Sybil-proof Mechanisms in Query Incentive Networks

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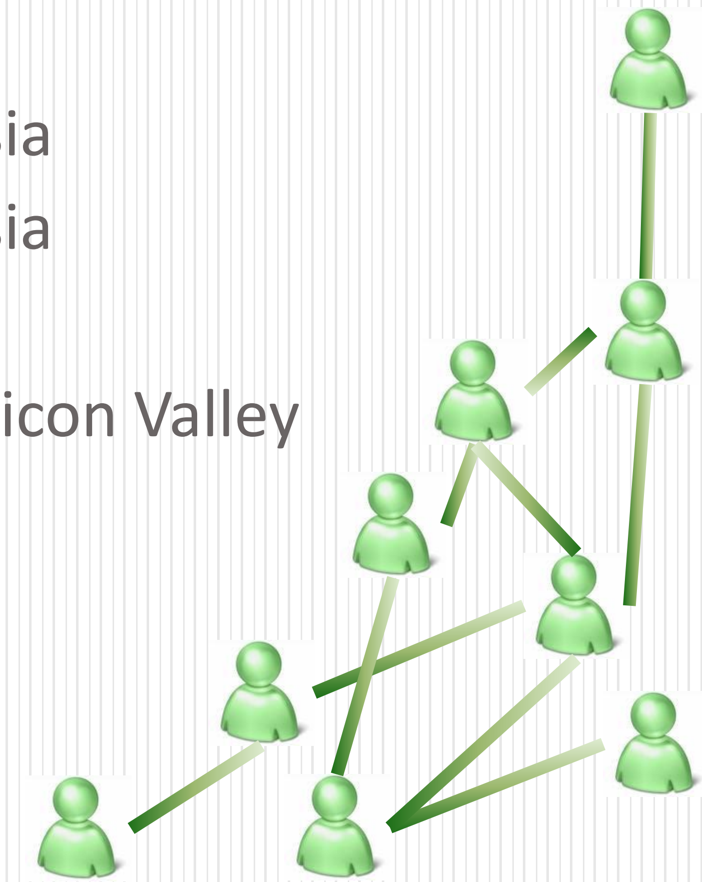

