



CMU 15-896

**SOCIAL CHOICE 4:
RANKING/SELECTION SYSTEMS**

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AXIOMATIC APPROACH

- Social choice theory often uses axioms to guide the design of voting rules
- Representation theorem: a set of axioms that uniquely characterize a popular rule
- This approach has been applied to ranking systems, collaborative filtering, recommendation systems, etc.
- Coming up: representation theorem for PageRank



THE PAGE RANKING PROBLEM

- The internet is represented by a directed graph $G = (V, E)$
- Vertices V are webpages
- $(u, v) \in E$ represents a hyperlink from u to v
- Given G , a **ranking system** produces a ranking over V that represents the “power” or “relevance” of webpages
- From a social choice point of view, the sets of voters and alternatives coincide



PAGERANK

- Rank the vertices based on the stationary probability of a random walk on the graph
- Assume that the graph is strongly connected
- Define the matrix A_G

$$[A_G]_{ij} = \begin{cases} \frac{1}{|S(v_j)|} & (v_j, v_i) \in E \\ 0 & \text{Otherwise} \end{cases}$$

PAGERANK

- The PageRank of G is \mathbf{r} such that

$$A_G \mathbf{r} = \mathbf{r}$$

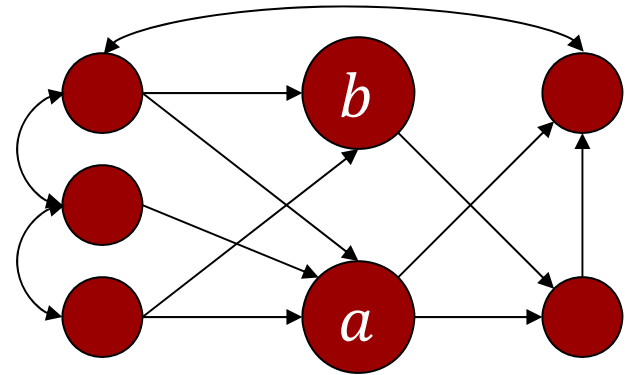
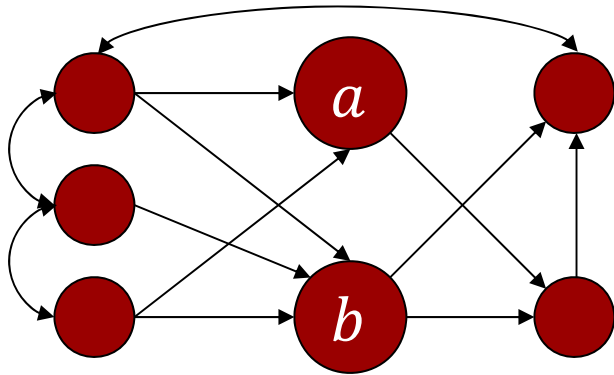
- The PageRank ranking system ranks V according to \mathbf{r} :

$$v_i \succcurlyeq_{PR} v_j \iff r_i \geq r_j$$



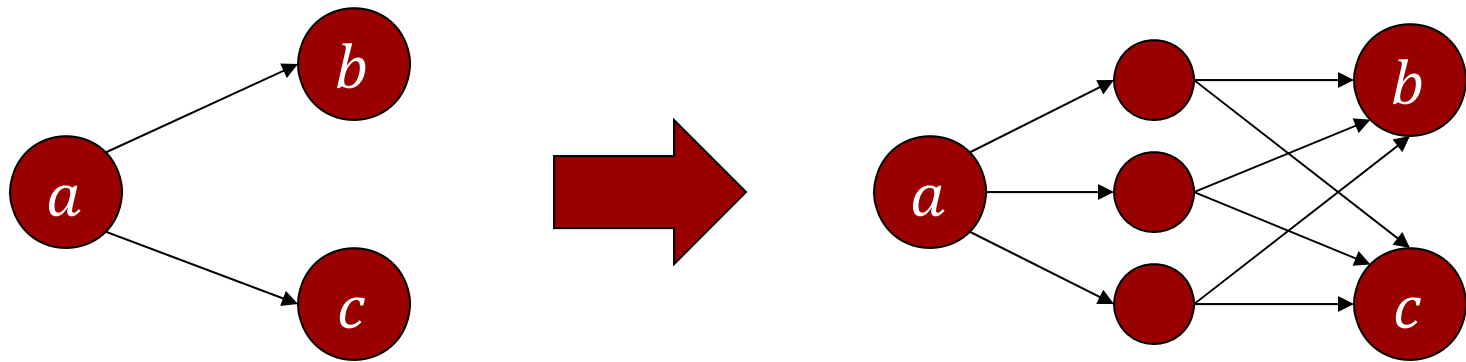
AXIOM 1: ISOMORPHISM

- The ranking must not rely on the names of the vertices, only on the voting structure
- Clearly satisfied by PageRank



