CSC 143 Java

Program Efficiency &
Introduction to Complexity Theory

GREAT IDEAS IN COMPUTER SCIENCE

ANALYSIS OF ALGORITHMIC COMPLEXITY

Overview

- Topics
  - Measuring time and space used by algorithms
  - Machine-independent measurements
  - Costs of operations
  - Comparing algorithms
  - Asymptotic complexity – O( ) notation and complexity classes

Comparing Algorithms

- Example: We've seen two different list implementations
  - Dynamic expanding array
  - Linked list
- Which is "better"?
- How do we measure?
  - Stopwatch? Why or why not?

Program Efficiency & Resources

- Goal: Find way to measure "resource" usage in a way that is independent of particular machines/implementations
- Resources
  - Execution time
  - Execution space
  - Network bandwidth
  - others
- We will focus on execution time
  - Basic techniques/vocabulary apply to other resource measures

Example

- What is the running time of the following method?

```
// Return the maximum value of the elements of an array of doubles
public double max(double[ ] a) {
    double max = a[0]; // why not max = 0?
    for ( int k = 1; k < a.length; k++) {
        if (a[k] > max) {
            max = a[k];
        }
    }
    return max;
}
```

- How do we analyze this?

Analysis of Execution Time

1. First: describe the *size* of the problem in terms of one or more parameters
   - For max, size of array makes sense
   - Often size of data structure, but can be magnitude of some numeric parameter, etc.
2. Then, count the number of steps needed as a function of the problem size

- Need to define what a "step" is.
  - First approximation: one simple statement
  - More complex statements will be multiple steps

Cost of operations: Constant Time Ops

- Constant-time operations: each take one abstract time “step”
  - Simple variable declaration/initialization (double x = 0.0;)
  - Assignment of numeric or reference values (var = value;)
  - Arithmetic operation (+, -, *, /, %)
  - Array subscripting (a[index])
  - Simple conditional tests (x < y, p != null)
  - Operator *new* itself (not including constructor cost)

    Note: *new* takes significantly longer than simple arithmetic or assignment, but its cost is independent of the problem we’re trying to analyze
- Note: watch out for things like method calls or constructor invocations that look simple, but are expensive

Cost of operations: Zero-time Ops

- Compiler can sometimes pay the whole cost of setting up operations
  - Nothing left to do at runtime
- Variable declarations without initialization

  `double[ ] overdrafts;`
- Variable declarations with compile-time constant initializers

  `static final int maxButtons = 3;`
- Casts (of reference types, at least)

  ... (Double) checkBalance

Sequences of Statements

- Cost of

  S1; S2; … Sn

  is sum of the costs of S1 + S2 + … + Sn

Conditional Statements

- The two branches of an if-statement might take different times. What to do??

```
if (condition) {
    S1;
} else {
    S2;
}
```

- Hint: Depends on analysis goals
  - "Worst case": the longest it could possibly take, under any circumstances
  - "Average case": the expected or average number of steps
  - "Best case": the shortest possible number of steps, under some special circumstance
- Generally, worst case is most important to analyze

Analyzing Loops

- Basic analysis
  1. Calculate cost of each iteration
  2. Calculate number of iterations
  3. Total cost is the product of these

  Caution -- sometimes need to add up the costs differently if cost of each iteration is not roughly the same
- Nested loops
  - Total cost is number of iterations or the outer loop times the cost of the inner loop
  - same caution as above

Method Calls

- Cost for calling a function is cost of...
  - cost of **evaluating** the arguments (constant or non-constant)
  - + cost of actually **calling** the function (constant overhead)
  - + cost of **passing** each parameter (normally constant time in Java for both numeric and reference values)
  - + cost of **executing** the function body (constant or non-constant?)

```
System.out.print(this.lineNumber);
System.out.println("Answer is " + Math.sqrt(3.14159));
```

- Terminology note: "evaluating" and "passing" an argument are two different things!

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Exact Complexity Function

- Careful analysis of an algorithm leads to an algebraic formula
- The "exact complexity function" gives the number of steps as a function of the problem size
- What can we do with it:
  - Predict running time in a particular case (given n, given type of computer)?
  - Predict comparative running times for two different n (on same type of computer)?
  - ***** Get a general feel for the potential performance of an algorithm
  - ***** Compare predicted running time of two different algorithms for the same problem (given same n)

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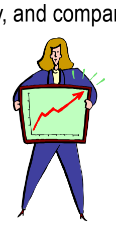
A Graph is Worth A Bunch of Words

- Graphs are a good tool to illustrate, study, and compare complexity functions



- Fun math review for you
  - How do you graph a function?
  - What are the shapes of some common functions? For example, ones mentioned in these slides or the textbook.

