# Influence diffusion dynamics and influence maximization in complex social networks


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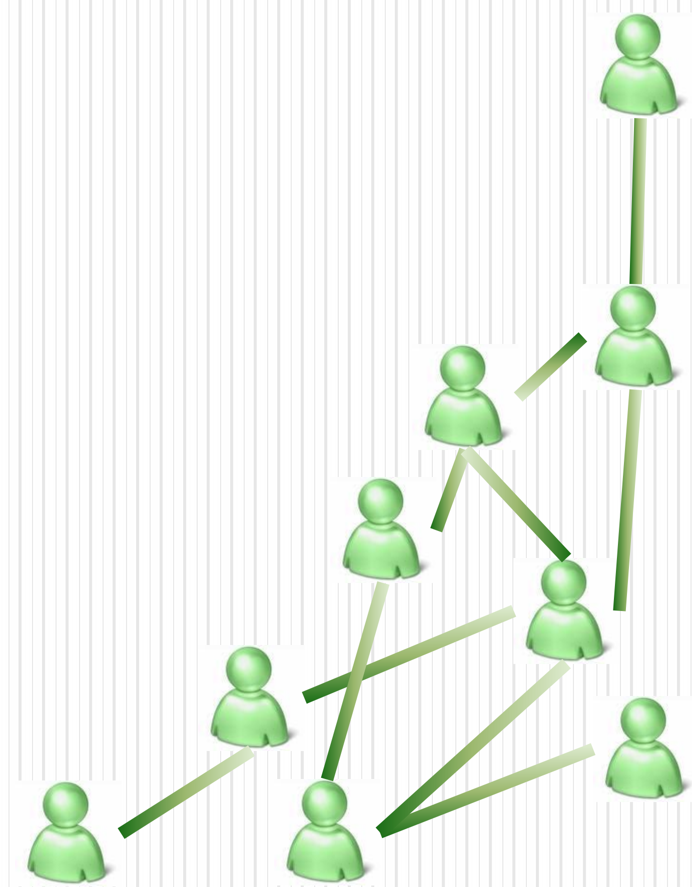
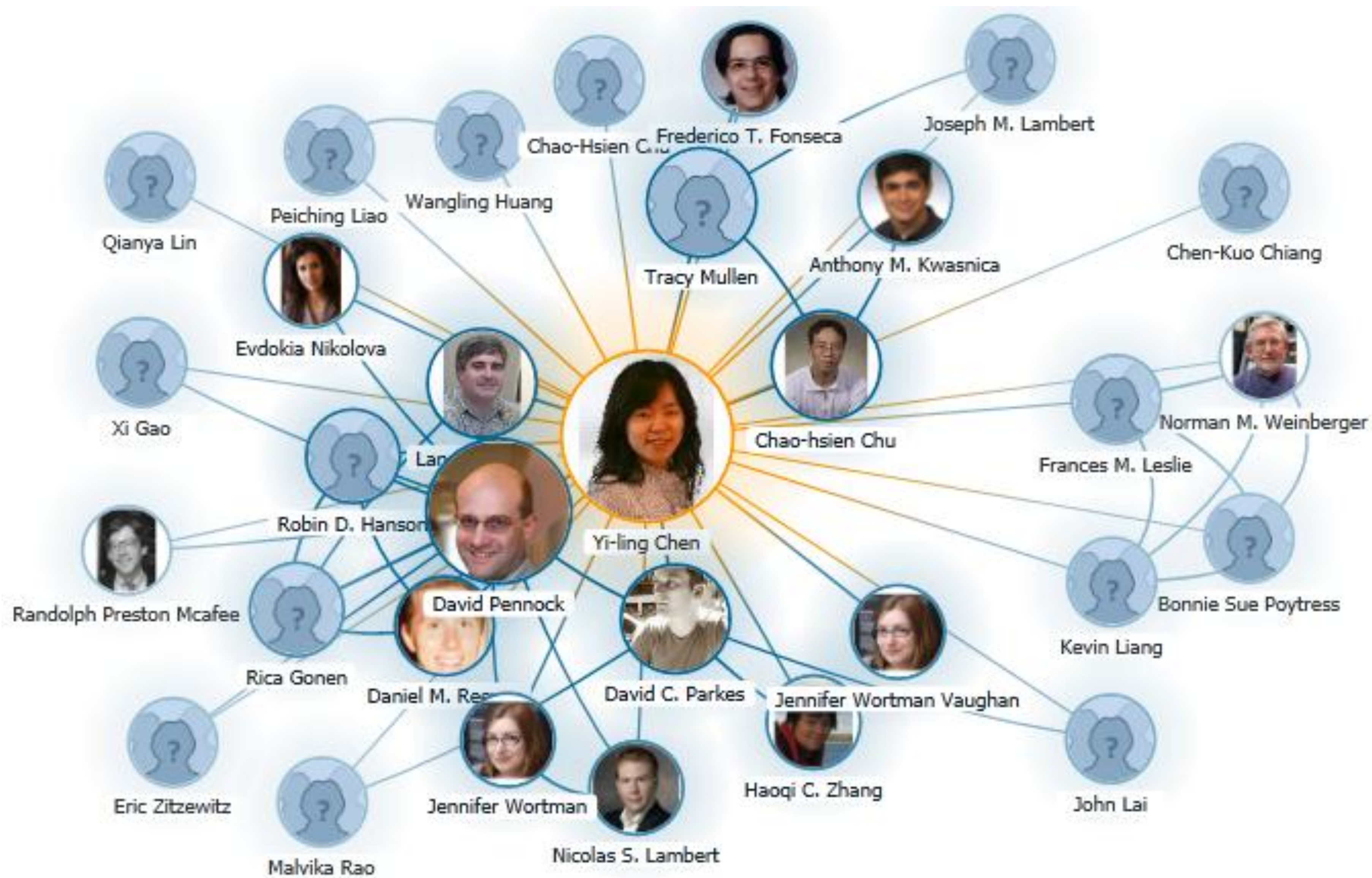


Harvard, Oct. 18, 2011

# (Social) networks are natural phenomena



# Booming of online social networks

# Opportunities and challenges on the research of online social networks

- Opportunities
  - massive data set, real time, dynamic, open
  - help social scientists to understand social interactions in a large scale
  - help marketing people to target to the right audience
  - help economists to understand social economic networks
- Challenges
  - graph structure based large scale data analysis
  - scalable graph algorithm design
  - realistic modeling of network formation, evolution, and information/influence diffusion in networks

# Our recent work on social network related research

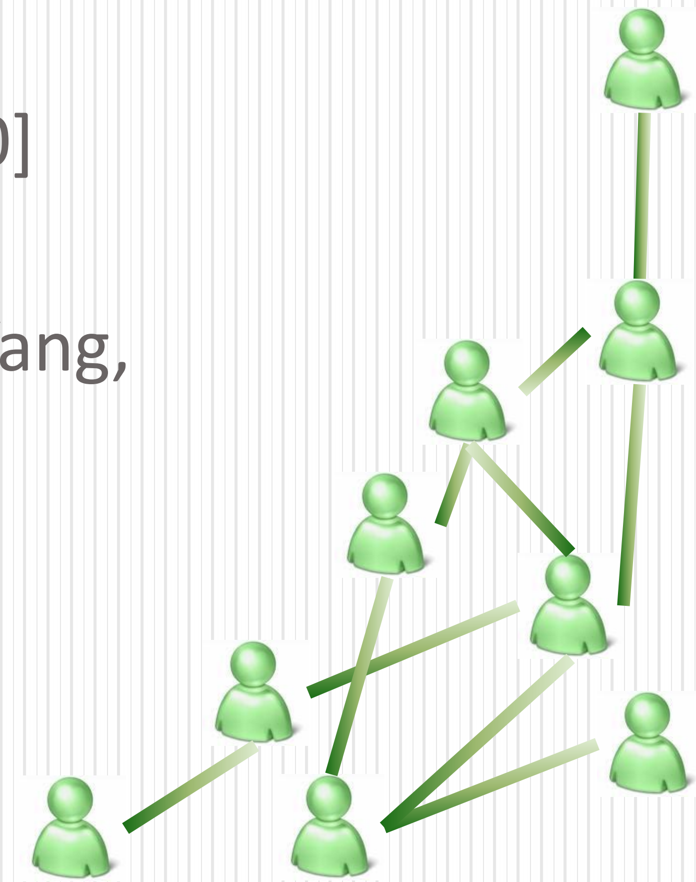
- Social influence in social networks
  - scalable influence maximization
  - influence maximization with complex social interactions
- Game-theoretic based modeling of social interaction
  - bounded budget betweenness centrality game for network formation
  - Optimal pricing in social networks with networked effect
- Fundamental algorithms for large graphs
  - fast distance queries in power-law graphs
  - game-theoretic approach to community detection

