Introduction
Principles of System Design

COS 518: *Advanced Computer Systems*
Lecture 1

Mike Freedman

Goals of this course

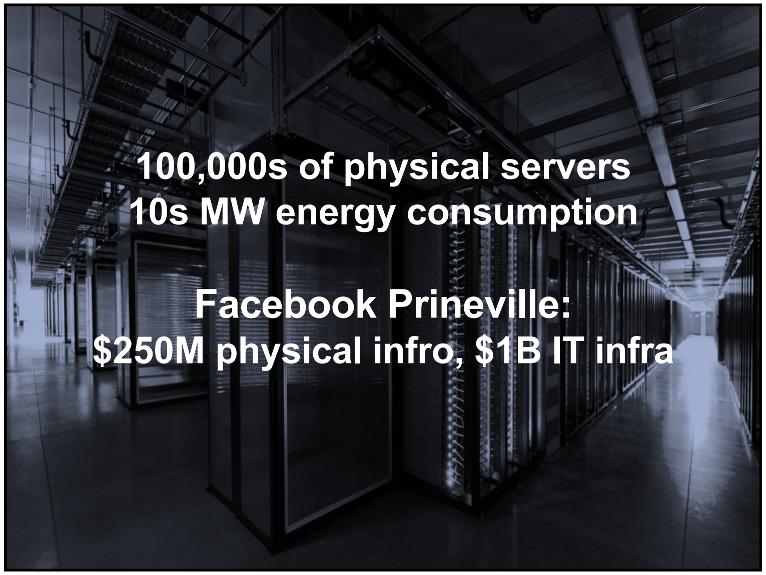
- Introduction to
  - Computer systems **principles**
  - Computer systems **research**
    - Historical and cutting-edge research
    - How “systems people” think
- Learn how to
  - **Read** and **evaluate** papers
  - **Give talks** and evaluate talks
  - **Perform basic** system design and programming
  - **Build and evaluate** systems

What is a system?

- **System**
  - Inside v. outside: defines interface with environment
  - A system achieves specific external behavior
  - A system has many components
- This class is about the design of **computer** systems
- Much of class will operate at the design level
  - Guarantees (semantics) exposed by components
  - Relationships of components
  - Internals of components that help structure

Backrub (Google) 1997

Google 2012



100,000s of physical servers
10s MW energy consumption

Facebook Prineville:
$250M physical infro, $1B IT infra

The central problem: Complexity

- Complexity's hard to define, but symptoms include:

1. Large number of **components**
2. Large number of **connections**
3. Irregular **structure**
4. No short description
5. Many people required to design or maintain

Course Organization

Learning the material

- Instructors
  - Professor Mike Freedman
  - TA Zhenyu Song
  - Office hours immediately after lecture or by appt
- Main Q&A forum: http://www.piazza.com/
- Optional textbooks
  - *Principles of Computer System Design*. Saltzer & Kaashoek
  - *Distributed Systems: Principles and Paradigms.* Tanenbaum & Van Steen
  - *Guide to Reliable Distributed Systems.* Birman.

Format of Course

- Introducing a subject
  - Lecture + occasional 1 background paper
  - Present lecture class *before* reading
- Current research results
  - Signup to read 1 of ~2 papers per class
  - Before class: Carefully read selected paper
  - Beginning of class (before presentations): answer a few questions about readings (“quizlet”)
  - During class: 1 person presents, others add to discussion

Course Project: Schedule

- Groups of 2 per project
- Project schedule
  - Team selection (2/15)
  - Project proposal (3/1)
  - Finalized project (3/15)
  - Interim project presentation (4/3)
  - Final project presentation (before 5/13)
  - Final project report (5/14, Dean’s Date)

Course Project: Options

- **Choice #1: Reproducibility**
  - Select paper from class (or paper on related topic)
  - Re-implement and carefully re-evaluate results
  - See detailed proposal instructions on webpage
- **Choice #2: Novelty** (less common)
  - Must be in area closely related to 518 topics
  - We will take a **narrow** view on what’s permissible
- Both approaches need working code, evaluation

Course Project: Process

- **Proposal selection process**
  - See website for detailed instructions
  - Requires research and evaluation plan
  - Submit plan via Piazza, get feedback
  - For “novelty” track, important to talk with us early
- **Final report**
  - Public blog-like post on design, eval, results
  - Source code published

