# Algorithmic Mechanisms for Reliably Executing Tasks on Master-Worker Internet-based Platforms

Evgenia Christoforou[1] Antonio Fernández Anta[2,3]
Chryssis Georgiou[1] Miguel A. Mosteiro[3,4]

[1]Dept. of Computer Science, University of Cyprus

[2]Institute IMDEA Networks

[3]LADyR, GSyC, Universidad Rey Juan Carlos

[4]Dept. of Computer Science, Rutgers University

This work is supported in part by the Cyprus Research Promotion Foundation grand ΤΠΕ/ΠΛΗΡΟ/0609(ΒΕ)/05



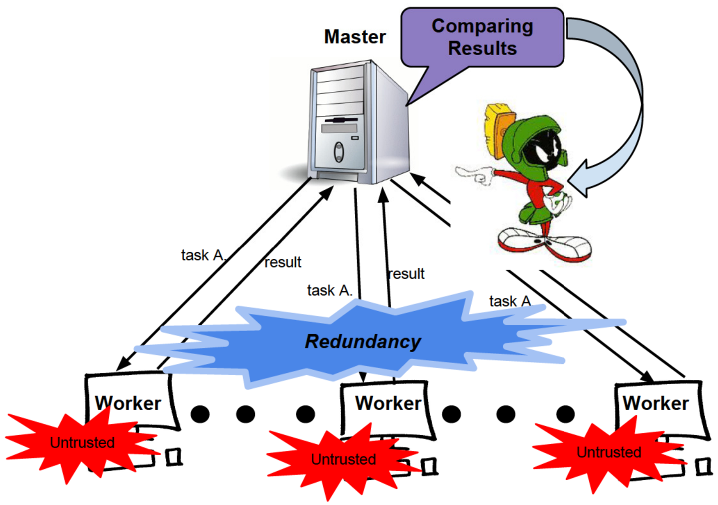
## Motivation

- Internet emerges as a viable platform for supercomputing
  - @home systems, volunteering computing (e.g., SETI@home [Korpela et al 01])
  - P2P and Grid computing [Foster, Iamnitchi 03]
- **Problem:** Great potentials of Internet-based computing limited by untrustworthy platforms components





## Motivation
### SETI@home








## Motivation
### Amazon's Mechanical Turk

- Master and worker humans
- Master processor
  - Has a problem to solve
  - Hires worker processors through the platform to compute it
- Worker processors
  - Contribute time in exchange to economic rewards

## Motivation

Redundant task-allocation recent approaches

- "Classical" distributed computing (pre-defined worker behavior)
  [Fernández et al 06; Konwar et al 06]
  - malicious workers always report incorrect result
    (sw/hw errors, Byzantine, etc.)
  - altruistic workers always compute and truthfully report result
    (the "correct" nodes)

  Malicious-tolerant voting protocols are designed
- Game-theoretic (no pre-defined worker behavior)
  [Yurkewych et al 05; Babaioff et al 06; Fernández Anta et al 08]
  - rational workers act selfishly maximizing own benefit

  Incentives are provided to induce a desired behavior
- BUT realistically, the three types of workers may coexist!





## Motivation
### Communication Issues

- Communication uncertainty
  - Messages exchanged may get lost or arrive late
- Possibility of workers not replying
  - Around 5% of the workers are available more than 80% of the time
    Half of the workers are available less than 40% of the time [Heien, Anderson and Hagihara 09 ]
  - Long computational length is incur by a task [Kondo et al. 07]
- Allowing workers to abstain from the computation (low network reliability)





## Our approach

In this work: combine all

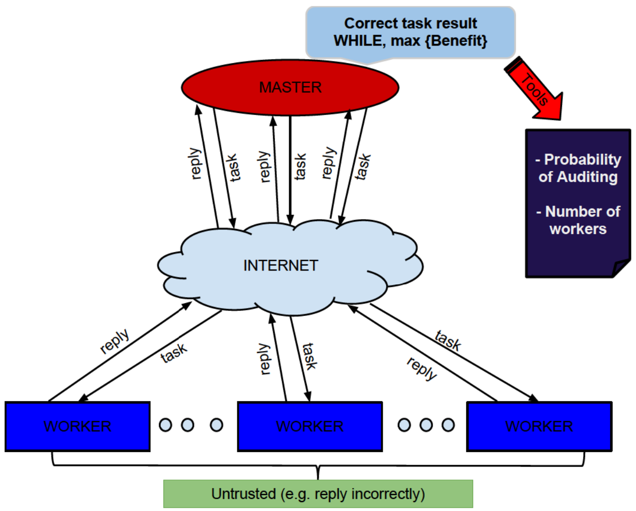
- Communication:
  - Reliable network, all workers reply
  - Unreliable network, workers may not reply
- Types of workers:
  - malicious: always report incorrect result
  - altruistic: always compute and report correct result
  - rational: selfishly choose to be honest, cheat or abstain

