

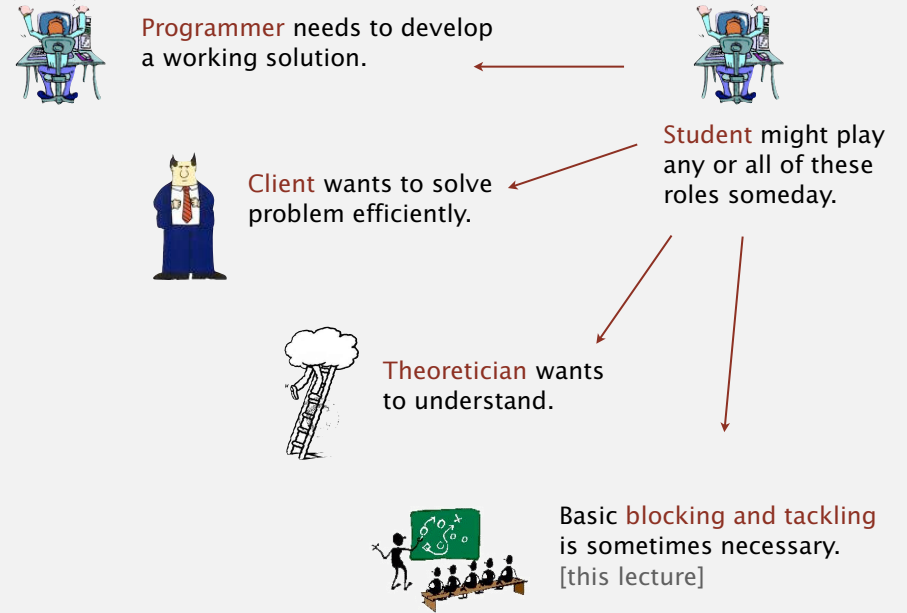
1.4 ANALYSIS OF ALGORITHMS



- ▶ observations
- ▶ mathematical models
- ▶ order-of-growth classifications
- ▶ dependencies on inputs
- ▶ memory

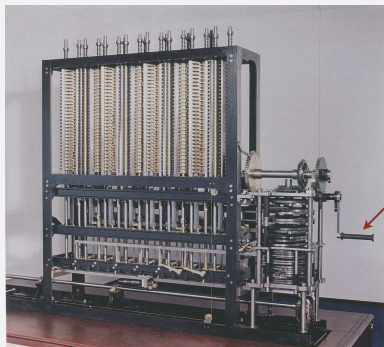
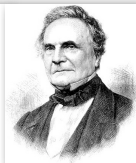
Algorithms, 4th Edition · Robert Sedgwick and Kevin Wayne · Copyright © 2002–2011 · February 8, 2012 5:59:31 AM

Cast of characters



Running time

“As soon as an Analytic Engine exists, it will necessarily guide the future course of the science. Whenever any result is sought by its aid, the question will arise—By what course of calculation can these results be arrived at by the machine in the shortest time?” — Charles Babbage (1864)



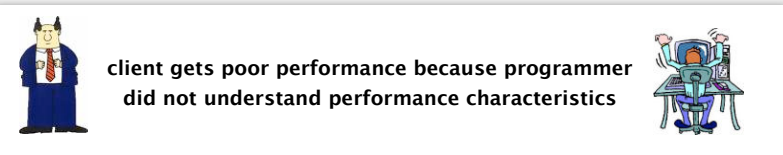
Analytic Engine

how many times do you have to turn the crank?

Reasons to analyze algorithms

- Predict performance.
 - Compare algorithms.
 - Provide guarantees.
 - Understand theoretical basis.
- this course (COS 226)
- theory of algorithms (COS 423)

Primary practical reason: avoid performance bugs.



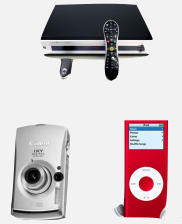
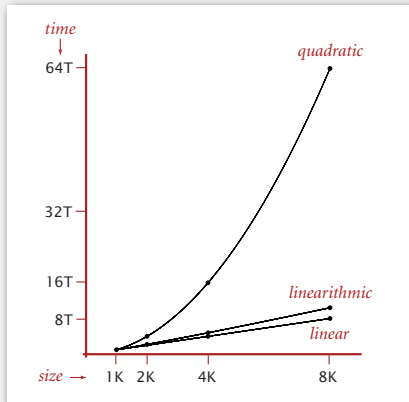
Some algorithmic successes

Discrete Fourier transform.

