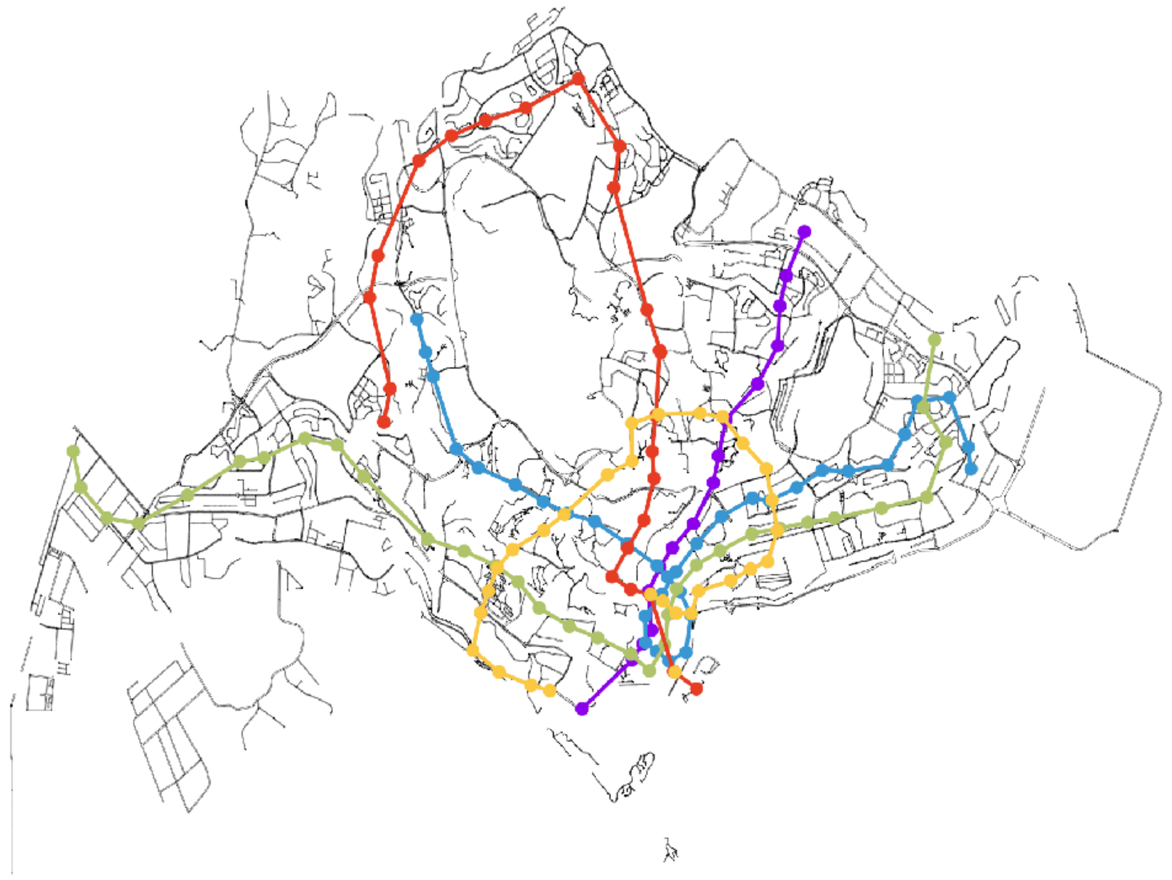
CSCI 357: Algorithmic Game Theory

Lecture 19: Nash in Routing Games

Shikha Singh



Announcements and Logistics

- Project deadlines:
  - 2-Page report due via Github
  - Sign up for check-in next week through sheet: http://tinyurl.com/357sheet
  - In-class presentations on Friday: 10 mins + 2 mins for Q&A
- Leave 15 mins for SCS form on Tuesday May 13
  - Please bring your laptop to class!

Questions?

End of Semester Get Together

Lunch Wed 14, 11.30 am - 12.30 pm (Spice Root)

Colloquium Today

5/05 Colloquium - Steve Skiena, Stony Brook

Colloquium:

Friday, May 09

2:35pm in Wege

Stony Brook, NY; Stony Brook University: Steve Skiena, Distinguished Teaching Professor of Computer Science

Reading Books and People

I will talk about two projects my lab works on. The first project concerns NLP on books: How can you quantify the similarity of different narrative texts, like the degree of faithfulness between a novel and its screen adaptation, or the quality of translation of a source book into a given language?

The second project concerns building models to predict life course outcomes from nation-scale social registry and social network data. How predictable is your future income, when you will retire, or who you will marry? We work with social scientists in Europe on these questions.

Today: Few Highlights

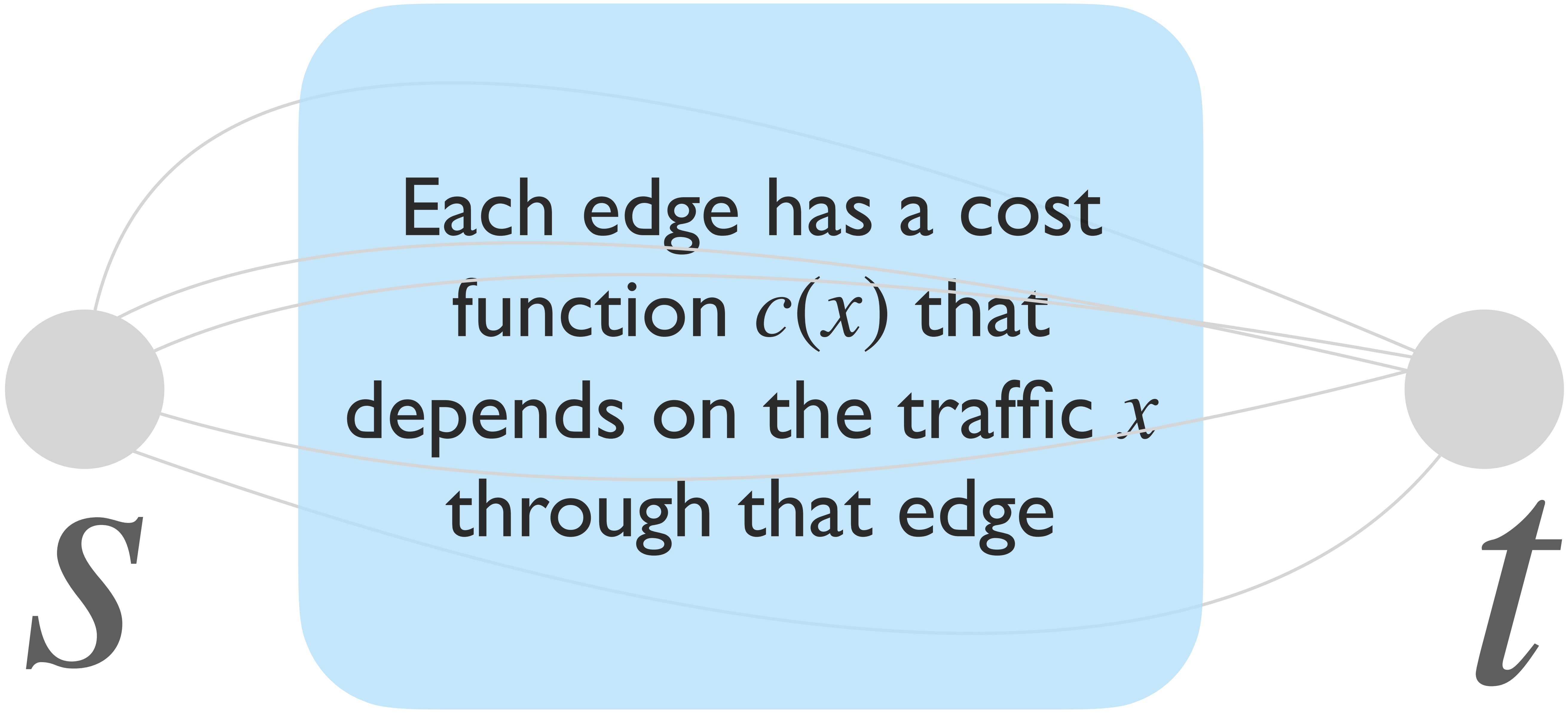
- Braess's Paradox and Price of Anarchy
- Incentives in Network routing
- Complexity class of FindNash

Incentives: Network Routing

- Last week we discussed incentives in P2P systems
- Today I want to talk about incentives when it comes to routing protocols in computer networks
- Two types of routing:
  - Selfish routing in local area networks
  - Inter-domain routing in the Internet

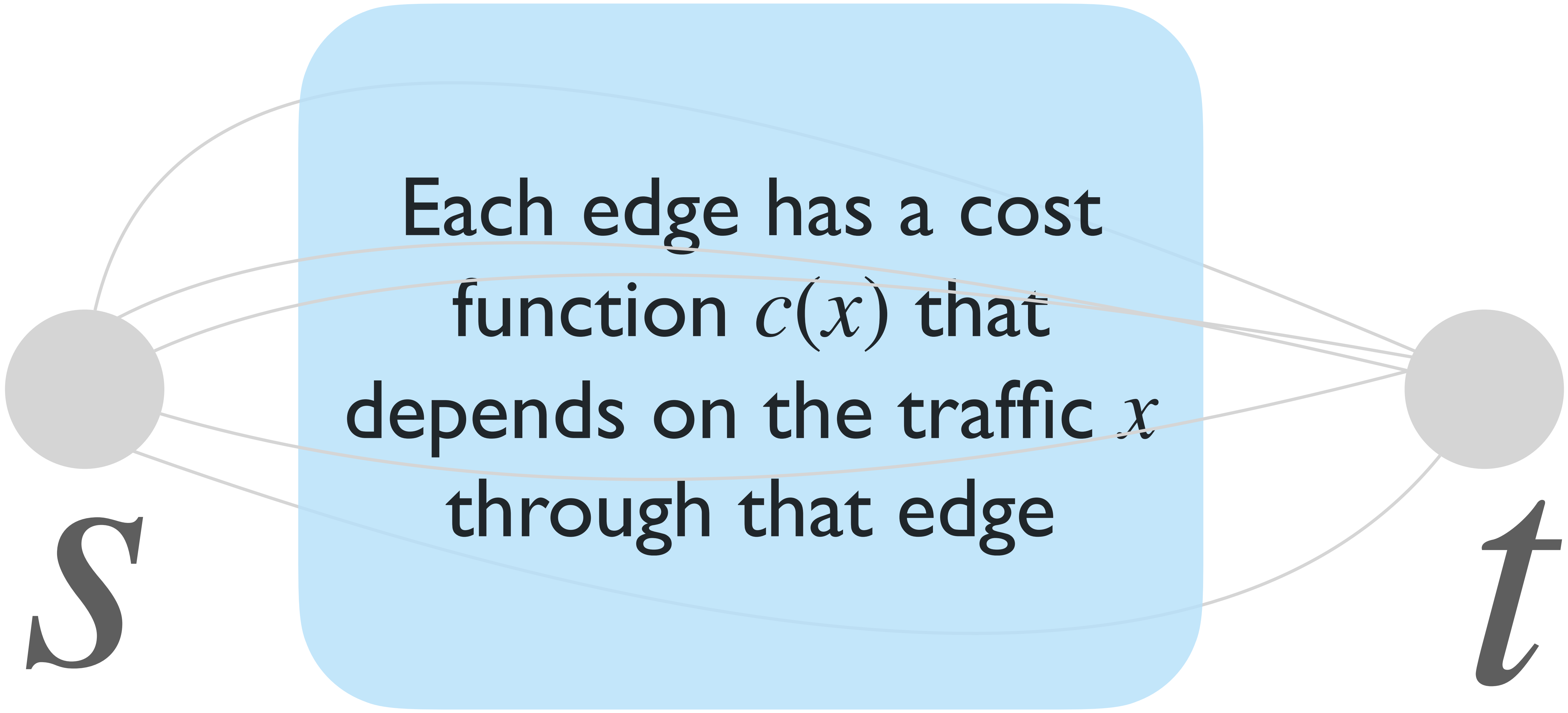
Routing Games

- Also called congestion games
- Simple model that captures many routing applications:
- Routing in traffic networks, routing in local-area-networks, communication networks, etc



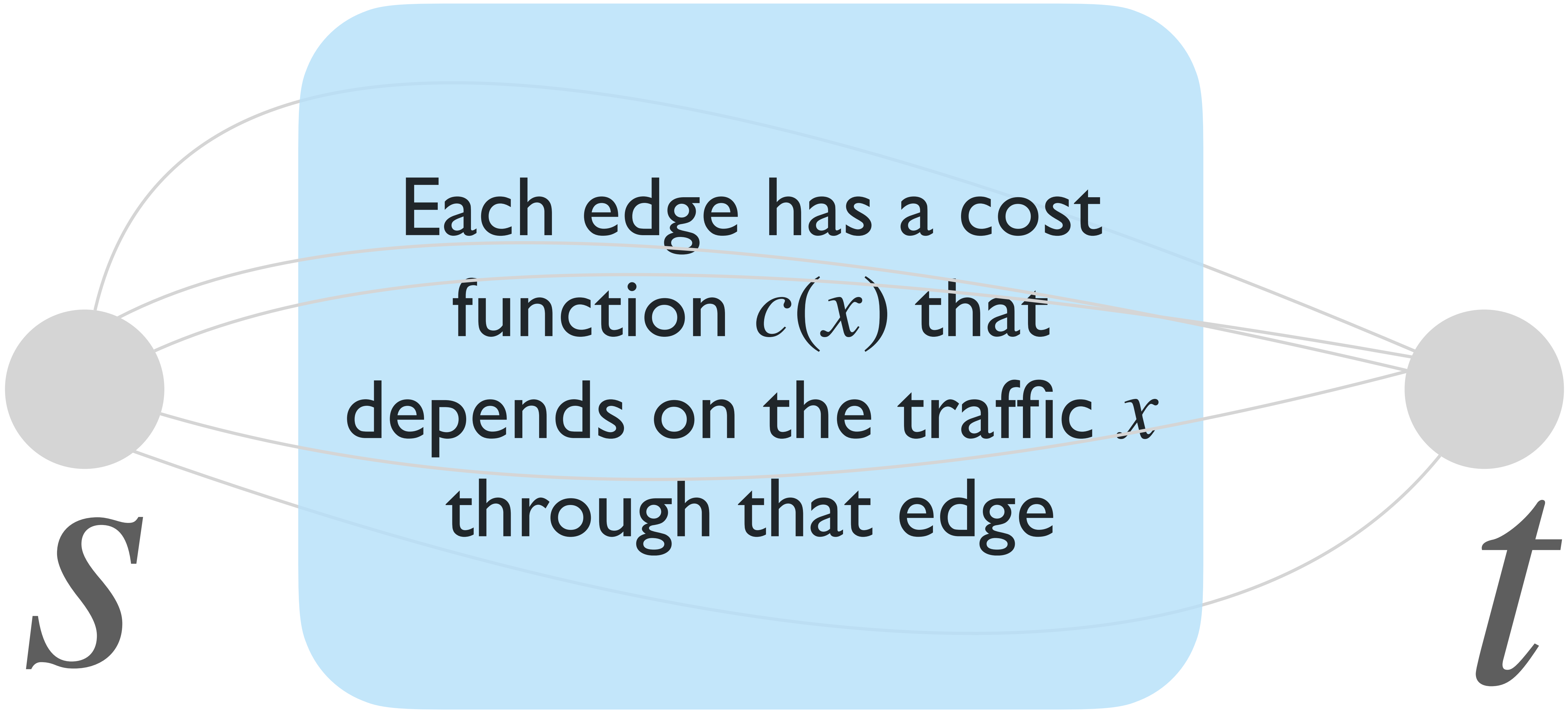
Routing Games

- Directed graph (edges have a direction: think of one-way streets)
- Single source s and destination t (can be generalized)
  - All traffic originates at s and is going to t
- Assume there is some fixed number of drivers n (say 100 or 1000)



