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Optimization

Code Tuning

Performance

- Goal:
  - another non-functional requirement (quality)
    - besides correctness, flexibility, maintainability, etc.
  - running more efficiently
    - less time or less space or less power
    - no change in functional behavior
  - often works against other qualities
    - make sure of *correctness* first

Software Optimization

- Quote:
  - “Premature optimization is the root of all evil.”
    — Donald Knuth

Software Optimization

- Quotes:
  - “First Rule of Program Optimization: Don’t do it.”
  - “Second Rule of Program Optimization:
    Don’t do it yet.”

    — Michael A. Jackson

Optimization Levels

- Requirements:
  - what is acceptable performance?
  - can the problem be simplified?

  - how much data as input?
  - how many results to generate?
    - in memory or on disk or over the network, etc.

  - e.g., combinatorial generation
    - array of size n, but n! permutations

Optimization Levels

- High-level design:
  - how does generality affect performance?
  - hinders through indirection
  - improves by easier replacement of slow parts

Optimization Levels

- Detailed design:
  - consider time and space complexity of data structures and algorithms

Algorithm A has O(n log n) time complexity

a1 n log n + a2 n + a3

Algorithm B has O(n2) time complexity

b1 n2 + b2 n + b3

which is faster in practice?

  - it depends (what algorithms and size of n)
    - e.g., quicksort slower than insertion sort for small n

Optimization Levels

- Detailed design:
  - may trade off time and space
    - more space / less time or less space / more time
  - e.g., table lookup
    - consult table of pre-computed results rather than a complex calculation each time
  - e.g., caching or memoization
    - store fetched or computed values for later fast retrieval and reuse

Memoization Example

- ```
  // fibonacci numbers 1, 1, 2, 3, 5, 8, …
  public static int fib( int n ) { // no memoization
      if (n == 0 || n == 1) {
          return 1;
      } else {
          return fib( n-1 ) + fib( n-2 );
      }
  }
  ```

- ```
  public static int fib( int n ) { // with memoization
      if (result[n] == 0) { // result not yet known
          if (n == 0 || n == 1) {
              result[n] = 1;
          } else {
              result[n] = fib( n-1) + fib( n-2 );
          }
      }
      result result[n];
  }
  ```

Optimization Levels

- Detailed design:
  - may choose algorithms with relatively fewer *expensive* operations
  - e

evaluating a polynomial

y = a4 x4 + a3 x3 + a2 x2 + a1 x + a0

how many multiplications to compute?

Horner’s method

y = (((a4 x + a3) x + a2) x + a1) x + a0

Expensive Operations Example

monotonic function

(x1, y1) *expensive to know*

known (x0, y0)

given another point anywhere on the horizontal line (x, y1), is it left, on, or right of the red point (x1, y1) ?

Optimization Levels

- Operating system and libraries:
  - slow routines, input/output
  - e.g., memory allocation in heap (C malloc)

C Memory Allocation Example

- ```
  typedef struct Node { /* linked list node */
      int info;
      …
      struct Node *link;
  } Node;
  ```

- ```
  #include <stdlib.h>

  /* allocating a list node */
  Node *node = malloc( sizeof( Node ) );
  …
  ```

- ```
  …
  /* freeing a list node */
  free( node );
  ```
  ```

Using a Free List

- ```
  Node *freenodes;
  …
  freenodes = (Node *)0;
  ```

- ```
  /* allocating a list node */
  Node *n;
  if (freenodes == (Node *)0) {
      node = (Node *)malloc( sizeof( Node ) );
  } else {
      node = freenodes;
      freenodes = node->link;
  }
  …
  ```

- ```
  /* “freeing” a list node */
  node->link = freenodes;
  freenodes = node;
  ```
  ```

Optimization Levels

- Optimizing compilers:
  - let a “good compiler” optimize the code
  - e.g., constant folding/propagation
    - solve constant expressions at compile time
  - e.g., common subexpression elimination
    - solve common subexpressions once

Optimization Levels

- Optimizing compilers:
  - e.g., loop invariant code motion
    - move invariant parts of a loop outside the loop
  - e.g., strength reduction
    - replace costly operations with cheaper ones

integer x, y

Costly	Replacement
`y = x * 2;`	`y = x + x;`
`y = x * 8;`	`y = x << 3;`
`y = x / 4;`	`y = x >> 2;`
`y = x * 31;`	`y = (x << 5) – x;`
`y = x * 9;`	`y = (x << 3) + x;`

Loop Strength Reduction

- ```
  int c = 9;
  for (int i = 0; i < n; i++) {
      a[i] = i * c;
  }
  ```

- ```
  /* replace multiplication with additions */

  int c = 9;
  int t = 0;
  for (int i = 0; i < n; i++) {
      a[i] = t;
      t += c;
  }
  ```