- Break down waveform of N samples into periodic components.
- Applications: DVD, JPEG, MRI, astrophysics,
- Brute force: N^2 steps.
- FFT algorithm: $N \log N$ steps, **enables new technology.**



Friedrich Gauss
1805



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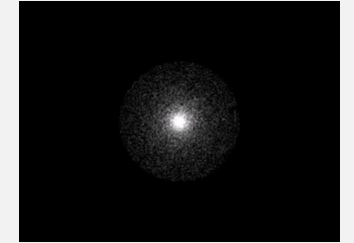
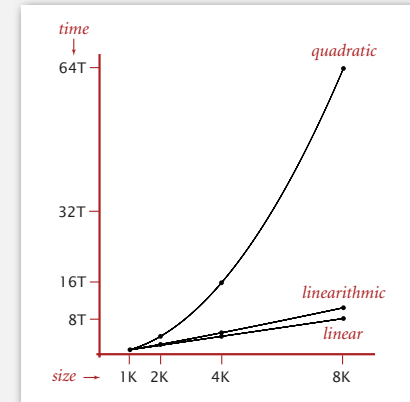
Some algorithmic successes

N-body simulation.

- Simulate gravitational interactions among N bodies.
- Brute force: N^2 steps.
- Barnes-Hut algorithm: $N \log N$ steps, **enables new research.**



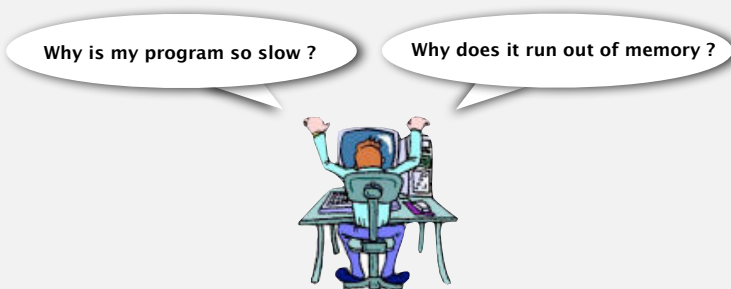
Andrew Appel
PU '81



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The challenge

Q. Will my program be able to solve a large practical input?



Key insight. [Knuth 1970s] Use **scientific method** to understand performance.

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Scientific method applied to analysis of algorithms

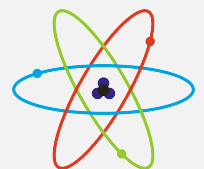
A framework for predicting performance and comparing algorithms.

Scientific method.

- **Observe** some feature of the natural world.
- **Hypothesize** a model that is consistent with the observations.
- **Predict** events using the hypothesis.
- **Verify** the predictions by making further observations.
- **Validate** by repeating until the hypothesis and observations agree.

Principles.

- Experiments must be **reproducible**.
- Hypotheses must be **falsifiable**.



Feature of the natural world = computer itself.

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Example: 3-sum

3-sum. Given N distinct integers, how many triples sum to exactly zero?

```
% more 8ints.txt
8
30 -40 -20 -10 40 0 10 5

% java ThreeSum 8ints.txt
4
```

	a[i]	a[j]	a[k]	sum
1	30	-40	10	0
2	30	-20	-10	0
3	-40	40	0	0
4	-10	0	10	0

▶ observations

- ▶ mathematical models
- ▶ order-of-growth classifications
- ▶ dependencies on inputs
- ▶ memory

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Context. Deeply related to problems in computational geometry.

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3-sum: brute-force algorithm

```
public class ThreeSum
{
    public static int count(int[] a)
    {
        int N = a.length;
        int count = 0;
        for (int i = 0; i < N; i++)
            for (int j = i+1; j < N; j++)
                for (int k = j+1; k < N; k++)
                    if (a[i] + a[j] + a[k] == 0)
                        count++;
        return count;
    }

    public static void main(String[] args)
    {
        int[] a = In.readInts(args[0]);
        StdOut.println(count(a));
    }
}
```

- ← check each triple
- ← for simplicity, ignore integer overflow

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Measuring the running time

Q. How to time a program?

A. Manual.

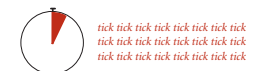


```
% java ThreeSum 1Kints.txt
```



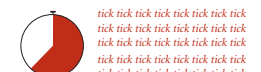
70

```
% java ThreeSum 2Kints.txt
```



528

```
% java ThreeSum 4Kints.txt
```



4039

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Measuring the running time

Q. How to time a program?

A. Automatic.

```
public class Stopwatch (part of stdlib.jar)
{
    Stopwatch() create a new stopwatch
    double elapsedTime() time since creation (in seconds)
}
```

```
public static void main(String[] args)
{
    int[] a = In.readInts(args[0]);
    Stopwatch stopwatch = new Stopwatch();
    StdOut.println(ThreeSum.count(a));
    double time = stopwatch.elapsedTime();
}
```

