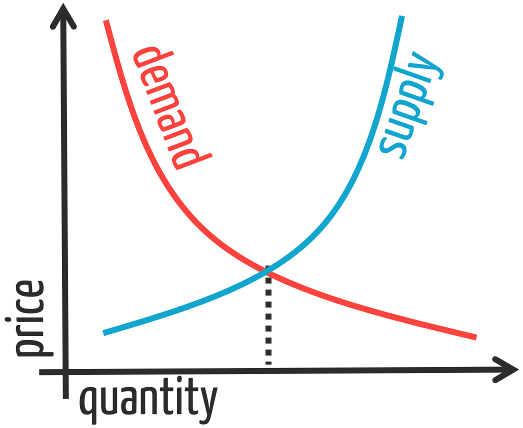
Networked Markets: *Market makers & market power*

Adam Wierman, Caltech
Joint work with Subhonmesh Bose, Desmond Cai, Niangjun Chen, Navid Ruhi, and Yunjian Xu.

Traditional economic models have "a market"

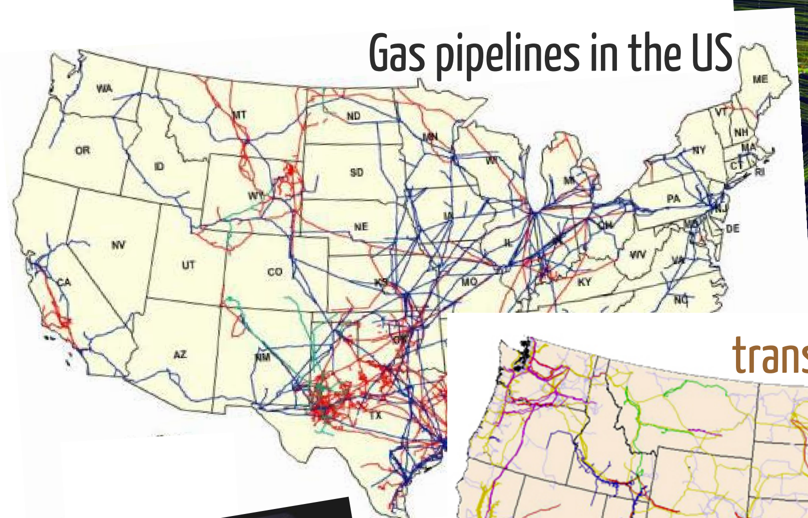


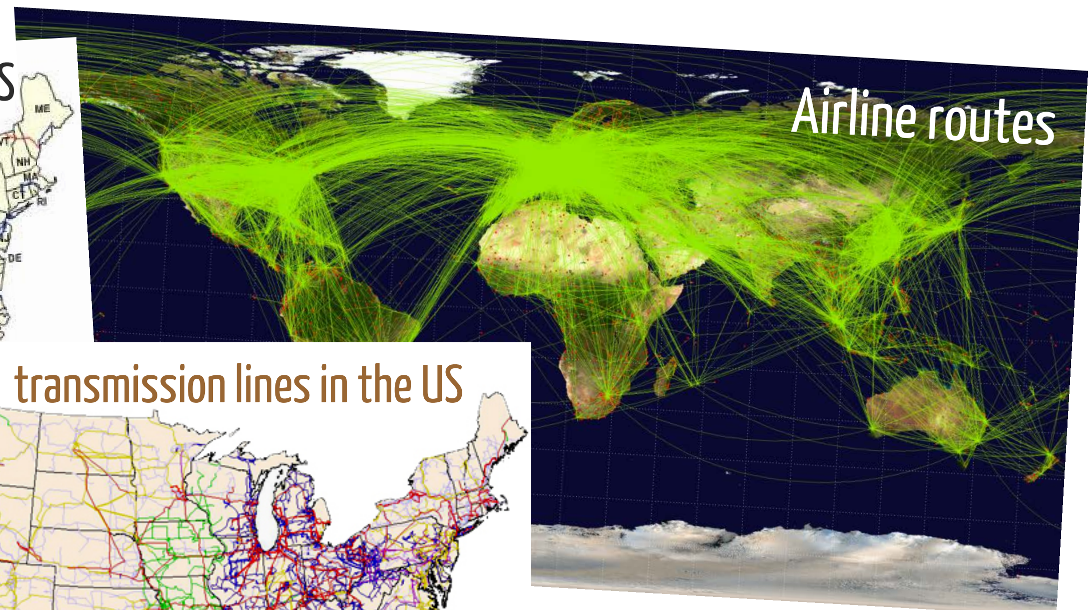
Traditional economic models have "a market"

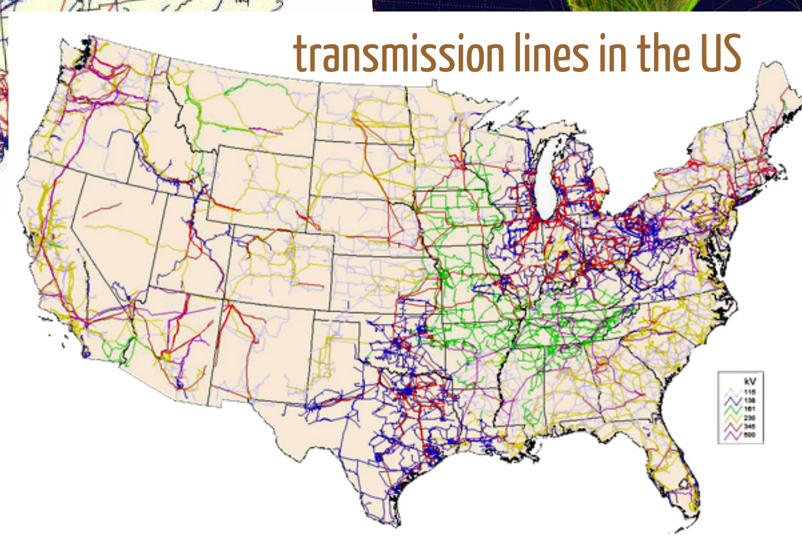
BUT, rarely is competition in a single, well defined market

...firms typically compete across a variety of markets

(examples: gas, airlines, construction, ad auctions, energy)







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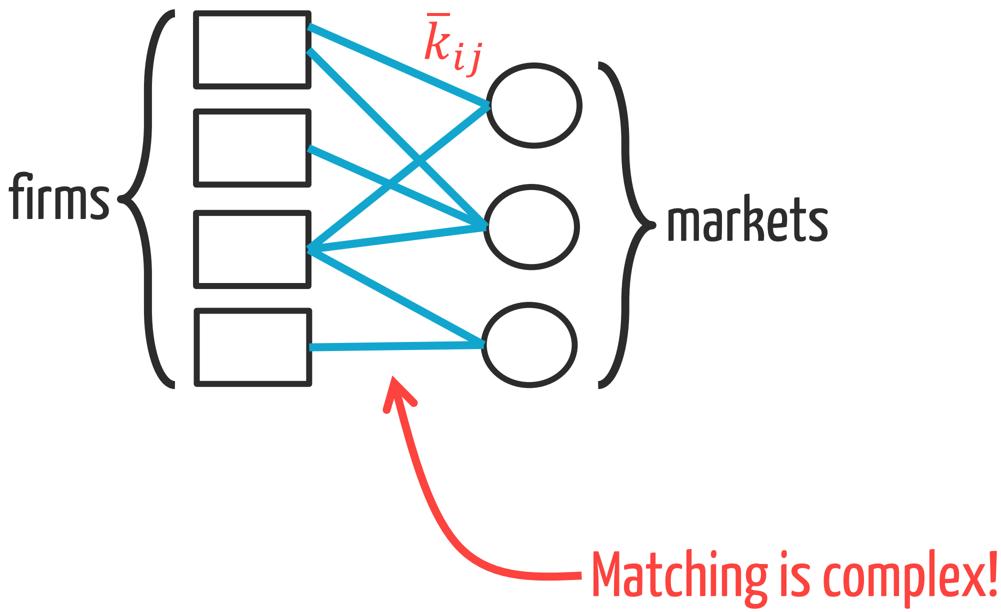

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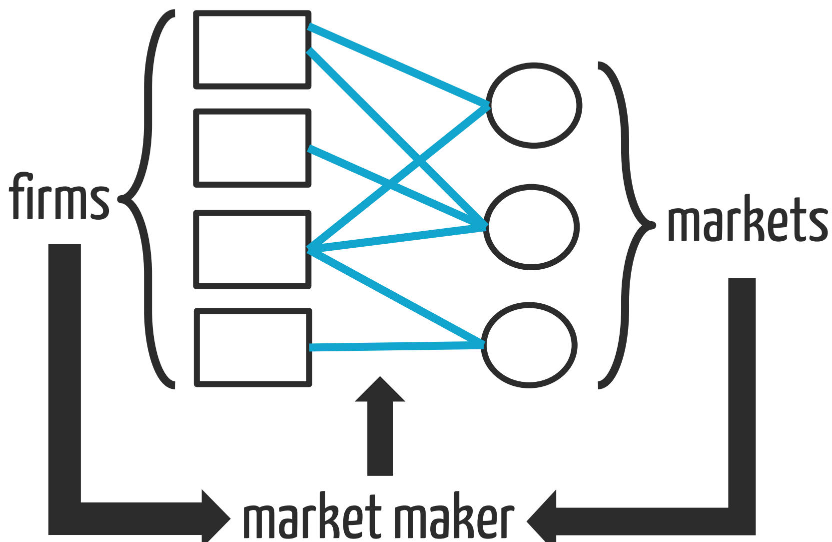
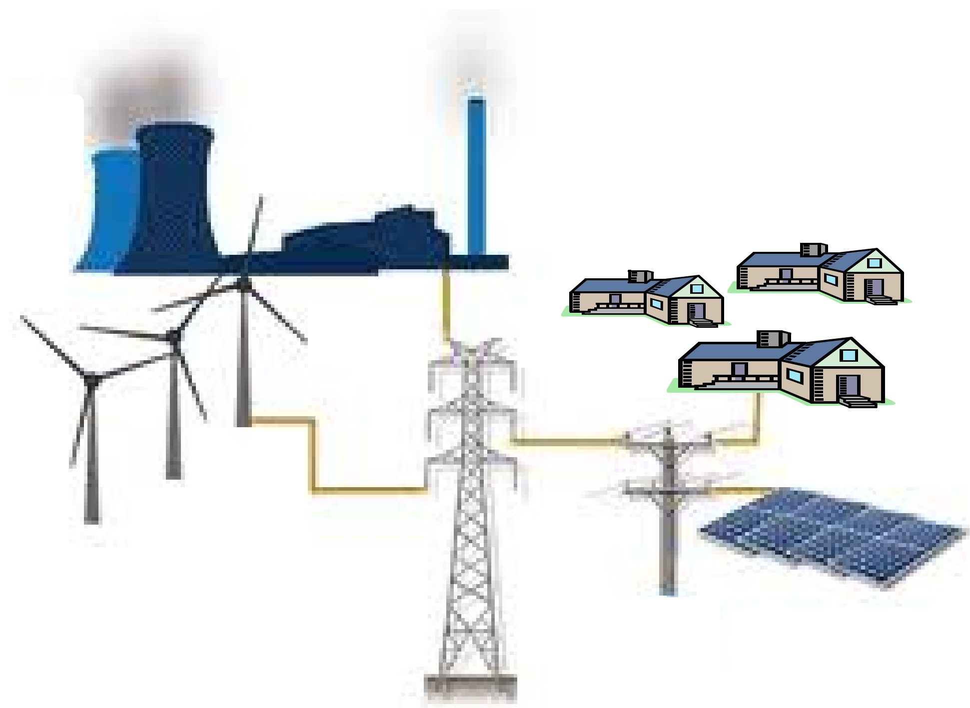
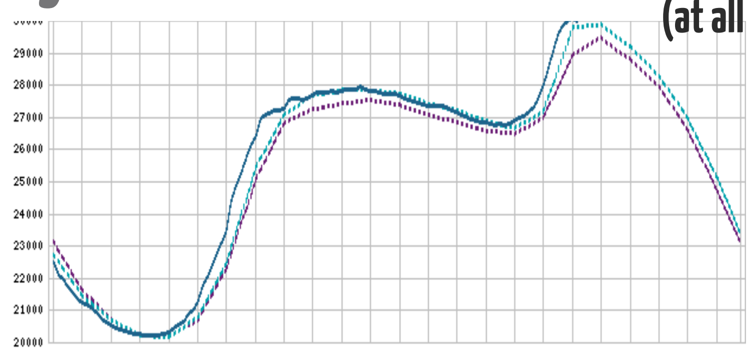


(examples: commodity exchanges, ISO, Walmart)

