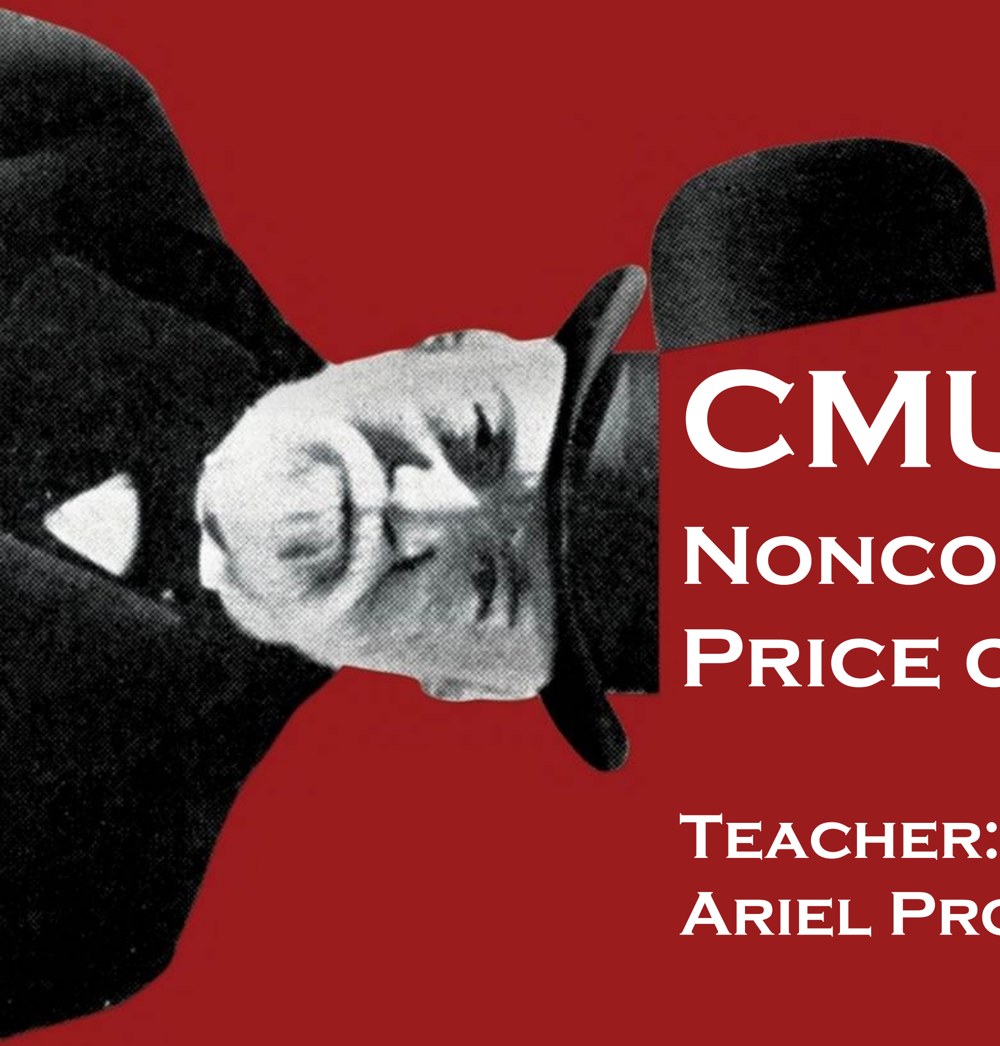

CMU 15-896

Noncooperative games 3: Price of anarchy

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Back to prison

- The only Nash equilibrium in Prisoner's dilemma is bad; but how bad is it?
- Objective function: social cost = sum of costs
- NE is six times worse than the optimum

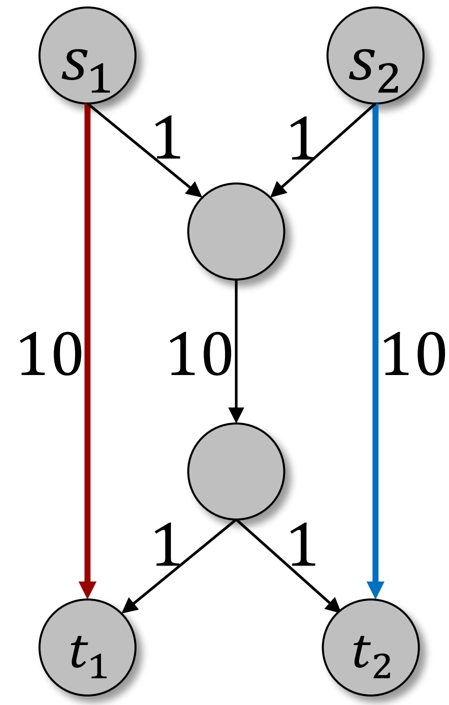
	Cooperate	Defect
Cooperate	-1,-1	-9,0
Defect	0,-9	-6,-6

