(Social Choice and) Mechanism Design on Social Networks

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A tutorial @ AAMAS 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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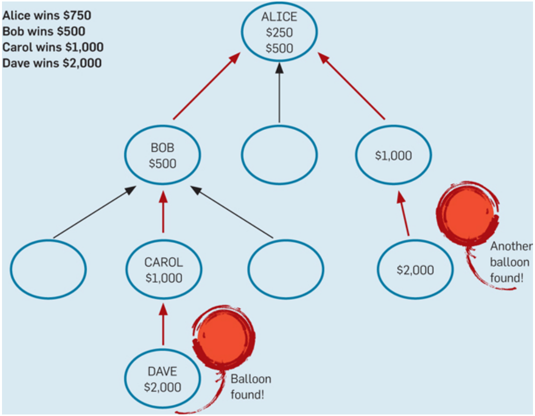

- Pickard, G., et al., Time-Critical Social Mobilization. Science, 2011. 334(6055): p. 509-12.

PinDuoDuo (like Groupon)

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Achievements:

- went online in Sep 2015
- got over 2 million users in two weeks
- by Feb 2016, got over 20 million users
- IPO in Jul 2018

PinDuoDuo (like Groupon)

Their group buying model:

1. choose one product
2. join a group buying deal or initiate a new group buying deal
3. wait or invite friends to join the deal
4. when the required number of buyers is reached, they all buy the product with a cheaper price

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 such as auctions
- task allocation

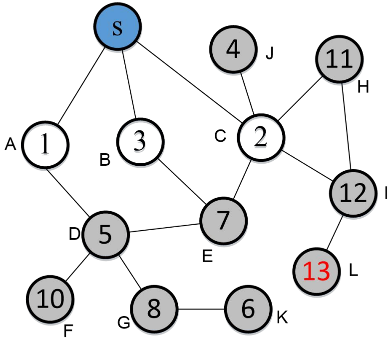
More participants means lower chance to win!!!

Diffusion Mechanism Design

Mechanism Design on Social Networks

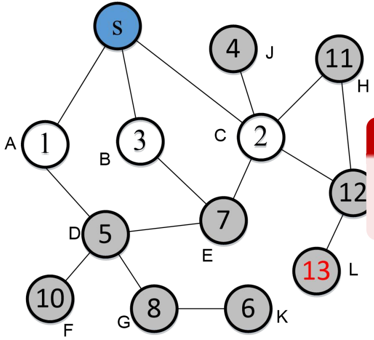
Design mechanisms/markets under competitive environment such that participants are incentivized to invite more participants/competitors to join the mechanisms.

Starter: Promote a Sale in 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 without promotion is 2.
- but the highest willing payment of the network is 13.

Starter: Promote a Sale in Social Networks



Question

How the seller could do to increase her profit?

Traditional Sale Promotions

Traditional sale promotions:

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

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- 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.
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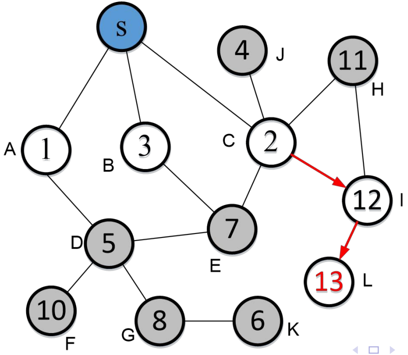
"Diffusion Mechanism Design"

New Challenges

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

- only if their efforts 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.



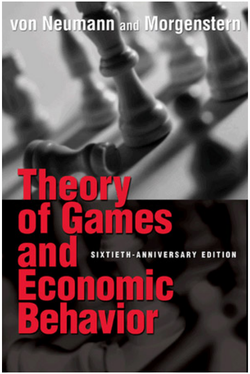
What is Mechanism Design

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].



