CS412/413

Introduction to Compilers
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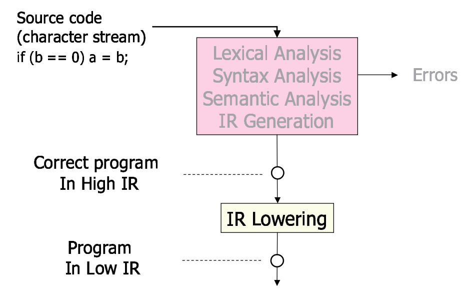
Lecture 17: Introduction to Optimizations
27 Feb 02

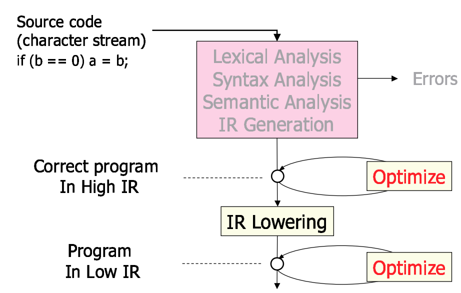
Where We Are



What Next?

- At this point we could generate assembly code from the low-level IR
- Better:
  - Optimize the program first
  - Then generate code
- If optimization performed at the IR level, then they apply to all target machines

Optimizations



What are Optimizations?

- Optimizations = code transformations which improve the program
- Different kinds
  - space optimizations: improve (reduce) memory use
  - time optimizations: improve (reduce) execution time
- Code transformations must be safe!
  - They must preserve the meaning of the program

Why Optimize?

- Programmers don't always write optimal code – can recognize ways to improve code (e.g. avoid recomputing same expression)
- High-level language may make some optimizations inconvenient or impossible to express

  a[i][j] = a[i][j] + 1
- High-level unoptimized code may be more readable: cleaner, modular

  int square(x) { return x*x; }

Where to Optimize?

- Usual goal: improve time performance
- Problem: many optimizations trade off space versus time
- Example: loop unrolling
  - Increases code space, speeds up one loop
  - Frequently executed code with long loops: space/time tradeoff is generally a win
  - Infrequently executed code: may want to optimize code space at expense of time
- Want to optimize program hot spots

Many Possible Optimizations

- Many ways to optimize a program
- Some of the most common optimizations:
  - Function Inlining
  - Function Cloning
  - Constant folding
  - Constant propagation
  - Dead code elimination
  - Loop-invariant code motion
  - Common sub-expression elimination
  - Strength reduction
  - Constant folding & propagation
  - Branch prediction/optimization
  - Loop unrolling
- Covered in more detail in Muchnick

Constant Propagation

- If value of variable is known to be a constant, replace use of variable with constant
- Example:

```
n = 10
c = 2
for (i=0; i<n; i++) { s = s + i*c; }
```

- Replace n, c:

```
for (i=0; i<10; i++) { s = s + i*2; }
```

- Each variable must be replaced only when it has know constant value:
  - Forward from a constant assignment
  - Until next assignment of the variable

Constant Folding

- Evaluate an expression if operands are known at compile time (i.e. they are constants)
- Example:

```
x = 1.1 * 2;   ⇒   x = 2.2;
```

- Performed at every stage of compilation
  - Constants created by translations or optimizations

```
int x = a[2]  ⇒  t = addr a
                 t1 = 2*4
                 t = t + t1
                 x = [t]
```


Algebraic Simplification

- More general form of constant folding: take advantage of usual simplification rules

```
a * 1    ⇒ a        a * 0    ⇒ 0
a / 1    ⇒ a        a + 0    ⇒ a
b | false ⇒ b       b & true ⇒ b
```

- Repeatedly apply the above rules

```
(y*1+0)/1  ⇒  y*1+0 ⇒ y*1 ⇒ y
```

- Must be careful with floating point!

