Analytic Methods for Optimizing Realtime Crowdsourcing

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MIT CSAIL and Adobe Systems

CSAIL Adobe

MIT HUMAN-COMPUTER INTERACTION

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]

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Crowd-assisted photography

[Bernstein et al. 2011]

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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]

Retainer Recruitment

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Wait at most:

5 minutes

Task:

Click on the verbs in the paragraph

He leapt the fence and dashed toward the door.

`alert()`

Start now! OK

[Bernstein et al. 2011]

Retainer Recruitment

Workers sign up in advance
½¢ per minute to remain on call
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

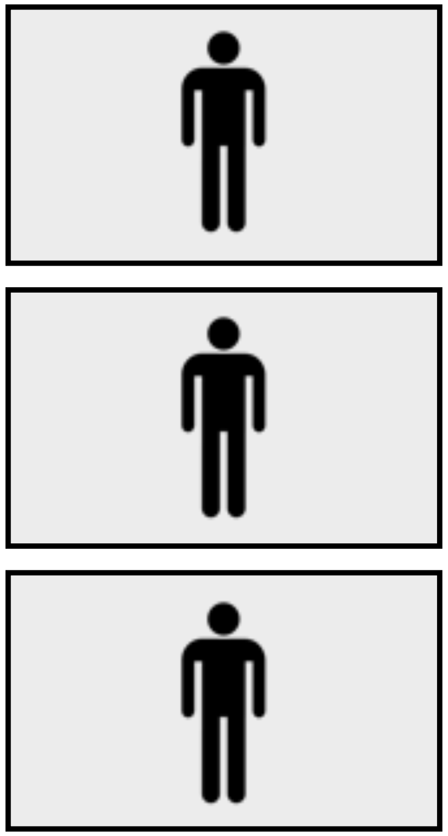
Realtime Crowds

- 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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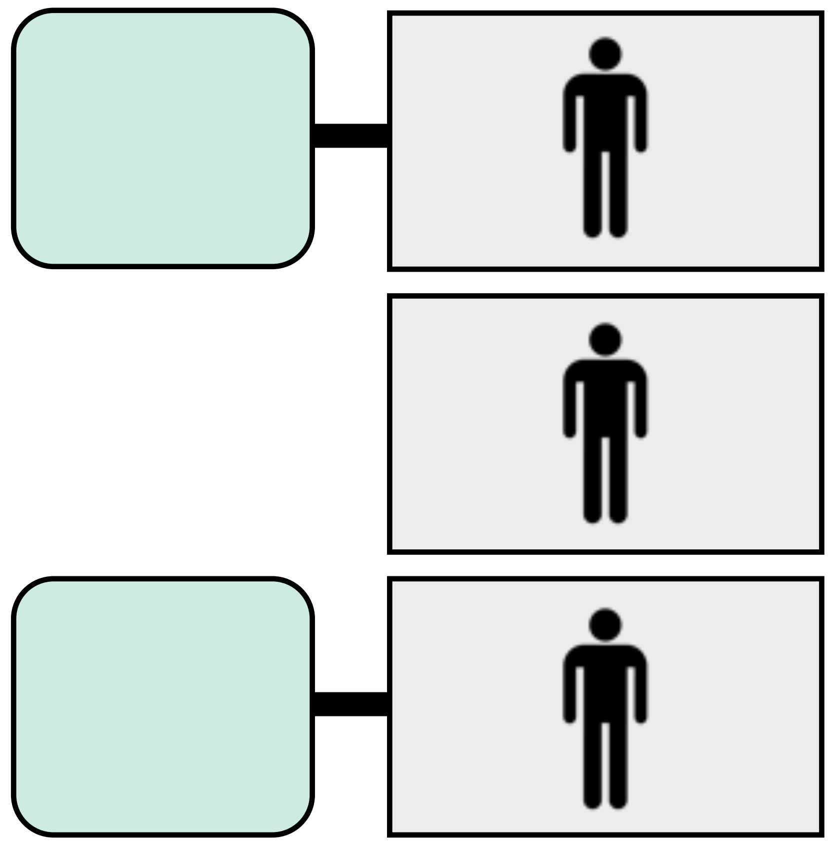

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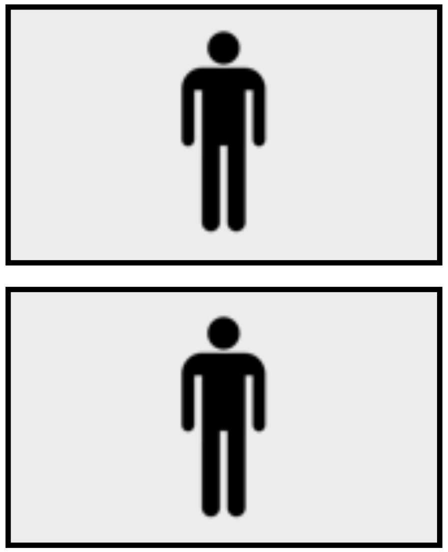

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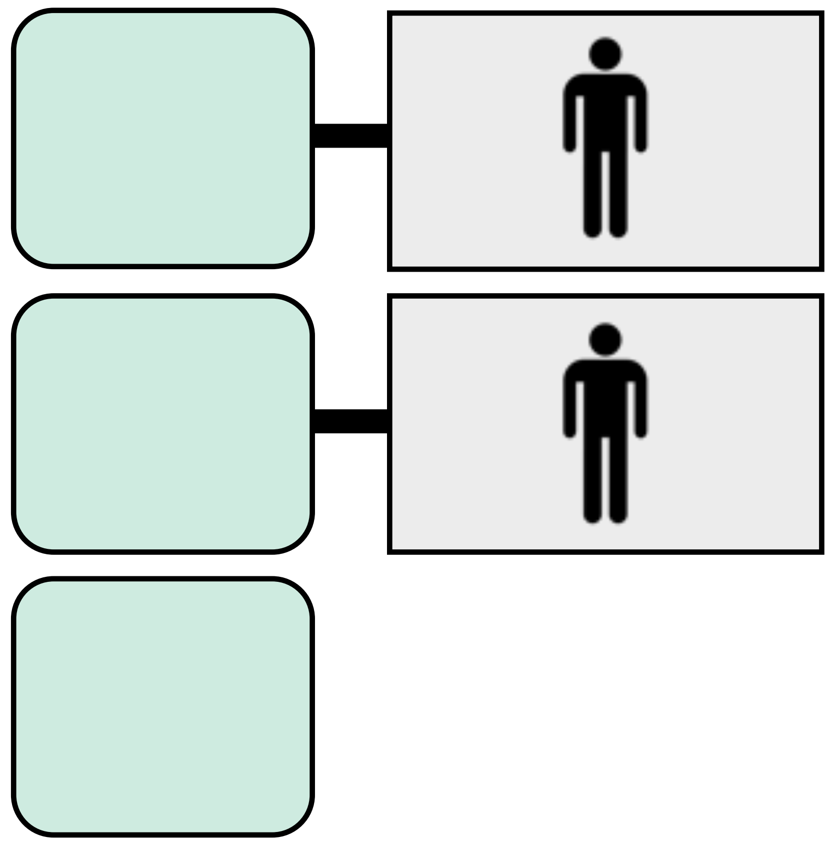

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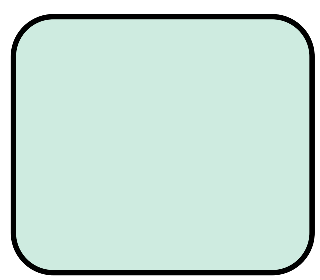

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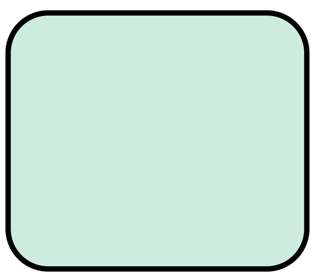
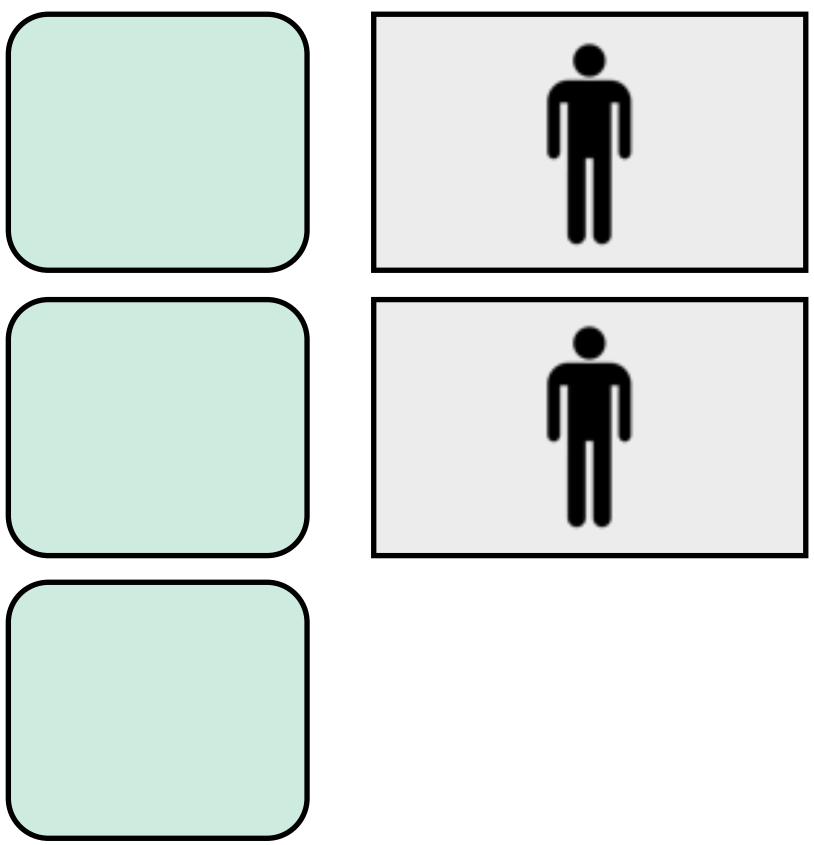


Loss

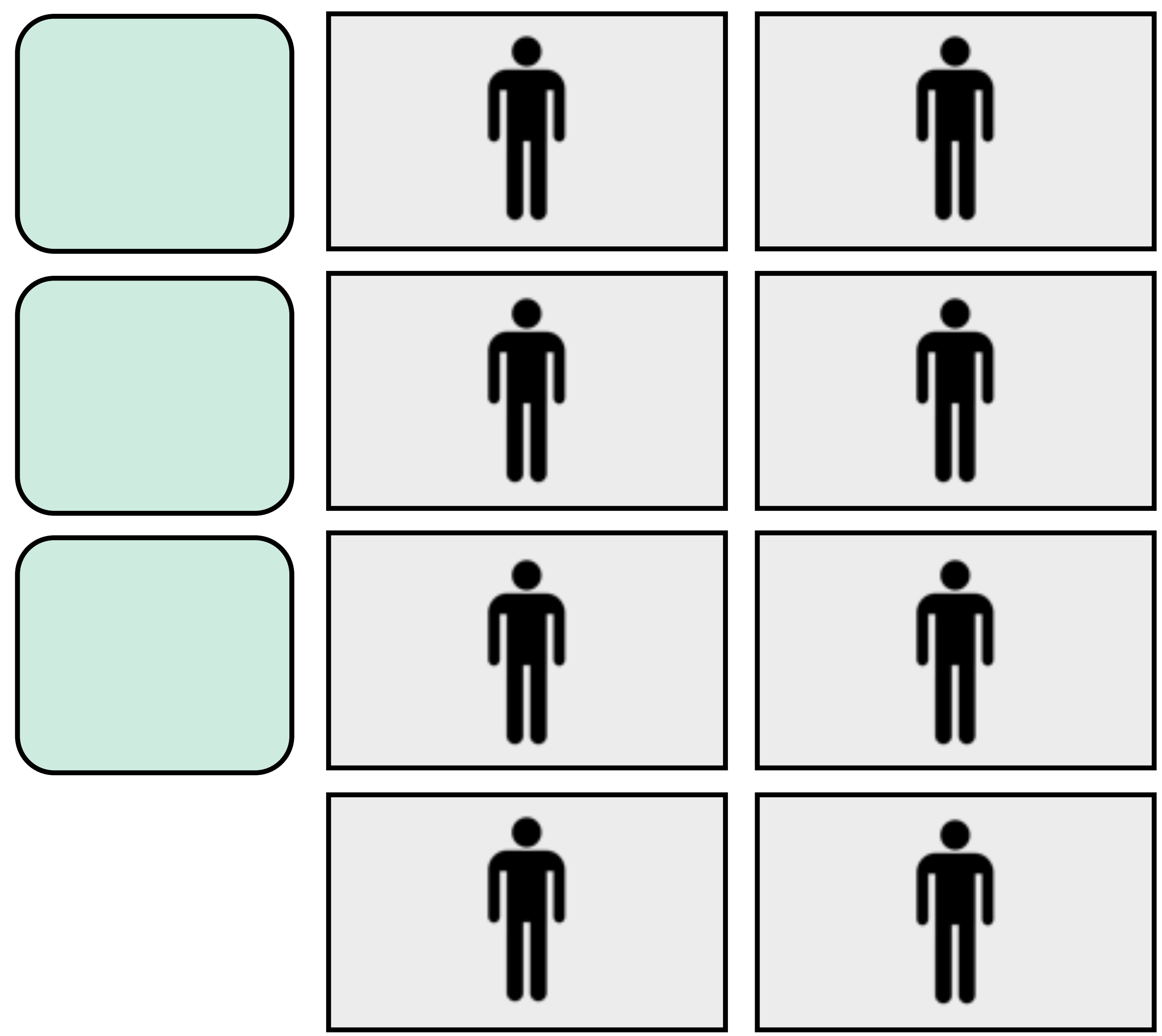
Non-realtime response

The Tradeoff

Missed tasks,
non-realtime results



Extra retainer workers,
extra cost



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]

Outline

1 Model

2 Optimization

3 Platform

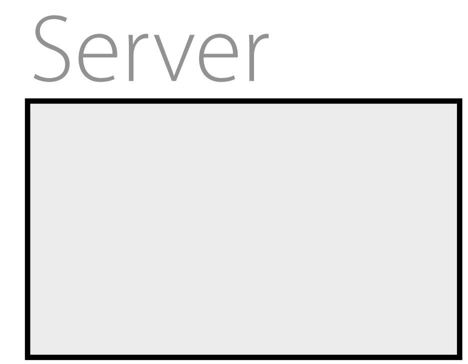
Queueing Theory

- 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



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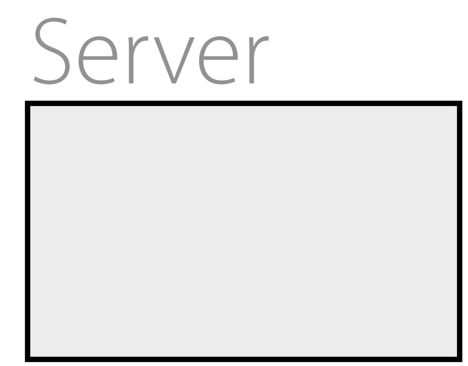
M Markovian (Poisson process) server work time, rate μ

