Mechanism Design for Resource Critical Task Execution via Crowdsourcing

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Outline of Talk

1 Motivation
   - The DARPA Network Challenge

2 Potential Dangers in Strategic Setting
   - Sybil Attack
   - Node Collapse Attack
   - Design Desiderata

3 Main Results
   - Impossibility and Possibility Results
   - Approximate Versions of Desirable Properties
   - Incentives for Task Forwarding and Execution
   - Cost Critical Setting
   - Time Critical Setting

4 Summary and Future Work
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4 Summary and Future Work
The challenge is to identify the locations of 10 balloons

Whoever locates all of them in the shortest time will get a reward of $40,000

Balloons are spread across the continental USA
  - Impossible for any individual to travel to all the places
  - Time-critical competition

Crowdsourcing with some help from modern technology is a natural approach
The Winning Solution: MIT Media Lab

- Winning solution: MIT Media Lab
- Efficiently harnesses the collective intelligence and collaborative effort of a social network
- Incentive scheme is a geometric reward mechanism, decreasing from leaf to root

![Diagram of the incentive structure]

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We are considering **Atomic Tasks**
Indivisible tasks, accomplished by a single individual
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Indivisible tasks, accomplished by a single individual

- Human participants of the social network are **strategic**.
- Can manipulate the mechanism in order to maximize their own **payoff**.
- Two major problems with the incentive mechanism: **sybil attack** and **node collapse attack**.
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Sybil Attack

Nodes can multiply their identities by creating clones or fake nodes below themselves in the referral tree. Example: Carol can create two fake nodes to earn $750 more in the MIT scheme.
Sybil Attack

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Sybil attack is undesirable because,
- Increases the expenditure of the task owner, as the sybils are getting paid.
- Reduces the reward of the ancestors of the sybil-creating nodes.
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Node Collapse Attack

- To combat the sybil attack, one can think of a naïve reward scheme.
- TOP-DOWN: if the number of nodes in the winning chain (call this ‘length’) is $t$, node at depth $d$ gets $\frac{4000}{2^d + t}$.
- This could lead to a different problem: node collapse problem

Bob, Carol, and Dave together gets

$4000(\frac{1}{2^5} + \frac{1}{2^6} + \frac{1}{2^7})$
To combat the sybil attack, one can think of a naïve reward scheme.

TOP-DOWN: if the number of nodes in the winning chain (call this ‘length’) is $t$, node at depth $d$ gets $\frac{4000}{2^{d+t}}$.

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Bob, Carol, and Dave together gets $\frac{4000}{2^3}$ which is larger than earlier $\frac{4000}{2^5 + 1/2^6 + 1/2^7}$
Node collapse is undesirable:

- Costs more to the social planner
- Sharing of this surplus could lead to bargaining among the agents
- Hides the structure of the actual network, which could otherwise be used for different purposes.
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4 Summary and Future Work
Desirable Properties

Definition (Downstream Sybil-Proofness (DSP))

Given the depth \(k\) of a node in a recruitment tree, a reward mechanism \(R\) is called \textit{downstream sybilproof}, if the node cannot gain by adding fake nodes below itself in the current subtree. Formally,

\[
R(k, t) \geq \sum_{i=0}^{n} R(k + i, t + n) \quad \forall k \leq t, \forall t, n.
\]

Definition (Collapse-Proofness (CP))

Given a depth \(k\) in a winning chain, a reward mechanism \(R\) is called \textit{collapse-proof}, if the user in the subchain of length \(p\) lying beneath \(k\) collectively cannot gain by collapsing to depth \(k\). Mathematically,

\[
\sum_{i=0}^{p} R(k + i, t) \geq R(k, t - p) \quad \forall k + p \leq t, \forall t.
\]
Desirable Properties

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\]

- This asks for a **Dominant Strategy** implementation
Desirable Properties (Contd.)