Copy Propagation

- After assignment x = y, replace uses of x with y
- Replace until x is assigned again

```
x = y;                     x = y;
if (x > 1)          ⇒      if (y > 1)
  s = x * f(x - 1);          s = y * f(y - 1);
```

- What if there was an assignment y = z before?
  - Transitively apply replacements

Common Subexpression Elimination

- If program computes same expression multiple time, can reuse the computed value
- Example:

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

- Common subexpressions also occur in low-level code in address calculations for array accesses:

```
a[i] = b[i] + 1;
```


Unreachable Code Elimination

- Eliminate code which is never executed
- Example:

```
#define debug false
s = 1;                  ⇒     s = 1;
if (debug)
    print("state = ", s);
```

- Unreachable code may not be obvious in low IR (or in high-level languages with unstructured "goto" statements)

Unreachable Code Elimination

- Unreachable code in while/if statements when:
  - Loop condition is always false (loop never executed)
  - Condition of an if statement is always true or always false (only one branch executed)

```
if (false) S            ⇒  ;

if (true) S else S'     ⇒  S
if (false) S else S'    ⇒  S'

while (false) S         ⇒  ;
while (2>3) S           ⇒  ;
```


Dead Code Elimination

- If effect of a statement is never observed, eliminate the statement

```
x = y+1;
y = 1;          ⇒     y = 1;
x = 2*z;              x = 2*z;
```

- Variable is dead if never used after definition
- Eliminate assignments to dead variables
- Other optimizations may create dead code

Loops

- Program hot spots are usually loops (exceptions: OS kernels, compilers)
- Most execution time in most programs is spent in loops: 90/10 is typical
- Loop optimizations are important, effective, and numerous

Loop-invariant Code Motion

- If result of a statement or expression does not change during loop, and it has no externally-visible side-effect (!), can hoist its computation out of the loop
- Often useful for array element addressing computations – invariant code not visible at source level
- Requires analysis to identify loop-invariant expressions

Code Motion Example

- Identify invariant expression:

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

- Hoist the expression out of the loop:

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


Another Example

- Can also hoist statements out of loops
- Assume x, y not updated in the loop body:

```
…                        …
while (b) {              z = x*x;
      z = x*x;     ⇒     while (b) {
      …                        …
}                        }
…                        …
```

- … Is it safe?

Strength Reduction

- Replaces expensive operations (multiplies, divides) by cheap ones (adds, subtracts)
- Strength reduction more effective in loops
- Induction variable = loop variable whose value is determined only by the iteration number
- Apply strength reduction to induction variables

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


Strength Reduction

- Can apply strength reduction to computation other than induction variables:

$x * 2 \Rightarrow x + x$

$i * 2^c \Rightarrow i << c$

$i / 2^c \Rightarrow i >> c$

Induction Variable Elimination

- If there are multiple induction variables in a loop, can eliminate the ones which are used only in the test condition
- Need to rewrite test using the other induction variables
- Usually applied after strength reduction

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


Loop Unrolling

- Execute loop body multiple times at each iteration
- Example:

```
for (i = 0; i< n; i++) { S }
```

- Unroll loop four times:

```
for (i = 0; i < n-3; i+=4) { S; S; S; S; }
for (      ; i < n; i++) S;
```

- Gets rid of ¾ of conditional branches!
- Space-time tradeoff: program size increases

Function Inlining

- Replace a function call with the body of the function:

```
int g(int x)  { return f(x)-1; }
int f(int n)  { int b=1; while (n--) { b = 2*b }; return b; }
```

```
int g(int x)  { int r;
                int n = x;
                { int b =1; while (n--) { b = 2*b }; r = b }
                return r – 1; }
```

- Can inline methods, but more difficult
- … how about recursive procedures?

Function Cloning

- Create specialized versions of functions that are called from different call sites with different arguments

```
void f(int x[], int n, int m) {
    for(int i=0; i<n; i++) { x[i] = x[i] + i*m; }
}
```

- For a call f(a, 10, 2), create a specialized version of f:

```
void f1(int x[]) {
    for(int i=0; i<10; i++) { x[i] = x[i] + i; }
}
```

- For another call f(b, p, 0), create another version f2(…)

When to Apply Optimizations

High IR	Function inlining Function cloning Constant folding Constant propagation
Low IR	Value numbering Dead code elimination Loop-invariant code motion Common sub-expression elimination Strength reduction Constant folding & propagation Branch prediction/optimization Loop unrolling
Assembly	Register allocation Cache optimization

Summary

- Many useful optimizations that can transform code to make it faster
- Whole is greater than sum of parts: optimizations should be applied together, sometimes more than once, at different levels
- Problem: when are optimizations are safe?