Pricing of Bandwidth and Communication on Demand Services

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Issues

- Bandwidth is a finite divisible resource.
- Users compete for that resource and value it differently.
- Providing end-to-end bandwidth requires a combination of links that belong to different operators.
- Communication services differ in quality.
- Signaling between users and providers cannot be exceedingly complex.
- Who should pay? End users or providers or both?

Pricing of Bandwidth and Communication on Demand Services

- Issues
- Users & Providers
- General Pricing
- Externality: Congestion Pricing
- Service Differentiation: Paris Metro Pricing
- Competition of Providers
- Pricing QoS
- Uncertainty
- One-Sided Auctions
- Net Neutrality
- References

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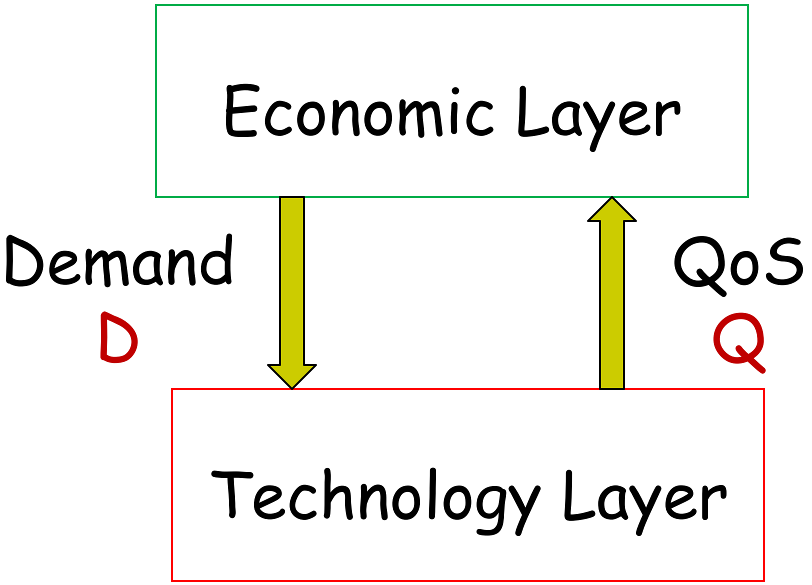
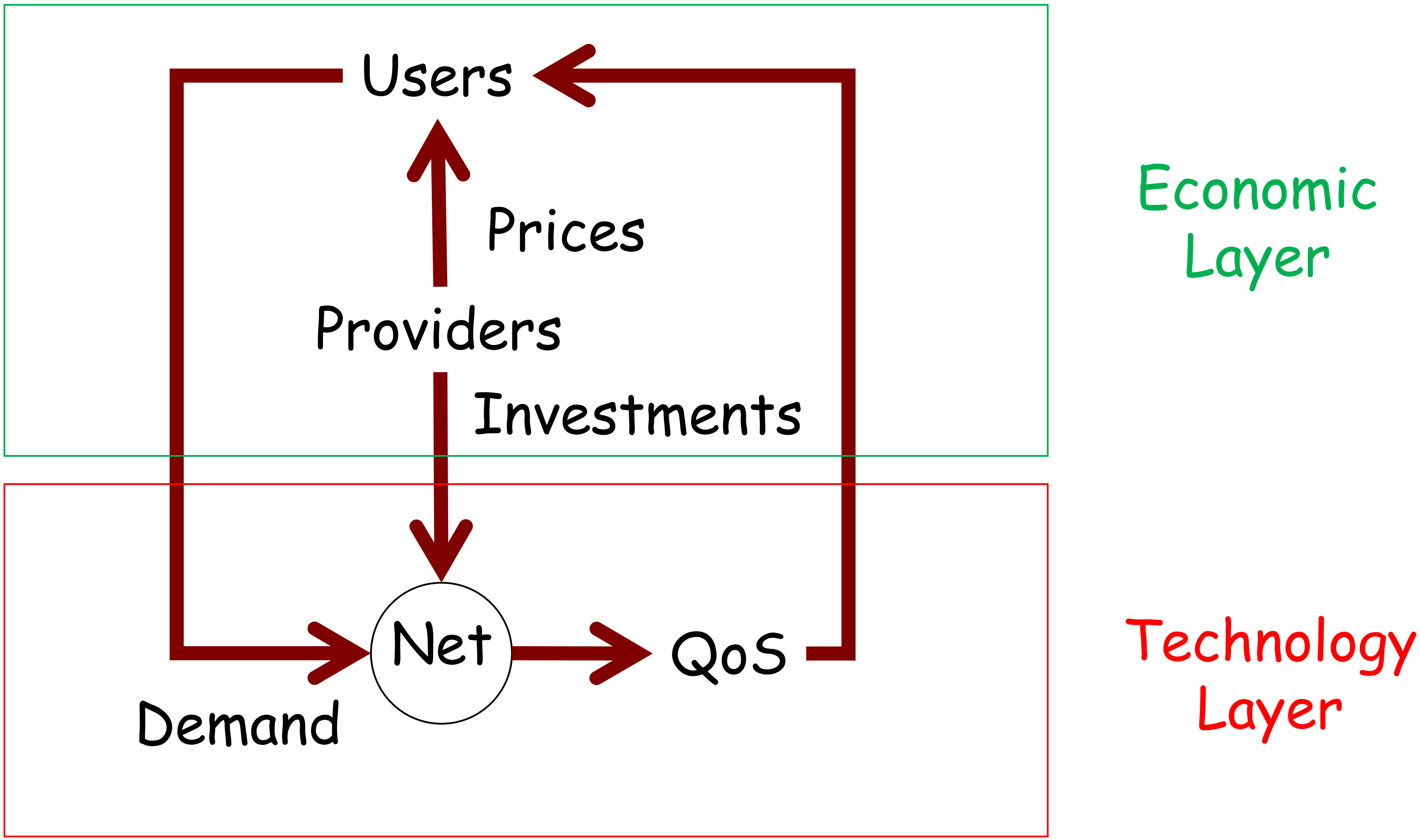
Users & Providers



Users & Providers



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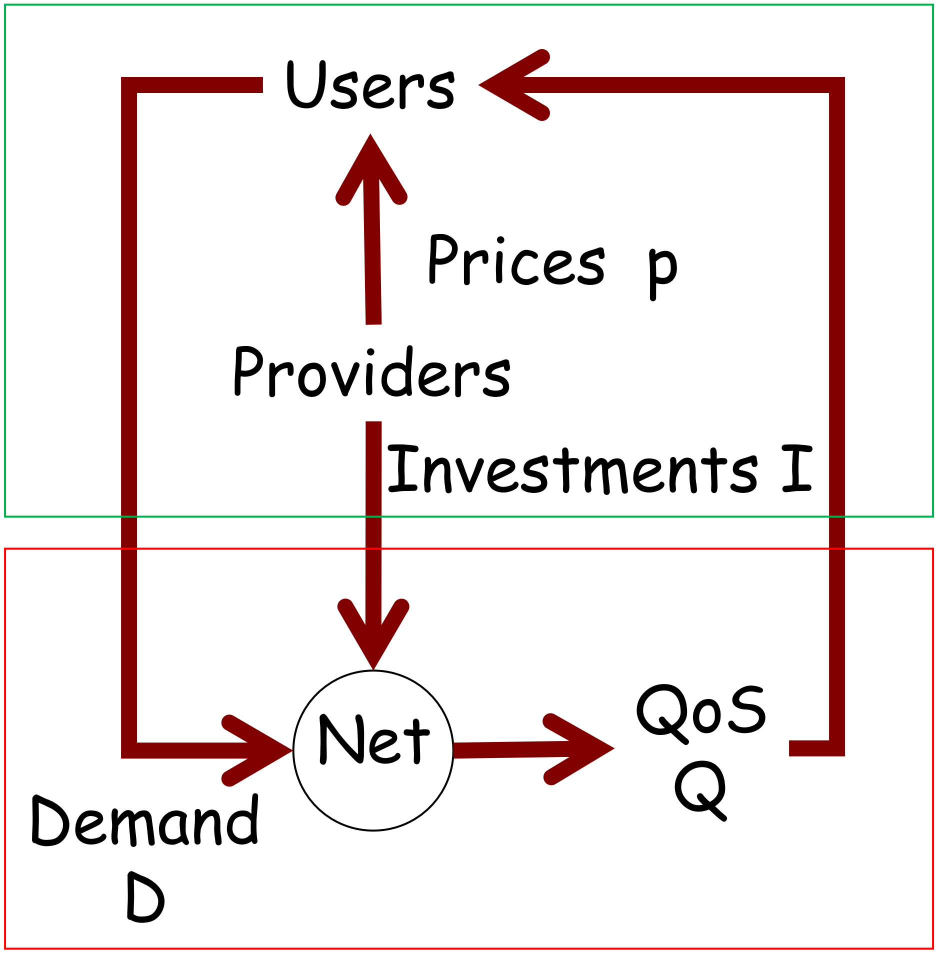

$$D = \text{argmax } U(D, Q, p)$$

$$(p, I) = \text{argmax } \{p.D - \alpha I\}$$

$$Q = Q(D, I)$$

Note: Protocol choice is another important element

Users & Providers

Strategic Behavior:

Users:
- Usage of services: which network, when, how, …
- P2P: What to make available?
- Modify "technology": cheat protocol, bigger antenna, 🡐??

