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Modeling and Analyzing Dynamically Adaptive Software

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High Assurance Computing Systems…

Designed to tolerate failures,
even direct attack,
in order to continue operation and
preserve system integrity

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Two Ongoing Revolutions

- Pervasive (or ubiquitous) computing
  - Dissolves boundaries for how when and where humans and computers interact
- Autonomic computing
  - Focuses on developing systems that can manage and protect themselves with only high-level human guidance

Pervasive Computing

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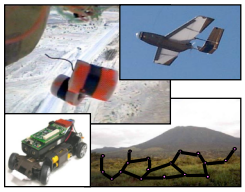
- Driving Factors
  - Convergence of advanced electronic technologies (wireless, handheld, sensors, etc) and the Internet.
  - Promises anywhere, anytime access to data and computing.
- Need for assurance
  - Heterogeneity of hardware, network, software.
  - Dynamics of the environmental conditions, especially at the wireless edge of the Internet
  - Limited resources (such as battery lifetime).

Handheld/Wearable Computing

Military Applications

Sensor Networks



Autonomic Computing

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- Promises self-managed and long-running systems that require only limited human guidance.
- Key driving force: Needed to manage and protect critical infrastructure: financial networks, transportation systems, and water and power systems.
- Systems must continue to ***operate correctly*** during exceptional situations, upgrades, and evolution
- Need for assurance
  - hardware component failures
  - network outages
  - software faults
  - security attacks
- Prediction: Autonomic will be essential to every future computing system.

Physical Cyberinfrastructure

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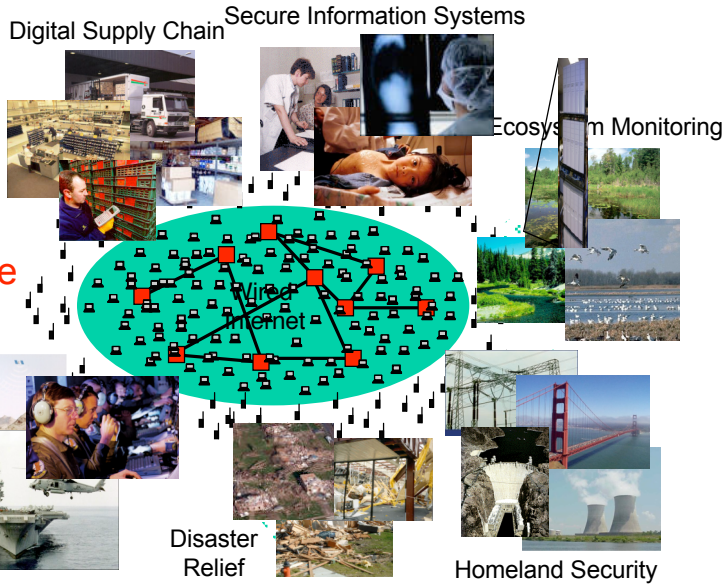
Remote
Safety-critical
Real-time
All the above
Privacy
Adaptable



The Software Crisis

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- Our increasing reliance on computing technology often fails to recognize that software is:
  - Brittle
  - Insecure
  - Continuously evolving
- Occasional wake-up calls…
  - Telephone service failure in 1990
  - Cell phone service on 9/11
  - Power outage of 2003
  - Breaches of credit card company databases…
  - Etc.

The Evolving Cyberinfrastructure

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- First Generation (proof-of-concept)
  - Driven by applications in science and engineering
  - Advanced sensor hardware
  - Efficient systems software, network protocol
  - Understanding issues, brittle prototypes
- Second Generation (sustainable infrastructure)
  - Driven by applications in science and engineering
  - Advanced sensor hardware
  - Efficient systems software, network protocols
  - High-assurance (generated) adaptable software
  - Intelligent systems that can ***learn*** how to respond and adapt
  - Designing and building robust, self-healing (autonomic) systems for deployment

Related Work

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- Where adaptations are applied
  - Programming languages [Adve01,Kasten02,Redmond02]
  - Adaptive frameworks [Fickas97,Sousa00]
  - Adaptive middleware [Blair98,Kon00]
  - Extensible operating systems [Bershad94, Appavoo03]
- Aspects in adaptation
  - Adaptation enabling techniques
  - Condition-monitoring techniques
  - Decision-making techniques
  - **Assurance techniques**

Related Work

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- Behavioral modeling approaches (process algebra)
  - CSP in Dynamic Wright [Allen08]
  - π-calculus in LEDA [Canal99]
  - FSP in Darwin [Kramer98]
- Architectures for dynamic systems
  - Darwin [Kramer98]
  - C2 Style [Taylor95]
  - Dynamic Wright [Allen98]
  - LEDA [Canal99]

Related Work

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- Safe adaptation protocols
  - Hot swapping in K42 [Appavoo03]
  - Graceful adaptation process in Cactus [Chen01]
  - Distributed safe adaptation [Kulkarni03]
  - Safe adaptation protocol [WADS04,ADS05]
- None of the above provides a software (or model-driven) development process that crosscuts requirements, design, and implementation to provide assurance in adaptive software

Model-Based Development of Adaptive Software

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- Objective: A software development process that provides assurance to dynamically adaptive software
- Approach: Focus on the design and analysis of formal design models and their relationships to requirements and implementations.

Outline

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- Requirements analysis
- Design models (focus)
- Implementation
- Discussion and conclusions

What Is Dynamic Adaptation

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- Program that changes its behavior at runtime
  - A set of programs P_1, P_2, …, P_N (FSA)
  - Changing from running in source program P_i to target program P_j
  - May involve intermediate states and transitions

Audio-Streaming Case Study

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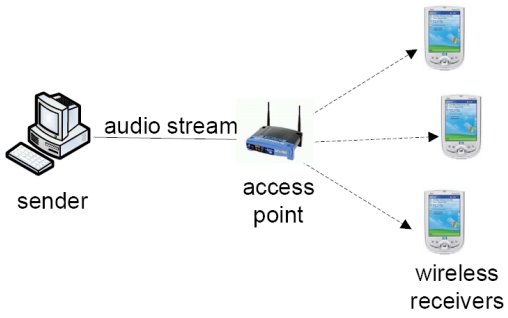

Packet loss-rate in the wireless communication is dynamic
- •High loss-rate
- •Low loss-rate

Adaptive error correction protocols
- •High loss-tolerant and low performance
- •Low loss-tolerant and high performance