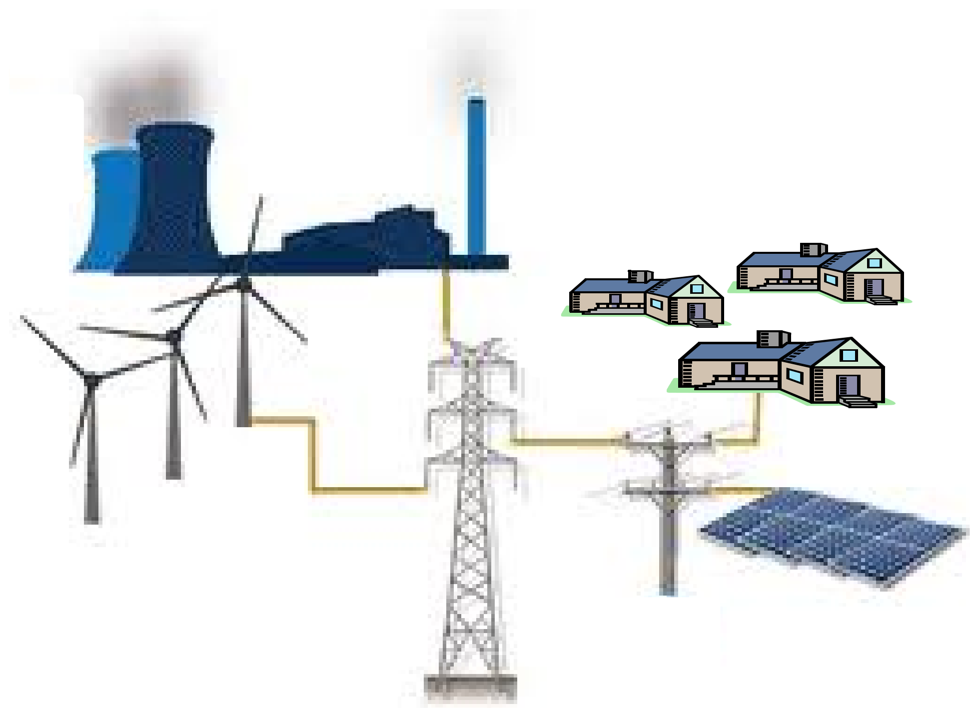
Motivating example: Electricity markets



Key Constraint: Generation = Load
(at all times)



low uncertainty



Key Constraint: Generation = Load

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controllable
(via markets)

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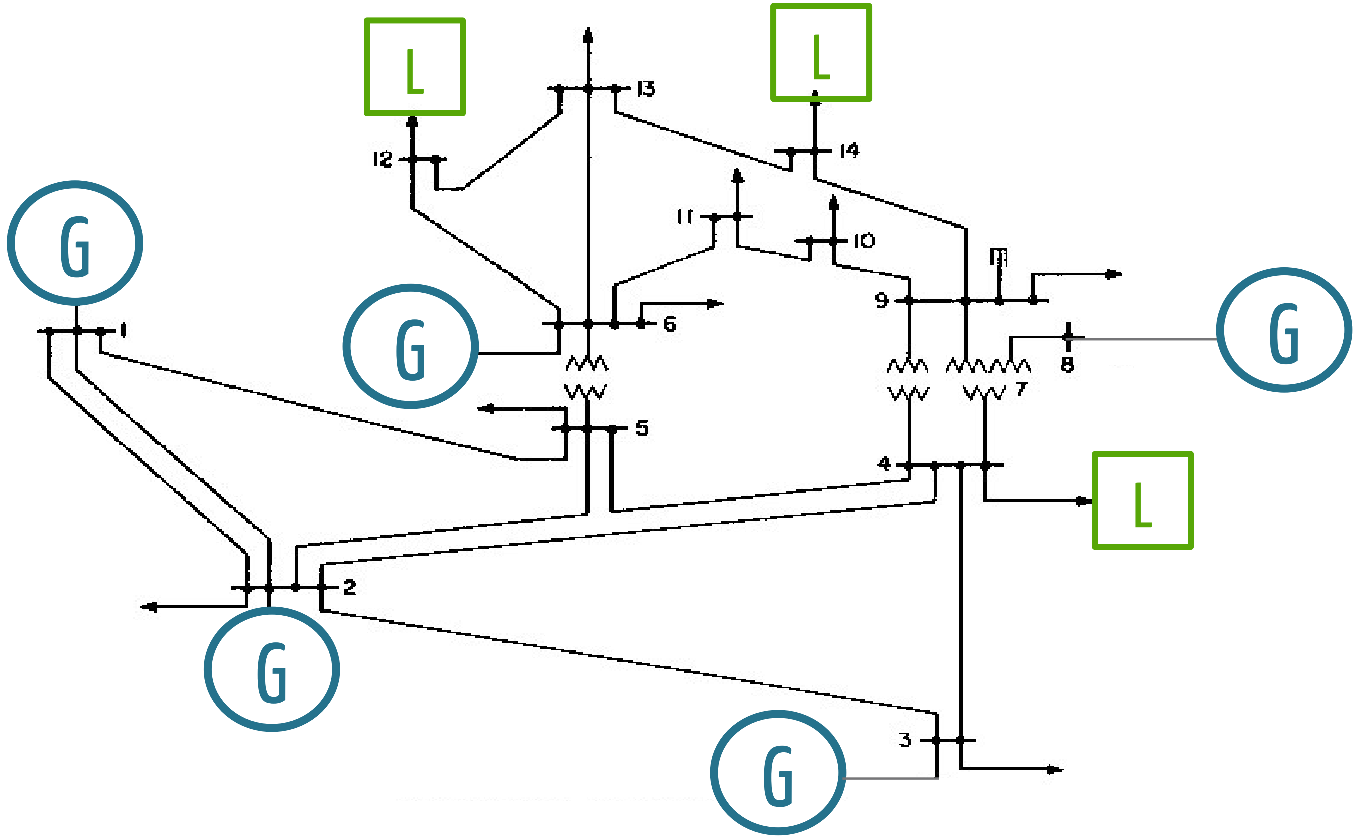

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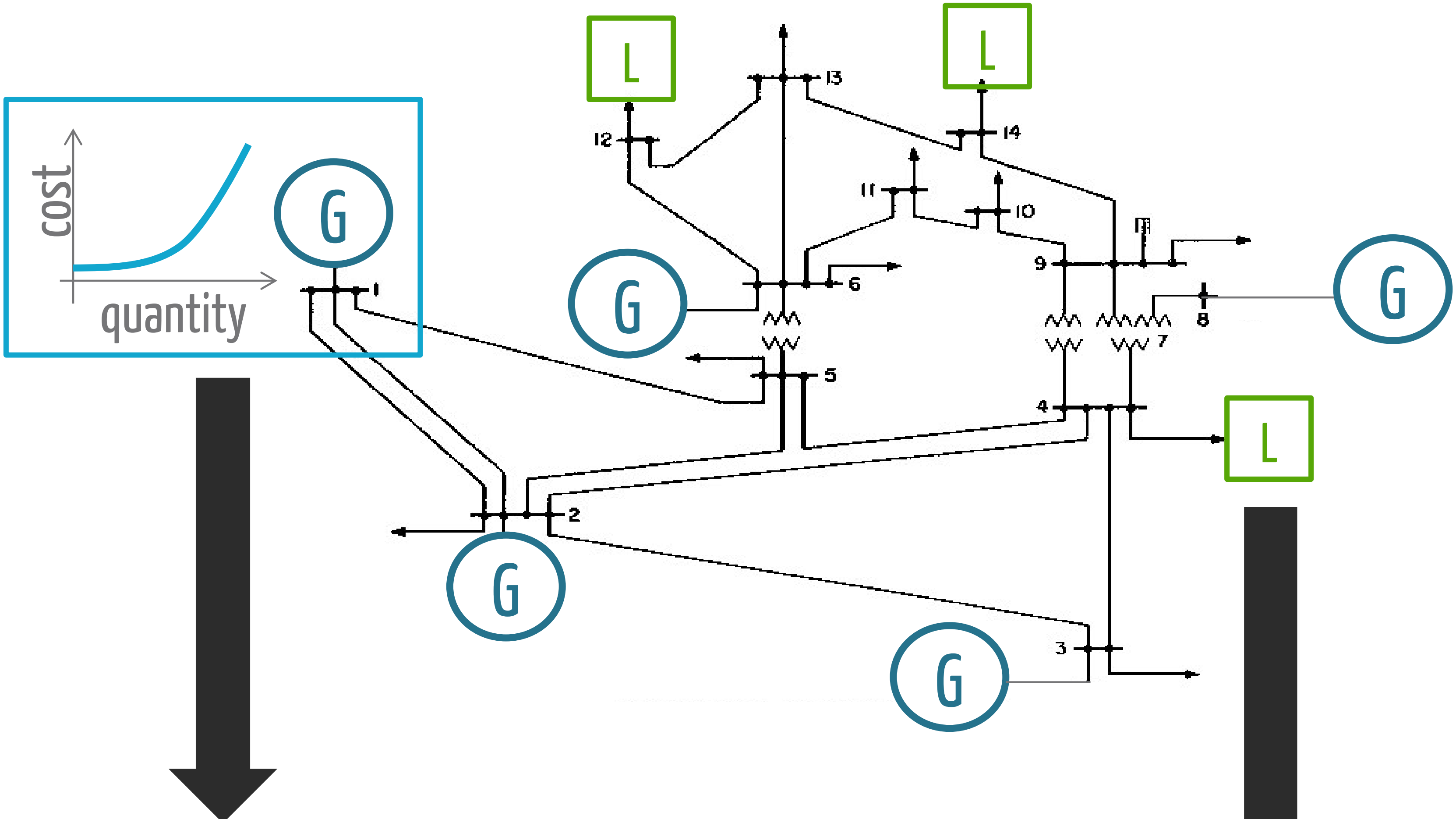
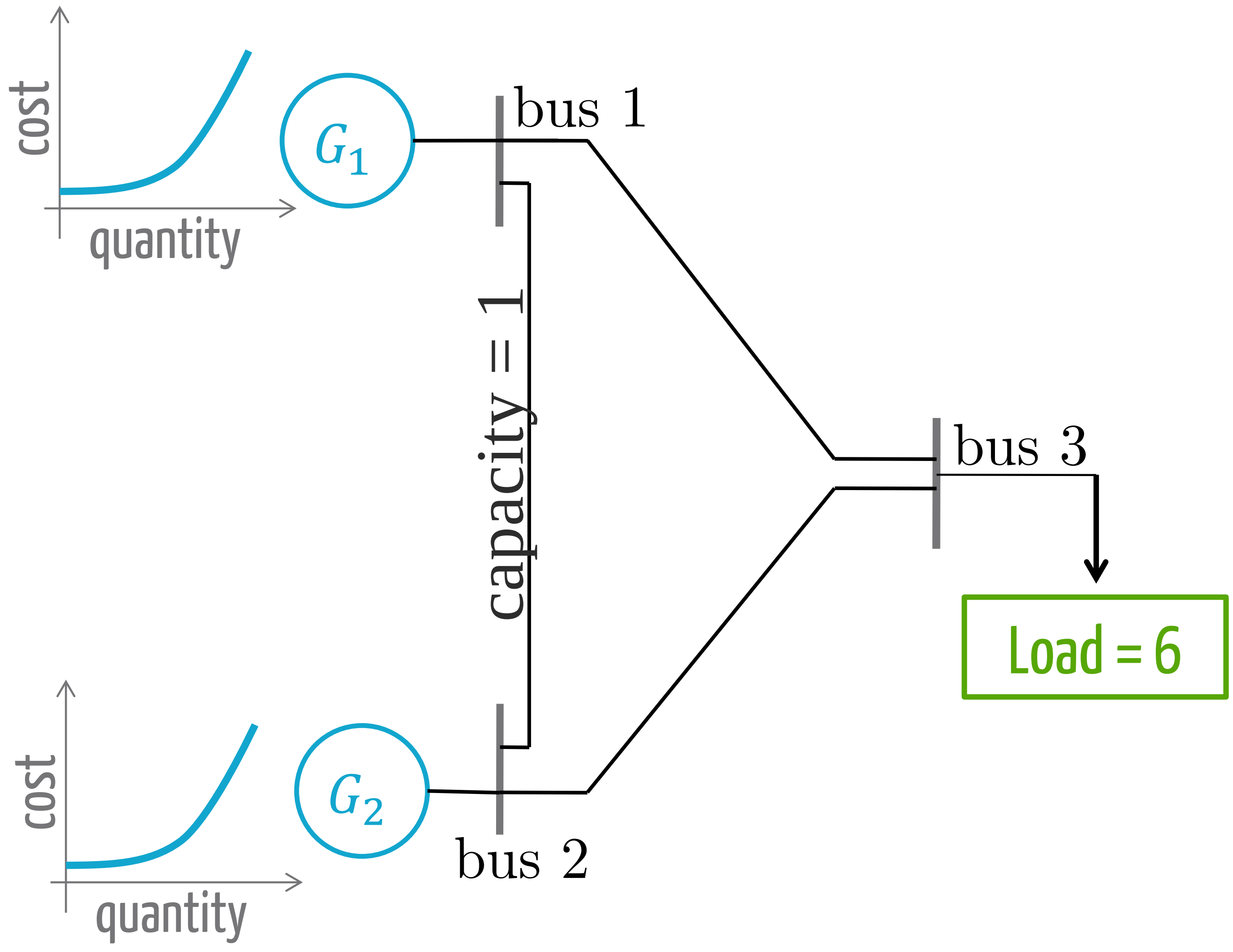