**Definition (Strict Contribution Rationality (SCR))**

This ensures a positive payoff to the nodes belonging to the winning chain. For all \( t \geq 1 \):

\[
R(k, t) > 0, \quad \forall k \leq t, \text{ if } t \text{ is the length of the winning chain.}
\]

**Definition (Weak Contribution Rationality (WCR))**

This ensures a non-negative payoff to the nodes in the winning chain. For all \( t \geq 1 \):

\[
R(k, t) \geq 0, \quad \forall k \leq t - 1, \text{ if } t \text{ is the length of the winning chain.}
\]

\[
R(t, t) > 0, \quad \text{winner gets positive reward.}
\]
Desirable Properties (Contd.)

**Definition (Budget Balance (BB))**

Suppose the maximum budget allocated by the planner for executing a task is $R_{\text{max}}$. Then, a mechanism $R$ is budget balanced if,

$$\sum_{k=1}^{t} R(k, t) \leq R_{\text{max}}, \quad \forall t.$$
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Not all these properties are simultaneously satisfiable.

**Theorem (Impossibility Result)**

*For* $t \geq 3$, no reward mechanism can simultaneously satisfy DSP, SCR, and CP.
Not all these properties are simultaneously satisfiable.

**Theorem (Impossibility Result)**

For \( t \geq 3 \), no reward mechanism can simultaneously satisfy DSP, SCR, and CP.

**Theorem (Possibility Result A)**

For \( t \geq 3 \), a mechanism satisfies DSP, WCR, CP, and BB iff it is a Winner Takes All (WTA) mechanism. A reward mechanism \( R \) is called WTA if \( R_{\text{max}} \geq R(t, t) > 0 \), and \( R(k, t) = 0 \), \( \forall k < t \).
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Approximate Sybil-proofness

Potential way outs:

- **Relax the equilibrium**: Nash implementation\(^3\)
- **Relax the properties**: equilibrium in dominant strategies (this talk)

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Approximate Sybil-proofness

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**Definition (\(\epsilon\)-Downstream Sybil-Proofness (\(\epsilon\)-DSP))**

A reward mechanism \(R\) is called \(\epsilon\) - DSP, if no node can gain by more than a factor of \((1 + \epsilon)\) by adding fake nodes below herself in the current subtree. Mathematically,

\[
(1 + \epsilon) \cdot R(k, t) \geq \sum_{i=0}^{n} R(k + i, t + n) \quad \forall k \leq t, \forall t, n.
\]

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Question: Can we design mechanisms with limited sybil attacks?
A Possibility Result

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**Answer:** Yes!

**Theorem (Possibility Result B)**

For all $\epsilon > 0$, there exists a mechanism that is $\epsilon$-DSP, CP, BB, and SCR.
A Possibility Result

**Question:** Can we design mechanisms with limited sybil attacks?

**Answer:** Yes!

**Theorem (Possibility Result B)**

For all $\epsilon > 0$, there exists a mechanism that is $\epsilon$-DSP, CP, BB, and SCR.

- $R(t, t) = (1 - \delta)R_{\max} \quad \forall t$ where $\delta \leq \frac{\epsilon}{1+\epsilon}$
- $R(k, t) = \delta R(k + 1, t) \quad \forall \ k, t$
The Mechanism Design Space

Theorem 1: Impossibility Result
DSP, CP, and SCR is impossible
The Mechanism Design Space

**Theorem 1:** Impossibility Result
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**Corollary:** DSP, CP, SCR, and BB is impossible
The Mechanism Design Space

**Theorem 1:** Impossibility Result
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**Theorem 2:** Possibility Result A
DSP, CP, WCR, and BB ⇔ WTA mechanism
The Mechanism Design Space

- **Theorem 1**: Impossibility Result
  DSP, CP, and SCR is impossible
  **Corollary**: DSP, CP, SCR, and BB is impossible

- **Theorem 2**: Possibility Result A
  DSP, CP, WCR, and BB $\iff$ WTA mechanism

- **Theorem 3**: Possibility Result B
  $\epsilon$-DSP, CP, BB, and SCR is possible, for all $\epsilon > 0$
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Not all mechanisms in the non-empty space would be interesting
Leads us to define two additional fairness criteria.