    Known probability distribution over types
    Each worker is malicious, altruistic or rational with probs $p_\mu$, $p_\alpha$, $p_\rho$,
    s.t. $p_\mu + p_\alpha + p_\rho = 1$
- Game-theoretic approach:
  - Computations modeled as strategic games
  - Provide incentives to induce desired rationals behavior
    - Deploy reward/punishment schemes
    - Master chooses whether to audit the returned result or not
- Classical distributed computing approach:
  - Design malice/altruism-aware voting protocols





## General Framework



# Background

**Definition**

"A game consists of a set of players, a set of moves (or strategies) available to those players, and a specification of payoffs for each combination of strategies." [Wikipedia]

- Game Theory:
  - Players (processors) act on their self-interest
  - Rational behavior:
    seek to increase own utility choosing strategy according to payoffs
  - Protocol is given as a game
  - Design objective is to achieve equilibrium among players





# Background

**Definition**

Nash Equilibrium (NE): players do not increase their expected utility by changing strategy, if other players do not change [Nash 50]

- Algorithmic Mechanism Design [Nisan, Ronen 01]
  Games designed to provide incentives s.t. players act "correctly"
  - Behave well: reward
  - Otherwise: penalize

  The design objective is to induce a desired behavior (e.g. unique NE)

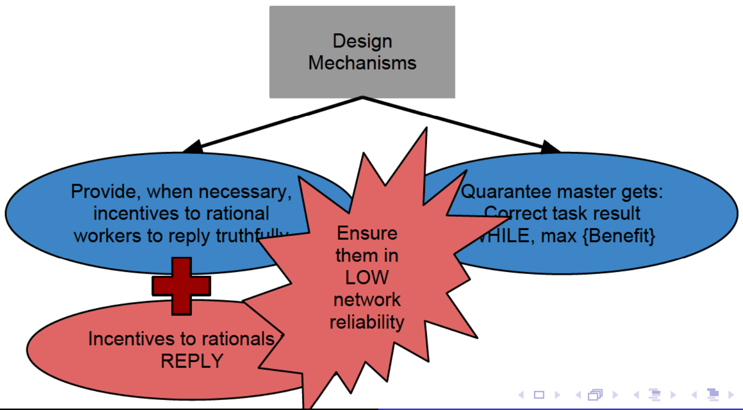




# Problem Statement

First Step (Reliable Network)

Second Step (Unreliable Network)








# Contributions

- Develop and analyze realistic game-theoretic mechanisms
  - Master-worker communication reliable
  - Unreliable communication, workers unavailable or choose to abstain
- Mechanisms provide, when necessary, incentives for rational workers to truthfully compute and return the task result, despite:
  - Malicious workers actions
  - Network unreliability
- Apply the mechanisms to two realistic settings:
  - SETI-like volunteer computing applications
  - Contractor-based applications(e.g. Amazon's mechanical turk)

    Develop plots that illustrate the trade-off between reliability and cost, under different system parameters

# Reliable Communication





## General protocol

- Master assigns a task to $n$ workers
- Rational worker cheats with probability $p_{\mathcal{C}}$ (seeking a NE)
- Master audits the responses with probability $p_{\mathcal{A}}$
- If master audits
  - rewards honest workers and
  - penalizes the cheaters
- If master does not audit
  - Accepts value returned by majority of workers
  - Rewards/penalizes according to one of four models

| | |
|---|---|
| $\mathcal{R}_{\mathrm{m}}$ | the master rewards the majority only |
| $\mathcal{R}_{\mathrm{a}}$ | the master rewards all workers |
| $\mathcal{R}_{\emptyset}$ | the master does not reward any worker |
| $\mathcal{R}_{\pm}$ | the master rewards the majority and penalizes the minority |

Note: reward models may be fixed exogenously or chosen by the master





## Payoff parameters

| | |
|---|---|
| $WP_{\mathcal{C}}$ | worker's punishment for being caught cheating |
| $WC_{\mathcal{T}}$ | worker's cost for computing the task |
| $WB_{\mathcal{Y}}$ | worker's benefit from master's acceptance |
| $MP_{\mathcal{W}}$ | master's punishment for accepting a wrong answer |
| $MC_{\mathcal{Y}}$ | master's cost for accepting the worker's answer |
| $MC_{\mathcal{A}}$ | master's cost for auditing worker's answers |
| $MB_{\mathcal{R}}$ | master's benefit from accepting the right answer |

