Mechanism Design Powered by Social Interactions

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A tutorial @ AAMAS, IJCAI 2019

2009 DARPA Red Balloon Challenge

- The $40,000 challenge award would be granted to the first team to submit the locations of 10 moored, 8-foot, red weather balloons at 10 previously undisclosed fixed locations in the continental United States.

2009 DARPA Red Balloon Challenge

MIT Crowdsourced Solution (The Winner):

- "*We're giving $2000 per balloon to the first person to send us the correct coordinates, but that's not all – we're also giving $1000 to the person who invited them. Then we're giving $500 whoever invited the inviter, and $250 to whoever invited them, and so on ...*"
- got over 5,000 of participants, won the competition in under 9 hours.

2009 DARPA Red Balloon Challenge

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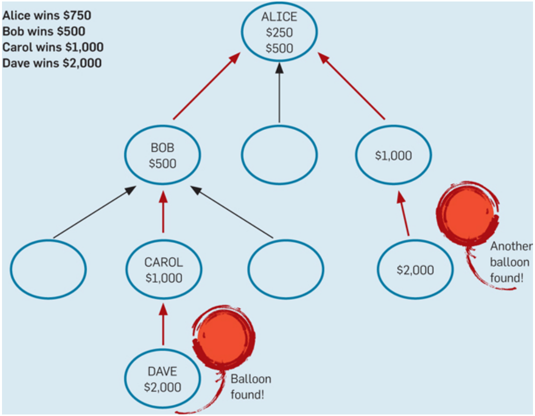


- Pickard, G., et al., Time-Critical Social Mobilization. Science, 2011. 334(6055): p. 509-12.

PinDuoDuo (like Groupon)

What are the incentives?

More participants, higher chance to win!!!

- 2009 DARPA Red Balloon Challenge
  - Inviting more friends has higher chance to win (higher utility)
- PinDuoDuo
  - Inviting more friends has higher chance to get cheap items (higher utility)

What if it is a competition?

- Resource allocation (auctions)
- Task allocation (crowdsourcing)
- Information propagation with budget
- Social choice (voting)

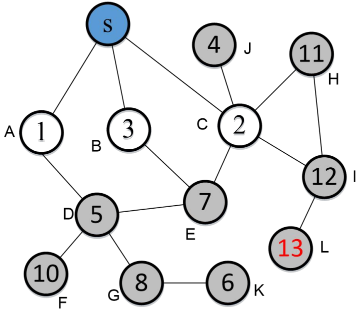
More participants means lower chance to win!!!

Diffusion Mechanism Design

Mechanism Design on Social Networks

Design mechanisms/markets under competitive environment such that participants are incentivized to invite more participants/competitors to join the mechanisms.

Starter: Promote a Sale via Social Networks



- The seller (blue node) sells one item and has only three connections/neighbours in the network (A,B,C).
- Each node is a potential buyer and the value is her highest willing payment to buy the item (valuation).
- The seller's revenue of applying second price auction (VCG) without promotion is 2.
- but the highest willing payment in the network is 13.

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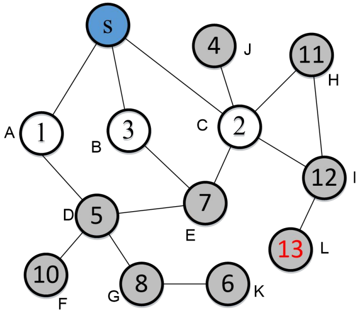

Question

How the seller could do to increase her profit?

Traditional Sale Promotions

Traditional sale promotions:

- Promotions via agents
- Keywords based ads via search engines such as Google
- Ads via social media such as WeChat, Facebook, Twitter

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Challenge

- The return of these promotions are unpredictable.
- The seller may LOSE from the promotions.

Tackle the Challenge

Build promotion inside the market mechanism such that

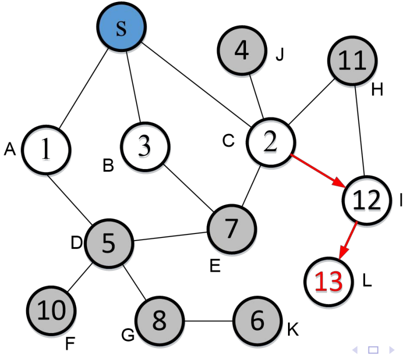
1. the promotion will never bring negative utility/revenue to the seller.
2. all buyers who are aware of the sale are incentivized to diffuse the sale information to all her neighbours.

