Achieving Reliability in Master-Worker Computing via Evolutionary Dynamics

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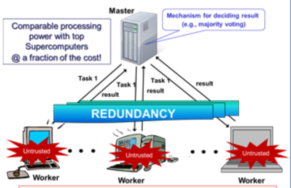
Motivation

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
- Internet emerges as a viable platform for supercomputing
  - P2P, Grid and Cloud computing
    - e.g., EGEE Grid, TERA Grid, Amazon's EC2
  - Volunteer Master-Worker computing: @home projects
    - e.g., SETI@home, AIDS@home, Folding@home, PrimeNet
  - Amazon's Mechanical Turk (Contractor-based approach)

  Internet-based Computing

SETI-like Internet-based Computing



Great potential limited by untrustworthy entities

Prior Work

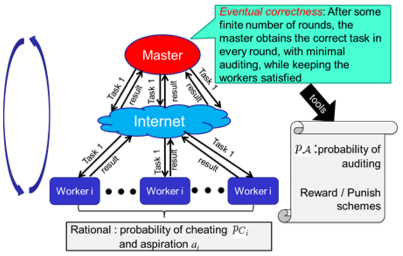
- Rational workers: act upon their best interest, i.e., choose the strategy that maximizes their own benefit [Shneidman Parkes 03]
- Workers with predefined behavior:
  - Malicious: fabricate and report a bogus result
  - Altruistic: compute and truthfully report correct result
- In Internet-based master-worker task computation
  - Honest: compute and report correct result
  - Cheat: fabricate and return a bogus result
- Mechanisms with reward/punish schemes that provide incentives to workers to be honest
  - One shot: in each round a task is performed and no knowledge is forwarded to the next round [Yurkewych et al 2005, Fernandez et al 2008]

Can the repeated interaction between the master and the workers be exploited effectively?

Our Approach

- We introduce the concept of *evolutionary dynamics* under the biological and social perspective and relate them to Internet-based master-worker task computing
- Employ *reinforcement learning* both on Master and Workers [Camerer 03, Szepesvari 10]
- Objective: Develop a reliable computation platform where the master obtains the correct task results

Framework



Eventual correctness: After some finite number of rounds, the master obtains the correct task in every round, with minimal auditing, while keeping the workers satisfied

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

Evolutionary Mechanism (No Reputation)

Master's Protocol

Set initial $p_{\mathcal{A}}$ (e.g., 0.5)
Repeat
  Send a task to all n workers
  Upon receiving all answers **do**
    Audit the answers with probability $p_{\mathcal{A}}$
    If the answers were *not* audited **then**
    Accept the value returned by the majority
    Else
    $p_{\mathcal{A}} \leftarrow p_{\mathcal{A}} + \alpha_m \cdot \left(\frac{cheaters}{n} - \tau\right)$

Give appropriate payoff Π_i to each worker i

α_m : learning rate (tunes the extent of change)
τ : tolerance (tolerable fraction of cheaters, e.g., 0.5)

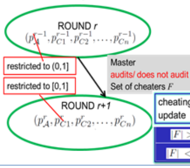
Protocol for Worker i

Set initial p_{C_i} (e.g., 0.5)
Repeat
  Receive a task from the master
  Set S_i = -1 *with* probability p_{C_i}, S_i = 1 otherwise
  If S_i = 1 then **compute** the task and **send** the result
  Else send an arbitrary result
  Get payoff Π_i

$p_{C_i} \leftarrow p_{C_i} - \alpha_w \cdot (\Pi_i - a_i) \cdot S_i$

α_w: learning rate (tunes the extent of change)

- We analyze the evolution of the master-worker system as a *Markov chain*:



Audit

Master's audit prob. update: $p_{\mathcal{A}}^r = p_{\mathcal{A}}^{r-1} + \alpha_m(|F|/n - \tau)$

worker's cheating prob. update:
- cheating worker: $p_{Ci}^r = p_{Ci}^{r-1} - \alpha_w(a_i + WP_C)$
- honest worker: $p_{Ci}^r = p_{Ci}^{r-1} + \alpha_w(a_i - (WB_y - WC_T))$

No Audit

cheating prob. update	Cheating worker	Honest worker
$\lvert F\rvert > n/2$	$p_{Ci}^{r-1} + \alpha_w(WB_y - a_i)$	$p_{Ci}^{r-1} + \alpha_w(a_i + WC_T)$
$\lvert F\rvert < n/2$	$p_{Ci}^{r-1} - \alpha_w \cdot a_i$	$p_{Ci}^{r-1} + \alpha_w(a_i - (WB_y - WC_T))$

Background

Evolutionary Dynamics

- Evolutionary dynamics applied first in biology
  - Tool to study the mathematical principles according to which life is evolving
  - Inspiration for many fields: sociology, economics, artificial intelligence (multi-agent systems) etc.
- **Inspired by dynamics of evolution as a mean to model workers adaptation to a truthful behavior**

Evolutionary Stable Strategy

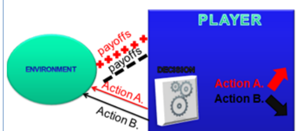
Evolutionary Game Theory

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]