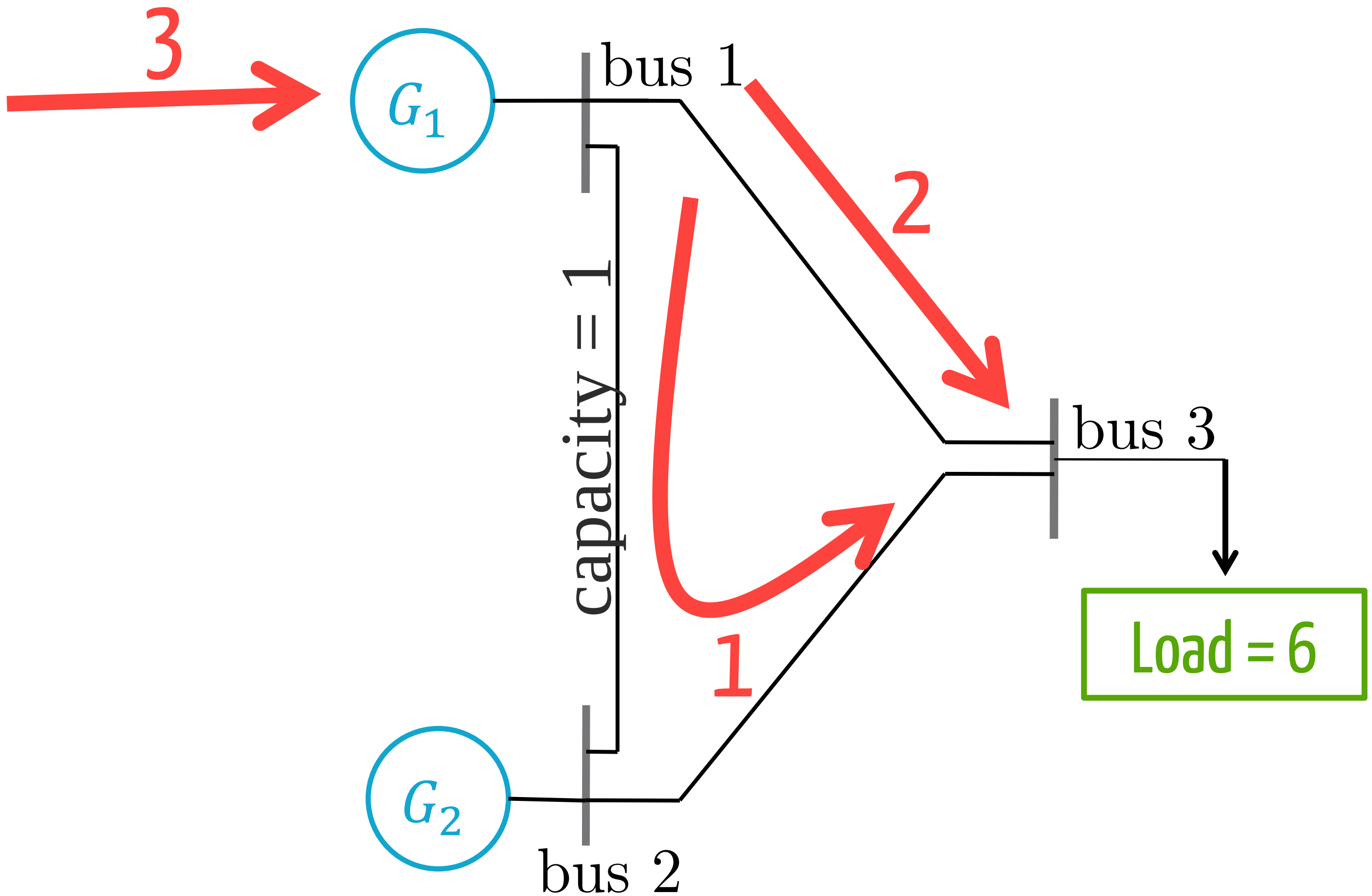
Market run by a <u>market maker</u> (ISO, Independent System Operator)

Determines the quantity to procure and price to charge each generator in order to meet the load s.t. network constraints.

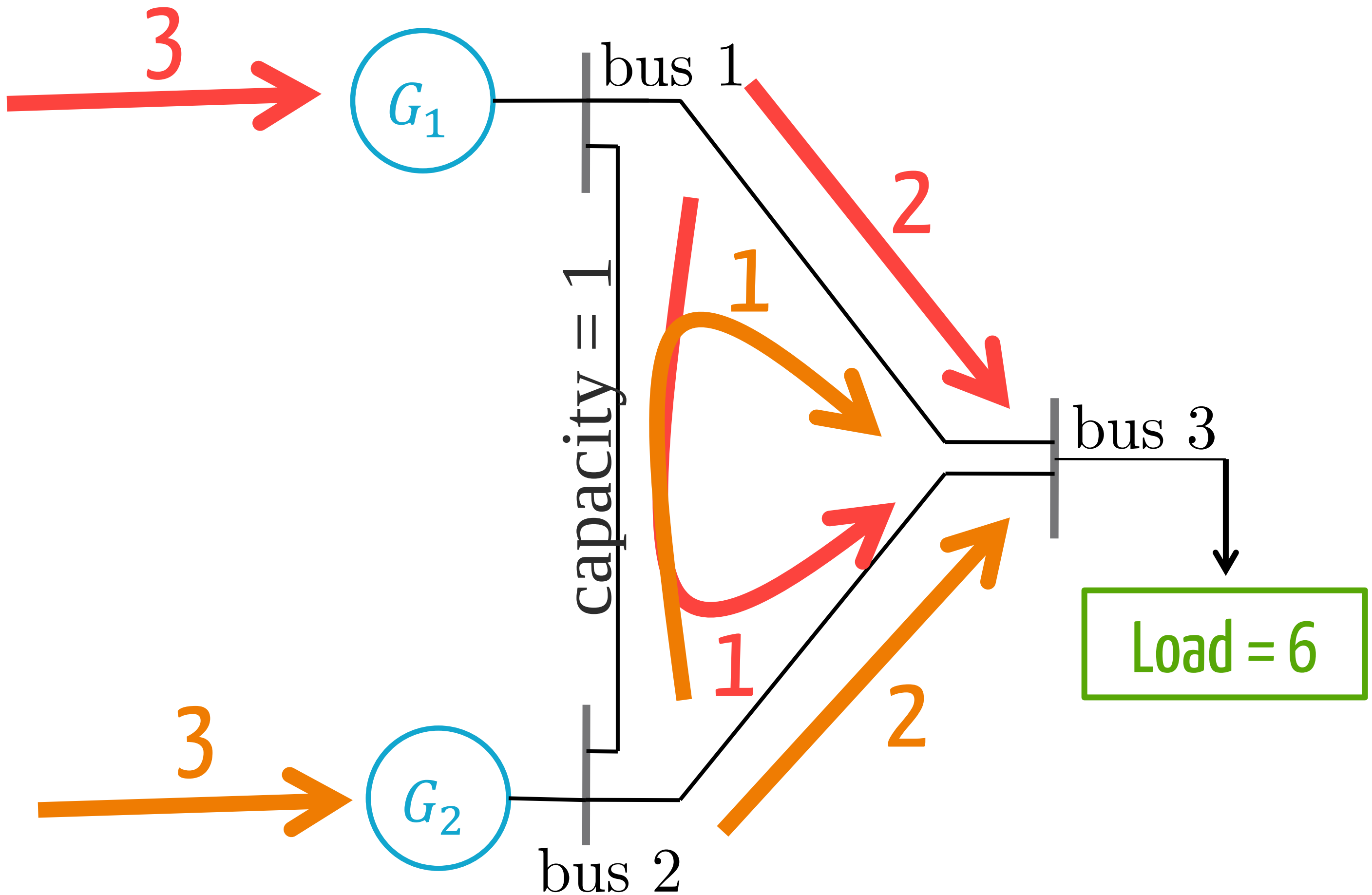
Line constraints & Kirchhoff's laws

A toy example





3
G_1
bus 1
2
capacity = 1
bus 3
1
Load = 6
G_2
bus 2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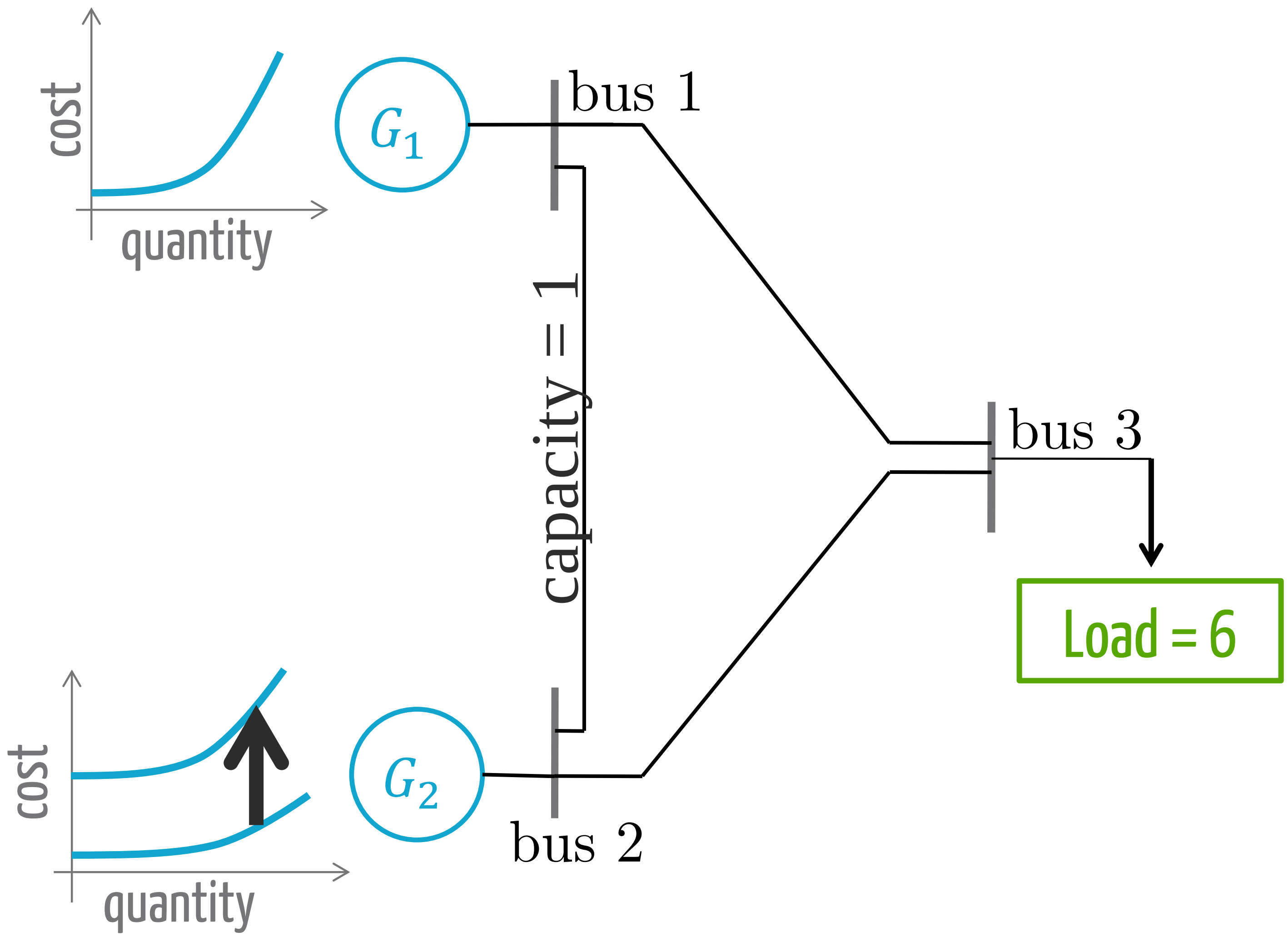
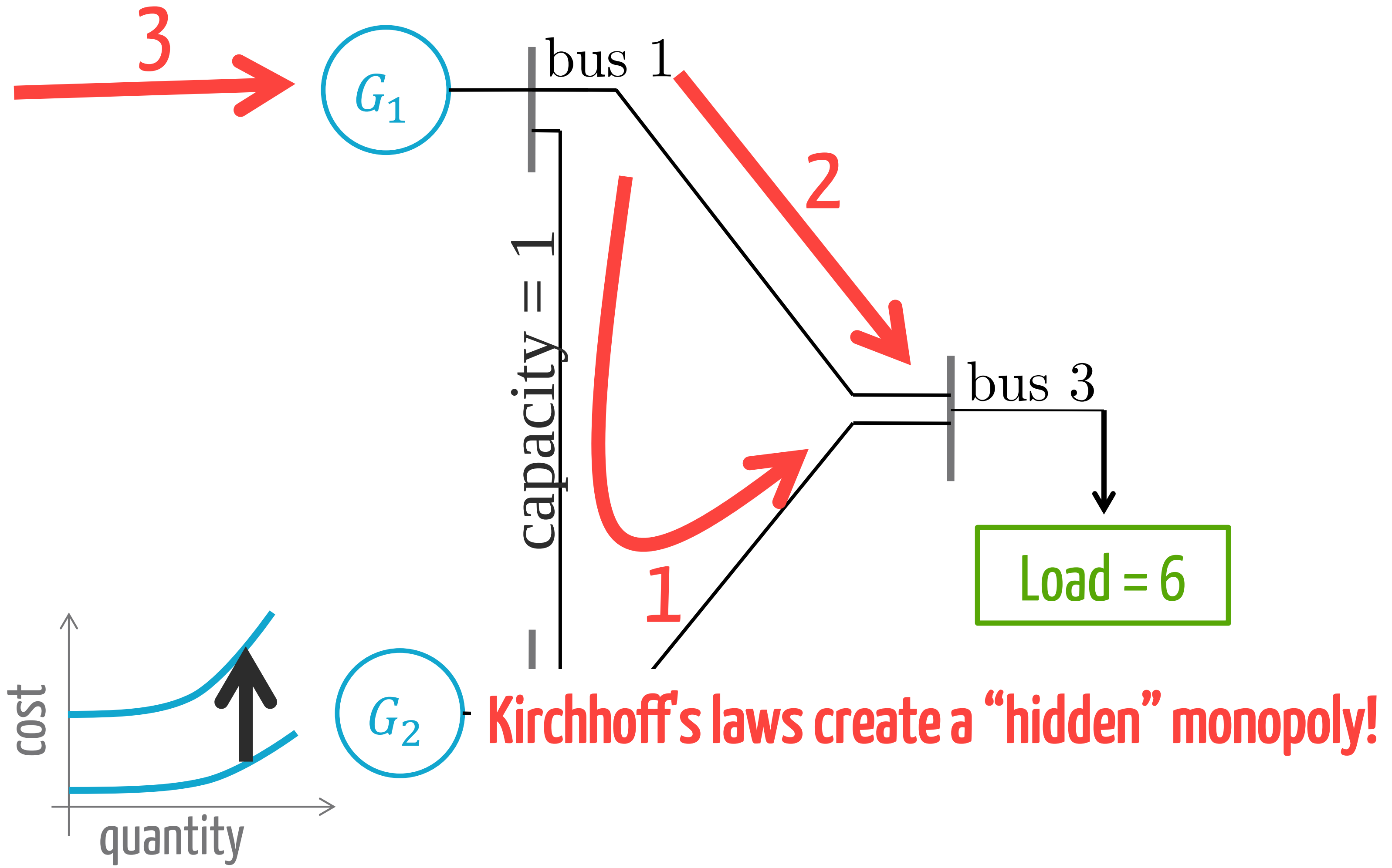
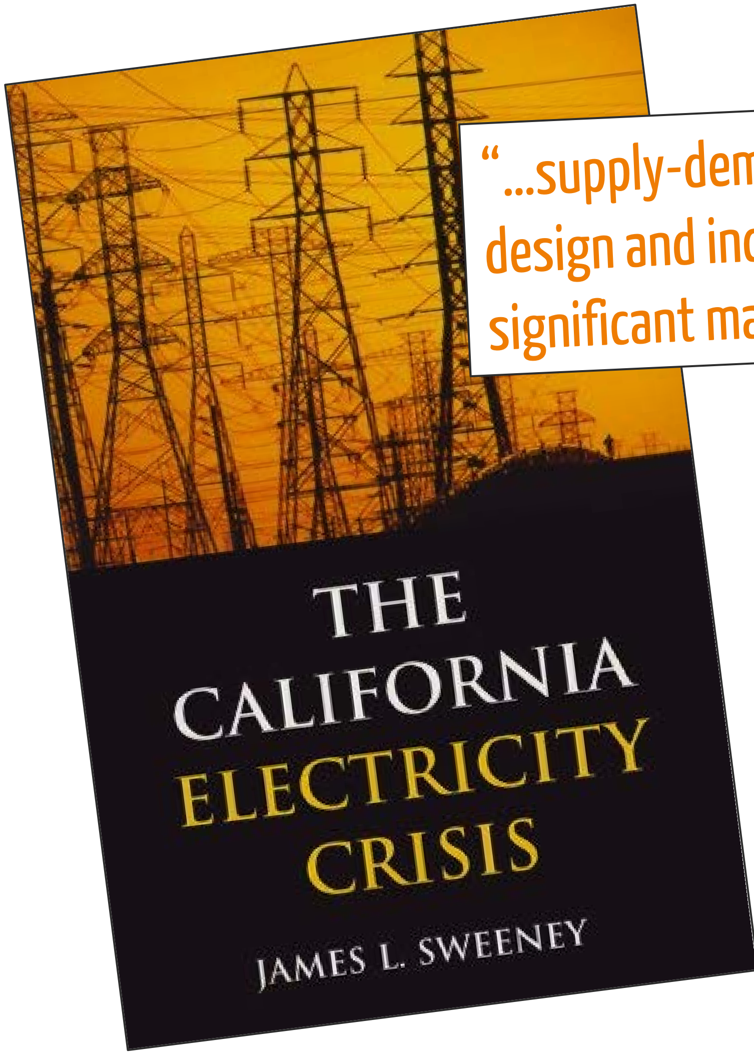
But what if G_2 is strategic?



