



Randomized algorithms 4

Distributed computing

CS240

Spring 2020

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Distributed computing

- Distributed system
 - Set of autonomous nodes, working independently of each other.
 - Nodes may be able to communicate, at a cost.
 - Ex Internet, computer cluster, sensor network.
- Nodes need to coordinate to solve some problem.
- Coordination can be done using communication. But communication is expensive.
- By making nodes randomized, they can coordinate with minimal communication.
- Randomization also simplifies symmetry breaking between nodes.
- Today we'll look at randomized contention resolution and maximal independent set.



Contention resolution

- Set of n nodes (e.g. cellphones) want to send each other messages.
- Only one node can send at a time.
 - If two nodes send at same time, their signals interfere and both transmissions fail.
- Nodes can't communicate.
 - Communicating requires sending messages, which is the problem we're trying to solve!
 - Nodes can't coordinate to work out a schedule. They have to randomize.



Contention resolution

- Assume system is synchronous.
 - Nodes work in rounds.
 - Each node can try to send once per round. It succeeds if and only if it's the only node to try to send in that round.
- ❖ **Algorithm** Each node tries to send with probability $1/n$ in every round.



Analysis

- How many rounds before all the nodes can send?
- Let $S_{i,t}$ be the event that node i successfully sends in t 'th round.
 - $S_{i,t}$ occurs iff i tries to send in t 'th round and all other nodes do not.
- $\Pr[S_{i,t}] = 1/n \cdot (1 - 1/n)^{n-1}$.
 - i tries to send with prob. $1/n$, and each of i 's $n-1$ neighbors don't send with prob. $1 - 1/n$.
- **Fact** For all $n \geq 2$, $1/e \leq (1 - 1/n)^{n-1} \leq 1/2$, and $1/4 \leq (1 - 1/n)^n \leq 1/e$.
- So $\Pr[S_{i,t}] \geq 1/en$.
- $\Pr[i \text{ fails to send in } t\text{'th round}] = 1 - \Pr[S_{i,t}] \leq 1 - 1/en$.

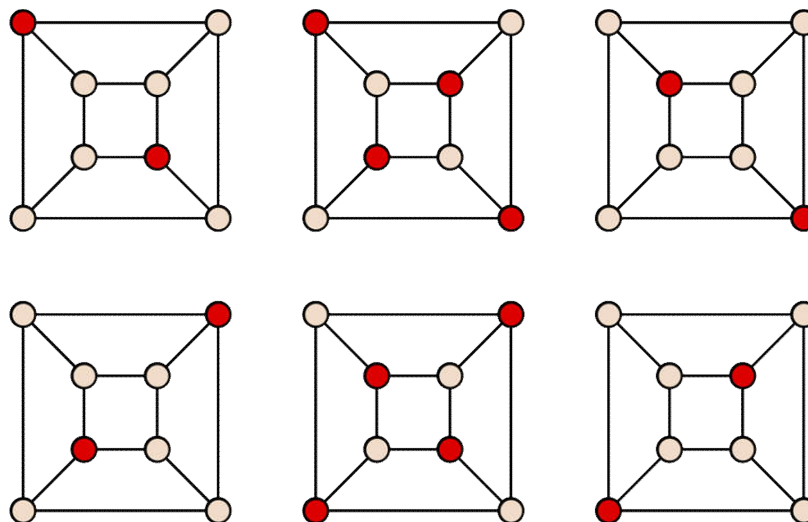


Analysis

- **Thm** After $2e \cdot n \ln(n)$ rounds, all nodes succeed sending with probability $\geq 1 - 1/n$.
- **Proof** Let F_i denote event that node i fails to send after $2e \cdot n \ln(n)$ rounds, and let F denote event that any node fails to send after $2e \cdot n \ln(n)$ rounds.
 - $\Pr[F_i] \leq (1 - 1/en)^{2e \cdot n \ln(n)} \leq (1/e)^{2 \ln(n)} \leq 1/n^2$.
 - In each round i fails independently with prob. $\leq (1 - 1/en)$.
 - $\Pr[F] \leq \sum_i \Pr[F_i] \leq n \cdot 1/n^2 = 1/n$, by the union bound.
 - So all nodes succeed with prob. $\geq 1 - 1/n$.

