The Internet is an Economic System
(whether we like it or not)

- Highly decentralized and diverse
  - allocation of scarce resources; conflicting incentives
- Disparate network administrators operate by local incentives
  - network growth; peering agreements and SLAs
- Users may subvert/improvise for their own purposes
  - free-riding for shared resources (e.g. in peer-to-peer services)
  - spam and DDoS as economic problems
- Regulatory environments for networking technology
  - for privacy and security concerns in the Internet
  - need more “knobs” for society-technology interface
Can Economic Principles Provide Guidance?

• Game theory and economics, competitive and cooperative
  - strategic behavior and the management of competing incentives
• Markets for the exchange of standardized resources
  - goods & services
  - efficiency and equilibrium notions for performance measurement
• Learning and adaptation in economic systems
• Certain nontraditional topics in economic thought
  - behavioral and agent-based approaches
• Active research at the CS-economics boundary
The Internet: What is It?

- A massive network of connected but decentralized computers
- Began as an experimental research NW of the DoD (ARPAnet), 1970s
  - note: Web appeared considerably later
- All aspects evolved over many years
  - protocols, services, hardware, software
- Many individuals and organizations contributed
- Designed to be open, flexible, and general from the start
  - “layered” architecture with progressively strong guarantees/functionality
  - layers highly modular, promotes clean interfaces and progressive complexity
  - highly agnostic as to what services are provided
- Completely unlike prior centralized, managed NWs
  - e.g. the AT&T telephone switching network
Internet Basics

- Can divide all computers on the Internet into two types:
  - computers and devices at the “edge”
    - your desktop and laptop machines
    - big compute servers like Eniac
    - your web-browsing cell phone, your Internet-enabled toaster, etc.
  - computers in the “core”
    - these are called routers
    - they are very fast and highly specialized; basically are big switches

- Every machine has a unique Internet (IP) address
  - IP = Internet Protocol
  - like phone numbers and physical addresses, IP addresses of “nearby” computers are often very similar
  - your IP address may vary with your location, but it’s still unique

- IP addresses are how everything finds everything else!
- Note: the Internet and the Web are not the same!
  - the Web is one of many services that run on the Internet
Internet Packet Routing

• At the lowest level, all data is transmitted as packets
  - small units of data with addressing and other important info
  - if you have large amounts of data to send (e.g. a web page with lots of graphics), it must be broken into many small packets
  - somebody/thing will have to reassemble them at the other end
• All routers do is receive and forward packets
  - forward packet to the “next” router on path to destination
  - they only forward to routers they are physically connected to
  - how do they know which neighboring router is “next”?
• Routing tables:
  - giant look-up tables
  - for each possible IP address, indicates which router is “next”
    • e.g. route addresses of form 128.8.*.* to neighbor router A
    • route 128.7.2.* to neighbor router B, etc.
  - need to make use of subnet addressing (similar to zip codes)
  - distributed maintenance of table consistency is complex
    • must avoid (e.g.) cycles in routing
    • requires distributed communication/coordination among routers
• Handy programs: ipconfig, traceroute, ping and nslookup
The IP (Internet Protocol)

- There are many possible conventions or protocols routers could use to address issues such as:
  - what to do if a router is down?
  - who worries about lost packets?
  - what if someone wants their packets to move faster?
- However, they all use a single, simple protocol: IP
- IP offers only one service: “best effort” packet delivery
  - with no guarantee of delivery
  - with no levels of service
  - with no notification of lost or delayed packets
  - knows nothing about the applications generating/receiving packets
  - this simplicity is its great strength: provides robustness and speed
- Higher-level protocols are layered on top of IP:
  - TCP: for building connections, resending lost packets, etc.
  - http: for the sending and receiving of web pages
  - ssh: for secure remote access to edge computers
  - etc. etc. etc.
Autonomous Systems (ASes)

- Q: So who owns and maintains all these routers?
- A: Networking companies/orgs called “Autonomous Systems”
- ASes come in several different flavors:
  - large, long-haul “backbone” network providers (AT&T, UUNET, Sprint)
  - consumer-facing Internet Service Providers (ISPs) (Comcast, Earthlink)
  - companies/organizations needing to provide Internet access to members (Penn)
- The path of a “typical” packet would usually travel through many ASes
  - email, web page request, Skype call,…
- Q: How do the ASes make money?
- A: Some do, some don’t
  - consumers and organizations near the edge pay their ISP/upstream provider
  - ISPs may in turn pay backbone providers
  - backbone providers typically have “peering agreements”
- Let’s revisit traceroute…
- Q: How do the ASes coordinate the movement/handoff of traffic?
- A: It’s complicated… we’ll return to this shortly.
Commercial Relationships in Internet Routing

