Randomized Algorithms for Network Security and Peer-to-Peer Systems

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Talk Outline

- Probabilistic Packet Marking for IP Traceback
  - Network Security
  - Appeared in STOC 2002

- Load balancing in Peer-to-peer networks
  - A Stochastic Process on the Hypercube
  - Joint work with Eran Halperin, Richard Karp, and Vijay Vazirani.
  - Appeared in STOC 2003

- More details: `www.cs.umass.edu/~micah`

The IP Traceback Problem

- Denial of Service Attacks:
  - Attacker sends MANY packets to victim.
  - Denies access to legitimate users.
- Difficulties:
  - Source of packets can be forged.
  - Tools for coordinating from multiple locations.
- Enforcing accountability: the IP Traceback problem.
  - Determine the source of a stream of packets.

Probabilistic Packet Marking

- Suggested in [BurchC2000].
- Protocol of [SavageWKA2000]
  - Reserve header bits for IP Traceback
  - Each router on path of packet:
    - With small probability:
      - Write IP address into header; reset hop count.
    - Otherwise: increment hop count.
  - Victim of attack receives many packets:
    - Can reconstruct entire path (with high probability.)

Existing Work

- Elegant protocol: produced flurry of research.
  – [DoeppnerKK2000]
  – [LeeS2001]
  – [DeanFS2001]
  – [ParkL2001]
  – [SongP2001]
- Objectives include:
  – Reducing header bits required.
    - Full protocol of Savage *et al*: 16 bits.
  – Robustness against multiple paths of attack.

New results: single path of attack

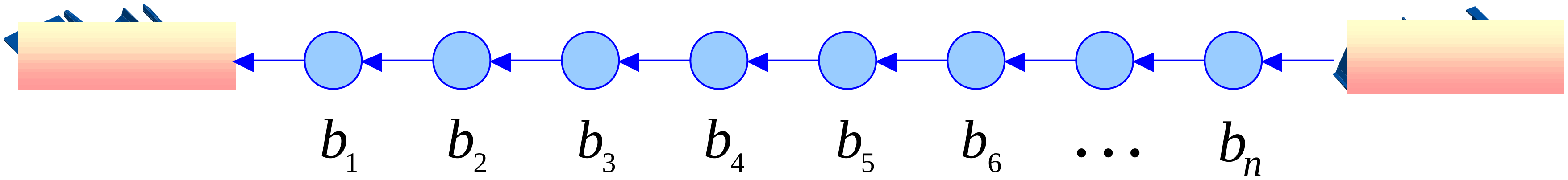
- New technique for probabilistic marking:
  - **One** header bit is sufficient.
  - Number of packets required: $O(2^{2n})$
    - *n:* number of bits to describe path.
  - Any protocol that uses one bit: $\Omega(2^{2n})$
- Number of header bits used: *b*
  - Packets required by optimal protocol: $2^{\Theta\left(n/2^b\right)}$
    - Grows exponentially with *n*.
    - Decreases DOUBLY exponentially with *b*.

New results: many paths of attack

- Number of paths attacker can use: k
- Lower bound:
  - For any valid protocol $b = \log(2k-1)$.

- Protocol: $b = \log(2k+1)$ sufficient.
  - Requires restrictions on attacker.
  - Introduces powerful new coding technique.
    - New use of Vandermonde matrices.

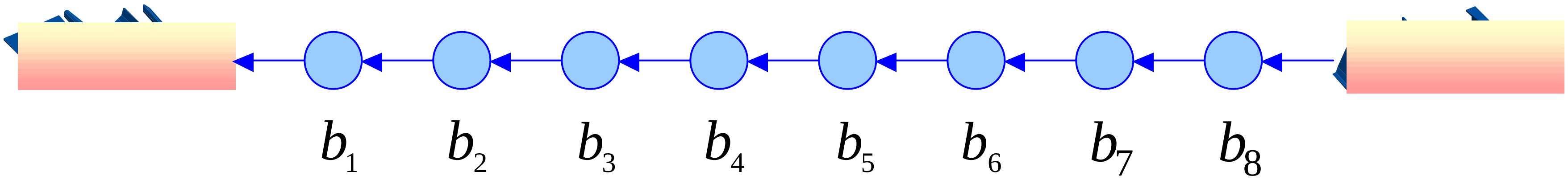
Model for protocols



- Path of length *n:* each node has one bit.
- Objective: inform victim of all *n* bits.
  - Easy to adapt to IP Traceback over Internet.
- Attacker sends *b*-bit packets along path.
  - Chooses initial setting of packets.
- Requirement on intermediate nodes:
  - No state information.