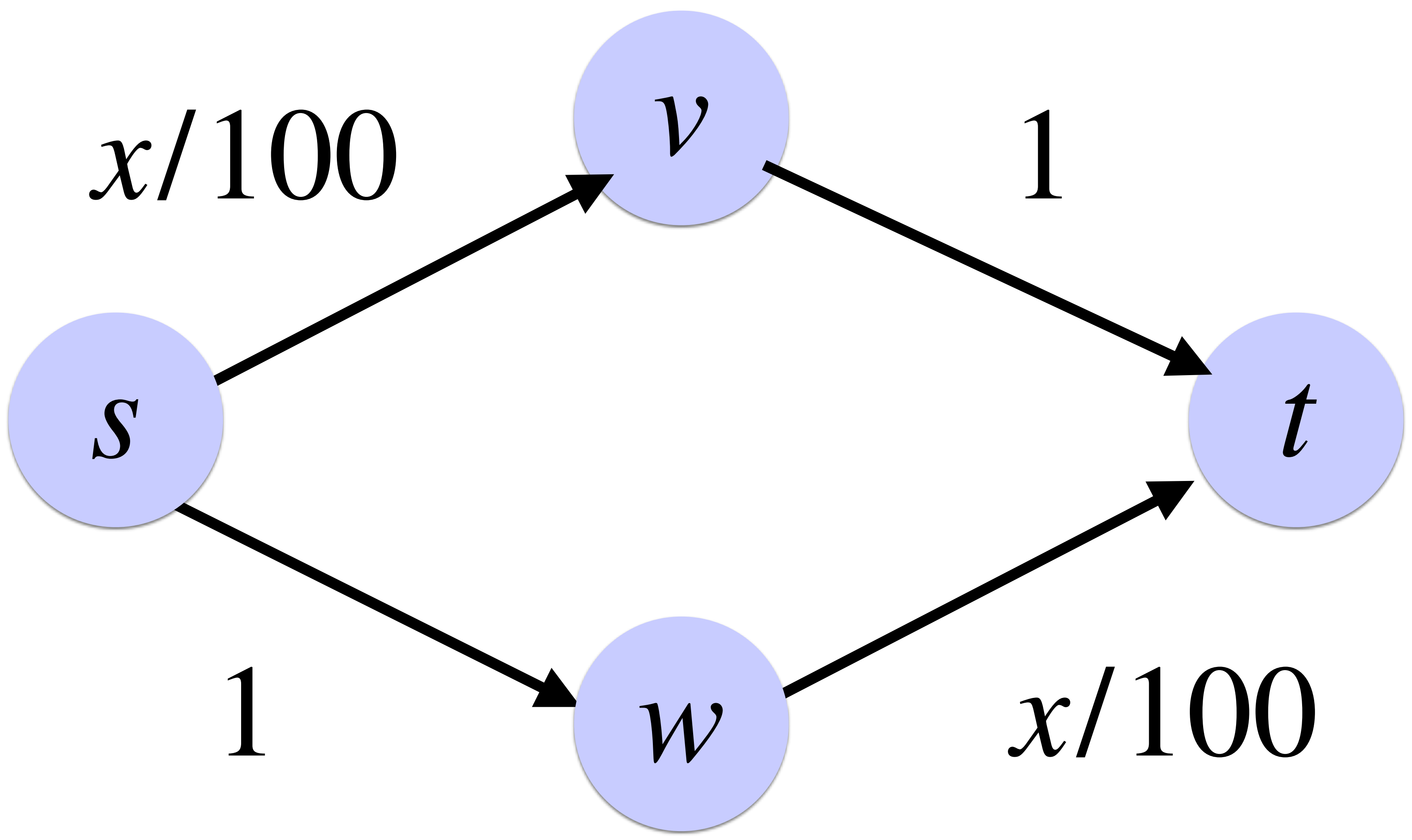
Routing Games

- **Driver's goal:** minimize their own commute time, defined as sum of costs of edges in their s to t path
- **Non-cooperative game:** your commute time depends on what path other drivers are choosing



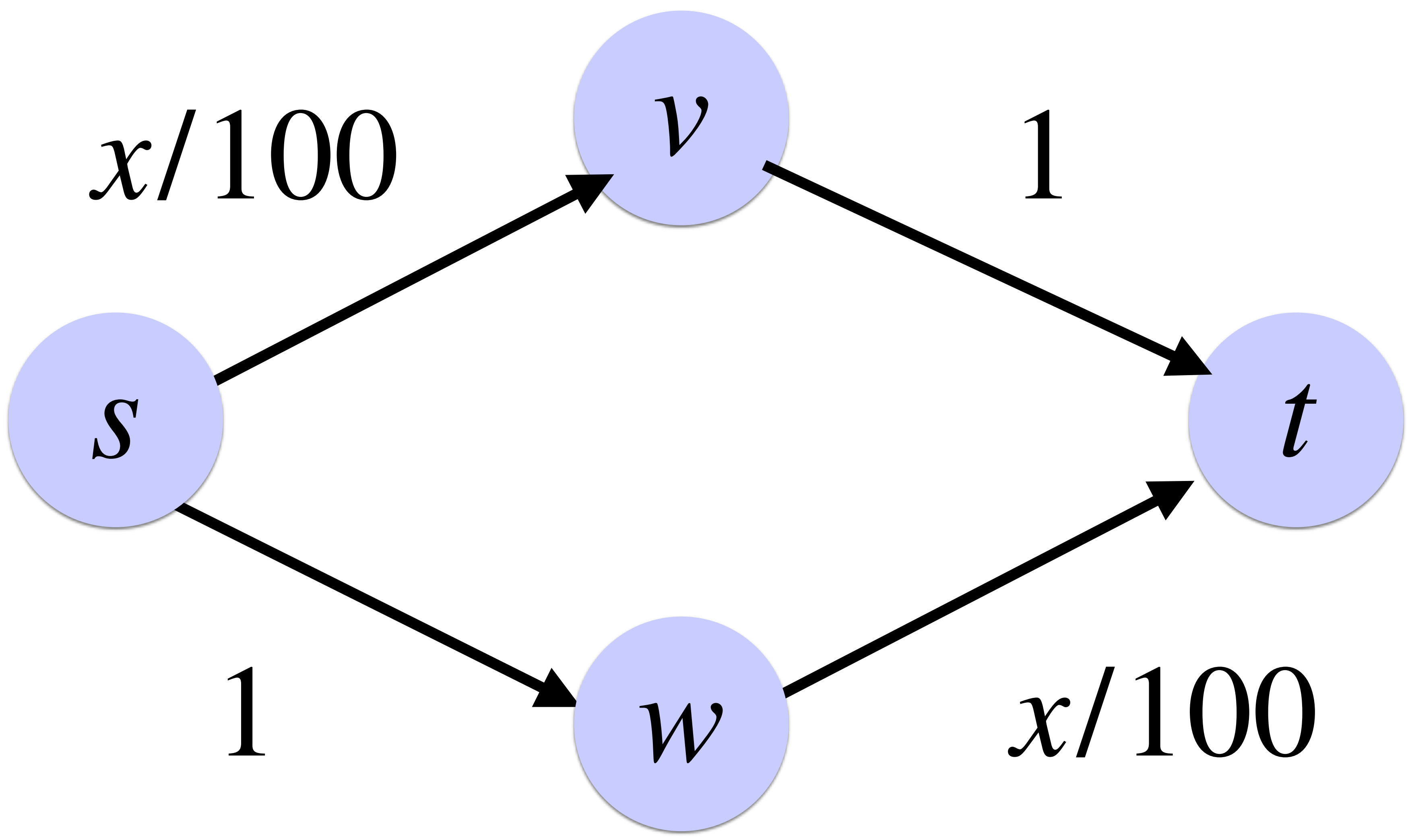
Example Network

- Suppose there are 100 drivers
- Cost function $c(x)$ on an edge which maps x (the number of players using it) to their commute cost on that edge
- Commute time on a given route (s to t): **sum of edge costs**



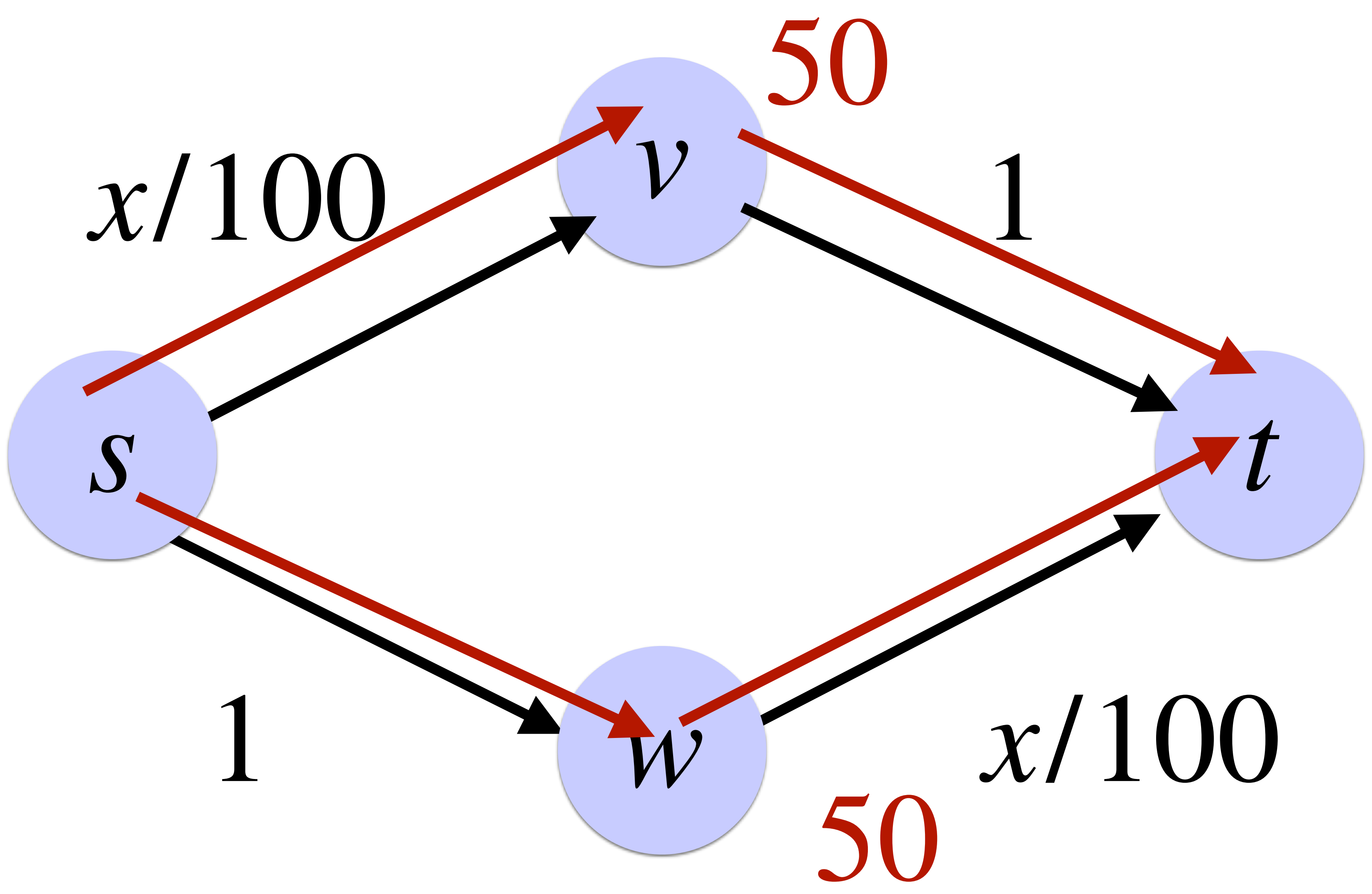
Nash Equilibrium

- At Nash equilibrium, what do we expect the state of traffic to be?
- **(Aside:** notice that in these types of graphical games, enumerating the entire payoff matrix is not reasonable: 100^2 action profiles)



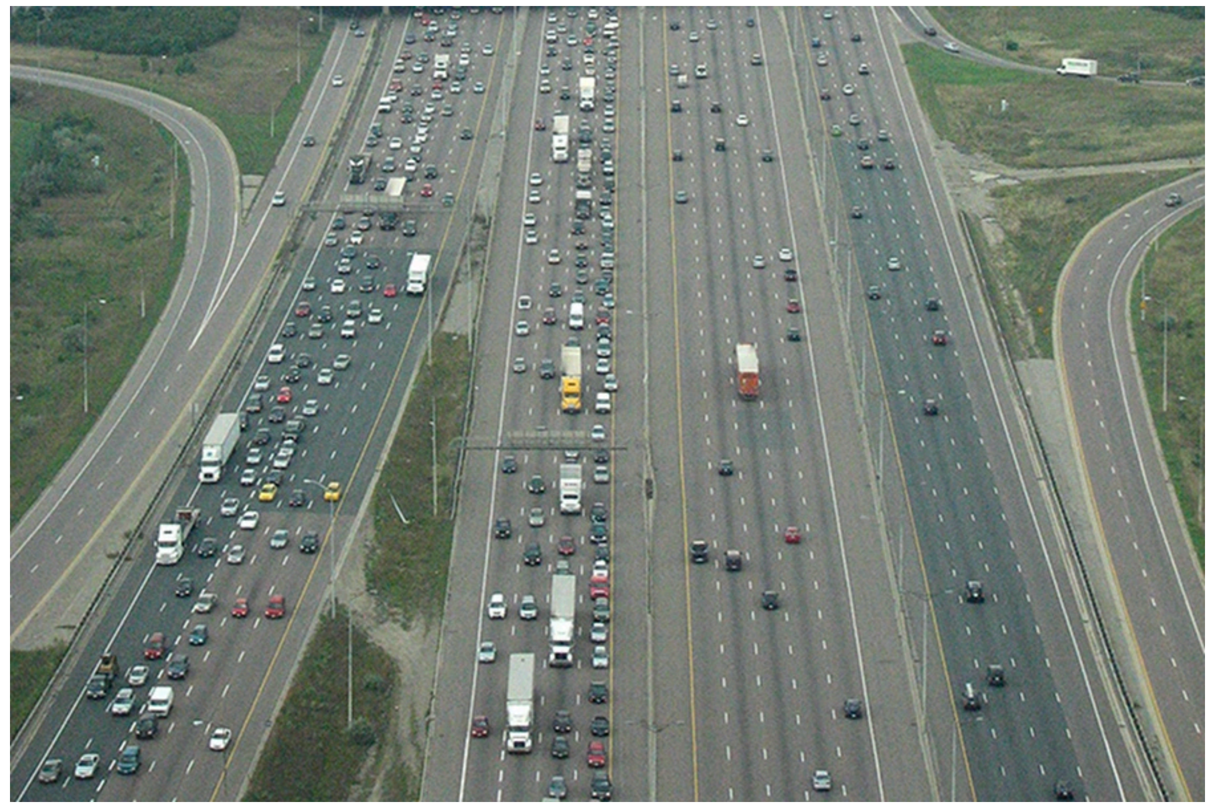
Nash Equilibrium

- At a Nash equilibrium, traffic splits $50 - 50$ across the routes
- What is the commute time of each agent?
  - $1 + 1/2 = 1.5$ (say hours)

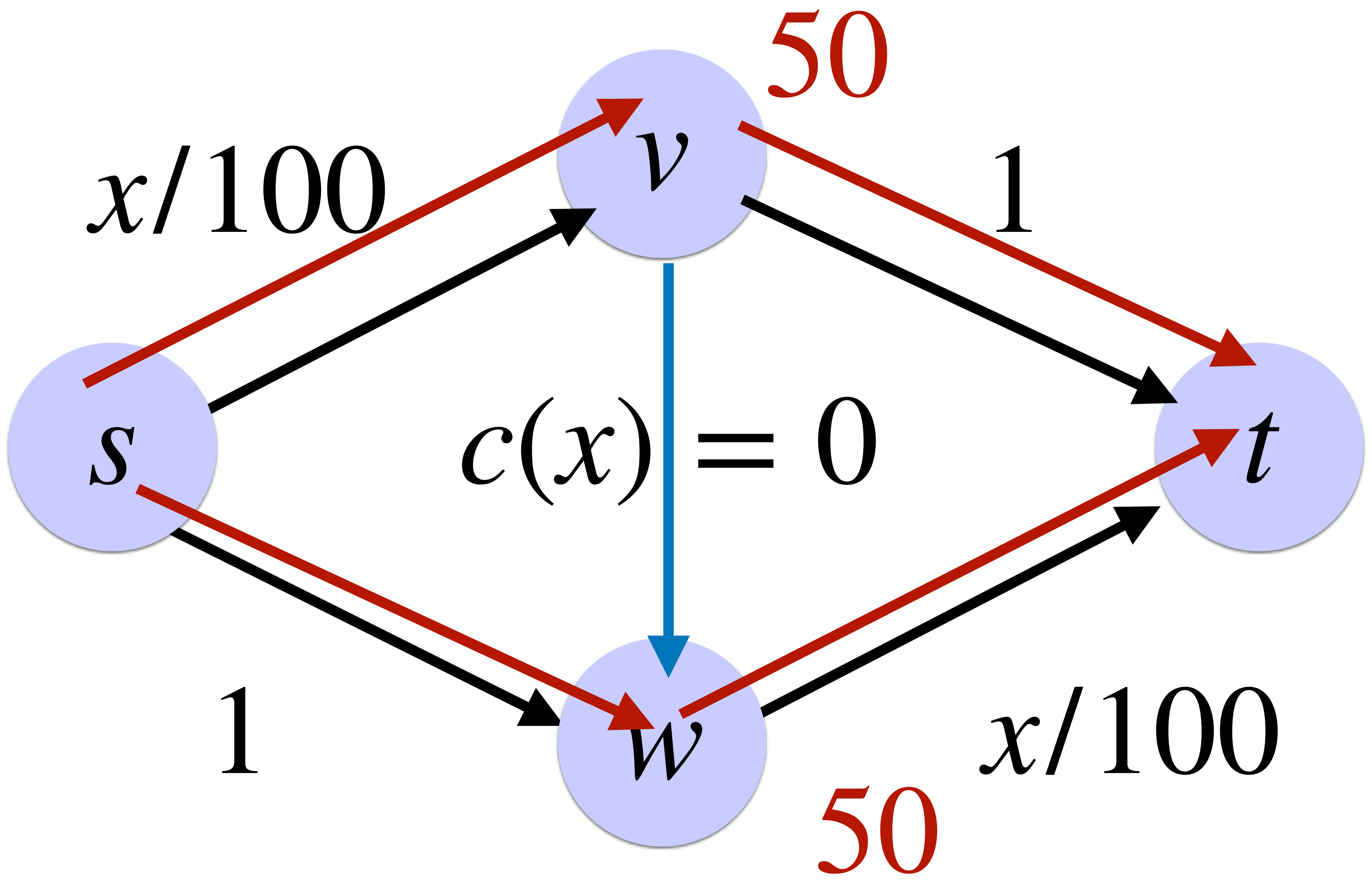


Braess Paradox

- Now suppose, to improve congestion, we introduce a "super highway" between v and w
  - Cost of this edge does not depend on traffic and is zero
  - Essentially "teleports everyone"
- How does this change effect the equilibrium flow?

