Systems Resilience and I
(Inoue Lab 10th Anniversary Symposium)

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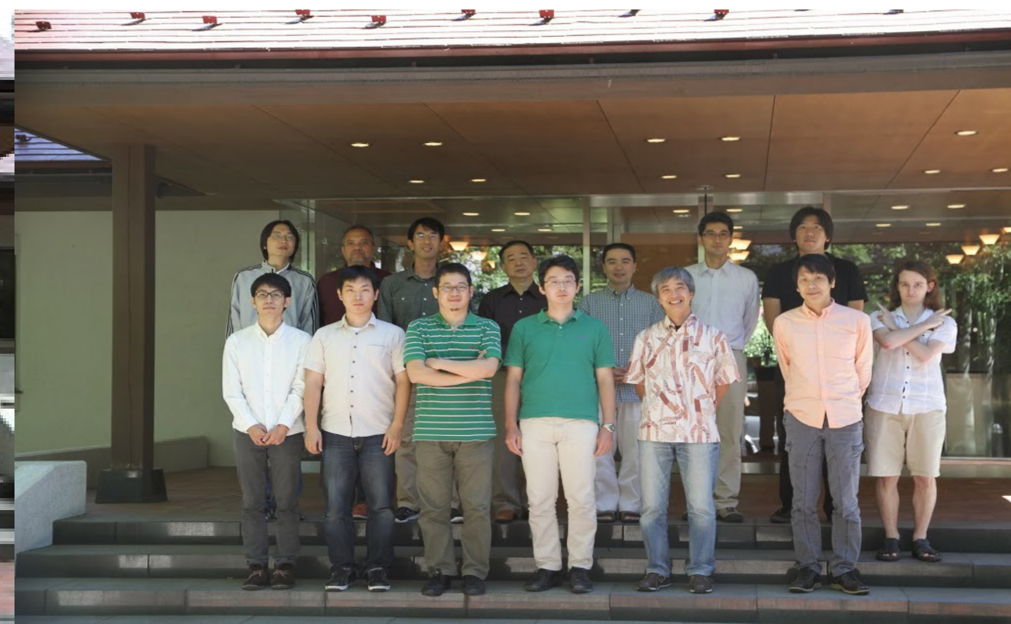
Systems Resilience

- Project of the Transdisciplinary Research Integration Center since 2012
  - Institute of Statistical Mathematics (ISM)
  - National Institute of Informatics (NII)
  - National Institute of Genetics (NIG)
  - Plus researchers from other institutes