Anarchy and Stability

- Fix a class of games, an objective function, and an equilibrium concept
- The price of anarchy (stability) is the worst-case ratio between the worst (best) objective function value of an equilibrium of the game, and that of the optimal solution
- In this lecture:
    - Objective function = social cost
    - Equilibrium concept = Nash equilibrium

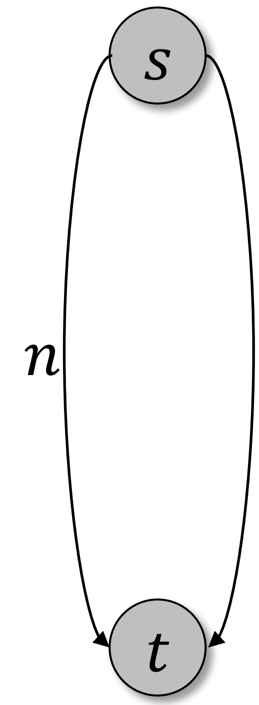
Example: Cost sharing

- n players in weighted directed graph G
- Player i wants to get from s_i to t_i; strategy space is $s_i \to t_i$ paths
- Each edge e has cost c_e
- Cost of edge is split between all players using edge
- Cost of player is sum of costs over edges on path



Example: Cost sharing

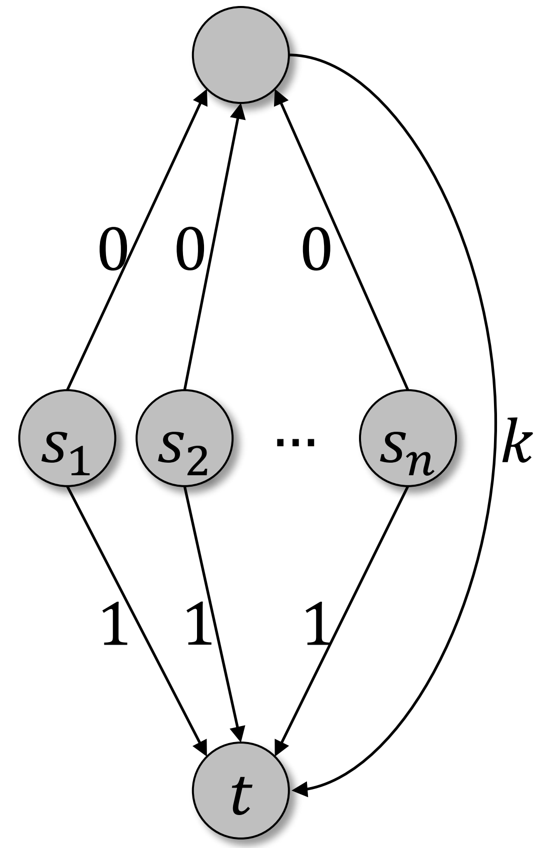
- With n players, the example on the right has an NE with social cost n
- Optimal social cost is 1
- $\Rightarrow$ Price of anarchy $\geq n$



