Routing Money, Not Packets: A Tutorial on Internet Economics

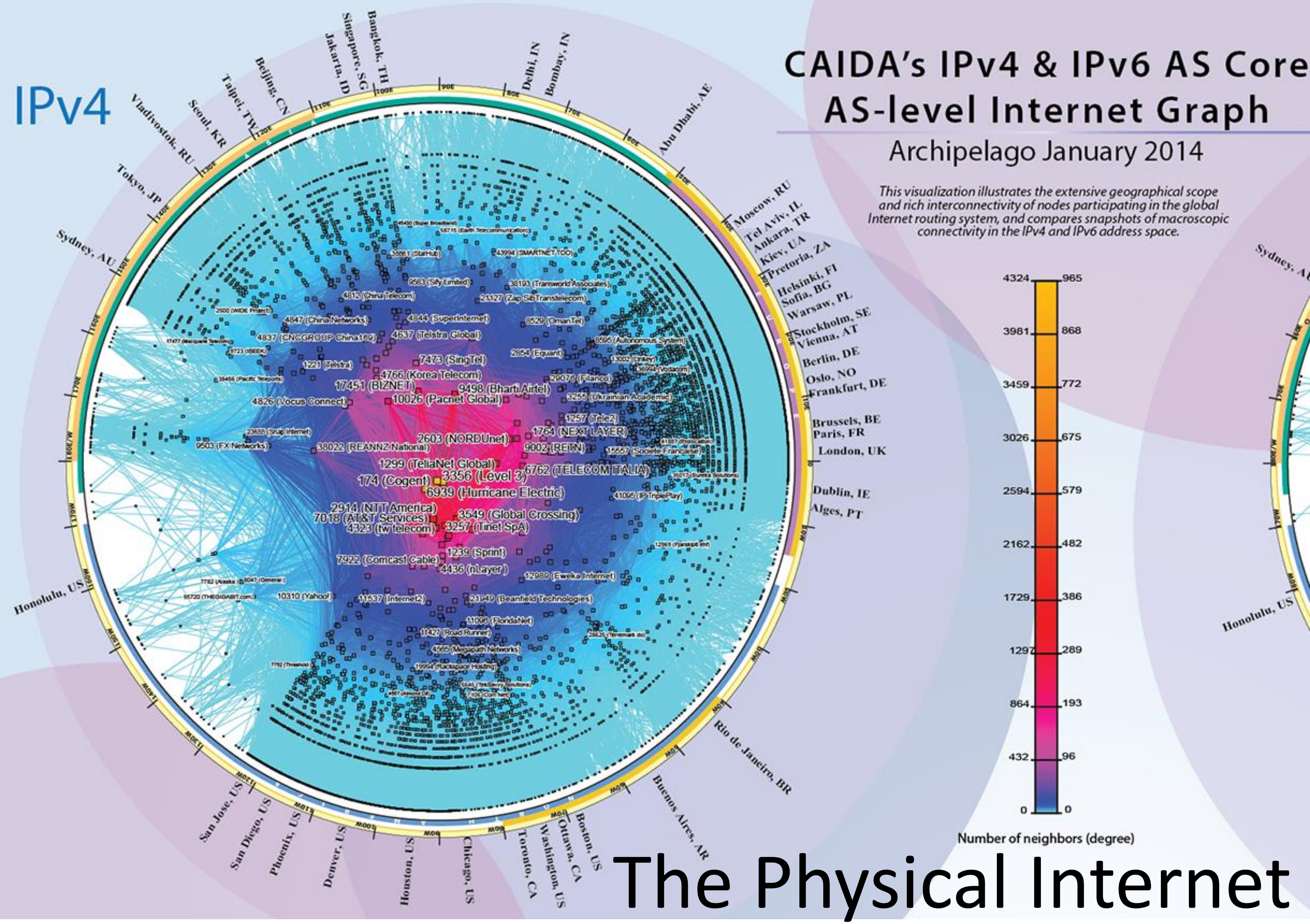
Richard Ma,
National University of Singapore
and
Vishal Misra,
Columbia University

Structure of the tutorial

- Background
- Analyzing ISP interaction
  - Cooperative Game Theory
- Two-sided market model
  - Congestion Equilibrium
- Analyzing Access Provider-Content Provider interaction
  - AP’s paid prioritization and its impact on net neutrality
  - CP’s peering decisions and competition
- Differential Pricing and Zero Rating
  - (re)Defining Net Neutrality

Conversation between a prominent Economist and Dave Clark (Foundational Architect of the Internet)

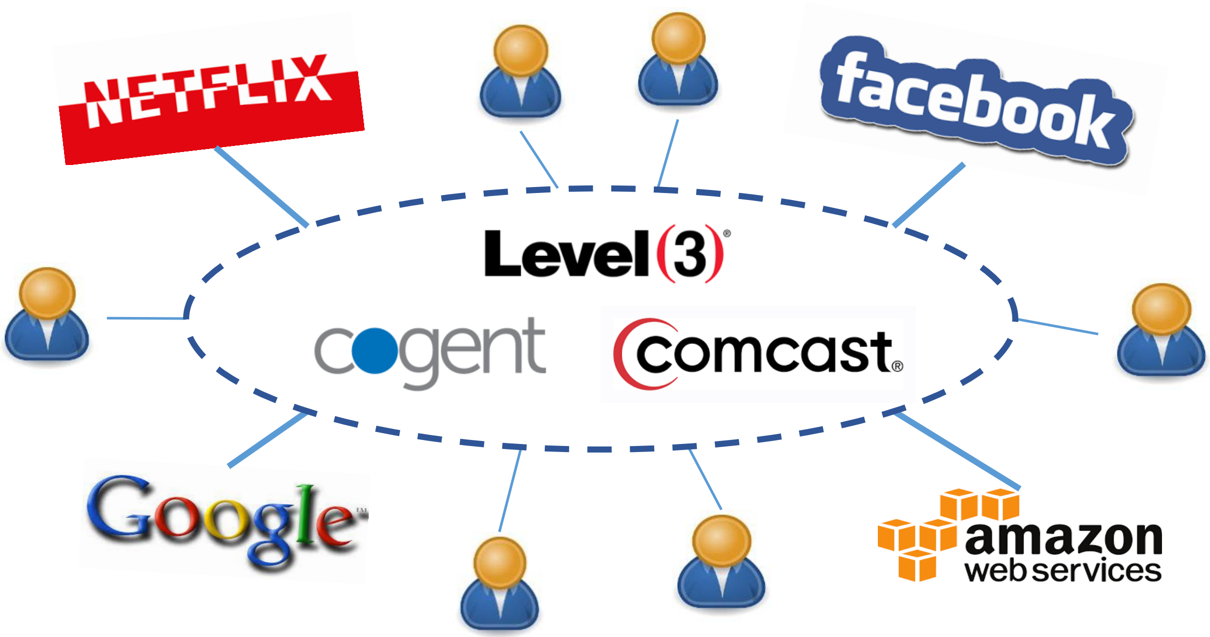
- Economist: “The Internet is about routing money. Routing packets is a side-effect.”
- Economist: “You really screwed up the money-routing protocols”.
- Dave: “We did not design any money-routing protocols”.
- Economist: “That’s what I said”.



The Physical Internet

http://www.caida.org/research/topology/as_core_network/pics/2014/ascore-2014-jan-ipv4v6-poster-2000x1294.png

The Conceptual Internet Platform



Net Neutrality Debate

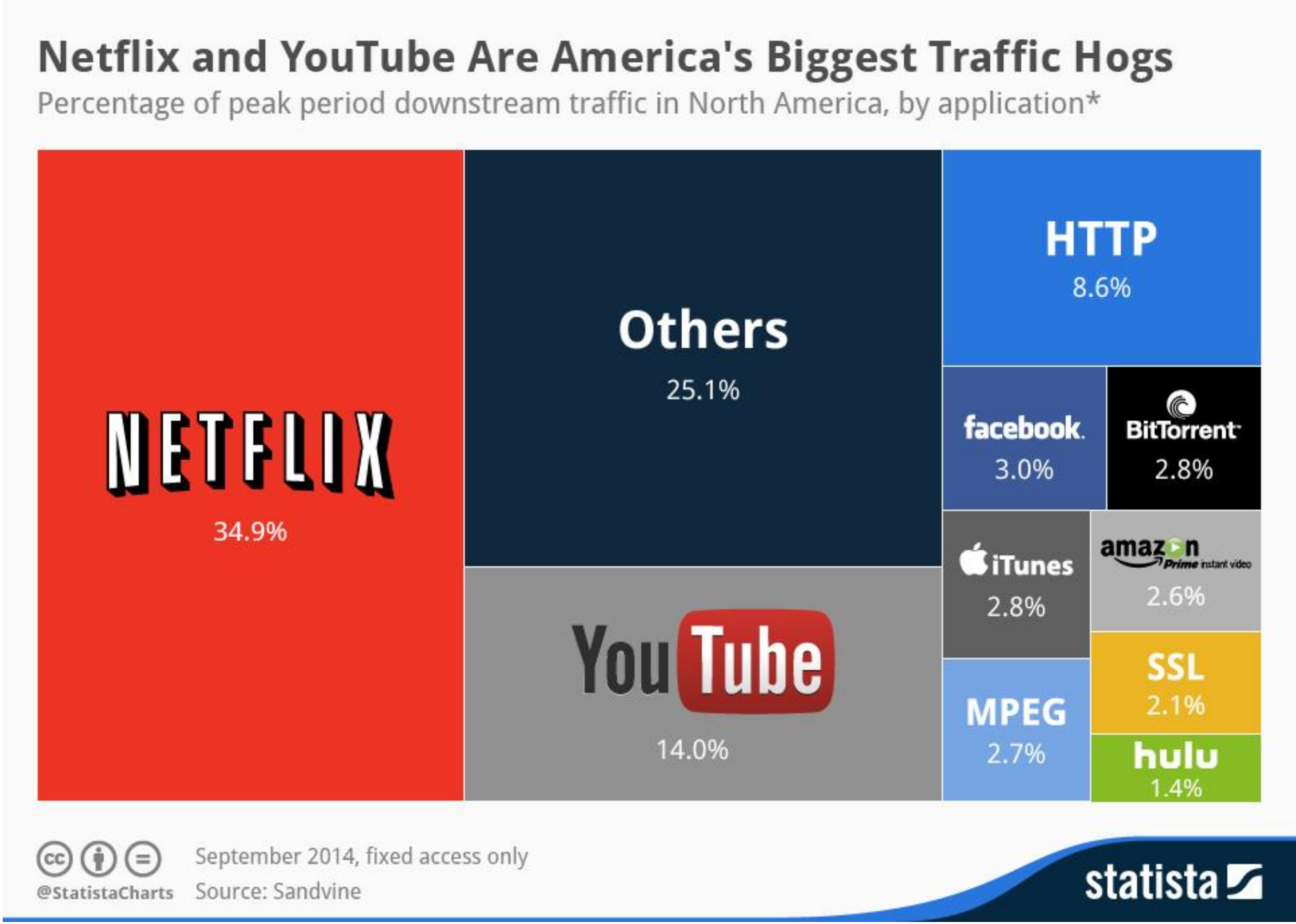
- Folk definition of net neutrality
  - “All data (packets) should be treated equally”
  - (Didn’t make sense to networking people)

- Failure to “routing the money” makes it difficult to price packets based on their values
  - Causes to economics problems like peering disputes

Peering Disputes Among ISPs

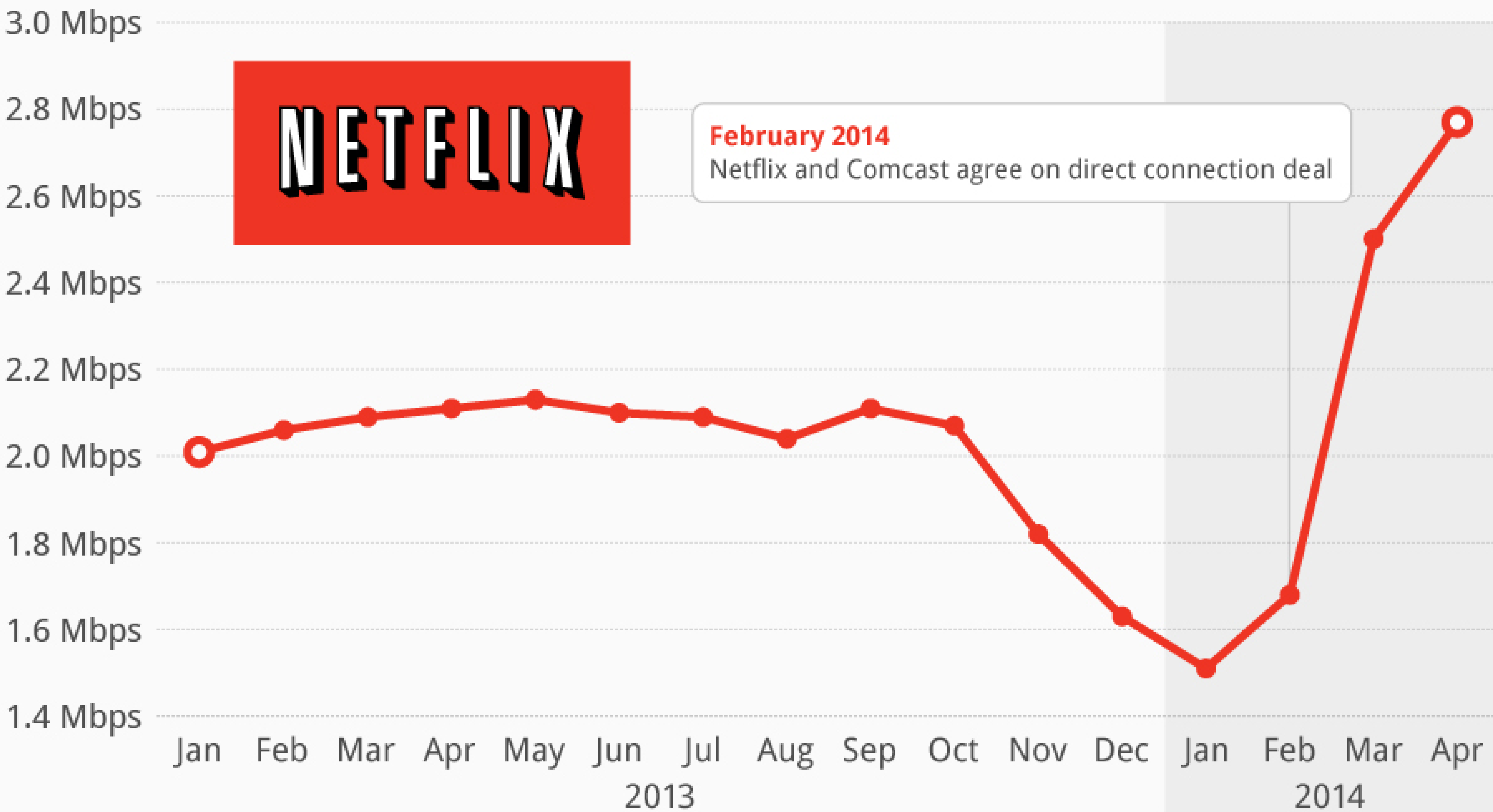
S.No.	Conflicting Companies	Month/Year	Reason
1.	Telecom Italia - Other ISPs	July'13	Telecom Italia was reducing the number of neutral access points
2.	Cogent - Verizon	June'13	Verizon neglected upgrading the peering connection
3.	FT Orange - Cogent + Google	Jan'13	FT-Orange restricted bandwidth for online video service Youtube
4.	Cogent - China Telecom	Mar'12	Parties de-peered for unknown reasons
5.	Cogent - France Telecom	Aug'11	France Telecom didn't allow Cogent to connect with its Customers
6.	Cogent - ESNet	June'11	ESNet was below the Cogent's minimum traffic volume threshold
7.	Level3 - Comcast	2010	Comcast started charging new fee to deliver Level3 traffic
8.	Cogent - Hurricane Electric	Oct'09	Both are IPv6 Tier 1 backbone, cogent de-peered HE
9.	Chunghwa Telecom - TFN	Apr'09	Reason not known
10.	Sprint - Cogent	Sept'08	Traffic Exchange Criteria not met
11.	Telia - Cogent	Mar'08	Imbalanced Traffic Ratios
12.	Cogent - Limelight	Sept'07	Cogent de-peered Limelight for unknown reasons
13.	Cogent - Level3	Oct-05	Link Terminated due to imbalanced Traffic Ratio
14.	AOL - MSN	Sept'03	Reasons unknown, but AOL users were not able to access MSN
15.	Cogent - AOL	Dec'02	Imbalanced Traffic Ratio
16.	C&W - PSINet	2001	C&W dropped the peering agreement
17.	BBN/Genuity/GTE - Exodus	Before 2001	Battle over imbalanced traffic flows
18.	BBN/GTE - MCI/Worldcom	Around '99	Nature of peering agreement was not clarified
19.	UUNet Whole Earth Networks Inc	May'97	UUNet demanded for paid peering
20.	UUNet- Others	May'97	UUNet notified its peers that they would terminate their peering
21.	AGIS - Others	Before '97	AGIS announced its new peering policy at the NANOG meeting
22.	Digex Inc - AGIS	Oct'96	Reasons not known
23.	Sprint - Other ISPs	Before '96	Sprint refused to upgrade its connection at the CIX router
24.	BBN - Other ISPs	Around '95	BBN terminated its connection at CIX router
25.	BBN - ANS	Around '95	BBN broke the agreement
26.	DANTE - EUNet	Oct'94	DANTE asked EUnet to increase their connection rate

S. Bafna et al.,"Anatomy of the Internet Peering Disputes", 2014


Netflix and YouTube Are America's Biggest Traffic Hogs
Percentage of peak period downstream traffic in North America, by application*
NETFLIX
34.9%
Others
25.1%
YouTube
14.0%
HTTP
8.6%
facebook
3.0%
BitTorrent
2.8%
iTunes
2.8%
amazon Prime instant video
2.6%
MPEG
2.7%
SSL
2.1%
hulu
1.4%
September 2014, fixed access only
Source: Sandvine
@StatistaCharts
statista

Netflix-Comcast Deal Marks The End Of Net Neutrality

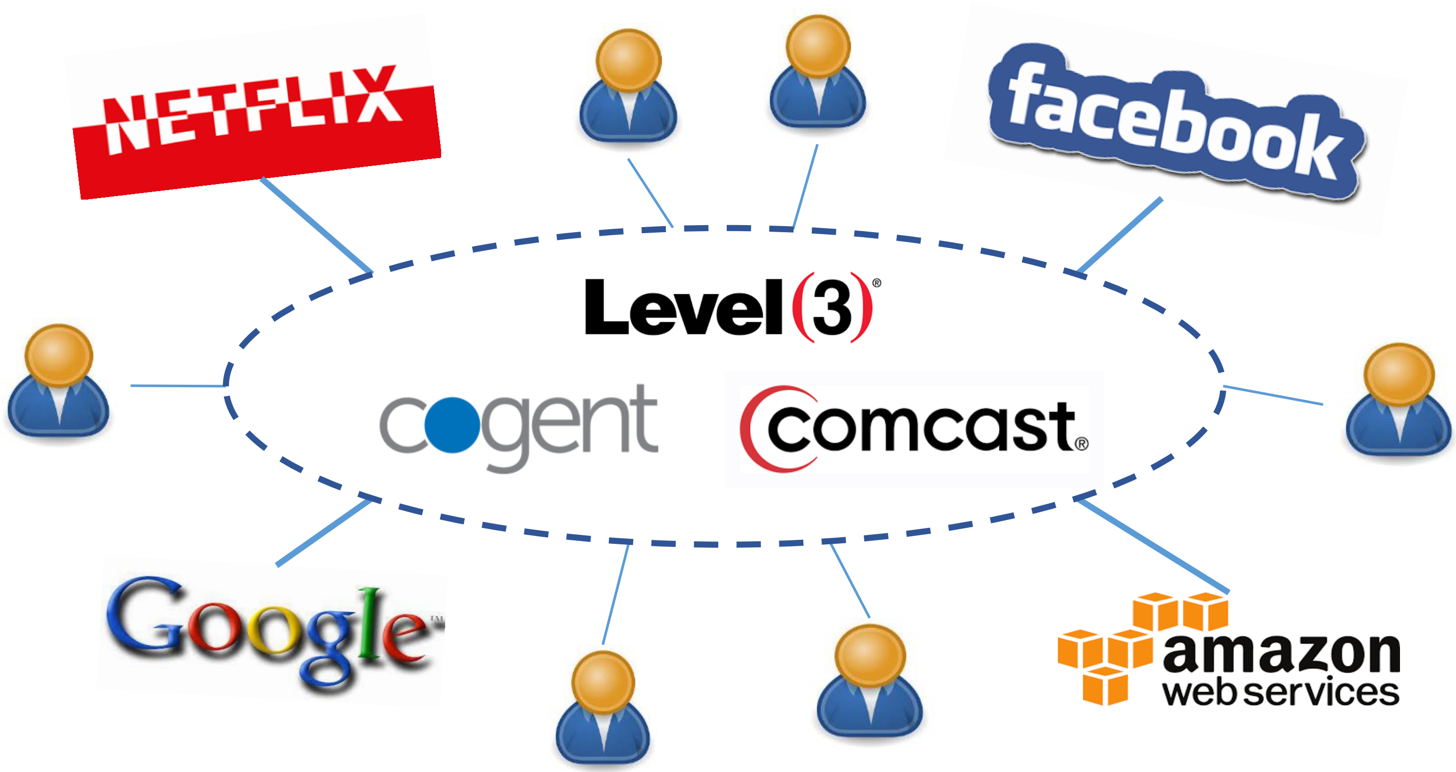
Average Netflix connection speeds on Comcast's broadband network



 Source: Netflix

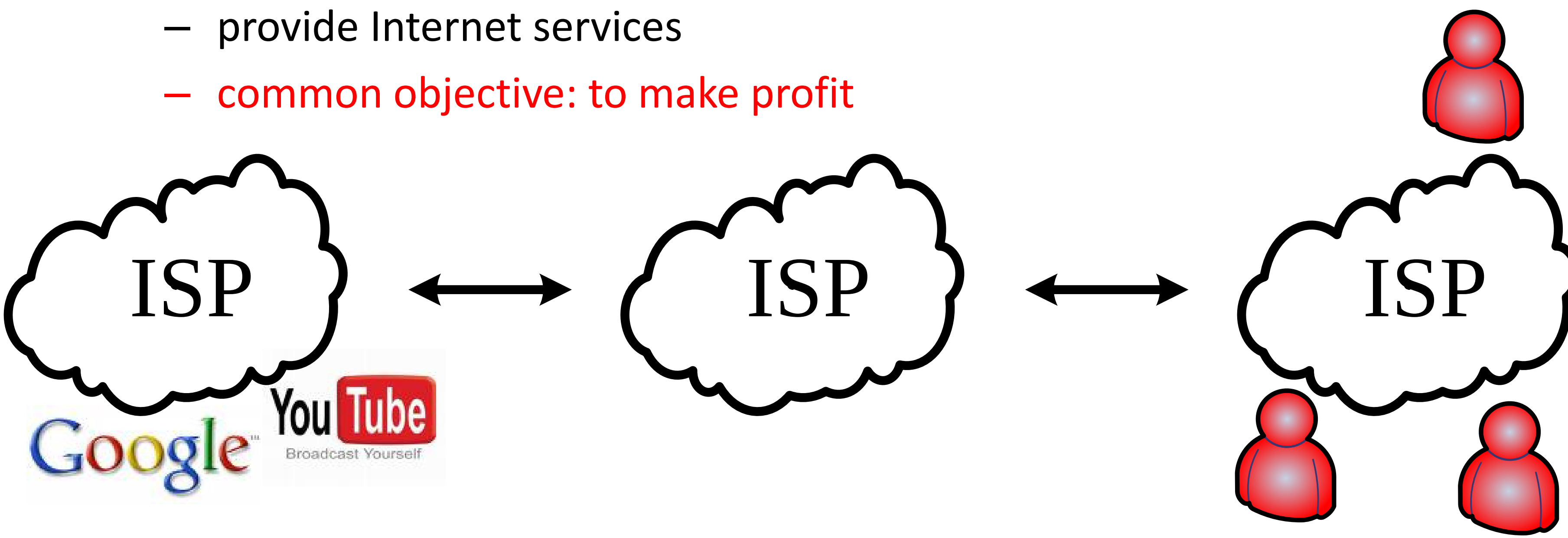
A cooperative lens of the Internet

- We first focus on the ISPs



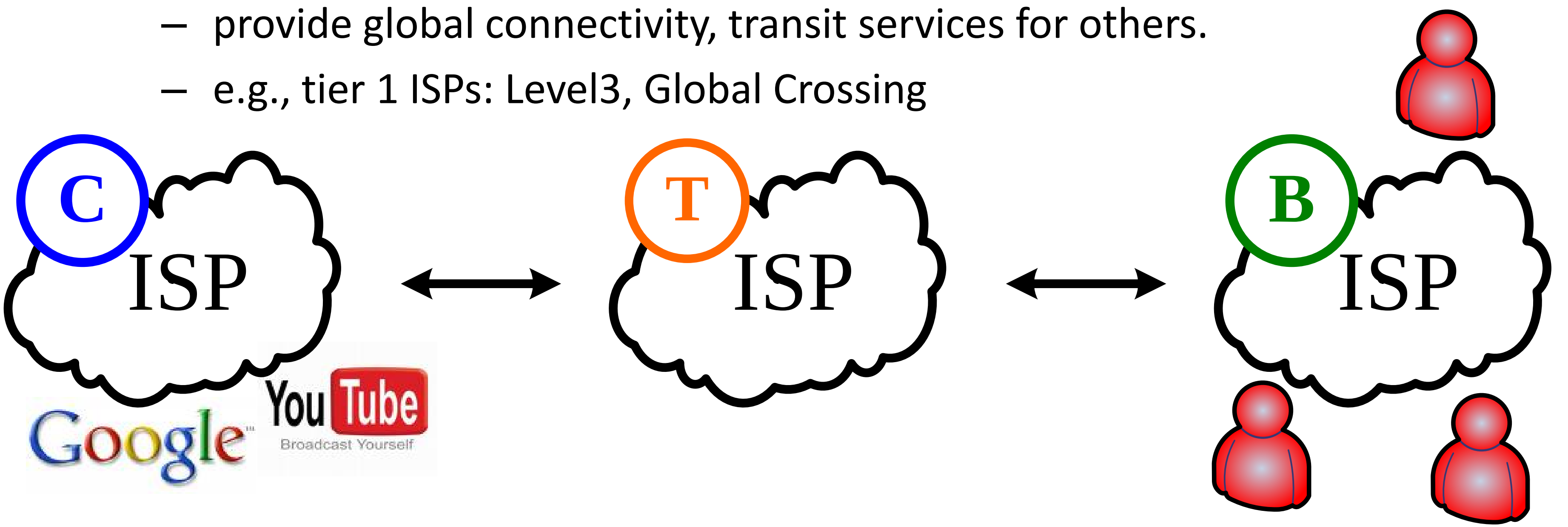
Building blocks of the Internet: ASes

- The Internet is operated by thousands of interconnected Autonomous Systems (Ases)
  - Internet Service Providers (ISPs)
  - Commercial and nonprofit organizations
- An ISP is an autonomous business entity
  - provide Internet services
  - common objective: to make profit

