15-213

Code Optimization
October 3, 2000

Topics

- **Machine-Independent Optimizations**
  - Code motion
  - Reduction in strength
  - Common subexpression sharing
- **Machine-Dependent Optimizations**
  - Pointer code
  - Unrolling
  - Enabling instruction level parallelism
- **Advice**

Great Reality #4

There's more to performance than asymptotic complexity

Constant factors matter too!

- **easily see 10:1 performance range depending on how code is written**
- **must optimize at multiple levels:**
  - algorithm, data representations, procedures, and loops

Must understand system to optimize performance

- **how programs are compiled and executed**
- **how to measure program performance and identify bottlenecks**
- **how to improve performance without destroying code modularity and generality**

Optimizing Compilers

Provide efficient mapping of program to machine

- **register allocation**
- **code selection and ordering**
- **eliminating minor inefficiencies**

Don't (usually) improve asymptotic efficiency

- **up to programmer to select best overall algorithm**
- **big-O savings are (often) more important than constant factors**
  - but constant factors also matter

Have difficulty overcoming "optimization blockers"

- **potential memory aliasing**
- **potential procedure side-effects**

Limitations of Optimizing Compilers

Operate Under Fundamental Constraint

- **Must not cause any change in program behavior under any possible condition**
- **Often prevents it from making optimizations when would only affect behavior under pathological conditions.**

Behavior that may be obvious to the programmer can be obfuscated by languages and coding styles

- **e.g., data ranges may be more limited than variable types suggest**
  - e.g., using an "`int`" in C for what could be an enumerated type

Most analysis is performed only within procedures

- **whole-program analysis is too expensive in most cases**

Most analysis is based only on *static* information

- **compiler has difficulty anticipating run-time inputs**

When in doubt, the compiler must be conservative

Machine-Independent Optimizations

- **Optimizations you should do regardless of processor / compiler**

Code Motion

- **Reduce frequency with which computation performed**
  - If it will always produce same result
  - Especially moving code out of loop

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
for (i = 0; i < n; i++) {
  int ni = n*i;
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
}
```


Machine-Independent Opts. (Cont.)

Reductions in Strength:

- **Replace costly operation with simpler one**
- **Shift, add instead of multiply or divide**

  `16*x    -->    x << 4`
  - **Utility machine dependent**
  - **Depends on cost of multiply or divide instruction**
  - **On Pentium II or III, integer multiply only requires 4 CPU cycles**

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
int ni = 0;
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
  ni += n;
}
```

- **Keep data in registers rather than memory**
  - Compilers have trouble making this optimization

Machine-Independent Opts. (Cont.)

Share Common Subexpressions

- **Reuse portions of expressions**
- **Compilers often not very sophisticated in exploiting arithmetic properties**

```
/* Sum neighbors of i,j */
up =    val[(i-1)*n + j];
down =  val[(i+1)*n + j];
left =  val[i*n   + j-1];
right = val[i*n   + j+1];
sum = up + down + left + right;
```

3 multiplications: i*n, (i–1)*n, (i+1)*n

```
int inj = i*n + j;
up =    val[inj - n];
down =  val[inj + n];
left =  val[inj - 1];
right = val[inj + 1];
sum = up + down + left + right;
```

1 multiplication: i*n

Important Tools

Measurement

- **Accurately compute time taken by code**
  - Most modern machines have built in cycle counters
- **Profile procedure calling frequencies**
  - Unix tool gprof
- **Custom-built tools**
  - E.g., L4 cache simulator

Observation

- **Generating assembly code**
  - Lets you see what optimizations compiler can make
  - Understand capabilities/limitations of particular compiler

Optimization Example

```
void combine1(vec_ptr v, int *dest)
{
  int i;
  *dest = 0;
  for (i = 0; i < vec_length(v); i++) {
    int val;
    get_vec_element(v, i, &val);
    *dest += val;
  }
}
```

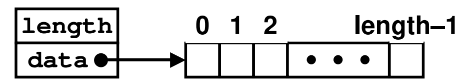
Procedure

- Compute sum of all elements of integer vector
- Store result at destination location
- Vector data structure and operations defined via abstract data type

Pentium II/III Performance: Clock Cycles / Element

- 40.3 (Compiled -g)   28.6 (Compiled -O2)