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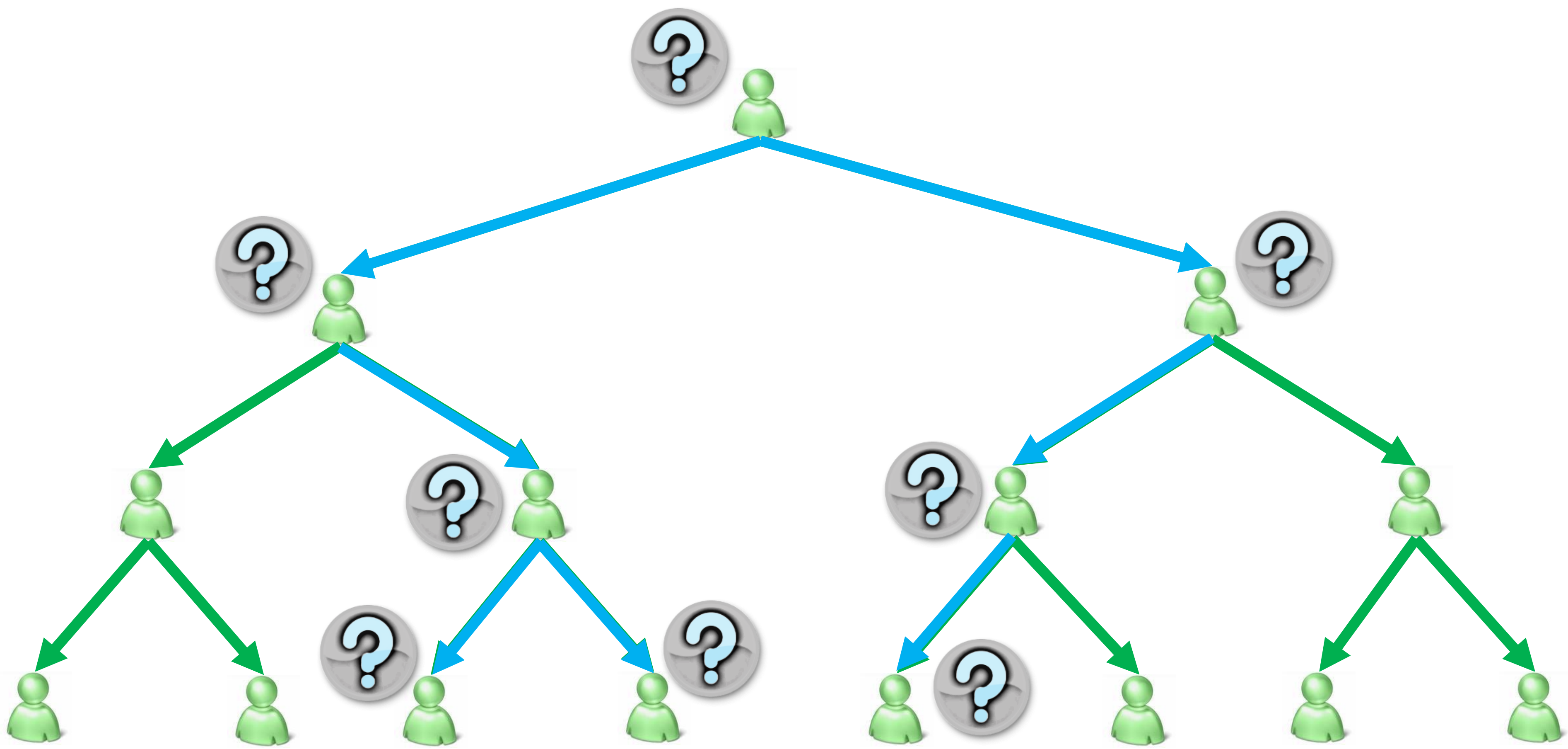
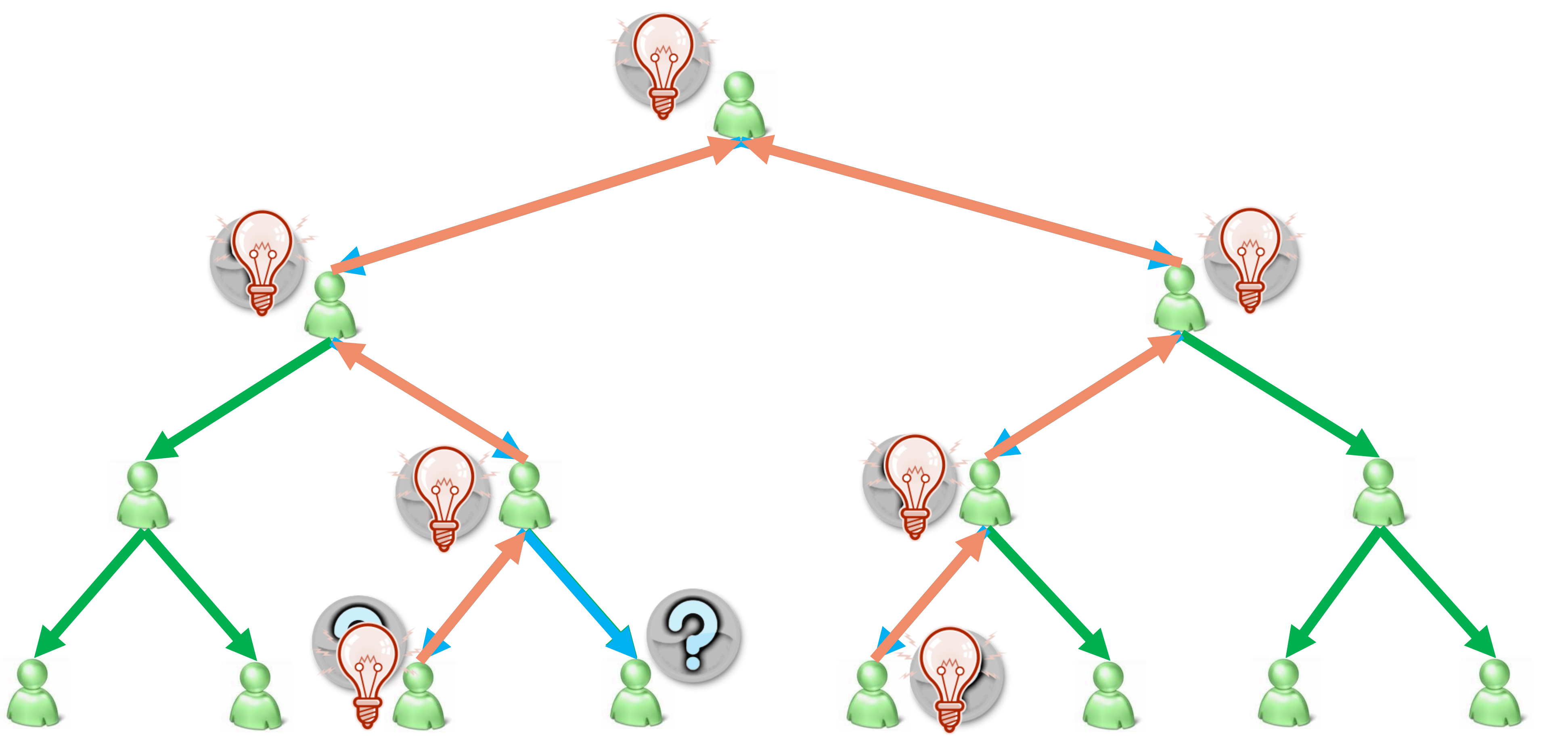
Query incentive networks