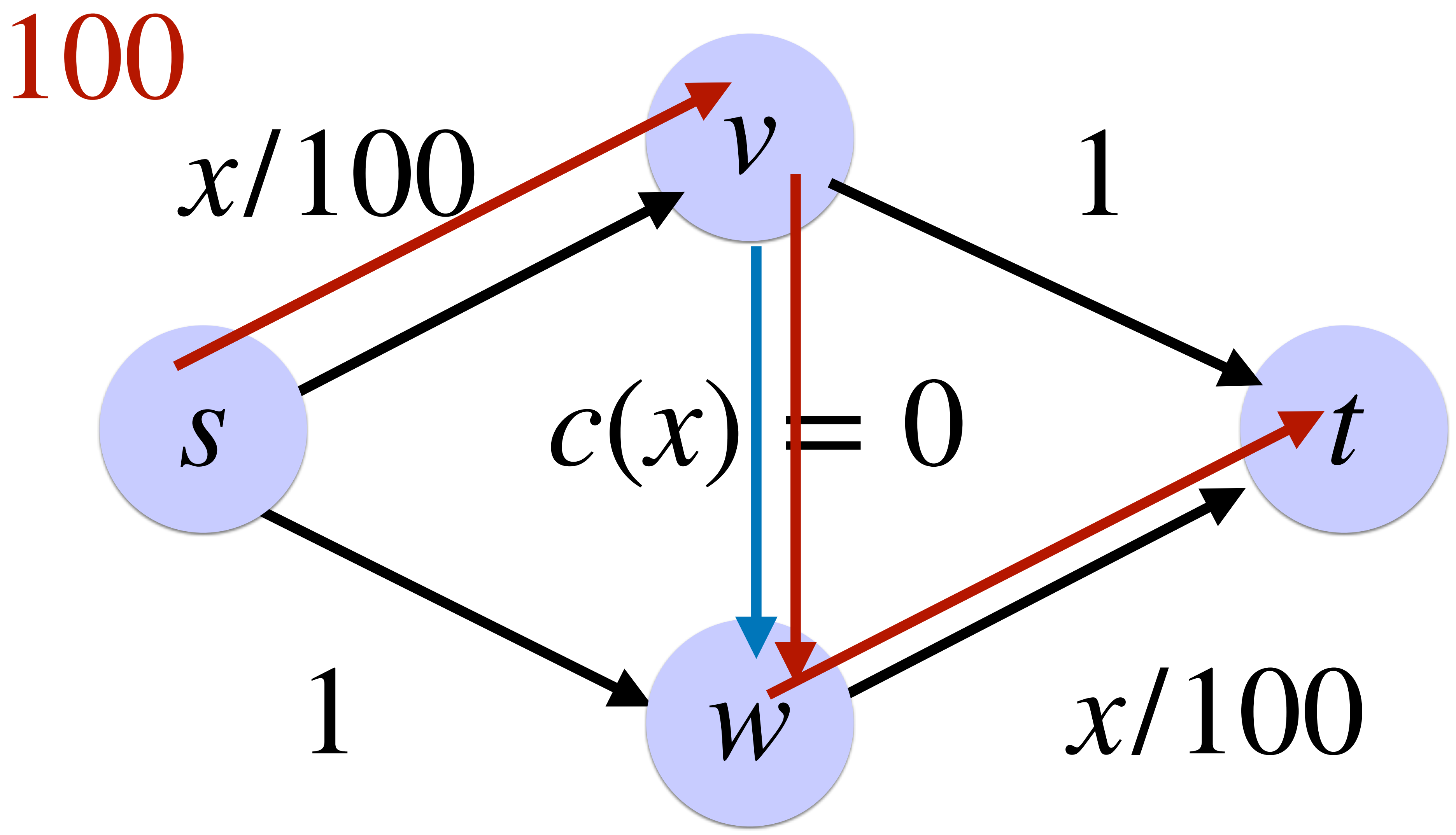


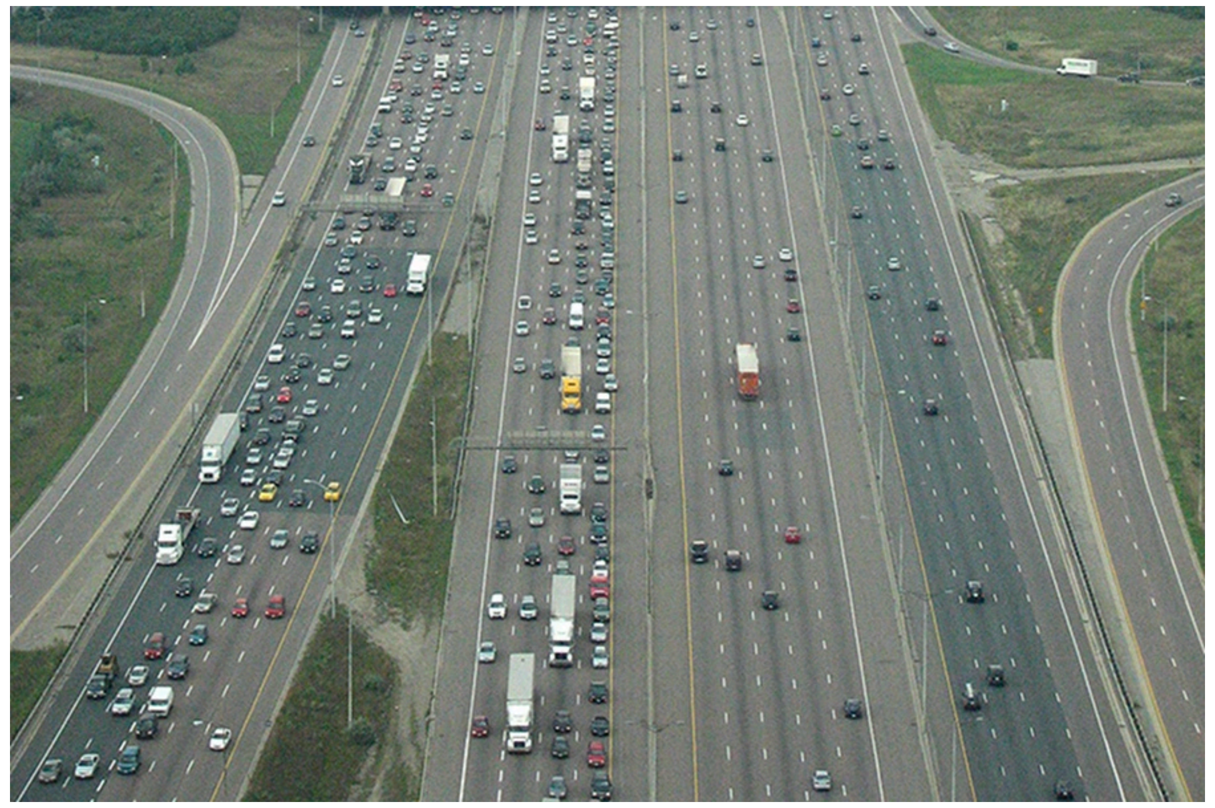
Katy free highway in Texas



Braess Paradox

- Everyone taking s -> v -> w -> t is a Nash eq, why?
  - Can anyone gain by deviating unilaterally?
- What is the commute time now?
  - 2 hours (compared to 1.5 before)

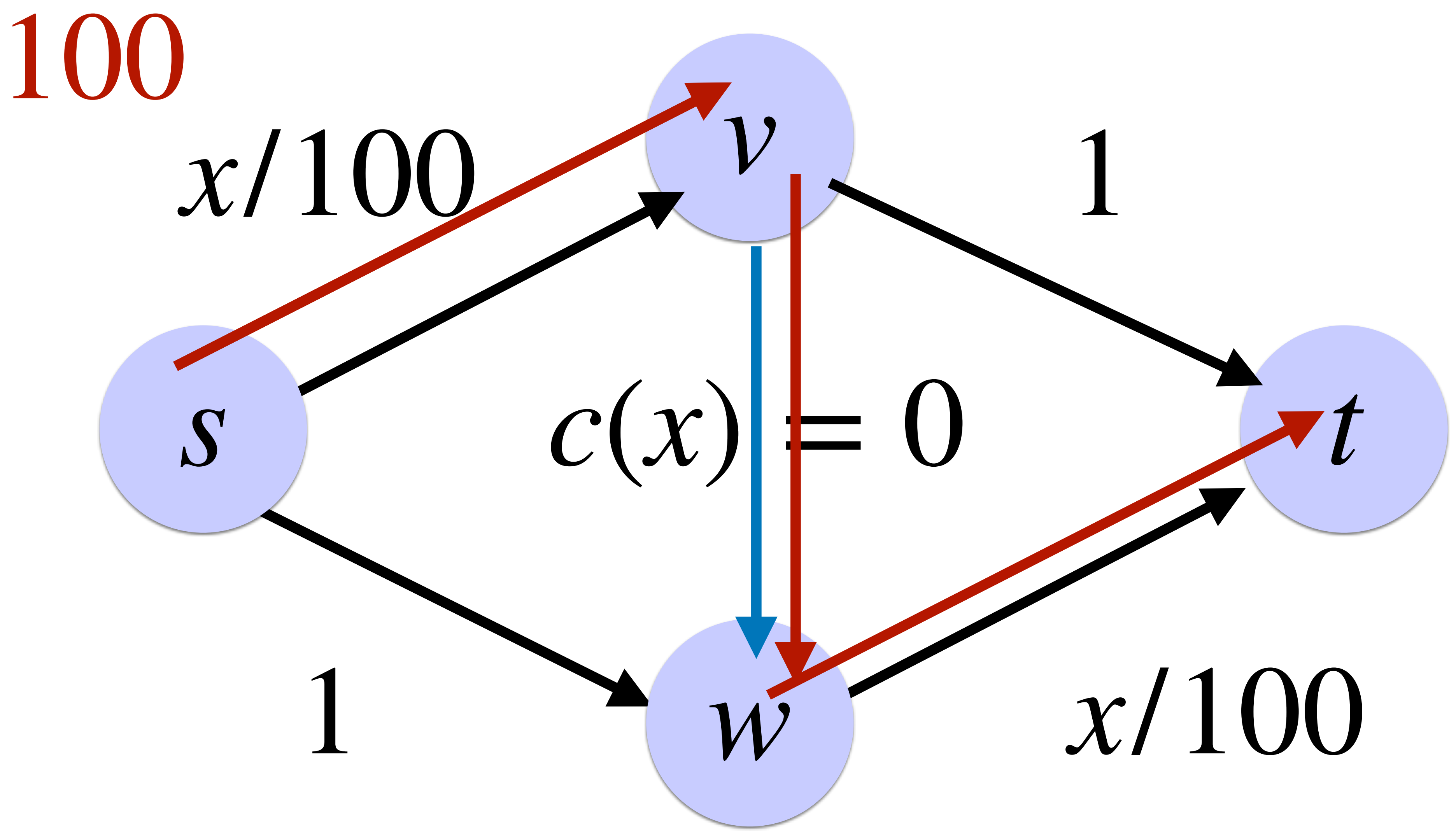


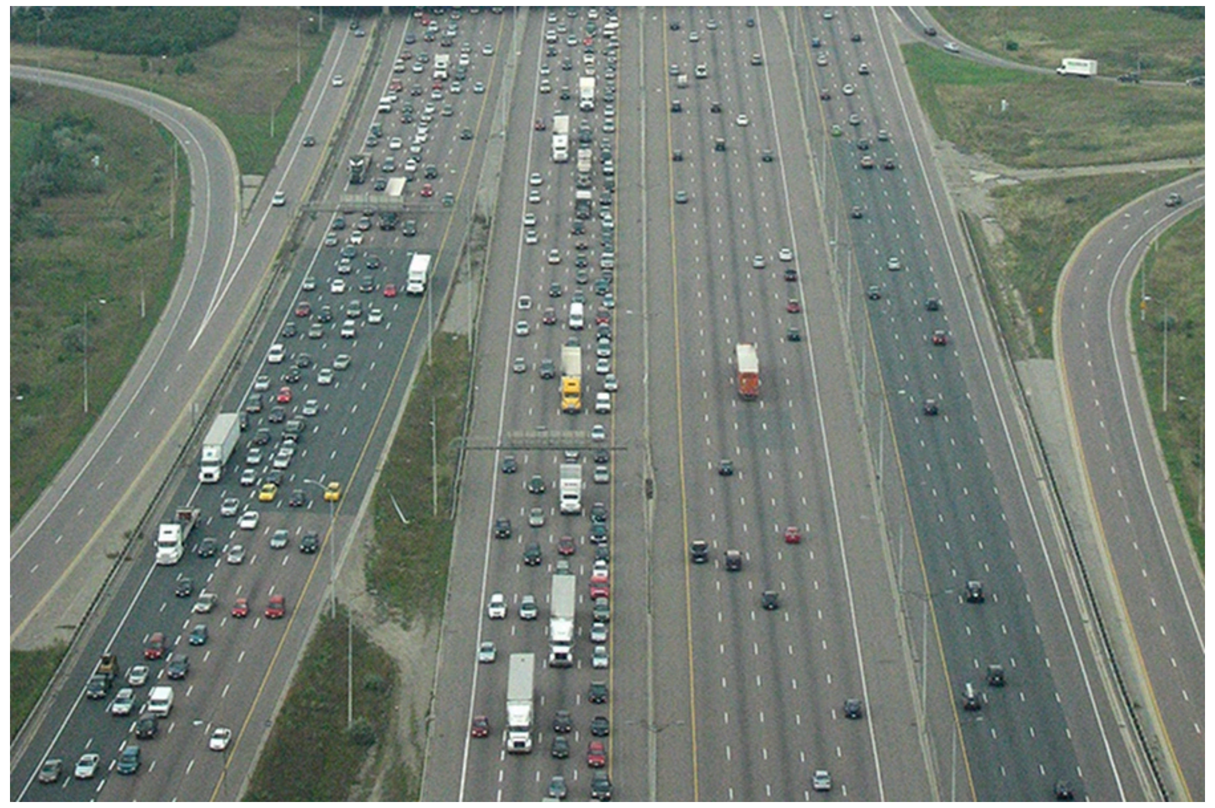


Katy free highway in Texas

Braess Paradox

- Adding a super-highway made things much worse!
- Is this a phenomenon we experience in our lives?