Systems Resilience

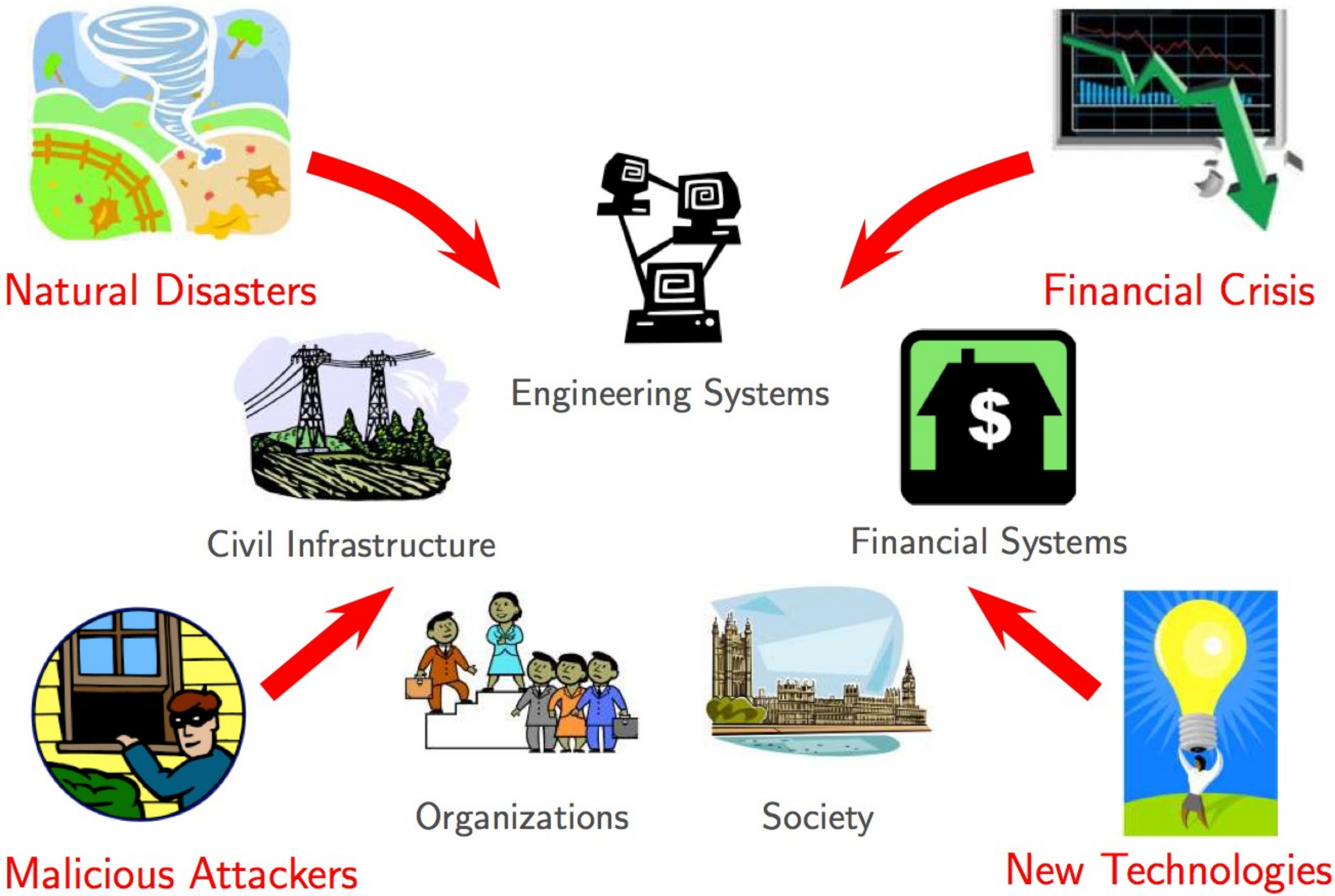
Subprojects

- Resilience General Strategies (Maruyama et al, ISM)
- Resilience in Biological Systems (Akashi et al, NIG)
- Resilience in Social Systems (Okada & Ikegai, NII)
- **Computational Theory of Resilience** (Inoue et al, NII)

Resilience

- "Resilience": Maintain a dynamic system's core purpose and integrity in the face of dramatically changed circumstances (e.g., the 3.11 earthquake in Japan, economic crisis, a new strain of virus)
- Many researchers of different fields have recognized the importance of resilience of complex agent systems

Systems Resilience



Aspects of Resilience

- Types of shock: Natural/Intentional, Frequent/Rare, Predictable/Unpredictable, Acute/Chronicle, External/Internal, etc.
- Target system domain: Biological, Engineering, Financial, Legal, Infrastructure, Organization, Community, Society, etc.
- Phase of resiliency: Design time, Early warning, Emergency response, Recovery etc.
- Types of resiliency: Structural, Functional, Adaptive, etc.

Computational Theory of Resilience

1. What are general **computational principles of resilient (or nonresilient) systems**?
2. How resilience is **measure**d, **maintaine**d or **improve**d?
3. How can we **compute new acceptable states** in the face of new or unexpected events?
4. How can we **design resilient systems**?

Research Topics

1. SR-model: Modeling Resilience of Dynamic Constraint-based Systems
2. Modeling and Solving Cyber-Security Tradeoff Problems using Constraint Optimization
3. Sensitivity Analysis of Dynamic Systems

Motivation and Goals

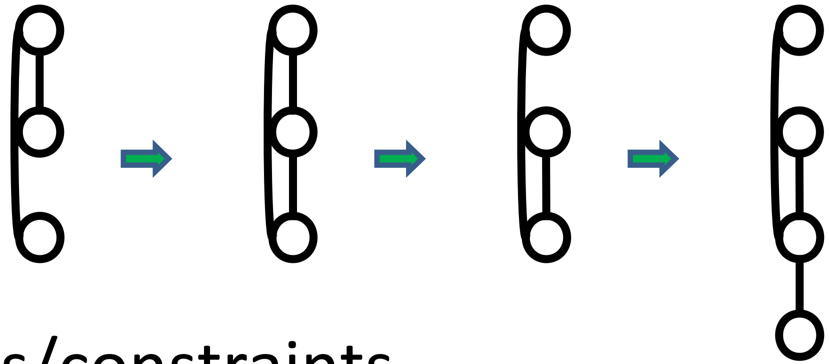
- There are almost as many definitions of resilience as publications on resilience
- Here, we provide general principles underlying the resilience of constraint-based dynamic systems:
  - General formalization of a dynamic system
  - Set of properties characterizing the resilience