Providers:
- Prices
- Capacity
- Content (more, new, …)
- New technology (WiMax, metro Wi-Fi, 3G, QoS, Vcast, …)

Users & Providers

General Observations:

Users and Providers interact in a network

In general,

Selfish optimal ≠ Social optimal (price of anarchy)

- Selfish users over-consume
- Selfish providers over-price, under-invest

"Internalize the externality"

- Congestion pricing
- Revenue-sharing agreement

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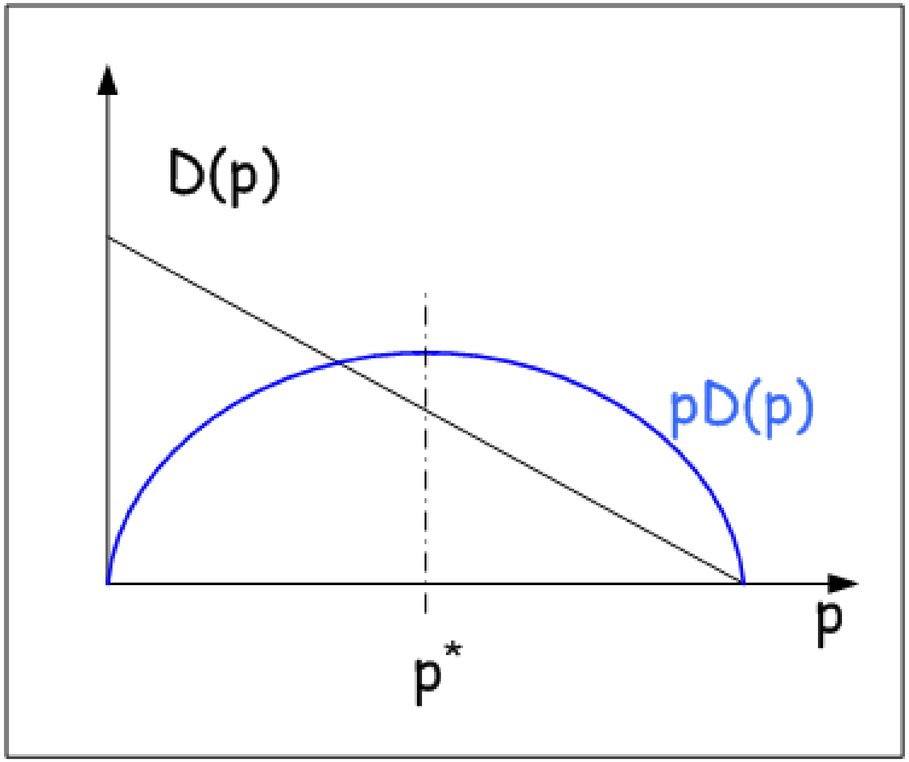
General Pricing

This is the simplest idea: Max pD(p)



More complete: Max pD(p) – C(D(p))

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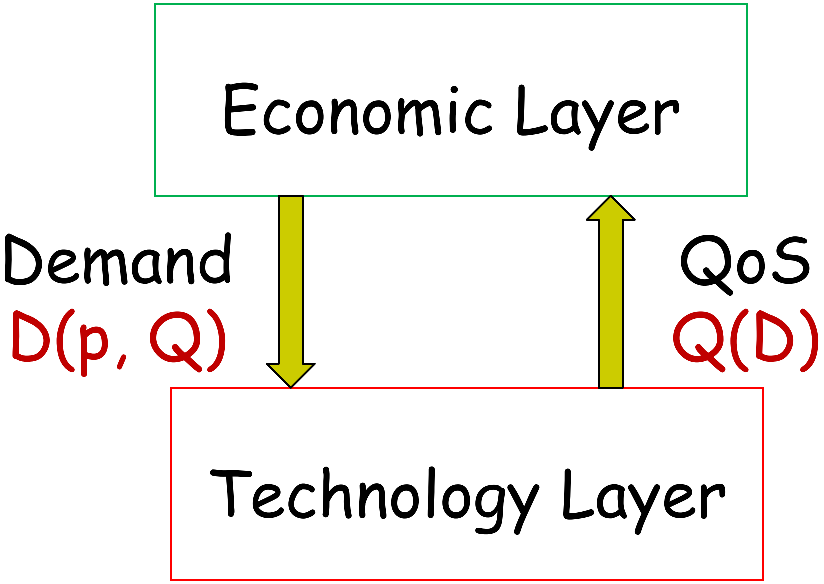
Externality: Congestion Pricing

In fact, D depends on Q and Q depends on D ….



The actions of one user affect other users:
externality.

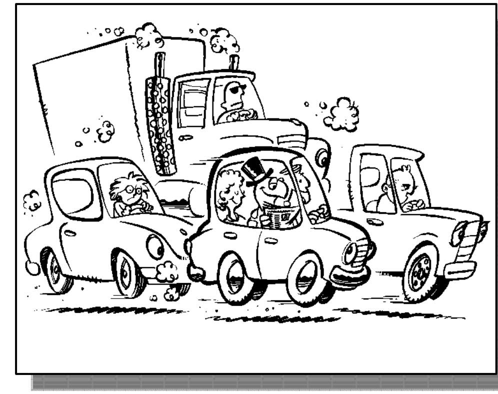
Externality: Congestion Pricing

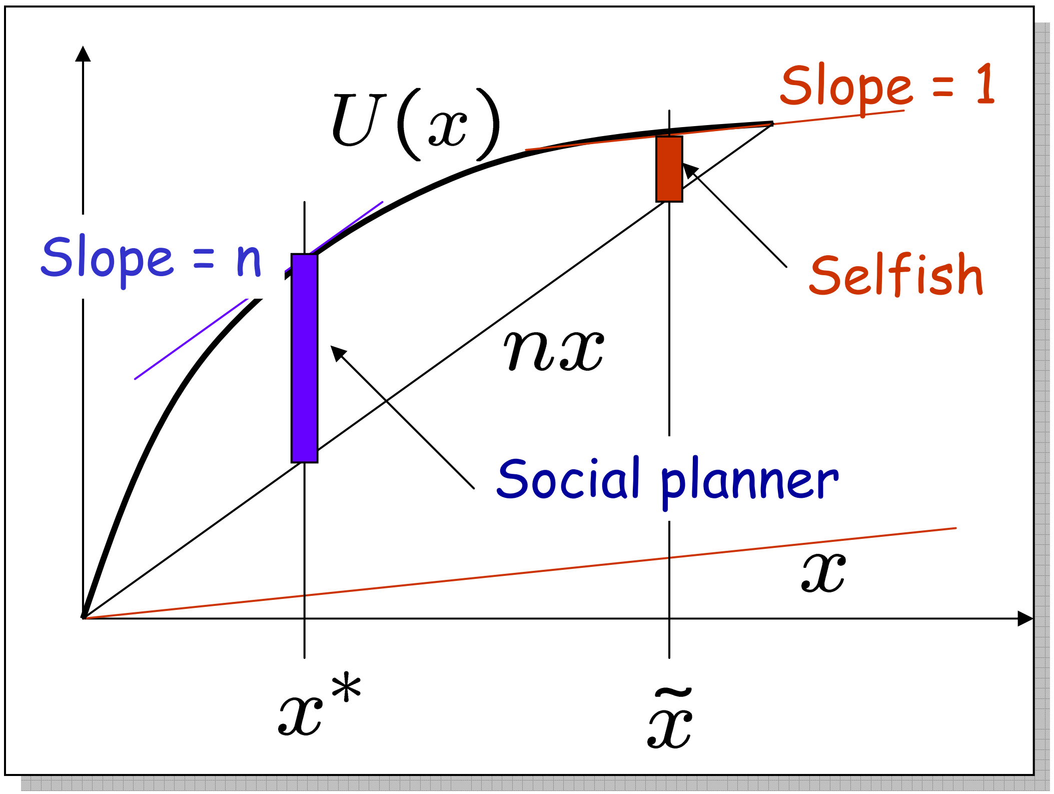
Assume N users share a network.

User i chooses his activity level $\tilde{x}$ to maximize

$$U(x_i) - [x_1 + \cdots + x_N]$$

where the sum is the congestion disutility.





A *social planner* chooses the common activity level $x_i = x^*$ to maximize $U(x) - Nx$.

Selfish users over-consume: They neglect their impact on others.

Externality: Congestion Pricing

Assume congestion price: $p = (N-1)x$.

User i chooses his activity level to maximize

$U(x_i) - [x_1 + \cdots + x_N] - (N-1)x_i$.

Now, user i chooses the socially optimal x.

The congestion price is the cost imposed by each user on all the other users.

The activity x_i of user i imposes a congestion cost x_i on each of the $N-1$ other users. The total "externality" cost is $(N-1)x_i$.

> When users face their externality cost,
> their selfish behaviour is socially optimal.

