Agenda

- Survey some code “optimizations” (improvements)
  - Get a feel for what’s possible
- Some organizing concepts
  - Basic blocks
  - Control-flow and dataflow graph
Optimizations

- Use added passes to identify inefficiencies in intermediate or target code
- Replace with equivalent ("has the same externally visible behavior") but better sequences
- Target-independent optimizations best done on IL code
- Target-dependent optimizations best done on target code
- "Optimize" overly optimistic: "usually improve" is generally more accurate
  - And "clever" programmers can outwit you!
An example

\[
x = a[i] + b[2];
\]

\[
c[i] = x - 5;
\]

\[
t1 = *(fp + ioffset); \quad // \; i
\]
\[
t2 = t1 * 4;
\]
\[
t3 = fp + t2;
\]
\[
t4 = *(t3 + aoffset); \quad // \; a[i]
\]
\[
t5 = 2;
\]
\[
t6 = t5 * 4;
\]
\[
t7 = fp + t6;
\]
\[
t8 = *(t7 + boffset); \quad // \; b[2]
\]
\[
t9 = t4 + t8; *(fp + xoffset) = t9; \quad // \; x = ...
\]
\[
t10 = *(fp + xoffset); \quad // \; x
\]
\[
t11 = 5;
\]
\[
t12 = t10 - t11;
\]
\[
t13 = *(fp + ioffset); \quad // \; i
\]
\[
t14 = t13 * 4;
\]
\[
t15 = fp + t14;
\]
\[
*(t15 + coffset) = t12; \quad // \; c[i] := ...
\]
Kinds of optimizations

- peephole: look at adjacent instructions
- local: look at straight-line sequence of statements
- intraprocedural: look at whole procedure
  - Commonly called “global”
- interprocedural: look across procedures
  - “whole program” analysis

- Larger scope => better optimization but more cost and complexity
Peephole Optimization

- After target code generation, look at adjacent instructions (a “peephole” on the code stream)
  - try to replace adjacent instructions with something faster

```
sw $8, 12($fp)
lw $12, 12($fp)
sw $8, 12($fp)
mv $12, $8
```
More Examples: 68K

| sub sp, 4, sp | mov r1, -(sp) |
| mov r1, 0(sp) | |
| mov 12(fp), r1 | inc 12(fp) |
| add r1, 1, r1 | |
| mov r1, 12(fp) | |

- One way to do complex instruction selection
Peephole Optimization of Jumps

- Eliminate jumps to jumps
- Eliminate jumps after conditional branches
- “Adjacent” instructions = “adjacent in control flow”

Source code
```java
if (a < b) {
    if (c < d) { // do nothing
    } else {
        stmt1;
    }
} else {
    stmt2;
}
```
Algebraic Simplification

- “constant folding”, “strength reduction”
  - \( z = 3 + 4; \)
  - \( z = x + 0; \)
  - \( z = x * 1; \)
  - \( z = x * 2; \)
  - \( z = x * 8; \)
  - \( z = x / 8; \)

- \texttt{double } x, y, z;
- \( z = (x + y) - y; \)

- Can be done by peephole optimizer, or by code generator
- Why do these examples happen?
Local Optimizations

- Analysis and optimizations within a basic block
- *Basic block*: straight-line sequence of statements
  - no control flow into or out of middle of sequence
- Better than peephole
- Not too hard to implement

- Machine-independent, if done on intermediate code
Local Constant Propagation

- If variable assigned a constant, replace downstream uses of the variable with constant

```
final int count = 10;
...  
x = count * 5;
y = x ^ 3;
```

```
t1 = 10;
t2 = 5;
t3 = t1 * t2;
x = t3;
t4 = x;
t5 = 3;
t6 = exp(t4, t5);
y = t6;
```
Local Dead Assignment Elimination