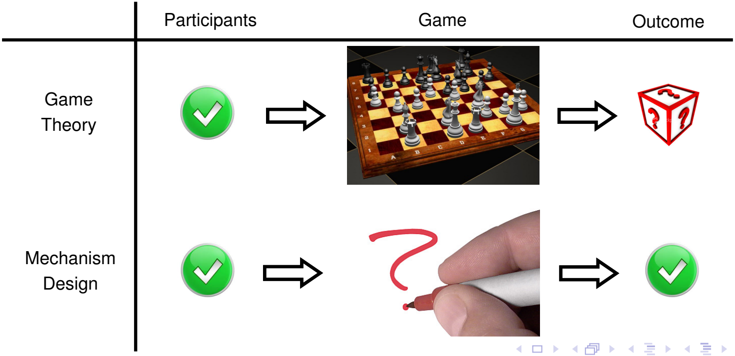
- Non-cooperative games: Go, poker, rock-paper-scissors
- Cooperative games: coordination games

Mechanism Design (Reverse Game Theory)

Mechanism Design is to answer...

Question

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



Mechanism Design (Reverse Game Theory)

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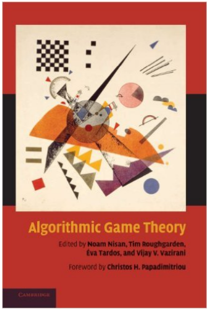
Roger B. Myerson (born March 29, 1951, University of Chicago, US)

- 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].



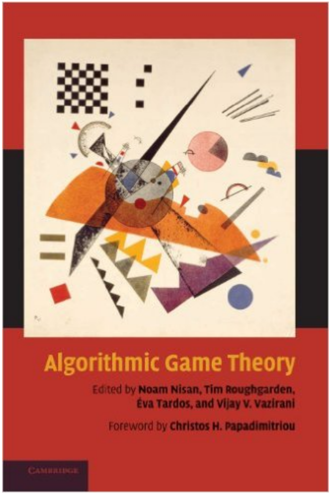
- *Computing in Games*: algorithms for computing equilibria
- *Algorithmic Mechanism Design*: design games that have both good game-theoretical and algorithmic properties
- ...

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)

AGT on Networks

- Algorithmic Game Theory started with Routing Networks



AGT on Networks

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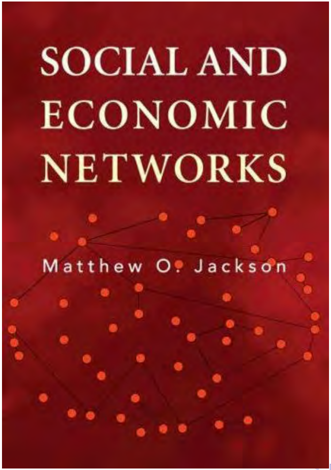
AGT on Networks

- Another book regarding Game Theory and Networks



A Simple Mechanism Design Example

Design Goal

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

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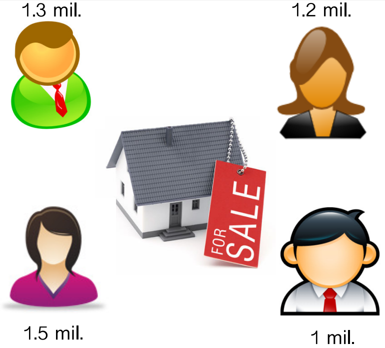

- **Challenge**: the seller doesn't know how much the buyers are willing to pay (their valuations).

A Mechanism Design Example

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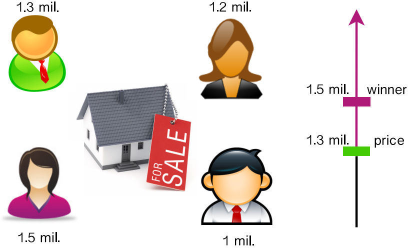

Solution: Second Price Auction (Vickrey Auction/VCG)

- 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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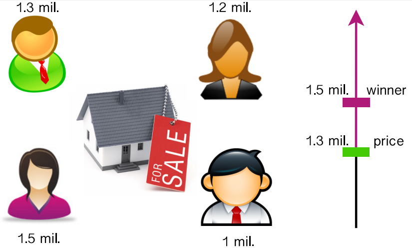

Solution: Second Price Auction (Vickrey Auction/VCG)

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?

