CSE P 501 – Compilers

Optimizing Transformations

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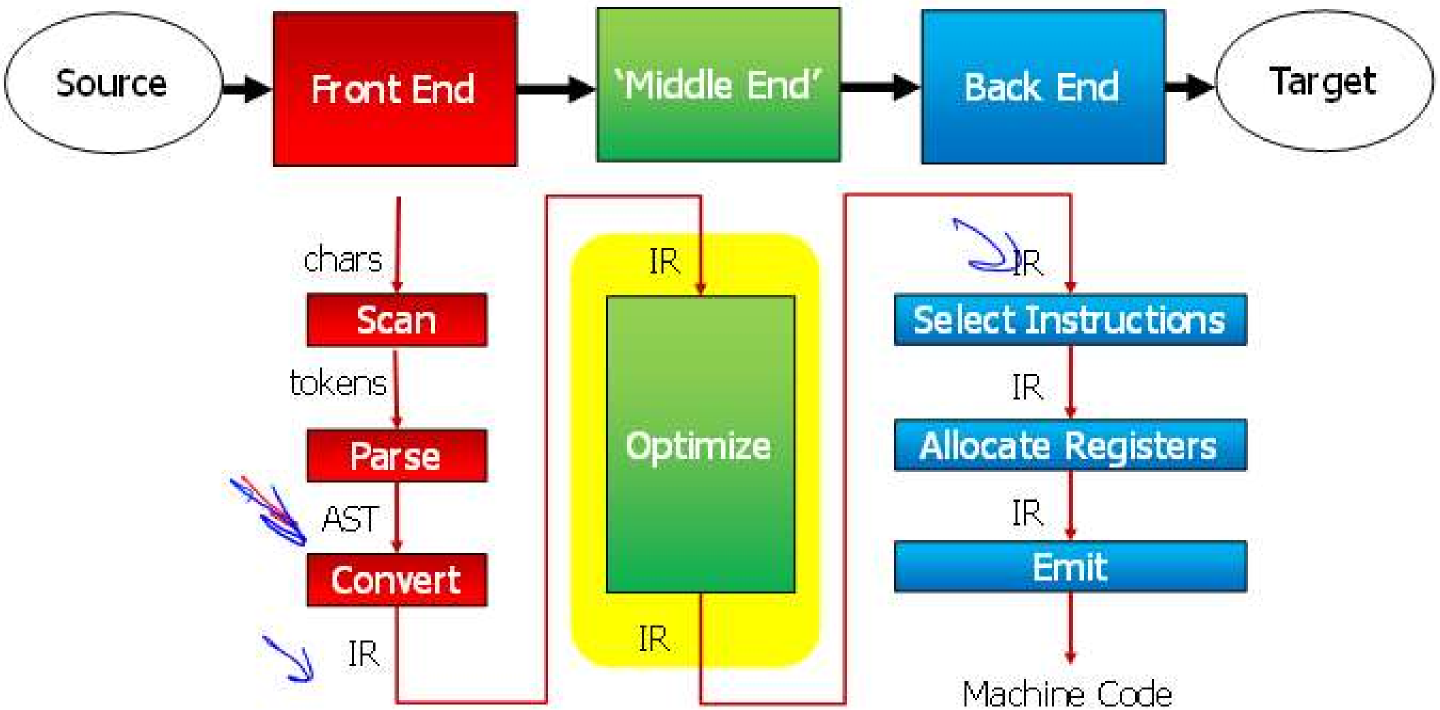
Agenda

- A more detailed look at some common optimizing transformations
- More details and examples later when we look at analysis algorithms

Optimizations in a Compiler



AST = Abstract Syntax Tree

IR = Intermediate Representation

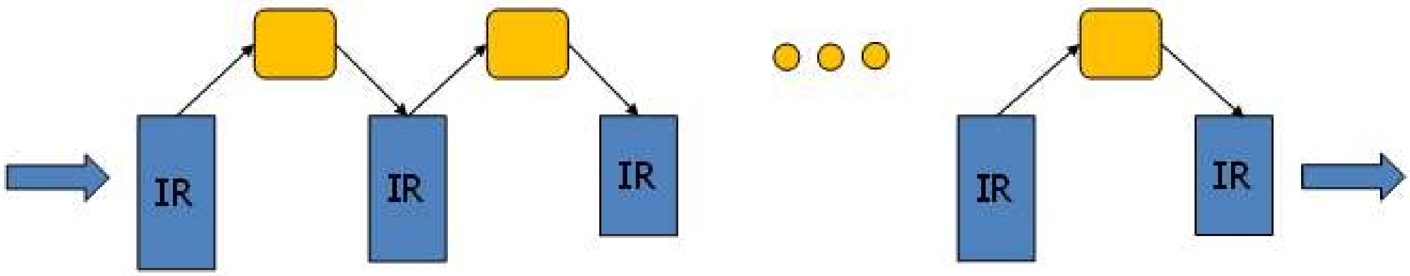
Role of Transformations

- Dataflow analysis discovers opportunities for code improvement
- Compiler rewrites the (IR) to make these improvements
  - Transformation may reveal additional opportunities for further optimization
  - May also block opportunities by obscuring information