The one bit scheme

- Idea: encode bits $b_1 \ldots b_n$ into
  - p = Pr[bit received by victim = 1]
- Packets provide estimate of p.



- $$p = \sum_{i=1}^{n} (1/2)^i b_i$$

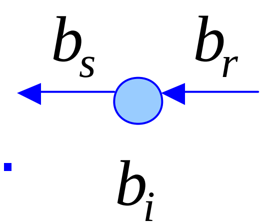
The one bit scheme

- Protocol for each node *i*:
  - b_r: bit received from predecessor.
  - b_i: bit known to *i*.
  - Probability node *i* forwards 1:

	$b_r = 0$	$b_r = 1$
$b_i = 0$	0	½
$b_i = 1$	½	1

The one bit scheme

- Claim: if initial bit set to 0: $p = \sum_{i=1}^{n} (\tfrac{1}{2})^i b_i$
- Proof:



  – b_s : bit sent by node.

  – If $b_i = 0$ then $\Pr[b_s = 1] = \Pr[b_r = 1]/2$

  – If $b_i = 1$ then $\Pr[b_s = 1] = \Pr[b_r = 1]/2 + 1/2$

- Problem: attacker might set initial bit to 1.

$$p = (\tfrac{1}{2})^n + \sum_{i=1}^{n} (\tfrac{1}{2})^i b_i$$

  – Result:

The one bit scheme

- Solution:

	$b_r = 0$	$b_r = 1$
$b_i = 0$	0	$\frac{1}{2} - e$
$b_i = 1$	$\frac{1}{2}$	$1 - e$

- If victim knows p within $\pm \frac{1}{e}\left(\frac{1}{2} - e\right)^{-n}$
  - All bits in path can be decoded.
- $O\left(\left(\frac{1}{2} - e\right)^{-2n}\right)$ packets sufficient (w.h.p.)

Extension to *b* bits.

- Computing *p* w/precision $1/2^n$:
  - requires $\theta\left(2^{2n}\right)$ packets.
- Idea: use added bits to reduce precision needed.

p	(*b*-*1*)-bit counter

- Protocol for each node:
  - Increment (*b*-*1*)-bit counter.
  - If counter overflows, perform 1 bit protocol.
- Effective path length reduced by 2^{b-1}

Extension to *b* bits.

- Problem: How to guarantee victim sees all bits?
  - – If attacker always sets initial bits the same

    Victim only sees one type of counter.
    - Only provides $n/2^{b-1}$ bits on path.
- Solution:
  - – Each node resets counter w/small probability.

Extension to *b* bits.

- Decoding:
  - More involved than single bit case.
  - Practical algorithm for decoding in software. $O\left(bn^2 2^b 2^{2n/2^{b-1}}\right)$
  - Sufficient: packets.
- Proof of correctness fairly involved.

$$\Omega\left(2^b 2^{n/2^b}\right)$$

- Lower bound for any protocol:

Lower Bound.

- Theorem: for any protocol using less than $\Omega\left(2^b 2^{n/2^b}\right)$ packets, $\Pr[wrong] \geq 1/2$
- Model:

  - Network sends *n*-bit string to victim.
  - Communication: *b*-bit packets.
  - Requirement: network has no memory.

Wrapup of Probabilistic Packet Marking

- Summary:
  - Significantly more efficient new encoding technique.
  - Tradeoff header bits for packets.
  - Simple enough to be practical.
  - Multiple paths (many open problems . . .).
- Other related work:
  - Simulation experiments: tradeoffs seen in practice.
    - Joint work with Q. Dong and K. Hirata
  - Applications of PPM to congestion control.
    - Joint work with J. Cai, J. Shapiro, and D.