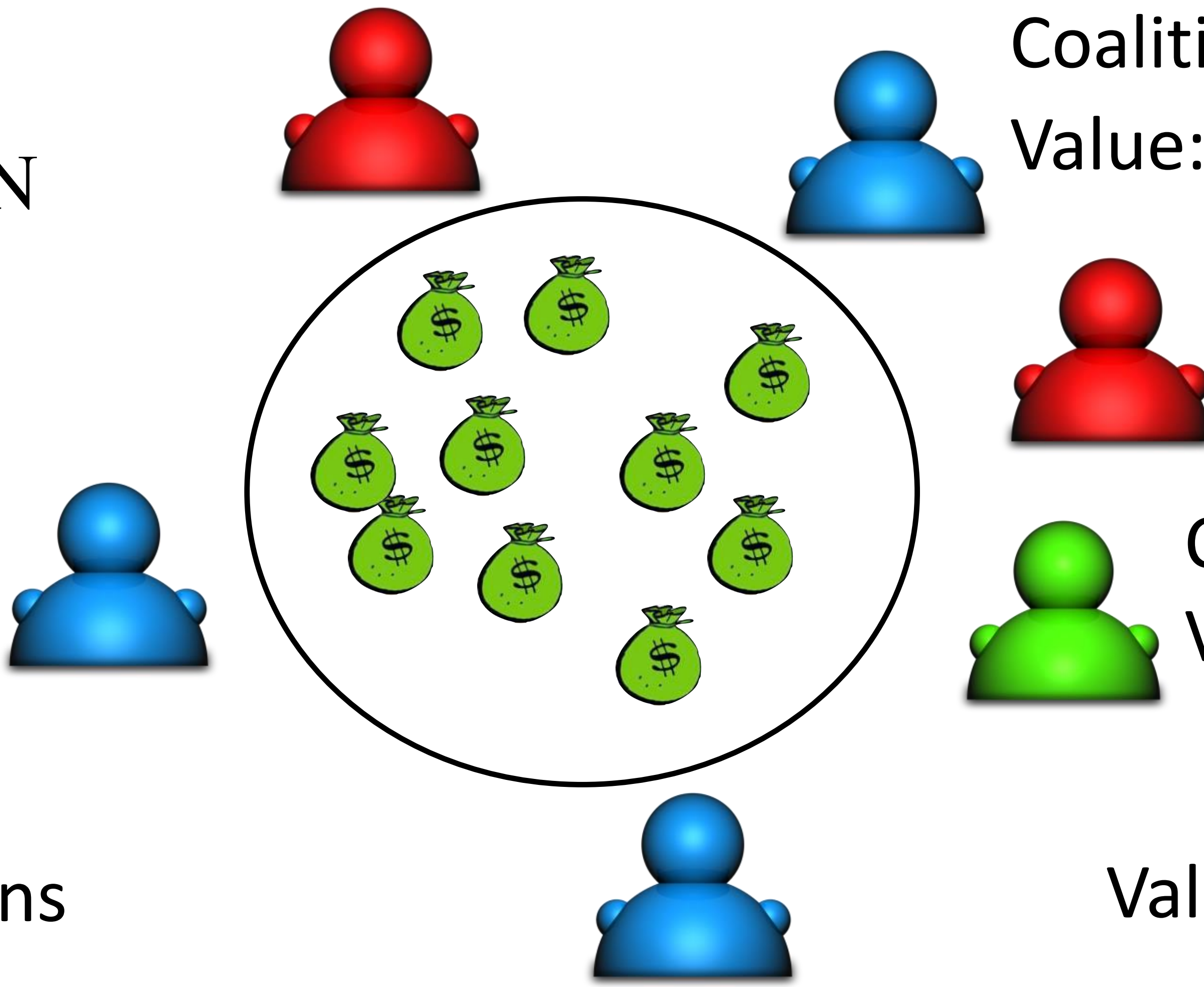


Three types of ISPs

- **Eyeball (local) ISPs:**
  - provide Internet access to residential users.
  - e.g., Singtel in SG and Comcast in US
- **Content ISPs:**
  - server content providers and upload information.
  - e.g., Cogent, Google, Akamai (Content Delivery Networks)
- **Transit ISPs:**
  - provide global connectivity, transit services for others.
  - e.g., tier 1 ISPs: Level3, Global Crossing



Cooperative Games



Players: N

Coalition: A
Value: $v(A)$

Coalition: B
Value: $v(B)$

Coalitions

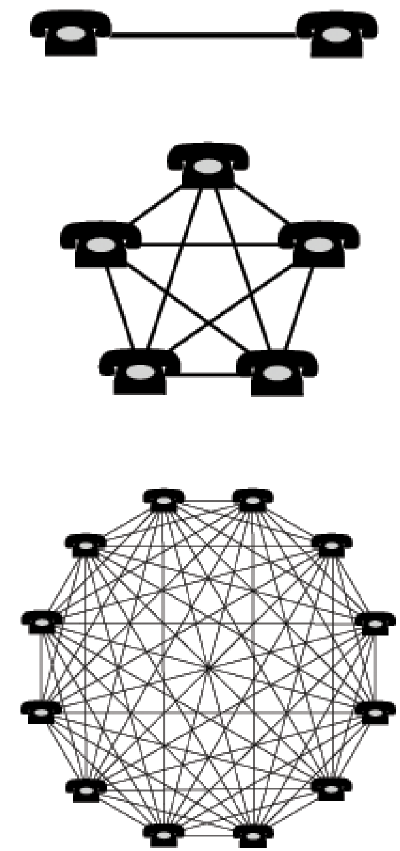
Value: v

Cooperative Game Theory

- Analyses coalition formation given value allocation
- Value allocation characterizes a solution of a game
- Some properties of interest in a solution
  - Stability: Players do not want to deviate from the solution
  - Fairness: Allocation to players reflects their contribution

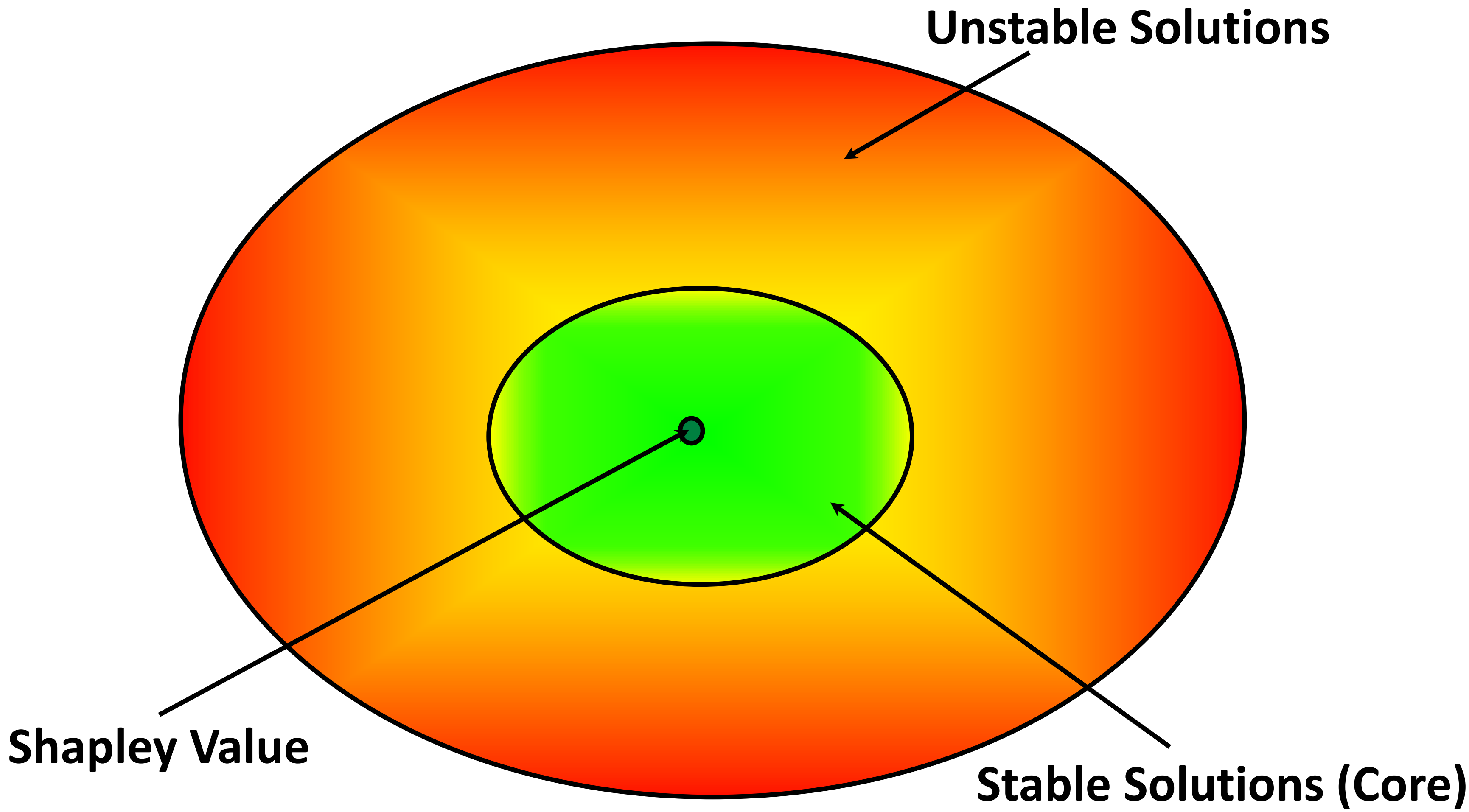
Convex coalition games

- The value function v is convex if for all coalitions $\mathcal{S}$ and $\mathcal{T}$
  - $v(\mathcal{S} \cup \{i\}) - v(\mathcal{S}) \leq v(\mathcal{T} \cup \{i\}) - v(\mathcal{T}),\ \forall \mathcal{S} \subseteq \mathcal{T}$
  - marginal profit increases with the size of the coalition



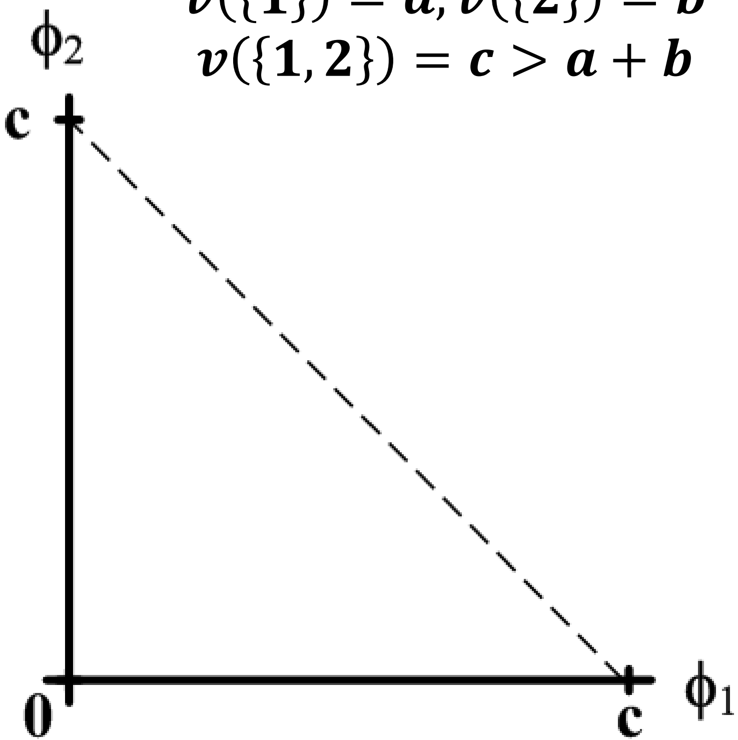
- Natural models for networks
  - Metcalfe's law: $v(\mathcal{N}) = O\left(|\mathcal{N}|^2\right)$
  - Odlyzko's law: $v(\mathcal{N}) = O(|\mathcal{N}| \log|\mathcal{N}|)$

Core and Shapley Value of Convex Games



Stability: an example

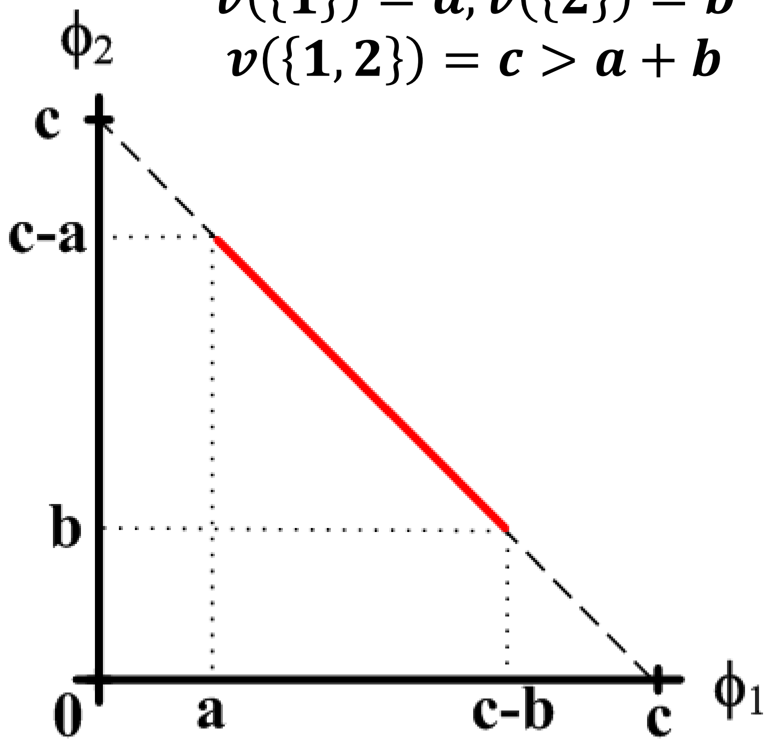
$$v(\{1\}) = a, v(\{2\}) = b$$
$$v(\{1,2\}) = c > a + b$$



- Convex game:
  - $v(\mathcal{S} \cup \mathcal{T}) \geq v(\mathcal{S}) + v(\mathcal{T})$
  - whole is bigger than the sum of parts

Stability: an example

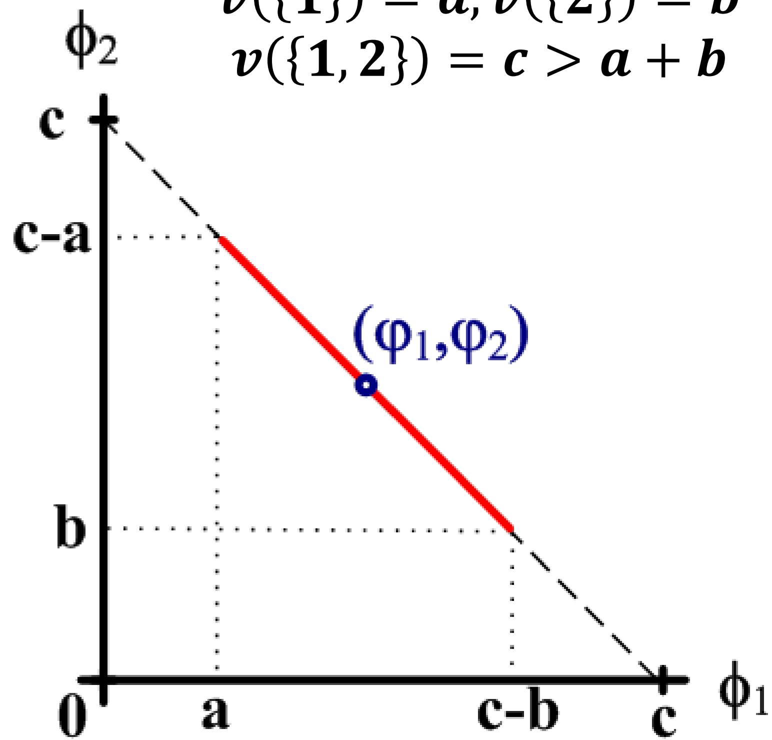
$$v(\{1\}) = a, v(\{2\}) = b$$
$$v(\{1,2\}) = c > a + b$$



- Convex game:
  - $v(\mathcal{S} \cup \mathcal{T}) \geq v(\mathcal{S}) + v(\mathcal{T})$
  - whole is bigger than the sum of parts
- Core:
  - the set of efficient profit-share that no coalition can improve upon or block

Stability: an example

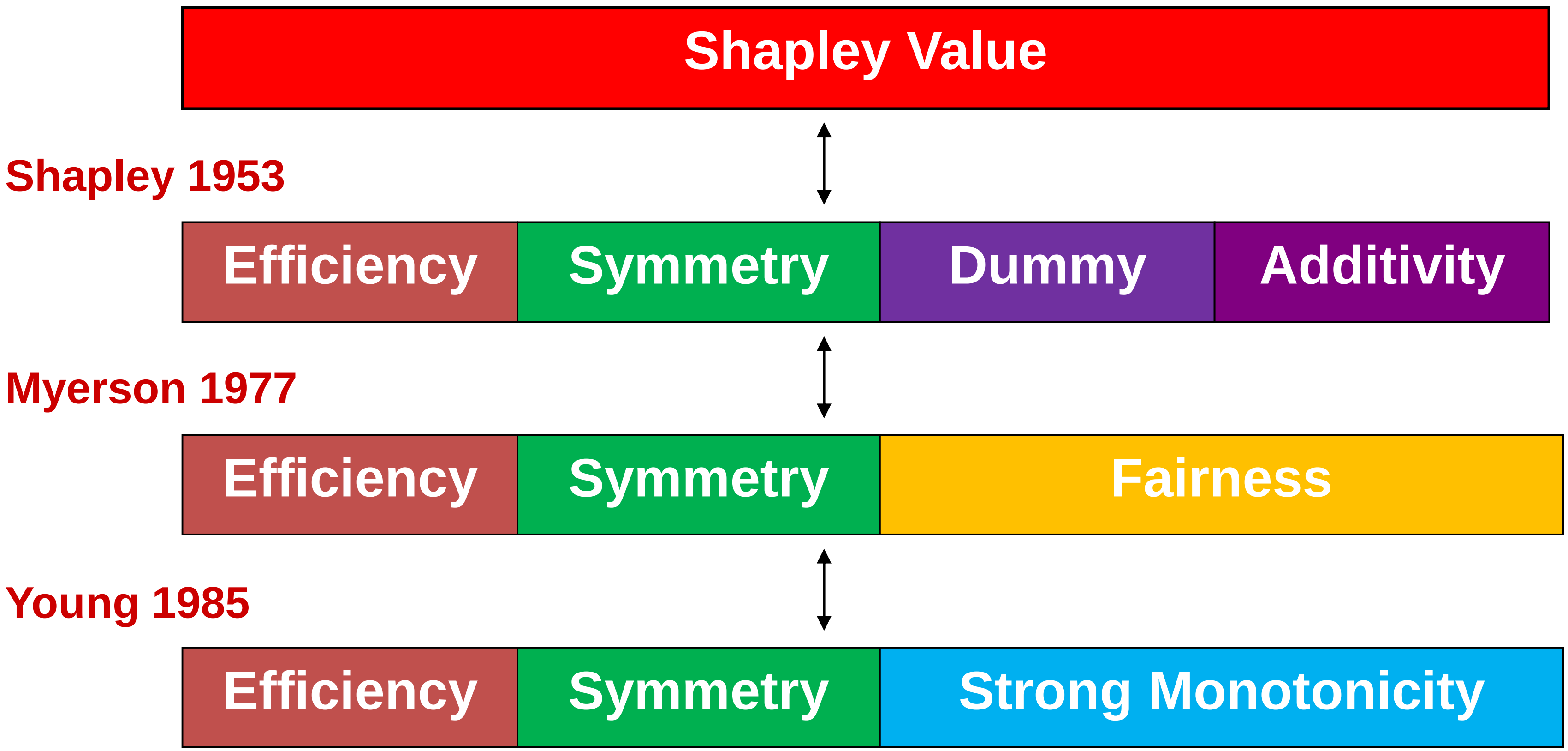
$$v(\{1\}) = a, v(\{2\}) = b$$
$$v(\{1,2\}) = c > a + b$$



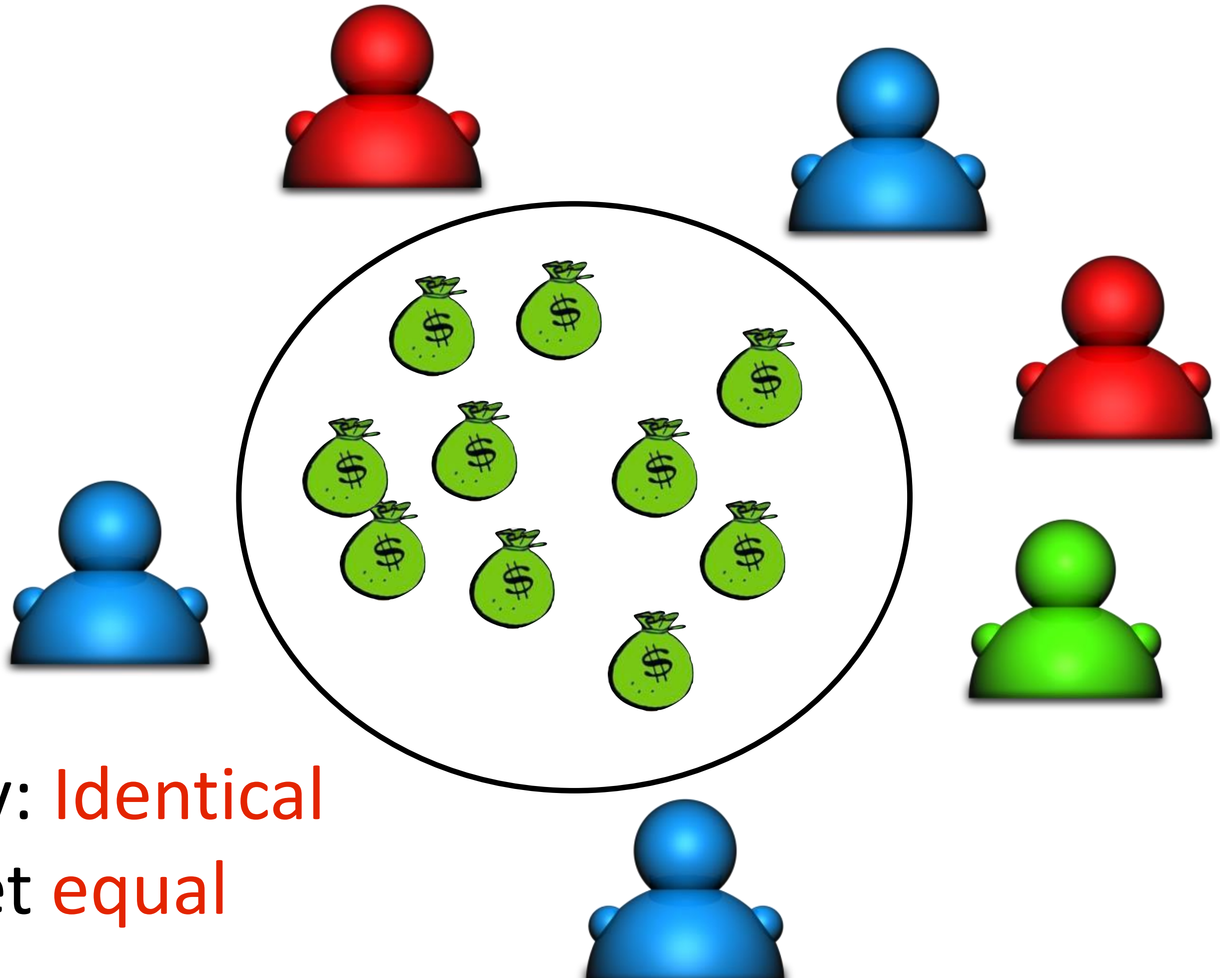
- Convex game:
  - $v(\mathcal{S} \cup \mathcal{T}) \geq v(\mathcal{S}) + v(\mathcal{T})$
  - whole is bigger than the sum of parts
- Core:
  - the set of efficient profit-share that no coalition can improve upon or block
- Shapley value:
  - core is a convex set.
  - located at the center of gravity of the core

Axiomatic characterization of the Shapley value

What is the Shapley value? – A measure of one's contribution to different coalitions that it participates.