RAPIDware Approach

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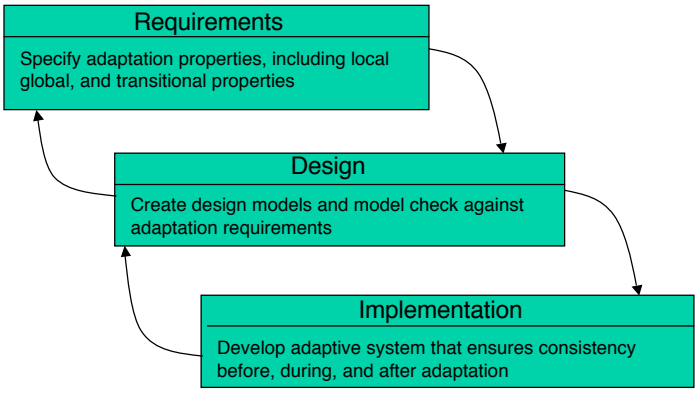
- Gain assurance in adaptive software through
  - A systematic software development process
  - Application of formal methods at every stage



Overall Process

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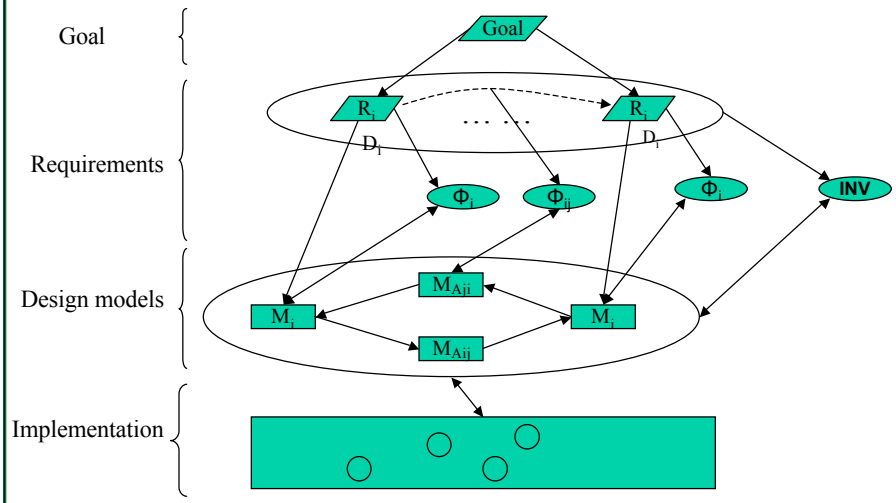

Goal – Requirements

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- Four Level requirements engineering [REFSQ05]
  - Adaptive program is running in a set of domains *D*
  - Each domain D_i is a set of inputs
  - Level 1 RE: Determine D_i and software's reaction to each input in D_i
- Goal-driven models (Mylopolous, van Lamsweerde, et al)
  - Use goal-driven model to analyze possible execution conditions and requirements in each condition

Goal

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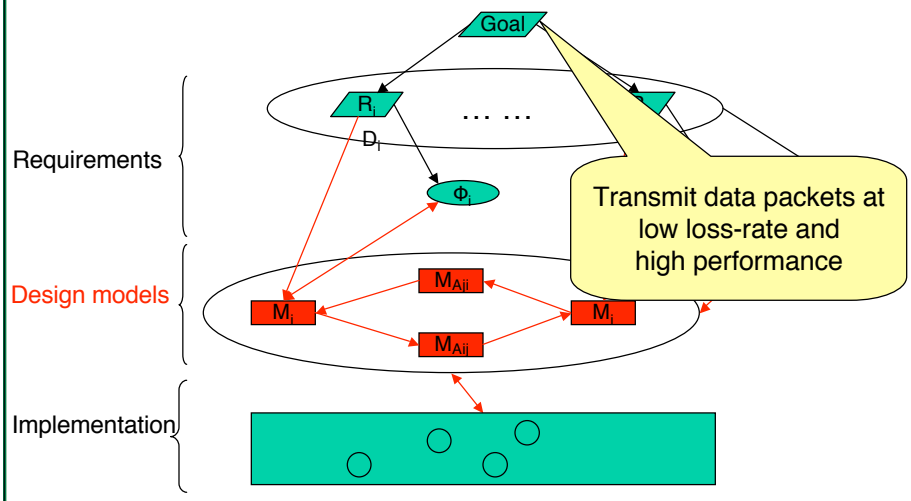

Goal to Domains and Requirements

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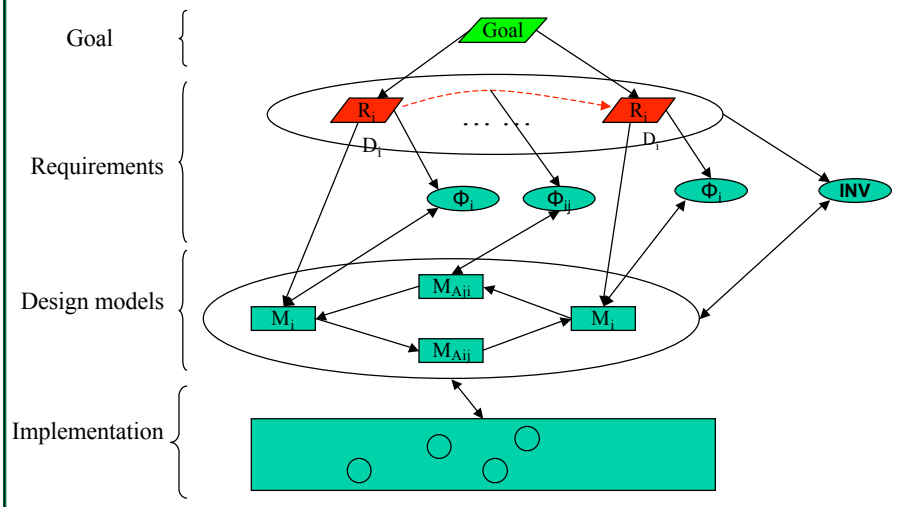

Requirements Stage

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- Use temporal logics to specify adaptation semantics
  - Developed A-LTL to specify adaptation semantics. [WADS05, JSS06]
  - Developed TA-LTL to express real-time constraints in DASs (dynamically adaptive systems). [EASe06]
  - Precise specification
  - Enable automated analysis

Requirements: Temporal Logic

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- We have investigated using temporal logic to specify critical properties in adaptive programs [WADS05,JSS06,EASe06]
  - **Local properties:** Use LTL to specify program properties in each execution domain
  - **Global invariants**: Use LTL to specify properties of the adaptive program
  - **Transitional properties:** Use A-LTL to specify adaptations from one domain to another