1 One server

Queueing Theory

M/M/1 queue



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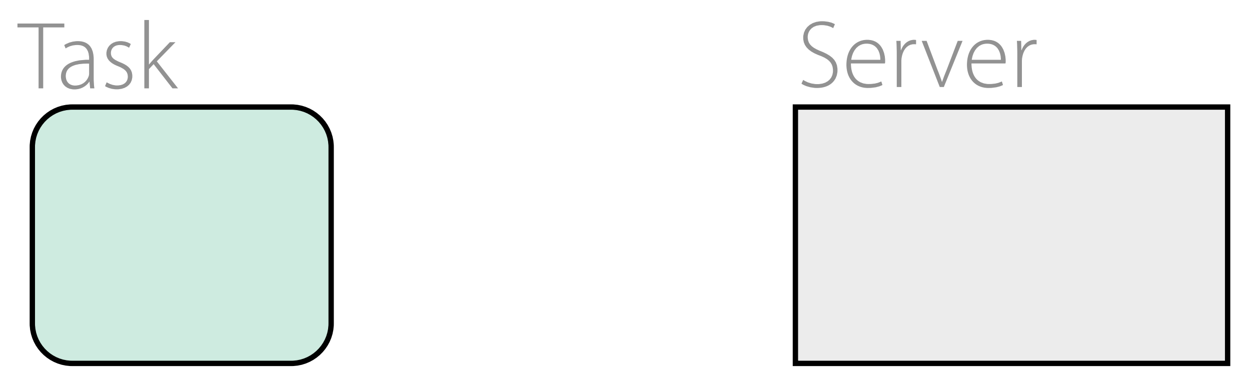

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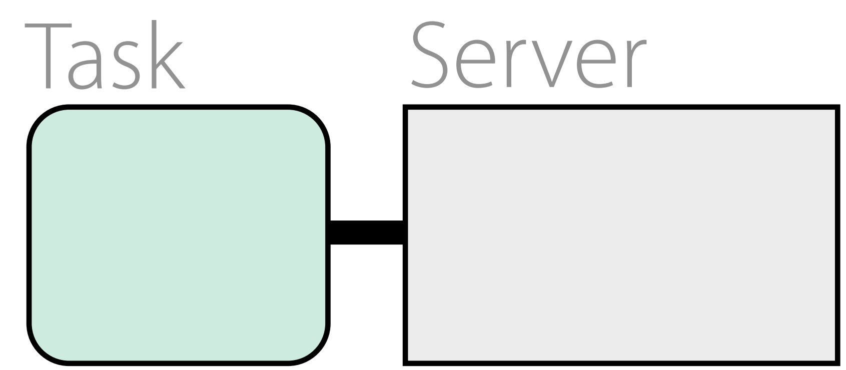

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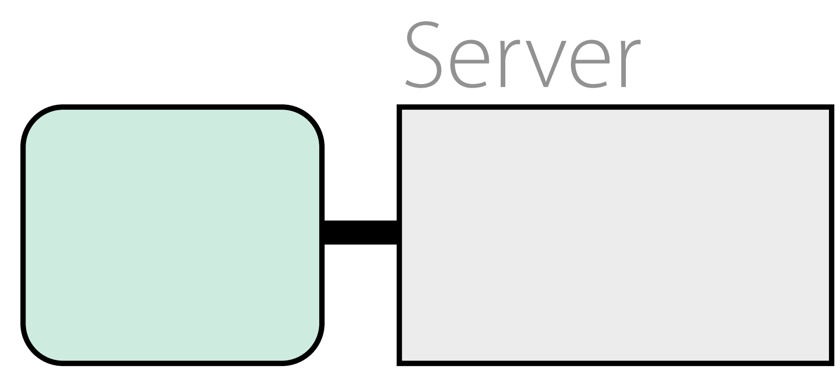

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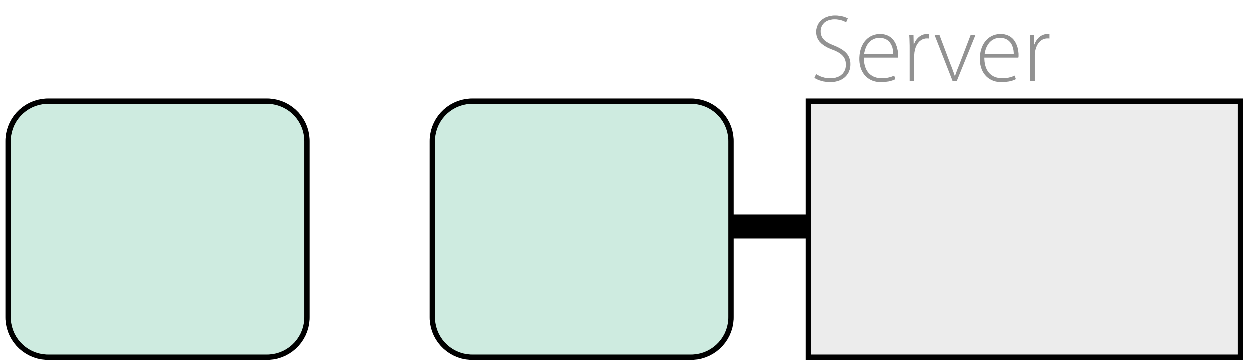

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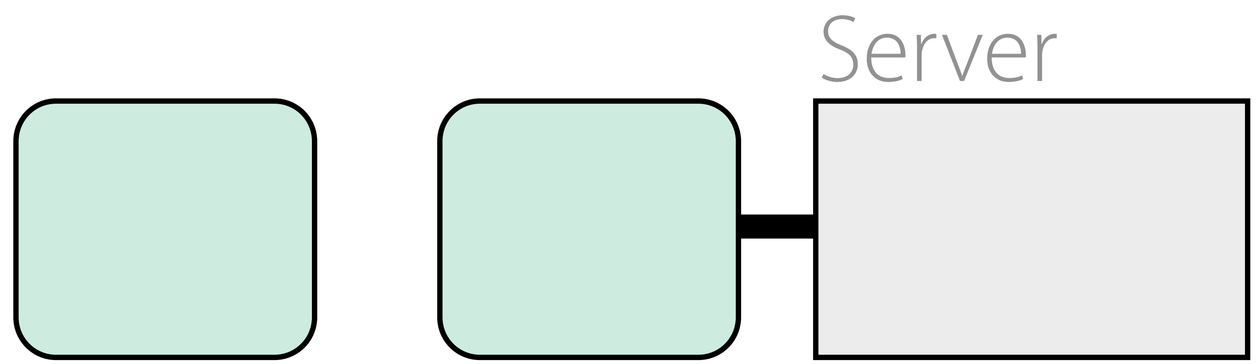

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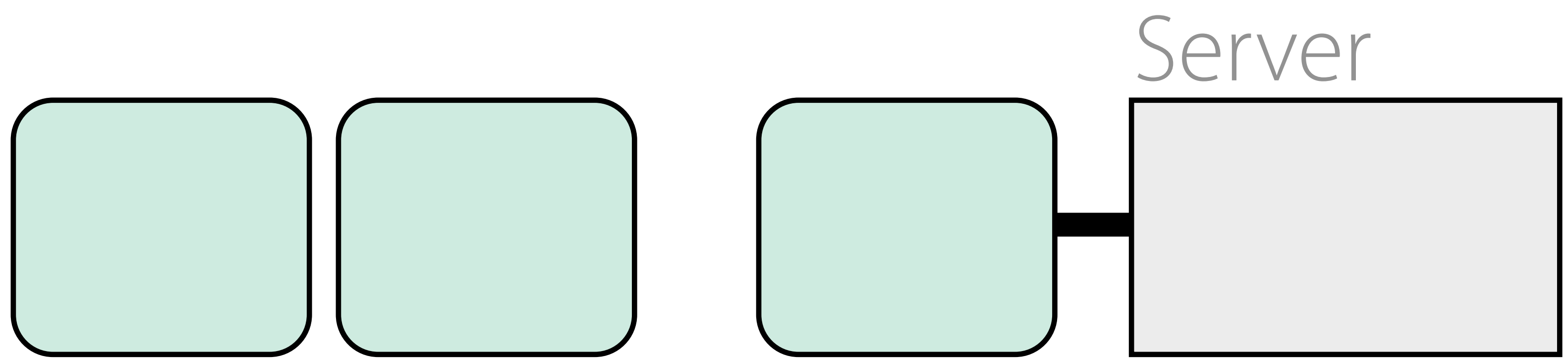

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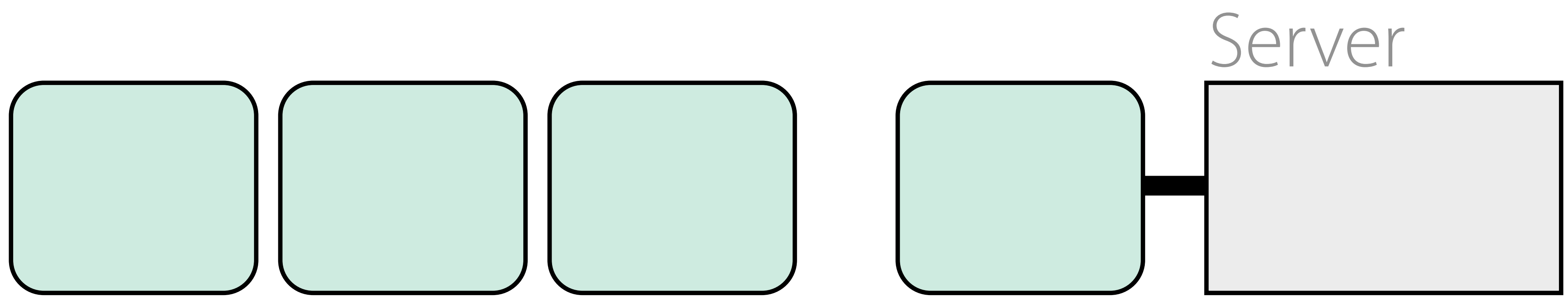

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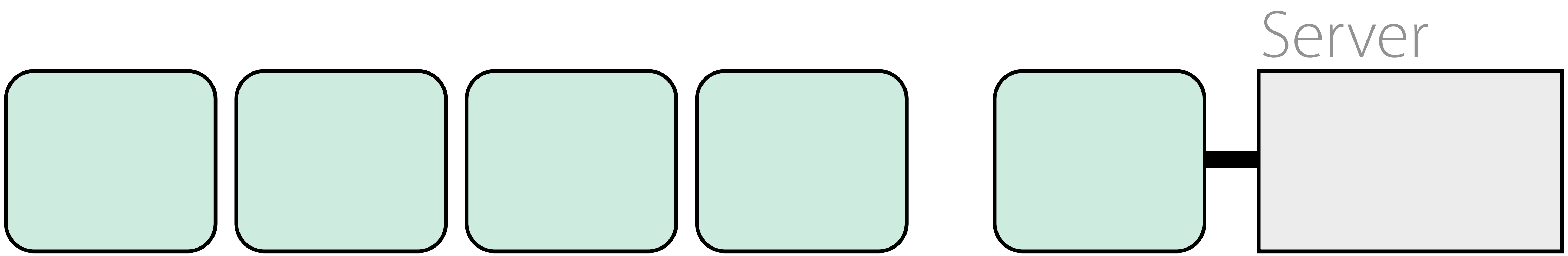

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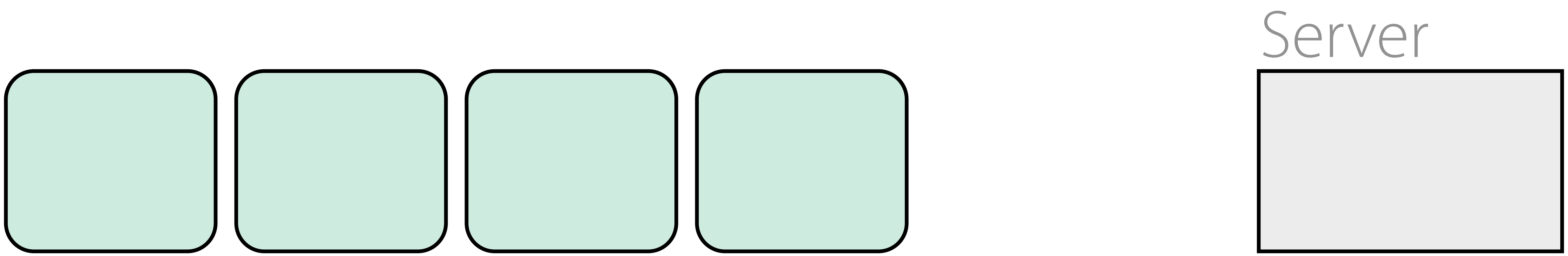

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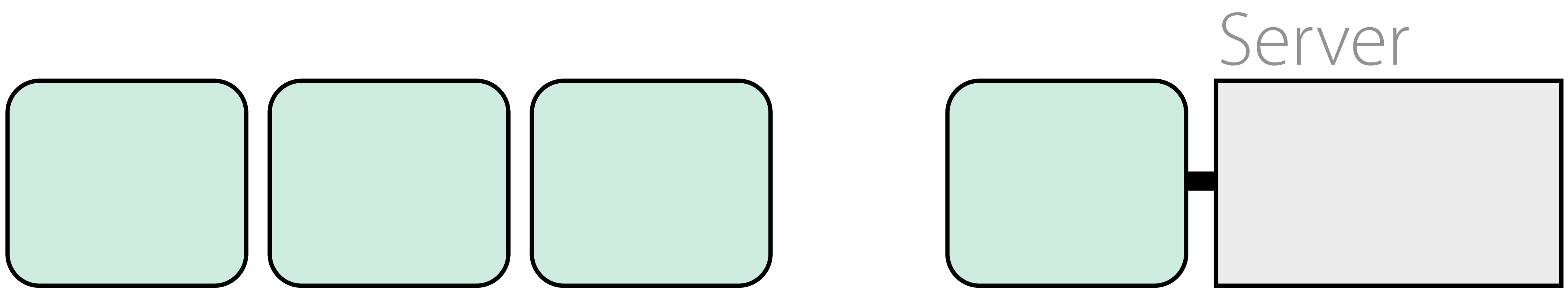