Reinforcement Learning



Notion of Aspiration

- Bush and Mosteller's model, aspiration based
  - player's adapt by comparing their experience with an aspiration level [Bush Mosteller 55]
  - an aspiration a_i for player i
    - the minimum benefit it expects to obtain in an interaction

Reputation

- Accumulated information about an entity
- Induce learning by signaling the true abilities of involved entities
- Computer science:
  - On-line community exchange, eBay
    - Buyers, sellers: positive, negative and neutral rating
  - P2P systems
    - bitTorrent: increase reputation by uploading => increase download speed (tit for tat)
    - Gnutella (who to download from?)
- A reputation system can be:
  - Centralized [Sonnek et al. 2007]
  - Decentralized [Damiani et al. 2002]

Conditions for Eventual Correctness (No Reputation)

For the system to achieve eventual correctness, it is necessary and sufficient to set

$$WB_y \geq a_i + WC_T, \ \forall i \in Z, \ |Z| > n/2$$

Given that $p_{\mathcal{A}} > 0$

Terminology

- Covered worker is one that receives at least its aspiration a_i and the computing WC_T cost
- In any given round r, honest worker is one for which $p_C^{r-1} = 0$
- Honest state is one where the majority of workers are honest
- Honest set is any set of honest states
- Opposite cases: uncovered worker, cheater worker, cheat state, and cheat set respectively
- 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 $s' \notin S$

Lemma 1. *Consider any set of workers $Z \subseteq W$ such that $\forall i \in Z : WB_y \geq a_i$. If $|Z| > n/2$, then the set of states*
$$S = \{(p_{\mathcal{A}}, p_{C1}, \ldots, p_{Cn}) | (p_{\mathcal{A}} = 0) \wedge (\forall w \in Z : p_{Cw} = 1)\},$$
is a closed cheat set.

Lemma 1: Motivates the necessity of $p_{\mathcal{A}} > 0$

Lemma 2. *If there exists a set of workers $Z \subseteq W$ such that $|Z| > n/2$ and $\forall i \in Z : WB_y < a_i + WC_T$ and $\forall i \in W : \alpha(a_i + WP_C) < 1$, then no honest set is closed.*

Lemma 2: Motivates the necessity of a covered majority

Lemma 3. *Consider any set of workers $Z \subseteq W$ such that $\forall i \in Z : WB_y \geq a_i + WC_T$ and $\forall j \notin Z : WB_y < a_j + WC_T$. If $|Z| > n/2$, then the set of states*
$$S = \{(p_{\mathcal{A}}, p_{C1}, \ldots, p_{Cn}) | \forall w \in Z : p_{Cw} = 0\},$$
is a closed set.

Lemma 3: Proves that there exists at least one honest closed set

Lemma 4. *Consider any set of workers $Z \subseteq W$ such that $\forall i \in Z : WB_y \geq a_i + WC_T$ and $\forall j \notin Z : WB_y < a_j + WC_T$. Then, for any set of states*
$$S = \{(p_{\mathcal{A}}, p_{C1}, \ldots, p_{Cn}) | \exists Y \subseteq W : (|Y| > n/2) \wedge (\forall w \in Y : p_{Cw} = 0) \wedge (Z \not\subseteq Y)\}$$
S is not a closed set.

Lemma 5. *Consider any set of workers $Z \subseteq W$ such that $\forall i \in Z : WB_y \geq a_i + WC_T$ and $\forall j \notin Z : WB_y < a_j + WC_T$. If $|Z| > n/2$ and $p_{\mathcal{A}} > 0$, then for any set of states*
$$S = \{(p_{\mathcal{A}}, p_{C1}, \ldots, p_{Cn}) | \exists Y \subseteq W : (|Y| > n/2) \wedge (\forall w \in Y : p_{Cw} > 0)\},$$
S is not a closed set.

Lemma 4-5: Proves that all closed sets are honest and that one honest closed set is reachable from any initial state

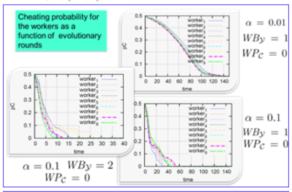
- To show eventual correctness, we must show eventual convergence to a closed honest set
- We need to show
  - that there exists at least one such closed honest set
  - that all closed sets are honest
  - that one honest closed set is reachable from any initial state

Simulations

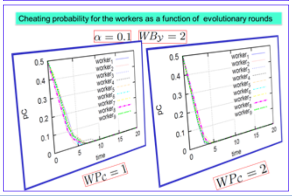
No Reputation Mechanism

- 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_{C_i} = 0.5
  - initial $p_{\mathcal{A}}$ = 0.5
  - τ = 0.5 (master does not tolerate a majority of cheaters)
  - aspiration a_i = 0.1 for each worker
  - $\alpha = \alpha_m = \alpha_w, \ \alpha \in \{0.1, 0.01\}$
  - $WB_y \in \{1, 2\}$ set as our normalizing
  - $WC_T = 0.1$
  - $WP_C \in \{0, 1, 2\}$