Note: it is possible that $WB_{\mathcal{Y}} \neq MC_{\mathcal{Y}}$





## Conditions for mixed-strategy NE (MSNE)

**Definition**

For a finite game, a mixed strategy profile $\sigma^*$ is a MSNE iff, for each player $i$

$$U_i(s_i, \sigma_{-i}) = U_i(s_i', \sigma_{-i}), \forall s_i, s_i' \in supp(\sigma_i)$$
$$U_i(s_i, \sigma_{-i}) \geq U_i(s_i', \sigma_{-i}), \forall s_i, s_i' : s_i \in supp(\sigma_i), s_i' \notin supp(\sigma_i)$$

[Osborne 2003]

$s_i$ : strategy of player $i$ in strategy profile $s$

$\sigma_i$ : probability distribution over pure strategies of player $i$ in $\sigma$

$U_i(s_i, \sigma_{-i})$ : expected utility of player $i$ using strategy $s_i$ in $\sigma$

$supp(\sigma_i)$ : set of positive-probability strategies in $\sigma$

## Strategic payoffs

| | $\mathcal{R}_{\pm}$ | $\mathcal{R}_{\mathrm{m}}$ | $\mathcal{R}_{\mathrm{a}}$ | $\mathcal{R}_{\emptyset}$ |
|---|---|---|---|---|
| $w_{\mathcal{C}}^{\mathcal{A}}$ | $-WP_{\mathcal{C}}$ | $-WP_{\mathcal{C}}$ | $-WP_{\mathcal{C}}$ | $-WP_{\mathcal{C}}$ |
| $w_{\overline{\mathcal{C}}}^{\mathcal{A}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ |
| $w_{\mathcal{C}}^{\mathcal{C}}$ | $WB_{\mathcal{Y}}$ | $WB_{\mathcal{Y}}$ | $WB_{\mathcal{Y}}$ | $0$ |
| $w_{\overline{\mathcal{C}}}^{\mathcal{C}}$ | $-WP_{\mathcal{C}} - WC_{\mathcal{T}}$ | $-WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $-WC_{\mathcal{T}}$ |
| $w_{\mathcal{C}}^{\overline{\mathcal{C}}}$ | $-WP_{\mathcal{C}}$ | $0$ | $WB_{\mathcal{Y}}$ | $0$ |
| $w_{\overline{\mathcal{C}}}^{\overline{\mathcal{C}}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $-WC_{\mathcal{T}}$ |

$w_{s_i}^{\mathcal{X}}$ payoff of player $i$ using strategy $s_i \in \{\mathcal{C}, \overline{\mathcal{C}}\}$ if

$$\mathcal{X} = \begin{cases} \mathcal{A} & \text{master audits} \\ \mathcal{C} & \text{majority of workers cheat and master does not audit} \\ \overline{\mathcal{C}} & \text{majority of workers does not cheat and master does not audit} \end{cases}$$





## Conditions for mixed-strategy NE (MSNE)

For each player $i$ and each reward model, enforce unique NE in

$$\Delta U = U_i(s_i = \mathcal{C}, \sigma_{-i}) - U_i(s_i = \overline{\mathcal{C}}, \sigma_{-i})$$

$$\Delta U = (w_{\mathcal{C}}^{\mathcal{A}} - w_{\overline{\mathcal{C}}}^{\mathcal{A}})p_{\mathcal{A}} + (1-p_{\mathcal{A}})\Big((w_{\mathcal{C}}^{\mathcal{C}} - w_{\overline{\mathcal{C}}}^{\mathcal{C}})\mathbf{P}_q^{(n-1)}(\lceil n/2 \rceil, n-1) + (w_{\mathcal{C}}^{\overline{\mathcal{C}}} - w_{\overline{\mathcal{C}}}^{\overline{\mathcal{C}}})\mathbf{P}_q^{(n-1)}(0, \lfloor n/2 \rfloor - 1) + (w_{\mathcal{C}}^{\mathcal{C}} - w_{\overline{\mathcal{C}}}^{\overline{\mathcal{C}}})\binom{n-1}{\lfloor n/2 \rfloor} q^{\lfloor n/2 \rfloor}(1-q)^{\lfloor n/2 \rfloor}\Big)$$

where $q = p_\mu + p_\rho p_{\mathcal{C}}$, $\mathbf{P}_q^{(n)}(a,b) = \sum_{i=a}^{b} \binom{n}{i} q^i (1-q)^{n-i}$

Computational issues: together with the task, the master sends a "certificate" ($p_{\mathcal{A}}$, payoffs, $n$) of the uniqueness of the desired NE to the worker