- If l.h.s. of assignment never referenced again before being overwritten, then can delete assignment
  - Why would this happen? CleaO-up after previous optimizations, often

```
final int count = 10;
...
x = count * 5;
y = x ^ 3;
x = 7;
t1 = 10;
t2 = 5;
t3 = 50;
x = 50;
t4 = 50;
t5 = 3;
t6 = 125000;
y = 125000;
x = 7;
```

Intermediate code after constant propagation
Local Common Subexpression Elimination

- Avoid repeating the same calculation
- Eliminate redundant loads
- Keep track of available expressions

\[
\begin{array}{ll}
\text{... a[i] + b[i] ...} & \text{t1 = *(fp + ioffset);} \\
& \text{t2 = t1 * 4;} \\
& \text{t3 = fp + t2;} \\
& \text{t4 = *(t3 + aoffset);} \\
& \text{t5 = *(fp + ioffset);} \\
& \text{t6 = t5 * 4;} \\
& \text{t7 = fp + t6;} \\
& \text{t8 = *(t7 + boffset);} \\
& \text{t9 = t4 + t8;} \\
\end{array}
\]
Intraprocedural optimizations

- Enlarge scope of analysis to whole procedure
  - more opportunities for optimization
  - have to deal with branches, merges, and loops
- Can do constant propagation, common subexpression elimination, etc. at “global” level
- Can do new things, e.g. loop optimizations
- Optimizing compilers usually work at this level (−O2)
Code Motion

- Goal: move loop-invariant calculations out of loops
- Can do at source level or at intermediate code level

```c
for (i = 0; i < 10; i = i+1) {
    a[i] = a[i] + b[j];  
    z = z + 10000;
}

t1 = b[j];
t2 = 10000;
for (i = 0; i < 10; i = i+1) {
    a[i] = a[i] + t1;
    z = z + t2;
}
```
**Code Motion at IL**

```c
for (i = 0; i < 10; i = i+1) {
    a[i] = b[j];
}

*(fp + ioffset) = 0;
label top;
    t0 = *(fp + ioffset);
    iffalse (t0 < 10) goto done;
    t1 = *(fp + joffset);
    t2 = t1 * 4;
    t3 = fp + t2;
    t4 = *(t3 + boffset);
    t5 = *(fp + ioffset);
    t6 = t5 * 4;
    t7 = fp + t6; *(t7 + aoffset) = t4;
    t9 = *(fp + ioffset);
    t10 = t9 + 1;
    *(fp + ioffset) = t10;
goto top;
label done;
```

Unoptimized intermediate code
Loop Induction Variable Elimination

- For-loop index is induction variable
  - incremented each time around loop
  - offsets & pointers calculated from it
- If used only to index arrays, can rewrite with pointers
  - compute initial offsets/pointers before loop
  - increment offsets/pointers each time around loop
  - no expensive scaling in loop
  - can then do loop-invariant code motion

```c
for (i = 0; i < 10; i = i+1) {
    a[i] = a[i] + x;
}
```

=> transformed to

```c
for (p = &a[0]; p < &a[10]; p = p+4) {
    *p = *p + x;
}
```
Interprocedural Optimization

- Expand scope of analysis to procedures calling each other
- Can do local & intraprocedural optimizations at larger scope
- Can do new optimizations, e.g. inlining
Inlining: replace call with body

- Replace procedure call with body of called procedure
- Source:
  ```java
  final double pi = 3.1415927;
  double circle_area(double radius) {
      return pi * (radius * radius);
  }
  ...
  double r = 5.0;
  ...
  double a = circle_area(r);
  ```
- After inlining:
  ```java
  ...
  double r = 5.0;
  ...
  double a = pi * r * r;
  ```
- (Then what?)
Intraprocedural (Global) Optimizations

- Need a convenient representation of procedure body
- Control flow graph (CFG) captures flow of control
  - nodes are IL statements, or whole basic blocks
  - edges represent (possible) control flow
  - node with multiple successors = branch/switch
  - node with multiple predecessors = merge
  - loop in graph = loop
- Data flow graph (DFG) capture flow of data, e.g. def/use chains:
  - nodes are def(inition)s and uses
  - edge from def to use
  - a def can reach multiple uses
  - a use can have multiple reachingdefs
Analysis and Transformation

