Constant factors matter too!
- You can easily see 10:1 performance range depending on how your code is written.
- Must optimize at multiple levels: algorithm, data representations, procedures, loops.

Must understand the 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.
Provide efficient mapping of program to machine:
- register allocation
- code selection and ordering
- eliminating minor inefficiencies

Don’t (usually) improve asymptotic efficiency.
- It’s up the programmer to select best overall algorithm.
- Big-O savings are often more important than constant factors.
- But constant factors also matter.
Optimizing compilers have difficulty overcoming “optimization blockers”:

- potential memory aliasing
- potential procedure side-effects.

Compilers operate under a fundamental constraint:

- They must not cause any change in program behavior under any possible condition.
- This often prevents making optimizations when they would only affect behavior under pathological conditions.
Behavior obvious to the programmer may be hidden by languages and coding styles.

- e.g., data ranges may be more limited than the variable type suggests.

Most analysis is performed only within procedures; whole-program analysis is too expensive in most cases.

- Most analysis is based only on static information.
- When in doubt, the compiler must be conservative.
Machine-Independent Optimizations

Some optimizations you should do regardless of the processor / compiler.

**Code Motion:**
- Reduce frequency with which computation is performed, if it will always produce the same result.
- Move code out of loops if possible.

The unoptimized version:

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

The optimized version:

```c
for (i=0; i<n; i++)
    { int ni = n*i;
      for (j=0; j<n; j++)
          a[ni + j] = b[j];
    }
```
Most compilers do a good job with array code and simple loop structures.

Compiler-generated code motion:

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

Compiler generates the equivalent of:

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

Code generated by gcc:

```
testl %edx, %edx
jle .L1
movslq %edx, %r9
xorl %r8d, %r8d
salq $2, %r9
.L3: xorl %eax, %eax
.L5: movl (%rsi,%rax,4), %ecx
movl %ecx, (%rdi,%rax,4)
addq $1, %rax
cmpl %eax, %edx
jg .L5
addl $1, %r8d
addq %r9, %rdi
cmpl %edx, %r8d
jne .L3
.L1: ret
```
Reduction in Strength

- Replace costly operations with simpler ones.
- Shift, add instead of multiply or divide: $16 \times x$ becomes $x << 4$.
- The utility of this is machine dependent; depends on the cost of multiply and divide instructions.
- On Pentium II or III, integer multiply only requires 4 CPU cycles.

**Recognize a sequence of products:**

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

**Optimize as follows:**

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

Reading and writing registers is much faster than reading / writing memory.

Limitations:

- Compiler is not always able to determine whether a variable can be held in a register.
- There’s the possibility of aliasing.
int adder(int *p, int *q) {
    *p = 2;
    *q = 3;
    return (*p + *q);
}

What value is returned? Couldn’t we just return 5 and save two memory references?
What value is returned? Couldn’t we just return 5 and save two memory references?

Not so fast! What if \( p \) and \( q \) point to the same location (i.e., contain the same address)?

*Aliasing* means that a location may have multiple names. Often, the compiler must assume that aliasing is possible.
Share Common Subexpressions:
- Reuse portions of expressions.
- Compilers often are not very sophisticated in exploiting arithmetic properties.

```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;
```

Uses 3 multiplications:
```
leal -1(%edx),%ecx
imull %ebx,%ecx
leal 1(%edx),%eax
imull %ebx,%eax
imull %ebx,%edx
```

Uses 1 multiplication:
```
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;
```
**Time Scales**

**Absolute time:** Typically uses nanoseconds ($10^{-9}$ seconds).

**Clock cycles:**

- Most computers are controlled by a high frequency clock signal.
- **Typical range:**
  - Low end: 100 MHz: $10^8$ cycles per second; clock period = 10ns.
  - High end: 2 GHz: $2 \times 10^9$ cycles per second; clock period = 0.5 ns.
**Loop unrolling:** Perform more in each iteration of the loop. (Assume even number of elements.)