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Coupon Collector's Problem

- Objective: collect each of n coupons.
  - Each step: receive one random coupon.
  - Well known: $n \log n \pm o(n \log n)$ steps required to obtain every coupon (whp).
- Natural variant:
  - Each step: check $\log n$ random coupons.
  - Receive one coupon if any are

Structured Coupon Collector's Problem

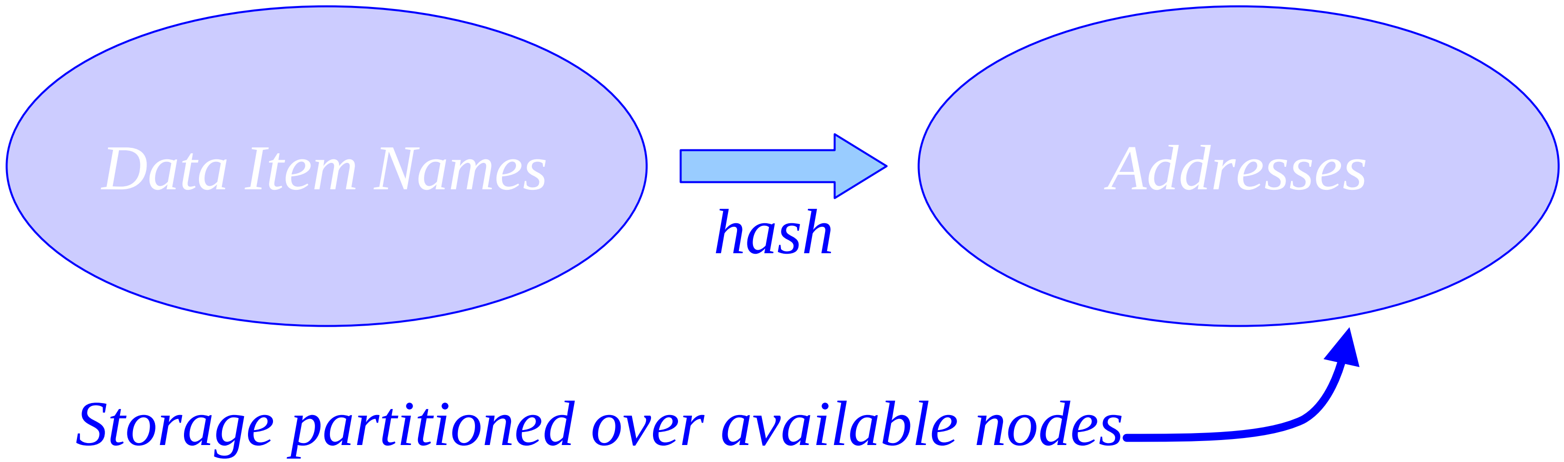
- Underlying graph $G=(V,E)$.
- Initially: all vertices uncovered.
- Each step: choose random vertex v.
  - If v uncovered, cover it.
  - Else if any neighbors of v uncovered,
    - cover random neighbor.
- How many steps until all vertices covered?

Outline of rest of talk

- Application: distributed hash tables (DHTs).
  - Fundamental tool for Peer-to-Peer Networks.
- Load balancing in DHTs:
  - Analyze w/vertex covering process on hypercube.
- Theorem:

  $O(n)$ steps enough for $\log n$-degree hypercube (whp)
- Implication: asymptotically optimal load

