Collaborative Location Privacy with Rational Users

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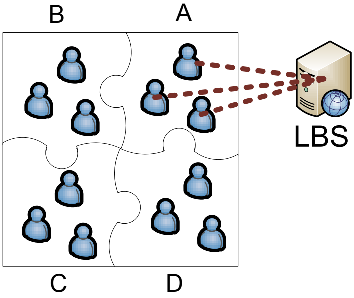
Presentation Outline

Privacy in Location Based Systems

- Users have GPS devices
- Communicate wirelessly
- Access location based service (LBS)
- Find shops, restaurants, hotels, etc...



Privacy threat

What will the LBS do with the collected data?

Operating Principle of MobiCrowd
(R. Shokri et al., 2011)

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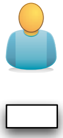
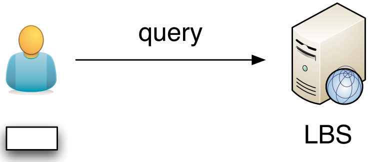
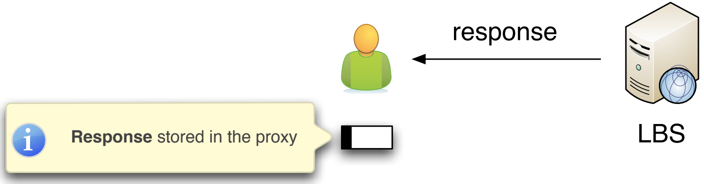


Mobile Proxy does not contain the required data.

Operating Principle of MobiCrowd
(R. Shokri et al., 2011)



Operating Principle of MobiCrowd
(R. Shokri et al., 2011)



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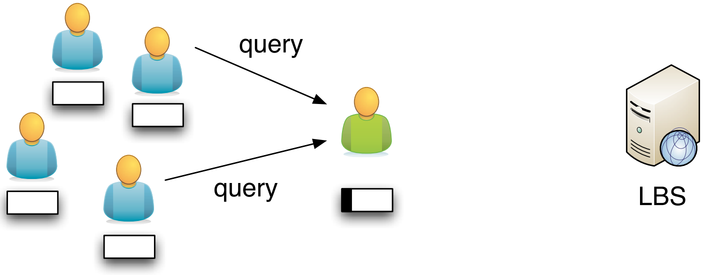


Sharing also has Costs

Advantages

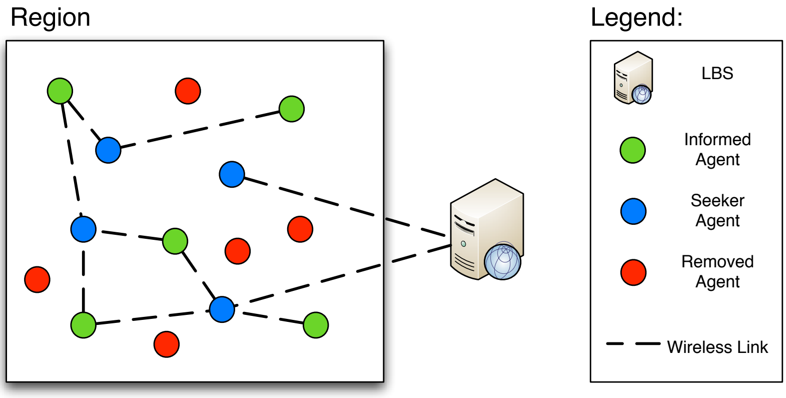
- Fewer queries to LBS
- Users gain privacy

Problems

- Some users still need to query the LBS
- Sharing data has costs

Are users willing to cooperate by sharing regional data ***to avoid the privacy threat*** *of connecting to the LBS?*

