Collective Intelligence

PI: David Wolpert

Co-I: Kagan Tumer

NASA Ames Research Center

kagan@ptolemy.arc.nasa.gov

http://ic.arc.nasa.gov/~kagan

http://ic.arc.nasa.gov/projects/COIN/index.html

What the **** is a Collective?

- A **collective** is a system:
  - With a **world utility** function which measures the full system's performance
  - Composed of many **agents**
  - Where each agent has a **private utility** it is trying to optimize
- Important issues:
  - *How should one set private utility functions?*
  - *How should one update them (team formation)?*
  - *How should utilities be modified in presence of communication restrictions?*

An Analogy: A Company

- World utility ⟷ Valuation of company
- Agents ⟷ Employees
- Private Utilities ⟷ Compensation packages

- Design problem (faced by the board):
  - *How to set/modify compensation packages (private utilities) of the agents to increase valuation of company (world utility)*
    - *Salary/bonus*
    - *Benefits*
    - *Stock options*
  - Note: Board does not tell each individual what to do. They set the “incentive packages” for employees (including the CEO).

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Collectives of Interest to IS

- – Control of a constellation of communication satellites
- – Routing data/vehicles over a communication network/highway
- – Dynamic data migration over large distributed databases
- – Dynamic job scheduling across a (very) large computer grid
- – Coordination of rovers/submersibles on Mars/Europa
- – Control of the elements of an amorphous telescope
- – Construction of distributed algorithms for optimization
- – Selection of components to minimize aggregate error
- – Compilation in randomly assembled nanocomputers

Collective intelligence is an enabling technology

Key Concepts for Collectives

- **Factoredness:** Degree to which an agent's private utility is "aligned" with the world utility
  - e.g. stock options are factored w.r.t. company valuation.

- **Learnability:** Based on sensitivity of an agent's private utility to changes in its state (signal-to-noise).
  - e.g., performance bonuses increase learnability of agent's utility

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- Interesting question: If you could, would you want everyone's utility to be valuation of company?
  - Factored, yes; but what about learnability?

Brief Illustration of Theory

- Our ability to control system consists of setting some parameters *s* (e.g, compensation packages):

$$\boxed{P(G|s)}$$

$\underbrace{\qquad\qquad}_{\text{Explore vs. Exploit}}$ $\underbrace{\qquad\qquad}_{\text{Factoredness}}$ $\underbrace{\qquad}_{\text{Learnability}}$

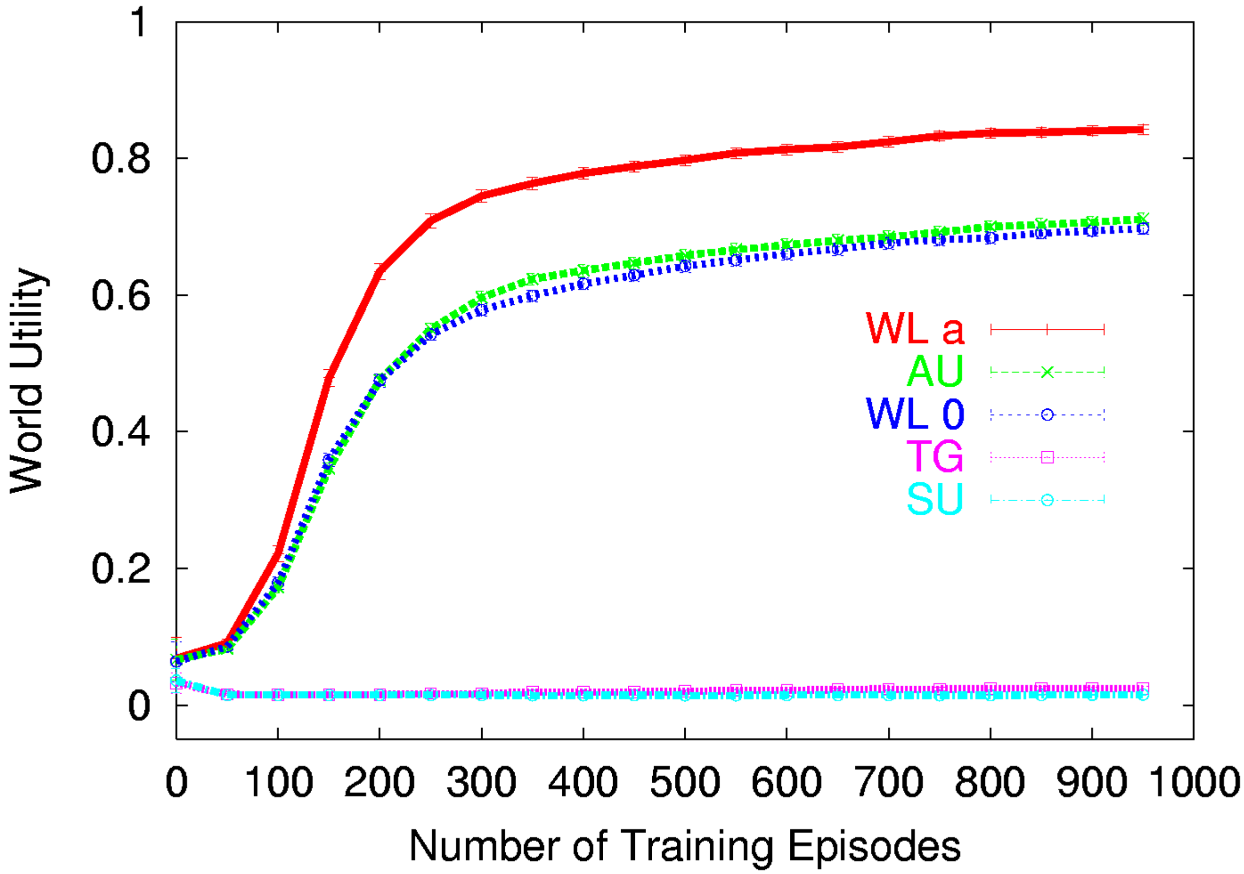
Explore vs. Exploit	Factoredness	Learnability
Operations Research Search	Economics Mechanism Design	Machine Learning Computer Science

