Reliability in Distributed Computing and HPC: United We Stand?

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Outline

- 3 problems
  - Byzantine Agreement
  - Networks of Noisy Gates
  - Secure Multiparty Computation
- Problem of Mutual Interest?

HPC vs DC

- HPC: Adding nodes makes the problem easier
- DC: Adding nodes makes the problem harder

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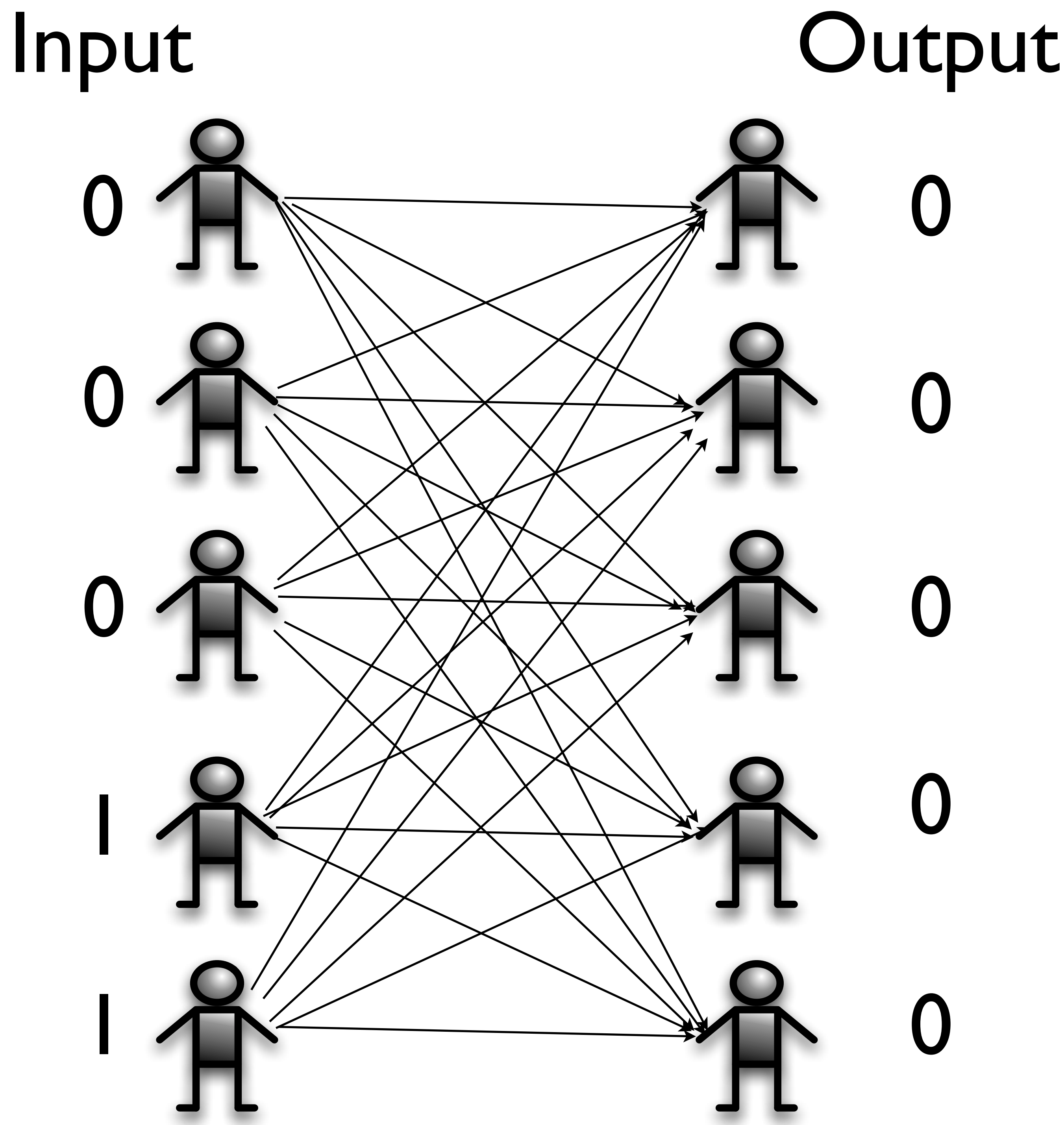
Example: Byzantine Agreement

Byzantine Agreement

- Many nodes, some are **faulty**
- Periodically, nodes unite in a decision
- How? Who counts the votes?

Naive: Majority Filtering



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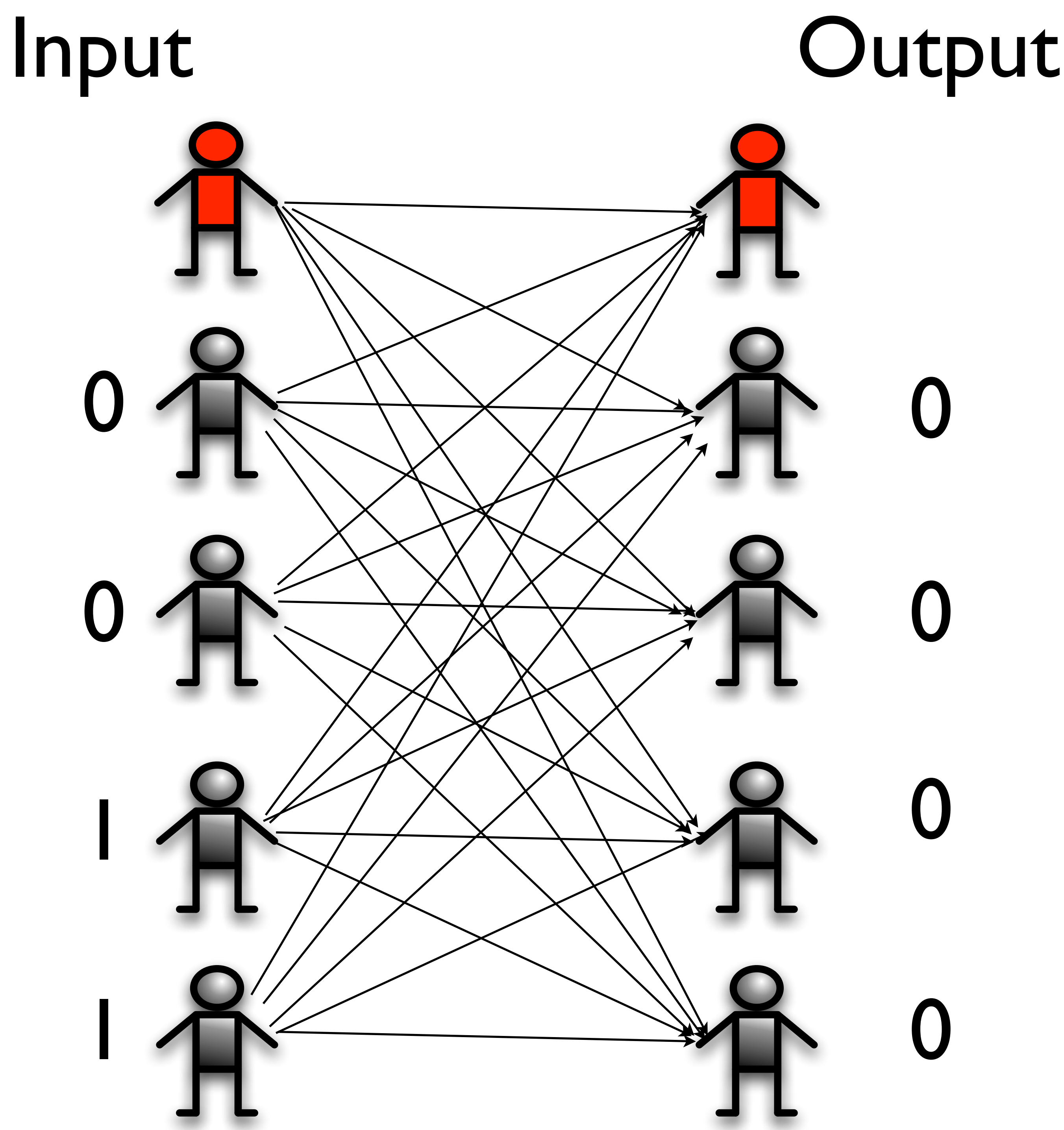
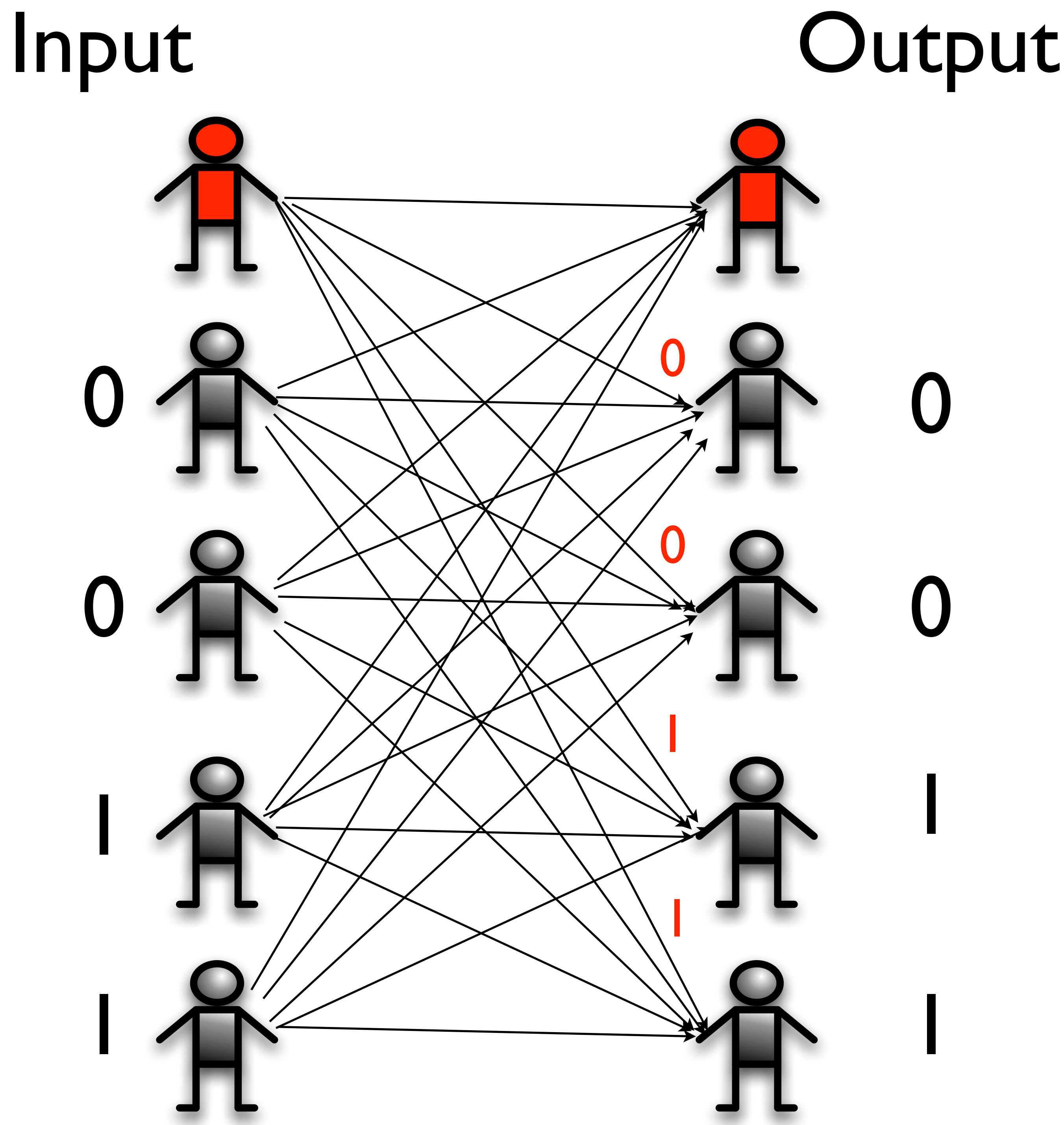


