Exploring Network Economics

Dah Ming Chiu
Department of Information Engineering
Chinese University of Hong Kong

Outline

- What is network economics?
  - Why are we interested
  - Examples
  - Some classic models and tools
  - Some opinions and advices

DM Chiu, WY Ng, "Exploring network economics", arxiv preprint server, (http://arxiv.org/pdf/1106.1282v1.pdf), Jun 2011

Why are we interested?

- Engineering:
  - Is about building things
- But a network (especially the Internet) is
  - Basic infrastructure (like air, water)
  - Shared by many users
  - Managed, owned by different entities

  → Faced with many economic issues

Consider congestion control

- It is an engineering problem:
  - How to detect congestion?
  - How to control it without oscillation…
- It is also an economic problem:
  - E.g. who should yield first?
  - Whose resource is allowed to congest more?
  - One person welfare affected by others' actions, known as "externalities" in economics

Congestion control with fairness

- A fairness measure derived axiomatically:
  - R Jain, DM Chiu and W Hawe, “A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer Systems”, DEC Tech Report 301, 1984, Arxiv preprint cs.NI/9809099, 1998.
- A simple distributed algorithm – Additive Increase Multiplicative Decrease (AIMD)
  - DM Chiu and R Jain, “Analysis of Increase and Decrease Algorithms for Congestion Avoidance in Computer Networks”, Journal of Computer Networks and ISDN, 17(1), 1989

Utility maximization – Frank Kelly

- Maximize $U(x_1)+U(x_2)+\ldots U(x_n)$
  - Subject to capacity constraints on x_i, $Ax<c$
  - U() is concave, non-decreasing, "elastic"
  - If all flows sharing a single bottleneck
    - Clearly, more equal more optimal
  - If flows sharing different paths in a network
    - **Proportional fairness** suggested by model

F Kelly, AK Maulloo and D Tan, "Rate control for communication networks: shadow prices, proportional fairness and stability", Journal of the Operational Research Society, 49(237-252), 1998.

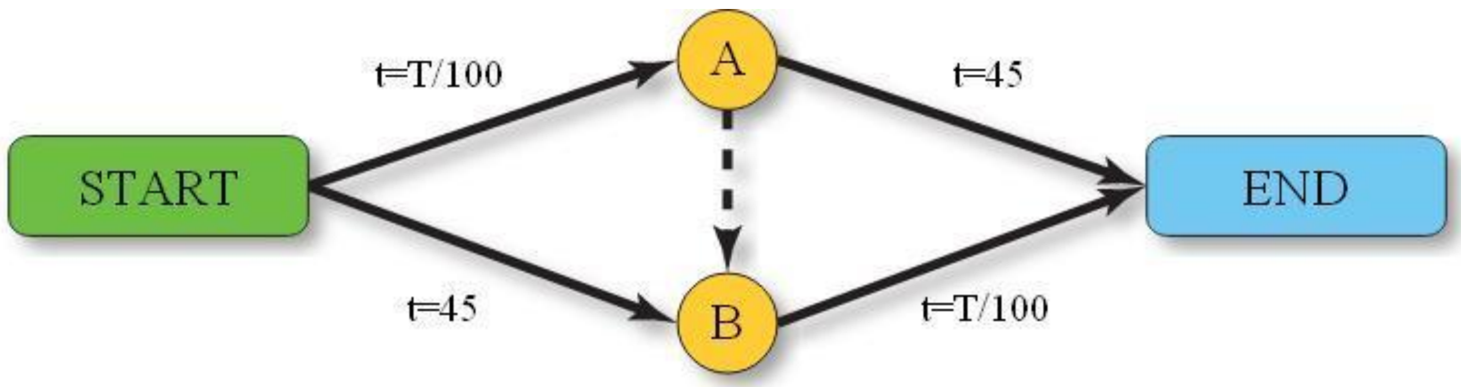
The issue is hardly settled

- What if flows are selfish?
  - "Price of anarchy": study gap between optimal and anarchy
  - Game theory concepts used
- What if utility functions are not elastic?
  - TCP-friendly congestion control
  - Admission control together with congestion control
- When users have different utility functions
  - Auction, submodular utility maximization, matching algorithms
  - Combinatorial algorithms, theoretical computer science
- Should network operators interfere?
  - Net neutrality
  - Cloud computing, private networks…