  – ε_G and ε_g are intelligences for the agents w.r.t the world utility (G) and their private utilities (g) , respectively

Current/Future Projects

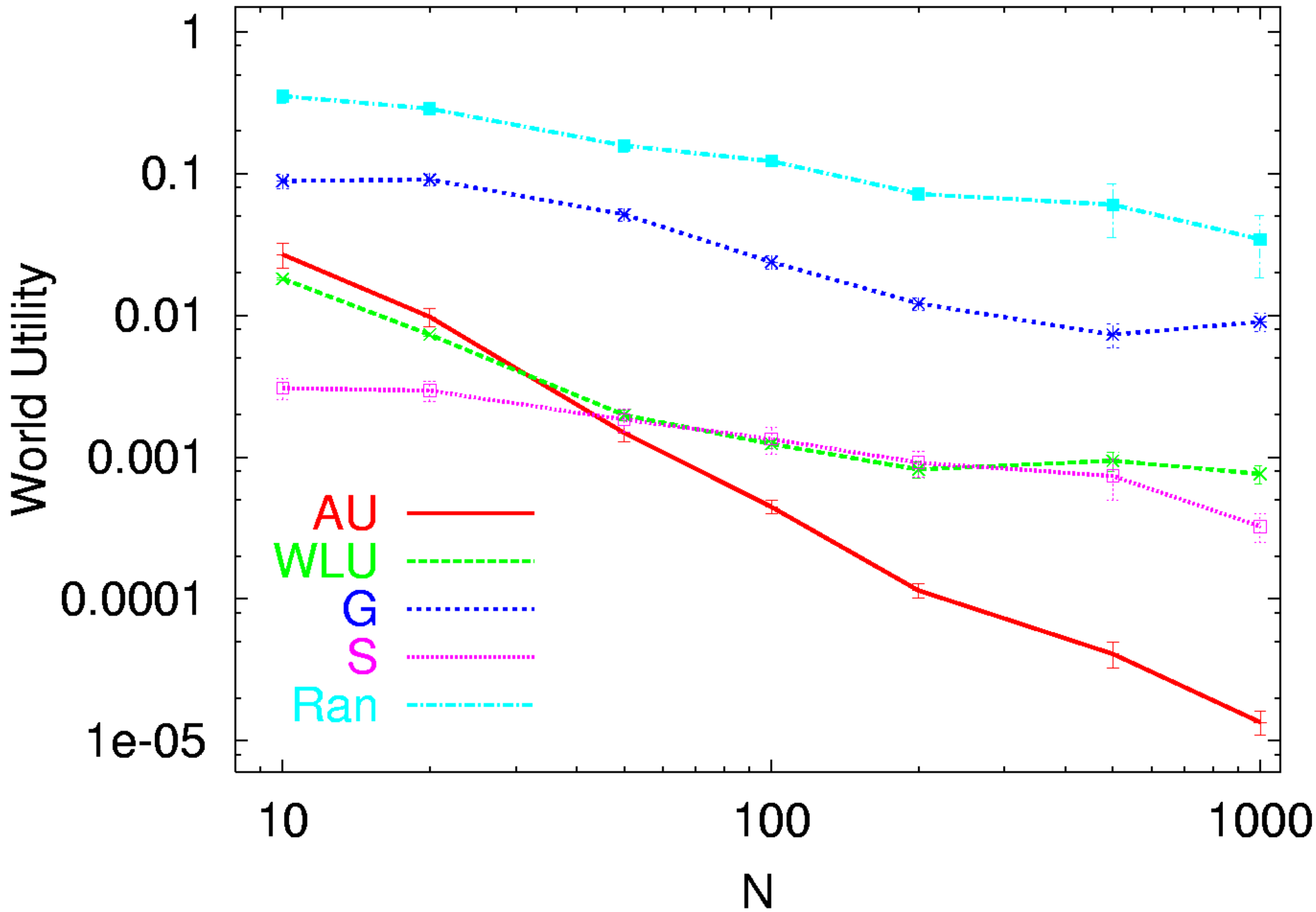
- Application Domains:
  - Multi-rover coordination (Tumer, Agogino)
  - Distributed optimization (Wolpert, Tumer)
  - Dynamic job scheduling (Tumer, Lawson)
  - Distributed resource allocation 1 (Wolpert, Tumer, Aireau)
  - Autonomous defect problem (Wolpert, Tumer)
  - Nanocomputer compilation (Wolpert, Millonas)
  - Distributed resource allocation 2 (Tumer, Agogino)
- Scientific Issues:
  - Communication restrictions
  - Team formation
  - Factoredness/Learnability trade-offs