Problem



Byzantine Agreement

- Each proc starts with a bit
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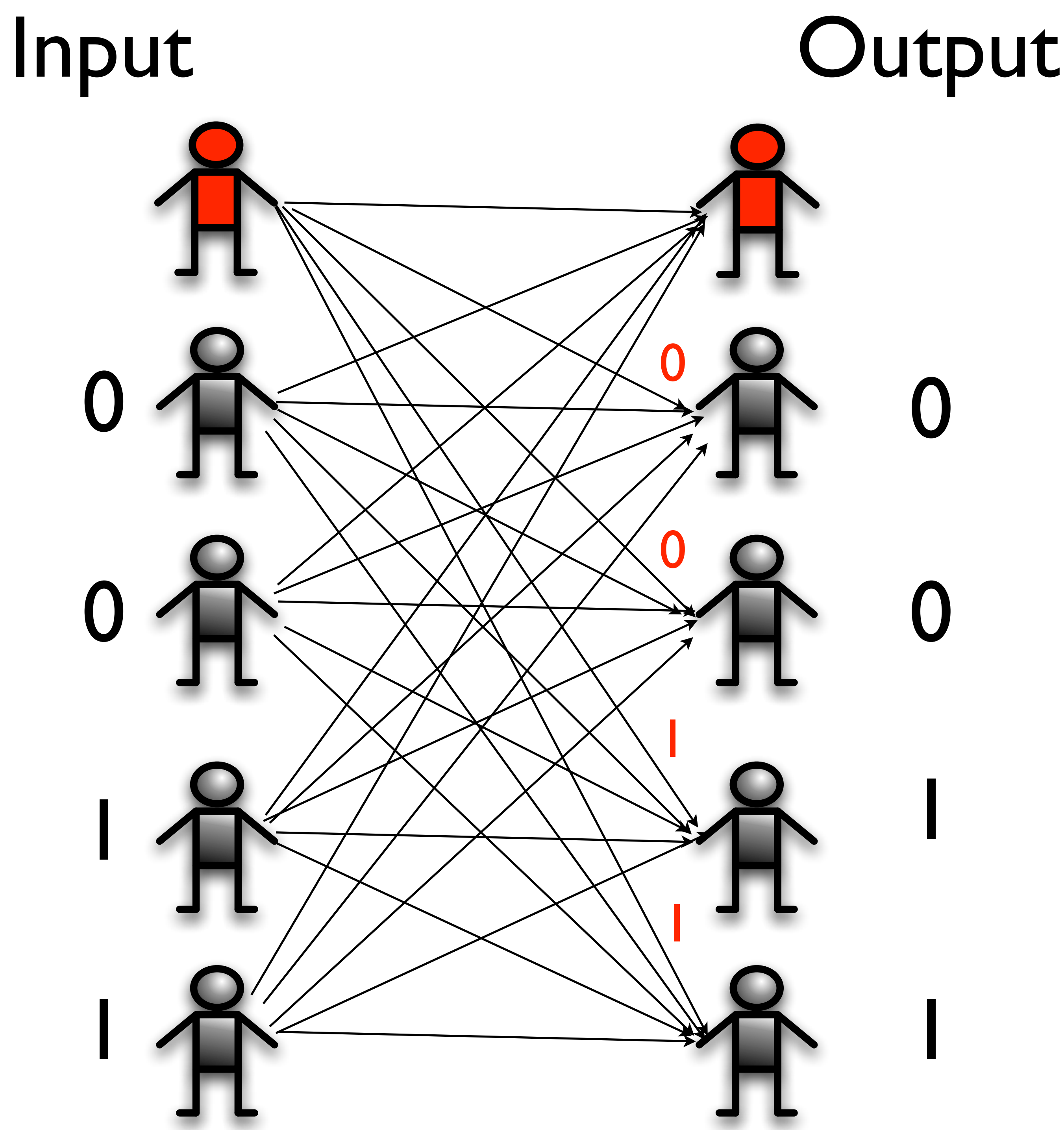
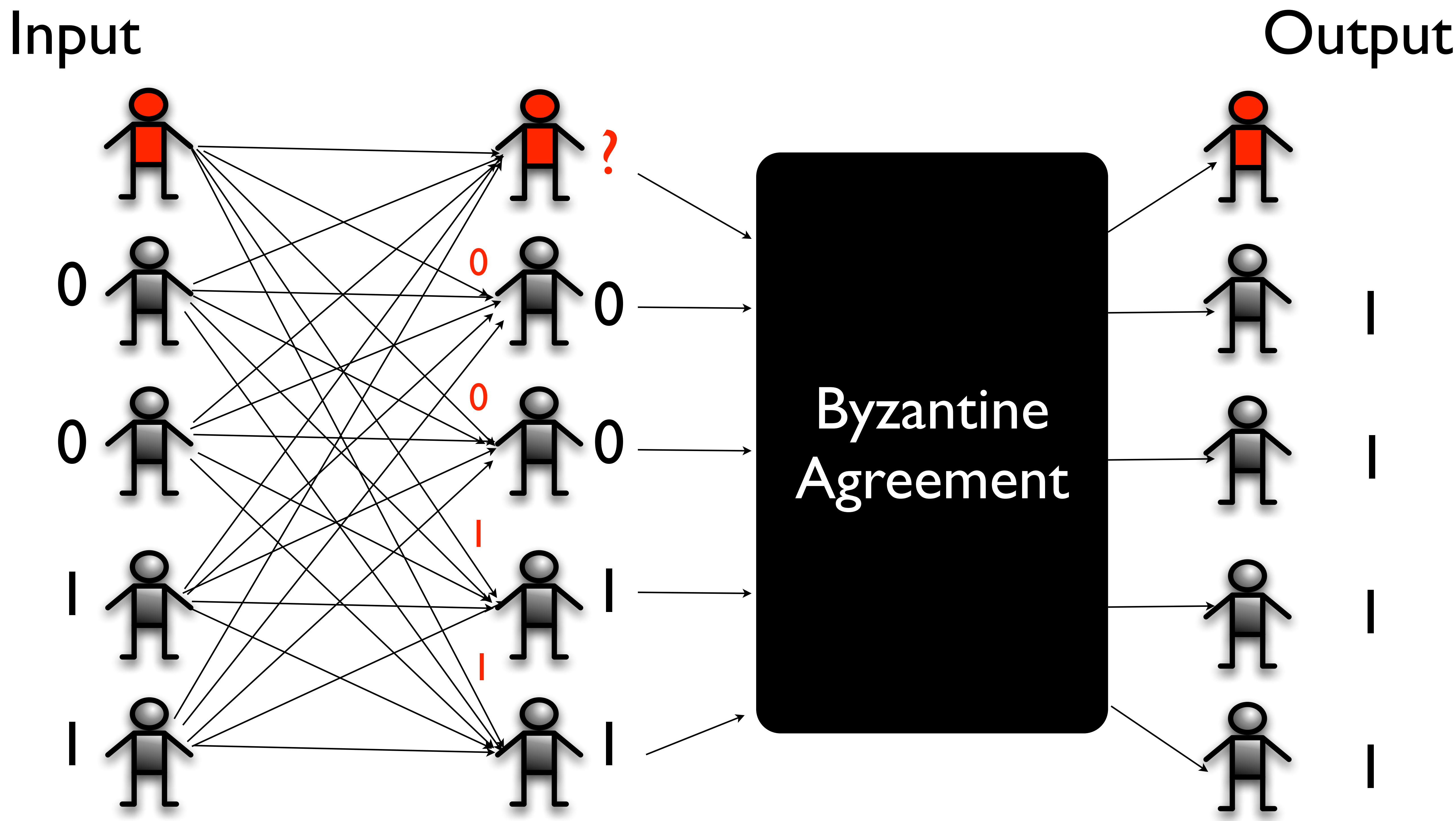
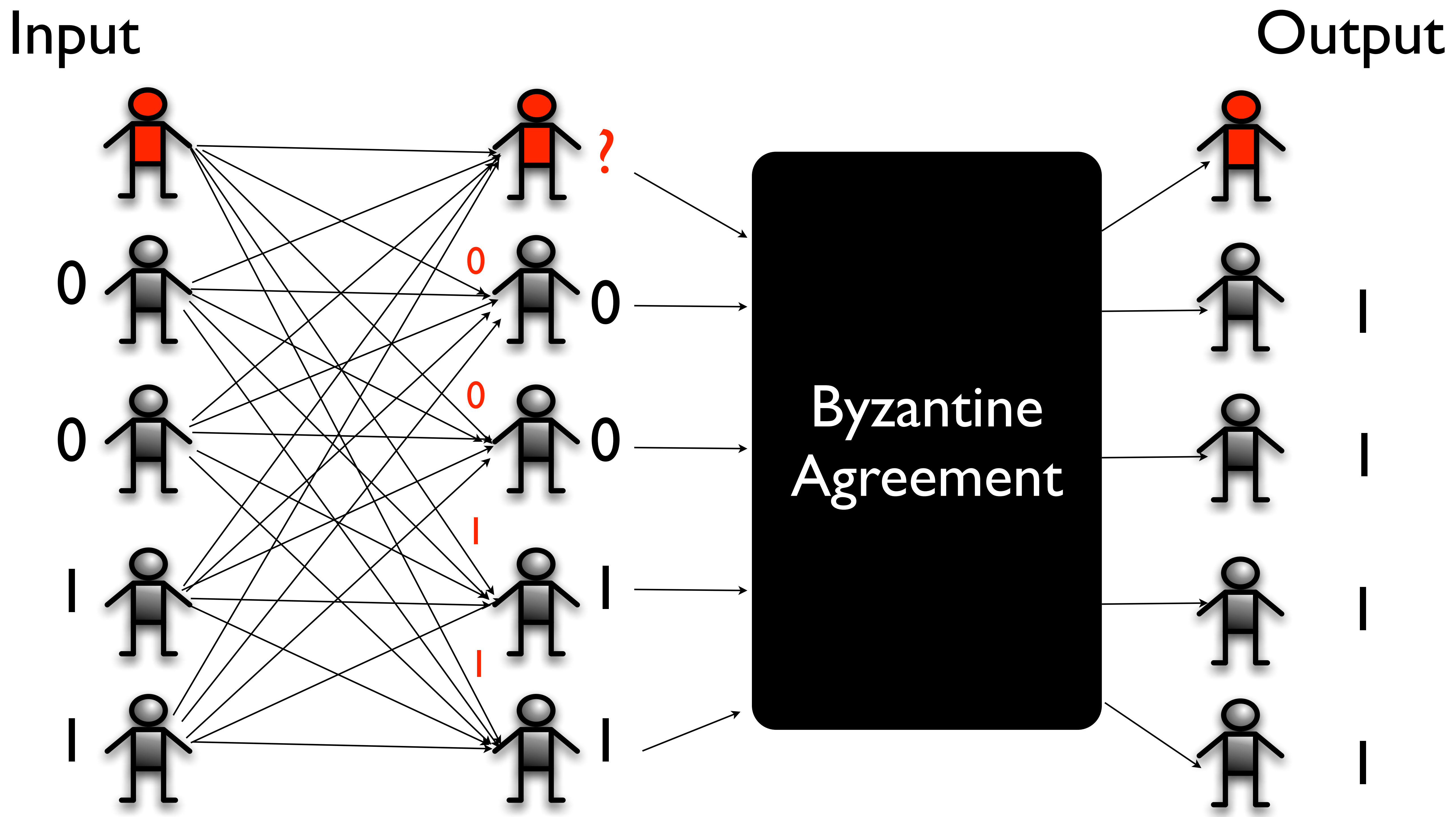