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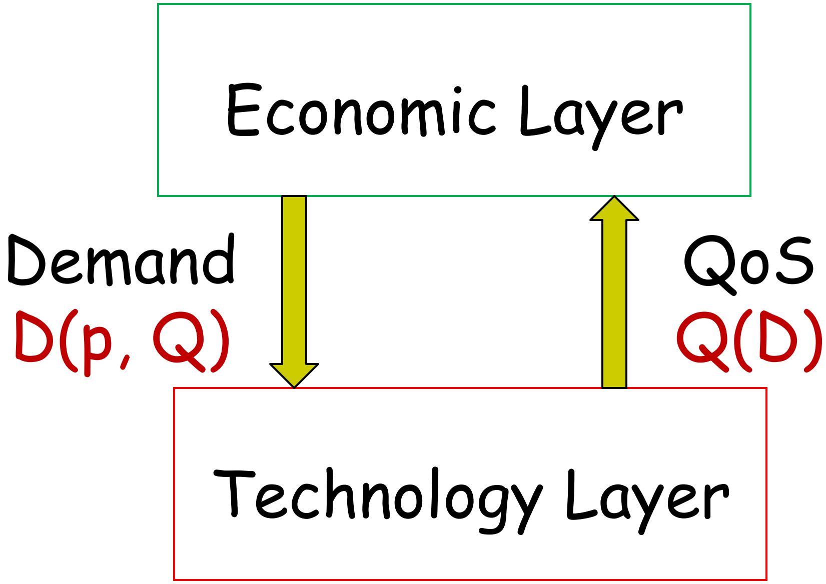
Service Differentiation: Paris Metro Pricing



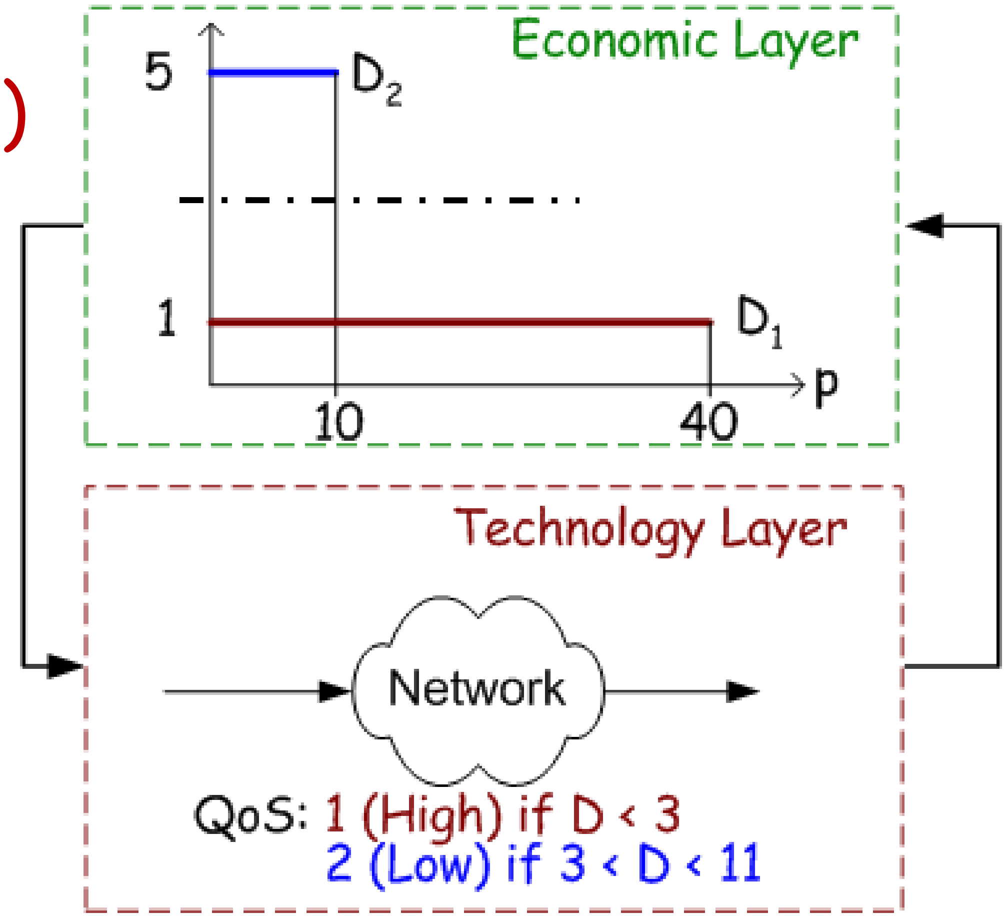
In fact, services require a different QoS:

$$D_i(p, Q),\ i = 1, 2, \ldots$$

Service Differentiation: Paris Metro Pricing

$D_i(p, Q)$

$i = 1, 2$



$Q(D)$

$p \rightarrow D_1, D_2$

$\rightarrow$ Revenue

Question:

How to price?

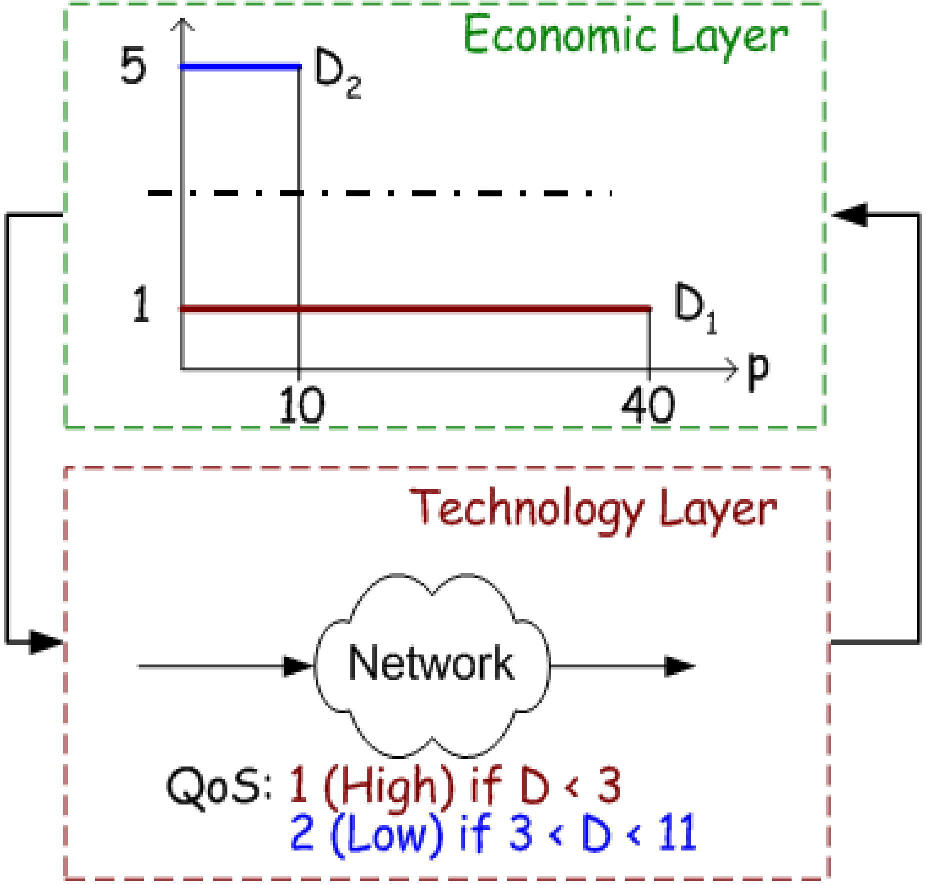
Service Differentiation: Paris Metro Pricing

Solution 1:

$p = 10 \rightarrow D_2$

$\rightarrow$ Revenue = 5x10

(Note: $p = 40 \rightarrow D_1 \rightarrow$ 1x40)



Service Differentiation: Paris Metro Pricing

Solution 2:

$p_1 = 40$ ➔ D_1

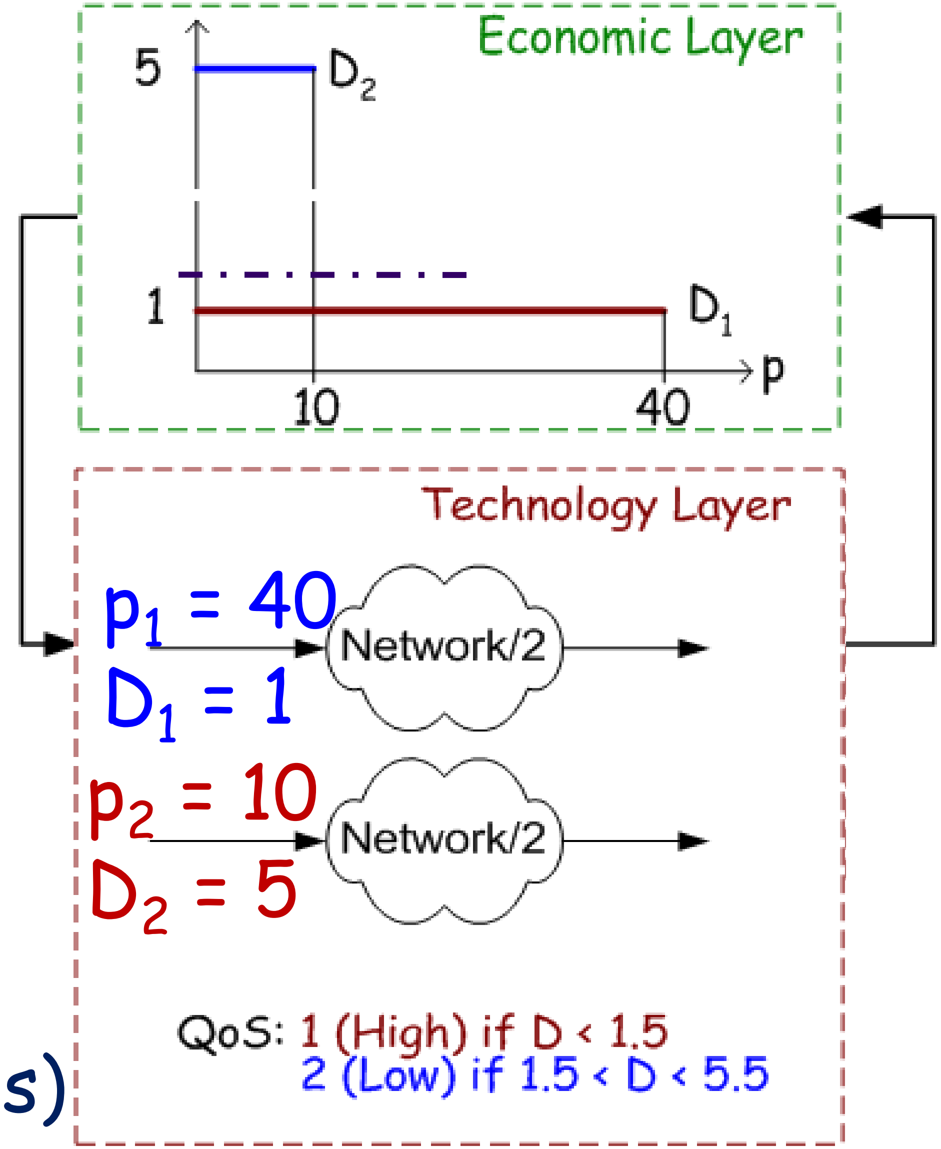
➔ Revenue = 1x40

$p_2 = 10$ ➔ D_2

➔ Revenue = 5x10

Total Revenue: 90

Note: QoS achieved
by pricing
(not by QoS mechanisms)