**Incentive for Task Forwarding**

**Definition (δ - Strict Contribution Rationality (δ-SCR))**

This property ensures that a node in the winning chain gets at least $\delta \in (0, 1)$ fraction of her successor. Also the winner gets a positive reward. For all $t \geq 1$,

$$R(k, t) \geq \delta R(k + 1, t), \forall k \leq t - 1, \text{ if } t \text{ is the length of the winning chain.}$$

$$R(t, t) > 0, \text{ winner gets positive reward.}$$
Incentive for Task Execution

Definition (Winner’s $\gamma$ Security, $\gamma$-SEC)

This property ensures that payoff to the winning node is at least $\gamma$ fraction ($0 < \gamma < 1$) of the total available budget.

$$R(t, t) \geq \gamma \cdot R_{\text{max}}, \quad t \text{ is the length of the winning chain}$$
Incentive for Task Execution

Definition (Winner’s $\gamma$ Security, $\gamma$-SEC)
This property ensures that payoff to the winning node is at least $\gamma$ fraction ($0 < \gamma < 1$) of the total available budget.

$$R(t, t) \geq \gamma \cdot R_{\text{max}}, \quad t \text{ is the length of the winning chain}$$

- Properties $\epsilon$-DSP, $\delta$-SCR, and $\gamma$-SEC, parametrized by $\epsilon$, $\delta$, and $\gamma$, ensure fairness to the participants and limit the spread of fake nodes.
- We characterize the space of mechanisms that satisfy this set of properties.
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Cost Critical Setting

**Goal**: Accomplishing the task at minimum cost
**Note**: $\gamma$-SEC property is essential, otherwise the solution would be all-zero.

**Definition (MINCOST over $\mathcal{C}$)**
A reward mechanism $R$ is called MINCOST over a class of mechanisms $\mathcal{C}$, if it minimizes the total reward distributed to the participants in the winning chain. That is, $R$ is MINCOST over $\mathcal{C}$, if

$$
R \in \arg\min_{R' \in \mathcal{C}} \sum_{k=1}^{t} R'(k, t), \quad \forall t.
$$
A Characterization Theorem

Let us define, \( \mathcal{E} = \{ (\delta, \epsilon, \gamma) : \delta \leq \min\{1 - \gamma, \frac{\epsilon}{1 + \epsilon}\} \} \), a technical condition on the parameters

Theorem (Characterization of Cost Critical Setting)

If \((\delta, \epsilon, \gamma) \in \mathcal{E}\), a mechanism is MINCOST over the class of mechanisms satisfying \(\epsilon\)-DSP, \(\delta\)-SCR, \(\gamma\)-SEC, and BB iff it is \((\gamma, \delta)\)-GEOM.
A Characterization Theorem

Let us define, $\mathcal{E} = \{(\delta, \epsilon, \gamma) : \delta \leq \min\{1 - \gamma, \frac{\epsilon}{1+\epsilon}\}\}$, a technical condition on the parameters.

Theorem (Characterization of Cost Critical Setting)

If $(\delta, \epsilon, \gamma) \in \mathcal{E}$, a mechanism is MINCOST over the class of mechanisms satisfying $\epsilon$-DSP, $\delta$-SCR, $\gamma$-SEC, and BB iff it is $(\gamma, \delta)$-GEOM.