Maximal independent set

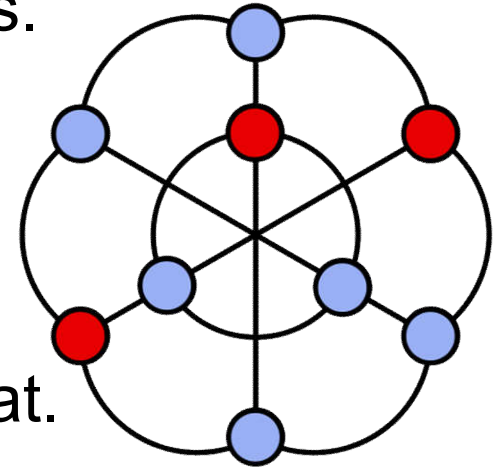
- Given a graph, an independent set is a set of vertices, none of which are connected to each other.
- A maximal independent set (MIS) is an independent set such that if we add any other vertex, it would be connected to some vertex in the independent set.
 - I.e. An MIS can't be made any larger.
- A maximum independent set (MaxIS) is an independent set of maximum cardinality in the graph.
- Note that an MIS might not be a MaxIS. An MIS is a “local” max, while a MaxIS is the “global” max.



All 6 MIS's of the cube graph. Note only the two center MIS's are MaxIS.

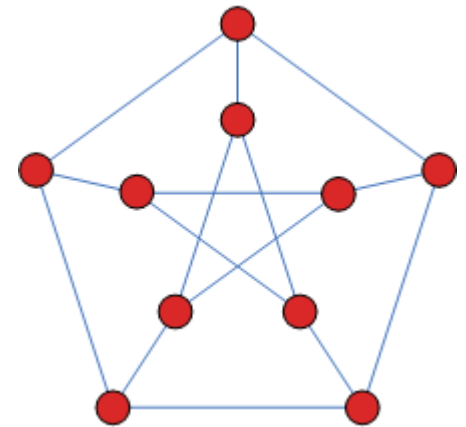
Distributed MIS

- Compute an MIS on a network of n nodes.
 - The MIS nodes can be “leaders”, used to coordinate the other nodes in some distributed computation.
- A simple algorithm is to continually add a node to the MIS, then remove its neighboring nodes and edges, then repeat.
- This algorithm takes $O(n)$ time.
- It's also sequential. We have to remove all the neighbors of a selected node before we select the next node.
 - Otherwise we can add two neighboring nodes both to the MIS.
- We want a fast, distributed MIS algorithm.



Distributed MIS

- Again consider synchronous model where all nodes work in rounds.
- Each node can broadcast a message to its neighbors in each round.
- ❖ Each node v chooses a random number $r(v) \in [0, 1]$ and sends it to its neighbors.
- ❖ If $r(v) < r(w)$ for all neighbors w of v , then v adds itself to the MIS and informs its neighbors.
- ❖ If v or one of its neighbors entered the MIS, v terminates. Remove all of v 's edges.
- ❖ Otherwise go back to first step, until graph is empty.
- Call these three steps a phase.
- Assume no ties, i.e. for any u, v , either $r(u) < r(v)$ or vice versa.



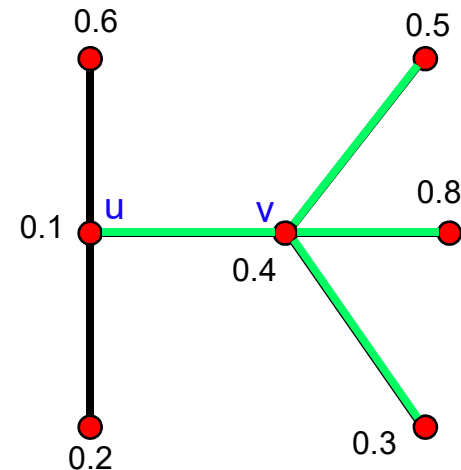


Analysis

- We show this algorithm outputs an MIS, and terminates quickly.
- The output is an independent set.
 - For every two neighbors, only the one with smaller r value can join MIS.
 - When a node joins the MIS, all its neighbors are removed and can't join the MIS.
- It's a maximal IS because we only ever take away a node if its neighbor is in the MIS.