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Competition of Providers

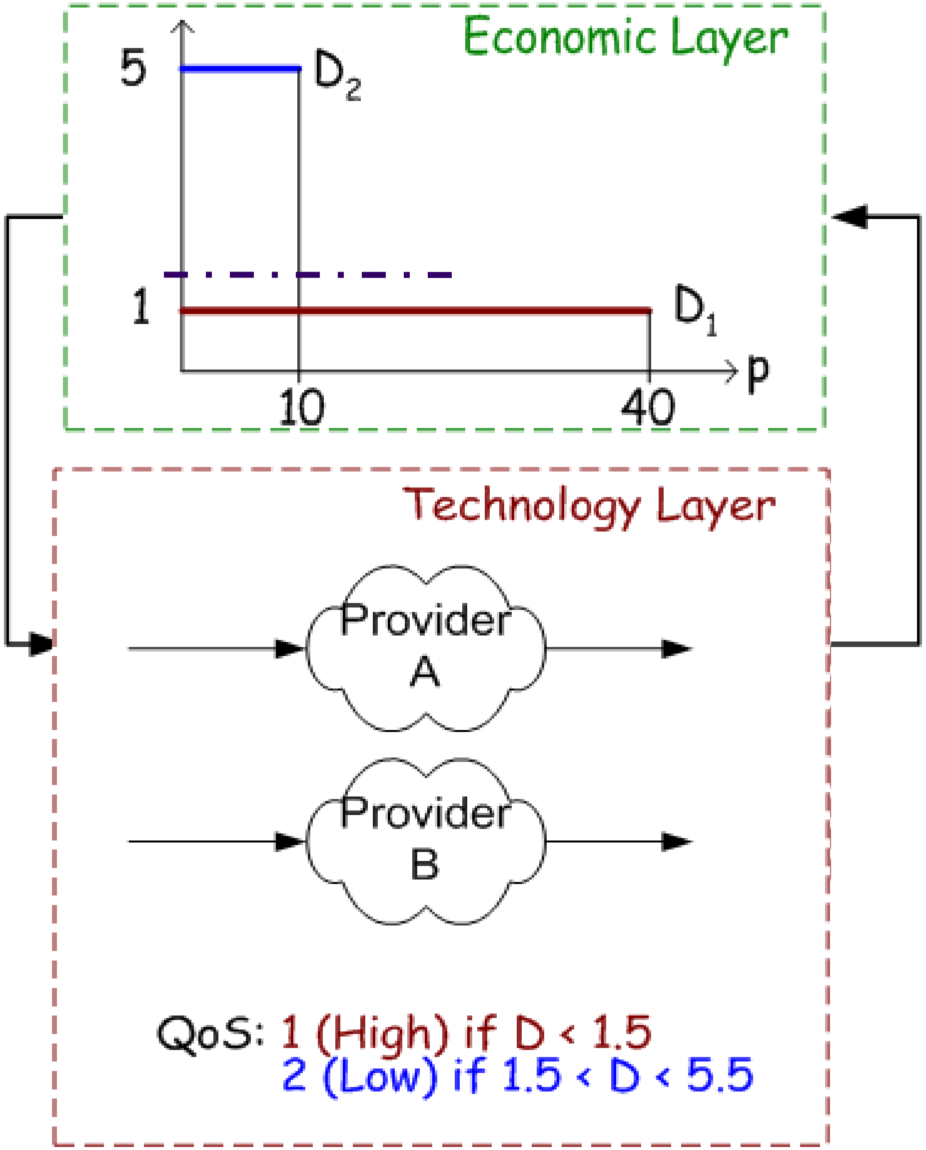
Question:

Will providers "specialize" with D_1 → Prov. A
D_2 → Prov. B

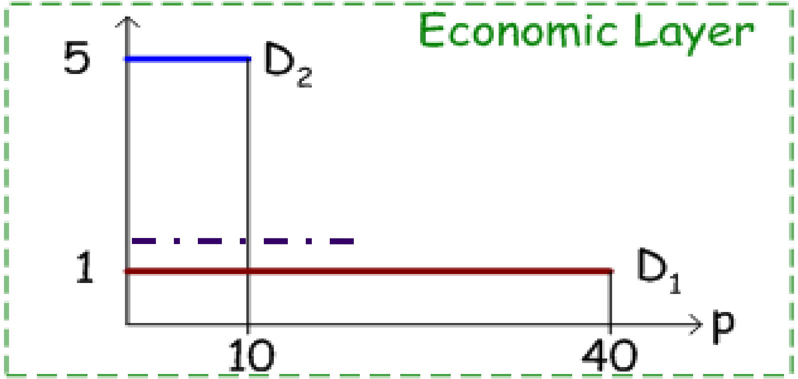
Intuition: No

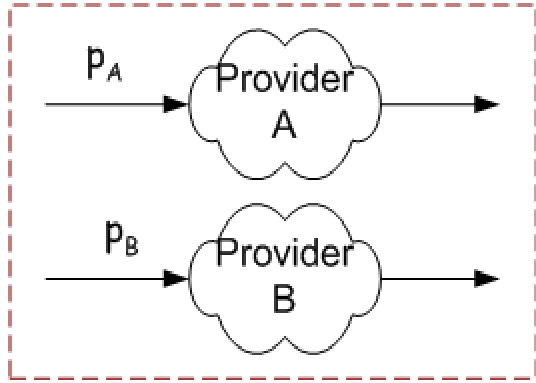
D_2 brings more revenue than D_1

→ Providers may compete for it ….



Competition of Providers





Best Response of A to p_B: (Assume prices must be integers)

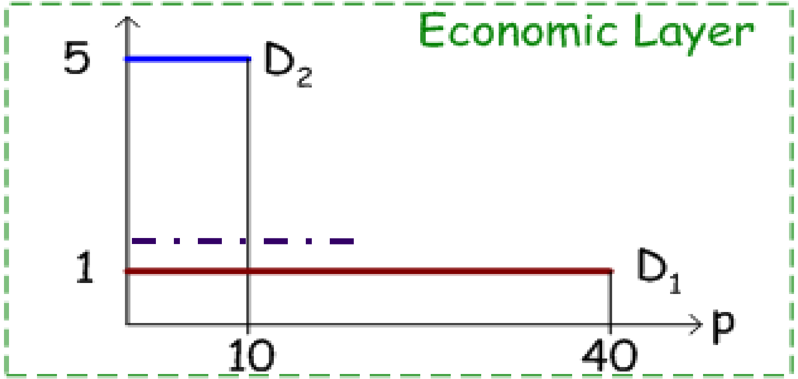
Assume $p_B = p$ in $\{0, 1, \ldots, 10\}$

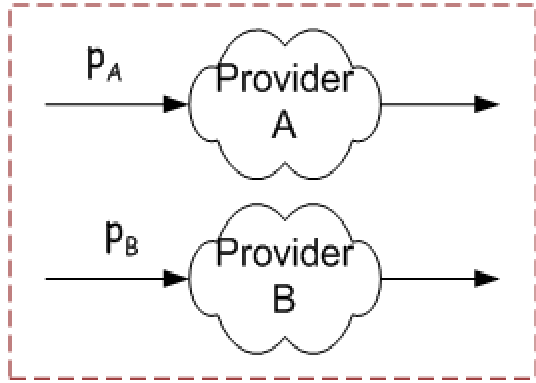
- If $p_A = p$, then $R_A = 5p/2$
- If $p_A = p - 1$, then $R_A = 5(p - 1)$
- If $p_A = 40$, then $R_A = 40$

