

(CMS/CS/EE 144)

Networks: Structure & Economics

>Adam Wierman

What is this course about?
& what will it require of you?

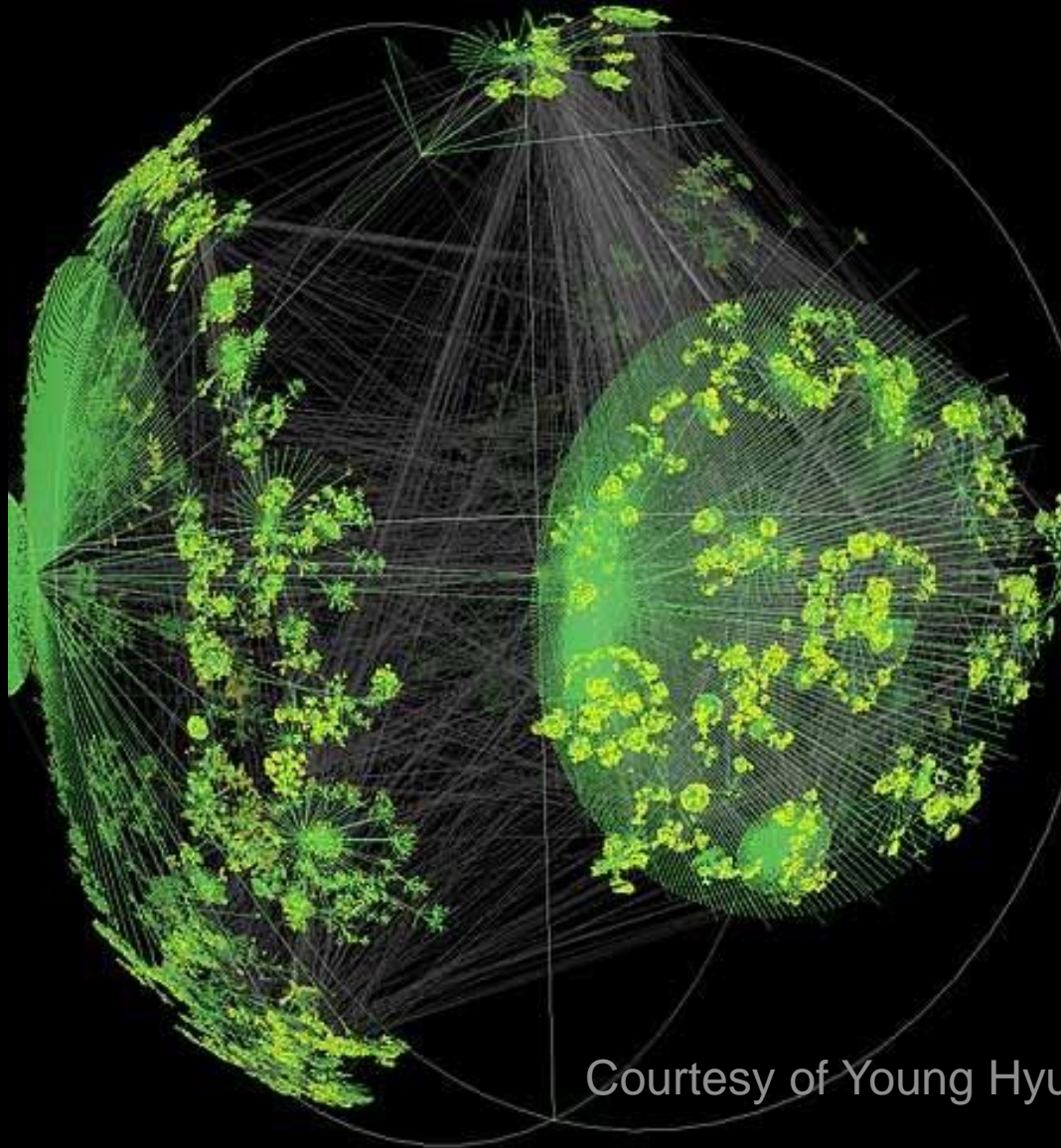
This course is about what the **NETWORKS** we interact with in our lives “look” like

... how they “work”

... and how to exploit them!

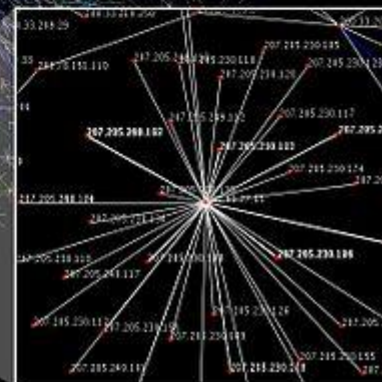
“networks” not “networking”

The web



Courtesy of Young Hyun, CAIDA

The image displays a massive, intricate network graph, likely representing the Internet's structure. The graph is composed of numerous nodes (represented as small, bright, multi-colored stars) and a dense web of edges (thin, colored lines). The colors of the nodes and edges vary, including shades of blue, green, yellow, and red, possibly indicating different types of connections or geographical regions. The overall shape is roughly circular, with a high density of connections in the center and more sparse connections towards the periphery. In the bottom right corner, there is a zoomed-in inset showing a specific cluster of nodes and edges, highlighting the complex, multi-layered nature of the network. The inset shows a central node with many radiating edges, each connecting to other nodes, some of which are further connected to each other, forming a dense, interconnected sub-network.