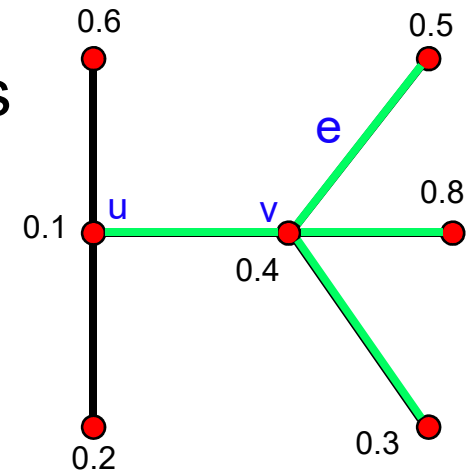
Analysis

- How many rounds does it take to terminate?
- **Lemma** In each phase, at least half the edges are removed in expectation.
 - We'll prove this after proving Claims 1-4.
- **Def** Let u, v be two nodes. Say u preemptively removes v if $u \in N(v)$, and $r(u) < r(u')$ for all $u' \in N(u) \cup N(v)$.
 - Denote as $u \ll v$.
 - Given an edge $e = (v, w)$, we say e is preemptively removed by u if $u \ll v$.
- **Claim 1** For any v , there's at most one u s.t. $u \ll v$.
 - **Proof** If $u \ll v$, then u is the neighbor of v with min r value.



Analysis

- Let $P = \{\text{all preemptively removed edges in phase}\}$, $R = \{\text{all edges removed in phase}\}$.
- **Claim 2** $P \subseteq R$
 - Let $e=(v,w) \in P$. Then v has nbr u s.t. $r(u) < r(u')$ for all $u' \in N(u) \cup N(v)$.
 - So u will get removed.
 - So v is also removed. All edges incident to v , including e , are also removed. So $e \in R$.
- Let $X_{u < v} = 1$ if $u < v$ and 0 otherwise.
- If $X_{u < v} = 1$, all edges incident to v are removed.
 - So if $X_{u < v} = 1$, $d(v)$ edges get removed, where $d(v)$ is degree v .



Analysis

- **Claim 3** $\sum_u \sum_{v \in N(u)} X_{u \ll v} * d(v) \leq 2 * |P|.$
 - Given any edge $e=(v,w)$, the sum counts e once each time e is preemptively removed by some other node u .
 - How many such u 's are there?
 - u preemptively removes e only if $u \ll v$ or $u \ll w$.
 - By claim 1, there's only at most one u that $\ll v$, and at most one that $\ll w$.
 - So e is preemptively removed by at most 2 other nodes.
 - So any e in the sum is a preemptively removed edge that's counted at most twice.
 - Since P is set of all preemptively removed edges, then the sum $\leq 2 * |P|$.
- **Cor 1** $\sum_u \sum_{v \in N(u)} X_{u \ll v} * d(v) \leq 2 * |R|.$
 - Because $P \subseteq R$ by Claim 2.

Analysis

- **Claim 4** $E[\sum_u \sum_{v \in N(u)} X_{u < v} * d(v)] \geq |H|$, where $H = \{\text{edges}\}$.
 - For any u and $v \in N(u)$, $E[X_{u < v} * d(v)] = \Pr[u < v] * d(v)$.
 - $u < v$ only if $r(u) < r(u')$ for all $u' \in N(u) \cup N(v)$.
 - There are at most $d(u) + d(v)$ nodes in $N(u) \cup N(v)$.
 - Each node picks a random value r . Probability it's min among $\leq d(u) + d(v)$ random values is $\geq 1/(d(u) + d(v))$.
 - So $\Pr[u < v] \geq 1/(d(u) + d(v))$.
 - So $E[X_{u < v} * d(v)] \geq d(v)/(d(u) + d(v))$.
 - $E[\sum_u \sum_{v \in N(u)} X_{u < v} * d(v)] =$
 $\sum_{e=(u,v) \in H} (E[X_{u < v} * d(v)] + E[X_{v < u} * d(u)]) \geq$
 $\sum_{e=(u,v) \in H} d(v)/(d(u) + d(v)) + d(u)/(d(u) + d(v)) =$
 $\sum_{e=(u,v) \in H} 1 = |H|$.



Analysis

■ Proof of Lemma

- By Claim 4 and Cor. 1, $|H| \leq 2 \cdot E[|P|] \leq 2 \cdot E[|R|]$.
- So $E[|R|] \geq |H|/2$, i.e. half the edges get removed in expectation every phase.