➔ Best response is $p_A = 40$ if $p < 9$

$p - 1$ if $p = 9$ or 10

Competition of Providers





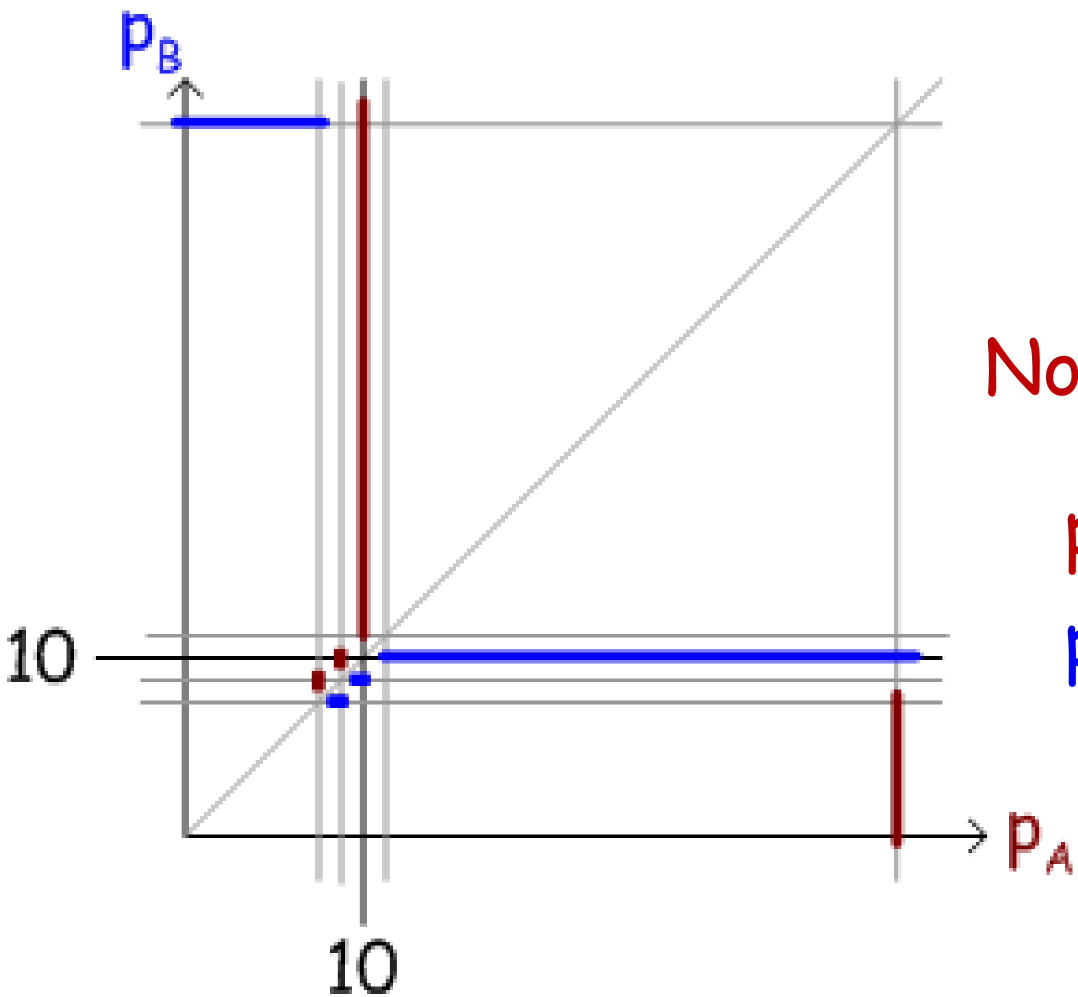
Best Response of A to p_B: (continued)

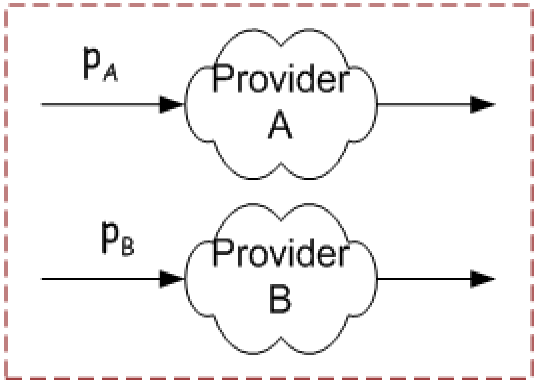
Assume $p_B = p$ in {11, 12, …, 40}

➔ Best response is $p_A = 10$

Competition of Providers

Best Responses: (continued)

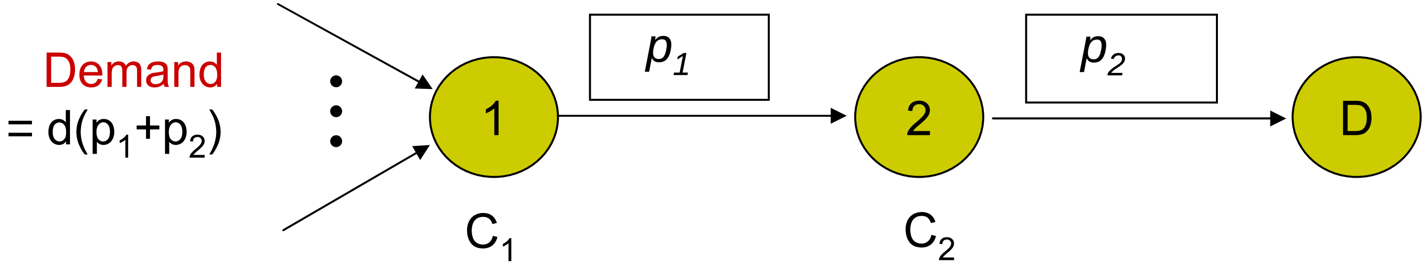




No Nash Equilibrium

p_A		10		8		10		…
p_B	40		9		40		9	

Competition of Providers



Provider 1	Provider 2
$\max_{p_1} \quad p_1\, d(p_1+p_2)$ ← J_1	$\max_{p_2} \quad p_2\, d(p_1+p_2)$ ← J_2
s.t. $\quad d(p_1+p_2) \le C_1$	s.t. $\quad d(p_1+p_2) \le C_2$

- A game between two providers
- Different solution concepts may apply, depend on actual implementation
- First we consider a Nash game

Competition of Providers

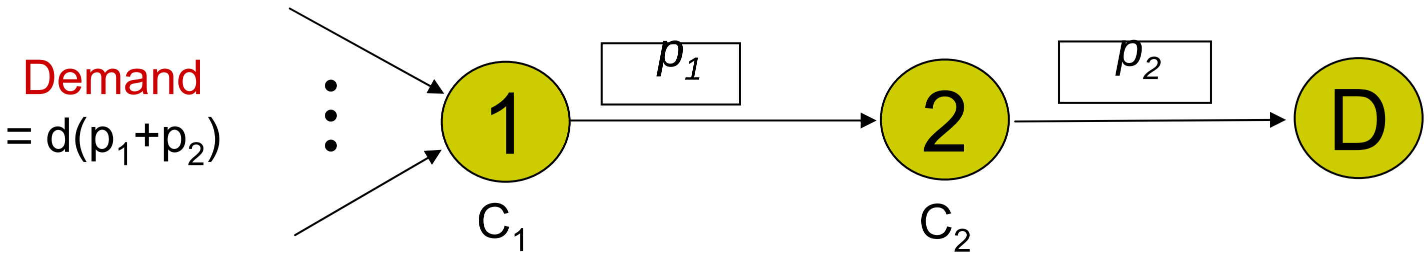
Analysis of Nash game shows:

1. Bottleneck providers get more share of revenue than others
2. Bottleneck providers may not have incentive to upgrade
3. Efficiency decreases quickly as network size gets larger (revenues/provider drop with size)

Competition of Providers

Revenue Sharing Game:

Providers agree to share the revenue equally, but still choose their prices independently



Provider 1

$$\max_{p_1} \quad \frac{1}{2}(p_1 + p_2)\, d(p_1 + p_2)$$
$$\text{s.t.} \quad d(p_1 + p_2) \leq C_1$$

Provider 2

$$\max_{p_2} \quad \frac{1}{2}(p_1 + p_2)\, d(p_1 + p_2)$$
$$\text{s.t.} \quad d(p_1 + p_2) \leq C_2$$

Competition of Providers

In this revenue-sharing game,

- A Nash Equilibrium always exists
- Incentive to upgrade
  - Upgrade will always increase bottleneck providers' revenue
- Efficient when capacities are adequate
  - It is the same as that in centralized allocation
  - Revenue per provider strictly dominates that in Nash game
- A distributed algorithm exists to compute prices.

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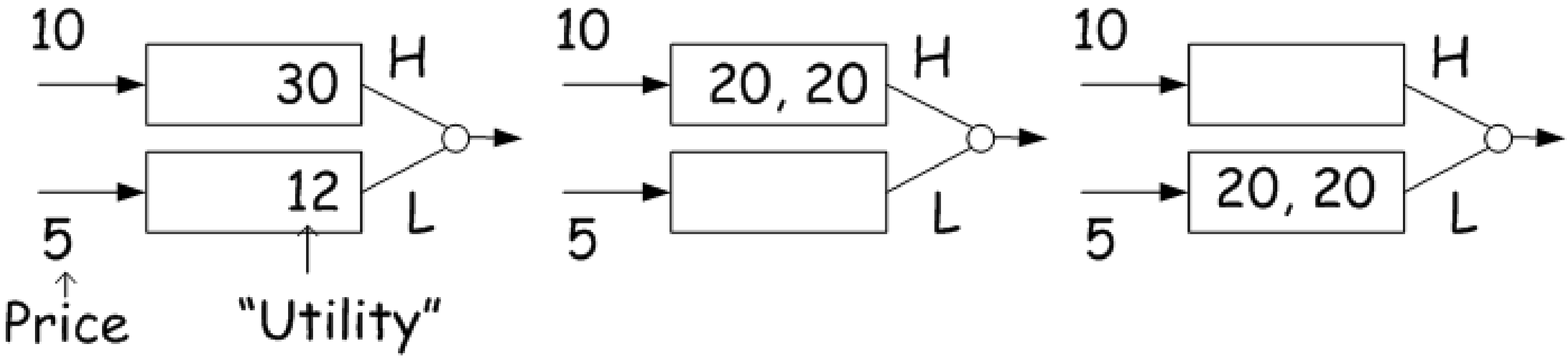
Pricing QoS



Prisoner's Dilemma

A \ B	H	L
H	20 - 10 = 10 20 - 10 = 10	30 - 10 = 20 12 - 5 = 7
L	12 - 5 = 7 30 - 10 = 20	20 - 5 = 15 20 - 5 = 15

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Uncertainty

Uncertainty may cause missing markets

Market for Lemons

Dealer buy used car for θ uniform in $[0, 1]$.