Goal to Requirements

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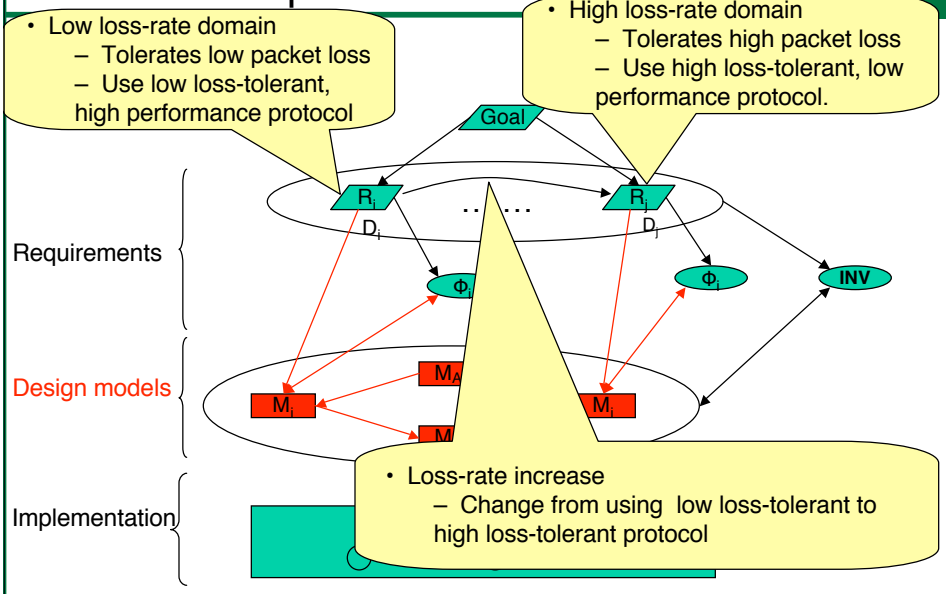

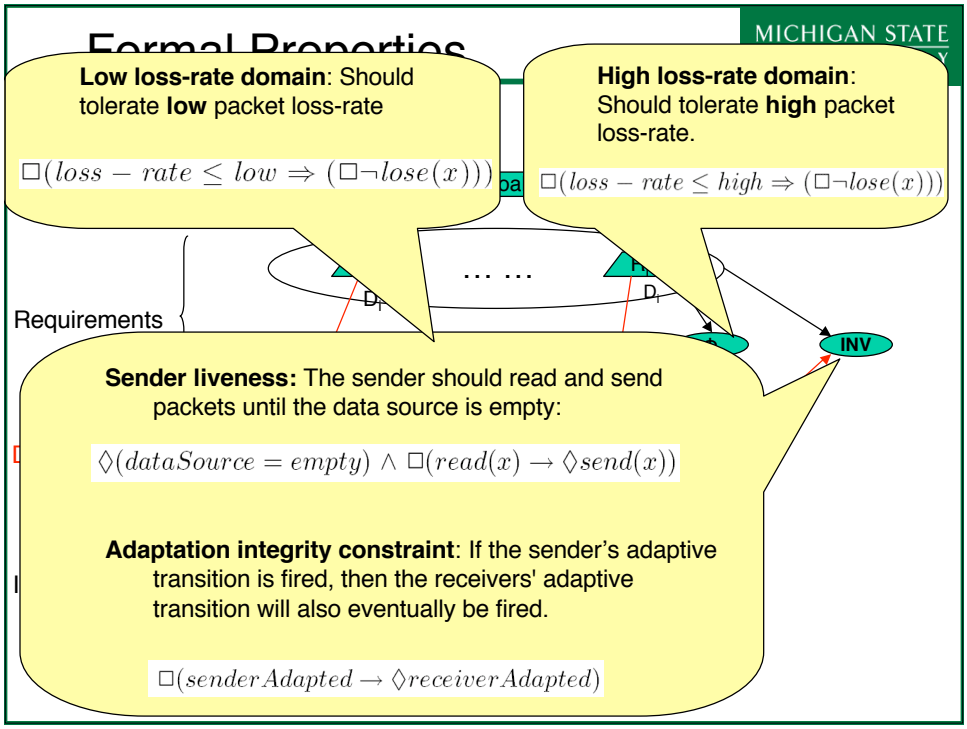

Design Stage

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- Model-based design technique
  - Use finite state machine to model DAS [ICSE06]
  - Non-adaptive models are separated from adaptive models.
  - Support state transfer
  - Support analyses
    - Simulation
    - Model checking

Design to Implementation

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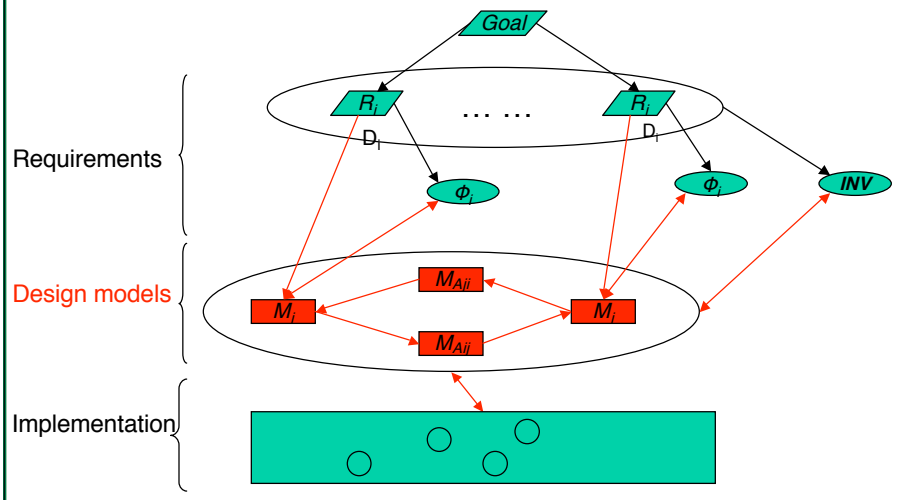

Model-Based Development

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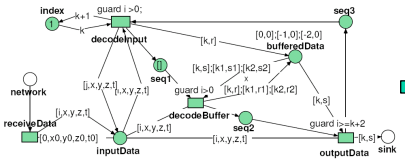
- Model adaptive system using Petri Nets
  - Steady-state models M_i for each D_i
  - Adaptation models M_{Aij} from D_i to D_j

[ICSE06]

- Model check against global invariants
- Automatically generate adaptive programs

Petri Nets



control

Java program

```
pubic class sender extends…{
   readData(){...}
   encode() {…}
   sendData(){…}
    …
}
```

Objectives

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- Separation of concerns
  - Separate adaptive behavior from non-adaptive behavior
- General
  - Can be used for other state-based formalisms
- Flexible
  - Support state transfer.
- Formal
  - Amenable to analysis, e.g., model checking, simulation, etc

Requirements to Design

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- Requirements vs Design
  - Requirements: declarative
  - Design: operational
- State-based model design
  - Petri nets
  - graphical (intuitive)
  - Formal
  - Numerous analysis tools e.g. Renew, Maria
- Two types of models
  - Steady-state models M_i for each D_i
  - Adaptation models M_{Aij} from D_i to D_j
- Verify the models against local properties and global properties

