Introduction

What do we Optimize?
### What do we Optimize I?

1. **Optimize everything, all the time.** The problem is that optimization interferes with debugging. In fact, many (most) compilers don’t let you generate an optimized program with debugging information. The problem of debugging optimized code is an important research field. Furthermore, optimization is probably the most time consuming pass in the compiler. Always optimizing everything (even routines which will never be called!) wastes valuable time.

2. **The programmer decides what to optimize.** The problem is that the programmer has a local view of the code. When timing a program programmers are often very surprised to see where most of the time is spent.

### What do we Optimize II?

3. **Turn optimization on when program is complete.** Unfortunately, optimizers aren’t perfect, and a program that performed OK with debugging turned on often behaves differently when debugging is off and optimization is on.

4. **Optimize inner loops only.** Unfortunately, procedure calls can hide inner loops:

   ```plaintext
   PROCEDURE P(n);
   BEGIN
   FOR k:=1 TO n DO · · ·END;
   END P;
   FOR i:=1 TO 10000 DO P(i) END;
   ```

### What do we Optimize III?

5. **Use profiling information to guide what to optimize.**

6. **Runtime code generation/optimization.** We delay code generation and optimization until execution time. At that time we have more information to guide the optimizations:

### Local vs. Global vs. Inter-procedural Optimization
Some compilers optimize more **aggressively** than others. An aggressive compiler optimizes over a large piece of code, a simple one only considers a small chunk of code at a time.

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**Local Optimization**
- Consider each basic block by itself.
- All compilers do this.

**Global Optimization**
- Consider each procedure by itself.
- Most compilers do this.

**Inter-Procedural Opt.**
- Consider the control flow between procedures.
- A few compilers do this.

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**Original Code**

```plaintext
FUNCTION P (X,n): INT;
IF n = 3 THEN RETURN X[1]
ELSE RETURN X[n];
CONST R = 1;
BEGIN
K := 3; ...
IF P(X,K) = X[1] THEN
```

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**After Local Opt**

```plaintext
FUNCTION P (X,n): INT;
IF n = 3 THEN RETURN X[1]
ELSE RETURN X[n]
BEGIN
K := 3; ...
IF P(X,K) = X[1] THEN
```

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**After Global Opt**

```plaintext
FUNCTION P (X,n): INT;
IF n = 3 THEN RETURN X[1]
ELSE RETURN X[n]
BEGIN
...
IF P(X,3) = X[1] THEN
```
Local Optimization IV

BEGIN
IF TRUE THEN

Delete P if it isn’t used elsewhere. This can maybe be deduced by an inter-procedural analysis.

Local Optimization

Transformations
- Local common subexpression elimination.
- Local copy propagation.
- Local dead-code elimination.
- Algebraic optimization.
- Jump-to-jump removal.
- Reduction in strength.

Peephole Optimization
- On machine and/or interm. code.
- Examine a “window” of instructions.
- Improve code in window.
- Slide window.
- Repeat until “optimal”.

Redundant Loads
- A naive code generator will generate the same address or variable several times. Peephole optimization over the generated code will easily remove these.

```
A := A + 1;
↓
set A, %10
set A, %11
ld [%11], %11
add %11, 1, %11
st %11, [%10]
↓
set A, %10
ld [%10], %11
add %11, 1, %11
st %11, [%10]
```
Complicated boolean expressions (with many and, or, nots) can easily produce lots of jumps to jumps. A peephole optimization pass over the generated code can remove these.

\[
\begin{align*}
\text{if } a < b & \text{ goto L1 } \\
\ldots & \\
L1: & \text{ goto L2 } \\
\ldots & \\
L2: & \text{ goto L3 } \\
\downarrow & \\
\text{if } a < b & \text{ goto L3 } \\
\ldots & \\
L1: & \text{ goto L3 } \\
\ldots & \\
L2: & \text{ goto L3 }
\end{align*}
\]

Beware of numerical problems:

4. \( (x \times 0.00000001) \times 10000000000.0 \) may produce a different result than \( (x \times 1000.0) \)!

FORTRAN requires that parenthesis be honored:

\( (5.0 \times x) \times (6.0 \times y) \) can't be evaluated as \( (30.0 \times x \times y) \).