## Conditions for mixed-strategy NE (MSNE)

Guaranteeing : $P_{wrong} \leq \varepsilon$ While maximizing $U_M$

Pr(master obtains wrong answer):

$$P_{wrong} = (1-p_{\mathcal{A}})\mathbf{P}_q^{(n)}(\lceil n/2 \rceil, n)$$

E(utility of master):

$$U_M = p_{\mathcal{A}}\big(MB_{\mathcal{R}} - MC_{\mathcal{A}} - n(1-q)MC_{\mathcal{Y}}\big) + (1-p_{\mathcal{A}})\big(MB_{\mathcal{R}}\mathbf{P}_q^{(n)}(0, \lfloor n/2 \rfloor) - MP_{\mathcal{W}}\mathbf{P}_q^{(n)}(\lceil n/2 \rceil, n) + \gamma\big)$$

where

$$\gamma = \begin{cases} -MC_{\mathcal{Y}}(\mathbf{E}_{1-q}^{(n)}(\lceil n/2 \rceil, n) + \mathbf{E}_q^{(n)}(\lceil n/2 \rceil, n)) & \mathcal{R}_{\mathrm{m}} \text{ and } \mathcal{R}_{\pm} \text{ models} \\ -nMC_{\mathcal{Y}} & \mathcal{R}_{\mathrm{a}} \text{ model} \\ 0 & \mathcal{R}_{\emptyset} \text{ model} \end{cases}$$

$$\mathbf{E}_p^{(n)}(a,b) = \sum_{i=a}^{b} \binom{n}{i} i p^i (1-p)^{n-i}, p \in [0,1]$$





## Mechanism design

### Master protocol to choose $p_{\mathcal{A}}$

- Free rationals (master does not rely on rational workers )
  - Case 1: probability of malicious workers $p_\mu$ very large, high $p_{\mathcal{A}}$
    $p_{\mathcal{A}} \leftarrow 1 - \varepsilon / \mathbf{P}_{p_\mu + p_\rho}^{(n)}(\lceil n/2 \rceil, n)$
  - Case 2: probability of altruistic workers $p_\alpha$ big
    $p_{\mathcal{A}} \leftarrow 0$
  - Case 3: rationals probability of being honest $p_{\mathcal{H}}$ is 1, even if $p_{\mathcal{A}} = 0$
    $p_{\mathcal{A}} \leftarrow 0$
- Guided rationals (enforce the behavior of rational workers $p_{\mathcal{C}} = 0$)

$$p_{\mathcal{A}} \leftarrow \begin{cases} 1 - \frac{WP_{\mathcal{C}} + WB_{\mathcal{Y}} - WC_{\mathcal{T}}}{WP_{\mathcal{C}} + WB_{\mathcal{Y}}(\mathbf{P}_{p_\mu+p_\rho}^{(n-1)}(\lfloor n/2 \rfloor, n-1) + \mathbf{P}_{p_\mu+p_\rho}^{(n-1)}(\lceil n/2 \rceil, n-1))} & \mathcal{R}_{\mathrm{m}} \\ \frac{WC_{\mathcal{T}}}{WP_{\mathcal{C}} + WB_{\mathcal{Y}}} + \psi, \text{ for any } \psi > 0 & \mathcal{R}_{\mathrm{a}} \ \& \ \mathcal{R}_{\emptyset} \\ 1 - \frac{WP_{\mathcal{C}} + WB_{\mathcal{Y}} - WC_{\mathcal{T}}}{(WP_{\mathcal{C}} + WB_{\mathcal{Y}})(\mathbf{P}_{p_\mu+p_\rho}^{(n-1)}(\lfloor n/2 \rfloor, n-1) + \mathbf{P}_{p_\mu+p_\rho}^{(n-1)}(\lceil n/2 \rceil, n-1))} & \mathcal{R}_{\pm} \end{cases}$$

- if $U_M(p_{\mathcal{A}}, q) < U_M(1-\varepsilon, p_\mu + p_\rho)$ then $p_{\mathcal{A}} \leftarrow 1 - \varepsilon$

## Mechanism design
Optimality

Only feasible approach for $P_{wrong} \leq \varepsilon$

**Theorem**

*In order to achieve $P_{wrong} \leq \varepsilon$, the only feasible approaches are either to enforce a NE where $p_C = 0$ or to choose $p_A$ so that $P_{wrong} \leq \varepsilon$ even if all rationals cheat.*

**Proof.**

$\Delta U$ is increasing in $q$ $(\Delta U(p_C < 1) \leq \Delta U(p_C = 1))$

$\rightarrow$ the only unique NE corresponds to $p_C = 0$.