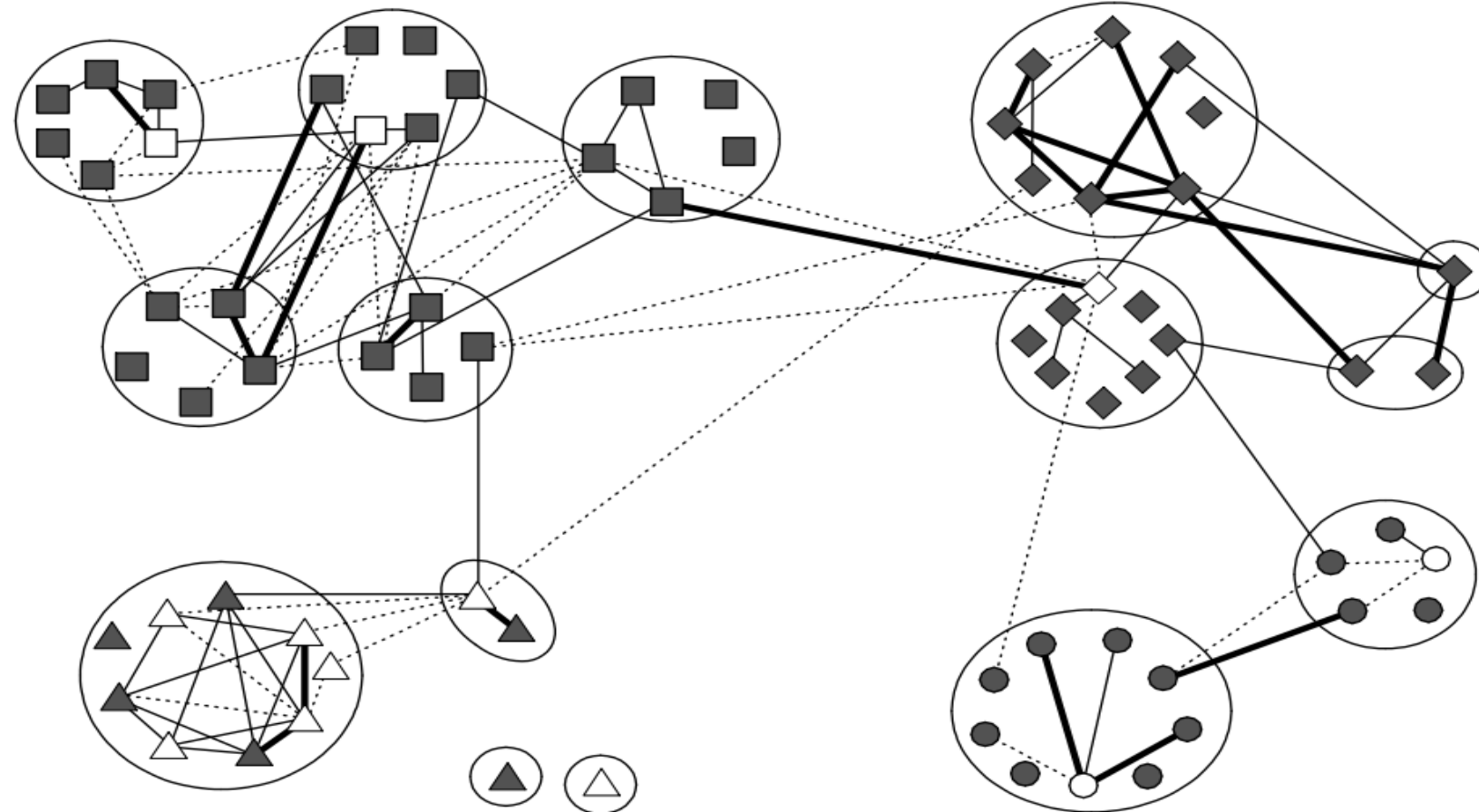




twitter

Department 1

Department 2

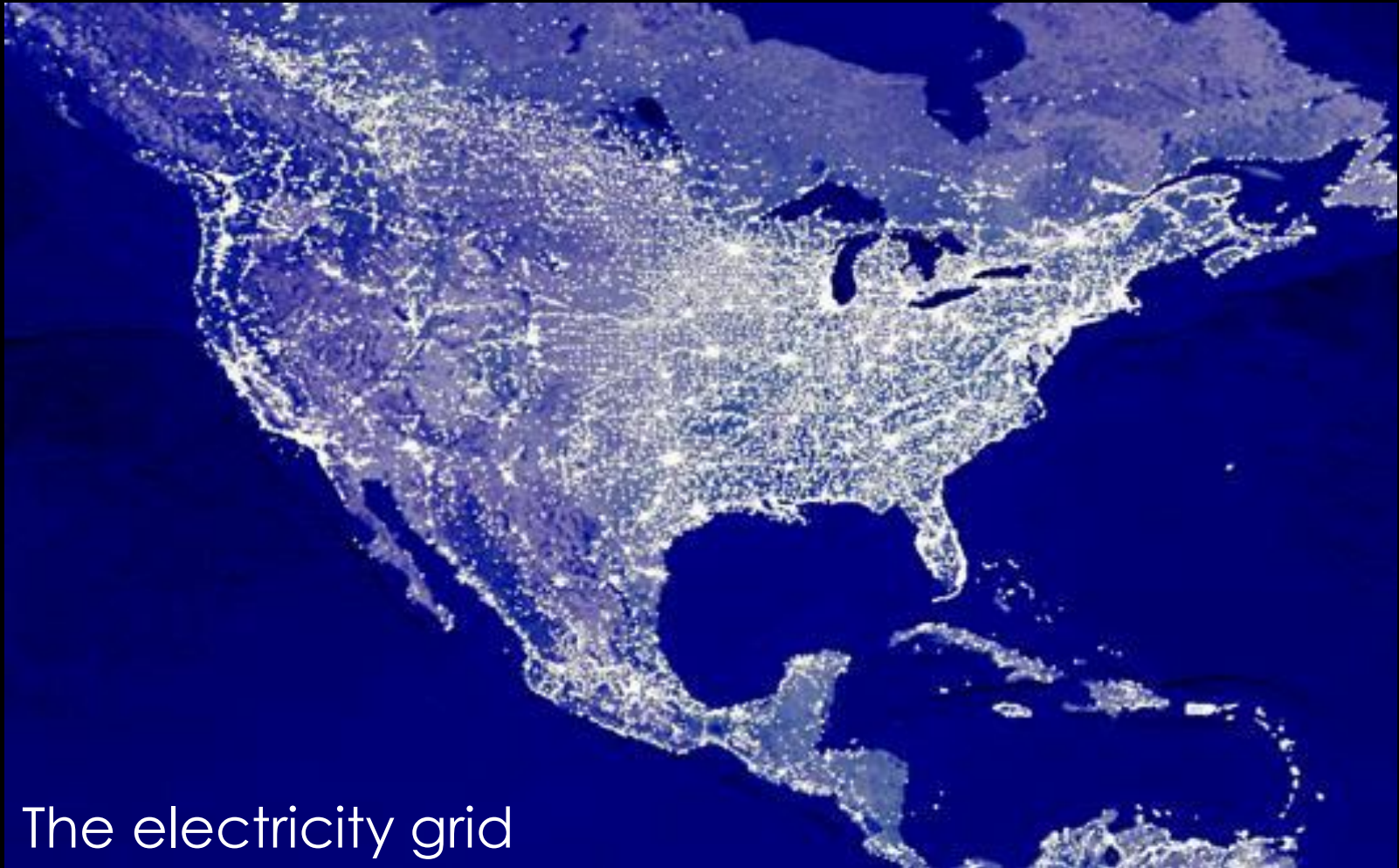


Department 3

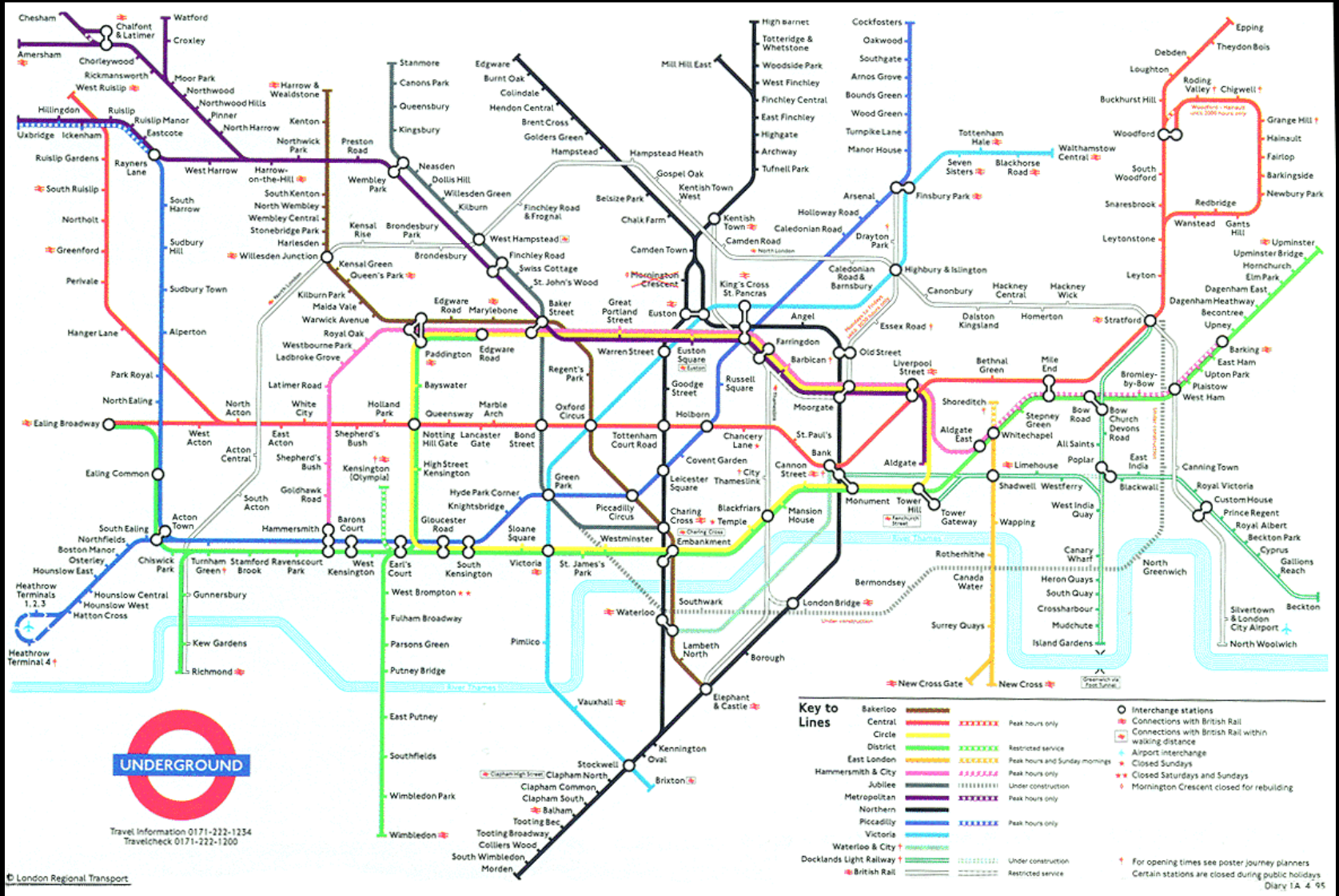
Department 4

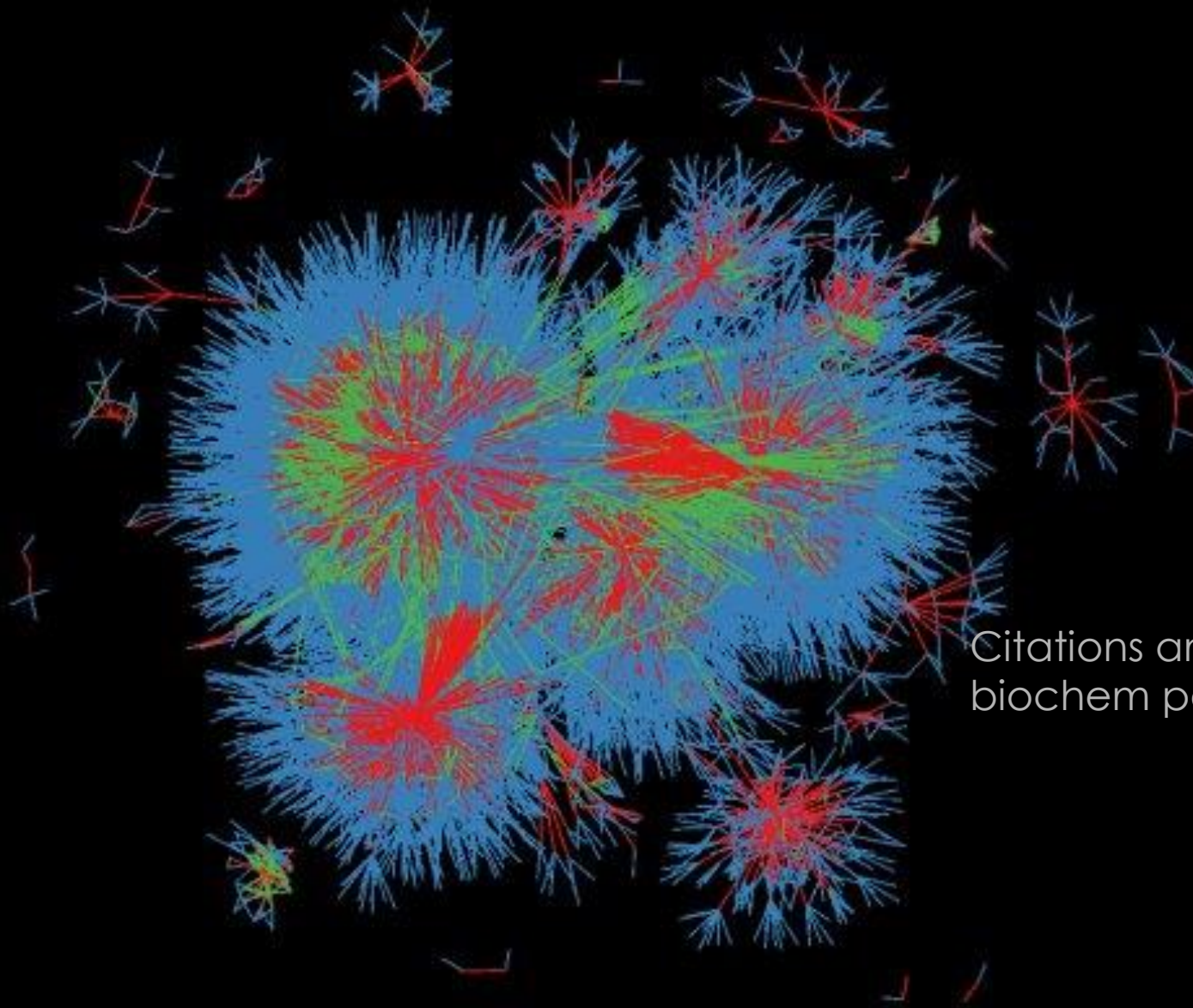


(from Leeat Yariv)

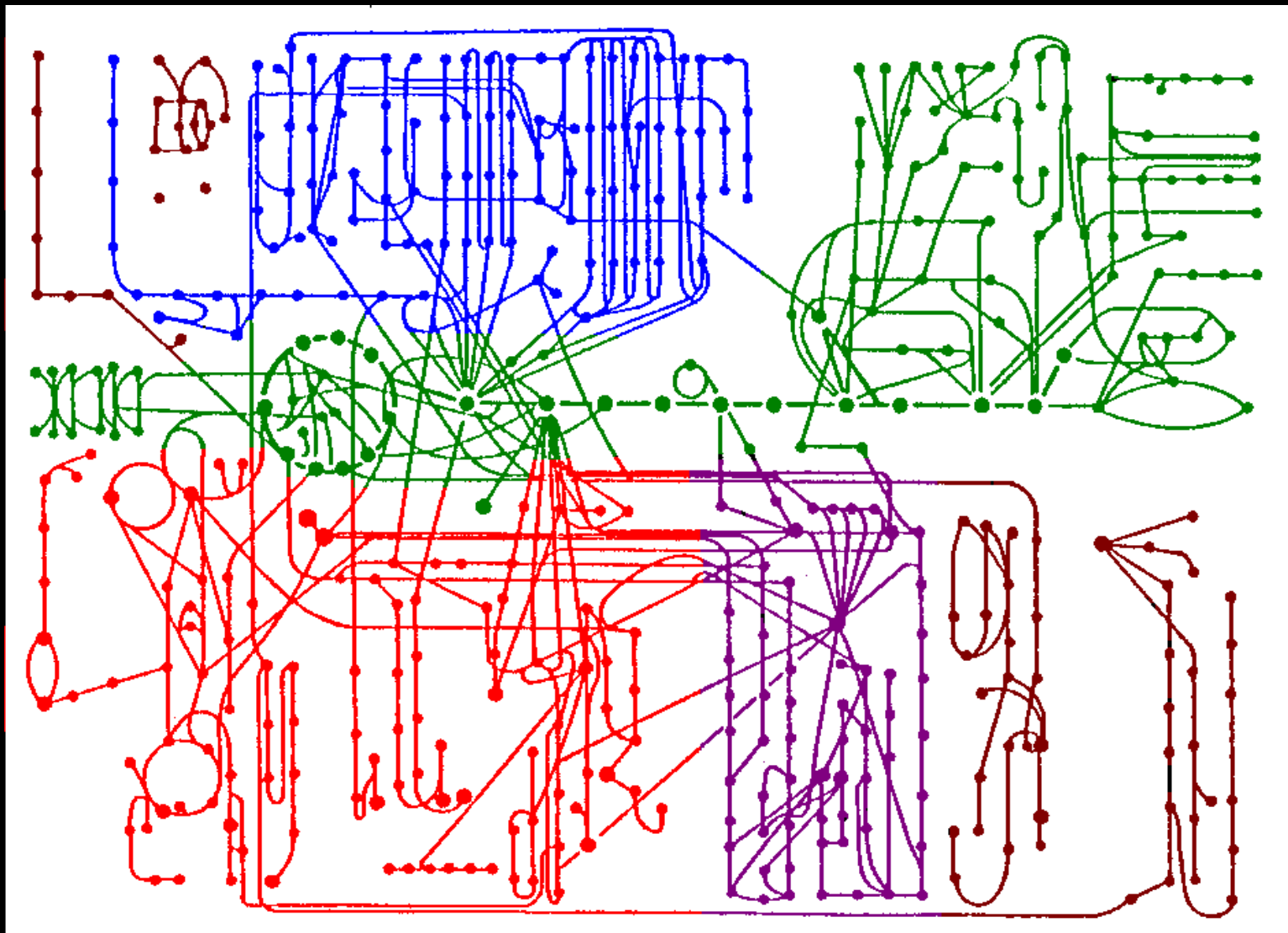


The electricity grid





Citations among
biochem patents



Biochemical
pathways of
malaria

What structural properties do networks have?
...what causes these properties to emerge?
...why do many networks look so similar?