System Model



System Model

- **Cumulative cooperation effort**:
  # of times agent *i* receives help $-$ # of times helps others:

$$\phi_i(t) = \mathrm{rc}_i(t) - \mathrm{tr}_i(t)$$

- **State of an agent**:
  current role $\times$ cumulative cooperation effort $\phi = \phi_i(t)$:

$$\mathcal{K}_\phi, \mathcal{I}_\phi, \mathcal{R}_\phi$$

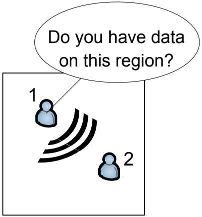
- **Threshold strategy**:
  i cooperates if it is informed and $\phi_i(t)$ above threshold α:

$$s_i(t) = \begin{cases} \text{cooperate} & \text{if } \phi_i(t) > \alpha \land i \in \mathcal{I}_{\phi_i(t)} \\ \text{defect} & \text{otherwise} \end{cases}$$

Two-Agent Game

- 2-agents confined to one region
- Information expires after one game stage
- One agent randomly picked to query the LBS server
- Will it cooperate by sharing this data with its peer?

$$0 \le c_{\text{com}} < c_{\text{srv}} < b_{\text{inf}} \le 1$$



Utility Function

$$u_i(t) = \begin{cases} b_{\text{inf}} & s_j(t) = \text{C} \\ b_{\text{inf}} - c_{\text{srv}} & s_j(t) = \text{D} \\ -c_{\text{com}} & s_i(t) = \text{C} \\ 0 & s_i(t) = \text{D} \end{cases}$$

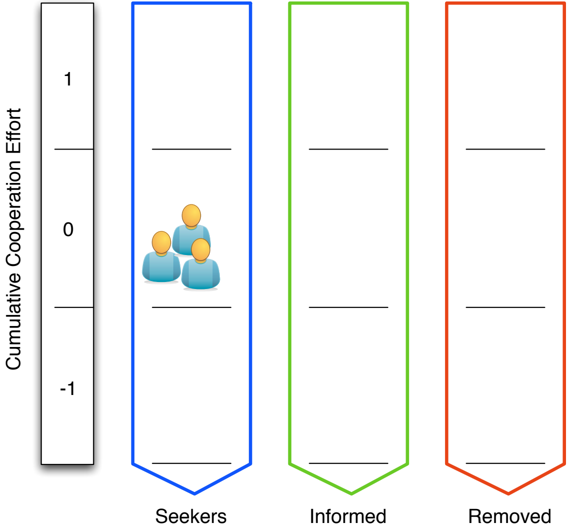
Two-Agent Game Analysis

Expected Aggregate Discounted Reward

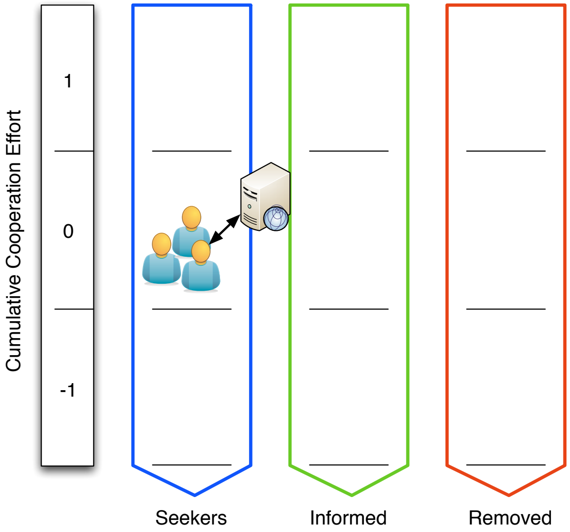
$$U_i^*(\alpha) = \begin{cases} \frac{1}{1-\delta}\left(b_{\text{inf}} - c_{\text{com}}\right) & \text{if } \alpha \leq -1 \\ \frac{1}{1-\delta}\left(b_{\text{inf}} - c_{\text{srv}}\right) & \text{otherwise} \end{cases}$$

- **Nash** equilibrium for $\alpha \geq 0$: both defect
- **Nash** equilibrium for $\alpha = -1$: mutual cooperation
  maximal payoff, minimizes sharing
- Choice of $\alpha = -1$ is **Pareto** optimal