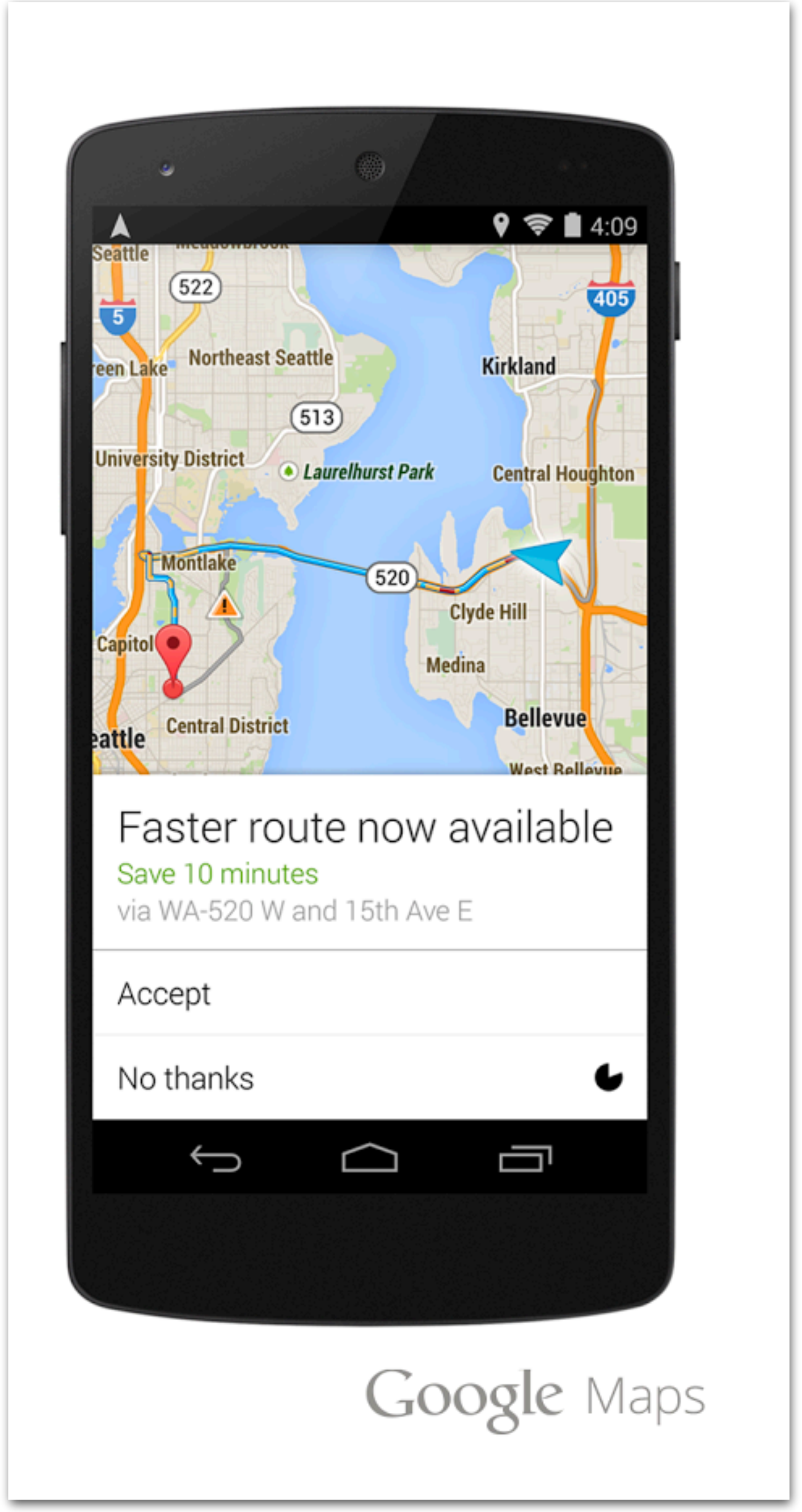


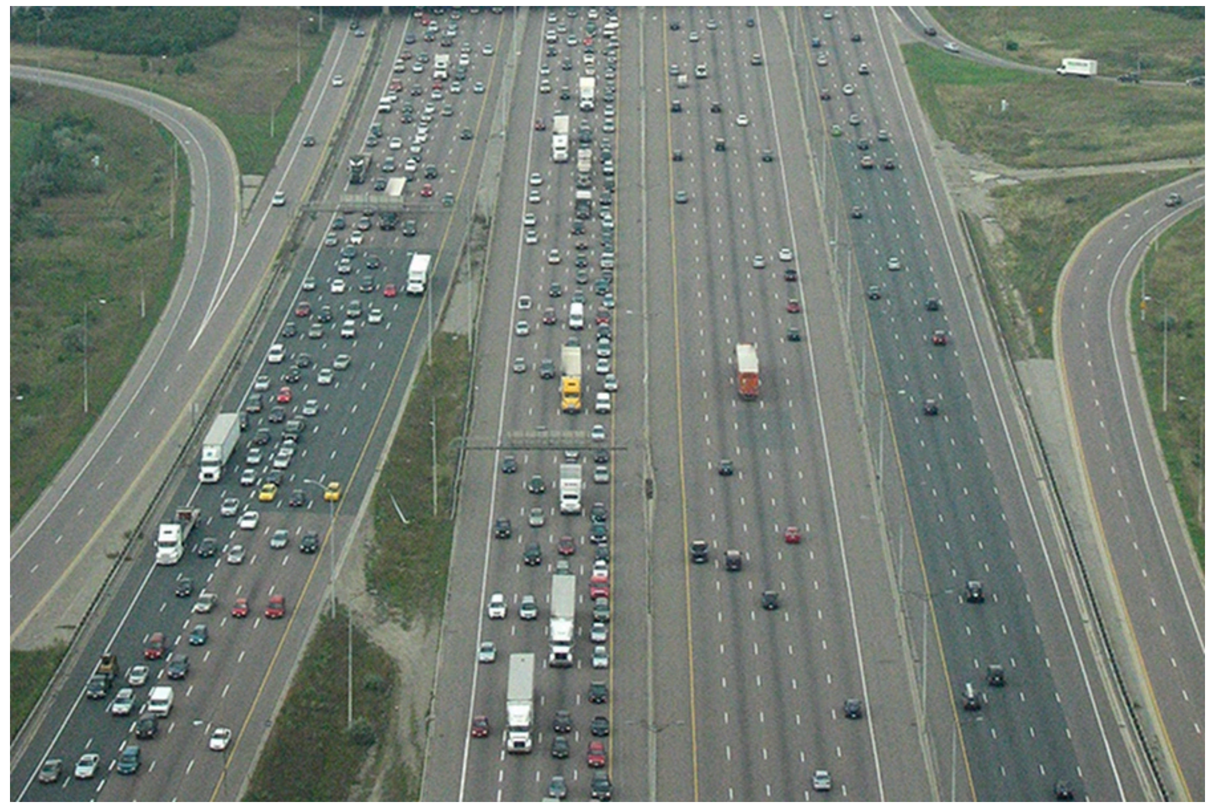


Katy free highway in Texas

Braess Paradox in Practice

- Adding a super-highway made things much worse!
- Is this a phenomenon we experience in our lives?
- Google updates best route due to congestion
  - What if all drivers change that switch?





Katy free highway in Texas

Braess Paradox in Practice

- In Seoul, the mayor undertook a massive revitalization project
  - Demolished a six-lane highway over the Cheonggyecheon river
  - Turned it into a recreation space
- Initially unpopular decision
- Since then has significantly improved traffic congestion

https://wwf.panda.org/wwf_news/?204454/Seoul-Cheonggyecheon-river

Braess Paradox in Practice

- In 2009, NYC experimented with road closures in 2009 to reduce congestion
- Closed off Broadway/Times Sq and Herald Sq
- Overall congestion improved
- Experiment considered to be a success and the road closures were made permanent

WIRED

FEATURED MOTHER'S DAY GIFT IDEAS HOW TO DOWNLOAD VIDEOS TO WATCH OFFLINE BEST STRENGTH TRAINING GEAR HOW TO SUBMIT NEW EMOJI IDEAS BUYING GUIDES GADGET LAB NEWSLETTER

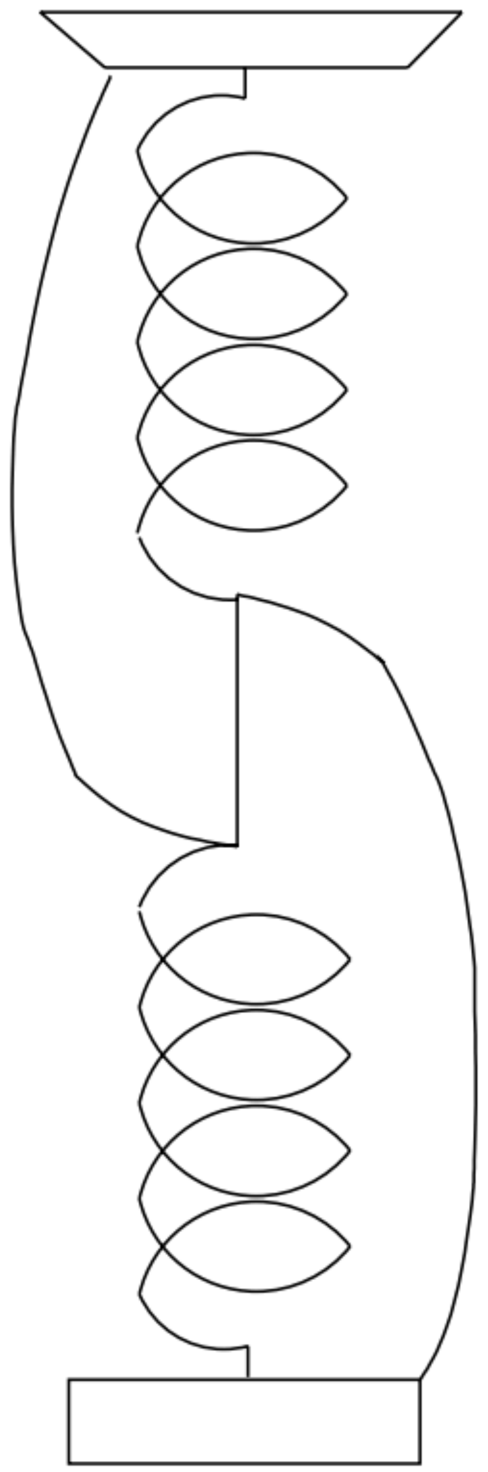
ADAM MANN GEAR JUN 17, 2014 6:30 AM

What's Up With That: Building Bigger Roads Actually Makes Traffic Worse

The concept is called induced demand, which is economist-speak for when increasing the supply of something (like roads) makes people want that thing even more. Though some traffic engineers made note of this phenomenon at least as early as the 1960s, it is only in recent years that social scientists have collected enough data to show how this happens pretty much every time we build new roads.

Braess Paradox: Strings & Springs

- Not only a traffic phenomenon: strings and springs
- https://youtu.be/cALezV_Fwi0?t=415



(a) Before

Takeaways

- Braess's Paradox is observed in any system that can be modeled as a network
  - Water systems, electric systems, any flow network
- Recurring theme: selfish behavior does not always lead to globally efficient outcomes
  - Seen this in Prisoner's dilemma
- **Question:** "how bad is selfish behavior?"
- Quantify the loss in welfare caused by letting the game play out in the wild, rather than centrally controlling it

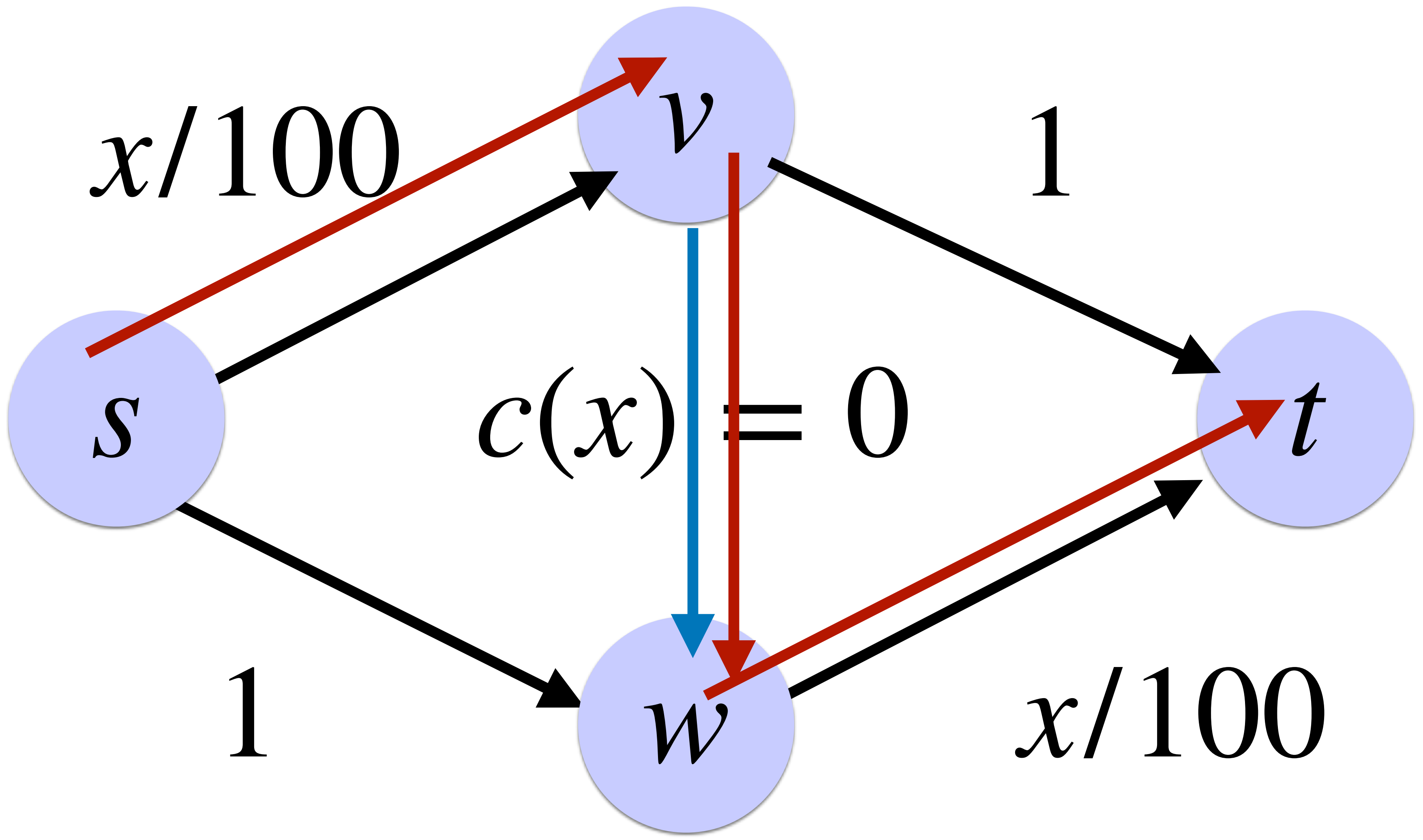
Price of Anarchy

- Concept that measures how the social welfare of a system degrades due to selfish behavior of its agents
- Captures how well equilibria approximates social welfare
- CS driven area in AGT: Introduced and studied primarily by computer scientists
- Does the PoA definition remind you of something from 256?

$$\text{PoA} = \frac{\text{Opt SW}}{\text{SW at (Worst) Eqm}} \qquad \text{PoA} = \frac{\text{SC at (Worst) Eqm}}{\text{Opt SC}}$$

PoA is not too Bad

- Turns out, **pure Nash eq always exists in routing networks**
- In Braess Paradox, equilibrium commute time is 2
  - Optimal commute time is at least as good as splitting traffic 50-50: $\geq 3/2$
- PoA $\leq 4/3$
- **Theorem**. (Roughgarden & Tardos) PoA of any selfish routing network with linear costs $c(x) = ax + b$) is at most $4/3$.
  - Regardless of the network topology!
  - Linear cost function:
- We will show a weaker bound of 2 today



The Internet

Routing in the Internet

- So far, we have discussed **"delay-based" routing** which is common in local-area-networks
- Now we discuss a different type of routing:
  - When routing traffic between different local networks
- The **Inter**net is not one network
  - A "network of networks"
- An **autonomous system (AS)** is a centrally controlled collection of routers: a bunch of routers with a common admin
- The internet has around **42,000 ASes**
  - ISPs, universities, businesses, etc.