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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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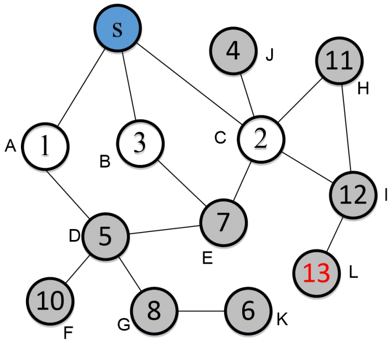
Recap: Promote a Sale in Social Networks



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"Diffusion Mechanism Design"

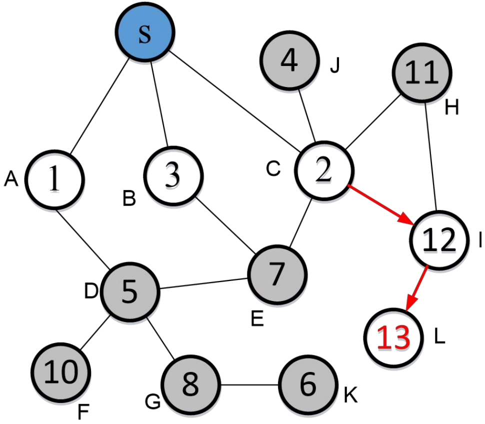
Our Solutions

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: *Auction and Diffusion on Graphs*. IJCAI'19.

Information Diffusion Paths

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



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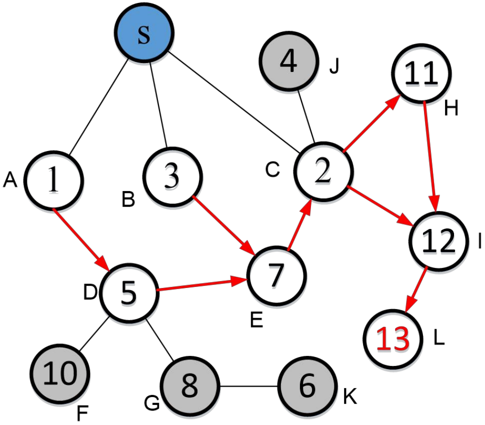
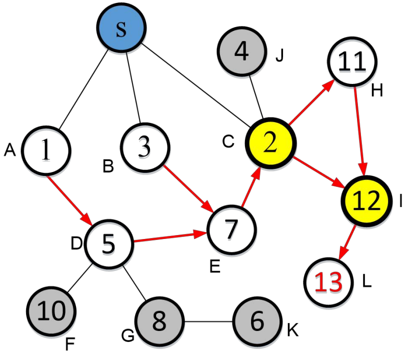


Diffusion Critical Nodes



Definition

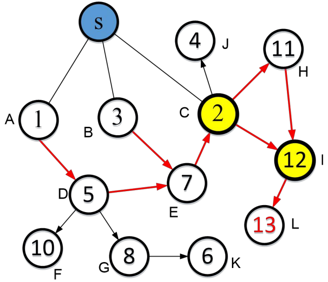
i is *j*'s diffusion critical node if all the information diffusion paths started from the seller *s* to *j* have to pass *i*.

- 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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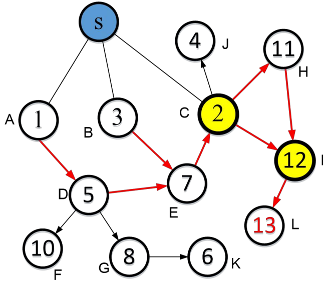


If the item is allocated to *L*, the payments of C, I and L are 10, 11, 12 respectively .