AXIOM 2: VOTE BY COMMITTEE

- A node may vote indirectly through intermediate nodes, each of which has the original votes



VOTE BY COMMITTEE FORMALIZED

- Ranking system f satisfies **vote by committee** if for every $G = (V, E)$, for every $v \in V$, and for every $k \in \mathbb{N}$, if $G' = (V', E')$ where

$$V' = V \cup \{u_1, \dots, u_k\}$$

and

$$E' = E \setminus \{(v, x) \mid x \in S_G(v)\} \cup \{(v, u_i) \mid i = 1, \dots, k\} \\ \cup \{(u_i, x) \mid x \in S_G(v), i = 1, \dots, k\},$$

then for all $v', v'' \in V$, $v' \succcurlyeq_G^f v'' \Leftrightarrow v' \succcurlyeq_{G'}^f v''$

- **Lemma:** PageRank satisfies vote by committee



PROOF

- Let \mathbf{r} be a solution to $A_G \mathbf{r} = \mathbf{r}$
- $\mathbf{r}' = \left(r_1, \dots, r_n, \frac{r_1}{k}, \dots, \frac{r_1}{k} \right)^T$; claim that $A_{G'} \mathbf{r}' = \mathbf{r}'$

- $A_{G'} = \begin{pmatrix} 0 & a_{12} & \dots & a_{1n} & a_{11} & \dots & a_{11} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & a_{n2} & \dots & a_{nn} & a_{n1} & \dots & a_{n1} \\ \frac{1}{k} & & & & & & \\ \vdots & & & & & & \\ \frac{1}{k} & & & & & & \end{pmatrix}$

- For $i = 1, \dots, n$: $[A_{G'} \mathbf{r}']_i = \sum_{j=2}^n a_{ij} r_j + k a_{i1} \cdot \frac{r_1}{k} = r_i = r'_i$
- For $i = n + 1, \dots, n + k$: $[A_{G'} \mathbf{r}']_i = \frac{1}{k} r_1 = r'_i$ ■



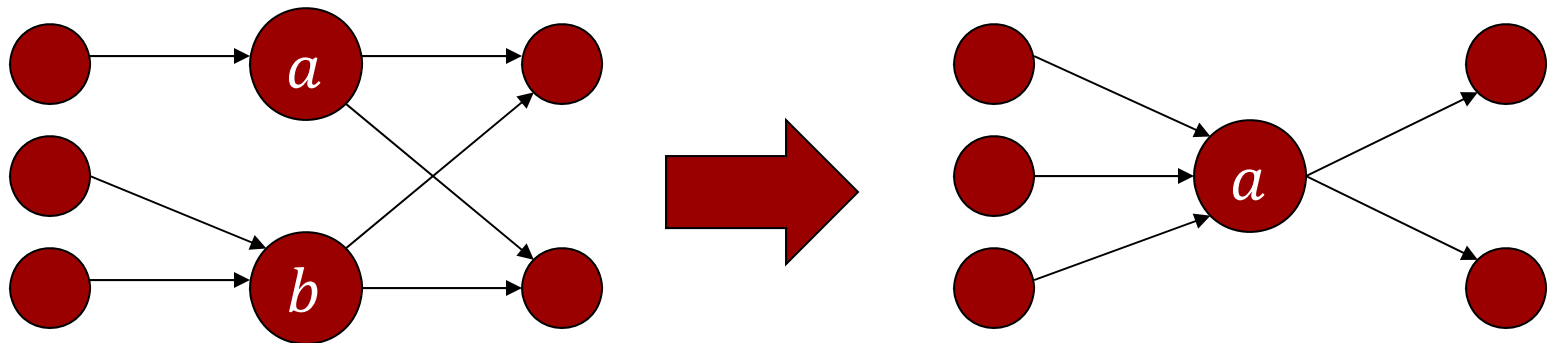
AXIOM 3: SELF EDGE

- Adding a self edge to v strengthens v but does not change the ranking of other vertices