Autonomous System: controlled by one entity

Comcast network. Source: business.comcast.com

Routing in the Internet

- How do we transmit information from one AS to another?
    - Some ASes are physically connected
    - Others are not and may need to route through one or many intermediate ASes
- **Questions**.
    - Who pays whom?
    - How do we route traffic within an AS
    - How do we coordinate routing across ASes?
    - All of this is relevant to study incentives

Routing Within an AS

- Routing within an AS: usually **shortest path protocols**
- Resemble Dijkstra and Bellman-Ford algorithms from 256
- What are the edge weights?
    - If all edge weights are 1, we only care about "number of hops"
        - Can use a simpler algorithm than Dijkstra/Bellman-Ford
        - Just breadth-first search works
    - Edge weights might depend on "recently delay"
- All routers essentially agree on the best paths
    - Dictated by a central administrator

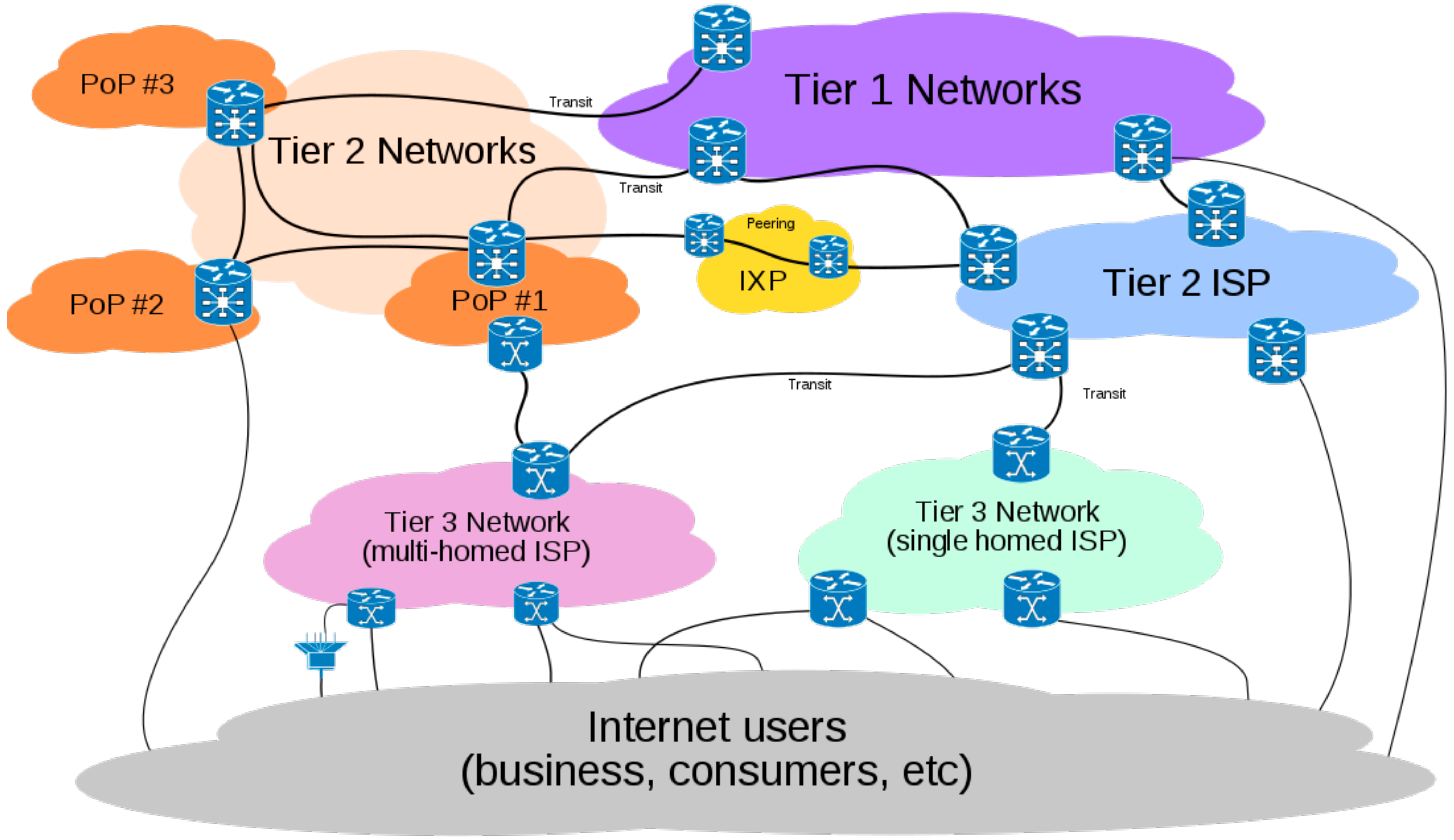
Comcast network. Source: business.comcast.com

Routing Between ASes

- No central administrator to coordinate
- Completely decentralized network (ASes span the whole globe)
- Traffic is routed based on various agreements:
    - **Paid transit**: An ISP might buy access from another larger ISP, e.g. Williams probably does this
    - **Peering**: two ISPs may agree to exchange traffic for free/reduced rate
- To understand this:
    - ISPs are classified into tiers

Tiers of ISPs

- **Tier 1**: Never buys traffic.
    - Can reach the entire internet through peering or its own infrastructure
- **Examples**: **AT&T**, Sprint, Tata, Telia, Level3 (now part of CenturyLink)
- **Tier 2/3**: Has to pay other providers for access to some parts of the internet
- **Examples**: Williams, **Comcast** (barely), small cable companies
- Different ISPs work out mutual agreements

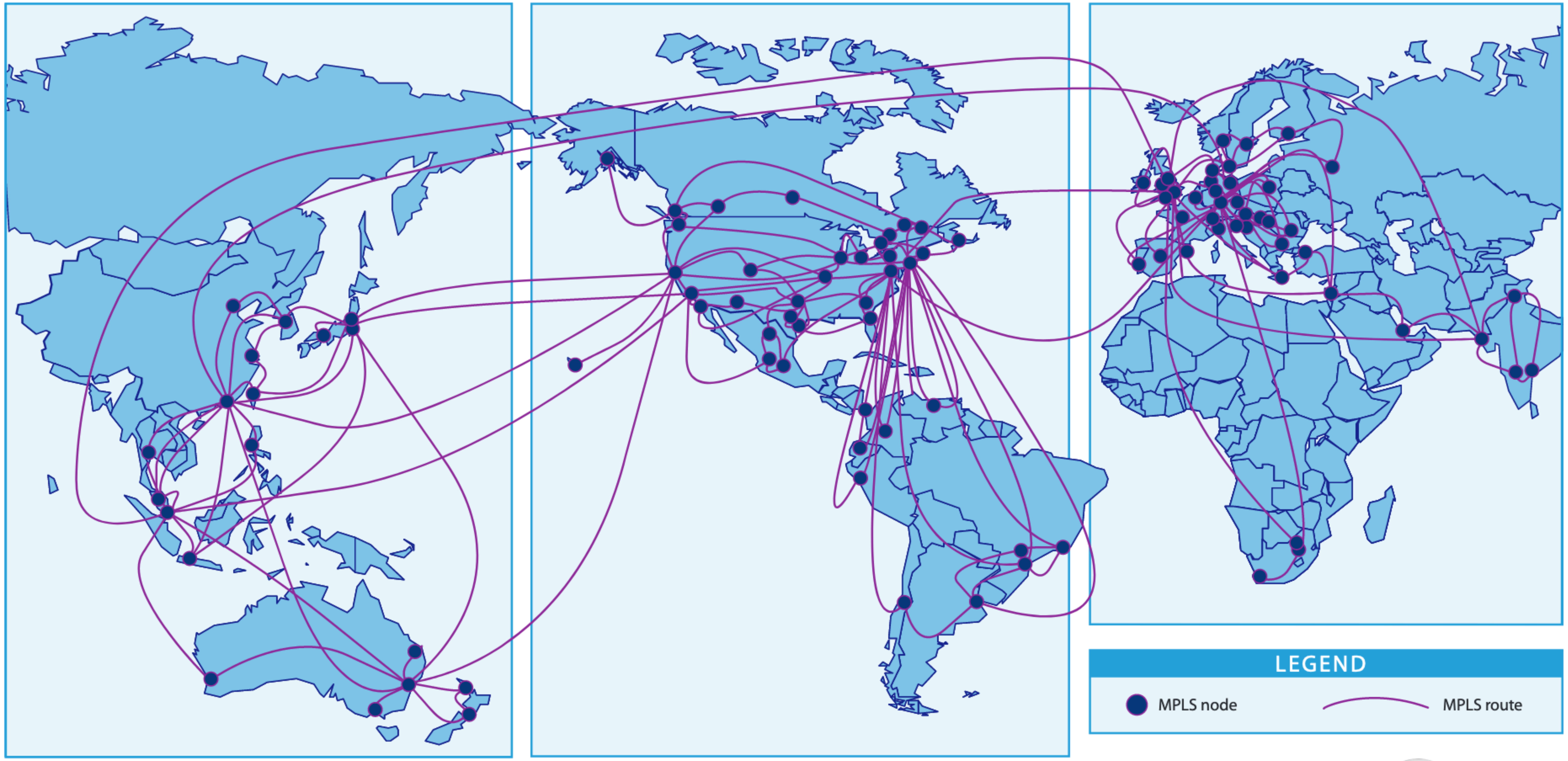


https://en.wikipedia.org/wiki/Tier_1_network#List_of_Tier_1_networks

The AT&T Global Network —

Advanced and Powerful Network Carries More Than 8.52 Petabytes of Data Traffic* on Average Business Day

- Multiprotocol Label Switching (MPLS)-based services** available to 137 countries over 1,600+ nodes.
- 130,000 MPLS customer ports.
- 32 Internet data centers across the globe.
- 535,000 fiber route miles.

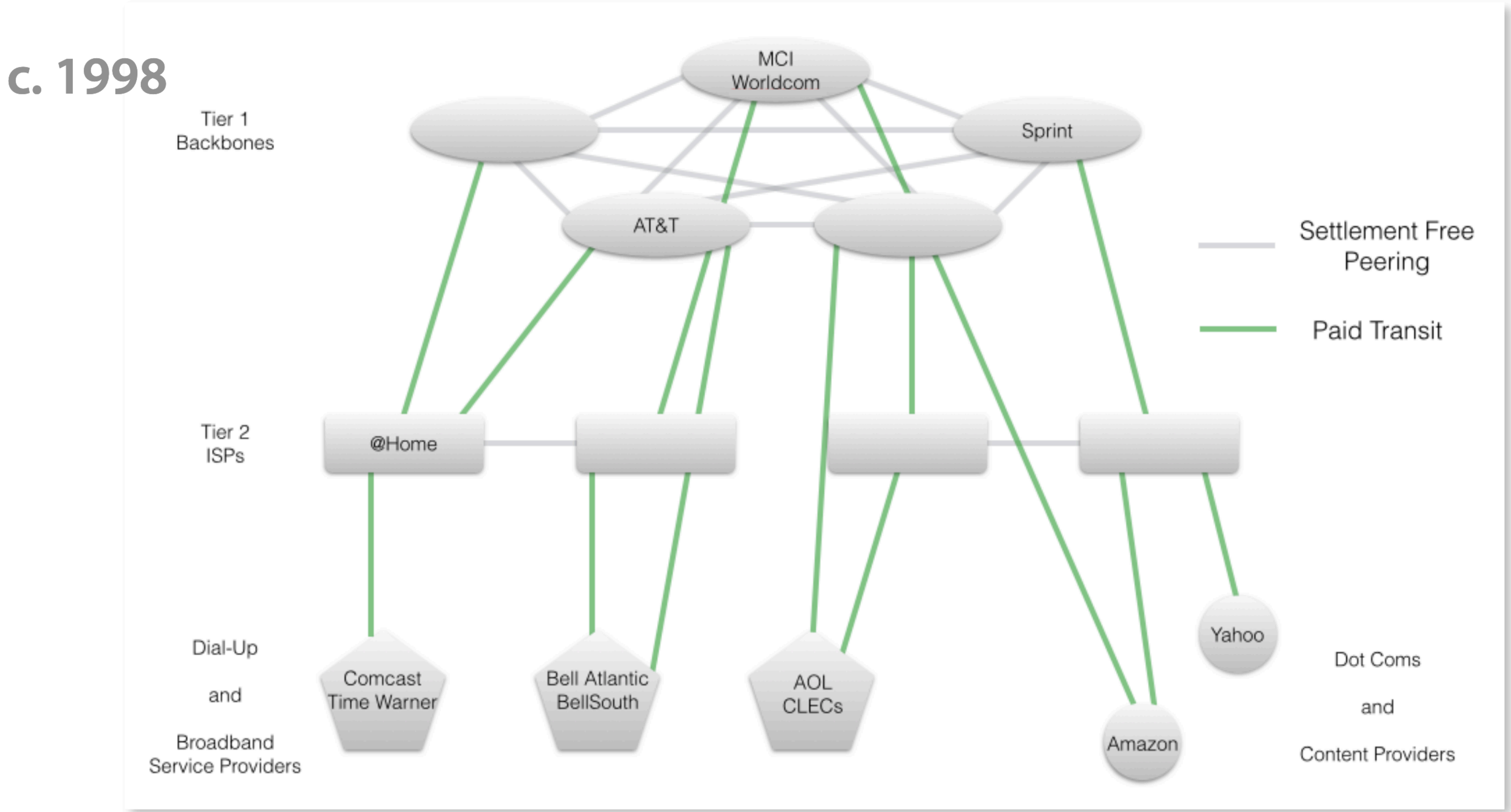


Simplified map: not all nodes/links/routes shown

* Enough data to transmit the digitized contents of the Library of Congress more than 400 times every day.

** MPLS technology enables high-quality delivery of multiple services over a single IP network infrastructure.

How Does Traffic Work



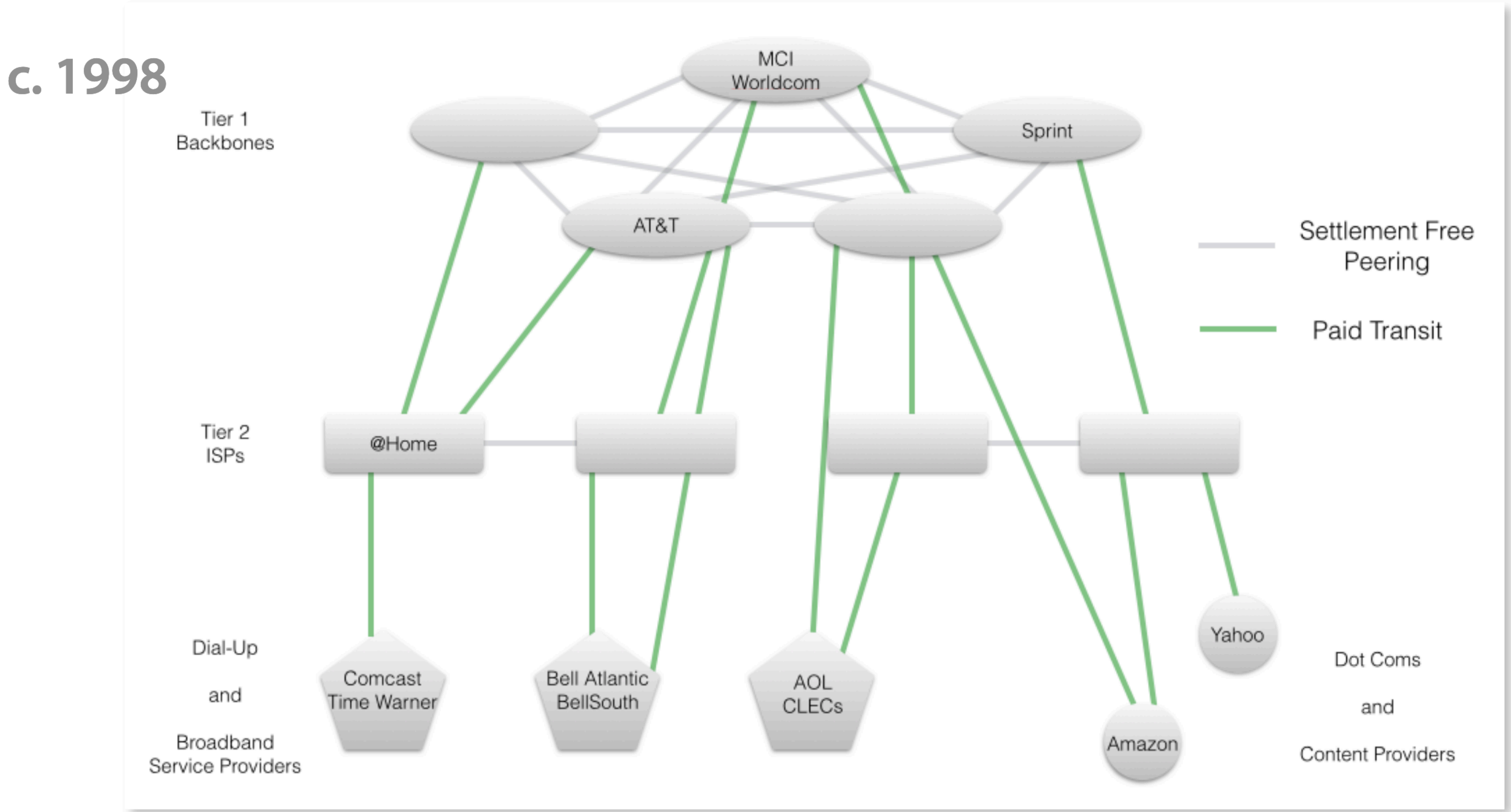
From "How the Net Works: !A Brief History of Internet Interconnection" by Bret Swanson

