Computational Models of Systems Resilience

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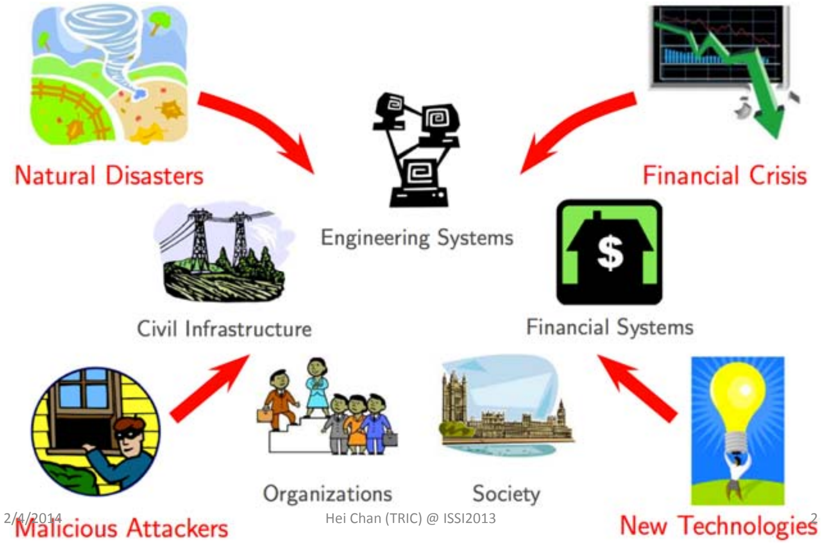
Systems Resilience



Computational Theory of Resilience: Goals

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**?

Computer Science for Resilience

1. **Suitable abstraction of problems**:
   - Mathematical foundations/models – computational principles
   - Symbolic representation (AI) – *dynamic constraint networks*
2. **Logic for systems resilience**:
   - *Semantics*: possible worlds of dynamic systems
   - *Inference*: prediction/abduction – *theory of unpredictability*
   - *Update*: reasoning about change
3. **Computation of resilience**:
   - Exact/approximation (robust) algorithms – *acceptable recovery*
   - Decision/optimization problems – tradeoff between criteria
4. **Design of resilient systems**:
   - Machine leaning – *robust design*
   - Sensitivity analysis
   - Multi-agent systems/simulation

Network Dynamics

- In an increasingly inter-connected world, even small local perturbations in the world may cause complex effects on a global scale.
- Examples: resources, transportation, infrastructures (power, internet, telecommunication), biological/social systems, etc.
- Existence of **positive and negative feedback loops** makes analysis of network dynamics very difficult.
- Modeling **dynamics** of networks in *physics*:
  - **Differential equations**
- Modeling **dynamics** of networks in *informatics*:
  - Discrete: **FSM**, **Boolean networks**, **Constraint networks**
  - Probabilistic: **Baysian/Markov networks**, **Causal networks**

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

1. SR-model: Modeling Resilience of Dynamic Constraint-based Systems

Motivation and Goals

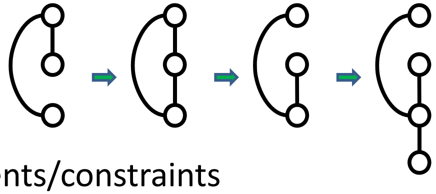
- There are almost as many definitions of resilience as publications on resilience
- Here, we provide general principles underlying the resilience of constraint-based dynamic systems:
  - General formalization of a dynamic system
  - Set of properties characterizing the resilience

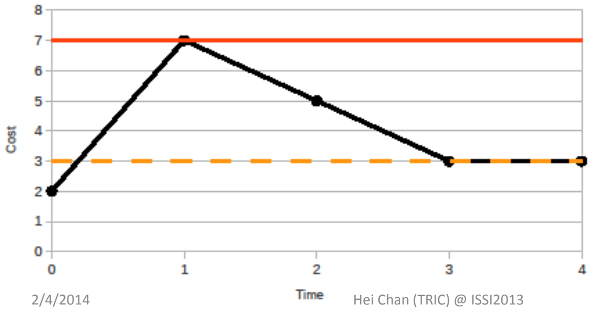
Related Publications:

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

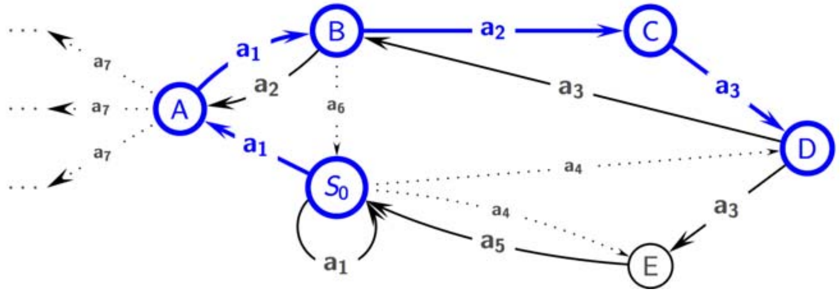




Resistance
+
Recoverability
=
Resilience

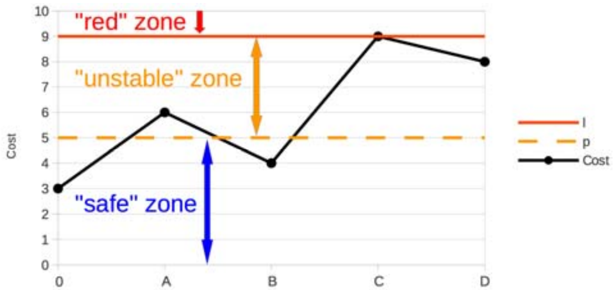
Shape of a Dynamic System

- 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.

