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Algorithmic Mechanisms for Reliable Internet Supercomputing

Chryssis Georgiou

Assistant Professor
University of Cyprus

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Outline

- Motivation and preliminaries
- Framework and accomplishments
- Algorithmic Mechanism
- Application of the mechanism
  - SETI-like scenario
  - Contractor scenario
- Conclusions

Motivation and Preliminaries

K Computer

Top Three Supercomputers (2012)

- **K Computer**, RIKEN Advanced Institute for Computational Science (2011), Japan
  - CPUs: 88,128 SPARC64 VIIIfx 8-core 2.0GHz
  - 11,280 TFLOPS (11.2 PetaFLOPS)
- **Tianhe-1A,** Tianjin National Supercomputer Center, (2010), China
  - CPUs: 186,368 NUDT X5670 6-core 2.93GHz
  - 4,701 TFLOPS (4.7 PetaFLOPS)
- **Jaguar Cray XT5-HE,** Cray Inc (2009), USA
  - CPUs: 224,162 AMD x86_64 Opteron 6-core 2.6GHz

  2,331 TFLOPS (2.33 PetaFLOPS)

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Computational Tasks

- Increasing demand for processing complex computational tasks
  - One-processor machines have limited computational resources
  - Powerful parallel machines (supercomputers) are expensive and are not globally available
- Intern… emerges as a viable platform for supercomputing
  - P2P, …d computing
    - e.g., EGEE Grid, … Amazon's EC2
  - Volunteer Master-Worker … me projects
    - e.g., SETI@home, AIDS@home, Folding… PrimeNet

Internet-based Computing

SETI

- Search for ExtraTerrestrial Inteligence
- Internet-based public volunteer computing project
  - Employs the BOINC software platform
  - Hosted by the Space Sciences Laboratory, at the University of California, Berkeley, USA
- Purpose: analyze radio (telescopic) signals, searching for signs of extra terrestrial intelligence
- How to use it:
  - Register your PC
  - Downloads the SETI data analyzer (screensaver mode)
  - When PC is idling, it starts analyzing data
  - When done, sends results, gets new data chunk to analyze

http://setiathome.berkeley.edu/

Arecibo Radio Telescope, Puerto Rico

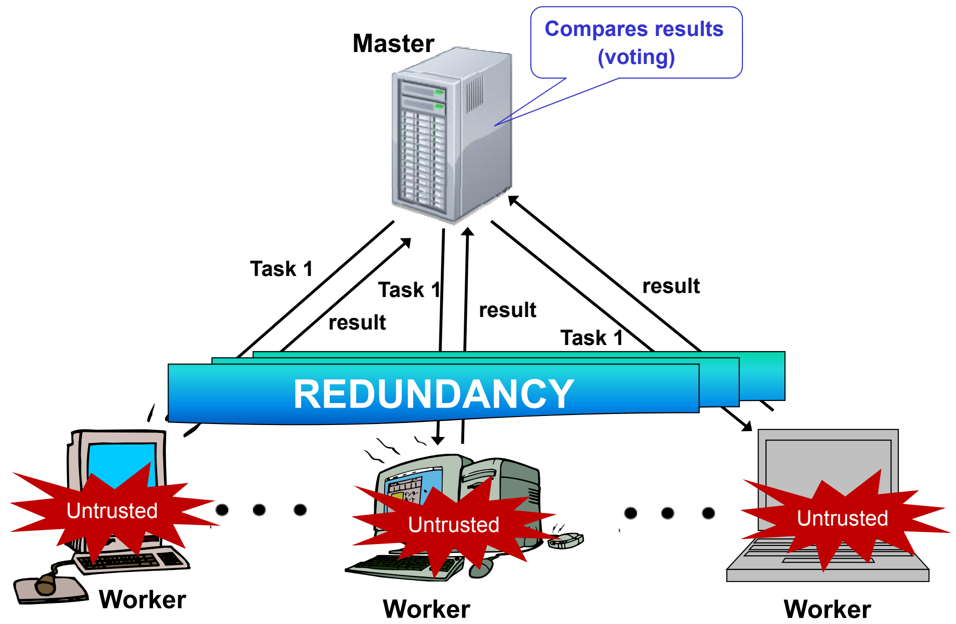
SETI@home by the numbers

- As reported in November 2009
  - 278,832 active CPUs (out of a total of 2.4 million) in 234 countries
  - 769 TFLOPs

Comparable processing power with top Supercomputers @ a fraction of the cost!

