

COS 226, SPRING 2014

ALGORITHMS AND DATA STRUCTURES

KEVIN WAYNE



PRINCETON
UNIVERSITY

<http://www.princeton.edu/~cos226>

COS 226 course overview

What is COS 226?

- Intermediate-level survey course.
- Programming and problem solving, with applications.
- **Algorithm:** method for solving a problem.
- **Data structure:** method to store information.

topic	data structures and algorithms
data types	stack, queue, bag, union-find, priority queue
sorting	quicksort, mergesort, heapsort, radix sorts
searching	BST, red-black BST, hash table
graphs	BFS, DFS, Prim, Kruskal, Dijkstra
strings	KMP, regular expressions, tries, data compression
advanced	B-tree, k-d tree, suffix array, maxflow

Why study algorithms?

Their impact is broad and far-reaching.

Internet. Web search, packet routing, distributed file sharing, ...

Biology. Human genome project, protein folding, ...

Computers. Circuit layout, file system, compilers, ...

Computer graphics. Movies, video games, virtual reality, ...

Security. Cell phones, e-commerce, voting machines, ...

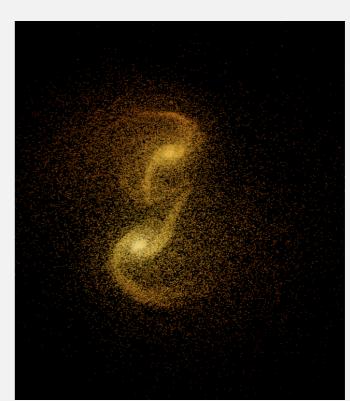
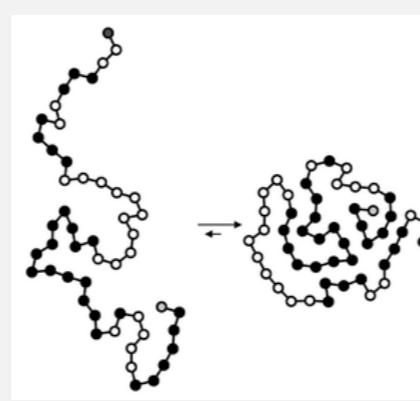
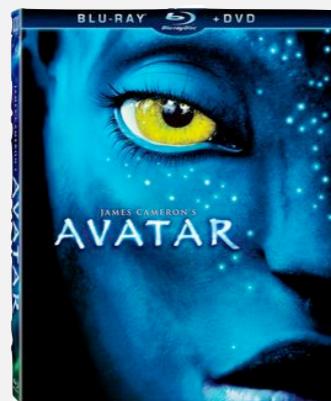
Multimedia. MP3, JPG, DivX, HDTV, face recognition, ...

Social networks. Recommendations, news feeds, advertisements, ...

Physics. N-body simulation, particle collision simulation, ...

:

Google
YAHOO![®]
bing[™]



Why study algorithms?

Their impact is broad and far-reaching.

Mysterious algorithm was 4% of trading activity last week

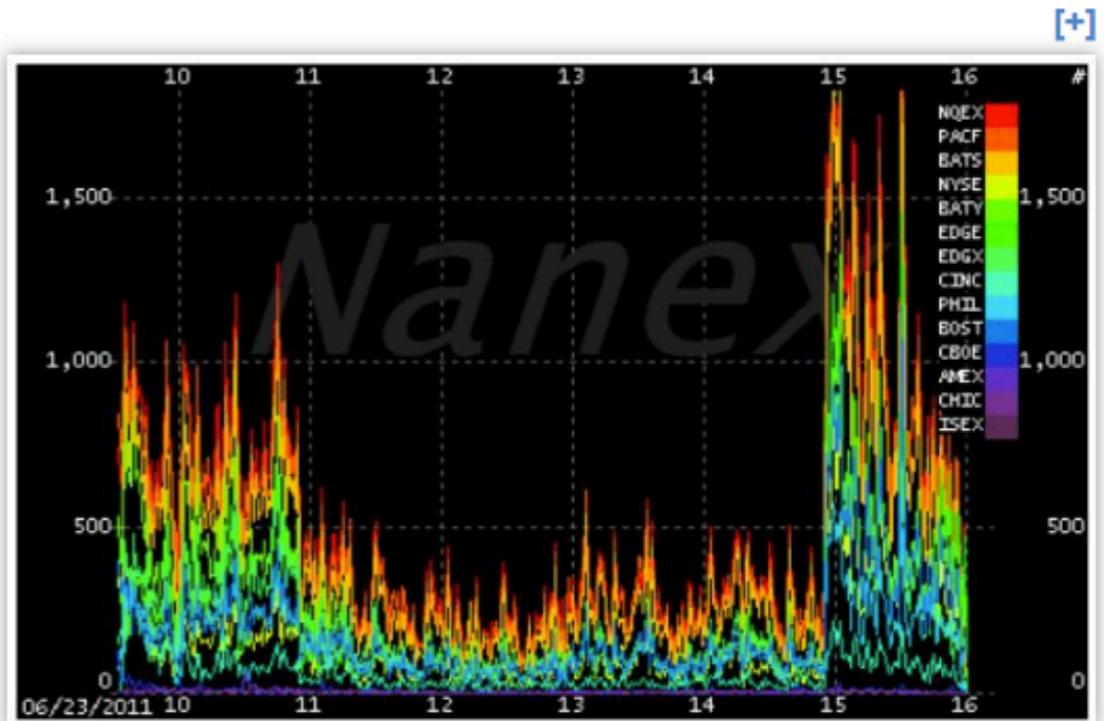
October 11, 2012

A single mysterious computer program that placed orders — and then subsequently canceled them — made up 4 percent of all quote traffic in the U.S. stock market last week, according to the top tracker of [high-frequency trading](#) activity.

The motive of the algorithm is still unclear, [CNBC](#) reports.

The program placed orders in 25-millisecond bursts involving about 500 stocks, according to Nanex, a market data firm. The algorithm never executed a single trade, and it abruptly ended at about 10:30 a.m. ET Friday.

