Special topics

CompCert: a formally verified compiler

What would you like to hear about?

Course evaluations

Please complete them

Optimization

Roadmap

Last time:

– CodeGen for the remainder of AST nodes

– Introduced the control-flow graph

This time:

– Optimization Overview

– Discuss a couple of optimizations

- Review CFGs

OPTIMIZATION OVERVIEW

Optimization goals

What are we trying to accomplish?

- Traditionally, speed
- Lower power
- Smaller footprint
- Bug resilience?

The fewer instructions the better

Optimization guarantees

Informally: Don’t change the program’s output

– We may relax this to “Don’t change the program’s output *on good input*”
– This can actually be really hard to do

Optimization difficulties

There's no perfect way to check equivalence of two arbitrary programs

- If there was we could use it to solve the halting problem
- We'll attempt to perform behavior-preserving transformations

Program analysis

A perspective on optimization

- Recognize some behavior in a program
- Replace it with a “better” version

Constantly plagued by the halting problem

- We can only use approximate algorithms to recognize behavior

Program behavior

Two terms in program analysis / behavior detection:

– Soundness: All results that are output are valid

– Completeness: All results that are valid are output

These terms are necessarily mutually exclusive

– If an algorithm was sound *and* complete, it would either:

1. Solve the halting program
2. Detect a trivial property

Back to optimization

We want our optimizations to be *sound* transformations

– In other words, they are always valid, but will miss some behaviors

You may be thinking…

I’m sad because this makes optimization seem pretty limited

Cheer up! Our optimization may be able to detect many *practical* instances of the behavior

Now you may be thinking…

I’m happy because I’m guaranteed that my optimization won’t do any harm

Settle down! Our optimization still needs to be efficient

Or maybe you are thinking…

I don't know how to feel about any of this without understanding how often it comes up

What can we do?

We can pick some low-hanging fruit

EXAMPLE OPTIMIZATIONS

Peephole optimization

A naïve code generator tends to output some silly code

– Err on the side of correctness over efficiency

Pattern-match the most obvious problems

CFG for program analysis

Consider the following sequence of instructions:

```
push { sw   $t0 0($sp)
       subu $sp $sp 4
pop  { lw   $t0 4($sp)
       addu $sp $sp 4
```

We'd like to remove this sequence…

– Is it sound to do so?

– Maybe not!

Review: the CFG

Program as a flowchart

Nodes are “Basic Blocks”

Edges are control transfers

- Fallthrough
- Jump
- *Maybe* function calls

CFG for optimization

We can limit our peephole optimizations to *intra-block* analysis

– This ensures, by definition, that no jumps will intrude on the sequence

We will assume for the rest of our peephole optimizations that instruction sequences are in one block

Peephole examples

Called “peephole” optimization because we are conceptually sliding a small window over the code, looking for small patterns

Outline

Four different optimizations

- Peephole optimization
- Loop-Invariant Code Motion
- For-loop strength reduction
- Copy propagation

Performed *after* machine code generation

Performed *before* machine code generation

Peephole optimization 1

Remove no-op sequences

– Push followed by pop

$$\text{push}\left\{\begin{array}{l}\texttt{sw \ \ \ \$t0 0(\$sp)}\\ \texttt{subu \$sp \$sp 4}\end{array}\right.$$

$$\text{pop}\left\{\begin{array}{l}\texttt{lw \ \ \ \$t0 4(\$sp)}\\ \texttt{addu \$sp \$sp 4}\end{array}\right.$$

– Add/sub 0

```
addu $t1 $t1 0
```

– Mul/div 1

```
mul $t2 $t2 1
```

Peephole optimization 2

Simplify sequences

- Ex. Store then load
- Strength reduction

```
sw   $t0 -8($fp)
lw   $t0 -8($fp)
```

