Optimization

- Identify inefficiencies in target or intermediate code
- Replace with equivalent but "better" sequences
- "Optimize" is a lie. "Usually improve" is more honest.

Example

\[
\begin{align*}
11 & := \ast (fp + \text{loffset}) \quad \text{// i} \\
12 & := \ast i \cdot 4 \\
13 & := fp + 12 \\
14 & := \ast (i3 + \text{aoffset}) \quad \text{// a[i]} \\
15 & := 2 \\
16 & := i5 \cdot 4 \\
17 & := fp + 16 \\
18 & := \ast (fp + \text{loffset}) \quad \text{// b[j]} \\
19 & := i4 + i8 \\
20 & := \ast (fp + \text{loffset}) \quad \text{// x := ...} \\
21 & := 10 + i0 \\
22 & := 110 + i11 \\
23 & := \ast (fp + \text{loffset}) \quad \text{// i} \\
24 & := i4 \cdot i3 \cdot 4 \\
25 & := fp + i4 \\
26 & := \ast (fp + \text{loffset}) \quad \text{// c[i] := ...} \\
27 & := i5 \cdot i0 + i14 \\
28 & := \ast (fp + \text{loffset}) \quad \text{// c[j] := ...} \\
\end{align*}
\]

Kinds of optimizations

- Scope of analysis is central to what optimizations can be performed. A larger scope may expose better optimizations, but is more complex
  - Peephole: look at adjacent instructions
  - Local: look at straight-line sequences of instructions
  - Global (intraprocedural): look at whole procedure
  - Interprocedural: look across procedures

Peephole

- After codegen, look at a few adjacent instructions
- Try to replace them with something better
- If you have
  - `sw $8, 12($fp)`
  - `lw $12, 12($fp)`
- You can replace it with
  - `sw $8, 12($fp)`
  - `mv $12, $8`
Peephole examples: 68k

If you have Replace it with

\begin{align*}
\text{sub } sp, 4, sp & \quad \text{mov } r1, -(sp) \\
\text{mov } r1, 0(sp) & \\
\text{mov } l2(fp), r1 & \quad \text{inc } l2(fp) \\
\text{add } r1, 1, r1 & \\
\text{mov } r1, l2(fp) &
\end{align*}

Peephole optimization of jumps

- Eliminate
  - Jumps to jumps
  - Conditional branch over unconditional branch
- “Adjacent instructions” means “adjacent in control flow”

How to do peephole opts

- Could be done at IR and/or target level
- Catalog of specific code rewrite templates
- Scan code with moving window looking for matches

Peephole summary

- You could consider peephole optimization as increasing the sophistication of instruction selection
- Relatively easy to do
- Relatively easy to extend
- Relatively easy to ensure correctness
- Relatively high payoff

Algebraic simplifications by peephole or codegen

- “constant folding” and “strength reduction” are common names for this kind of optimization

```plaintext
z := 3 + 4 
z := x + 0 
z := x * 1 
z := x * 2 
z := x * 8 
z := x / 8 
float x,y; 
z := (x + y) - y;
```

Local optimization

- Analysis and optimizations within a basic block
- A basic block is a straight-line sequence of statements with no control flow into or out of the middle of the sequence
- Local optimizations are more powerful than peephole (e.g., block may be longer than peephole window)
  - Not too hard to implement
  - Can be machine-independent, if done on intermediate code
Local constant propagation (aka "constant folding")

- If a constant is assigned to a variable, replace downstream uses of the variable with the constant
- If all operands are const, replace with result
- May enable further constant folding

Example

```
const count : int = 10;
...
x := count * 5;
y := x + 3;
```

Intermediate code after constant propagation

Local dead assignment elimination

- If the left hand side of an assignment is never read again before being overwritten, then remove the assignment
- This sometimes happens while cleaning up from other optimizations (as with many of the optimizations we consider)

Example

```
const count : int = 10;
...
x := count * 5;
y := x + 3;
x := input;
```

Intermediate code after constant propagation

Common subexpression elimination

- Avoid repeating the same calculation
- Requires keeping track of available expressions

CSE example:

```
... a[i] + b[i]...
```

```
t1 := *(fp + ioffset)
t2 := t1 * 4
t3 := fp + t2
t4 := *(t3 + offset)
t5 := *(fp + ioffset)
t6 := t5 + 4
t7 := fp + t6
t8 := *(t7 + boffset)
t9 := t4 + t8
```
Intraprocedural optimizations

- Enlarge scope of analysis to entire procedure
- Provides more opportunities for optimization
- Have to deal with branches, merges and loops
- Can do constant propagation, common subexpression elimination, etc. at this level
- Can do new things, too, like loop optimizations
- Optimizing compilers usually work at this level

Code motion

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

```c
for i := 1 to 10 do
  a[i] := a[i] + b[j];
z := z + 10000
end
```