"My guess is that the algo was testing the market, as high-frequency frequently does," says Jon Najarian, co-founder of TradeMonster.com. "As soon as they add bandwidth, the HFT crowd sees how quickly they can top out to create latency." ([Read More: Unclear What Caused Kraft Spike: Nanex Founder.](#))

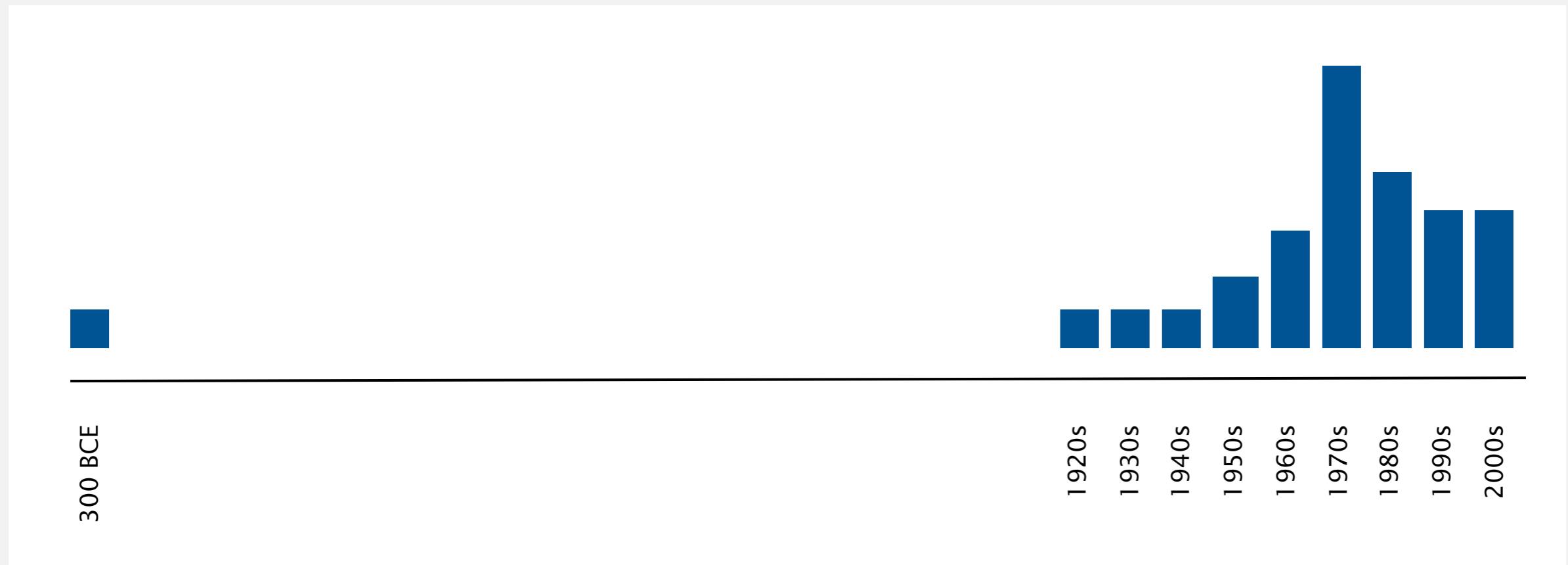


Generic high frequency trading chart (credit: Nanex)

Why study algorithms?

Old roots, new opportunities.

- Study of algorithms dates at least to Euclid.
- Formalized by Church and Turing in 1930s.
- Some important algorithms were discovered by undergraduates in a course like this!



Why study algorithms?

For intellectual stimulation.

“For me, great algorithms are the poetry of computation. Just like verse, they can be terse, allusive, dense, and even mysterious.

But once unlocked, they cast a brilliant new light on some aspect of computing. ” — Francis Sullivan

FROM THE
EDITORS

THE JOY OF ALGORITHMS

Francis Sullivan, Associate Editor-in-Chief

 **T**HE THEME OF THIS FIRST-OF-THE-CENTURY ISSUE OF COMPUTING IN SCIENCE & ENGINEERING IS ALGORITHMS. IN FACT, WE WERE BOLD ENOUGH—AND PERHAPS FOOLISH ENOUGH—to call the 10 examples we've selected “THE TOP 10 ALGORITHMS OF THE CENTURY.”

Computational algorithms are probably as old as civilization. But once unlocked, they cast a brilliant new light on some aspect of computation. A colleague recently told me, “I’m not sure what I’m doing, but I’m doing it well.” He was referring to his whole life. He wasn’t joking, because he was referring to the 13 minutes during which he’d sketched out a fundamental operation of the DPLL algorithm for solving Boolean satisfiability problems. The algorithm is a central part of modern computer science, and it’s based on a simple idea of thought and investigation as a sunk cost that might or might have paid off.

The DPLL algorithm cracked many hard problems since 1 January 1990, but we are posing some even harder ones on to the next century. In spite of a lot of good work, many questions of scientific inquiry remain unanswered. There are still very big challenges coming from more “well-posed” tasks. For instance, the algorithmic solution of one of the eight problems of the Marilyn Monroe when solving a crossword puzzle.

“Who first ate a crab? After all, they don’t look very appetizing.” After the usual question-and-answer session, the respondent will be asked to give what must be the right answer—namely, “A very hungry person first ate a crab.”

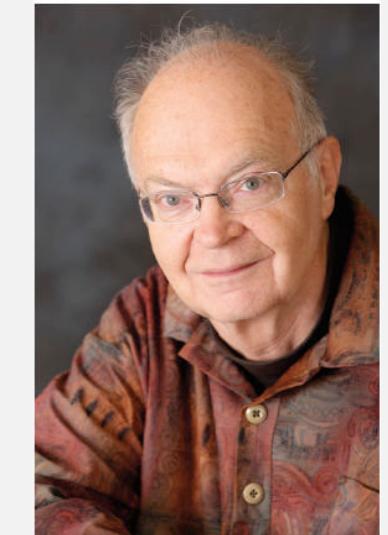
The question is “What is the number of blossoms?” To answer creates its own necessity. Our need for powerful methods for solving specific cases of “impossible” problems always exceeds their availability. Each significant computational problem is a challenge to be solved by a team larger, computation to be done. New algorithms are an attempt to bridge the gap between the demand for cycles and the available time. The search for better ways to do computation is a Moore’s Law factor of two every 18 months. In effect, Moore’s Law changes the constant in front of the estimate of running time. The search for better ways to do computation does not come along every 1.5 years, but when they do, they change the exponent of the computation.

For me, great algorithms are the poetry of computation. Just like verse, they can be terse, allusive, dense, and even

is not going to be dull either.”