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Exercise

- Analyze the running time of printMultTable
  - Pick the problem size
  - Count the number of steps

```
// print triangular multiplication table
// with n rows
void printMultTable( int n) {
    for ( int k=0; k <=n; k++) {
        printRow(k);
    }
}
```

```
// print row r with length r of a
// multiplication table
void printRow( int r) {
    for ( int k = 0; k <= r; k++) {
        System.out.print( r * k + “ ”);
    }
    System.out.println( );
}
```

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Comparing Algorithms

- Suppose we analyze two algorithms and get these times (numbers of steps):
  - Algorithm 1: $37n + 2n^2 + 120$
  - Algorithm 2: $50n + 42$

  How do we compare these? What really matters?
- Answer: In the long run, the thing that is most interesting is the cost as the problem size n gets large
  - What are the costs for n=10, n=100; n=1,000; n=1,000,000?
  - Computers are so fast that how long it takes to solve small problems is rarely of interest

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Orders of Growth

- Examples:

N	$\log_2 N$	5N	$N \log_2 N$	N^2	2^N
8	3	40	24	64	256
16	4	80	64	256	65536
32	5	160	160	1024	$\sim 10^9$
64	6	320	384	4096	$\sim 10^{19}$
128	7	640	896	16384	$\sim 10^{38}$
256	8	1280	2048	65536	$\sim 10^{76}$
10000	**13**	**50000**	$\mathbf{10^5}$	$\mathbf{10^8}$	$\mathbf{\sim 10^{3010}}$

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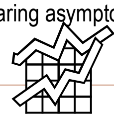
Asymptotic Complexity

- Asymptotic: Behavior of complexity function as problem size gets large
  - Only thing that really matters is higher-order term
  - Can drop low order terms and constants
- The asymptotic complexity gives us a (partial) way to answer "which algorithm is more efficient"
  - Algorithm 1: $37n + 2n^2 + 120$ is proportional to n^2
  - Algorithm 2: $50n + 42$ is proportional to n
- Graphs of functions are handy tool for comparing asymptotic behavior



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Big-O Notation

- Definition: If f(n) and g(n) are two complexity functions, we say that

  $f(n) = O(g(n))$ (pronounced f(n) is O(g(n)) or is order g(n))

  if there is a constant c such that

  $f(n) \leq c \cdot g(n)$

  for all sufficiently large n

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Exercises

- Prove that 5n+3 is O(n)
- Prove that $5n^2 + 42n + 17$ is $O(n^2)$

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Implications

- The notation f(n) = O(g(n)) is *not* an equality
- Think of it as shorthand for
  - "f(n) grows at most like g(n)" or
  - "f grows no faster than g" or
  - "f is bounded by g"
- O( ) notation is a *worst-case* analysis
  - Generally useful in practice
  - Sometimes want *average-case* or *expected-time* analysis if worst-case behavior is not typical (but often harder to analyze)

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Complexity Classes

- Several common complexity classes (problem size n)
  - Constant time: O(k) or O(1)
  - Logarithmic time: O(log n) [Base doesn't matter. Why?]
  - Linear time: O(n)
  - "n log n" time: O(n log n)
  - Quadratic time: $O(n^2)$
  - Cubic time: $O(n^3)$
  - …
  - Exponential time: $O(k^n)$
- $O(n^k)$ is often called *polynomial time*

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Rule of Thumb

- If the algorithm has polynomial time or better: practical
  - typical pattern: examining all data, a fixed number of times
- If the algorithm has exponential time: impractical
  - typical pattern: examine ***all combinations*** of data
- What to do if the algorithm is exponential?
  - Try to find a different algorithm
  - Some problems can be proved not to have a polynomial solution
  - Other problems don't have known polynomial solutions, despite years of study and effort.
  - Sometimes you settle for an approximation:
    - The correct answer most of the time, or
    - An almost-correct answer all of the time