"Diffusion Mechanism Design"

New Challenges

Why a buyer would bring more buyers to compete with her?

- only if their diffusion are rewarded, *but the seller doesn't want to lose*!
- we cannot just pay each node a fixed amount to incentivise them to diffuse the information.



Outline

1. Mechanism Design Review
   - The History
   - Second Price Auction (VCG)
2. Diffusion Mechanism Design

Outline

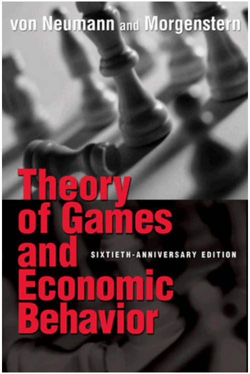
What is Mechanism Design

What is Mechanism/Market Design?

- it is known as Reverse Game Theory

What is Game Theory

- **Game theory** is the study of mathematical models of conflict and cooperation between intelligent rational decision-makers (wiki) [von Neumann and Morgenstern 1944].



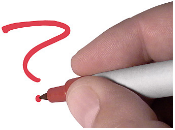
- Non-cooperative games: Go, poker, rock-paper-scissors
- Cooperative games: coordination games

Mechanism Design (Reverse Game Theory)

Mechanism Design is to answer...

Question

How to design a mechanism/game, toward desired objectives, in strategic settings?

	Participants	Game	Outcome
Game Theory	 ⇒	 ⇒	
Mechanism Design	 ⇒	 ⇒	

Mechanism Design (Reverse Game Theory)

Mechanism Design is to answer...

Question

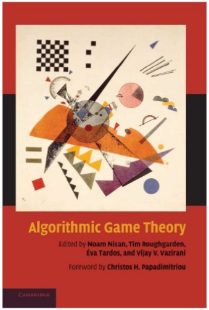
How to design a mechanism/game, toward desired objectives, in strategic settings?

Roger B. Myerson (born March 29, 1951, University of Chicago, US)

- Nobel Prize for economics (2007), for "having laid the foundations of mechanism design theory."
- *Eleven game-theorists have won the economics Nobel Prize.*

Algorithmic Game Theory (AGT)

- **Algorithmic game theory** is an area in the intersection of game theory and algorithm design, whose objective is to design algorithms in strategic environments (wiki) [Nisan et al. 2007].



- *Computing in Games*: algorithms for computing equilibria
- *Algorithmic Mechanism Design*: design games that have both good game-theoretical and algorithmic properties
- ...

Algorithmic Game Theory in Artificial Intelligence

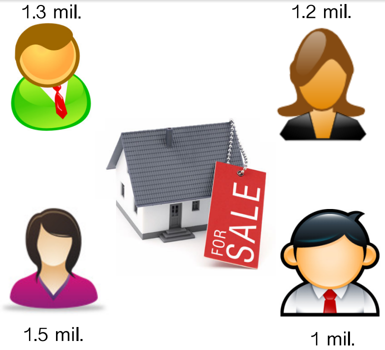
- Algorithmic game theory research in AI:
  - Game Playing: computation challenges, AlphaGo, poker
  - Social Choice: preferences aggregation, voting, prediction
  - Mechanism Design: the allocation of scarce resources, ad auctions
- Many IJCAI Computers and Thought Award (outstanding young scientists in artificial intelligence) winners had worked on AGT:
  - Sarit Kraus (1995), Nicholas Jennings (1999), Tuomas Sandholm (2003), Peter Stone (2007), Vincent Conitzer (2011), and Ariel Procaccia (2015)

Outline

A Mechanism Design Example

Design Goal

How can a house-seller sell her house with the "highest" revenue?



- **Challenge**: the seller doesn't know how much the buyers are willing to pay (their valuations).

A Mechanism Design Example

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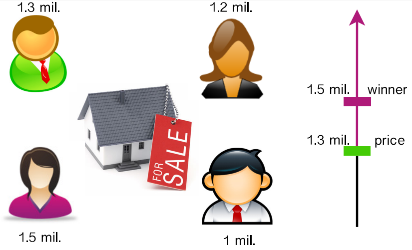

Solution: Second Price Auction (Vickrey Auction/VCG)

- Input: each buyer reports a price/bid to the seller
- Output: the seller decides
  - *allocation*: the agent with the highest price wins.
  - *payment*: the winner pays the second highest price.