# Scalable Influence Maximization in Social Networks

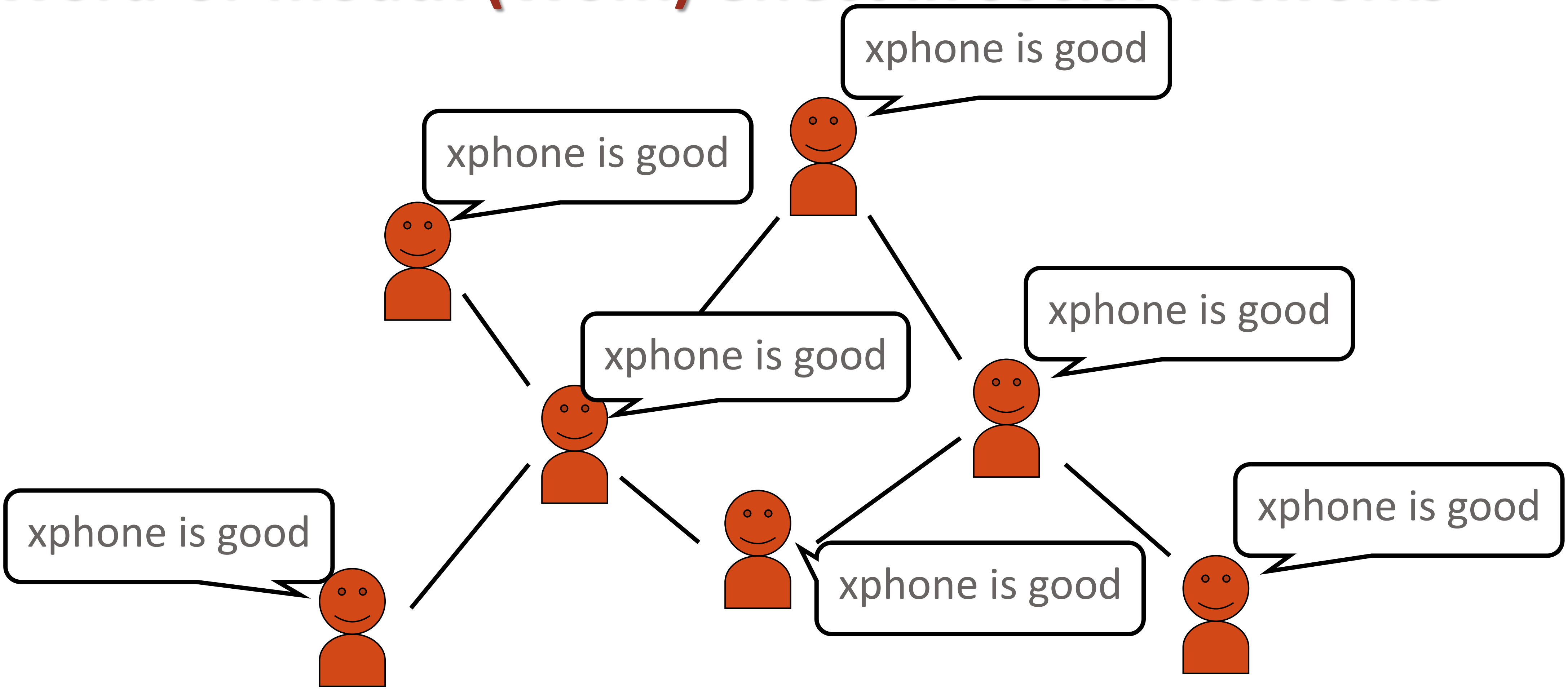
[KDD'09, KDD'10, ICDM'10]

Collaborators:

Chi Wang, Yajun Wang, Siyu Yang, Yifei Yuan, Li Zhang



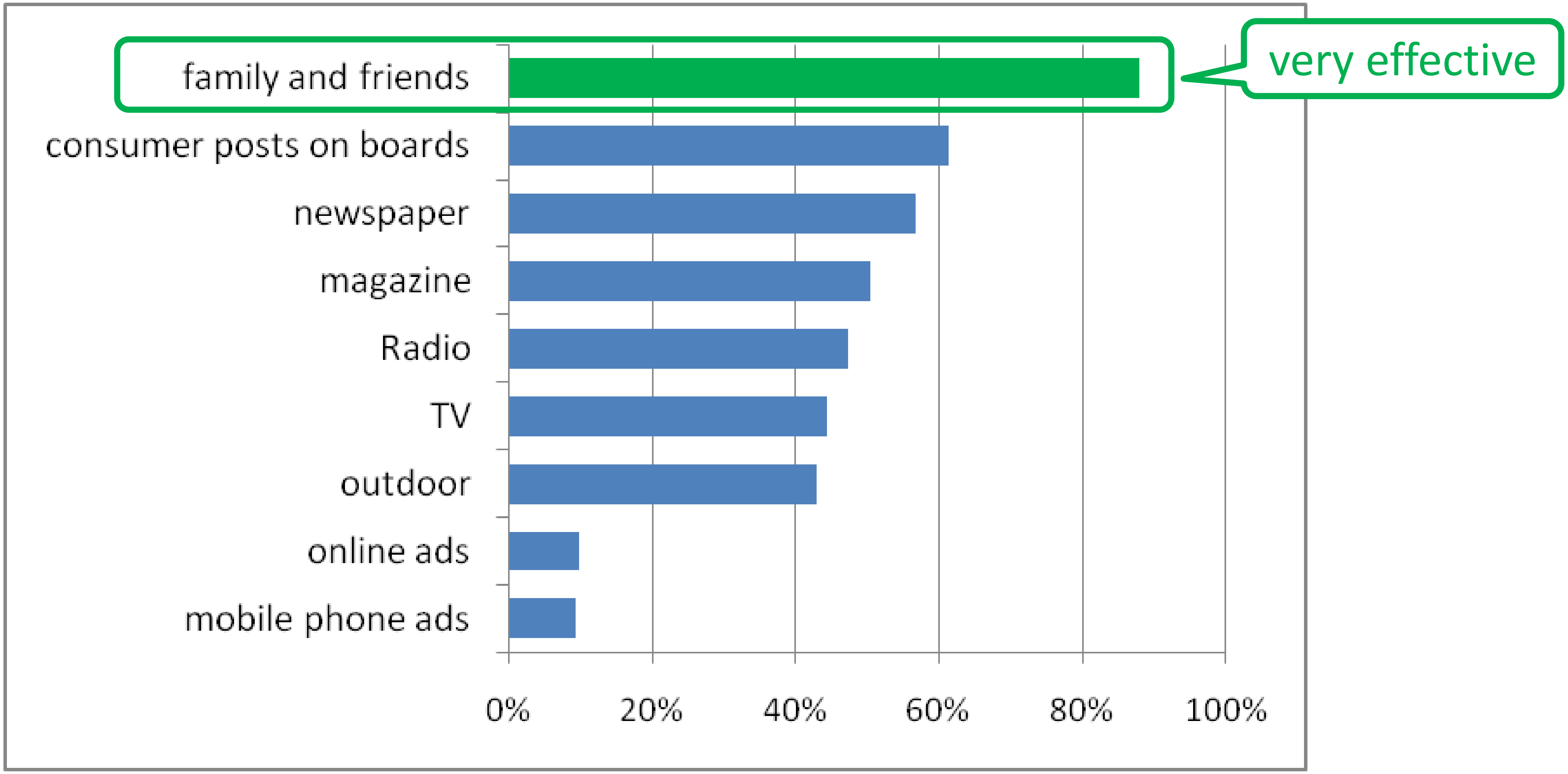
# Word-of-mouth (WoM) effect in social networks




- Word-of-mouth effect is believed to be a promising advertising strategy.
- Increasing popularity of online social networks may enable large scale WoM marketing

# WoM (or Viral) Marketing

level of trust on different types of ads *



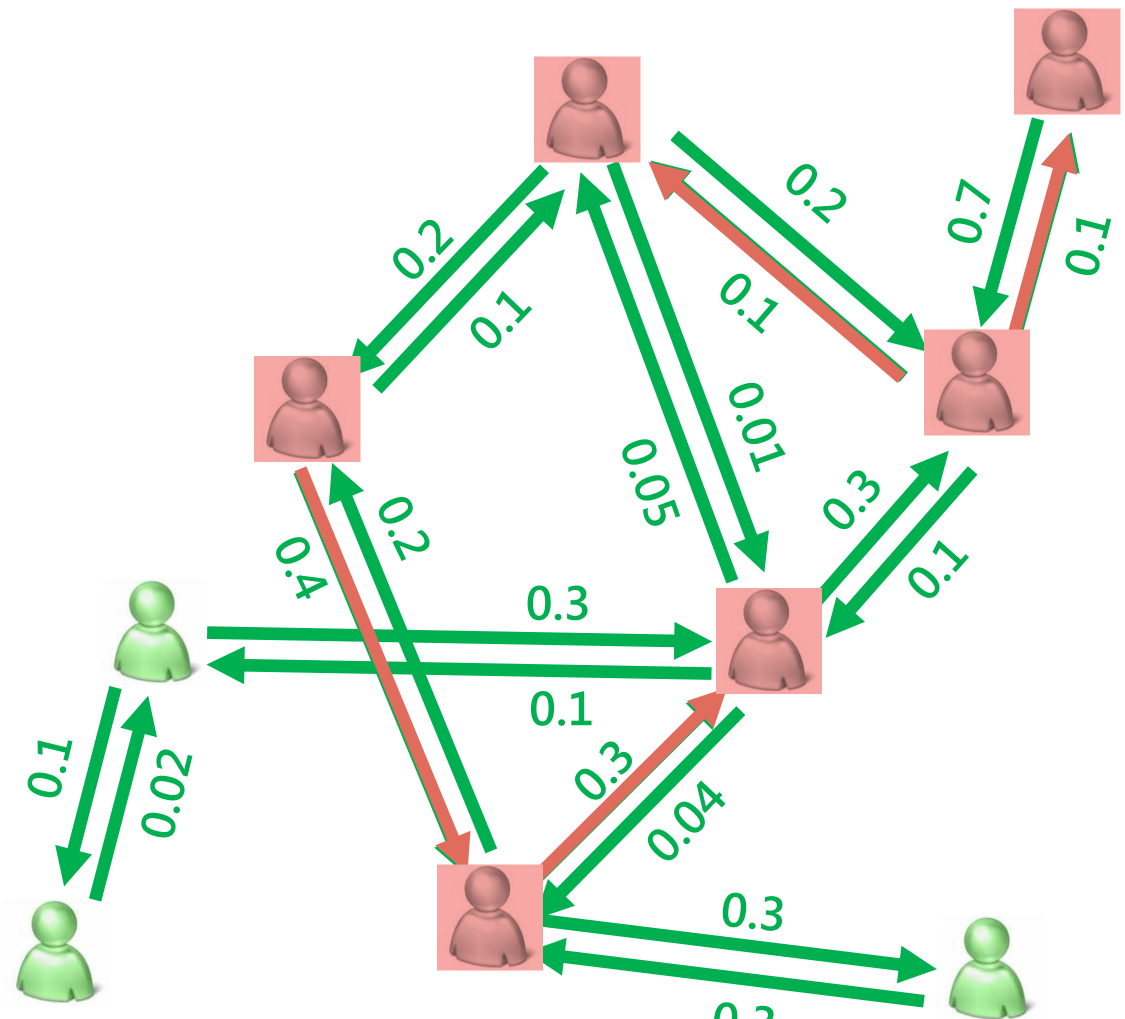

*source from Forrester Research and Intelliseek

# Two key components for studying WoM marketing

- Modeling influence diffusion dynamics, prior work includes:
  - independent cascade (IC) model
  - linear threshold (LT) model
  - voter model
- Influence maximization, prior work includes:
  - greedy approximation algorithm
  - centrality based heuristics