These properties underlie the design of
many modern tech companies & startups!

You use Google, Facebook, etc every day,
BUT you probably know very little about
how they work...

...these are the companies you want a job from!

...the ideas behind these companies are where
the modern “networks” research problems are!

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What goes into data centers?
How do we build applications for them?



Google's Oregon data center
A 1.2 million core warehouse-sized computer

How does Facebook exploit its knowledge of the social network?

The screenshot shows a Facebook profile for Adam Wierman. The left sidebar contains navigation links: FAVORITES (News Feed, Messages, Events, Photos), ADS (Ads Manager), PAGES (The ideas behind the Web, Pages Feed, Like Pages), GROUPS (Next Year's Our Year, Carnegie Mellon Alumni, Carnegie Mellon Los..., IEEE STC on Sustain..., Create Group...), APPS (App Center, Games Feed, Music, Notes, Links, Pokes, Course Finder), and MORE. The main content area shows a status update from Adam Wierman asking "How are you doing, Adam?". Below this is a post from Fred Zhao liking Professor Dalves's School of Pedantry. Further down is a link shared by Frank Pfenning titled "Press Release: Frank Pfenning Named Head of Carnegie Mellon's Computer Science Department -Carnegie." The right sidebar, highlighted by a red box, contains sponsored content and ads: Alan Rutledge's birthday, Create Event, 1 request from Linda Höglund, Sponsored section with Fred Zhao liking Professor Dalves's School of Pedantry, Professor Dalves's School of Pedantry ad, Do You Dream in Code? ad, Love the Steelers? ad, Professors Travel Free ad, and Ironman Lake Placid ad.

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Adam Wierman

Update Status Add Photos/Video

How are you doing, Adam?

Fred Zhao likes Professor Dalves's School of Pedantry.

Professor Dalves's School of Pedantry Teacher 222 likes

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Frank Pfenning shared a link.

Press Release: Frank Pfenning Named Head of Carnegie Mellon's Computer Science Department -Carnegie. www.cmu.edu Contact: Byron Spice / 412-268-9068 /

Like · Comment · Share · 2 hours ago ·

Luis von Ahn, Vyas Sekar, Aaron Roth and 54 others like this.

1 share

View all 22 comments

Guy Lebanon congratulations 27 minutes ago · Like

Arbab Basu Go Frank!! Happy new year 😊 25 minutes ago · Like

Eva Funderburgh Hollis Congratulations! 14 minutes ago via mobile · Like

Tim Andrianoff CSD is in good hands. Do your best! 6 minutes ago via mobile · Like

Write a comment...

Alan Rutledge's birthday is today

Create Event

1 request from Linda Höglund

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Fred Zhao likes Professor Dalves's School of Pedantry.

Professor Dalves's School of Pedantry Like

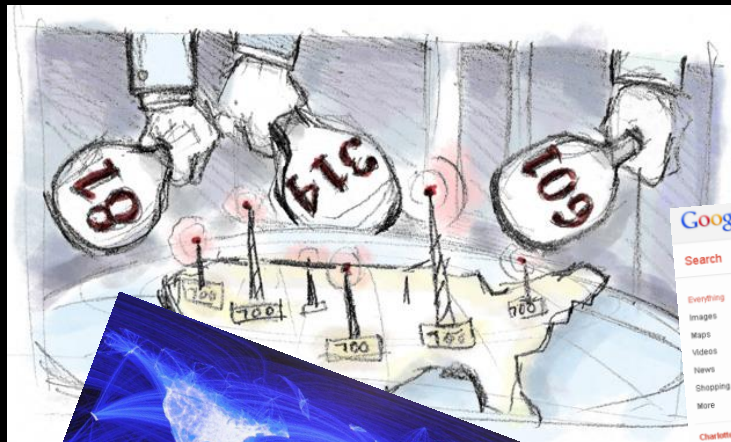
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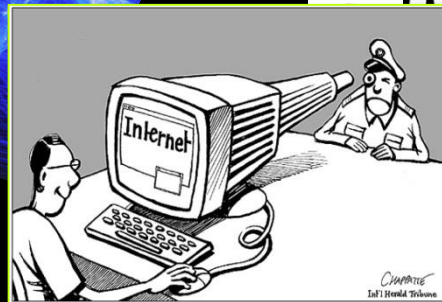
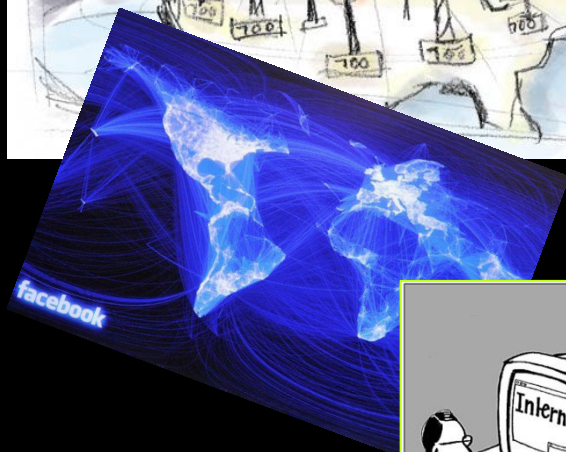
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You can't talk about networking without thinking about economics anymore...



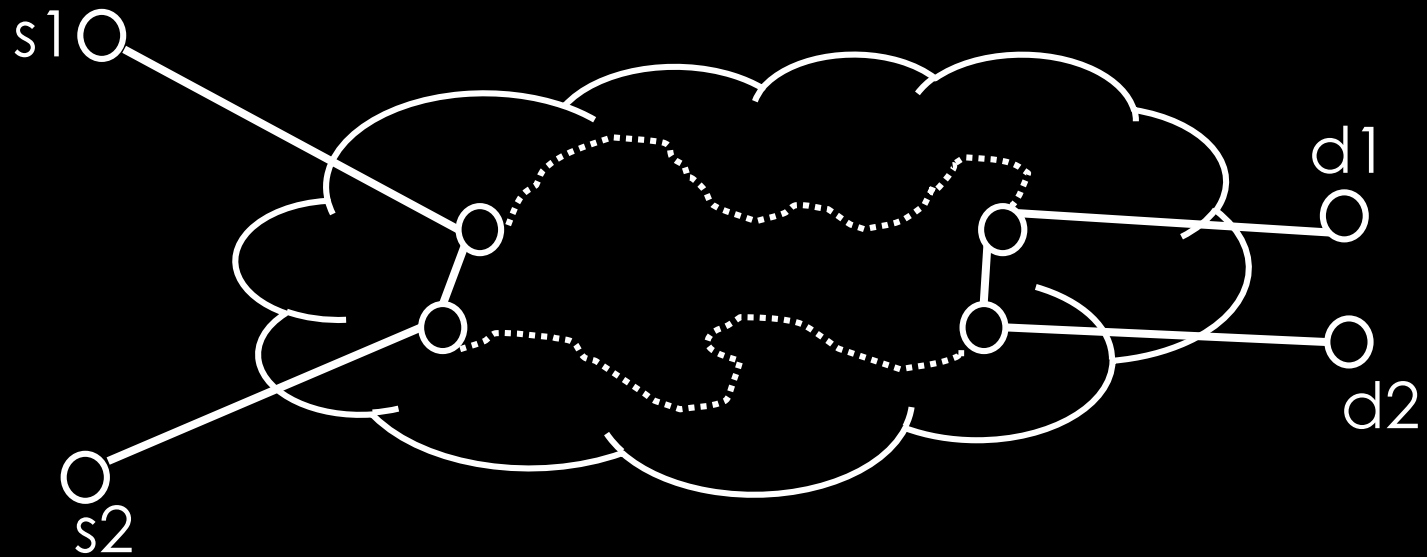
Invented at Caltech
(sorry!)



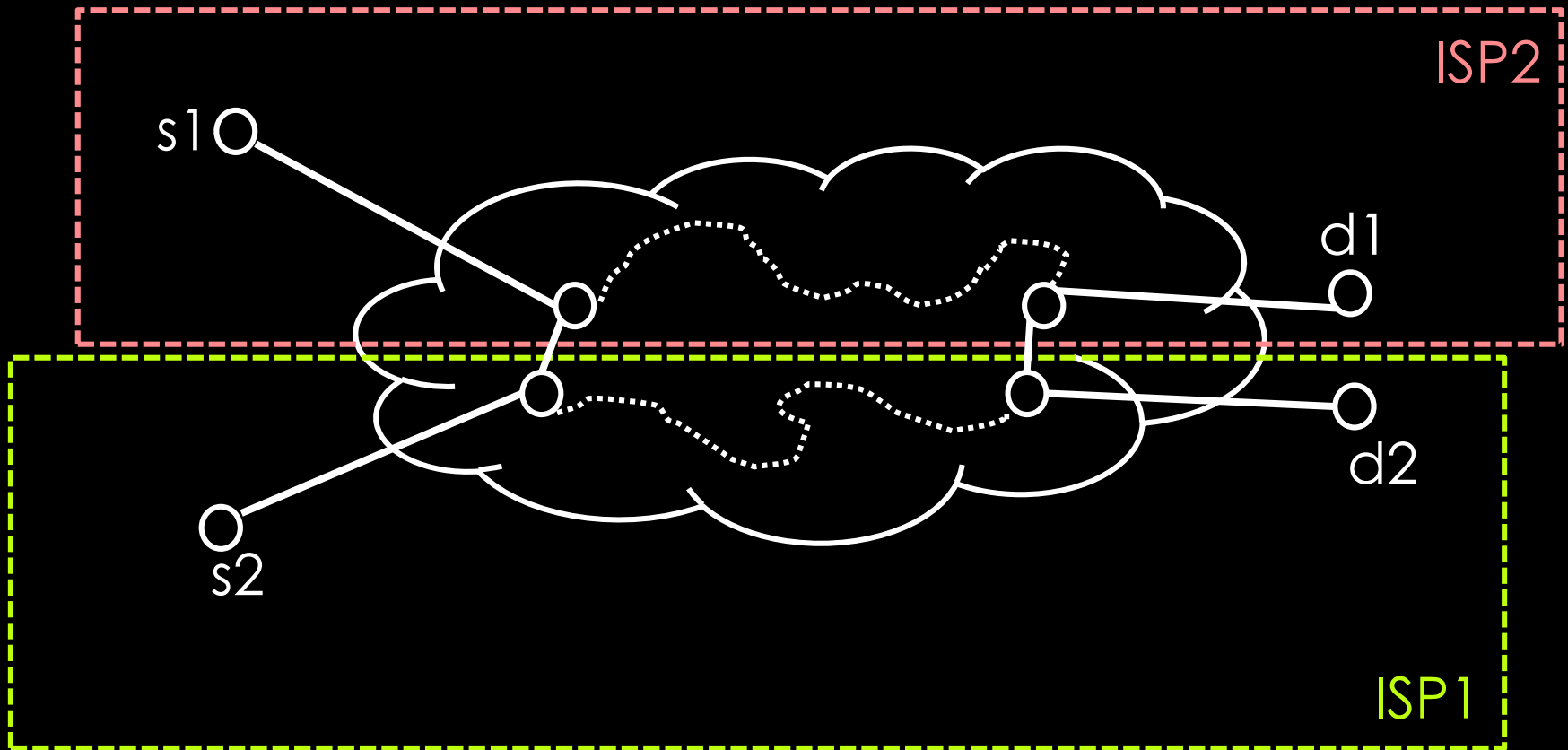
NET NEUTRALITY
ALL BITS ARE CREATED EQUAL
It's not just a good idea,
It ought to be the LAW.

...all these others have Caltech roots too!

How do ISPs make routing decisions?



How do ISPs make routing decisions?