For any other NE where $p_C > 0$, $p_C = 1$ is also a NE

$\rightarrow$ $P_{wrong}$ worst case when all players cheat. □



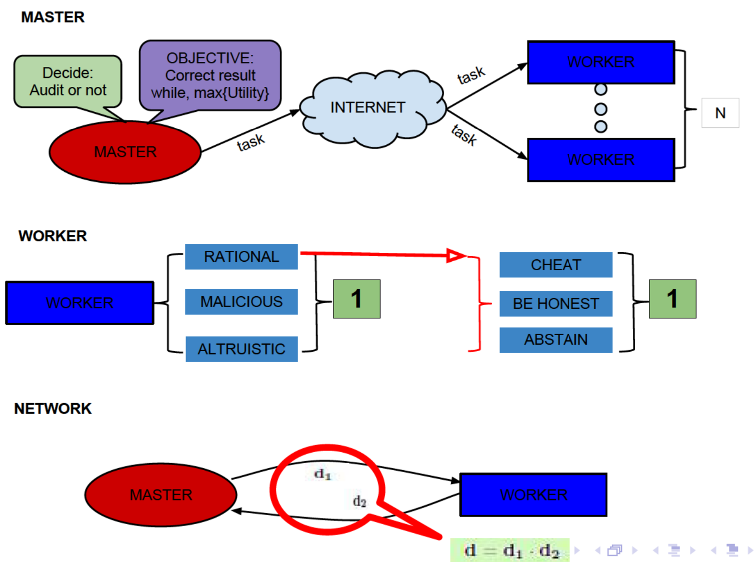


## Unreliable Communication





## Framework








## General Protocol

- Master assigns a task to $n$ workers
- Rational worker cheats with probability $p_C$ (seeking a NE)
- Master audits the responses with probability $p_A$
- If master audits (computes the task itself)
  - rewards honest workers and
  - penalizes the cheaters
- If master does not audit
  - Accepts value returned by majority of workers
  - Rewards/penalizes according to one of three models

| | |
|---|---|
| $\mathcal{R}_m$ | the master rewards the majority only |
| $\mathcal{R}_a$ | the master rewards all workers whose reply was received |
| $\mathcal{R}_\emptyset$ | the master rewards no worker |

Note: reward models may be fixed exogenously or chosen by the master

## Algorithms

- Time-based protocol
  - Master fixes a time $T$, once it is reached gathers all received replies
  - Ties are broken at random

- Reply-based protocol
  - Master fixes $k$, minimum estimated number of replies, by choosing $n$
  - If at least $k$ replies are received, audit with $p_{\mathcal{A}}$
  - Else it does nothing, and incurs penalty $MC_{\mathcal{S}}$

- Note: When $d = 1$ both protocols fall into the communication-reliable protocol





## Algorithms

$d_2$ is the probability value that master achieves by

- Waiting $T$ time, time-based mechanism
- Hiring $n$ workers, reply-based mechanism

Why two protocols?

- Master may have knowledge to only one of two settings
  - For example based on statistics
  - Uses the mechanism designed for that setting
- Time-based mechanism, more likely to use auditing
- Reply-based mechanism may not receive enough replies
- Consequently
  - Time-based mechanism preferred when auditing cost low
  - Reply-based mechanism preferred when auditing cost high and $MC_{\mathcal{S}}$ small





## Payoff Parameters

| | |
|---|---|
| $WP_{\mathcal{C}}$ | worker's punishment for being caught cheating |
| $WC_{\mathcal{T}}$ | worker's cost for computing the task |
| $WB_{\mathcal{Y}}$ | worker's benefit from master's acceptance |
| $MP_{\mathcal{W}}$ | master's punishment for accepting a wrong answer |
| $MC_{\mathcal{Y}}$ | master's cost for accepting the worker's answer |
| $MC_{\mathcal{A}}$ | master's cost for auditing worker's answers |
| $MC_{\mathcal{S}}$ | master's cost for not getting any reply |
| $MB_{\mathcal{R}}$ | master's benefit from accepting the right answer |