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Empirical analysis

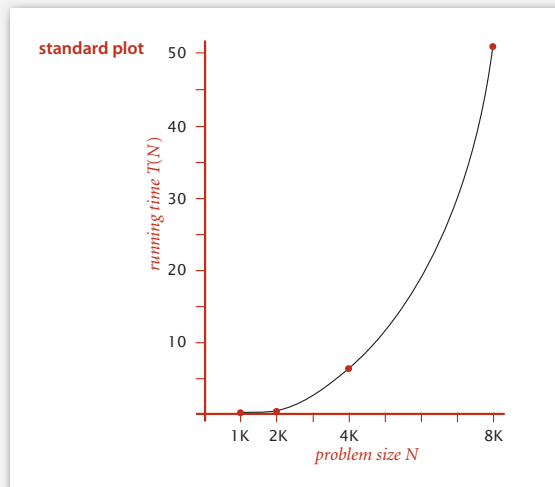
Run the program for various input sizes and measure running time.

N	time (seconds) †
250	0.0
500	0.0
1,000	0.1
2,000	0.8
4,000	6.4
8,000	51.1
16,000	?

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Data analysis

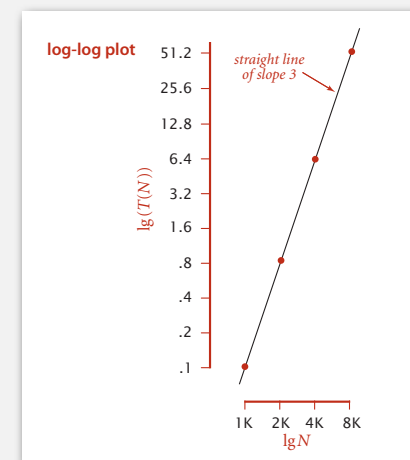
Standard plot. Plot running time $T(N)$ vs. input size N .



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Data analysis

Log-log plot. Plot running time $T(N)$ vs. input size N using log-log scale.



$$\lg(T(N)) = b \lg N + c$$
$$b = 2.999$$
$$c = -33.2103$$

$$T(N) = a N^b, \text{ where } a = 2^c$$

Regression. Fit straight line through data points: $a N^b$.
Hypothesis. The running time is about $1.006 \times 10^{-10} \times N^{2.999}$ seconds.

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Prediction and validation

Hypothesis. The running time is about $1.006 \times 10^{-10} \times N^{2.999}$ seconds.

"order of growth" of running time is about N^3 [stay tuned]

Predictions.

- 51.0 seconds for $N = 8,000$.
- 408.1 seconds for $N = 16,000$.

Observations.

N	time (seconds) †
8,000	51.1
8,000	51.0
8,000	51.1
16,000	410.8

validates hypothesis!

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Doubling hypothesis

Doubling hypothesis. Quick way to estimate b in a power-law relationship.

Run program, **doubling** the size of the input.

N	time (seconds) †	ratio	lg ratio
250	0.0		-
500	0.0	4.8	2.3
1,000	0.1	6.9	2.8
2,000	0.8	7.7	2.9
4,000	6.4	8.0	3.0
8,000	51.1	8.0	3.0

seems to converge to a constant $b \approx 3$

Hypothesis. Running time is about $a N^b$ with $b = \lg \text{ratio}$.

Caveat. Cannot identify logarithmic factors with doubling hypothesis.

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Doubling hypothesis

Doubling hypothesis. Quick way to estimate b in a power-law hypothesis.

Q. How to estimate a (assuming we know b)?

A. Run the program (for a sufficient large value of N) and solve for a .

N	time (seconds) †
8,000	51.1
8,000	51.0
8,000	51.1

$$51.1 = a \times 8000^3 \\ \Rightarrow a = 0.998 \times 10^{-10}$$

Hypothesis. Running time is about $0.998 \times 10^{-10} \times N^3$ seconds.

almost identical hypothesis to one obtained via linear regression

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Experimental algorithmics

System independent effects.

- Algorithm.
 - Input data.
- determines exponent b in power law

System dependent effects.