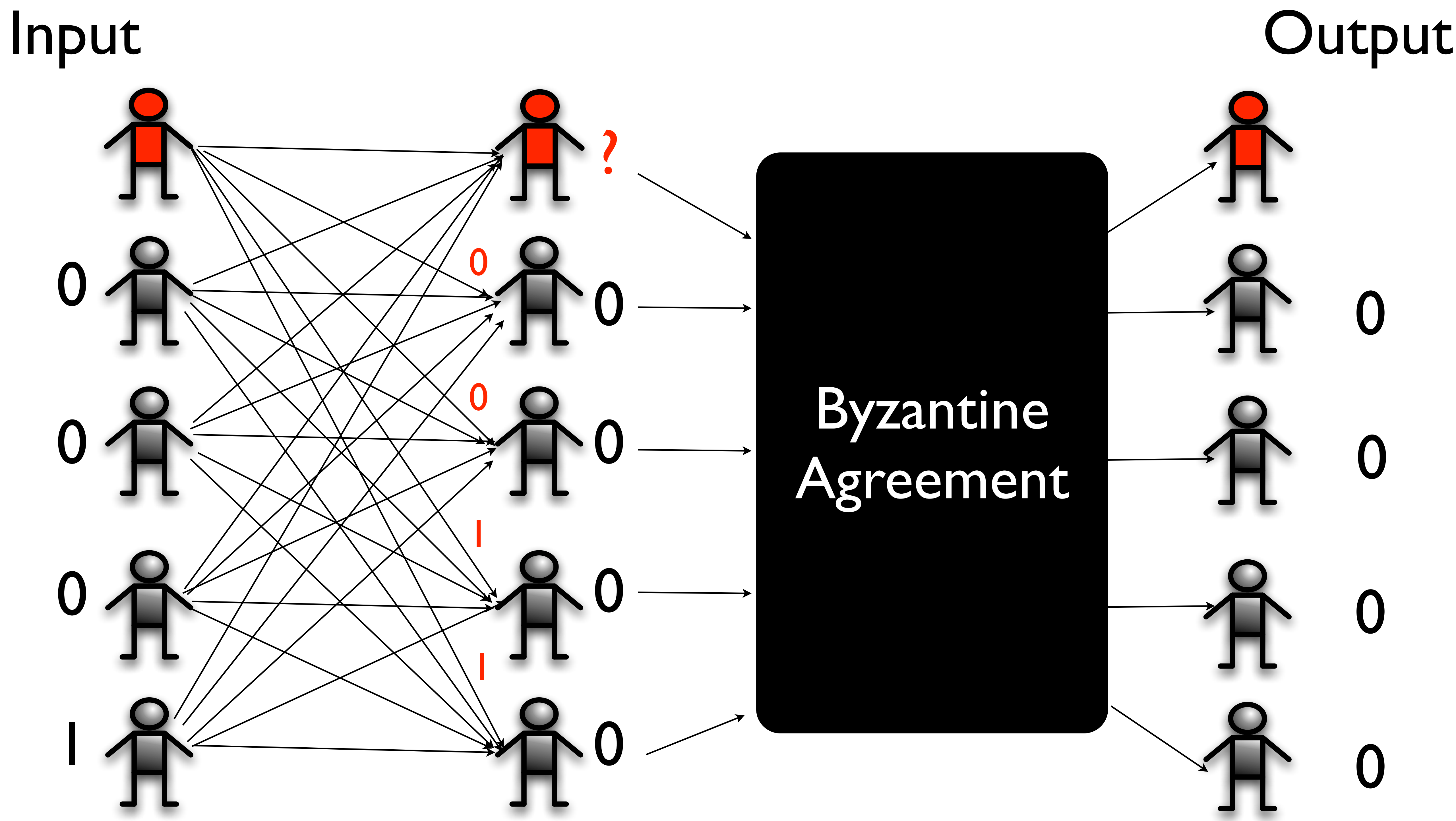
Majority Filtering + BA



All good procs always output same bit



If majority bit held by > 2 good procs, then all procs output majority bit



Impossibility Result

- 1982: FLP show that 1 fault makes deterministic BA impossible in asynch model
- 2007: Nancy Lynch wins Knuth Prize for this result, called "fundamental in all of Computer Science"

Solution: Randomization

- A randomized algorithm can solve BA [Ben-Or '83]
- Ben-or's algorithm solves with probability 1, but requires exponential time in expectation
- Many subsequent improvements

Applications

- Databases, State Machine Replication, Secure Multiparty Computation, Control systems, Sensor Networks, Cloud Computing, etc.

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- Peer-to-peer networks

  "These replicas cooperate with one another in a ***Byzantine agreement*** *protocol to choose the final commit order for updates." [KBCCEGGRWWWZ '00]*

- Game Theory (Mediators)

  "deep connections between implementing mediators and various agreement problems, such as ***Byzantine agreement****" [ADH '08]*

- Rule Enforcement

  "... requiring the manager set to perform a ***Byzantine agreement protocol"*** *[NWD '03]*

Recent Improvements

- Decades of work improved runtime to constant expected time [CKS ’05]
- But message cost remained high: O(n^2)
- Recent results: each proc. sends $\tilde{O}(\sqrt{n})$ bits [KS ’11]