Rover Problem: Utility Comparison



100 rovers on a 32x32 grid

Autonomous Defects Problem: Scaling



Summary

- A collective is a set of “selfish” agents pursuing their own private utilities along with a world utility rating performance of full system.
- Theory of collectives shows *how to configure and/or update the private utilities of the agents so that they “unintentionally cooperate” to optimize the world utility*
- Private utilities based on this theory successfully applied to many domains (e.g., autonomous rovers, constellations of communication satellites, data routing, autonomous defects)
- Associated improvement in performance ***increase*** with size of problem
- **A fully mature “science of collectives” would benefit the IS project and enable many NASA applications**

THEORY DETAILS:

Nomenclature

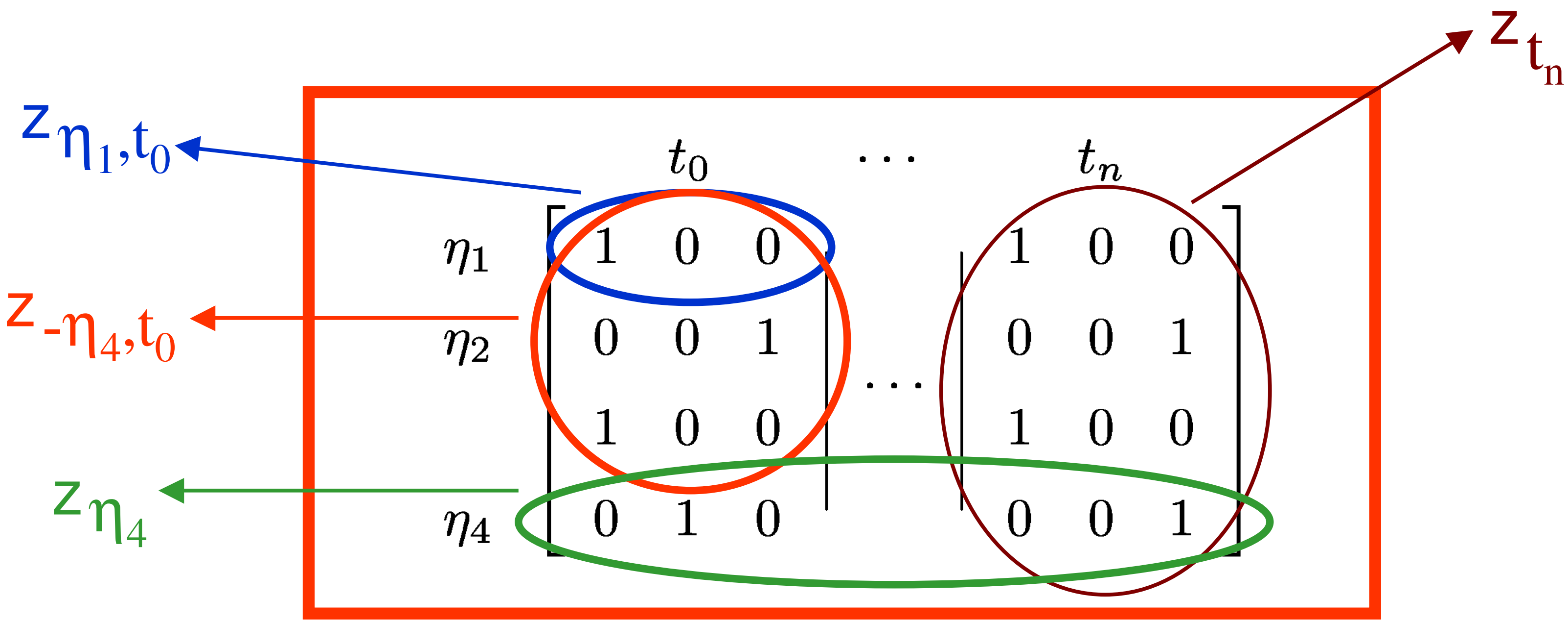
Aristocrat Utility

Clamping

Wonderful Life Utility

Nomenclature

η : an agent
z : state of all agents across all time
$z_{\eta,t}$: state of agent η at time t
$z_{-\eta,t}$: state of all agents other than η at time t



Aristocrat Utility

- One can solve for factored *U* with maximal learnability, i.e., a *U* with good term 2 and 3 in central equation:

$$
\begin{aligned}
AU_{\eta}(z) &\equiv G(z) - E[G(z) \mid z_{-\eta}] \\
&= G(z) - \sum_{i} p_{i}.G(z_{-\eta}, CL_{\eta}^{\vec{s}_i})
\end{aligned}
$$

