Optimization

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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

An example

```c
x = a[i] + b[2];
c[i] = x - 5;
t1 = *(fp+i+offset); // i
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + a+offset); // a[i]
t5 = 2;
t6 = t5 + 4;
t7 = fp + t6;
t8 = *(t7 + b+offset); // b[2]
t9 = t4 + t8; *(fp+a+offset) = t9; // x = ...
t10 = *(fp+a+offset); // x
t11 = 5;
t12 = t10 - t11;
t13 = *(fp+i+offset); // i
t14 = t13 + 4;
t15 = fp + t14;
* (t15 + c+offset) = t12; // c[i] := ...
```

Kinds of optimizations

- peephole: look at adjacent instructions
- local: look at straight-line sequence of statements
- intraprocedural: look at whole procedure
- interprocedural: look across procedures
- Larger scope => better optimization but more cost and complexity

An example: local common subexpression elimination

- Avoid repeating the same calculation
- Eliminate redundant loads
- Keep track of available expressions: \( a[i] + b[i] \)
  ```c
t1 = *(fp+i+offset); // i
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + a+offset); // a[i]
t5 = 2;
t6 = t5 + 4;
t7 = fp + t6;
t8 = *(t7 + b+offset); // b[2]
t9 = t4 + t8;
```

But which are common subexpressions?

- Use data-flow analysis to determine the set of "available expressions"
- Based on that, if an expression is available, reuse it rather than recompute it
- Data-flow setup (see p. 419 in book)
  ```c
  DEExpr[n] = downward exposed expressions
  ExprKill[n] = expressions killed by block n
  Avail[n] = \( \cap \text{Expr}(m) \cup (\text{Avail}(m) \cap \neg\text{ExprKill}(m)) \)
  Avail[\emptyset] = \emptyset
  ```
Peephole Optimization

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

<table>
<thead>
<tr>
<th>sw $8, 12($fp)</th>
<th>sw $8, 12($fp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lw $12, 12($fp)</td>
<td>mv $12, $8</td>
</tr>
</tbody>
</table>

More Examples: 68K

- Do complex instruction selection through peephole optimization

<table>
<thead>
<tr>
<th>sub sp, 4, sp</th>
<th>mov r1, -(sp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mov 12(fp), rl</td>
<td>add rl, 1, rl</td>
</tr>
<tr>
<td>inc 12(fp)</td>
<td>mov r1, 12(fp)</td>
</tr>
</tbody>
</table>

Peephole Optimization of Jumps

- Eliminate jumps to jumps
- Eliminate jumps after conditional branches
- “Adjacent” instructions = “adjacent in control flow”
- Source code
  ```c
  if (a < b) {
    if (c < d) { // do nothing
      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;
  - 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
- Can enable more constant folding
  - Code; unoptimized intermediate code:
  ```c
  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? Clean-up after previous optimizations, often

```
final int count = 10;
x = count * 5;
y = x ^ 3;
x = 7;
```

*Intermediate code after constant propagation*

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**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

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**Code Motion**

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

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

- Unoptimized intermediate code

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

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**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

```
for (i = 0; i < 10; i = i+1) {
    a[i] = a[i] + x;
} => transformed to
for (p = &a[0]; p < &a[10]; p = p+4) {
    *p = *p + x;
}
```

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**Intraprocedural Optimizations (reprise)**

- Control flow graph (CFG) captures flow of control
  - nodes are IL statements, or whole basic blocks
  - edges represent 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/init/assign and uses
  - edge from def to use
  - a def can reach multiple uses
  - a use can have multiple reaching defs
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

\[
\begin{array}{c}
\text{int } x \\
\text{x := 5} \\
x \equiv ?
\end{array} \quad \begin{array}{c}
\text{int } x \\
\text{x := 4} \\
x \equiv ?
\end{array}
\]

Example Merges

\[
\begin{array}{c}
\text{int } x \\
x := 5 \\
x :=? \\
x := 5 \\
x := 5 \\
x :=? \\
x := 4 \\
x :=?
\end{array}
\]

How to analyze loops

- Safe but imprecise: 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

```java
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)

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

```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
  ... double r = 5.0;
  ... double a = pi * r * r;
• (Then what?)```
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