Many startups exploit properties such as network formation, heavy-tails, auctions, centrality, virality, etc. that we will study in this class.

COURSE OUTLINE

Understanding network structure

- Universal properties of networks
- What causes these properties?

Exploiting network structure

- How search works
- Virality & epidemics

Economics and networks

- Routing & ISP games
- Ad auctions

KEY GOAL:

Mix “theory” and “practice” throughout

This is a unique course

... that comes with pluses and minuses

- + modern material
- + can't take a course like this anywhere else
- + topics chosen to match research & industry focus
- + you have input into forming the course

- new material is being developed on the fly each year
- assignments may have bugs
- textbook only covers pieces of what I'll teach

WARNING:

This course...

- covers challenging material
- has time consuming homeworks & mini-projects
- requires you to both program & prove theorems

Administrivia

The staff

Professor

→ Adam Wierman

TAs

→ Yu Su (lead)

→ Joon Hee Lee

→ Catherine Ma

→ Rachael Morton

→ Carly Robson

→ Irene Wang

Writing Support

→ Christina Burch

We'll be guinea pigs this term!

The lectures

Tue & Thu 10:30-noon

...check Piazza for topics and lectures that I will miss due to travel

Please attend lectures... The class works much better if everyone attends and interacts!

Until this year we started at 9:30, so you're lucky!

Office hours



TAs: Tue & Wed 7-9pm

Adam: Thu after class

Please attend and work on your homework there!
Don't wait until you have questions before coming...

The course webpage

(CMS/CS/EE 144) Networks: Structure & Economics

Course details

The course meets TR 10:30-12 in Annenberg 105. **The first lecture will be on Jan 4, 2018.**

The course will be managed using Piazza. All communication will happen and all materials will be posted through <https://piazza.com/caltech/winter2018/cmscsee144/home>. Email Adam if you have problems enrolling yourself at the site.

Course Description

Social networks, the web, and the internet are an essential parts of our lives and we all depend on them every day, but do you really know what makes them work? This course studies the "big" ideas behind our networked lives. Things like, what do networks actually look like (and why do they all look so similar)? How do search engines work? Why do memes spread the way they do? How does web advertising work? For all these questions and more, the course will provide a mixture of both mathematical analysis and hands-on labs. *This course can be combined with CS/EE 145 and CS 142 or CS/EE 143 to satisfy the project requirement for CS undergraduate degree, but CS/EE 143 and CS 141a are not required prerequisites. The course assumes students are comfortable with graph theory, probability, and basic programming.*

Instructor

[Adam Wierman](mailto:adamw@caltech.edu), adamw@caltech.edu

The course webpage

CMS/CS/EE 144 ▾Q & AResourcesStatisticsManage Class

California Institute of Technology (Caltech) - Winter 2018
CMS/CS/EE 144: Networks: Structure & Economics
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Course InformationStaffResources

Description

Social networks, the web, and the internet are essential parts of our lives and we all depend on them every day, but do you really know what makes them work? This course studies the "big" ideas behind our networked lives. Things like, what do networks actually look like (and why do they all look seemingly look so similar)? How do search engines work? Why do memes spread the way they do? How does computational advertising work? For all these questions and more, the course will provide a mixture of both mathematical analysis and hands-on projects.

This course can be combined with a second networks course (CS 142 or CS/EE 143) and a networking project course (CS/EE 141, 145, or 147) in order to satisfy the project requirement for CS undergraduate degree, but CS/EE 142 and CS 143 are not required prerequisites. The course assumes students are comfortable with graph theory, probability, and basic programming.

General Information

Course Details

We will meet weekly on TR 10:30-12 in Annenberg 105.

Professor

Adam Wierman

Teaching Assistants

Joon Hee Lee
Catherine Ma
Rachael Morton
Carly Robison
Yu Su
Irene Wang

Announcements

Welcome to 144!
12/22/17 12:13 PM
Welcome to 144! This is now the 8th year I've taught 144, but the course is still changing each year and there are still a few new things that we're incorporating this year for the first time. In particular, we're attempting to "upgrade" the pandemaniac and clickmaniac mini-projects and we're using a new approach for embedding writing/communication education into courses using the writing center. So, I'm looking forward to the term!

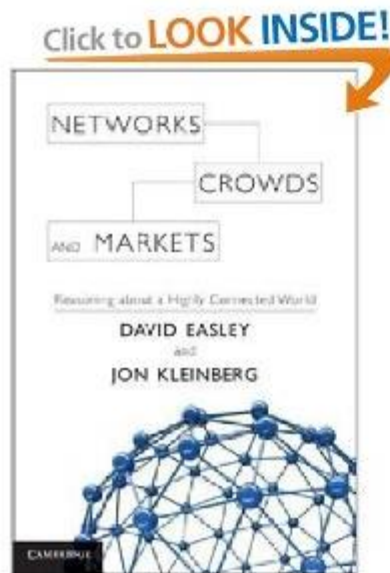
Most of the information that is typically in a syllabus is posted under the course Resources section of Piazza at <https://piazza.com/caltech/winter2018/cmscsee144/home>, so be sure to read that. A few of the more important notes are the following:

We'll be using Piazza for all course-related communication. As you can see, Piazza is sort of a cross between a course management tool and a Q&A service. I'll be posting all the course resources here, but that's not the main reason to use Piazza. The main reason is the Q&A. I hope that you quickly get used to checking Piazza frequently and posting questions here about lectures, homework, policies, etc. Also, I hope that you quickly get used to posting answers to each other's questions too!

I'll be trying a new approach to collaboration on the HWs this year. Each homework will include "collaboration" and "no-collaboration" problems. In collaboration problems you can work with your peers and TAs, but you

"there's an app for that"

The textbook



Networks, Crowds, and Markets: Reasoning About a Highly Connected World [Hardcover]

[David Easley](#) (Author), [Jon Kleinberg](#) (Author)

★★★★★ (2 customer reviews)

Like (3)

List Price: ~~\$50.00~~

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29 new from **\$40.40** **16 used** from **\$34.93**

- > You can get a pdf copy if you don't want to buy it
- > I will also post pdfs of my notes on piazza

Useful background

Basic Probability

Basic Graph Theory

Basic Game Theory (not required)

Programming experience (python)



We will have “bonus” lectures to refresh/teach these.

Probability refresher will be scheduled for next week...check Piazza

Your grade

Homeworks & mini-projects – 65%

Quizzes – 10%

Blog post – 5%

Project proposal – 10%

Project plan – 10%

** I reserve the right to add a final and adjust percentages accordingly

Your grade

Homeworks & mini-projects – 65%

Quizzes – 10%

Blog post – 5%

Project proposal – 10%

Project plan – 10%

Homeworks will mix theory and practice.

They will hopefully be challenging and fun.

→ The first is already up on Piazza and is due next Thu.

If you can do it in 6-9hrs, you have the necessary background.

Turn in electronically via moodle

→ Two types of problems: “Collaboration” and “No-collaboration”
(and then there will be no exam)

→ Come to office hours!

→ Mini-projects this year: rankmaniac, pandemaniac, clickmaniac

Your grade

Homeworks & mini-projects – 65%

Quizzes – 10%

Blog post – 5%

Project proposal – 10%

Project plan – 10%

We will have unannounced in-class quizzes 5-10 times during the term. These will be easy, so I do not expect you to study, they will be meant only to verify your understanding of basic definitions in the class (and to give me feedback on what everyone is retaining from lectures).

-- 50% will be guaranteed just by being present for the quiz!

Your grade

Homeworks & mini-projects – 65%

Quizzes – 10%

Blog post – 5%

Project proposal – 10%

Project plan – 10%

We won't be doing a project, we'll just be preparing for the project in the third term. This prep has three phases:

- Blog: Everyone is required to post one short blog post during the term. See Piazza for details... These are useful in finding ideas for projects!
- Proposal: Describe three ideas in 1-2 pages in a public post on piazza so that you can get feedback from the class. You do this whether you're taking 141/145 or not.
- Plan: Describe your detailed plan for 145 in 5-10 pages. You do this whether you're taking 141/145 or not.

Your grade

Homeworks & mini-projects – 65%

Quizzes – 10%

Blog post – 5%

Project proposal – 10%

Project plan – 10%

I'm expecting lots of great ideas!

Over the past few years we've had, among other things,

-- a patent filed

-- a startup incorporated

-- a paper accepted to a conference

-- an idea "crushed" by facebook

Your grade

Homeworks & mini-projects – 65%

Quizzes – 10%

Blog post – 5%

Project proposal – 10%

Project plan – 10%

Any questions?

Things you should do TODAY!

- HW1 is out... Read it and get started!
- Consider coming to the “Probability Refresher”
- Blog post assignment is out... Start to read articles and think about blog posts

Course warmup...

The evolution and structure of the web



Does anyone know when the web was invented?

→ 1989

...but the ideas that led to the
web are from much earlier

The web is an implementation of an information network



A graph where nodes are pieces of information and edges link related pieces of information


What was new and exciting about the web?

The web is an implementation of an information network

This is what was
new & exciting



Information networks have
been used & studied for ages.
e.g. citation networks,
cross-refs in encyclopedias



1945



Vannevar Bush

As We May Think - The Atlantic (July 1945) - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www.theatlantic.com/doc/194507/bush

Internet Archive Wayback Machine - W... As We May Think - The Atlantic (...)

by *Vannevar Bush*

As We May Think

Director of Scientific Research and Development, Dr. Bush coordinated the activities of some six thousand scientists in the application of science to warfare. In the article, he holds up an incentive for scientists when the war ends: "The war has not been a scientist's war; it has been a war in which all have had a part. The scientists, burying their old professional competition in the demand of a common cause, have shared greatly and learned much. It has been exhilarating to work in effective partnership. Now, for many, this appears to be approaching an end. What are the scientists to do next?"

He urges that men of science should then turn to the task of making more accessible our bewildering store of knowledge. "Inventions have extended man's physical powers of his mind. Trip hammers that multiply the fists, microscopes that reveal the hidden, engines of destruction and detection are new results, but not the end of the road. Now, says Dr. Bush, instruments are at hand which, if properly used, will give access to and command over the inherited knowledge of the ages. The first objective of our scientists as war work. Like Emerson's famous address of 1837 on "The American Scholar," Dr. Bush calls for a new relationship between thinking man and the machine."

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his has not been a scientist's war; it has been a war in which all have had a part. The scientists, burying their old professional competition in the demand of a common cause, have shared greatly and learned much. It has been exhilarating to work in effective partnership. Now, for many, this appears to be approaching an end. What are the scientists to do next?

For the biologists, and particularly for the medical scientists, there can be little indecision, for their war has hardly required them to leave the old paths. Many indeed have been able to carry on their war research in their familiar peacetime laboratories. Their objectives remain much the same.

It is the physicists who have been thrown most violently off stride, who have left academic pursuits for the making of strange destructive gadgets, who have had to devise new methods

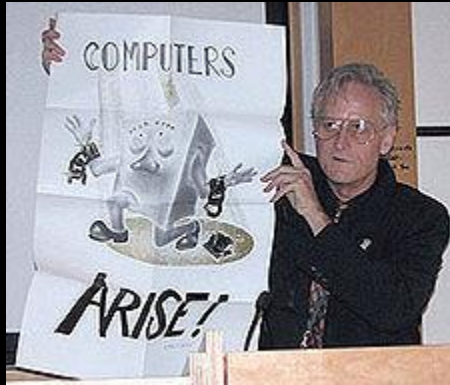
Done

1945



- 1) When we store information in books,
it is highly linear
 - 2) When we think, we use a
semantic network
- Technology will allow us to digitize
knowledge and mimic the
semantic network connections.