# The Problem of Influence Maximization

- Social influence graph
  - vertices are individuals
  - links are social relationships
  - number p(u,v) on a directed link from u to v is the probability that v is activated by u after u is activated
- Independent cascade model
  - initially some *seed* nodes are activated
  - At each step, each newly activated node u activates its neighbor v with probability p(u,v)
- Influence maximization:
  - find *k* seeds that generate the largest expected influence



# Prior Work

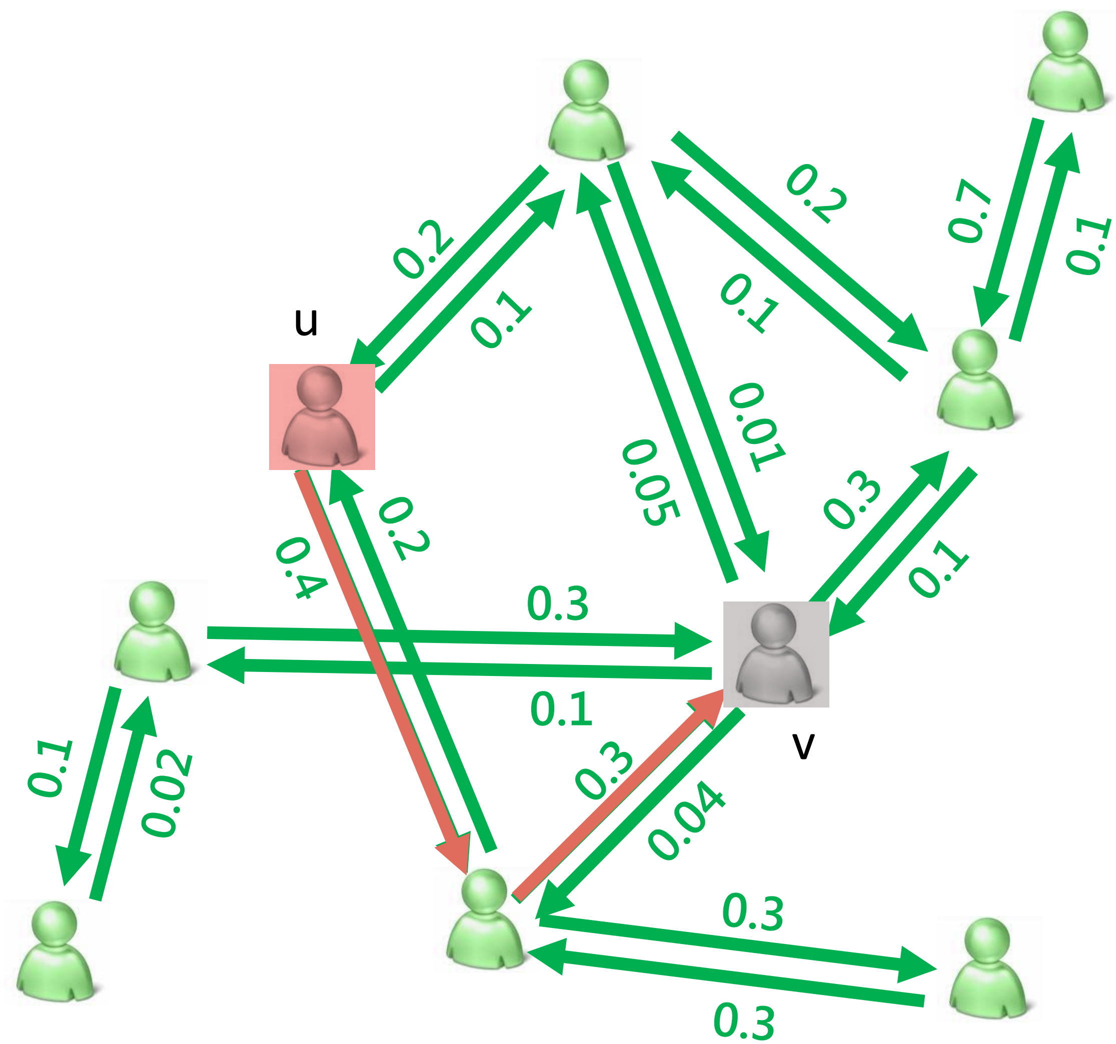
- Influence maximization as a discrete optimization problem proposed by Kempe, Kleinberg, and Tardos, 2003
  - Introduce Independent Cascade (IC) and Linear Threshold (LT) models
  - Finding optimal solution is provably hard (NP-hard)
  - Greedy approximation algorithm, 63% approximation of the optimal solution
    - select k seeds in k iterations
    - in each iteration,  select one seed that provides the largest marginal increase in influence spread
- Several subsequent studies improved the running time
- Serious drawback:
  - very slow, not scalable: > 3 hrs on a 30k node graph for 50 seeds

# Our Work

- Exact influence computation is #P hard, for both IC and LT models --- computation bottleneck
- Design new heuristics
  - MIA (maximum influence arborescence) heuristic [KDD'10]
    - for general independent cascade model (more realistic)
    - $10^3$ speedup --- from hours to seconds
    - influence spread close to that of the greedy algorithm of [KKT'03]
  - Degree discount heuristic [KDD'09]
    - for uniform independent cascade model
    - $10^6$ speedup --- from hours to milliseconds
  - LDAG (local directed acyclic graph) heuristic [ICDM'10]
    - for the linear threshold model
    - $10^3$ speedup --- from hours to seconds

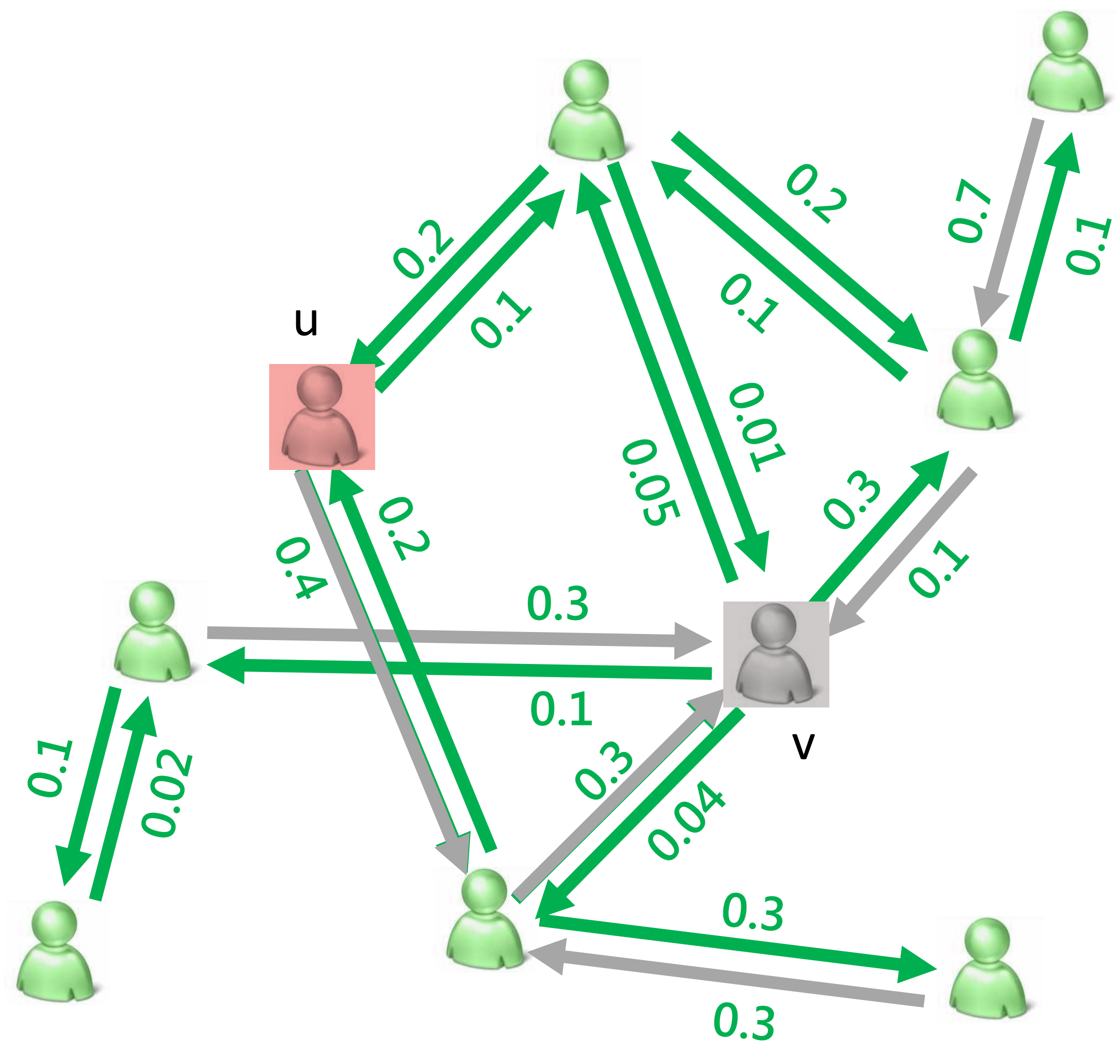
# Maximum Influence Arborescence (MIA) Heuristic