Note that multiplication is often faster than division.

\[
\begin{align*}
x := x + 0; & \Rightarrow \\
x := x - 0; & \Rightarrow \\
x := x \times 1; & \Rightarrow \\
x := 1 \times 1; & \Rightarrow \\
x := x / 1; & \Rightarrow \\
x := x \times 2; & \Rightarrow \\
f := f / 2.0; & \Rightarrow 
\end{align*}
\]

Global Optimization

\[ \text{SHL}(x, y) = \text{shift } x \text{ left } y \text{ steps.} \]

\[ \text{Multiplication (and division) by a constant is a common operation. They can be replaced by cheaper sequences of shifts and adds.} \]

\[
\begin{align*}
x := x \times 32; & \\
\downarrow & \\
x := \text{SHL}(x, 5); & \\
\end{align*}
\]

\[
\begin{align*}
x := x \times 100; & \\
\downarrow & \\
x := x \times (64 + 32 + 4) & \\
\downarrow & \\
x := x \times 64 + x \times 32 + x \times 4 & \\
\downarrow & \\
x := \text{SHL}(x, 6) + \text{SHL}(x, 5) + \text{SHL}(x, 2) & \\
\end{align*}
\]
Global Optimization I

- Makes use of control-flow and data-flow analysis.

**Transformations**
- Dead code elimination.
- Common subexpression elimination (local and global).
- Loop unrolling.
- Code hoisting.
- Induction variables.
- Reduction in strength.
- Copy propagation.
- Live variable analysis.
- Uninitialized Variable Analysis.

Control Flow Graphs

- We perform our optimizations over the control flow graph of a procedure.

**Common Sub-Expr. Elimination**

No changes to \( j \) here!

**Copy Propagation**

Many optimizations produce \( X := Y \).

- After an assignment \( X := Y \), replace references to \( X \) by \( Y \). Remove the assignment if possible.
Dead Code Elimination

- A piece of code is dead if we can determine at compile time that it will never be executed.

```plaintext
x := 23
if x > 20 goto B4
t1 := 4 * j
A[t3] := 20
```

No changes to x here!

Induction Variables

- If i and j are updated simultaneously in a loop, and
  \( j = i \times c_1 + c_2 \) (\( c_1, c_2 \) are constants) we can remove one of them, and/or replace \( \times \) by +.

```plaintext
t1 := 4 * j
j := j + 1;
t4 := A[4*j]
x := 23;
REPEAT
UNTIL ....;
```

Code Hoisting

- Move code that is computed twice in different basic blocks to a common ancestor block.

```plaintext
IF a < 5 THEN X := A[i+3] + 9;
ELSE X := A[i+3] * 6 END
```

Loop Unrolling

- Loop Unrolling
Loop Unrolling

FOR i := 1 TO 5 DO A[i]:=i END
⇓

Variable Bounds

FOR i := 1 TO n DO A[i] := i END
⇓
i := 1;
WHILE i <= (n-4) DO
  A[i]:=i; A[i+1]:=i+1; A[i+2]:=i+2;
  A[i+3]:=i+3; A[i+4]:=i+4; i:=i+5;
END;
WHILE i<=n DO A[i]:=i; i:=i+1; END

Loop unrolling increases code size. How does this effect caching?

Inter-procedural Optimizations

Consider the entire program during optimization.

How can this be done for languages that support separately compiled modules?

Transformations

- Inline expansion
  - Replace a procedure call with the code of the called procedure.
- Procedure Cloning
  - Create multiple specialized copies of a single procedure.
- Inter-procedural constant propagation
  - If we know that a particular procedure is always called with a constant parameter with a specific value, we can optimize for this case.

Original Code:

FUNCTION Power (n, exp:INT):INT;
  IF exp < 0 THEN result := 0;
  ELSIF exp = 0 THEN result := 1;
  ELSE result := n;
  FOR i := 2 TO exp DO
    result := result * n;
  END;
END Power;
BEGIN X := 7; PRINT Power(X,2) END;
Inline Expansion Ib

Expanded Code:
BEGIN
  X := 7;
  result := X;
  FOR i := 2 TO 2 DO
    result := result * X;
  END;
  PRINT result;
END

Inline Expansion IIa

After copy propagation
BEGIN
  X := 7;
  result := 7;
  FOR i := 2 TO 2 DO
    result := result * 7;
  END;
  PRINT result;
END

Inline Expansion IIb

After loop unrolling
BEGIN
  X := 7;
  result := 7;
  result := result * 7;
  PRINT result;
END

Procedure Cloning Ia

Original Code:
FUNCTION Power (n, exp:INT):INT;
  IF exp < 0 THEN result := 0;
  ELSIF exp = 0 THEN result := 1;
  ELSE result := n;
    FOR i := 2 TO exp DO
      result := result * n;
    END;
  END;
  RETURN result;
END Power;
BEGIN PRINT Power(X,2), Power(X,7) END;
Machine Dependent vs. Machine Independent Optimization

Optimizations such as inline expansion and loop unrolling seem pretty machine independent. You don’t need to know anything special about the machine architecture to implement these optimizations, in fact, both inline expansion and loop unrolling can be applied at the source code level. (May or may not be true for inline expansion, depending on the language).