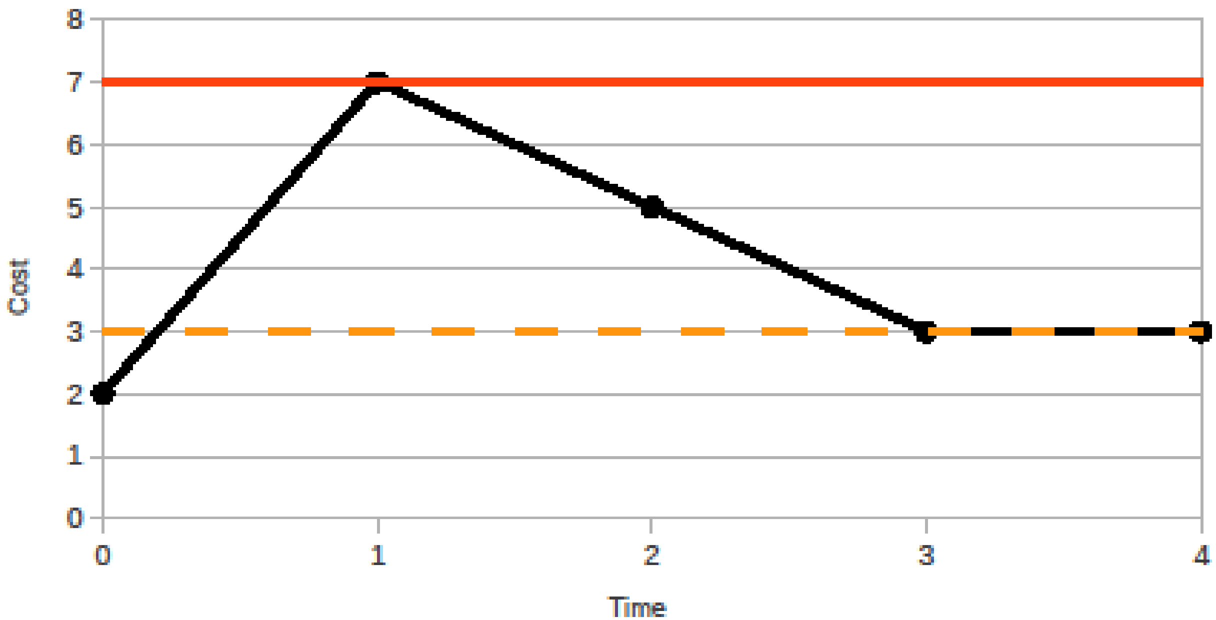
Related Publications:

1. Nicolas Schwind, Tenda Okimoto, Katsumi Inoue, Hei Chan, Tony Ribeiro, Kazuhiro Minami, Hiroshi Maruyama: **Systems Resilience : a Challenge Problem for Dynamic Constraint-Based Agent Systems**. In: *Proceedings of the 12th International Conference on Autonomous Agents and Multiagent Systems* (AAMAS 2013; Saint Paul, Minnesota, USA, May 2013), pp.785-788. Received The 3rd Prize of Best Challenges and Visions Papers.

SR-Model (Schwind *et al.*, AAMAS 2013)

