Analytic Methods for Optimizing Realtime Crowdsourcing

Michael Bernstein, David Karger, Rob Miller, and Joel Brandt
MIT CSAIL and Adobe Systems
Use *queueing theory* to understand and *optimize performance* of a paid, realtime crowdsourcing platform.

- Relationship between crowd size and response time
- Algorithm for optimizing crowd size & cost vs. response time
- Improvements to the platform: 500 millisecond feedback
Realtime Crowds

Answering visual questions for blind users

[Bigham et al. 2010]
Realtime Crowds

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Crowd-assisted photography

[Bernstein et al. 2011]
Realtime Crowds

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Paid Crowdsourcing

Pay small amounts of money for short tasks

Amazon Mechanical Turk: Roughly five million tasks completed per year at 1-5¢ each [Ipeirotis 2010]

Label an image

Requester: Matt C.
Reward: $0.01

Transcribe short audio clip

Requester: Gordon L.
Reward: $0.04
Retainer Recruitment

Workers sign up in advance
½¢ per minute to remain on call
Alert when the task is ready

Wait at most:
5 minutes

Task:
Click on the verbs in the paragraph

He leapt the fence and dashed toward the door.

[Bernstein et al. 2011]
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Alert when the task is ready

50% of workers return in two seconds, and
75% of workers return in three seconds.

[Bernstein et al. 2011]
State of the Literature

Realtime Crowds

- Recruit crowds in two seconds, execute traditional tasks (e.g., votes) in five seconds
- Maintain continuous control of remote interfaces
- Opportunities in deployable, intelligently reactive software

[Bigham et al. 2010, Bernstein et al. 2011, Lasecki et al. 2011]
The Challenge

Running Out of Retainer Workers
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Running Out of Retainer Workers

Loss
Non-realtime response
The Tradeoff

Missed tasks, non-realtime results

Extra retainer workers, extra cost

Tuesday, May 8, 12
The Goal

Optimize the tradeoff between recruiting too many workers and dropping too many tasks.
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Optimize the tradeoff between recruiting too many workers and dropping too many tasks.

Budget-optimal crowdsourcing is possible in non-realtime scenarios

[Dai, Mausam and Weld 2010; Kamar, Hacker and Horvitz 2012; Karger, Oh, and Shah 2011]
Queueing Theory

- Formal framework for stochastic arrival and service processes
- Basic idea: random task arrivals and random processing times for workers
- Quantify how long tasks will need to wait in line

Queueing theory for completion times: [Ipeirotis 2010]
Queueing Theory

M/M/1 queue

Markovian (Poisson process) task arrivals, rate $\lambda$
Markovian (Poisson process) server work time, rate $\mu$
One server
Queueing Theory

M/M/1 queue

\( \lambda \) Markovian (Poisson process) task arrivals, rate \( \lambda \)

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Queueing Theory

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M/M/c/c queue

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c $c$ servers
c $c$ max tasks in servers and queue
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Queueing Theory

M/M/c/c queue

All servers busy

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M/M/c/c queue

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\[ \text{c servers} \]
\[ \text{c max tasks in servers and queue} \]
Retainer Queue

M/M/c/c queue

c workers, no waiting queue
Task arrivals: Poisson process, rate $\lambda$
Worker recruitment time: Poisson process, rate $\mu$
Retainer Queue

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Loss

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Retainer Queue

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Retainer Queue

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\[ \Pr(\text{i servers busy}) \]

All servers busy
Retainer Queue

Loss

\[ P(i \text{ servers busy}) = \pi(i) \]
Retainer Queue

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\[ P(\text{all servers busy}) \]
Retainer Queue

Loss

\[ P(i \text{ servers busy}) = \pi(i) \]
\[ P(\text{all servers busy}) = \pi(c) \]
Model Predictions

1. Probability that all workers are busy: $\pi(c)$
   $\rightarrow$ the task has to wait for expected time $1/\mu$

2. Cost of keeping a retainer pool of size $c$
   $\rightarrow$ cost depends on number of idle servers
Probability of Loss

- Draw on Erlang’s Loss Formula from queueing theory: probability of a rejected request in an M/M/c/c queue

- Let $\rho$ be the traffic intensity:
  
  $\rho = \lambda/\mu$

  (roughly, the number of new tasks that will arrive in the time it takes to recruit a worker)
Probability of Loss

Erlang’s Loss Formula says:

\[ \pi(c) = P(c \text{ servers busy}) \]

\[ = \frac{\rho^c / c!}{\sum_{i=0}^{c} \rho^i / i!} \]

Remarkably, this result makes no assumptions about the arrival distribution.
Expected Waiting Time

\[ P(c \text{ servers busy}) \times (\text{expected recruitment time}) \]

\[ = \pi(c) \frac{1}{\mu} \]

\[ = \frac{\rho^c / c!}{\sum_{i=0}^{c} \rho^i / i!} \frac{1}{\mu} \]
Expected Cost

How much do we pay in steady-state?