- Intuitively, AU reflects the difference between the actual *G* and the average *G* (averaged over all actions you could take).
- For simplicity, when evaluating AU here, we make the following approximation:

$$
p_i(z_\eta) = \frac{1}{\text{Number of possible actions for } \eta}
$$

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Clamping

- **Clamping** parameter $CL_{\eta}^{\vec{v}}$: replace η's state (taken to be unary vector) with constant vector $\vec{\mathbf{v}}$
- Clamping creates a new "virtual" worldline
- In general $\vec{\mathbf{v}}$ need not be a "legal" state for η
- Example: four agents, three actions. Agent η_2 clamps to "average action" vector $\vec{\mathbf{a}}$ = (.33 .33 .33):

$$
\begin{array}{c}
 \\ \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4
\end{array}
\begin{array}{c}
z \\
\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}
\end{array}
\;\underset{\text{Clamp } \eta_2}{\Longrightarrow}\;
\begin{array}{c}
(z_{-\eta}, \vec{a}) \\
\begin{bmatrix} 1 & 0 & 0 \\ [illegible] & [illegible] & [illegible] \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}
\end{array}
$$

Wonderful Life Utility

- The Wonderful Life Utility (WLU) for η is given by:

$$WLU_{\eta}(z) \equiv G(z) - G(z_{-\eta}, CL_{\eta}^{\vec{v}})$$

  - Clamping to "null" action ($\vec{v} = \vec{0}$) removes player from system (hence the name).
  - Clamping to "average" action disturbs overall system minimally (can be viewed as approximation to AU).
  - Theorem: WLU is factored regardless of $\vec{v}$
  - Intuitively, WLU measures the impact of agent η on the world
    - Difference between world as it is, and world without η
    - Difference between world as it is, and world where η takes average action
  - WLU is "virtual" operation. System is **not** re-evolved.

DETAILS FOR THE ROVER PROBLEM:

Formulation

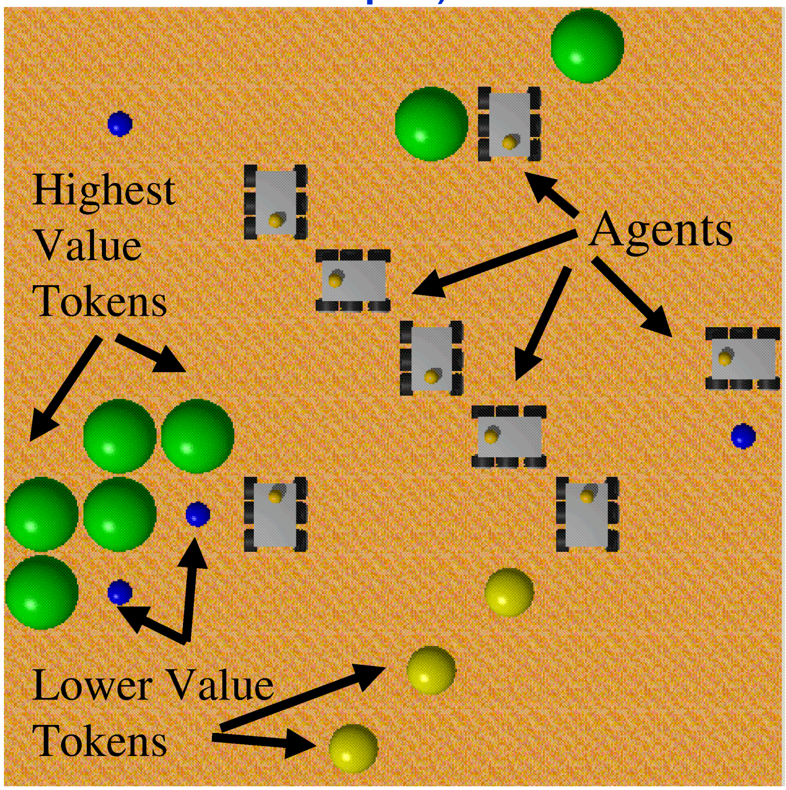
World Utility

Payoff Utilities

Results

Collectives of Rovers

- Design a collective of autonomous agents to gather scientific information (e.g., rovers on Mars, submersibles under Europa)



  - Some areas have more valuable information than others
  - World Utility: Total importance weighted information collected
  - Both the individual rovers and the collective need to be flexible so they can adapt to new circumstances
  - Collective-based payoff utilities result in better performance than more "natural" approaches

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Rover Problem: World Utility

- Token value function:

$$V(L,\Theta) = \sum_{x,y} \Theta_{x,y} \min(1, L_{x,y})$$

  - L : Location Matrix for all agents
  - L_η : Location Matrix agent η
  - $L_{\eta,t}^a$: Location Matrix of agent η at time t, had it taken action a at t-1
  - Θ: Initial token configuration

- World Utility :

$$G(z) = V(L,\Theta)$$

- Note: Agents' payoff utilities reduce to figuring out what "*L*" to use.