- For any pair of nodes u and v, find the maximum influence path (MIP) from u to v
- ignore MIPs with too small probabilities ( < parameter $\theta$)



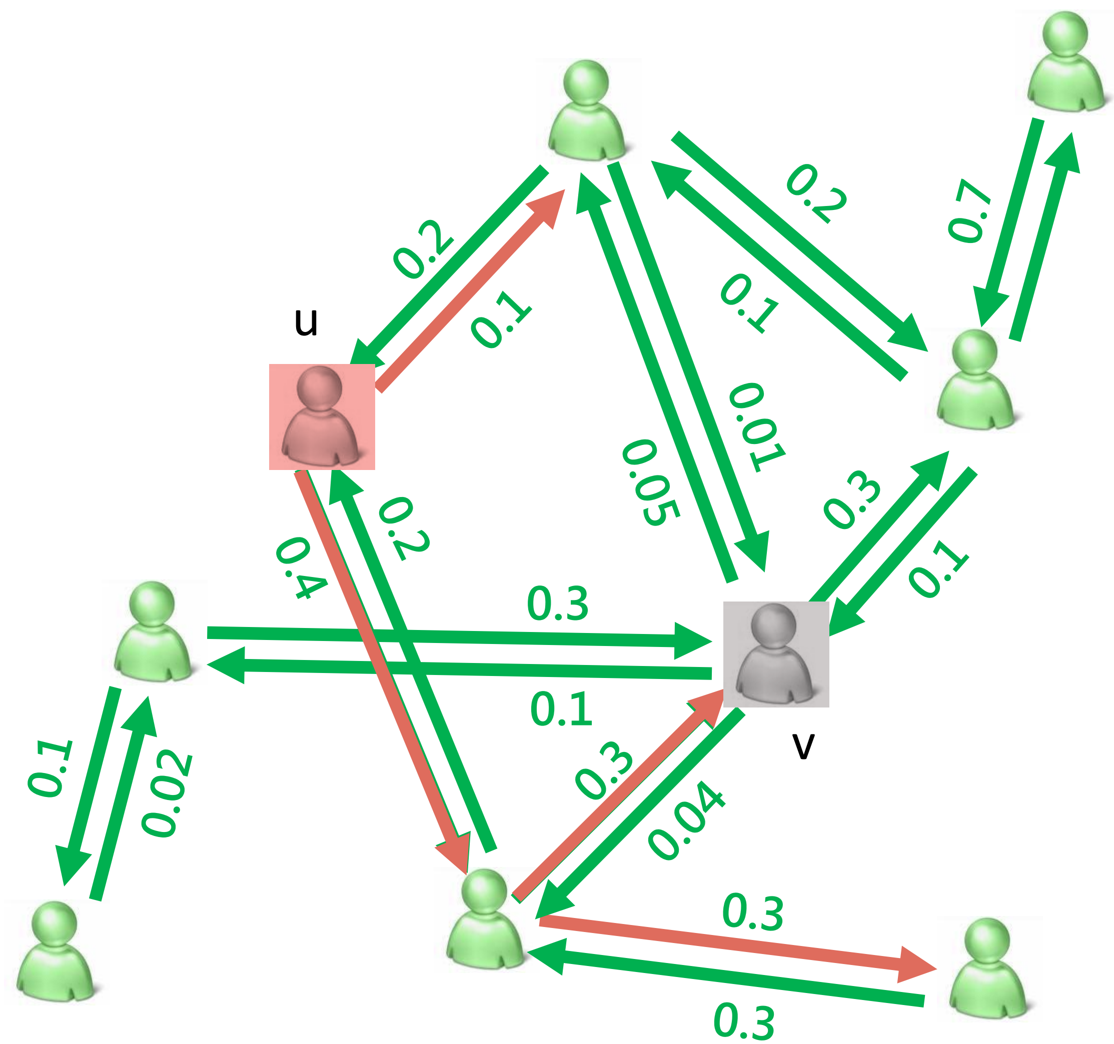
# MIA Heuristic (cont'd)

- Local influence regions
  - for every node v, all MIPs to v form its maximum influence in-arborescence (MIIA )



# MIA Heuristic (cont'd)

- Local influence regions
  - for every node v, all MIPs to v form its maximum influence in-arborescence (MIIA )
  - for every node u, all MIPs from u form its maximum influence out-arborescence (MIOA )
  - computing MIAs and the influence through MIAs is fast



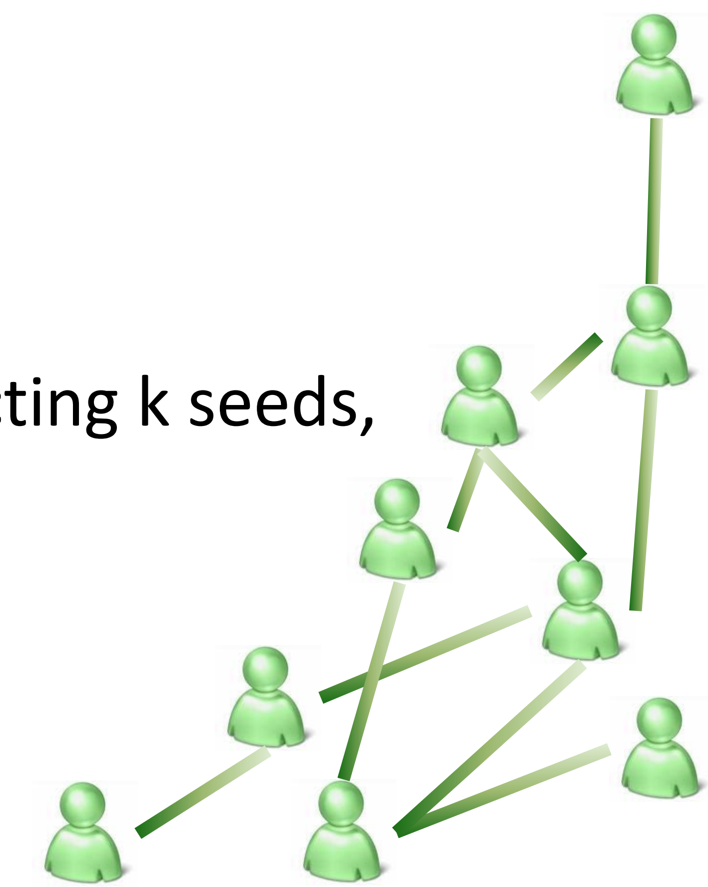
# MIA Heuristic III: Computing Influence through the MIA structure

- Recursive computation of activation probability ap(u) of a node u in its in-arborescence, given a seed set S

**Algorithm 2** $ap(u, S, MIIA(v, \theta))$

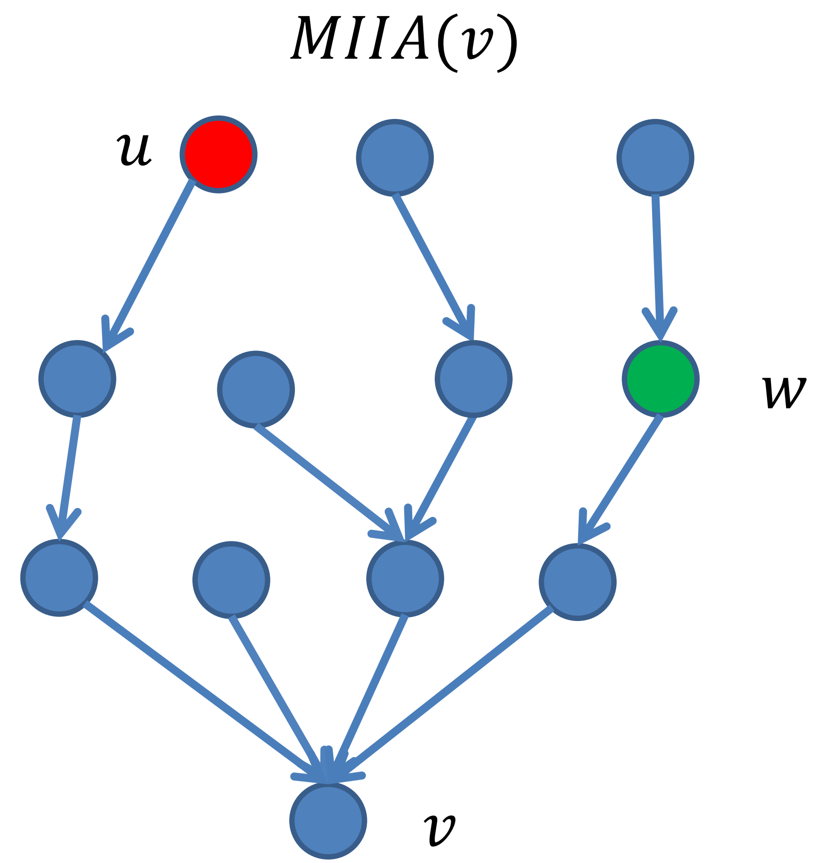
**if** $u \in S$ **then**
  $ap(u) = 1$
**else if** $Ch(u) = \emptyset$ **then**
  $ap(u) = 0$
**else**
  $ap(u) = 1 - \Pi_{w \in Ch(u)}(1 - ap(w) \cdot pp(w, u))$
**end if**

- Can be used in the greedy algorithm for selecting k seeds, but not efficient enough



# MIA Heuristic IV: Efficient updates on incremental activation probabilities

- $u$ is the new seed in $MIIA(v)$
- Naive update: for each candidate $w$, redo the computation in the previous page to compute $w$'s incremental influence to $v$
  - $O(|MIIA(v)|^2)$
- Fast update: based on linear relationship of activation probabilities between any node $w$ and root $v$, update incremental influence of all $w$'s to $v$ in two passes
  - $O(|MIIA(v)|)$