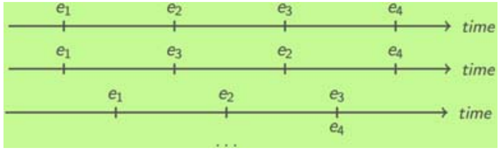


Functionality + Stabilizability

- ➢ <u>Functionality</u>: the ability to provide a guaranteed average degree of quality for a period of time.
- ➢ <u>Stabilizability</u>: 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.

Resilience of Event-Driven Dynamic Systems (1/2)

- Logical event-based scheme coming from the natural language:
  - *"Two earthquakes are expected to occur independently. It is expected that the first earthquake will be followed by a tsunami and that the second earthquake will be be followed by an other tsunami. No other event is expected."*
  - α = (e1 ≼ e3)∧¬(e3 ≼ e1)∧(e2 ≼ e4)∧¬(e4 ≼ e2)



- Insertion of controlled actions between the uncontrollable events:

Resilience of Event-Driven Dynamic Systems (2/2)

- Many structures are embedded into the framework to design logical-based resilient dynamic systems:
  - **Strategy:** *what is the best plan (insertion of controlled actions between exogenous events) so that the system satisfies a certain property P in each possible scenario?*
  - **Representing each state of the system using propositional logic**
  - **Update operators coming from the literature:** *each state is updated by either exogenous events or controlled actions*
  - **Properties analyzed on each scenario:** *formalism rich enough to express properties from [Schwind et al., AAMAS'13] such as resistance, recoverability, stabilizability, and the new property of consistency (reflects the ability to provide and maintain a minimal level of service in the face of faults / disasters.)*
  - **Efficiency of property checking compared to previous logical approaches**

Related Publication:

1. **'Resilience of Event-Driven Dynamic Systems'**. *Nicolas Schwind, Morgan Magnin, Katsumi Inoue*, in the 27th Annual Conference of the Japanese Society for Artificial Intelligence (JSAI'13), International Organized Session on Modern Approaches for Intelligence Design – From Mining to Inference. Toyama, Japan, June 2013.

2. Modeling and Solving Cyber-Security Tradeoff Problems using Constraint Optimization

Enemies of resilience in the *information* society

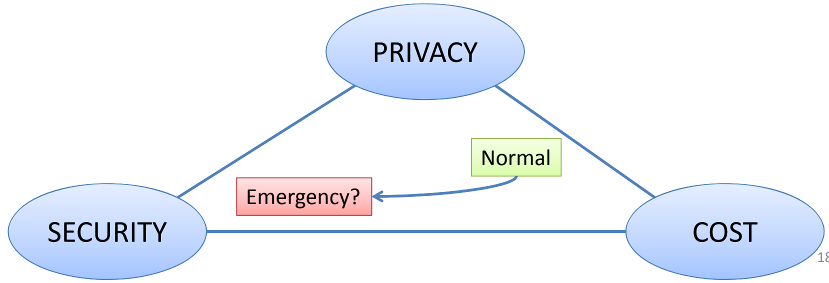
- Malwares and computer viruses
- Intensive cyber attacks
- International cyber war
- Online criminal activities (including terrorist's communication)
- Large scale system down of networked critical infrastructures (e-government, electric power, hospital systems)

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 <u>SECURITY</u>, <u>PRIVACY</u> and <u>COST</u>.
- 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>

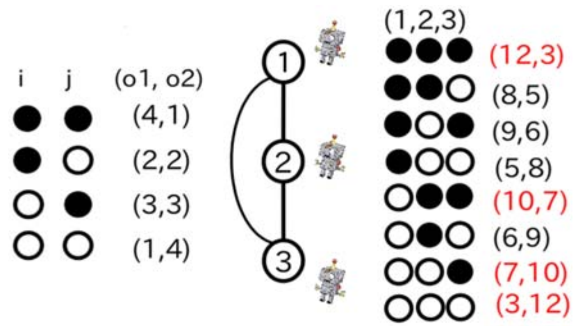


Example

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

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

- Many real world problems involve multiple criteria that should be considered separately and optimized simultaneously.



<u>Relevance to Resilience</u>
- Model and compute a resilient system
- Handle multiple criteria (pareto solutions)

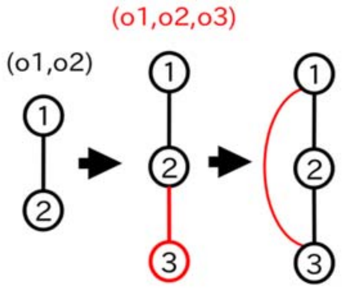
Multi-Objective DCOP

Results

- Developed complete and incomplete algorithms for solving a MO-DCOP.
- Defined SR-model using DCOP as a component of a dynamic system.