Selfish behavior

- “Tragedy of the Commons”
  – William Forster Lloyd, Cambridge professor, in his critique of Adam Smith’s “Invisible Hand”, in 1800s
  – Garrett Harding, ecologist, wrote the article with that title, published in Science in1968.
- Price of anarchy
  – A phrase coined by C Papadimitriou (UC Berkeley)
  – Focus on determining the gap between the decentralized equilibrium, and the optimal
  – E.g. R Johari (MIT, Stanford) showed the gap is not big (for congestion control) under some assumptions

Braess Paradox



- T = number of cars going from START to END = 4000
- t = time it takes on each road
- Adding a super highway between A and B makes the time longer for everyone!

Selfish routing

- For general networks of the kind in Braess Paradox, what is the gap between “selfish routing” and optimal routing?
  - T Roughgarder’s PhD thesis (Cornell), around 2002
  - He answered the question for some special cases only

Accommodating different interests

- In general, different users have different utility functions
  - How to maximize social welfare, or profit?
  - Usually combinatorial problem: computationally hard
- Some mechanisms studied/used commonly:
  - Auctions
  - Matching algorithms

  While more optimal, harder to apply in real-time

Excellent book:

"Combinatorial Auctions", Edited by Peter Cramton, Yoav Shoham and Richard Steinberg, The MIT press, 2006

Auctions

- Many variations for different applications:
  - Single good, divisible vs non-divisible goods, multiple copies of same good, combinations of goods…
  - Application to communication network resources need to consider their characteristics
  - Notable use: wireless spectrum allocation
- Strategy-proof auctions
  - Attracts a lot of theoretical interests
  - Most well-known: 2^{nd} price auction, or VCG auction

The Stable Marriage Problem

- A different formulation
  - Preference lists instead of utility functions
  - Stable matching vs optimal matching
  - Very practical problem/formulation
  - Less general than utility based formulation, but existence of simple practical algorithms

D. Gale and L. S. Shapley: "College Admissions and the Stability of Marriage", *American Mathematical Monthly* 69, 9-14, 1962

Jian Liu, Dah Ming Chiu: Reciprocating Preferences Stablizes Matching: College Admissions Revisited CoRR abs/1011.1135: (2010)

Mechanism design

- Set some rules, so that the “selfish behavior” automatically leads to optimal solution (social welfare or profit)
  - “Allow only to catch lobsters less than one pound”
  - At the HK Internet Exchange, only multi-lateral peering is accepted
  - VCG auctions

Game theory

- Formulation
  - Two or more players
  - Each players payoff (utility) is defined as a function of the actions of all players
  - Many types of games, different rules etc
- The important concept is **equilibrium**:
  - The choice of an action by each player that she will not deviate from given actions by the other players
- Theorist also care about uniqueness, stability, computation complexity

Network effect

- Congestion -> negative externality
- Network effect -> positive externality
- What is network effect?
  - The value brought by population of a network
- Examples
  - Communications network
  - Social network
  - Content distribution network