Useless instruction

```
mul   $t1 $t1 2
```

shift-left $t1

```
add   $t2 $t2 1
```

inc $t2

Peephole optimization 3

Jump to next instruction

Remove this instruction

```
        j Lab1
Lab1    …
```

Loop invariant code motion

Loop Invariant Code Motion (LICM)

– Don’t duplicate effort in a loop

Goal

– Pull code out of the loop

– “Loop hoisting”

Important due to “hot spots”

– Most execution time due to small regions of deeply-nested loops

LICM example

```
for (i=0; i<100; i++) {
     for (j=0; j<100; j++) {
          for (k=0; k<100; k++) {
               A[i][j][k] = i*j*k
          }
     }
}
```

Sub-expression *invariant* with respect to Innermost loop

```
for (i=0; i<100; i++) {
     for (j=0; j<100; j++) {
          temp = i * j
          for (k=0; k<100; k++) {
               A[i][j][k] = temp *k
          }
     }
}
```

LICM: When should we do it?

In the previous example, showed LICM on source code

At IR level, more candidate operations

Assembly might be *too* low-level

- Need a guarantee that the loop is *natural*
  - No jumps into the loop

```
tmp0 = FP + offsetA
for (i=0; i<100; i++){
   tmp1 = tmp0 - i*40000
   for (j=0; j<100; j++){
       tmp2 = ind2
       tmp3 = i*j
       for (k=0; k<100; k++){
          T0 = tmp3 * k
          T1 = tmp2 - k*4
          store T0, 0(T1)
       }
   }
}
```

LICM: How should we do it?

Two factors, which really generalize to optimization:

- Safety
  - Is the transformation semantics-preserving?
    - Make sure the operation is truly loop-invariant
    - Make sure ordering of events is preserved
- Profitability
  - Is there any advantage to moving the instruction?
    - May end up moving instructions that are never executed
    - May end up performing more intermediate computation than necessary

Other loop optimizations

Loop unrolling

– For a loop with a small, constant number of iterations, we may actually save time by just placing every copy of the loop body in sequence (no jumps)
– May also consider doing multiple iterations within the body

Loop fusion

– Merge two sequential, independent loops into a single loop body (fewer jumps)

Jump optimizations

Disclaimer: Require some extra conditions

Jump around jump

```
        beq $t0,$t1,Lab1
        j    Lab2
Lab1:   …
        …
Lab2:   …
```

```
        bne $t0,$t1,Lab2
Lab1:   …
        …
Lab2:   …
```

Jump to jump

```
        j   Lab1
        …
Lab1:   j   Lab2
        …
Lab2:   …
```

```
        j   Lab2
        …
Lab1:   j   Lab2
        …
Lab2:   …
```