Multiple-Agent Game Example



Multiple-Agent Game Example



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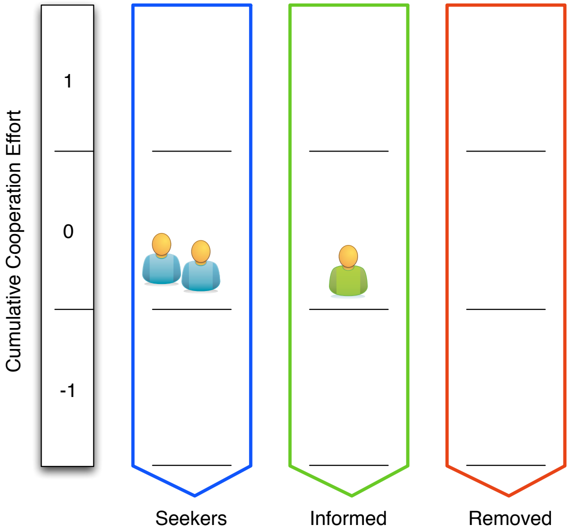

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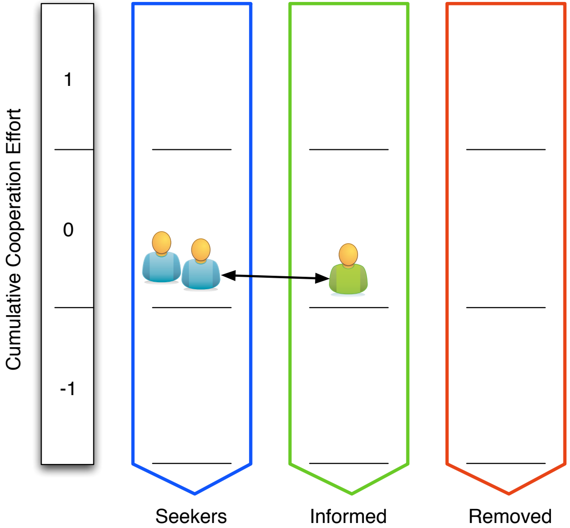

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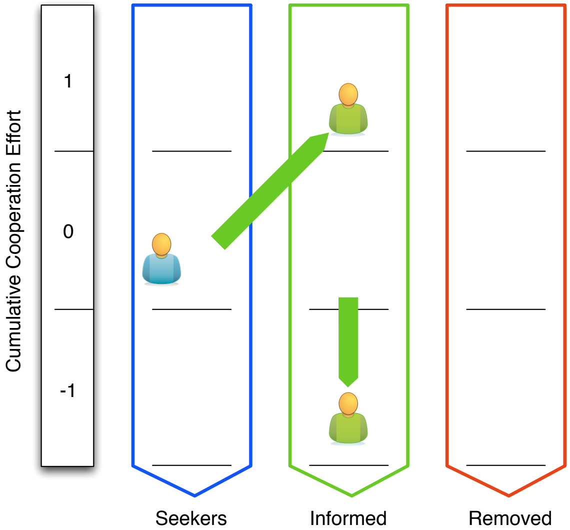

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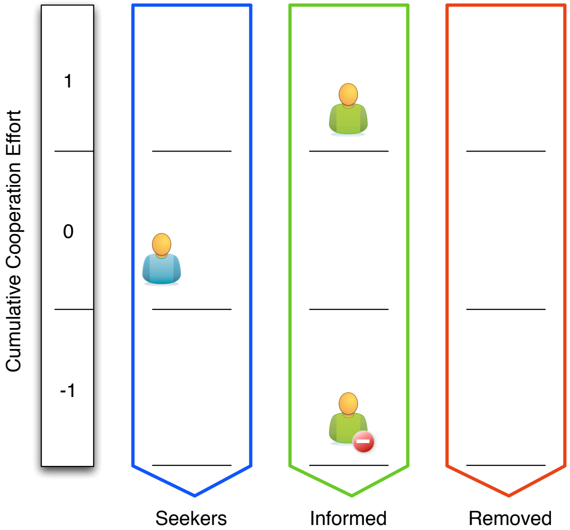