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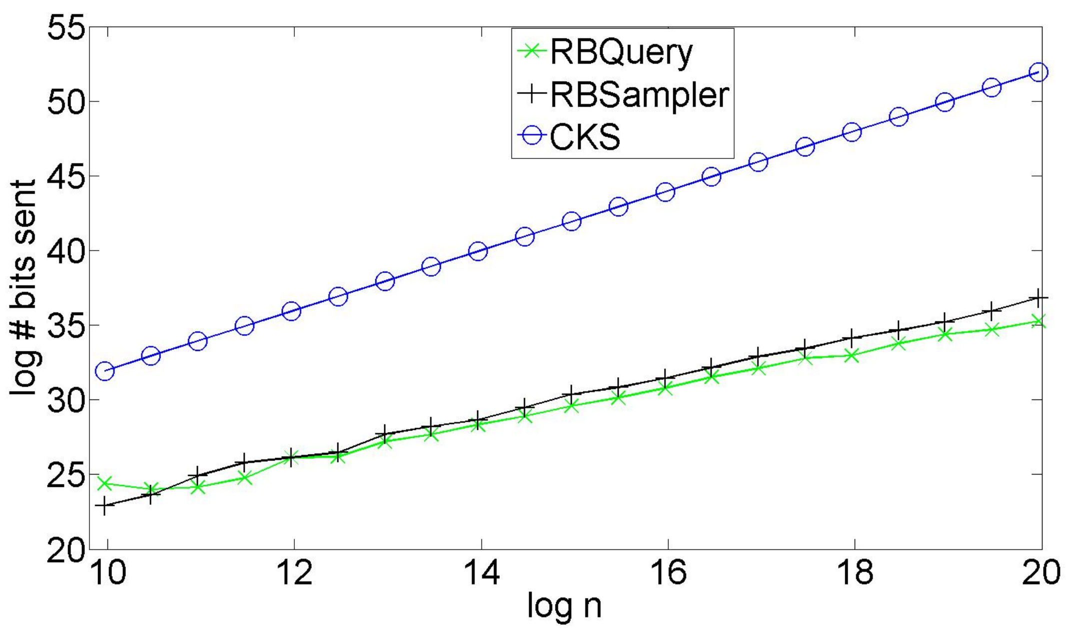
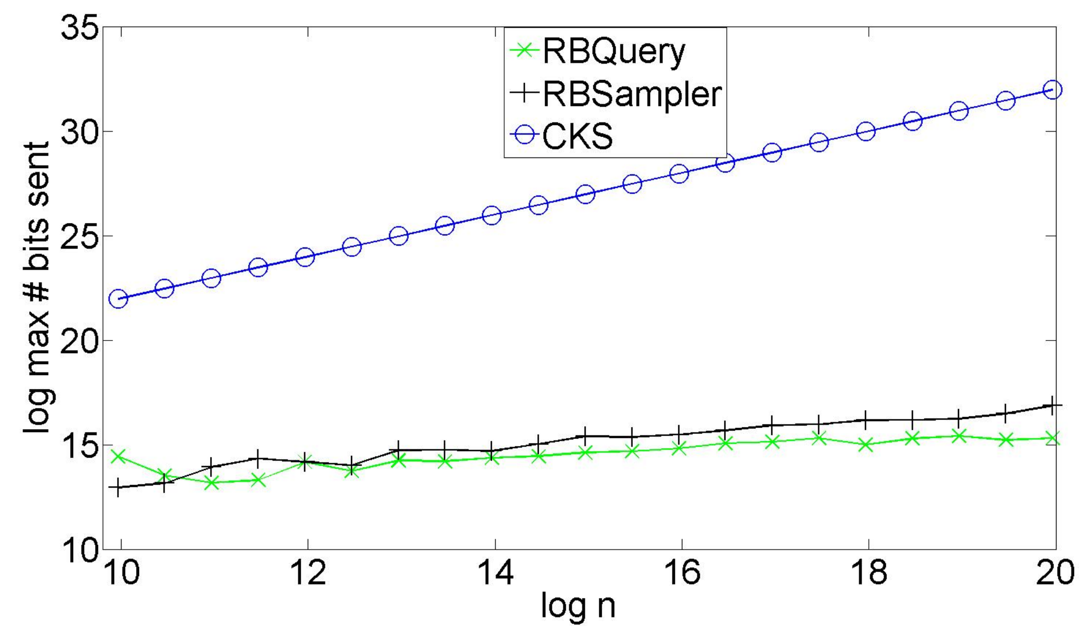
- Recent results: each proc. sends $\tilde{O}(\sqrt{n})$ bits [KS ’11]
- Can achieve O(log n) bits with a random beacon

BA Scalability





Both RBQuery and RBSampler assume a random beacon [MS '12]

BA for HPC?

- Problem: Factor of 4 blowup in resource cost just to tolerate one “soft” (Byzantine) fault

Networks of Noisy Gates

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- Must build a network to compute f with *unreliable* gates
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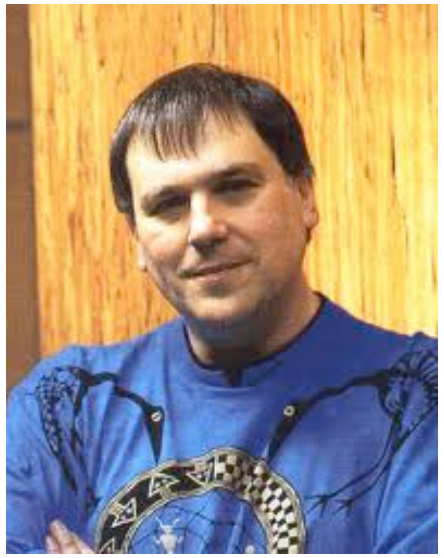
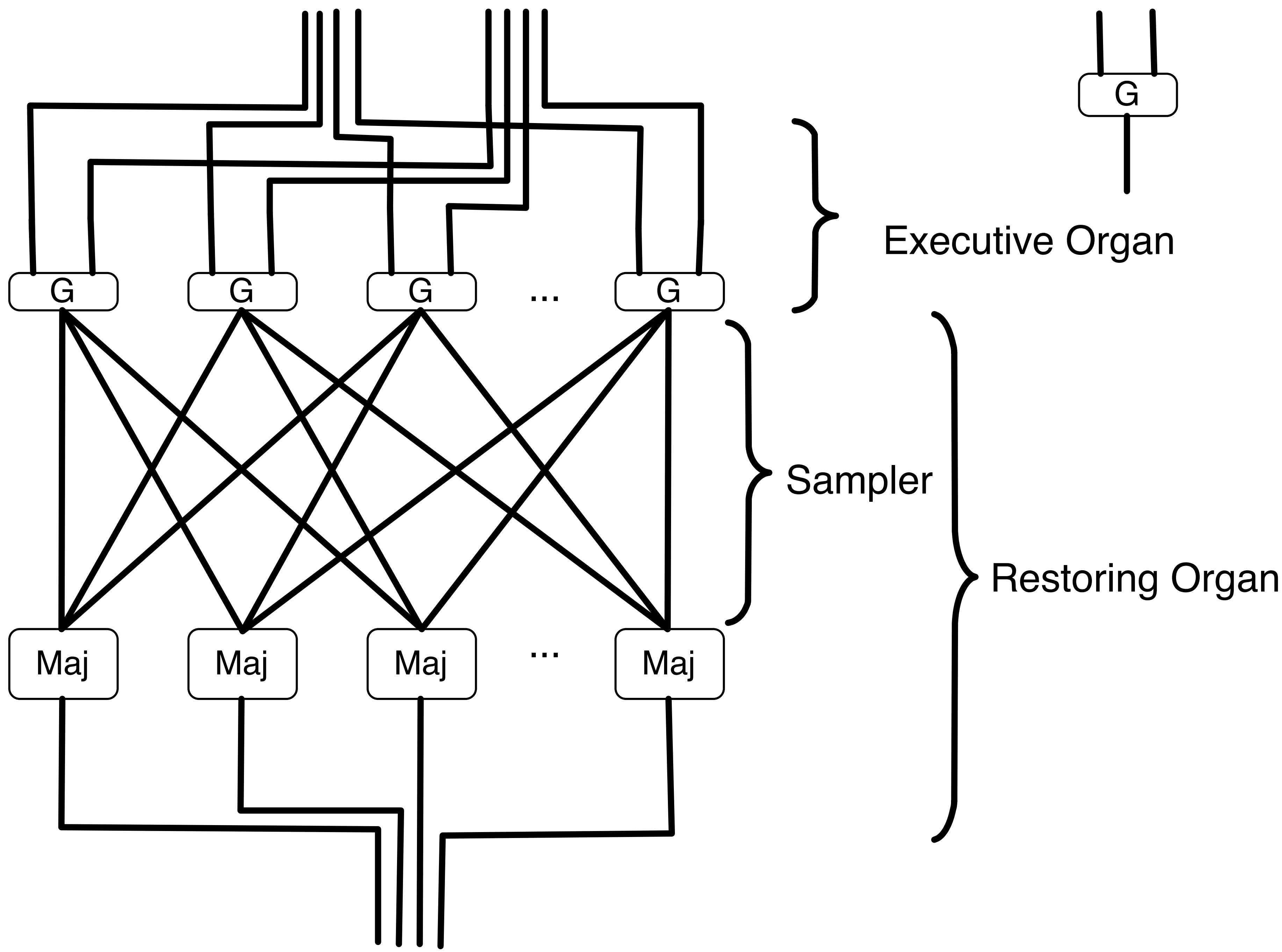


Q: How many unreliable gates do we need to compute f with probability 1-o(1)

- O(n log n) gates suffice [Von Neumann '56]
- $\Omega(n \log n)$ gates necessary [PST '91]