- Acquire rare information from networked agents
  - The system is decentralized with limited connectivity
  - Only small number of agents in the crowd have answers
  - Agents are self-interested
- Call for incentive mechanisms
  - Encourage answer-holders to return answers
  - Encourage non-answer-holders to participate, i.e., propagate the query and route the answers
  - Discourage disruptive behaviors (e.g. sybil-attacks)

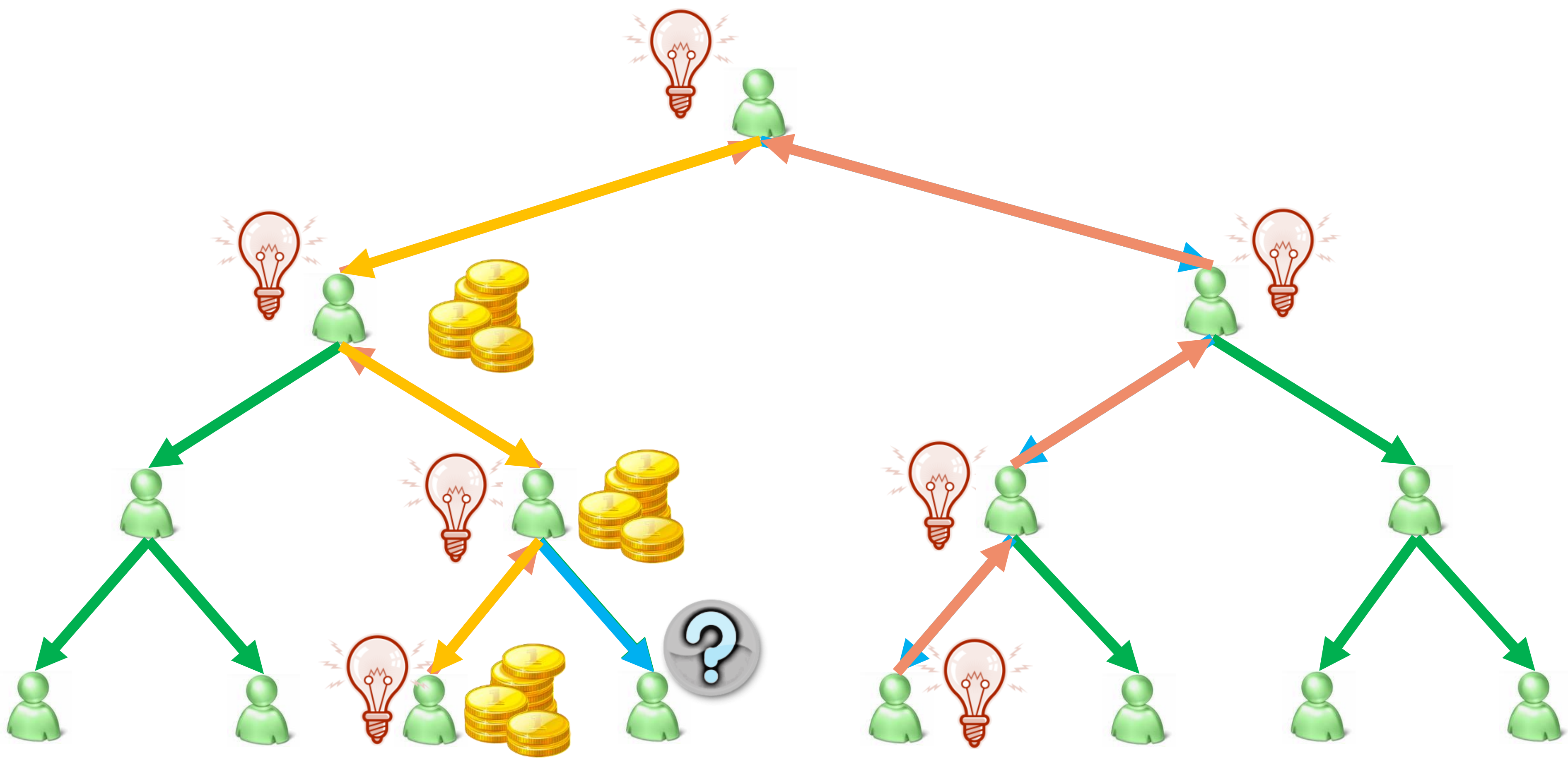
Query incentive networks: propagating the query