A Mechanism Design Example

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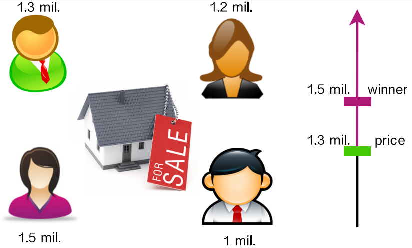

Solution: Second Price Auction (Vickrey Auction/VCG)

Properties:

- Efficient: maximising social welfare
- Truthful: buyers report their valuations truthfully

Is this the BEST the seller can do?

Question

What can the seller do to FURTHER increase her profit?

- estimate a good reserve price [Myerson 1981]
  - *requires a good estimation of buyers' valuations*
- promotions: let more people know/participate in the auction

Is this the BEST the seller can do?

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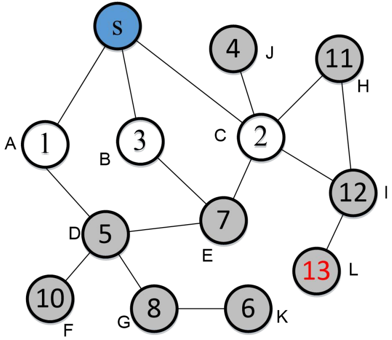
Recap: Promote a Sale via Social Networks



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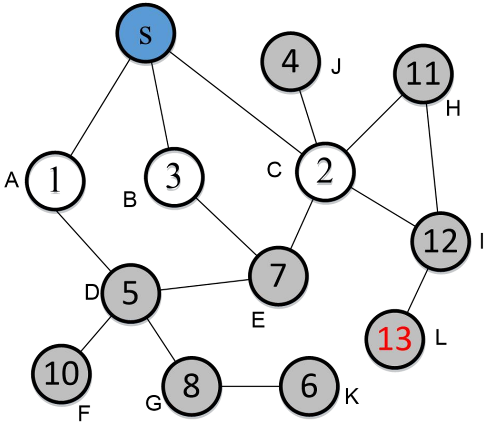
Our Solutions: Information Diffusion Mechanisms

- Bin Li, Dong Hao, Dengji Zhao, Tao Zhou: Mechanism Design in Social Networks. AAAI'17.
- Dengji Zhao, Bin Li, Junping Xu, Dong Hao, Nick Jennings: Selling Multiple Items via Social Networks. AAMAS'18.
- Bin Li, Dong Hao, Dengji Zhao, Tao Zhou: *Customer Sharing in Economic Networks with Costs*. IJCAI-ECAI'18.
- Bin Li, Dong Hao, Dengji Zhao, Makoto Yokoo: *Diffusion and Auction on Graphs*. IJCAI'19.
- Wen Zhang, Dengji Zhao, Hanyu Chen: *Redistribution Mechanism on Networks*. AAMAS'20.
- Wen Zhang, Dengji Zhao, Yao Zhang: *Incentivize Diffusion with Fair Rewards*. ECAI'20.
- Bin Li, Dong Hao, Dengji Zhao: Incentive-Compatible Diffusion Auctions. IJCAI'20.

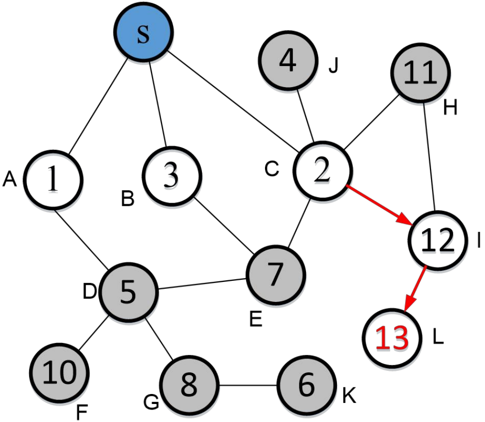
The First Diffusion Mechanism

- Bin Li, Dong Hao, Dengji Zhao, Tao Zhou: **Mechanism Design in Social Networks.** AAAI'17.