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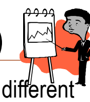
Big-O Arithmetic

- For most commonly occurring functions, comparison can be enormously simplified with a few simple rules of thumb.
- Memorize complexity classes in order from smallest to largest: O(1), O(log n), O(n), O(n log n), O(n^2), etc.
- Ignore constant factors
  - $300n + 5n^4 + 6 + 2^n = O(n + n^4 + 2^n)$
- Ignore all but highest order term
  - $O(n + n^4 + 2^n) = O(2^n)$

Analyzing List Operations (1)



- We can use O( ) notation to compare the costs of different list implementations
- Operation Dynamic Array Linked List
  - Construct empty list
  - Size of the list
  - isEmpty
  - clear

Analyzing List Operations (2)

- Operation Dynamic Array Linked List
  - Add item to end of list
  - Locate item (contains, indexOf)
  - Add or remove item once it has been located

Wait! Isn't this totally bogus??

- Write better code!!
  - More clever hacking in the inner loops
    - (assembly language, special-purpose hardware in extreme cases)
- Moore's law: Speeds double every 18 months
  - Wait and buy a faster computer in a year or two!

- But …

How long is a Computer-Day?

- If a program needs f(n) microseconds to solve some problem, what is the largest single problem it can solve in one full day?
- One day = 1,000,000*24*60*60 = 10^6*24*36*10^2 = **$8.64 * 10^{10}$** microseconds.
- To calculate, set f(n) = **$8.64 * 10^{10}$** and solve for n in each case

f(n)	n such that f(n) = one day
n	$8.64 * 10^{10} \approx 10^{11}$
5n	$1.73 * 10^{10} \approx 10^{10}$
n $\log_2$n	$2.75 * 10^9 \approx 10^9$
n^2	$2.94 * 10^5 \approx 10^5$
n^3	$4.42 * 10^3 \approx 10^3$
2^n	36

The size of the problem that can be solved in one day becomes smaller and smaller

Speed Up The Computer by 1,000,000 = 10^6

- Suppose technology advances so that a future computer is 1,000,000 times faster than today's.
- In one day there are now = **$8.64*10^{10}*10^6$** ticks available
- To calculate, set f(n) = **$8.64*10^{16}$** and solve for n in each case

f(n)	original n for one day	**new n for one day**
n	$8.64 * 10^{10}$	8.64×10^{16}
5n	$1.73 * 10^{10}$	1.73×10^{16}
n $\log_2$n	$2.75 * 10^9$	etc.
n^2	$2.94 * 10^5$	
n^3	$4.42 * 10^3$	
2^n	36	

How Much Does 1,000,000-faster Buy?

- Divide the new max n by the old max n, to see how much more we can do in a day

f(n)	n for 1 day	new n for 1 day
n	8.64×10^{10}	8.64×10^{16} = million times larger
5n	1.73×10^{10}	1.73×10^{16} = million times larger
n $\log_2$n	2.75×10^9	1.71×10^{15} = 600,000 times larger
n^2	2.94×10^5	2.94×10^8 = 1,000 times larger
n^3	4.42×10^3	4.42×10^5 = 100 times larger!
2^n	36	56 = 1.55 times larger!

Practical Advice For Speed Lovers

- First pick the right algorithm and data structure
  - Implement it carefully, insuring correctness
- Then optimize for speed – but only where it matters

  Constants do matter in the real world

  Clever coding can speed things up, but result can be harder to read, modify
- Current state-of-the-art approach: Use measurement tools to find hotspots, then tweak those spots.

"Premature optimization is the root of all evil" – Donald Knuth

"It is easier to make a correct program efficient than to make an efficient program correct"

-- Edsgar Dijkstra

Summary

- Analyze algorithm sufficiently to determine complexity
- Compare algorithms by comparing asymptotic complexity
- For large problems an asymptotically faster algorithm will always trump clever coding tricks

"Premature optimization is the root of all evil"

– Donald Knuth

Computer Science Note

- Algorithmic complexity theory is one of the key intellectual contributions of Computer Science
- Typical problems
  - What is the worst/average/best-case performance of an algorithm?
  - What is the best complexity bound for all algorithms that solve a particular problem?
- Interesting and (in many cases) complex, sophisticated math
  - Probabilistic and statistical as well as discrete
- Still some key open problems
  - Most notorious: P ?= NP