Upper bound



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...
G
Executive Organ
Sampler
Restoring Organ
Maj
Maj
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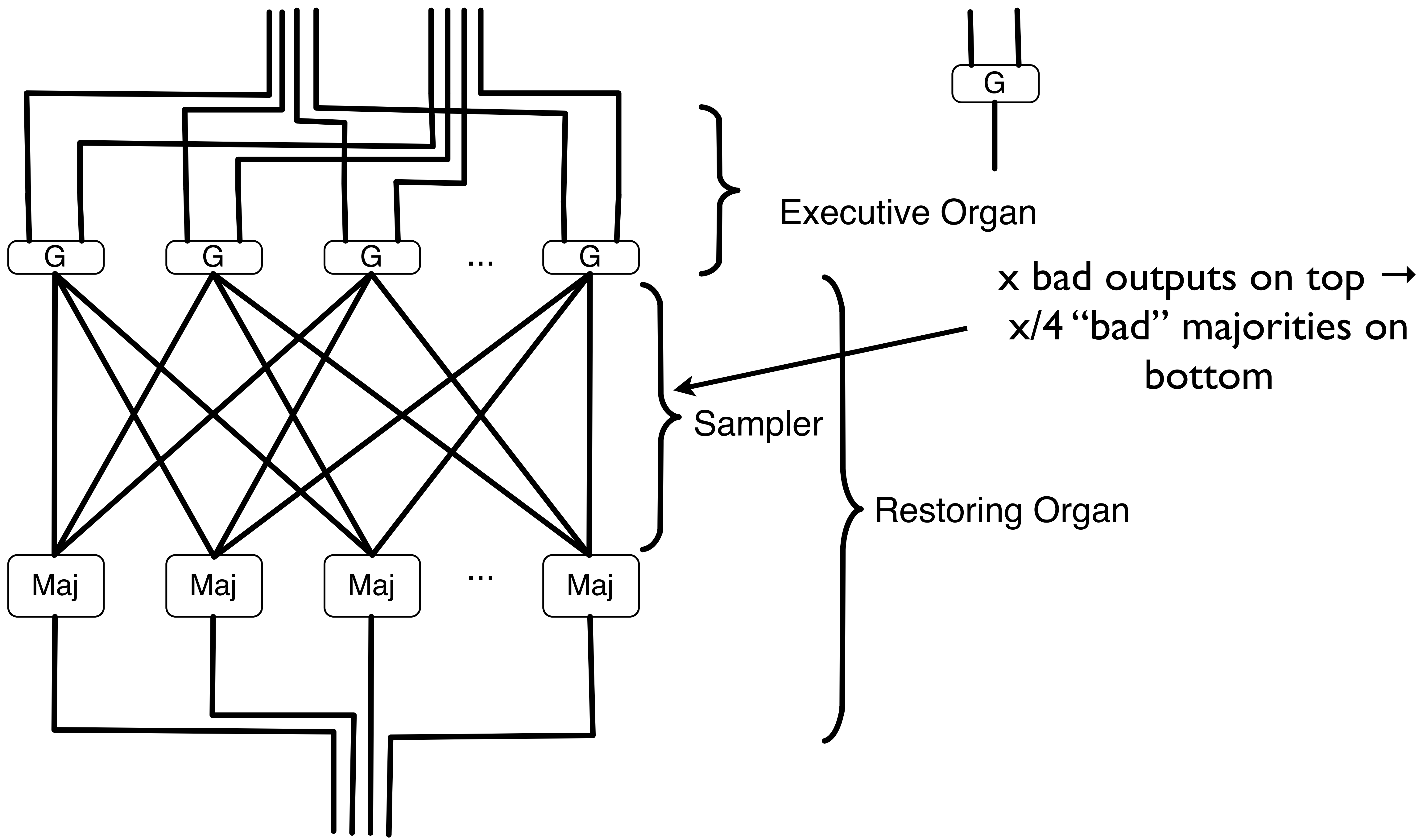
Upper bound


G
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x bad outputs on top →
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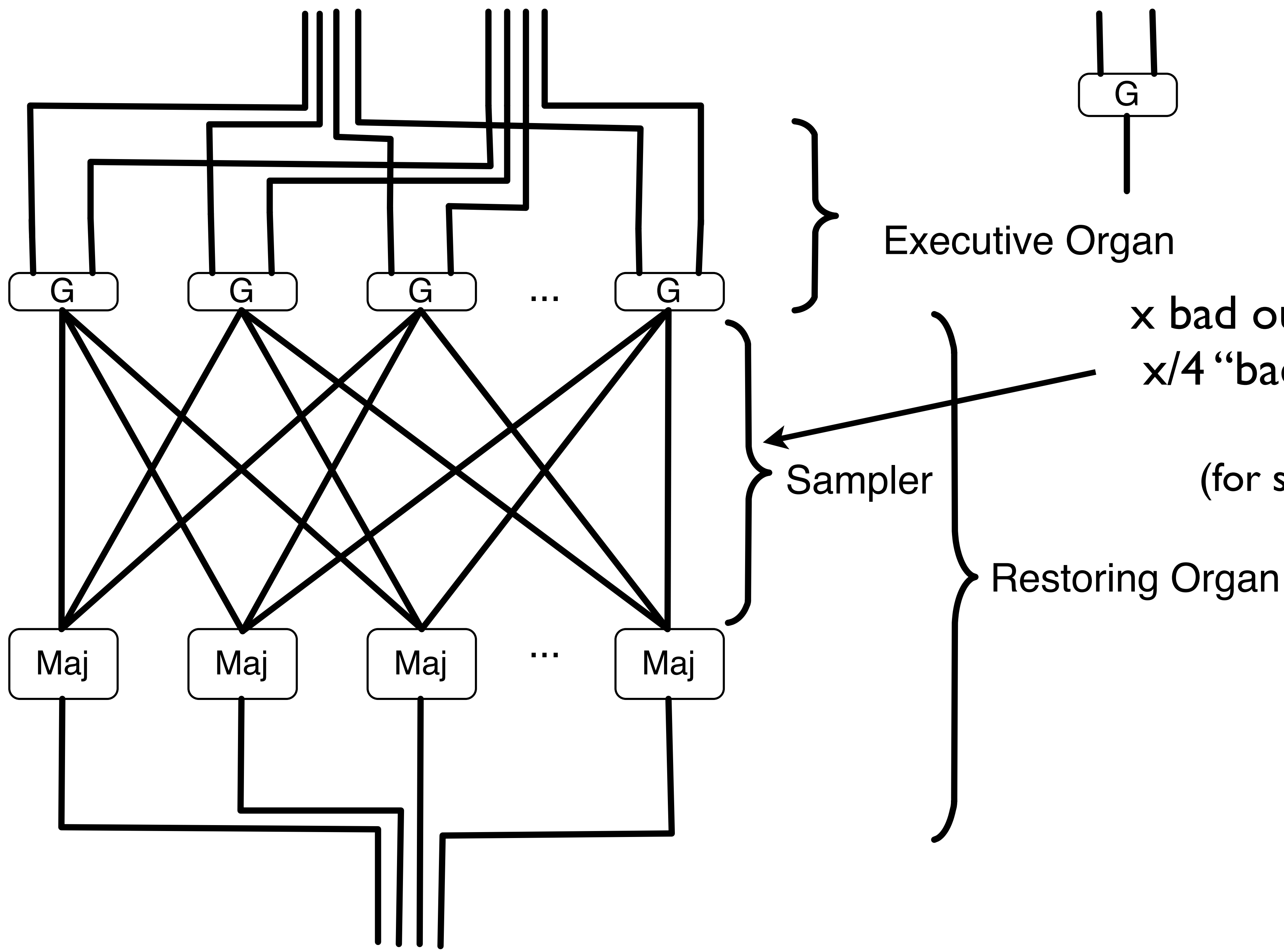
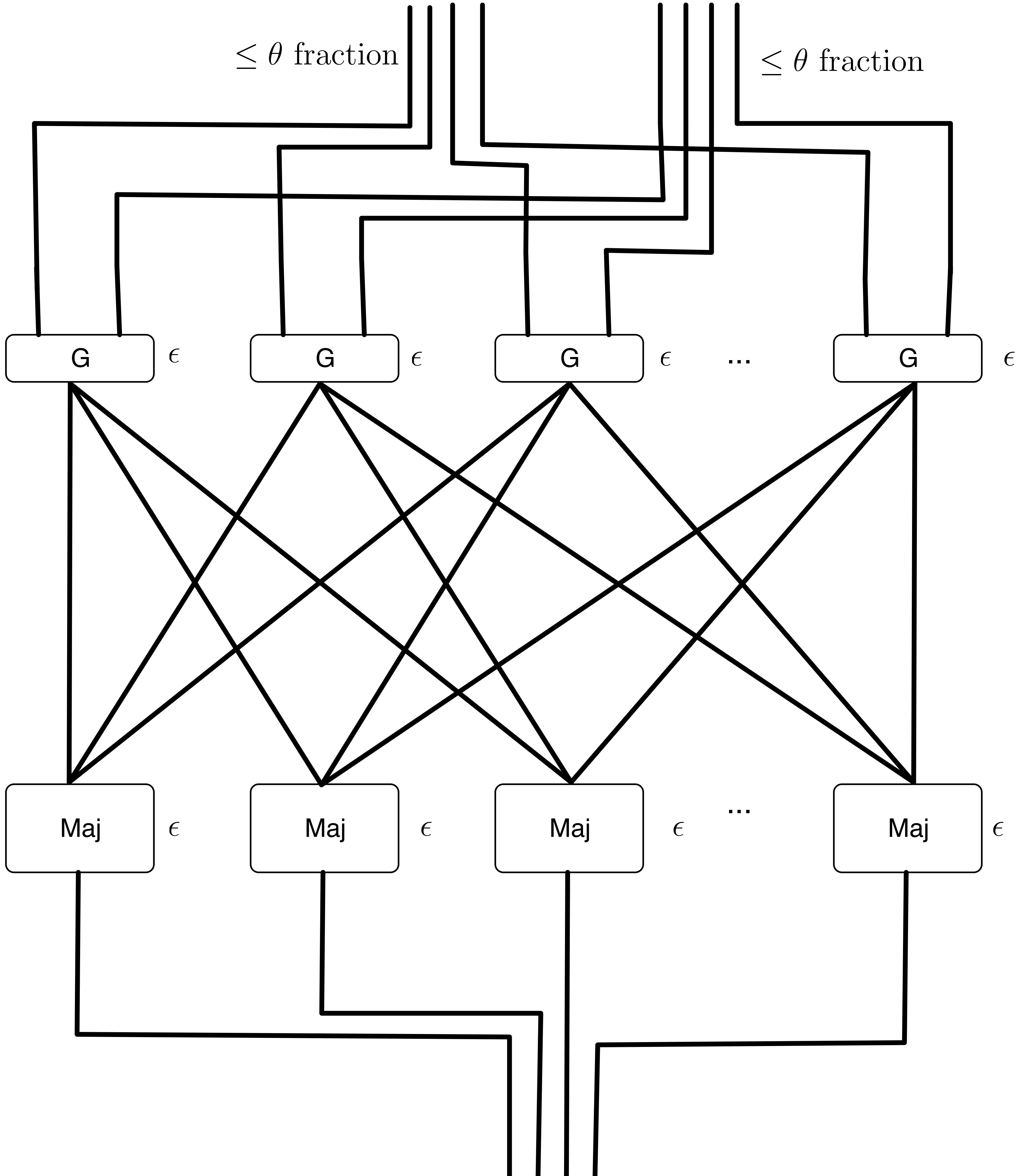


x bad outputs on top → x/4 “bad” majorities on bottom
(for suff. small x)