Buyer values a car that costs θ at 1.5θ.

Dealer asks X for a given used car.

Given X, potential buyer thinks that

θ is uniformly distributed in $[0, X]$.

The expected value of the car to the potential buyer is

$$E[1.5\theta|X] = 1.5 \times 0.5X = 0.75X < X.$$

Hence, the potential buyer does not buy.

If θ were known to the potential buyer, the dealer could ask 1.25θ and both the dealer and the buyer would be happy with the trade.

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Auction – Vickrey

One item. N buyers with valuations v_i.

- Items goes to highest bidder
- Winner pays second highest bit.

> Dominant strategy: (Vickrey)
> Bid true valuation ($\Rightarrow$ efficient).

Buyer 1's reward is

$$(v_1 - z)1\{b_1 > z\}$$

where z is the second highest bid.

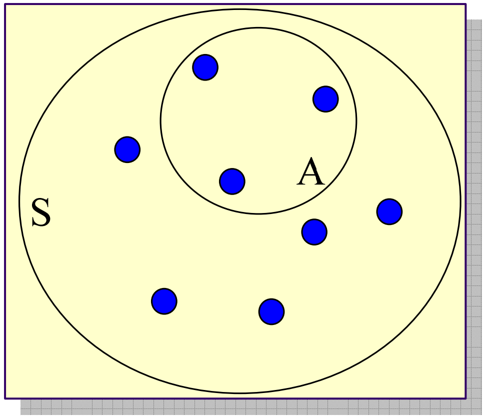
Note that $(v_1 - z)1\{v_1 > z\} \geq (v_1 - z)1\{b_1 > z\}$,

as you see by looking at $v_1 > z$ and $v_1 < z$.

Auction - VCG

Scheme: There is a set S of items. User i has a real utility $v_i(A)$ and declares a utility $b_i(A)$ for every subset $A \subset S$, for $i = 1, \dots, n$. The auctioneer solves Maximize $\sum_{i=1}^{n} b_i(A_i)$ over the possible partitions $(A_1, \dots, A_n, A_{n+1})$ of S. The optimum determines the allocations A_i. To calculate the payments, repeat without agent i and find the optimum allocations B_j^i. The payment of agent i is then

$$\pi_i = \sum_{j \neq i} [b_j(B_j^i) - b_j(A_j)].$$

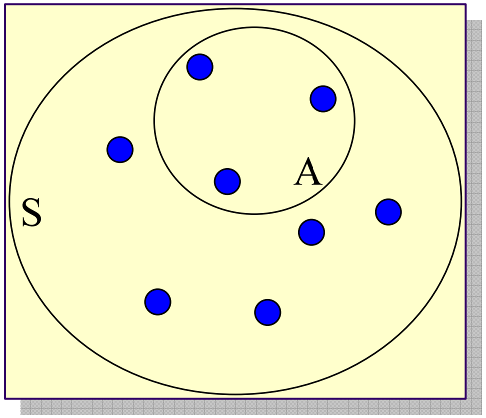


Auction - VCG

The payment of agent i:

$\pi_i = \sum_{j \neq i}[b_j(B_j^i) - b_j(A_j)]$.

(Externaiity Price)



Theorem:

A dominant strategy is to declare the true valuations. The resulting NE is efficient since it maximizes the social welfare.

Auction – Bidding for QoS

Model (Shu, Varaiya)

Utility of i in class c: $v_i g_c$ (g_c = goodput)

True valuations:

$\{v_1, \ldots, v_N\}$

Actual bids:

$\{x_1, \ldots, x_N\}$

Assignments and prices:

$\{p_1, \ldots, p_N\}$

g_c

g_c	Max. # connections	Class
0,9	10	$c = 1$
0,7	10	$c = 2$
0,4	10	$c = 3$
0,2	∞	$c = 4$

Max. # connections

Auction – Bidding for QoS

VCG:

Rank in decreasing order of x_i

Fill up classes 1, 2, ... in that order

Price = reduction of value imposed on others

Say $x_1 \geq x_2 \geq \ldots \geq x_{35}$

1, ..., 10	0.9	10
11, ..., 20	0.7	10
21, ..., 30	0.4	10
31, ..., 35	0.2	∞

What is p_{13}?

13 pushes 21 and 31 down

$\Rightarrow p_{13} = (0.4 - 0.2)x_{31} + (0.7 - 0.4)x_{21}$

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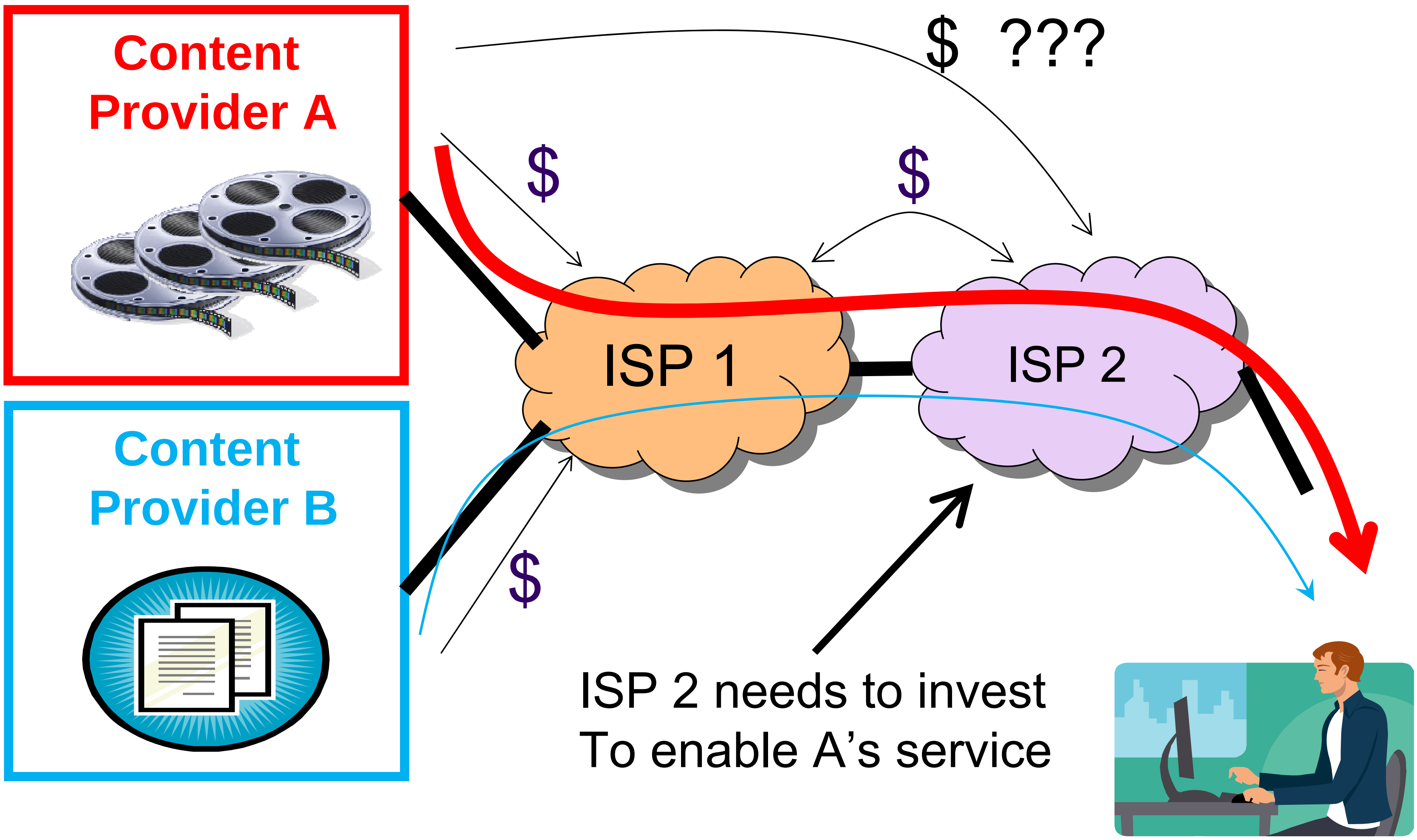
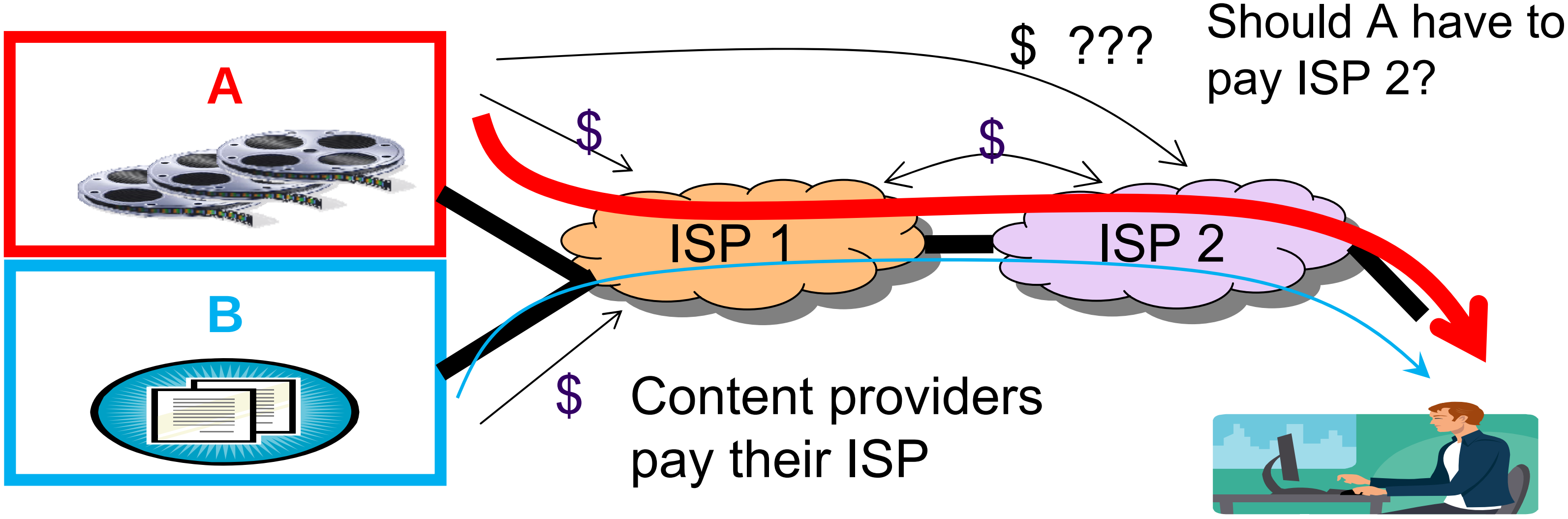
Neutrality: Issues

- Contentious Debate
- But, what (if any) bearing should the issues have on the future network architecture?
- Does future architecture need features for
  - Revenue sharing between content and transit providers?