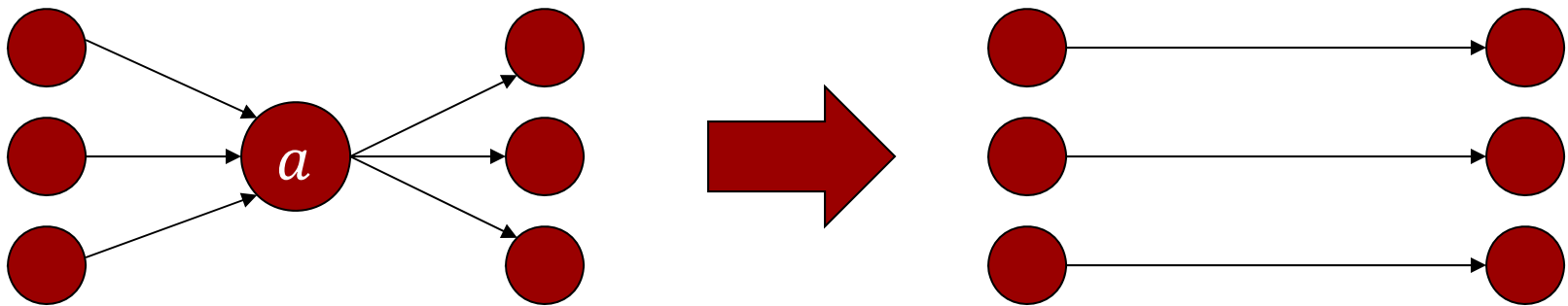
AXIOM 4: COLLAPSING

- Vertices that vote identically can be merged into a single vertex, with all the incoming edges of the original vertices
- The ranking of vertices that were not collapsed remains unchanged



AXIOM 5: PROXY

- k vertices of equal rank that voted for k alternatives via proxy can achieve the same result by voting for one alternative each



REPRESENTATION THEOREM

- Theorem [Altman and Tennenholtz 2005]:
a ranking system satisfies axioms 1-5 if and only if it is the PageRank ranking system
- To show “only if”: prove that the five axioms imply a unique ranking on each graph!

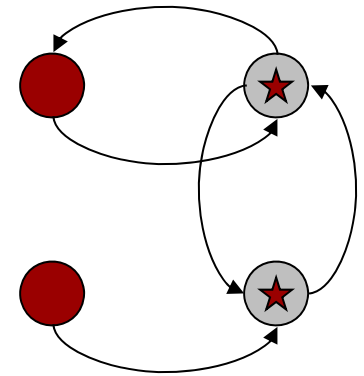


SELECTING A SUBSET

- A *k*-selection system receives a directed graph as input and outputs $V' \subseteq V$ such that $|V'| = k$
- Edges are interpreted as approval votes, trust, or support
- Think of graph as directed social network
- A *k*-selection system f is *impartial* if $i \in f(G)$ does not depend on the votes of i

IMPARTIAL APPROXIMATIONS

- Optimization target: sum of indegrees of selected agents
- Optimal solution: not impartial
- Our goal is to design impartial k -selection systems that give a worst-case multiplicative approximation to the sum of indegrees



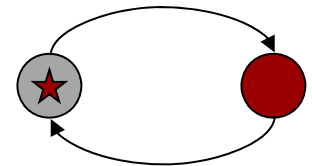
IMPARTIAL APPROXIMATIONS

Poll 1: $k = 1$, select the lowest index that v_1 is voting for, if no votes select v_2 . This is:

1. Impartial + constant approx
2. Impartial + bad approx
3. Not impartial + constant approx
4. Not impartial + bad approx