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Queueing Theory

M/M/c/c queue

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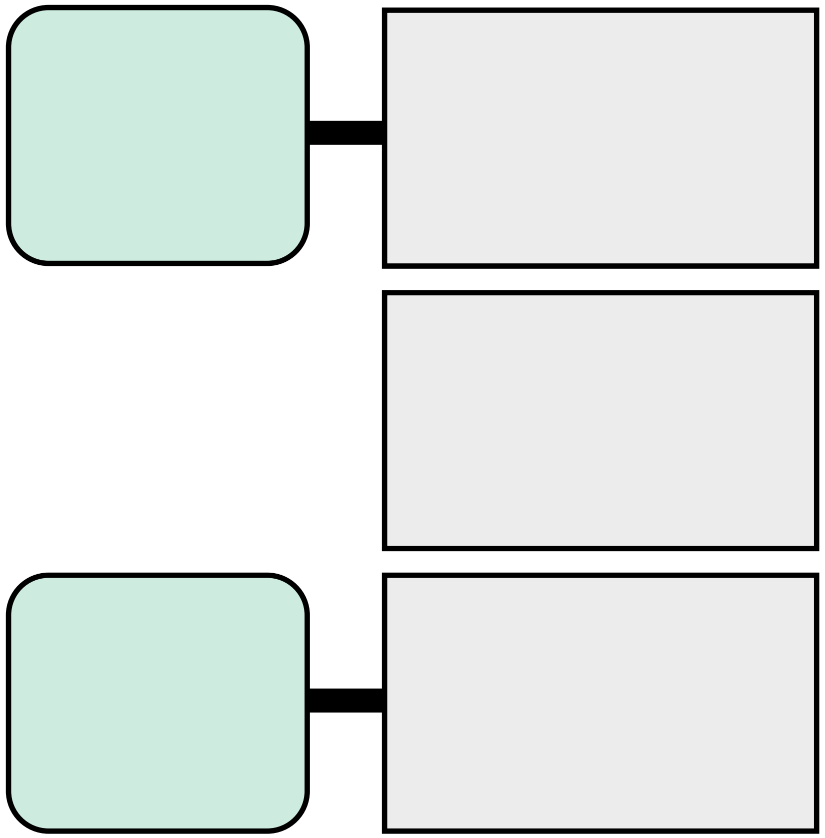
c c servers

c c max tasks in servers and queue

Queueing Theory

M/M/c/c queue



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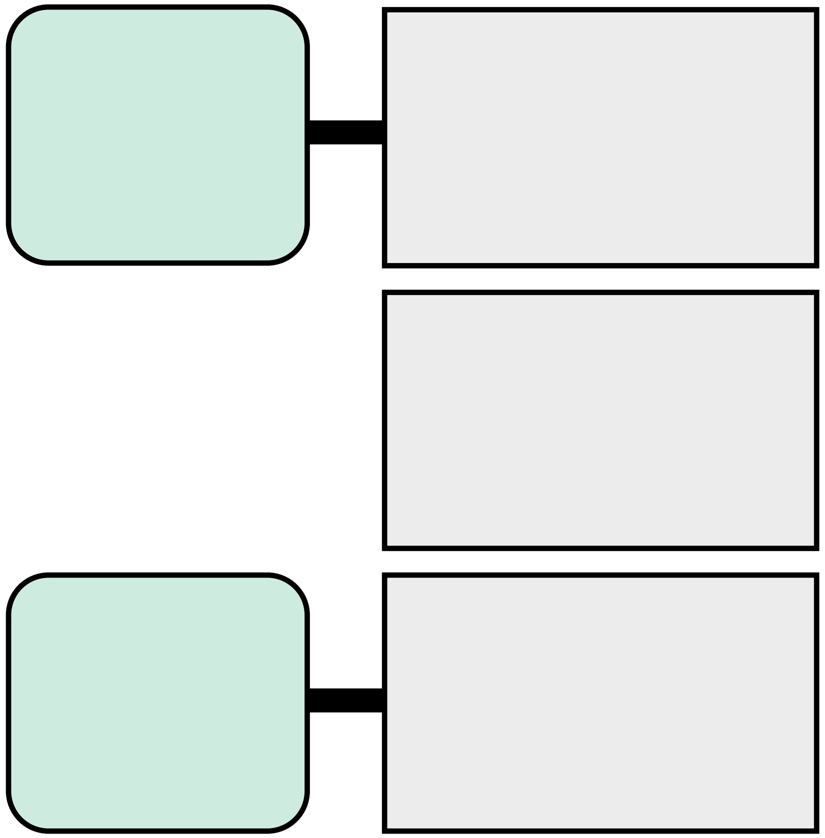

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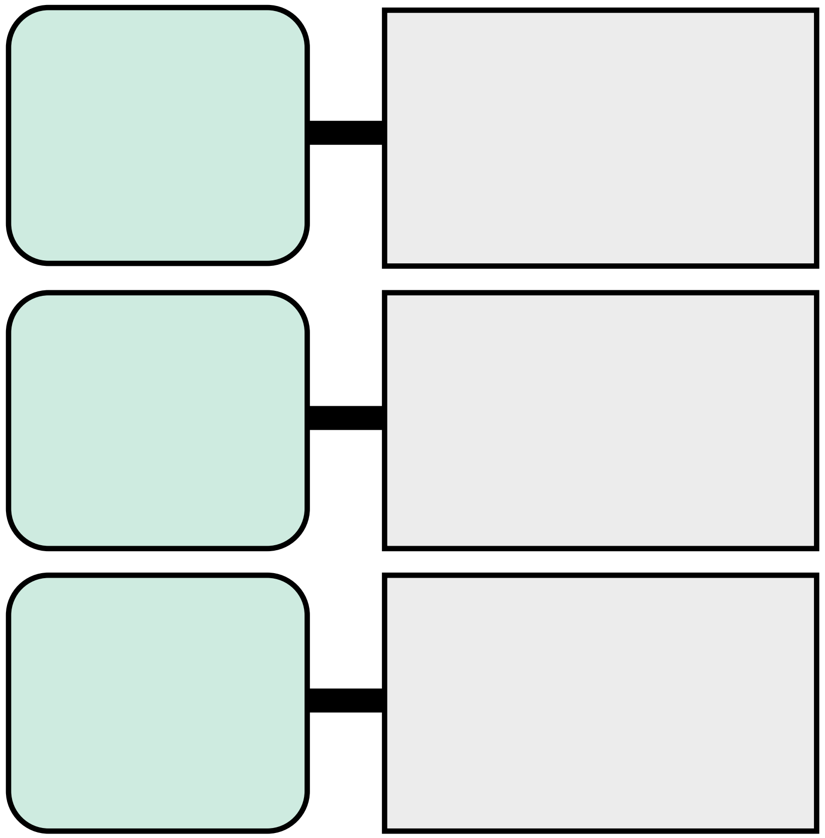

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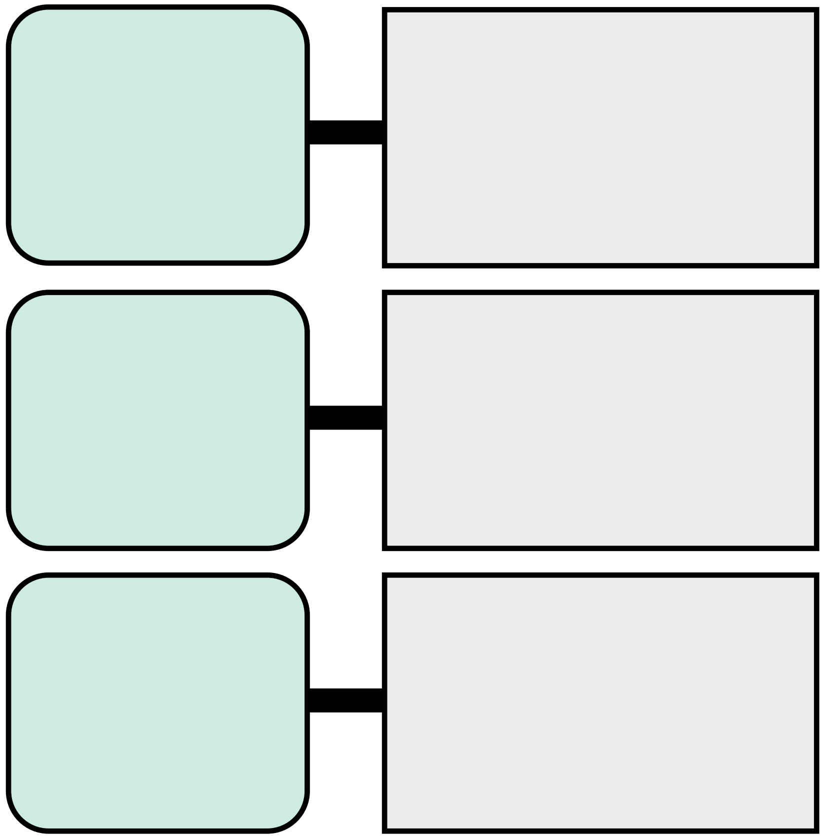

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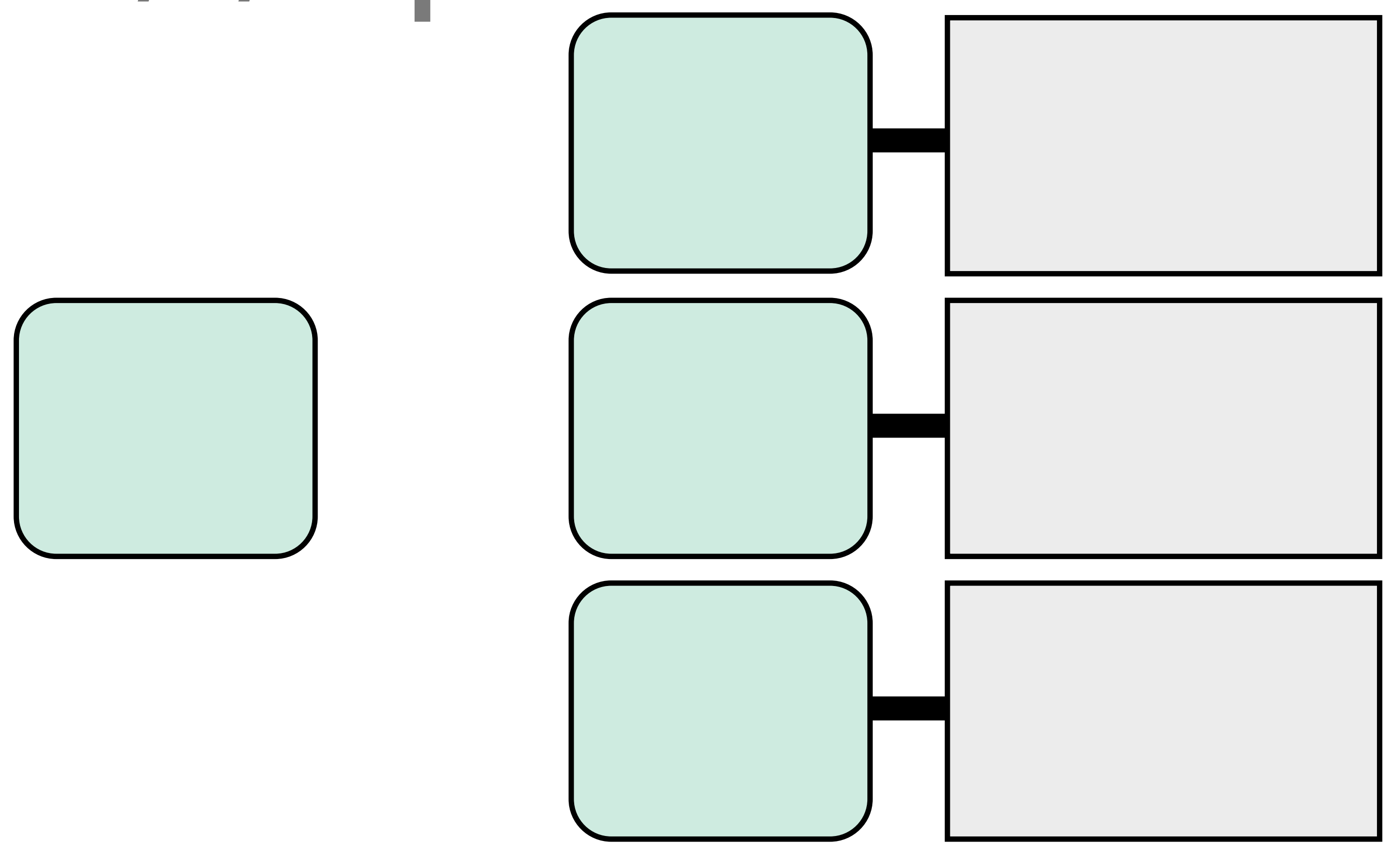

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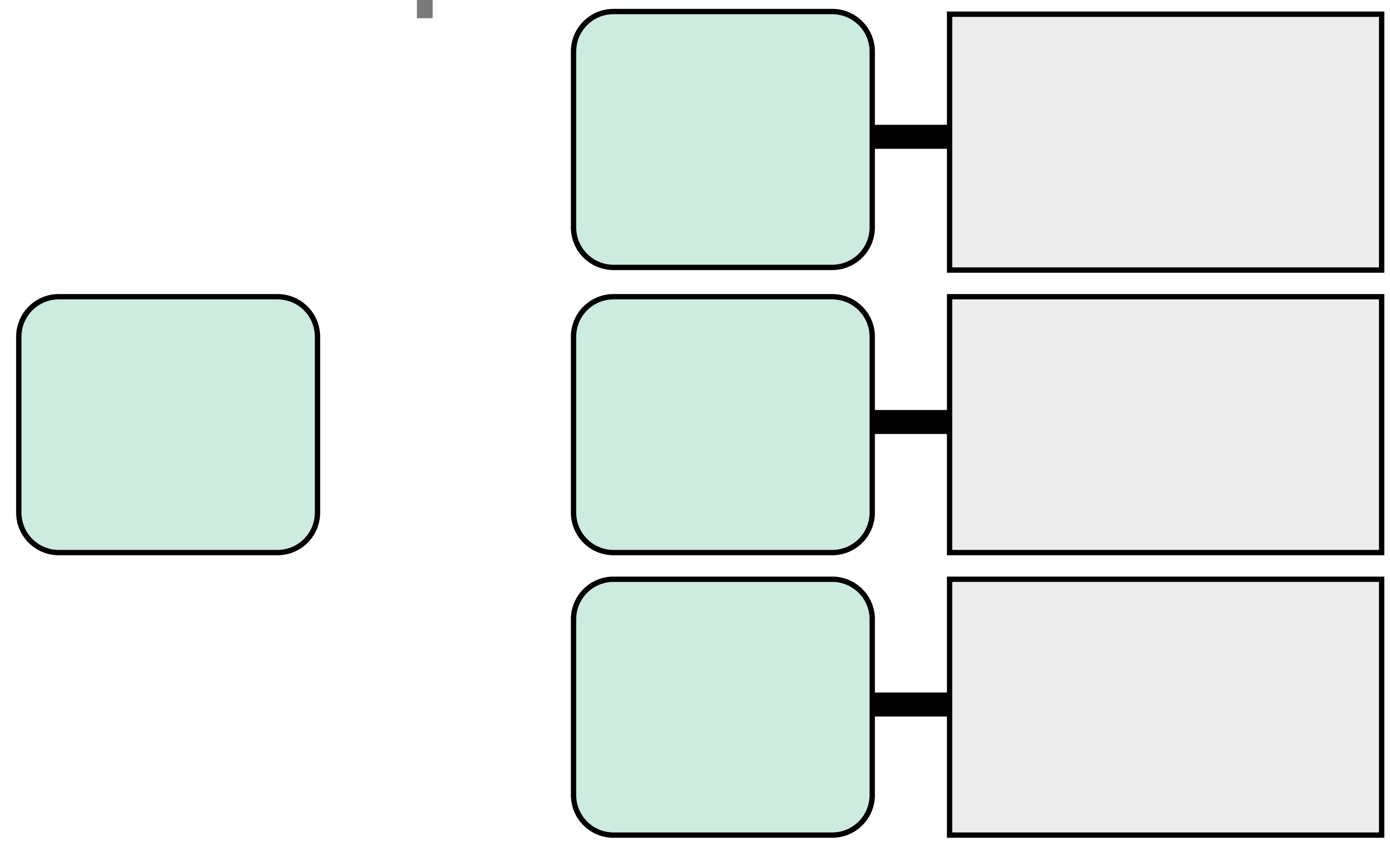