But what if G_2 is strategic?



Kirchoff's laws can have nasty market consequences...



"...supply-demand imbalance, flawed market design and inconsistent rules made possible significant market manipulation" -- FERC

Kirchoff's laws can have nasty market consequences...

"JPMorgan Chase & Co. will pay $410 million to settle U.S. Federal Energy Regulatory Commission allegations that the bank manipulated power markets, enriching itself at the expense of consumers in California and the Midwest from 2010 to 2012."

Bloomberg News Quick Markets Personal

BREAKING Siemens Said to See Little Chance of Winning Alstom Bid TWEET

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JPMorgan to Pay $410 Million in U.S. FERC Settlement

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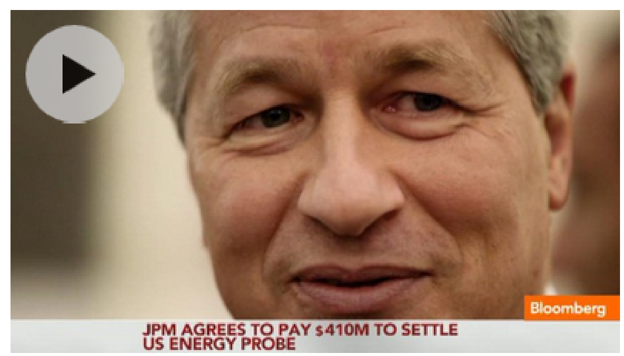
By Brian Wingfield and Dawn Kopecki | Jul 30, 2013 12:09 PM PT | 27 Comments | Email | Print

JPMorgan Chase & Co. (JPM) will pay $410 million to settle U.S. Federal Energy Regulatory Commission allegations that the bank manipulated power markets, enriching itself at the expense of consumers in **California** and the Midwest from 2010 to 2012.

The bank agreed to pay a U.S. civil penalty of $285 million and return $125 million in ill-gotten profits to electricity ratepayers, according to a FERC order today. JPMorgan also agreed to give up claims to $262 million worth of disputed payments from California's grid operator, the state authority said in a separate statement.



July 30 (Bloomberg) -- Bloomberg News' Dawn Kopecki breaks down JPMorgan's agreement to pay $410 million to settle a U.S. Federal Energy Regulatory Commission investigation that the company manipulated energy markets in California and the Midwest. The agreement includes also giving up $125 million in profits. She speaks on Bloomberg Television's "In The Loop."

Kirchoff's laws can have nasty market consequences…

International Editions

ALJAZEERA AMERICA

"Energy Capital Partners … paid $650 million last year to acquire three generating plant complexes, including the second largest electric power plant in New England, Brayton Point. Five weeks after the deal closed, Energy partners moved to shutter Brayton Point. Why would anyone spend hundreds of millions of dollars to buy the second largest electric power plant in New England and then quickly take steps to shut it down?"

Enron-style price gouging is making a comeback

Wall Street makes naked attempt to jack up electricity prices in New England

May 2, 2014 4:15AM ET

by **David Cay Johnston** - @DavidCayJ

The price of electricity would soar under the latest scheme by Wall Street financial engineers to game the electricity markets.

...and things could get much worse with distributed generation (solar, storage, etc.)

SolarCity

Aggregators of distributed generation may have the ability to manipulate prices via geographic curtailment that is "hidden" in the variability of renewable generation.

→ Our initial work hints that < 1% curtailment can yield 25+% extra profit!
[Ruhi et al., Under preparation]

How can market power be quantified & mitigated?

"easy" to quantify and mitigate market power via regulation of market concentration

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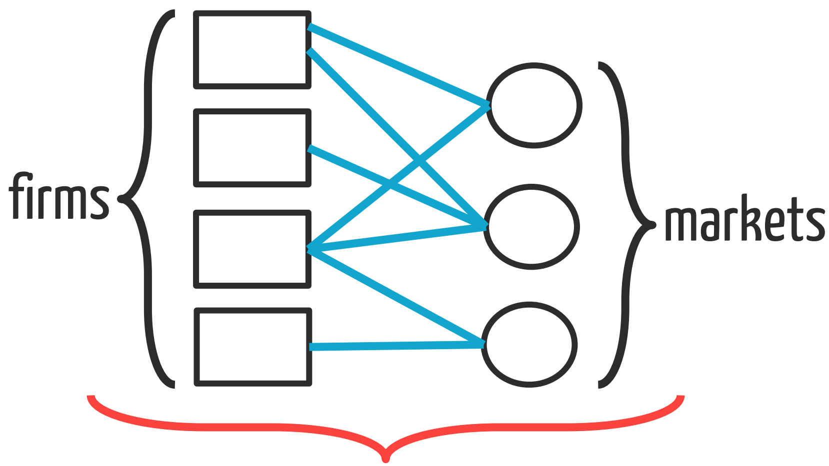

market power is amorphous & "hidden" monopolies are common

Today: How can networked markets be designed to mitigate market power?

Model: Networked Cournot competition (with a market maker)

Outline:

1. Classical Cournot competition (warmup)
2. Networked Cournot competition [Bimpkis et al., 2014], [Abolhassani et al., 2015]
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Classical Cournot competition – Quantity Competition

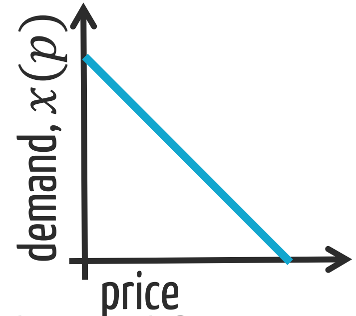
In contrast to : Bertrand competition, i.e., price competition


Antoine Cournot

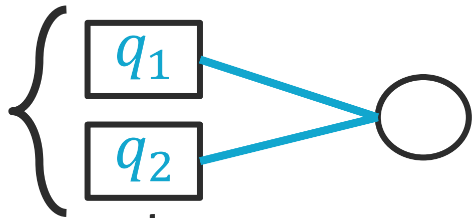
Firms compete via production quantities (and then the market sets the price)

Examples:
- Farmers bringing crops to market
- Generators deciding generation quantities

Classical Cournot competition – Quantity Competition



We'll start with two firms



cost: c

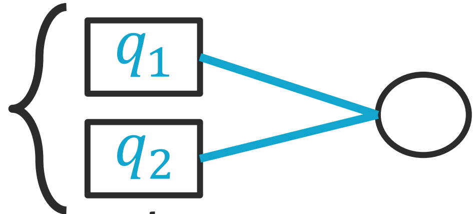
market, demand function $x(p)$

price: $p(q_1 + q_2) = x^{-1}(q_1 + q_2)$

1. Firms decide production quantities, q_i, at a cost per unit of c
2. Price adjusts to the level that clears the market

Classical Cournot competition – Quantity Competition

We'll start with two firms



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Goal: Maximize Profit

For firm 1 (given q_2): $\max_{q_1 \geq 0} \underbrace{p(q_1 + q_2)q_1}_{\text{revenue}} - \underbrace{cq_1}_{\text{cost}}$

Classical Cournot competition – Quantity Competition

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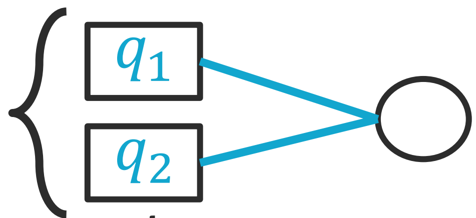

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A Nash equilibrium must satisfy:

$p'(q_1^* + q_2^*)q_1 + p(q_1^* + q_2^*) \leq c$, with equality if $q_1^* > 0$

$p'(q_1^* + q_2^*)q_2 + p(q_1^* + q_2^*) \leq c$, with equality if $q_2^* > 0$

Classical Cournot competition – Quantity Competition

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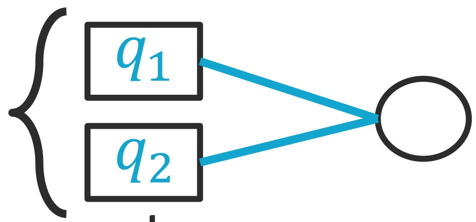

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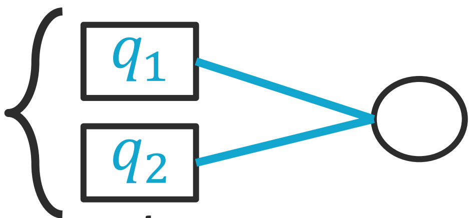
A Nash equilibrium must satisfy:

$$p'(q_1^* + q_2^*)\left(\frac{q_1^* + q_2^*}{2}\right) + p(q_1^* + q_2^*) = c$$

Classical Cournot competition – Quantity Competition

We'll start with two firms



cost: c

market, demand function $x(p)$

price: $p(q_1 + q_2) = x^{-1}(q_1 + q_2)$

<u>Theorem:</u> Consider p s.t. $p'(q) < 0$ for all $q \geq 0$ and $p(0) > c$.
Any equilibirum price is $>$ the competitive price & $<$ the monopoly price

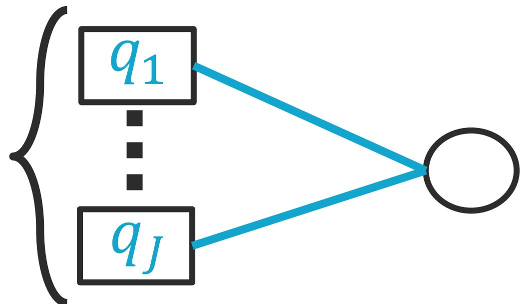
c

Homework #1: Prove this result.

Homework #2: Work out the precise equilibrium in the case of linear inverse demand functions, i.e., $p(q) = a - bq$.