Query incentive networks: propagating the answer



Query incentive networks: selecting winning path and distributing rewards



Key aspects of QIN

- Random branching process
- Low probability of holding the answer
- Winning path selection
- Reward allocation along the path

Network Model

- Following [Kleinberg and Raghavan 2005]
- Branching process in an underlying d-ary tree
  - Offspring distribution $D = \{c_i\}$ for $i = \{0,1,\ldots,d\}$ with branching factor b
  - Each node u samples its # of children $C(u)$ from D
  - u randomly selects $C(u)$ children to connect
  - The final tree is the connected component containing the root.
- Answer distribution
  - Each node has an answer with probability $p = 1/n$. On expectation, we need $O(n)$ nodes to retrieve an answer
- Cost
  - Free to propagate, unit cost to forward back an answer

Fixed-payment contract [Kleinberg and Raghavan 2005]

Contract	• u enters a contract with its parent on a fixed price • Condition: the selected answer is in u's subtree
The strategy function of u	• Mapping payment from parent to its children
Fundamental tradeoff	• Higher chance of reaching answers • Smaller reward when the answer is selected.
Efficiency	• Constant probability case: (1) $b > 2$: $O(\log n)$ (2) $b < 2$: $\Omega(n)$ • High probability case, prob. $1 - 1/n$: $\Omega(n)$ [Arcaute, Kirsch, Kumar, Liben-Nowell, and Vassilvitskii 2007]

Split contract [Cebrian, Coviello, Vattani, and Voulgaris 2012]

- Root offers a final reward for an answer
- Each node u enters a contract with its parent on the splitting ratio $q < 1$
  - Eg., if the reward of u at hand (after settling payments with its children) is r, u's parent will grab $r \cdot q$, leaving $r \cdot (1 - q)$ to u.
- The strategy function of u
  - mapping from the ratio by its parent to ratio to the children
- Efficiency respect to branching factor b
  - Constant probability case: $O(\log n)$
  - High probability case, prob. $1 - 1/n$: $\Omega(n)$
  - Intuition: conditional rewards does not depend on the distance to root => easy to propagate

Sybil proof mechanism

- Sybil attack:
  - a user fakes a chain of fake users connecting his parent and his children
  - try to collect more rewards collectively from the fake users
- Sybil-proof mechanism
  - a mechanism in which users have no incentive to create sybils
- Split-contract mechanism is not Sybil-proof
  - a user can fake a child and sign a contract with the fake child such that the child gets all the money

Our offer of Direct Referral Mechanism

Incentive mechanisms	• An answer selection scheme • A global reward scheme, [vs. (local) contract-based scheme]
Sybil-proof	• DR mechanism is Sybil-proof • Fixed-payment contract is “Sybil-proof” • Split contract is not Sybil-proof
Efficient	• h is desired level of propagation • $O(nh^2)$ on a chain. (optimal) • $O(h^2)$ on a branching process
Simple	• Mainly reward: answer holder, as well as its parent • Others receive minimum compensation