Francis Sullivan, Associate Editor-in-Chief

“An algorithm must be seen to be believed. ” — Donald Knuth



Why study algorithms?

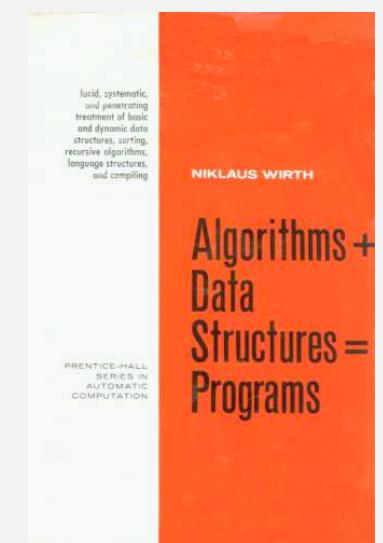
To become a proficient programmer.

“I will, in fact, claim that the difference between a bad programmer and a good one is whether he considers his code or his data structures more important. Bad programmers worry about the code. Good programmers worry about data structures and their relationships. ”

— Linus Torvalds (creator of Linux)



“Algorithms + Data Structures = Programs. ” — Niklaus Wirth



Why study algorithms?

They may unlock the secrets of life and of the universe.

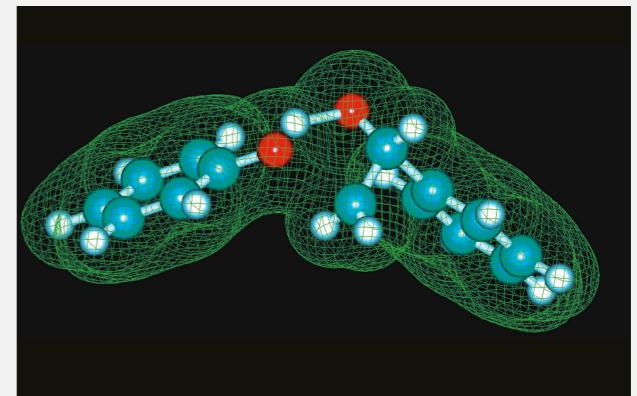
“ Computer models mirroring real life have become crucial for most advances made in chemistry today.... Today the computer is just as important a tool for chemists as the test tube. ”

— Royal Swedish Academy of Sciences

(Nobel Prize in Chemistry 2013)

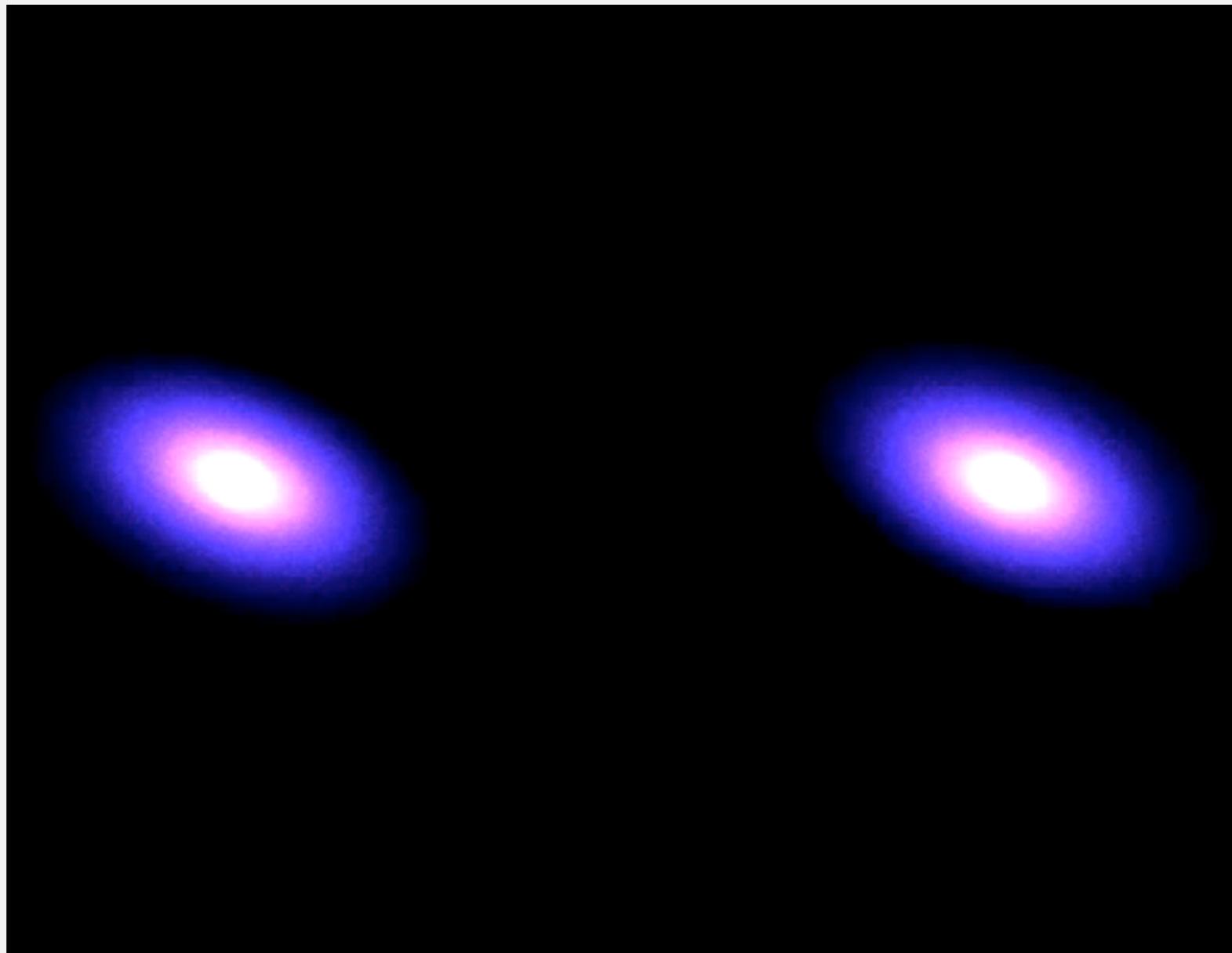


Martin Karplus, Michael Levitt, and Arieh Warshel



Why study algorithms?