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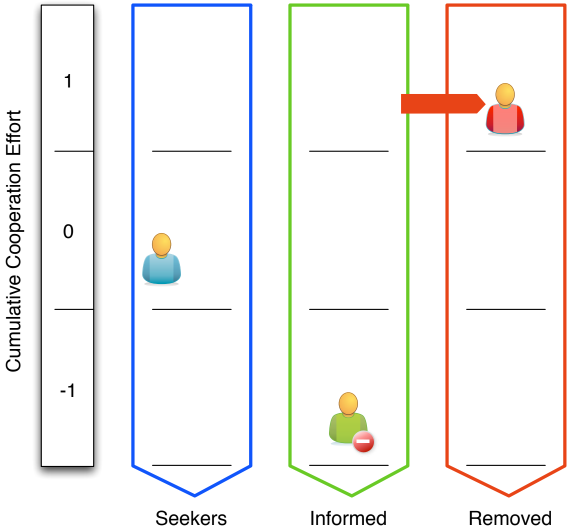

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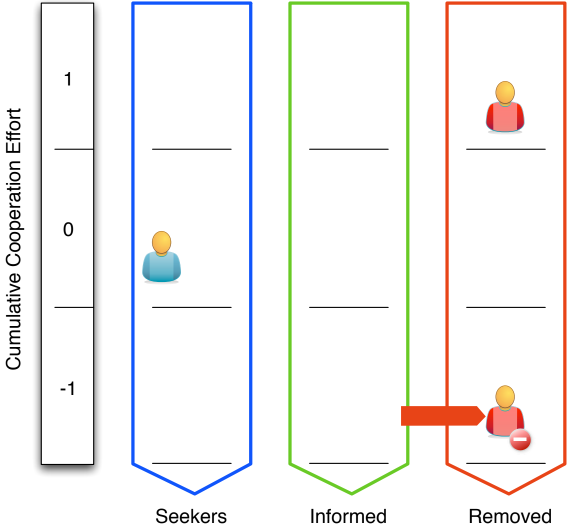

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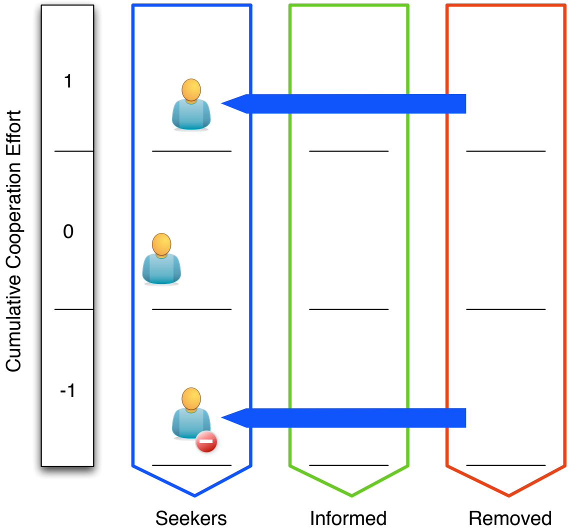

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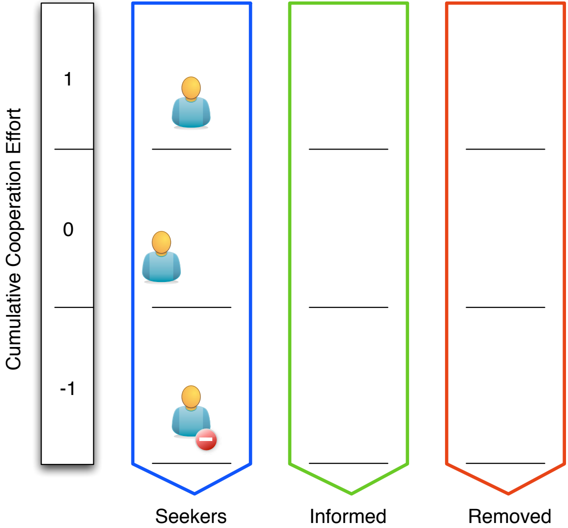
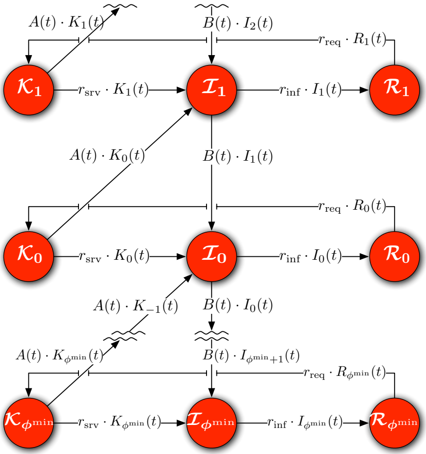