- Hardware: CPU, memory, cache, ...
 - Software: compiler, interpreter, garbage collector, ...
 - System: operating system, network, other applications, ...
- determines constant a in power law

Bad news. Difficult to get precise measurements.

Good news. Much easier and cheaper than other sciences.

e.g., can run huge number of experiments

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Q. How long does this program take as a function of N ?

```
String s = StdIn.readString();
int N = s.length();
...
for (int i = 0; i < N; i++)
    for (int j = 0; j < N; j++)
        distance[i][j] = ...
...
```

N	time
1,000	0.11
2,000	0.35
4,000	1.6
8,000	6.5

Jenny $\sim c_1 N^2$ seconds

N	time
250	0.5
500	1.1
1,000	1.9
2,000	3.9

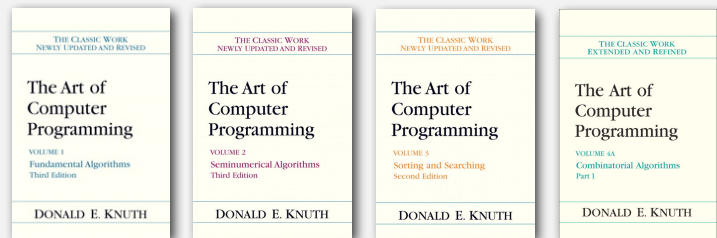
Kenny $\sim c_2 N$ seconds

- observations
- mathematical models
- order-of-growth classifications
- dependencies on inputs
- memory

Mathematical models for running time

Total running time: sum of cost \times frequency for all operations.

- Need to analyze program to determine set of operations.
- Cost depends on machine, compiler.
- Frequency depends on algorithm, input data.



Donald Knuth
1974 Turing Award

In principle, accurate mathematical models are available.

Cost of basic operations

operation	example	nanoseconds †
integer add	$a + b$	2.1
integer multiply	$a * b$	2.4
integer divide	a / b	5.4
floating-point add	$a + b$	4.6
floating-point multiply	$a * b$	4.2
floating-point divide	a / b	13.5
sine	<code>Math.sin(theta)</code>	91.3
arctangent	<code>Math.atan2(y, x)</code>	129.0
...

† Running OS X on Macbook Pro 2.2GHz with 2GB RAM

Cost of basic operations

operation	example	nanoseconds †
variable declaration	<code>int a</code>	C_1
assignment statement	<code>a = b</code>	C_2
integer compare	<code>a < b</code>	C_3
array element access	<code>a[i]</code>	C_4
array length	<code>a.length</code>	C_5
1D array allocation	<code>new int[N]</code>	$C_6 N$
2D array allocation	<code>new int[N][N]</code>	$C_7 N^2$
string length	<code>s.length()</code>	C_8
substring extraction	<code>s.substring(N/2, N)</code>	C_9
string concatenation	<code>s + t</code>	$C_{10} N$

Novice mistake. Abusive string concatenation.

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Example: 1-sum

Q. How many instructions as a function of input size N ?

```
int count = 0;
for (int i = 0; i < N; i++)
    if (a[i] == 0)
        count++;
```

operation	frequency
variable declaration	2
assignment statement	2
less than compare	$N + 1$
equal to compare	N
array access	N
increment	N to $2N$

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Example: 2-sum

Q. How many instructions as a function of input size N ?

```
int count = 0;
for (int i = 0; i < N; i++)
    for (int j = i+1; j < N; j++)
        if (a[i] + a[j] == 0)
            count++;
```

$$0 + 1 + 2 + \dots + (N-1) = \frac{1}{2}N(N-1) = \binom{N}{2}$$

operation	frequency
variable declaration	$N + 2$
assignment statement	$N + 2$
less than compare	$\frac{1}{2}(N+1)(N+2)$
equal to compare	$\frac{1}{2}N(N-1)$
array access	$N(N-1)$
increment	$\frac{1}{2}N(N-1)$ to $N(N-1)$

tedious to count exactly

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Simplifying the calculations

*“It is convenient to have a **measure of the amount of work involved in a computing process**, even though it be a very crude one. We may count up the number of times that various elementary operations are applied in the whole process and then given them various weights. We might, for instance, count the number of additions, subtractions, multiplications, divisions, recording of numbers, and extractions of figures from tables. In the case of computing with matrices most of the work consists of multiplications and writing down numbers, and we shall therefore only attempt to count the number of multiplications and recordings.”* — Alan Turing

ROUNDING-OFF ERRORS IN MATRIX PROCESSES

By A. M. TURING

(National Physical Laboratory, Teddington, Middlesex)

[Received 4 November 1947]

SUMMARY

A number of methods of solving sets of linear equations and inverting matrices are discussed. The theory of the rounding-off errors involved is investigated for some of the methods. In all cases examined, including the well-known ‘Gauss elimination process’, it is found that the errors are normally quite moderate: no exponential build-up need occur.