≤ θ fraction
≤ θ fraction
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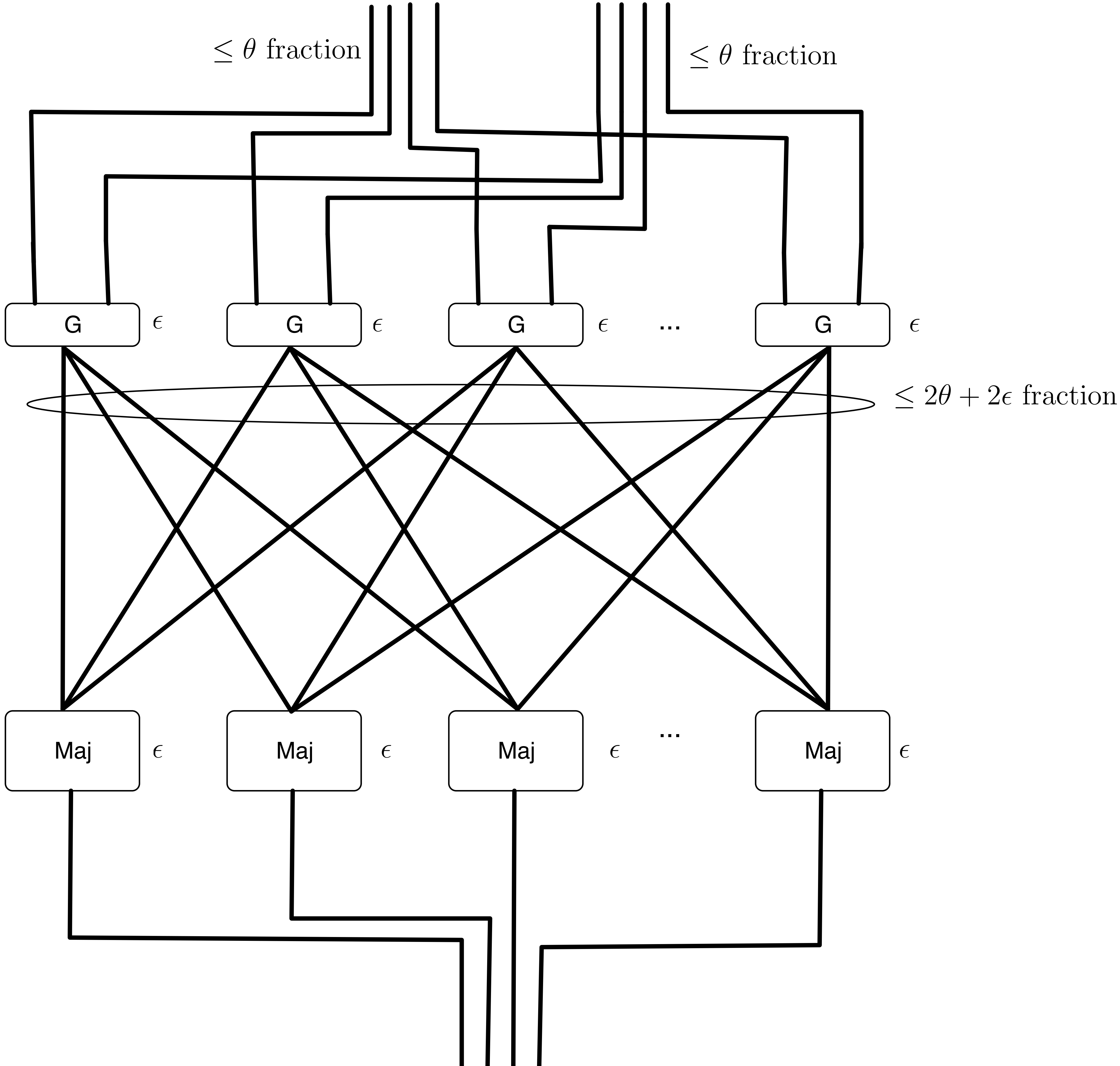
Maj ϵ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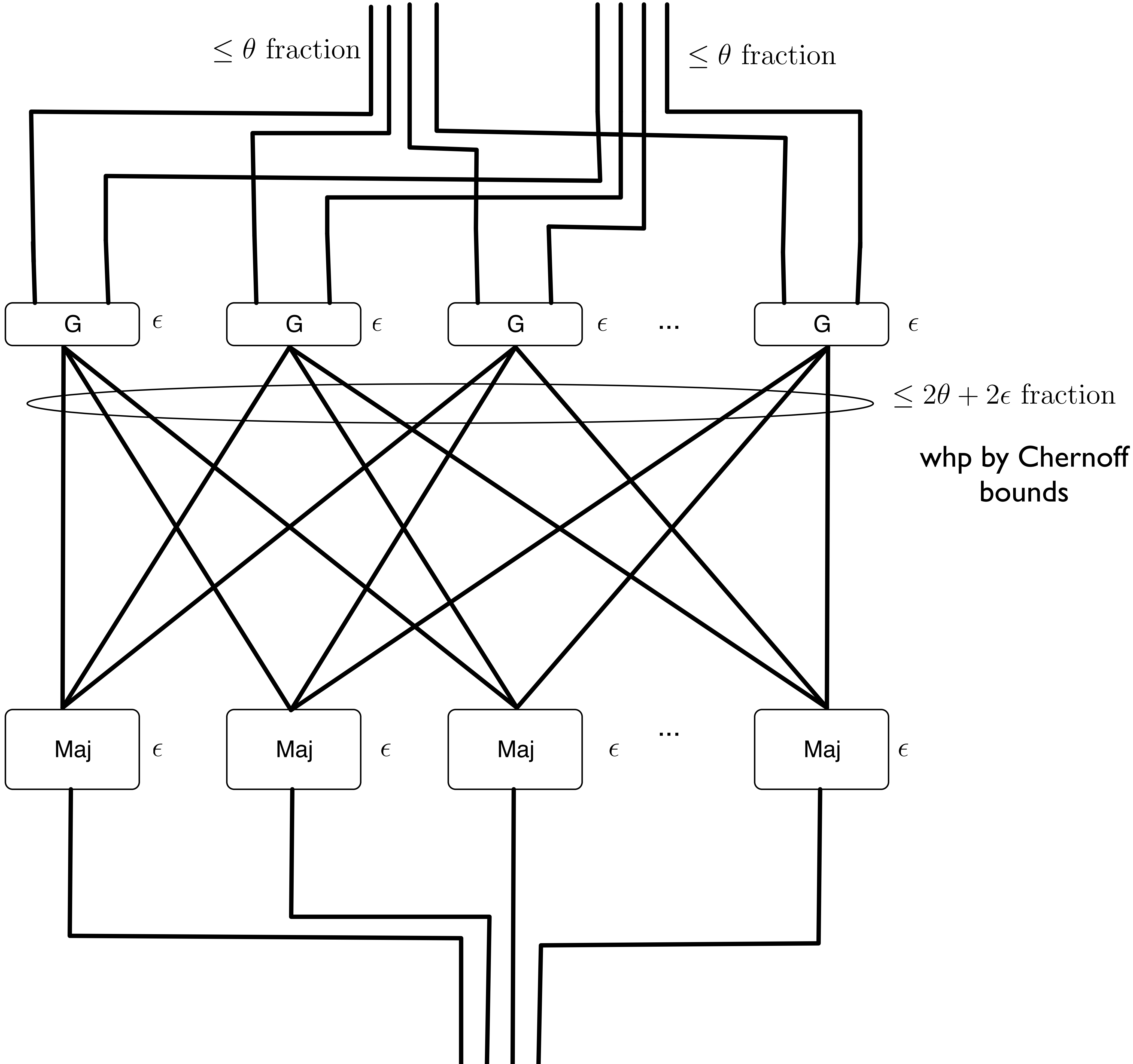
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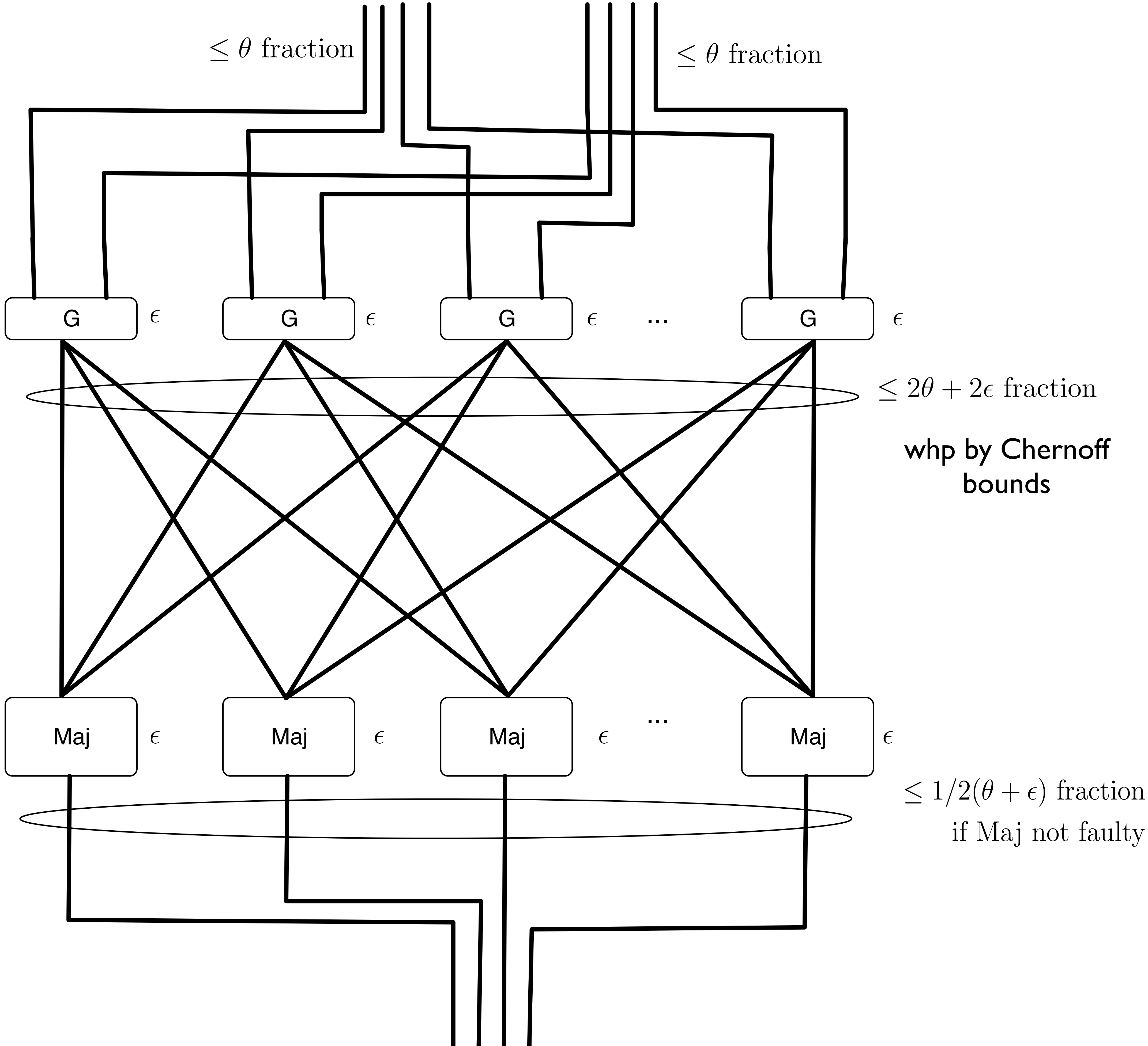

