CS429: Computer Organization and Architecture

Optimization I

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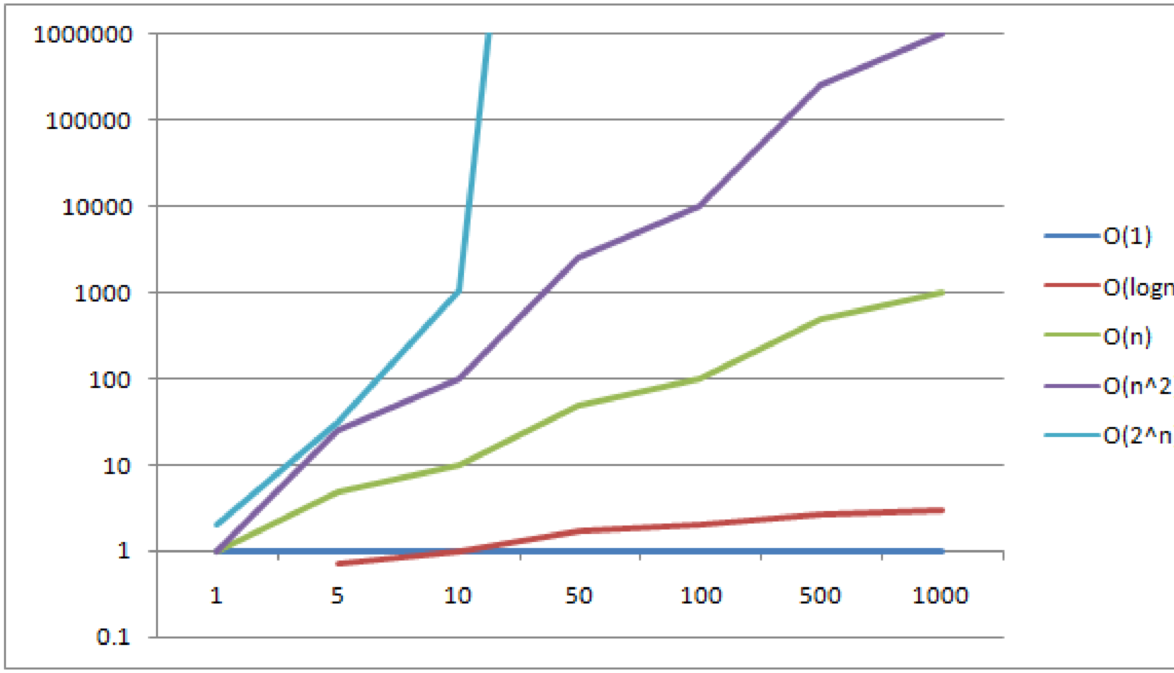
Performance: More than Asymptotic Complexity

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.



Performance: More than Asymptotic Complexity

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.

Optimizing Compilers

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.

Limitations of Optimizing Compilers

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.

Limitations of Optimizing Compilers

- 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:

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

The optimized version:

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

Compiler-Generated Code Motion

Most compilers do a good job with array code and simple loop structures.

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

Compiler generates the equivalent of:

```
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*x` becomes `x << 4`.
- The utility of this is machine dependent; depends on the cost of multiply and divide instructions.
- On x86, integer multiply only requires 4 CPU cycles.

Recognize a sequence of products:

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

Optimize as follows:

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

Can We Optimize?

```
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?

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```

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

Aliasing means that a location may have multiple names. Often, the compiler must assume that aliasing is possible.

Make Use of Registers

Reading and writing registers is *much faster* than reading / writing memory. So, if you can ensure that frequently accessed variables are in registers, your program will execute better. But how do you do that?

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- The compiler should do that for you, if possible.
- Compiler is not always able to determine whether a variable can be held in a register.
- Especially when there's the possibility of *aliasing*. What's the problem?

Share Common Subexpressions

- Reuse portions of expressions.
- Compilers often are 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;
```

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;
```

Measuring Performance: 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: 2×10^9 cycles per second; clock period $=$ 0.5 ns.

Example of Performance Measurement

Loop unrolling: Perform more in each iteration of the loop. (Assume even number of elements.)

Original loop:

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

Loop unrolled:

```
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];
    }
}
```