Note: it is possible that $WB_{\mathcal{Y}} \neq MC_{\mathcal{Y}}$





## Strategic payoffs

| | | $\mathcal{R}_{\mathrm{m}}$ | $\mathcal{R}_{\mathrm{a}}$ | $\mathcal{R}_{\emptyset}$ |
|---|---|---|---|---|
| $\boldsymbol{w}_{\mathcal{C}}$ | $w_{\mathcal{C}}^{\mathcal{AR}}$ | $-WP_{\mathcal{C}}$ | $-WP_{\mathcal{C}}$ | $-WP_{\mathcal{C}}$ |
| | $w_{\mathcal{C}}^{\mathcal{CR}}$ | $WB_{\mathcal{Y}}$ | $WB_{\mathcal{Y}}$ | $0$ |
| | $w_{\mathcal{C}}^{\mathcal{HR}}$ | $0$ | $WB_{\mathcal{Y}}$ | $0$ |
| | $w_{\mathcal{C}}^{\mathcal{X}\overline{\mathcal{R}}}$ | $0$ | $0$ | $0$ |
| $\boldsymbol{w}_{\mathcal{H}}$ | $w_{\mathcal{H}}^{\mathcal{AR}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ |
| | $w_{\mathcal{H}}^{\mathcal{CR}}$ | $-WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $-WC_{\mathcal{T}}$ |
| | $w_{\mathcal{H}}^{\mathcal{HR}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $WB_{\mathcal{Y}} - WC_{\mathcal{T}}$ | $-WC_{\mathcal{T}}$ |
| | $w_{\mathcal{H}}^{\mathcal{X}\overline{\mathcal{R}}}$ | $-WC_{\mathcal{T}}$ | $-WC_{\mathcal{T}}$ | $-WC_{\mathcal{T}}$ |
| $\boldsymbol{w}_{\mathcal{N}}$ | $w_{\mathcal{N}}^{\mathcal{XX}}$ | $0$ | $0$ | $0$ |

# Conditions for mixed-strategy NE (MSNE)

Desired condition for enforcing a unique NE at $p_{\mathcal{C}} = 0$ and $p_{\mathcal{N}} = 0$

$$\Delta U_{\mathcal{HC}} = \boldsymbol{\pi}_{\mathcal{H}} \cdot \boldsymbol{w}_{\mathcal{H}} - \boldsymbol{\pi}_{\mathcal{C}} \cdot \boldsymbol{w}_{\mathcal{C}} \geq 0$$
$$\Delta U_{\mathcal{HN}} = \boldsymbol{\pi}_{\mathcal{H}} \cdot \boldsymbol{w}_{\mathcal{H}} - \boldsymbol{\pi}_{\mathcal{N}} \cdot \boldsymbol{w}_{\mathcal{N}} \geq 0$$

$\Delta U_{S_1 S_2}$: difference on the expected utilities of a rational worker when choosing strategy $S_1$ over strategy $S_2$

$\boldsymbol{w}_X$: vector corresponding to different payoffs received by the given worker for each event when choosing strategy $X$

$\boldsymbol{\pi}_X$: vector corresponding to possibility that of the events occurring when the given worker choses strategy $X$





# Analysis and Notations

Pr(worker cheats|worker replies): $q = \frac{p_\mu + p_\rho p_{\mathcal{C}}}{1 - p_\rho p_{\mathcal{N}}}$

Pr(worker does not cheat|worker replies): $\overline{q} = \frac{p_\alpha + p_\rho p_{\mathcal{H}}}{1 - p_\rho p_{\mathcal{N}}} = 1 - q$

Pr(reply received): $r = d(1 - p_\rho p_{\mathcal{N}})$

Pr(reply not received): $\overline{r} = 1 - r$

Then, $r(q + \overline{q}) + \overline{r} = 1$.

Pr($i$ out of $n$ replies received): $r_i = \binom{n}{i} r^i \overline{r}^{n-i}$

Pr(majority honest | $i$ replies received): $h_i$
Pr(majority cheats | $i$ replies received): $c_i$





# Equilibria Conditions

Guaranteeing : $P_{succ} \geq 1 - \varepsilon$ While maximizing $U_M$

Pr(master obtains correct answer):

$$P_{succ} = \sum_{i=k}^{n} r_i \left(p_{\mathcal{A}} + (1 - p_{\mathcal{A}}) h_i\right)$$

E(utility of master):

$$\textbf{master's utility } U_M = -\sum_{i=0}^{k-1} r_i MC_{\mathcal{S}} + \sum_{i=k}^{n} r_i (p_{\mathcal{A}} \alpha_i + (1 - p_{\mathcal{A}}) \beta_i)$$

where,

$$\alpha_i = MB_{\mathcal{R}} - MC_{\mathcal{A}} - nd(p_\alpha + p_\rho p_{\mathcal{H}}) MC_{\mathcal{Y}}$$
$$\beta_i = MB_{\mathcal{R}} h_i - MP_{\mathcal{W}} c_i - MC_{\mathcal{Y}} \gamma_i$$

and where, $\gamma_i = 0$ for $\mathcal{R}_\emptyset$, $\gamma_i = i$ for $\mathcal{R}_{\mathrm{a}}$, and for $\mathcal{R}_{\mathrm{m}}$ is expected number of worker's majority (as calculated in the paper),