Great potential limited by untrustworthy entities

SETI-like Internet-based Computing



Redundant Task-Allocation

Two different approaches:

- "Classical" distributed computing: pre-defined worker behavior
  - Malicious workers fabrigate and report a bogus result
  - Altruistic workers compute and truthfully report correct result

  Malicious-tolerant voting protocols are designed

  [Sarmenta 2002, Fernandez et al 2006, Konwar et al 2006]
- Game-theoretic: workers act upon their best interest
  - Workers are Rational, i.e., they act selfishly aiming to maximize their own benefit

  Incentives are provided to induce a desired behavior

  [Yurkewych et al 2005, Fernandez et al 2008]

BUT realistically, the three types of workers may coexist!

Our Approach

Consider all worker types

- Types of workers:
  - **malicious:** always report incorrect result
  - **altruistic:** always compute and report correct result
  - **rational:** selfishly choose to be honest or a cheater
- Combine the two approaches
  - Game-theoretic approach:
    - Computations modeled as strategic games
    - Provide incentives to induce desired rationals behavior
    - Master chooses whether to audit the returned result or not
  - Classical distributed computing approach:
    - Design malice-aware voting protocols
- Objective: Reliable Internet-based Master-Worker Computing with *provable guarantees*

Background

A game consists of a set of players, a set of strategies available to those players, and a specification of payoffs (utilities) for each combination of strategies [wikipedia]

- Game Theory:
  - Players (processors) act on their self-interest
  - Rational [Golle Mironov 01] behavior: seek to increase their utility
  - Protocol is given as a game
  - Design objective is to achieve equilibrium among players

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

Algorithmic Mechanism Design

- Games are designed to provide necessary incentives such that rational players act "correctly"
  - Behave well: Reward
  - Otherwise: Penalize
- The design objective is to induce a desired behavior (e.g., a unique NE)

[Nisan Ronen 01]

Framework and Accomplishments

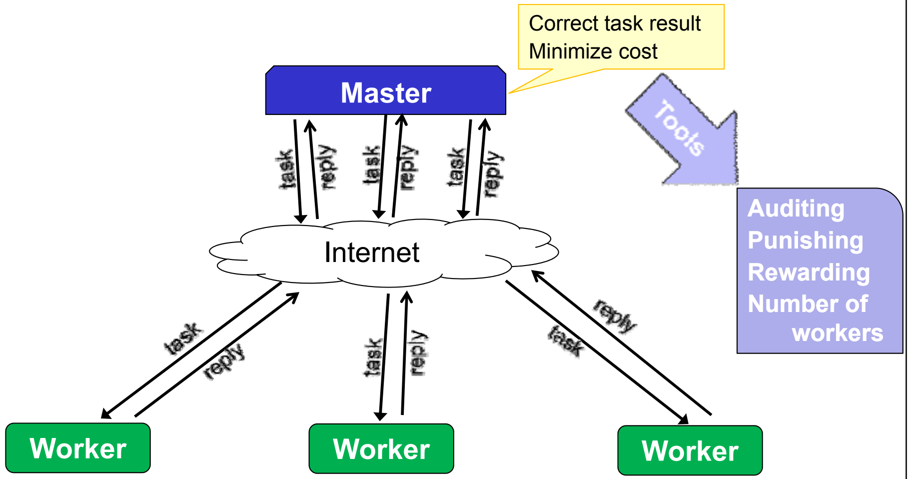
Framework

- Developed a general framework that captures the essential characteristics of existing Master-Worker platforms
  - Assuming communication between the master and the workers is reliable
  - Assuming that communication might be unreliable and workers may be unavailable
- Workers' types:
  - Unknown type of workers → Bayesian game [Harsanyi '67]
  - Known probability distribution over types

p_ρ : Rational p_μ : Malicious p_α : Altruistic

such that $p_\rho + p_\mu + p_\alpha = 1$

General Framework (reliable com.)



Untrusted: malicious or selfish

Reply with an incorrect result (cheat)

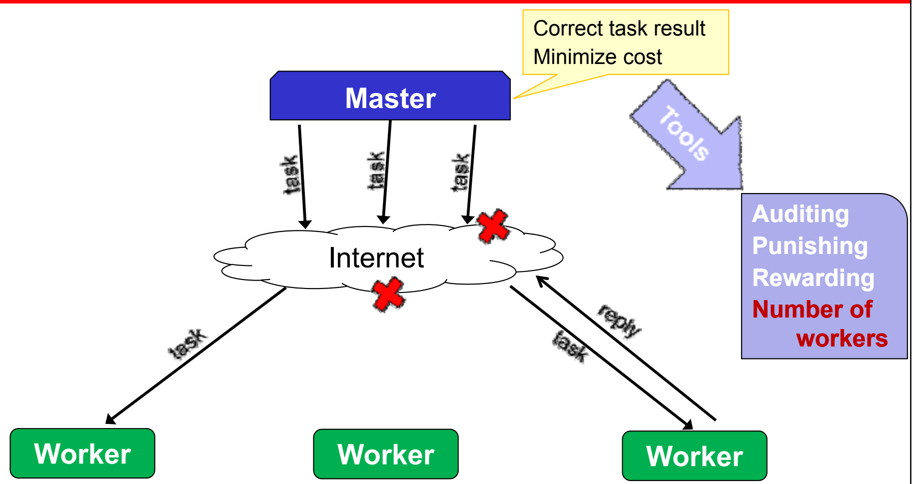
Accomplishments (reliable com.)