Related work on Sybil-proofness

- Bitcoin system [Babaioff, Dobzinski, Oren, and Zohar 2012]
  - Network is part of the design (additional freedom)
- Multi-level marketing [e.g., Drucker, and Fleischer 2012]
  - Fixed cost for sybil (price), enforcing sybil-proofness by capping referral fee
- Others:
  - Lottery tree [Douceur and Moscibroda 2007], reputation mechanisms [Cheng and Friedman 2005], combinatorial auctions [Todo et al. 2009], social choice [Wagman and Conitzer 2008; Conitzer and Yokoo 2010], and cost-sharing games [Penna et al. 2009].
  - All with static configuration

Incentive mechanisms

- Answer selection scheme
  - Random Walk (RW): Each step, we select one child uniformly at random from those children who have reported answers
  - Shortest Path (SP): Perform RW process only for closest answers
- Global reward allocation scheme
  - $f: (\mathrm{Tree}, P) \rightarrow [1, \infty]^{|P|}$
  - Oblivious reward scheme: f only depends on $|P|$
- Remark: contract-based mechanisms imply global reward allocation schemes

Direct referral mechanisms

- Adopt the Shortest Path answer selection scheme
- Reward the answer holder and its direct referral (parent)
  - Other routing nodes receives minimum compensation, e.g., unit payment
  - Oblivious reward scheme, can be characterized as
    - $r(i, s)$: the reward for the i-th agent, when the selected answer is at level $i + s$
    - $r(i, s) = 1$ for $s > 1$

DR mechanism on chains

- Desired level of exploration h

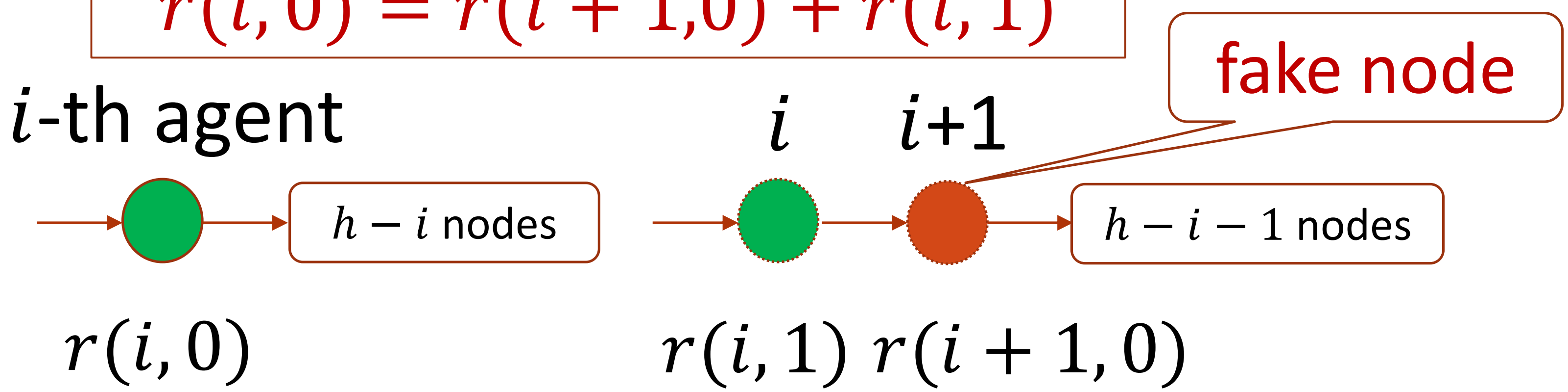
$$r(i,s) = \begin{cases} n \cdot R_{i+1} + P_{h-i-1}. & \text{if } i \leq h-1 \wedge s = 1, \\ \sum_{t=i}^{h-1} r(t,1) + 1, & \text{if } 1 \leq i \leq h \wedge s = 0, \\ 1 & i + s \leq h \wedge s > 1, \\ 0, & \text{otherwise.} \end{cases}$$

- $P_i = \sum_{j=1}^{i} \frac{1}{n}\left(1 - \frac{1}{n}\right)^{j-1}$:
  - the probability that there is an answer in i consecutive nodes
- $R_i = \frac{r(i,1)}{n} + \left(1 - \frac{1}{n}\right) P_{h-i-1} = R_{i+1} + P_{h-i-1}$:
  - the expected reward of the i-th node (w.o. answer)
- Notice: $r(i,0) = r(i+1,0) + r(i,1)$