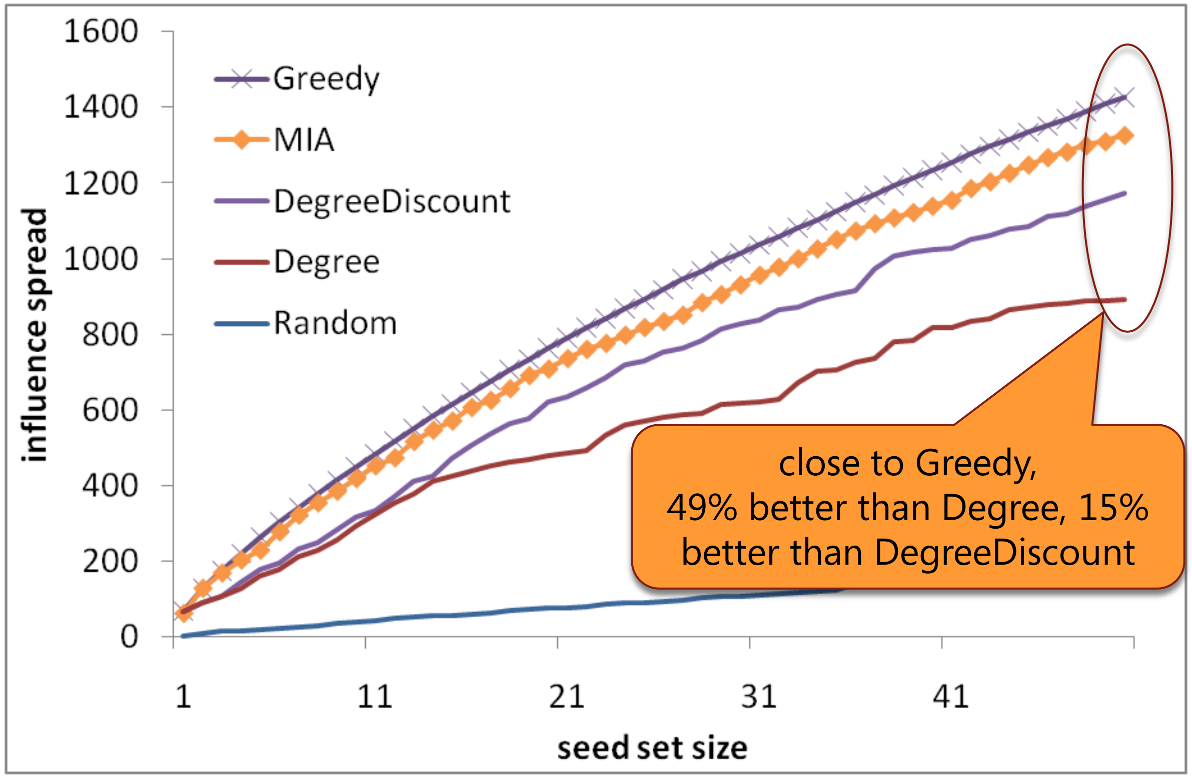


# MIA Heuristic (cont'd)

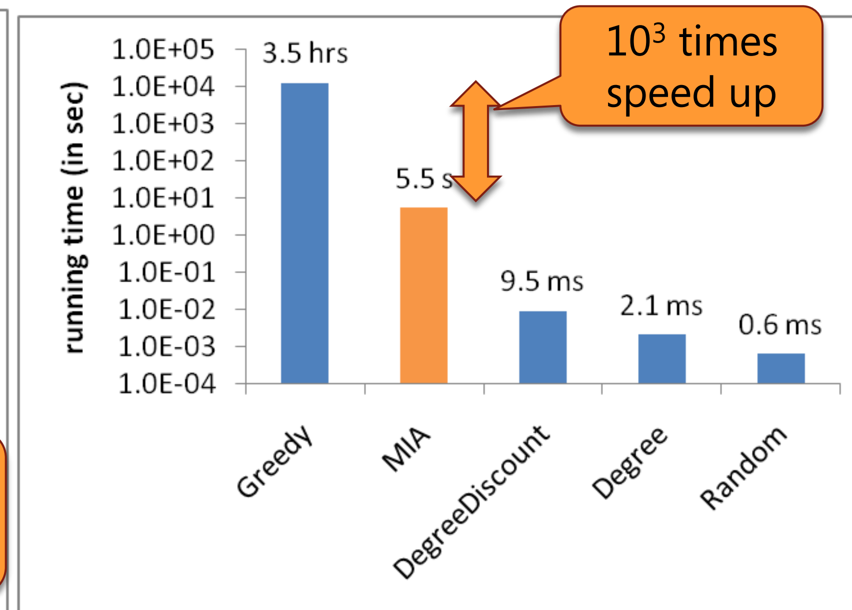
- Iteration between two steps
  - Selecting the node v giving the largest marginal influence
  - Update MIAs after selecting v as the seed
- Key features:
  - updates are local
  - local updates are linear to the local tree structure

# Experiment Results on MIA heuristic

Influence spread vs. seed set size



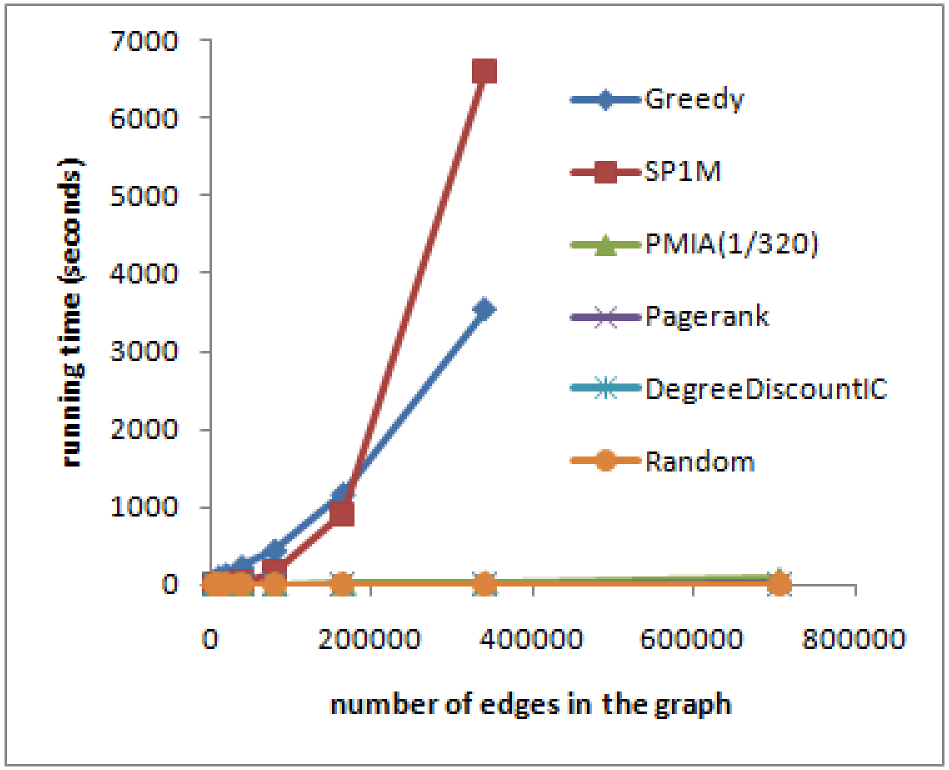

running time




Experiment setup:

- 35k nodes from coauthorship graph in physics archive
- influence probability to a node v = 1 / (# of neighbors of v)
- running time is for selecting 50 seeds

# Scalability of MIA heuristic




Experiment setup:

- synthesized graphs of different sizes generated from power-law graph model
- influence probability to a node v = 1 / (# of neighbors of v)
- running time is for selecting 50 seeds

# Summary

- Scalable influence maximization algorithms
  - MixedGreedy and DegreeDiscount [KDD'09]
  - PMIA for the IC model [KDD'10]
  - LDAG for the LT model [ICDM'10]
- PMIA/LDAG have become state-of-the-art benchmark algorithms for Inf. Max.
- Collective citation count above 110 in less than 2 years

# Handling Complex Social Interactions

[SDM'11, others under submissions]

Alex Collins, Rachel Cummings, Te Ke, Zhenming Liu, David Rincon, Xiaorui Sun, Yajun Wang, Wei Wei, Yifei Yuan, Xinran He, Guojie Song, Yanhua Li, Katie Everett, Zhi-Li Zhang