# Mechanism Design

## Master protocol to chose $p_{\mathcal{A}}$

- Free rationals (master does not rely on rational workers )
  - Case 1: probability of malicious workers $p_\mu$ very large, high $p_{\mathcal{A}}$

    $$p_{\mathcal{A}} \leftarrow 1 - \varepsilon / \sum_{i=k}^{n} r_i c_i$$

  - Case 2: probability of altruistic workers $p_\alpha$ big

    $$p_{\mathcal{A}} \leftarrow 0$$

  - Case 3: rationals probability of being honest $p_{\mathcal{H}}$ is 1, even if $p_{\mathcal{A}} = 0$

    $$p_{\mathcal{A}} \leftarrow 0$$

- Guided rationals(force the behavior of rational workers)
  - Rationals enforced to reply correctly ($p_{\mathcal{C}} = 0$ and $p_{\mathcal{N}} = 0$)
  - $p_{\mathcal{A}}$ is set according to worker's equilibria conditions depending on the reward model

# SETI-like Scenario

## Volunteering Computing

- each worker
  - incurs in no cost to perform the task ($WC_{\mathcal{T}} = 0$)
  - obtains a benefit ($WB_{\mathcal{Y}} > WC_{\mathcal{T}} = 0$) (recognition, prestige)
- master
  - incurs in a (possibly small) cost to reward a worker ($MC_{\mathcal{Y}} > 0$) (advertise participation)
  - may audit results at a cost ($MC_{\mathcal{A}} > 0$)
  - obtains a benefit for correct result ($MB_{\mathcal{R}} > MC_{\mathcal{Y}}$)
  - suffers a cost for wrong result ($MP_{\mathcal{W}} > MC_{\mathcal{A}}$)
- $d > 0$, as it is considered in the analysis as well
- Master can choose $p_{\mathcal{A}}$ and $n$ so that $U_M$ is maximized for $P_{wrong} \leq \varepsilon$ / $P_{succ} \geq 1 - \varepsilon$ for any given worker-type distribution, reward model, and set of payoff parameters in the SETI scenario





# SETI-like Scenario

## Reliable Network ($d = 1$)

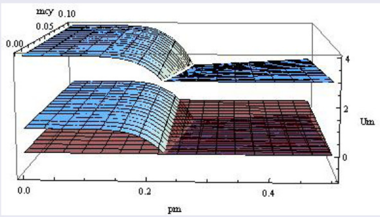
- Plots illustrating trade-off between reliability and cost
- Parameters' value:
  - $MC_{\mathcal{A}} = 1$, normalizing parameter
  - $MP_{\mathcal{W}} = 100$
  - Different values, don't change qualitatively the results
- 3D plots : Graphical characterization of the master's utility
  - $p_{\mu} \in [0, 0.5]$ ($p_{\mu} < 0.1$ in empirical evaluations on SETI-like system, Einstein@home, Estrada, Taufer and Anderson 09. )
  - $MC_{\mathcal{Y}} \in [0, 0.1]$, small maintenance cost of contribution list



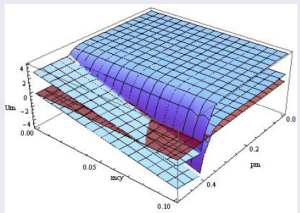


# SETI-like Scenario

## Reliable Network ($d = 1$)



- $\mathcal{R}_{\emptyset}$, $n = 15$
- Upper plane $MB_{\mathcal{R}} = 4$, lower plane $MB_{\mathcal{R}} = 1$, red plane $U_M = 0$
- Master audits around $p_{\mu} = 0.2$



- $\mathcal{R}_{\emptyset}$, $n = 75$
- Upper plane $MB_{\mathcal{R}} = 4$, lower plane $MB_{\mathcal{R}} = 1$, red plane $U_M = 0$
- Master audits around $p_{\mu} = 0.4$

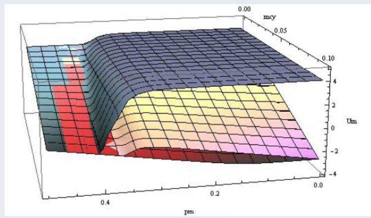




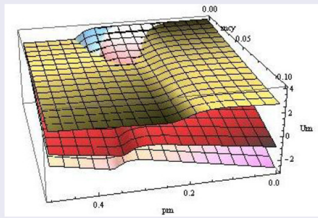
# SETI-like Scenario

## Unreliable Network ($d > 0$)

**Time-based Mechanism**



- $d = 0.9$, $n = 75$
- Upper plane $\mathcal{R}_{\emptyset}$, middle $\mathcal{R}_{\mathrm{m}}$ and lower plane $\mathcal{R}_{\mathrm{a}}$
- Master audits around $p_{\mu} = 0.35$