1965



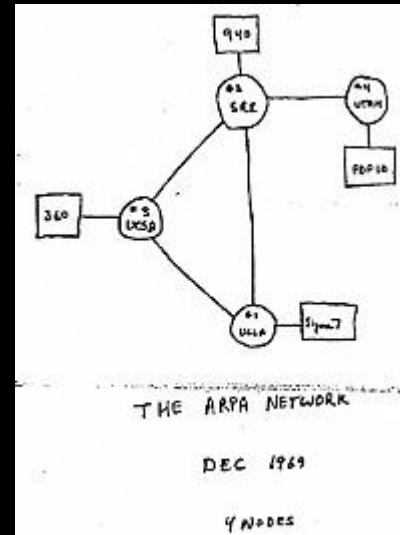
Ted Nelson coins the
term "hypertext"



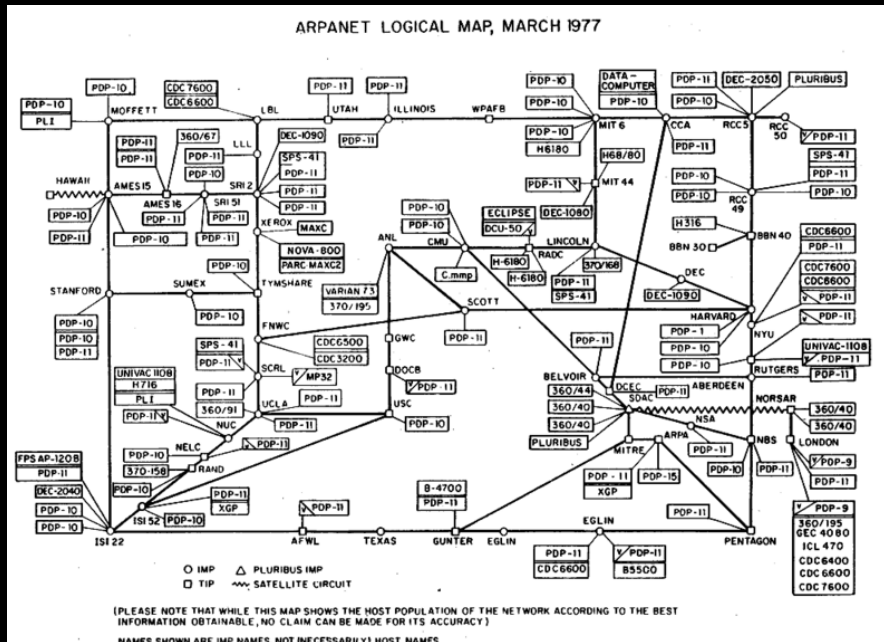
A computer assisted form of authoring
meant to replace the linear structure of
text with a network.

1969

1969→



←1977



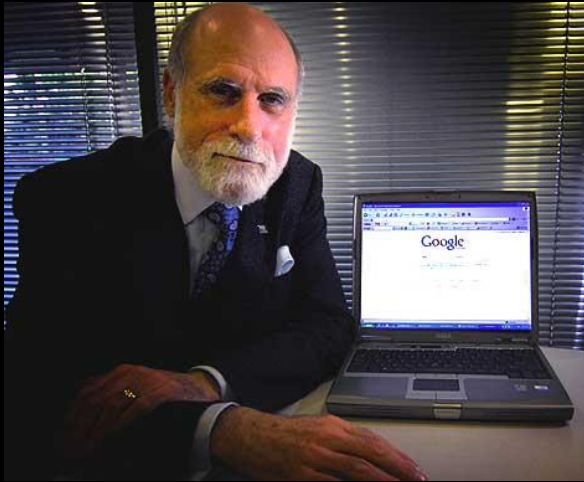
ARPANET begins...with a deployment at UCLA, Stanford, UCSB, and Utah

1971



Ray Tomlinson creates first email program

1974



TCP was defined by Vint Cerf & Bob Kahn

1978

TCP splits to become TCP & IP

1984



Paul Mockapetris introduces DNS

1989 – The web emerges



The original proposal of the WWW, HTMLized - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www.w3.org/History/1989/proposal.html

Information Management: A Proposal

Tim Berners-Lee, CERN
March 1989, May 1990

This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext system.

Overview

Many of the discussions of the future at CERN and the LHC era end with the question - "Yes, but how will we ever keep track of such a large project?" This proposal provides an answer to such questions. Firstly, it discusses the problem of information access at CERN. Then, it introduces the idea of linked information systems, and compares them with less flexible ways of finding information.

It then summarises my short experience with non-linear text systems known as "hypertext", describes what CERN needs from such a system, and what industry may provide. Finally, it suggests steps we should take to involve ourselves with hypertext now, so that individually and collectively we may understand what we are creating.

Find: broder Next Previous Highlight all Match case

Done

Tim Berners-Lee writes "Information Management: A proposal" at CERN

The goal was to improve project management by building a network interface for hypertext.

1989

The original proposal of the WWW, HTMLized - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www.w3.org/History/1989/proposal.html

The original proposal of the WWW, H...

What will the system look like?

Let us see what components a hypertext system at CERN must have. The only way in which sufficient flexibility can be incorporated is to separate the information storage software from the information display software, with a well defined interface between them. Given the requirement for network access, it is natural to let this clean interface coincide with the physical division between the user and the remote database machine.

This division also is important in order to allow the heterogeneity which is required at CERN (and would be a boon for the world in general).

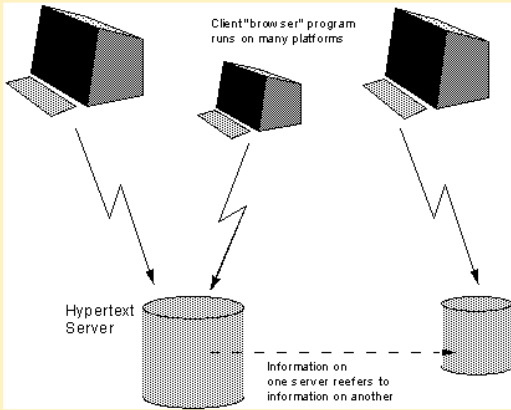
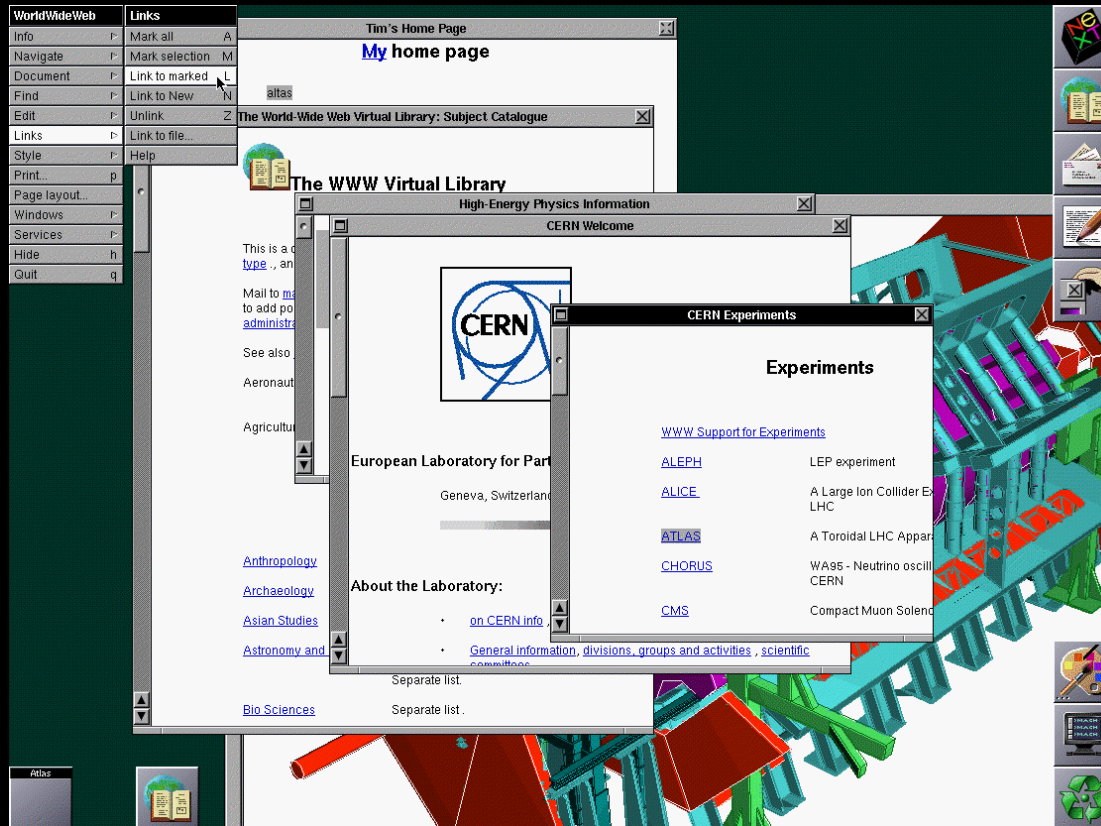


Fig 2. A client/server model for a distributed hypertext system.

Therefore, an important phase in the design of the system is to define this interface. After that, the development of various forms of display program and of database server can proceed in parallel. This will have been done well if many different information sources, past, present and future, can be mapped onto the definition, and if many different human interface programs can be written over the years to take advantage of new technology and standards.

Done

1990



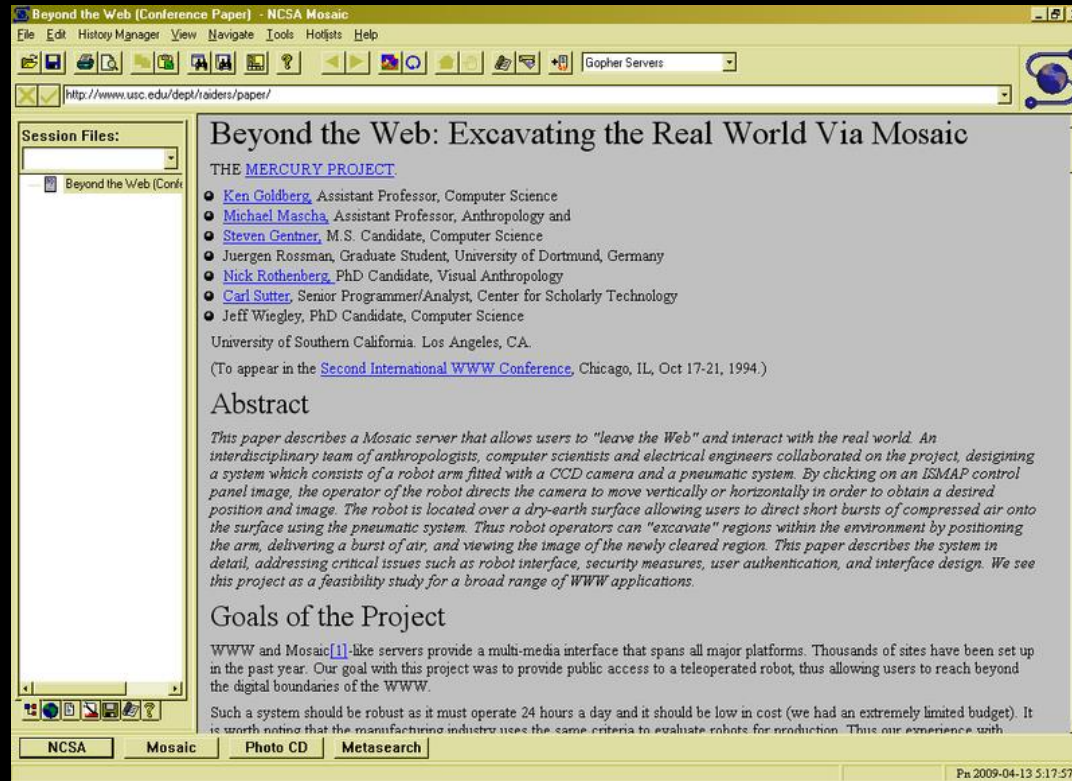
First browser developed at CERN

1991



First paper appears on the project at
Hypertext conference
→ Only accepted as a poster!

1993



Mosaic became the first graphical browser
(My first browser!)