1. Dynamical systems
2. Multi-agent systems
3. Constraint-based systems
4. Flexible, can add/delete agents/constraints





Resistance

+

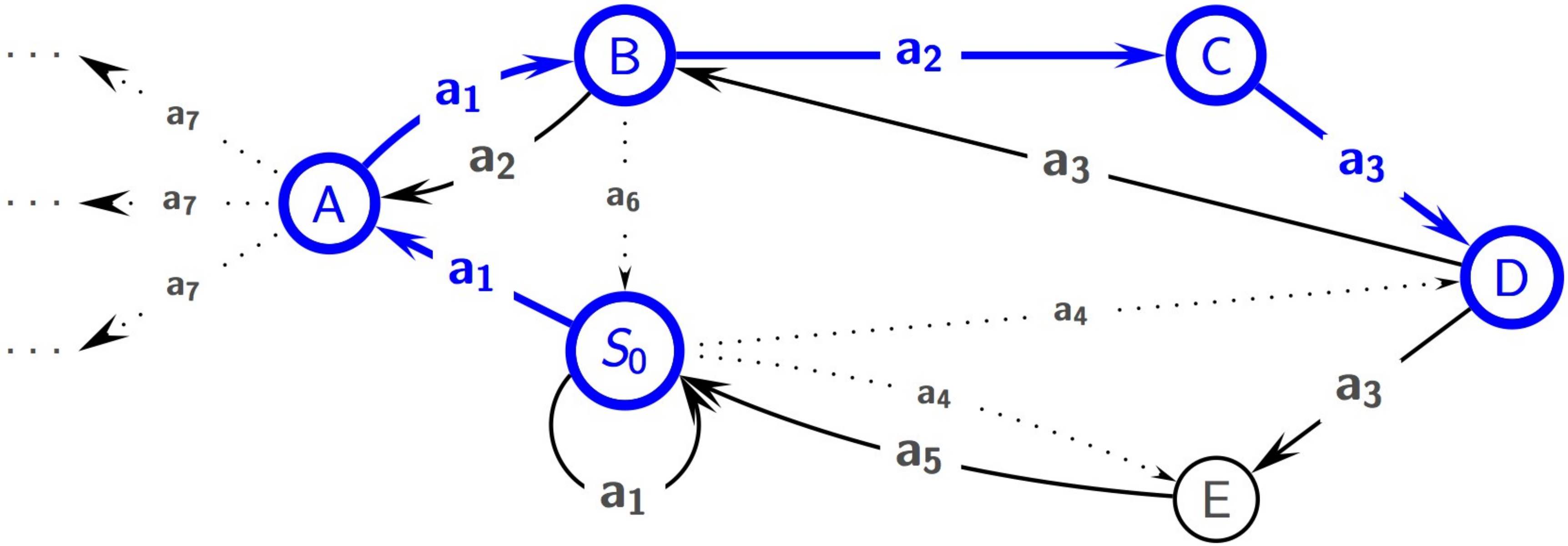
Recoverability

=

Resilience

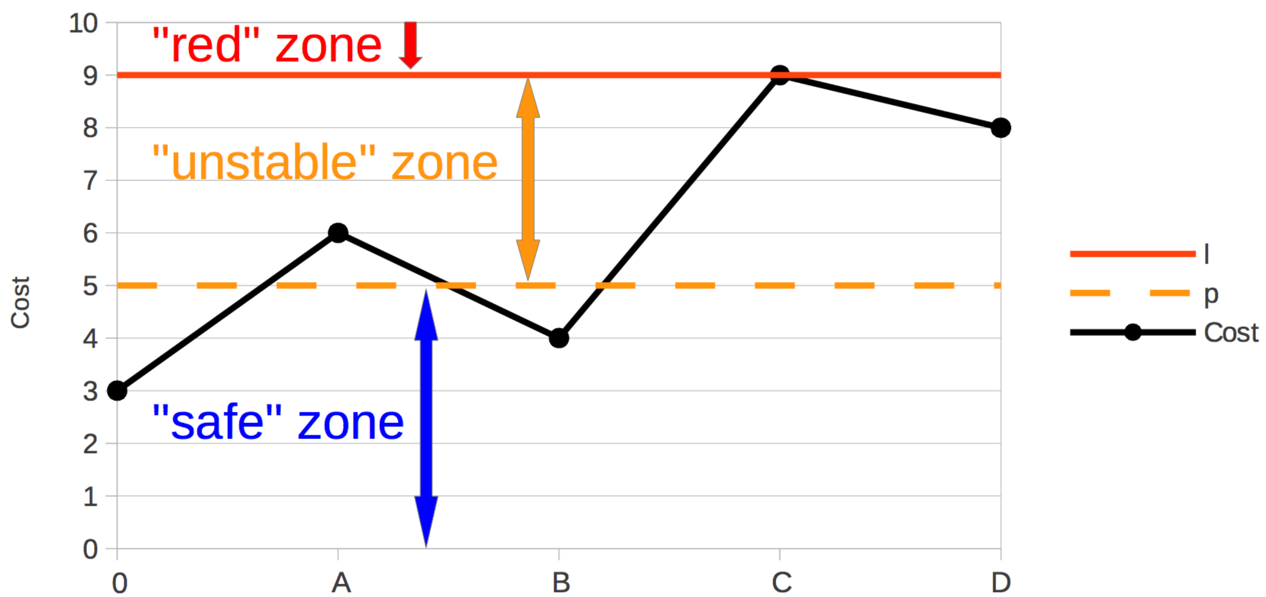
Shape of a Dynamic System

- At each time step, a decision is made
- Depending on the environment (uncontrolled event), the specifications of the system may change without any restriction



