Programming Languages & Translators

GLOBAL OPTIMIZATION

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These slides are motivated from Prof. Alex Aiken and Prof. Calvin Lin

Other Global Optimization:

- Constant Propagation
- Dead-code elimination
- Liveness analysis
- Common subexpression elimination
- Loop optimization

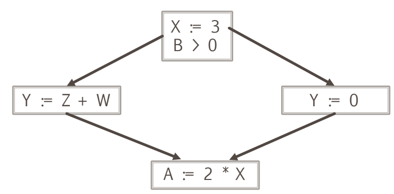
Local Optimization

- Recall the simple basic-block optimizations
  - Constant propagation
  - Dead code elimination

```
X := 3          X := 3
Y := Z * W  →   Y := Z * W  →   Y := Z * W
Q := X + Y      Q := 3 + Y      Q := 3 + Y
```

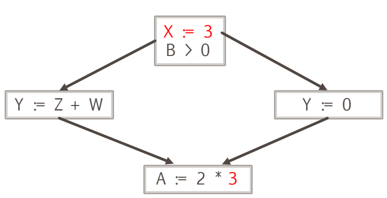
Global Optimization

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



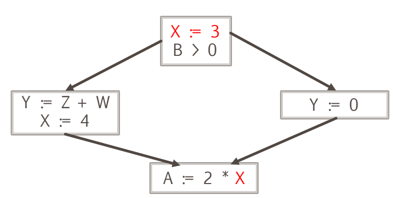
Global Optimization

- 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:



Correctness (cont.)

To replace a use of x by a constant k we must know that:

On every path to the use of x, the last assignment to x is

x := k **

- 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 of the entire control-flow graph

Global Analysis

- Global optimization tasks share several traits:
  - The optimization depends on knowing a property X at a particular point in program execution
  - Proving X at any point requires knowledge of the entire program
  - It is OK to be conservative. If the optimization requires X to be true, then want to know either
    - X is definitely true
    - Don't know if X 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

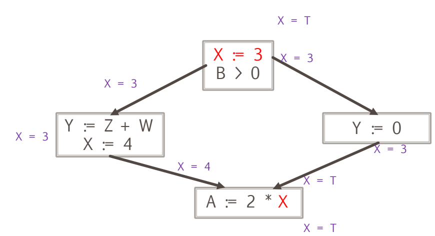
- Global constant propagation can be performed at any point where ** holds
- Consider the case of computing ** for a single variable X at all program points

Global Constant Propagation (Cont.)

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

value	interpretation
⊥	This statement never executes
c	X = constant c
T	X is not a constant

Example



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 = ?

Using the Information

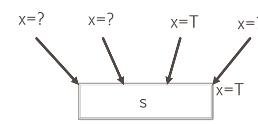
- The idea is to "push" or "transfer" information from one statement to the next
- For each statement s, we compute information about the value of x immediately before and after s

C(s,x,in) = value of x before s
C(s,x,out) = value of x after s

Transfer Functions

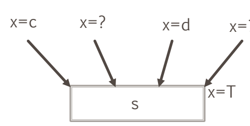
- Define a transfer function that transfers information one statement to another
- In the following rules, let statement s have immediate predecessor statements $p_1,\ldots,p_n$

Rule 1



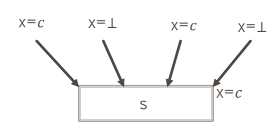
if $C(p_i, x, out) = T$ for any i, then $C(s, x, in) = T$

Rule 2



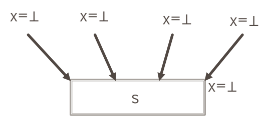
$C(p_i, x, out) = c$ & $C(p_j, x, out) = d$ & d <> c
then $C(s, x, in) = T$

Rule 3



if $C(p_i, x, out) = c$ or $\perp$ for all i,
then $C(s, x, in) = c$

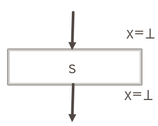
Rule 4



if $C(p_i, x, out) = \perp$ for all i,
then $C(s, x, in) = \perp$

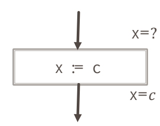
- Rules 1-4 relate the out of one statement to the in of the next statement
- Now we need rules relating the in of a statement to the out of the same statement

Rule 5



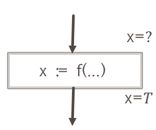
$C(s, x, out) = \perp$
if $C(s, x, in) = \perp$

Rule 6



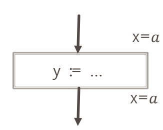
C(x := c, x, out) = c if c is a constant

Rule 7



C(x := f(...), x, out) = T

Rule 8



C(y := ..., x, out) = C(y := ..., x, in) if x <> y

Algorithm

1. For every entry s to the program, set C(s, x, in) = T
2. Set C(s, x, in) = C(s, x, out) = ⊥ everywhere else
3. Repeat until all points satisfy 1-8:
   - Pick s not satisfying 1-8 and update using the appropriate rule

- **Ordering:**
  - We can simplify the presentation of the analysis by ordering the values ⊥ < c < T

Common subexpression elimination

- Example:

```
a := b + c              a := b + c
c := b + c      ⇒       c := a
d := b + c              d := b + c
```