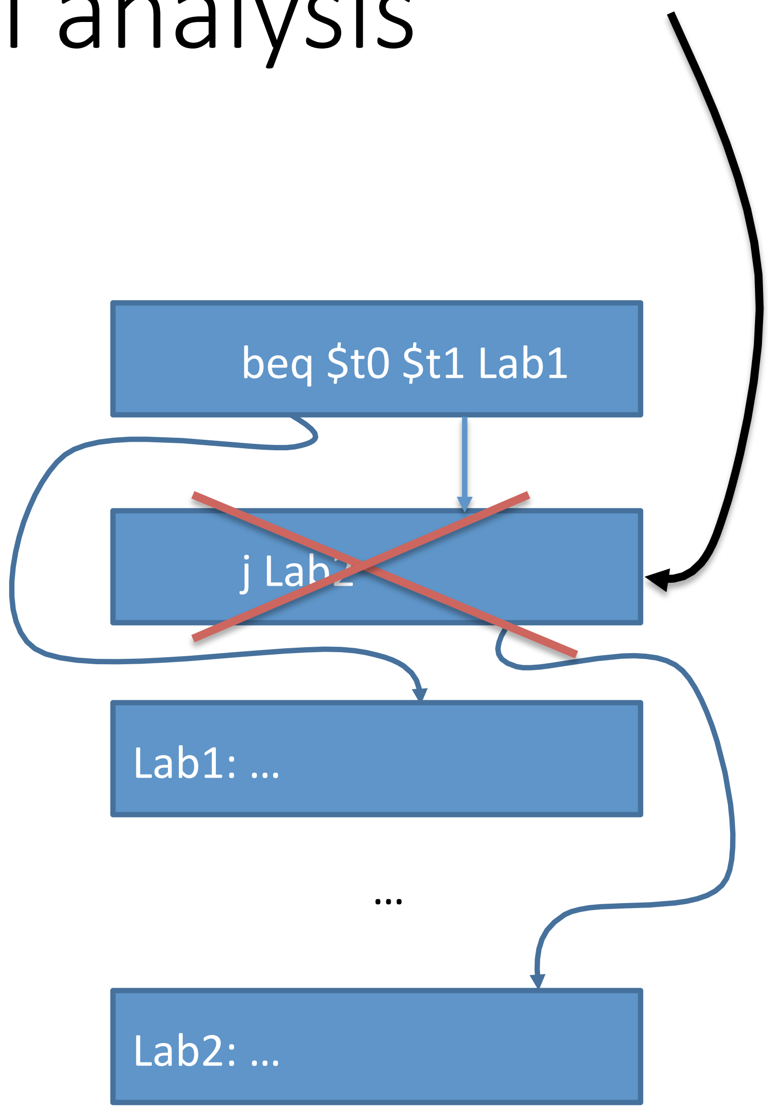
Intraprocedural analysis

The past two optimizations had some caveats

- There may be a jump into your eliminated code

We'd like to introduce a control-flow concept beyond basic blocks:

- Guarantee that block1 must be executed in order to get to block2
  - This goes by a pretty boring name



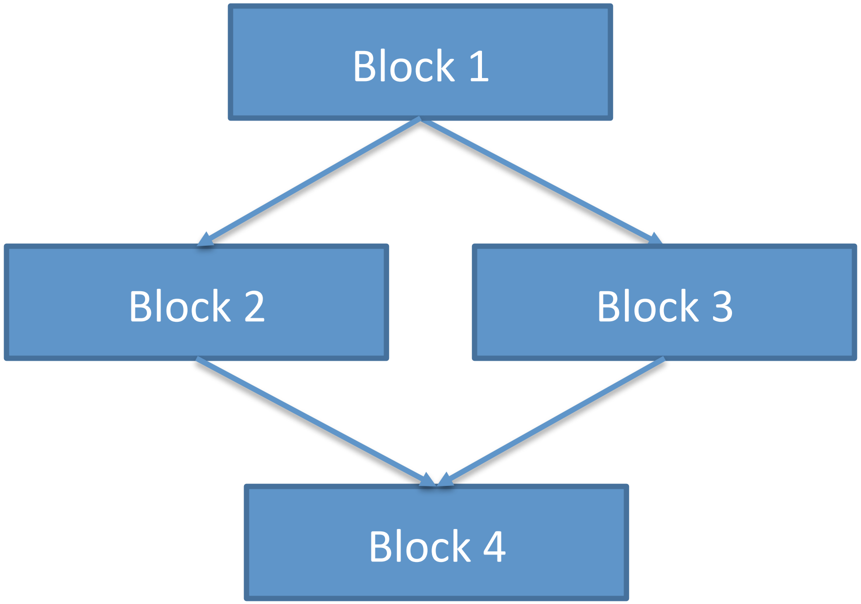
Domination

Dominators and post-dominators

We say that block A dominates block B if A **must** be executed before B is executed

We say that block A postdominates block B if A **must** be executed after B

Control Flow Graph



Semantics preserving

Do we really need semantics preserving optimizations?

Are there examples where we don’t?

In summary

Today

- Saw the basics of optimizations
- Soundness vs completeness
- Peephole and simple optimizations

Next time

- Wrap up optimizations
- Basics of static analysis