Agenda

- A sampler of typical optimizing transformations
  - Mostly a teaser for more details 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 systematic theory for the 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.

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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
- Note: 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
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 ($k \times \text{elements size}$) and addition
Implementing Strength Reduction

- Idea: look for operations in a loop involving:
  - A value that does not change in the loop, the \textit{region constant}, and
  - A value that varies systematically from iteration to iteration, the \textit{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

- Already mentioned
  - Inline substitution (procedure bodies)
  - Block cloning
- A few other examples
  - Loop Unrolling
  - Loop Unswitching
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];
  ```

- 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 Unswitching Example

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

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