Sybil-proofness of DR scheme on chains

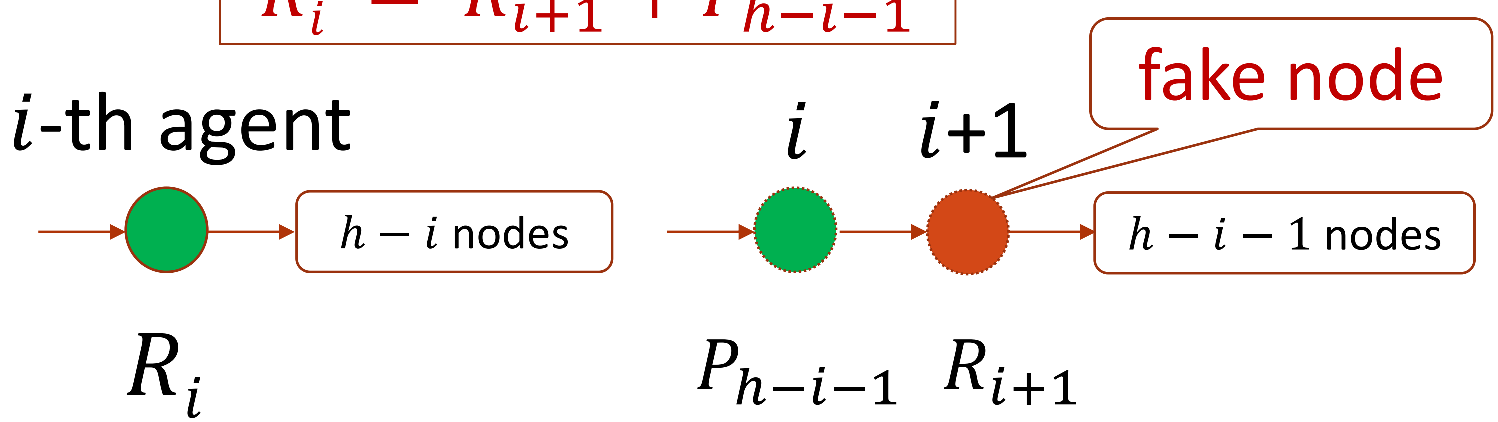
- Sybil-proof for nodes with answers

$$r(i,0) = r(i+1,0) + r(i,1)$$



- Sybil-proof for nodes without answers

$$R_i = R_{i+1} + P_{h-i-1}$$



Efficiency of DR scheme on chains

- Efficiency:
  - $R_i = O(h)$
  - $r(i,1) = O(nR_{i+1}) \; = \; O(nh)$
  - $r(i,0) = O(\sum_{j \geq i} r(i,1)) \; = \; O(nh^2)$
- It is optimal on chains

DR on branching process: Enforcing Sybil-proofness

- λ_i : the probability that the closest answer is at level i
- Node u at level i, suppose u has no answer,
  - Pr[u receives the direct referral fee] = $\frac{\lambda_{i+1}}{d^i}$
  - Pr[u receives compensation] = $\frac{\sum_{i+1\le k\le h} \lambda_k}{d^i}$
  - For any $i < j < h$, generating $(j - i + 1)$ total sybils

$$r(i,1) \cdot \frac{\lambda_{i+1}}{d^i} \ge r(j,1) \cdot \frac{\lambda_{i+1}}{d^i} + (j-i) \cdot \frac{\sum_{i+1\le k\le h} \lambda_k}{d^i}$$