Information Diffusion Mechanism

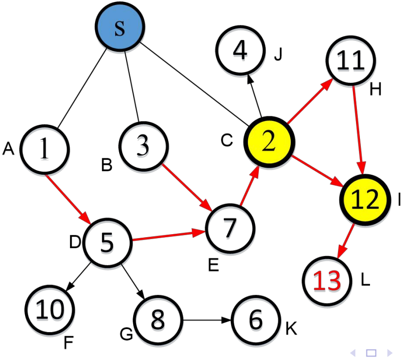
The allocation definition:

- 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

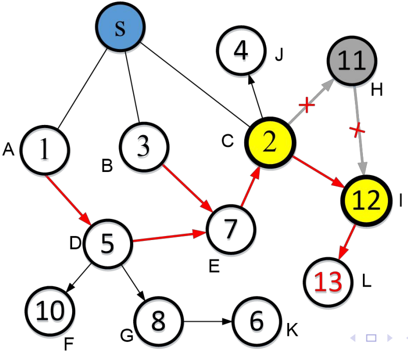
The outcome of the Information Diffusion Mechanism:

- 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 $1, 1, 10$.

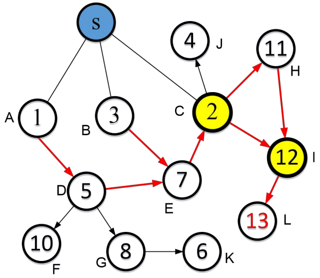


Why Buyers are Happy to Diffuse the Information?

- 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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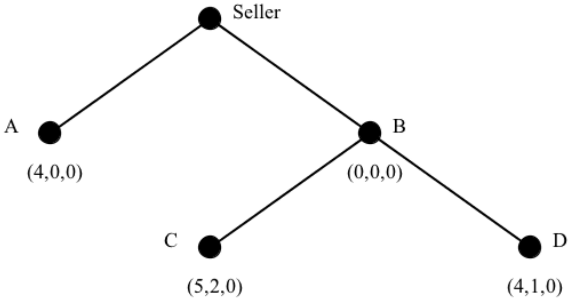
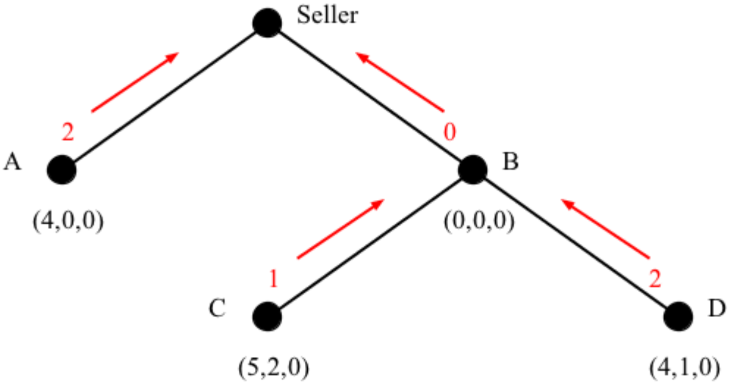


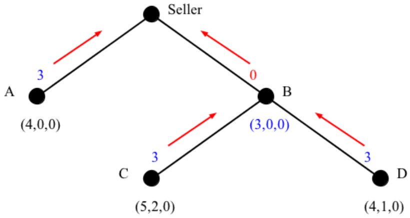
Diffusion Mechanisms for Combinatorial Exchanges

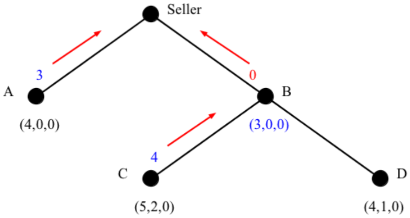
If we simply apply our information diffusion mechanism:



Diffusion Mechanisms for Combinatorial Exchanges

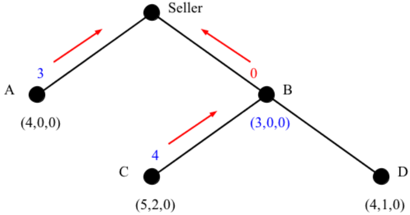
What if buyer B's valuation is $(3,0,0)$?