Local Requirements-Steady-State Models

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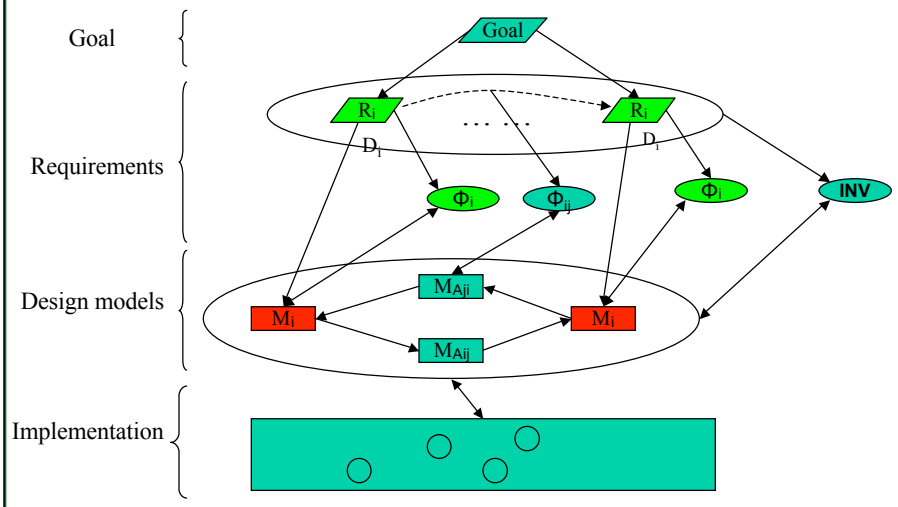

Steady-State Models

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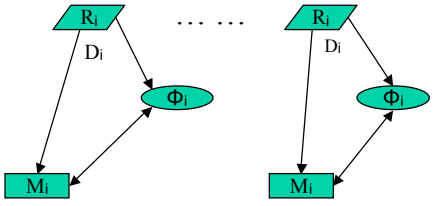
1. Build a design model for each domain.
2. Run simulation to validate the requirements of each domain
3. Model check the models against local properties



Global Invariants-Adaptation Models

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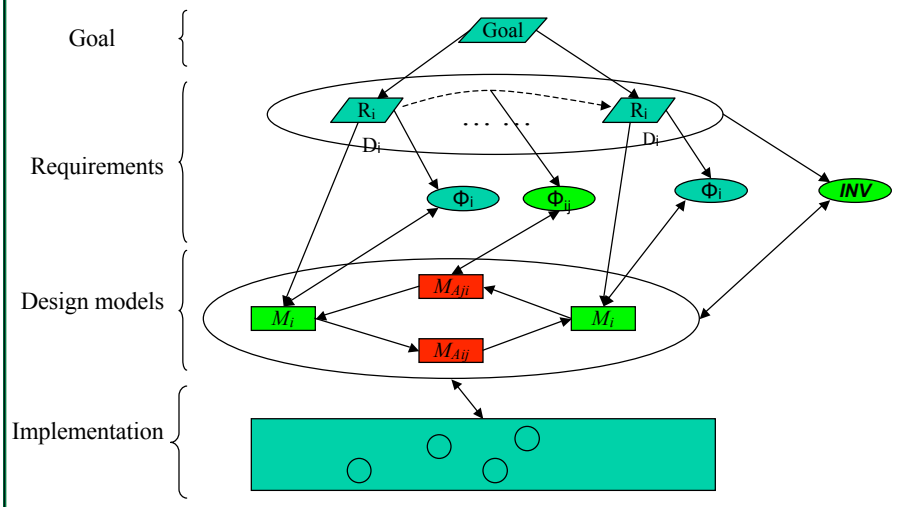

Adaptation Models

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1. Build an adaptation design model M_{Aij} for each adaptation from one steady-state program M_i to another M_j
2. Run simulation to validate the adaptation
3. Model check the adaptation models against global invariants and transitional properties.

Types of Design Models

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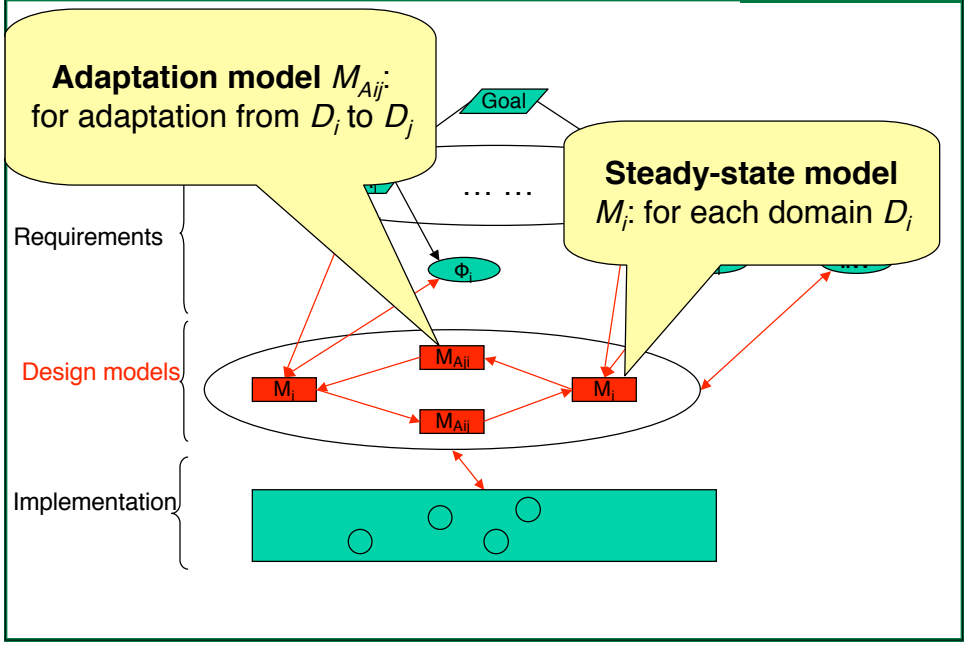