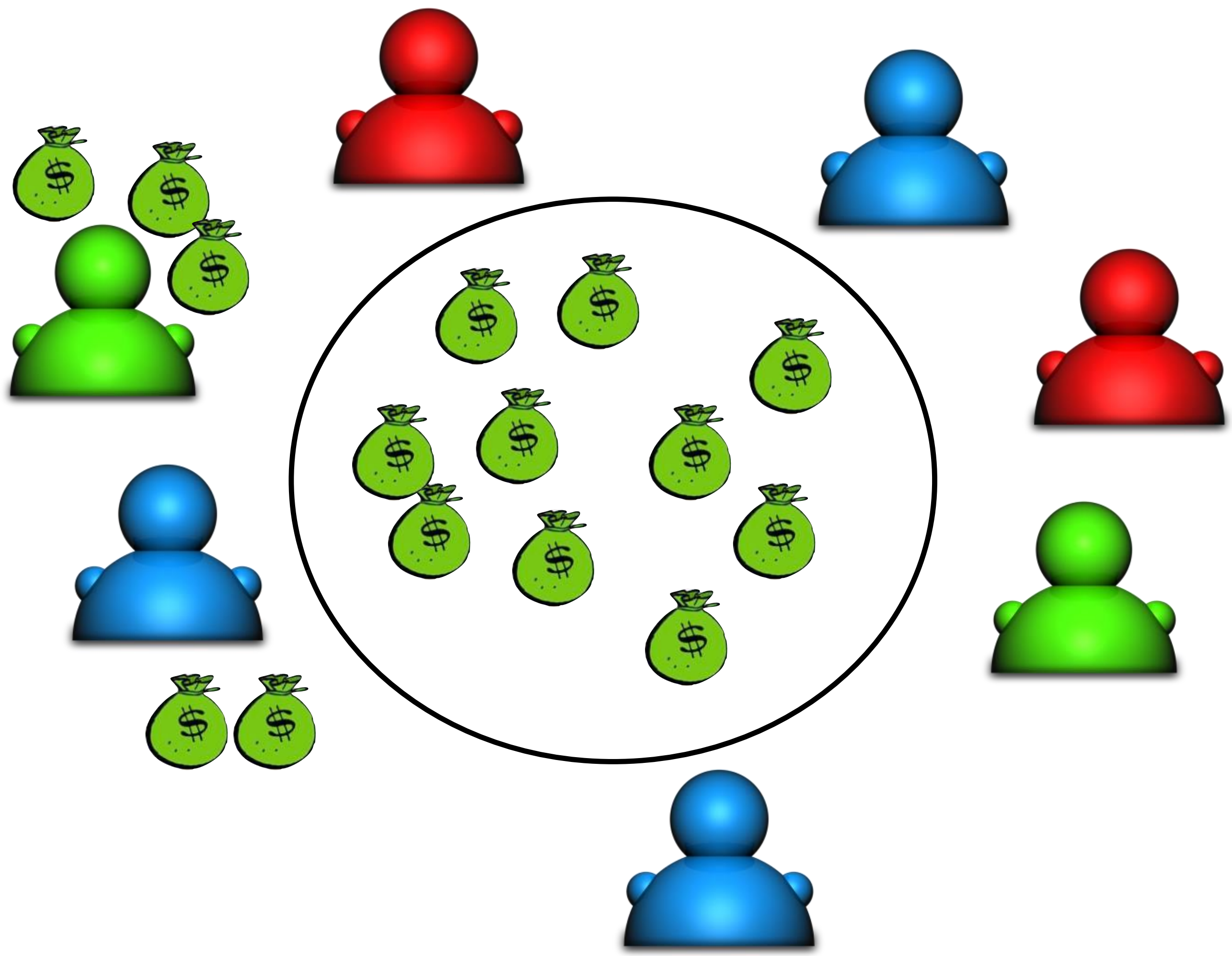


Efficiency, Symmetry

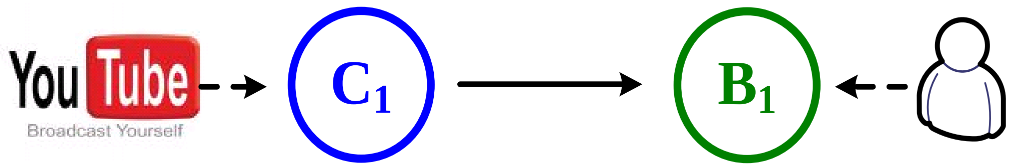


Symmetry: Identical players get equal shares

Balanced Contribution (Fairness)



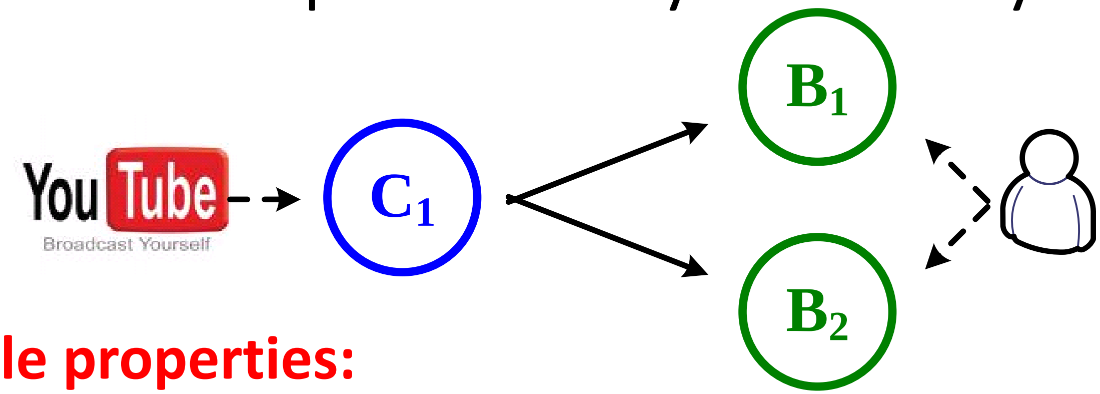
How do we share profit? -- the baseline case



- One content and one eyeball ISP
- Define total profit V
  - $=$ total revenue – total costs
  - $=$ content-side profit $+$ eyeball-side profit
- Fair profit sharing:

$$\varphi_{B_1} = \varphi_{C_1} = \frac{1}{2}V$$

How do we share profit? – 2 symmetric eyeball ISPs



- **Desirable properties:**

Symmetry: same profit for symmetric eyeball ISPs

$$\varphi_{B_1} = \varphi_{B_2} = \varphi_B$$

Efficiency: summation of individual ISP profits equals V

$$\varphi_{B_1} + \varphi_{B_2} + \varphi_{C_1} = V$$

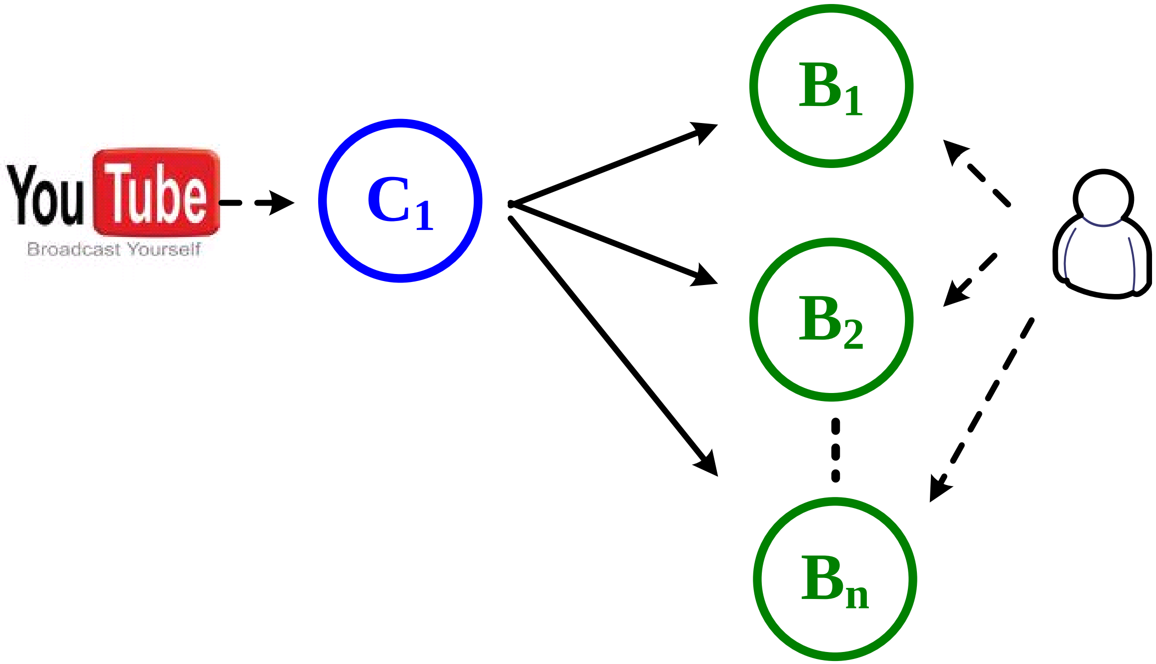
Fairness: same mutual contribution for any pair of ISPs

$$\varphi_{C_1} - \frac{1}{2}V = \varphi_{B_1} - 0$$

Unique solution (Llyod Shapley, 1953) ➔

$$\begin{cases} \varphi_{C_1} = \frac{2}{3}V \\ \varphi_{B_1} = \frac{1}{6}V \end{cases}$$

How do we share profit? – n symmetric eyeball ISPs

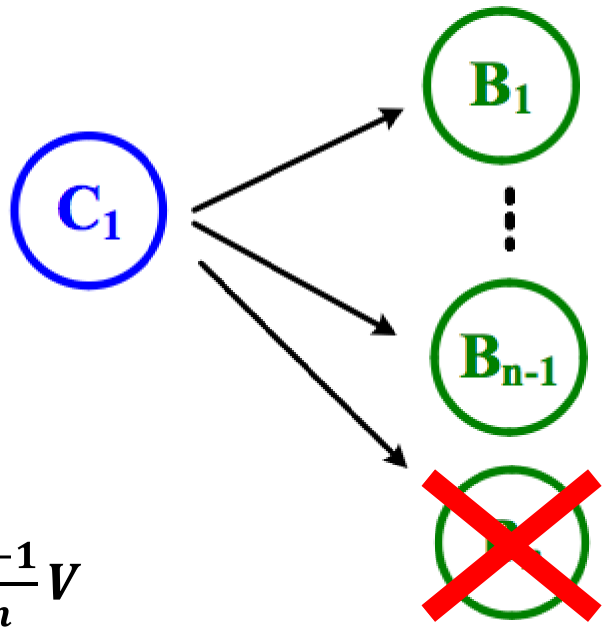


- **Theorem:** the Shapley profit sharing solution is

$$\varphi_C = \frac{n}{n+1}V; \quad \varphi_B = \frac{1}{n(n+1)}V$$

Implications of profit sharing

$$\varphi_C = \frac{n}{n+1}V; \quad \varphi_B = \frac{1}{n(n+1)}V$$



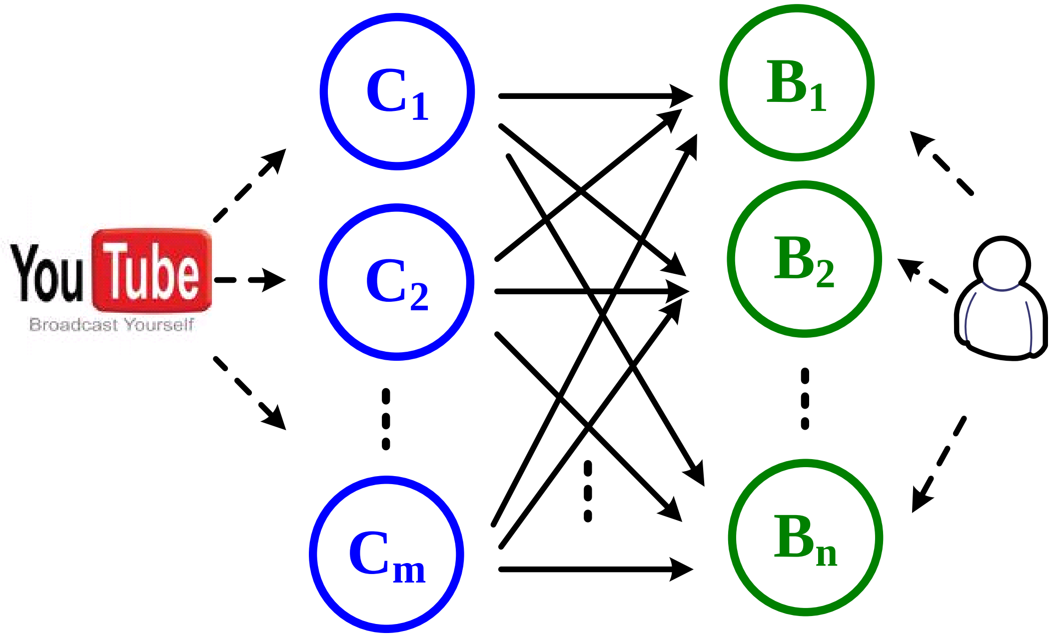
- With more eyeball ISPs, the content ISP gets a larger profit share.
  - Multiple eyeball ISPs provide redundancy ,
  - The single content ISP has leverage.

- Content's profit with one less eyeball: $\varphi'_C = \frac{n-1}{n}V$
- The marginal profit loss of the content ISP:

$$\varphi_C - \varphi'_C = \frac{n-1}{n}V - \frac{n}{n+1}V = -\frac{1}{n^2}\varphi_C$$

- If an eyeball ISP leaves
  - The content ISP will lose $1/n^2$ of its profit.
  - If n=1, the content ISP will lose all its profit.

Profit share -- multiple eyeball and content ISPs

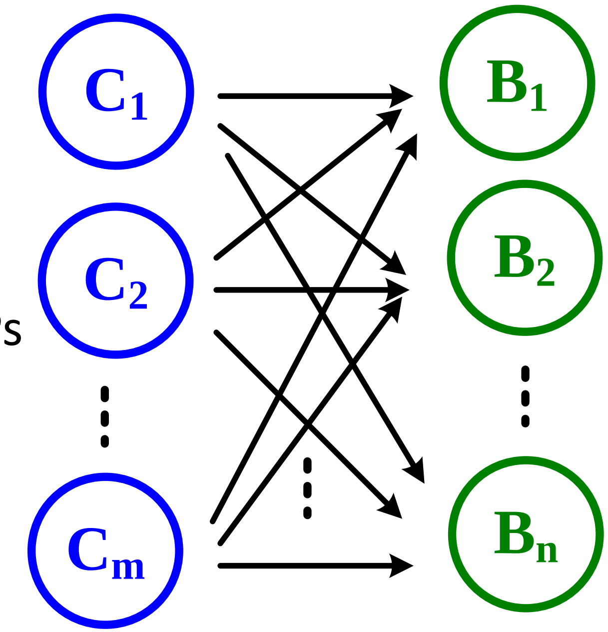


- **Theorem:** the Shapley profit sharing solution is

$$\varphi_C = \frac{n}{m(n+m)}V; \quad \varphi_B = \frac{m}{n(n+m)}V$$

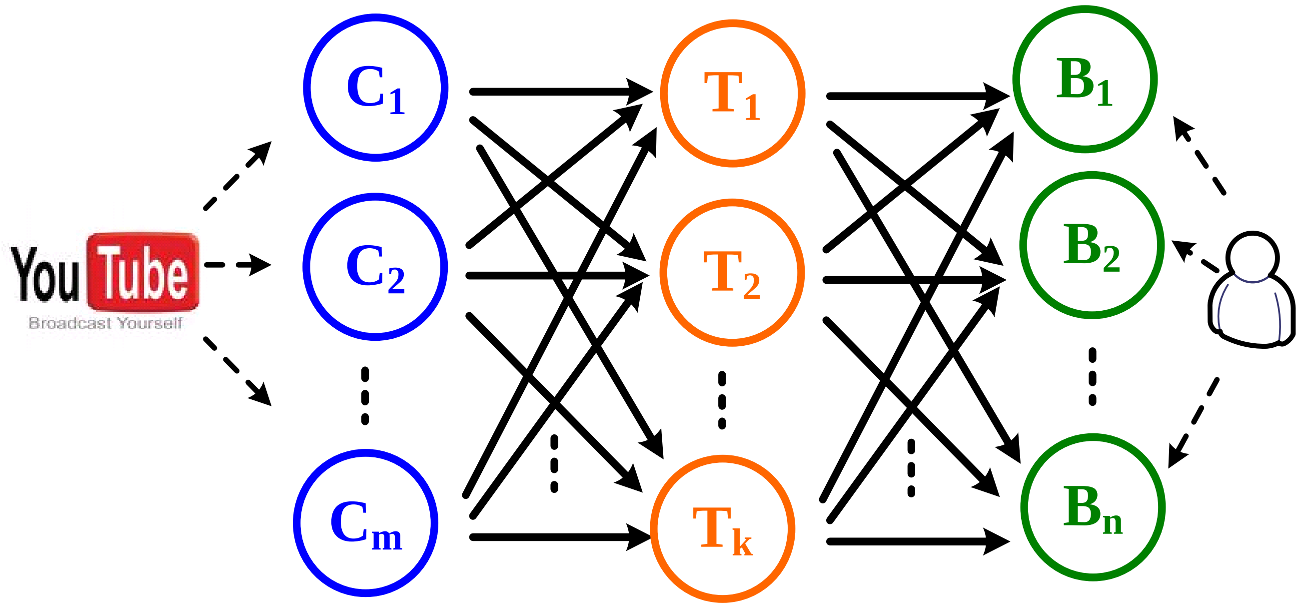
Results and implications of ISP profit sharing

$$\varphi_C = \frac{n}{m(n+m)} V; \quad \varphi_B = \frac{m}{n(n+m)} V$$



- Each ISP's profit share is
  - Inversely proportional to the number of ISPs of the same type.
  - Proportional to the number of ISPs of the other type.
- Intuition
  - When more ISPs provide the same service, each of them obtains less bargaining power.
  - When fewer ISPs provide the same service, each of them becomes more important.
- <u>Implication: market structure determines the value!</u>

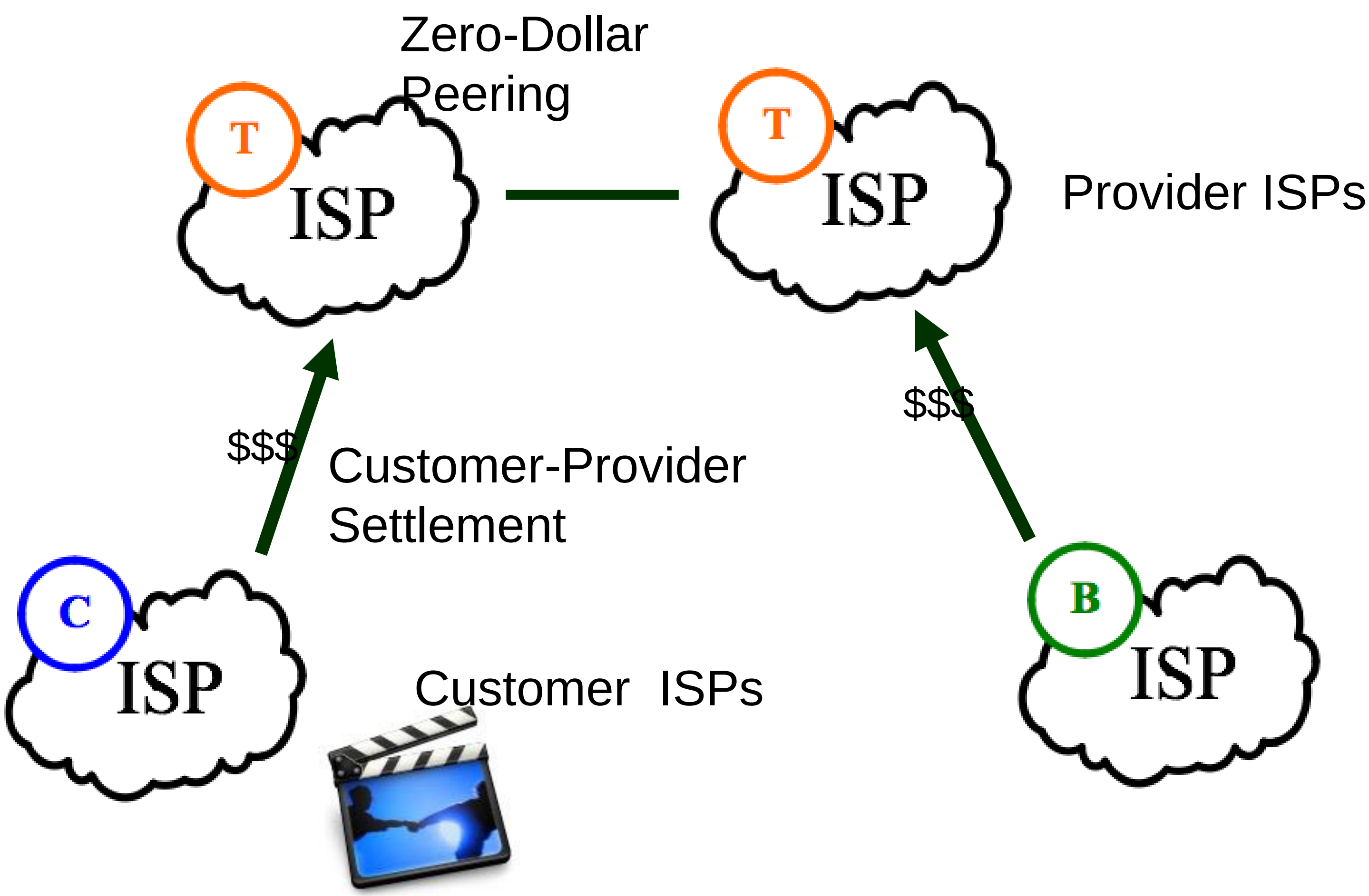
Profit share -- eyeball, transit and content ISPs



$$
\begin{cases}
\varphi_B = \dfrac{V}{n+m+k}\sum_{\mu=1}^{m}\sum_{\kappa=1}^{k}\binom{m}{\mu}\binom{k}{\kappa}\binom{n+m+k-1}{\mu+k}^{-1} \\
\varphi_C = \dfrac{V}{n+m+k}\sum_{\nu=1}^{n}\sum_{\kappa=1}^{k}\binom{n}{\nu}\binom{k}{\kappa}\binom{n+m+k-1}{\nu+k}^{-1} \\
\varphi_T = \dfrac{V}{n+m+k}\sum_{\mu=1}^{m}\sum_{\nu=1}^{n}\binom{m}{\mu}\binom{n}{\nu}\binom{n+m+k-1}{\mu+\nu}^{-1}
\end{cases}
$$