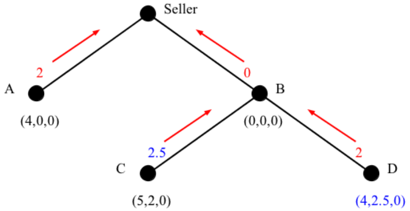




Diffusion Mechanisms for Combinatorial Exchanges

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

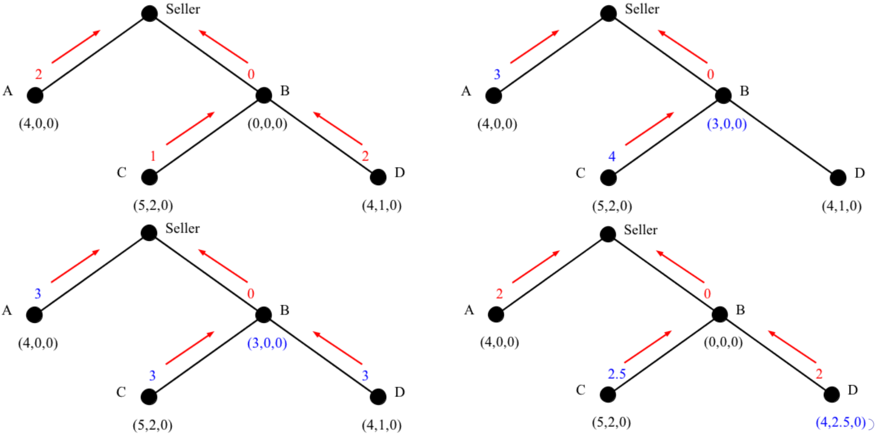




Diffusion Mechanisms for Combinatorial Exchanges

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 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 (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 Example: Sells Multiple Homogeneous Items

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

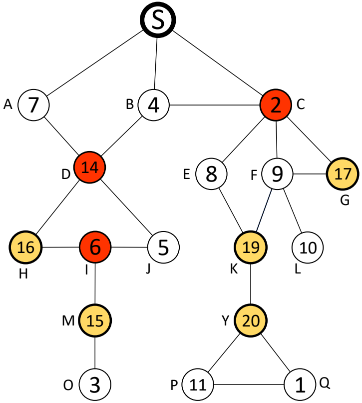
- generalises the result from [Li et al. 2017];
- agent *i*'s reward/payment doesn't depends on how many of *i*'s children received items;
- agent pays to the seller directly rather than to their parent;

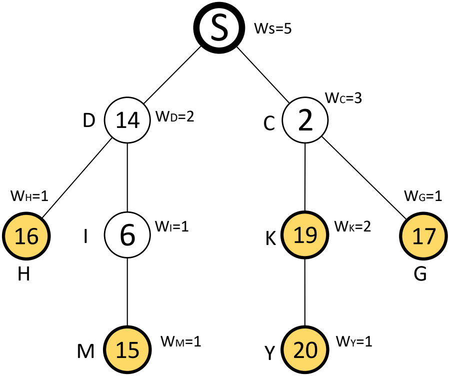
The Generalised Setting

- 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].

