CSE P 501 – Compilers

Optimizing Transformations

Hal Perkins

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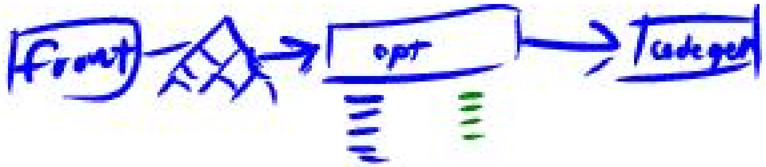
Agenda

- A sampler of typical optimizing transformations
  - Mostly a teaser for later, particularly once we've looked at analyzing loops



Role of Transformations

- Data-flow analysis discovers opportunities for code improvement
- Compiler must rewrite the code (IR) to realize these improvements
  - A transformation may reveal additional opportunities for further analysis & transformation
  - May also block opportunities by obscuring information

Organizing Transformations in a Compiler

- Typically middle end consists of many individual transformations that filter the IR and produce rewritten IR
- No formal theory for order to apply them
  - Some rules of thumb and best practices
  - Some transformations can be profitably applied repeatedly, particularly if others transformations expose more opportunities

A Taxonomy

- Machine Independent Transformations
  - Realized profitability may actually depend on machine architecture, but are typically implemented without considering this
- Machine Dependent Transformations
  - Most of the machine dependent code is in instruction selection & scheduling and register allocation
  - Some machine dependent code belongs in the optimizer

Machine Independent Transformations

- Dead code elimination
- Code motion
- Specialization
- Strength reduction
- Enable other transformations
- Eliminate redundant computations
  - Value numbering, GCSE

Machine Dependent Transformations

- Take advantage of special hardware
  - Expose instruction-level parallelism, for example
- Manage or hide latencies
  - Improve cache behavior
- Deal with finite resources

Dead Code Elimination

- If a compiler can prove that a computation has no external effect, it can be removed
  - Useless operations
  - Unreachable operations
- Dead code often results from other transformations
  - Often want to do DCE several times

Dead Code Elimination

- Classic algorithm is similar to garbage collection
  - Pass I – Mark all useful operations
    - Start with critical operations – output, entry/exit blocks, calls to other procedures, etc.
    - Mark all operations that are needed for critical operations; repeat until convergence
  - Pass II – delete all unmarked operations
  - Need to treat jumps carefully

Code Motion

- Idea: move an operation to a location where it is executed less frequently
  - Classic situation: move loop-invariant code out of a loop and execute it once, not once per iteration
- Lazy code motion: code motion plus elimination of redundant and partially redundant computations

1
f( ) {
}
2
return f(—)
}

Specialization

- Idea: Analysis phase may reveal information that allows a general operation in the IR to be replaced by a more specific one
  - Constant folding
  - Replacing multiplications and division by constants with shifts
  - Peephole optimizations
  - Tail recursion elimination

Strength Reduction

- Classic example: Array references in a loop

  ```
  for (k = 0; k < n; k++) a[k] = 0;
  ```

- Simple code generation would usually produce address arithmetic including a multiplication (k**elementsize*) and addition
- Optimization can produce `*p++ = 0;`

Implementing Strength Reduction

- Idea: look for operations in a loop involving:
  - A value that does not change in the loop, the *region constant*, and
  - A value that varies systematically from iteration to iteration, the *induction variable*
- Create a new induction variable that directly computes the sequence of values produced by the original one; use an addition in each iteration to update the value

Some Enabling Transformations

- Inline substitution (procedure bodies)
- Block cloning
- Loop Unrolling
- Loop Unswitching

Inline Substitution

- Idea: Replace method calls with a copy of the method body. Instead of

  `x = foo.getY();`

  use

  `x = foo.y`

  - Eliminates call overhead
  - Opens possibilities for other optimizations
- But: Possible code bloat, need to catch changes to inlined code
- Still, huge win for much object-oriented code

sum(x,y) {return x+y}

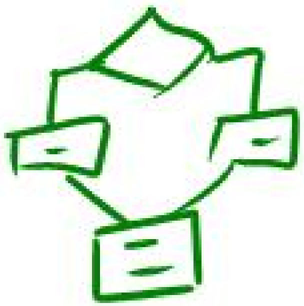
thing = sum(p,q)

Code Replication

- Idea: duplicate code to increase chances for optimizations, better code generation
- Tradeoff: larger code size, potential interactions with caches, registers

Code Replication Example

- Original



```
if (x < y) {
   p = x+y;
} else {
   p = z + 1;
}
q = p*3;
w = p + q;
```

- Duplicating code; larger basic blocks to optimize

```
if (x < y) {
   p = x+y;
   q = p*3;
   w = p + q;
} else {
   p = z + 1;
   q = p*3;
   w = p + q;
}
```

Loop Unrolling

- Idea: Replicate the loop body to expose inter-iteration optimization possibilities
  - Increases chances for good schedules and instruction level parallelism
  - Reduces loop overhead
- Catch – need to handle dependencies between iterations carefully

Loop Unrolling Example

- Original

```
for (i=1, i<=n, i++)
    a[i] = b[i]+a[i]
```

```
while (p < —)
  *p++ = *q++
```

```
switch ( — )
  while
  for ( —— k+=4) {
      case 0:
      case 1:
      case2:
      case3
      k+=4.
}
```

- Unrolled by 4

```
i=1;
while (i+3 <= n) {
    a[i  ] = a[i  ]+b[i  ];
    a[i+1] = a[i+1]+b[i+1];
    a[i+2] = a[i+2]+b[i+2];
    a[i+3] = a[i+3]+b[i+3];
    i+=4;
}
while (i <= n) {
    a[i] = a[i]+b[i];
    i++;
}
```

Loop Unswitching

- Idea: if the condition in an if-then-else is loop invariant, rewrite the loop by pulling the if-then-else out of the loop and generating a tailored copy of the loop for each half of the new if
  - After this transformation, both loops have simpler control flow – more chances for rest of compiler to do better

Loop UnswitchingExample

- Original

```
for (i=1, i<=n, i++)
  if (x > y)
    a[i] = b[i]*x;
  else
    a[i] = b[i]*y
```

- Unswitched

```
if (x > y)
  for (i = 1; i < n; i++)
    a[i] = b[i]*x;
  else
   for
    a[i] = b[i]*y;
```

Summary

- This is just a sampler
  - Hundreds of transformations in the literature
  - We will look at several in more detail, particularly involving loops
- Big part of engineering a compiler is to decide which transformations to use, in what order, and when to repeat them
  - Different tradeoffs depending on compiler goals