**Original loop:**
```c
void vsum1(int n) {
    int i;
    for (i = 0; i < n; i++)
        c[i] = a[i] + b[i];
}
```

**Loop unrolled:**
```c
void vsum2(int n) {
    int i;
    for (i = 0; i < n; i += 2) {
        c[i] = a[i] + b[i];
        c[i+1] = a[i+1] + b[i+1];
    }
}
```

Why would this make any difference in performance?
Cycles Per Element

CPE is a convenient way to express performance of a program that operates on vectors or lists.

If the vector length = $n$, then

$$T = \text{CPE} \times n + \text{Overhead}$$

![Graph showing the relationship between elements and cycles with two lines: vsum1 (slope = 4.0) and vsum2 (slope = 3.5).]
Procedure to convert a string to lower case:

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

Time quadruples when string length doubles (quadratic performance: $O(n^2)$). Why would that be?
Convert Loop to Goto Form

```c
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:
}
```

So what is the issue?
So what is the issue?

- `strlen` is executed every iteration.
- `strlen` is linear in length of the string; must scan string until it finds `\0`. Why is that?
- Overall performance is quadratic. What do you do?
Improving Performance

Can move the call to `strlen` outside of loop, since the result does not change from one iteration to another. This is a form of code motion.

```c
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');
}
```

Now, the run time doubles when the string length doubles (linear performance: $O(n)$).

Can you see other obvious optimizations in this code?
Why couldn’t the compiler move `strlen` out of the inner loop?

- Procedures may have side effects. E.g., might alter global state each time called.
- Function may not return the same value for given arguments; might depend on other parts of the global state.
- Procedure `lower` could interact with `strlen`.

Why doesn’t the compiler just look at the code for `strlen`?

- The linker might overload with a different version (unless it’s declared static).
- Inter-procedural optimization is rare because of the cost.

Warning:

- The compiler treats a procedure call as a black box.
- It applies weak optimizations in and around procedures.
Create a vector abstract data type similar to array implementations in Pascal, ML, Java. E.g., always do bounds checking.

**Procedures:**

```c
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
```
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

- 42.06 (compiled -g)
- 31.25 (compiled -O2)
Reduction in Strength

```c
void combine2( vec_ptr v, int *dest )
{
    int i;
    int length = 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 the loop just do pointer reference.
- Not as clean in terms of data abstraction.
- CPE: 6.00 (compiled -O2)
- *Procedure calls are expensive!*
- *Bounds checking is expensive!*
void combine3(vec_ptr v, int *dest) {
    int i;
    int length = 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 result in destination until the end.
- Local variable sum will be held in a register.
- Avoids 1 memory read and 1 memory write per cycle.
- CPE: 2.00 (compiled -O2)
- Memory references are expensive!
Detecting Unneeded Memory Refs

**Combine2**

```
.L18:
    movl (%ecx,%edx,4),%eax
    addl %eax,(%edi)
    incl %edx
    cmpl %esi,%edx
    jl .L18
```

**Combine3**