Information Diffusion Paths

An information diffusion path from the seller to node L:
$s \rightarrow C \rightarrow I \rightarrow L$



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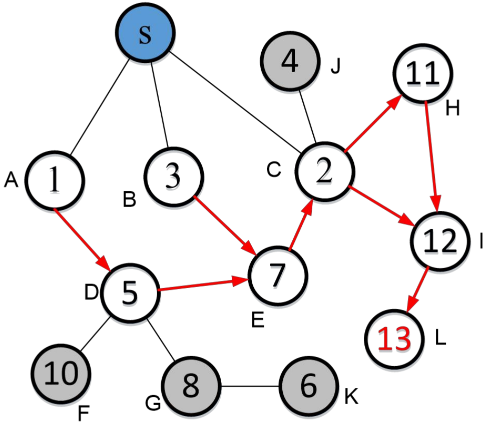
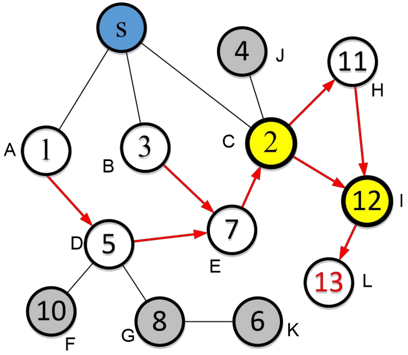


Diffusion Critical Nodes



Definition

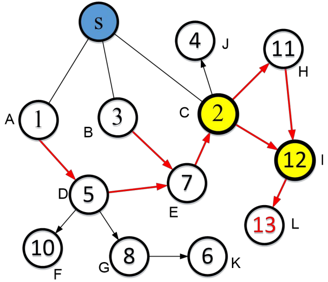
i is *j*'s diffusion critical node if all the information diffusion paths started from the seller *s* to *j* have to pass *i*.

- nodes C and I are L's only diffusion critical nodes.

Information Diffusion Mechanism [Li et al. AAAI'17]

The payment definition (second-price-like):

- If a buyer or one of her "*diffusion critical children*" gets the item, then the buyer pays the highest bid of the others (without the buyer's participation);
- otherwise, her payment is zero.



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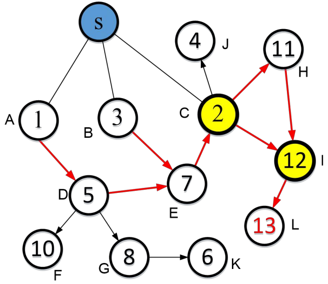


If the item is allocated to *L*, the payments of C, I and L are 10, 11, 12 respectively .

Information Diffusion Mechanism

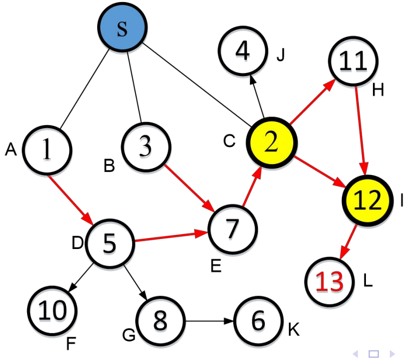
The allocation definition:

- Identify the node i with the highest bid and the node's diffusion critical node path $P_{c_i} = (c_i^1, c_i^2, ..., i)$.
- Give the item to the first node of P_{c_i}, the node pays to the seller and then decides to whether keep the item or pass it to the next node in P_{c_i}:
  - If the payment of the next node is greater than the bid of the current node, passes it to the next node and receives the payment from the next node; the next node makes a similar decision;
  - otherwise, keep the item.

The Information Diffusion Mechanism

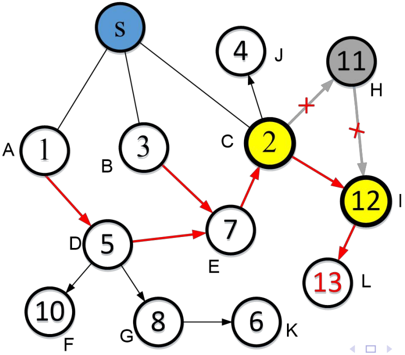
The outcome of the Information Diffusion Mechanism:

- the item is allocated to node I.
- node I pays 11 to C, C pays 10 to the seller.
- the utilities of I, C, the seller are 1, 1, 10.

