Optimizing Program Performance

CMPU 224 – Computer Organization
Jason Waterman
Performance Realities

• There’s more to performance than asymptotic complexity (big-O notation)

• Constant factors matter too!
  • Easily see 10x performance range depending on how code is written
  • Must optimize at multiple levels:
    • algorithm, data representations, procedures, and loops

• Must understand the computer system to optimize performance
  • How programs are compiled and executed
  • How modern processors + memory systems operate
  • 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 (scheduling)
  • Dead code elimination
  • Eliminating minor inefficiencies

• Have difficulty overcoming “optimization blockers”
  • Potential memory aliasing
  • Potential procedure side-effects

• 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
Limitations of Optimizing Compilers

• Operate under fundamental constraint
  • Must not cause any change in program behavior
• 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
• Most analysis is performed only within procedures
  • Whole-program analysis is too expensive in most cases
  • Newer versions of GCC do inter-procedural analysis within individual files
    • But, not between code in different files
• Most analysis is based only on static information
  • Compiler has difficulty anticipating run-time inputs
• When in doubt, the compiler must be conservative
Memory Matters

• Both functions seem to have identical behavior
• Both add twice the value at the memory location \( y_p \) to the value at memory location \( x_p \)
• \( \text{sum2} \) has less memory accesses
• However, the compiler won’t replace \( \text{sum2} \) for \( \text{sum1} \)
• What if \( x_p \) and \( y_p \) point to the same memory location?
  • \( \text{sum1} \) and \( \text{sum2} \) will give different answers

```c
void sum1(long *xp, long *yp) {
    *xp += *yp;
    *xp += *yp;
}

void sum2(long *xp, long *yp) {
    *xp += 2 * *yp;
}
```
When \( xp == yp \)

- \textit{sum1} will increase value at \( xp \) by a factor of 4
- \textit{sum2} will increase value at \( xp \) by a factor of 3

- Compiler must assume that different pointers may point to the same memory location

- Limits the set of possible optimizations

```c
void sum1(long *xp, long *xp) {
    *xp += *xp;
    *xp += *xp;
}

void sum2(long *xp, long *xp) {
    *xp += 2 * *xp;
}
```
Optimization Blocker #1: Memory Aliasing

• Aliasing
  • Two different memory references specify single location
  • Easy to have happen in C
    • Since allowed to do address arithmetic
    • Direct access to storage structures

• How to work around:
  • Get in habit of introducing local variables
    • Accumulating within loops
    • Your way of telling compiler not to check for aliasing

```c
void sum2(long *xp, long *yp) {
  *xp += 2 * *yp;
}

void sum3(long *xp, long *yp) {
  long sum;
  sum = *yp;
  sum += *yp;
  *xp += sum;
}
```
# Optimization Blocker #2: Procedure Calls

- Procedure to convert string to lower case

```c
#include <string.h>

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

Lower Case Conversion Performance

- Time quadruples when string length doubles
- $O(N^2)$
#include <string.h>

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

- **strlen performance**
  - Only way to determine length of string is to scan its entire length, looking for null character

- Overall performance for string of length N:
  - N calls to `strlen`
  - Each call to `strlen` iterates over all N characters in the string
  - Overall $O(N^2)$ performance

```c
/* My version of strlen */
size_t strlen(const char *s)
{
    size_t length = 0;
    while (*s != '\0') {
        s++;
        length++;
    }
    return length;
}
```
Improving Performance

- Move call to `strlen` outside of loop
- Since result does not change from one iteration to another

```c
#include <string.h>

void lower2(char *s)
{
    size_t i;
    size_t len = strlen(s);
    for (i = 0; i < len; i++)
        if (s[i] >= 'A' && s[i] <= 'Z')
            s[i] -= ('A' - 'a');
}
```
Lower Case Conversion Performance

- Time doubles when double string length
- Linear performance of lower2
Improving Performance

- Call to `strlen()` can be avoided
- But code is not as readable

```c
#include <string.h>

void lower2(char *s) {
    size_t i;
    size_t len = strlen(s);
    for (i = 0; i < len; i++)
        if (s[i] >= 'A' && s[i] <= 'Z')
            s[i] -= ('A' - 'a');
}
```