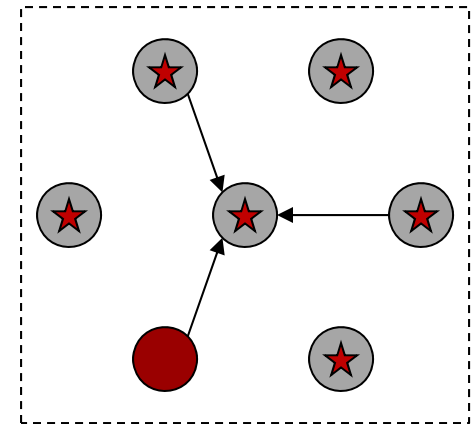
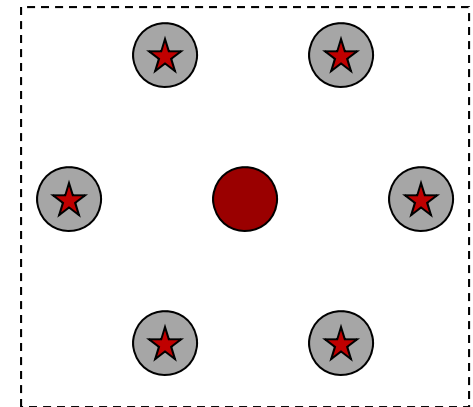


- $k = n$: no problem
- $k = 1$: no finite impartial approx
- $k = n - 1$: no finite impartial approx!



AN IMPOSSIBILITY RESULT

- **Theorem [Alon et al. 2011]:** For all $k \in \{1, \dots, n - 1\}$ there is no impartial k -selection system w. finite approx ratio
- **Proof ($k = n - 1$):**
 - Assume for contradiction that there is
 - Wlog n eliminated given empty graph
 - Consider stars with n as center, n cannot be eliminated due to finite approx
 - Function $f: \{0,1\}^{n-1} \setminus \{\vec{0}\} \rightarrow \{1, \dots, n - 1\}$ satisfies $f(\vec{x}) = i \Leftrightarrow f(\vec{x} + e_i) = i$
 - $|f^{-1}(i)|$ even for all $i = 1, \dots, n - 1 \Rightarrow |\text{dom}(f)|$ is even; but $|\text{dom}(f)| = 2^{n-1} - 1$ ■



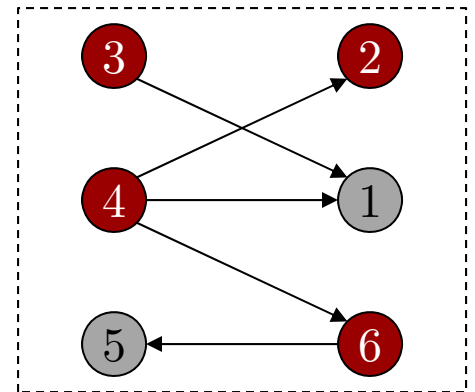
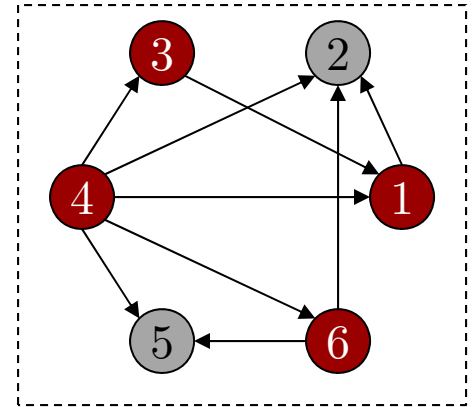
A MATHEMATICIAN'S SURVIVOR

- Each tribe member votes for at most one member
- One member must be eliminated
- Impartial rule cannot have property: if unique member received votes he is not eliminated



RANDOMIZED SYSTEMS

- The randomized m -partition system:
 - Assign vertices uniformly i.i.d. to m subsets
 - For each subset, select $\sim \frac{k}{m}$ agents with highest indegrees based on edges from other subsets
- The m -partition system is a distribution over impartial systems



APPROXIMATION

- Theorem [Alon et al. 2011]:
 1. The approx ratio is 4 with $m = 2$
 2. The approx ratio is $1 + O\left(\frac{1}{k^3}\right)$ for $m \sim k^{\frac{1}{3}}$
- Proof (only part 1):
 - Assume for ease of exposition: k is even
 - Let K be the optimal set
 - A partition $\pi = (\pi_1, \pi_2)$ divides K into two subsets $K_1^\pi = K \cap \pi_1$ and $K_2^\pi = K \cap \pi_2$
 - $d_1^\pi = \{(u, v) \in E \mid u \in \pi_2, v \in K_1^\pi\}$, d_2^π defined analogously
 - We select a set with total indegree $\geq \frac{d_1^\pi + d_2^\pi}{2}$
 - $\mathbb{E}[d_1^\pi + d_2^\pi] = \frac{OPT}{2}$ ■