Distributed hash tables

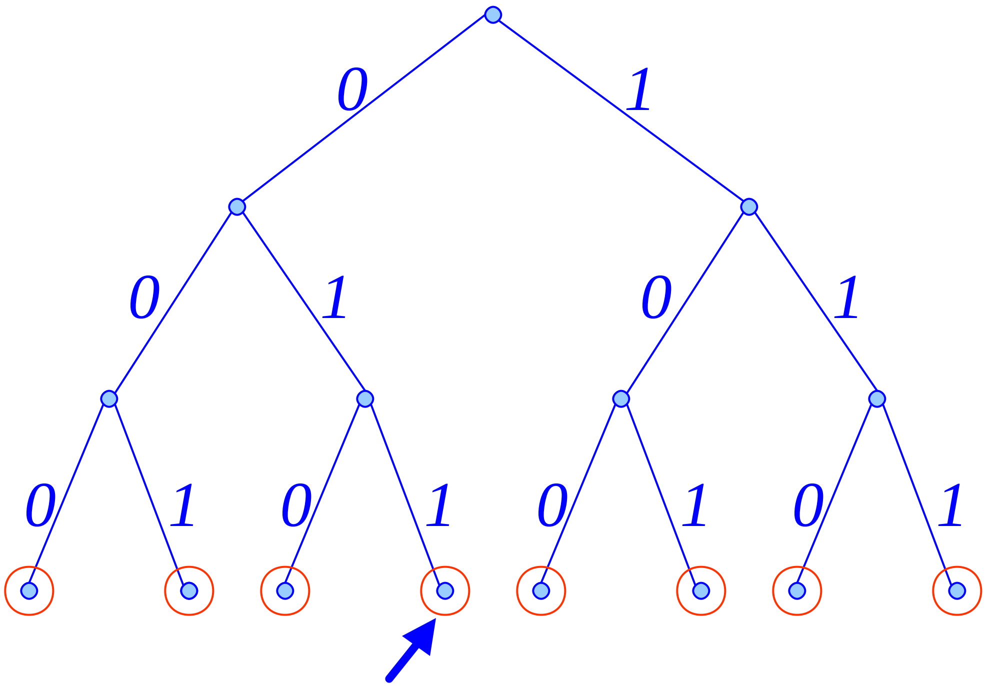


Objectives:

- Find data items quickly.
- Balance load fairly.