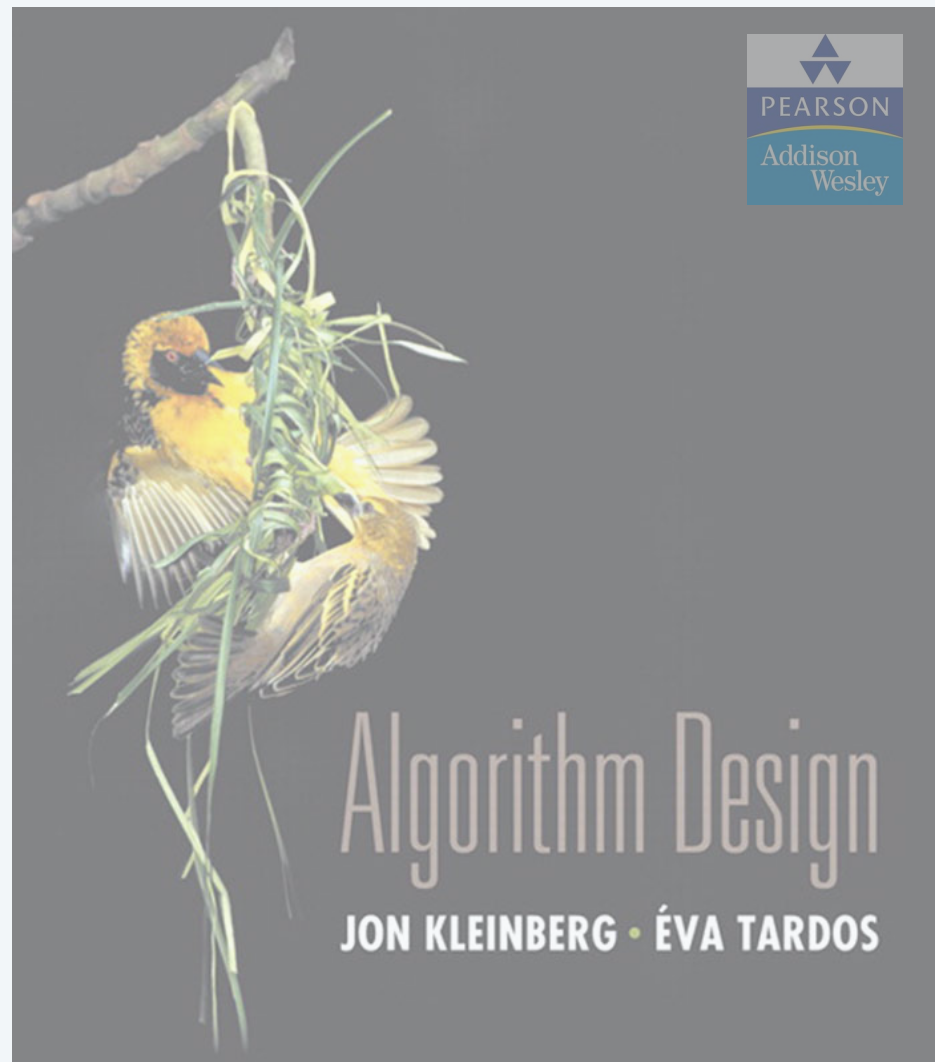
■ Cor 2 With probability $\geq 1/3$, at least $1/4$ the edges get removed in every phase.

- Otherwise, the probability less than $1/4$ edges get removed every phase is greater than $2/3$.
- So expected number of edges removed in the phase is $< 2/3 \cdot |E|/4 + 1/3 \cdot |E| = |E|/2$, contradicting the lemma.

■ Thm The algorithm computes an MIS in $42 \cdot \ln(n)$ phases with probability $\geq 1 - 1/n$.

Analysis

- **Proof** Say a phase is good if $\geq 1/4$ the edges get removed.
 - So $\Pr[\text{phase is good}] \geq 1/3$ by Cor 2. Also, these probabilities are independent.
 - In $42 \cdot \ln(n)$ phases, we expect $\geq \mu = 14 \cdot \ln(n)$ good phases.
 - $\Pr[< 7 \cdot \ln(n) \text{ good phases in } 42 \cdot \ln(n) \text{ rounds}] = \Pr[\text{number good rounds} < \frac{1}{2} \text{ expectation}] \leq e^{-14 \cdot \ln(n)/8} < 1/n$, by Chernoff bounds.
 - If we get $7 \cdot \ln(n)$ good phases, then fraction of remaining edges is $\leq (3/4)^{7 \cdot \ln(n)} = n^{7 \cdot \ln(3/4)} \approx n^{-2.01}$.
 - Since there are $O(n^2)$ edges, all the edges get removed after $7 \cdot \ln(n)$ good phases.
 - We get $7 \cdot \ln(n)$ good phases in $42 \cdot \ln(n)$ phases with probability $> 1 - 1/n$.