To solve problems that could not otherwise be addressed.



http://www.youtube.com/watch?v=ua7YIN4eL_w

Why study algorithms?

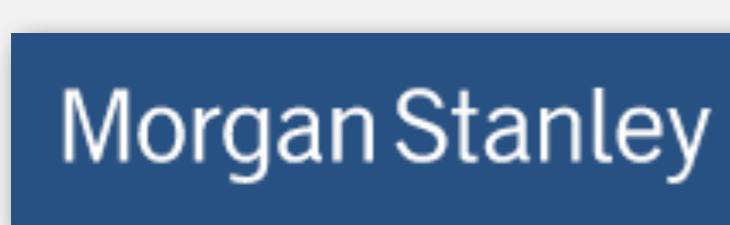
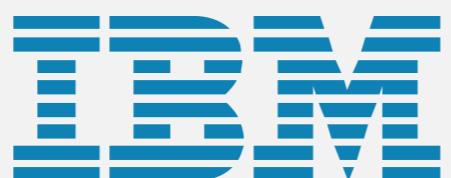
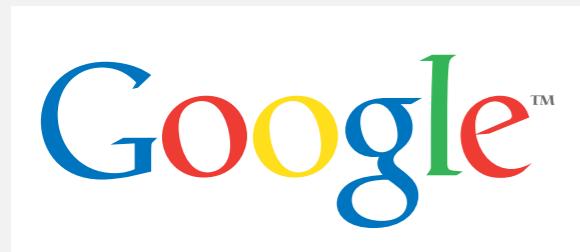
Everybody else is doing it.

```
% sort -rn PU2013-14.txt
```

774	COS 126	General Computer Science
615	ECO 100	Introduction to Microeconomics
471	ECO 101	Introduction to Macroeconomics
444	ENG 385	Children's Literature
440	MAT 202	Linear Algebra with Applications
414	COS 226	Algorithms and Data Structures
405	MAT 201	Multivariable Calculus
384	CHV 310	Practical Ethics
344	REL 261	Christian Ethics and Modern Society
320	PSY 101	Introduction to Psychology
300	COS 217	Introduction to Programming Systems
...		

Why study algorithms?

For fun and profit.



Why study algorithms?

- Their impact is broad and far-reaching.
- Old roots, new opportunities.
- For intellectual stimulation.
- To become a proficient programmer.
- They may unlock the secrets of life and of the universe.
- To solve problems that could not otherwise be addressed.
- Everybody else is doing it.
- For fun and profit.

Why study anything else?



Lectures

Traditional lectures. Introduce new material.

Electronic devices. Permitted, but only to enhance lecture.



no



no



no

What	When	Where	Who	Office Hours
L01	MW 11-12:20	McCosh 10	Kevin Wayne	see web

Lectures

Traditional lectures. Introduce new material.

Flipped lectures.

- Watch videos online **before** lecture.
- Complete pre-lecture activities.
- Attend only one "flipped" lecture per week (interactive, collaborative, experimental).
- Apply via web ASAP: results by 5pm today.



What	When	Where	Who	Office Hours
L01	MW 11-12:20	McCosh 10	Kevin Wayne	see web
L02	W 11-12:20	Frist 307	Josh Hug Andy Guna	see web

Precepts

Discussion, problem-solving, background for assignments.

What	When	Where	Who	Office Hours
P01	Th 11-11:50	CS 102	Andy Guna †	see web
P02	Th 12:30-1:20	Bobst 105	Andy Guna †	see web
P03	Th 1:30-2:20	Bobst 105	Nevin Li	see web
P04	F 10-10:50	Bobst 105	Jennifer Guo	see web
P05	F 11-11:50	Bobst 105	Madhu Jayakumar	see web
P05A	F 11-11:50	Sherrerd 001	Ruth Dannenfelser	see web
P06	F 2:30-3:20	Friend 108	Chris Eubank	see web
P06A	F 2:30-3:20	Friend 111	TBA	see web
P06B	F 2:30-3:20	Friend 109	Josh Hug †	see web
P07	F 3:30-4:20	Friend 108	Josh Hug †	see web



likely to change

† lead preceptor

Coursework and grading

Programming assignments. 45%

- Due on Tuesdays at 11pm via electronic submission.
- Collaboration/lateness policies: see web.

Exercises. 10%

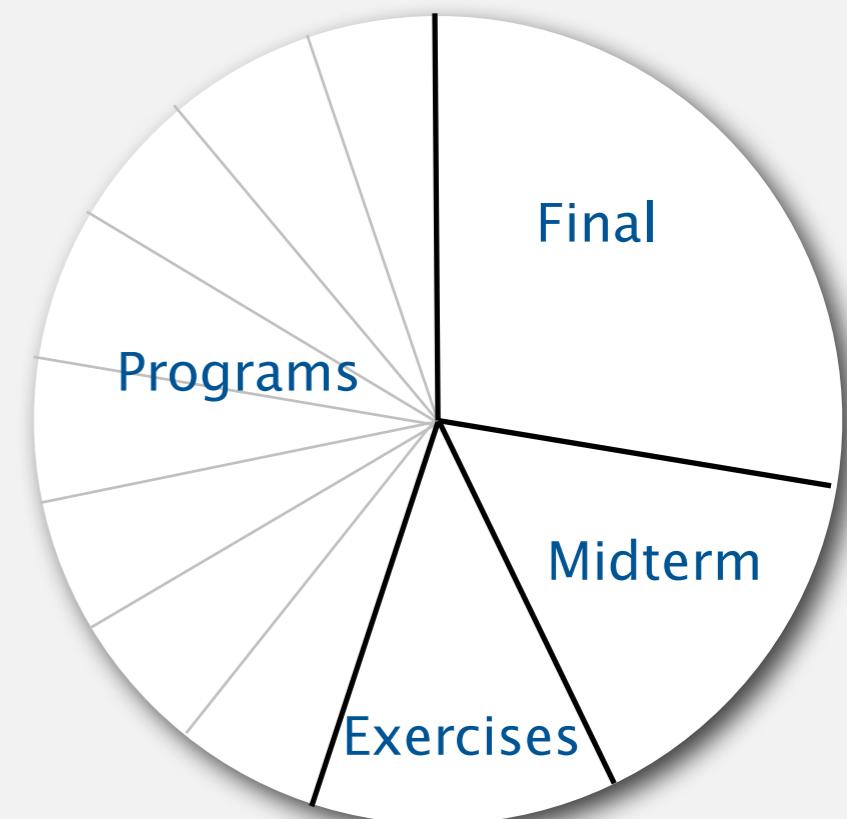
- Due on Sundays at 11pm in Blackboard.
- Collaboration/lateness policies: see web.