$(\gamma, \delta)$-Geometric Mechanism ($(\gamma, \delta)$-GEOM)

This mechanism gives $\gamma$ fraction of the total reward to the winner and geometrically decreases the rewards from leaf towards root by a factor $\delta$. For all $t$,

\[
R(t, t) = \gamma \cdot R_{\max}
\]
\[
R(k, t) = \delta^{t-k} \cdot \gamma R_{\max}, \quad k \leq t - 1
\]
The set of \((\delta, \varepsilon, \gamma)\) tuples, given by \(\mathcal{E}\), for which the \textit{MINCOST} mechanism is the \((\gamma, \delta)\)-GEOM mechanism, is the space below the shaded region. MIT mechanism \((\varepsilon = 1, \delta = 0.5, \gamma = 0.5)\) and the WTA mechanism \((\delta = 0, \text{the floor of the space in the figure above})\) are special cases.
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Time Critical Setting

**Goal:** Accomplishing the task at the minimum time. So, the entire budget $R_{\text{max}}$ can be exhausted to encourage faster *task execution* and *propagation*.

**Definition (MAXLEAF over $C$)**

A reward mechanism $R$ is called *MAXLEAF* over a class of mechanisms $C$, if it maximizes the reward of the leaf node in the winning chain. That is, $R$ is *MAXLEAF* over $C$, if

$$R \in \arg \max_{R' \in C} R'(t, t), \quad \forall t.$$
A Characterization Theorem

Theorem (A Characterization for Time Critical Setting)

If $\delta \leq \frac{\epsilon}{1+\epsilon}$, a mechanism is MAXLEAF over the class of mechanisms satisfying $\epsilon$-DSP, $\delta$-SCR, and BB iff it is $\delta$-GEOM mechanism.
A Characterization Theorem

Theorem (A Characterization for Time Critical Setting)

If \( \delta \leq \frac{\epsilon}{1+\epsilon} \), a mechanism is MAXLEAF over the class of mechanisms satisfying \( \epsilon\) - DSP, \( \delta\) - SCR, and BB iff it is \( \delta\) - GEOM mechanism.

\( \delta\) - Geometric mechanism (\( \delta\) - GEOM)

This mechanism gives \( \frac{1-\delta}{1-\delta^t} \) fraction of the total reward to the winner and geometrically decreases the rewards towards root with the factor \( \delta \); \( t \) is the length of the winning chain.

\[
R(t, t) = \frac{1-\delta}{1-\delta^t} \cdot R_{\text{max}}
\]

\[
R(k, t) = \delta \cdot R(k+1, t) = \delta^{t-k} \cdot R(t, t), \ k \leq t - 1
\]
A Characterization Theorem

Theorem (A Characterization for Time Critical Setting)

If \( \delta \leq \frac{\epsilon}{1+\epsilon} \), a mechanism is \textsc{MaxLeaf} over the class of mechanisms satisfying \( \epsilon\text{-DSP}, \delta\text{-SCR}, \) and \( \text{BB} \) iff it is \( \delta\text{-GEOM} \) mechanism.

\( \delta\text{-Geometric mechanism (}\delta\text{-GEOM}\)\n
This mechanism gives \( \frac{1-\delta}{1-\delta^t} \) fraction of the total reward to the winner and geometrically decreases the rewards towards root with the factor \( \delta \); \( t \) is the length of the winning chain.

\[
R(t, t) = \frac{1-\delta}{1-\delta^t} \cdot R_{\text{max}}
\]

\[
R(k, t) = \delta \cdot R(k+1, t) = \delta^{t-k} \cdot R(t, t), \ k \leq t - 1
\]

In addition:

- Both \((\gamma, \delta)\text{-GEOM}\) and \(\delta\text{-GEOM}\) are CP
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Summary and Future Work

Summary: The major contributions of this paper are
- Introducing the concept of **Collapse-Proofness**
- Exhibiting the conflict among the desirable properties
- Proposing an *approximate* Dominant Strategy Implementation
- Presenting a **Resource-critical Optimization** technique

Future work:
- Investigating tightness of the characterization results
- Approximating the CP property
- Extension to non-atomic tasks
- Efficiently fusing information
Thank you!