Classical Cournot competition – Quantity Competition

Let's go to J firms now



cost: c

market, demand function $x(p)$

price: $p(Q_J) = x^{-1}(Q_J)$

aggregate quantity

A Nash equilibrium must satisfy:

$$p'(Q_J^*)\,(Q_J^*/J) + p(Q_J^*) = c$$

$J = 1$: monopoly price

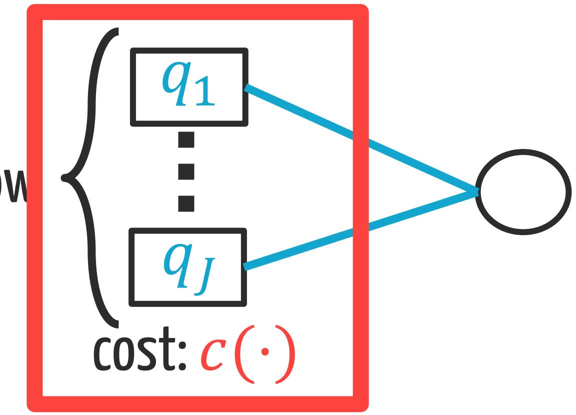
$J \to \infty$: competitive price, i.e., $p(Q_J^*) \to c$

Limiting market concentration is key to mitigating market power

How bad can market power exploits be?

Classical Cournot competition – Quantity Competition

Let's go to J firms now



market, demand function $x(p)$

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How bad can market power exploits be?

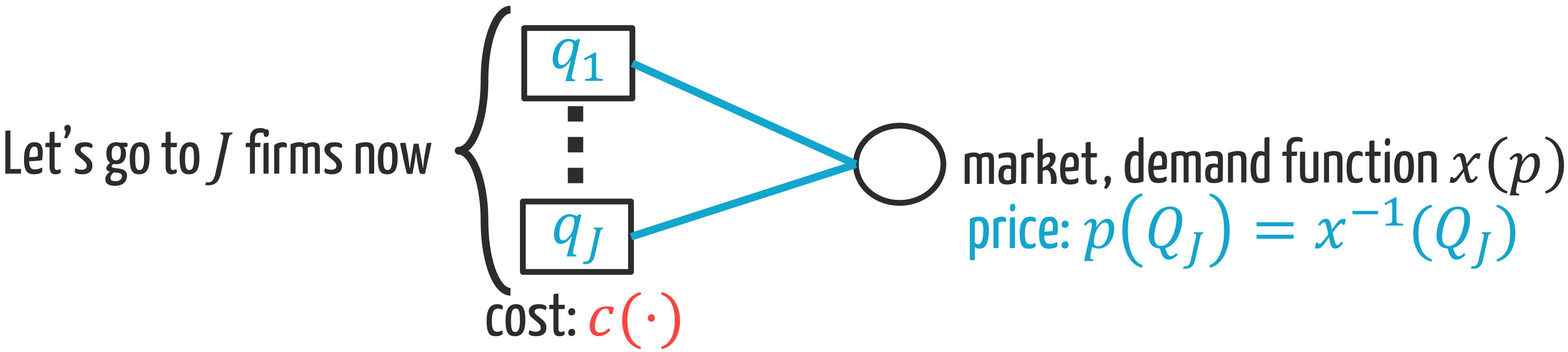
Classical Cournot competition – Quantity Competition

Let's go to J firms now

> Theorem [Johari & Tsitsiklis., 2005]: If firms have symmetric cost functions then the efficiency loss (compared the competitive market) is bounded by $\frac{1}{2J+1}$.

How bad can market power exploits be?

Classical Cournot competition – Quantity Competition

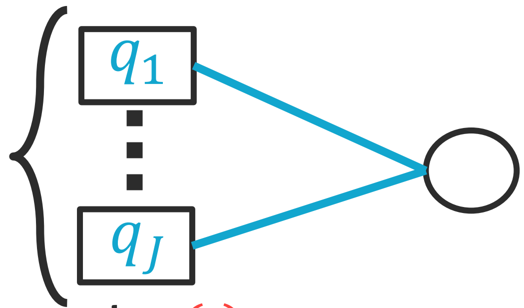


Theorem [Johari & Tsitsiklis., 2005]: If firms have symmetric cost functions then the efficiency loss (compared the competitive market) is bounded by $\frac{1}{2J+1}$.

Theorem [Johari & Tsitsiklis., 2005]: If the inverse demand function is affine then the efficiency loss (compared to the competitive market) is bounded by 1/3.

Classical Cournot competition – Quantity Competition

Let's go to J firms now



market, demand function $x(p)$

price: $p(Q_J) = x^{-1}(Q_J)$

cost: $c(\cdot)$

Some final thoughts:

- Do cost reductions always improve social welfare? No! Not even with 2 firms
- Does entry of a firm necessarily reduce the equilibrium price? Yes!

Homework #3 & #4: Prove the above statements.

Today: How can networked markets be designed to mitigate market power?

Model: Networked Cournot competition (with a market maker)

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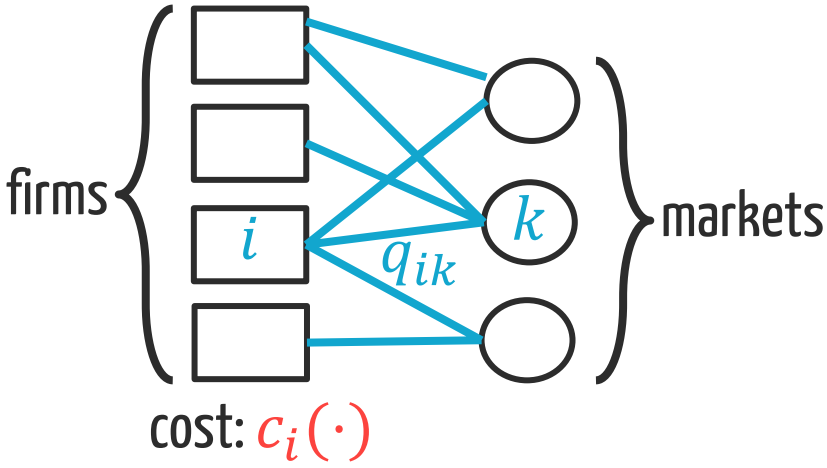
Networked Cournot competition



1. Firms decide production quantities for each market, q_{ik}, at a cost $c_i(\sum_{k \in F_i} q_{ik})$

Key: Firms are constrained to a limited set of markets (no capacity constraints yet)

Networked Cournot competition

1. Firms decide production quantities for each market, q_{ik}, at a cost $c_i(\sum_{k \in F_i} q_{ik})$
2. Market prices adjust to the level that clears each market, $p_k(\sum_{j \in M_k} q_{jk})$

Networked Cournot competition

Goal: Maximize Profit

For firm i (given other productions):

$$\max_{q_{ik}\geq 0} \underbrace{\sum_{M_k \in F_i} q_{ik}\, p_k\left(\sum_{j\in M_k} q_{jk}\right)}_{\text{revenue}} - \underbrace{c_i\left(\sum_{j\in F_i} q_{ij}\right)}_{\text{cost}}$$

Networked Cournot competition

<u>Goal: Maximize Profit</u>

For firm i (given other productions):

$$\max_{q_{ik} \geq 0} \sum_{M_k \in \mathrm{F}_i} q_{ik}\, p_k\left(\sum_{j \in M_k} q_{jk}\right) - c_i\left(\sum_{j \in F_i} q_{ij}\right)$$

Key: Profit is not separable across markets (unless c_i is linear)

Networked Cournot competition

Today: How can networked markets be designed to mitigate market power?

Theorem [Bimpkis et al., 2014]: There is a unique Nash equilibrium when p_k are twice differentiable, concave, and strictly decreasing, and c_i are twice differentiable, convex, and increasing.

...and this equilibrium is not too hard to compute [Abolhassani et al., 2015]:

- if inverse demand function p_k are linear → $O(E^3)$ ← ordinal potential game
- if inverse demand functions p_k are strongly monotone → $poly(E)$ ← linear complementarity problem
- if cost functions c_i are separable → $O(J \log^2 q_{\max})$ ← supermodular optimization

Homework #5: Prove existence in the case of linear inverse demand and quadratic costs.

Theorem [Bimpkis et al., 2014] : There is a unique Nash equilibrium when p_k are twice differentiable, concave, and strictly decreasing, and c_i are twice differentiable, convex, and increasing.

BUT, it's hard to characterize the equilibrium in general

The best we can do is results for quadratic costs c_i and linear inverse demand p_k

A measure of market power

$$q^* \propto -\Lambda$$

where Λ is termed the "price impact matrix"

$$\Lambda = -\beta \sum_{j \in M_l} \frac{\psi_{jl,ik}}{\psi_{ik,ik}} \text{ where } \Psi = \left[I - \frac{2W}{c+\beta}\right]^{-1}$$

Adjacency matrix of the "line graph" of the game

Key: Even distant connections have an impact on prices in a given market.

Theorem [Bimpkis et al., 2014] : There is a unique Nash equilibrium when p_k are twice differentiable, concave, and strictly decreasing, and c_i are twice differentiable, convex, and increasing.

BUT, it's hard to characterize the equilibrium in general

The best we can do is results for quadratic costs c_i and linear inverse demand p_k

$q^* \propto -\Lambda$

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A measure of market power

$\Lambda = -\beta \sum_{j \in M_l} \frac{\psi_{jl,ik}}{\psi_{ik,ik}}$ where $\Psi = \left[I - \frac{2W}{c+\beta}\right]^{-1}$

Adjacency matrix of the "line graph" of the game

Homework #6: Characterize the equilibrium for a 2 firm, 2 market example.

Networked Cournot competition

Some final thoughts:

- Do cost reductions always improve social welfare? No! Not even with 2 firms
- Does entry of a firm necessarily reduce the equilibrium price? ~~Yes!~~ No!
- Can mergers of firms that don't overlap markets increase market power? Yes!

Today: How can <u>networked markets</u> be designed to mitigate market power?

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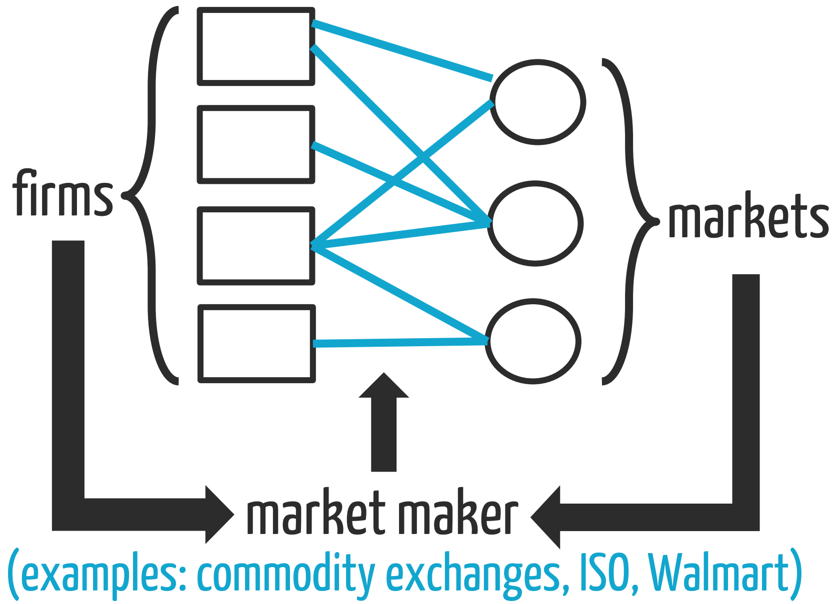
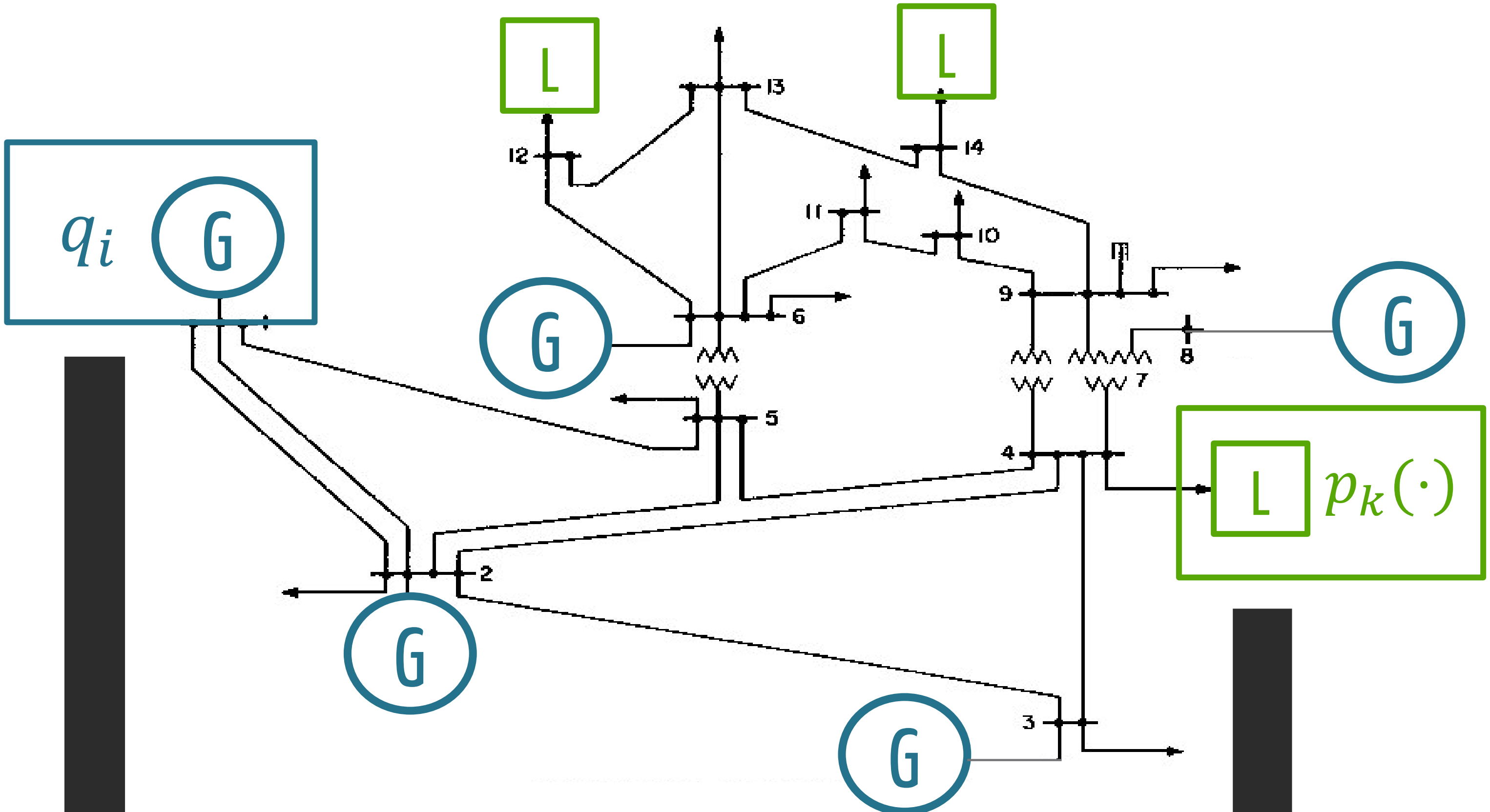
Networked Cournot competition with a market maker



Our model is motivated by electricity markets



Market run by a <u>market maker</u> (ISO, Independent System Operator)

Determines the quantity to procure and price to charge each generator in order to meet the load s.t. network constraints.