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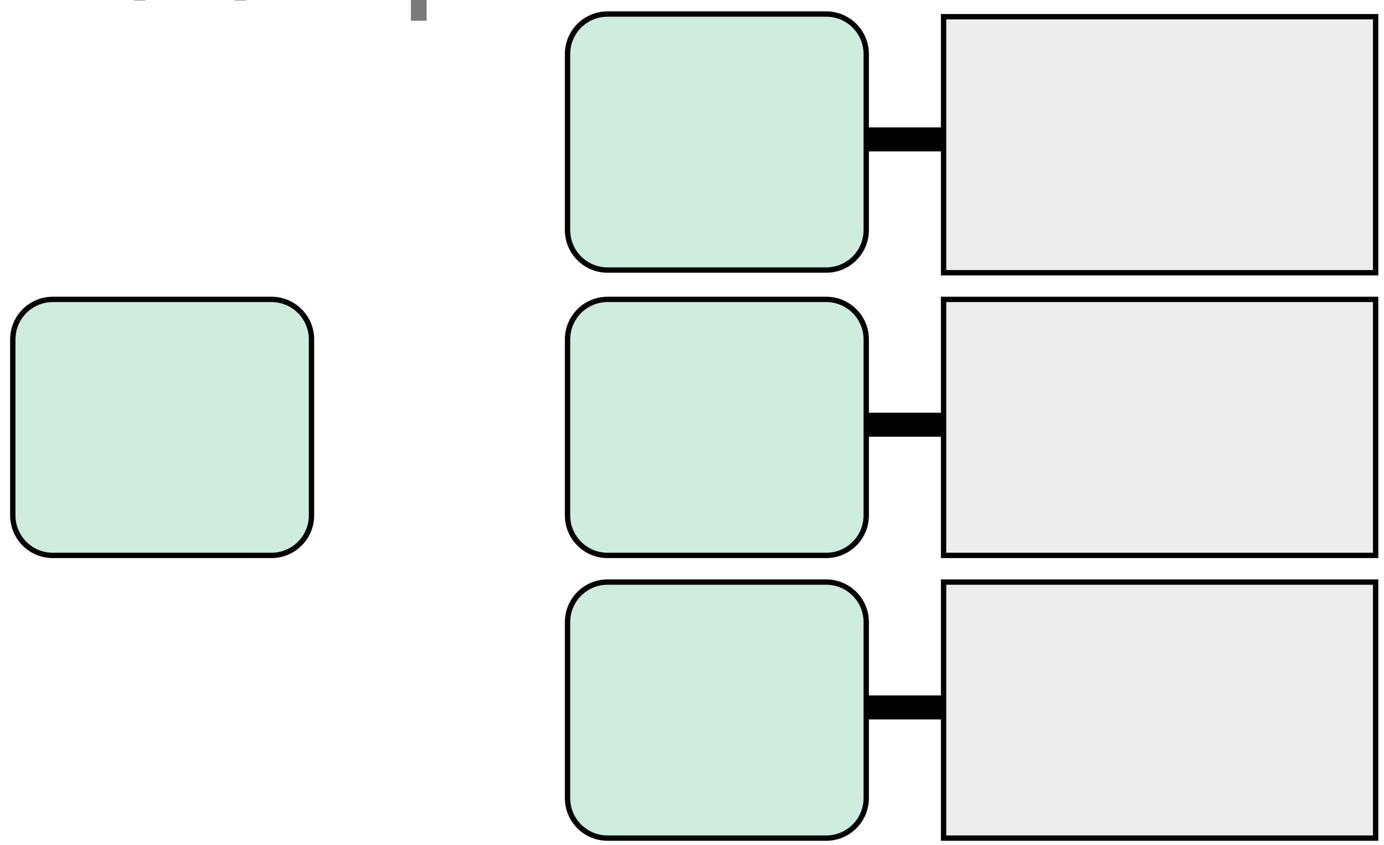
Queueing Theory

M/M/c/c queue

All servers busy



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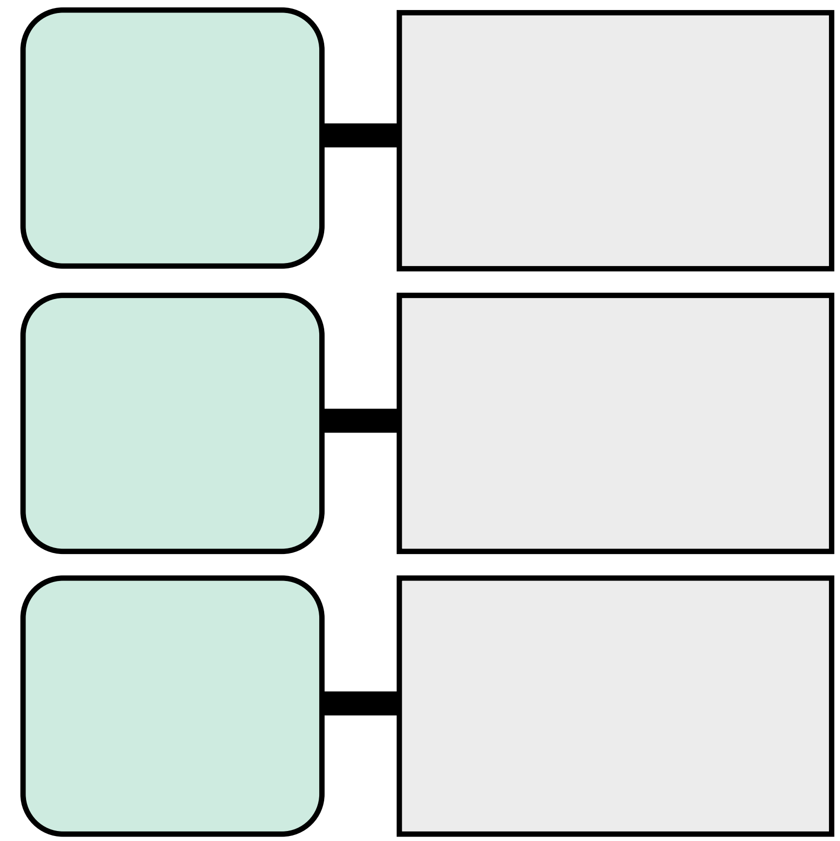

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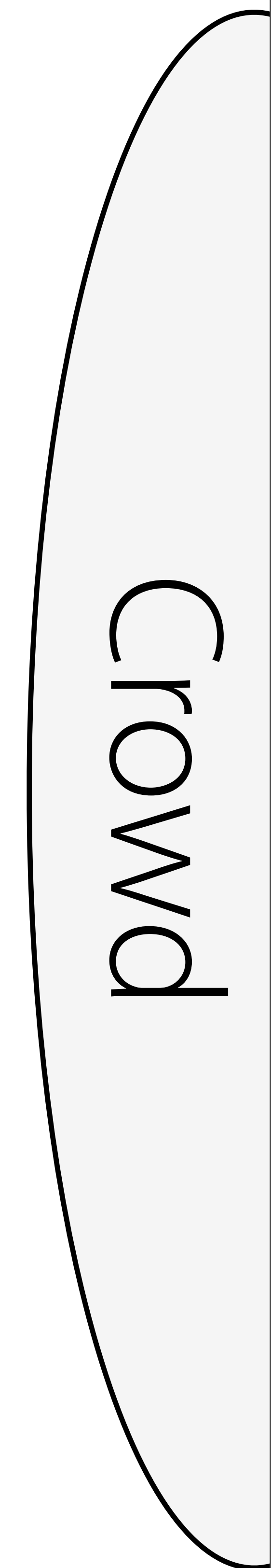
Modeling Retainer Recruitment

Retainer Queue

M/M/c/c queue



c workers, no waiting queue

Task arrivals: Poisson process, rate λ

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Retainer Queue

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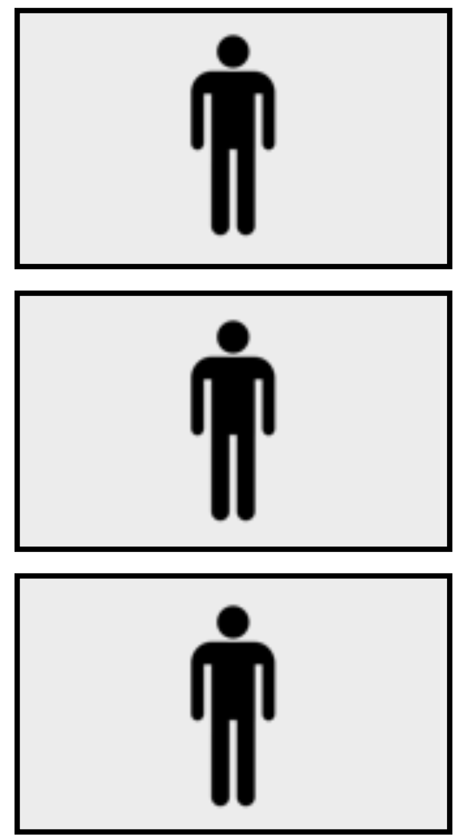

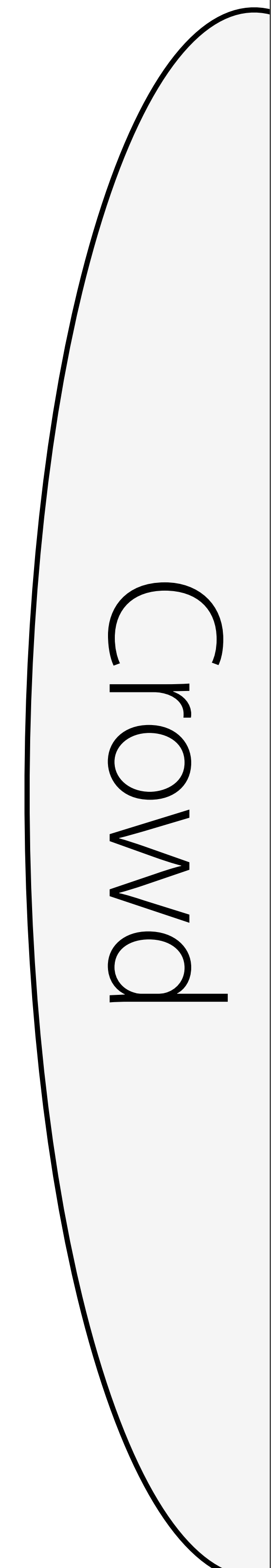

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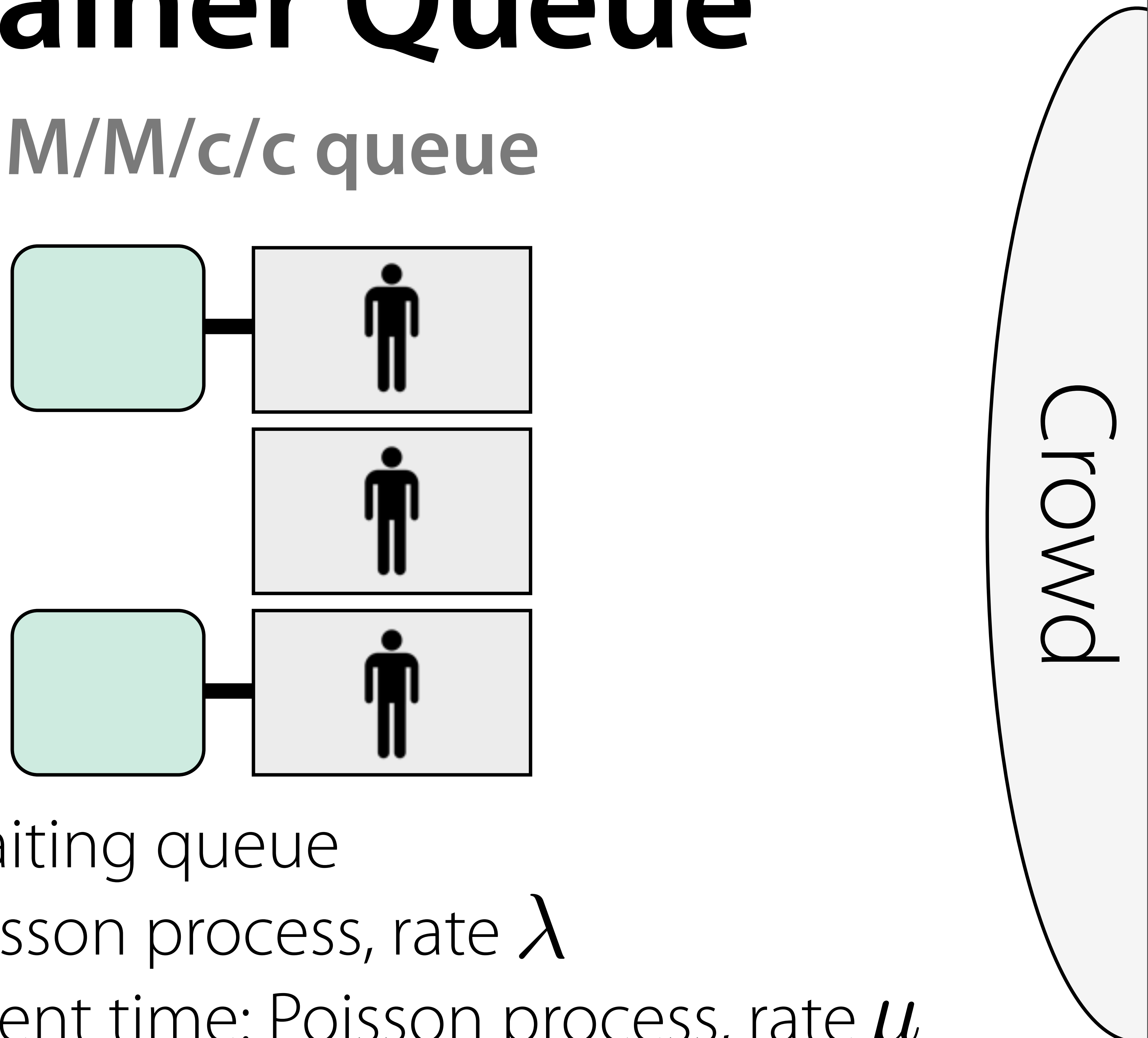