Depends on how many workers are usually waiting on retainer.
Expected Cost

Probability of \( i \) busy servers in an M/M/c/c queue is a more general version of Erlang’s Loss Formula:

\[
\pi(i) = \frac{\rho^i / i!}{\sum_{i=0}^{c} \rho^i / i!}
\]

Derive the expected number of busy workers:

\[
E[i] = \rho [1 - \pi(c)]
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Expected Cost

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Derive the expected number of busy workers:

\[
E[i] = \rho [1 - \pi(c)]
\]

Total cost is the number of \textit{idle} workers:

\[
c - \rho [1 - \pi(c)]
\]
Expected Cost

Cost goes down when $c < \rho$, but performance suffers.
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Cost goes down when $c < \rho$, but performance suffers.
Optimal Retainer Size

- Size of retainer pool is typically the only value that requesters can manipulate
- Minimize costs by keeping the retainer pool small while keeping $\pi(c)$ low
Optimal Retainer Size
Based on Maximum Miss Probability

Given a maximum desired probability of a miss $p_{max}$:

Minimize $c$ subject to $\pi(c) \leq p_{max}$
Optimal Retainer Size
Based on Maximum Miss Probability

Given a maximum desired probability of a miss $p_{max}$:

Minimize $c$ subject to $\pi(c) \leq p_{max}$
Optimal Retainer Size
Based on Joint Cost

If the “pizza delivery” property holds: we can quantify the cost of loss
Improving the Retainer Model

1. Subscriptions
2. Shared Pools
3. Predictive Recruitment
Retainer Subscriptions

• Proposal: increase $\mu$ by allowing workers to subscribe to realtime tasks

• Instead of posting to the global task list, the platform sends a message to subscribers

• Change crowdsourcing from a pull model to a push model
Global Retainer Pools

• Sharing one global retainer pool across requesters improves performance

• Intuition: Most workers are padding for unlikely runs of arrivals)
Global Retainer Pools

- Sharing one global retainer pool across requesters improves performance
- Intuition: Most workers are padding for unlikely runs of arrivals

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Global Retainer Pools

- Through approximation, individual pools:
  \[ \pi(c) \approx \sqrt{2\pi c} \left( e^{-\rho} (e \rho / c)^c \right) \]

- Shared pools across \( k \) requesters:
  \[ \pi(c) \approx \sqrt{2\pi k c} \left( e^{-\rho} (e \rho / c)^c \right)^k \]

- Loss rate declines exponentially with the number of bundled retainer pools
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Global Retainer Pools

Cost dramatically decreases as you combine retainers: $k$ dollars to $\log(k)$ dollars
Global Retainer Routing

- Not every worker in a global retainer pool is good at every task
- If we assigned each worker to any task they could do, some tasks would starve
Global Retainer Routing

- We want to maintain a buffer of workers to respond to all kinds of tasks
- A linear programming technique can balance the traffic intensities across all tasks
Precruitment

- Predictive Recruitment: notify workers before the task arrives
- Recall workers in expectation of having a task by the time they arrive 2–3 seconds later
Precruitment

Formative Study, N=373 tasks

• 3¢ for 3-minute retainer task: whack-a-mole
• ‘Loading...’ screen for randomly-selected time [0, 20] seconds after worker returns
• Click on randomly-placed mole
Precruitment

Formative Study, N=373 tasks

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Recruitment

Results

- Median time to mouse move: 0.50 seconds

- Standard retainer model (start timer @ alert): median mouse move in 1.36 seconds
Discussion

• Empirics: Can deployed crowdsourcing platforms support lots of realtime tasks?
• Theory: Crowds as queueing systems
• Reputation: median response time, overall response rate
Use *queueing theory* to understand and *optimize performance* of a paid, realtime crowdsourcing platform.

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