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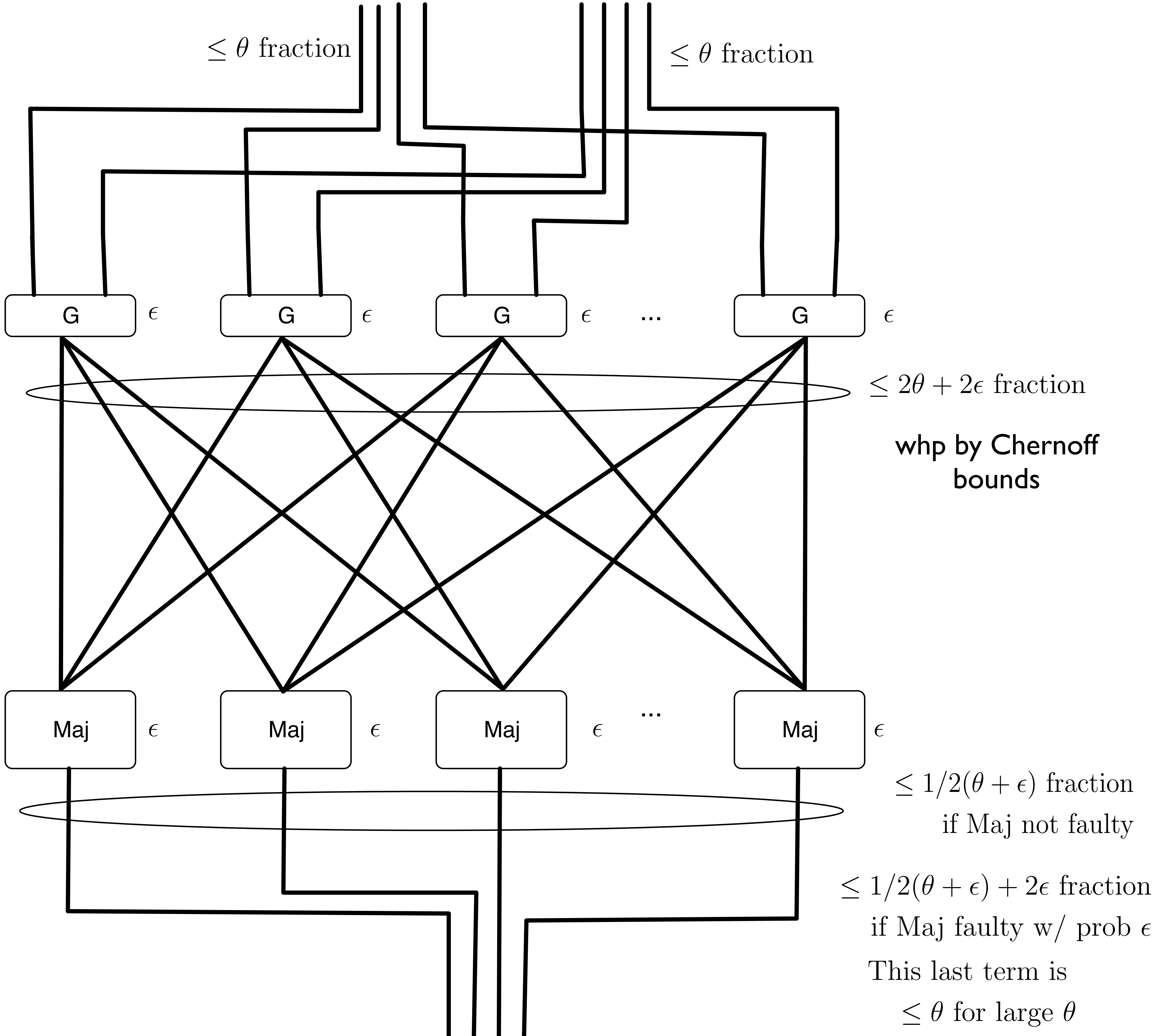
$\leq 1/2(\theta + \epsilon)$ fraction
if Maj not faulty



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...
Maj ϵ
$\leq 1/2(\theta + \epsilon)$ fraction
if Maj not faulty
$\leq 1/2(\theta + \epsilon) + 2\epsilon$ fraction
if Maj faulty w/ prob ϵ
This last term is
$\leq \theta$ for large θ

Issues

- Problem 1: Gates more constrained than processors.
- Problem 2: Faults assumed to be uncorrelated
- How to update the problem for distributed systems?

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- Problem 2: Faults assumed to be uncorrelated
- How to update the problem for distributed systems?

- Idea: Given a circuit. Use procs to simulate it. $t < n/3$ procs controlled by an adversary

SMC

[Yao '82]

- n procs want to compute a function f over n inputs. f can be computed with m gates.
- Each proc has one input of f
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Note: The traditional SMC definition has additional privacy requirements that are ignored here

Applications as Functions

- Auctions

$$f = \max(x_1, x_2, \ldots, x_n)$$

- Threshold cryptography

$$f = M^s \mod pq$$

- Information aggregation

$$f = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n} - \left(\frac{\sum_{i=1}^{n} x_i}{n}\right)^2}$$

Applications as Functions

- Auctions

$$f = \max(x_1, x_2, \ldots, x_n)$$

- Threshold cryptography

$$f = M^s \mod pq$$

1) M, p, q are parameters of the function;
2) s is the y intercept of a degree $(d-1)$ function with points given by the x_i values.

- Information aggregation

$$f = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n} - \left(\frac{\sum_{i=1}^{n} x_i}{n}\right)^2}$$

Previous Work

- f has n variables and requires m gates
- Previous work [see e.g. Goldreich '98]
  - Each player sends O(nm) messages
  - Each player performs O(nm) computation.

Our Contribution

[DKMS '12]

- Much improved computation & message cost
  - Each player sends $\tilde{O}(\frac{m+n}{n} + \sqrt{n})$ messages
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  - Each player performs $\tilde{O}(\frac{m+n}{n} + \sqrt{n})$ computation.
- We solve SMPC w.h.p. meaning

$$1 - O(1/n^k) \text{ for any fixed } k$$

Algorithm Overview

- Make critical use of *quorums*
- Each gate is computed by a quorum

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  has $\theta(\log n)$ procs; less than *1/3* are bad

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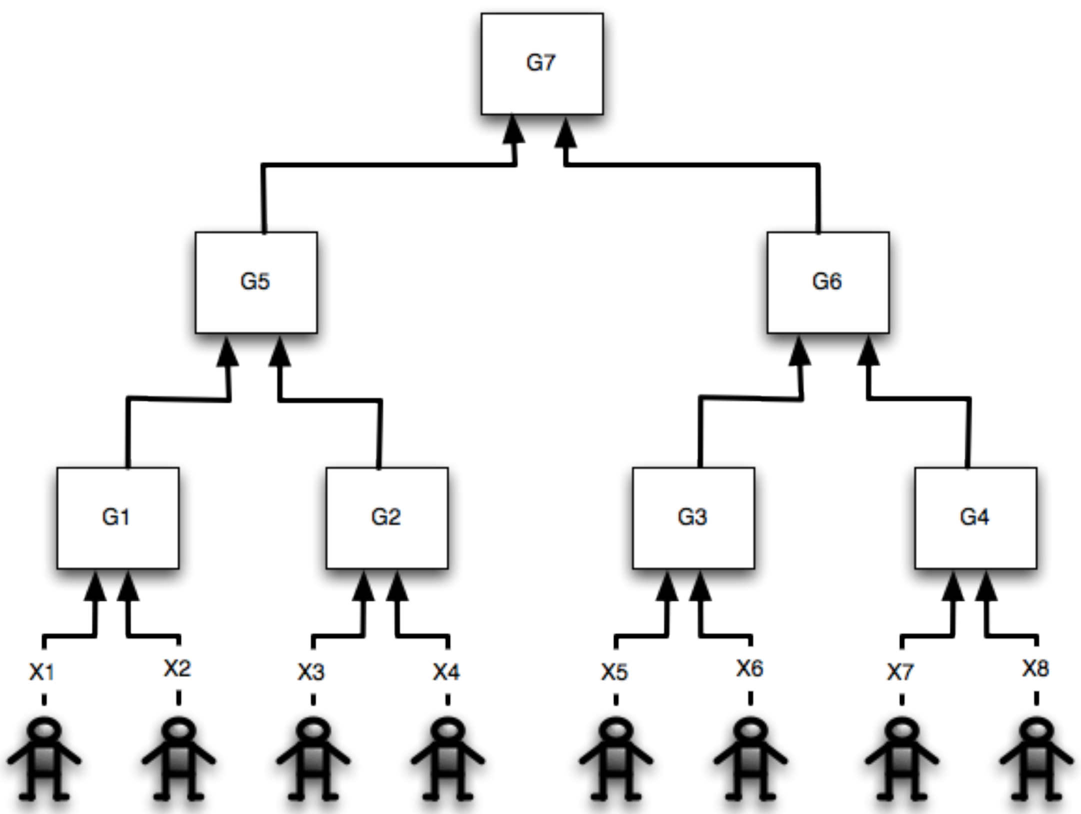
Tools Used