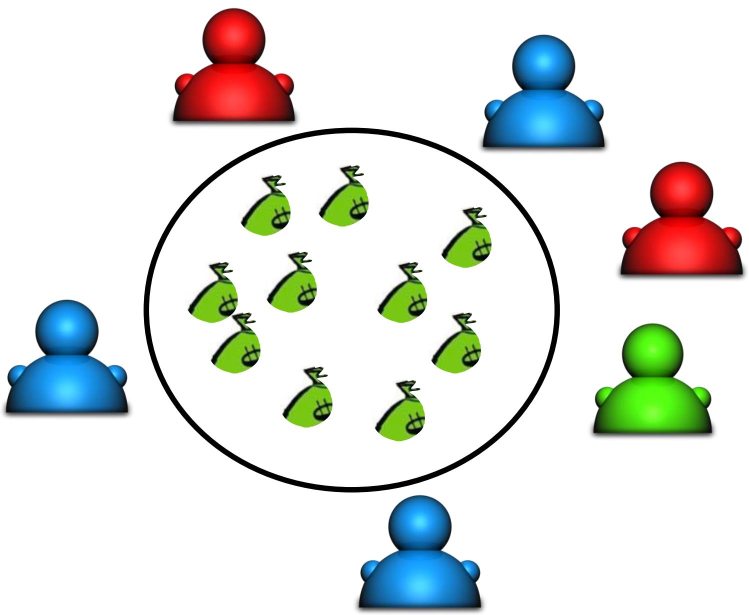
Common ISP Business Practices: A Macroscopic View

Two forms of bilateral settlements:

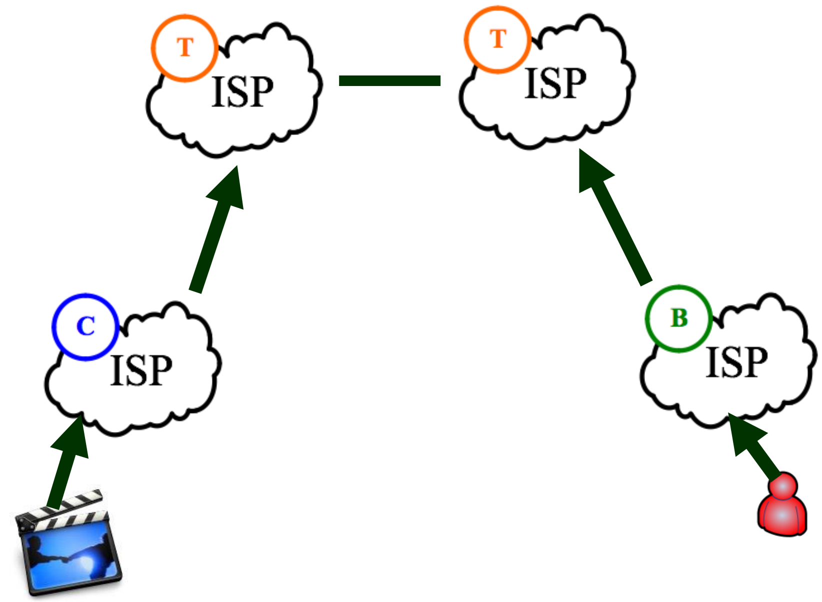


Achieving A Stable Solution: Theory v Practice

Shapley

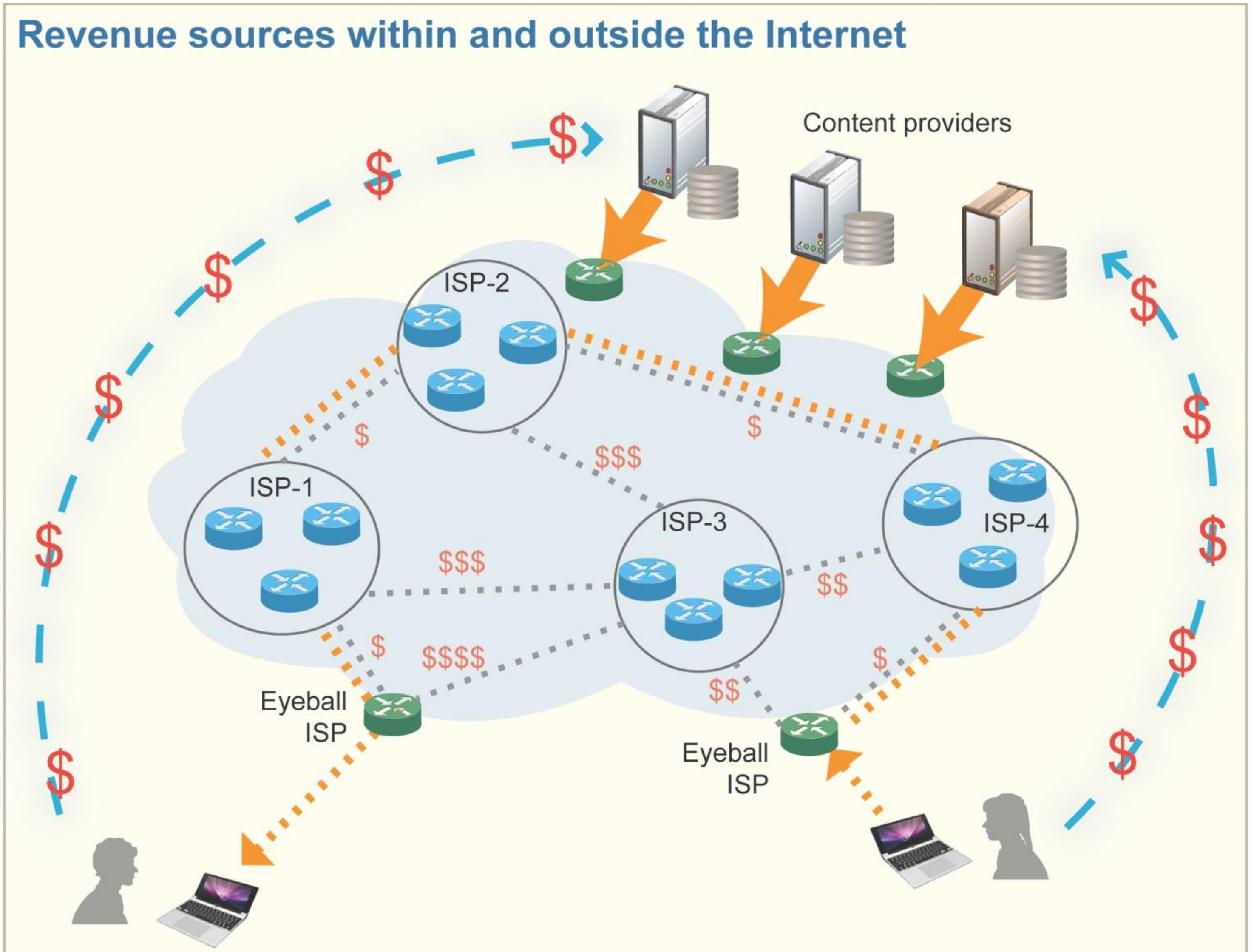


Reality

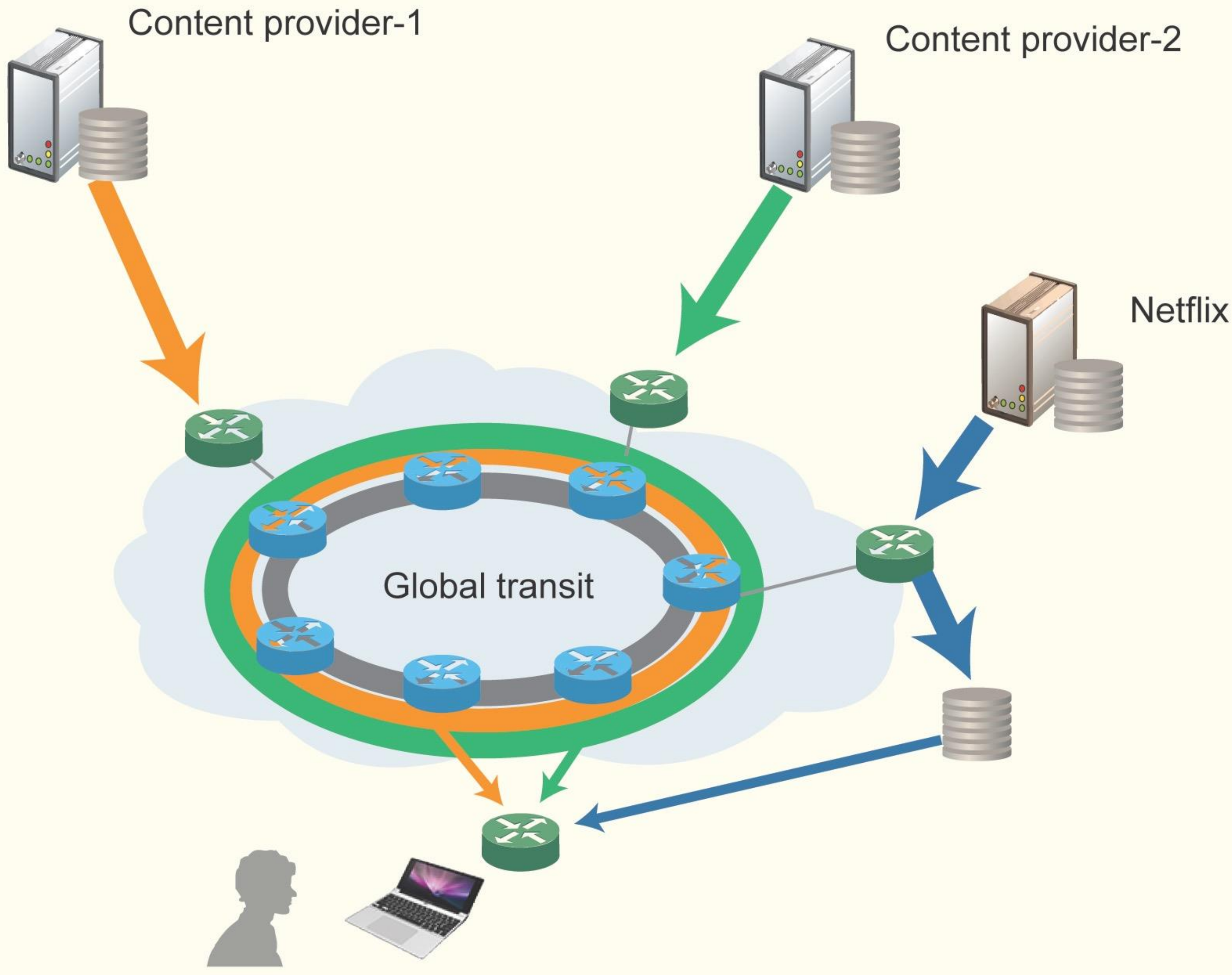


Implications

- If **CR** ≈ **BR**, bilateral implementations
  – Customer-Provider settlements (Transit ISPs as providers)
  – Zero-dollar Peering settlements (between Transit ISPs)
  – Common settlements can achieve fair profit-share for ISPs.
- If **CR** >> **BR**, bilateral implementations
  – Reverse Customer-Provider (Transits compensate Eyeballs)
  – Paid Peering (Content-side compensates eyeball-side)
  – New settlements are needed to achieve fair profit-share.
- <u>Implication: When Customer Side Competition << Content Side Competition, Paid Peering Will Dominate</u>

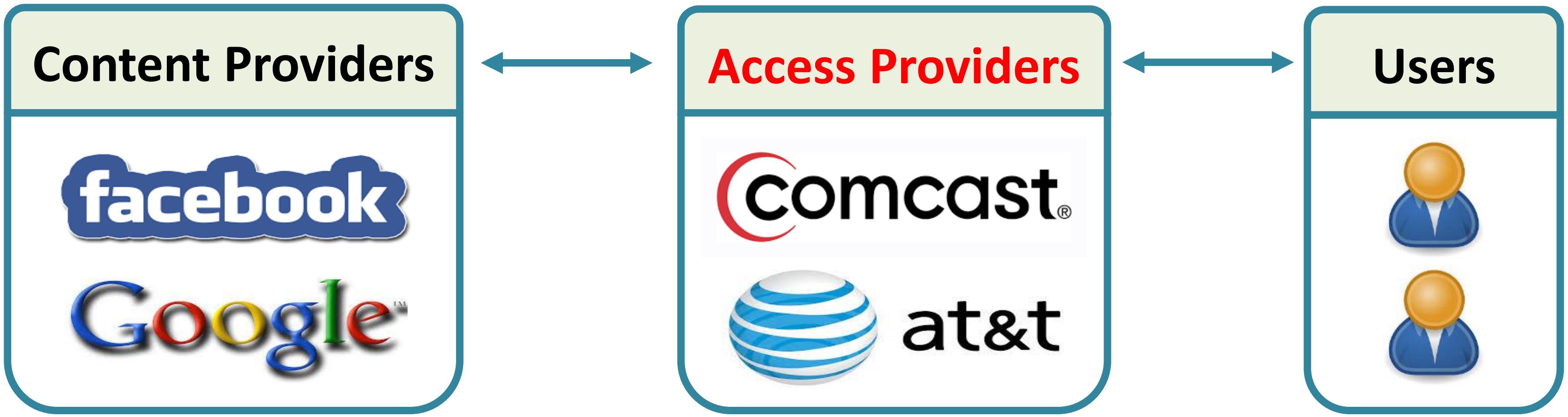

Revenue sources within and outside the Internet
Content providers
ISP-1
ISP-2
ISP-3
ISP-4
Eyeball ISP
Eyeball ISP
$
$$$
$
$$$
$$
$
$$$$
$
$$

Netflix-Comcast deal



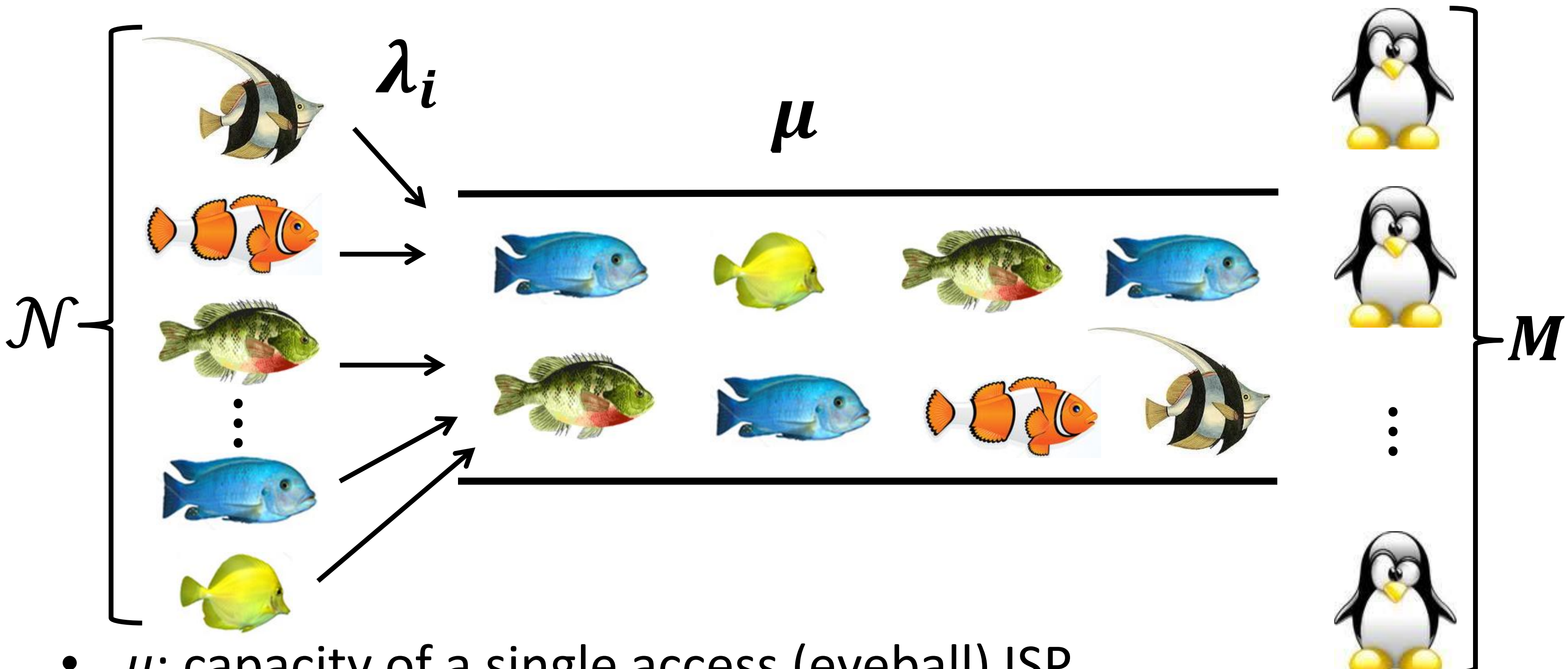
SIMPLIFIED 2-SIDED MODEL

Two-sided market view of the Internet



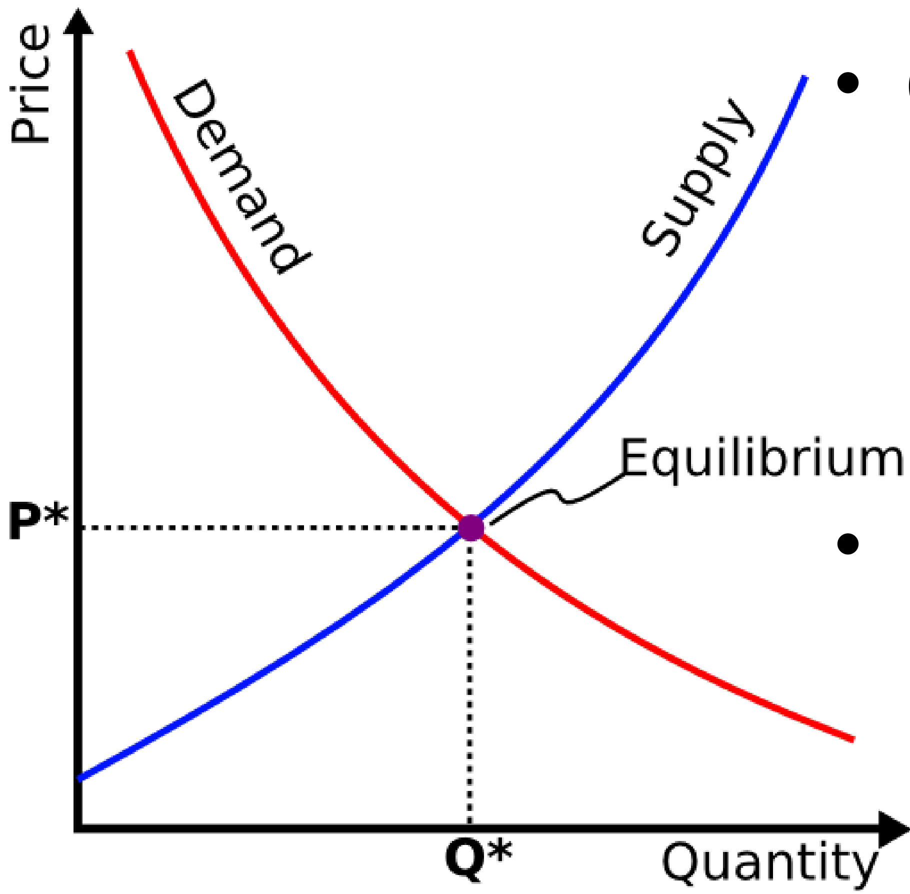
- CPs bypass many transit ISPs for better service
- Very competitive transit markets, not an issue
- Lack of competition in the AP markets
- Tussles between CPs and APs

A canonical two-sided model $(M, \mu, \mathcal{N})$



- μ: capacity of a single access (eyeball) ISP
- M: # of users of the ISP (# of active users)
- $\mathcal{N}$: set of all content providers (CPs)
- λ_i: throughput rate of CP $i \in \mathcal{N}$

