in this ordering

- Rules 1-4 can be written using \( l\text{ub} \):
  \[
  C_{\text{in}}(x, s) = \text{lub} \{ C_{\text{out}}(x, p) \mid p \text{ is a predecessor of } s \}
  \]
Termination

• Simply saying “repeat until nothing changes” doesn’t guarantee that eventually we reach a point where nothing changes

• The use of lub explains why the algorithm terminates
  - Values start as # and only increase
  - # can change to a constant, and a constant to *
  - Thus, $C_(x, s)$ can change at most twice
Termination (Cont.)

Thus the algorithm is linear in program size

Number of steps =

Number of $C_\text{__}(\ldots)$ values computed * 2 =

Number of program statements * 4
Liveness Analysis

Once constants have been globally propagated, we would like to eliminate dead code

After constant propagation, \( x := 42 \) is dead (assuming \( x \) is not used elsewhere)
Live and Dead Variables

• The first value of $x$ is *dead* (never used)

• The second value of $x$ is *live* (may be used)

• Liveness is an important concept for the compiler
Liveness

A variable $x$ is live at statement $s$ if
- There exists a statement $s'$ that uses $x$
- There is a path from $s$ to $s'$
- That path has no intervening assignment to $x$
Global Dead Code Elimination

- A statement $x := \ldots$ is dead code if $x$ is dead after the assignment
- Dead statements can be deleted from the program
- But we need liveness information first . . .
Computing Liveness

- We can express liveness in terms of information transferred between adjacent statements, just as in copy propagation.

- Liveness is simpler than constant propagation, since it is a boolean property (true or false).
Liveness Rule 1

\[ L_{out}(x, p) = \lor \{ L_{in}(x, s) \mid s \text{ a successor of } p \} \]
Liveness Rule 2

\[ L_{in}(x, s) = \text{true} \quad \text{if } s \text{ refers to } x \text{ on the RHS} \]
Liveness Rule 3

\[ L_{in}(x, x := e) = \text{false} \quad \text{if } e \text{ does not refer to } x \]
Liveness Rule 4

\[ L_{in}(x, s) = L_{out}(x, s) \quad \text{if } s \text{ does not refer to } x \]
Algorithm

1. Let all $L(...) = false$ initially

2. Repeat until all statements $s$ satisfy rules 1-4
   Pick $s$ where one of 1-4 does not hold and update using the appropriate rule
Termination

• A value can change from \textit{false} to \textit{true}, but not the other way around

• Each value can change only once, so termination is guaranteed

• Once the analysis information is computed, it is simple to eliminate dead code
Forward vs. Backward Analysis

We have seen two kinds of analysis:

- Constant propagation is a *forwards* analysis: information is pushed from inputs to outputs

- Liveness is a *backwards* analysis: information is pushed from outputs back towards inputs
Global Flow Analyses

• There are many other global flow analyses

• Most can be classified as either forward or backward

• Most also follow the methodology of local rules relating information between adjacent program points