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Simplification 1: cost model

Cost model. Use some basic operation as a proxy for running time.

```
int count = 0;
for (int i = 0; i < N; i++)
  for (int j = i+1; j < N; j++)
    if (a[i] + a[j] == 0)
      count++;
```

$$0 + 1 + 2 + \dots + (N-1) = \frac{1}{2}N(N-1) = \binom{N}{2}$$

operation	frequency
variable declaration	$N + 2$
assignment statement	$N + 2$
less than compare	$\frac{1}{2}(N+1)(N+2)$
equal to compare	$\frac{1}{2}N(N-1)$
array access	$N(N-1)$
increment	$\frac{1}{2}N(N-1)$ to $N(N-1)$

cost model = array accesses

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Simplification 2: tilde notation

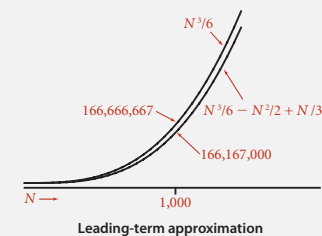
- Estimate running time (or memory) as a function of input size N .
- Ignore lower order terms.
 - when N is large, terms are negligible
 - when N is small, we don't care

Ex 1. $\frac{1}{6}N^3 + 20N + 16 \sim \frac{1}{6}N^3$

Ex 2. $\frac{1}{6}N^3 + 100N^{4/3} + 56 \sim \frac{1}{6}N^3$

Ex 3. $\frac{1}{6}N^3 - \frac{1}{2}N^2 + \frac{1}{3}N \sim \frac{1}{6}N^3$

discard lower-order terms
(e.g., $N = 1000$: 500 thousand vs. 166 million)



Technical definition. $f(N) \sim g(N)$ means $\lim_{N \rightarrow \infty} \frac{f(N)}{g(N)} = 1$

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Simplification 2: tilde notation

- Estimate running time (or memory) as a function of input size N .
- Ignore lower order terms.
 - when N is large, terms are negligible
 - when N is small, we don't care

operation	frequency	tilde notation
variable declaration	$N + 2$	$\sim N$
assignment statement	$N + 2$	$\sim N$
less than compare	$\frac{1}{2}(N+1)(N+2)$	$\sim \frac{1}{2}N^2$
equal to compare	$\frac{1}{2}N(N-1)$	$\sim \frac{1}{2}N^2$
array access	$N(N-1)$	$\sim N^2$
increment	$\frac{1}{2}N(N-1)$ to $N(N-1)$	$\sim \frac{1}{2}N^2$ to $\sim N^2$

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Example: 2-sum

Q. Approximately how many array accesses as a function of input size N ?

```
int count = 0;
for (int i = 0; i < N; i++)
  for (int j = i+1; j < N; j++)
    if (a[i] + a[j] == 0)
      count++;
```

"inner loop"

$$0 + 1 + 2 + \dots + (N-1) = \frac{1}{2}N(N-1) = \binom{N}{2}$$

A. $\sim N^2$ array accesses.

Bottom line. Use cost model and tilde notation to simplify frequency counts.

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Example: 3-sum

Q. Approximately how many array accesses as a function of input size N ?

```
int count = 0;
for (int i = 0; i < N; i++)
  for (int j = i+1; j < N; j++)
    for (int k = j+1; k < N; k++)
      if (a[i] + a[j] + a[k] == 0) ← "inner loop"
        count++;
```

A. $\sim \frac{1}{2} N^3$ array accesses.

$$\binom{N}{3} = \frac{N(N-1)(N-2)}{3!} \sim \frac{1}{6} N^3$$

Bottom line. Use **cost model** and **tilde notation** to simplify frequency counts.

Estimating a discrete sum

Q. How to estimate a discrete sum?

A1. Take COS 340.

A2. Replace the sum with an integral, and use calculus!