# Handling complex social interactions

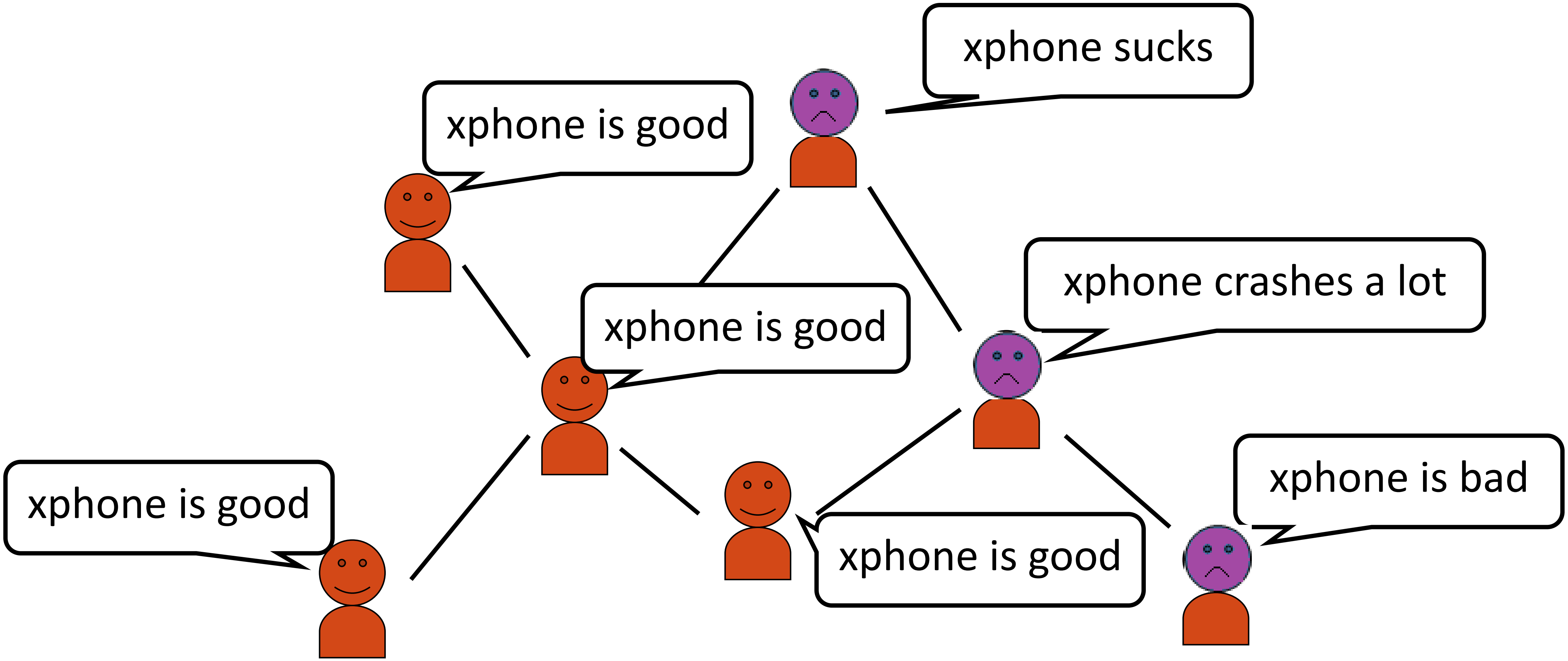
- people may dislike a product after usage and spread bad words about it
- a competing product may compete for social influence in the social network
- social relationships may be friends or foes

# Our solutions

- people may dislike a product after usage and spread bad words about it
  - IC-N model and MIA-N algorithm
- a competing product may compete for social influence in the social network
  - CLT model and CLDAG algorithm for influence blocking maximization
- social relationships may be friends or foes
  - voter model in signed networks with exact inf. max. algorithm

# IC-N model and MIA-N algorithm for the emergence and propagation of negative opinions

# Negative opinions may emerge and propagate

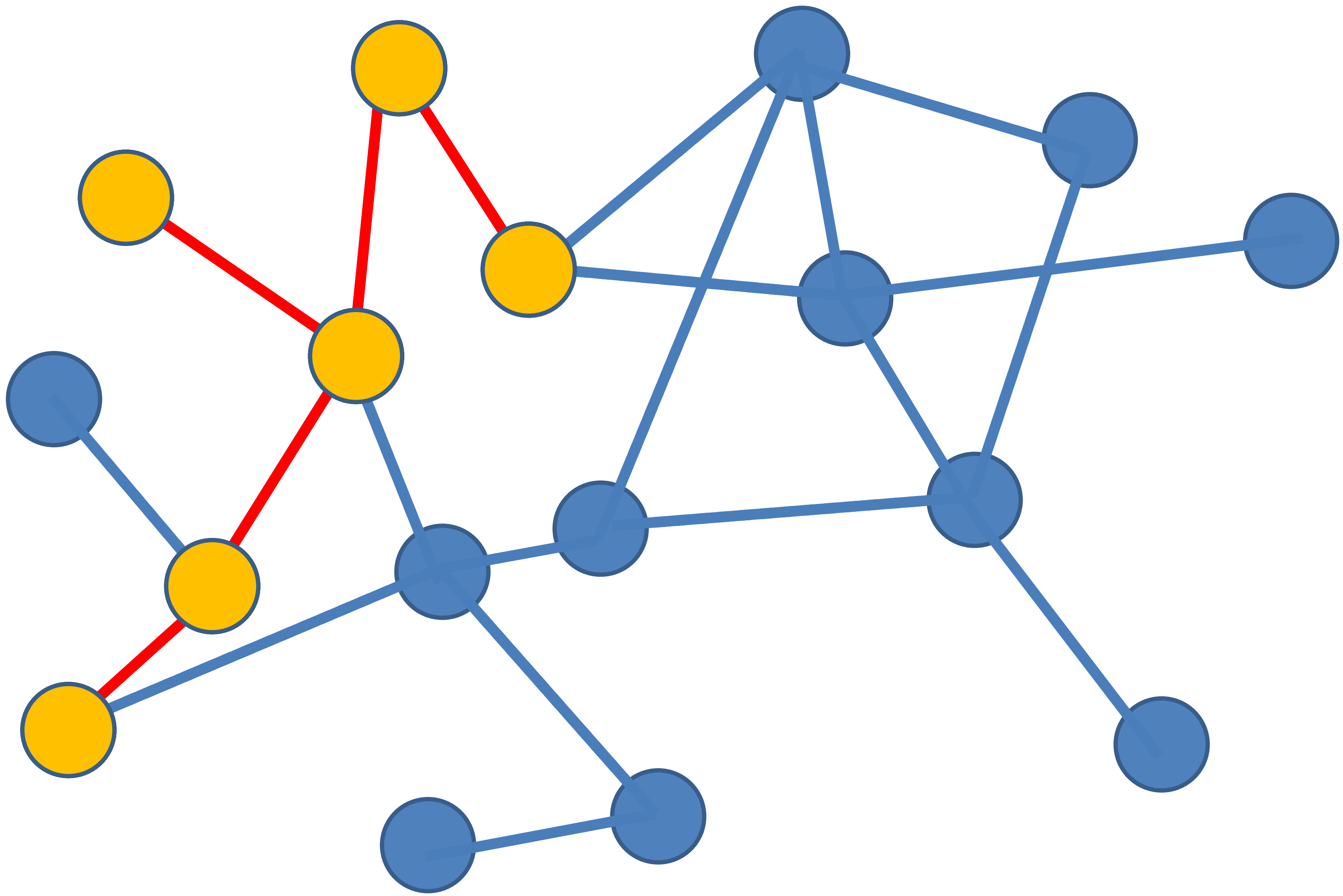



- Negative opinions originates from poor product/service quality
- Negative opinions may be more contagious --- *negativity bias*

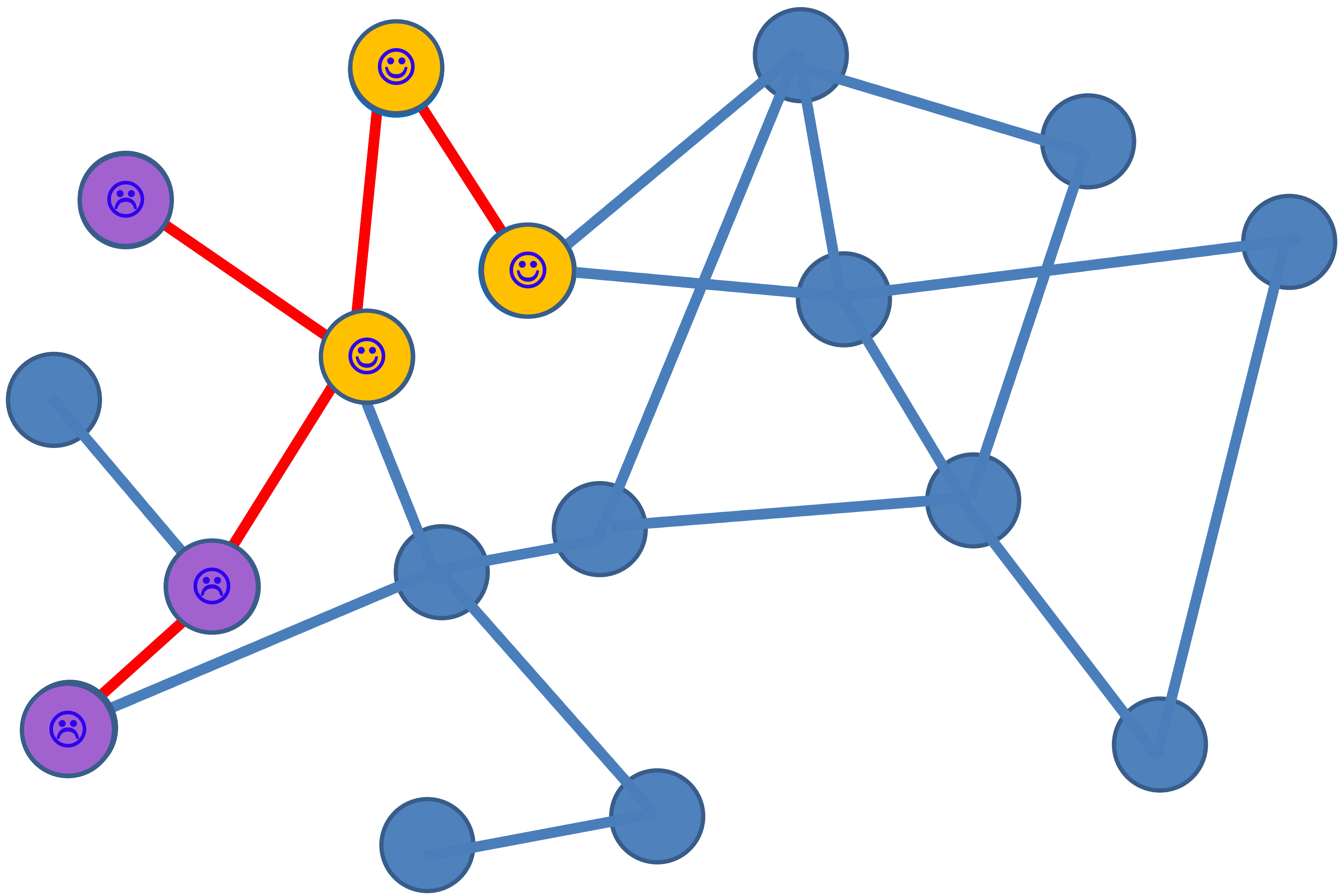
# Negative opinion model

- Extention of the independent cascade model
- The quality of the product to be advertised is characterized by the quality factor (QF) $q \in [0,1]$.
- Each node could be in 3 states
  - Inactive, positive, and negative.
- When node $v$ becomes active,
  - If the influencer is negative, the activated influencee is also negative (negative node generates negative opinions).
  - If the influencer is positive, the activated influencee
    - is positive with prob. $q$.
    - is negative with prob. $1 - q$.
  - If multiple activations of a node occur at the same step, randomly pick one
  - Asymmetric --- negativity bias