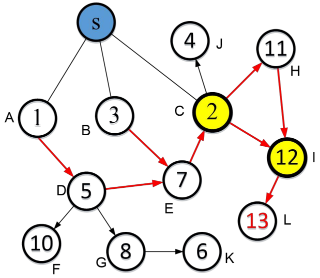


Why Buyers are Happy to Diffuse the Information?

- buyers receive the information earlier have higher priority to win the item (*C* chooses before *I* and *I* chooses before *L*).
- diffuse the information to more buyers will potentially increase their reward (if *C* does not invite *H*, her utility is 0).



Properties of the Information Diffusion Mechanism



- Truthful: report true valuation and diffuse the sale information to all her neighbours is a dominate strategy.
- Individually Rational: no buyer will receive a negative utility to join the mechanism.
- Seller's Revenue Improved: the seller's revenue is non-negative and is $\geq$ that of the VCG without diffusion.

What Next?

- Diffusion mechanisms for combinatorial exchanges
- Diffusion with costs and delays
- Network structure based revenue analysis
- Applications/implementations in the existing social networks
- Other mechanisms to further improve the revenue and/or the efficiency

Diffusion Mechanisms for Combinatorial Exchanges

Challenge

How to generalise the mechanism to combinatorial settings?

Diffusion Mechanisms for Combinatorial Exchanges

Consider the following simple setting:

- A seller sells three units of one commodity, e.g. MacBook computers.
- Each buyer has a diminishing marginal utility for consuming the goods.

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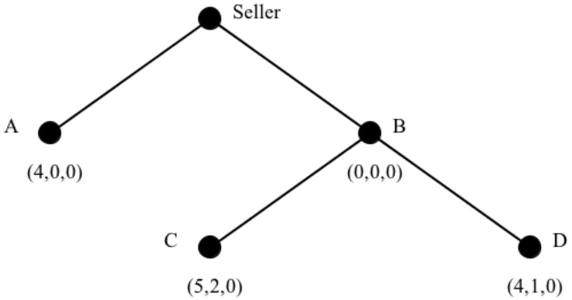
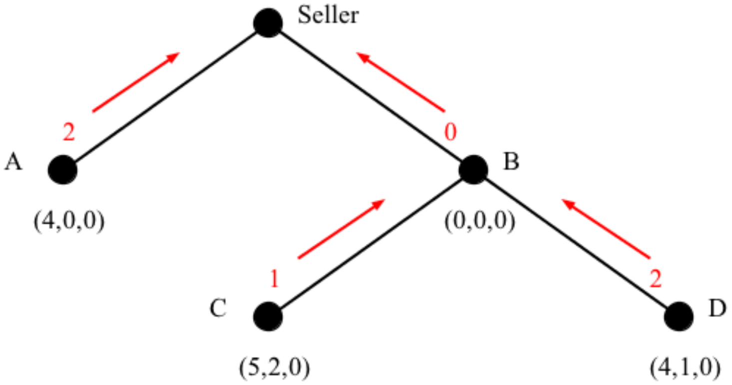


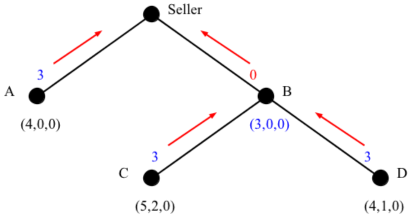
Diffusion Mechanisms for Combinatorial Exchanges

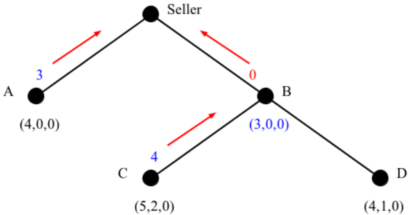
If we simply apply our information diffusion mechanism:



Diffusion Mechanisms for Combinatorial Exchanges

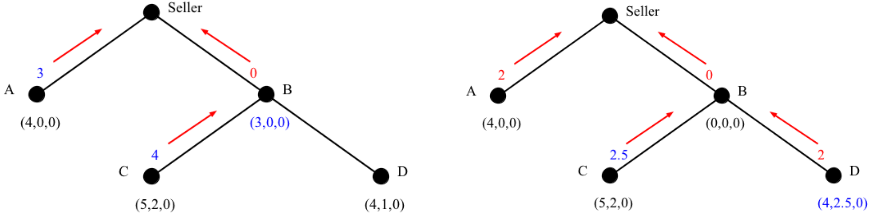
What if buyer B's valuation is $(3, 0, 0)$?