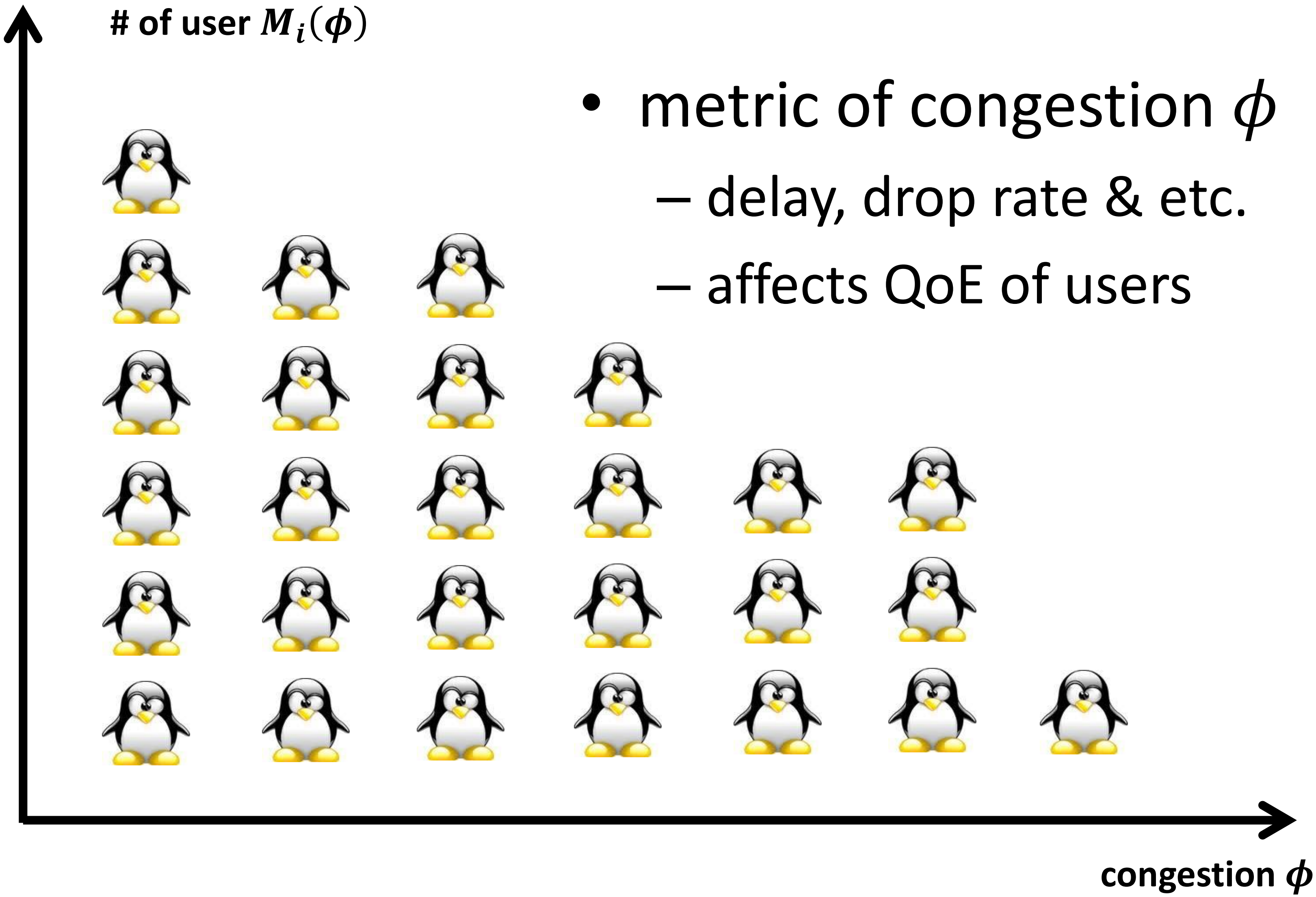
Econ 101: Market Equilibrium



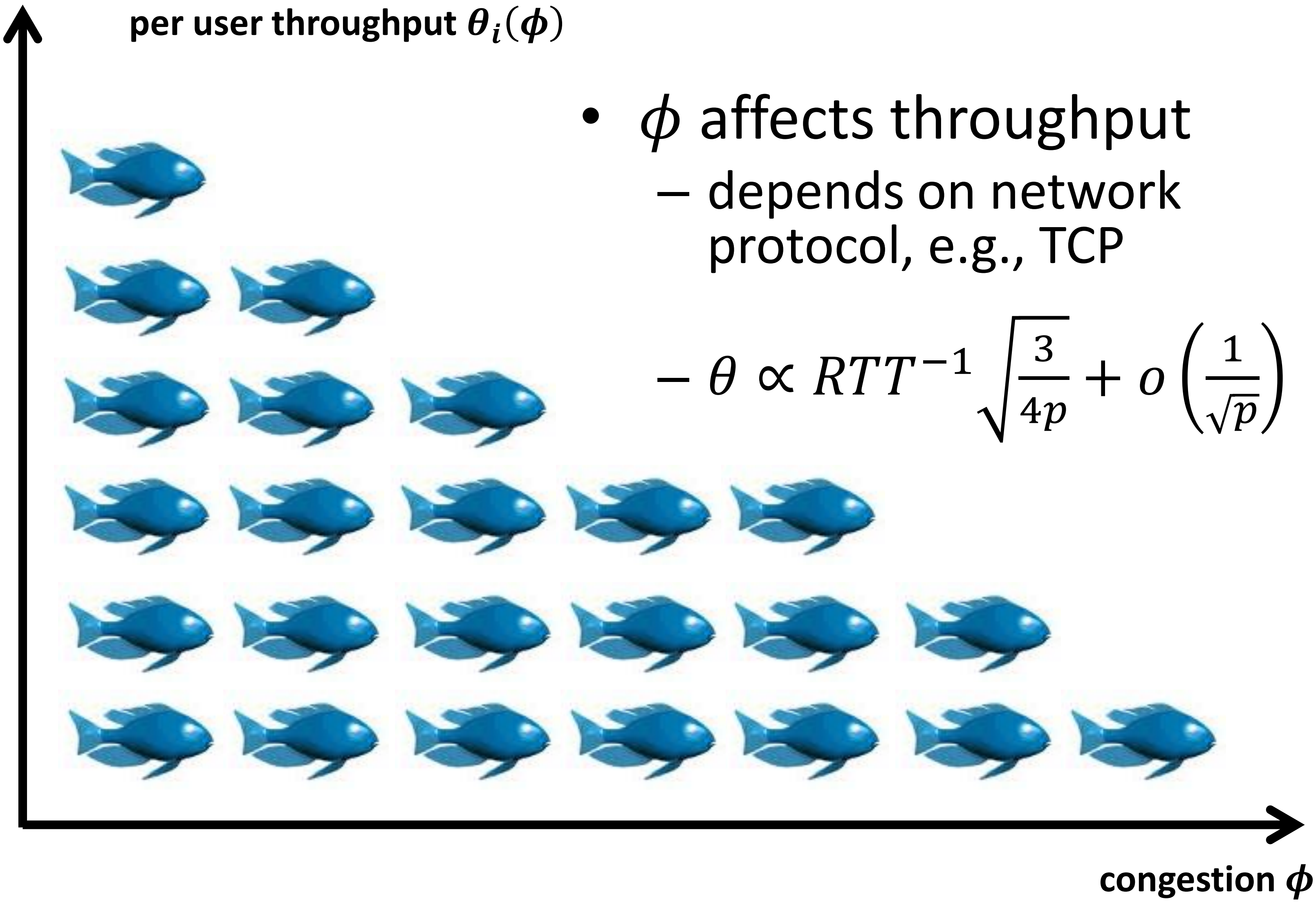
- Competitive market
  - many buyers & sellers
  - price-taking assumption
- Fixed point equilibrium
  - uniqueness
  - monotonicity

User Demand

- metric of congestion ϕ
  - delay, drop rate & etc.
  - affects QoE of users



Per user throughput



- ϕ affects throughput
  - depends on network protocol, e.g., TCP
  - $\theta \propto RTT^{-1}\sqrt{\frac{3}{4p}} + o\left(\frac{1}{\sqrt{p}}\right)$

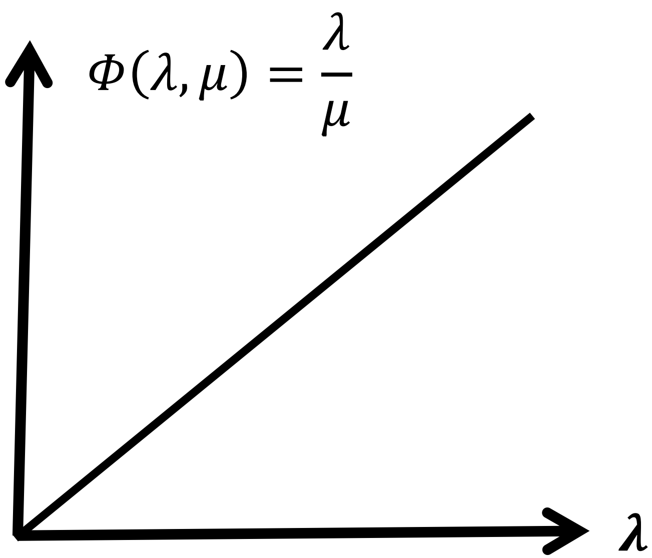
Supply side: congestion function

- congestion level ϕ depends on
  - input rate λ
  - capacity μ

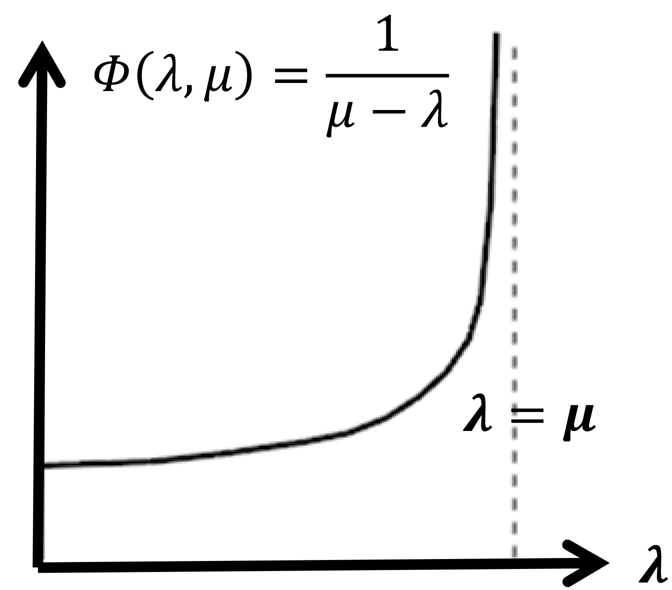
- Congestion function

$$\phi = \Phi(\lambda, \mu)$$

  - increasing in λ
  - decreasing in μ

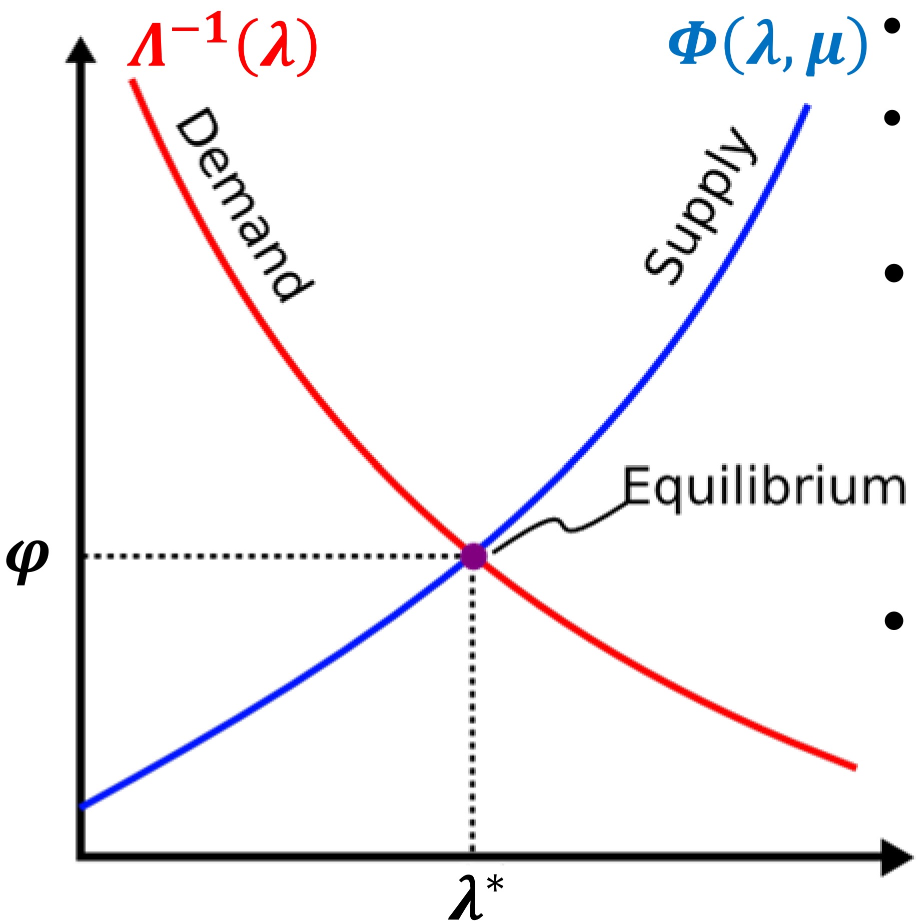


capacity sharing



M/M/1 queueing latency

Congestion Equilibrium



- $\lambda_i = \Lambda_i(\phi) = M_i(\phi)\theta_i(\phi)$
- $\lambda = \Lambda(\phi) = \sum_{i \in \mathcal{N}} \Lambda_i(\phi)$
- Express equilibrium as congestion φ that solves

$$\phi = \Phi(\Lambda(\phi), \mu)$$

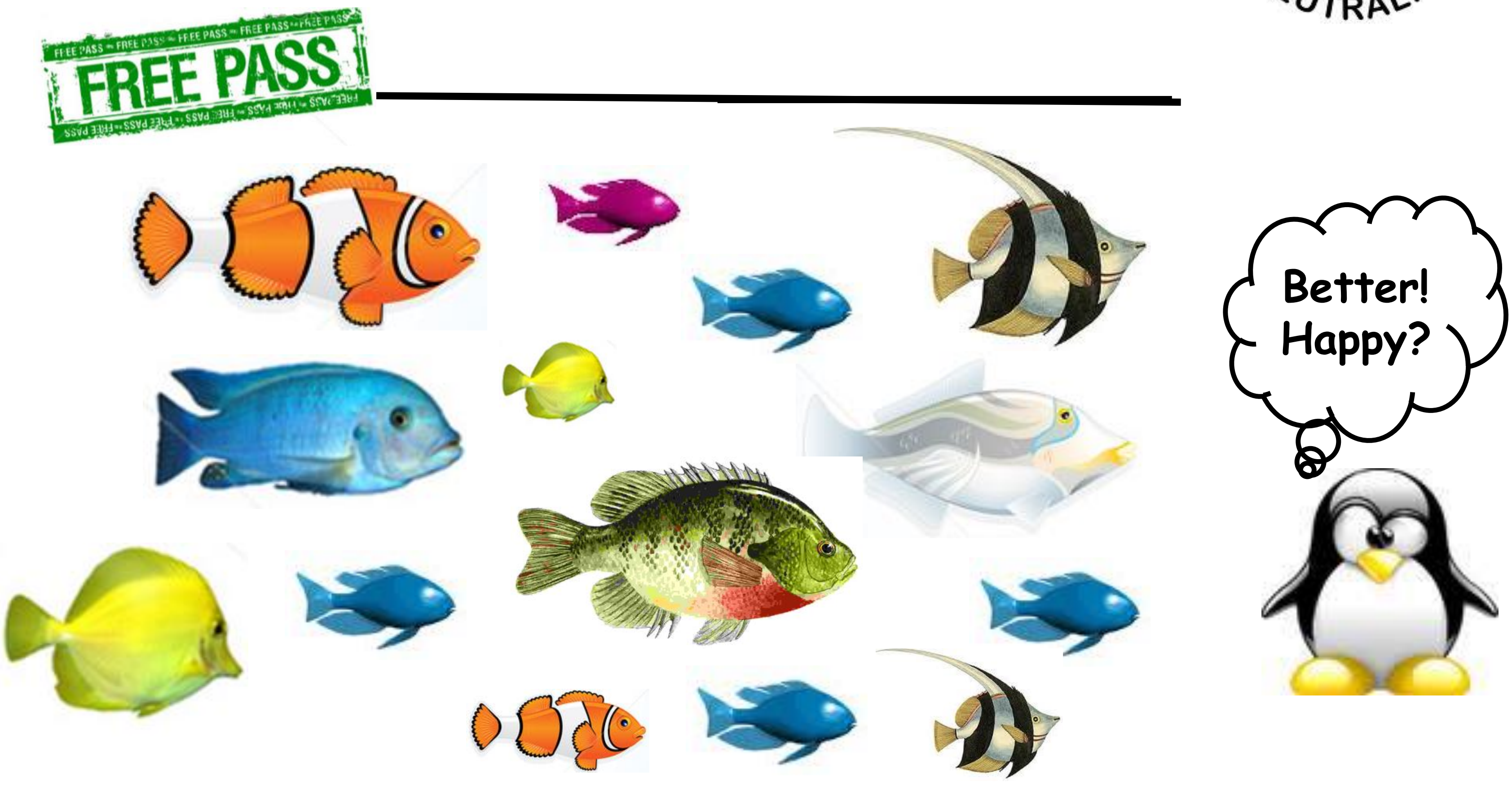
- Justifications
  - many end-users
  - congestion-taking assumption

Fixed-point network analysis

- R. T. B. Ma and V. Misra. Congestion and Its Role in Network Equilibrium. IEEE JSAC 30(11), 2012.
- V. Firoiu, J.-Y. Le Boudec, D. Towsley, and Z.-L. Zhang. Theories and models for Internet quality of service. Proceedings of the IEEE, 90(9), 2002.
- R. J. Gibbens et al. Fixed-point models for the end-to-end performance analysis of IP networks. In the 13th ITC Specialist Seminar 2000.
- F. P. Kelly. Fixed point models of loss networks. The Journal of the Australian Mathematical Society, 31(2), 1989.

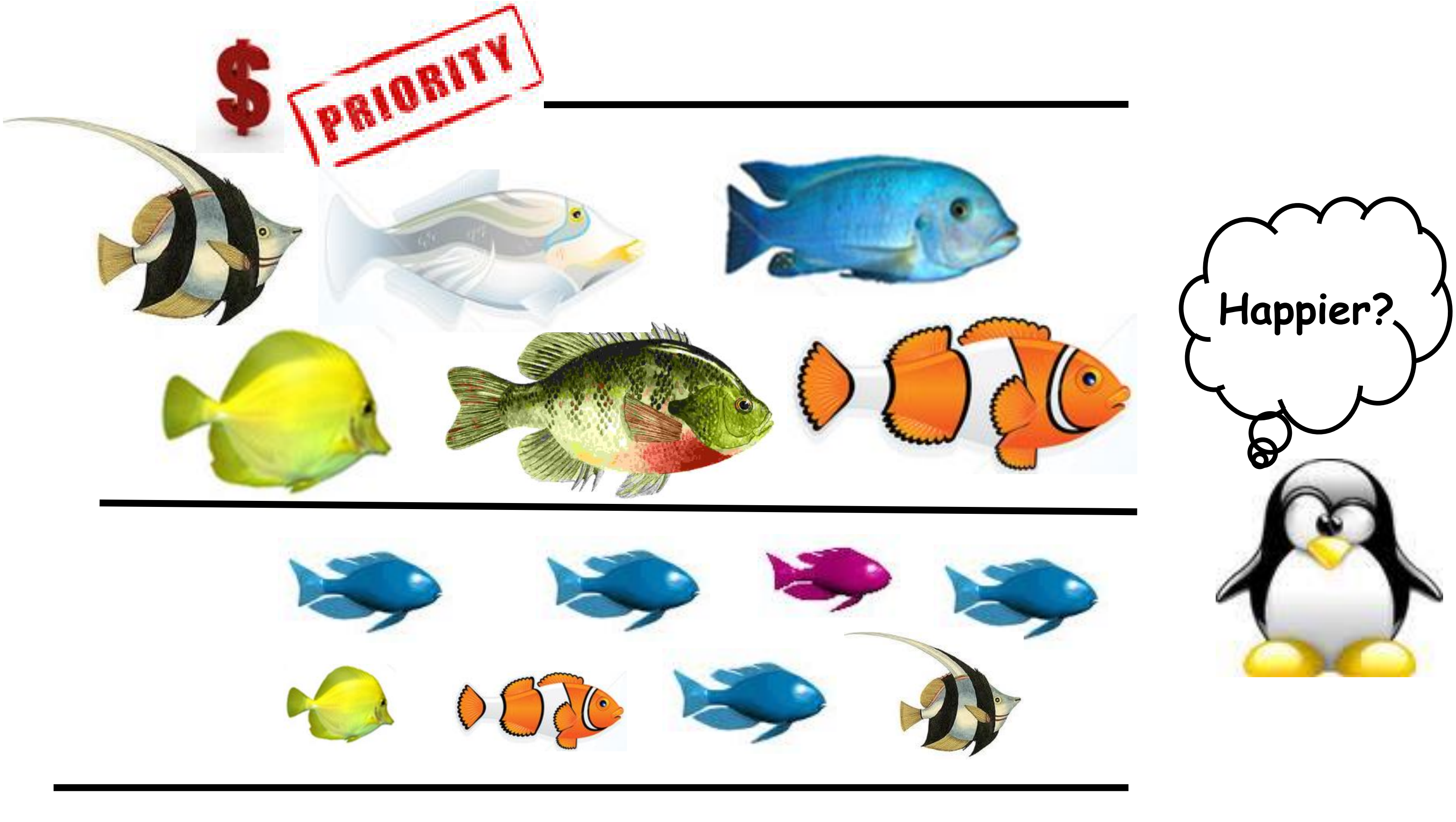
AP’S PAID PRIORITIZATION AND ITS IMPACT ON NET NEUTRALITY

Network Neutrality (NN)



Paid Prioritization (PP)

Hands Off the Internet



ISP Paid Prioritization

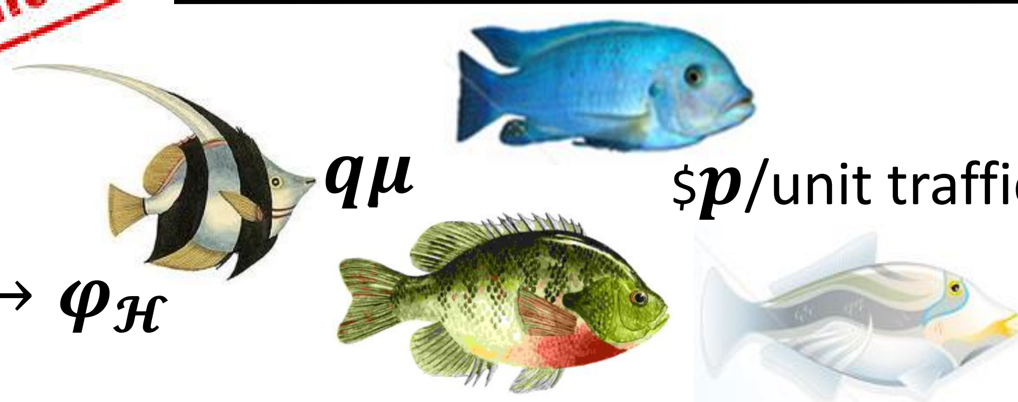
ISP's revenue: $p\sum_{i\in\mathcal{H}}\lambda_i = p\lambda_{\mathcal{H}}$

Capacity

Charge

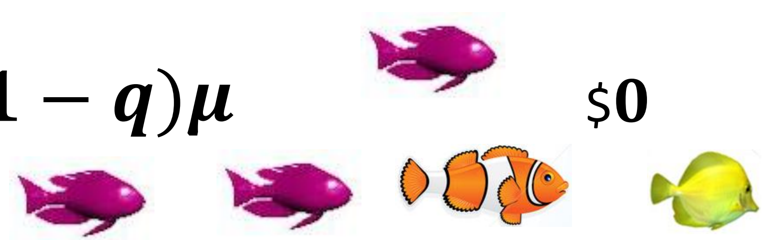
Premium Class

$\boldsymbol{(M, q\mu, \mathcal{H}) \rightarrow \varphi_{\mathcal{H}}}$



$\boldsymbol{q\mu}$

\$$\boldsymbol{p}$/unit traffic



Ordinary Class

$\boldsymbol{(M, (1-q)\mu, \mathcal{L}) \rightarrow \varphi_{\mathcal{L}}}$

$\boldsymbol{(1-q)\mu}$

\$$\boldsymbol{0}$

Monopolistic Analysis

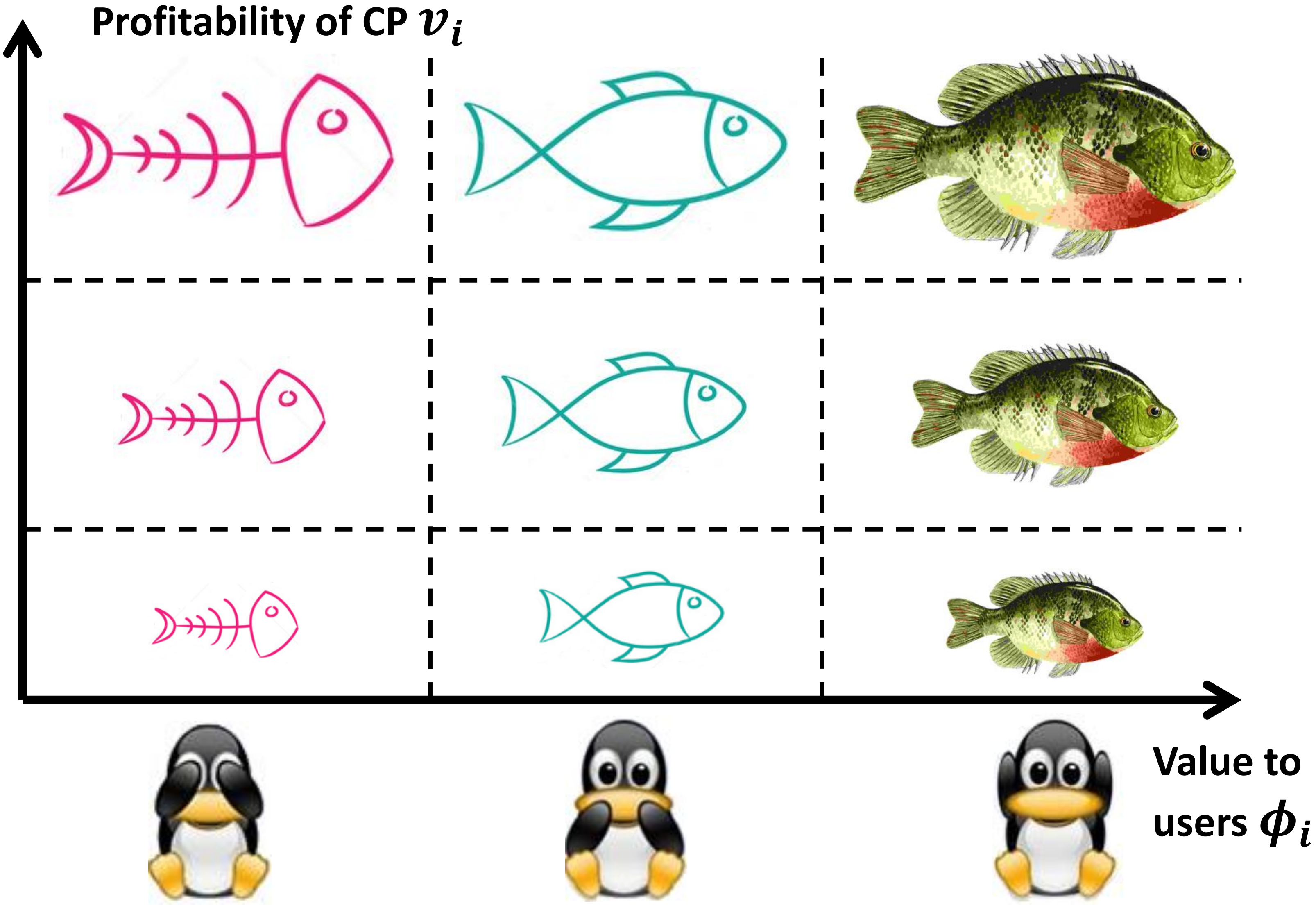
- Players: monopoly ISP I and the set of CPs $\mathcal{N}$
- A Two-stage Game Model $(M, \mu, \mathcal{N}, I)$
  - 1st stage, ISP chooses $s_I = (p, q)$ announces s_I.
  - 2nd stage, CPs simultaneously choose service classes reach a joint decision $s_{\mathcal{N}} = (\mathcal{H}, \mathcal{L})$.
- Outcome (two subsystems):
  - $(M, q\mu, \mathcal{H})$: set $\mathcal{H}$ (of CPs) share capacity $q\mu$
  - $(M, (1-q)\mu, \mathcal{L})$: set $\mathcal{L}$ share capacity $(1-q)\mu$

Utilities

- ISP Revenue: $p \sum_{i \in \mathcal{H}} \lambda_i = p\lambda_{\mathcal{H}}$;
- Consumer Welfare: $W = \sum_{i \in \mathcal{N}} \phi_i \lambda_i$
  - ϕ_i : per unit traffic value to the users
- Content Provider:
  - v_i : per unit traffic profit of CP i

$$u_i = \begin{cases} v_i \Lambda_i(\varphi_{\mathcal{L}}) & \text{if } i \in \mathcal{L}, \\ (v_i - p)\Lambda_i(\varphi_{\mathcal{H}}) & \text{if } i \in \mathcal{H}. \end{cases}$$

Type of Content



Monopolistic Analysis

- Players: monopoly ISP I and the set of CPs $\mathcal{N}$
- A Two-stage Game Model $(M, \mu, \mathcal{N}, I)$
  - 1st stage, ISP chooses $s_I = (p, q)$ announces s_I.
  - 2nd stage, CPs simultaneously choose service classes reach a joint decision $s_\mathcal{N} = (\mathcal{H}, \mathcal{L})$.