Optimizing Loops (Before)

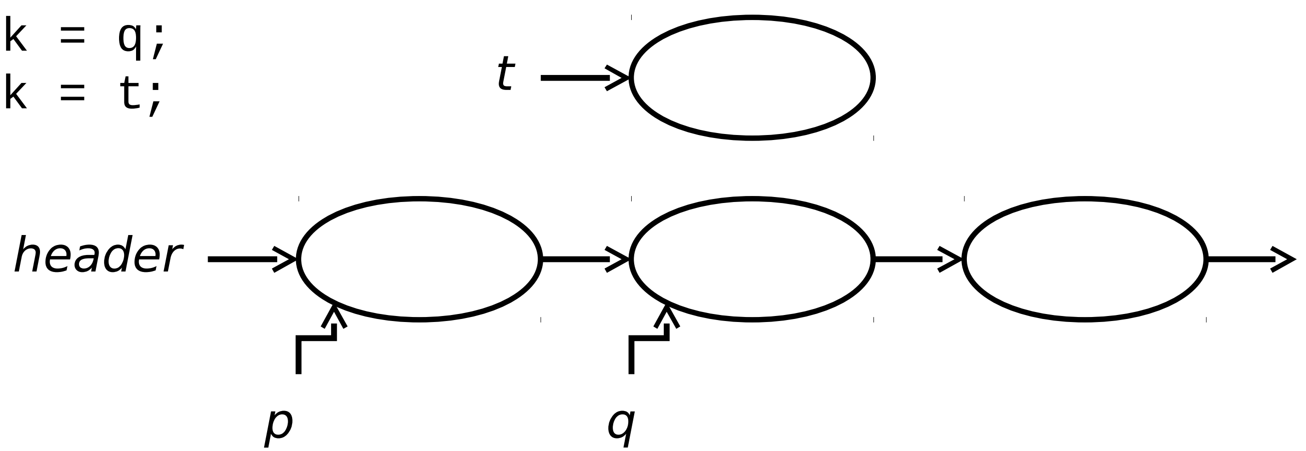
```
// insert t in a
// sorted linked list

p = header;
q = p.link;

while (q.info <= t.info) {
    p = q;
    q = q.link;
}

t.link = q;
p.link = t;
```

2 assignments per comparison



Optimizing Loops (After)

```
p = header;
for ( ;; ) {
    q = p.link;
    if (q.info <= t.info) {
        t.link = q;
        p.link = t;
        break;
    }
    p = q.link;
    if (p.info <= t.info) {
        t.link = p;
        q.link = t;
        break;
    }
}
```

1 assignment per comparison

Optimizing Loops

- ```
  i = 0;
  while (i < n) {
      a[i] = i;
      i++;
  }
  ```

- ```
  // unrolled once

  i = 0;
  while (i < n-1) {
      a[i] = i;
      a[i+1] = i+1;
      i += 2;
  }
  if (i < n) {
      a[n-1] = n-1;
  }
  ```

reducing
loop housekeeping
by loop unrolling

Optimization Levels

- Optimizing compilers:
  - some static compilers can use profiling data
  - e.g., reorder if-then-else tests by frequency
    - tests that are more likely to be true come earlier
  - just-in-time compilation in virtual machine
    - converts interpreted bytecode to natively executed binary code at run time
    - JIT itself takes time and space, however

Optimization Levels

- Assembly language:
  - write slow parts in handcrafted assembly code
  - but very hard to beat an optimizing compiler

  - for portability reasons, compilers might avoid using certain machine instructions
(even if more efficient)

  - handcrafted assembly code can use these instructions

Optimization Levels

- Hardware:
  - “throw more hardware at the problem”
  - understand the performance characteristics of the hardware you have
  - e.g., input/output, cache, processing cores, etc.

Avoid Superstitions

- Myth:
  - "shorter code is faster code"
    - fewer statements in source code does not mean fewer executed instructions

```
for (i = 0; i < 10; i++) {
    a[i] = i;
}
```

performance factor of fully unrolled loop?

```
a[0] = 0;
a[1] = 1;
a[2] = 2;
a[3] = 3;
a[4] = 4;
a[5] = 5;
a[6] = 6;
a[7] = 7;
a[8] = 8;
a[9] = 9;
```

Performance

Environment	for Loop	Straightline	Time Savings	Ratio
java 1.5.0_19	5.838	2.957	49%	2:1
gcc 4.0.1	12.207	4.364	64%	2.8:1
gcc 4.0.1 -O	2.826	1.564	45%	1.8:1
gcc 4.0.1 -O2	2.345	1.563	33%	1.5:1
gcc 4.0.1 -O3	1.503	0.631	58%	2.4:1
perl 5.10.1	694.671	300.776	57%	2.3:1

times in seconds for 100 million trials

Apple PowerBook G4
PowerPC 7447B 1.67 GHz, 64 KB L1, 512 KB L2, 1 GB RAM
Mac OS X 10.4.11