```
.L24:
    addl (%eax,%edx,4),%ecx
    incl %edx
    cmpl %esi,%edx
    jl .L24
```

**Performance:**

- **Combine2:** 5 instructions in 6 clock cycles; `addl` must read and write memory.
- **Combine3:** 4 instructions in 2 clock cycles.
**Aliasing**: two different memory references specify a single location.

**Example:**
- `let v: [3, 2, 17]`
- `combine2( v, get_vec_start(v)+2 ) → ?`
- `combine3( v, get_vec_start(v)+2 ) → ?`

**Observations:**
- This can easily occur in C, since you’re allowed to do address arithmetic.
- You have direct access to storage structures.
- Get into the habit of introducing local variables and accumulating within loops.
- This is your way of telling the compiler not to check for potential aliasing.
void combine3( vec_ptr v, int *dest )
{
    int i;
    int length = vec_length(v);
    int *data = get_vec_start(v);
    int sum = 0;
    for( i = 0; i < length; i++ )
        sum += data[i];
    *dest = sum;
}

Task:
- Compute sum of all elements in vector.
- Vector is represented by C-style abstract data type.
- Achieved cycles per element (CPE) of 2.00.
```c
void abstract_combine3( vec_ptr v, data_t *dest )
{
    int i;
    int length = vec_length(v);
    data_t *data = get_vec_start(v);
    data_t t = IDENT;
    for( i = 0; i < length; i++ )
    {
        t = t OP data[i];
    }
    *dest = t;
}
```

**Data Types:** Use different declarations for `data_t` (int, float, double, etc.)

**Operations:** Use different definitions of OP and IDENT (+/0, */1, etc.)
## Machine Independent Optimization Results

<table>
<thead>
<tr>
<th>Method</th>
<th>Integer</th>
<th>Floating Point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+</td>
<td>×</td>
</tr>
<tr>
<td>abstract -g</td>
<td>42.06</td>
<td>41.44</td>
</tr>
<tr>
<td></td>
<td>41.86</td>
<td>160.00</td>
</tr>
<tr>
<td>abstract -O2</td>
<td>31.25</td>
<td>31.25</td>
</tr>
<tr>
<td></td>
<td>33.25</td>
<td>143.00</td>
</tr>
<tr>
<td>move vec_length</td>
<td>20.66</td>
<td>21.15</td>
</tr>
<tr>
<td></td>
<td>21.25</td>
<td>135.00</td>
</tr>
<tr>
<td>data access</td>
<td>6.00</td>
<td>8.00</td>
</tr>
<tr>
<td></td>
<td>9.00</td>
<td>117.00</td>
</tr>
<tr>
<td>accum in temp</td>
<td>2.00</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>4.00</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Optimizations: reduce function calls and memory references within loop.

Performance anomaly:

- Computing FP product of all elements exceptionally slow.
- Very large speedup when accumulate in temporary.
  - Caused by quirk in IA32 floating point.
  - Memory uses 64-bit format; register uses 80-bit format.
  - Benchmark data caused overflow in 64 bits, but not in 80 bits.
void combine3p( 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.
  • CPE: 3.00 (compiled -O2) – Oops! We’re making reverse progress.

Warning: Some compilers do a better job of optimizing array code.
Pointer vs. Array Code Inner Loops

Array Code:

.L24:

\[ \text{addl} \ (\%eax,\%edx,4), \%ecx \quad \# \text{sum += data[i]} \]
\[ \text{incl} \ \%edx \quad \# i++ \]
\[ \text{cmpl} \ \%esi,\%edx \quad \# i:length \]
\[ \text{jl} \ .L24 \quad \# \text{if < goto Loop} \]

Pointer Code:

.L30:

\[ \text{addl} \ (\%eax), \%ecx \quad \# \text{sum += *data[i]} \]
\[ \text{addl} \$4,\%eax \quad \# \text{data++} \]
\[ \text{cmpl} \ \%edx,\%eax \quad \# \text{data : dend} \]
\[ \text{jl} \ .L30 \quad \# \text{if < goto Loop} \]

Performance:

- Array code: 4 instructions in 2 clock cycles
- Pointer code: almost same 4 instructions in 3 clock cycles
**Code Motion**
- Compilers are good at this for simple loop/array structures.
- They don’t do well in the presence of procedure calls and potential memory aliasing.

**Reduction in Strength**
- Shift, add instead of multiply, divide
  - Compilers are (generally) good at this.
  - The exact trade off is machine-dependent.
- Keep data in registers rather than memory.
  - Compilers are not good at this, since they are concerned with potential aliasing.

**Share Common Subexpressions**
- Compilers have limited algebraic reasoning capabilities.
Measurement

- Accurately compute time taken by code.
  - Most modern machines have built-in cycle counters.
  - Using them to get reliable measurements is tricky.
- Profile procedure calling frequencies (Unix tool `gprof`).

Observation: Generating assembly code:

- lets you see what optimizations the compiler can make;
- allows you to understand the capabilities / limitations of a particular compiler.
Task
- Count word frequencies in a text document.
- Produce sorted list of words from most frequent to least.

Steps
- Convert strings to lowercase.
- Apply hash function.
- Read words and insert into hash table:
  - Mostly list operations.
  - Maintain counter for each unique word
- Sort the results.

Data Set
- Collected works of Shakespeare.
- 946,596 total words; 26,596 unique words.
- Initial implementation: 9.2 seconds.

Shakespeare’s most frequent words.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Word</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>the</td>
</tr>
<tr>
<td>2</td>
<td>and</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
</tr>
<tr>
<td>4</td>
<td>to</td>
</tr>
<tr>
<td>5</td>
<td>of</td>
</tr>
<tr>
<td>6</td>
<td>a</td>
</tr>
<tr>
<td>7</td>
<td>you</td>
</tr>
<tr>
<td>8</td>
<td>my</td>
</tr>
<tr>
<td>9</td>
<td>in</td>
</tr>
<tr>
<td>10</td>
<td>that</td>
</tr>
</tbody>
</table>
Augment executable program with timing functions.
- Computes the (approximate) amount of time spent in each function.
- Time Computation method:
  - Periodically (∼ every 10ms) interrupt program.
  - Determine what function is currently executing.
  - Increment the timer by interval (e.g., 10ms).
- Also maintains counter for each function indicating the number of times it is called.

**Using:**