Ongoing:

- Extend to a dynamic environment.



Publications

- Tenda Okimoto, Yuko Sakurai, Makoto Yokoo, and Katsumi Inoue: "Complete/Incomplete Algorithms for MO-DCOPs", *Joint Agent Workshop and Symposium* (JAWS 2012) (Shizuoka, Japan), received the best paper award.
- Tenda Okimoto, Naoto Ikegai, Tony Ribeiro, Katsumi Inoue, Hitoshi Okada, Hiroshi Maruyama. Cyber Security Problem Based on Multi-Objective Distributed Constraint Optimization Technique. *Proceedings of the 1st Workshop on Systems Resilience* (WSR 2013; Budapest, Hungary, June 24th, 2013).

3. Sensitivity Analysis of Dynamic Systems

Sensitivity Analysis of Dynamic Models

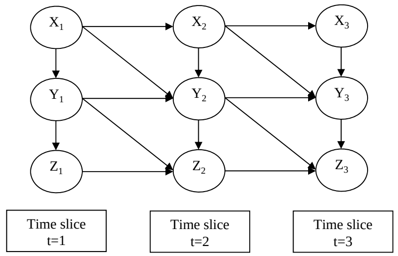
- **Sensitivity Analysis:** Study how outputs of model change given perturbations (e.g., environmental changes, unexpected events, estimation errors) in inputs of model
- **Dynamic Models:** Represent systems that evolve over time due to actions and/or external events

- **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 (5^{th} Symposium on Resilience Engineering, Soesterberg, Netherlands, 2013)

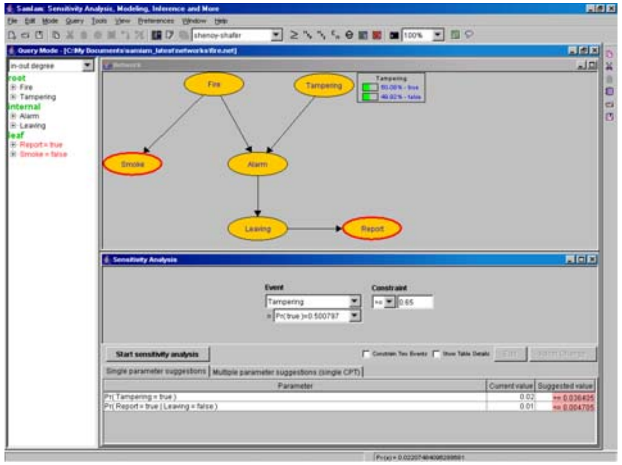
Example 1: Bayesian networks

- 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 query constraints
- 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



Sensitivity analysis of Bayesian networks



Example 2: Cellular Automata

Cellular automata are ubiquitous:

- Artificial intelligence
- Complexity science
- Theoretical biology
- Statistical mechanics

e.g. Cymbiola innexa

They are simple models that produce complex behavior.

Cellular automata (rule 90)

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Cellular Automata

- Classical cellular automata are closed and synchronous, which is inadequate for real world
- Extensions of classical cellular automata:
  - **Asynchronous updating:** Every cell has a chance of keeping its state instead of having its state determined by the rule
  - **Stochastic perturbations:** Every cell determined to live has some probability of dying instead

Cellular Automata

Classical cellular automata

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Asynchronous updating + Stochastic perturbations

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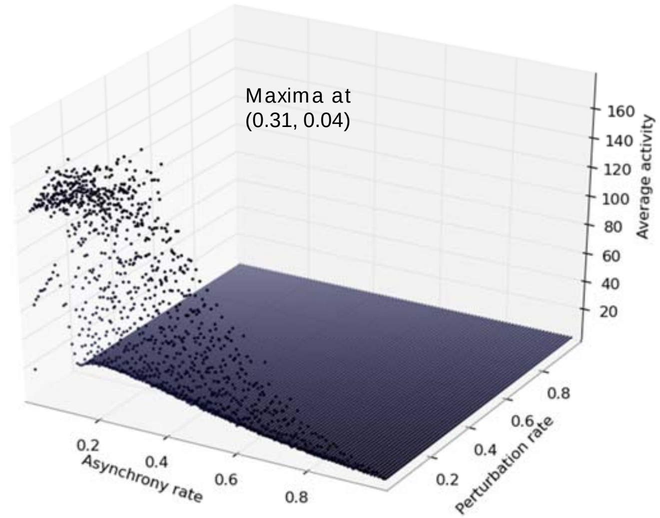
Cellular Automata



Future Research

- Find interesting real-life domains suitable for resilience research
  - E.g., cyber security, power grid, supply chain, ecosystem
- Identify suitable dynamic models for complex systems, with extension to asynchronous & probabilistic transitions and continuous domains
- Analyze computational complexity of several problems related to systems resilience
- Develop tools and software for better testing and understanding of systems resilience

Thank you!