Vector ADT



Procedures

`vec_ptr new_vec(int len)`
- Create vector of specified length

`int get_vec_element(vec_ptr v, int index, int *dest)`
- Retrieve vector element, store at *dest
- Return 0 if out of bounds, 1 if successful

`int *get_vec_start(vec_ptr v)`
- Return pointer to start of vector data

- **Similar to array implementations in Pascal, ML, Java**
  - E.g., always do bounds checking

Understanding Loop

```
void combine1-goto(vec_ptr v, int *dest)
{
    int i = 0;
    int val;
    *dest = 0;
    if (i >= vec_length(v))
      goto done;
  loop:
    get_vec_element(v, i, &val);
    *dest += val;
    i++;
    if (i < vec_length(v))
      goto loop
  done:
}
```

1 iteration

Inefficiency

- Procedure vec_length called every iteration
- Even though result always the same

Move `vec_length` Call Out of Loop

```
void combine2(vec_ptr v, int *dest)
{
  int i;
  int len = vec_length(v);
  *dest = 0;
  for (i = 0; i < len; i++) {
    int val;
    get_vec_element(v, i, &val);
    *dest += val;
  }
}
```

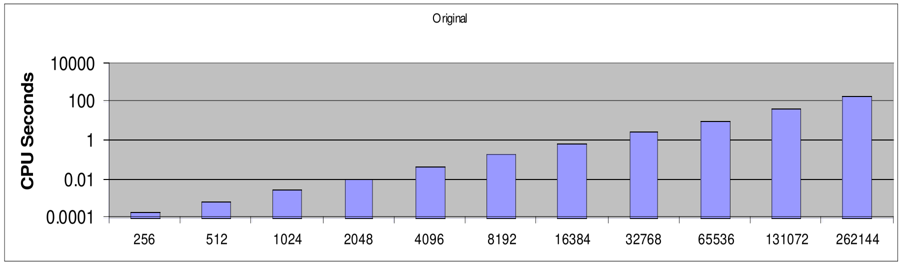
Optimization

- **Move call to `vec_length` out of inner loop**
  - Value does not change from one iteration to next
  - Code motion
- **CPE: 20.2 (Compiled -O2)**
  - `vec_length` requires only constant time, but significant overhead

Code Motion Example #2

Procedure to Convert String to Lower Case

```
void lower(char *s)
{
  int i;
  for (i = 0; i < strlen(s); i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```



CPU time quadruples every time double string length

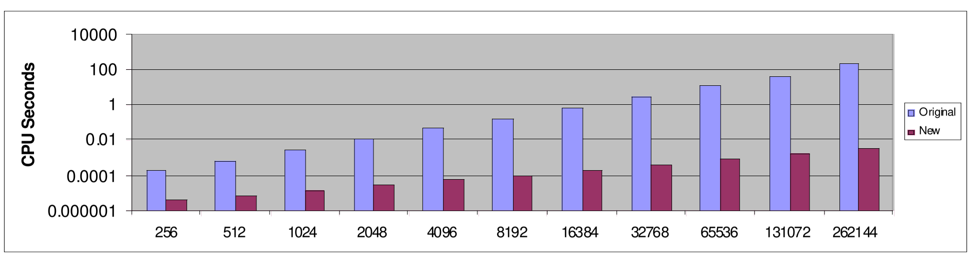
Convert Loop To Goto Form

```
void lower(char *s)
{
   int i = 0;
   if (i >= strlen(s))
     goto done;
 loop:
   if (s[i] >= 'A' && s[i] <= 'Z')
       s[i] -= ('A' - 'a');
   i++;
   if (i < strlen(s))
     goto loop;
 done:
}
```

- **`strlen` executed every iteration**
- **`strlen` linear in length of string**
  - Must scan string until finds `'\0'`
- **Overall performance is quadratic**

Improving Performance

```
void lower(char *s)
{
  int i;
  int len = strlen(s);
  for (i = 0; i < len; i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```



CPU time doubles every time double string length

Optimization Blocker: Procedure Calls

Why couldn't the compiler move `vec_len` or `strlen` out of the inner loop?

- **Procedure May Have Side Effects**
  - i.e, alters global state each time called
- **Function May Not Return Same Value for Given Arguments**
  - Depends on other parts of global state
  - Procedure `lower` could interact with `strlen`

Why doesn't compiler look at code for `vec_len` or `strlen`?