- Example in array index calculations
  - c[i+1] := a[i+1] + b[i+1]
  - During address computation, i+1 should be reused
  - Not visible in high level code, but in intermediate code

Code Elimination

- Unreachable code elimination
  - Construct the control flow graph
  - Unreachable code block will not have an incoming edge
  - After constant propagation/folding, unreachable branches can be eliminated
- Dead code elimination
  - Ineffective statements
    - x := y + 1 (immediately redefined, eliminate!)
    - y := 5 ⇒ y := 5
    - x := 2 * z x := 2 * z
  - A variable is dead if it is never used after last definition
    - Eliminate assignments to dead variables
  - Need to do data flow analysis to find dead variables

Function Optimization

- Function inlining
  - Replace a function call with the body of the function
  - Save a lot of copying of the parameters, return address, etc.
- Function cloning
  - Create specialized code for a function for different calling parameters

Loop Optimization

- Loop optimization
  - Consumes 90% of the execution time
    ⇒ a larger payoff to optimize the code within a loop
- Techniques
  - Loop invariant detection and code motion
  - Induction variable elimination
  - Strength reduction in loops
  - Loop unrolling
  - Loop peeling
  - Loop fusion

Loop Optimization

- Loop invariant detection
  - If the result of a statement or expression does not change within a loop, and it has no external side-effect
  - Computation can be moved to outside of the loop
  - Example

```
for (i=0; i<n; i++) a[i] := a[i] + x/y;
```

  - Three address code

```
for (i=0; i<n; i++) { c := x/y; a[i] := a[i] + c; }
⇒ c := x/y;
  for (i=0; i<n; i++) a[i] := a[i] + c;
```

Loop Optimization

- Code Motion
  - Reduce frequency with which computation performed
    - If it will always produce same result
    - Especially moving code out of loop

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
for (i = 0; i < n; i++) {
  int ni = n*i;
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
}
```

Loop Optimization

- Strength reduction in loops
  - Replace costly operation with simpler one
  - Shift, add instead of multiply or divide
    16*x --> x << 4
    - Depends on cost of multiply or divide instruction
  - Recognize sequence of products

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
int ni = 0;
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
  ni += n;
}
```

Loop Optimization

- Strength reduction in loops
  - Replace costly operation with simpler one
  - Shift, add instead of multiply or divide
    16*x --> x << 4
    - Depends on cost of multiply or divide instruction
  - Recognize sequence of products

```
s := 0;
for (i=0; i<n; i++)
{
  v := 4 * i;
  s := s + v;
}
```

→

```
s := 0;
for (i=0; i<n; i++)
{
  v := v + 4;
  s := s + v;
}
```

Loop Optimization

- Induction variable elimination
  - If there are multiple induction variables in a loop, can eliminate the ones which are used only in the test condition
  - Example
    s := 0; for (i=0; i<n; i++) { s := 4 * i; … } -- i is not referenced in loop
    ⇒ s := 0; e := 4*n; while (s < e) { s := s + 4; }

```
s := 0;
for (i=0; i<n; i++)
{ s := 4 * i; … }
-- i is not referenced in loop
```

→

```
s := 0;
e := 4*n;
while (s < e) {
  s := s + 4;
}
```

Code Optimization Techniques

- Loop unrolling
  - Execute loop body multiple times at each iteration
  - Get rid of the conditional branches, if possible
  - Allow optimization to cross multiple iterations of the loop
    - Especially for parallel instruction execution
  - Space time tradeoff
    - Increase in code size, reduce some instructions
- Loop peeling
  - Similar to unrolling
  - But unroll the first and/or last few iterations

Loop Optimization

- Loop fusion
  - Example

```
for i=1 to N do
  A[i] = B[i] + 1
endfor
for i=1 to N do
  C[i] = A[i] / 2
endfor
for i=1 to N do
  D[i] = 1 / C[i+1]
endfor
```

Before Loop Fusion

```
for i=1 to N do
  A[i] = B[i] + 1
  C[i] = A[i] / 2
  D[i] = 1 / C[i+1]
endfor
```

Loop Optimization

- Loop fusion
  - Example

```
for i=1 to N do
    A[i] = B[i] + 1
endfor
for i=1 to N do
    C[i] = A[i] / 2
endfor
for i=1 to N do
    D[i] = 1 / C[i+1]
endfor
```

Before Loop Fusion

```
for i=1 to N do
    A[i] = B[i] + 1
    C[i] = A[i] / 2
    D[i] = 1 / C[i+1]
endfor
```

Is this correct?
Actually, cannot fuse the third loop

Limitations of Compiler Optimization

- Operate Under Fundamental Constraint
  - Must not cause any change in program behavior under any possible condition
  - Often prevents it from making optimizations when would only affect behavior under pathological conditions.
- Behavior that may be obvious to the programmer can be obfuscated by languages and coding styles
  - e.g., data ranges may be more limited than variable types suggest
- Most analysis is performed only within procedures
  - whole-program analysis is too expensive in most cases
- Most analysis is based only on *static* information
  - compiler has difficulty anticipating run-time inputs
- When in doubt, the compiler must be conservative