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Rover Problem: Payoff Utilities

- Selfish Utility :

$$SU_\eta(z) = V(L_\eta, \Theta)$$

- Team Game Utility :

$$TG_\eta(z) = V(L, \Theta)$$

- Collectives-Based Utility (theoretical):

$$AU_\eta(z) = G(z) - \sum_{\vec{a} \in A_\eta} p_{\vec{a}} V(L_{\hat{\eta}} + L_\eta^{\vec{a}}, \Theta)$$

- Collectives-Based Utility

$$WLU_\eta^{\vec{a}}(z) = G(z) - V(L_{\hat{\eta}} + \sum_{\vec{a} \in A_\eta} p_{\vec{a}} L_\eta^{\vec{a}}, \Theta)$$

$$WLU_\eta^{\vec{0}}(z) = G(z) - V(L_{\hat{\eta}}, \Theta)$$

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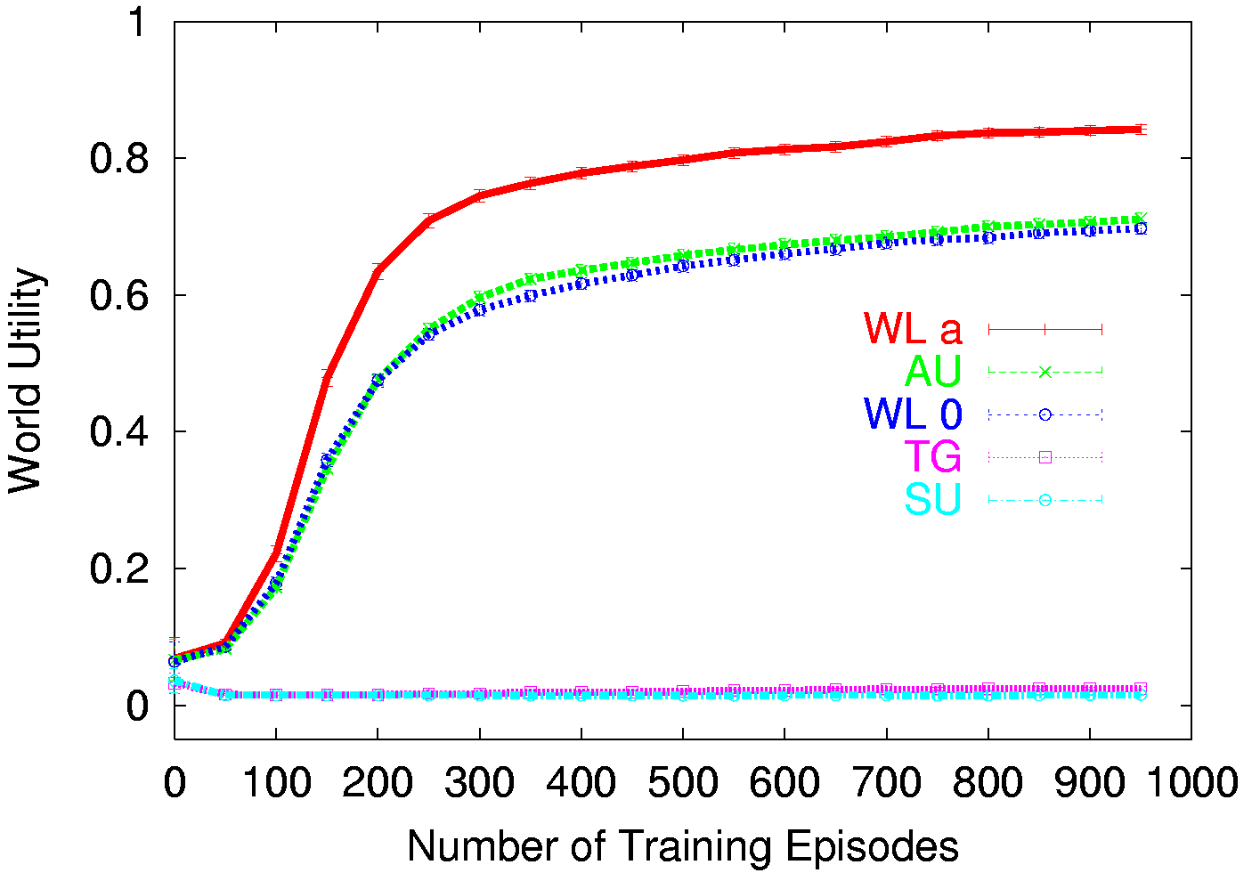
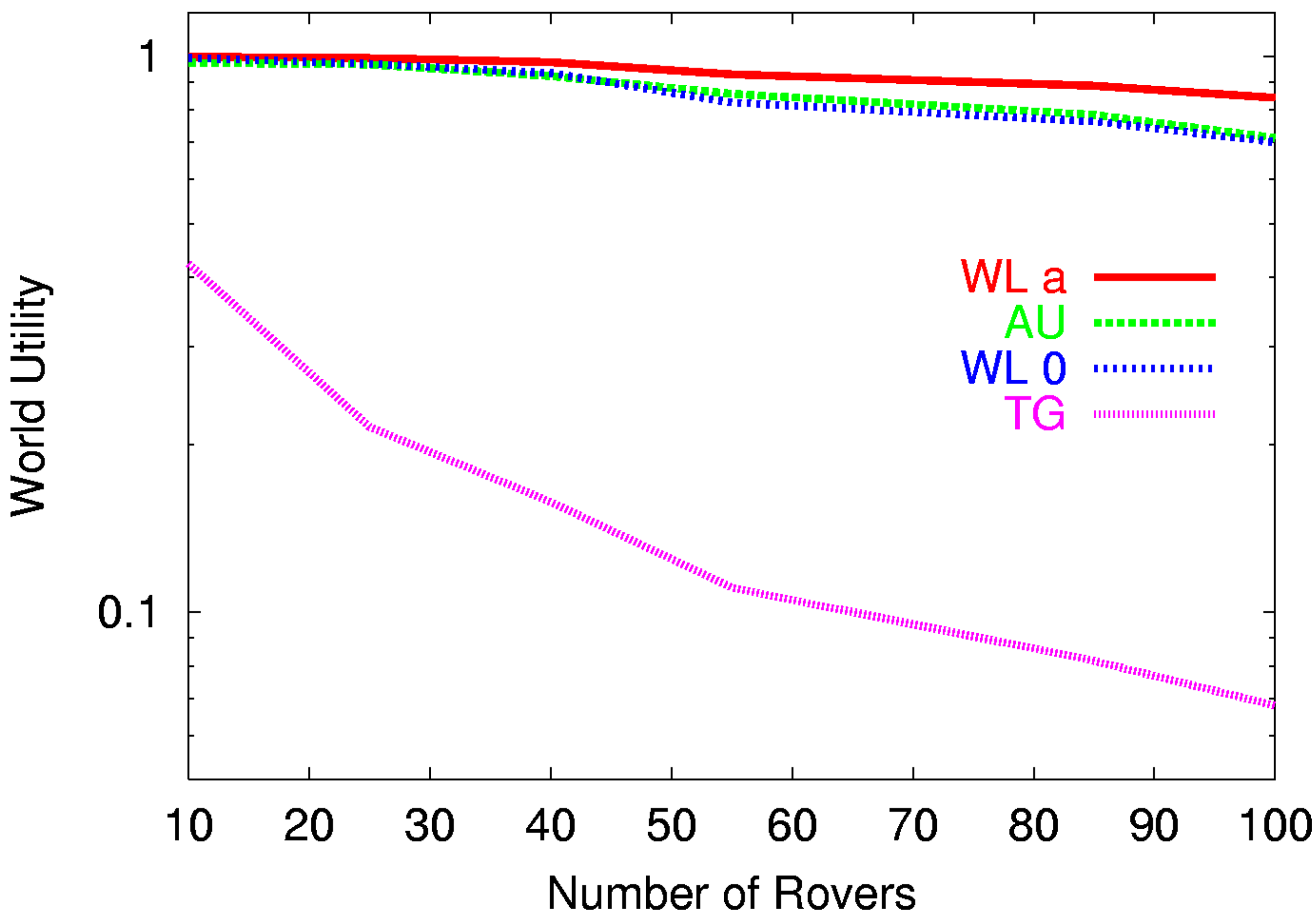
Rover Problem: Utility Comparison