Exams. 15% + 30%

- Midterm (in class on Wednesday, March 12).
- Final (to be scheduled by Registrar).

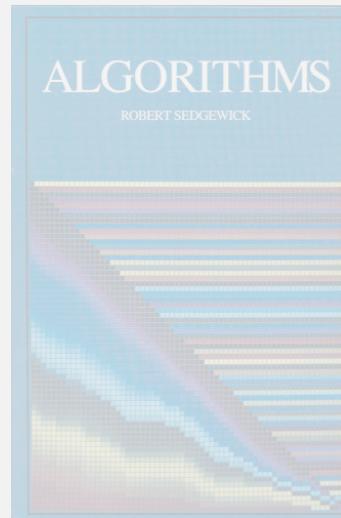
Staff discretion. [adjust borderline cases]

- Report errata.
- Contribute to Piazza discussion forum.
- Attend and participate in precept/lecture.

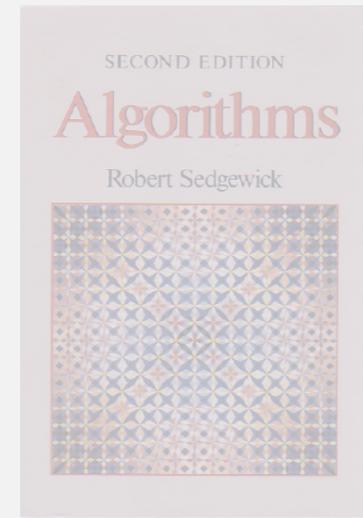


Resources (textbook)

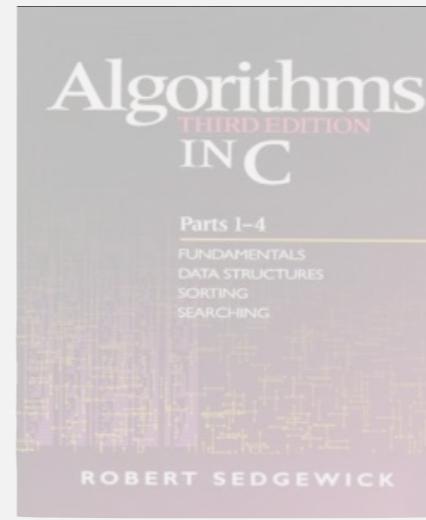
Required reading. Algorithms 4th edition by R. Sedgewick and K. Wayne, Addison-Wesley Professional, 2011, ISBN 0-321-57351-X.



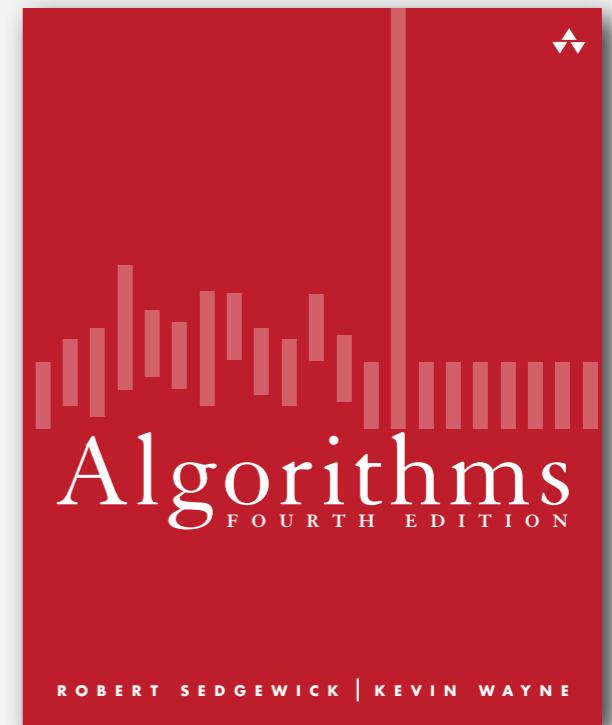
1st edition (1982)



2nd edition (1988)



3rd edition (1997)



4th edition (2011)

3rd book scanned
by Google books

Available in hardcover and Kindle.

- Online: Amazon (\$60/\$35 to buy), Chegg (\$25 to rent), ...
- Brick-and-mortar: Labyrinth Books (122 Nassau St).
- On reserve: Engineering library.

Resources (web)

Course content.

- Course info.
- Lecture slides.
- Flipped lectures.
- Programming assignments.
- Exercises.
- Exam archive.

 PRINCETON
UNIVERSITY

COMPUTER SCIENCE 226
ALGORITHMS AND DATA STRUCTURES
SPRING 2014

[Course Information](#) | [Lectures](#) | [Flipped](#) | [Precepts](#) | [Assignments](#) | [Exercises](#) | [Exams](#)

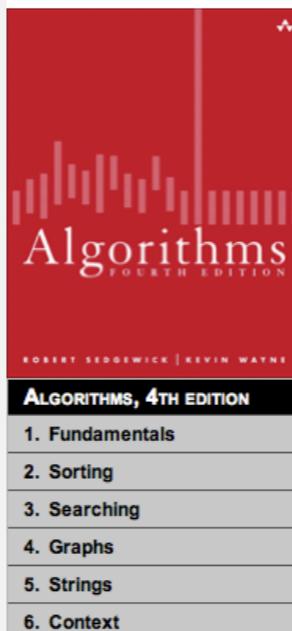
COURSE INFORMATION

Description. This course surveys the most important algorithms and data structures in use on computers today. Particular emphasis is given to algorithms for sorting, searching, and string processing. Fundamental algorithms in a number of other areas are covered as well, including geometric and graph algorithms. The course will concentrate on developing implementations, understanding their performance characteristics, and estimating their potential effectiveness in applications.

<http://www.princeton.edu/~cos226>

Booksite.

- Brief summary of content.
- Download code from book.
- APIs and Javadoc.



