Internet-based Task Computing

- Increasing demand for processing computation intensive tasks
  - One-processor machines have limited computational resources
  - Powerful parallel machines (supercomputers) are expensive and are not globally available

- Growing use and capabilities of Personal Computers

- Wide access to the Internet

- Internet emerges as a viable platform for supercomputing
  - Master-Worker volunteer computing: @home projects
    - e.g., SETI@home, AIDS@home, Folding@home
  - Profit-seeking computing
    - e.g., Amazon’s Mechanical Turk (human-based computing)
SETI-like Internet-based computing

Mechanism for deciding result (e.g., majority voting)

Task 1

Master

Redundancy

Untrusted

Worker

Untrusted

Worker

Untrusted

Worker

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Reputation-based Mechanisms for Evolutionary Master-Worker Computing
Prior Work

- **Classical Distributing Computing approach:**
  - **Malicious workers:** always incorrect result
  - **Altruistic workers:** always return a correct result

  [Fernández et al.; Konwar; Sarmenta]

- **Game Theoretic approach:**
  - **Rational workers:** act upon their best interest, i.e., choose the strategy that maximizes their own benefit

  [Abraham et al.; Golle and Mironov; Shneidman and Parkes]

- **All three types are considered**
  - Mechanisms with reward/punish schemes that provide incentives to workers to be honest and alleviate malicious action consequences

  [Fernández et al.]

- **Multi-round interaction but only rational workers are assumed**

  [Christoforou et al.]
## Motivation

### What's your main reason for running SETI@home? (73110 responses)

| Reason                                      | Percentage |
|---------------------------------------------|------------|
| Find ET for the good of humanity           | 58.88%     |
| Find ET to become famous                    | 2.93%      |
| Keep my computer productive                 | 15.15%     |
| Get my name on a top 100 list on the website| 2.26%      |
| Other                                       | 20.78%     |

Other examples:

- Not sure: 4.07%
- Should Earth send a signal for aliens to hear? (7489 responses)
  - Yes: 78.16%
  - No: 10.42%
  - Not sure: 11.41%
- How many hours is your computer running on a typical day? (74820 responses)
  - Less than 24: 35.42%
  - 24, because of SETI@home: 36.46%
  - 24, but not because of SETI@home: 28.12%
- When do you think humans will detect the first ET signal? (73982 responses)
  - Within the next 2 years: 8.67%
  - Within the next 10 years: 38.69%
  - Within the next 100 years: 41.97%
  - More than 100 years from now: 7.15%
  - Never: 3.56%
- Should the U.S. government fund SETI research? (74089 responses)
  - Yes: 80.10%
  - No: 11.43%
  - Not sure: 8.47%
Motivation

• Several studies have showed that volunteer Internet-based computing is unreliable, with malicious behavior

  [Aderson; Heien et al.; Kondo et al.]

• In commercial platforms we should not expect the existence of altruistic workers
Evolutionary Game Theory

In biological terms: the application of game theory to evolving populations of life forms

Our aim: Evolutionary Stable Strategy

A strategy is called evolutionary stable if, when the whole population is using this strategy, any group of invaders (mutants) using a different strategy will eventually die over multiple generations (evolutionary rounds).

[Gintis 2000]
Reputation-based Mechanisms for Evolutionary Master-Worker Computing

**Background/ Rational Worker Approach**

• Bush and Mosteller's model, aspiration based
  - players adapt by comparing their experience with an aspiration level

  - an aspiration $a_i$ for player $i$

  • the minimum benefit it expects to obtain in an interaction

[Bush Mosteller 55]
Background/ Master Approach

• The master can apply a reputation technique to identify which workers should be trusted.

• Central authority that objectively calculates the reputation of each worker.

• Based on the master’s observations about the workers behavior.

• Master reinforces its strategy as a function of the reputation calculated for each worker.
BOINC (i.e., SETI@home, AIDS@home, Folding@home, etc.) has a reputation mechanism, called adaptive replication.

- Replication is avoided when a task is sent to a highly reliable worker

Sonnek et al. use an adaptive reputation-based technique for task scheduling in volunteer setting

- Reputation is used as a mechanism to reduce the degree of redundancy while keeping it possible for the master to verify the results by allocating more reliable nodes.

We design a mechanism that forces the system to evolve to a reliable state.
Our Approach

• **Objective:** Develop a reliable computation platform where the master obtains the correct task results always.

• We design an algorithmic mechanism that uses reinforcement learning to induce the correct behavior to rational workers while coping with malice using reputation.

• We consider three different reputation types to calculate each worker’s reputation.

• We analyze our reputation-based mechanism:
  - we model it as a Markov chain
  - we identify conditions under which truthful behavior can be ensured
  - we prove that reliable computation is eventually achieved, by using a reputation type introduced in this work.