Partitioning the address space

Strategy: maintain binary tree w/nodes at leaves

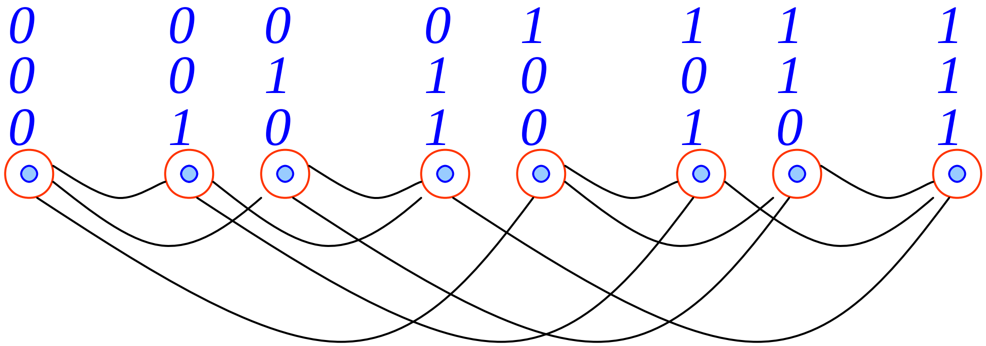


Handles addresses with prefix 011

Based on DHT of [RFHKS 2001] called CAN

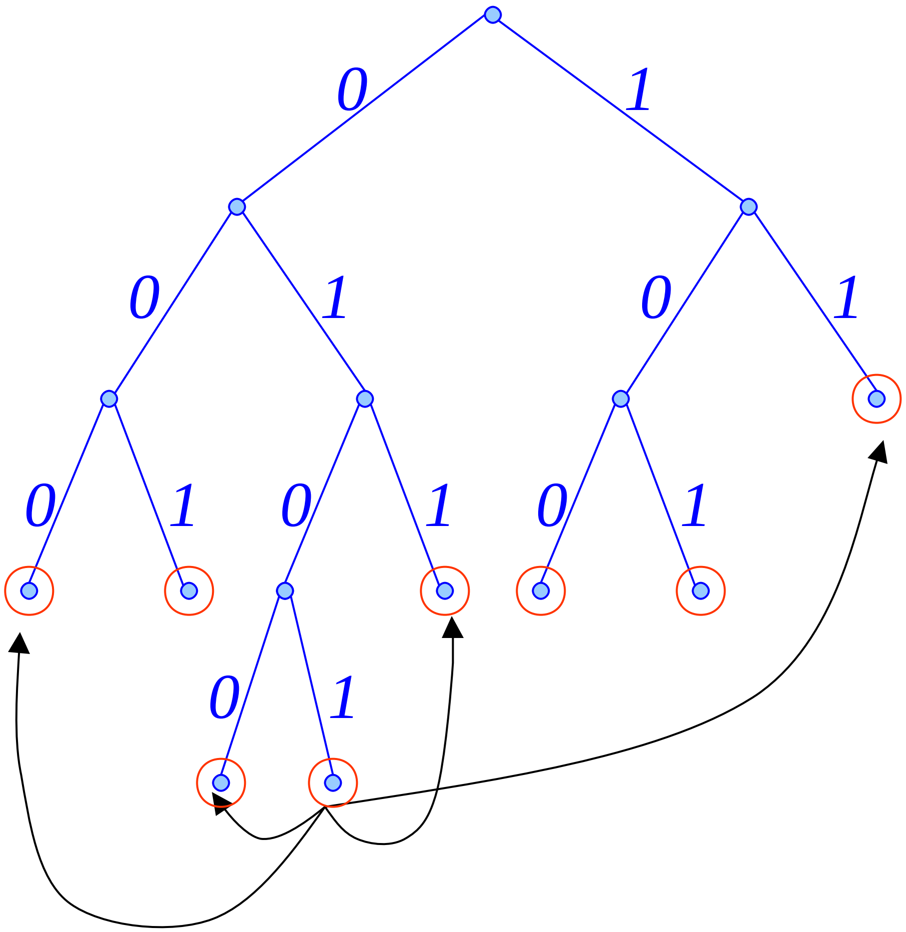
Finding region of address space

- Nodes maintain pointers to each other:



- Complete binary tree: pointers are hypercube
  - Nodes adjacent iff hamming distance = 1.
- New arrival:
  - Choose leaf node; split into two new leaves.
  - Node adjacency rule: truncate longer string.

Resulting distributed hash table:



Performance of DHT with n nodes:

- Depends on rule for choosing node to split.
- Pointers per node: $O(\log n)$
- Queries to locate content: $O(\log n)$
- Load balance: $\max_{x \in \text{nodes}} V(x) \Big/ \min_{x \in \text{nodes}} V(x)$
  - $V(x)$: fraction of address space stored at x.
    - $V(x) = 2^{-\text{depth}(x)}$

Rules for choosing node to split

- Simple rule:
  - Choose hash address uniformly at random.
  - Split node storing that address.
  - Resulting load balance: $\mathrm{T}(\log n)$ w.h.p.
- Our main contribution: analyze a better rule.
  - Choose node as in simple rule.
  - Split shallowest neighbor of that node.
  - Resulting load balance: $O(1)$ w.h.p.
    - First $O(1)$ with $O(\log n)$ pointers,