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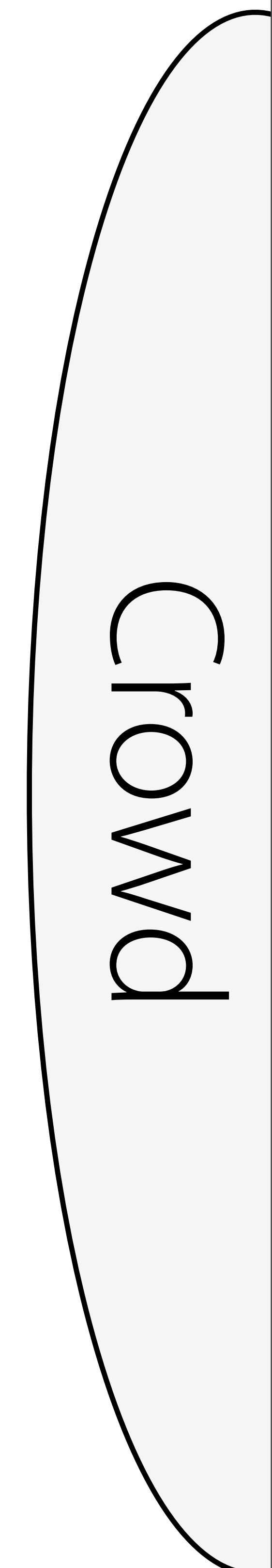

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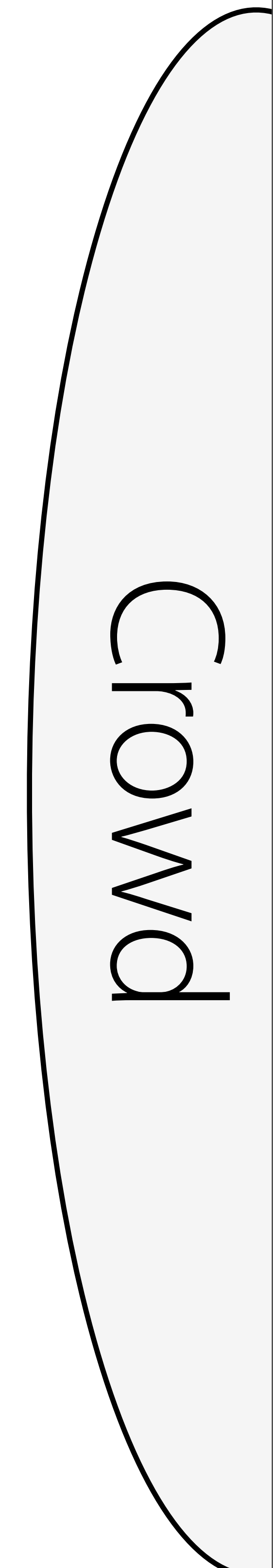

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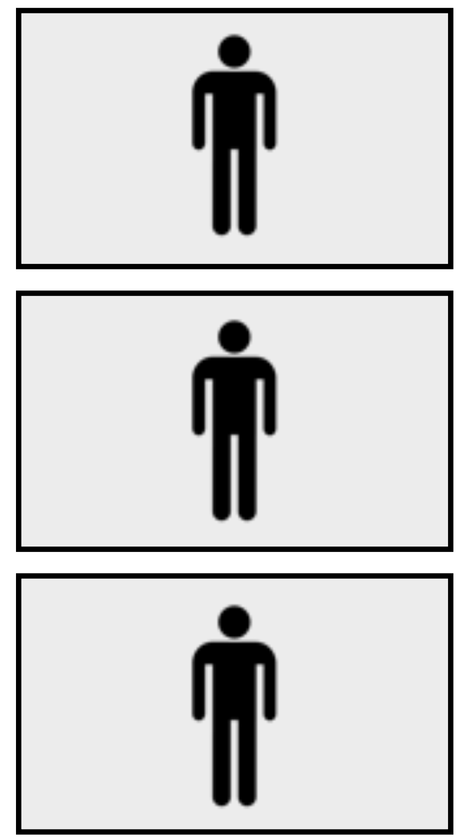

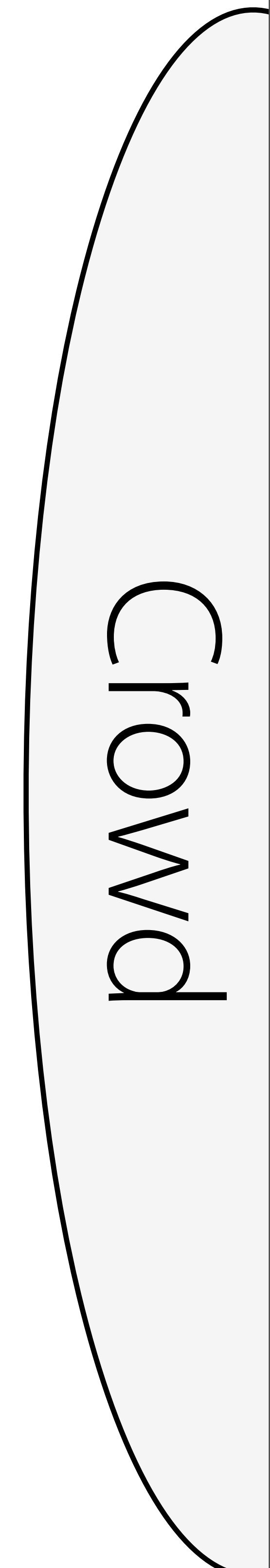

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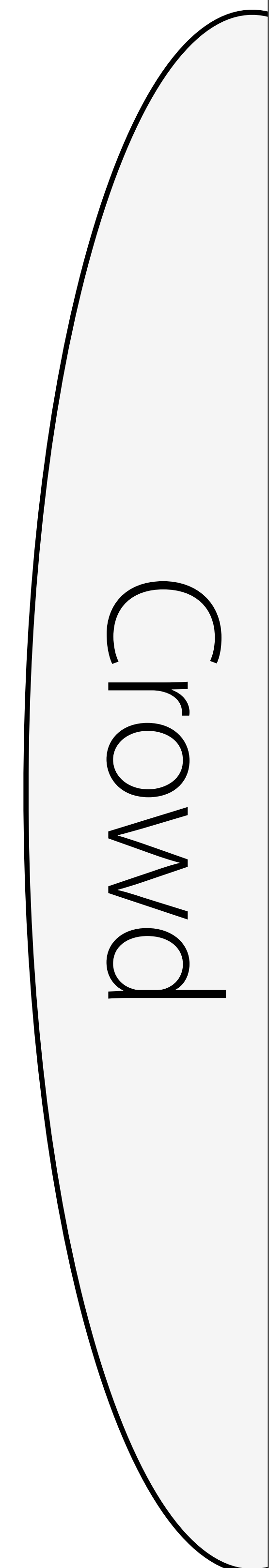
Retainer Queue

Loss



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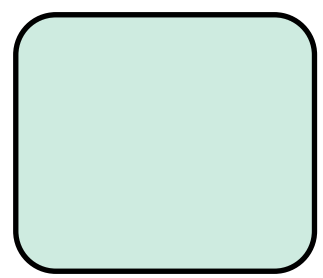

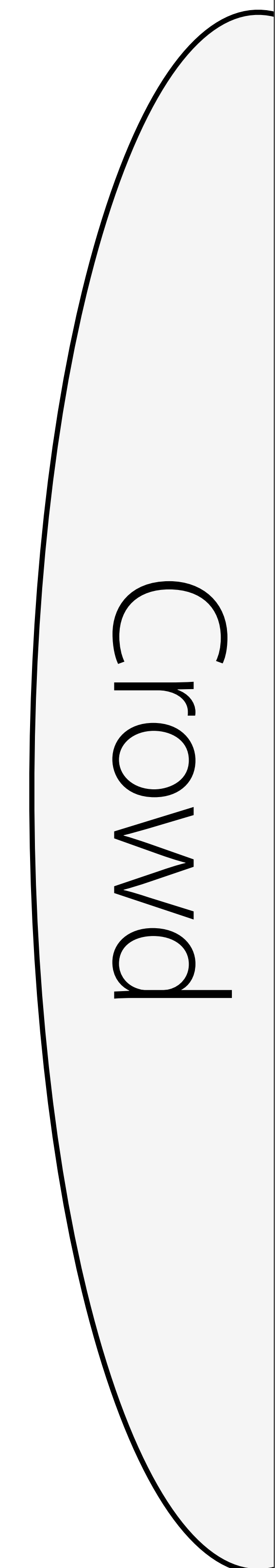

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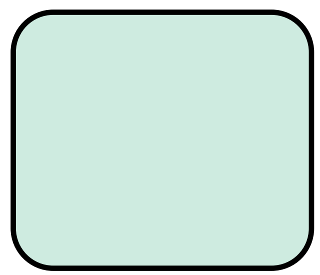
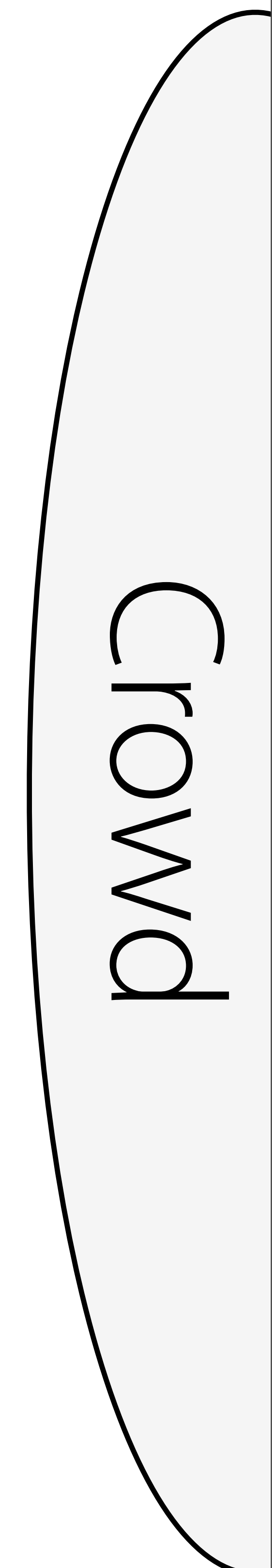
Retainer Queue