Ex 1. $1 + 2 + \dots + N.$ $\sum_{i=1}^N i \sim \int_{x=1}^N x dx \sim \frac{1}{2} N^2$

Ex 2. $1 + 1/2 + 1/3 + \dots + 1/N.$ $\sum_{i=1}^N \frac{1}{i} \sim \int_{x=1}^N \frac{1}{x} dx = \ln N$

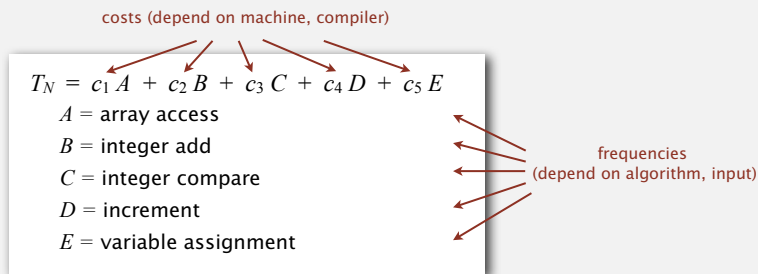
Ex 3. 3-sum triple loop. $\sum_{i=1}^N \sum_{j=i}^N \sum_{k=j}^N 1 \sim \int_{x=1}^N \int_{y=x}^N \int_{z=y}^N dz dy dx \sim \frac{1}{6} N^3$

Mathematical models for running time

In principle, accurate mathematical models are available.

In practice,

- Formulas can be complicated.
- Advanced mathematics might be required.
- Exact models best left for experts.



Bottom line. We use **approximate** models in this course: $T(N) \sim c N^3$.

- ▶ observations
- ▶ mathematical models
- ▶ **order-of-growth classifications**
- ▶ dependencies on inputs
- ▶ memory

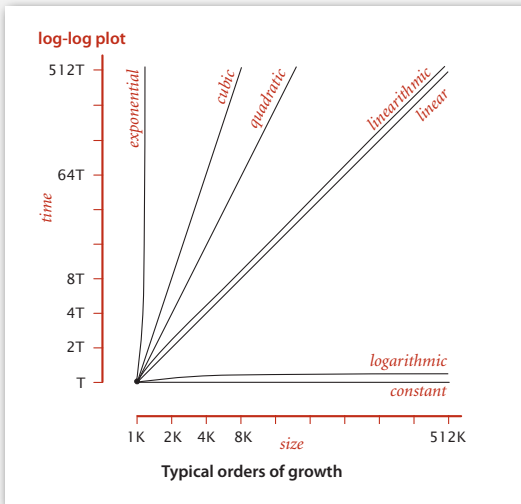
Common order-of-growth classifications

Good news. the small set of functions

1, $\log N$, N , $N \log N$, N^2 , N^3 , and 2^N

order of growth discards leading coefficient

suffices to describe order-of-growth of typical algorithms.



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Common order-of-growth classifications

order of growth	name	typical code framework	description	example	$T(2N) / T(N)$
1	constant	<code>a = b + c;</code>	statement	add two numbers	1
$\log N$	logarithmic	<pre>while (N > 1) { N = N / 2; ... }</pre>	divide in half	binary search	~ 1
N	linear	<pre>for (int i = 0; i < N; i++) { ... }</pre>	loop	find the maximum	2
$N \log N$	linearithmic	[see mergesort lecture]	divide and conquer	mergesort	~ 2
N^2	quadratic	<pre>for (int i = 0; i < N; i++) for (int j = 0; j < N; j++) { ... }</pre>	double loop	check all pairs	4
N^3	cubic	<pre>for (int i = 0; i < N; i++) for (int j = 0; j < N; j++) for (int k = 0; k < N; k++) { ... }</pre>	triple loop	check all triples	8
2^N	exponential	[see combinatorial search lecture]	exhaustive search	check all subsets	$T(N)$

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Practical implications of order-of-growth

growth rate	problem size solvable in minutes			
	1970s	1980s	1990s	2000s
1	any	any	any	any
$\log N$	any	any	any	any
N	millions	tens of millions	hundreds of millions	billions
$N \log N$	hundreds of thousands	millions	millions	hundreds of millions
N^2	hundreds	thousand	thousands	tens of thousands
N^3	hundred	hundreds	thousand	thousands
2^N	20	20s	20s	30

Bottom line. Need linear or linearithmic alg to keep pace with Moore's law.

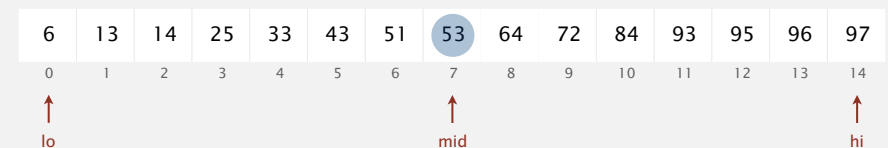
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Binary search

Goal. Given a sorted array and a key, find index of the key in the array?