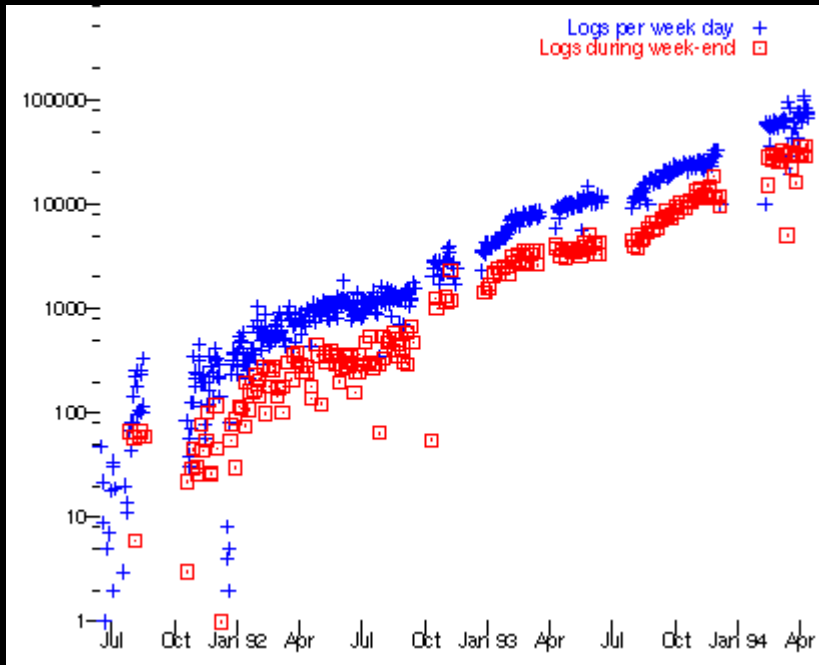
1993

CERN agrees to allow public use of
web protocol royalty-free!

1994

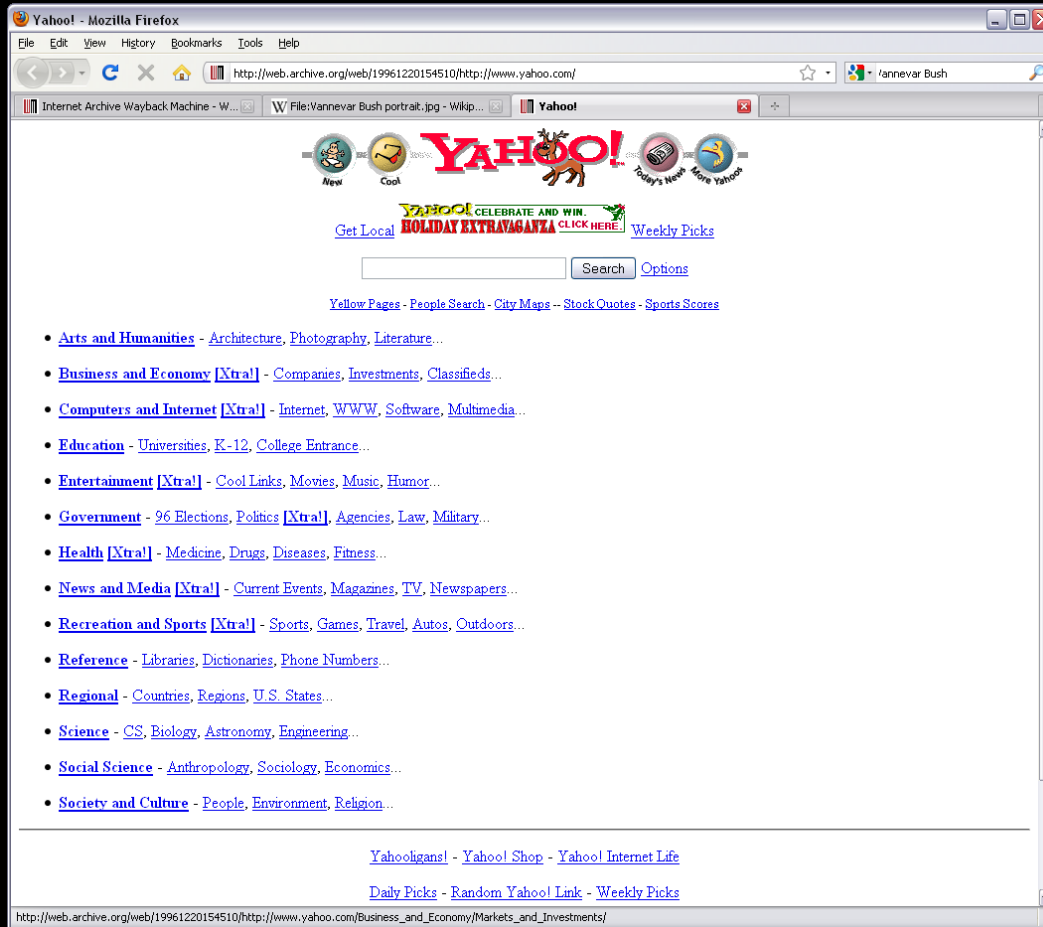
→ Mosaic goes commercial
(later becomes Netscape)

→ Traditional dialups (AOL, CompuServe, Prodigy) begin to sell Internet access.



Load on 1st
web server

1994

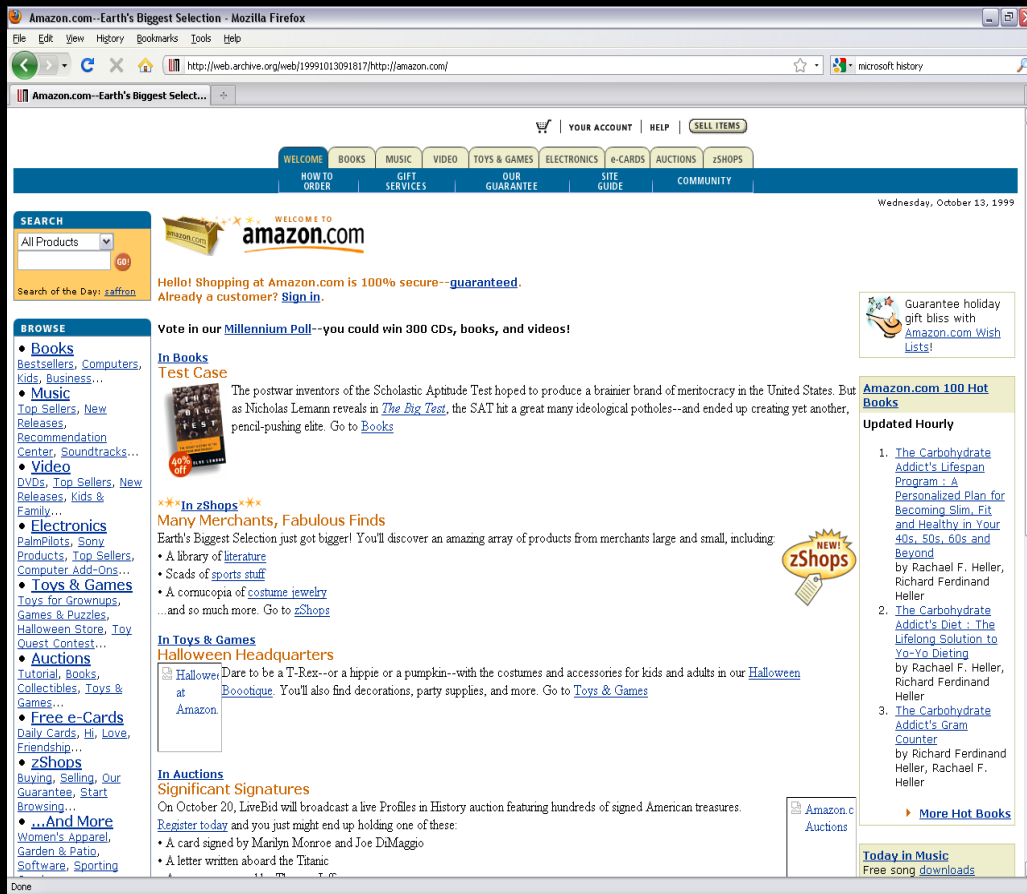


Yahoo
circa
1996

“Jerry’s Guide to the world wide web”
started ... it eventually became Yahoo

1995+

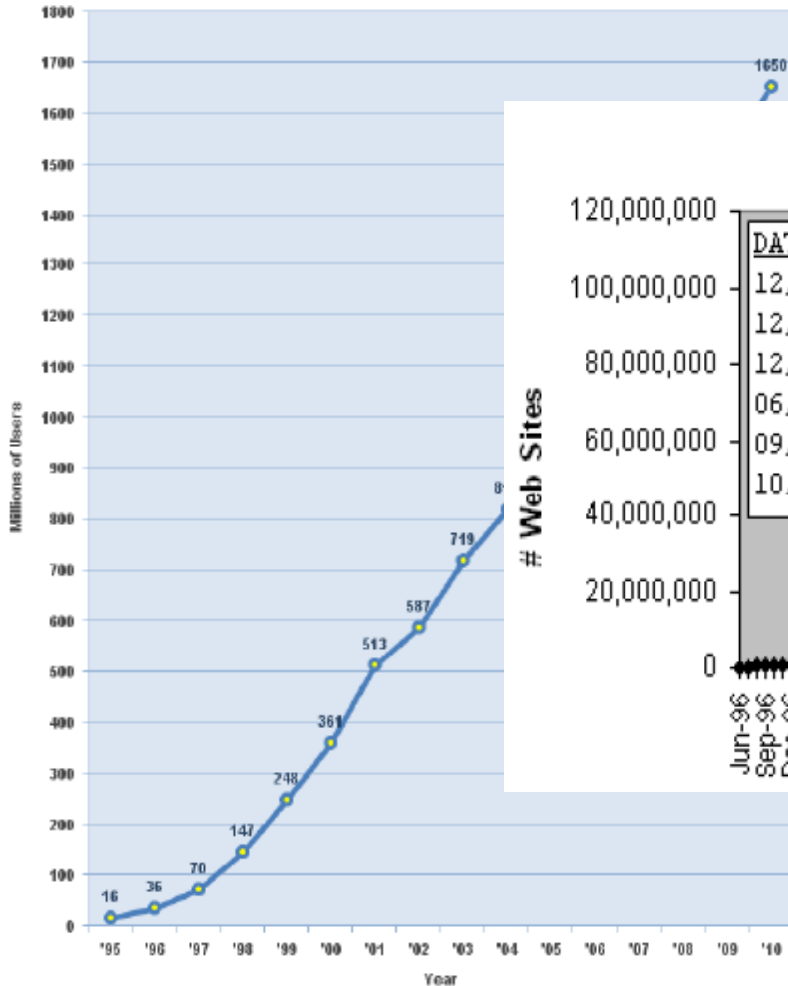
Amazon arrives and the commercialization of the web begins



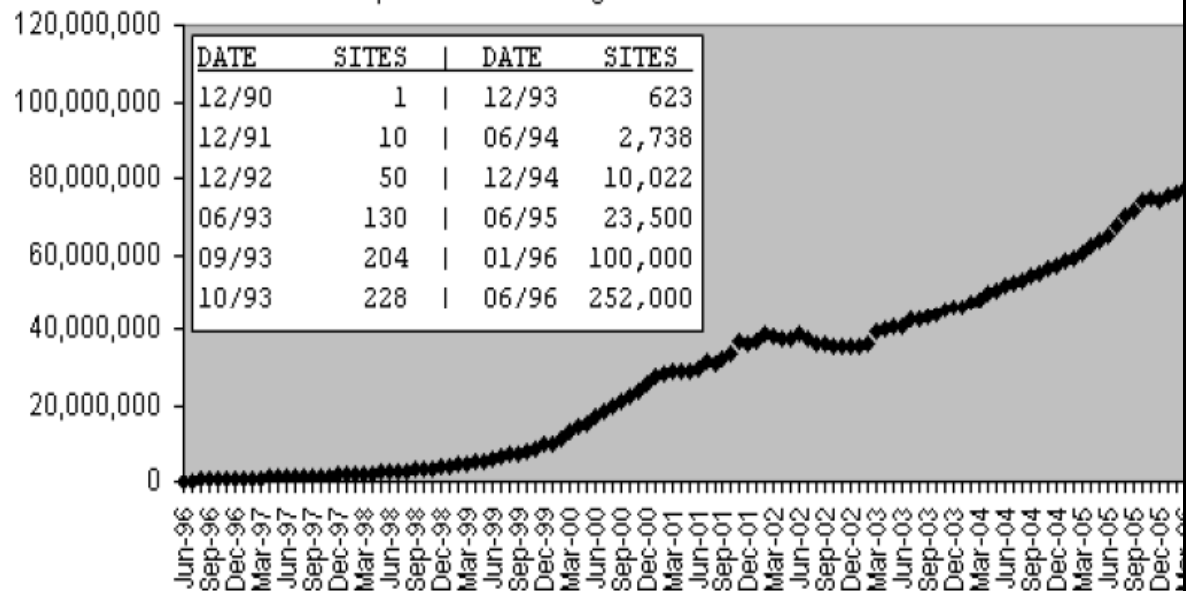
Amazon
circa
1999

The growth of the web

Internet Users in the World
Growth 1995 - 2010



Hobbes' Internet Timeline Copyright ©2006 Robert H Zakon
<http://www.zakon.org/robert/internet/timeline/>