- **Linker may overload with different version**
  - Unless declared static
- **Interprocedural optimization is not used extensively due to cost**

Warning:

- **Compiler treats procedure call as a black box**
- **Weak optimizations in and around them**

Reduction in Strength

```
void combine3(vec_ptr v, int *dest)
{
  int i;
  int len = vec_length(v);
  int *data = get_vec_start(v);
  *dest = 0;
  for (i = 0; i < length; i++) {
    *dest += data[i];
}
```

Optimization

- **Avoid procedure call to retrieve each vector element**
  - Get pointer to start of array before loop
  - Within loop just do pointer reference
  - Not as clean in terms of data abstraction
- **CPE: 6.76 (Compiled -O2)**
  - Procedure calls are expensive!
  - Bounds checking is expensive

Eliminate Unneeded Memory References

```
void combine4(vec_ptr v, int *dest)
{
  int i;
  int len = vec_length(v);
  int *data = get_vec_start(v);
  int sum = 0;
  for (i = 0; i < length; i++) {
    sum += data[i];
  *dest = sum;
}
```

Optimization

- **Don't need to store in destination until end**
- **Local variable `sum` held in register**
- **Avoids 1 memory read, 1 memory write per cycle**
- **CPE: 3.06 (Compiled -O2)**
  - Memory references are expensive!

Optimization Blocker: Memory Aliasing

Aliasing

- **Two different memory references specify single location**

Example

- **`v: [3, 2, 17]`**
- **`combine3(v, get_vec_start(v)+2)   -->   ?`**
- **`combine4(v, get_vec_start(v)+2)   -->   ?`**

Observations

- **Easy to have happen in C**
  - Since allowed to do address arithmetic
  - Direct access to storage structures
- **Get in habit of introducing local variables**
  - Accumulating within loops
  - Your way of telling compiler not to check for aliasing

Machine-Independent Opt. Summary

Code Motion

- *compilers are not very good at this, especially with procedure calls*

Reduction in Strength

- **Shift, add instead of multiply or divide**
  - *compilers are (generally) good at this*
  - *Exact trade-offs machine-dependent*
- **Keep data in registers rather than memory**
  - *compilers are not good at this, since concerned with aliasing*

Share Common Subexpressions

- *compilers have limited algebraic reasoning capabilities*

Machine-Dependent Optimizations

Pointer Code
- Can be more efficient than array referencing

Loop Unrolling
- Combine bodies of several iterations
- Optimize across iteration boundaries
- Amortize loop overhead
- Improve code scheduling

Enabling Instruction Level Parallelism
- Making it possible to execute multiple instructions concurrently

Warning:
- Benefits depend heavily on particular machine
- Best if performed by compiler
  - But often stuck with mediocre compiler

Pointer Code

```
void combine5(vec_ptr v, int *dest)
{
  int length = vec_length(v);
  int *data = get_vec_start(v);
  int *dend = data+length;
  int sum = 0;
  while (data != dend) {
    sum += *data;
    data++;
  }
  *dest = sum;
}
```

Optimization
- Use pointers rather than array references
- GCC generates code with 1 less instruction in inner loop
- CPE: 2.06 (Compiled -O2)
  - Less work to do on each iteration

***Warning*: Some compilers do better job optimizing array code**

Pointer vs. Array Code Inner Loops

```
L23:
  addl (%eax),%ecx
  addl $4,%eax
  incl %edx       # i++
  cmpl %esi,%edx # i < n?
  jl L23
```

```
L28:
  addl (%eax),%edx
  addl $4,%eax
  cmpl %ecx,%eax # data == dend?
  jne L28
```

Array Code
- GCC does partial conversion to pointer code
- Still keeps variable i
  - To test loop condition

Pointer Code
- Loop condition based on pointer value

Performance
- Array Code: 5 instructions in 3 clock cycles
- Pointer Code: 4 instructions in 2 clock cycles

CPU Capabilities

Multiple Instructions Can Execute in Parallel
- 1 load
- 1 store
- 2 integer (one may be branch)
- 1 FP

Some Instructions Take > 1 Cycle, but Can be Pipelined

Instruction	Latency	Cycles/Issue
Integer Multiply	4	1
Integer Divide	36	36
Double/Single FP Multiply	5	2
Double/Single FP Add	3	1
Double/Single FP Divide	38	38