Diffusion Mechanisms for Combinatorial Exchanges

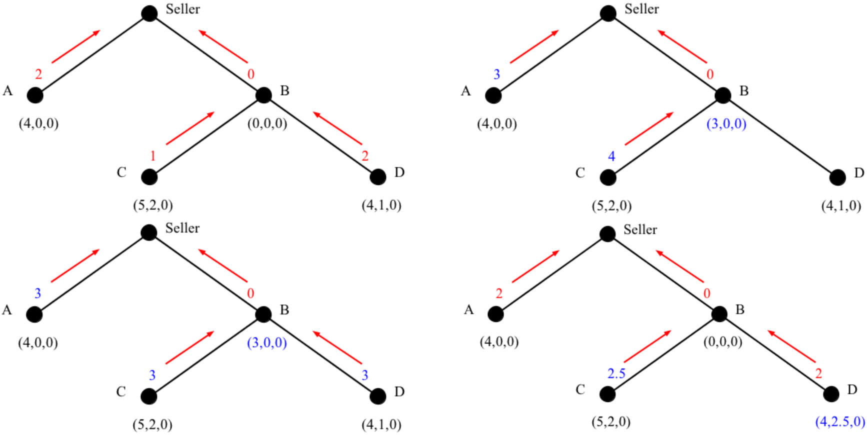
What if buyer D's valuation is $(4, 2.5, 0)$?



Diffusion Mechanisms for Combinatorial Exchanges

Challenge

There is a very complex **Decision Making** at each node!!!



Why is it so complex when there are multiple items?

To achieve truthfulness:

- The mechanism has to maximise each node's utility under truthful reporting.
- Each node's payment should not depend on her valuation.

The complexity we had:

- A node can influence her payments by controlling the items passed to her children.
- A node can influence the payments of her peers, without changing her own allocation and payments.
- This leads to a decision loop (very complex optimization) and may not able to maximise everyone's utility.

Reduce the Complexity

The Main Idea

A node CANNOT influence the payments she receives by controlling the items passed to her children.

Simplify the decision complexity we had:

- ~~A node can influence her received payments by controlling the items passed to her children.~~
- A node can influence the payments of her peers, without changing her own allocation and payments.
- ~~This leads to a decision loop and may not able to maximise everyone's utility.~~

Solution: Sells Multiple Homogeneous Items

Selling Multiple Items via Social Networks [Zhao et al. AAMAS'18]

- generalises the result from [Li et al. 2017];
- agent *i*'s reward/payment doesn't depends on how many of *i*'s children received items;
- agent pays to the seller directly rather than to their parent;

The setting:

- A seller sells $\mathcal{K} \geq 1$ homogeneous items;
- each buyer requires at most one item (single-unit demand);
- the rest is the same as [Li et al. 2017].

Are the mechanisms fair?

- According to the theorem of small-world networks, the chance for a node to be a cut-point in a well-connected network is very low.
- We hope to give rewards to all the related buyers not only the cut-points on the paths to the winner.

Solution: Redistribute Rewards among Agents

Incentivize Diffusion with Fair Rewards [Zhang et al. ECAI'20]

- redistribute rewards among critical ancestors based on IDM
- all critical ancestors have positive expected utilities
- seller's revenue is not reduced

What if for non-profit purpose?

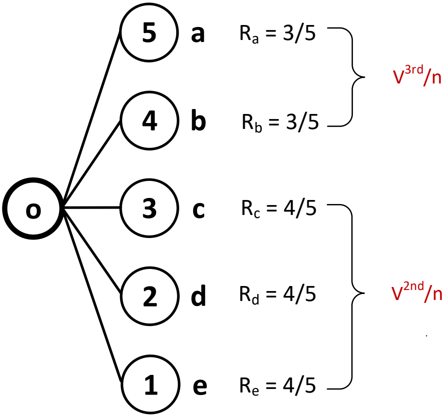
Redistribution mechanism is:

- to do the efficient resource allocation
- not for profit

Challenges:

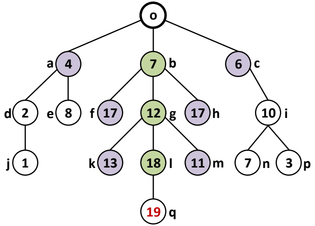
- how to achieve a more efficient allocation?
- how to maintain wealth among agents?