The growth of the web

3 data points about the google index

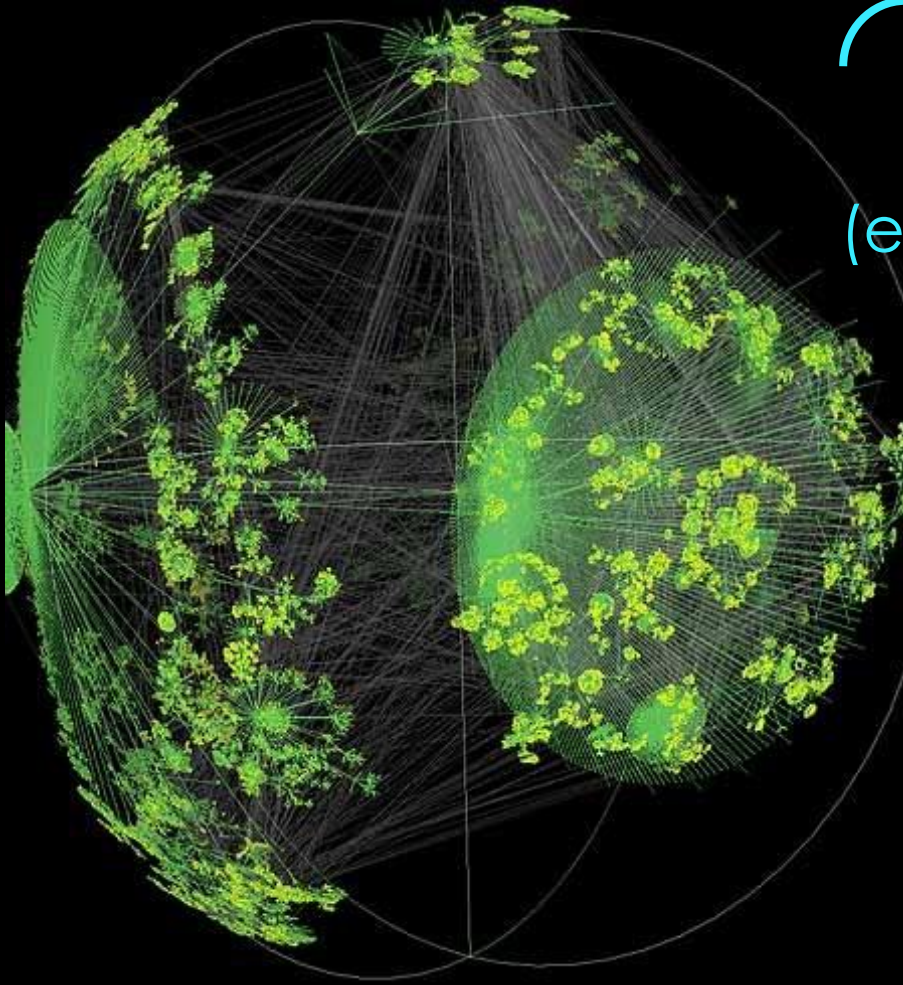
1998 → 28 million pages

2000 → 1 billion pages

2008 → 1 trillion pages

2014 → so big that it doesn't matter any more...

Our goal: What “structure” does the web graph have?



Nodes = pages

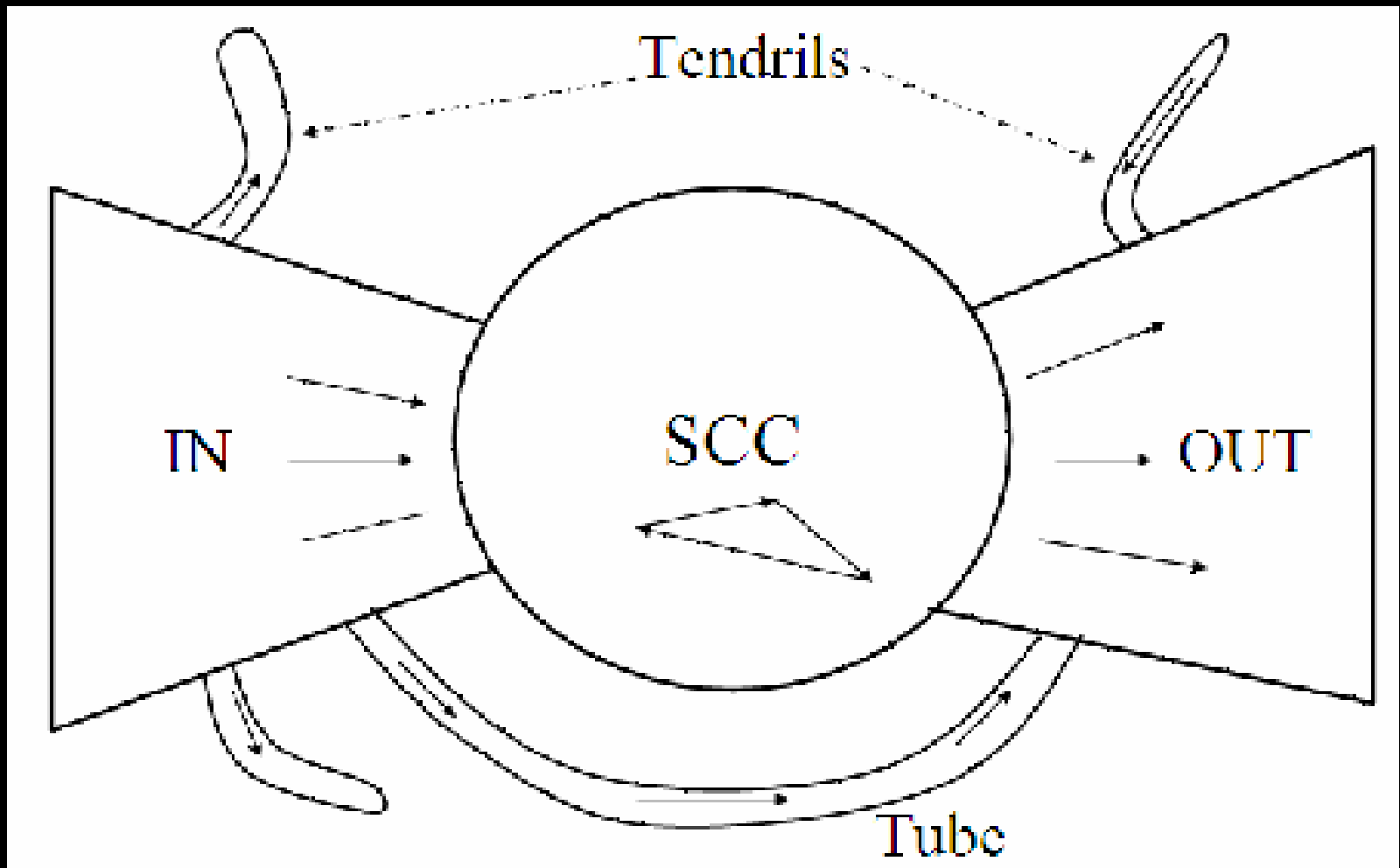
Edges = links
(edges are directed)

Our goal: What “structure” does the web graph have?

What properties should we look at?

Our goal: What “structure” does the web graph have?

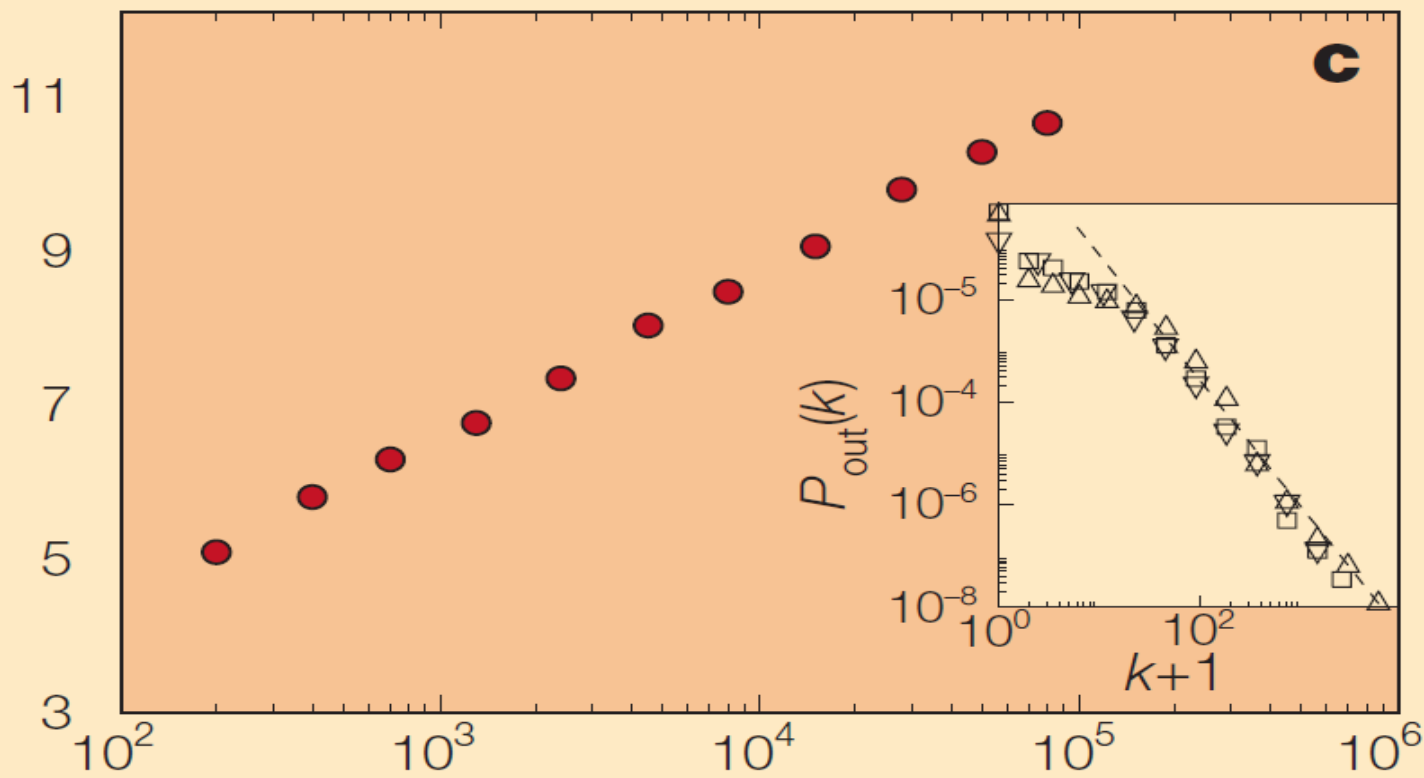
- 1) Connectivity?
- 2) Diameter?
- 3) Degree?
- 4) Clustering?



Our goal: What “structure” does the web graph have?

- 1) Connectivity? There is a giant connected component
- 2) Diameter?
- 3) Degree?
- 4) Clustering?