Line constraints & Kirchhoff's laws

ISO behavior is typically regulated

Often forced to maximize one of :

1) <u>Social welfare</u>: Consumers' utility – generation costs
2) <u>Residual social welfare</u>: Consumers' utility – generator profits
3) <u>Consumer surplus</u>: Consumers' utility – consumer payments

Market run by a <u>market maker</u> (ISO, Independent System Operator)

Determines the quantity to procure and price to charge each generator in order to meet the load s.t. network constraints.

Determine the "rebalancing quantities" r_i to

Maximize $W(q, r)$

s.t. $\sum_i r_i = 0$

$-f \leq |Hr| \leq f$

Shift factor matrix (Kirchhoff's Laws)

line constraints

Market run by a <u>market maker</u> (ISO, Independent System Operator)

Determines the quantity to procure and price to charge each generator in order to meet the load s.t. network constraints.

Networked Cournot competition with a market maker

[Barquin & Vasquez 2005, 2008], [Iklic 2009], [Neuhoff et at, 2005], [Yao, Oren, Adler, 2005, 2007] ...

Firms

Bid: quantity q_i

Quadratic Costs: $c(q_i) = c_i q_i^2$

Profit: $p_i q_i - c_i q_i^2$

Demands

Linear inverse demand function

$p_i(d_i) = a_i - b_i d_i$

Existence?

Market run by a market maker (ISO)

Maximize $W(q, r)$

s. t. $\sum_i r_i = 0$ & $-f \leq |Hr| \leq f$

Just think of this as general linear constraints

Theorem [Bose et al., 2014]

A generalized Nash equilibrium always exists when the ISO maximizes social welfare or residual social welfare.

However, a generalized Nash equilibrium may not exist if the ISO maximizes consumer surplus.

very susceptible to market power manipulations (market maker optimization is not convex)

A toy example: “Path 15”

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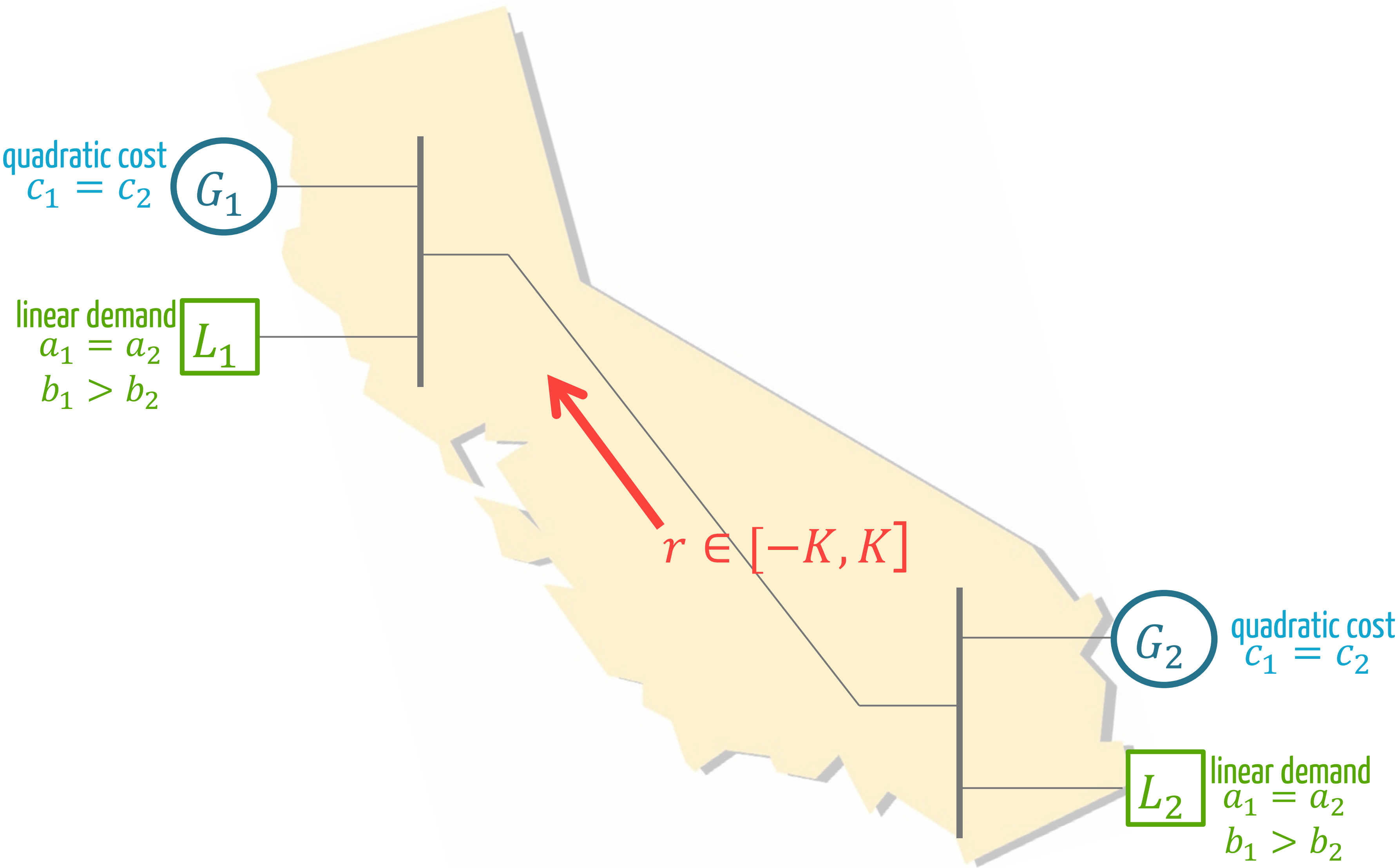
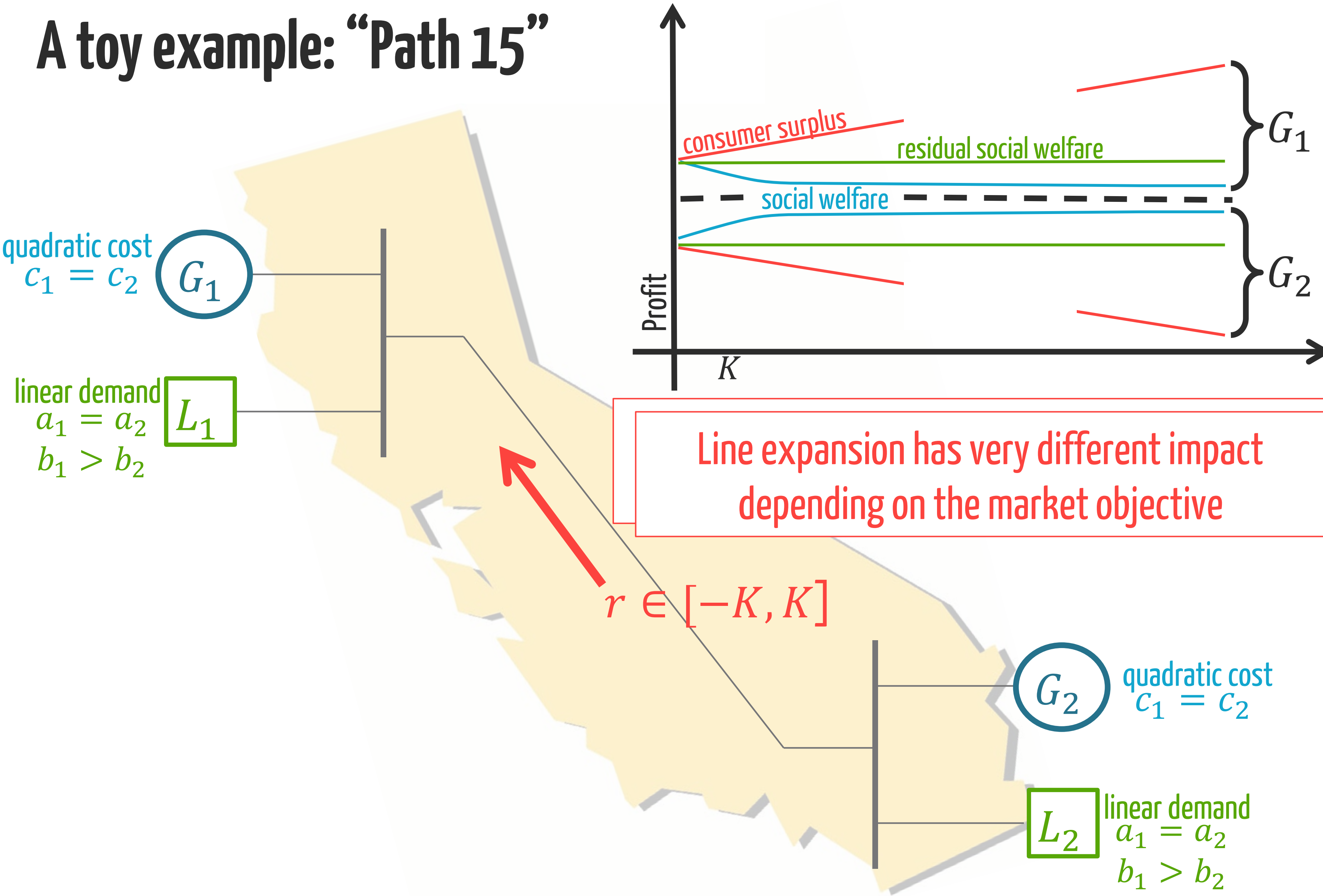


A toy example: "Path 15"



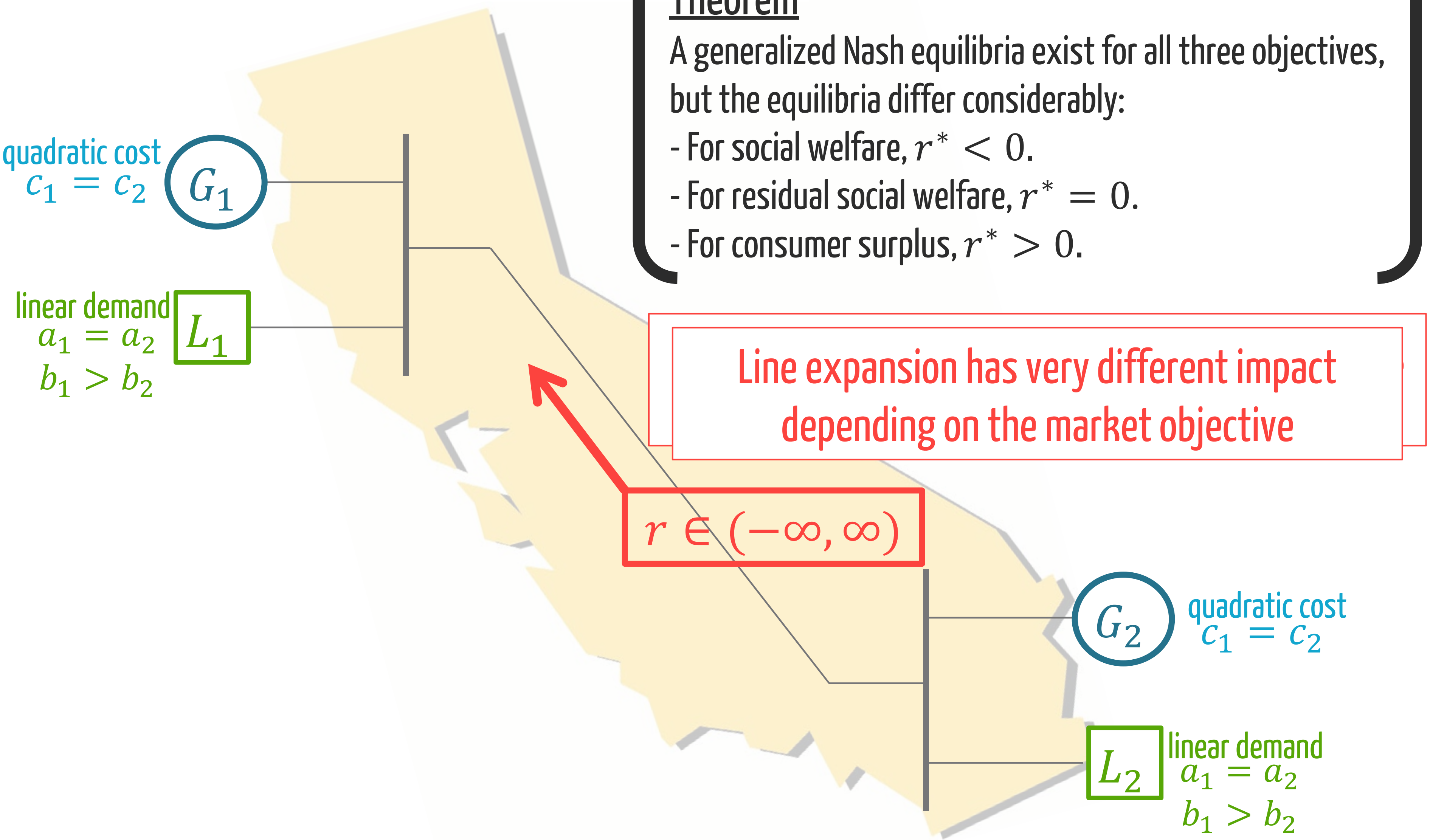
Line expansion has very different impact depending on the market objective

A toy example: “Path 15”

Theorem

A generalized Nash equilibria exist for all three objectives, but the equilibria differ considerably:

- For social welfare, $r^* < 0$.
- For residual social welfare, $r^* = 0$.
- For consumer surplus, $r^* > 0$.