• We evaluate our mechanism with simulations.
**Eventual correctness:** After a finite number of rounds
- the master obtains the correct result in every round
- with minimal auditing
- the rational workers are satisfied

**Rational : probability of cheating** $pC_i$,

**Altruistic:** always honest

**Malicious:** always cheat

**Reward / Punish schemes**

$p_A$: probability of auditing

**REPUTATION**
Reputation-based Mechanisms for Evolutionary Master-Worker Computing

**Payoffs**

| Payoff      | Description                                           |
|-------------|-------------------------------------------------------|
| $WP_C$      | Worker’s punishment for being caught cheating         |
| $WC_T$      | Worker’s cost for computing a task                    |
| $WB_y$      | Worker’s benefit from master’s acceptance             |

$PA$: probability of auditing

**Reward / Punish schemes**

**REPUTATION**

Punishment

Cost

Benefit
$\rho_A$: probability of auditing

Reward / Punish schemes

$\text{aud}(r)$: the number of rounds that the master audited up to round $r$

$v_i(r)$: the number of auditing rounds where worker $i$ was found truthful up to round $r$

$\rho_i(r)$: the reputation of worker $i$ after round $r$

**Type 1:**

$$\rho_i(r) = \frac{(v_i(r) + 1)}{(\text{aud}(r) + 2)}$$

**Type 2:**

$$\rho_i(r) = \varepsilon^{\text{aud}(r) - v_i(r)} \quad \varepsilon \in (0, 1)$$
\[ \beta_i(r) : \text{the error rate of worker } i \text{ at round } r \]
initialized by \( \beta_i(0) = 0.1 \)

\( A = 0.05 \) is the error bound

**Type 3:**

**Step 1:**

if worker truthful then
\[ \beta_i(r) \leftarrow \beta_i(r) \cdot 0.95 \quad \text{calculating error rate} \]
else \( \beta_i(r) \leftarrow \beta_i(r) + 0.1 \)

**Step 2:**

if \( \beta_i(r) > A \) then
\[ \rho_i(r) \leftarrow 0 \quad \text{calculating reputation} \]
else \( \rho_i(r) \leftarrow 1 - \sqrt{\frac{\beta_i(r)}{A}} \)
Reputation-based Mechanisms for Evolutionary Master-Worker Computing

- **Type 1:** $\rho_i(r) = (v_i(r) + 1)/(aud(r) - v_i(r))$
- **Type 2:** $\rho_i(r) = \varepsilon^{aud(r)} - v_i(r)$
- **Type 3:**
  
  \[ \beta_i(r) \text{ initialized by } \beta_i(0) = 0.1 \]
  
  $A = 0.04$ is the error bound

  \[ \beta_i(r) \text{ is recomputed when master audits} \]

- If the master does not audit, the result is obtained by the weighted majority
Markov Chain Modeling

Round $r-1$
\[ \langle p_A(r-1), aud(r-1), p_{C1}(r-1), p_{C2}(r-1), \ldots, p_{Cn}(r-1), v_1(r-1), v_2(r-1), \ldots, v_n(r-1) \rangle \]

- **Master audits**
- **Set of cheaters $F$**

Round $r$
\[ \langle p_A(r), aud(r), p_{C1}(r), p_{C2}(r), \ldots, p_{Cn}(r), v_1(r), v_2(r), \ldots, v_n(r) \rangle \]

**Master’s updates**
\[
\begin{align*}
  aud(r) &= aud(r - 1) + 1 \\
  p_A(r) &= p_A(r - 1) + \alpha_m \left( \frac{\rho_F(r)}{\rho_W(r) - \tau} \right)
\end{align*}
\]

**Workers’ updates**
\[
\begin{align*}
  \text{cheating workers:} & \quad v_i(r) = v_i(r - 1) \\
  & \quad p_{Ci}(r) = p_{Ci}(r - 1) - \alpha_w(a_i + WP_C) \\
  \text{honest worker:} & \quad v_i(r) = v_i(r - 1) + 1 \\
  & \quad p_{Ci}(r) = p_{Ci}(r - 1) + \alpha_w(a_i - (WB_Y - WC_T))
\end{align*}
\]
Markov Chain Modeling

Round $r-1$

$$\langle p_A(r-1), aud(r-1), p_{C1}(r-1), p_{C2}(r-1), \ldots, p_{Cn}(r-1), v_1(r-1), v_2(r-1), \ldots, v_n(r-1) \rangle$$

**Master does not audit**
Set of cheaters $F$

Round $r$

$$\langle p_A(r), aud(r), p_{C1}(r), p_{C2}(r), \ldots, p_{Cn}(r), v_1(r), v_2(r), \ldots, v_n(r) \rangle$$