- Reward model $\mathcal{R}_{\mathrm{m}}$, $d = 0.9$
- Upper plane $n = 15$, middle $n = 55$, lower plane $n = 75$
- For $n = 15$, earlier change to auditing strategy

## SETI-like Scenario
### Unreliable Network ($d > 0$)

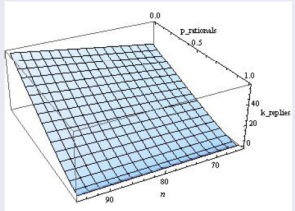
**Reply-based Mechanism**

- $k \geq 1$
- Chernoff bounds for calculating $k$

$$k = \boldsymbol{E} - \sqrt{2\boldsymbol{E}\ln(1/\zeta)}$$

with probability at least $1 - \zeta$, $0 < \zeta < 1$, where $\boldsymbol{E} = nd(p_\alpha + p_\mu)$

- $\zeta = 1/n$ (used in plot)




- $n \in [65, 95]$, $p_\rho \in [0, 1]$
- Appropriate value of $n$ to get at least $k$ replies
- $p_\rho$ increase, $k$ decrease





## Contractor scenario

- master
  - pays each worker an amount ($MC_\mathcal{Y} > 0$)
  - receives a benefit (from consumers for the provided service) ($MB_\mathcal{R} > MC_\mathcal{Y}$)
  - may audit and has a cost for wrong result ($MP_\mathcal{W} > MC_\mathcal{A} > 0$)
- each worker
  - receives payment for computing the task (not volunteers) ($S = WB_\mathcal{Y} = MC_\mathcal{Y}$)
  - incurs in a cost for computing ( $WC_\mathcal{T} > 0$)
  - must have economic incentive ($U > 0$)
- $d > 0$, as it is considered in the analysis as well
- Master can choose $p_\mathcal{A}$ and $n$ so that $U_M$ is maximized for $P_{wrong} \leq \varepsilon$ / $P_{succ} \geq 1 - \varepsilon$ for any given worker-type distribution, reward model, and set of payoff parameters in the contractor scenario





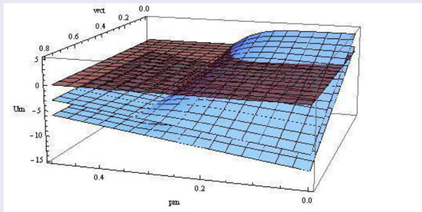
## Contractor scenario
### Reliable Network ($d = 1$)

- Plots illustrating trade-off between reliability and cost
- Parameters' value:
  - $MC_\mathcal{A} = 1$, normalizing parameter
  - $MP_\mathcal{W} = 100$
  - $S = 0.8$
  - Different values,don't change qualitatively the results
- 3D plots : Graphical characterization of the master's utility
  - $p_\mu \in [0, 0.5]$ ($p_\mu < 0.1$ in empirical evaluations on SETI-like system, Einstein@home, Estrada, Taufer and Anderson 09. )
  - $WC_\mathcal{T} \in [0, S]$

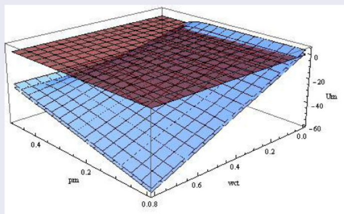




## Contractor scenario
### Reliable Network ($d = 1$)



- $\mathcal{R}_\emptyset$, $n = 15$
- Upper plane $MB_\mathcal{R} = 4$, lower plane $MB_\mathcal{R} = 1$, red plane $U_M = 0$
- Master audits around $p_\mu = 0.35$



- $\mathcal{R}_\emptyset$, $n = 75$
- Upper plane $MB_\mathcal{R} = 4$, lower plane $MB_\mathcal{R} = 1$, red plane $U_M = 0$
- Master audits around $p_\mu = 0.48$

## Conclusions

- Combined classical distributed computing approach with game-theoretic to obtain reliability on Master-Worker Internet-based Platforms that executes tasks
- We presented mechanisms for reliable computation
- Different types of workers
- Reliable and Unreliable network
- Applied developed mechanisms to volunteering and contractor-based computing
- Illustrate the trade-off between reliability and cost in depicted plots





## Future Work

- We plan to explore systems with a continuous flow of tasks over multiple rounds
- View the computations in the Master-Worker model as an *Evolutionary Game*
- Master use previous knowledge gained in past rounds to:
  - Increase its utility
  - Decrease its probability of error in future rounds.
- Workers aspiration level, issue that must be taken into account.



# Gracias!

Presentation available at:
http://www.cs.ucy.ac.cy/ric/dissemination.html

For further questions:
christoforou.evgenia@ucy.ac.cy