- **Customer-Provider**
  - customer pays to send and receive traffic
  - provider transits traffic to the rest of Internet

- **Peer-peer**
  - settlement free, under near-even traffic exchanges
  - transit traffic to and from their respective customers

- These are *existing economic realities*

- They create specific economic *incentives* that must co-exist with technology, routing protocols, etc.
**Border Gateway Protocol (BGP)**

- **Within its **_own network_,** an AS may choose to route traffic as it likes
  - typically might follow a shortest path between the entry router and the exit router
- **Interfaces** _between ASes_ are formed by special _border routers_
  - these are the routers where a packet travels from one AS to the “next”
- **Communication at border routers** governed by the Border Gateway Protocol:
  - border routers “announce” paths to neighboring ASes
  - e.g. “I have a 13-hop path through my AS to [www.cis.upenn.edu](http://www.cis.upenn.edu)”
  - ASes use neighboring announcements to decide where to forward traffic & determine own paths
  - paths actually specify _complete list_ of ASes: e.g. 13-hop path Comcast → AT&T → UUNET → Penn
- Fair amount of **trust** and **honesty** expected for effective operation of BGP
- **What are the incentives to cheat or deviate from expected behavior?**
  - announce false paths to get more traffic
  - announce false paths to omit
  - deliberately avoid shortest announced path (UUNET is my competitor, don’t give them traffic)
- **Very recent research:** try to make announced paths truthful
  - crypto/security approach: monitor/measure announced vs. actual paths
  - very difficult, high overhead
  - alternative approach: game theory
  - establish conditions under which “rational” ASes will announce truthful paths
  - rational: use announced paths which give best route to outbound traffic; announce paths which will maximize revenue
Economic Incentives for Peering

• How to select peers?
  - need to reach some other part of the Internet
  - improve end-to-end customer performance
  - avoid payments to upstream providers

• How to route the traffic?
  - today: early-exit routing to use less bandwidth
  - tomorrow: negotiate for lower total resource usage?
Game Theory of Internet Routing

• Strong analogy between routing and driving on a network of roads
  - each driver has their own starting (source) point and ending (destination) points
  - each driver (packet flow) wants to minimize their own latency
  - each driver chooses their sequence of roads ("source" vs. default routing)
  - delays on each road depend on how much traffic they carry

• Very similar to navigation problem in social networks, but now:
  - network is technological instead of social
  - many source/destination pairs instead of one
  - flows are selfish

• Formalize as a game on a network:
  - network: network of roads or routers
  - players: individual drivers or traffic flows
  - payoff for a player: negative of their total driving time
  - assume delay on each road proportional to traffic

• Huge number of players; huge number of possible actions
  - actions: all possible routes from source to destination
  - still, we know there is a Nash equilibrium...

• What could we hope to say?
Routing Equilibrium Example

- Suppose we have only two roads/connections in the network:
  - “normal” road: delay/latency is equal to the amount of traffic $x$
  - “mountain” road: delay/latency is 1 unit no matter how much traffic
- Imagine 1 fully divisible unit of traffic that wants to travel from $s$ to $t$:
  
  At equilibrium, all traffic takes the normal road and everyone has latency = 1

  A better collective solution: half the population has latency 0.5, half has latency 1... But upper flow is envious
Braess's Paradox

Initial Network:

Delay = 1.5
Braess's Paradox

Initial Network:

Augmented Network:

Delay = 1.5

Now what?
Braess's Paradox

Initial Network:
Delay = 1.5

Augmented Network:
Delay = 2
The Price of Anarchy

• In principle (only), could imagine computing a centralized solution
  - “Centralized Traffic Authority” assigns each driver/flow their route
  - does so to minimize total population latency; may not be optimal for individuals
  - “maximum social welfare” solution; game-theoretic equilibrium can only be worse

• Surprising result: total latency of Nash equilibrium only 33% worse!
  - no matter how big or complex the network
  - “Price of Anarchy” (selfish, distributed behavior) is relatively small
  - compare to Prisoner’s Dilemma
  - network structure irrelevant; contrast earlier results (e.g. networked trading)
  - can be worse than 33% for more complex latency assumptions
Case Study: QoS

- **QoS = Quality of Service**
  - many varying services and demands on the Internet
    - email: real-time delivery not critical
    - chat: near real-time delivery critical; low-bandwidth
    - voice over IP: real-time delivery critical; low-bandwidth
    - teleconferencing/streaming video: real-time critical; high-bandwidth
  - varying QoS guarantees required
    - email: not much more than IP required; must retransmit lost packets
    - chat/VoIP: two-way connection required
    - telecon/streaming: high-bandwidth two-way connections