Loop Unrolling

```
void combine6(vec_ptr v, int *dest)
{
  int length = vec_length(v);
  int *data = get_vec_start(v);
  int *dend = data+length-7;
  int sum = 0;
  while (data < dend) {
    sum += data[0]; sum += data[1];
    sum += data[2]; sum += data[3];
    sum += data[4]; sum += data[5];
    sum += data[6]; sum += data[7];
    data += 8;
  }
  dend += 7;
  while (data < dend) {
    sum += *data; data ++;
  }
  *dest = sum;
}
```

Optimization

- Combine multiple iterations into single loop body
- Amortizes loop overhead across multiple iterations
- CPE = 1.43
  - Only small savings in this case
- Finish extras at end

Loop Unrolling Assembly

```
L33:
  addl (%eax),%edx      # data[0]
  addl -20(%ecx),%edx   # data[1]
  addl -16(%ecx),%edx   # data[2]
  addl -12(%ecx),%edx   # data[3]
  addl -8(%ecx),%edx    # data[4]
  addl -4(%ecx),%edx    # data[5]
  addl (%ecx),%edx      # data[6]
  addl (%ebx),%edx      # data[7]
  addl $32,%ecx
  addl $32,%ebx
  addl $32,%eax
  cmpl %esi,%eax
  jb L33
```

Strange "Optimization"

`%eax = data`

`%ebx = %eax+28`

`%ecx = %eax+24`

- Wasteful to maintain 3 pointers when 1 would suffice

General Forms of Combining

```
void abstract_combine(vec_ptr v, data_t *dest)
{
  int i;
  *dest = IDENT;
  for (i = 0; i < vec_length(v); i++) {
    data_t val;
    get_vec_element(v, i, &val);
    *dest = *dest OP val;
  }
}
```

Data Types

- Use different declarations for data_t
- Int
- Float
- Double

Operations

- Use different definitions of OP and IDENT
- + / 0
- * / 1

Optimization Results for Combining

Method	Integer		Floating Point	
	+	*	+	*
Abstract -g	40.26	43.52	41.70	146.61
Abstract -O2	28.61	31.12	29.38	139.41
Move vec_length	20.22	20.32	20.48	133.23
data access	6.76	9.06	8.06	110.66
Accum. in temp	3.06	4.09	3.20	5.20
Pointer	2.06	4.06	3.06	5.20
Unroll 8	1.43	4.06	3.06	5.19
Worst : Best	*28.15*	*10.72*	*13.63*	*28.25*

- Double & Single precision FP give identical timings
- Up against latency limits

Integer	Add: 1	Multiply: 4
FP	Add: 3	Multiply: 5

Particular data used had lots of overflow conditions, causing fp store to run very slowly

Parallel Loop Unrolling

```
void combine7(vec_ptr v, int *dest)
{
  int length = vec_length(v);
  int *data = get_vec_start(v);
  int *dend = data+length-7;
  int sum1 = 0, sum2 = 0;
  while (data < dend) {
    sum1 += data[0]; sum2 += data[1];
    sum1 += data[2]; sum2 += data[3];
    sum1 += data[4]; sum2 += data[5];
    sum1 += data[6]; sum2 += data[7];
    data += 8;
  }
  dend += 7;
  while (data < dend) {
    sum1 += *data;  data ++;
  }
  *dest = sum1+sum2;
}
```

Optimization

- **Accumulate in two different sums**
  - Can be performed simultaneously
- **Combine at end**
- **Exploits property that integer addition & multiplication are associative & commutative**
- **FP addition & multiplication not associative, but transformation usually acceptable**

Parallel Loop Unrolling Assembly

```
L43:
  addl (%eax),%ebx        # data[0], sum1
  addl -20(%edx),%ecx     # data[1], sum2
  addl -16(%edx),%ebx     # data[2], sum1
  addl -12(%edx),%ecx     # data[3], sum2
  addl -8(%edx),%ebx      # data[4], sum1
  addl -4(%edx),%ecx      # data[5], sum2
  addl (%edx),%ebx        # data[6], sum1
  addl (%esi),%ecx        # data[7], sum2
  addl $32,%edx
  addl $32,%esi
  addl $32,%eax
  cmpl %edi,%eax
  jb L43
```