Not updated

$$p_A(r) = p_A(r-1) \quad aud(r) = aud(r-1)$$
$$i \in W: v_i(r) = v_i(r-1)$$

**Updated**

| Cheating worker | Honest worker |
|-----------------|--------------|
| $p_F(r) > p_{WF}(r)$ | $p_{Ci}(r) = p_{Ci}(r-1) + \alpha_w(WB_Y - a_i)$ | $p_{Ci}(r) = p_{Ci}(r-1) + \alpha_w(a_i + WC_T)$ |
| $p_F(r) < p_{WF}(r)$ | $p_{Ci}(r) = p_{Ci}(r-1) - \alpha_w \cdot a_i$ | $p_{Ci}(r) = p_{Ci}(r-1) + \alpha_w(a_i - (WB_Y - WC_T))$ |
We analyze the evolution of the master-worker system as a Markov chain and we show:

For the system to achieve eventual correctness and the master to audit with sufficient to have $p_{\text{min}}$ is necessary and sufficient to have $WB_Y \geq a_i + WC_T$ for all rational workers and at least one altruistic or rational worker to be present.
Eventual correctness analysis

- Universal class of reputation functions characterized by the following properties

**Property 1:** For any constant $\delta > 0$, there is a bounded value $\gamma(\delta)$ such that, for any non-empty $X \subseteq W$ and any initial state $s_r$ in which $v_i(r) = 0, \forall i \notin X$, if the Markov chain evolves in such a way that $\forall k = 1, \ldots, \gamma(\delta)$, it holds that $aud(r + k) = aud(r) + k, \forall i \in X, v_i(r + k) = v_i(r) + k$ and $\forall j \in W \setminus X, v_j(r + k) = v_j(r)$, then $\rho_X(r + \gamma(\delta)) > \delta \cdot \rho_W \setminus X(r + \gamma(\delta))$.

- If the master audits in $k$ consecutive rounds and players in set $X$ are honest while players in set $W \setminus X$ cheat then the aggregated reputation of the players in $X$ is $\delta$ times larger than the aggregated reputation of $W \setminus X$ set.

**Property 2:** For any $X \subseteq W$ and $Y \subseteq W$, if $aud(r + 1) = aud(r) + 1$ and $\forall j \in X \cup Y$ it is $v_j(r + 1) = v_j(r) + 1$ then $\rho_X(r) > \rho_Y(r) \Rightarrow \rho_X(r + 1) > \rho_Y(r + 1)$.

- If the aggregated reputation of workers in $X$ is larger than the aggregated reputation of set $Y$ then if the master audits and all workers are honest the inequality should continue to be the same.
Lemma 1. Consider any set of workers $Z \subseteq W$ such that $WB_Y > a_i$, for every rational worker $i \in Z$. Consider the set of states

$$S = \{ s | (p_A(s) = 0) \land (\forall w \in Z : p_{Cw}(s) = 1) \land (\rho_Z(s) > \rho_{W-Z}(s)) \}.$$

Then,

(i) $S$ is a closed untruthful set, and
(ii) if $p_A(0) = 0$, $\rho_Z(0) > \rho_{W-Z}(0)$, and for all $i \in Z$ it is $p_{C_i}(0) > 0$, then, $S$ is reachable.

**Lemma 1:** Motivates the necessity of $p_A^{\min} > 0$ unless altruistic workers outnumber the rest

**Lemma 2.** If all workers are malicious or uncovered rationals, no truthful set $S$ is closed, if the reputation type satisfies Property 2.

**Lemma 2:** Having an altruistic or rational worker is necessary
Lemma 3. Consider a reputation type that satisfies Properties 1 and 2. If all rational workers are covered and at least one worker is altruistic or rational, a closed truthful set $S$ is reachable from any initial state. Moreover, in every state $s \in S$, $p_A(s) = p_A^{min}$.

Theorem 1. From any initial state, if all rational workers are covered, having at least one worker altruist or rational is necessary and sufficient to eventually reach a closed truthful set $S$ where the master audits with probability $p_A^{min}$, and hence to guarantee eventual correctness, if the reputation type satisfies Properties 1 and 2.

Eventual correctness is reached with auditing being minimal, if all rational workers are covered, Properties 1 & 2 are satisfied and at least one altruistic or rational worker is present.
Simulations

- We created our own simulation setup by implementing our mechanism
- Choose parameters likely to be encountered:
  - 9 workers (e.g. SETI@home 3 workers)
  - initial $P_A = 0.5$
  - $P_A^{min} = 0.01$
  - $\tau = 0.5$ (master does not tolerate a majority of cheaters)
  - aspiration $a_i = 0.1$ for each worker
  - learning rate $\alpha = \alpha_m = \alpha_w = 0.1$
  - $\varepsilon = 0.5$ in reputation type 2
  - Benefit is 1
  - Punishment is zero
  - Cost is 0.1
Reputation-based Mechanisms for Evolutionary Master-Worker Computing

Only Rational Workers

\[ p_C = 0.5 \]

\[ p_C = 1 \]
Reputation types (Only Rational workers)

![Graph showing reputation over time for different worker types]

- **Type 1**: Rising reputation over time.
- **Type 2**: Initial high reputation followed by decline.
- **Type 3**: Nearly constant reputation with slight variations.