Cheating probability for the workers as a function of evolutionary rounds



Cheating probability for the workers as a function of evolutionary rounds



Evolutionary Mechanism with Reputation

Reputation

- Master maintains a reputation for each worker
- Workers are ignorant towards the reputation scheme
- Update when master audits
- Calculated based on:
  - number of audits up to round r: $audit(r)$
  - number of times worker i was honest when master audited up to round r: $correct\_audit_i(r)$
- Reputation types:
  - Type 1: $\rho_i = \frac{correct\_audit_i(r) + 1}{audit(r) + 2}$ [based on Sonnek et al. 2007]
  - Type 2: $\rho_i = \varepsilon^{audit(r) - correct\_audit_i(r)}$ where $\varepsilon \in (0, 1)$
- Need to cope with malicious workers

Master's Protocol

Set initial $p_{\mathcal{A}}$ (e.g., 0.5)
Repeat
  Send a task to all n workers
  Upon receiving all answers **do**
    Audit the answers with probability $p_{\mathcal{A}}$
    If the answers were *not* audited **then**
    Accept the value returned by ~~the majority~~ workers in W_j where $j \in \{0, 1\}$ and $\sum_{i \in W_j} \rho_i > \sum_{i \in W \setminus W_j} \rho_i$
    Else
    Update worker's i reputation, and
    $$p_{\mathcal{A}} = p_{\mathcal{A}} + a_m \cdot \left(\frac{\sum_{i \in F} \rho_i}{\sum_{i \in W} \rho_i} - \tau\right)$$

Give appropriate payoff Π_i to each worker i

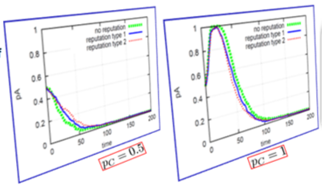
α_m: learning rate
τ: tolerance
W: set of workers
F: set of cheaters
W_j: workers in W with the same answer

Simulations

- Choose parameters likely to be encountered:
  - 9 workers (e.g. SETI@home 3 workers)
  - initial p_{C_i} = {0.5, 1}
  - initial $p_{\mathcal{A}}$ = 0.5
  - τ = 0.5 (master does not tolerate a majority of cheaters)
  - aspiration a_i = 0.1 for each worker
  - $\alpha = \alpha_m = \alpha_w, \alpha = 0.1$
  - $WB_y = 1$ set as our normalizing
  - $WC_T = 0.1$
  - $WP_C = 0$

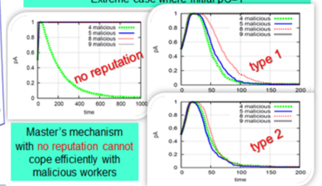
Only Rational Workers

Auditing probability of the master as a function of time



Malicious and Rational Workers

Auditing probability of the master as a function of time
Extreme case where initial pC=1



Master's mechanism with no reputation cannot cope efficiently with malicious workers

Evolutionary Mechanism, choose n *workers* out of a pool of N

Choosing from a Pool

- There is a pool of N workers available to the master
- In each round the master selects n out of these workers, the most reputable ones
- In a round
  - If the master audits
    - updates the reputation of the workers
    - updates the set of the n most reputable workers to be used in the next round
  - Otherwise, it uses the same set of workers for the next round
- In our simulations: Take 5 most reputable workers out of 9

Master's Protocol

Set initial $p_{\mathcal{A}}$ (e.g., 0.5)
Choose n most reputable workers
Repeat
  Send a task to all n workers
  Upon receiving all answers **do**
    Audit the answers with probability $p_{\mathcal{A}}$
    If the answers were *not* audited **then**
    Accept the value returned by workers in W'_j where $j \in \{0, 1\}$ and $\sum_{i \in W'_j} \rho_i > \sum_{i \in W' \setminus W'_j} \rho_i$
    Else
    Update worker's i reputation, and
    $$p_{\mathcal{A}} = p_{\mathcal{A}} + a_m \cdot \left(\frac{\sum_{i \in F'} \rho_i}{\sum_{i \in W'} \rho_i} - \tau\right)$$

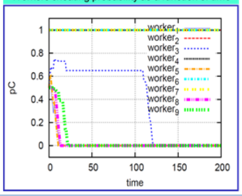
Give appropriate payoff Π_i to each worker i in W'
If master audited **then** update the n most reputable workers

α_m: learning rate
τ: tolerance
W': set of n most reputable workers
F: cheaters in W'
W'_j: workers in W' with the same answer

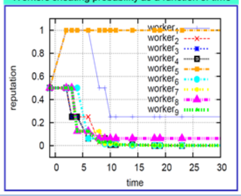
Malicious and Rational Workers

4 malicious, 5 rational workers, reputation type 2

Workers cheating probability as a function of time



Workers cheating probability as a function of time



Dealing with communication uncertainty

- Reputation is based both on auditing and responsiveness
- Master's protocol outline:
  - Send task to the n most reputable workers
  - Wait for time T:
    - For workers that do not reply reduce their reputation (using reputation type)
    - Then proceed as usual on the workers that have replied

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