Binary search. Compare key against middle entry.

- Too small, go left.
- Too big, go right.
- Equal, found.



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Trivial to implement?

- First binary search published in 1946; first bug-free one published in 1962.
- Java bug in `Arrays.binarySearch()` discovered in 2006.

```
public static int binarySearch(int[] a, int key)
{
    int lo = 0, hi = a.length-1;
    while (lo <= hi)
    {
        int mid = lo + (hi - lo) / 2;
        if (key < a[mid]) hi = mid - 1;
        else if (key > a[mid]) lo = mid + 1;
        else return mid;
    }
    return -1;
}
```

← one "3-way compare"

Invariant. If `key` appears in the array `a[]`, then `a[lo] ≤ key ≤ a[hi]`.

Binary search: mathematical analysis

Proposition. Binary search uses at most $1 + \lg N$ compares to search in a sorted array of size N .

Def. $T(N)$ = # compares to binary search in a sorted subarray of size at most N .

Binary search recurrence. $T(N) \leq T(N/2) + 1$ for $N > 1$, with $T(1) = 1$.

↑ left or right half ↑ possible to implement with one 2-way compare (instead of 3-way)

Pf sketch.

$T(N) \leq T(N/2) + 1$ $\leq T(N/4) + 1 + 1$ $\leq T(N/8) + 1 + 1 + 1$ \dots $\leq T(N/N) + 1 + 1 + \dots + 1$ $= 1 + \lg N$	given apply recurrence to first term apply recurrence to first term stop applying, $T(1) = 1$
--	--

An $N^2 \log N$ algorithm for 3-sum

Algorithm.

- **Sort** the N (distinct) numbers.
- For each pair of numbers $a[i]$ and $a[j]$, **binary search** for $-(a[i] + a[j])$.

input	30 -40 -20 -10 40 0 10 5
sort	-40 -20 -10 0 5 10 30 40
binary search	
(-40, -20)	60
(-40, -10)	30
(-40, 0)	40
(-40, 5)	35
(-40, 10)	30
⋮	⋮
(-40, 40)	0
⋮	⋮
(-10, 0)	10
⋮	⋮
(-20, 10)	10
⋮	⋮
(10, 30)	-40
(10, 40)	-50
(30, 40)	-70

only count if $a[i] < a[j] < a[k]$ to avoid double counting

Analysis. Order of growth is $N^2 \log N$.

- Step 1: N^2 with insertion sort.
- Step 2: $N^2 \log N$ with binary search.

Comparing programs

Hypothesis. The $N^2 \log N$ three-sum algorithm is significantly faster in practice than the brute-force N^3 algorithm.

N	time (seconds)
1,000	0.1
2,000	0.8
4,000	6.4
8,000	51.1

ThreeSum.java

N	time (seconds)
1,000	0.14
2,000	0.18
4,000	0.34
8,000	0.96
16,000	3.67
32,000	14.88
64,000	59.16

ThreeSumDeluxe.java

Guiding principle. Typically, better order of growth \Rightarrow faster in practice.

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- observations
- mathematical models
- order-of-growth classifications
- dependencies on inputs
- memory

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Types of analyses

Best case. Lower bound on cost.

- Determined by "easiest" input.
- Provides a goal for all inputs.

Worst case. Upper bound on cost.

- Determined by "most difficult" input.
- Provides a guarantee for all inputs.

Average case. Expected cost for random input.

- Need a model for "random" input.
- Provides a way to predict performance.

Ex 1. Array accesses for brute-force 3 sum.

Best: $\sim \frac{1}{2} N^3$

Average: $\sim \frac{1}{2} N^3$

Worst: $\sim \frac{1}{2} N^3$

Ex 2. Compares for binary search.

Best: ~ 1

Average: $\sim \lg N$

Worst: $\sim \lg N$

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Commonly-used notations

notation	provides	example	shorthand for	used to
Tilde	leading term	$\sim 10 N^2$	$10 N^2$ $10 N^2 + 22 N \log N$ $10 N^2 + 2 N + 37$	provide approximate model
Big Theta	asymptotic growth rate	$\Theta(N^2)$	$\frac{1}{2} N^2$ $10 N^2$ $5 N^2 + 22 N \log N + 3 N$	classify algorithms
Big Oh	$\Theta(N^2)$ and smaller	$O(N^2)$	$10 N^2$ $100 N$ $22 N \log N + 3 N$	develop upper bounds
Big Omega	$\Theta(N^2)$ and larger	$\Omega(N^2)$	$\frac{1}{2} N^2$ N^5 $N^3 + 22 N \log N + 3 N$	develop lower bounds

Common mistake. Interpreting big-Oh as an approximate model.