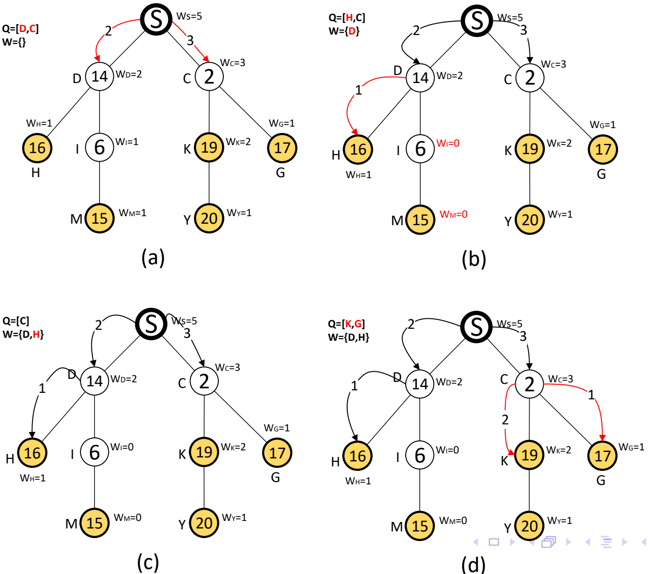
The Generalised Diffusion Mechanism

Consider $\mathcal{K} = 5$:





The Generalised Diffusion Mechanism



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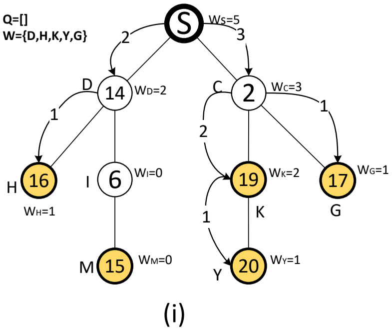

The Allocation Policy of the Generalisation

Node/buyer *i* receives one item if and only if

1. the top $\mathcal{K}$-highest valued children of *i* (and their parents, who are also *i*'s children) do not participate
2. and *i* wins under the efficient allocation with their absence

given that all *i*'s (critical) parents' allocation is determined and fixed.

The Payment Policy of the Generalisation

Node i's utility is the social welfare difference of the efficient allocation between

1. the top $\mathcal{K}$-highest valued children of i (and their parents, who are also i's children) do not participate (guarantees that i's payment does not depend on how many items i's children get)
2. and i (and all her children) does not participate

Formally, i's payment is:

$$\begin{cases} \mathcal{SW}_{-D_i} - (\mathcal{SW}_{-\mathcal{C}_i^{\mathcal{K}}} - v_i') & \text{if } i \in W, \\ \mathcal{SW}_{-D_i} - \mathcal{SW}_{-\mathcal{C}_i^{\mathcal{K}}} & \text{if } i \in \bigcup_{j \in W} \mathcal{P}_j(\theta') \setminus W, \\ 0 & \text{otherwise.} \end{cases}$$

where W is the set of nodes each of whom received one item.

Properties of the Generalisation

- Truthful: report true valuation and diffuse the sale information to all her neighbours is a dominate strategy for each node.
- Individually Rational: no node 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.

Truthfulness and IR

Given i's payment:

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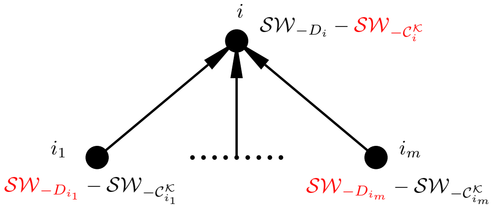
if i reports truthfully, i's utility is:

$$\mathcal{SW}_{-\mathcal{C}_i^{\mathcal{K}}} - \mathcal{SW}_{-D_i}$$

- $\mathcal{SW}_{-D_i}$ is the optimal social welfare without i's participation
- $\mathcal{SW}_{-\mathcal{C}_i^{\mathcal{K}}}$ is the optimal social welfare when the top $\mathcal{K}$-highest valued children of i (and their parents, who are also i's children) do not participate