Neutrality: Issues



Neutrality: Issues



- Would allowing 2 to charge A
  - encourage 2 to invest?
  - discourage A to invest?
- What revenue sharing mechanisms should new Internet have?

Neutrality: Model

(Content Investment, ISP Investment) → Usage

Usage → (Ad Revenue to Content, User Revenue to ISPs)

ISP

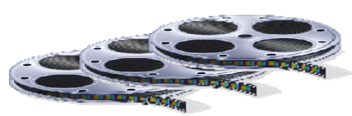
NEUTRAL →

Each Chooses:
- Investment level
- User Price

NOT NEUTRAL →

- Investment level
- User Price
- Price for <u>each</u> content provider

Content Prov.

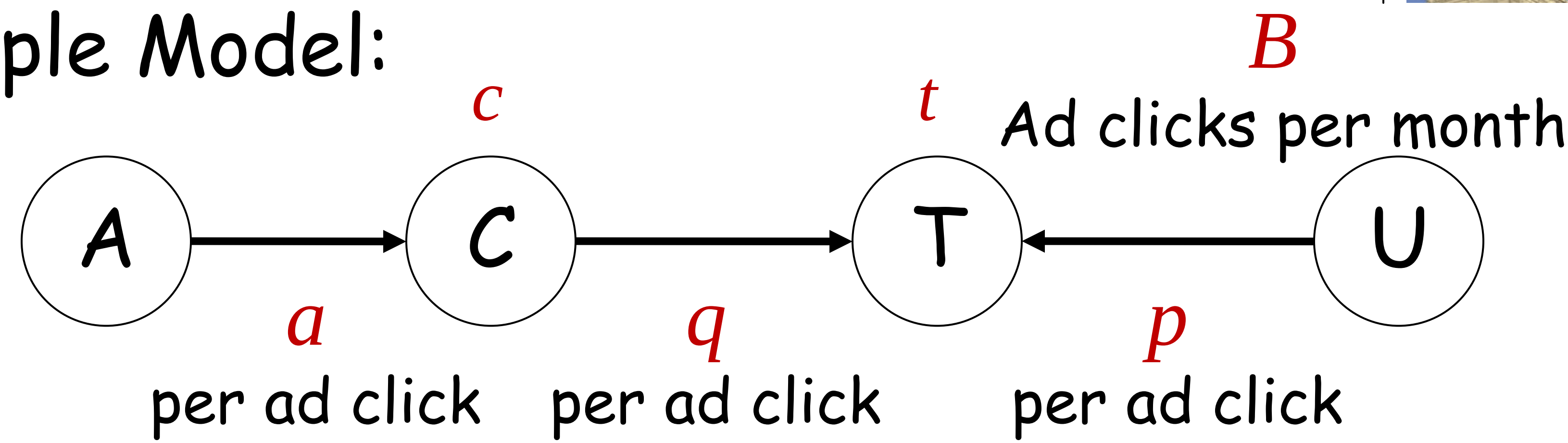


→

Each Chooses
- Investment level

Neutrality: Model

Simple Model:



$$B = c^v t^w e^{-p/\theta} \quad 0 < v, w; v + w < 1$$

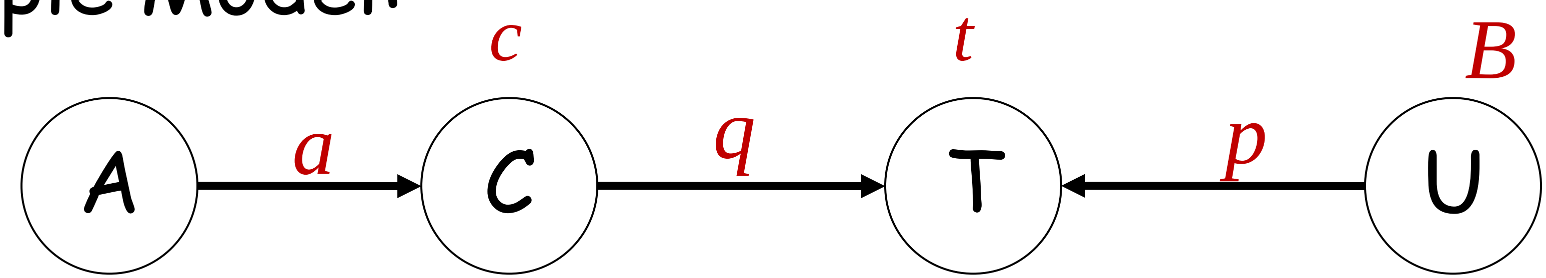
$$R_C = (a - q)B - \alpha c$$

$$R_T = (q + p)B - \beta t$$

A = advertisers
C = content provider
T = transport provider
U = regular users

Neutrality: Model

Simple Model:



$$B = c^v t^w e^{-p/\theta} \quad 0 < v, w; v + w < 1$$

$$R_C = (a - q)B - \alpha c$$

$$R_T = (q + p)B - \beta t$$

Question:

$$q \uparrow \Rightarrow R_T \uparrow$$

or

$$q \uparrow \Rightarrow R_C \downarrow \Rightarrow c \downarrow \Rightarrow B \downarrow \Rightarrow R_T \downarrow$$

Neutrality: Model

Simple Model:

$$B = c^v t^w e^{-p/\theta} \quad 0 < v, w; v + w < 1$$

$$R_C = (a - q)B - \alpha c$$

$$R_T = (q + p)B - \beta t$$

Assume T chooses (t, p, q). Then C chooses c to max

$$R_C = (a - q)c^c t^w e^{-p/\theta} - \alpha c$$

Given this c(t, p, q), T then chooses (t, p, q) to max

$$R_B = (p + q)c^c t^w e^{-p/\theta} - \beta t$$

Neutrality: Model

Simple Model:

$$B = c^v t^w e^{-p/\theta} \quad 0 < v, w; v + w < 1$$

$$R_C = (a - q)B - \alpha c$$

$$R_T = (q + p)B - \beta t$$

In the neutral case, T chooses (t, p, q = 0). Then C chooses c to max $R_C = ac^c t^w e^{-p/\theta} - \alpha c$

Given this c(t, p, 0), T then chooses (t, p, 0) to max

$$R_B = pc^c t^w e^{-p/\theta} - \beta t$$

Neutrality: Results

Result 1:

The revenues per click and ROIs are the same under both regimes for content and transport providers.

Result 2:

The size of the market is larger in the neutral case only if a/θ is neither very large nor very small.

Neutrality: Results

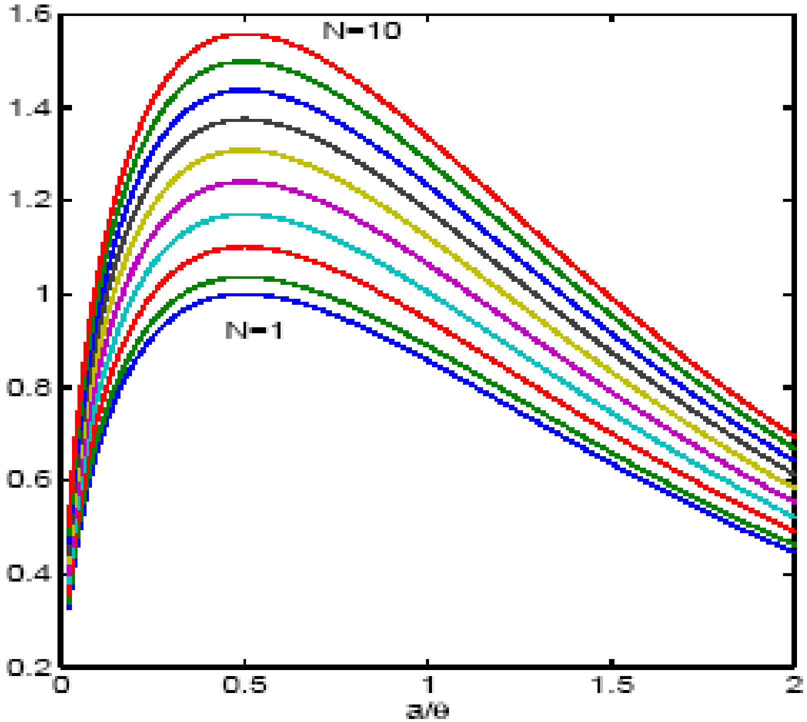
$$\left(\frac{B(neutral)}{B(non\text{-}neutral)}\right)^{1-v-w}$$