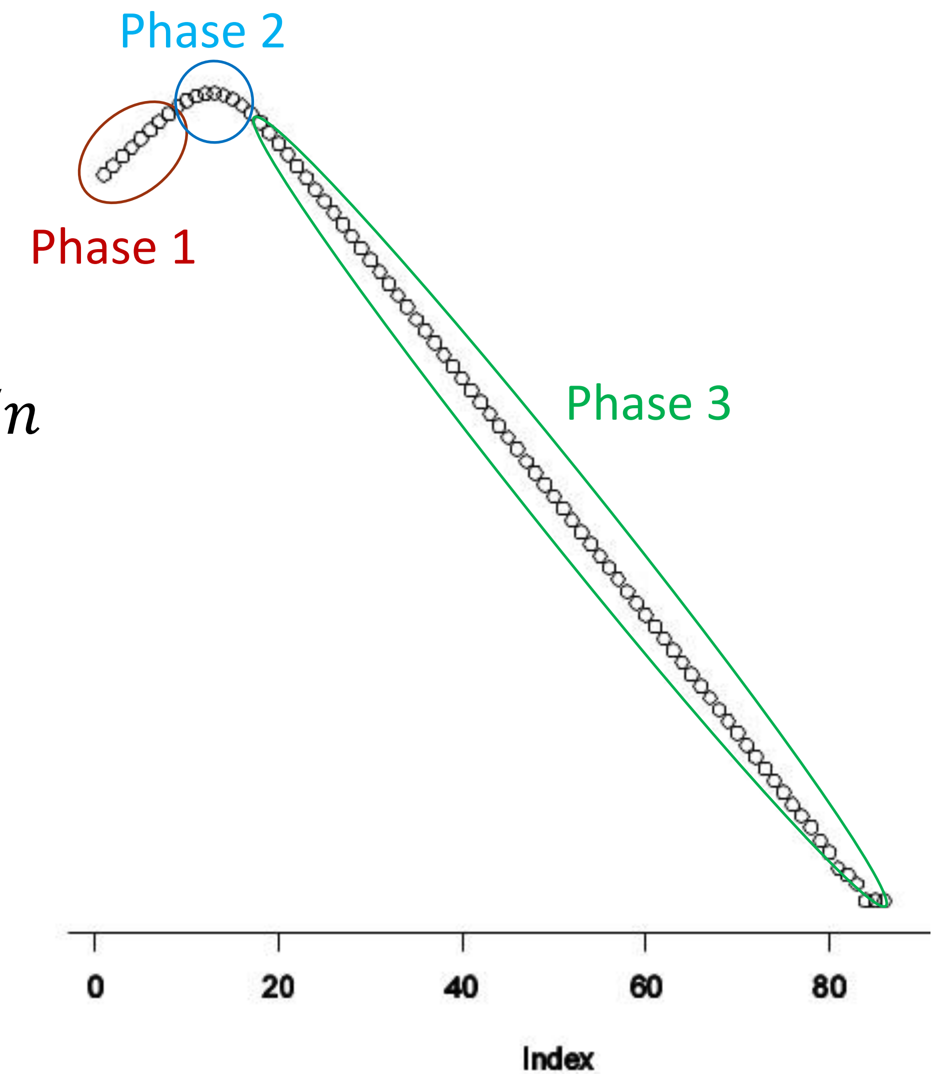
Thus, we have:

$$r(i,1) = \max_{i+1\le j\le h} \left[r(j,1) + \frac{j-i}{\lambda_{i+1}} \cdot \sum_{\ell=i+1}^{h} \lambda_\ell \right]$$

$r(i,0) = 1 + \sum_{\ell=i}^{h} r(i,1)$ (for node with answer)

Branching processes: a key property

- The distribution of the closest answer
  - λ_i : the probability that the closest answer is at level i
  - Assumption: $b > 1$ is a constant
  - Asymptotic behavior resp. to $p = 1/n$
- Property: single-peaked sequence.
  - Phrase 1: geometrically increases to a constant
  - Phrase 2: stays constant for constant number of levels
  - Phrase 3: geometrically decreases



Log plot ($b = 1.5, d = 5, p = 1/1000$)

Efficiency

- $r(i,1) \approx r(i+1,1) + \frac{1}{\lambda_{i+1}} \cdot \sum_{\ell=i+1}^{h} \lambda_\ell$
- For i in phrase 3 (geometrically decreasing phrase)
  - $r(i,1) = O(h)$
- For i in the increasing phrase
  - $r(i,1) \cdot \lambda_{i+1} \leq r(i+1,1) \cdot \lambda_{i+2} + 1 = O(h)$
- The total referral fee is
  - $\sum_{i=1}^{h-1} r(i,1)\lambda_{i+1} = O(h^2)$

  - It is similar to bound the reward to answer holders

Conclusion

- Formulation of incentive mechanisms
  - Permits systematic study on various incentive mechanisms
- Direct referral mechanisms
  - Simple structure
  - Sybil-proof
  - Efficient on expectation
- Open questions
  - More efficient mechanisms, lower bounds.
  - Improving the worst case cost: $\Omega(n)$ --- a consequence: it is not collusion-free

Thanks!
and
questions?