SIR Model for the Multiple-Agent Game

Key

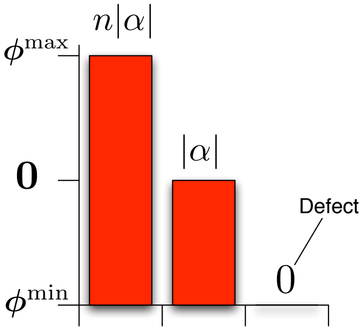
- $\mathcal{X}_\phi$: agent state
- $X_\phi(t)$: fraction agents
- r_{srv}: LBS contact rate
- $1/r_{\text{inf}}$: info lifetime
- r_{req}: rate $\mathcal{R} \to \mathcal{K}$
- $A(t)$: $\propto$ informed agents
- $B(t)$: $\propto$ seeker agents



Cumulative Cooperation Effort Bounds

Maximum & Minimum

- $\phi^{\text{max}} = (1 - n)\alpha$
- $\phi^{\text{min}} = \alpha$

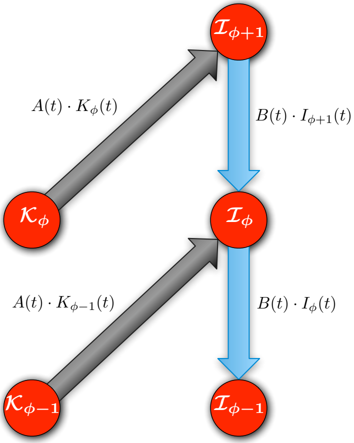


- Amount of cooperation is limited
- Proportional to number of agents n and threshold α
- i cooperates, at most, $n|\alpha|$ times when $\phi_i(t) = \phi^{\text{max}}$
- At ϕ^{min} agent defects
- Total agent-states:

  $|\mathcal{S}| = 3\,(1 - n\alpha)$

Conservation of Information

- Total information received
  =
  Total information shared
- No loss of data
- Lost pkts retransmitted



Transition Payoffs

- $\mathcal{K}_\phi \to \mathcal{I}_{\phi+1}$: seekers contact informed peers

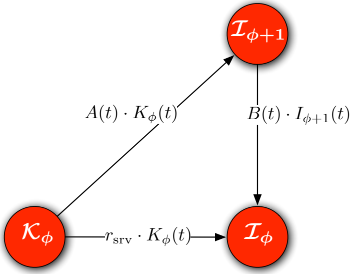
  Payoff: b_{inf}

- $\mathcal{K}_\phi \to \mathcal{I}_\phi$: seekers connect to LBS

  Payoff: $b_{\text{inf}} - c_{\text{srv}}$

- $\mathcal{I}_{\phi+1} \to \mathcal{I}_\phi$: informed agents share data

  Payoff: $-c_{\text{com}}$



$$0 \leq c_{\text{com}} < c_{\text{srv}} < b_{\text{inf}} \leq 1$$

Total Discounted Payoff

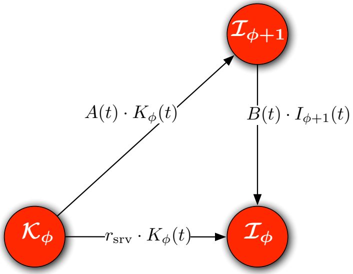
- Benefit $b(\alpha, t)$:

  $R_{\{\mathcal{K}_\phi \to \mathcal{I}_{\phi+1}\}}(\alpha, t) \cdot b_{\text{inf}}$

  $+ \; R_{\{\mathcal{K}_\phi \to \mathcal{I}_\phi\}}(\alpha, t) \cdot (b_{\text{inf}} - c_{\text{srv}})$

- Cost $c(\alpha, t)$:

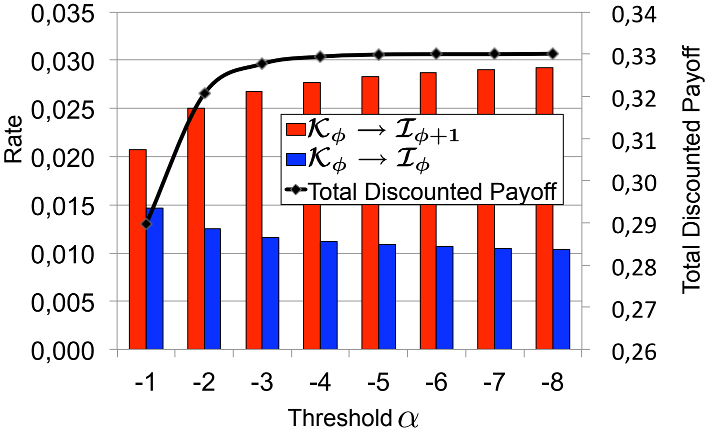
  $R_{\{\mathcal{I}_{\phi+1} \to \mathcal{I}_\phi\}}(\alpha, t) \cdot c_{\text{com}}$



Total Discounted Payoff

$$U^*_{\text{total}}(\alpha) = \int_0^\infty \delta^t \left(b(\alpha, t) - c(\alpha, t)\right) \, \mathrm{d}t$$

Example Total Discounted Payoff



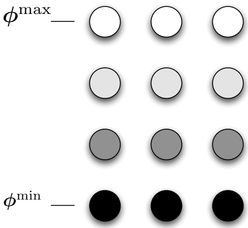
$\mathcal{K}_\phi \rightarrow \mathcal{I}_\phi$

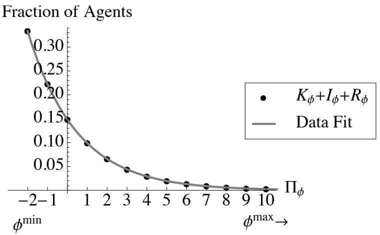
Payoff: $b_{\text{inf}} - c_{\text{srv}}$

$\mathcal{K}_\phi \rightarrow \mathcal{I}_{\phi+1}$

Payoff: b_{inf}

Estimating Distribution of Cumulative Cooperation Effort



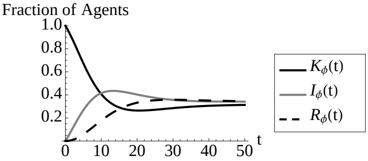


Probability an agent *i* has $\phi_i(t) = \phi$

$$\Pr\{\exists_i : \phi_i(t) = \phi\} \approx \frac{1}{1-\alpha} \cdot \frac{1}{(1-1/\alpha)^{\phi-\alpha}}$$

Optimal Threshold Maximizes Agent Payoff

- Agent i in state $\mathcal{X}_\phi$: $(1/3) \cdot \Pr\{\exists_i : \phi_i(t) = \phi\}$
- Estimate rates and total discounted payoff: $\widehat{U}^*_{\text{total}}(\alpha)$
- An agent's expected total pay: $\widehat{U}^*(\alpha) = \frac{1}{n} \cdot \widehat{U}^*_{\text{total}}(\alpha)$



Homogeneous K, I, R

Optimal Threshold

$$\alpha^{\text{opt}} = \max\{\alpha \leq -1 : \widehat{U}^*(\alpha - 1) - \widehat{U}^*(\alpha) < \epsilon\}$$

Conclusion

Goal

Are users willing to share data to gain privacy?

- 2-agents: Pareto optimal equilibrium favoring cooperation

$$\alpha^{\text{opt}} = -1$$

- *n*-agents: Found α that maximizes an agent's payoff

$$\alpha^{\text{opt}} \leq -1$$

- To maximize their payoffs, agents benefit by sharing

How will <u>humans</u> behave?

Future Steps

- Consider threshold strategies with an independent (per agent) threshold
- Experiment with different types of reactive strategies
- Introduce statistical processes describing the rate at which agents enter and leave a region

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