Performance

```
/* C code:
 * t and s point at null terminated char arrays
 */
while (*t++ = *s++);
```

or just use strcpy()

```
while (*s != '\0') {
      *t = *s;
      t++;
      s++;
}
*t = '\0';
```

Compiler	Version 1	Version 2	Time Savings	Ratio
gcc 4.0.1	32.944	27.714	16%	1.19:1
gcc 4.0.1 -O	5.651	4.509	20%	1.25:1
gcc 4.0.1 -O2	4.449	4.449	0%	1.00:1
gcc 4.0.1 -O3	4.208	4.389	-4%	0.96:1

times in seconds for 100 million copies of 20 character strings

Avoid Superstitions

- Myth:
  - certain operations are typicall faster than others
    - careful with “typically” or rules of thumb
  - *measure* (and re-measure) effect after changes
    - time the operations to see actual performance?

Benchmarking Pitfalls

- ```
  #define LIMIT 100000000

  int main() {
      double x, y, z;

      x = 5.0;
      y = 7.0;

      int i;
      for (i = 0; i < LIMIT; i++) {
          // floating-point multiplication test
          z = x * y;
      }
  }
  ```

with constant folding,
*the compiler knows that x * y is 35,*
so no actual multiplication at run time

with loop invariant code motion,
the compiler knows that z = 35 can
be moved outside the loop,
making the loop empty

since z is not used,
the compiler does not even
assign z
  ```

Avoid Superstitions

- Myth:
  - optimize as you write the code
    - hard to optimize before the code correct
    - micro-optimizations may have insignificant benefit
    - detracts from other quality concerns
  - don’t optimize indiscriminately

Bottlenecks

- Observation:
  - 80% of the execution time resides in about 20% of a program's routines — Barry Boehm
  - Pareto principle (80/20 rule)

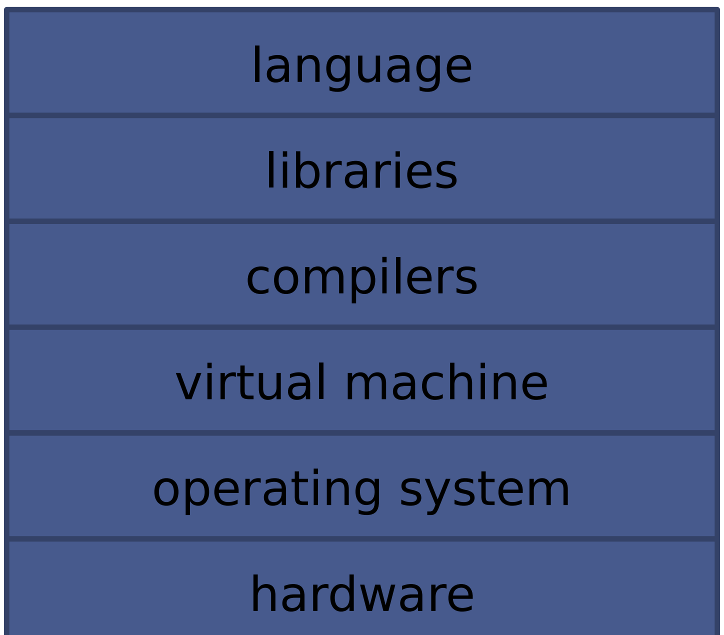
Bottlenecks

- Quote:
  - “Bottlenecks occur in surprising places, so don’t try to second guess and put in a speed hack until you have proven that’s where the bottleneck is.”

    — Rob Pike

Bottlenecks

- Huge semantic gap:
  - programmers are very poor at guessing the cause of bottlenecks



performance depends on many layers

Bottlenecks

- Profilers:
  - reports performance hotspots
    - time spent in each routine
    - frequency counts of each routine
    - frequency counts of each statement
    - heap usage

Bottlenecks

- Code tuning:
  - what works well in one environment may not work well in another (non-portable)
  - code tuning itself might defeat compiler optimizations

Code Tuning Example

- ```
  // given array a, currently with n elements,
  // return index of x, otherwise return -1

  public static int indexOf( int[] a, int n, int x ) {
      int answer = -1;
      for (int i = 0; i < n; i++) {
          if (a[i] == x) answer = i;
      }
      return answer;
  }
  ```

should stop when you know the answer