Peering Agreements

- Tier 2 ISPs can help each other out by directly exchanging traffic for free (avoiding paid network)
- Tier 2s can come to a peering agreement and exchange traffic through an "**internet exchange point"**
  - Many of these: https://www.internetexchangemap.com/
- Side note: who controls these?
  - Many owned by **Packet Clearing House**
  - International nonprofit
  - Also controls DNS

PCH
Packet Clearing House

Internet in 1998



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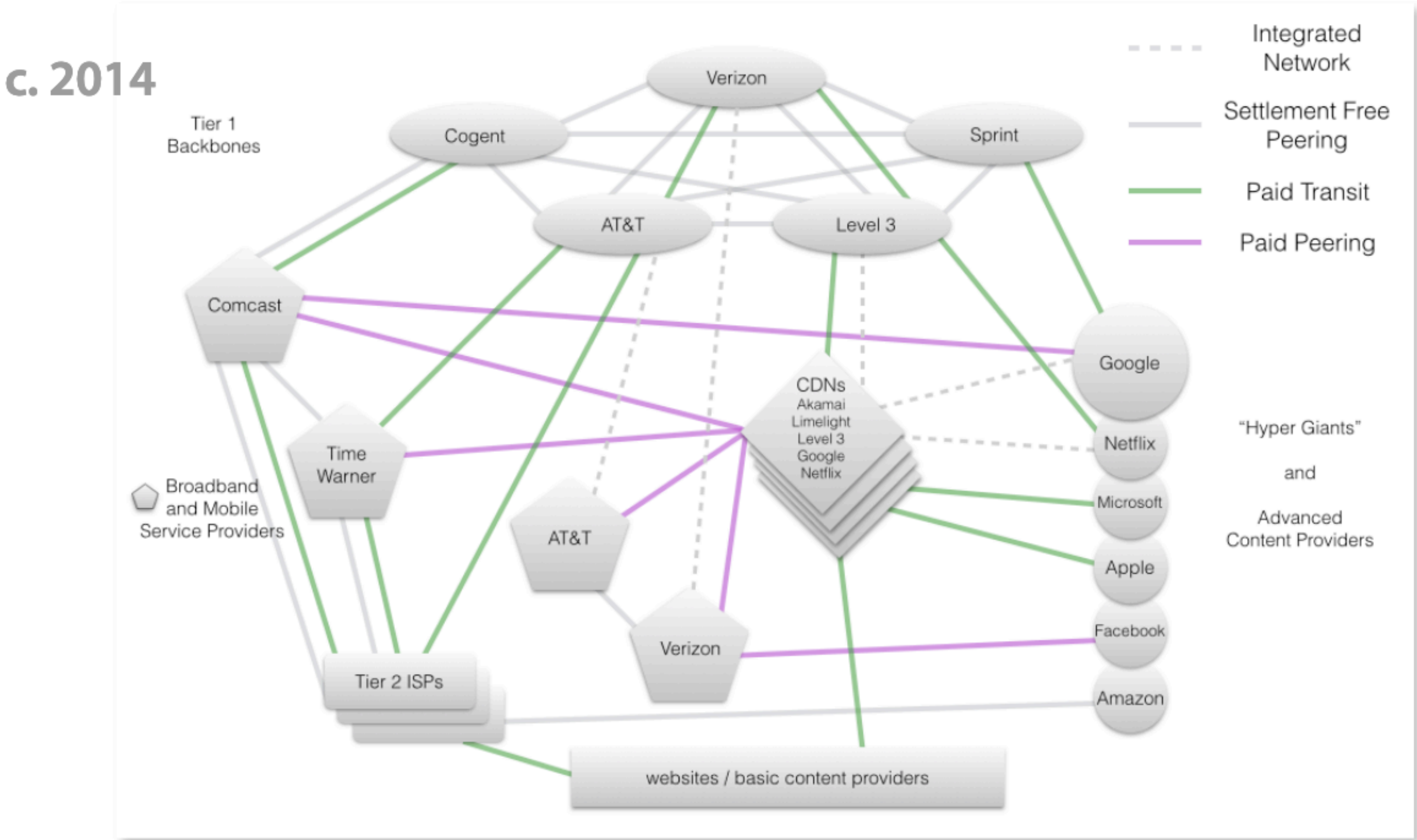
Internet in 2014



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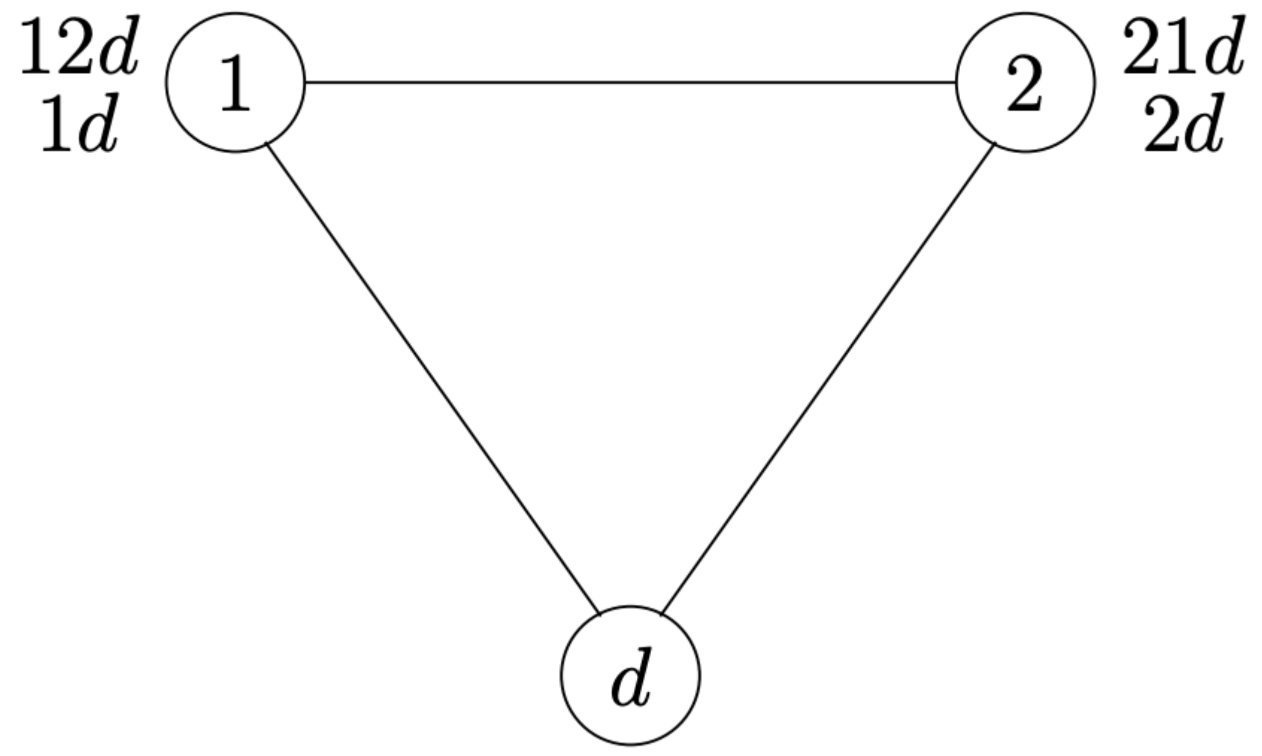
Routing Between ASes

- Completely decentralized
- Many incentives that are not entirely delay based
- Requires them to trust each other
- Requires routers that connect ASes to broadcast information every second or so

Routing Between ASes

- How can you find a route from point A to B when they are located in different ASes
    - Potentially requires traversing multiple ASes
- Different ASes may have different preferences:
    - May want to minimize monetary cost of paths
- For example: consider the network given in figure
    - Suppose d is destination for all traffic
    - ASes 1,2 have their preferences labelled
    - Both prefer to route through the other than direct



Credit: Roughgarden

Border Gateway Protocol (BGP)

- In the internet, routing between ASes is done using the **Border Gateway Protocol** (BGP)
- We will only discuss a sketch of how it works
    - Ignore many details of the actual protocol
- Fix a destination d (BGP runs in parallel for all choices of d)
- Each destination d broadcasts their presence to neighbor ASes
- Each AS is then supposed to update their own path to d and broadcast to their neighboring ASes
    - All messages are asynchronous

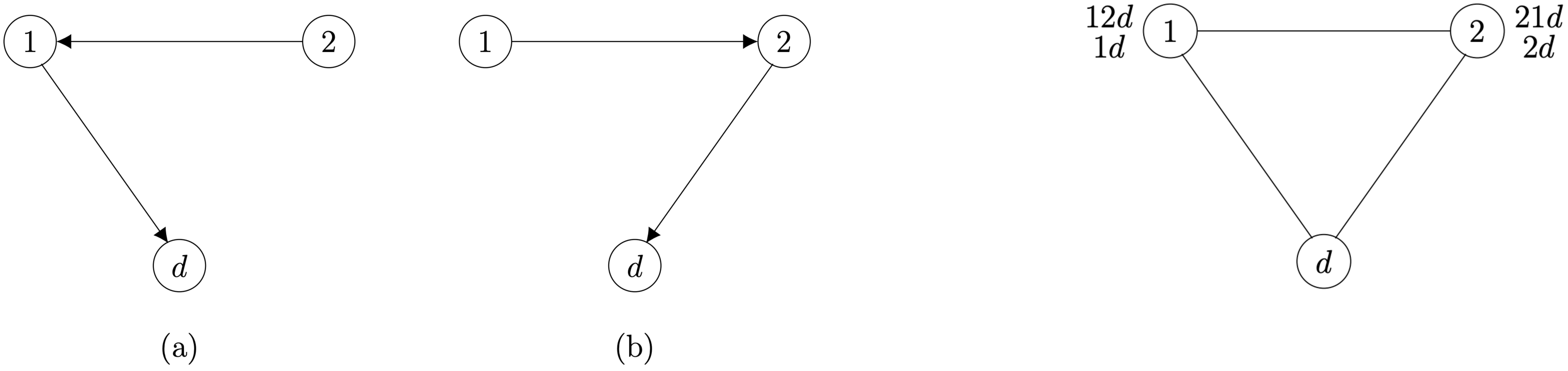
BGP Updates

This is the "intended behavior": of course ASes may not follow it!

- At an AS u , for each neighbor v of u
  - Let P_v be the last path (from v to d) that v announced to u
  - Update P_u to u's favorite cycle-free path of the form (u, v) concatenated with P_v
  - If P_u changes, announce the new value to all neighbors
- Note that AS u has to avoid cycles: if P_v includes u, cannot route traffic through P_v

BGP Example

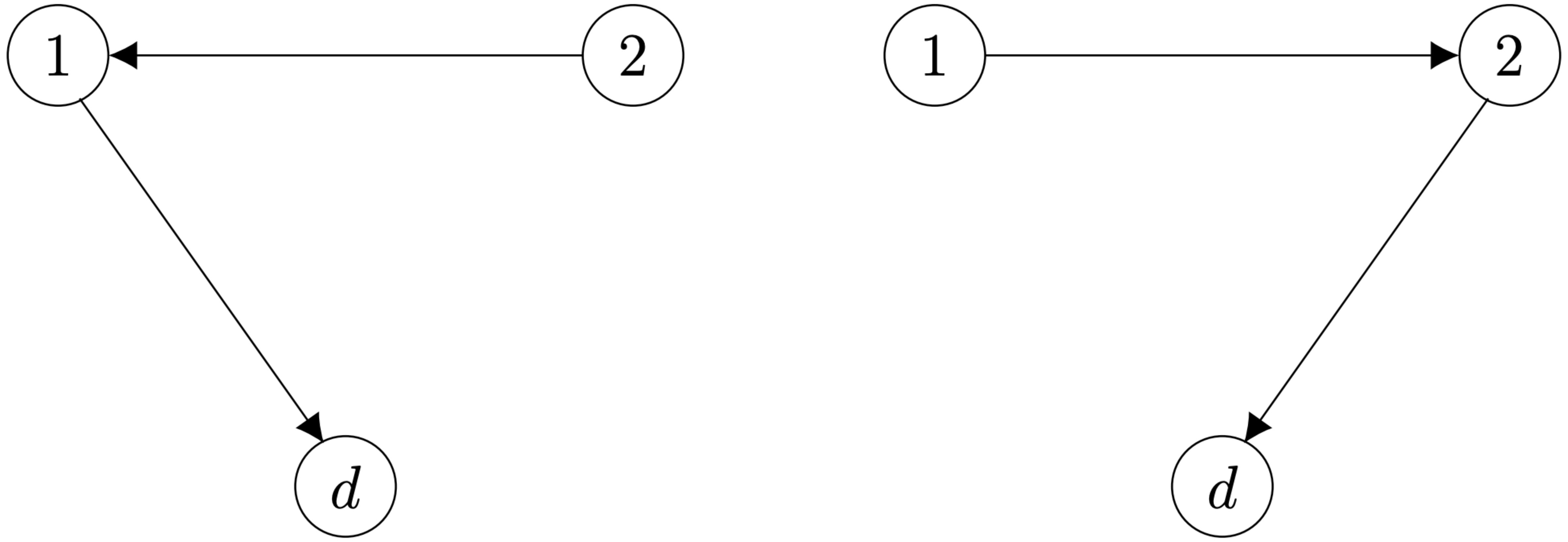
- The output of BGP is not very well defined
- For example, two outcomes are possible for this network, depending on which AS (1 or 2) announces their path to d first



Credit: Roughgarden

BGP Example

- Multiple **possible fixed points** of running BGP
- Which fixed point do we expect to reach?
    - Depends on timing of messages: whichever 1 or 2 finds out first that the other is using a direct path to d can switch and "win"