Organizing Transformations in a Compiler

- Typically middle end consists of many phases
  - Analyze IR
  - Identify optimization
  - Rewrite IR to apply optimization
  - And repeat (50 phases in a commercial compiler is typical)
- Each individual optimization is supported by rigorous formal theory
- But no formal theory for what order or how often to apply them(!)
  - Some rules of thumb and best practices
  - May apply some transformations several times as different phases reveal opportunities for further improvement

Optimization 'Phases'



- Each optimization requires a 'pass' (linear scan) over the IR
- IR may sometimes shrink, sometimes expand
- Some optimizations may be repeated
- 'Best' ordering is heuristic
- Don't try to *beat* an optimizing compiler - you will lose!

- Note: not all programs are written by humans!
- Machine-generated code can pose a challenge for optimizers
  - eg: a single function with 10,000 statements, 1,000+ local variables, loops nested 15 deep, spaghetti of "GOTOs", etc

A Taxonomy

- Machine Independent Transformations
  - Mostly independent of target machine
    (e.g., loop unrolling will likely make it faster regardless of target)
  - "Mostly"? – e.g., vectorize only if target has SIMD ops
  - Worthwhile investment – applies to all targets
- Machine Dependent Transformations
  - Mostly concerned with instruction selection & scheduling, register allocation
  - Need to tune for different targets
  - Most of this in the back end, but some in the optimizer

Machine Independent Transformations

- Dead code elimination
  - unreachable or not actually used later
- Code motion
  - "hoist" loop-invariant code out of aloop
- Specialization
- Strength reduction
  - 2*x => x+x; @A+((i*numcols+j)*eltsize => p+=4
- Enable *other* transformations
- Eliminate redundant computations
  - Value numbering, GCSE

Machine Dependent Transformations

- Take advantage of special hardware
  - e.g., expose instruction-level parallelism (ILP)
  - e.g., use special instructions (VAX polyf; x86 sqrt, strings)
  - e.g., use SIMD instructions and registers
- Manage or hide latencies
  - e.g., tiling/blocking and loop interchange
  - Improves cache behavior – hugely important
- Deal with finite resources - # functional units
- Compilers generate for a vanilla machine, e.g., SSE2
  - But provide switches to tune (arch:AVX, arch:IA32)
  - JIT compiler knows its target architecture!

Optimizer Contracts

- **Prime directive**
  - No optimization will change observable program behavior!
  - This can be subtle. e.g.:
    - What is "observable"? (via IO? to another thread?)
    - Dead-Code-Eliminate a *throw* ?
    - Language Reference Manual may be ambiguous/undefined/negotiable for edge cases
- Avoid harmful optimizations
  - If an optimization does not improve code significantly, don't do it: it harms throughput
  - If an optimization degrades code quality, don't do it

Is this *hoist* legal?

```
for (int i = start; i < finish; ++i) a[i] += 7;
```

```
        i = start
loop:
        if (i >= finish) goto done
        if (i < 0 || i >= a.length) throw OutOfBounds
        a[i] += 7
        goto loop
done:
```

```
        if (start < 0 || finish >= a.length) throw OutOfBounds
        i = start
loop:
        if (i >= finish) goto done
        a[i] += 7
        goto loop
done:
```

Another example: "volatile" pretty much kills all attempts to optimize

Dead Code Elimination

x = y op z

- If a compiler can prove that a computation has no external effect, it can be removed
  - Unreachable operations – always safe to remove
  - Useless operations – reachable, may be executed, but results not actually required
- Dead code often results from other transformations
  - Often want to do DCE several times

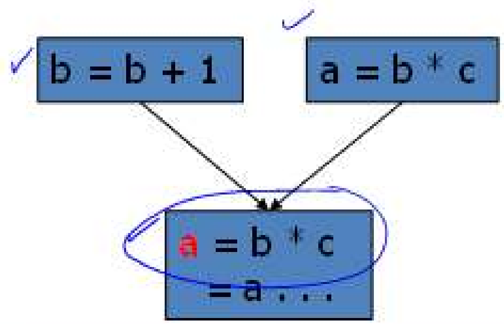
Dead Code Elimination

- Classic algorithm is similar to garbage collection
  - Pass I – Mark all useful operations
    - Instructions whose result does, or can, affect visible behavior:
      - Input or Output
      - Updates to object fields that might be used later
      - Instructions that may throw an exception (e.g.: array bounds check)
      - Calls to functions that might perform IO or affect visible behavior
      - (Remember, for many languages, compiler does not process entire program at one time – but a JIT compiler might be able to)
    - Mark all useful instructions
    - Repeat until no more changes
  - Pass II – delete all unmarked operations