Loss

All servers busy





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Retainer Queue

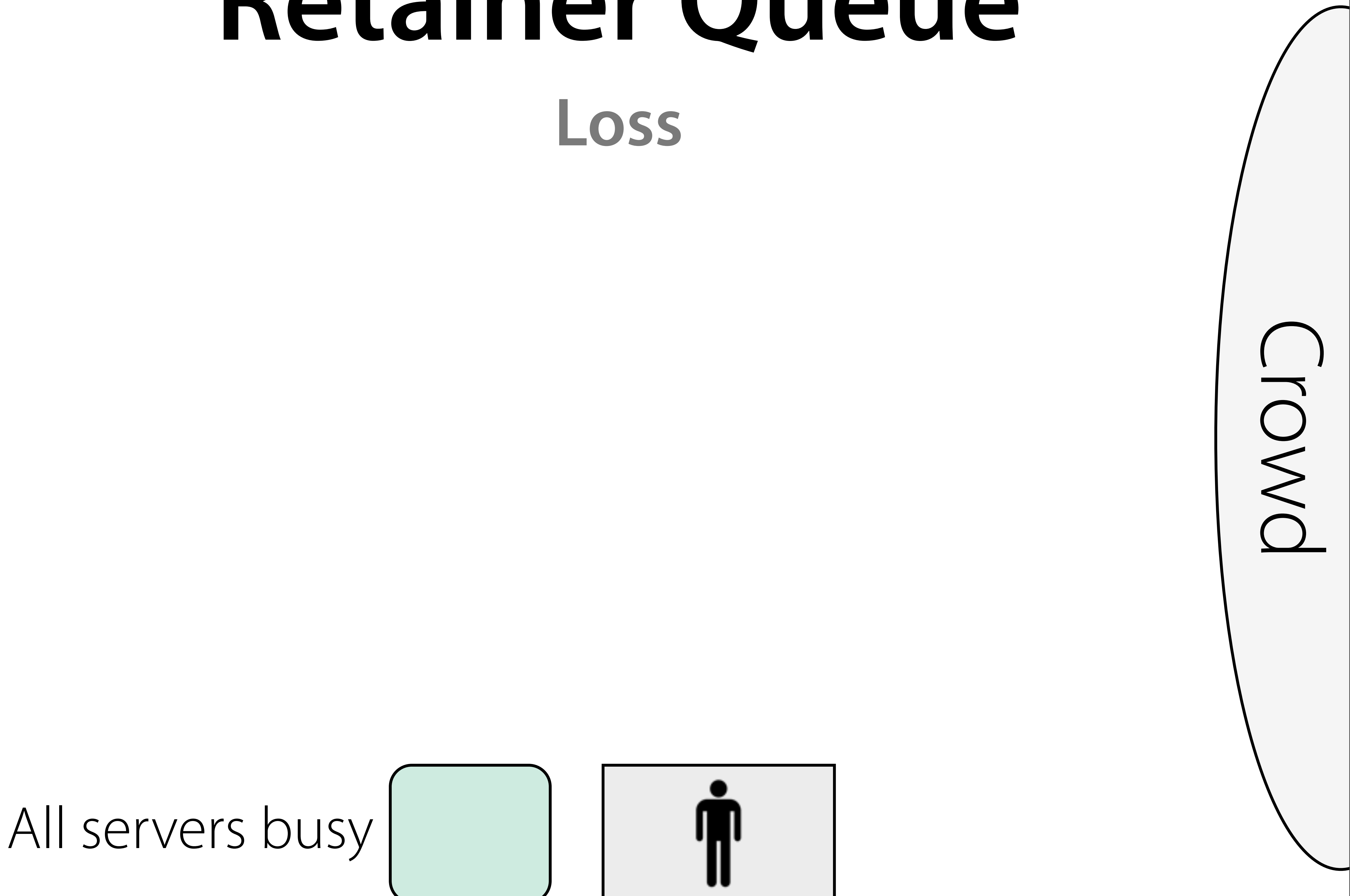
Loss

Crowd

All servers busy

Retainer Queue

Loss

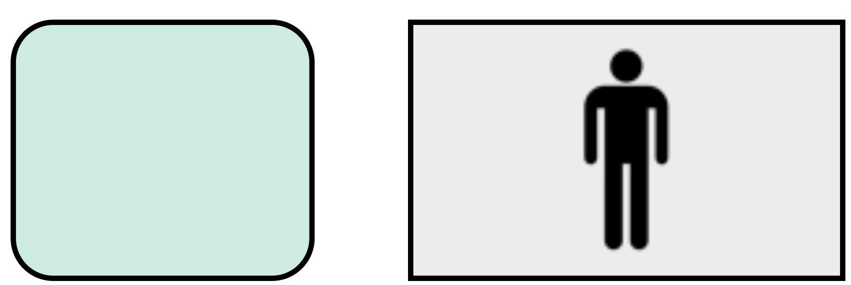


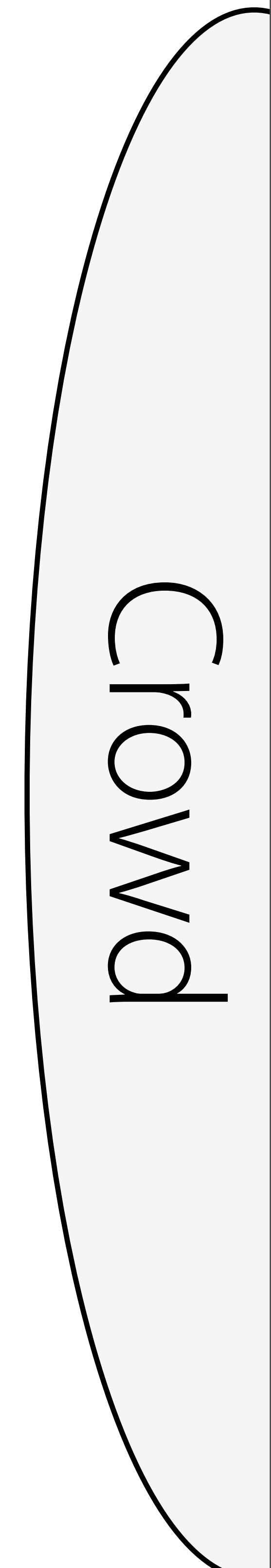
Retainer Queue

Loss

$$P(i \text{ servers busy})$$

All servers busy

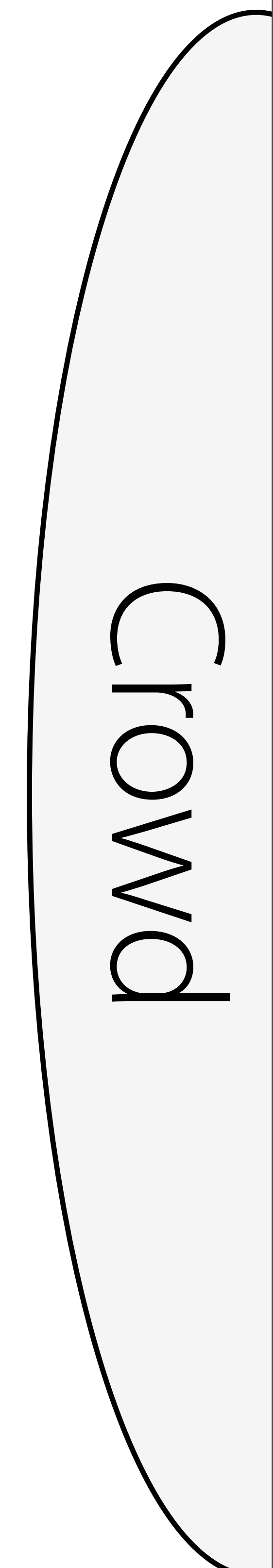




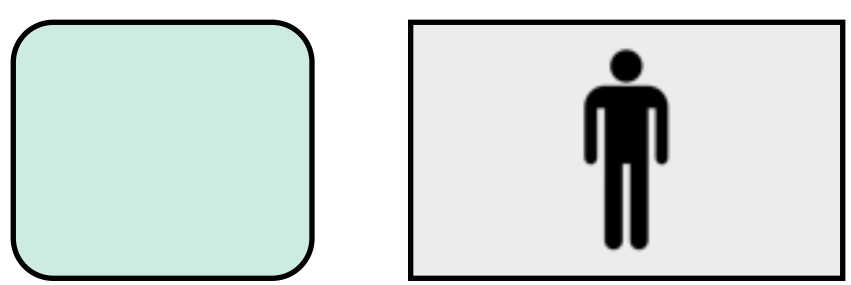
Retainer Queue

Loss

$$P(i \text{ servers busy}) = \pi(i)$$



All servers busy



Retainer Queue

Loss

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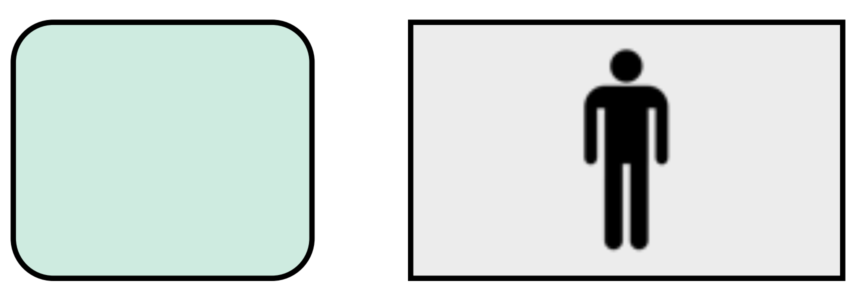
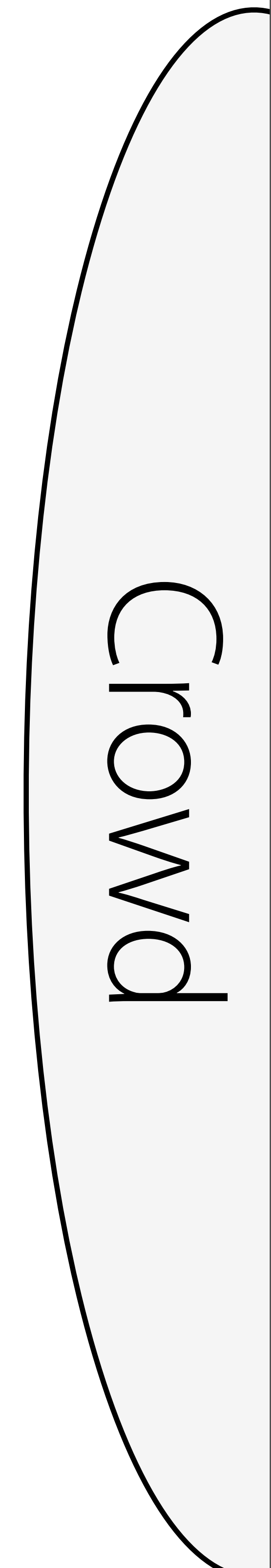
$$P(\text{all servers busy})$$

All servers busy



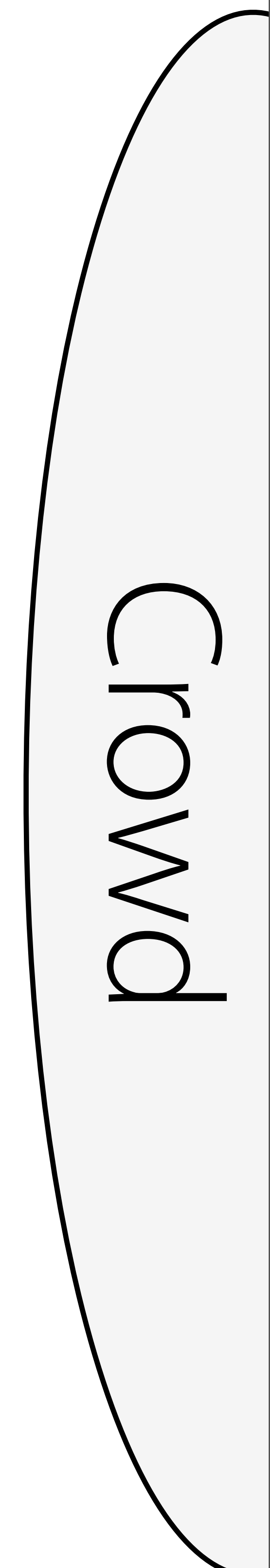


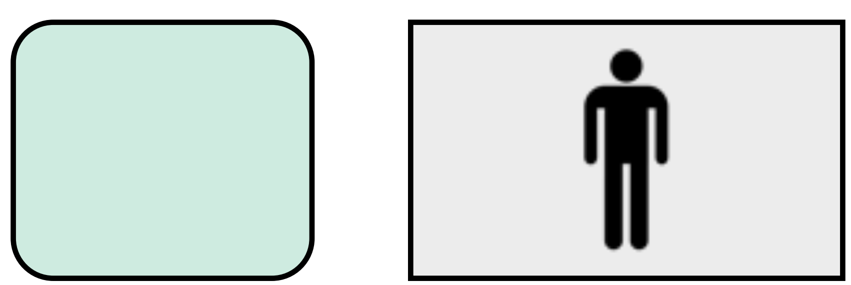
Retainer Queue

Loss

$$P(i \text{ servers busy}) = \pi(i)$$

$$P(\text{all servers busy}) = \pi(c)$$



All servers busy 

Model Predictions

1. Probability that all workers are busy: $\pi(c)$
   → the task has to wait for expected time $1/\mu$
2. Cost of keeping a retainer pool of size *c*
   → 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 ρ 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)

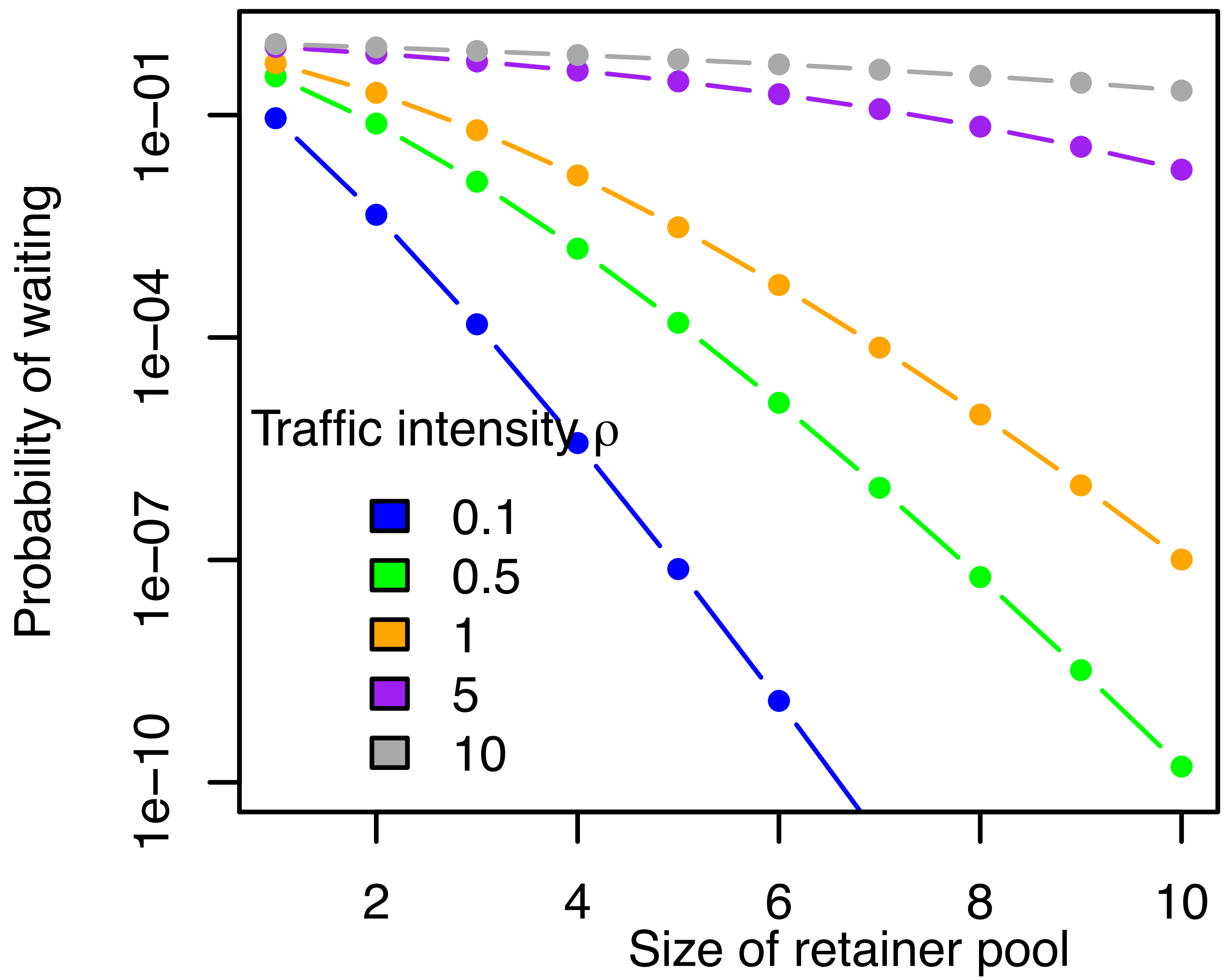
Probability of Loss

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.