- Must somehow be built *on top of IP*
- Whose going to pay for all of this? How much?
  - presumably companies offering the services
  - costs passed on to their customers
- What should the protocols/mechanism look like?
- There are many elaborate answers to these questions...
QoS and the Paris Metro

• Paris Metro (until recently)
  - two classes of service: first (expensive) and coach (cheaper)
  - exact same cars, speed, destinations, etc.
  - people pay for first class:
    • because it is less crowded
    • because the type of person willing/able to pay first class is there
    • etc.
  - self-regulating:
    • if too many people are in first class, it will be come less attractive

• Andrew Odlyzko’s protocol for QoS:
  - divide the Internet into a small number of identical virtual NWs
  - simply charge different prices for each
  - an entirely economic solution
  - California toll roads
Case Study: Sponsored Search

- Organic vs. sponsored web search
- Generalized second price auctions
- Two-sided networked markets
Organic vs. Sponsored Web Search

• Already (briefly) studied organic web search:
  - use words in user’s query and web sites to rank results
  - other, non-language features also important
  - our emphasis: PageRank algorithm for web site importance
• Sponsored web search: a market/auction for ad placement
  - user query may signal “purchasing intent”
  - advertisers bid/compete for attention
• Rules of auction broadly similar across search engines
  - Google, Bing, Yahoo!
• We’ll describe these auctions and their properties
How Does It Work?

• Interested advertisers submit their bids for a query
  - $0.25 for “philadelphia mountain bike”, $0.17 for “philadelphia discount mountain bike”
• Search engine gathers all the bids and determines advertiser ranking
• Advertisers only pay if a user clicks on their ad
  - “price per click” (PPC)
  - distinguishes from display advertising
• They may pay less than what they bid
Generalized Second Price Auctions

• **Multiple bidders for a single item**
  - each bidder $i$ has a private valuation $v(i)$ for the item
  - each bidder $i$ privately submits a bid $b(i) \leq v(i)$ for the item

• **If you give the item to the highest bidder at their bid, everyone will bid less than their valuation**
  - bid “shaving”

• **If you give the item to the highest bidder, but only make them pay the second highest bid, the optimal strategy is to be “truthful”**
  - all $b(i) = v(i)$

• **Search engines rank advertisers by their bids**

• **Advertiser’s PPC is the bid below them**
Other Details

• Actually order advertisers by combination of bids and “quality scores”
  - e.g. incorporate click-through rates (CTRs); higher CTRs boosted in ranking
  - prevents display of high bidders who never receive clicks
  - reduces irrelevant advertisers
• Search engines sometimes employ reserve prices
  - e.g. minimum bid for “philadelphia mountain bike” is $0.05
  - balancing revenue with ad clutter
• Exact match vs. broad match
  - “philadelphia mountain bike” vs. “mountain bike” vs. “bike” vs. “philadelphia”
• Permit advertisers to condition bid on other information about user
  - e.g. geotargeting using user location
• Running a sponsored search advertising campaign is complex
  - all these decisions for a large portfolio of search phrases
• Associated industries/services:
  - Search Engine Optimization (SEO): improve organic ranking
    - e.g. optimize landing page, improve PageRank
  - Search Engine Marketing (SEM): improved sponsored ranking
    - e.g. optimize phrases, bids, quality score
Where's the Network?

- **Market is a two-sided network:**
  - users and their various interests determine which advertisers they will click on
  - advertisers and their products/services determine which users they want to reach
  - bipartite network with overlapping neighbor sets
  - cosmetically similar to our networked trading model

- **Rich Get Richer aspects of two-sided markets:**
  - advertisers most want to be on that search engine with the most users
  - users want to be on that search engine with the best search results
  - the more advertisers and users a search engine has, the more data
  - better estimates of advertiser quality, CTRs, good results for rare queries

- **The “long tail of search”**
Case Study: FCC Incentive Auction

- Problem: Repurpose broadcast TV spectrum for mobile communications
- “Reverse” auction: pay (some) broadcasters to go off the air
- “Forward” auction: mobile carriers purchase vacated spectrum
- Closing condition: forward revenues must cover reverse expenditures
- Many conceptual and technical challenges:
  - “repacking” constraints on remaining broadcasters: network of forbidden adjacencies
  - computing set of repackable broadcasters with highest bids is intractable
  - must keep auction rules as simple as possible for broadcasters
  - some carriers want national footprint → exposure problems
Summary

• Internet: distributed, self-interested behavior; competing incentives
• Leads to economic/game-theoretic situations:
  – routing, sponsored search, Quality of Service, spam, peer-to-peer systems
• Can seek economic as well as technological solutions:
  – auction rules in sponsored search; pricing schemes for QoS, spam, etc.
  – payments could be real or virtual
• Sometimes the game-theoretic behavior may not be an issue
  – Price of Anarchy for routing