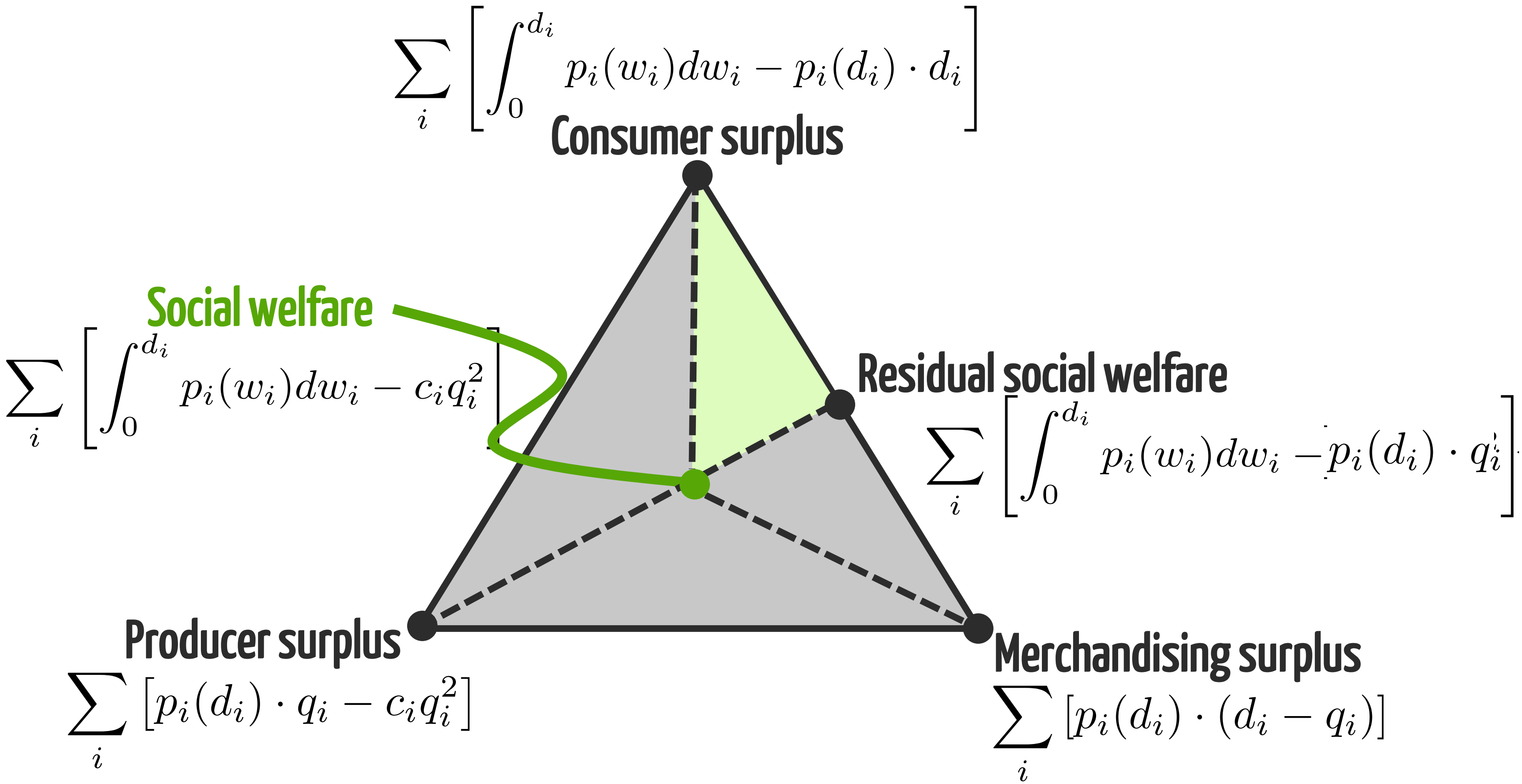
Today: How can networked markets be designed to mitigate market power?

↓

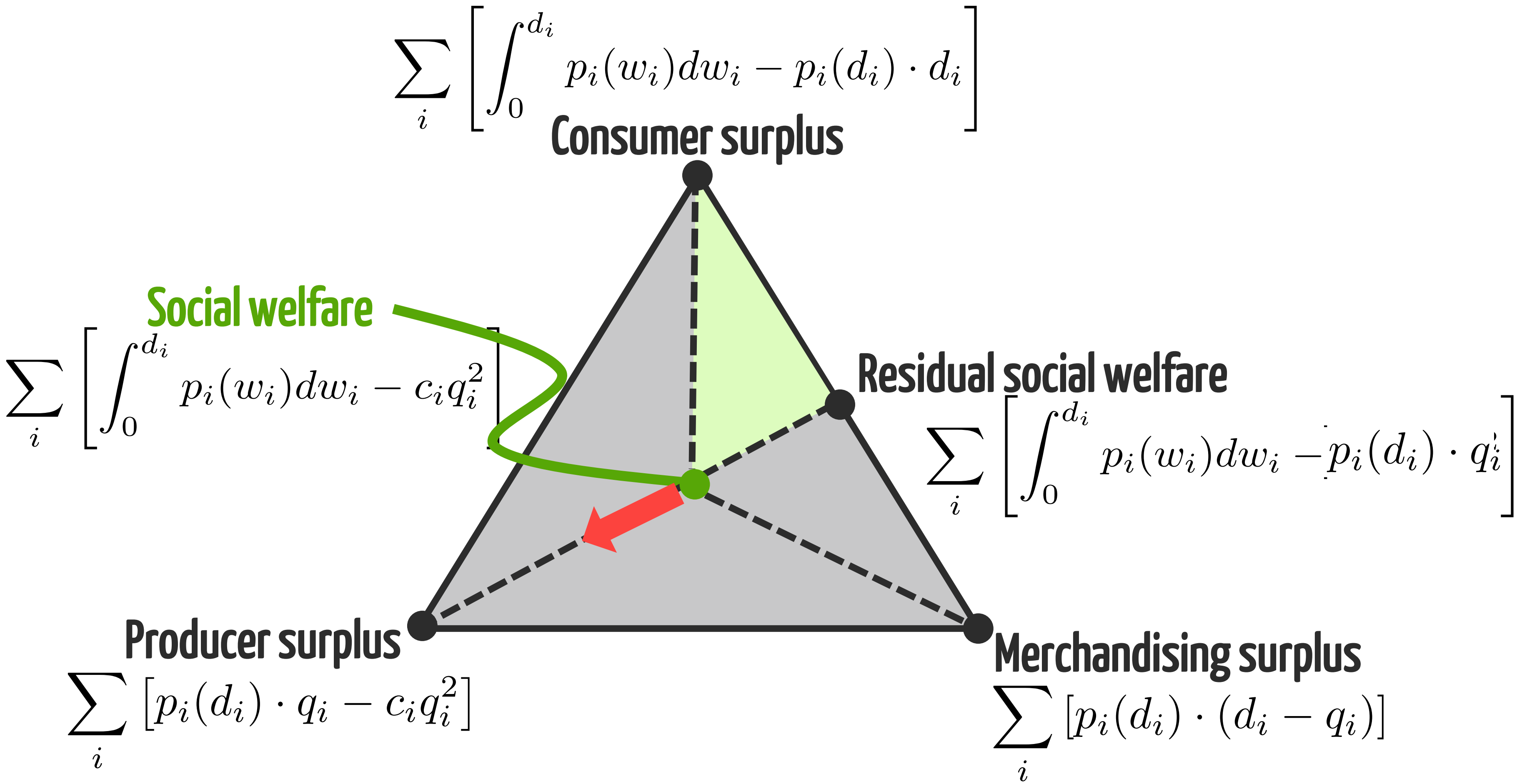
What is the "right" market objective?

What market maker objective maximizes social welfare?

Social welfare? Not always...

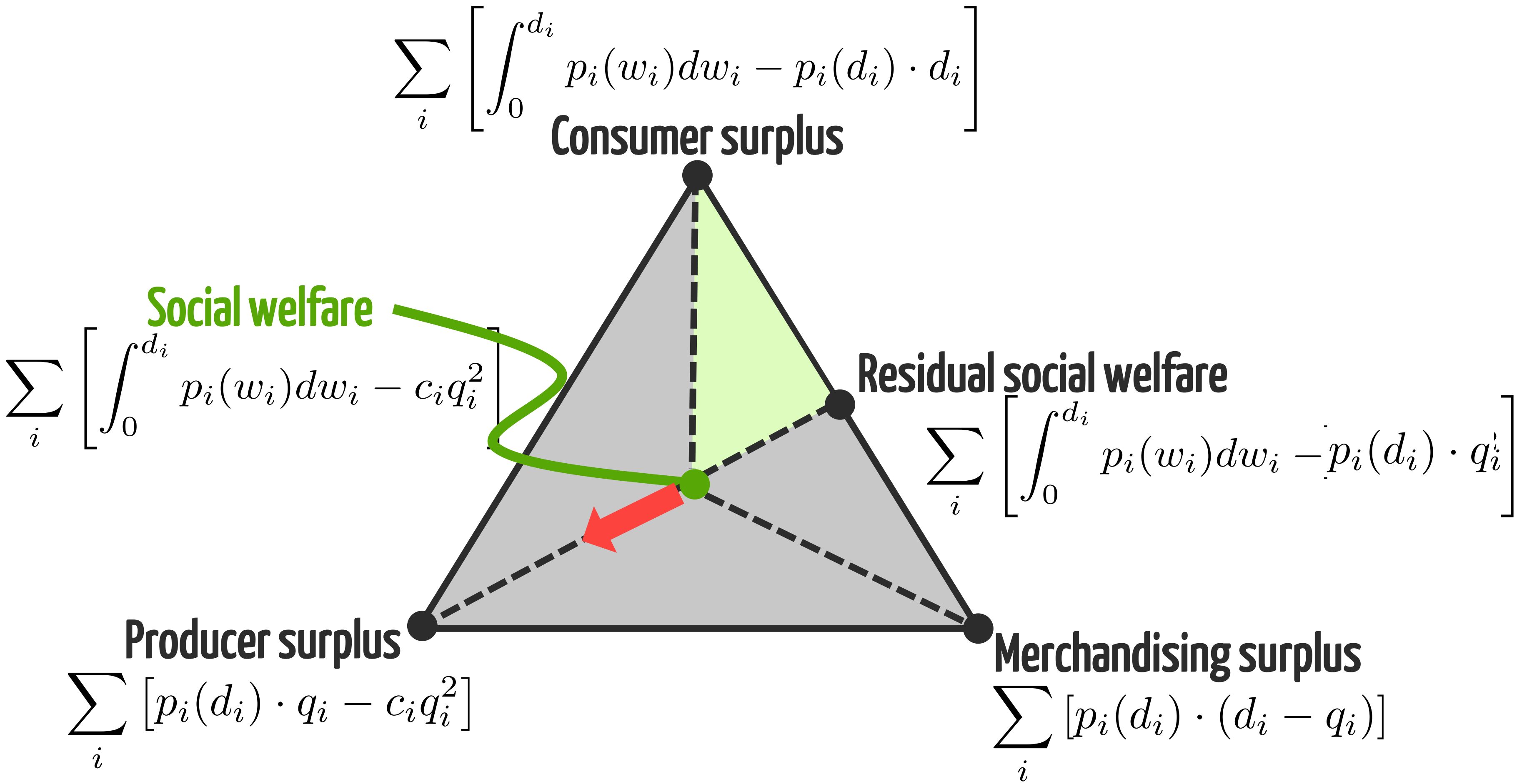


$\sum_i \left[\int_0^{d_i} p_i(w_i) dw_i - p_i(d_i) \cdot d_i \right]$
Consumer surplus
Social welfare
$\sum_i \left[\int_0^{d_i} p_i(w_i) dw_i - c_i q_i^2 \right]$
Residual social welfare
$\sum_i \left[\int_0^{d_i} p_i(w_i) dw_i - p_i(d_i) \cdot q_i \right]$
Producer surplus
$\sum_i \left[p_i(d_i) \cdot q_i - c_i q_i^2 \right]$
Merchandising surplus
$\sum_i \left[p_i(d_i) \cdot (d_i - q_i) \right]$



Using social welfare does not always optimize social welfare!