- Each optimization is made up of
  - some number of analyses
  - followed by a transformation
- Analyze CFG and/or DFG by propagating info forward or backward along CFG and/or DFG edges
  - edges called program points
  - merges in graph require combining info
  - loops in graph require iterative approximation
- Perform improving transformations based on info computed
  - have to wait until any iterative approximation has converged
- Analysis must be conservative/safe/sound so that transformations preserve program behavior
Example: Constant Propagation, Folding

- Can use either the CFG or the DFG
- CFG analysis info: table mapping each variable in scope to one of
  - a particular constant
  - NonConstant
  - Undefined
- Transformation at each instruction:
  - if reference a variable that the table maps to a constant, then replace with that constant (constant propagation)
  - if r.h.s. expression involves only constants, and has no side-effects, then perform operation at compile-time and replace r.h.s. with constant result (constant folding)
- For best analysis, do constant folding as part of analysis, to learn all constants in one pass
Merging data flow analysis info

- Constraint: merge results must be sound
  - if something is believed true after the merge, then it must be true no matter which path we took into the merge
  - only things true along all predecessors are true after the merge

- To merge two maps of constant information, build map by merging corresponding variable information

- To merge information about two variable
  - if one is Undefined, keep the other
  - if both same constant, keep that constant
  - otherwise, degenerate to NonConstant
Example Merges

```
int x
x := 5
```

```
int x
x := 5
x := 5
```

```
int x
x := 5
x := 4
```

```
int x
x := 5
x := 5
```

```
x ==?
```

```
x ==?
```

```
x ==?
```

```
x ==?
```
Example Merges

int x

x := 5

x ==?

int x

x := 5

x := f(...)

x ==?
How to analyze loops

```cpp
i = 0;
x = 10;
y = 20;
while (...) {
    // what's true here?
    ...
    i = i + 1;
y = 30;
}
// what's true here?
... x ... i ... y ...
```

- Safe but precise: forget everything when we enter or exit a loop
- Precise but unsafe: keep everything when we enter or exit a loop
- Can we do better?
Loop Terminology
Optimistic Iterative Analysis

- Assuming information at loop head is same as information at loop entry
- Then analyze loop body, computing information at back edge
- Merge information at loop back edge and loop entry
- Test if merged information is same as original assumption
  - If so, then we’re done
  - If not, then replace previous assumption with merged information,
  - and go back to analysis of loop body
Example

```c
i = 0;
x = 10;
y = 20;
while (...) {
    // what’s true here?
    ...
    i = i + 1;
    y = 30; }
// what’s true here?
... x ... i ... y ...
```
Why does this work?

Why are the results always conservative?
Because if the algorithm stops, then
- the loop head info is at least as conservative as both the loop entry info and the loop back edge info
- the analysis within the loop body is conservative, given the assumption that the loop head info is conservative

Why does the algorithm terminate?
It might not!
But it does if:
- there are only a finite number of times we could merge values together without reaching the worst case info (e.g. NotConstant)
More interprocedural analyses

- Needed to support interprocedural optimizations
- Alias analysis
  - Different references referring to the same memory locations
  - may-alias vs. must-alias, context- and flow-sensitivity
- Escape analysis (pointers that are live on exit from procedures), shape analysis (static analysis of the properties of dynamic data structures), ...
Supporting representations include:

- Call graph
- Program dependence graph
- …
Summary

- Enlarging scope of analysis yields better results
  - today, most optimizing compilers work at the intraprocedural (a\k\a global) level
- Optimizations organized as collections of passes, each rewriting IL in place into better version
- Presence of optimizations makes other parts of compiler (e.g. intermediate and target code generation) easier to write