13. RANDOMIZED ALGORITHMS

- ▶ *contention resolution*
- ▶ ***global min cut***
- ▶ *linearity of expectation*
- ▶ *max 3-satisfiability*
- ▶ *universal hashing*
- ▶ *Chernoff bounds*
- ▶ *load balancing*

Global minimum cut

Global min cut. Given a connected, undirected graph $G = (V, E)$, find a cut (A, B) of minimum cardinality.

Applications. Partitioning items in a database, identify clusters of related documents, network reliability, network design, circuit design, TSP solvers.

Network flow solution.

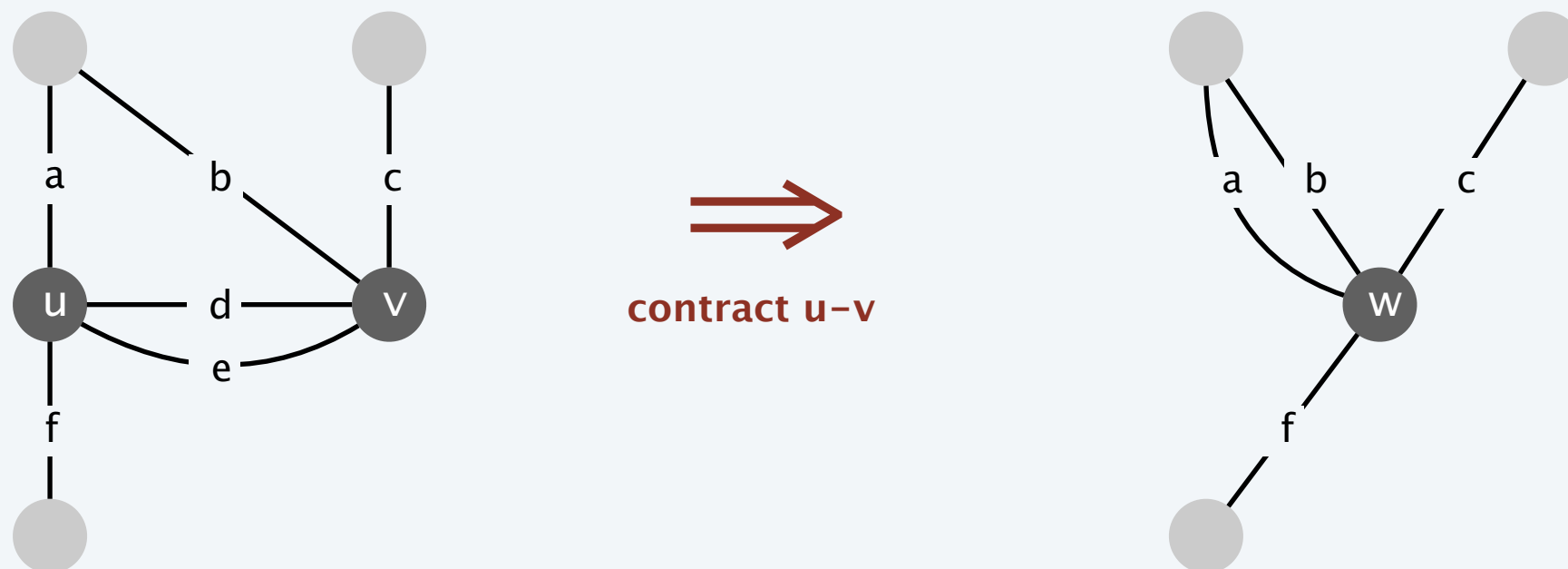
- Replace every edge (u, v) with two antiparallel edges (u, v) and (v, u) .
- Pick some vertex s and compute min $s-v$ cut separating s from each other node $v \in V$.

False intuition. Global min-cut is harder than min $s-t$ cut.