Previous Work

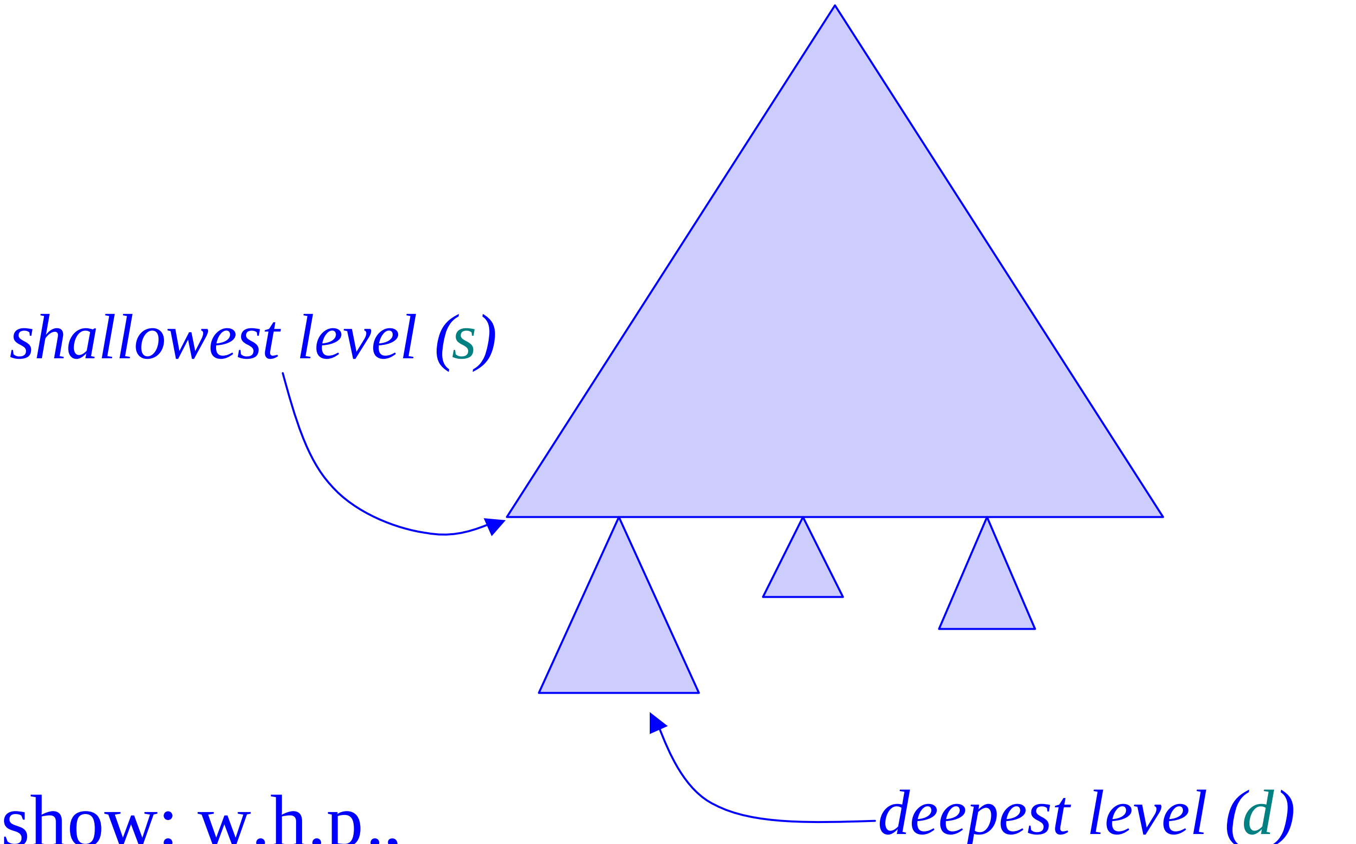
- CAN [RFHKS 2001]: k-Dim. Torus
  – Our hypercubic DHT is CAN with $k = 8$
  – Suggested both splitting rules.
    - No analysis of resulting load balance.

- Pastry [RD 2001], Tapestry [ZKJ 2001]
  – Based on [PRR 1997]
  – Pointers, queries, load balance, all $\Theta(\log n)$

More Previous Work

- Chord [SMKKB 2001]:
  - Pointers, queries, load balance, all $\mathrm{T}(\log n)$
  - Additional techniques:
    - load balance $O(1)$ but pointers $\mathrm{T}(\log^2 n)$
- Viceroy [MNR 2002]:
  - Pointers $O(1)$, queries $\mathrm{T}(\log n)$.
  - Does not address load balance.
  - Combine with technique from [SMKKB 2001]:
    - Results similar to ours.