Mathematical notation:

\[ p_C = 0.5 \]
Rationals and Malicious

\[ p_C = 1 \]

4 malicious; 5 rationals

5 malicious; 4 rationals

8 malicious; 1 rationals
One covered worker and changes of personality

Correct reply percentage as a function of time

Left Fig: Initially Reputations 1 & 3: $p_C = 0.5$ reputation 2: $p_C = 1$

Right Fig: Initial $p_C = 1$

5 malicious
Malicious-tolerant generic mechanism that uses reputation
- Reputation type 2 fits better in a commercial application
- Reputation type 3 fits better in a volunteering setting

Only reputation type 2 guarantees eventual correctness

**Future Work:** Workers can be connected to each other forming a social network, malicious players developing intelligent strategy, pool of workers, workers reinforcing their aspiration level
Appendix
Master’s Algorithm

\[ p_A \leftarrow x, \text{ where } x \in [p_A^{\text{min}}, 1] \]
\[ \text{aud} = 0 \]
\[ // \text{ initially all workers have the same reputation} \]
\[ \forall i \in W : v_i = 0; \rho_i = 0.5 \]
\[ \text{for } r \leftarrow 1 \text{ to } \infty \text{ do} \]
\[ \text{send a task } T \text{ to all workers in } W \]
\[ \text{upon receiving all answers do} \]
\[ \text{audit the answers with probability } p_A \]
\[ \text{if the answers were not audited then} \]
\[ // \text{ weighted majority, coin flip in case of a tie} \]
\[ \text{accept the value returned by workers in } W_m \subseteq W, \]
\[ \text{where } \rho_{W_m} > \rho_{W \setminus W_m} \]
\[ \text{else } // \text{ the master audits} \]
\[ \text{aud} \leftarrow \text{aud} + 1 \]
\[ \text{Let } F \subseteq W \text{ be the set of workers that cheated.} \]
\[ \forall i \in W : \]
\[ \text{if } i \notin F \text{ then } v_i \leftarrow v_i + 1 // \text{ honest workers} \]
\[ \text{update reputation } \rho_i \text{ of worker } i \]
\[ \text{if } \rho_W = 0 \text{ then } p_A \leftarrow \min\{1, p_A + \alpha_m\} \text{ else} \]
\[ p_A \leftarrow \min\{1, \max\{p_A^{\text{min}}, p_A + \alpha_m(\frac{\rho_F}{\rho_W} - \tau)\}\} \]
\[ \forall i \in W : \text{return payoff } \Pi_i \text{ to worker } i \]

\[ \alpha_m : \text{ learning rate (tunes the extent of change)} \]
\[ \tau : \text{ tolerance (tolerable fraction of cheaters, e.g., 0.5)} \]
Rational Workers Algorithm

\[ p_{C_i} \leftarrow y, \text{ where } y \in [0, 1] \]

\[ \text{for } r \leftarrow 1 \text{ to } \infty \text{ do} \]

\[ \text{receive a task } T \text{ from the master} \]

\[ S_i \leftarrow -1 \text{ with probability } p_{C_i}, \]

\[ \text{and } S_i \leftarrow 1 \text{ otherwise} \]

\[ \text{if } S_i = 1 \text{ then} \]

\[ \sigma \leftarrow \text{compute}(T), \]

\[ \text{else} \]

\[ \sigma \leftarrow \text{arbitrary solution} \]

\[ \text{send response } \sigma \text{ to the master} \]

\[ \text{get payoff } \Pi_i \]

\[ \text{if } S_i = 1 \text{ then} \]

\[ \Pi_i \leftarrow \Pi_i - WC_T \]

\[ p_{C_i} \leftarrow \max\{0, \min\{1, p_{C_i} - \alpha_w (\Pi_i - a_i) S_i\}\} \]

\[ \alpha_w : \text{learning rate (tunes the extent of change)} \]
• A set $X$ of workers is called a reputable set if 
  \[ \rho_X(r) > \rho_{W \setminus X}(r) \]
• A worker is honest if \[ p_{Ci}(s) = 0 \]
• A state $s$ is a truthful state if the set of honest workers in state $s$ is reputable
• A truthful set is any set of truthful states
• A worker is covered worker if 
  \[ WB_y \geq a_i + WC_T \]
• Opposite cases: uncovered worker, untruthful state, untruthful set, cheater worker
• Let a set of states $S$ be called closed if, once the chain is in any state $s \in S$, it will not move to any state $s' \notin S$