```
gcc -O2 -pg prog.c -o prog
./prog
```

This executes in normal fashion, but also generates file `gmon.out`.

```
gprof prog
```
Generates profile information based on `gmon.out`.
### Profiling Results

<table>
<thead>
<tr>
<th>% time</th>
<th>cumulative seconds</th>
<th>self seconds</th>
<th>calls</th>
<th>self ms/call</th>
<th>total ms/call</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>86.60</td>
<td>8.21</td>
<td>8.21</td>
<td>1</td>
<td>8210.00</td>
<td>8210.00</td>
<td>sort_words</td>
</tr>
<tr>
<td>5.80</td>
<td>8.76</td>
<td>0.55</td>
<td>946596</td>
<td>0.00</td>
<td>0.00</td>
<td>lower1</td>
</tr>
<tr>
<td>4.75</td>
<td>9.21</td>
<td>0.45</td>
<td>946596</td>
<td>0.00</td>
<td>0.00</td>
<td>fine_ele_rec</td>
</tr>
<tr>
<td>1.27</td>
<td>9.33</td>
<td>0.12</td>
<td>946596</td>
<td>0.00</td>
<td>0.00</td>
<td>h_add</td>
</tr>
</tbody>
</table>

**Call Statistics:** Number of calls and cumulative time for each function.

**Performance Limiter:**
- Using inefficient sorting algorithm.
- Single call uses 87% of CPU time.

*The first obvious step in optimization is to use a more efficient sorting algorithm.* Replacing the initial slow sort with the library function qsort (QuickSort), brought the time down from 9 seconds to around 1 second!
Iter first: use iterative function to insert elements into the linked list; actually causes code to slow down.

Iter last: iterative function that places new entries at end of the list rather than front; tends to place common words near the front of the list.

Big table: increase the number of hash functions.

Better hash: use a more sophisticated hash function.

Linear lower: move `strlen` out of the loop.

By applying these optimizations successively and profiling the result, the overall runtime was reduced to around 0.5 seconds.
Profiling Observations

**Benefits**
- Helps identify performance bottlenecks.
- Especially useful for complex systems with many components.

**Limitations**
- Only shows performance for the data tested.
- E.g., linear lower did not show a big gain, since words are short.
  - Quadratic inefficiency could remain lurking in the code.
- The timing mechanism is fairly crude; it only works for programs that run for $> 3$ seconds.
How should I write my programs, given that I have a good optimizing compiler?

- Don’t: Smash code into oblivion.
  - Becomes hard to read, maintain, and assure correctness.

- Do:
  - Select the best algorithm.
  - Write code that’s readable and maintainable.
    - Use procedures and recursion and eliminate built-in limits.
    - Even though these factors can slow down code.
  - Eliminate optimization blockers to allow the compiler to do its job.

- Focus on inner loops.
  - Do detailed optimizations where code will be executed repeatedly.
  - You’ll get the most performance gain here.
Optimization blocker: procedure calls
Optimization blocker: memory aliasing
Tools (profiling) for understanding performance