Grading

- 15% paper presentation(s)
- 15% participation (in-class, Piazza)
- 20% in-class Q&A quizlets
- 50% project
  - 10% proposal
  - 40% final project

Organization of semester

- Introduction / Background
- Storage Systems
- Big Data Systems
- Applications

Storage Systems

- Consistency
- Consensus
- Transactions
- Database recovery and indexing
- Column Stores
- Modern storage technologies

Big Data Systems

- Distributed queuing & Kafka
- Batch processing & MapReduce
- Stream processing
- Approximate computing
- Scheduling
- Coding in systems

Applications

- Distributed Hash Tables (DHTs)
- Content Delivery Networks
- Secure Systems
- Blockchain and Decentralized Trust
- Computing on Small Devices

Principles of System Design

Systems challenges common to many fields

1. **Emergent properties (“surprises”)**
   - Properties not evident in **individual** components become clear when **combined** into a system
   - **Millennium bridge,** London example

Millennium bridge

- Small lateral movements of the bridge **causes** synchronized stepping, which **leads to** swaying
- Swaying **leads to** more forceful synchronized stepping, **leading to** more swaying
  - – Positive feedback loop!
- Nicknamed *Wobbly Bridge* after charity walk on Save the Children
- Closed for two years soon after opening for modifications to be made (**damping**)

Systems challenges common to many fields

1. Emergent properties (“surprises”)

2. **Propagation of effects**
   - – **Small/local** disruption → **large/systemic** effects
   - – Automobile design example (S & K)

Propagation of effects: Auto design

- **Want a better ride** so increase tire size
- Need larger trunk for larger spare tire space
- Need to move the back seat forward to accommodate larger trunk
- Need to make front seats thinner to accommodate reduced legroom in the back seats
- **Worse ride** than before

Systems challenges common to many fields

1. Emergent properties ("surprises")

2. Propagation of effects

3. **Incommensurate scaling**
   - Design for a smaller model may not scale

Galileo in 1638

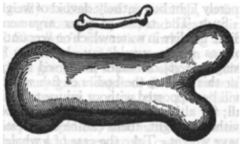


Fig. 27

> "To illustrate briefly, I have sketched a bone whose natural length has been increased three times and whose thickness has been multiplied until, for a correspondingly large animal, it would perform the same function which the small bone performs for its small animal…
>
> Thus a small dog could probably carry on his back two or three dogs of his own size; but I believe that a horse could not carry even one of his own size."
>
> —Dialog Concerning Two New Sciences, 2nd Day

Incommensurate scaling

- **Scaling a mouse into an elephant?**
  - Volume grows in proportion to O(x^3) where x is the linear measure
  - Bone strength grows in proportion to cross sectional area, O(x^2)
  - [Haldane, "On being the right size", 1928]

- Real elephant **requires** different skeletal arrangement than the mouse

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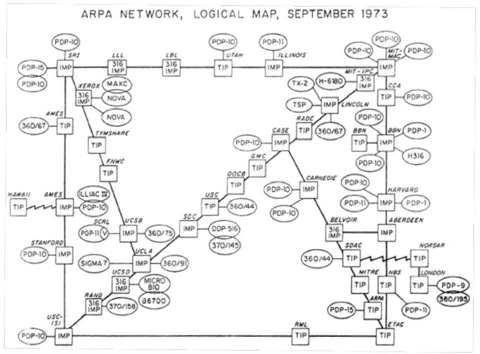
Incommensurate scaling: Scaling routing in the Internet

- Just **39 hosts** as the **ARPA net** back in **1973**

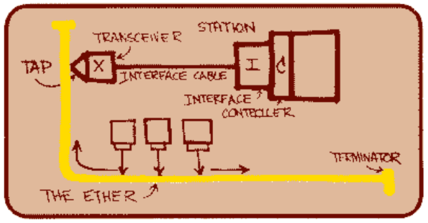


Incommensurate scaling:
Scaling routing in the Internet

- Total size of routing tables (for shortest paths): **O(n^2)**
- Today's Internet: Techniques to **cope with scale**
  - Hierarchical routing on network numbers
    - 32 bit address =16 bit network # and 16 bit host #
  - Limit # of hosts/network: Network address translation

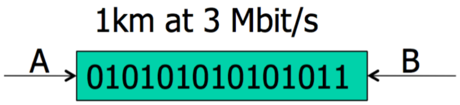
Incommensurate Scaling: Ethernet

- All computers share single cable
- Goal is reliable delivery
- **Listen-while-send** to avoid collisions



Will listen-while-send detect collisions?