Reliable communication assumed

- Designed an algorithmic mechanism
  - Provides, when necessary, incentives to rational workers to act correctly so that
    - Master obtains correct task result (whp)
    - Despite malicious workers actions
- Analyzed the mechanism under two existing Internet-based Master-Worker settings
  - SETI-like volunteer computing systems
  - Profit-seeking Internet-based computational service

  Provide clear tradeoffs between reliability and cost under different system parameters

General Framework (unreliable com.)



Untrusted: malicious or selfish

Cheat or abstain (do not reply)

Accomplishments (unreliable com.)

Unreliable communication, worker unavailability

- Designed two algorithmic mechanisms
  - Provides, when necessary, incentives to rational workers to act correctly so that
    - Master obtains correct task result (whp)
    - Despite malicious workers actions and network unreliability

  Both mechanisms are useful in different situations

  When communication is reliable, we get the mechanism of the reliable communication case
- Analyzed the mechanisms under the two mentioned application-examples
  - Provides clear tradeoffs between reliability, cost and network unreliability

ALGORITHMIC MECHANISM
[RELIABLE COMMUNICATION]

Master Protocol

- Master assigns a task to n workers and collect replies
- Rational workers cheat with probability p_C
- 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 reward models

$\mathcal{R}_m$	the master rewards the majority only
$\mathcal{R}_a$	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

Payoff parameters

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

Master's Goals

- Obtain the correct task result with a parameterized probability: $P_{wrong} \leq \varepsilon$
- Then increase its utility (benefit): U_M
- Depending on the type distribution, the master might or might not rely on rational workers
- The master must choose the auditing probability $p_{\mathcal{A}}$ in such a way, to "force", when needed, the rational workers to act correctly ($p_C = 0$)
- We computed the equilibrium conditions under general payoffs values and system parameters

Equilibrium Conditions

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):

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

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_μ 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_α 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 $p_{\mathcal{A}} \leftarrow 1 - \varepsilon$

Optimality

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 $p_{\mathcal{A}}$ so that $P_{wrong} \leq \varepsilon$ even if all rational workers cheat.

Computational Issues

- The mechanism for the master to choose appropriate values of $p_{\mathcal{A}}$ involves
  - Simple arithmetic calculations
  - Computing binomial probabilities
  - Verification of conditions for NE

  All these computations can be carried out using well-known numerical tools of polynomial cost.

- Together with the task, the master sends a ***certificate*** (p_A, *payoffs, n, reward*) of the uniqueness of the desired NE to the workers

PUTTING THE MECHANISM INTO ACTION

Volunteering Computing (SETI-like)

- Each worker
  - Incurs in no cost to perform the task: $WC_{\mathcal{T}} = 0$
  - Obtains a benefit: $WB_{\mathcal{Y}} > 0$
    (recognition, prestige – top contributors list)
- Master
  - Incurs in a (possibly small) cost to reward a worker (advertise participation): $MC_{\mathcal{Y}} > 0$
  - 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: $MP_{\mathcal{W}} > MC_{\mathcal{A}}$

Mechanism Instantiation

Instantiating the mechanism designed on these conditions the master can choose $p_{\mathcal{A}}$ and n so that U_M is maximized for $P_{wrong} \leq \varepsilon$ for any given worker-type distribution, reward model, and set of payoff parameters in the SETI scenario.

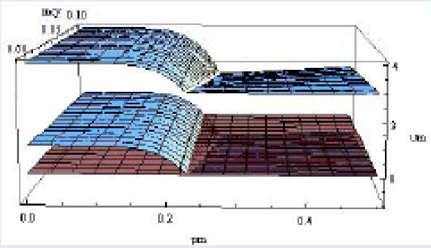
$$U_M \approx \max\{MB_{\mathcal{R}} - MC_{\mathcal{A}} - n(1-p_\mu)MC_{\mathcal{Y}},$$
$$MB_{\mathcal{R}}\mathbf{P}_{p_\mu}^{(n)}(0, \lfloor n/2 \rfloor) - MP_{\mathcal{W}}\mathbf{P}_{p_\mu}^{(n)}(\lceil n/2 \rceil, n) + \gamma\}$$

$$\gamma = \begin{cases} -MC_{\mathcal{Y}}(\mathbf{E}_{1-p_\mu}^{(n)}(\lceil n/2 \rceil, n) + \mathbf{E}_{p_\mu}^{(n)}(\lceil n/2 \rceil, n)) & \text{for the } \mathcal{R}_m \text{ and } \mathcal{R}_\pm \text{ models.} \\ -nMC_{\mathcal{Y}} & \text{for the } \mathcal{R}_a \text{ model.} \\ 0 & \text{for the } \mathcal{R}_\emptyset \text{ model.} \end{cases}$$