Probability of Loss



Expected Waiting Time

$$P(c\ servers\ busy) \times (expected\ recruitment\ time)$$

$$= \pi(c)\frac{1}{\mu}$$

$$= \frac{\rho^c/c!}{\sum_{i=0}^{c} \rho^i/i!}\frac{1}{\mu}$$

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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Derive the expected number of busy workers:

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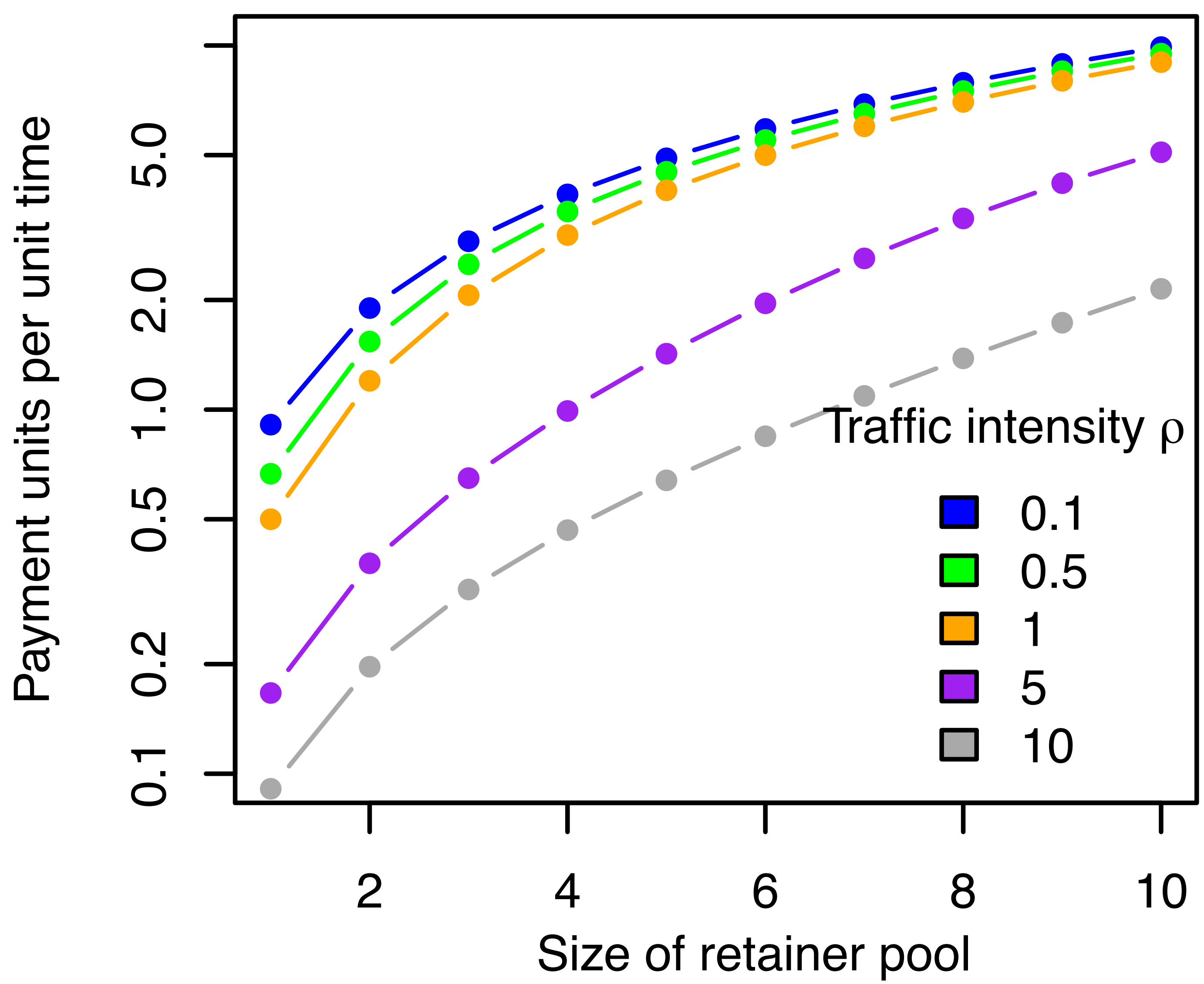
Total cost is the number of *idle* workers:

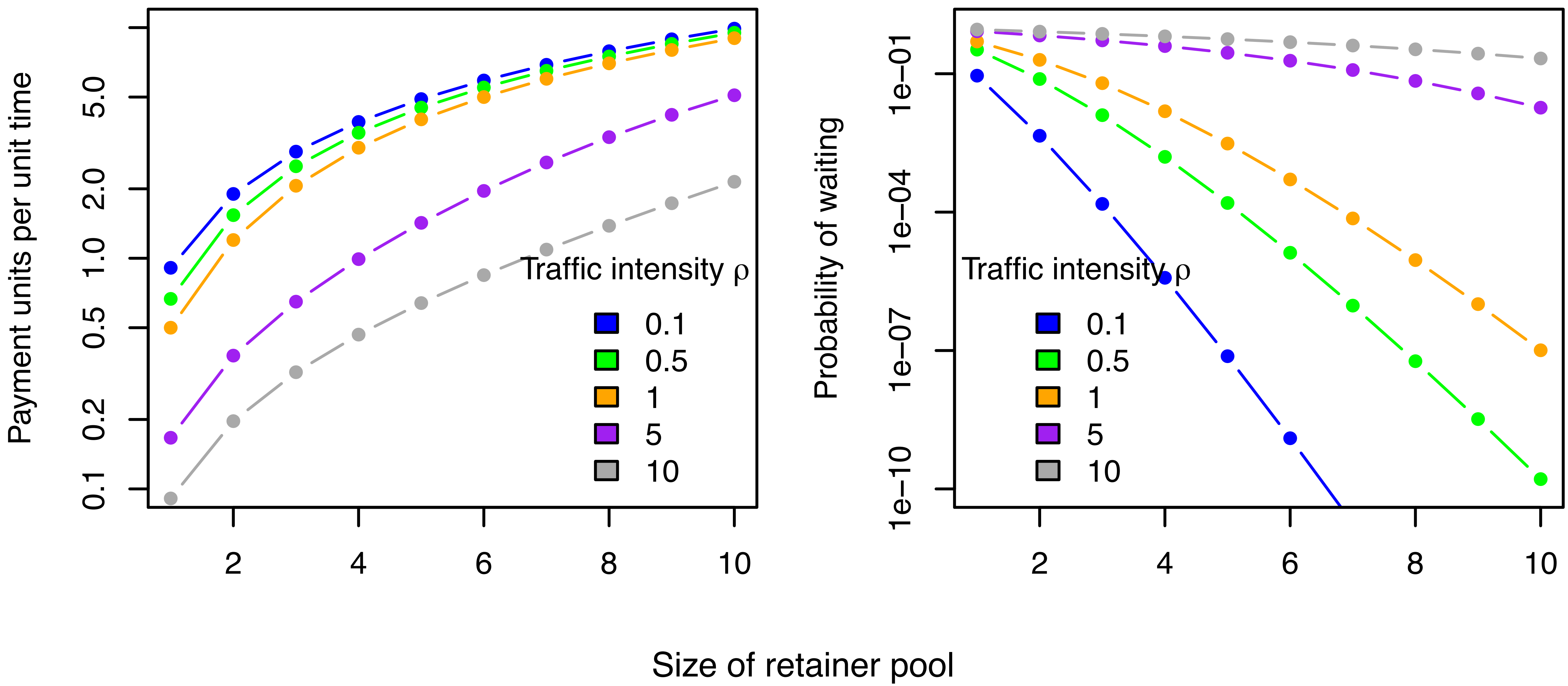
$$c - \rho[1 - \pi(c)]$$

Expected Cost



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

Expected Cost



Cost goes down when $c < \rho$,

but performance suffers.

Optimal Retainer Size

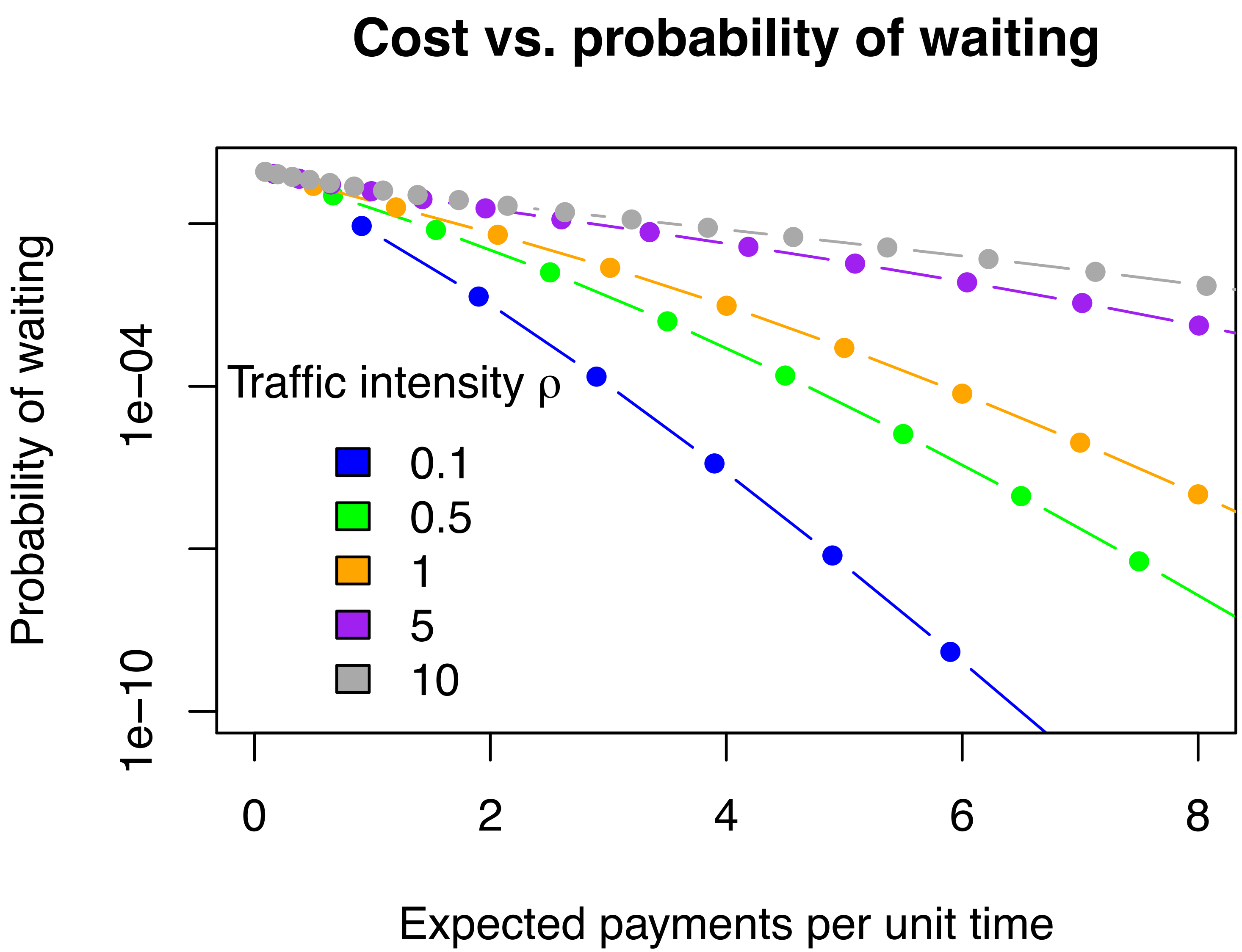
- Size of retainer pool is typically the only value that requesters can manipulate
- Minimize costs by keeping the retainer pool small while keeping $\pi(c)$ low

Optimal Retainer Size

Based on Maximum Miss Probability

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

Minimize c subject to $\pi(c) \leq p_{max}$



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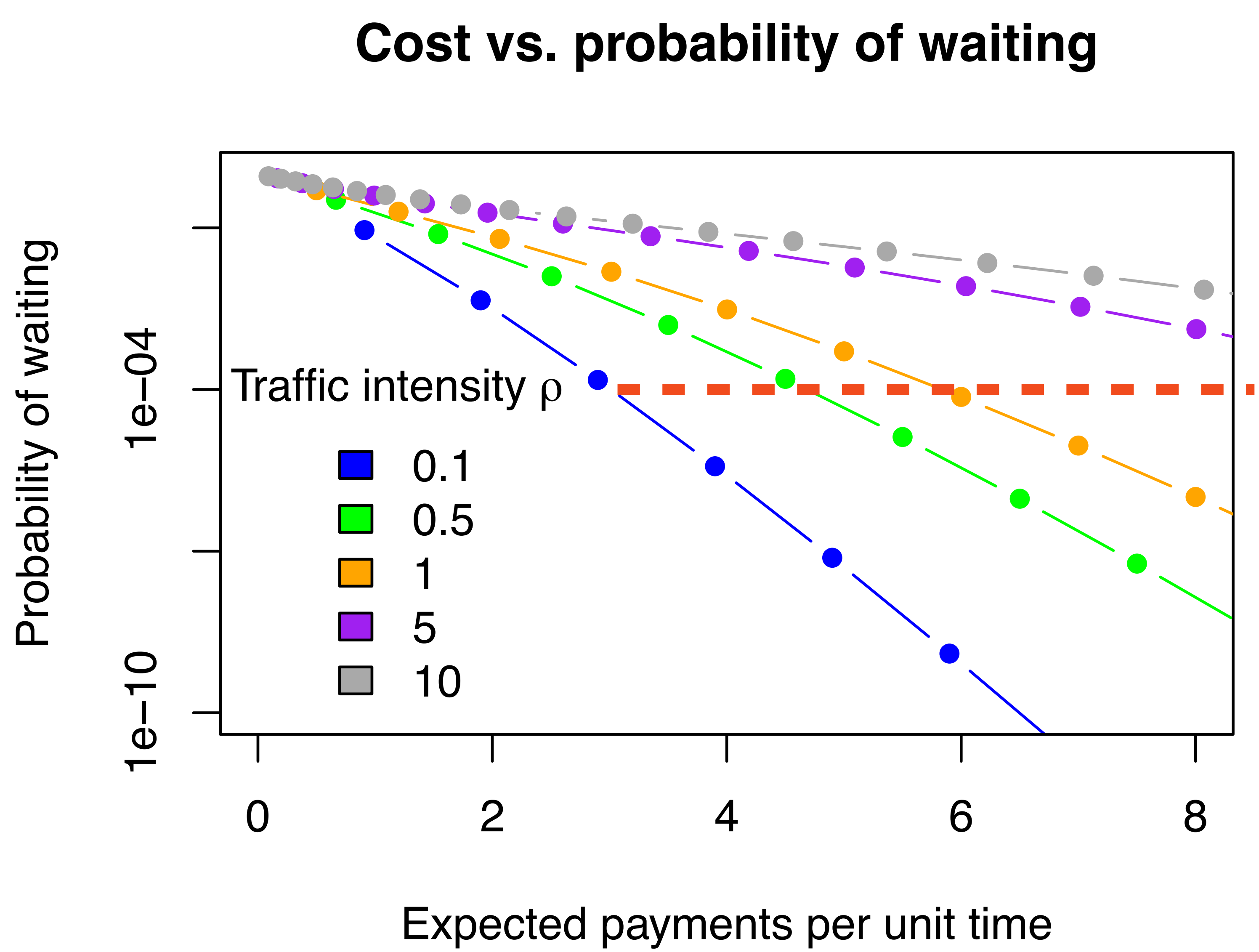
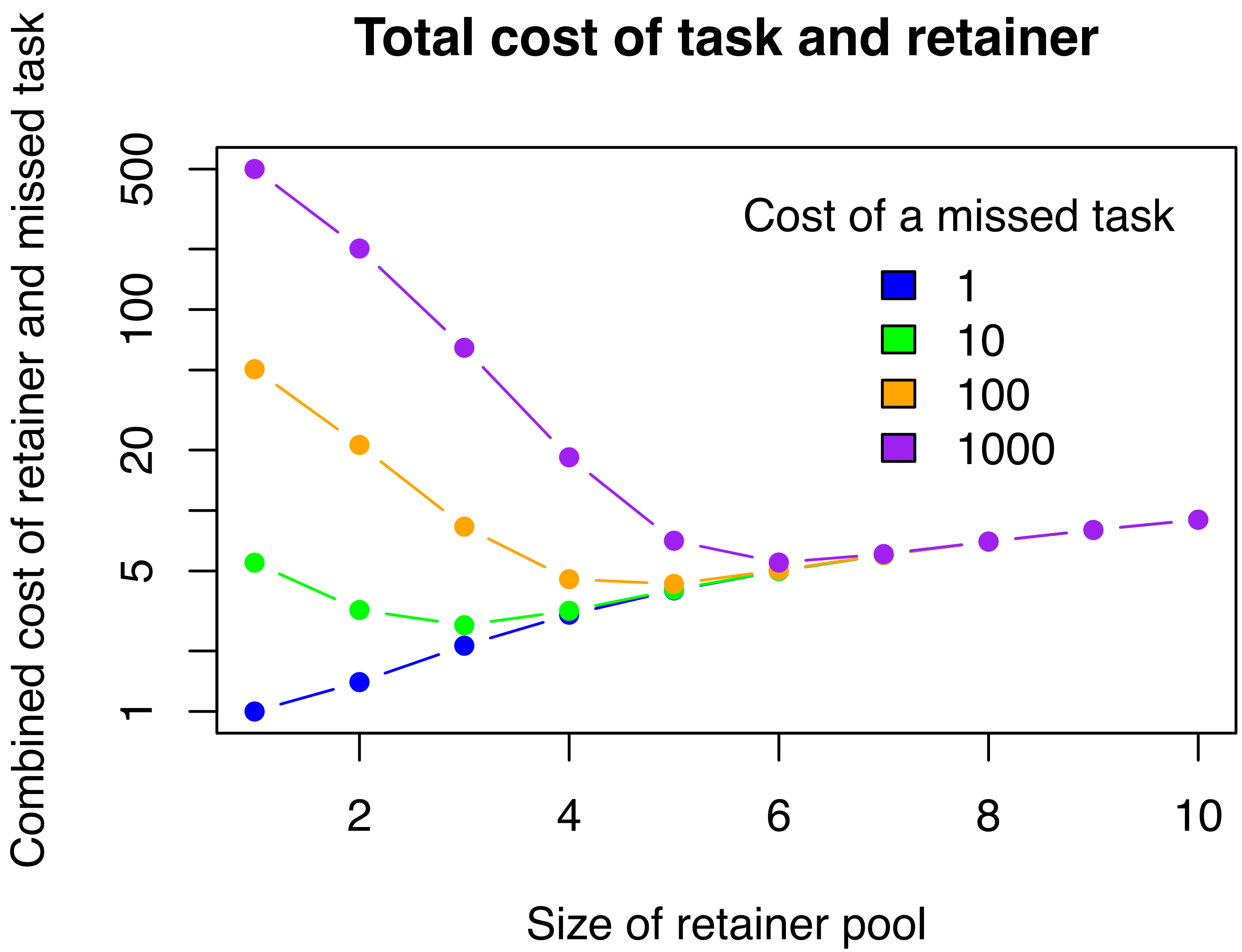