❖ Theorem: Given a fixed charge p, strategy $s_I = (p, q)$ is dominated by $s_I' = (p, 1)$.

➢ The monopoly ISP has incentive to allocate all capacity for the premium service class.

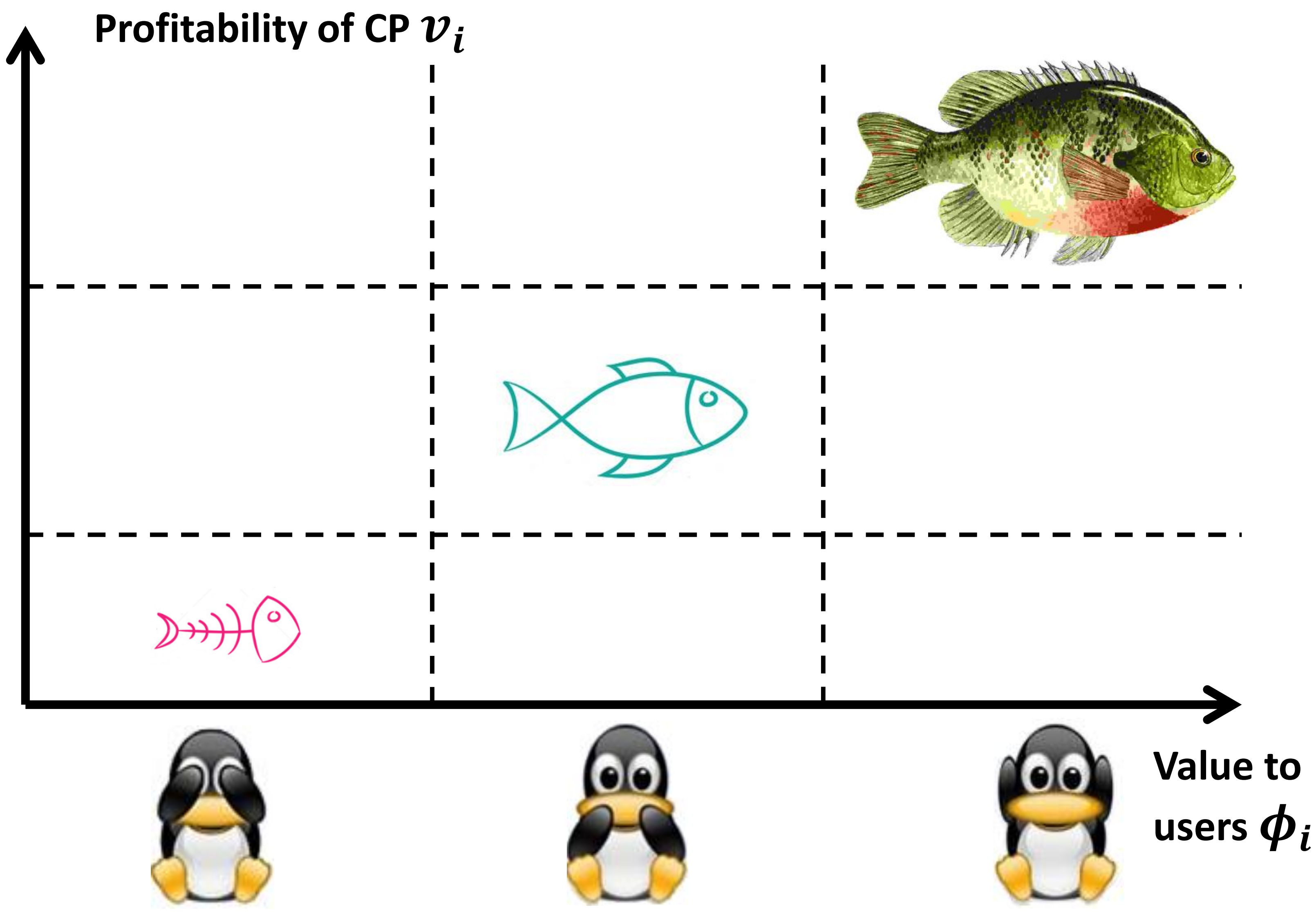
Regulatory Implications

- Ordinary service can be made “damaged goods”, which hurts the user utility.

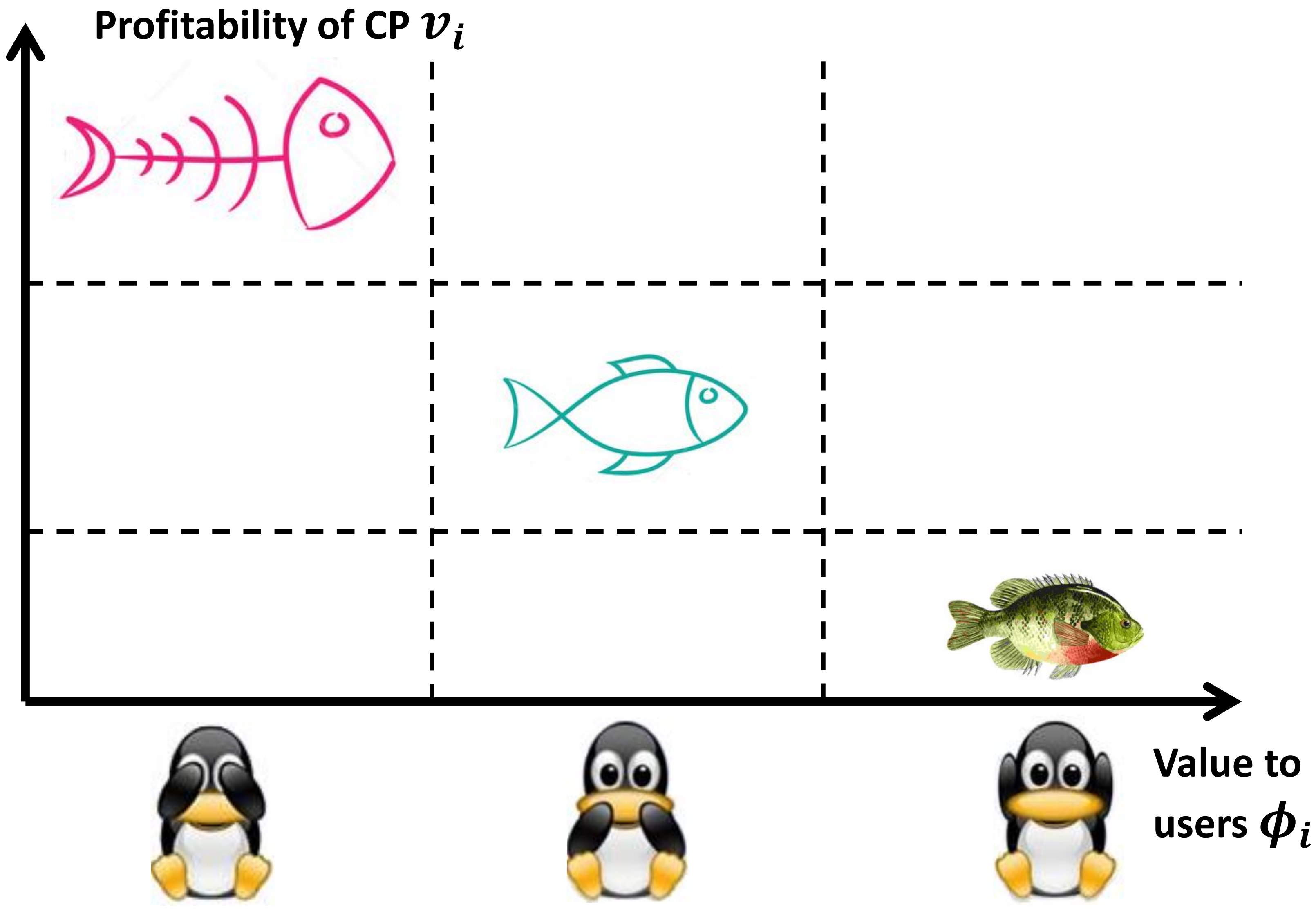
➢ Implication: should not allow ISPs to use non-work-conserving policies (q can’t be too big).

❖ Should we allow the ISP to charge an arbitrarily high price p?

High price c is good when



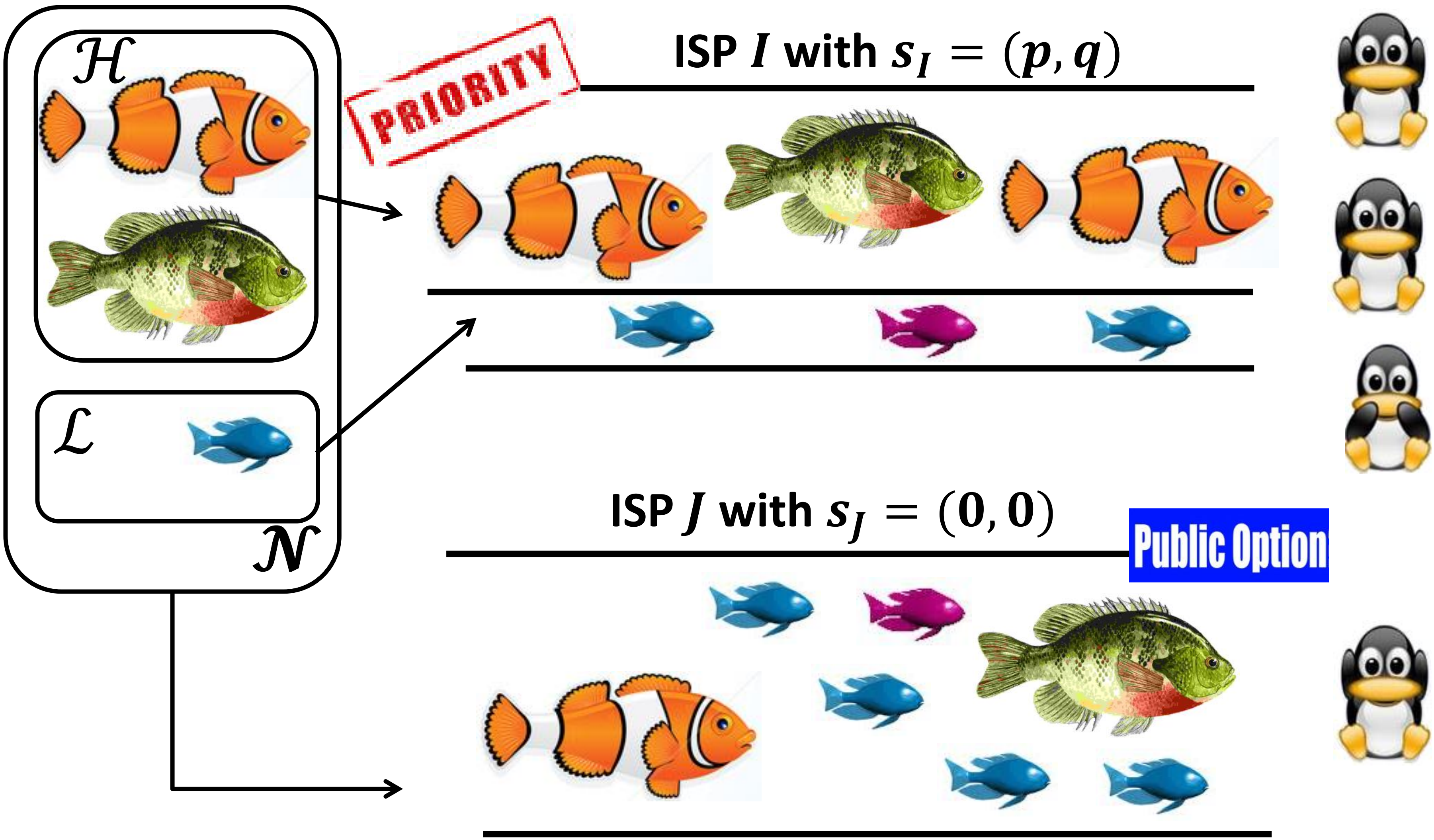
High price c is bad when



Oligopolistic Analysis

- A Two-stage Game Model $(M, \mu, \mathcal{N}, \mathcal{I})$
  - 1st stage: for each ISP $I \in \mathcal{I}$ chooses $s_I = (p_I, q_I)$ simultanously.
  - 2nd stage: at each ISP $I \in \mathcal{I}$, CPs choose service classes with $s_{\mathcal{N}}^I = (\mathcal{H}_I, \mathcal{L}_I)$
- Difference with monopolistic scenarios:
  - Users move among ISPs until the per user utility $\Phi_I = W_I / M_I$ is the same, which determines the market share of the ISPs
  - ISPs try to maximize their market share.

Duopolistic Analysis



Duopolistic Analysis

- Theorem: In the duopolistic game, where an ISP J is a Public Option, i.e. $s_J = (0,0)$, if s_I maximizes the non-neutral ISP I's market share, s_I also maximizes user welfare.

➢ Regulatory implication for monopoly cases:

Public Option > Network Neutrality > Hands Off the Internet

Oligopolistic Analysis

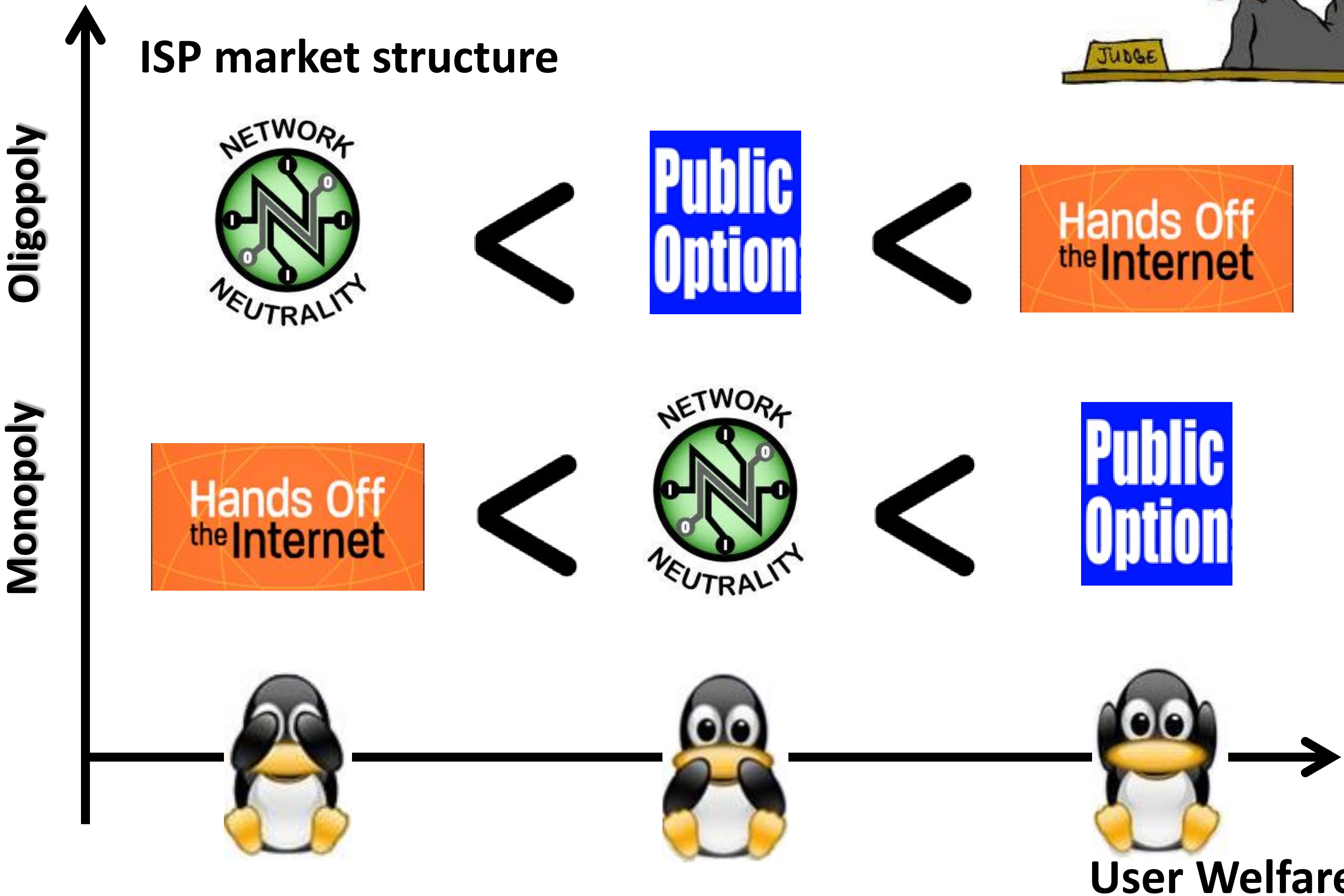
- Theorem: Under any strategy profile s_{-I}, if s_I is a best-response to s_{-I} that maximizes market share, then s_I is an ϵ–best-response for per-user utility Φ_I.

➢ The Nash equilibrium of market share is an ϵ-Nash equilibrium of user welfare.

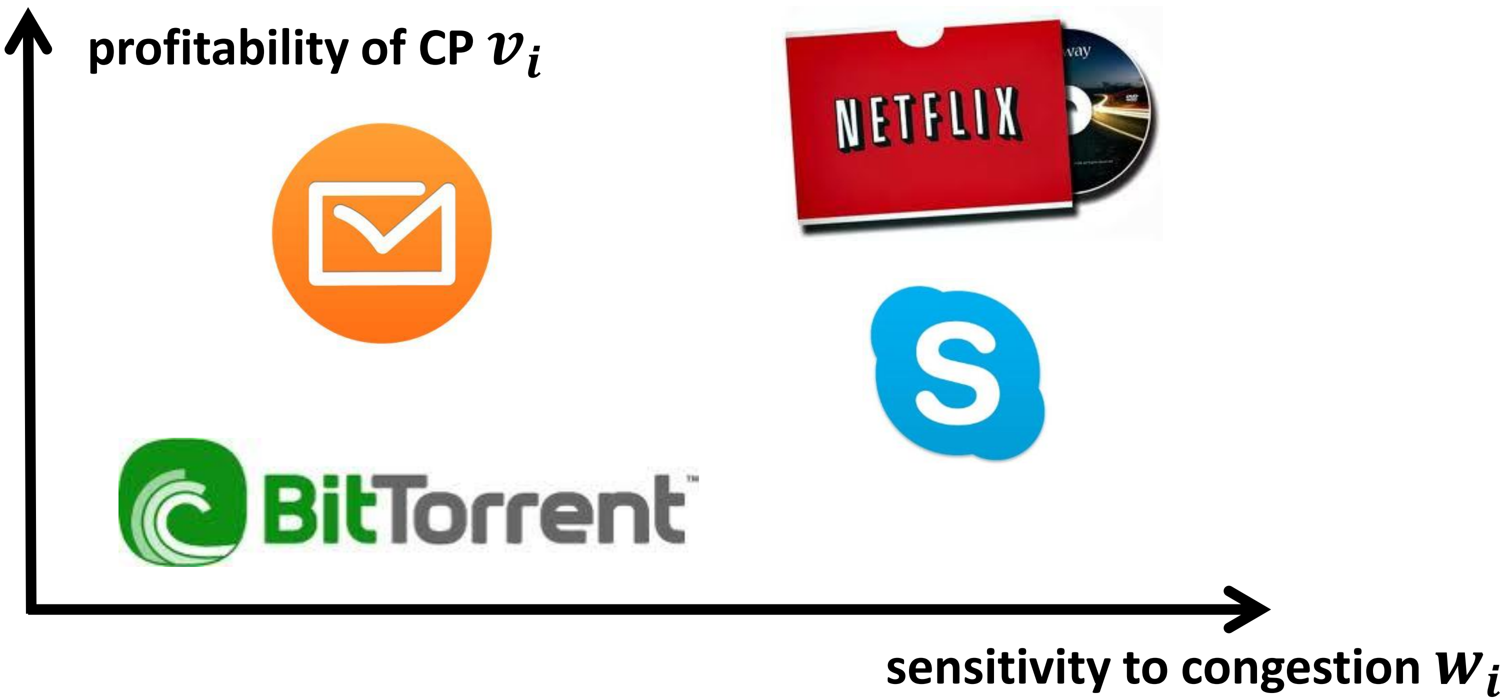
➢ Oligopolistic scenarios:

Hands Off the Internet > Public Option > Network Neutrality

Regulatory Preference



Two-dimensional CP model



$$u_i(\mathcal{H}, \mathcal{L}) = \begin{cases} v_i \Lambda_i(\varphi_{\mathcal{L}}) & \text{if } i \in \mathcal{L}, \\ (v_i - p)\Lambda_i(\varphi_{\mathcal{H}}) & \text{if } i \in \mathcal{H}. \end{cases}$$

– e.g., $\Lambda_i(\varphi) = \Lambda(w_i, \varphi) = e^{-w_i \varphi}$

Nash vs. Congestion Equilibrium

- Strategy profile $(\mathcal{H}, \mathcal{L})$ is a Nash equilibrium iff:

$$\begin{cases} (v_i - p)\Lambda_i(\varphi_{\mathcal{H}}) > v_i \Lambda_i\left(\varphi_{\mathcal{L}\cup\{i\}}\right), \forall i \in \mathcal{H}; \\ (v_i - p)\Lambda_i\left(\varphi_{\mathcal{H}\cup\{i\}}\right) \leq v_i \Lambda_i(\varphi_{\mathcal{L}}), \forall i \in \mathcal{L}. \end{cases}$$