Reduction to hypercube covering process



To show: w.h.p.,

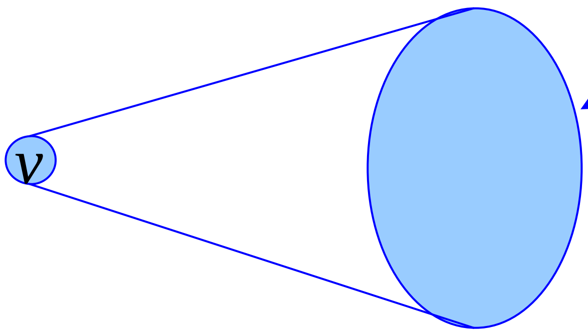
- $d - \log n$ not too large.
- $\log n - s$ not too large (hypercube process).

No node “falls behind”

- Consider progress of nodes at level s:
  - Each arrival is step of covering process.
  - Node is covered when it is split.
- Theorem:
  - Vertex covering process on n-node hypercube: $O(n)$ steps sufficient w.h.p.
- Corollary:
  - $\log n - s$ is always O(1) w.h.p.

Easier result: O(n loglog n) steps.

- loglog n phases of O(n) steps each.
- w.h.p.: at end of phase i:
  - Each node has $< log\ n / 2^i$ uncovered neighbors.

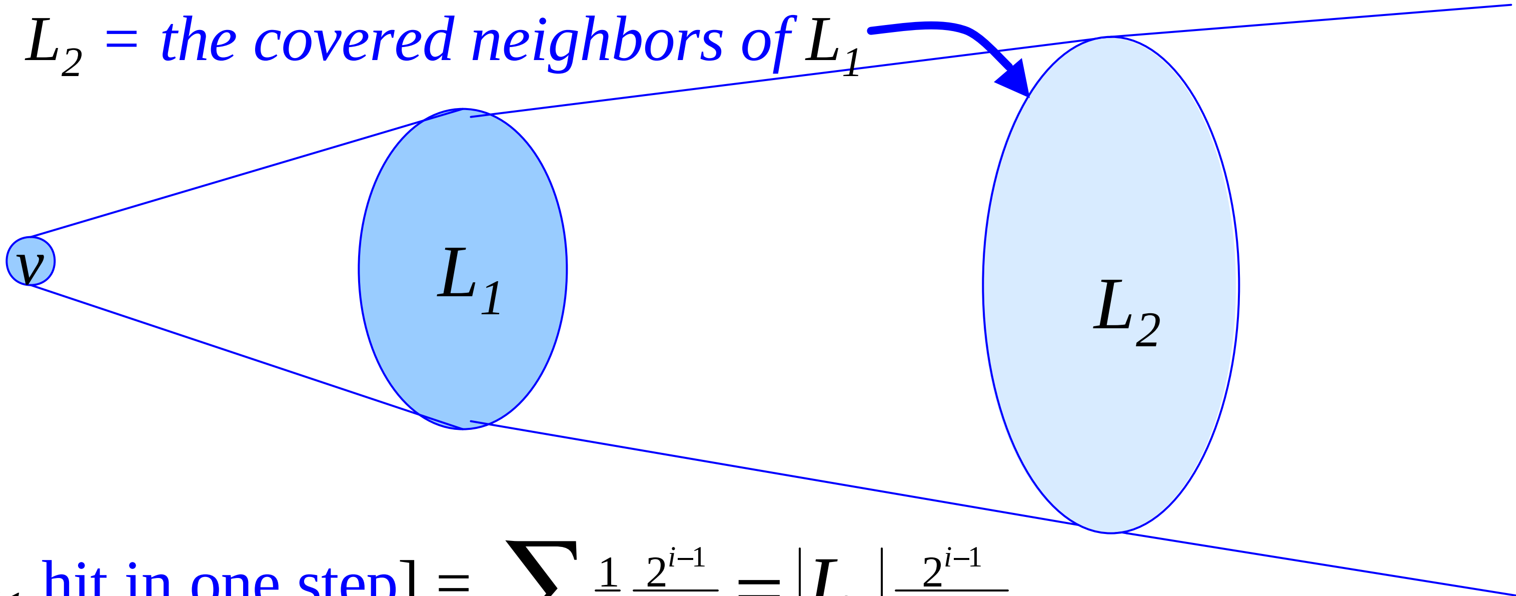


L_1: uncovered neighbors of v.

What is Pr[hit L_1 during step of phase i]?