At intermediate code level

```c
for i := 1 to 10 do
  a[i] := a[i] + x;
end
  p := p + x;
end
```

Loop induction variable elimination

- For-loop index is an induction variable
  - Incremented each time through the 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 the loop

Example

```c
for i := 1 to 10 do
  a[i] := a[i] + x;
  p := p + x;
end
```
Global register allocation
- Try to allocate local variables to registers
- If two locals don’t overlap, then give them the same register
- Try to allocate most frequently used variables to registers first

Register allocation by coloring
- As before, IR gen as if infinite regs avail
- Build interference graph:
  - x := a+5;
  - y := b+2;
  - z := x/3;
  - a := y-2;
- Colorable with few colors (regs)?
  - NP-hard, but …
- If not, pick a node & generate spill code

Interprocedural optimizations
- What happens if we expand the scope of the optimizer to include procedures calling each other
  - In the broadest scope, this is optimization of the program as a whole
  - We can do local, intraprocedural optimizations at a bigger scope
  - For example, constant propagation
  - But we can also do entirely new optimizations, such as inlining

Interprocedural opt: Issues
- procedure P() {
  - x: int;
  - x := 10;
  - Q( );
  - x := x+1;
  - if x == 11 then
    - …
- Q() by value
- Q(x by reference)
- Q(const x by reference)
- Q(), but Q declared in P
- …

Inlining
Replace procedure call with the body of the called procedure

Questions about inlining:
- How to decide where the payoff is sufficient to inline?
  - The real decision depends on dynamic information about frequency of calls
  - In most cases, inlining causes the code size to increase; when is this acceptable?
  - Others?
Optimization and debugging
- Debugging optimized code is often hard
- For example, what if:
  - Source code statements have been reordered?
  - Source code variables have been eliminated?
  - Code is inlined?
- In general, the more optimization there is, the more complex the back-mapping is from the target code to the source code … which can confuse a programmer.

Summary of optimization
- Larger scope of analysis yields better results
  - Most of today’s optimizing compilers work at the intraprocedural level, with some doing some work at the interprocedural level
  - Optimizations are usually organized as collections of passes
  - The presence of optimizations may make other parts of the compiler (e.g., code gen) easier to write
    - E.g., use a simple instruction selection algorithm, knowing that the optimizer can, in essence, act to improve these instruction selections

Implementing intraprocedural optimizations
- The heart of implementing optimizations is the definition and construction of a convenient representation
- We’ll look a bit more closely at two common and useful representations
  - The control flow graph (CFG)
  - The data flow graph (DFG)

CFG
- Nodes are intermediate language statements
  - Or whole basic blocks
- Edges represent control flow
- Node with multiple successors is a branch/switch
- Node with multiple predecessors is a merge
- Loop in a graph represents a loop in the program

Example
```
while x > y do
  x := x + 1;
end;
if x > 0 then
  output := x;
end;
```

DFG: def/use chains
- Nodes are def(initions) and uses
- Edge from def to use
- A def can reach multiple uses
- A use can have multiple reaching def's
Example

```
x := input; y := input;
while x > y do
  x := x + 1;
end;
if x > 0 then output := x;
end;
```

Example program

```
x := 3;
y := x * z;
if x > 10 then
  x := 5;
y := y + 1;
else
  x := 6;
y := x + 4;
end;
w := y / 3;
while y > 0 do
  z := w * w;
x := x – z;
y := y – 1;
end;
output := x;
```

Analysis and transformation

- Each optimization is one or more analyses followed by a transformation
- Analyze CFG and/or DFG by propagating information forward or backward along CFG and/or DFG edges.
  - Merges in graph require combining information
  - Loops in graph require iterative approximation
- Perform improving transformations based on information computed
  - Have to wait until any iterative approximation has converged
- Analysis must be conservative, so that transformations preserve program behavior

```
proc foo(j, k, l : int) : int
begin
  int a, b, c, n, x;
  a := 17 * j;
b := k * k;
c := a + b;
a := k * l;
return c;
end
```

Liveness analysis

- This analysis is a form of liveness analysis
  - Can help identify assignments to remove
  - It can also form the basis for memory and register optimizations
- The goal is to identify which variables are live and which are dead at given program points
- The analysis is usually performed backwards
  - When a variable is used, it becomes live in that statement and code before it
  - When a variable is assigned to, it becomes dead for all code before it
- Note the relationship to def-use, as we saw in the data flow graph

```
proc foo(j, k, l:int):int
begin
  int a, b, c, n, x;
a := 17 * j;
b := k * k;
c := a + b;
a := k * l;
return c;
end
```

A simple analysis

- Let's start with a simple analysis that can help us determine which assignments can be eliminated from a basic block
- The example is unreasonable as source, but perhaps not as intermediate code

```
proc foo(j, k, l : int):int
begin
  int a, b, c, n, x;
a := 17 * j;
b := k * k;
c := a + b;
a := k * l;
return c;
end
```