100 rovers on a 32x32 grid

Rover Problem: Scaling Properties



DETAILS FOR THE AUTONOU□MOUS DEFECTS PROBLEM

Formulation

World Utility

Results

Autonomous Defects Problem

- Given a collection of faulty devices, how to choose the subset of those devices that, when combined with each other, gives optimal performance (Johnson & Challet).

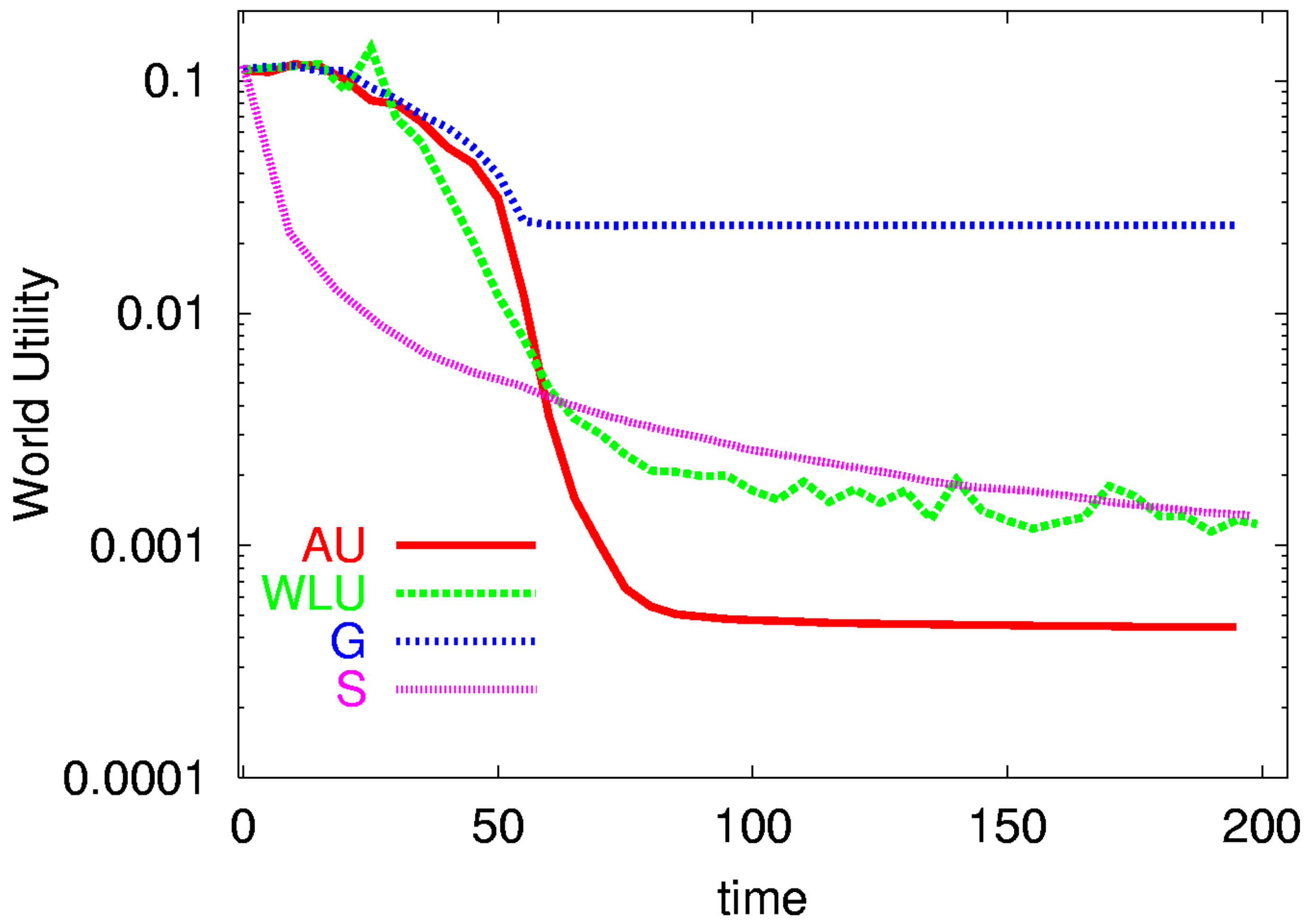
$$G(z) = \frac{\sum_{j=1}^{N} n_j a_j}{\sum_{k=1}^{N} n_k}$$

