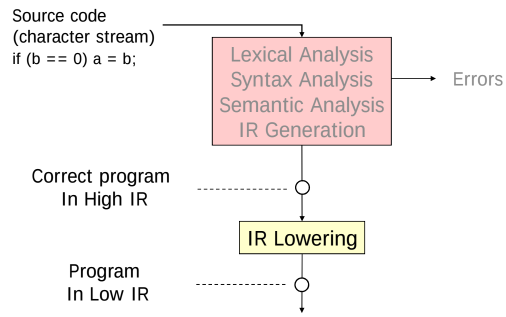
Optimizations



## Where We Are



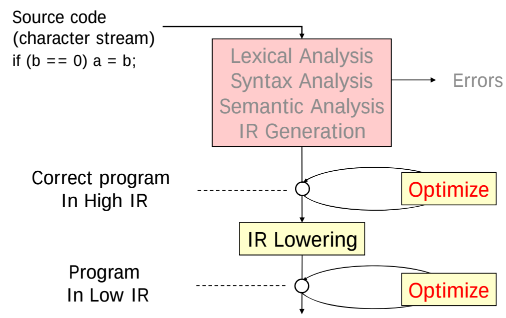



## What Next?

- 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 that *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

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## 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; }

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## 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

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## 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
  Branch prediction/optimization
  Loop unrolling

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## 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 known 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!



## 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;
```

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## Unreachable Code Elimination

- Eliminate code that 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)

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## 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           ⇒   ;
```

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

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## 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

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## 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

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## 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;
```

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## 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?

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## 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 depends linearly on 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:

$x * 2 \Rightarrow x + x$

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

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



## Induction Variable Elimination

- If there are multiple induction variables in a loop, can eliminate the ones that 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;                        s = 0; v = -4;
for (i = 0; i < n; i++) {           for (; v < (4*n-4);) {
    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, 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<br>Function cloning |
| Low IR | Constant folding<br>Constant propagation<br>Value numbering<br>Dead code elimination<br>Loop-invariant code motion<br>Common sub-expression elimination<br>Strength reduction<br>Constant folding & propagation<br>Branch prediction/optimization<br>Loop unrolling |
| Assembly | Register allocation<br>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?