Contraction algorithm

Contraction algorithm. [Karger 1995]

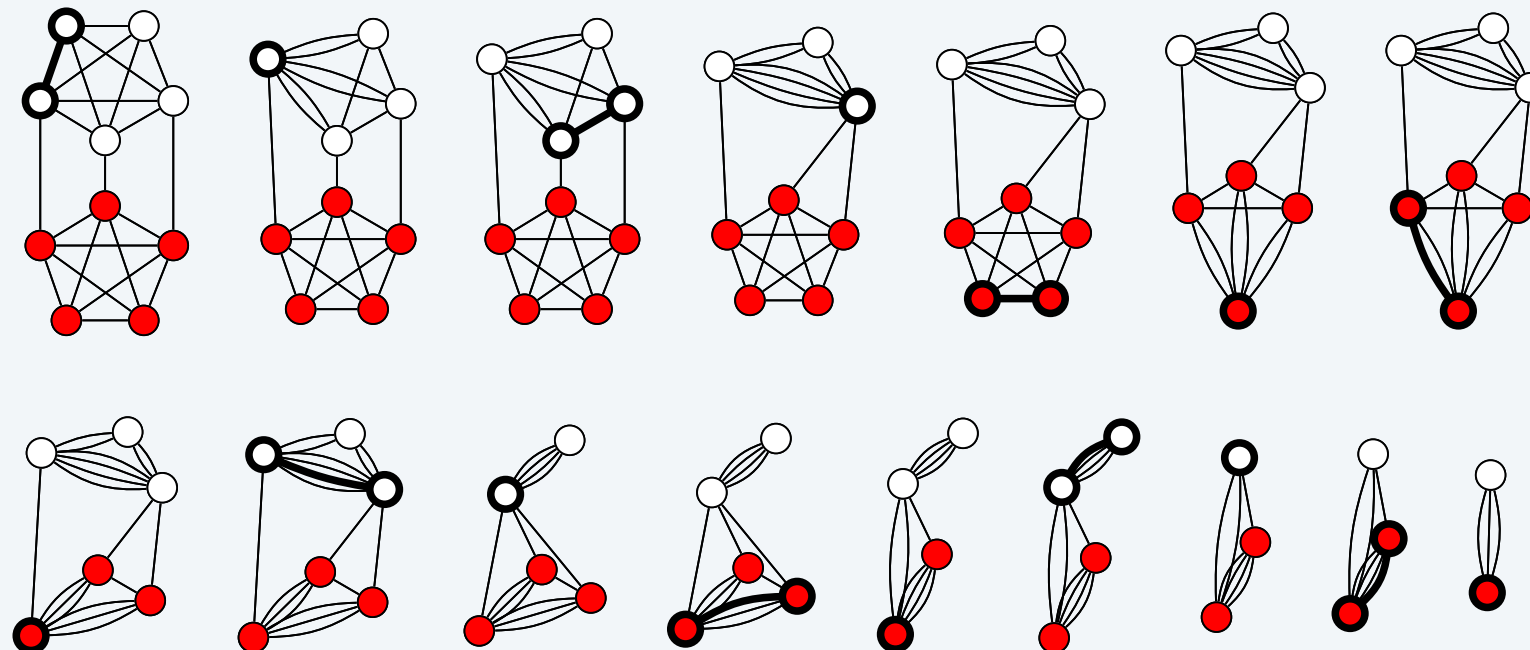
- Pick an edge $e = (u, v)$ uniformly at random.
- **Contract** edge e .
 - replace u and v by single new super-node w
 - preserve edges, updating endpoints of u and v to w
 - keep parallel edges, but delete self-loops
- Repeat until graph has just two nodes u_1 and v_1 .
- Return the cut (all nodes that were contracted to form v_1).