Resistance + Recoverability

- At each time step, the state of the system is associated with a cost
- ➢ <u>Resistance</u>: The ability to maintain some underlying costs under a certain "threshold", such that the system satisfies certain hard constraints and does not suffer from irreversible damages
- ➢ <u>Recoverability</u>: The ability to recover to a baseline of acceptable quality as quickly and inexpensively as possible.



Functionality + Stabilizability

- Functionality: the ability to provide a guaranteed average degree of quality for a period of time.
- Stabilizability: the ability to avoid undergoing changes that are associated with high transitional costs.

- A dynamic system is resilient if one can find a “strategy” (i.e., the “right decisions”) and a state trajectory within this strategy that is resistant, recoverable, functional, and stabilizable.

How can we evaluate resilience?

Algorithm

Apply MO-DCOP techniques

Multi-Objective Distributed Constraint Optimization Problem (MO-DCOP)

- MO-DCOP is the extension of mono-objective DCOP which can formalize various applications related to multi agent cooperation.
  - MO-DCOP involves multiple criteria
  - Security
  - Privacy
  - Cost
  - …
- Goal: find all trade-off solutions.

Application

Cyber Security Problem based on Multi-Objective Distributed Constraint Optimization Technique

Tenda Okimoto*, Naoto Ikegai*, Tony Ribeiro**, Katsumi Inoue*, Hitoshi Okada*, Hiroshi Maruyama***

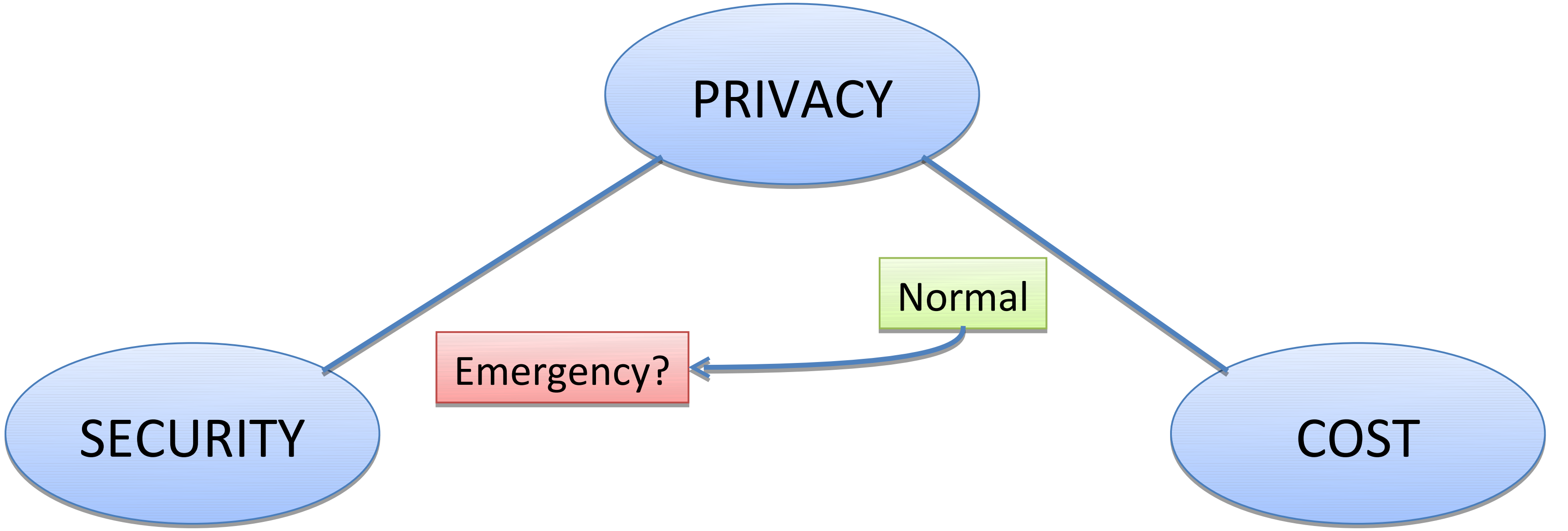
*=National Institute of Informatics
**= The Graduate University for Advanced Studies
***=The Institute of Mathematical Statistics

Cyber Security Trade-off Problem

- Interception and communications data retention measures, even if the purpose is social security, are under the difficult trade-off between SECURITY, PRIVACY and COST.
- How to solve this trade-off and build the societal consensus?