- Assume $\log n / 2^{i-1} = |L_1| = \log n / 2^i$

Easier result: O(n loglog n) steps.



- $\Pr[L_1$ hit in one step$] = \sum_{u \in L_2} \frac{1}{n} \frac{2^{i-1}}{\log n} = |L_2| \frac{2^{i-1}}{n \log n}$
- $|L_2| = \frac{1}{4} |L_1| \log n = \frac{\log^2 n}{2^{i+2}}$

•Thus: $\Pr[L_1$ hit in one step$] = \frac{\log n}{8n}$

•Chernoff bounds: Pr[Any L_1 not halved in phase]: $1/\text{poly}(n)$.

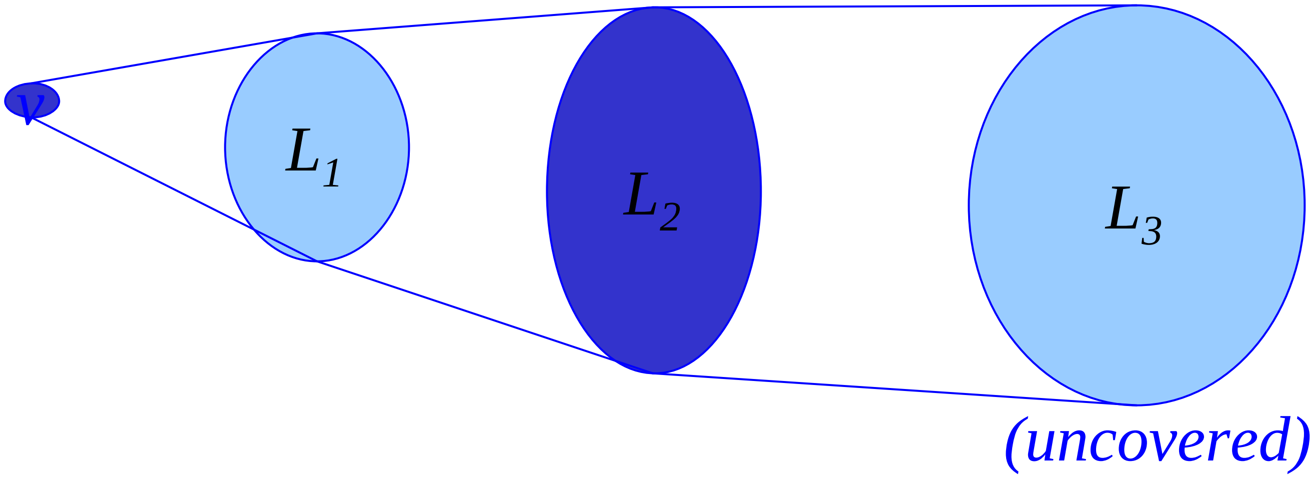
Why O(n) seems possible.

Phase i: expected steps until L_1 halved:

- L_1 has size $\log n / 2^i$.
- $\Pr[L_1$ hit in one step$] = \frac{\log n}{8n}$
- Expected steps: $O\left(\frac{n}{2^i}\right)$
- $O(n)$ steps guarantees $O(\log n)$ expected hits.
    - $\Pr[\text{not halving}] = 1/n^c$

Intuition for a bound of O(n).

- Idea:



- Phase i:
  - $O\left(\frac{ni}{2^i}\right)$ steps to shrink L_3
    - L_3 larger, so more likely to be close to expectation
  - Pr[L_1 hit in a step] = $\frac{2^i \log n}{n}$
  - $O\left(\frac{n}{2^i}\right)$ steps sufficient to halve all L_1s whp.

Extensions:

- Sufficient (whp) for any *d*-regular graph:

$$O\left(n\left(1+\frac{\log n \cdot \log d}{d}\right)\right)$$

- Sufficient whp for random *d*-regular graphs:

$$O\left(n\left(1+\frac{\log n}{d}\right)\right)$$

- All results hold if never cover chosen node.

Open problems for stochastic process

- Adding deletions
- Improving the constants
- $O(n)$ for all $\log n$-regular graphs ?