```c
#include <string.h>

void lower3(char *s) {
    size_t i;
    for (i = 0; s[i] != '\0'; i++) {
        if (s[i] >= 'A' && s[i] <= 'Z') {
            s[i] -= ('A' - 'a');
        }
    }
}
```
Optimization Blocker: Procedure Calls

• Why couldn’t compiler move `strlen` out of inner loop?
  • Procedure may have side effects
    • May alter some global state each time it is called
  • Function may not return same value for the same given arguments
    • Depends on other parts of global state
    • Procedure `lower` could interact with `strlen`

• Warning:
  • Compiler treats a procedure call as a black box

• Remedies:
  • Move code if it is safe to do
  • Use of inline functions
    • GCC does this with `-O1`
      • Within single file
Generally Useful Optimizations

• Optimizations that you or the compiler should do regardless of processor or compiler

• Code Motion
  • Reduce frequency with which computation is performed
    • If it will always produce same result
    • Especially moving code out of loop

```c
void set_row(double *a, double *b, long i, long n)
{
    long j;
    for (j = 0; j < n; j++)
        a[n*i+j] = b[j];
}
```

```c
long j;
int ni = n*i;
for (j = 0; j < n; j++)
    a[ni+j] = b[j];
```
Reduction in Strength

• Replace costly operation with simpler one
• Shift, add instead of multiply or divide
  • $16 \times x \rightarrow x << 4$
• Machine dependent
• Depends on cost of multiply or divide instruction
  • On modern Intel processors, integer multiply requires 3 CPU cycles
• Recognize sequence of products

```
for (i = 0; i < n; i++) {
    int ni = n*i;
    for (j = 0; j < n; j++)
        a[ni + 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;
}
```
Share Common Subexpressions

- Reuse portions of expressions
- GCC will do this with \-O1

```c
/* 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;
```

```
long 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;
```

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

```
leaq 1(%rsi), %rax  # i+1
leaq -1(%rsi), %r8  # i-1
imulq %rcx, %rsi  # i*n
imulq %rcx, %rax  # (i+1)*n
imulq %rcx, %r8  # (i-1)*n
addq %rdx, %rsi  # i*n+j
addq %rdx, %rax  # (i+1)*n+j
addq %rdx, %r8  # (i-1)*n+j
```

1 multiplication: i*n

```
imulq %rcx, %rsi  # i*n
addq %rdx, %rsi  # i*n+j
movq %rsi, %rax  # i*n+j
subq %rcx, %rax  # i*n+j-n
leaq (%rsi,%rcx), %rcx  # i*n+j+n
```

11/26/2023
CMPU 224 -- Computer Organization
Benchmark Example: Abstract Data Type for Vectors

```c
/* data structure for vectors */
typedef struct {
    size_t len;
    data_t *data;
} vec;
```

```c
/* retrieve vector element and store at val */
/* return 1 if successful, 0 otherwise */
int get_vec_element(*vec v, size_t idx, data_t *val) {
    if (idx >= v->len){
        return 0;
    }
    *val = v->data[idx];
    return 1;
}
```

- **Data Types**
  - Use different declarations for `data_t`
    - `int`
    - `long`
    - `float`
    - `double`
Benchmark Computation

```c
void combine1(vec_ptr v, data_t *dest) {
    long 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;
    }
}
```

Compute sum or product of vector elements

**Data Types**
- Use different declarations for `data_t`
  - int
  - long
  - float
  - double

**Operations**
- Use different definitions of `OP` and `IDENT`
  - + / 0
  - * / 1
Cycles Per Element (CPE)

• Convenient way to express performance of program that operates on vectors or lists
• Length = n
• In our case: CPE = cycles per OP
• \( T = CPE \times n + \text{Overhead} \)
  • CPE is slope of line

![Graph showing Cycles vs. Elements with two lines, psum1 and psum2, each with a slope of 9.0 and 6.0 respectively.](Image)
Benchmark Performance