Registers

`%eax = data   %esi = %eax+28   %edx = %eax+24`

`%ebx = sum1   %ecx = sum2`

- **Wasteful to maintain 3 pointers when 1 would suffice**

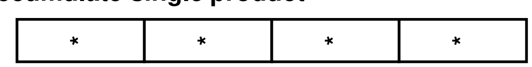
Optimization Results for Combining

Method	Integer		Floating Point	
	+	*	+	*
Abstract -g	41.43	42.01	41.80	135.77
Abstract -O2	31.42	33.22	31.38	124.69
Move vec_length	21.29	21.38	21.37	114.44
data access	6.06	9.07	8.06	96.87
Accum. in temp	2.06	4.06	3.06	5.20
Pointer	3.05	4.06	3.06	5.20
Unroll 8	1.32	4.08	3.07	5.19
Unroll 16	*1.12*	4.06	3.06	5.20
8 X 2	1.19	2.06	*1.56*	2.70
8 X 4	1.19	*1.31*	1.56	*2.19*
8 X 8	1.84	1.97	1.94	2.21
9 X 3	1.30	1.42	1.75	2.24
Worst : Best	***37.00***	***32.07***	***26.79***	***62.00***

Parallel/Pipelined Operation

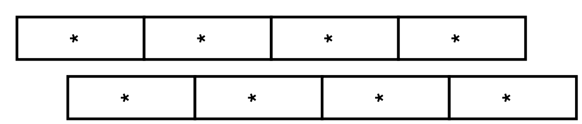
FP Multiply Computation

- **5 cycle latency, 2 cycles / issue**
- **Accumulate single product**



`prod`

  - Effective computation time: 5 cycles / operation
- **Accumulate two products**



`prod1`

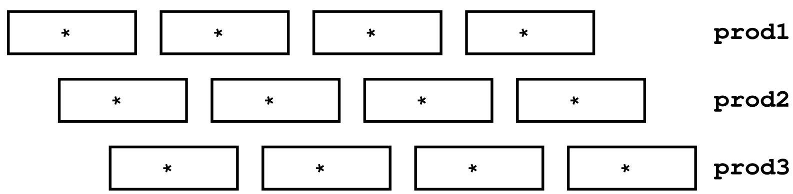
`prod2`

  - Effective computation time: 2.5 cycles / operation

Parallel/Pipelined Operation (Cont.)

FP Multiply Computation

- **Accumulate 3 products**
  - Effective computation time: 2 cycles / operation
  - Limited by issue rate



- **Accumulate > 3 products**
  - Can't go beyond 2 cycles / operation

Limitations of Parallel Execution

Need Lots of Registers

- **To hold sums/products**
- **Only 6 useable integer registers**
  - Also needed for pointers, loop conditions
- **8 FP registers**
- **When not enough registers, must *spill* temporaries onto stack**
  - Wipes out any performance gains

Example

- **X 4 integer multiply**
- **4 local variables must share 2 registers**

```
L53: imull (%eax),%ecx
     imull -20(%edx),%ebx
     movl -36(%ebp),%edi
     imull -16(%edx),%edi
     movl -20(%ebp),%esi
     imull -12(%edx),%esi
     imull (%edx),%edi
     imull -8(%edx),%ecx
     movl %edi,-36(%ebp)
     movl -8(%ebp),%edi
     imull (%edi),%esi
     imull -4(%edx),%ebx
     addl $32,%eax
     addl $32,%edx
     addl $32,%edi
     movl %edi,-8(%ebp)
     movl %esi,-20(%ebp)
     cmpl -4(%ebp),%eax
     jb L53
```


Machine-Dependent Opt. Summary

Pointer Code

- **Look carefully at generated code to see whether helpful**

Loop Unrolling

- **Some compilers do this automatically**
- **Generally not as clever as what can achieve by hand**

Exposing Instruction-Level Parallelism

- **Very machine dependent**

Warning:

- **Benefits depend heavily on particular machine**
- **Best if performed by compiler**
  - But GCC on IA32/Linux is particularly bad
- **Do only for performance critical parts of code**

Role of Programmer

How should I write my programs, given that I have a good, optimizing compiler?

Don't: Smash Code into Oblivion

- **Hard to read, maintain, & assure correctness**

Do:

- **Select best algorithm**
- **Write code that's readable & maintainable**
  - Procedures, recursion, without built-in constant limits
  - Even though these factors can slow down code
- **Eliminate optimization blockers**
  - Allows compiler to do its job

Focus on Inner Loops

- **Do detailed optimizations where code will be executed repeatedly**
- **Will get most performance gain here**