ALGORITHMS, 4TH EDITION

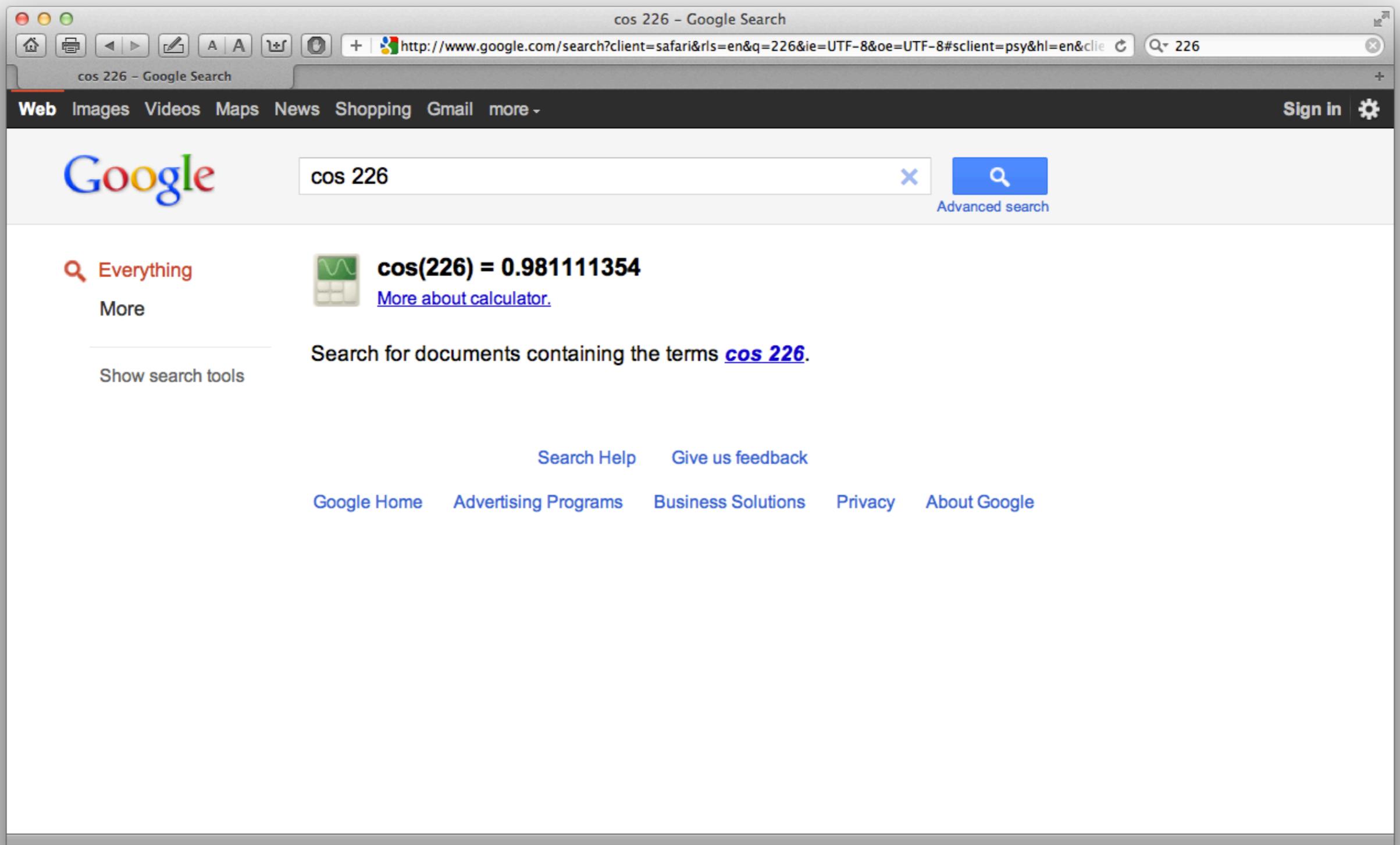
essential information that every serious programmer needs to know about algorithms and data structures

Textbook. The textbook *Algorithms, 4th Edition* by Robert Sedgewick and Kevin Wayne [[Amazon](#) · [Addison-Wesley](#)] surveys the most important algorithms and data structures in use today. The textbook is organized into six chapters:

- *Chapter 1: Fundamentals* introduces a scientific and engineering basis for comparing algorithms and making predictions. It also includes our programming model.
- *Chapter 2: Sorting* considers several classic sorting algorithms, including insertion sort, mergesort, and quicksort. It also includes a binary heap implementation of a priority queue.
- *Chapter 3: Searching* describes several classic symbol table implementations, including binary search trees, red-black trees, and hash tables.

<http://algs4.cs.princeton.edu>

Resources (web)



<http://www.princeton.edu/~cos226>

Resources (web)

226 – Google Search

http://www.google.com/#sclient=psy&hl=en&q=+226&aq=f&t

226 – Google Search

Web Images Videos Maps News Shopping Gmail more ▾ Web History | Search settings | Sign in

Google

226

About 236,000,000 results (0.18 seconds) Advanced search

Instant is on ▾

Everything

Images Videos News More

Any time Latest Past 2 days

All results Sites with images

More search tools

[Area codes 519 and 226 - Wikipedia, the free encyclopedia](#)
The 226 area code was first proposed as a result of an NPA exhaustion study conducted in the 1990s. The issue was raised with the CRTC by telecommunications ...
en.wikipedia.org/wiki/Area_codes_519_and_226 - Cached - Similar

[226 - Wikipedia, the free encyclopedia](#)
226. From Wikipedia, the free encyclopedia. Jump to: navigation, search. This article is about the year 226. For the number 226, see 226 (number). ...
en.wikipedia.org/wiki/226 - Cached - Similar

[COS 226, Fall 2010: Home Page](#)
Princeton COS 226: Data Structures and Algorithms. ... Computer Science 226. Algorithms and Data Structures Fall 2010 ...
www.princeton.edu/~cos226/ - Cached - Similar

[Images for 226 - Report images](#)

RAP226



<http://www.princeton.edu/~cos226>

Resources (web)