Optimal Retainer Size

Based on Joint Cost

If the "pizza delivery" property holds: we can quantify the cost of loss



Improving the Retainer Model

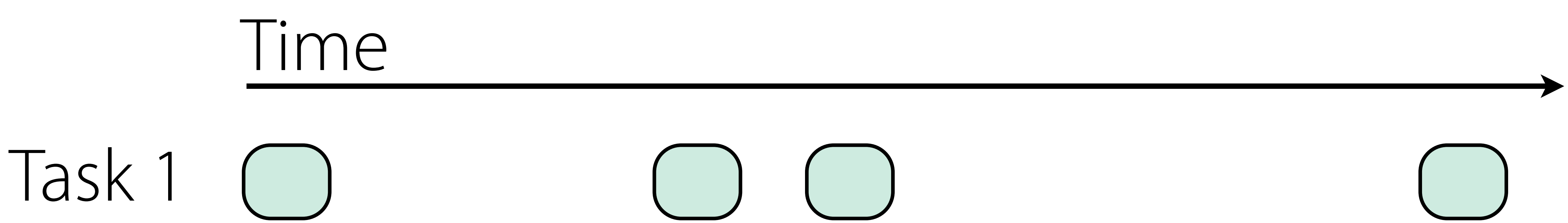
1. Subscriptions
2. Shared Pools
3. Predictive Recruitment

Retainer Subscriptions

- Proposal: increase μ 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)



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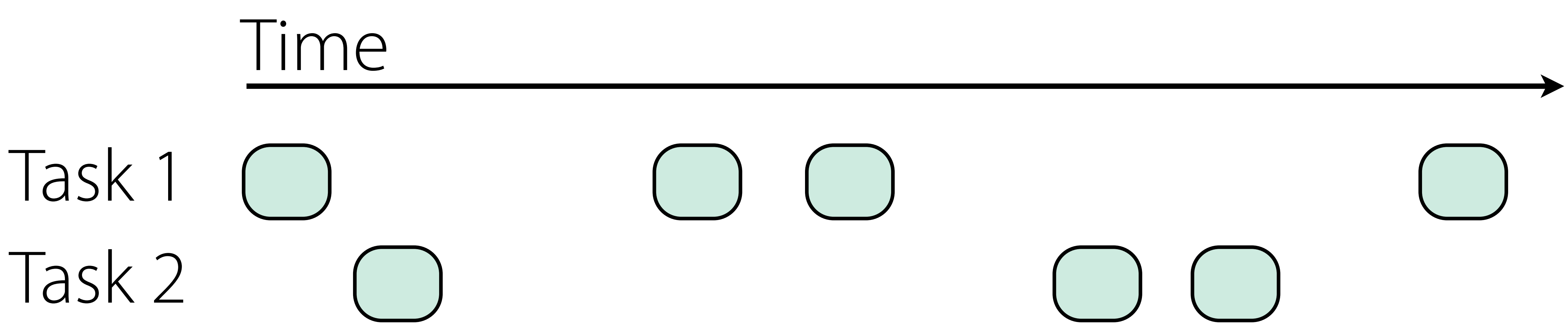

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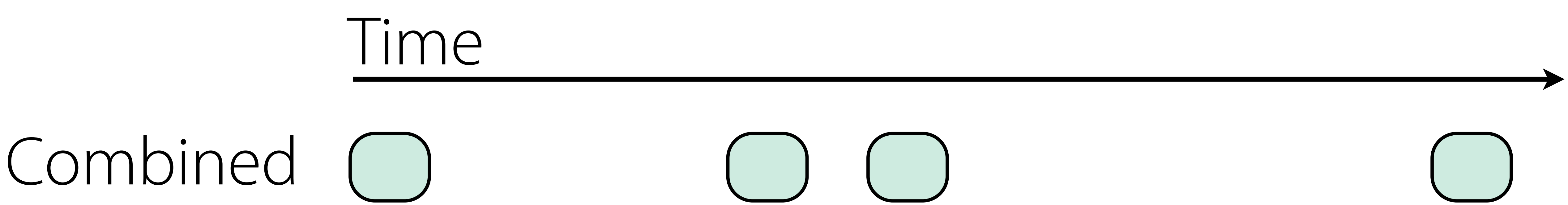

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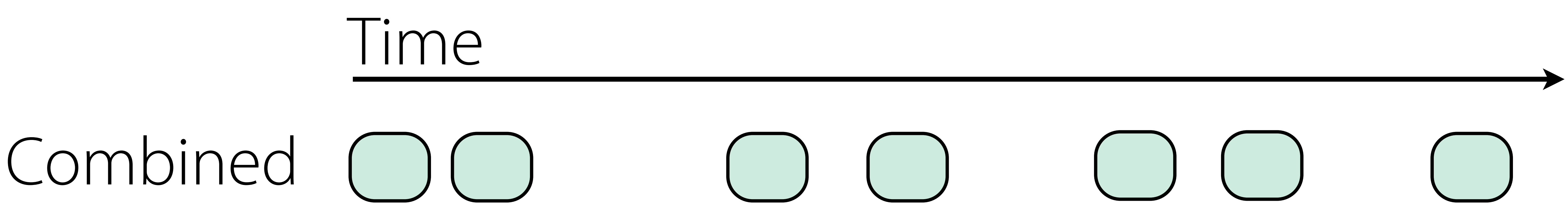

Global Retainer Pools

- Through approximation, individual pools:

$$\pi(c) \approx \sqrt{2\pi c}\left(e^{-\rho}(e\rho/c)^{c}\right)$$

- Shared pools across *k* requesters:

$$\pi(c) \approx \sqrt{2\pi kc}\left(e^{-\rho}(e\rho/c)^{c}\right)^{k}$$

- 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

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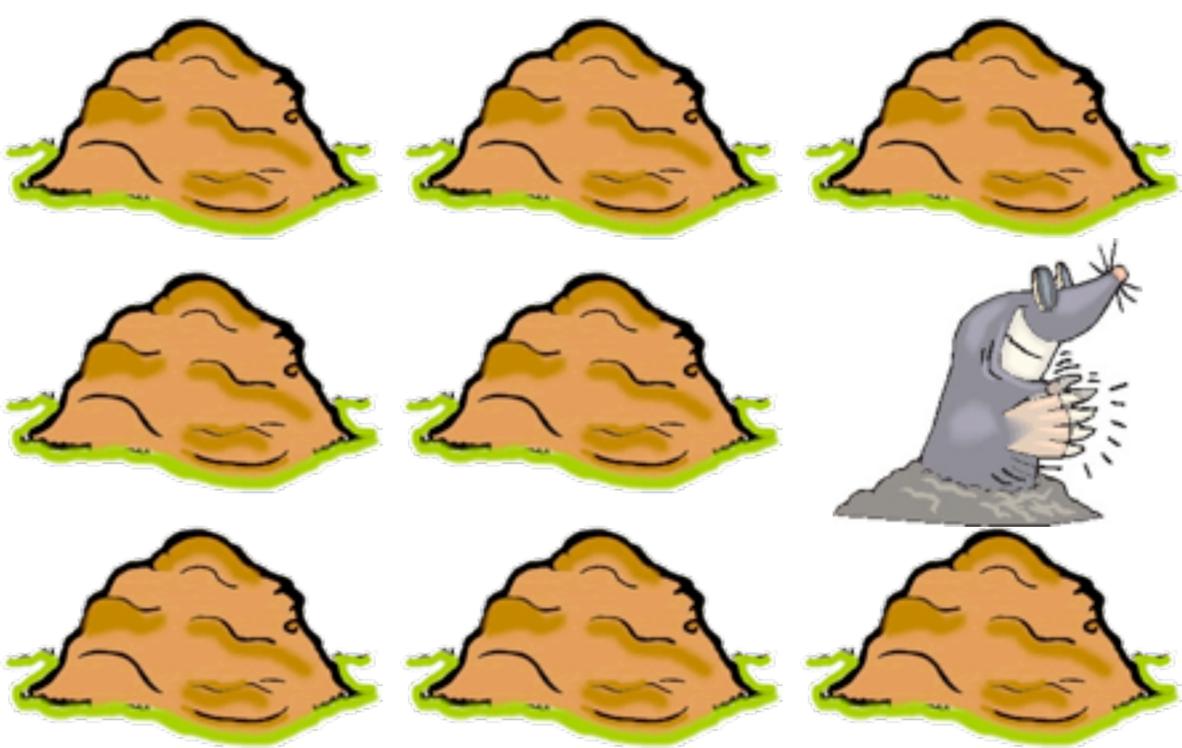
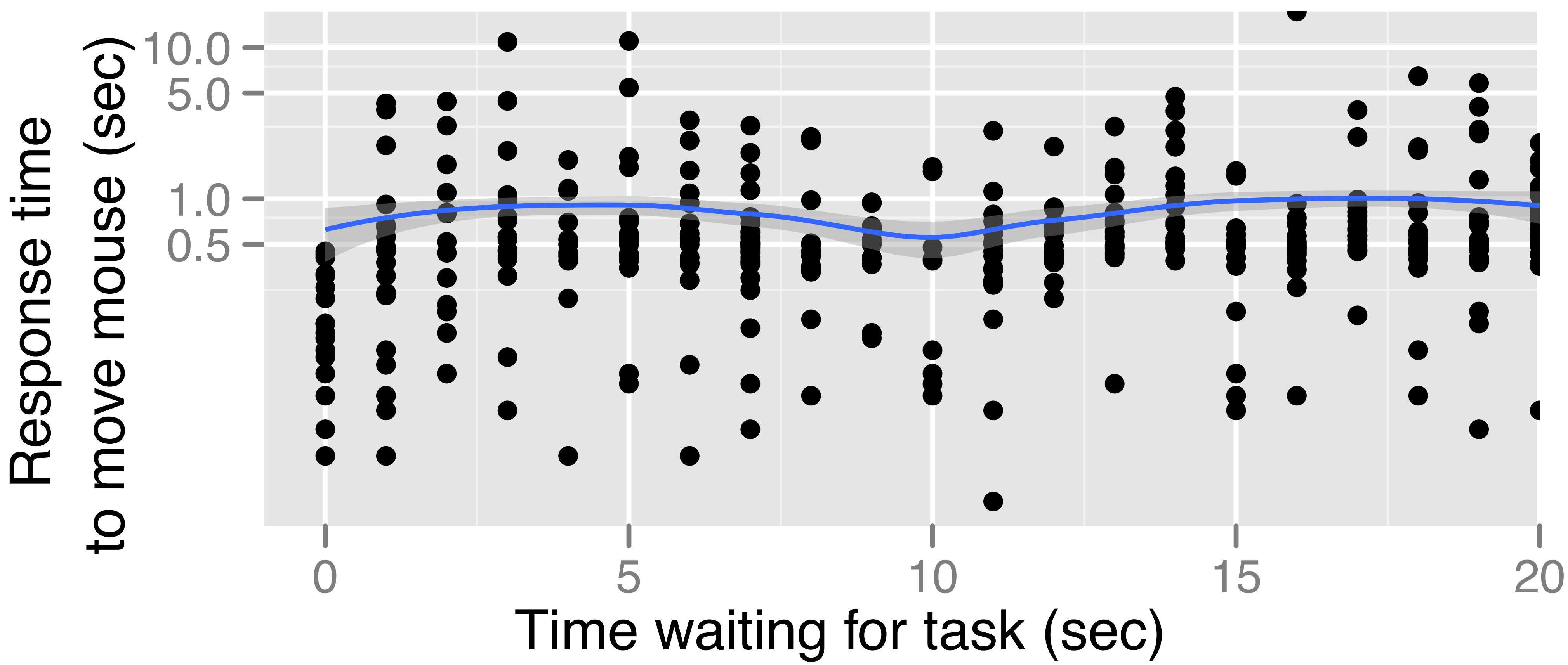


Precruitment

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.

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

Analytic Methods for Optimizing Realtime Crowdsourcing

Michael Bernstein, David Karger, Rob Miller, and Joel Brandt

MIT CSAIL and Adobe Systems

CSAIL Adobe

MIT HUMAN-COMPUTER INTERACTION