However, since both inline expansion and loop unrolling normally increase the code size of the program, these optimizations do, in fact, interact with the hardware.

A loop that previously might have fit in the instruction cache of the machine, may overflow the cache once it has been unrolled, and therefore increase the cache miss rate so that the unrolled loop runs slower than the original one.

The unrolled loop may even be spread out over more than one virtual memory page and hence affect the paging system adversely.

The same argument holds for inline expansion.
Example I

Example I/a – Loop Invariants

Find loop invariants:

```plaintext
FOR I:= 1 TO 100 DO
    T3 := ADR(A[I]);
    FOR J := 1 TO 100 DO
        T1 := ADR(T3[J]);
        T2 := I * J;
        FOR K := 1 TO 100 DO
            T1[K] := T2 * K
        END;
    END;
END;
```

Example I/b – Strength Reduct.

After strength reduction:

```plaintext
FOR I:= 1 TO 100 DO
    T3 := ADR(A[I]); T4 := I;
    FOR J := 1 TO 100 DO
        T1 := ADR(T3[J]);
        T2 := T4; (* T4 = I*J *)
        T5 := T2; (* Init T2*K *)
        FOR K := 1 TO 100 DO
            T1[K] := T5; T5 := T5 + T2;
        END;
        T4 := T4 + I;
    END;
END
```

- T4 holds \( I*J; I, I + I, I + I + I, \ldots I*J \).
- T5 holds \( T2*K = I*J*K \).
Example I/c – Copy Propagation

After Copy Propagation:

FOR I := 1 TO 100 DO
  T3 := ADR(A[I]); T4 := I;
  FOR J := 1 TO 100 DO
    T1 := ADR(T3[J]); T5 := T4;
    FOR K := 1 TO 100 DO
      T1[K] := T5; T5 := T5 + T4;
    END;
    T4 := T4 + I;
  END;
END

We replace T2 by T4.

Example I/d – Array Indexing

Expand subscripting operations. Pascal array indexing turns into C-like address manipulation!

VAR A: ARRAY[1..100,1..100,1..100] OF INT;
FOR I := 1 TO 100 DO
  T3 := ADR(A) + (10000*I)-10000;
  T4 := I;
  FOR J := 1 TO 100 DO
    T1 := T3 +(100*J)-100;
    T5 := T4;
    FOR K := 1 TO 100 DO
      (T1+K-1)↑ := T5;
      T5 := T5 + T4;
    END;
    T4 := T4 + I;
  END;
END

Example I/e – Array Indexing

Strength Red. + Copy Prop.:

T6 := ADR(A);
FOR I := 1 TO 100 DO
  T4 := I; T7 := T6;
  FOR J := 1 TO 100 DO
    T5 := T4; T8 := T7;
    FOR K := 1 TO 100 DO
      T8↑ := T5;
      T5 := T5 + T4;
      T8 := T8 + 1;
    END;
    T4 := T4 + I;
    T7 := T7 + I00;
  END;
  T6 := T6 + 10000;
END

Example I/f – Loop Unrolling

T6 := ADR(A);
FOR I := 1 TO 100 DO
  T4 := I; T7 := T6;
  FOR J := 1 TO 100 DO
    T5 := T4; T8 := T7;
    FOR K := 1 TO 10 DO
      T8↑ := T5;
      T5 += T4; T8 ++;
      T8↑ := T5;
      T5 += T4; T8 ++;
      T8↑ := T5;
      T5 += T4; T8 ++;
    (* Repeat 10 times *)
    T8 := T8 + 1;
  END;
  T4 := T4 + I;
  T7 := T7 + I00;
END;
T6 := T6 + 10000;
END
Example II

- ftp://cs.washington.edu/pub/pardo. The code has been simplified substantially...
- bitblt copies image regions while performing an operation on the moved part.
- s is the source, d the destination, i the index in the x direction, j the index in the y direction.
- Every time around the loop we have to execute a switch (case) statement, which is very inefficient.
- Here we'll show how bitblt can be optimized by inlining. It's also amenable to run-time (dynamic) code generation. I.e. we include the code generator in the executable and generate code for bitblt when we know what it's arguments are.

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**Example II/b – Inline Expansion**

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**Example II/c – Inline Expansion**
main () {
    d = src; s=dst;
    for (j=0; j<dy; ++j) {
        for (i=nw+1; i>0; --i) {
            d ^= ((s ^ *d) & mask);
        }
    }
    d++; s++;
    d++; s++;
}