Design Models

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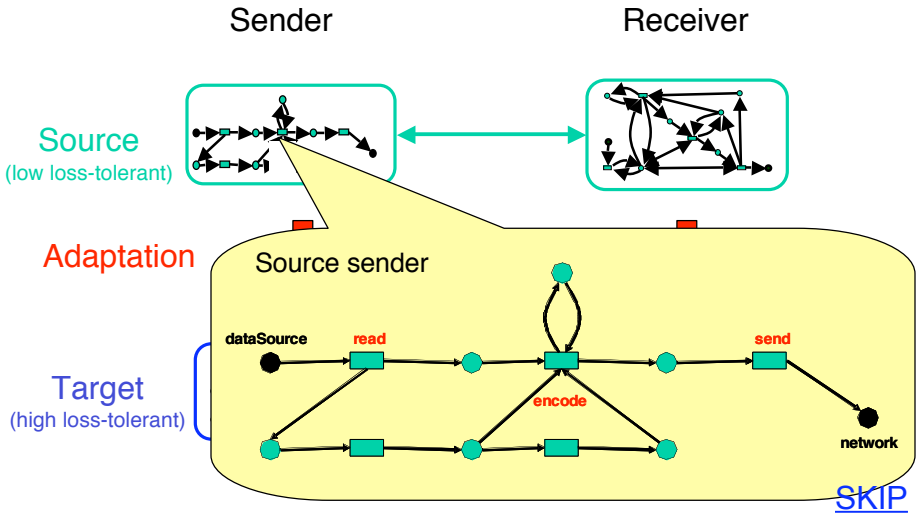

SKIP

Design Models

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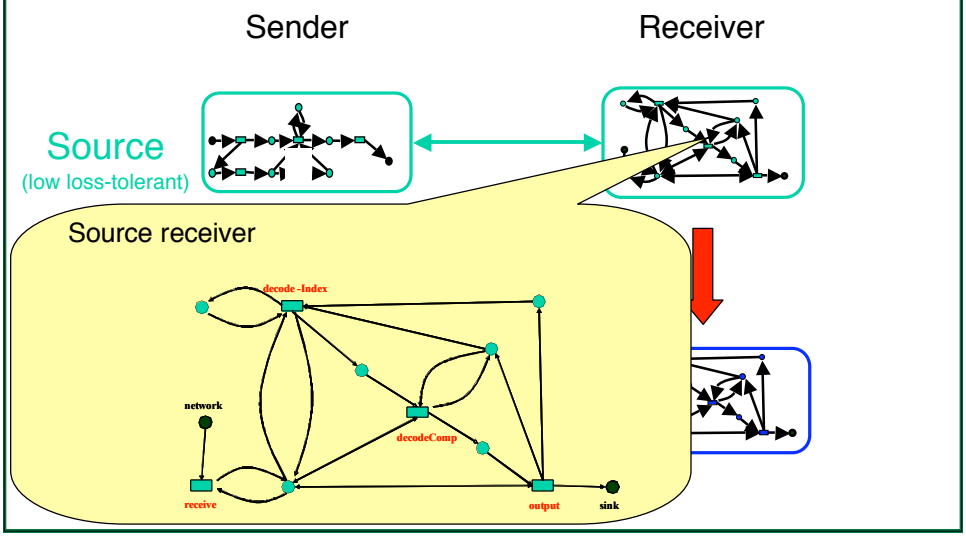

Design Models

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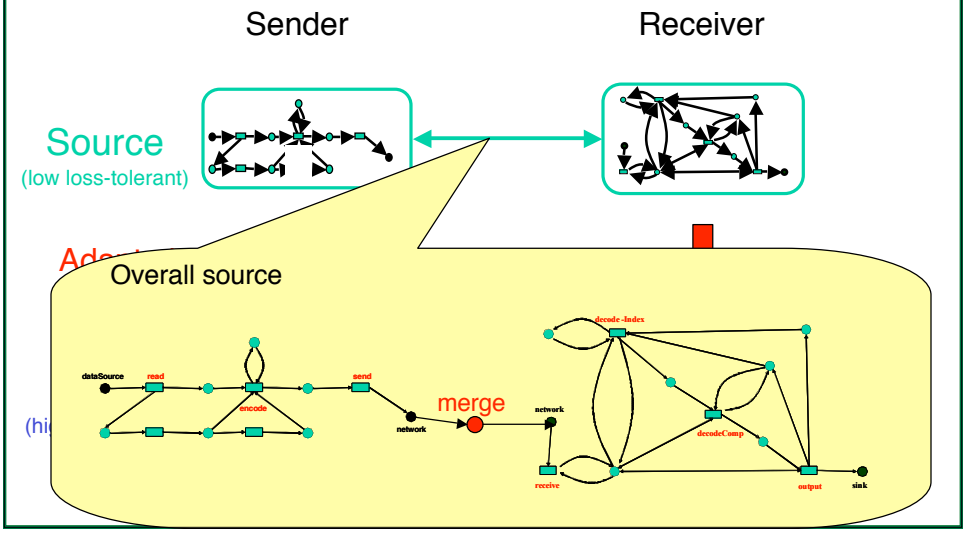

Design Models

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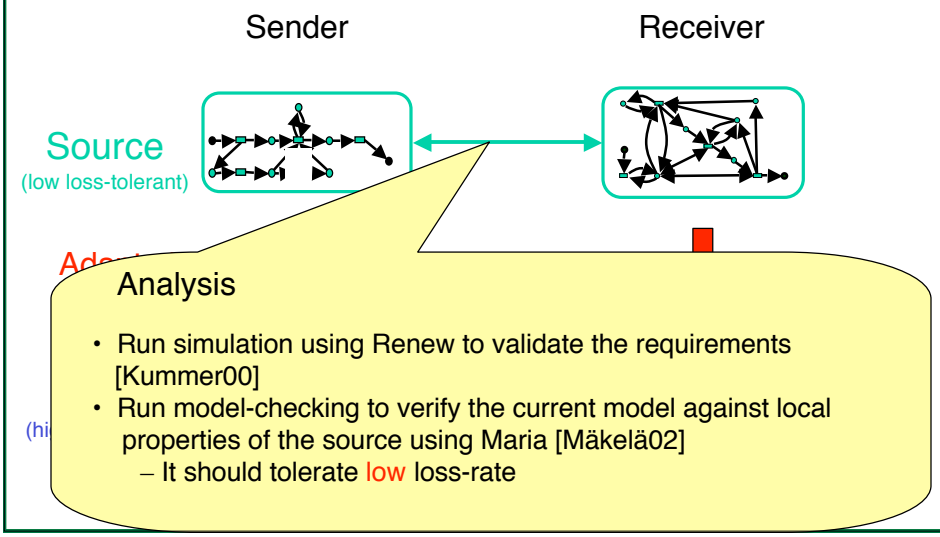