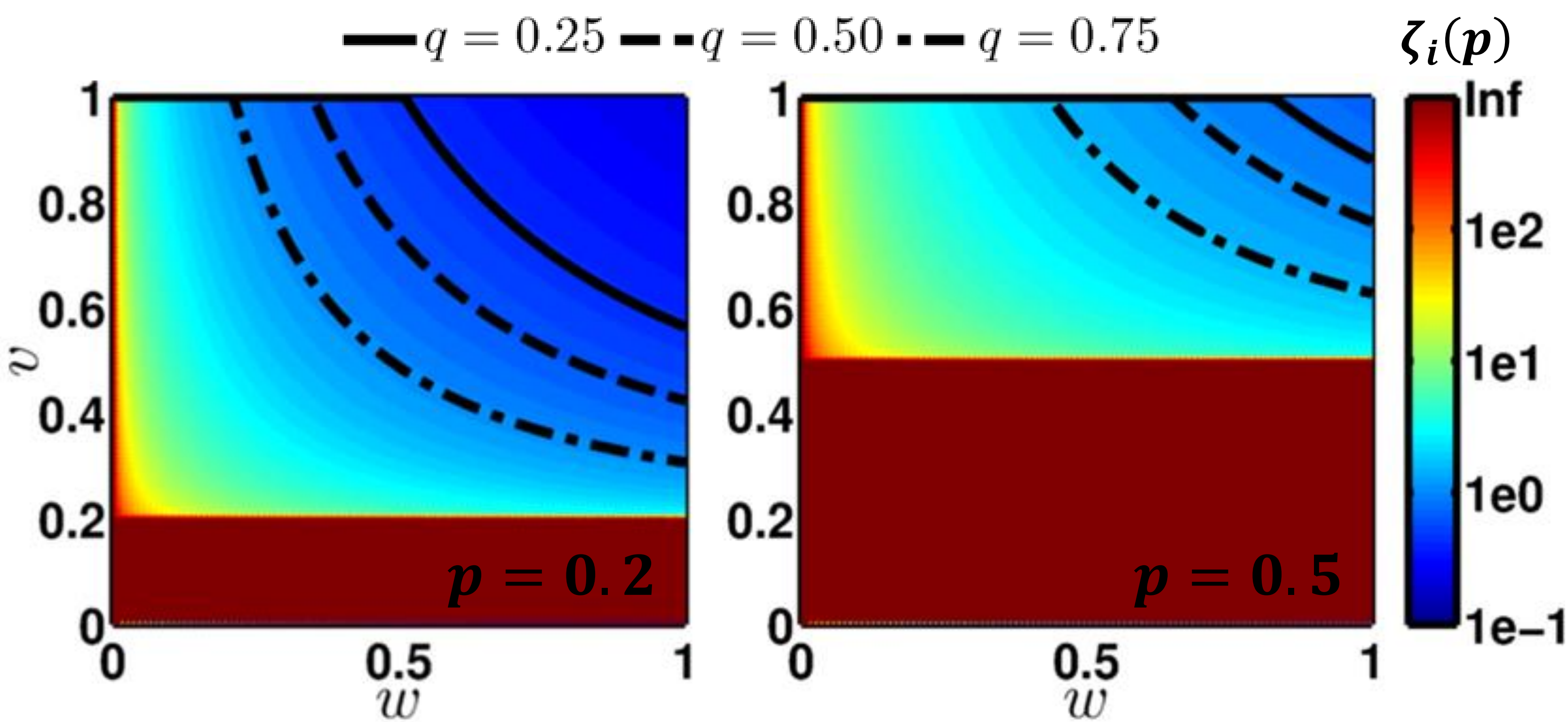
- Strategy profile $(\mathcal{H}, \mathcal{L})$ is a congestion equilibrium iff:

$$\begin{cases} (v_i - p)\Lambda_i(\varphi_{\mathcal{H}}) > v_i \Lambda_i(\varphi_{\mathcal{L}}), \forall i \in \mathcal{H}; \\ (v_i - p)\Lambda_i(\varphi_{\mathcal{H}}) \leq v_i \Lambda_i(\varphi_{\mathcal{L}}), \forall i \in \mathcal{L}. \end{cases}$$

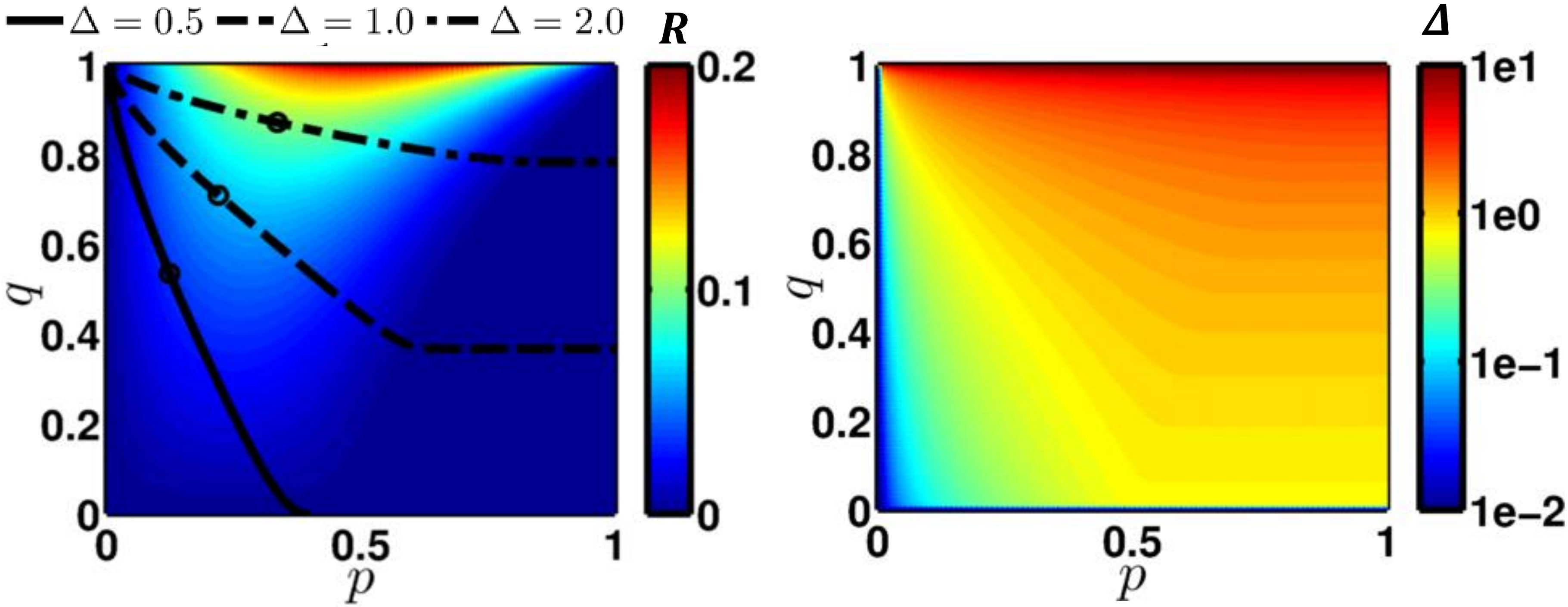
Unique congestion equilibrium (φ_H, φ_L)

- $\Delta(\varphi_H, \varphi_L)$ measures the difference in congestion levels

➢ Under any fixed p, $\zeta_i < \Delta(\varphi_H, \varphi_L) \leq \zeta_j,\ \forall i \in \mathcal{H}, j \in \mathcal{L}$.

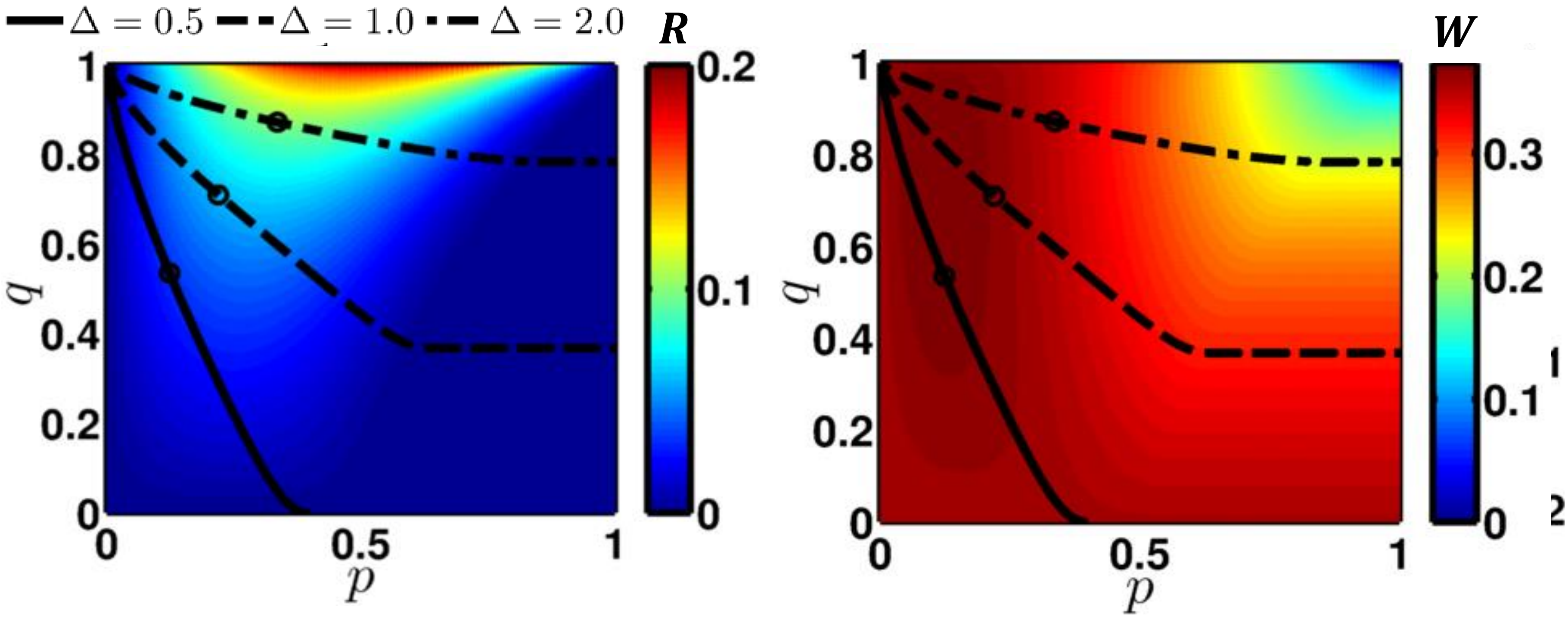


Regulating the monopoly



- Propose to restrict $\Delta(\varphi_H, \varphi_L) \leq \delta$
  - implication: if you make premium class better, you need to make ordinary class better too.

Impact on social welfare



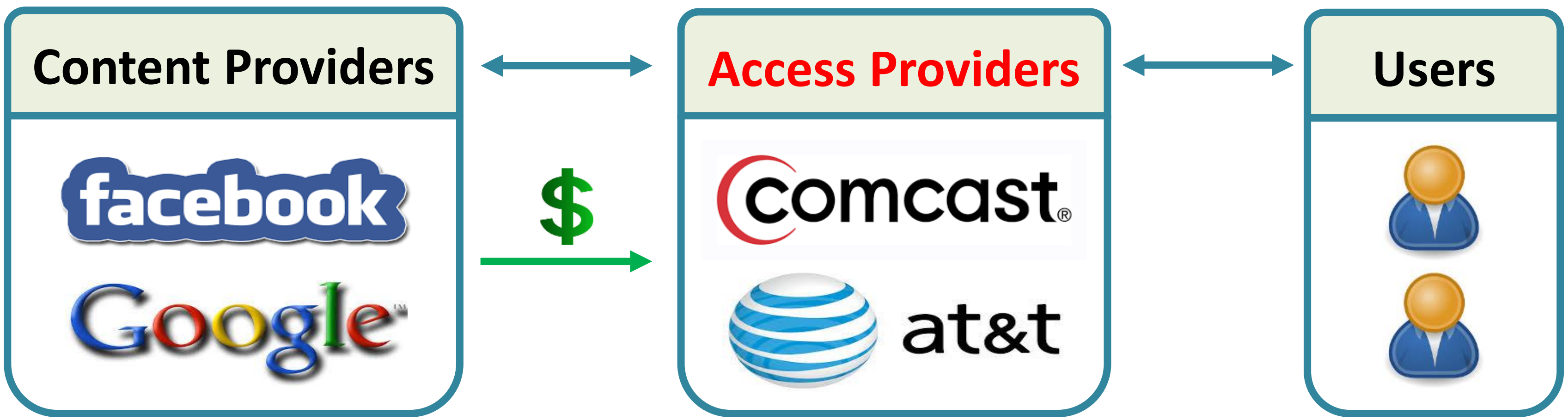
- Under any p, the optimal $q^*(p, \mu, \delta)$ satisfies

$$\Delta\big(\varphi_H(p, q^*), \varphi_L(p, q^*)\big) = \delta$$

Do we need Net Neutrality?

- Market structure matters
  - Competitive market does not need
  - Lack of competition might be a problem
  - Public option changes the market structure
- Under a natural monopoly
  - Net neutrality is just one (non-optimal) tool
  - Better alternatives exist to solve specific problems
- Net neutrality
  - a tool or an objective
  - not (an optimal) solution

Applications of congestion equilibrium: CP-side pricing and differentiation

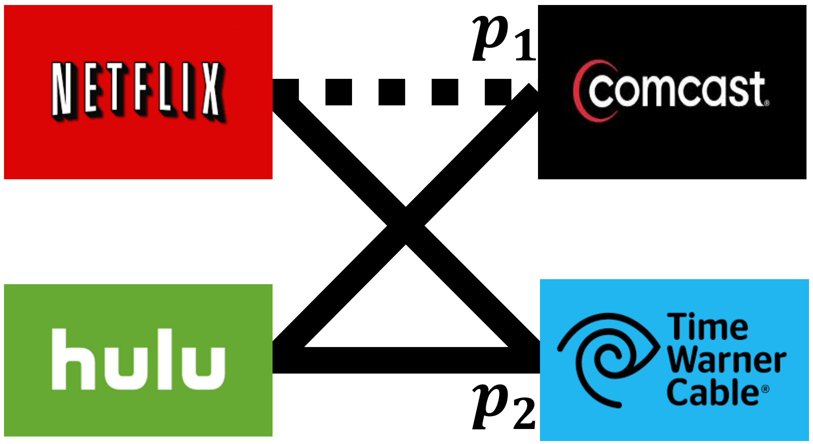


- Richard T. B. Ma and Vishal Misra. The Public Option: A Non-Regulatory Alternative to Network Neutrality. IEEE/ACM Transactions on Networking, 21(6), 2013.
- Jing Tang and Richard T. B. Ma. Regulating Monopolistic ISPs Without Neutrality. IEEE ICNP Conference, 2014.
- Richard T. B. Ma, Jingjing Wang, Dah Ming Chiu. Paid Prioritization and Its Impact on Net Neutrality. IEEE JSAC, 35(2), 2017.

CP'S PEERING DECISIONS AND COMPETITION

CP-side competition and premium peering

- Move focus from ISPs to CPs
  - Given premium peering prices, decide whether or not to use
  - Similar CPs compete in an oligopolistic market
  - Optimal decision depends on competitors decisions



- Richard T. B. Ma. Pay or Perish: The Economics of Premium Peering. IEEE JSAC, 35(2), 2017.

Discrete Choice Model

- Given a set $\mathcal{S}$ of choices, what is the probability that a (random) user choose any $i \in \mathcal{S}$?
- Independence of irrelevant alternatives
  - if i is preferred to j out of the choice set $\{i, j\}$, introducing an option k, expanding the choice set to $\{i, j, k\}$, must not make j preferable to i.

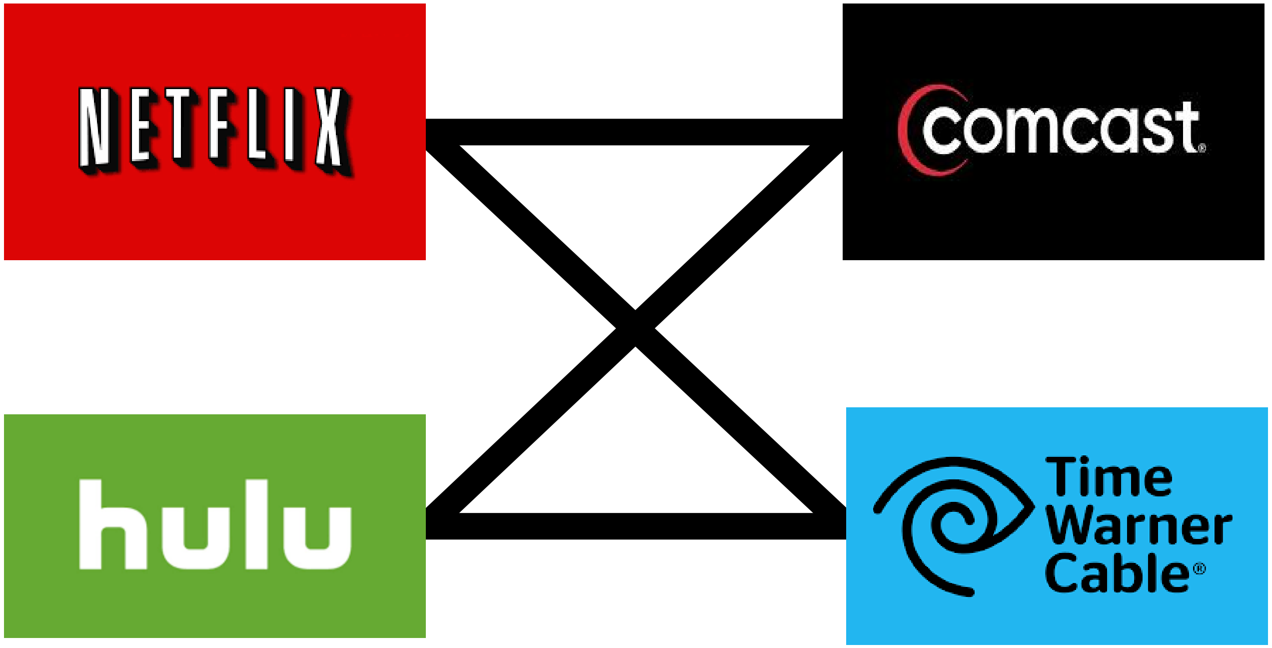
➢ Luce's Choice Axiom (1959): the probability of choosing i from a set $\mathcal{S}$ follows:

$$P_{\mathcal{S}}\{i\} = \frac{w_i}{\sum_{j \in \mathcal{S}} w_j}$$

Complementary Services

- To stream video online, each user needs
  - one access provider and one content provider
  - both are complementary to each other
- Set $\mathcal{N}$ of CPs and $\mathcal{M}$ of APs
  - each user chooses a pair $(i, j) \in \mathcal{N} \times \mathcal{M}$
- Model user choices by extending Luce's choice axiom for complementary services

Baseline Market Shares



- Under equal peering relationships
  - each CP $i \in \mathcal{N}$ has a baseline market share ϕ_i
  - each AP $j \in \mathcal{M}$ has a baseline market share ψ_j

Baseline Market Shares

- Example: Netflix has 70% of market share and Comcast has 60% of market share

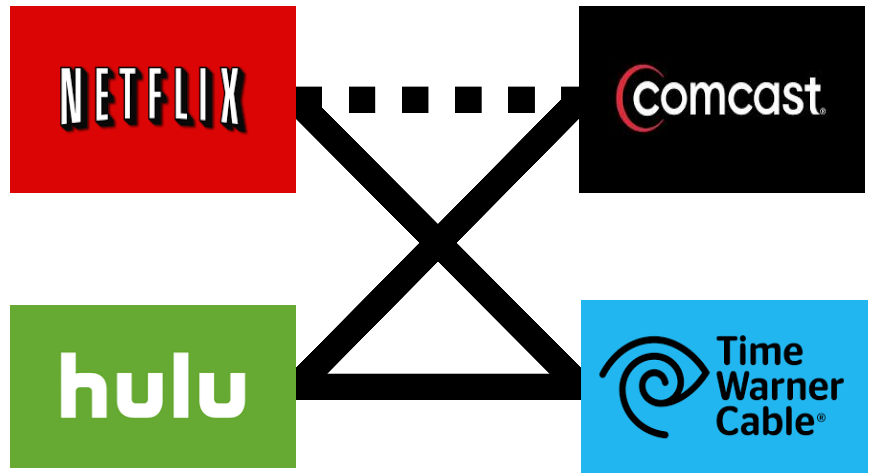
	Comcast	TimeWarner
Netflix	$\phi_i \psi_j = 42\%$	$\phi_i \psi_j = 28\%$
Hulu	$\phi_i \psi_j = 18\%$	$\phi_i \psi_j = 12\%$

- Probability that a user will use (i, j) is $\phi_i \psi_j$

❖ Captures intrinsic characteristics such as price and brand name, as in the Luce's rule

Stickiness of Users

- Existing users of (netflix, comcast) might seek for better alternatives
- Denote % of users of CP i and AP j that are sticky by α_i and β_j



	Sticky to Comcast	Non-sticky to Comcast
Sticky to Netflix	$\alpha_i\beta_j$	$\alpha_i(1-\beta_j)$
Non-sticky to Netflix	$(1-\alpha_i)\beta_j$	$(1-\alpha_i)(1-\beta_j)$

Option Set Available to User

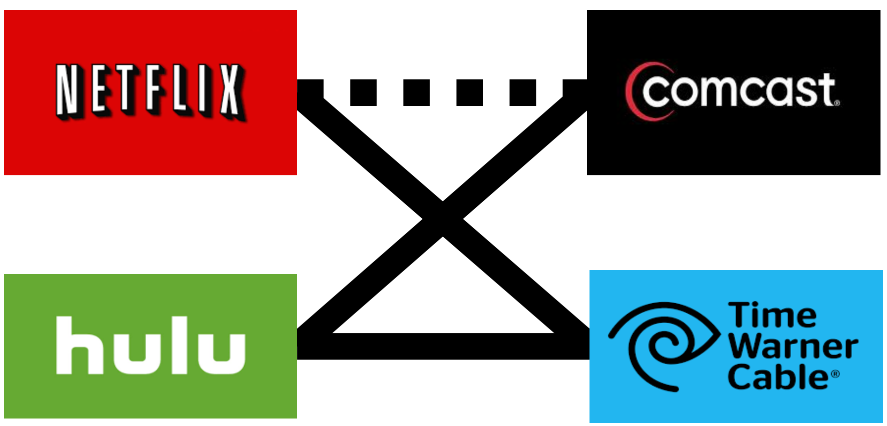
- Any existing users of (i, j) would have an option set $\mathcal{O} \subseteq \mathcal{N} \times \mathcal{M}$ defined as

$$\mathcal{O} = \begin{cases} \{(i,j)\} & \text{w. p.} \quad \alpha_i \beta_j \\ \{i\} \times \mathcal{M} & \text{w. p.} \quad \alpha_i (1 - \beta_j) \\ \mathcal{N} \times \{j\} & \text{w. p.} \quad (1 - \alpha_i) \beta_j \\ \mathcal{N} \times \mathcal{M} & \text{w. p.} \quad (1 - \alpha_i)(1 - \beta_j) \end{cases}$$

	Sticky to Comcast	**Non-sticky to Comcast**
Sticky to Netflix	$\boldsymbol{\alpha_i \beta_j}$	$\boldsymbol{\alpha_i (1 - \beta_j)}$
Non-sticky to Netflix	$\boldsymbol{(1 - \alpha_i) \beta_j}$	$\boldsymbol{(1 - \alpha_i)(1 - \beta_j)}$

Peering Relationship

- Denote peering between CP i & AP j by θ_{ij}, where $\theta_{ij} = 1$ if premium peering is used



$$\Theta = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix}$$

- Given an option set $\mathcal{O}$, better alternatives:

$$\mathcal{L}(\Theta|\mathcal{O}) \triangleq \{(i,j) \in \mathcal{O}: \theta_{ij} = 1\}$$

Generalized Luce's Choice Rule

- Any user will stick to original choice if

$$\emptyset = \mathcal{L}(\Theta|\mathcal{O}) \subseteq \mathcal{O} \subseteq \mathcal{N} \times \mathcal{M}$$

- Otherwise, chooses a pair $l = (i, j) \in \mathcal{L}(\Theta|\mathcal{O})$ of better alternative with probability

$$P_{\mathcal{L}}\{l = (i, j)\} = \frac{\phi_i \psi_j}{\sum_{(n,m)\in\mathcal{L}} \phi_n \psi_m}$$

- Key ideas of the model:
  - stickiness affects a user's option set $\mathcal{O}$ available to her
  - peering Θ affects a user's available choice set $\mathcal{L} \subseteq \mathcal{O}$

Choice Model $(\mathcal{N}, \mathcal{M})$ of Users

- Baseline market share and user stickiness

$$\boldsymbol{\phi} \triangleq (\phi_1, \cdots, \phi_N) \quad \boldsymbol{\psi} \triangleq (\psi_1, \cdots, \psi_M)$$
$$\boldsymbol{\alpha} \triangleq (\alpha_1, \cdots, \alpha_N) \quad \boldsymbol{\beta} \triangleq (\beta_1, \cdots, \beta_M)$$

- Under any peering matrix Θ, the number of users of (i, j) can be expressed as a function

$$X_{ij}(\Theta, \boldsymbol{\phi}, \boldsymbol{\psi}, \boldsymbol{\alpha}, \boldsymbol{\beta})$$

Utility Model of the Providers

- Revenue of any AP $j \in \mathcal{M}$:

$$R_j(\Theta) \triangleq p_j \sum_{i\in\mathcal{N}} \theta_{ij} X_{ij}(\Theta, \boldsymbol{\phi}, \boldsymbol{\psi}, \boldsymbol{\alpha}, \boldsymbol{\beta}).$$