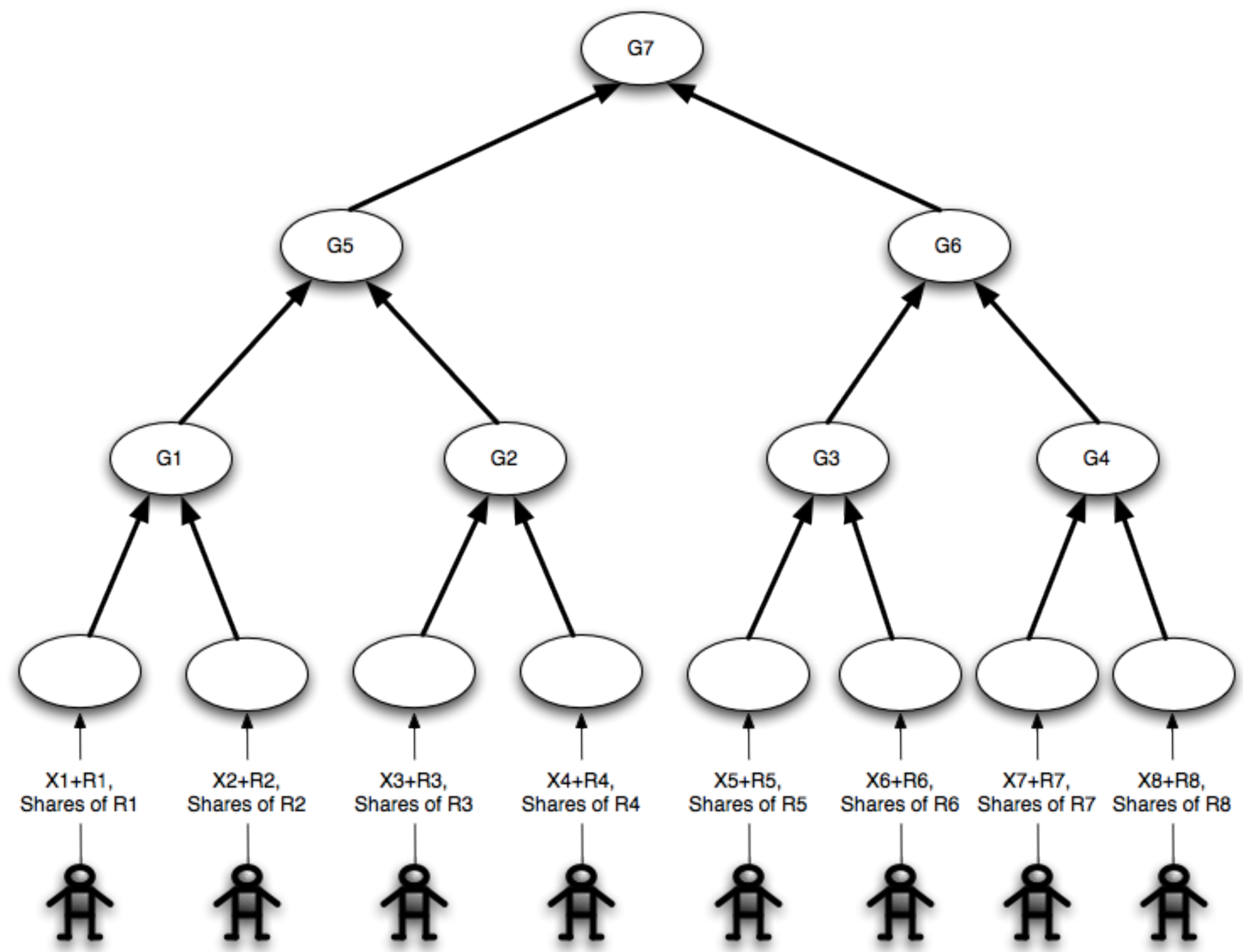
- Can get all processors to agree on *n* quorums w.h.p. [KS '11]
- HEAVY-WEIGHT-SMPC algorithm [BGW 88]

Algorithm Overview

- Translate function *f* to circuit C
- Build network G based on C
  - Gates → Internal nodes
  - Inputs → Input nodes
  - Wire → Communication Links
- Build quorums
- Each quorum is assigned to a node

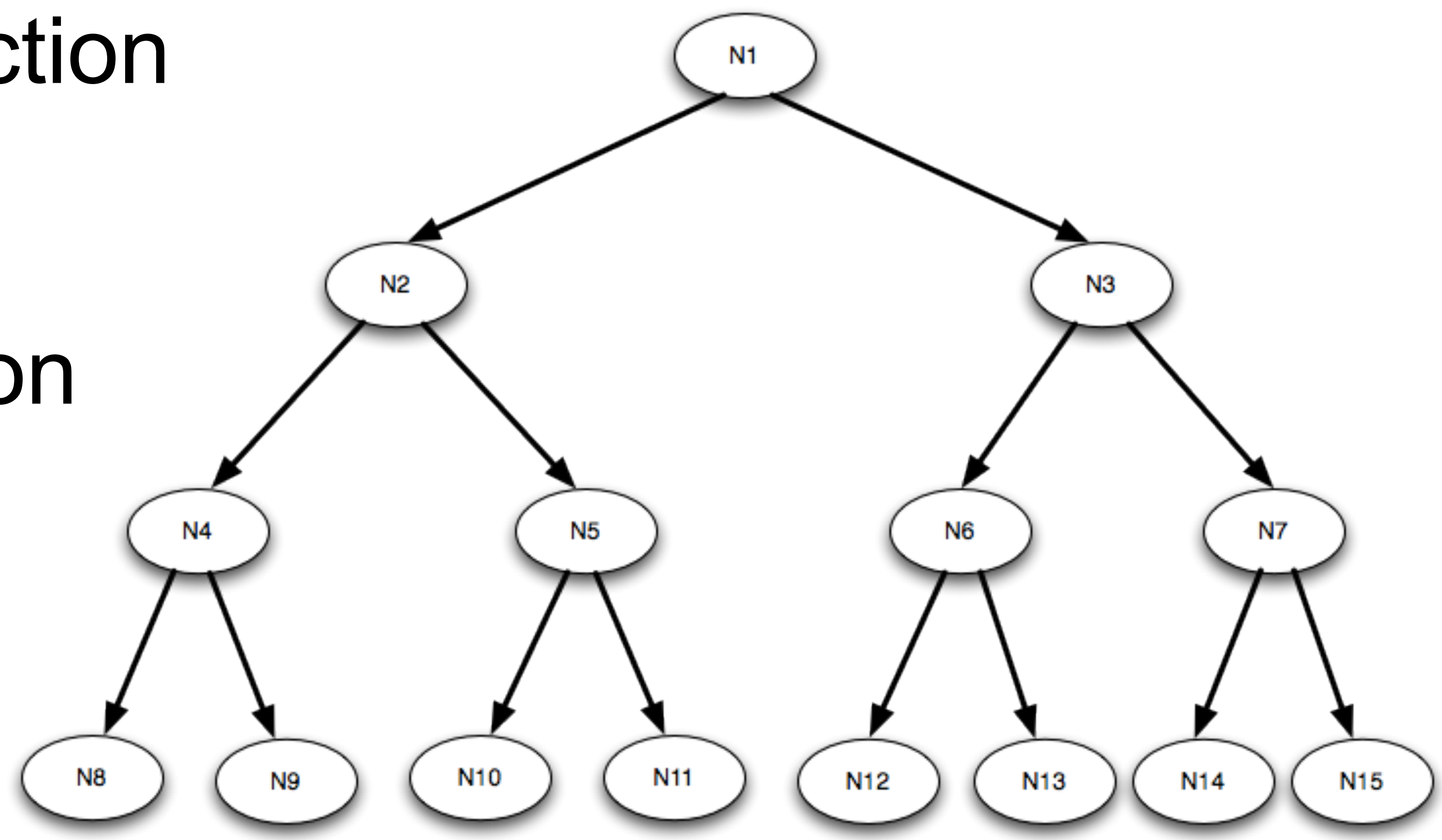
Circuit and Network





Propagating Output

- Output reconstruction
- Output propagation



HPC Connection

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- Need to design resilient tree-like circuit
- Solution: SMC

A Possible Agenda

- Step 1: Focus first on reliable OS tools

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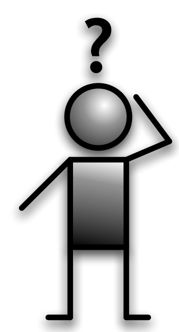
- Step 4: Build on algorithmic techniques to full-fledged reliable applications &/or 13 dwarves

Towards a Research Agenda

"Make no little plans"

- **Important** problems span disciplines
- **Succinct** problems are remembered
- **Hard** problems pull in smart people

Questions



Dream Result

- Given: a parallel algorithm for n reliable procs
- Goal:
  - Design a reliable algorithm that is correct even if t procs are unreliable
  - Reliable algorithm has resource costs that are O(t) larger in an additive sense

Problems with SMC

- Problem 1: To tolerate a linear number of faults, SMC requires logarithmic resource blowup
- This is still too large
- Idea: Amortization. Can we do better if same set of processors is used for many computations?

Problems with SMC

- Problem 2: SMC simulates a circuit
- Communication in a circuit is static
- Idea: develop version of SMC that simulates an arbitrary parallel algorithm