Design Models

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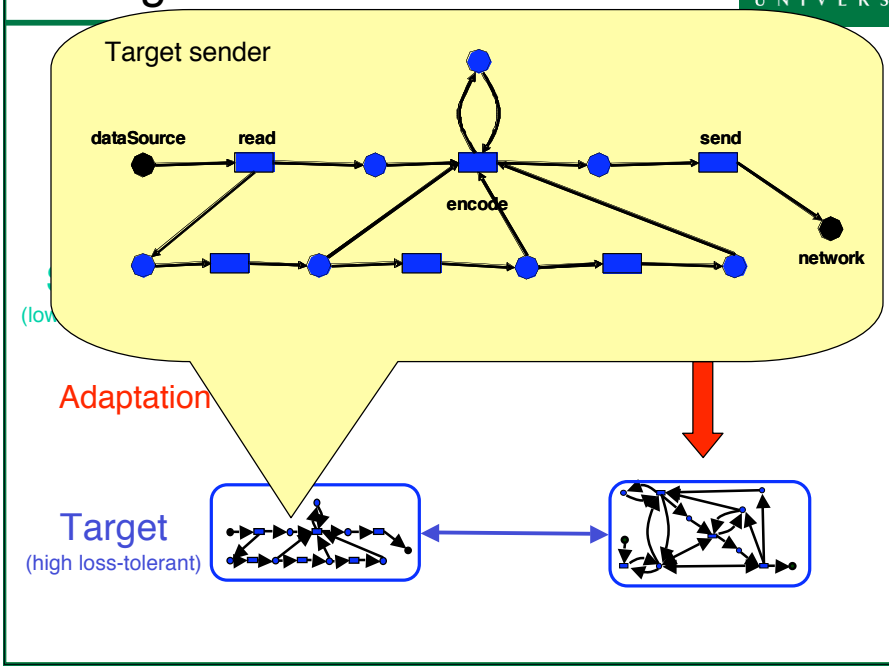

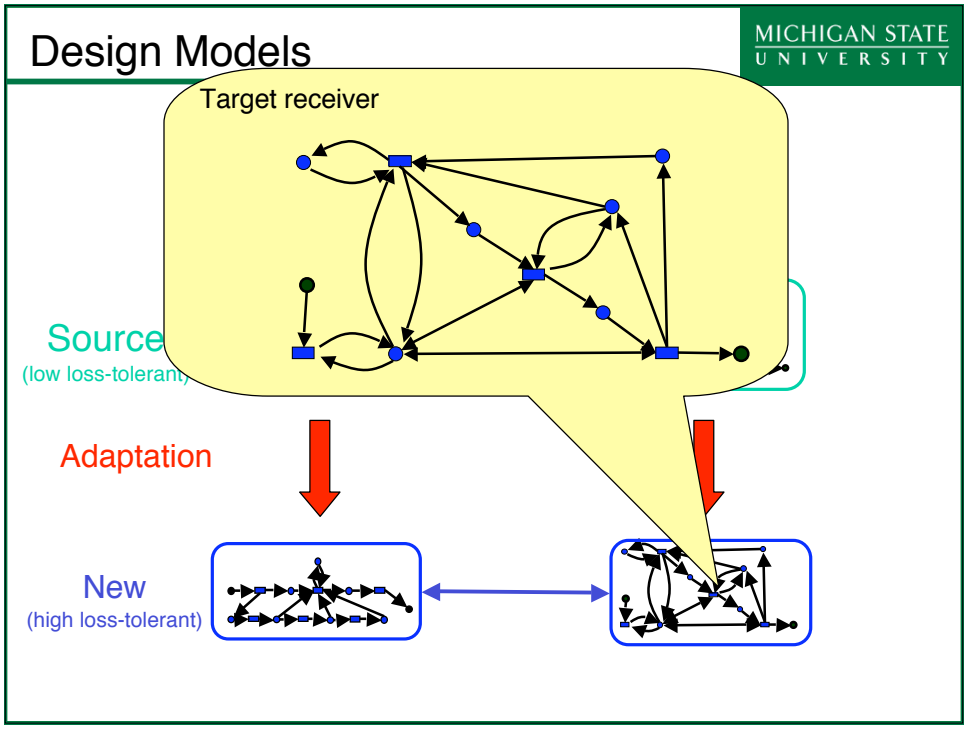
Design Models
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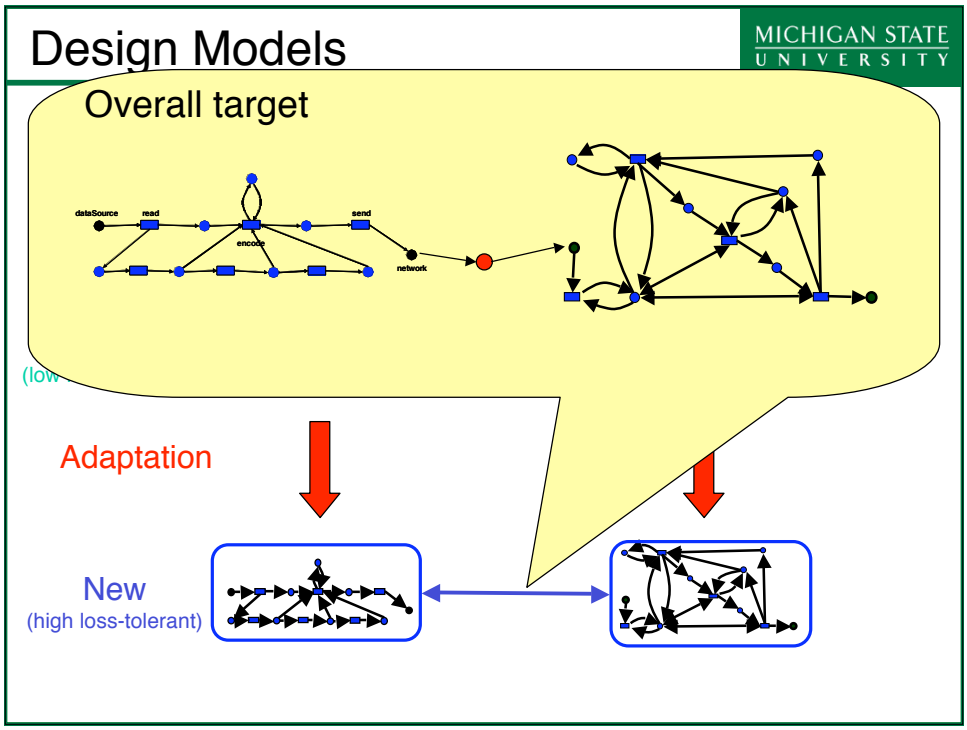
Target receiver
Source
(low loss-tolerant)
Adaptation
New
(high loss-tolerant)


Design Models
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Overall target
dataSource
read
send
encode
network
Adaptation
New
(high loss-tolerant)

Design Models

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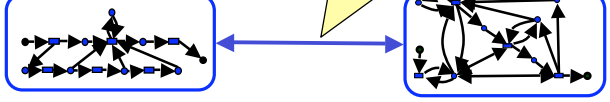
Analysis

- Run simulation using Renew to validate the requirements
- Run model-checking to verify target model against local properties of the source
  - It should tolerate high loss-rate

(low

Adaptation

New
(high loss-tolerant)