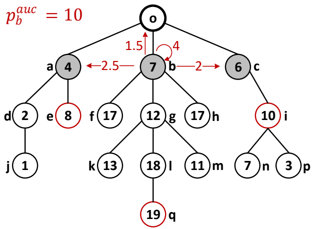
Cavallo Mechanism



- **Allocation**: agent with the highest valuation wins the item
- **Payment**: winner pays the second price
- **Redistribution**: each agent receives the owner's revenue without her participation divided by the total number of agents

Redistribution Mechanism in Trees [Zhang et al. AAMAS'20]





For each ancestor:

- **Allocation**: keep the item if her valuation is greater than or equal to her payment
- **Payment**: the highest valuation without her participation
- **Redistribution**: a monotone increasing function to the number of descendants

A General Characterization of Diffusion Auction Mechanisms

Incentive-Compatible Diffusion Auctions [Li et al. IJCAI'20]

- characterize a sufficient and necessary condition for all incentive-compatible and individually rational diffusion auctions.
- propose a class of natural monotonic allocation policies with optimal payment policy that maximizes the seller's revenue.

The sufficient and necessary condition

Theorem:

- A diffusion auction (π, x) is incentive-compatible and individually rational if and only if for all type profile **t** and all i, $P1 - P5$ are satisfied, where
  - $P1$: π is value-monotonic,
  - $P2$: $\tilde{x}_i$ and $\bar{x}_i$ are bid-independent,
  - $P3$: $\tilde{x}_i(r_i) - \bar{x}_i(r_i) = v_i^*(r_i)$,
  - $P4$: $\tilde{x}_i$ and $\bar{x}_i$ are diffusion-monotonic,
  - $P5$: $\bar{x}_i(\emptyset) \leq 0$.

Open Questions

- More general settings
  - characterize truthful diffusion mechanisms, revenue monotonicity is the key?
- When there is a diffusion cost
  - how to guarantee the seller will not lose?
- Privacy concern and the seller's strategies
  - the seller discovery the whole network and she may cheat as well!
- False-name manipulations
  - a node may create multiple ids as her neighbours to gain more payment?
- many more...

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2. Diffusion Mechanism Design
   - Resource Allocation
   - Task Allocation
   - Information Propagation

Diffusion Mechanism Design for Task Allocation

- Wen Zhang, Yao Zhang, Dengji Zhao: *Collaborative Data Acquisition*. AAMAS'20.
- Yao Zhang, Xiuzhen Zhang, Dengji Zhao: *Sybil-proof Answer Querying Mechanism*. IJCAI'20.

Diffusion Mechanism Design for Task Allocation

Resource allocation vs task allocation:

1. task requires more participants' contribution (collaboration)
2. but participants' contribution may conflict with each other (competition)

Crowdsourcing Data Acquisition [Zhang et al. AAMAS'20]

- a requester is collecting data from the crowd
- more participants gives richer dataset
- participants' contribution depends on the quality of their provided data
- if two participants offer the same data, how to calculate their contribution?

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Shapley Value?

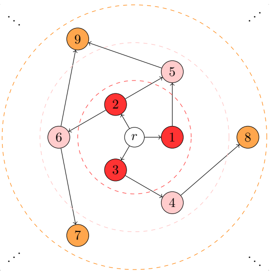
Shapley Value

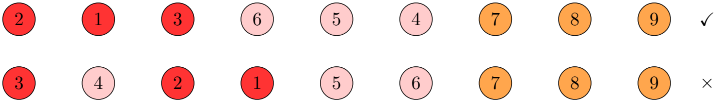
The problem of the Shapley value:

- two participants offer the same data will share the same Shapley value
  - the Shapley value is doubled if one of them didn't participate

Solution: Layered Shapley Value

- participants are layered
- the Shapley value is calculated for each lower layer first
- the calculation for higher layer assumes that lower layers' participants are always in the coalition





Solution: Layered Shapley Value

$$\hat{\phi}_i = \sum_{S \subseteq L_{l_i} - \{i\}} \frac{|S|!(|L_{l_i}| - |S| - 1)!}{|L_{l_i}|!} \cdot \left(v\left(D'_{L^*_{l_i - 1} \cup S \cup \{i\}}\right) - v\left(D'_{L^*_{l_i - 1} \cup S}\right)\right)$$