- ```
  // version 2
  public static int indexOf( int[] a, int n, int x ) {
      for (int i = 0; i < n; i++) {
          if (a[i] == x) return i;
      }
      return -1;
  }
  ```

reduce to one comparison per iteration?

Using a Sentinel

- ```
  public static int indexOf( int[] a, int n, int x ) {
      a[n] = x;
      int i = 0;
      while (a[i] != x) i++;

      return i == n ? -1 : i;
  }
  ```
  ```

Performance

Environment	Version 2	With Sentinel	Time Savings	Ratio
java 1.5.0_19	4.568	4.261	7%	1.07:1
gcc 4.0.1	11.227	9.405	16%	1.19:1
gcc 4.0.1 -O	2.709	2.258	17%	1.20:1
gcc 4.0.1 -O2	2.708	1.882	31%	1.44:1
gcc 4.0.1 -O3	2.332	1.881	19%	1.24:1

times in seconds for 100000 calls, n = 10000, worst case

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Java Tuning

- String concatenation:
  - how to append strings efficiently?

- ```
  String words[] = {
      “these”,
      “are”,
      “some”,
      “test”,
      “words”,
      …
  };
  ```
  ```

Java Tuning

- `// String plus operator`

```
String answer = "";

for (String s : words) {
    answer += s;
}
```

- `// using StringBuffer (synchronized)`

```
StringBuffer buffer = new StringBuffer( "" );

for (String s : words) {
    buffer.append( s );
}
String answer = buffer.toString();
```

- `// or use StringBuilder (un-synchronized)`

Performance

Environment	String +	StringBuffer	StringBuilder
java 1.5.0_19	3.286	1.585	1.314

times in seconds for 1000000 trials

use StringBuffer or StringBuilder when appending lots of Strings

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Java String + versus StringBuilder

- ```
  …
  new #4; // class StringBuilder
  …
  invokespecial #5; // method StringBuilder init
  …
  invokevirtual #6; // method StringBuilder append
  …
  invokevirtual #6; // method StringBuilder append
  invokevirtual #7; // method StringBuilder toString
  …
  ```

- ```
  …
  invokevirtual #6; // method StringBuilder append
  …
  ```

Java Tuning

- Accessing variables:
  - local variables in a method are faster to access and manipulate than static or instance variables in the class

```
public class Bar {
    private int instanceVar;
    private static int staticVar;

    public void access() {
        int localVar;
        …
    }
}
```

Performance

Environment	instance	static	local
java 1.5.0_19	6.086	5.625	2.522

times in seconds for 1 billion changes to int variable

Java virtual machine is stack-based,
and optimized to access stack data

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Java Tuning

- Inlining methods:
  - compiler replaces a method call with the actual body

useful for small methods, where the call overhead is relatively high compared to the work done

```
public class Counter {
    …
    public final int getCount() {
        …
    }
    …
}
```

```
…
Counter counter = new Counter();
int c = counter.getCount();
```

but only applicable if compiler knows what replacement code to use

i.e., no dynamic binding happening

Java Tuning

- Inlining methods:
  - static, final, or private methods can potentially be inlined since they are statically bound at compile time (no potential overriding)
  - however, Java compilers may actually do nothing to inline these methods, leaving the JIT to optimize method calls

Java Tuning

- Traversals:
  - how to traverse elements of an `ArrayList<T>`

```
// version 1
Enumeration e = Collections.enumeration( a );
while (e.hasMoreElements()) {
    // process object e.nextElement()
}
```

```
// version 2
ListIterator<T> iter = a.listIterator();
while (iter.hasNext()) {
    // process object iter.next()
}
```

Java Tuning

- ```
  // version 3
  Iterator<T> iter = a.iterator();
  while (iter.hasNext()) {
      // process object iter.next()
  }
  ```

- ```
  // version 4
  for (T each : a) {
      // process object each
  }
  ```

- ```
  // version 5
  int n = a.size();
  for (int i = 0; i < n; i++) {
      // process object a.get( i )
  }
  ```
  ```

Performance

	Enumeration	List Iterator	Iterator	for each	for get(i)
java 1.5.0_19	11.464	10.142	9.164	9.137	3.387

times in seconds for 10000 traversals of 10000 element ArrayList

*according to the bytecode, the
for each loop is just syntactic sugar
for an Iterator*

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Java Tuning

- Minimize the cost of object creation:
  - use “lazy evaluation”
    - not creating an object until you have to
  - be wary of deep inheritance hierarchies
    - many cascaded constructors

More Information

- Books:
  - Code Complete
    - S. McConnell
    - Microsoft Press, 2004
  - Writing Efficient Programs
    - J. Bentley
    - Prentice-Hall, 1982

More Information

- Links:
  - Java Performance Tuning
    - http://www.javaperformancetuning.com/