- 1 km at 60% speed of light is 5 μs
  - **A** can send 15 bits before first bit arrives at **B**
- Thus **A** must keep sending for 2 × 5 μs
  - To detect collision if **B** sends when first bit arrives
- Thus, min packet size is 2 × 5 μs × 3 Mbit/s = 30 bits



From experimental Ethernet to standard

- Experimental Ethernet design: **3 Mbit/s**
  - Default header is 5 bytes = 40 bits
  - No problem with detecting collisions
- First Ethernet standard: **10 Mbit/s**
  - Must send for 2 × 20 μs = 400 bits
    - But header is just 112 bits
  - **Need for a minimum packet size!**
- **Solution: Pad packets** to at least 50 bytes

Systems challenges common to many fields

1. Emergent properties (“surprises”)
2. Propagation of effects
3. Incommensurate scaling
4. **Trade-offs**
   - Many design constraints present as trade-offs
   - Improving one aspect of a system diminishes performance elsewhere

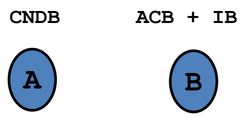
Binary classification trade-off

- Have a ***proxy signal*** that imperfectly captures **real signal of interest**
- **Example:** Household smoke detector

		Real categories	
		fire	no fire
Proxy categories	detector signals	TA: fire extinguished	FA: false alarm
	detector quiet	FR: house burns down	TR: all quiet

Sources of complexity

1. **Cascading and interacting requirements**
   - **Example:** Telephone system
     - Features: Call Forwarding, reverse billing (900 numbers), Call Number Delivery Blocking, Automatic Call Back, Itemized Billing
   - **A** calls **B, B** forwards to 900 number, who pays?



- A calls B, B is busy
- Once B done, B calls A
- A’s # appears on B’s bill

Interacting Features

- Each feature has a spec
- An interaction is bad if feature X breaks feature Y
- These bad interactions may be fixable…
  - But many interactions to consider: huge complexity
  - Perhaps more than n^2 interactions, *e.g.* triples
  - Cost of **thinking about / fixing interaction** gradually grows to dominate software costs
- Complexity is super-linear

Sources of complexity

1. Cascading and interacting requirements

2. **Maintaining high utilization of a scarce resource**
   - **Ex:** Single-track railroad line through long canyon
     - Use pullout and signal to allow bidirectional op
     - But now need careful scheduling
     - **Emergent property:** Train length < pullout length

Coping with complexity

1. **Modularity**
   - Divide system into ***modules,*** consider each separately
   - Well-defined interfaces give flexibility and isolation

- Example: **bug count** in a large, **N-line** codebase
  - Bug count $\propto$ N
  - Debug time $\propto$ N × bug count $\propto$ $\mathbf{N^2}$

- Now divide the N-line codebase into **K** modules
  - Debug time $\propto (N / K)^2 \times K =$ $\mathbf{N^2/K}$

Coping with complexity

1. Modularity

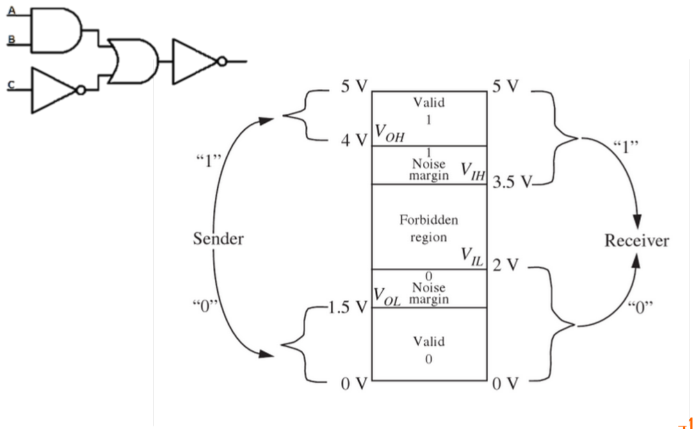
2. **Abstraction**
   - Ability of any module to treat others like "black box"
     - Just based on interface
     - Without regard to internal implementation
   - Symptoms
     - Fewer interactions between modules
     - Less ***propagation of effects*** between modules