- Profit of any CP $i \in \mathcal{N}$:

$$U_i(\Theta) \triangleq \sum_{j\in\mathcal{M}} U_i^j(\Theta), \qquad \text{where}$$

$$U_i^j(\Theta) \triangleq \begin{cases} q_i \delta_i X_{ij}(\Theta, \boldsymbol{\phi}, \boldsymbol{\psi}, \boldsymbol{\alpha}, \boldsymbol{\beta}) & \text{if} \quad \theta_{ij} = 0, \\ (q_i - p_j) X_{ij}(\Theta, \boldsymbol{\phi}, \boldsymbol{\psi}, \boldsymbol{\alpha}, \boldsymbol{\beta}) & \text{if} \quad \theta_{ij} = 1. \end{cases}$$

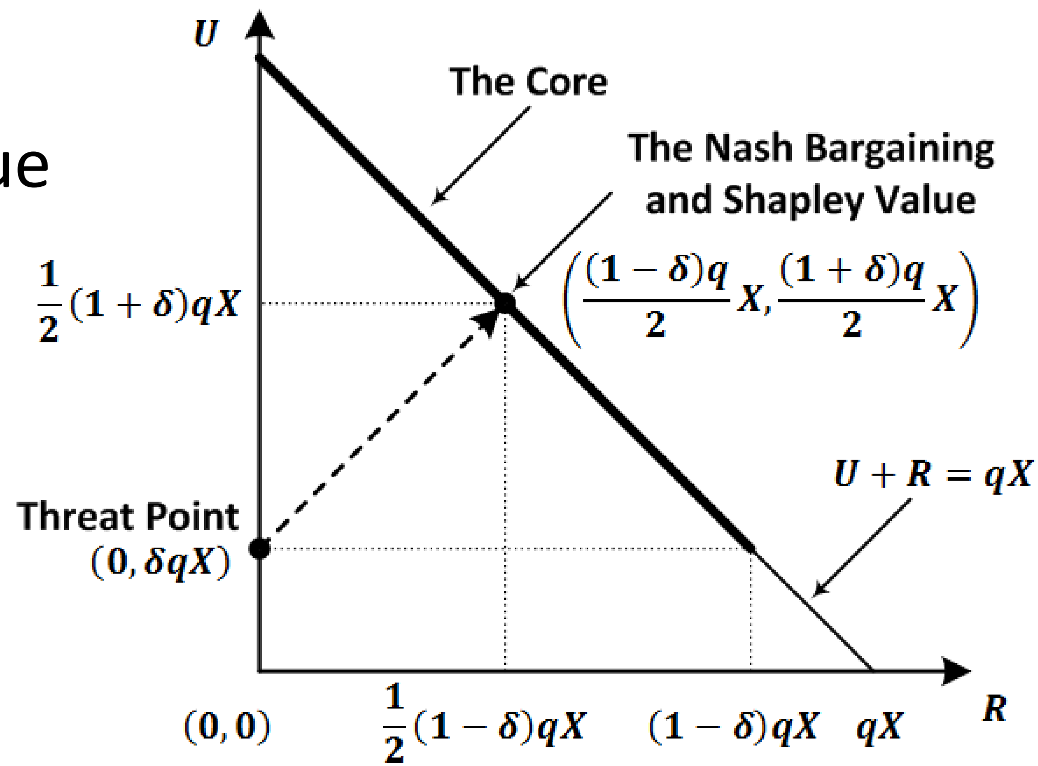
Complementary Monopoly

- CP uses premium peering iff AP's price

$$p \leq (1-\delta)q$$

- Both the Shapley value and Nash bargaining are achieved at

$$p = \frac{1}{2}(1-\delta)q$$



Value of Premium Peering (VoPP)

- Define the per-user intrinsic value of premium peering (VoPP) of a monopoly CP as

$$v \triangleq (1-\delta)q$$

- In a market of multiple CPs, the per-user intrinsic VoPP for any CP i is defined as

$$v_i \triangleq (1-\alpha_i\delta_i)q_i = \bar{\alpha}_i q_i + \alpha_i(1-\delta_i)q_i$$

  – Interpreted as the potential loss due to:

    1) elastic users and 2) quality degradation

Monopolistic Access Provider

- Any $\boldsymbol{\vartheta}$ is a Nash equilibrium if and only if

  $p \geq \tilde{v}_i(\boldsymbol{\vartheta}_{-i}), \forall \theta_i = 0$ and $p < \tilde{v}_i(\boldsymbol{\vartheta}_{-i}), \forall \theta_i = 1,$

  where $\tilde{v}_i(\boldsymbol{\vartheta}_{-i})$ denotes the effective VoPP:

$$\tilde{v}_i(\boldsymbol{\vartheta}_{-i}) \triangleq \left[1 - \frac{\boldsymbol{\vartheta}_{i=1}\boldsymbol{\phi}}{1 - \Phi_\alpha(\boldsymbol{\vartheta}_{i=1})}\left(\alpha_i + \bar{\alpha}_i \mathbf{1}_{\{\boldsymbol{\vartheta}_{-i}=\mathbf{0}\}}\right)\delta_i\right] q_i$$

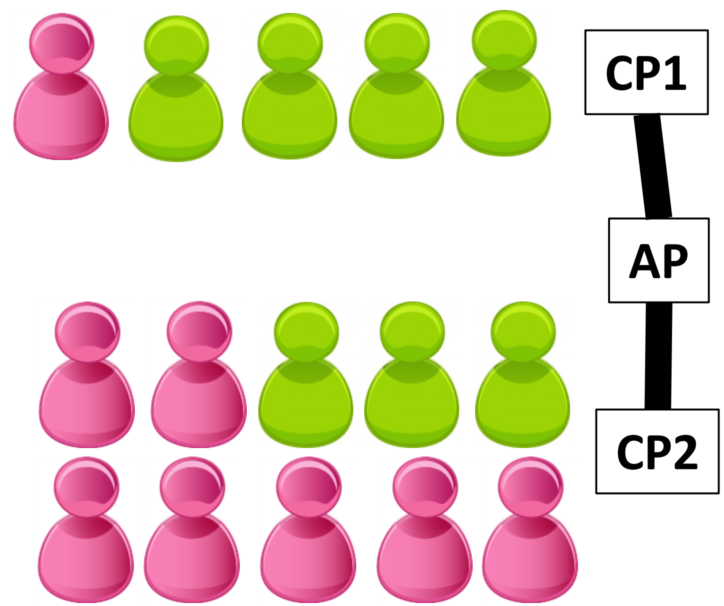
  and $\boldsymbol{\vartheta}_{i=1} \triangleq (\vartheta_i = 1; \boldsymbol{\vartheta}_{-i})$.

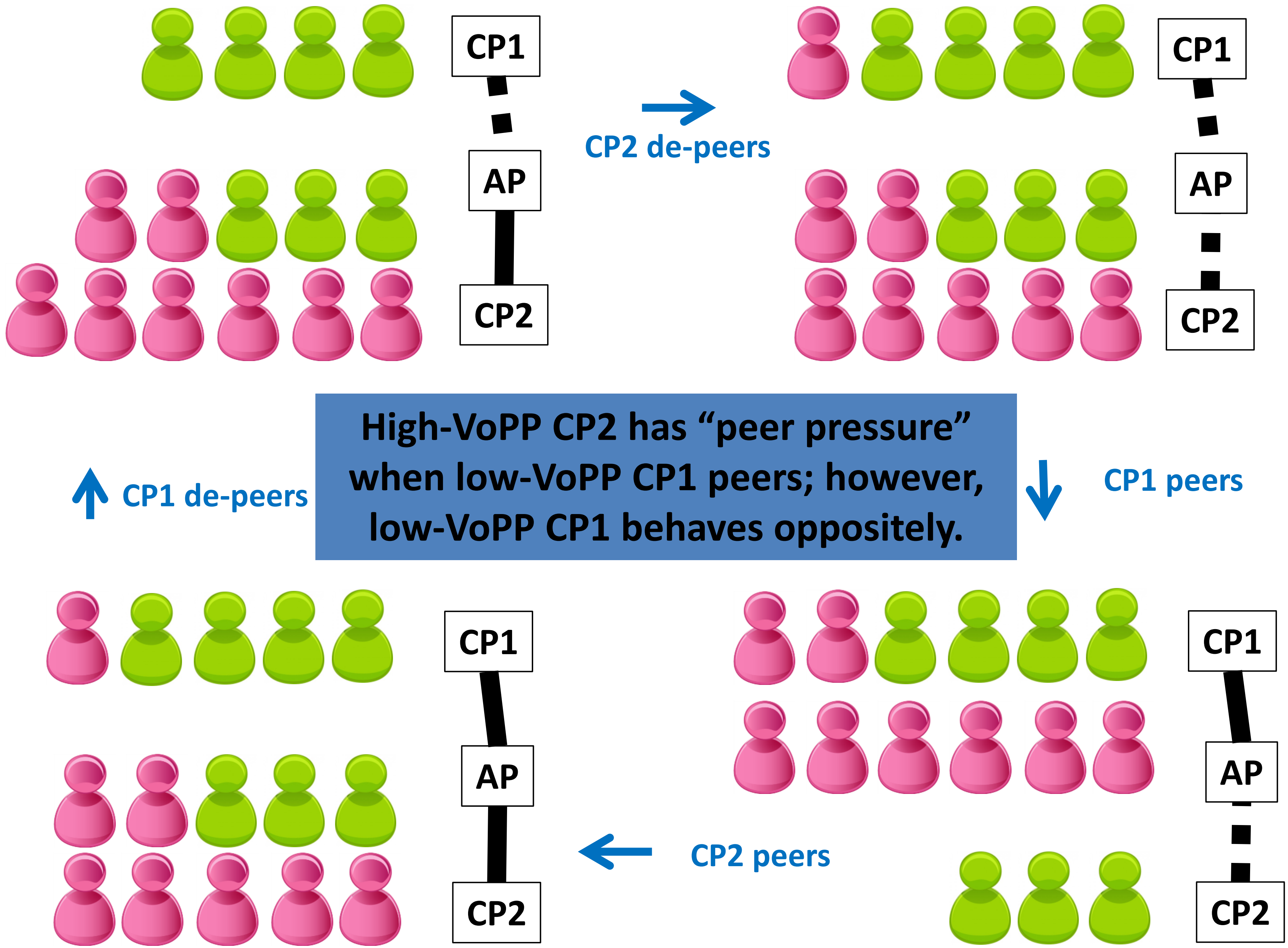
❖ A further generalization of the intrinsic VoPP v_i:

$$\tilde{v}_i(\boldsymbol{\vartheta}_{-i}) = (1 - \alpha_i \delta_i) q_i \quad \text{if } \boldsymbol{\vartheta}_{-i} = \mathbf{1} \text{ or } \boldsymbol{\alpha}_{-i} = \mathbf{1}$$

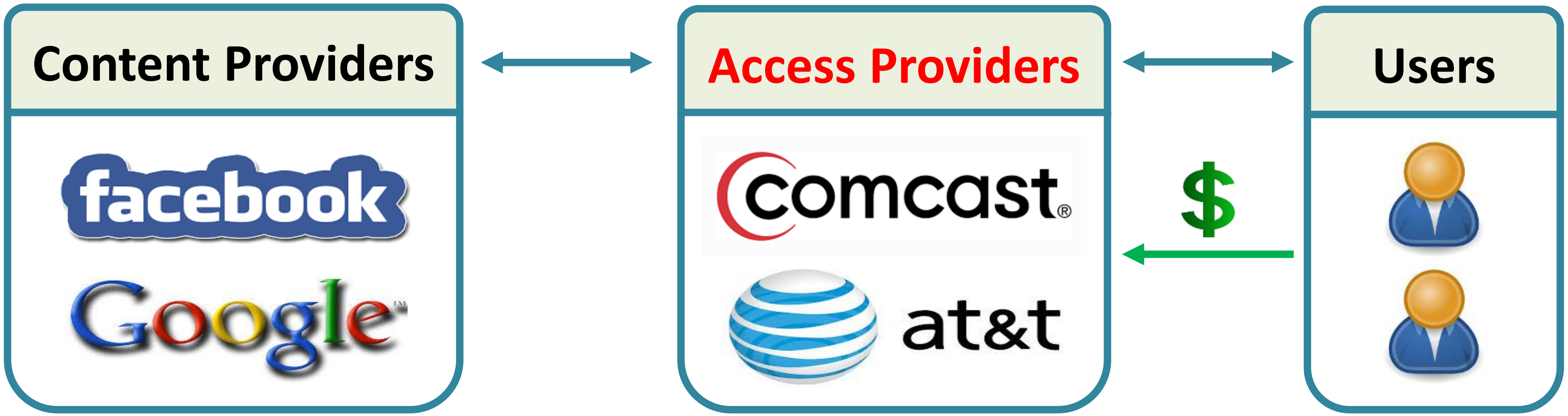
Non-existence of Nash equilibrium

- $\phi_1 = 1/3,\ \phi_2 = 2/3$
- $\alpha_1 = 80\%,\ \alpha_2 = 30\%$
- VoPP: $v_i \triangleq (1 - \alpha_i \delta_i) q_i$
- If both CPs provide similar contents, we have
  - $q_i = q_j$ and $\delta_i = \delta_j$
  - $v_1 < v_2$



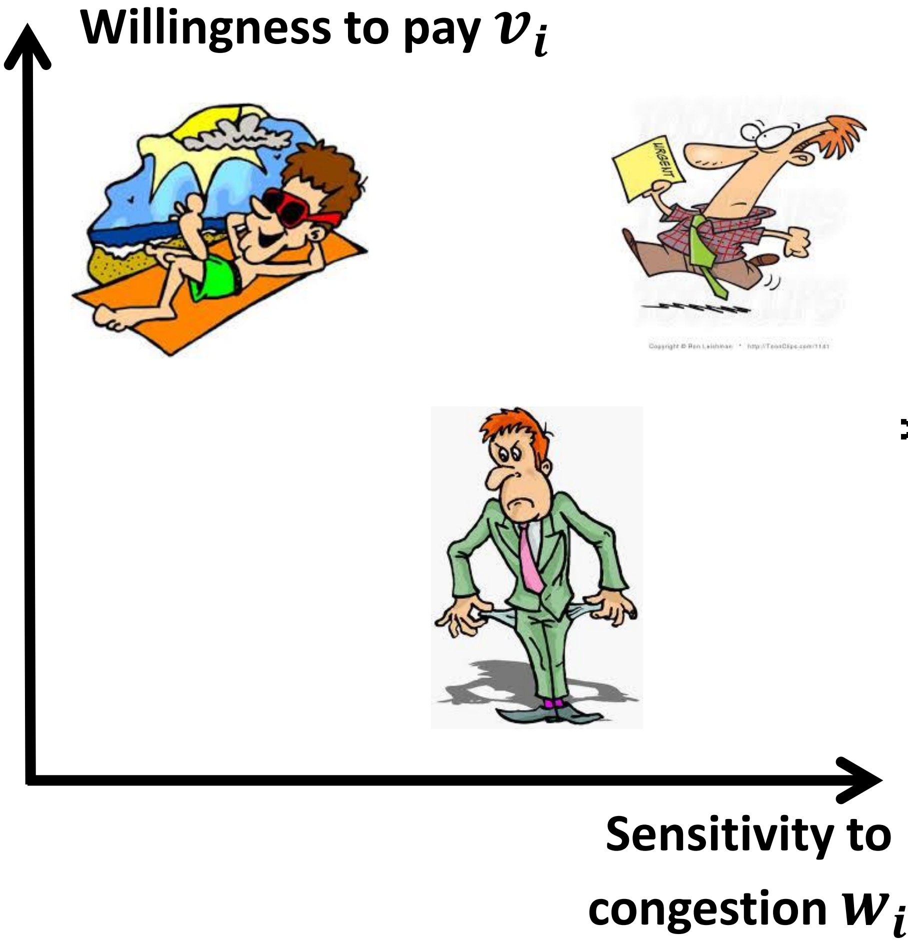

CP1
AP
CP2
CP2 de-peers
CP1
AP
CP2
High-VoPP CP2 has "peer pressure" when low-VoPP CP1 peers; however, low-VoPP CP1 behaves oppositely.
CP1 de-peers
CP1 peers
CP1
AP
CP2
CP2 peers
CP1
AP
CP2

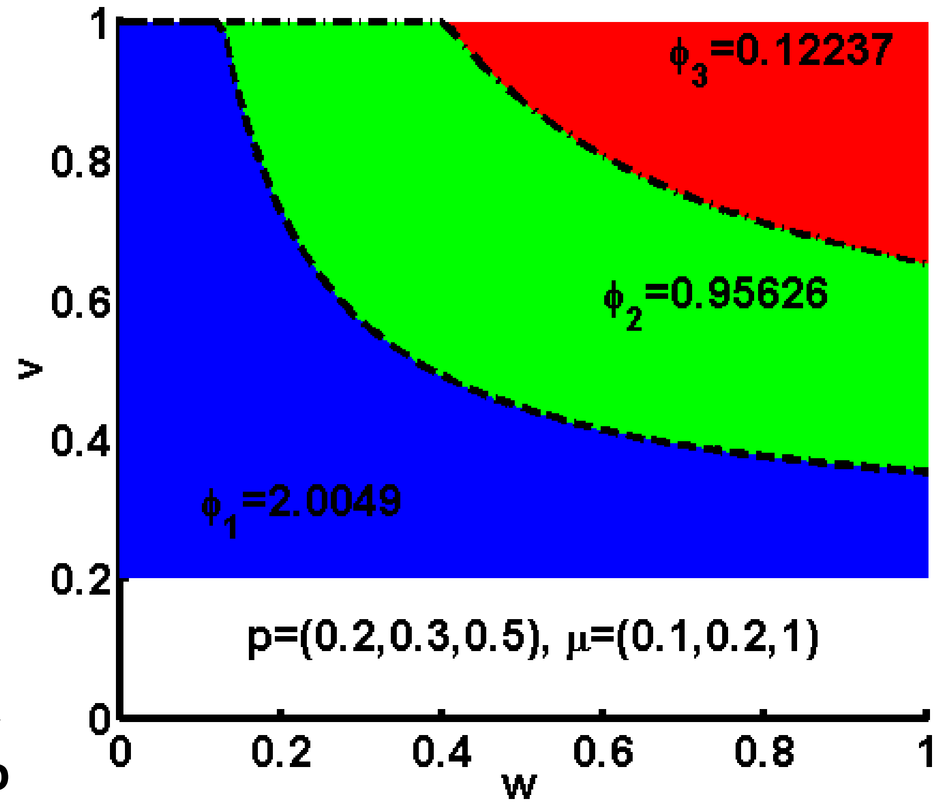
Applications of congestion equilibrium: user-side pricing and differentiation



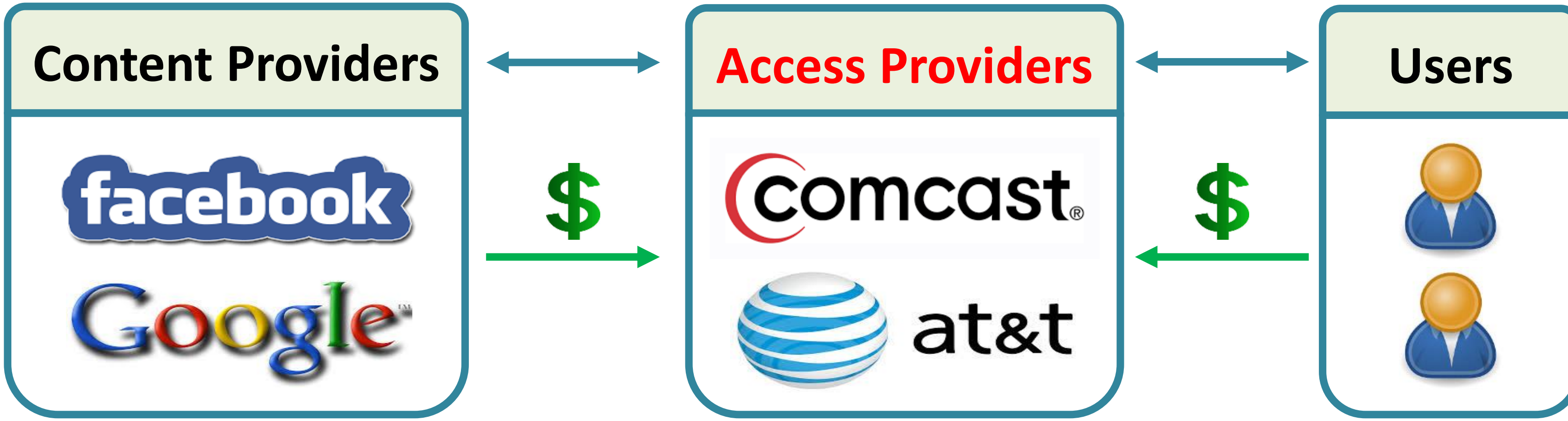
- Richard T. B. Ma. Usage-Based Pricing and Competition in Congestible Network Service Markets. IEEE/ACM Transactions on Networking, 24(5), 2016.
- Xin Wang, Richard T. B. Ma and Yinlong Xu. The Role of Data Cap in Optimal Two-part Network Pricing. WWW Conference, 2015.
- Mao Zou, Richard T. B. Ma, Xin Wang and Yinlong Xu. On Optimal Service Differentiation in Congested Network Markets. IEEE INFOCOM, 2017.

User model and market equilibrium





Applications of congestion equilibrium: two-sided pricing and variations



- Xin Wang, Richard T. B. Ma and Yinlong Xu. On Optimal Two-Sided Pricing of Congested Networks. ACM Sigmetrics Conference, 2017.

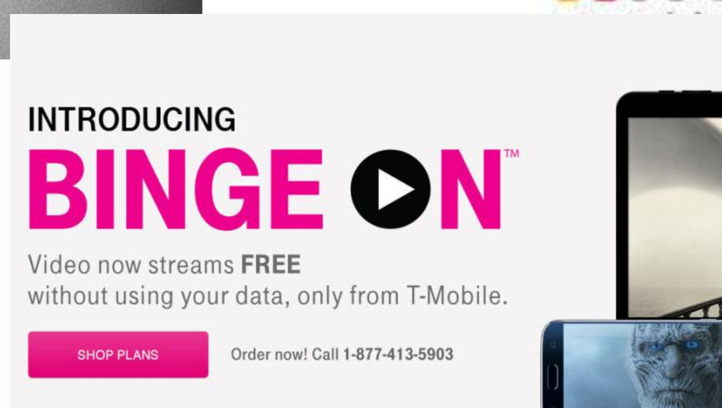
- Richard T. B. Ma. Subsidization Competition: Vitalizing the Neutral Internet. IEEE/ACM Transactions on Networking, Volume 24(4), 2016.

DIFFERENTIAL PRICING, ZERO RATING AND NET NEUTRALITY

What is Zero Rating?

- Zero-rating (also called toll-free data or sponsored data) is the practice of mobile network operators (MNO), mobile virtual network operators (MVNO), and Internet Service Providers (ISP) not to charge end customers for data used by specific applications or internet services through their network.

Examples of Zero-rating



~80 countries currently offer zero-rating type of services (not complete list)

[1] https://en.wikipedia.org/wiki/Facebook_Zero

[2] https://wikimediafoundation.org/wiki/Mobile_partnerships

Zero Rating and Consumer Surplus

- Consumer Surplus: Difference between what a consumer is *willing* to pay and what the the consumer *has* to pay (*Utility-Price*)
- Consumers choose commodity that gives them the most surplus
- Willingness to pay is property of content (quality, QoS etc.). FCC's definition (no blocking, throttling or paid prioritization) keeps willingness intact
- FCC silent on what consumer *has* to pay. Zero rating distorts consumer surplus and hence the market

Real World Data

- T-Mobile introduced the Binge On program in November 2015. Partner sites (Netflix, Hulu, HBO etc.) have videos Zero Rated, non-partners (YouTube etc.) not
- All videos are throttled down to 1.5 Mbps
- Two separate studies on impact of Binge On. One by T-Mobile, another by a consulting firm engaged by T-Mobile.
- T-Mobile claims Binge On *benefits everybody*

Results

- Consulting firm study: Partners showed an increase in average viewing time of 50%; the viewership of the most prominent non-partner, YouTube, increased by 16%.
- T-Mobile numbers: 79% benefit for partners, and 33% benefit for non-partners.
- Consumer Surplus isn’t just theory. Market distortion is *real*

(Re)Defining Network Neutrality

The Internet should provide a platform that does not provide a competitive advantage to specific content/app/services, either through pricing or quality of service