a_j : distortion of component j

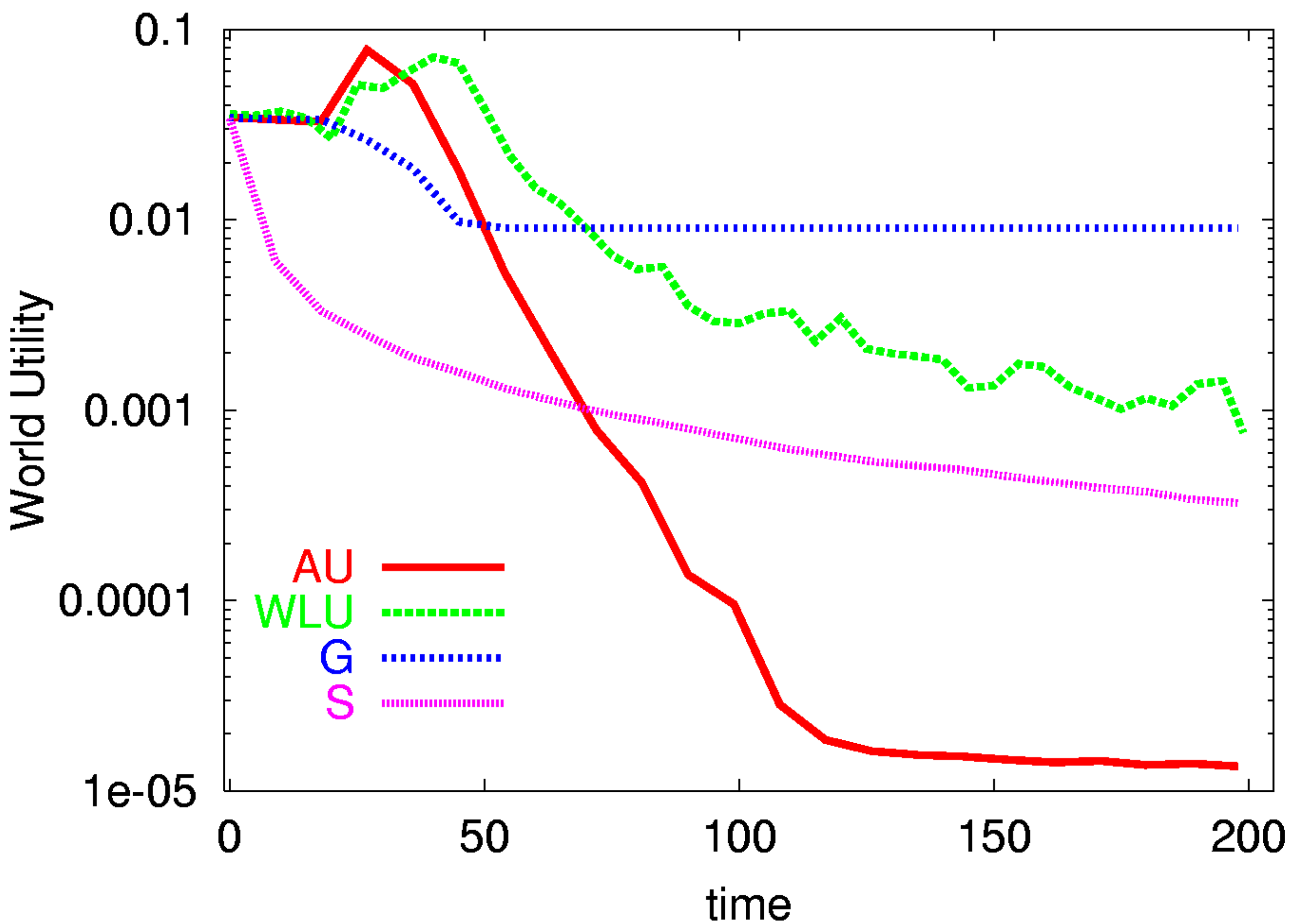
n_k: action of agent k ($n_k = 0 ; 1$)

- Collective approach: Identify each agent with a component.
- Question: what utility should each agent try to maximize?