Design Models

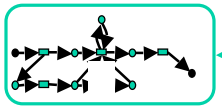
Sender adaptation

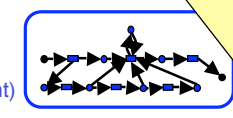
Sender

Source
(low loss-tolerant)

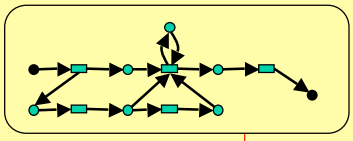
Adaptation

Target
(high loss-tolerant)



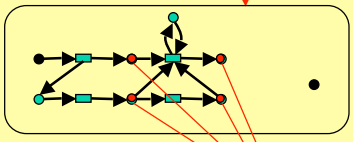


source sender



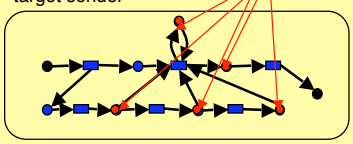
(1) restrict

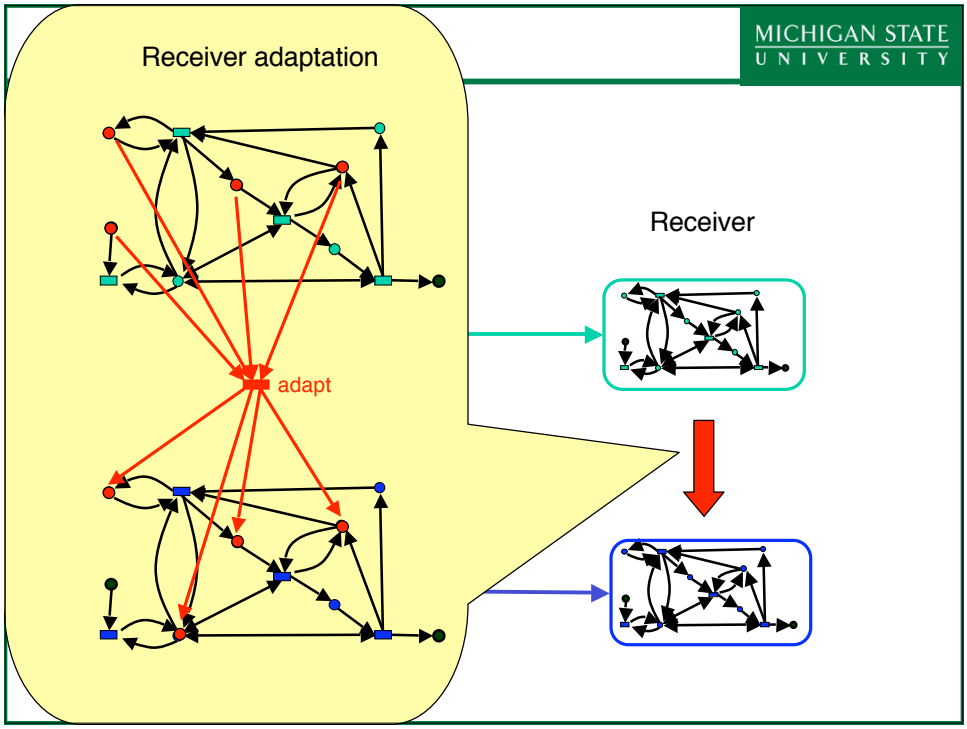
sender restricted



(2) adapt

target sender




Receiver adaptation
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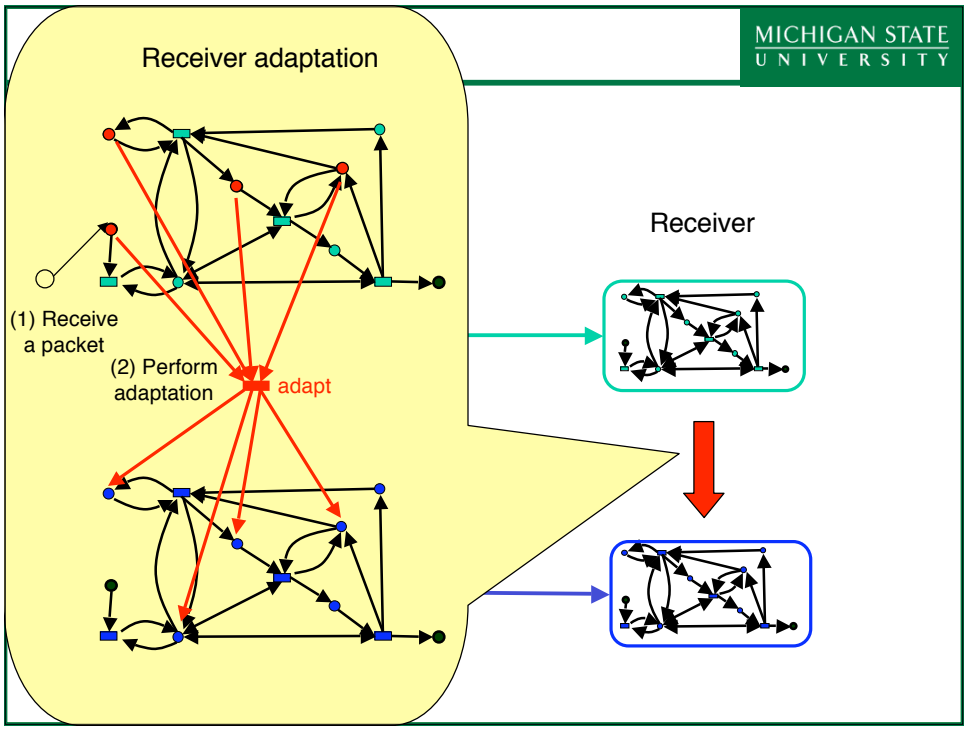
Receiver
adapt


Receiver adaptation
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Receiver
(1) Receive a packet
(2) Perform adaptation
adapt

Design Models

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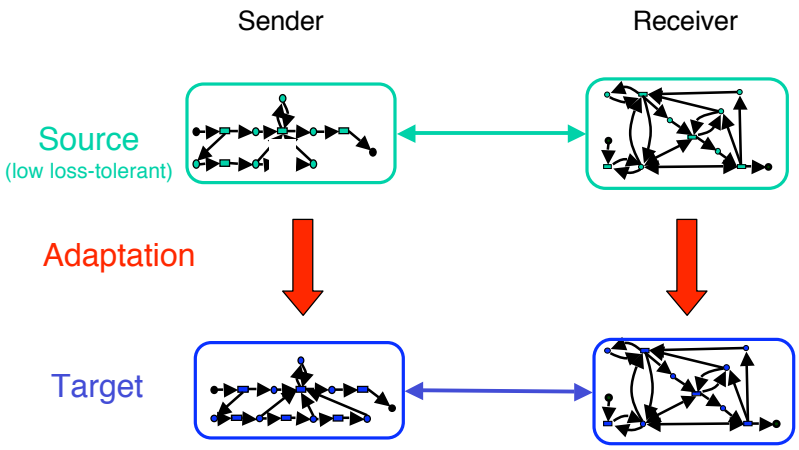