Basics

Bit. 0 or 1.

Byte. 8 bits.

Megabyte (MB). 1 million or 2^{20} bytes.

Gigabyte (GB). 1 billion or 2^{30} bytes.

NIST most computer scientists



- ▶ observations
- ▶ mathematical models
- ▶ order-of-growth classifications
- ▶ dependencies on inputs
- ▶ **memory**

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Old machine. We used to assume a 32-bit machine with 4 byte pointers.

Modern machine. We now assume a 64-bit machine with 8 byte pointers.

- Can address more memory.
- Pointers use more space.

some JVMs "compress" ordinary object pointers to 4 bytes to avoid this cost

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Typical memory usage for primitive types and arrays

Primitive types.

type	bytes
boolean	1
byte	1
char	2
int	4
float	4
long	8
double	8

for primitive types

Array overhead. 24 bytes.

type	bytes
char[]	$2N + 24$
int[]	$4N + 24$
double[]	$8N + 24$

for one-dimensional arrays

type	bytes
char[][]	$\sim 2MN$
int[][]	$\sim 4MN$
double[][]	$\sim 8MN$

for two-dimensional arrays

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Typical memory usage for objects in Java

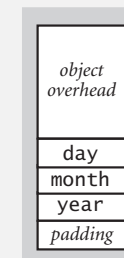
Object overhead. 16 bytes.

Reference. 8 bytes.

Padding. Each object uses a multiple of 8 bytes.

Ex 1. A Date object uses 32 bytes of memory.

```
public class Date
{
    private int day;
    private int month;
    private int year;
    ...
}
```



16 bytes (object overhead)

4 bytes (int)

4 bytes (int)

4 bytes (int)

4 bytes (padding)

32 bytes

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Typical memory usage for objects in Java

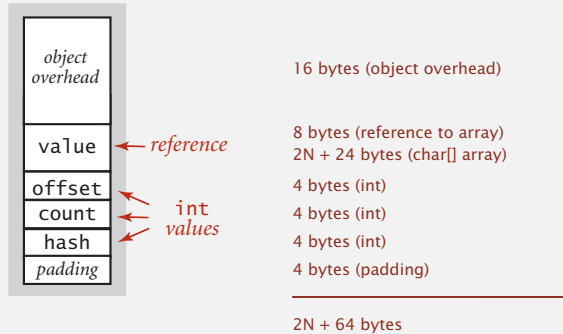
Object overhead. 16 bytes.

Reference. 8 bytes.

Padding. Each object uses a multiple of 8 bytes.

Ex 2. A virgin string of length N uses $\sim 2N$ bytes of memory.

```
public class String
{
    private char[] value;
    private int offset;
    private int count;
    private int hash;
    ...
}
```



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Typical memory usage summary

Total memory usage for a data type value:

- Primitive type: 4 bytes for `int`, 8 bytes for `double`, ...
- Object reference: 8 bytes.
- Array: 24 bytes + memory for each array entry.
- Object: 16 bytes + memory for each instance variable + 8 if inner class.

padding: round up to multiple of 8

extra pointer to enclosing class

Shallow memory usage: Don't count referenced objects.

Deep memory usage: If array entry or instance variable is a reference, add memory (recursively) for referenced object.

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Example

Q. How much memory does `WeightedQuickUnionUF` use as a function of N ?

Use tilde notation to simplify your answer.

```
public class WeightedQuickUnionUF
{
    private int[] id;
    private int[] sz;
    private int count;

    public WeightedQuickUnionUF(int N)
    {
        id = new int[N];
        sz = new int[N];
        for (int i = 0; i < N; i++) id[i] = i;
        for (int i = 0; i < N; i++) sz[i] = 1;
    }
    ...
}
```

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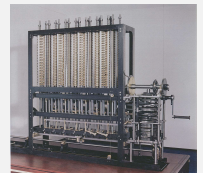
Turning the crank: summary

Empirical analysis.

- Execute program to perform experiments.
- Assume power law and formulate a hypothesis for running time.
- Model enables us to **make predictions**.

Mathematical analysis.

- Analyze algorithm to count frequency of operations.
- Use tilde notation to simplify analysis.
- Model enables us to **explain behavior**.



Scientific method.

- Mathematical model is independent of a particular system; applies to machines not yet built.
- Empirical analysis is necessary to validate mathematical models and to make predictions.

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