Difficulties of cyber security trade off

- Societal consensus can be moved dramatically in case of an emergency (Consider the 911 and 311 earthquake)= <u>How to obtain it quickly?</u>
- The most socially beneficial (pareto optimal) measure may needs some cooperation among actors = <u>How to calculate it?</u>



Difficulties

"You can't have 100% security and also then have 100% privacy and zero inconvenience. We're going to have to make some choices as a society."

- U.S. President Obama on NSA surveillance controversy

Example

- Consider 15 companies cooperate with each other and solve a cyber security problem.
  - There exists an agent who acts as a secretary for each company.
  - They want to optimize the security, privacy and cost.
  - It is hard to maintain the information of all agents.
- We can apply MO-DCOP technique.

Complete Algorithm

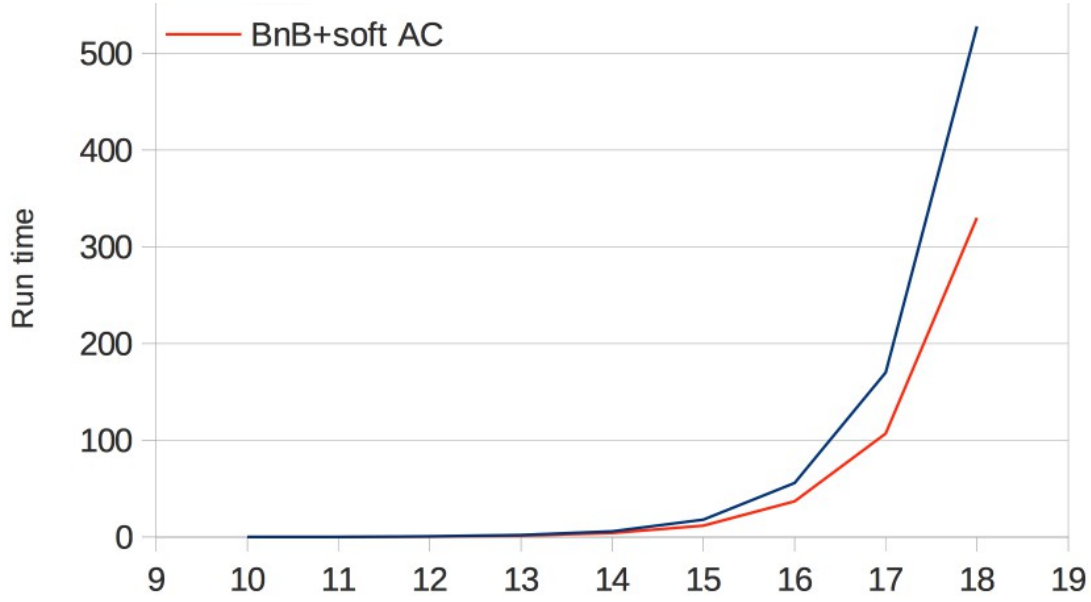
- Our algorithm can guarantee to find all trade-off solutions
- This algorithm utilizes
  - a widely used preprocessing technique (soft arc consistency)
  - a Branch-and Bound technique.

Evaluations

- We evaluate the runtime of our algorithm varying the number of agents/companies.
- Setting
  - Number of objectives: 3
  - Domain size: 3
  - Random number for each criteria: [0, 100]
- We show the average of 100 problem instances

Results

- Our algorithm (red) outperforms the standard Branch-and-Bound algorithm (blue).
- For the problem with 18 companies, our algorithm can find all trade-off solutions in less than 330s.



Sensitivity Analysis of Dynamic Models

- **Sensitivity Analysis:** Study how outputs of model change given perturbations (e.g., environmental changes, unexpected events, estimation errors) in inputs of model
- **Dynamic Models:** Represent systems that evolve over time due to actions and/or external events

- **Relevance to System Resilience:**
  - Check whether conclusions drawn from model are robust against perturbations
  - Determine whether changes in system design improve system robustness
  - Make tradeoffs in robustness and functionality

– **Publications:** Hei Chan and Katsumi Inoue. Applying Robustness Analysis of Dynamic Models to the Problem of Systems Resilience (5th Symposium on Resilience Engineering, Soesterberg, Netherlands, 2013)

Why sensitivity analysis?