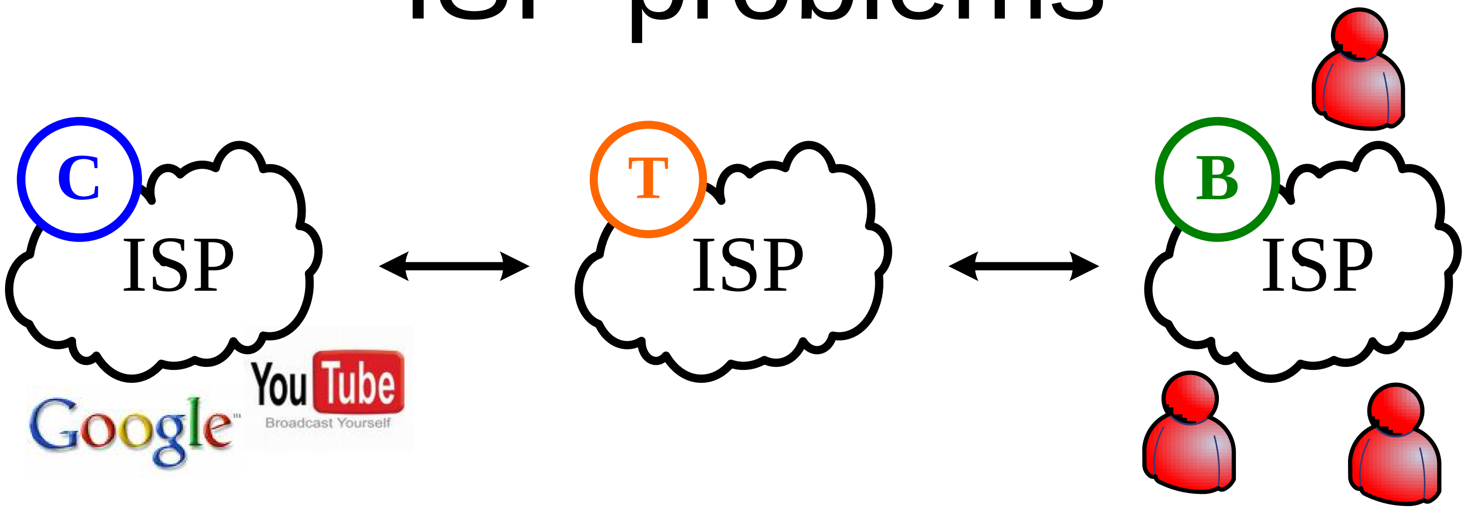
Network valuation

- Metcalf's Law
  - A network with n nodes allows up to $O(n^2)$ connections, hence value is $O(n^2)$
- Odlyzko's Law
  - Each node (user) only connects to a small subset of other nodes, e.g. log(n), hence value is O(nlog(n))
  - Blamed Metcalf's Law for Internet bubble of 2000
- Content distribution model
  - Value is number of **eyeballs**, = O(n)?

ISP networks and peering

- ISPs are collaborators as well as competitors
  - If networks are not connected, they are worth less
  - If connected, how to share the created value?
- In the Internet today → bilateral peering
  - Terms based on perceived service or value exchange
  - A transit provider charges access ISPs and content ISPs for **transit service**
  - Local (access ISPs) may peer with each other for free
  - Local ISPs = eyeballs, content ISPs has content
  - When local ISP peers with content ISP, who pays who?

ISP problems



1. When Content ISP peers with Eyeball ISP, who pays who?
2. How do they pay transit providers?
3. Can transit providers charge differently, e.g. by providing different services? → The **Net Neutrality** debate

For information, visit “Workshop of Internet Economics 2011”, http://www.caida.org/workshops/wie/1112/

Shapley Values

- A theory on cooperation
  - For a team of collaborators, how to evaluate each member's contribution?
  - Exhaustively remove each member to determine the value of that member

Lloyd S. Shapley. "A Value for *n*-person Games". In *Contributions to the Theory of Games*, volume II, by H.W. Kuhn and A.W. Tucker, editors. *Annals of Mathematical Studies* v. 28, pp. 307–317. Princeton University Press, 1953

- We tried to apply this to the ISP problem

RTB Ma, DM Chiu, JCS Lui, V Misra, D Rubenstein, "Internet Economics: The use of Shapley value for ISP settlement", IEEE/ACM Transcations on Networking, 18(3), pp 775-789, 2010

P2P Network formation

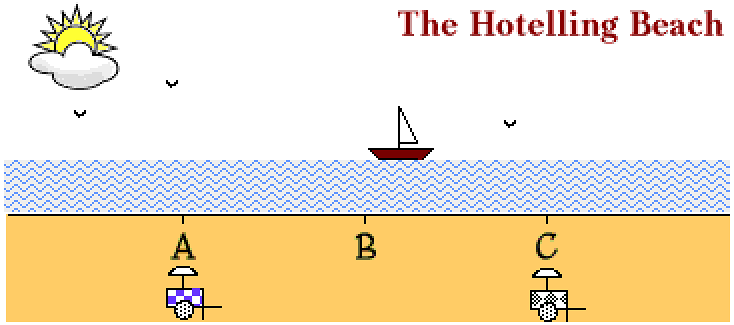
- Will a network form, given free-riders?
  - Assume cost of contributing depends inversely on number of contributors
  - Each peer has a “generosity” level, when it is higher than the cost, the peer contributes

M Feldman et al, “Free-riding and whitewashing in peer-to-peer systems”, PINS Workshop, part of Sigcomm 2004.