Guaranteed Revenue Improvement for the Seller



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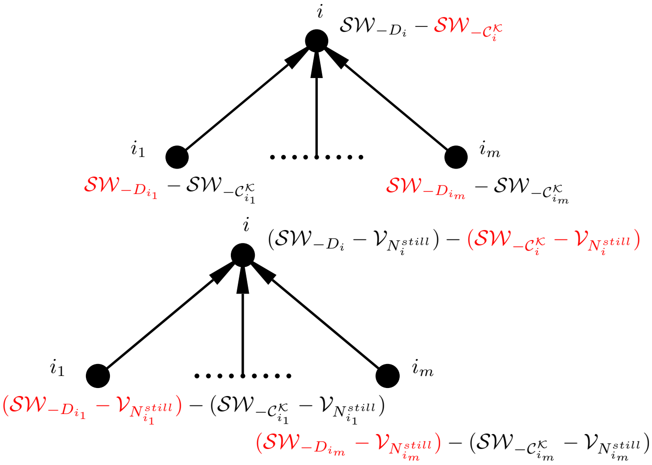
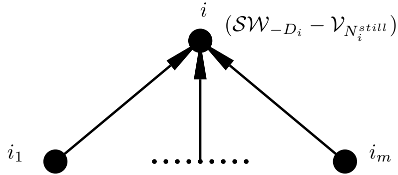


Guaranteed Revenue Improvement for the Seller



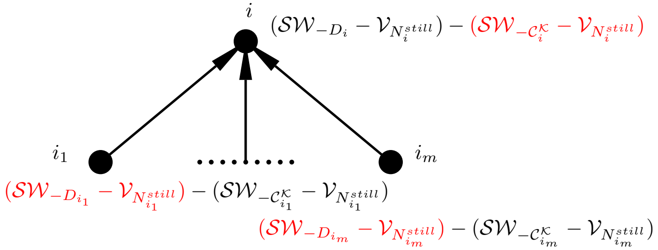
$(\mathcal{SW}_{-D_i} - \mathcal{V}_{N_i^{still}}) - (\mathcal{SW}_{-\mathcal{C}_i^{\mathcal{K}}} - \mathcal{V}_{N_i^{still}})$

$(\mathcal{SW}_{-D_{i_1}} - \mathcal{V}_{N_{i_1}^{still}}) - (\mathcal{SW}_{-\mathcal{C}_{i_1}^{\mathcal{K}}} - \mathcal{V}_{N_{i_1}^{still}})$

$(\mathcal{SW}_{-D_{i_m}} - \mathcal{V}_{N_{i_m}^{still}}) - (\mathcal{SW}_{-\mathcal{C}_{i_m}^{\mathcal{K}}} - \mathcal{V}_{N_{i_m}^{still}})$

$$\mathcal{SW}_{-\mathcal{C}_i^{\mathcal{K}}} - \mathcal{V}_{N_i^{still}} \leq \sum_{i_l} (\mathcal{SW}_{-D_{i_l}} - \mathcal{V}_{N_{i_l}^{still}})$$

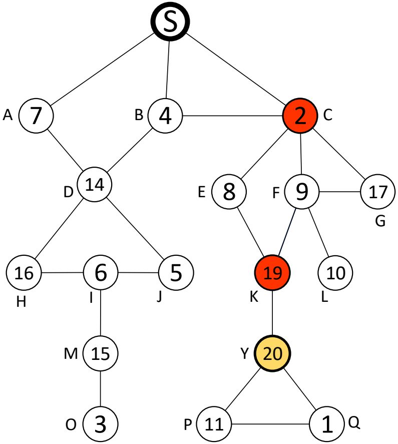
Guaranteed Revenue Improvement for the Seller



Theorem (Zhao et al. 2018)

The revenue of the generalised information diffusion mechanism is greater than or equal to $\mathcal{K} \times v_{\mathcal{K}+1}$, where $v_{\mathcal{K}+1}$ is the $(\mathcal{K}+1)$-th largest valuation report among r_s, assume that $|r_s| > \mathcal{K}$.

What happens when $\mathcal{K} = 1$?



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...

Diffusion Mechanism Design for Task Allocation

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

An Example: Crowdsourcing Data Acquisition

- 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

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

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

Summary

- Diffusion Mechanism for Resource Allocation (competitive environment)
  - for selling single item
  - for selling multiple items
- Diffusion Mechanism for Task Allocation (both competitive and collaborative)
  - crowdsourcing data acquisition

Related Work

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Related Work

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