Work backwards

```
```

Live  Dead
```

```
```

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This analysis shows we can eliminate the last assignment to \(a\), which is no surprise.

Technically, assignments to a dead variable can be removed.

The value isn’t needed below, so why do the assignment?

Furthermore, you could show for this example that the declarations for \(n\) and \(x\) aren’t needed, since \(n\) nor \(x\) is ever live.

After eliminating the last assignment (and these two declarations), you can redo the analysis.

This analysis now shows that \(a\) is dead everywhere in the block, and it can be removed as a parameter.

The stack can be reduced because of this.

And the caller could, in principle, be further optimized.

But that’s for basic blocks.

Once we have control flow, it’s much harder to do because we don’t know the order in which the basic blocks will execute.

We need to ensure (for optimization) that every possible path is accounted for, since we must make conservative assumptions to guarantee that the optimized code always works.

We’re going to need something called global data flow analysis.

The form we’re interested in for live variable analysis (across basic blocks) is any-path analysis.

An any-path property is true if there exists some path through the control flow graph such that the given property holds.

For example, a variable is live if there is some path leading to it being accessed.

For example, a variable is uninitialized if there is some path that does not initialize it.

All-path is the other major form of analysis.

Let’s now consider this analysis over a control flow graph:

- Basic blocks connected by edges showing possible control flow.
- We omit the conditionals and labels on edges, since that’s fine for any-path analysis.
- This is extremely conservative (safe).

A definition of a variable \(x\) is a statement that assigns a value to \(x\).

(The book discussed unambiguous vs. ambiguous definitions, but we’ll ignore this)

A definition \(d\) reaches a program point \(p\) if:

- There is a path from the point immediately following \(d\) to \(p\).
- And \(d\) is not killed along that path.

We’re now really giving formal definitions to these terms, but we’ve used them before.
Examples
- d1, d2, d5 reach the beginning of B2
- d2 does not reach B4, B5, or B6
- Note: this is a conservative analysis, since it may determine that a definition reaches a point even if it might not in practice

But how to compute in general?
- We’d like to be able to compute all reaching definitions (for example)
- Let’s consider a simple language
  - It turns out to be very material
  - Complex languages impose really serious demands on data flow analysis
- \( S \leftarrow \text{id} \mapsto \text{E} \mid \text{S} \mid \text{if E then S else S} \mid \text{do S while E} \)
  \( E \leftarrow \text{id} \mapsto \text{id} \mid \text{id} \)

Data flow equations
- We’re now going to define a set of equations that represent the flow through different constructs in the language
- For example
  - \( \text{out}[S] = \text{gen}[S] \cup (\text{in}[S] \setminus \text{kill}[S]) \)
  - “The information at the end of \( S \) is either generated within the statement \( \text{gen}(S) \) or enters at the beginning of the statement \( \text{in}(S) \) and is not killed by the statement \( \setminus \text{kill}(S) \)”

Example: \( d: \text{a} \mapsto \text{b+c} \)
- \( \text{gen}[S] = \{d\} \)
- \( \text{kill}[S] = \text{D}_a \setminus \{d\} \)
- \( \text{out}[S] = \text{gen}[S] \cup (\text{in}[S] \setminus \text{kill}[S]) \)
- \( \text{D}_a \) is the set of all definitions in the program for variable \( a \)

Example: \( S_1; S_2 \)
- \( \text{gen}[S] = \text{gen}[S_2] \cup (\text{gen}[S_1] \setminus \text{kill}[S_2]) \)
- \( \text{kill}[S] = \text{kill}[S_2] \cup (\text{kill}[S_1] \setminus \text{gen}[S_2]) \)
- \( \text{in}[S_1] = \text{in}[S] \)
- \( \text{in}[S_2] = \text{out}[S_1] \)
- \( \text{out}[S] = \text{out}[S_2] \)

Example: if E then S1 else S2 fi
- \( \text{gen}[S] = \text{gen}[S_1] \cup \text{gen}[S_2] \)
- \( \text{kill}[S] = \text{kill}[S_1] \cap \text{kill}[S_2] \)
- \( \text{in}[S_1] = \text{in}[S] \)
- \( \text{in}[S_2] = \text{in}[S] \)
- \( \text{out}[S] = \text{out}[S_1] \cup \text{out}[S_2] \)
Example: while E do S1
- gen[S] = gen[S1]
- kill[S] = kill[S1]
- in[S1] = in[S] ∪ gen[S1]
- out[S] = out[S1]

Then what?
- In essence, this defines a set of rules by which we can write down the relationships for gen/kill and in/out for a whole (structured) program
- This defines a set of equations that then need to be solved
- This solution can be complicated
  - We don't know if/when branches are taken
  - Loops introduce complications
  - Merges introduce complications
- Approaches to solutions: next lecture