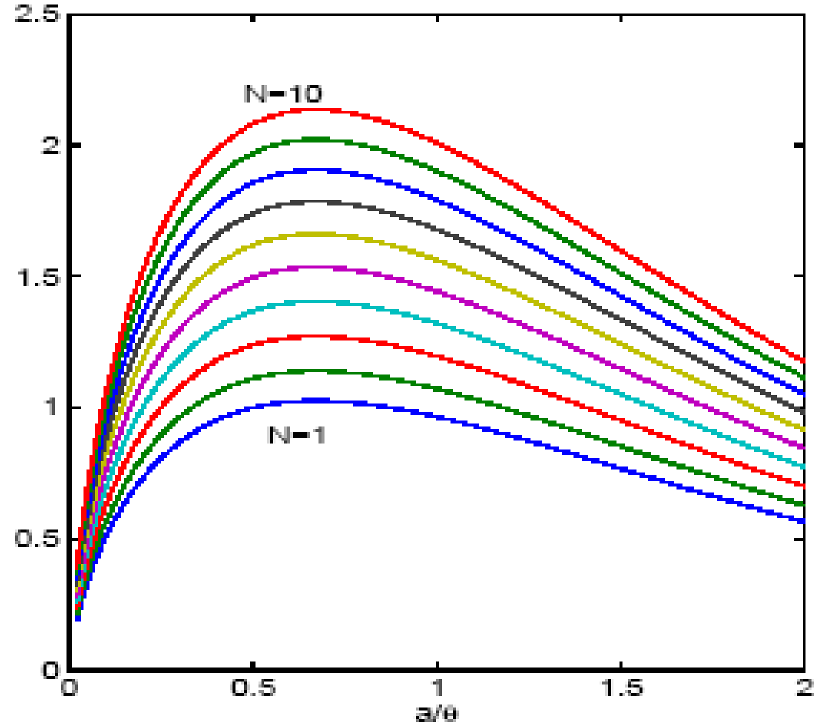
$$\left(\frac{t(neutral)}{t(non\text{-}neutral)}\right)^{1-v-w}$$

$$\left(\frac{R_T(neutral)}{R_T(non\text{-}neutral)}\right)^{1-v-w}$$

$$\left(\frac{c(neutral)}{c(non\text{-}neutral)}\right)^{1-v-w}$$

$$\left(\frac{R_C(neutral)}{R_C(non\text{-}neutral)}\right)^{1-v-w}$$





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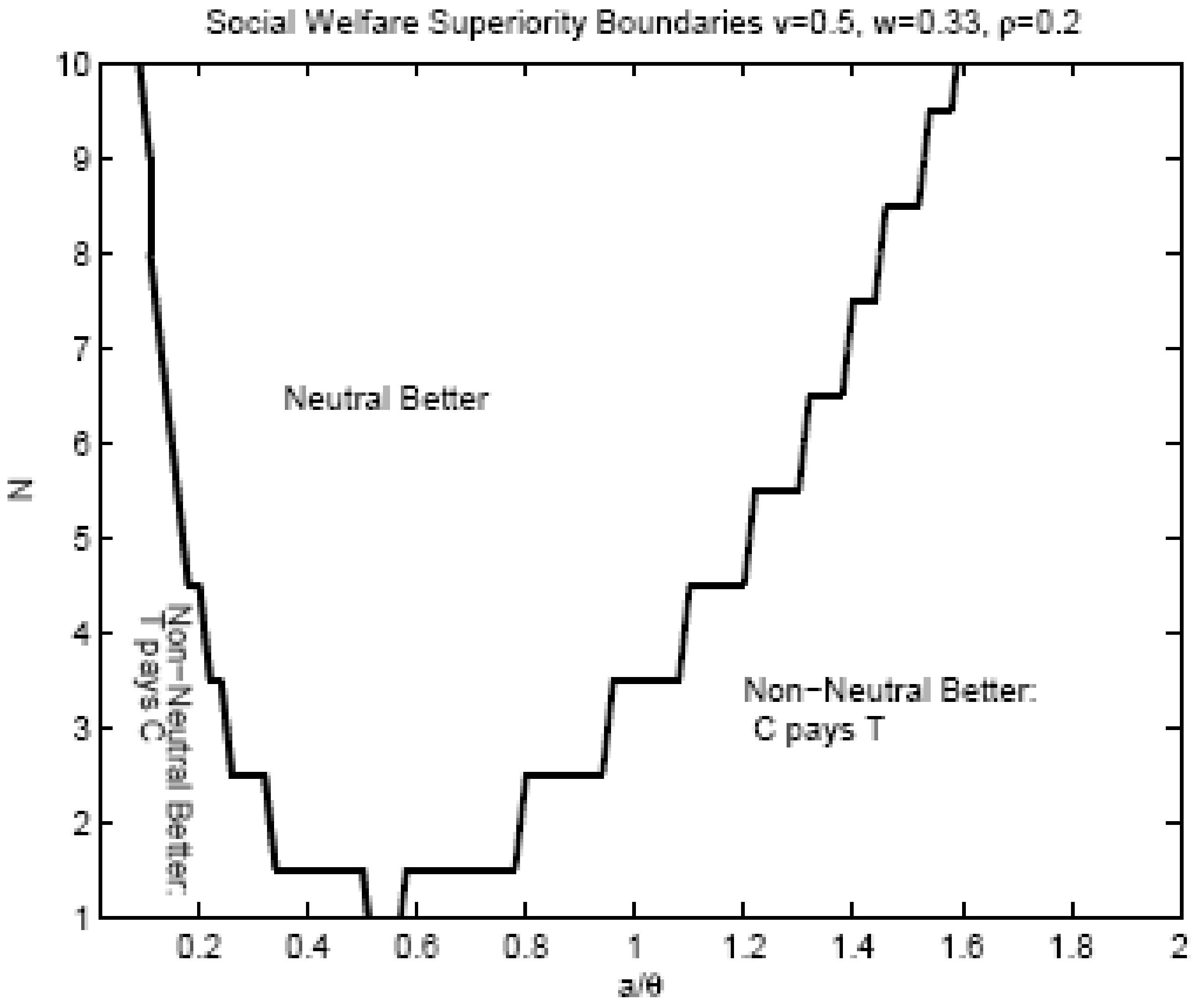

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- Service Differentiation: Paris Metro Pricing
- Competition of Providers
- Pricing QoS
- Uncertainty
- One-Sided Auctions
- Net Neutrality
- References ←

References

Here is a list of some references I used to prepare the material..

- George Akerlof, The Market for Lemons
- PioBaake, ThorstenWichmann-**On the Economics of Internet Peering -January 1998.**
- Chiu D-M and Jain R (1989). **Analysis of the increase and decrease algorithms for congestion avoidance in computer networks.Comp Networks and ISDN Sys 17: 1±14.**
- Courcoubetis, C and R.R. Weber(2003). **Pricing Network Services, Springer Verlag.**
- Cremer, J., P. Rey& J. Tirole,"**Connectivity in the Commercial Internet" Journal of Industrial Economics, December 2000,vol48, n°4, pp. 433-472**
- Feigenbaum, C. H. Papadimitriou, R. Sami, S. Shenker(2002) **A BGP-based Mechanism for Lowest-cost Routing,"in Proceedings of the 21st Symposium on Principles of Distributed Computing, ACM Press, New York, 2002, pp 173-182.**
- Fudenberg, D. and J. Tirole(1991). **Game Theory. MIT Press.**
- Geoff Huston–**Interconnection and Peering, November 2000.**
- Garrett Hardin, *The Tragedy of the Commons*, 1968
- P. Honeyman, G. Schwartz, “Interdependence of Reliability and Security,” Workshop on Economics of Information Security, CMU, June 2007
- ITS, Congestion Pricing
- J. Musacchio, S. Wu, “A Game Theoretic Model for Network Upgrade Decisions,” Allerton Conference 2006.

References

- J. Musacchio, S. Wu, " The Price of Anarchy in a Network Pricing Game," in submission.
- Musacchio, J. and J. Walrand. **Game-theoretic analysis of Wi-FiAccess Pricing, in preparation.**
- J. Musacchio, J. Walrand, "Economic Consequences of Weak Network Neutrality," to appear at Asilomar 2007.
- Tim Roughgarden, Selfish Routing and the Price of Anarchy
- Hal Varian, *System Reliability and Free Riding*, 2001
- Y. Jin and G. Kesidis, **Feasible pricing of differentiated services for the emerging Internet, in Proc. 40th AllertonConference on Communications, Control and Computing, Oct. 2002.**
- J.-J. Laffont, S. Marcus, P. Rey, and J. Tirole, "**Internet interconnection and the off-net-cost pricing principle," 2001.**
- Andrew Odlyzko,**Paris Metro Pricing for the Internet(1998),ACM Conference on Electronic Commerce**
- [PG93] AbhayK. Parekh, Robert G. Gallager: **A Generalized Processor Sharing Approach to Flow Control in Integrated Services Networks: The Multiple Node Case. INFOCOM 1993: 521-530.**
- [S90] Vernon Smith et al., "**Auction Design for Composite Goods," Journal of Economic Behavior and Organization, 14 (1990) 127-129.**
- [SV03] Jun Shu and PravinVaraiya, **Pricing Network Services.Infocom2003.**
- [V61] Vickrey, W.,1961, "**Counterspeculation, Auctions, and Competitive Sealed Tenders," Journal of Finance, XVI, 8-37.**