Prove that the price of anarchy is at most n

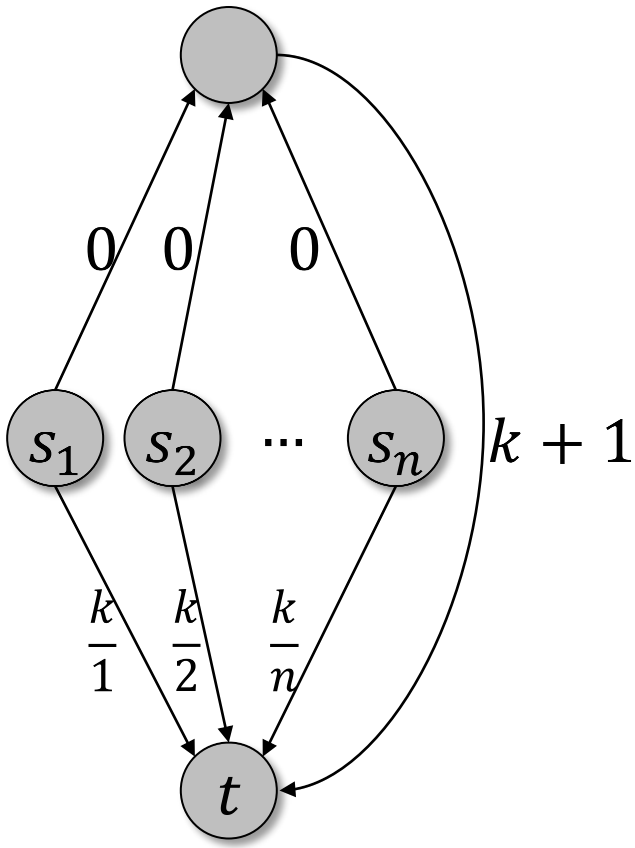
Example: Cost sharing

- Think of the 1 edges as cars, and the k edge as mass transit
- Bad Nash equilibrium with cost n
- Good Nash equilibrium with cost k
- Now let's modify the example...



Example: Cost sharing

- OPT$= k+1$
- Only equilibrium has cost $k \cdot H(n)$
- $\Rightarrow$ price of stability is at least $\Omega(\log n)$
- We will show that the price of stability is $\Theta(\log n)$



Potential games

- A game is an exact potential game if there exists a function $\Phi: \prod_{i=1}^{n} S_i \rightarrow \mathbb{R}$ such that for all $i \in N$, for all $\boldsymbol{s} \in \prod_{i=1}^{n} S_i$, and for all $s_i' \in S_i$,
  $\mathrm{cost}_i(s_i', \boldsymbol{s}_{-i}) - \mathrm{cost}_i(\boldsymbol{s}) = \Phi(s_i', \boldsymbol{s}_{-i}) - \Phi(\boldsymbol{s})$

Why does the existence of an exact potential function imply the existence of a pure Nash equilibrium?

Potential games

- Theorem: the cost sharing game is an exact potential game
- Proof:
  - Let $n_e(\boldsymbol{s})$ be the number of players using $\boldsymbol{e}$ under $\boldsymbol{s}$
  - Define the potential function

$$\Phi(\boldsymbol{s}) = \sum_{e} \sum_{k=1}^{n_e(\boldsymbol{s})} \frac{c_e}{k}$$

  - If player changes paths, pays $\frac{c_e}{n_e(\boldsymbol{s})+1}$ for each new edge, gets $\frac{c_e}{n_e(\boldsymbol{s})}$ for each old edge, so $\Delta\mathrm{cost}_i = \Delta\Phi$ ■

Potential games

- Theorem: The cost of stability of cost sharing games is $O(\log n)$
- Proof:
  - It holds that
  $$\mathrm{cost}(\boldsymbol{s}) \leq \Phi(\boldsymbol{s}) \leq H(n) \cdot \mathrm{cost}(\boldsymbol{s})$$
  - Take a strategy profile $\boldsymbol{s}$ that minimizes Φ
  - $\boldsymbol{s}$ is an NE
  - $\mathrm{cost}(\boldsymbol{s}) \leq \Phi(\boldsymbol{s}) \leq \Phi(\mathrm{OPT}) \leq H(n) \cdot \mathrm{cost}(\mathrm{OPT})$ ■

Cost sharing summary

- In every cost sharing game
  - $\forall$NE $\boldsymbol{s}$, $\text{cost}(\boldsymbol{s}) \leq n \cdot \text{cost}(\text{OPT})$
  - $\exists$NE $\boldsymbol{s}$ such that $\text{cost}(\boldsymbol{s}) \leq H(n) \cdot \text{cost}(\text{OPT})$
- There exist cost sharing games s.t.
  - $\exists$NE $\boldsymbol{s}$ such that $\text{cost}(\boldsymbol{s}) \geq n \cdot \text{cost}(\text{OPT})$
  - $\forall$NE $\boldsymbol{s}$, $\text{cost}(\boldsymbol{s}) \geq H(n) \cdot \text{cost}(\text{OPT})$

Congestion games

- Generalization of cost sharing games
- n players and m resources
- Each player i chooses a set of resources (e.g., a path) from collection S_i of allowable sets of resources (e.g., paths from s_i to t_i)
- Cost of resource j is a function $f_j(n_j)$ of the number n_j of players using it
- Cost of player is the sum over used resources