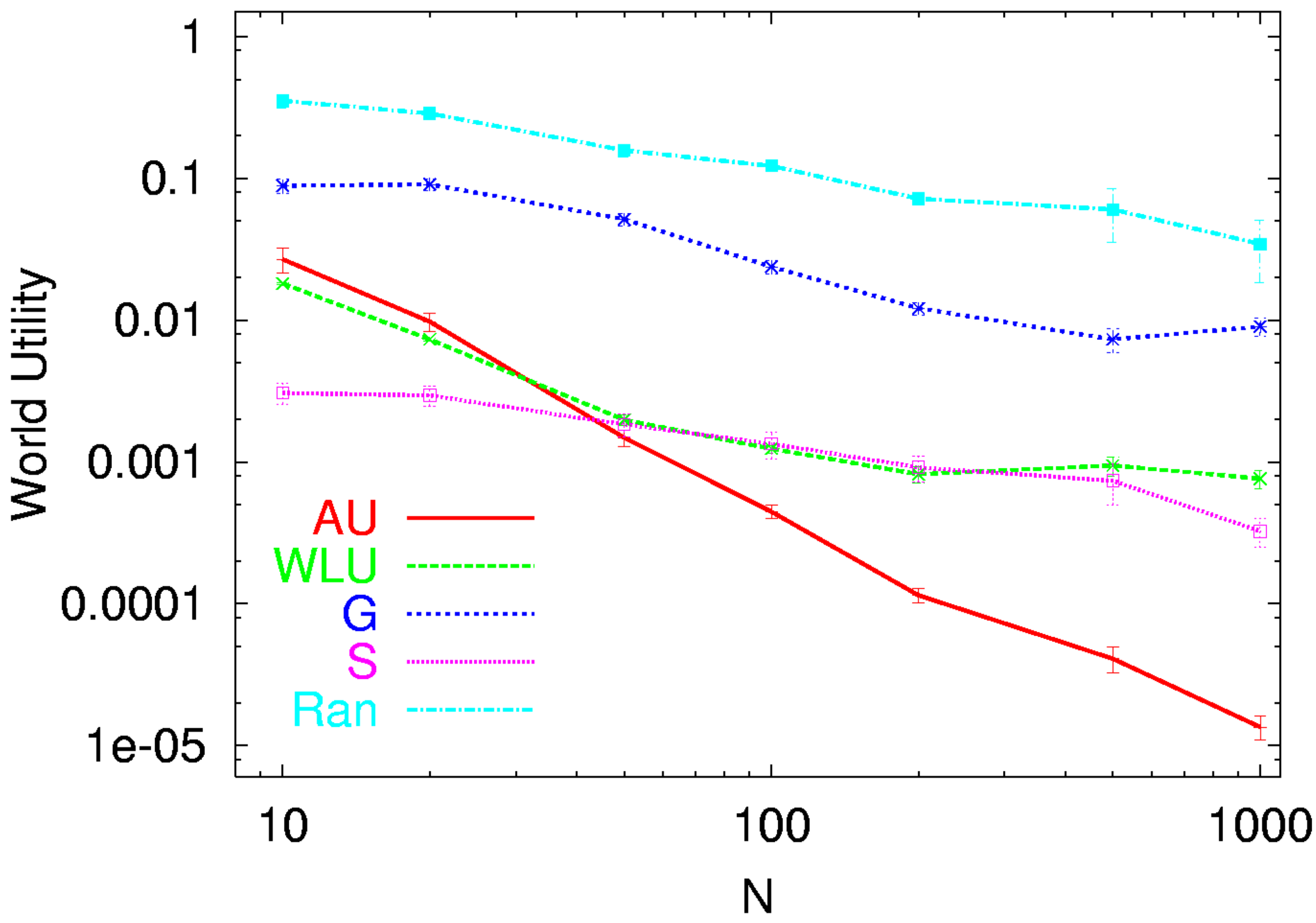
Autonomous Defects Problem (N=100)



Autonomous Defects Problem (N=1000)



Autonomous Defects Problem: Scaling



Constellation of Satellites

- Problem:
  - A set of satellites receives data faster than they can download (eg., in orbit around Earth, or for that matter Mars)
  - Cannot be centrally controlled (size, and communication delays)

- Approach:
  - Adaptively route data to minimize importance weighted data loss
  - Investigated “fooling” a baseline algorithm by introducing “ghost” traffic
  - Agents set ghost traffic using theory of collectives