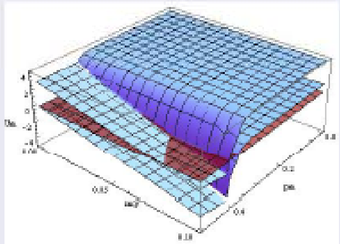
Plots

- 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

Examples



- $\mathcal{R}_\emptyset$, $n = 15$
- 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 $p_\mu = 0.4$

Contractor Scenario

- Each worker
  - Incurs in a cost for computing: $WC_\mathcal{T} > 0$
  - Receives payment for computing the task (not volunteers): $WB_\mathcal{Y} = MC_\mathcal{Y} > 0$
  - Must have economic incentive: $U_i > 0$
- Master
  - Pays each worker an amount: $MC_\mathcal{Y} > 0$
  - Receives a benet (from consumers for the provided service): $MB_\mathcal{R} > MC_\mathcal{Y}$
  - May audit and has a cost for wrong result:

$$MP_\mathcal{W} > MC_\mathcal{A} > 0$$

Mechanism Instantiation

Instantiating the mechanism designed on these conditions the master can choose $p_\mathcal{A}$ and n so that U_M is maximized for $P_{wrong} \le \varepsilon$ for any given worker-type distribution, reward model, and set of payoff parameters in the Contractor scenario.

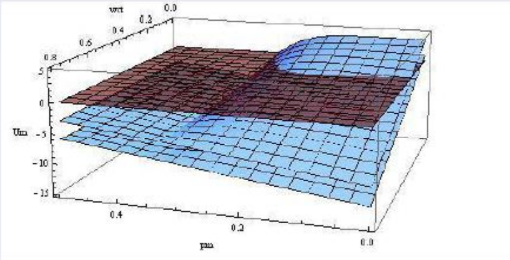
$$U_M \approx \max \Big\{ MB_\mathcal{R} - MC_\mathcal{A} - n(1-p_\mu)S,$$
$$\frac{WC_\mathcal{T}}{S}(MB_\mathcal{R} - MC_\mathcal{A} - n(1-p_\mu)S)$$
$$+ \left(1 - \frac{WC_\mathcal{T}}{S}\right)\left(MB_\mathcal{R}\mathbf{P}^{(n)}_{p_\mu}(0, \lfloor n/2 \rfloor) - MP_\mathcal{W}\mathbf{P}^{(n)}_{p_\mu}(\lceil n/2 \rceil, n)\right) \Big\}$$

(for $\mathcal{R}_\emptyset$ reward model)

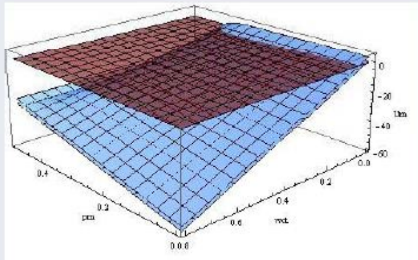
Plots

- 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.)
  - $WC_\mathcal{T} \in [0, S]$

Examples



- $\mathcal{R}_\emptyset$, $n = 15$
- 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

Summary

- Combined
  - Classical distributed computing approach WITH
  - Game-theoretic approach

  towards reliable Master-Worker Internet-based Task computing under
  - Malicious, altruistic and rational workers
  - Communication uncertainty and worker unavailability
- Mechanisms trade reliability (ε) and cost (U_M) (and network unreliability)

Added Value

- As an example: instantiation of such mechanism in two real-world scenarios

BOINC-based systems (such as SETI@home) send the same task to three (3) workers. Our analysis identifies rigorously, for any given system parameters, the best allocation that BOINC-based systems could deploy.

The analysis on the contractor scenario opens the way for commercial Internet-based supercomputing where a company, given specific system parameters, could calculate its profit (if any) before agreeing into providing a proposed computational service.

Ongoing and Future Work

- Consider task execution over multiple rounds over workers that their behavior changes over time
  - View the computations in the Master-Worker framework as Evolutionary Games
- Reinforcement learning
  - The Master uses knowledge gained in past rounds to
    - decrease of its probability of error in future rounds
    - increase its utility in future rounds
  - The workers use prior knowledge to increase their utility
- Worker reputation
  - Measure the workers' reputation based on prior behavior and use it as an additional incentive for rational workers to act correctly.

Presentation available at:

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

For further questions:

chryssis@cs.ucy.ac.cy