Congestion games

- Theorem [Rosenthal 1973]: Every congestion game is an exact potential game
- Proof: The exact potential function is

$$\Phi(\boldsymbol{s}) = \sum_{j} \sum_{i=1}^{n_j(\boldsymbol{s})} f_j(i)$$

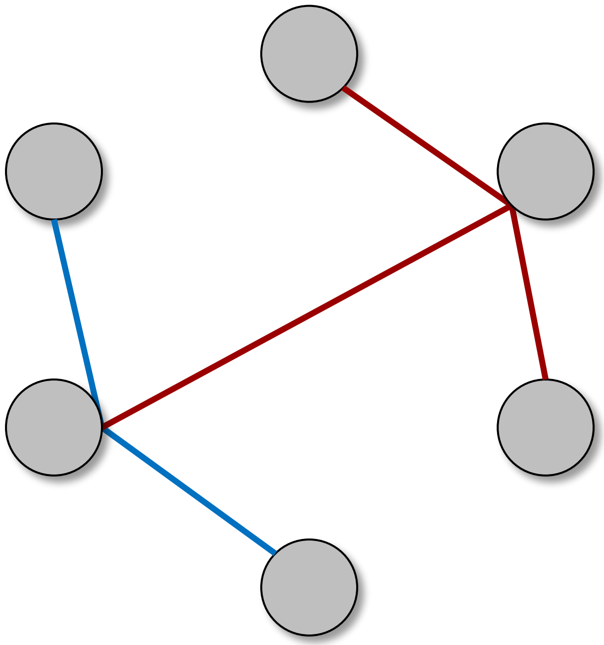
- Theorem [Monderer and Shapley 1996]: Every potential game is isomorphic to a congestion game

Network formation games

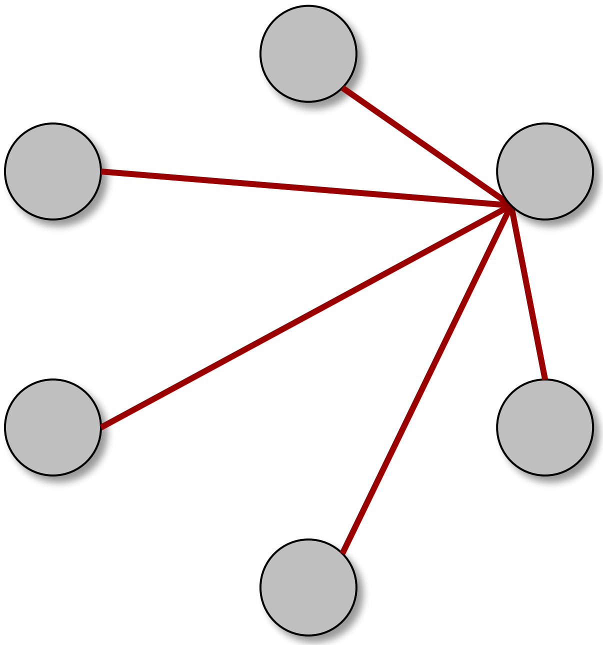
- Each player is a vertex v
- Strategy of v: set of undirected edges to build that touch v
- Strategy profile $\boldsymbol{s}$ induces undirected graph $G(\boldsymbol{s})$
- Cost of building any edge is α
- $\mathrm{cost}_v(\boldsymbol{s}) = \alpha n_v(\boldsymbol{s}) + \sum_u d(u,v)$, where $n_v =$ #edges bought by v, d is shortest path in #edges
- $\mathrm{cost}(\boldsymbol{s}) = \sum_{u \neq v} d(u,v) + \alpha|E|$

Example: Network formation

- NE with $\alpha = 3$



Suboptimal



Optimal

Example: Network formation

- Lemma: If $\alpha \geq 2$ then any star is optimal, and if $\alpha \leq 2$ then a complete graph is optimal
- Proof:
  - Suppose $\alpha \leq 2$, and consider any graph that is not complete
  - Adding an edge will decrease the sum of distances by at least 2, and costs only α
  - Suppose $\alpha \geq 2$ and the graph contains a star, so the diameter is at most 2; deleting a non-star edge increases the sum of distances by at most 2, and saves α $\blacksquare$

Example: Network formation

Poll: For which values of α is any star an NE, and any complete graph an NE

1. $\alpha \geq 1, \alpha \leq 1$
2. $\alpha \geq 2, \alpha \leq 1$
3. $\alpha \geq 1$, none
4. $\alpha \geq 2$, none