Coping with complexity

1. Modularity

2. **Abstraction**
   - **The Robustness Principle:**
     Be tolerant of inputs and strict on outputs

Robustness principle in action: The digital abstraction



Coping with complexity

1. Modularity

2. Abstraction

3. **Hierarchy**
   - Start with small group of modules, assemble
     - Assemble those assemblies, etc.
   - Reduces connections, constraints, interactions

Coping with complexity

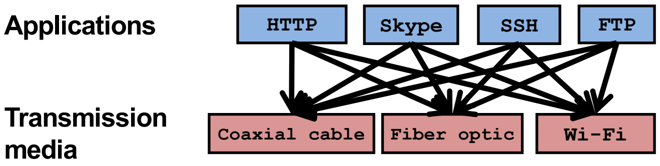
1. Modularity

2. Abstraction

3. Hierarchy

4. **Layering**
   - A form of modularity
   - Gradually build up a system, layer by layer
   - **Example: Internet protocol stack**

Layering on the Internet: The problem



Applications

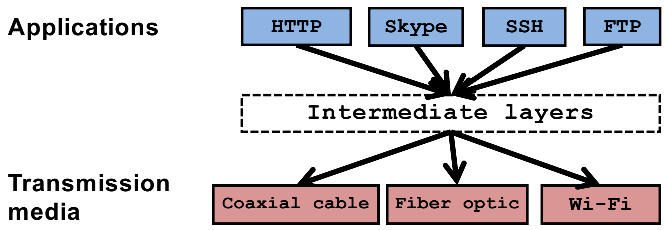
HTTP Skype SSH FTP

Transmission media

Coaxial cable Fiber optic Wi-Fi

- Re-implement every app for every new tx media?
- Change apps on any change to tx media (+ vice versa)?
- **No!** But how does the Internet design avoid this?

Layering on the Internet:
Intermediate layers provide a solution



- Intermediate layers provide abstractions for app, media
- New apps or media need only implement against intermediate layers' interface

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Computer systems: The same, but different

1. **Often unconstrained by physical laws**
   - Computer systems are **mostly digital**
   - **Contrast:** Analog systems have **physical limitations** (degrading copies of analog music media)
   - Back to the **digital static discipline**
     - Static discipline **restores signal levels**
     - Can **scale** microprocessors to billions of gates, encounter new, **interesting emergent properties**

Computer systems: The same, but different

1. Often unconstrained by physical laws

2. **Unprecedented *d*(technology)/*dt***
   - Many examples:
     - Magnetic disk storage price per gigabyte
     - RAM storage price per gigabyte
     - Optical fiber transmission speed
   - **Result:** Incommensurate scaling, with system redesign consequences

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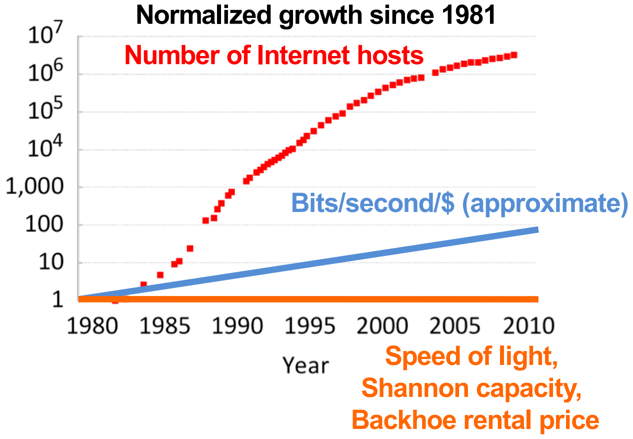
Incommensurate scaling on the Internet



Summary and lessons

- **Expect surprises** in system design
- There is **no small change** in a system
- 10-100 × increase? ⇒ perhaps re-design
- Complexity is **super-linear** in system size
- Performance cost is super-linear in system size
- Reliability cost is super-linear in system size
- **Technology's high rate of change** induces incommensurate scaling

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For Wed, everybody reads

1) How to read a paper
2) Lampson's Hints