```c
void combine1(vec_ptr v, data_t *dest) {
    long 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;
    }
}
```

Compute sum or product of vector elements

<table>
<thead>
<tr>
<th>Method</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td>Add</td>
<td>Mult</td>
</tr>
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<td>20.02</td>
</tr>
<tr>
<td>Combine1 –O1</td>
<td>10.12</td>
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</table>
Eliminating Loop Inefficiencies

• Move call to vec_length outside of loop

• Code motion

/* Move call to vec_length out of loop */
void combine2(vec_ptr v, data_t *dest) {
    long i;
    long length = vec_length(v);

    *dest = IDENT;
    for (i = 0; i < length; i++) {
        data_t val;
        get_vec_element(v, i, &val);
        *dest = *dest OP val;
    }
}

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Reducing Procedure Calls

• `get_vec_start` returns the starting address of the data array
  • This breaks the abstraction barrier!

• Remove call to `get_vec_element`
• We are no longer doing bounds checking!
• No effect on performance
  • Other operations are the bottleneck
• Will help us later when we remove these bottlenecks

```c
/* Direct access to vector data*/
void combine3(vec_ptr v, data_t *dest) {
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v)

    *dest = IDENT;
    for (i = 0; i < length; i++) {
        *dest = *dest OP data[i];
    }
}
```

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Eliminating Unneeded Memory References

- Disassembly of inner loop for integer addition
- One memory read and one memory write per cycle
- But \*dest doesn’t need to be updated till the end of the loop

```c
void combine3(vec_ptr v, data_t *dest) {
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v);

    *dest = IDENT;
    for (i = 0; i < length; i++) {
        *dest = *dest OP data[i];
    }
}
```

```
.L3: # i in %rdx, length in %rbp, data in %rax
    cmpq %rbp, %rdx         # i:length
    jge .L1                 # jump to end of loop
    movq (%rax,%rdx,8), %rcx # read data[i]
    addq %rcx, (%rbx)       # write *dest
    addq $1, %rdx           # i++
    jmp .L3
.L1:
```
Accumulate result in temporary

- Reduce to only one memory read per element using a temporary variable

```
void combine3(vec_ptr v, data_t *dest) {
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v);

    *dest = IDENT;
    for (i = 0; i < length; i++) {
        *dest = *dest OP data[i];
    }
}

void combine4(vec_ptr v, data_t *dest) {
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v);

    data_t acc = IDENT;
    for (i = 0; i < length; i++) {
        acc = acc OP data[i];
    }
    *dest = acc;
}
```

L3:  # i in %rdx, data in %rax
cmpq %rbp, %rdx     # i:length
jge .L1             # jump to end of loop
movq (%rax,%rdx,8), %rcx # read data[i]
addq %rcx, (%rbx)   # write *dest
addq $1, %rdx       # i++
jmp .L3
.L1:

L3:  # data in %rax, i in %rdx, acc in %rcx
cmpq %rbp, %rdx     # i:length
jge .L1             # jump to end of loop
addq (%rax,%rdx,8), %rcx # acc += data[i]
addq $1, %rdx       # i++
jmp .L3
.L1:
```
Accumulate result in temporary

• Why doesn’t the compiler perform this transformation automatically?
  • Memory aliasing
  • The `dest` could be one of the elements in the vector (e.g., the last element)
    • `combine3` and `combine4` could have different results in this case
  • Using a temporary register tells the compiler not to check for memory aliasing

```c
void combine3(vec_ptr v, data_t *dest) {
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v)

    *dest = IDENT;
    for (i = 0; i < length; i++) {
        *dest = *dest OP data[i];
    }
}

void combine4(vec_ptr v, data_t *dest) {
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v)

    data_t acc = IDENT;
    for (i = 0; i < length; i++) {
        acc = acc OP data[i];
    }
    *dest = acc;
}
```
Effect of Basic Optimizations

- 4x to 18x improvement over original unoptimized code
- To seek better performance, we must consider optimizations that exploit the *microarchitecture* of the processor
  - Code tuned for a specific processor
- We’ll tackle this next class

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<td>3.01</td>
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```c
void combine4(vec_ptr v, data_t *dest) {
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v);
    data_t acc = IDENT;
    for (i = 0; i < length; i++) {
        acc = acc OP data[i];
    }
    *dest = acc;
}
```