# Independent Cascading Process (**without** considering QF)



# Independent Cascading Process (**when** considering QF)



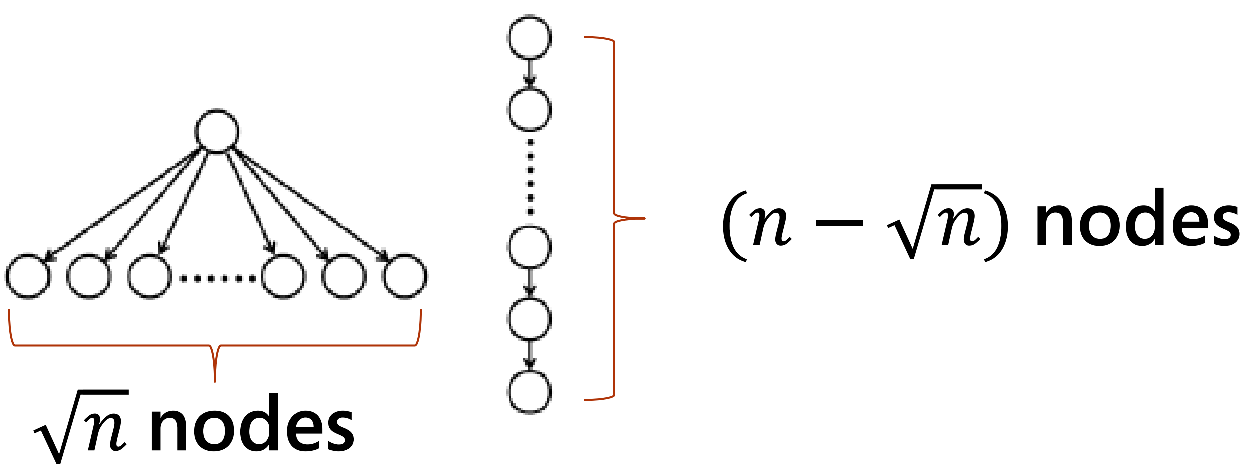
# Our results (1)

- Complexity and approximation algorithm results

| Scenario | Objective function | Algorithm result | Negative result |
|---|---|---|---|
| General directed graphs | Maximize expected positive nodes | $(1-\frac{1}{e}-\varepsilon)$-approx alg, due to submodularity | Exact sol. is NP hard. |
| General directed graphs | Maximize expected (positive – negative) nodes. | Exists an $(1-\frac{1}{e}-\varepsilon)$-approx alg. Only when $q$ is sufficiently large | Same as above |
| Directed graphs with different $q$ for different people | Maximize expected positive nodes | NA | Objective is non-submodular |

# Our results (2)

- Q: is the knowledge of quality factor important?
  - guess a "universally good" value $q$ so that regardless of the actual quality factor, the seeds are good?
  - No: ∃ social networks s.t. a wrong guess of $q$ could lead to a much worse result than the optimal one. ($\Theta(\sqrt{n/k})$)
  - Intuition: which one seed to select in the following graph?

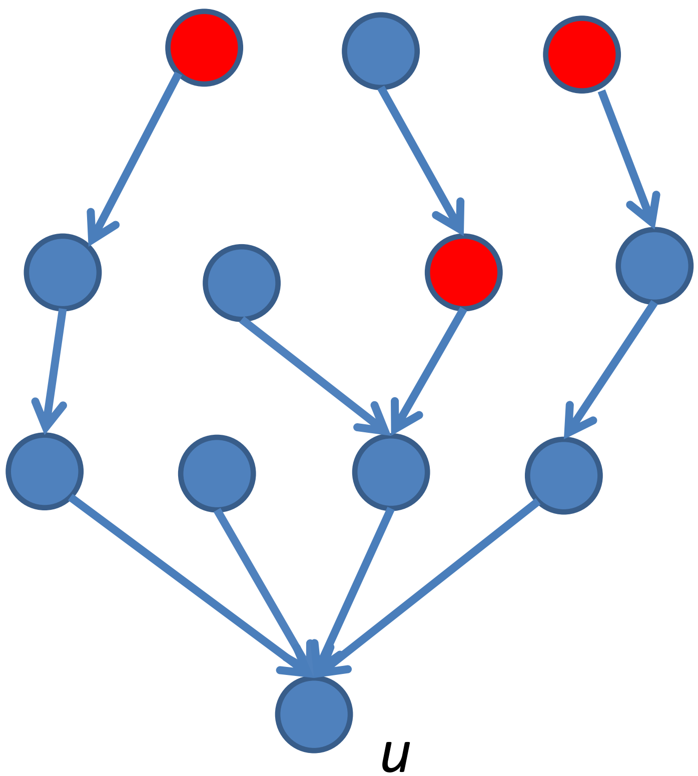


# Our results (3)

- Q: what is the bottleneck of the approx. alg.
  - Given a specific seed set *S*, can we evaluate the expected number of positive nodes?
    - In general, #P-hard; can use Monte Carlo to approximate.
    - But exists efficient exact algorithm for arborescence (trees).
  - Developed scalable heuristic MIA-N based on influence calculation alg. for arborescences.

# Computation in directed trees (in-arborescences)

- Without negative opinions, a simple recursion computes the activation probability of $u$:
  - $ap(u) = 1 - \prod_{w \in N^{in}(u)} (1 - ap(w)p(w,u))$
- Difficulty with negative opinions: needs to know whether the neighbors of $u$ is positive or negative --- because of negativity bias



# Solutions for in-arborescences

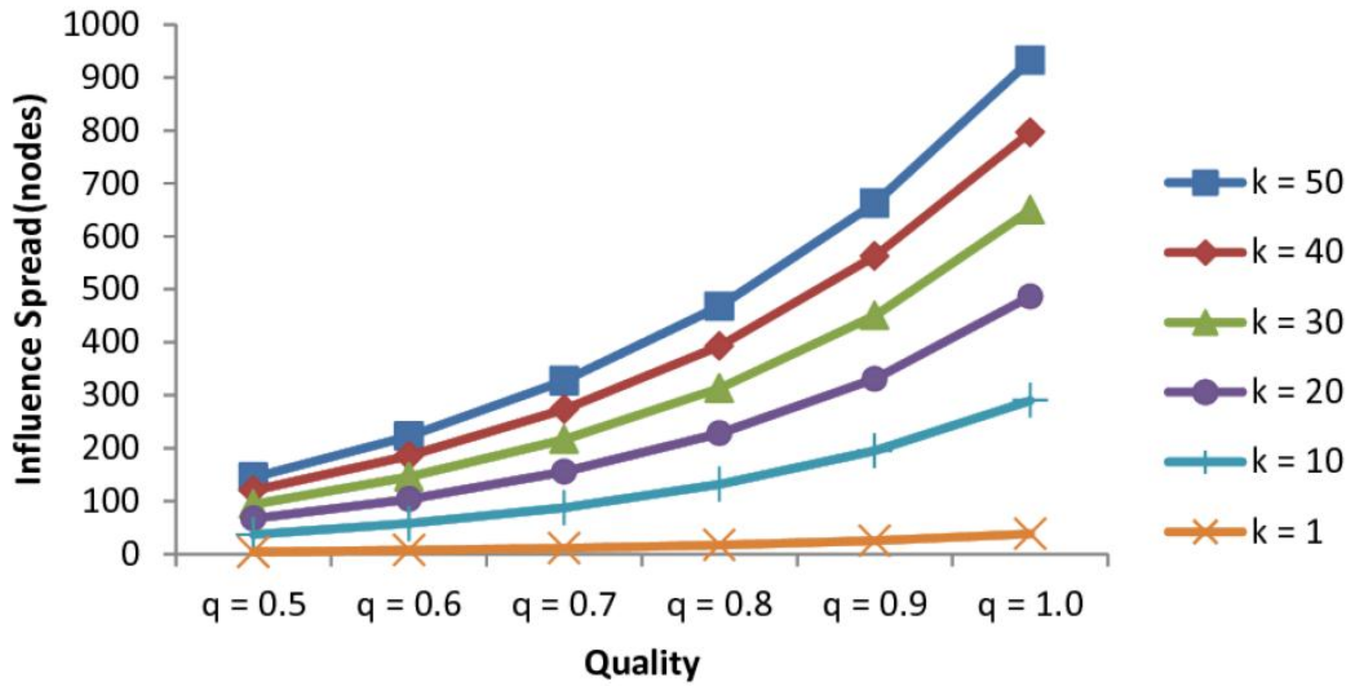
- Step 1: compute activation probability of $u$ at step $t$ (via dynamic programming):

$$ap(u,t) = \begin{cases} 1 & t = 0 \wedge u \in S, \\ 0 & t = 0 \wedge u \notin S, \\ 0 & t > 0 \wedge u \in S, \\ \begin{array}{l} \prod_{w \in N^{in}(u)} [1 - \sum_{i=0}^{t-2} ap(w,i) p(w,u)] \\ - \prod_{w \in N^{in}(u)} [1 - \sum_{i=0}^{t-1} ap(w,i) p(w,u)] \end{array} & t > 0 \wedge u \notin S. \end{cases}$$