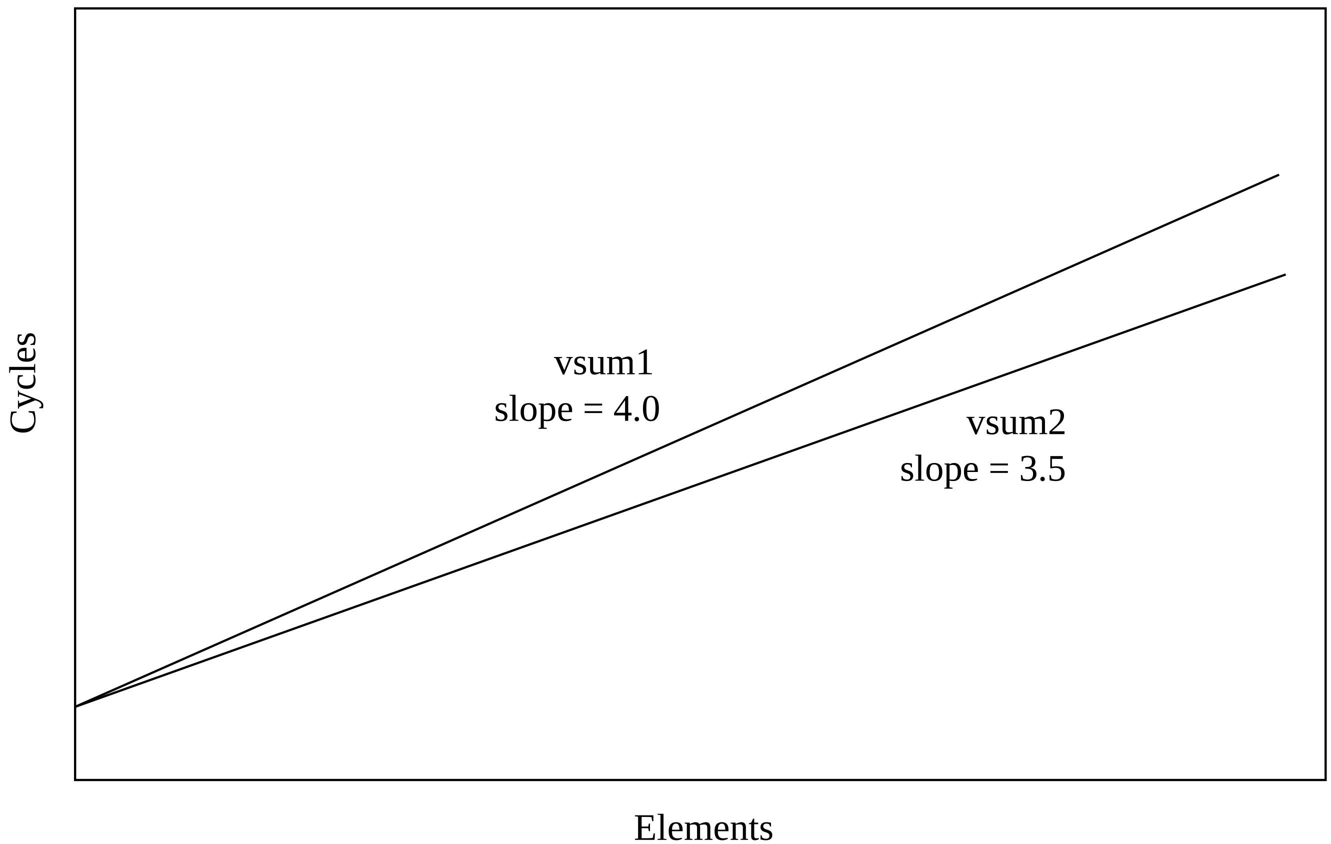
Why would this make any difference in performance?

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

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



Code Motion Example

Procedure to convert a 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' );
}
```

Observation: Time quadruples when string length doubles (quadratic performance: $O(n^2)$). Why would that be?

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:
}
```

So what is the issue?

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:
}
```

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*.

```
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?

Optimization Blocker: Procedure Calls

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`.

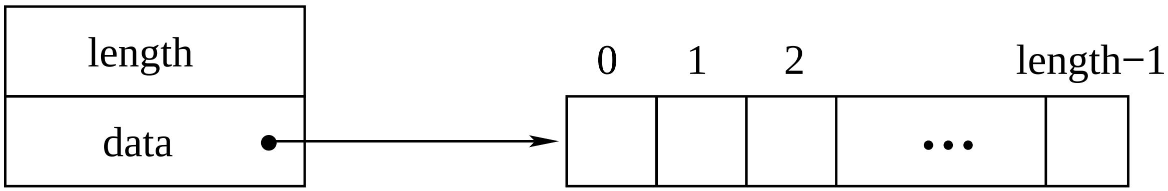
Why doesn't the compiler just look at the code for `strlen`?

- 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.

Optimization Example: Vector ADT



Create a vector abstract data type similar to array implementations in Pascal, ML, Java. E.g., always do bounds checking.

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

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.

x86 Performance: clock cycles / element

- 42.06 (compiled -Og)
- 31.25 (compiled -O2)

Reduction in Strength

```
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!*

Eliminate Unneeded Memory Refs

```
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.

Optimization Blocker: Memory Aliasing

Aliasing: two different memory references specify a single location.

Example:

- let `v: [3, 2, 17]`
- `combine2( v, get_vec_start(v)+2 )` $\rightarrow$?
- `combine3( v, get_vec_start(v)+2 )` $\rightarrow$?

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.

Previous Best Combining Code

```
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.

Previous Best Combining Code

```
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

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

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.

Pointer Code

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

Pointer Code:

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

Performance:

- Array code: 4 instructions in 2 clock cycles
- Pointer code: almost same 4 instructions in 3 clock cycles

Machine-Independent Optimization Summary

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.

Important Tools

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.

Code Profiling Example

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.

29,801	the
27,529	and
21,029	I
20,957	to
18,514	of
15,370	a
14,010	you
12,936	my
11,722	in
11,519	that

Code Profiling

Augment executable program with timing functions.

- Computes the (approximate) amount of time spent in each function.
- Time Computation method:
  - Periodically ($\sim$ 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

% time	cumulative seconds	self seconds	calls	self ms/call	total ms/call	name
86.60	8.21	8.21	1	8210.00	8210.00	sort_words
5.80	8.76	0.55	946596	0.00	0.00	lower1
4.75	9.21	0.45	946596	0.00	0.00	fine_ele_rec
1.27	9.33	0.12	946596	0.00	0.00	h_add

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!

Further Optimizations

- 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.

Role of the Programmer

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.

Summary

- Optimization blocker: procedure calls
- Optimization blocker: memory aliasing
- Tools (profiling) for understanding performance