- We tried a different formulation
  - Peers join if there is sufficient “interest”, based on other peers already joined

WY Ng, DM Chiu and WK Lin, “Club Formation by Rational Sharing: Content, Viability and Community Structure”, Algorithmica 52(1), 80-94, 2008

Hotelling's model



- Example of a simple model that can be adapted for analyzing ISP and its users
  - Competing ISPs need to make some decisions
  - Users decide their actions based on ISPs' actions
  - ISPs can decided based on known user reactions

H Hotelling, "Stability in Competition", *Economic Journal* **39** (153): 41–57, 1929

Paris Metro Pricing

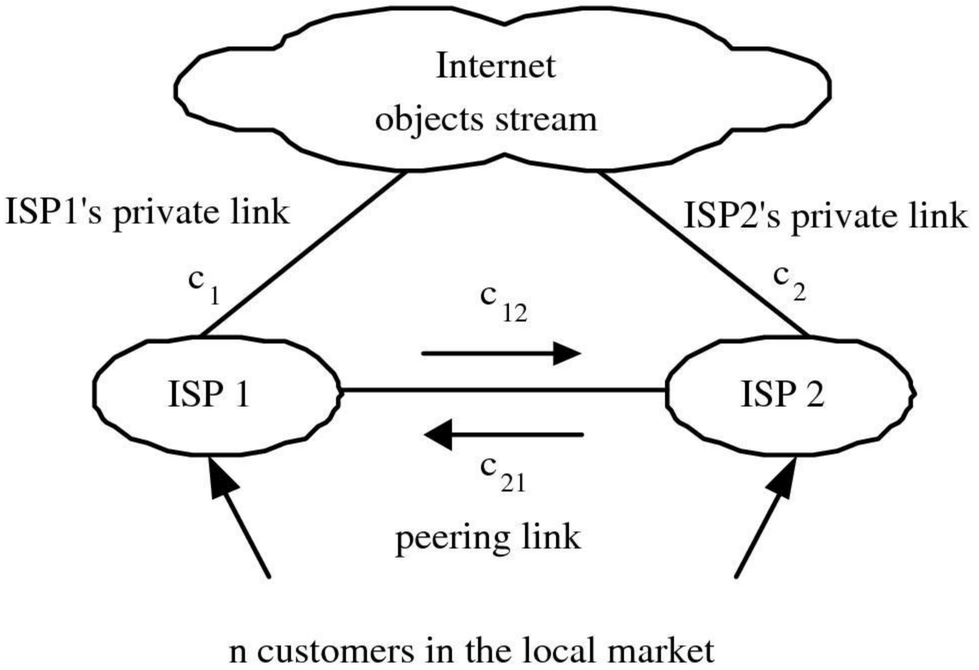
- Divide network into two parts, charging different (or the same) prices
  - Users decide which network to join
  - Will the overall network better than a single network, in terms of social welfare or profit?
  - We can analyze this using a similar approach as Hotelling's
  - The answer is, it depends on the user's utility function, which needs to be "multiplexing preferring" rather than "partitioning preferring".

Chi-Kin Chau, Qian Wang, Dah-Ming Chiu: On the Viability of Paris Metro Pricing for Communication and Service Networks. INFOCOM 2010: 929-937

The nightmare of P2P traffic

Problems:

- Strong local ISP providing transit service to users in other ISPs
- P2P users using unfair amount of bandwidth



Our works:

JH Wang, DM Chiu and JCS Lui, " Modeling the Peering and Routing Tussle between ISPs and P2P Applications", IEEE IWQoS, 2006

Q Wang, DM Chiu and JCS Lui, "ISP Uplink Pricing in a Competitive Market", ICT 2008, St Petersburg.

Some advices

- Be careful choosing "network economics" as a research area
  - Harder to publish papers, and make a career

  Instead, study networking problems using economics knowledge
- Good results tend to be qualitative
  - Key is to bring new **insights** to **real** problems
  - Formulate problem carefully, consider all important stakeholders
  - Check result with intuition, people in the trade

Advices continued

- Mathematical tools are important, but spend time to appreciate economic thinking

A couple of books for easy reading:

1) "Invitation to Economics – Understanding Argument and Policy" by T Harding, Wiley-Blackwell, 2009
2) "Principles of Economics", by NG Mankiw, South-Western Cengage Learning, textbook from Harvard University