Properties:

- participants are incentivized to invite more participants (new participants do not compete with them)
- the requester does not need to pay for redundant data

Sybil-proof Answer Querying [Zhang et al. IJCAI'20]

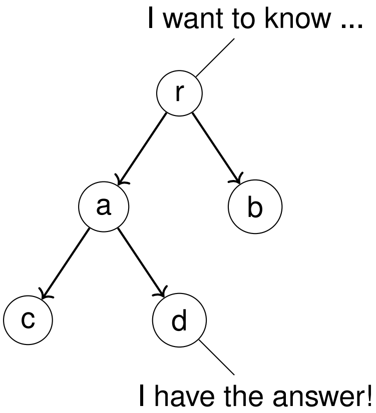


Figure: Query via Network

- Online networks has offered many opportunities for people to collaborate remotely in real time, e.g. P2P file sharing and Q&A platforms.
- Utilizing the social connections, we can enhance the power of answer querying via networks, e.g. DARPA Red Balloon Challenge.

Sybil-proof Answer Querying

- **Fact**: An SIR path mechanism cannot be both SP and CP.
- What if relax SIR to IR?
- **Theorem**: A path mechanism is IR, SP and CP if and only if it is a two-headed mechanism.

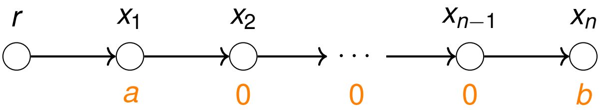


Figure: The rewards distributed by a two-headed mechanism

Sybil-proof Answer Querying

- What if relax CP to λ-CP?
- **New Idea**: Double Geometric Mechanism

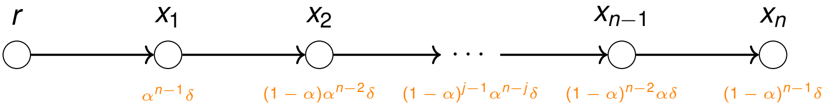


Figure: The rewards distributed by a double geometric mechanism

- **Characterization**: Under mild condition, the properties of IC, SIR, BC, SP, 2-CP and ρ-SS determines a DGM.

Outline

Mechanism Design for Information Propagation

- Haomin Shi, Yao Zhang, Zilin Si, Letong Wang, Dengji Zhao: *Maximal Information Propagation with Budgets*. ECAI'20.

Maximal Information Propagation with Budgets

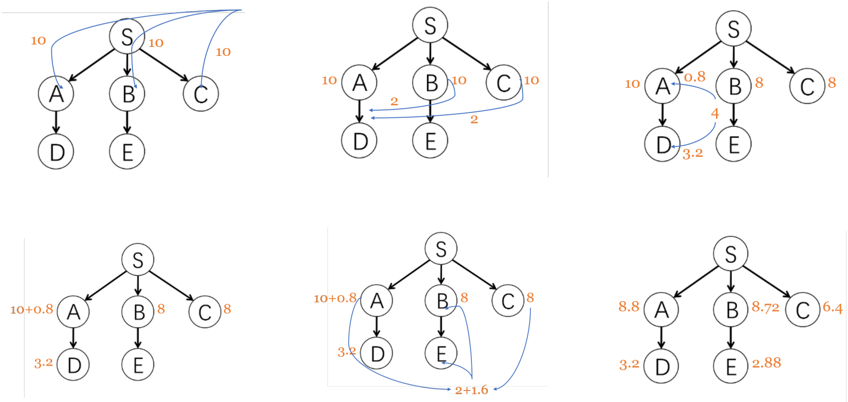
- The sponsor s wants to propagate some information to the social network modelled as a directed acyclic graph $G = (N, E)$.
- The sponsor holds a fixed budget B, which is prepared as agents' rewards.

Challenge

How to find a reward scheme that is propagation incentive compatible and budget balanced?

Maximal Information Propagation Example

- Example: Incentivies from Peer Pressure



What we have covered

Mechanism Design Powered by Social Interactions

- Diffusion Mechanism for Resource Allocation (competitive environment)
  - for selling single and multiple items
- Diffusion Mechanism for Task Allocation (both competitive and collaborative)
  - crowdsourcing, sybil-proof, execution uncertainty
- Diffusion Mechanism for Information Propagation
  - information propagation with budgets

http://dengji-zhao.net/ijcai19.html