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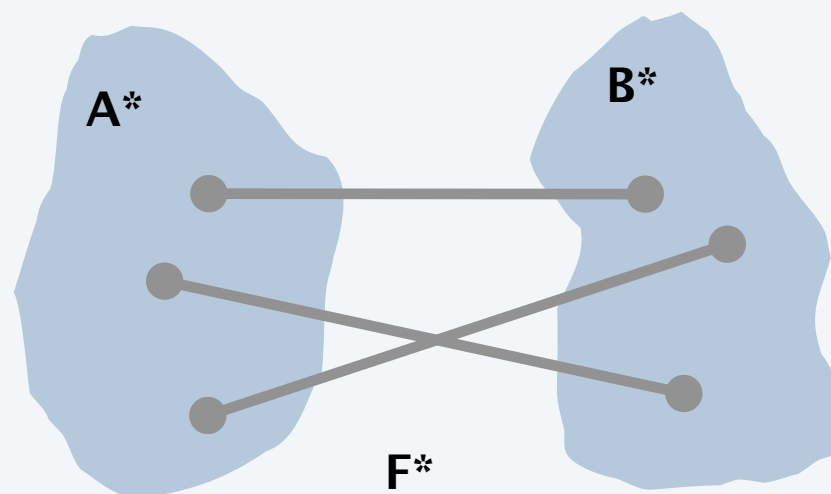
Reference: Thore Husfeldt

Contraction algorithm

Claim. The contraction algorithm returns a min cut with prob $\geq 2 / n^2$.

Pf. Consider a global min-cut (A^*, B^*) of G .

- Let F^* be edges with one endpoint in A^* and the other in B^* .
- Let $k = |F^*|$ = size of min cut.
- In **first step**, algorithm contracts an edge in F^* probability $k / |E|$.
- Every node has degree $\geq k$ since otherwise (A^*, B^*) would not be a min-cut $\Rightarrow |E| \geq \frac{1}{2} k n \Leftrightarrow k / |E| \leq 2 / n$.
- Thus, algorithm contracts an edge in F^* with probability $\leq 2 / n$.



Contraction algorithm

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Pf. Consider a global min-cut (A^*, B^*) of G .

- Let F^* be edges with one endpoint in A^* and the other in B^* .
- Let $k = |F^*|$ = size of min cut.
- Let G' be graph after j iterations. There are $n' = n - j$ supernodes.
- Suppose no edge in F^* has been contracted. The min-cut in G' is still k .
- Since value of min-cut is k , $|E'| \geq \frac{1}{2} k n' \Leftrightarrow k / |E'| \leq 2 / n'$.
- Thus, algorithm contracts an edge in F^* with probability $\leq 2 / n'$.
- Let E_j = event that an edge in F^* is not contracted in iteration j .

$$\begin{aligned} \Pr[E_1 \cap E_2 \cdots \cap E_{n-2}] &= \Pr[E_1] \times \Pr[E_2 \mid E_1] \times \cdots \times \Pr[E_{n-2} \mid E_1 \cap E_2 \cdots \cap E_{n-3}] \\ &\geq \left(1 - \frac{2}{n}\right) \left(1 - \frac{2}{n-1}\right) \cdots \left(1 - \frac{2}{4}\right) \left(1 - \frac{2}{3}\right) \\ &= \left(\frac{n-2}{n}\right) \left(\frac{n-3}{n-1}\right) \cdots \left(\frac{2}{4}\right) \left(\frac{1}{3}\right) \\ &= \frac{2}{n(n-1)} \\ &\geq \frac{2}{n^2} \end{aligned}$$

Contraction algorithm

Amplification. To amplify the probability of success, run the contraction algorithm many times.

Claim. If we repeat the contraction algorithm $n^2 \ln n$ times, then the probability of failing to find the global min-cut is $\leq 1 / n^2$.

with independent random choices,



Pf. By independence, the probability of failure is at most

$$\left(1 - \frac{2}{n^2}\right)^{n^2 \ln n} = \left[\left(1 - \frac{2}{n^2}\right)^{\frac{1}{2}n^2}\right]^{2 \ln n} \leq \left(e^{-1}\right)^{2 \ln n} = \frac{1}{n^2}$$

$(1 - 1/x)^x \leq 1/e$

Contraction algorithm: example execution



...

Reference: Thore Husfeldt

Global min cut: context

Remark. Overall running time is slow since we perform $\Theta(n^2 \log n)$ iterations and each takes $\Omega(m)$ time.

Improvement. [Karger–Stein 1996] $O(n^2 \log^3 n)$.

- Early iterations are less risky than later ones: probability of contracting an edge in min cut hits 50% when $n / \sqrt{2}$ nodes remain.
- Run contraction algorithm until $n / \sqrt{2}$ nodes remain.
- Run contraction algorithm **twice** on resulting graph and return **best** of two cuts.

Extensions. Naturally generalizes to handle positive weights.

Best known. [Karger 2000] $O(m \log^3 n)$.



faster than best known max flow algorithm or
deterministic global min cut algorithm