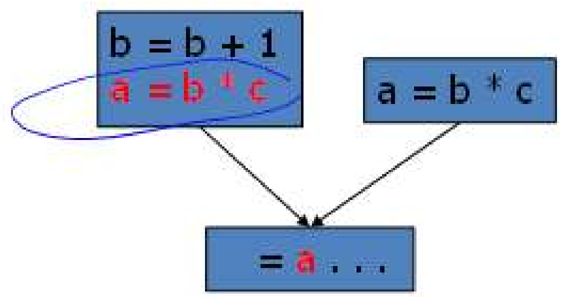
Code Motion

- Idea: move an operation to a location where it is executed less frequently
  - Classic situation: *hoist* loop-invariant code: execute once, rather than on every iteration

- Lazy code motion & *partial* redundancy



a must be re-calculated - wasteful if control took right-hand arm



Replicate, so a need not be re-calculated

Specialization I

- Idea: Replace general operation in IR with more specific
  - Constant folding:
    - feet_per_minute = mph * feet_per_mile/minutes_per_hour
    - feet_per_minute = mph * 5280 / 60
    - feet_per_minute = mph * 88
  - Replacing multiplications and division by constants with shifts (when safe)
  - Peephole optimizations
    - movl $0,%eax   =>   xorl %eax,%eax

Specialization:2 - Eliminate Tail Recursion

- Factorial - recursive
  - int fac(n) = if (n <= 2) return 1; else return n * fac(n - 1);
- 'accumulating' Factorial - tail-recursive
  - facaux(n, r) = if (n <= 2) return 1; else return facaux(n - 1, n*r)
  - call facaux(n, 1)
- Optimize-away the call overhead; replace with simple jump
  - facaux(n, r) = if (n <= 2) return 1;
    else n = n - 1; r = n*r; jump back to start of facaux
  - So replace recursive call with a loop and just one stack frame
- Issue?
  - Avoid stack overflow - good! - "observable" change?

Strength Reduction

- Classic example: Array references in a loop

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

- Naive codegen for a[k] = 0 in loop body

```
movl $4,%eax                  // elemsize = 4 bytes
imull offset_k(%rbp),%eax     // k * elemsize
addl  offset_a(%rbp),%eax     // &a[0] + k * elemsize
mov  $0,(%eax)                // a[k] = 0
```

- Better!

```
movl offset_a(%rbp),eax       // &a[0], once-off

movl $0,(%eax)                // a[k] = 0
addl $4,%eax                  // eax = &a[k+1]
```

Note: *pointers* allow a user to do this directly in C or C++
Eg: for (p = a; p < a + n;) *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

Other Common Transformations

- Inline substitution (procedure bodies)
- Cloning / Replicating
- Loop Unrolling
- Loop Unswitching

Inline Substitution - "inlining"

Class with trivial *getter*

```
class C {
  int x;
  int getx() { return x; }
}
```

Method f calls getx

```
class X {
  void f() {
    C c = new C();
    int total = c.getx() + 42;
  }
}
```

Compiler *inlines* body of getx into f

```
class X {
  void f() {
    C c = new C();
    int total = c.x + 42;
  }
}
```

- Eliminates call overhead
- Opens opportunities for more optimizations
- Can be applied to large method bodies too
- Aggressive optimizer will inline 2 or more deep
- Increases total code size (memory & cache issues)
- With care, is a huge win for OO code

Code Replication

Original

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

Replicated code

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

- + : extra opportunities to optimize in larger basic blocks (eg: LVN)
- - : increase total code size - may impact effectiveness of I-cache

Loop Unrolling

- Idea: Replicate the loop body
  - More opportunity to optimize loop body
  - Increases chances for good schedules and instruction level parallelism
  - Reduces loop overhead (reduce test/jumps by 75%)
- Catches
  - must ensure unrolled code produces the same answer: "loop-carried dependency analysis"
  - code bloat
  - don't overwhelm registers

Loop Unroll Example

Original

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

- Unroll 4x
- Need tidy-up loop for remainder

Unrolled

```
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 conditional
  - After this transformation, both loops have simpler control flow – more chances for rest of compiler to do better

Loop Unswitch Example

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 (i = 1; i <= n; i++) {
      a[i] = b[i]*y;
   }
}
```

- IF condition does not change value in this code snippet
- No need to check x > y on every iteration
- Do the IF check once!

Summary

- Just a sampler
  - 100s of transformations in the literature
  - Will examine several in more detail, particularly involving loops
- Big part of engineering a compiler is:
  - decide which transformations to use
  - decide in what order
  - decide if & when to repeat each transformation
- Compilers offer options:
  - optimize for speed
  - optimize for codesize
  - optimize for specific target micro-architecture
  - optimize for power consumption(!)
- Competitive bench-marking will investigate many permutations

What's next

- Careful look at several analysis and transformation algorithms
- Value numbering / dominators
- Dataflow
- Loops, loops, loops
  - Dominators – discovering loop structures
  - Loop-invariant code
  - Loop Transformations

- And an hour on (simple) code gen for the project