Overall Adaptation Model

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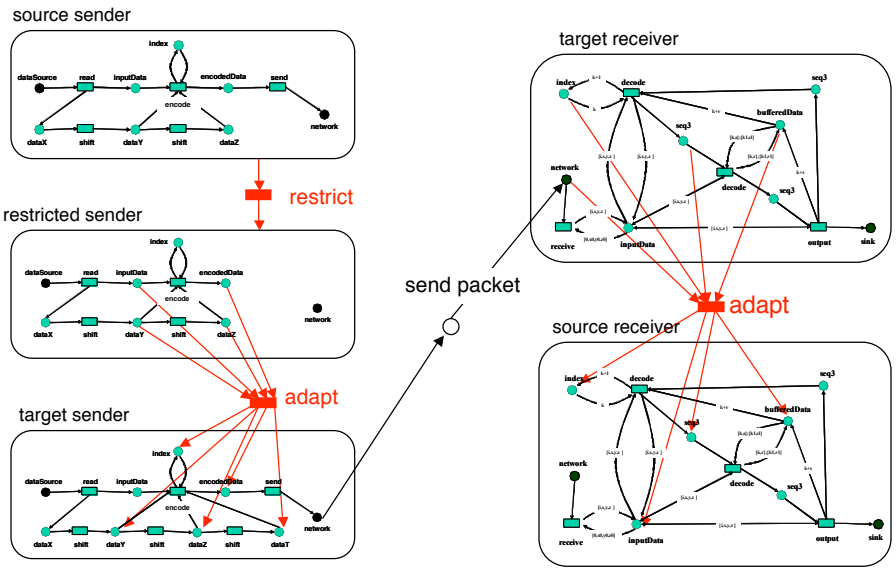

Design Models

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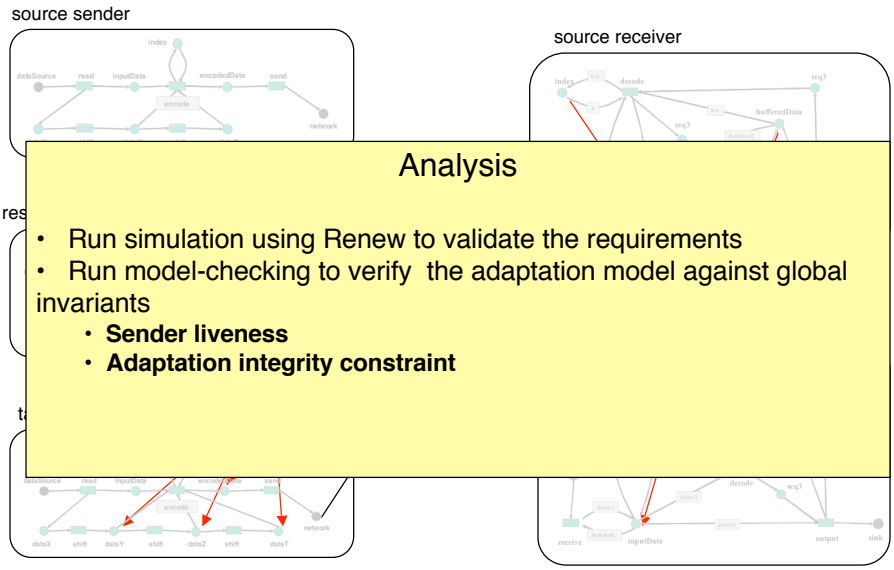

Design to Implementation

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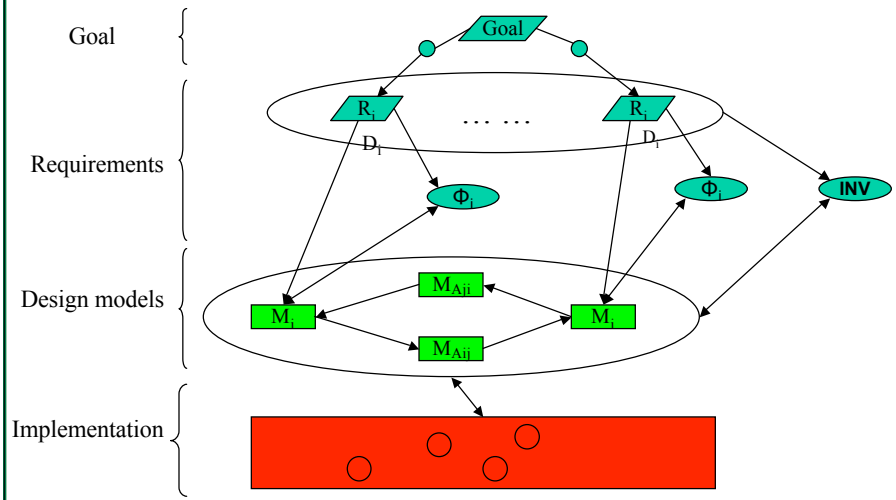

Reifying the Models

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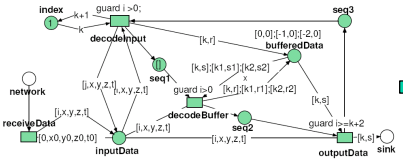
- Prototyping (supported by Renew)
  - Petri net models can be integrated in Java programs to drive Java function calls.

Petri Nets



control

Java program

```
pubic class sender extends…{
  readData(){...}
  encode() {…}
  sendData(){…}
   …
}
```

Reifying the Models

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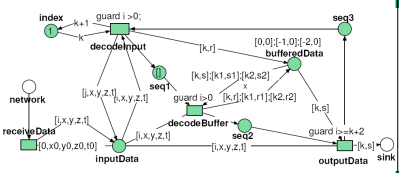
- Model-based testing (supported by Renew)
  - Java program can invoke corresponding Petri net transitions.
  - Use Petri nets to test allowable execution paths.

Java program

```
pubic class sender extends…{
  readData(){...}
  encode() {…}
  sendData(){…}
   …
}
```

control

Petri Nets



Discussion and Conclusions

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- A model-based adaptive software development process.
  - Crosscuts requirements, design, and implementation
  - Steady-state programs requirements and models are specified **separately** from those for adaptations
  - Identify **quiescent states** to be a property of the adaptation, rather than properties of each steady-state program
  - Support flexible **state transfer**

Future Work

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- Integrate our approach with ADL approaches
- Explore modular model-checking of global invariants [Modular06]
- Explore run-time model checking
- Further validation
  - Apply to other adaptation domains
  - Apply to other formalisms

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