CS412/413

Introduction to Compilers

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Lecture 21: Introduction to Optimizations

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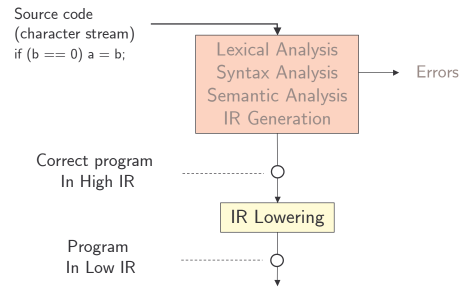
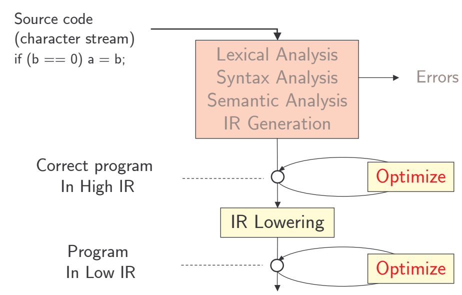
Where We Are



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

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]  ⇒    t1 = 2*4
                   t2 = a + t1
                   x = *t2
```


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 operations!

Copy Propagation

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

```
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?

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

Loop Optimizations

- 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 not updated in the loop body:

```
...                      ...
while (...) {            y = x*x;
    y = x*x;     ⇒       while (...) {
    ...                      ...
}                        }
...                      ...
```

- … 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 increases (or decreases) linearly with the iteration number
- Apply strength reduction to induction variables

```
s = 0;                          s = 0; v = -4;
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	⇒	x + x
i * 2^c	⇒	i << c
i / 2^c	⇒	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=-4;
for (i = 0; i < n; i++) {
    v = v + 4;
    s = s + v;              s = 0; v = -4;
}                           for (; v < (4*n+4);) {
                    ⇒           v = v + 4;
                                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 conditional branches!
- Space-time tradeoff: program size increases

Loop Fusion

- Combine multiple loops together
- Example:

```
for (i = 0; i< n; i++) { S1 }
for (i = 0; i< n; i++) { S2 }
```

- Unroll loop four times:

```
for (i = 0; i < n; i++) { S1; S2; }
```

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

Function/Method 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
- Is it always possible to inline functions?

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, 1)`, 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 Loop fusion Constant folding Constant propagation Value numbering Dead code elimination
Low IR	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?