- Step 2: compute positive activation probability of $u$ at step $t$:

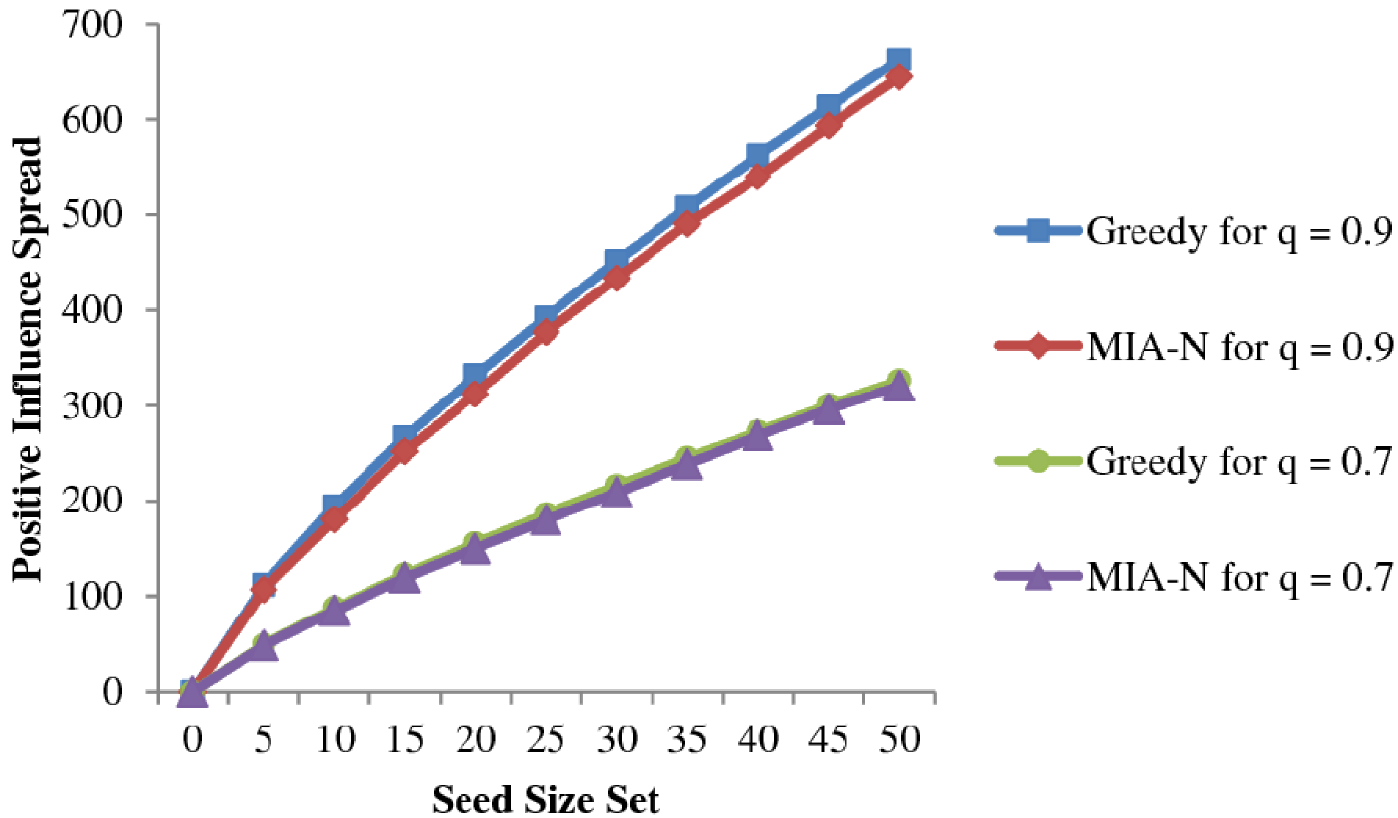
$$pap(u,t) = ap(u,t) \cdot q^{t+1}.$$

# Influence spread and QF



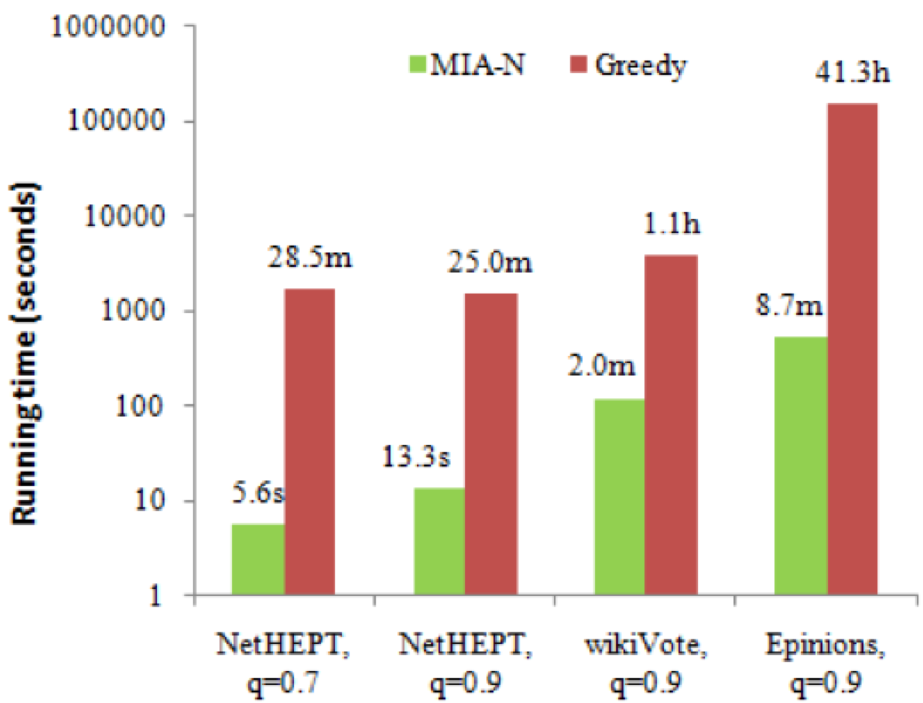

- Results on a collaboration network with 15K nodes.
- Convex function because of negativity bias

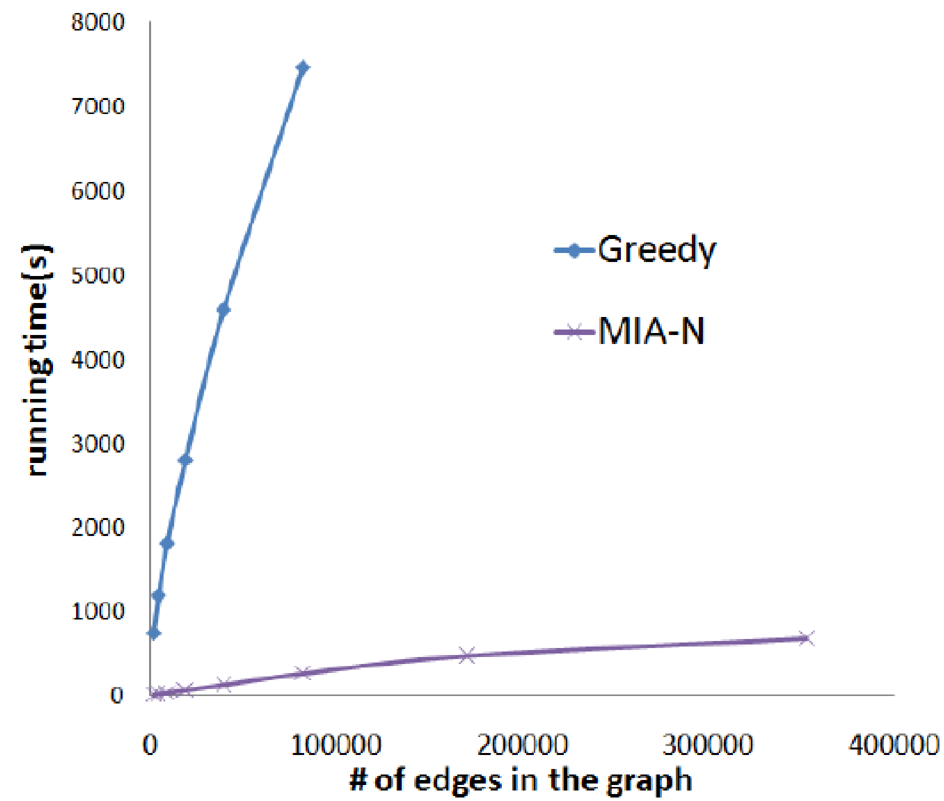
# Performance of the heuristic




- **MIA-N heuristic performs nearly as good as the original greedy algorithm.**

# Scalability




- **MIA-N heuristic is 3 orders of magnitude faster than Greedy**

# CLT model for competitive influence diffusion and CLDAG algorithm for the influence blocking maximization problem

# The problem

- Consider two competing influence diffusion process, one positive and one negative
- Inf. Blocking Max.: selecting positive seeds to block the negative influence diffusion as much as possible
  - e.g. stop rumors on a company, on a political candidate, on public safety events, etc.

# Our solution

- Competitive linear threshold model
  - positive influence and negative influence diffuse concurrently in the network
  - negative influence dominates in direct competition
- Prove that the objective function is submodular
- Design scalable algorithm CLDAG to achieve fast blocking effect

# Influence diffusion on networks with friends and foes

# The problem

- You would positively influence your friends, but influence your foes in the reverse direction
- How to model such influence?
- How to design influence maximization algorithm?

# Our solution

- Voter model in signed networks
  - suitable for opinion changes from positive to negative or reverse
  - individual takes the opposite opinion from his foe
- Provide complete characterization of short term dynamics and long-term steady state behavior
- Provide exact solutions to the influence maximization problem

# On going and future directions

- Model validation and influence analysis from real data
- Even faster heuristic algorithms
- Fast approximate algorithms
- Online and adaptive algorithms

# Questions?