Example: Network formation

- Theorem:
  1. If $\alpha \geq 2$ or $\alpha \leq 1$, $\text{PoS} = 1$
  2. For $1 < \alpha < 2$, $\text{PoS} \leq 4/3$
- Proof:
  - Part 1 is immediate from the lemma and poll
  - For $1 < \alpha < 2$, the star is an NE, while OPT is a complete graph
  - Worst case ratio when $\alpha \to 1$:

$$\frac{2n(n-1) - (n-1)}{n(n-1) + n(n-1)/2} = \frac{4n^2 - 6n + 2}{3n^2 - 3n} < \frac{4}{3} \quad \blacksquare$$

Example: Network creation

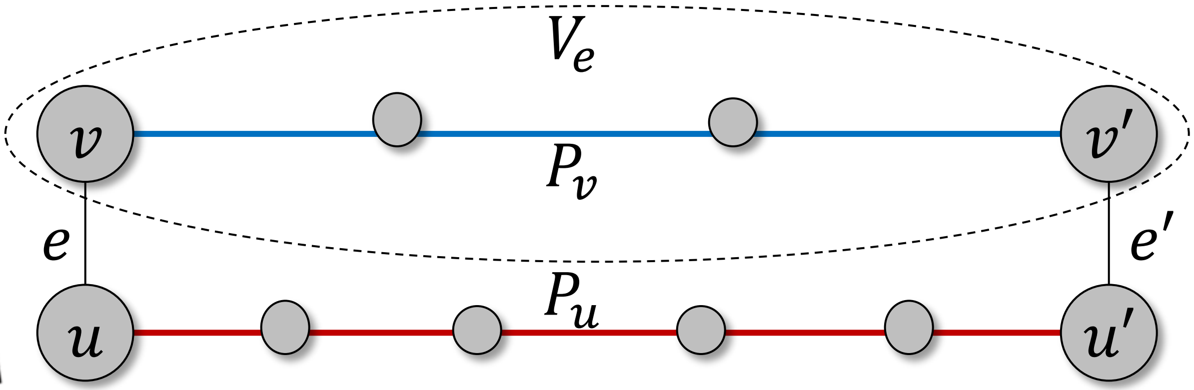
- Theorem [Fabrikant et al. 2003]: The price of anarcy of network creation games is $O(\sqrt{\alpha})$
- Lemma: If $\boldsymbol{s}$ is a Nash equilibrium that induces a graph of diameter d, then $\text{cost}(\boldsymbol{s}) \leq O(d) \cdot \text{OPT}$

Proof of lemma

- $\text{OPT} = \Omega(\alpha n + n^2)$
  - Buying a connected graph costs at least $(n-1)\alpha$
  - There are $\Omega(n^2)$ distances
- Distance costs $\leq dn^2 \Rightarrow$ focus on edge costs
- There are at most $n-1$ cut edges $\Rightarrow$ focus on noncut edges

Proof of lemma

- Claim: Let $e = (u, v)$ be a noncut edge, then the distance $d(u, v)$ with e deleted $\leq 2d$
  - $V_e =$ set of nodes s.t. the shortest path from u uses e
  - Figure shows shortest path avoiding e, $e' = (u', v')$ is the edge on the path entering V_e
  - P_u is the shortest path from u to $u' \Rightarrow |P_u| \leq d$
  - $|P_v| \leq d - 1$ as $P_v \cup e$ is shortest path from u to v' ■



Proof of lemma

- Claim: There are $O(nd/\alpha)$ noncut edges paid for by any vertex v
  - Let $e = (u, v)$ be an edge paid for by v
  - By previous claim, deleting e increases distances from v by at most $2d|V_e|$
  - G is an equilibrium $\Rightarrow \alpha \leq 2d|V_e| \Rightarrow |V_e| \geq \alpha/2d$
  - n vertices overall $\Rightarrow$ can't be more than $2nd/\alpha$ sets V_e ■

Proof of lemma

- $O(nd/\alpha)$ noncut edges per vertex
- $O(nd)$ total payment for these per vertex
- $O(n^2 d)$ overall $\blacksquare$

Proof of theorem

- By lemma, it is enough to show that the diameter at a NE $\leq 2\sqrt{\alpha}$
- Suppose $d(u,v) \geq 2k$ for some k
- By adding the edge (u,v), u pays α and improves distance to second half of the $u \rightarrow v$ shortest path by

$$(2k-1)+(2k-3)+\cdots+1=k^2$$

- If $d(u,v) > 2\sqrt{\alpha}$, it is beneficial to add edge ■