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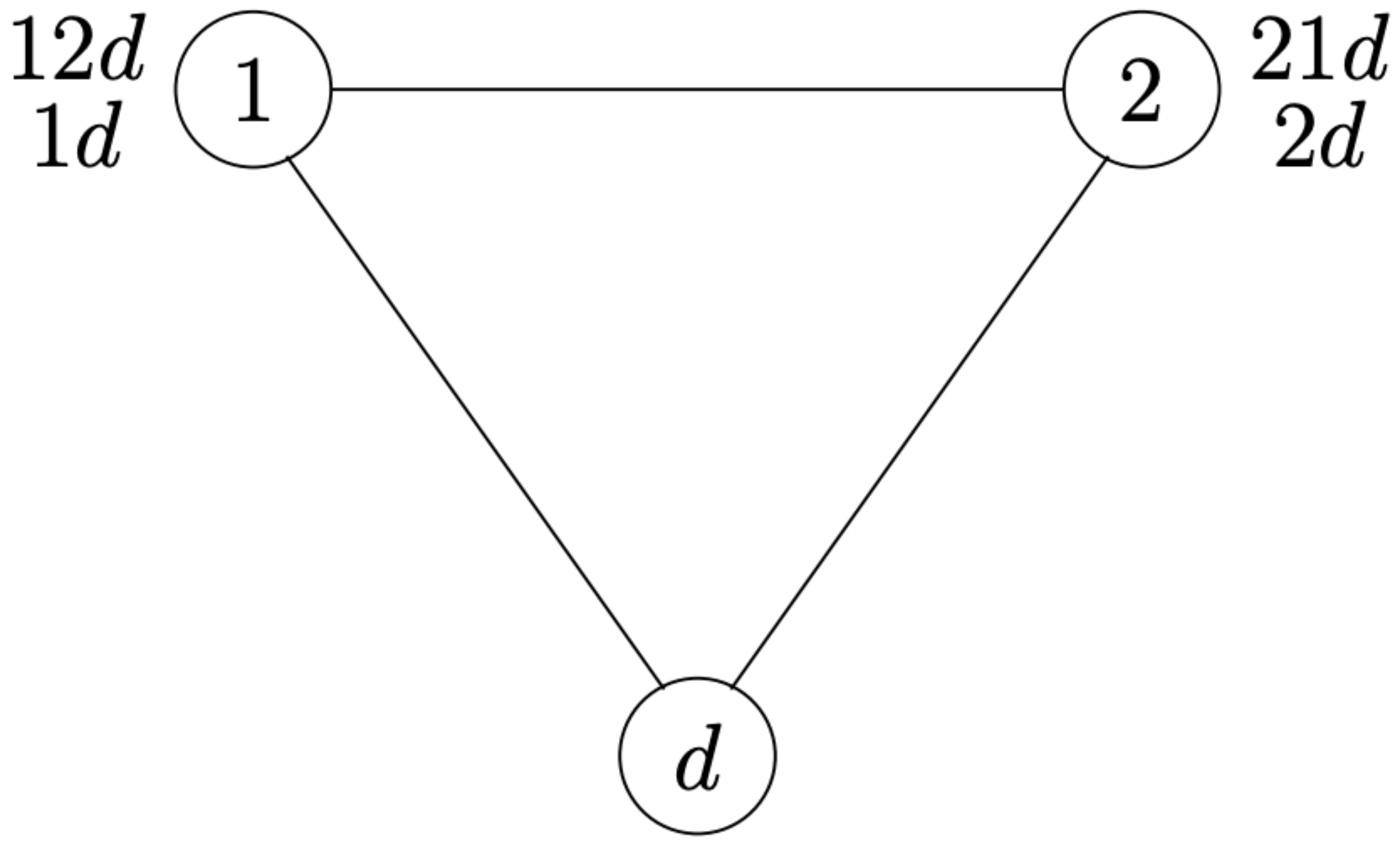
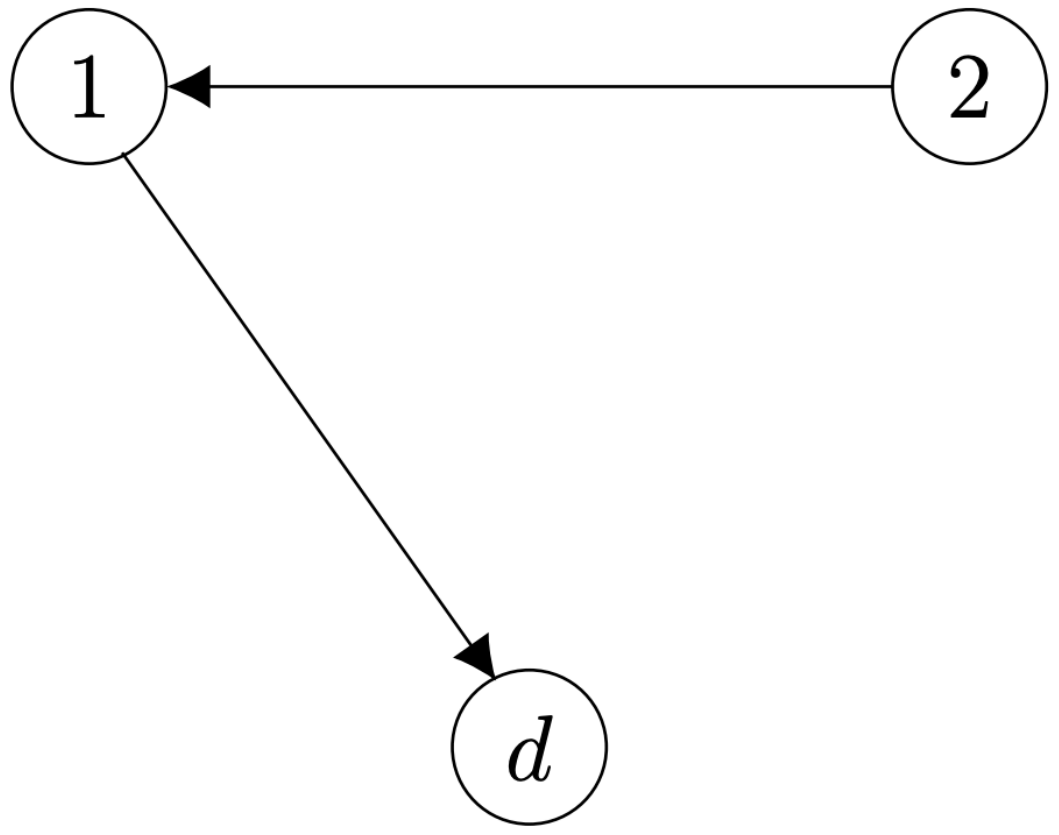


Credit: Roughgarden

Stable Routings: Equilibrium

- In a **stable routing**, no AS wants to unilaterally change its path to d, given the choices of other ASes and options available to u
- This is a **Nash equilibrium** in a game where
  - **Players**: AS, available **strategies**: neighboring ASes, **payoffs** induced by preferences over paths



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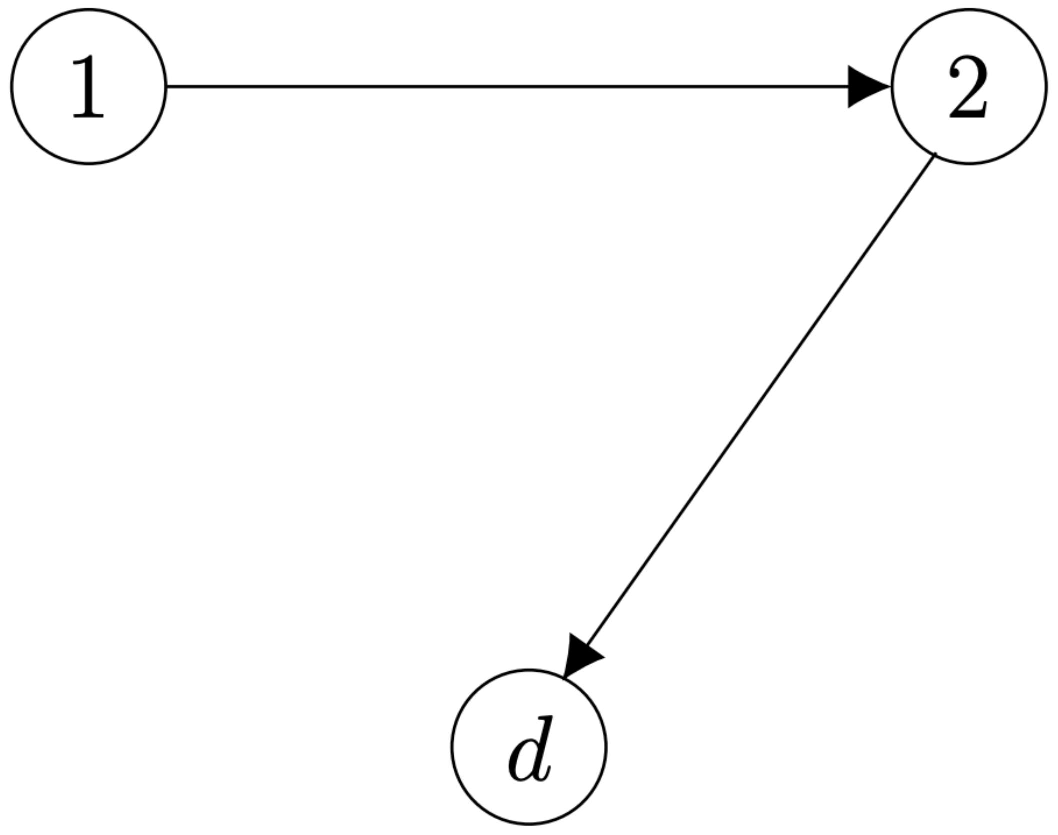

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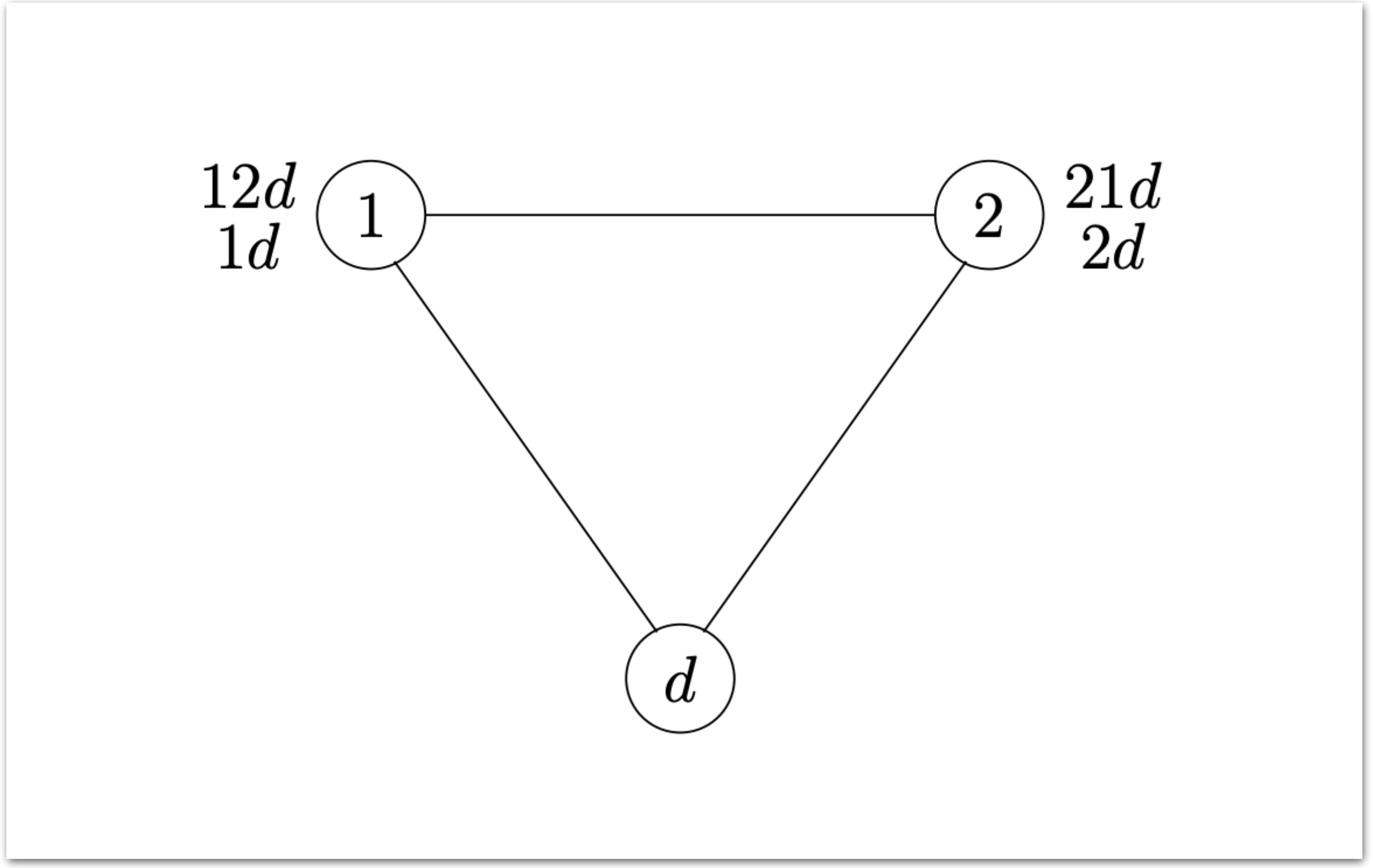
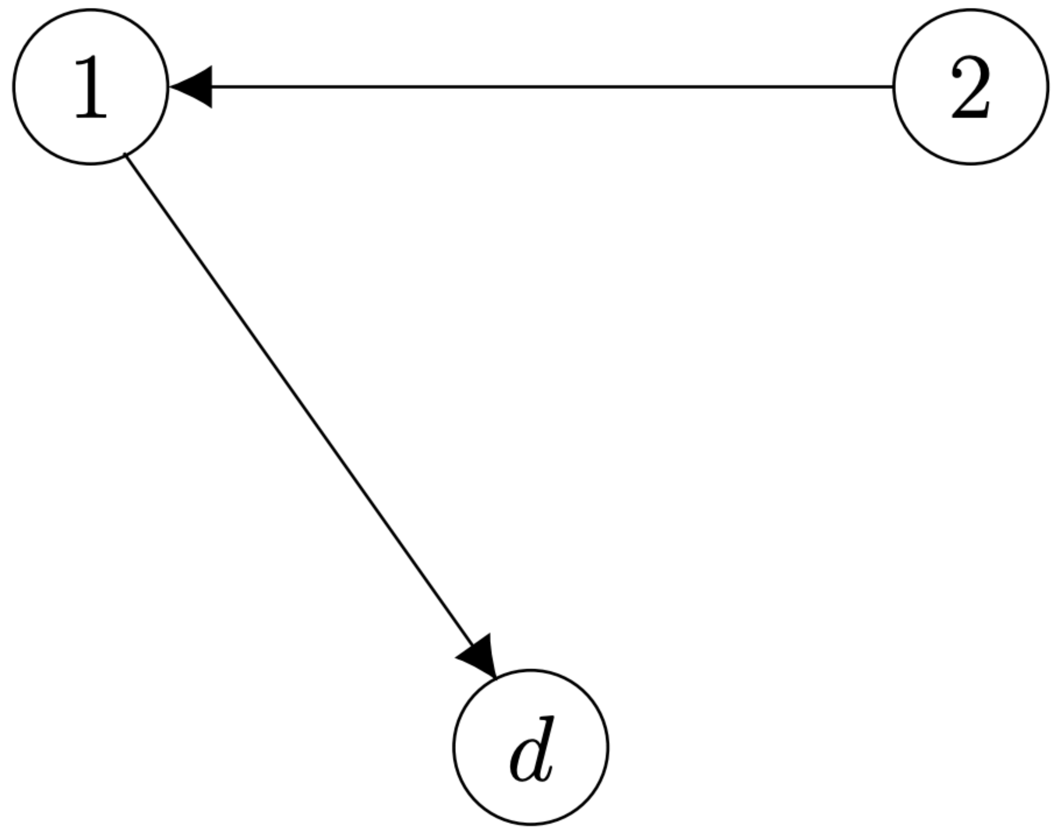


Credit: Roughgarden

Stable Routings: Equilibrium

- We saw that there can be multiple stable routings
- **Question**. Does a stable routing always exist?