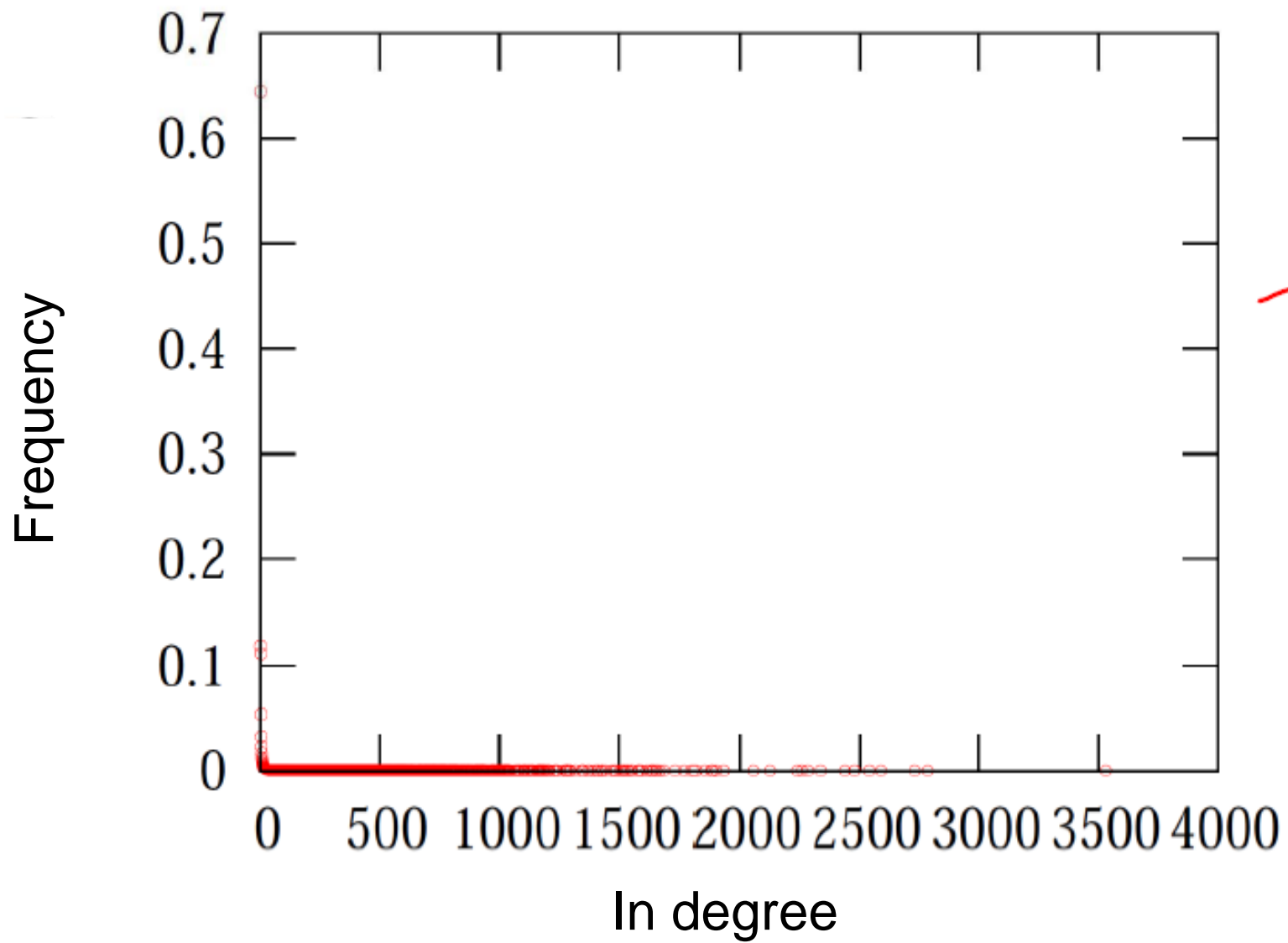
Average distance



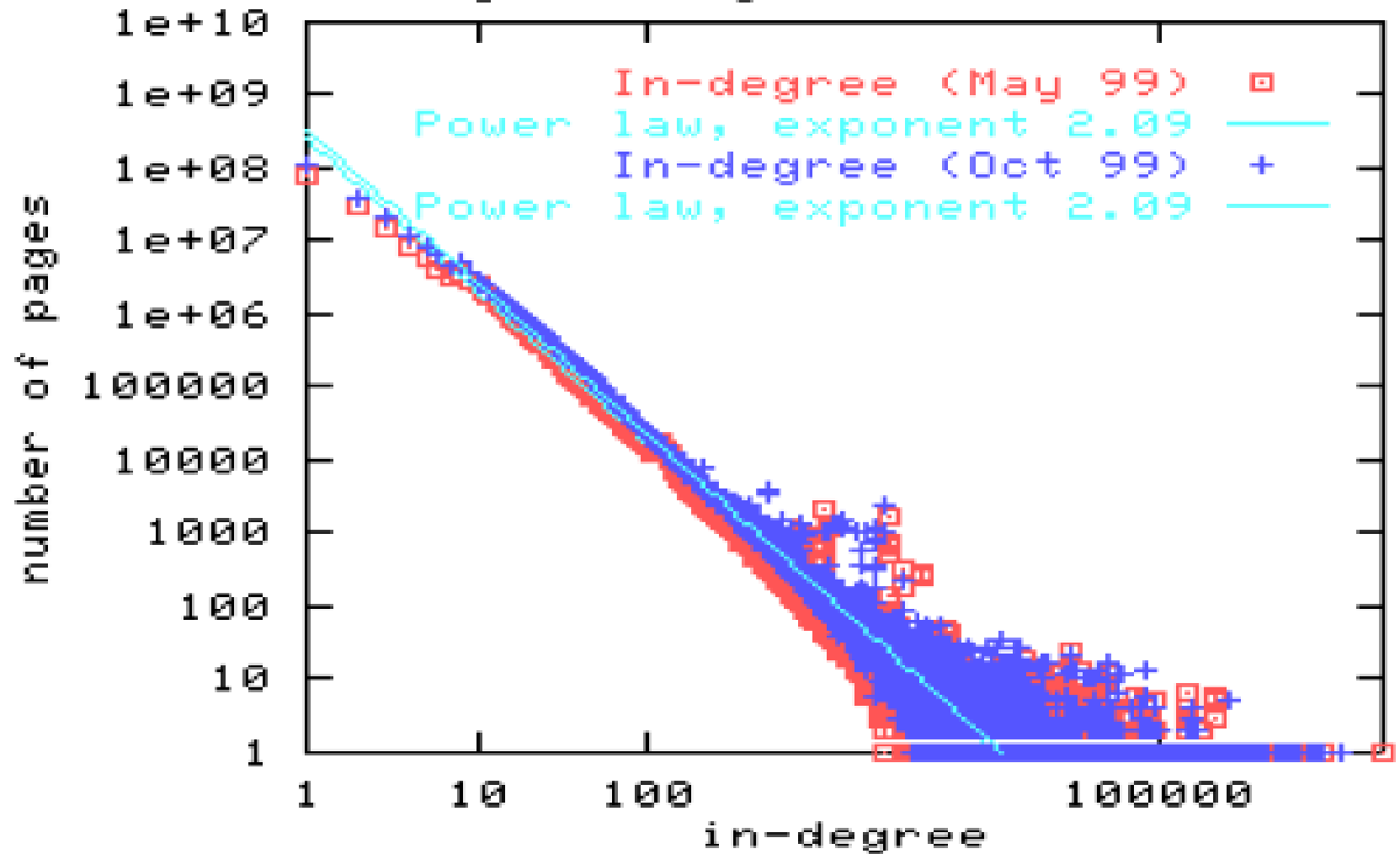
Size of graph

Our goal: What “structure” does the web graph have?

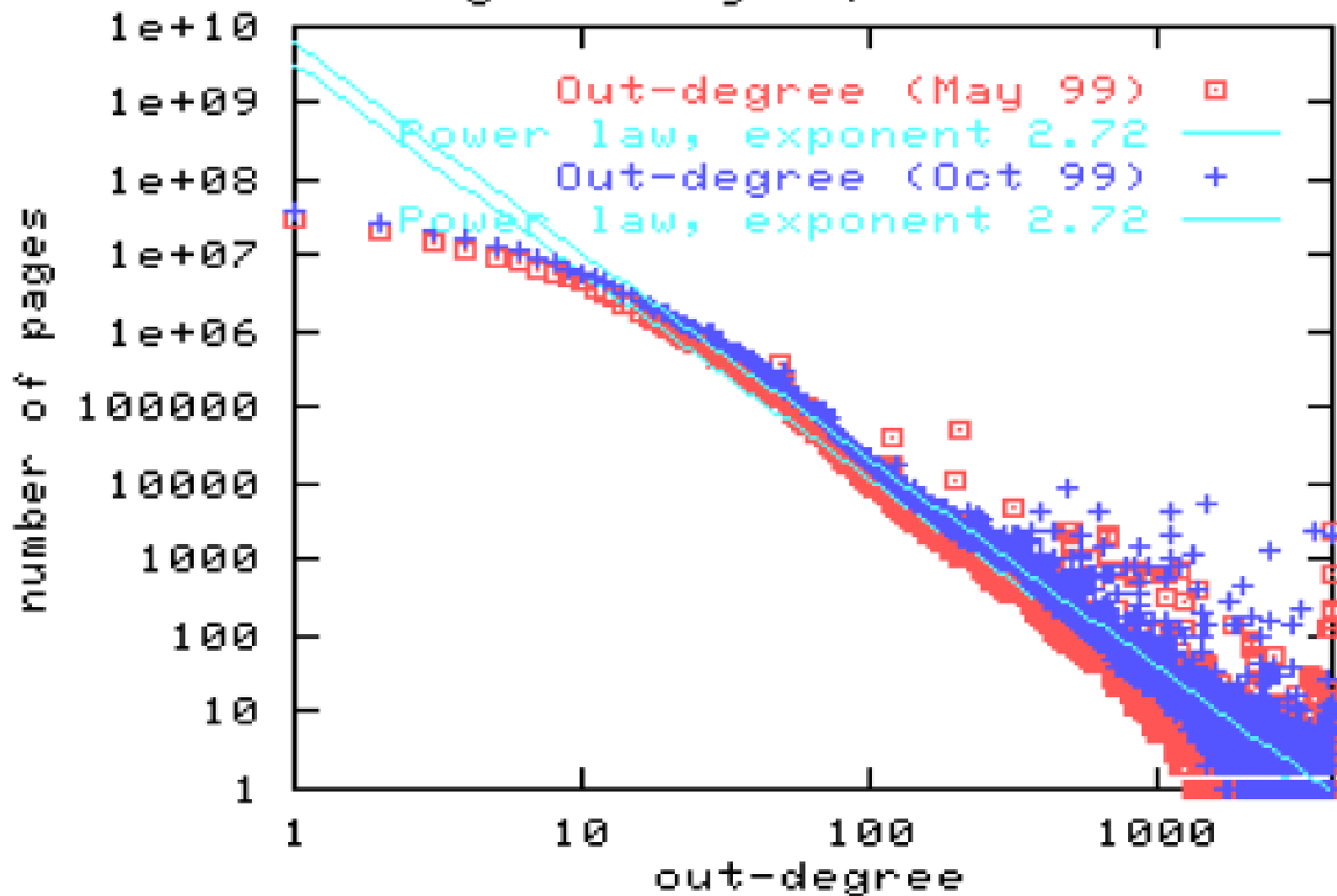
- 1) Connectivity? There is a giant connected component
- 2) Diameter? Small diameter
- 3) Degree?
- 4) Clustering?



In-degree (May 99, Oct 99) distr.



Out-degree (May 99, Oct 99) distr.

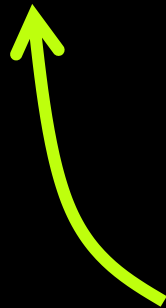


Our goal: What “structure” does the web graph have?

- 1) Connectivity? There is a giant connected component
- 2) Diameter? Small diameter
- 3) Degree? Heavy-tailed degree distribution
- 4) Clustering?

Our goal: What “structure” does the web graph have?

- 1) Connectivity? There is a giant connected component
- 2) Diameter? Small diameter
- 3) Degree? Heavy-tailed degree distribution
- 4) Clustering? Highly clustered



Next we'll see that these are “universal”