...even in 2-node examples, biasing toward producer surplus helps.



But, is using social welfare “near optimal” at least?

Recall that in classical (non-network) Cournot:

Theorem [Johari & Tsitsiklis, 2005]: If firms have symmetric cost functions then the efficiency loss (compared the competitive market) is bounded by $\frac{1}{2J+1}$.

Theorem [Johari & Tsitsiklis, 2005]: If the inverse demand function is affine then the efficiency loss (compared to the competitive market) is bounded by $1/3$.

But, is using social welfare "near optimal" at least?

Theorem [Xu et al., 2015]: Consider a market maker optimizing social welfare. The price of anarchy is unbounded, even in an unconstrained 2-node network with affine inverse demands and quadratic costs.

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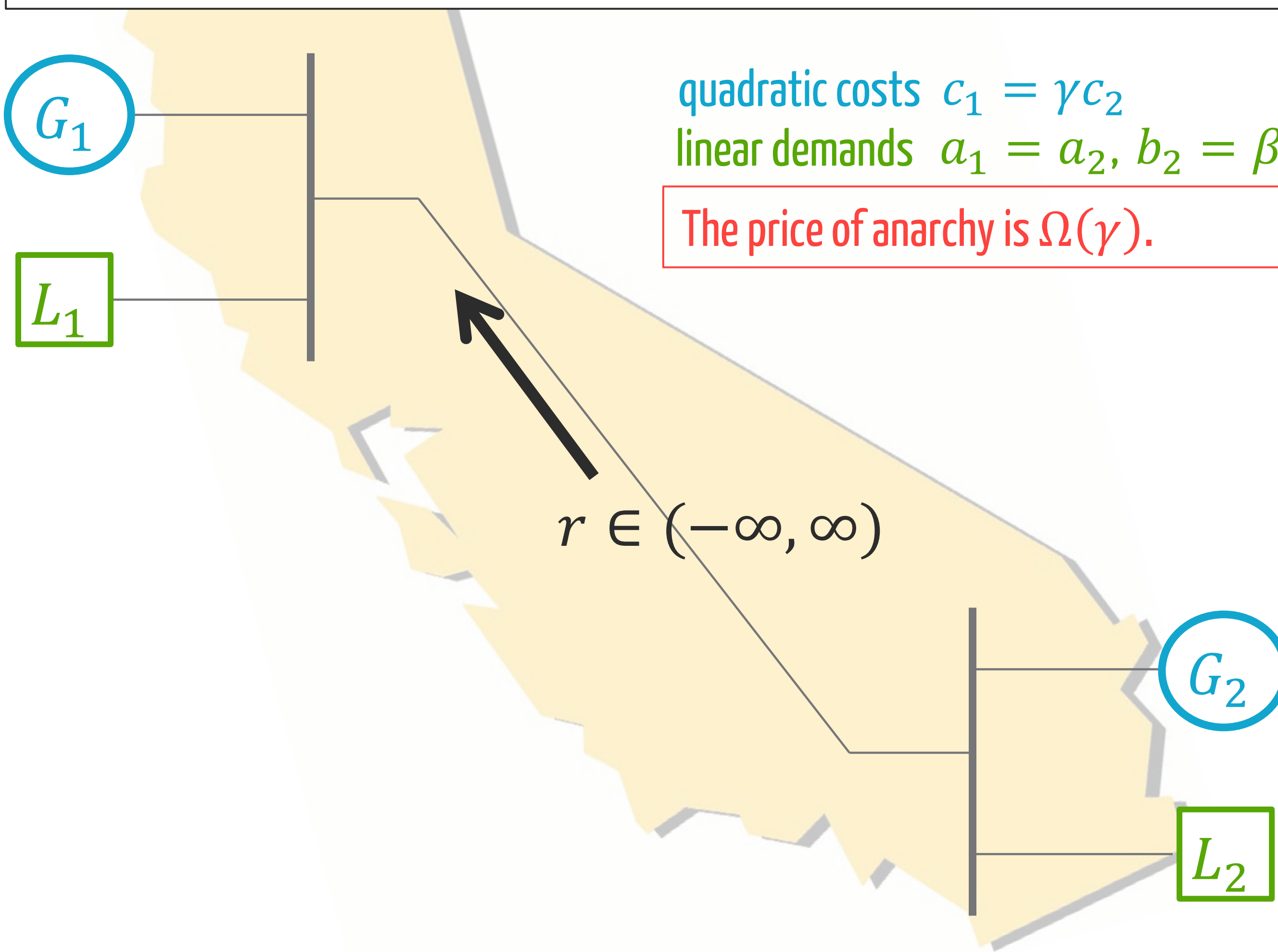


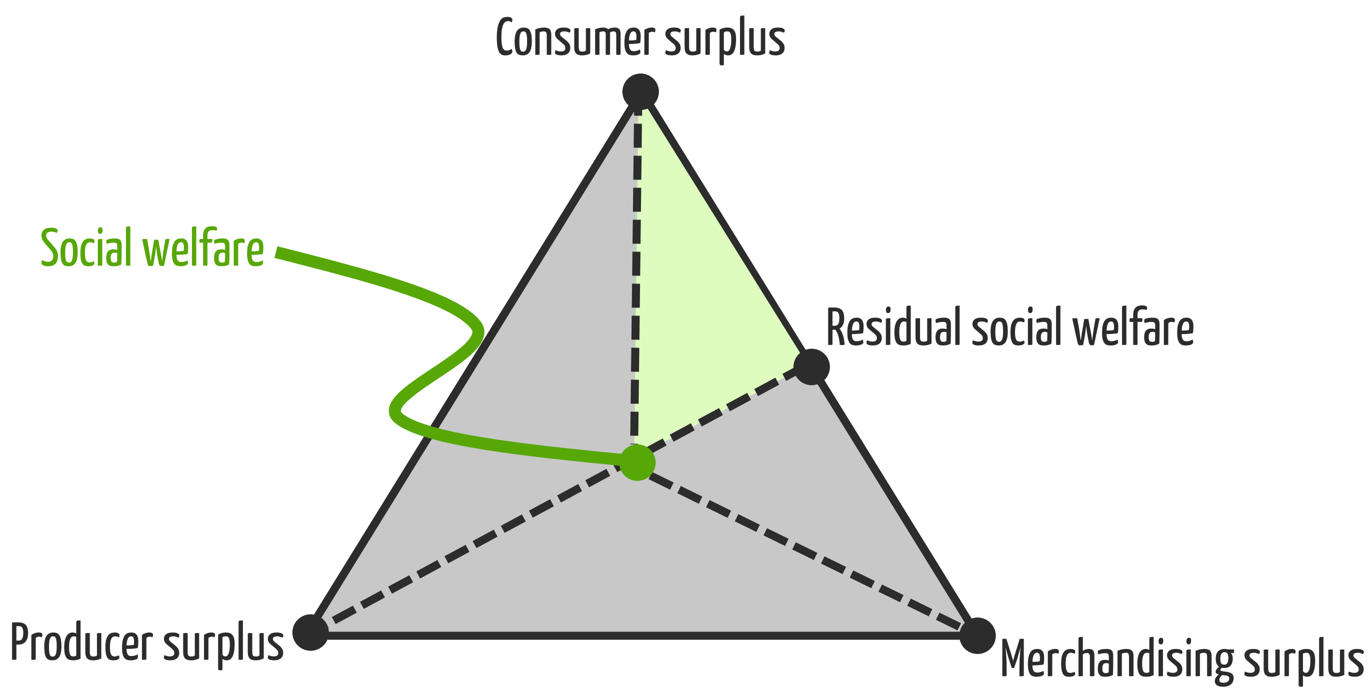
quadratic costs $c_1 = \gamma c_2$

linear demands $a_1 = a_2,\ b_2 = \beta b_1$

The price of anarchy is $\Omega(\gamma)$.

Theorem [Xu et al., 2015]: Consider a market maker optimizing social welfare. The price of anarchy is unbounded, even in an unconstrained 2-node network with affine inverse demands and quadratic costs.

Open Question: What market maker objective minimizes the Price of Anarchy?



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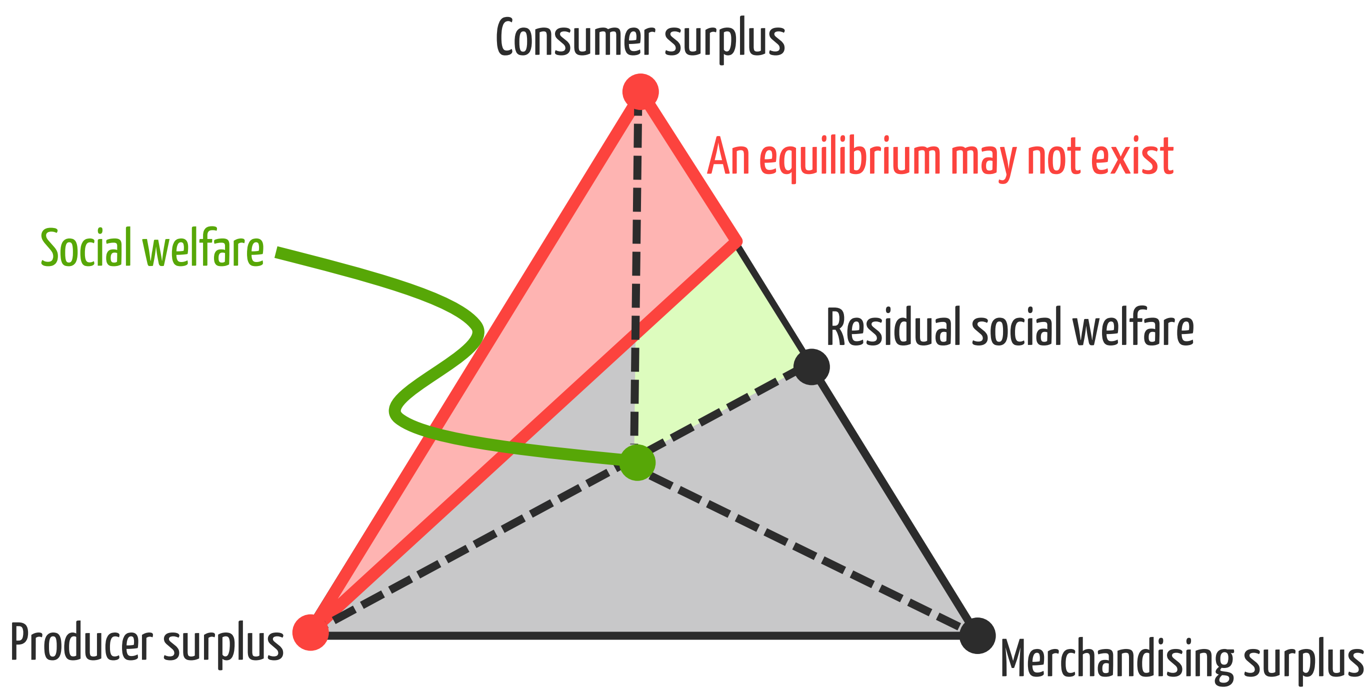

Today: How can networked markets be designed to mitigate market power?

Model: Networked Cournot competition (with a market maker)

Outline:

1. Classical Cournot competition (warmup)
2. Networked Cournot competition [Bimpkis et al., 2014], [Abolhassani et al., 2015]
3. Networked Cournot competition with a market maker [Bose et al., 2014] [Xu et al., 2015]

Today: How can <u>networked markets</u> be designed to mitigate market power?

Model: Networked Cournot competition (with a market maker)

Is Cournot the "right" model?

It depends on the setting...

↓

<u>There are many interesting variations!</u>

Today: How can <u>networked markets</u> be designed to mitigate market power?

Model: Networked Cournot competition (with a market maker)

Is Cournot the "right" model?

It depends on the setting...

There are many interesting variations!

very important for energy markets:

- More complex bidding forms (e.g. supply functions)
- Forward markets (e.g., real-time and day-ahead markets)
- Price anticipating firms (e.g. networked Stackelberg competition)
- Price competition (e.g., networked Bertrand competition)

⋮

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⋮

Anticipatory behavior improves efficiency!

Price of anarchy drops to 3/2 for affine inverse demands with spatially homogenous intercepts and quadratic costs. [Xu et al ., 2015]

But, social welfare is still not the optimal clearing rule in general

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Networked Markets: *Market makers & market power*

Adam Wierman, Caltech

Joint work with Subhonmesh Bose, Desmond Cai, Niangjun Chen, Navid Ruhi, and Yunjian Xu.

Our papers on the topic:

- Chenye Wu, Subhonmesh Bose, Adam Wierman and Hamed Mohsenian-Rad. "A unifying approach for assessing market power in deregulated electricity markets." Proceedings of IEEE PES General Meeting, 2013. ``Best Paper on System Operations and Market Economics" award recipient.
- Desmond Cai and Adam Wierman. "Inefficiency in Forward Markets with Supply Friction." Proceedings of IEEE CDC, 2013.
- Subhonmesh Bose, Desmond Cai, Steven Low and Adam Wierman. "The role of a market maker in networked Cournot competition." Proceedings of IEEE CDC 2014.
- Yunjian Xu, Desmond Cai, Subhonmesh Bose, and Adam Wierman. "On the efficiency of networked stackelberg competition." Under submission.
- Navid Ruhi, Niangjun Chen, and Adam Wierman. "Opportunities for price manipulation by aggregators in electricity markets." Under preparation.