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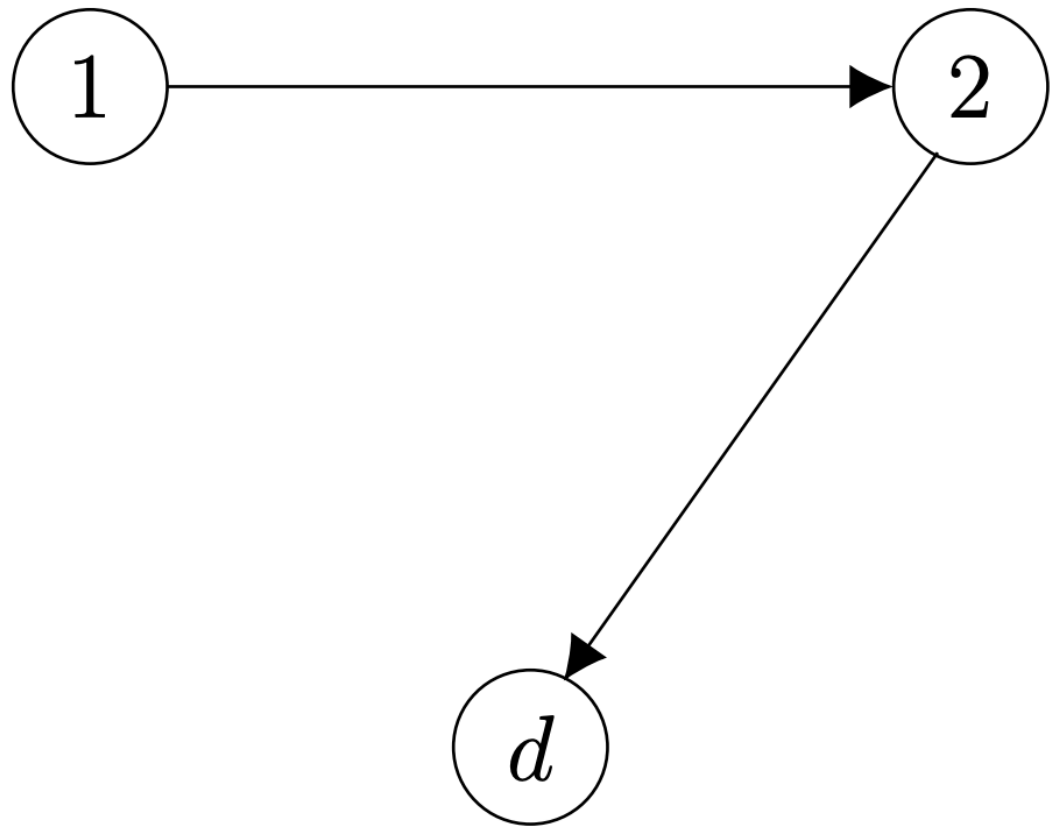

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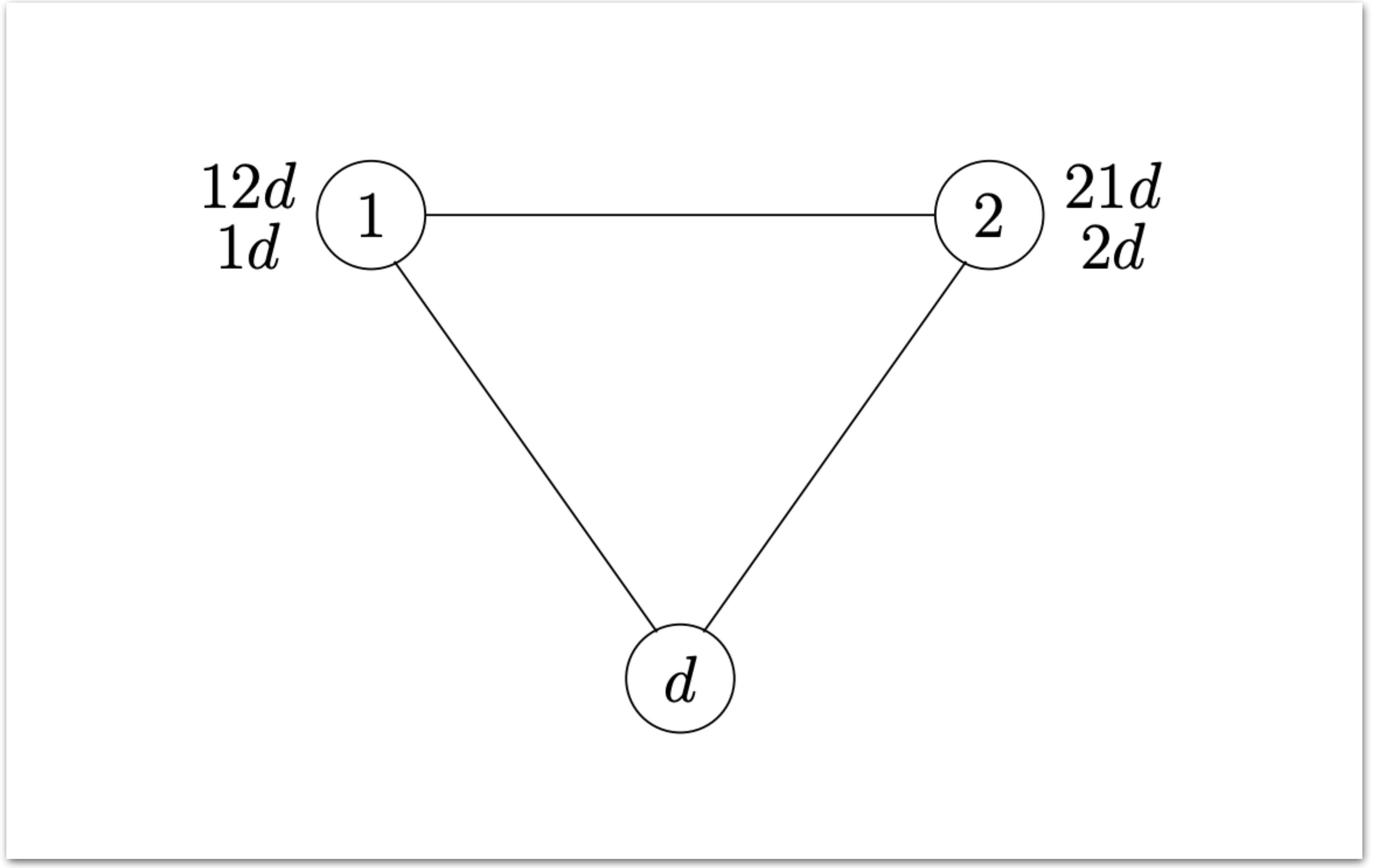
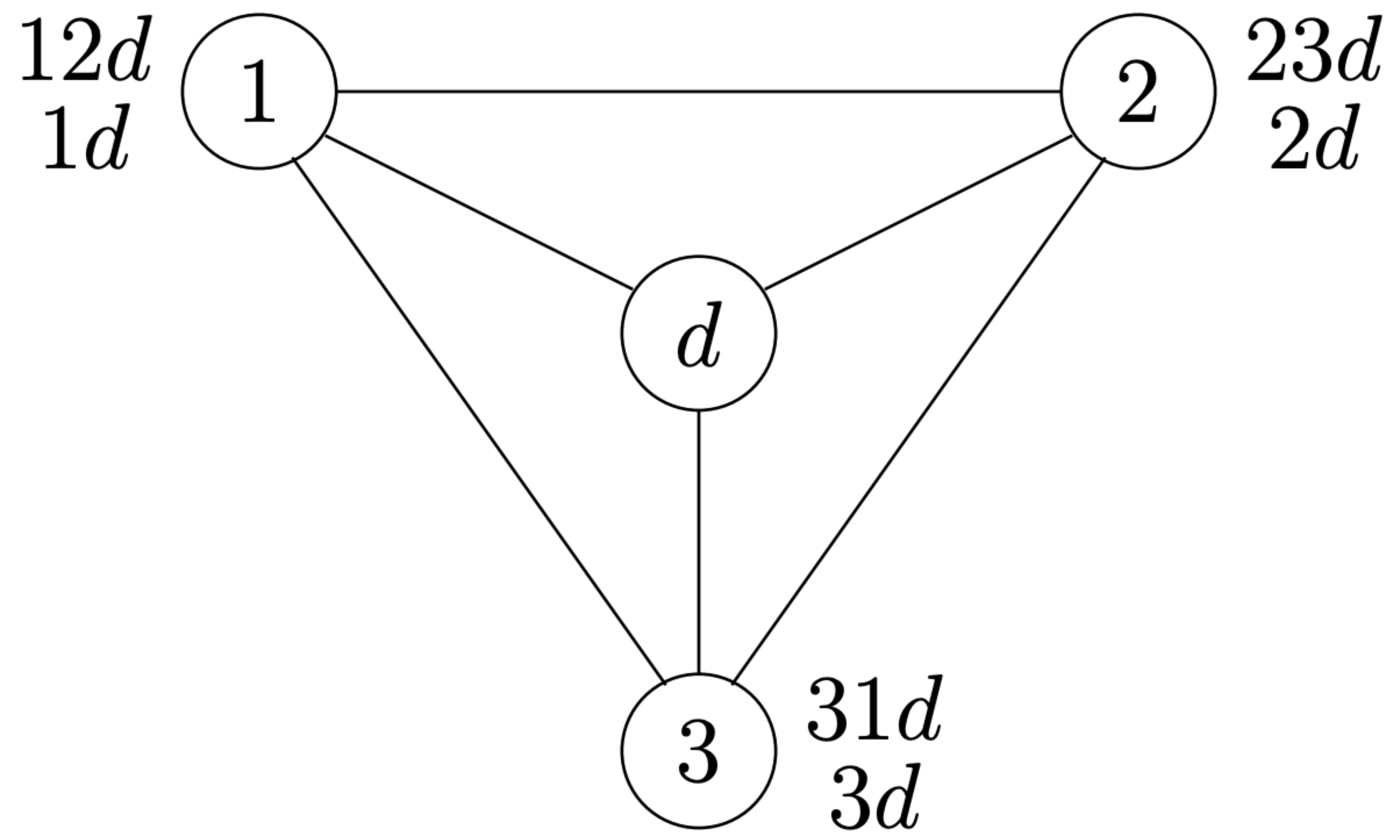


Credit: Roughgarden

Stable Routings: May Not Exist in General

- Consider the following stable routing network
- Every AS prefers a direct path to d over the empty path
    - Thus, one of the ASes must have a direct path to d



Credit: Roughgarden

Stable Routing Exists Under Mild Conditions

- BGP converges if there some mild conditions hold ("no dispute wheels")
- **Gao and Rexford** gave justifications about why no dispute wheel condition should generally hold for realistic AS preferences
- **Gao-Rexford conditions** (rule out dispute wheels): every AS prefers
  - to route through a customer over those through a peer
  - to route through a peer over a provider
- Empirical evidence the conditions are approximately true for most ASes

IEEE/ACM TRANSACTIONS ON NETWORKING, VOL. 9, NO. 6, DECEMBER 2001 681

Stable Internet Routing Without Global Coordination

Lixin Gao, *Member, IEEE,* and Jennifer Rexford, *Senior Member, IEEE*

Incentive Issues

- We restrict ourselves to AS graphs where BGP converges
- Do ASes have an incentive to follow the protocol?
    - Does any AS have a beneficial unilateral deviation?
- Types of deviations:
    - Choose your path P_u to be something other than the favorite path among the available options
    - **Withhold information** about your path to (some) neighbors
    - **Announce** a path to (some) neighbors that is different from the one you are actually using, possible even a non-existent **fake path**

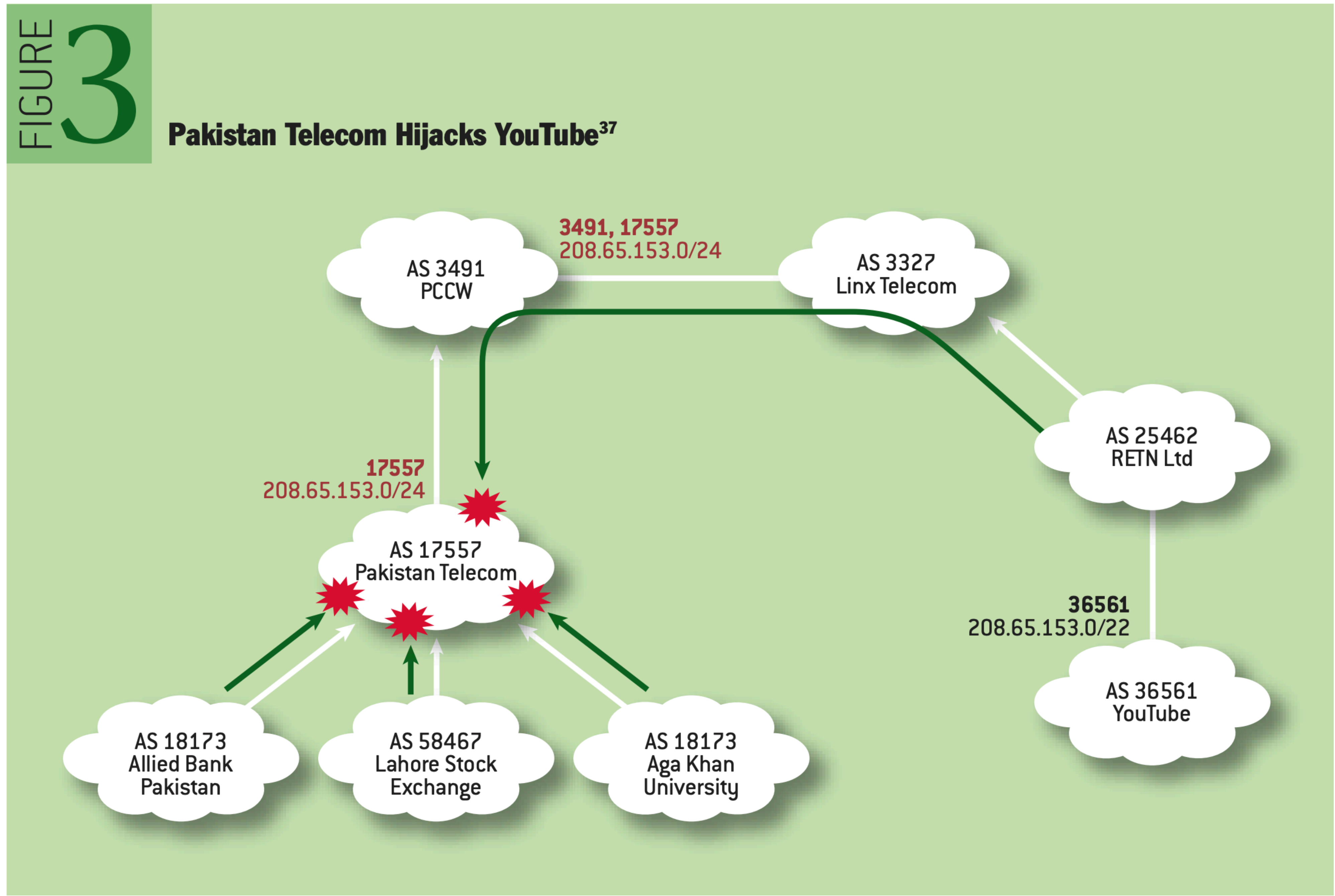
Fake Path Announcements

- Can and do ASes announce non-existent paths?
- Happens in BGP **all the time**
- In 2008 Pakistan telecom blocked access from Pakistan to Youtube

Pakistan Cuts Access to YouTube Worldwide

Activists in Pakistan on Sunday, protesting the publication of drawings depicting Muhammad. Pakistan blocked YouTube for containing material considered offensive to Muslims.

Rizwan Tabassum/Agence Free-Press — Getty Images



Sharon Goldberg, Boston University

China denies 'hijacking' internet traffic

US report claims Chinese telecoms company had access to 15% of global traffic, including military emails, for 18 minutes

State-owned China Telecom has rejected US claims that its servers 'hijacked' internet traffic. Photograph: STR/AFP/Getty Images

Mutually Agreed Norms for Routing Security (MANRS) 27 April 2018 EN ES

What Happened? The Amazon Route 53 BGP Hijack to Take Over Ethereum Cryptocurrency Wallets

By Aftab Siddiqui
Former Senior Manager, Internet Technology - Asia-Pacific

BGPSec: Path Verification

- While fake path announcements are possible and frequent in current BGP protocol, there is work being done to eliminate it
    - **BGPsec** protocol uses cryptographic signatures to verify the existence of announced paths

SIAM J. COMPUT.
Vol. 40, No. 6, pp. 1892–1912

INTERDOMAIN ROUTING AND GAMES*

HAGAY LEVIN†, MICHAEL SCHAPIRA‡, AND AVIV ZOHAR‡

Abstract. We present a game-theoretic model that captures many of the intricacies of *interdomain routing* in today's Internet. In this model, the strategic agents are source nodes located on a network, who aim to send traffic to a unique destination node. The interaction between the agents is dynamic and complex—asynchronous, sequential, and based on partial information. Best-reply dynamics in this model capture crucial aspects of the de facto standard interdomain routing protocol, namely, the Border Gateway Protocol (BGP). We study complexity and incentive-related issues in this model. Our main results show that in realistic and well-studied settings, BGP is incentive-compatible. That is, not only does myopic behavior of all players *converge* to a "stable" routing outcome, but no player has motivation to unilaterally deviate from BGP. Moreover, we show that even *coalitions* of players of *any* size cannot improve their routing outcomes by collaborating. Unlike the vast majority of works in mechanism design, our results do not require any monetary transfers (to or by the agents).

Adoption Remains a Challenge

LILY HAY NEWMAN SECURITY APR 17, 2020 12:04 PM

You Can Now Check If Your ISP Uses Basic Security Measures

"Is BGP Safe Yet" is a new site that names and shames internet service providers that don't tend to their routing.

BGP is like a GPS mapping service for the internet, enabling ISPs to automatically choose what route data should take. PHOTOGRAPH: TOMMY LEE WALKER/GETTY IMAGES