Eliciting Truthful Measurements from a Community of Sensors

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Health Impact of Air Pollution

Deaths from urban air pollution


The boundaries shown on this map do not imply the expression of any opinion whatsoever on the part of the World Health Organization concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dotted lines on maps represent approximate border lines for which there may not yet be full agreement.

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A Complex Phenomenon

EMISSIONS

DISPERSION
(transport and turbulence)

TRANSFORMATION
(Chemistry)

DEPOSITION
(dry and wet)

Primary Pollutants

Secondary Pollutants

Photo-oxidation
(ozone)

Acids

Humidity

Rain

Plant Growth

Human and Animal Health

Biogenic

Particles

Particules

EFFECTS

SOURCES

Industry

Heaters

Traffic

Heavy Metals

Nitrogen Oxides

Sulfur Oxides

Carbon Oxides

Sun

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Why Community Sensing

• Air pollution varies in space and time
  – A single station is not sufficient for analyzing exposure
  – A mass deployment is required for a detailed picture

• Results may be used for:
  – Everyday decisions
  – Health warnings
  – Exposure studies
  – Emission monitoring
Community Sensing

- A community of agents (sensors) making measurements and report values to a center
Community Sensing

- The center aggregates agent measurements, integrates them into an model, and publishes a pollution map as a public service
Community Sensing Challenges

- Sensing agents are self-interested:
  - Each agent (sensor) needs to be compensated for their investment and maintenance.
  - Agents will tend to minimize their efforts and may even be malicious.

- The center has only partial information:
  - The center cannot verify the accuracy of measurements.
  - The center does not know where measurements are the most needed.
Incentive Schemes

• Needed:
  • An incentive-compatible mechanism that makes agents cooperate with the center.
• Rewards:
  • Monetary: compensate sensors for providing measurements
  • Reputation: exclude sensors that provide wrong measurements (maliciously or otherwise)
A Game Theoretic Setting

At a given time $t$ and location $l$:

- the center publishes a current best estimate map of the pollution level. This provides a public probability distribution $R_{l,t}(x)$ that the pollution level is $x$.
- Agents adopt $R_{l,t}(x)$ as their prior belief $Pr(x)$.
- After observing measurement $o$, the agent has an updated posterior belief $Pr_{o}(x)$, skewed towards $o$. 

$p(x)$

Prior

Posterior

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Example

- Agents measure at location l and time t

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>M</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public map</td>
<td>R(L)=0.1</td>
<td>R(M)=0.5</td>
<td>R(H)=0.4</td>
</tr>
<tr>
<td>Agent 1:M</td>
<td>Pr_M(L)=0.05</td>
<td>Pr_M(M)=0.9</td>
<td>Pr_M(H)=0.05</td>
</tr>
<tr>
<td>Agent 2:M</td>
<td>Pr_M(L)=0.1</td>
<td>Pr_M(M)=0.7</td>
<td>Pr_M(H)=0.2</td>
</tr>
<tr>
<td>Agent 3:L</td>
<td>Pr_L(L)=0.3</td>
<td>Pr_M(M)=0.4</td>
<td>Pr_M(H)=0.3</td>
</tr>
</tbody>
</table>

- Every agent updates differently.
State of the Art

• Mechanism with Proper Scoring Rules [Savage, 1971; Papakonstantinou, Rogers, Gerding and Jennings 2011]
  – Agents report the posterior distribution \( \Pr_o \) to the center
  – The center compares it to a ground truth \( g \) and computes the reward \( \text{Pay}(g, \Pr_o) \)
  – Example: quadratic scoring rule \( \text{pay}(x, p) = 2p(x) - p(v)^2 \)

\[
p = [l : 0.1, m : 0.7, h : 0.2] \Rightarrow \text{pay}(m, p) = 2 \times 0.7 - (0.1^2 + 0.7^2 + 0.2^2) = 0.86
\]

• Incentive Compatible: highest expected payoff comes from reporting true private beliefs.
Problems with Applying Scoring Rules

1. Ground truth is required to evaluate the agent’s report.
   – Defeats the purpose of community sensing

2. Agent has to submit full posterior distribution.
   – Excessive costly communication
Overcoming Lack of Ground Truth

• Solution: use peer prediction [Miller, 2005]
  – Substitute ground truth with value m derived from peer reports using a model
  – Truthful reporting becomes a Nash-equilibrium
  • If all others report truthfully, best strategy is to report truthfully
Overcoming need for reporting distributions

- Agent only reports a single value \( s \).
- Assumption: agent posterior = prior with largest increase at the measured value \( o \):
  - \( \frac{Pr_o(o)}{Pr(o)} > \frac{Pr_o(o')}{Pr(o')} \) for all \( o' \neq o \)

\[
\begin{align*}
\text{Prior} & \quad \text{Posterior} \\
\end{align*}
\]

\[
p(x)
\]

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A New Incentive Scheme

• 2 assumptions:
  • Agents adopt public map as prior belief: $\Pr(x) = R(x)$
  • Agents believe in their measurement: $\Pr_o(o) / \Pr(o) > \Pr_o(o') / \Pr(o')$, all $o' \neq o$
• Peer Truth Serum: scoring rule based on prior rather than posterior belief
Peer Truth Serum

• Center rewards report $s$ by comparing with an unbiased peer estimate $m$.

• Payment function based on public map $R$:

\[
\text{Pay}(s,m) = T(s,m,R):
\]

- $T(s,m,R) = 1 / R(s)$ if $s = m$;
- $T(s,m,R) = 0$ otherwise.
Why it works

• Suppose agent measures o:
• Expected payment for reporting s:
  \[ = \frac{Pr_o(s)}{R(s)} \]
• By assumption:
  • \[ \frac{Pr_o(o)}{Pr(o)} > \frac{Pr_o(x)}{Pr(x)} \text{ for all } x \neq o \]
  • \[ Pr(s) \approx R(s) \text{ (tolerance given by } \frac{Pr_o(s)}{Pr(s)}) \]
• Truthful reporting s=o has the highest expected payoff.
• No other assumption about the posterior is required.
Informed Agents

• Agents know more about environment than center:
  – Obvious pollution
  – Exceptional situations

• Their prior belief Pr may be *more informed*: closer to reality than the public map R

• What if this causes non-truthful reports?
Helpful Reports

• Proposition: using PTS, no agent with an informed prior belief will ever falsely report a value \( b \) that is over-reported in \( R \) (\( \Pr(b) < R(b) \))
• \( \Rightarrow \) non-truthful reports are helpful: they increase the frequency of under-reported values.
• \( \Rightarrow \) \( R \) and \( \Pr \) will often converge faster than with truthful reporting.
Reward vs. Reputation

- PTS can be used to compensate agents for their efforts.
- What about malicious reports: small monetary incentives would be insufficient.
- => use PTS to accumulate reputation score: malicious agents will be disregarded.
- Influence limiter (Resnick 2007) provides an elegant scheme to prevent manipulation.
Summary

• Community sensing needs good incentive schemes
• A practical, incentive compatible mechanism for community sensing
• Future work: reputation scheme, possibilities for collusion