The screenshot shows a Google search results page for the query "226". The search bar at the top contains "226". Below the search bar, the "Web" tab is selected, followed by "Maps", "Images", "Videos", "Books", "More", and "Search tools". The search results section displays approximately 175 million results found in 0.15 seconds. The first result is a link to the "COS 226, Spring 2014: Home Page" from www.princeton.edu/~cos226/, which is associated with Princeton University. The snippet for this result mentions that if you have not taken COS 126 or COS 217 but want to place into COS 226, email Josh Hug. It also notes that assignments, lectures, and exercises are available. The second result is a link to the "226 - Wikipedia, the free encyclopedia" from en.wikipedia.org/wiki/226, which is associated with Wikipedia. The snippet for this result discusses the year 226 (CCXXVI) as a common year starting on Sunday. The third result is a link to "Area codes 519 and 226 - Wikipedia, the free encyclopedia" from en.wikipedia.org/wiki/Area_codes_519_and_226, which is also associated with Wikipedia. The snippet for this result provides information about the area code 226, noting its history and borders. The fourth result is a link to "Route 226 - King County Metro Transit" from metro.kingcounty.gov/schedules/226/, which is associated with King County Metro. The snippet for this result describes Route 226, mentioning its stops and travel options. A sidebar on the right side of the search results is titled "See results about" and lists "Area codes 519 and 226" with a brief description: "519 is the telephone area code which covers most of southwestern ...". There is also a "Feedback" link at the bottom of the sidebar.

226 – Google Search

Google 226

Web Maps Images Videos Books More Search tools

About 175,000,000 results (0.15 seconds)

COS 226, Spring 2014: Home Page
www.princeton.edu/~cos226/ Princeton University

If you have not taken COS 126 or COS 217 but want to place into COS 226, email Josh Hug. If you are unable to enroll because the only precepts you can attend ...
Assignments - Lectures - Exercises

226 - Wikipedia, the free encyclopedia
en.wikipedia.org/wiki/226 Wikipedia

Year 226 (CCXXVI) was a common year starting on Sunday (link will display the full calendar) of the Julian calendar. At the time, it was known as the Year of the ...

Area codes 519 and 226 - Wikipedia, the free encyclopedia
en.wikipedia.org/wiki/Area_codes_519_and_226 Wikipedia

It is mostly bounded by area code 905, except for Simcoe County which is bordered by 705. It was overlaid with the new area code 226 on October 21, 2006, ...
History - Dialing areas - See also - References

Route 226 - King County Metro Transit
metro.kingcounty.gov/schedules/226/ King County Metro

Mar 28, 2013 - You are in: Travel Options >; Bus >; Schedules >; Route 226. Fares & ORCA · Trip Planner · Go to Metro Online's Home Page ...
To Overlake, Eastgate - Route Map - Saturday - Sunday

Feedback

See results about
Area codes 519 and 226
519 is the telephone area code which covers most of southwestern ...

<http://www.princeton.edu/~cos226>

Resources (web)

The screenshot shows a Google search results page for the query "algorithms". The search bar at the top contains "algorithms". Below the search bar, there are tabs for "Web", "Images", "Maps", "Shopping", "News", "More", and "Search tools". A "Sign in" button is also visible. The main content area displays approximately 22,700,000 results found in 0.13 seconds. The first result is a link to the Wikipedia page on algorithms, followed by a snippet of text explaining what an algorithm is. Subsequent results include links to the book "Algorithms, 4th Edition" by Robert Sedgewick and Kevin Wayne, a HowStuffWorks article on computer algorithms, and a Coursera course on algorithms.

algorithms - Google Search

Google algorithms

Web Images Maps Shopping News More Search tools Sign in

About 22,700,000 results (0.13 seconds)

[Algorithm - Wikipedia, the free encyclopedia](#)
en.wikipedia.org/wiki/Algorithm ▾
In mathematics and computer science, an **algorithm** is a step-by-step procedure for calculations. **Algorithms** are used for calculation, data processing, and ...
[List of algorithms - Algorithm examples - Automated reasoning - Euclidean](#)

[List of algorithms - Wikipedia, the free encyclopedia](#)
en.wikipedia.org/wiki/List_of_algorithms ▾
The following is a list of algorithms along with one-line descriptions for each.

[Algorithms, 4th Edition by Robert Sedgewick and Kevin Wayne](#)
algs4.cs.princeton.edu/ ▾
The textbook **Algorithms**, 4th Edition by Robert Sedgewick and Kevin Wayne surveys the most important **algorithms** and data structures in use today. The broad ...

[HowStuffWorks "What is a "computer algorithm"?"](#)
computer.howstuffworks.com/question717.htm ▾
That's where computer **algorithms** come in. The **algorithm** is the basic technique used to get the job done. Let's follow an example to help get an understanding ...

[Algorithms, Part I | Coursera](#)
<https://www.coursera.org/course/algs4partI> ▾
Algorithms, Part I is a free online class taught by Kevin Wayne and Robert Sedgewick of Princeton University.

Where to get help?

Piazza discussion forum.

- Low latency, low bandwidth.
- Mark solution-revealing questions as private.

piazza

<http://piazza.com/princeton/spring2014/cos226>

Office hours.

- High bandwidth, high latency.
- See web for schedule.