- For model builders (build and debug models)
  - What are the “weak” points of model that may contribute to large variations in output?
  - What components we can change to improve model robustness?
- For decision makers (understand and evaluate models)
  - Why are certain decisions made based on model?
  - How confident are we in the decisions against uncertainty?

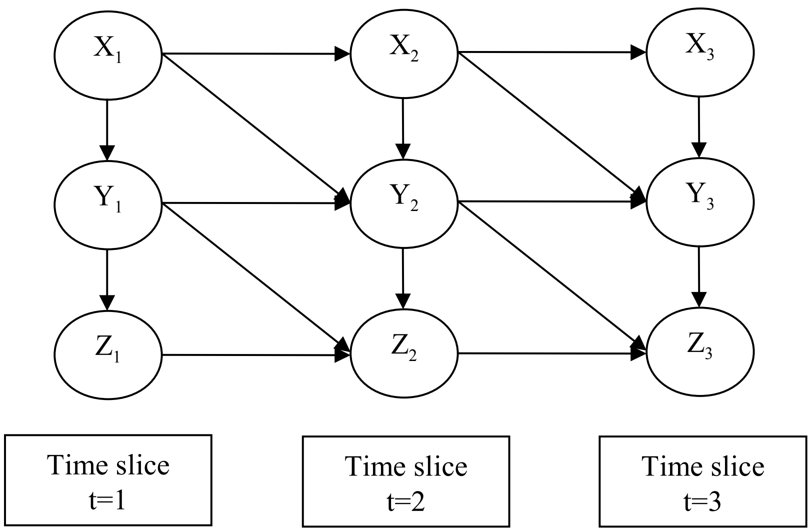
Methods of sensitivity analysis

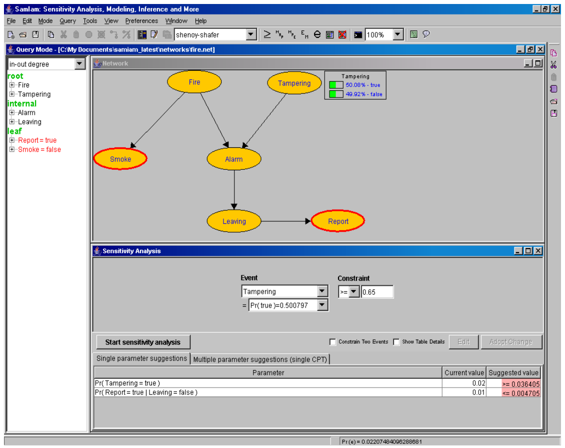
- Theoretical methods
  - Derivatives of outputs w.r.t. parameters at fixed point
  - Bounds of output changes w.r.t. input changes
  - Robustness intervals or neighborhood regions where decisions remain the same
- Empirical methods
  - Perturbing of model by “small” amount to compute changes in outputs
  - Sampling of variations in a subset of parameters

Example: Bayesian networks

- Bayesian networks can be used to model uncertain and dynamic systems
- For sensitivity analysis, compute derivatives of probabilities of interest w.r.t. parameters
- Find solutions where parameter changes can enforce constraints on queries posed to model
- Experts can make guarantees of systems resilience in the face of unexpected events, or whether changes in system design will affect current conclusions

Dynamic Bayesian network





Sample software for sentivitity analysis

Future Research

- Analyze computational complexity of problems related to SR-model, e.g., checking whether a system satisfies properties of resilience (resistance, recoverability, etc.)
- Incorporate uncertainty into SR-model using techniques such as dynamic Bayesian networks or probabilistic planning

Future Research

- To apply our MO-DCOP algorithm on real cyber security problem
- In previous work, we used the assumptive variables for calculating trade-offs. But we can also collect and analyze the real customer acceptance data by means of social investigation and online questionnaires.
- Especially, the algorithm must be a powerful way in case of emergency, which changes customer acceptance for tradeoffs between privacy, security and cost dramatically

Future Research

- Find interesting real-life domains suitable for resilience research, e.g., cybersecurity, power grid, supply chain, ecosystem
- Develop tools and software for better testing and understanding of systems resilience

Congratulations to the 10th anniversary!
Thanks to all people at the Inoue lab!