<http://www.princeton.edu/~cos226>

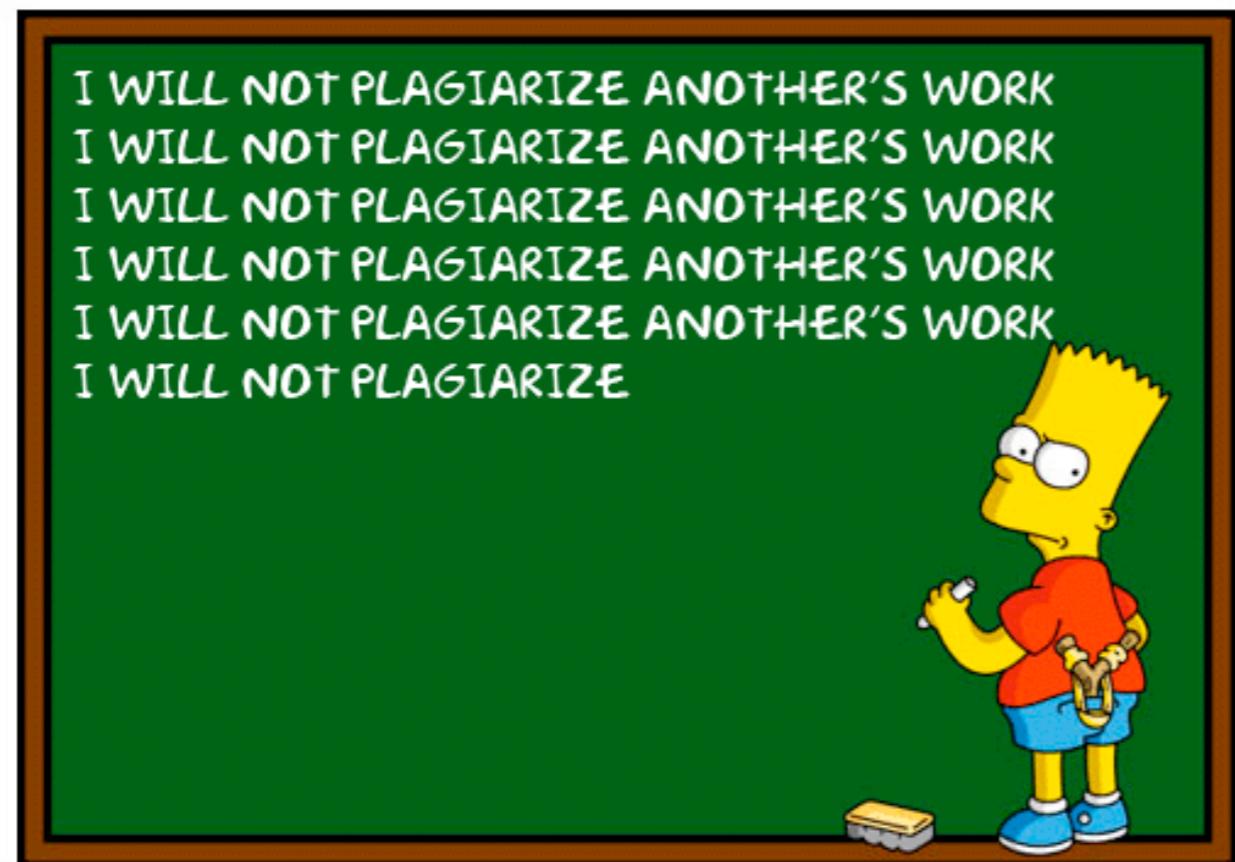
Computing laboratory.

- Undergrad lab TAs in Friend 017.
- For help with debugging.
- See web for schedule.

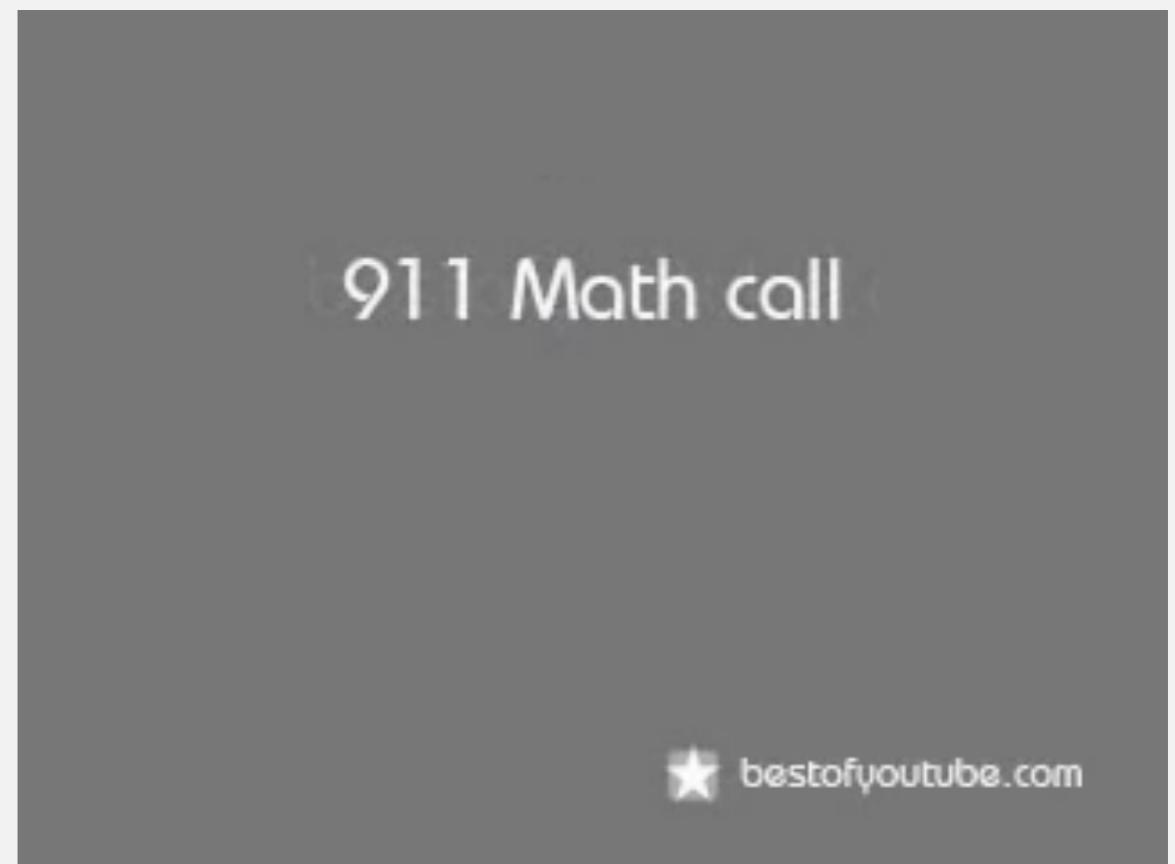


<http://www.princeton.edu/~cos226>

Where not to get help?



<http://world.edu/academic-plagiarism>



<http://www.youtube.com/watch?v=FT4NOe4vtoM>

What's ahead?

Lecture 1. [today] Union find.

Lecture 2. [Wednesday] Analysis of algorithms.

Flipped lecture 1. [Wednesday] Watch video beforehand.

Precept 1. [Thursday/Friday] Meets this week.



Exercise 1. Due via Bb submission at 11pm on Sunday.

Assignment 1. Due via electronic submission at 11pm on Tuesday.

protip: start early

Right course? See me.

Placed out of COS 126? Review Sections 1.1–1.2 of Algorithms 4/e.

Not registered? Go to any precept this week.

Change precept? Use SCORE.



see Colleen Kenny-McGinley
in CS 210 if the only precepts
you can attend are closed