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Toward an Equation-Oriented Framework for Diagnosis of Complex Systems

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Overview

- Motivation
- Related Work
  - LNG vs. Modelica
- Lydia-NG Overview
- Examples
  - Circuits
  - Thermo-Fluid Systems
- Summary

Motivation

- How can Modelica libraries be used for Model-Based Diagnosis (MBD)?
- Significant value in Modelica libraries
  - Can this be leveraged for MBD?
- Must understand difference between
  - Simulation (via Modelica)
  - MBD

Contributions

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- Equation-based framework for Model-Based Diagnosis
  - Generalisation of Modelica (inference)
  - Uses multiple simulation tools, as well as diagnosis inference tools
- Application to several systems
  - Circuits, thermo-fluid systems

Diagnostics Modeling

- Assume component-based framework
- Each component has *operating mode*
  - Mode defines a set of dynamical equations
  - Example
    - $\underline{y} = f(\underline{x}, \underline{h})$
    - $\underline{y}$: output; $\underline{x}$: state vector; $\underline{h}$: mode

Example: Boolean XOR


```
system xor2(bool o, i1, i2)
{
    bool h;
    attribute health(h) = h;

    h => (o = (i1 != i2));
    !h => (o = !(i1 != i2));
}
```

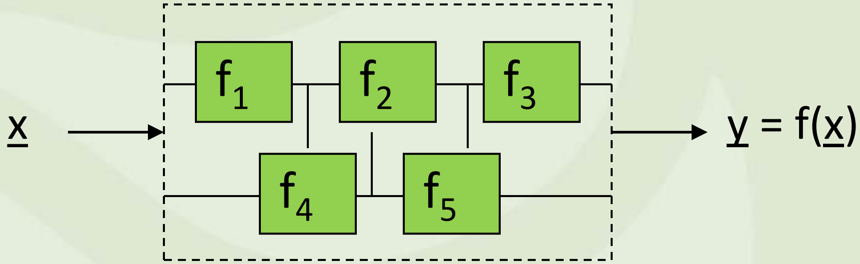
mode variable

like annotations

modes

Simulation

- Given inputs and a health state, compute outputs



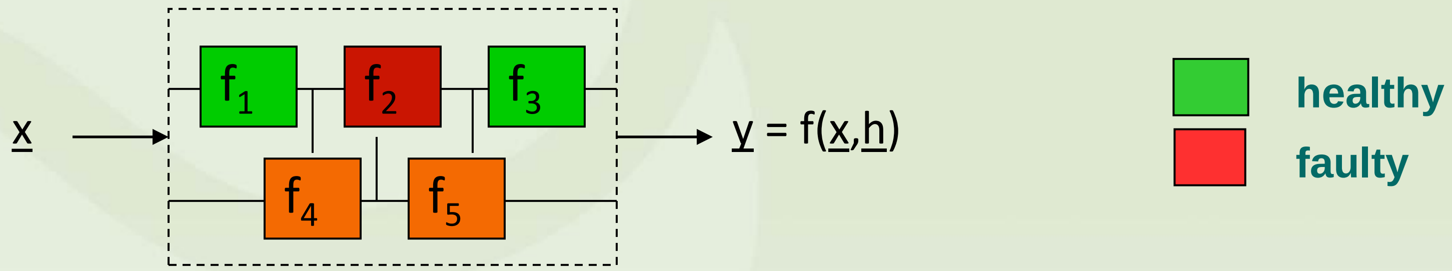
$\underline{x}$: input, $\underline{y}$: output,

f: system function, f_i: component functions

- Simulate: solve problem $\underline{y} = f(\underline{x})$

Fault Diagnosis

- Identify component(s) that are root cause of failure (error)



$\underline{x}$, $\underline{y}$: observation vectors

f: system function, f_i: component functions

$\underline{h}$: system health state vector, h_i: component health variables

- Diagnose failure: solve inverse problem $\underline{h} = f^{-1}(\underline{x},\underline{y})$
- Diagnosis: $\underline{h}_2$ = fault state, or $\underline{h}_4$ and $\underline{h}_5$ = fault state

Simulation vs. Diagnosis

- Simulation
  - solving a system of equations for some output variables
- Diagnosis
  - solving a system of equations for some set of health variables,
  - However:
    - Diagnostic systems typically under-constrained due to ignorance of abnormal behavior, etc.
    - Simulation systems often constructed to have one solution,
      - in diagnosis we want to compute multiple solutions (hypotheses/diagnostic candidates)

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Related Work

- Rodelica
  - Atemporal, interval-based approach
- Modelica
- Bond graphs

LYDIA-NG and MODELICA

- LYDIA-NG is very similar to Modelica
  – solves Modelica models for some parameters
  – we plan a Modelica translation tool for easy modeling
    - problem is some Modelica component libraries include non-declarative model entities

Lydia-NG vs. Modelica

- Lydia-NG
  - Braces (C/C++/Verilog)
  - Not object-oriented (may become in the future)
  - strongly-typed
  - quantified (existential, universal), static expansion
- Modelica
  - begin/end (Pascal/VHDL)
  - object-oriented
  - strongly-typed
  - less static

LYDIA-NG vs. MODELICA (cont.)

- LYDIA-NG
  - no connectors (only variables)
  - no flow variables (a.k.a. write your own "global" equations)
  - fairly complex data types: structures, arrays, array of structures, etc.
  - special treatment of Boolean systems (legacy)
- MODELICA
  - uses connectors
  - flow variables (equation sugar)

Compilation and Inference

- Lydia-NG
  - Compilation not a key aspect
    - Output C code can be used by any inference system
- Modelica
  - Compilation key aspect for efficiency
  - Compilation can lead to incompatibility among Modelica inference systems

LYDIA-NG Example

```
system HeatingCoil(PneumaticPort pneumaticCold, pneumaticHot,
                   HydraulicPort hydraulicCold, hydraulicHot)
{
    float c = 4180.0; // water specific heat

    float coldSideCapacitanceRate = pneumaticCold.mflow * c;
    float hotSideCapacitanceRate = hydraulicCold.mflow * c;

    float eff = 0.6;

    float minCapacitanceRate = min(coldSideCapacitanceRate,
                                   hotSideCapacitanceRate);
    float maxCapacitanceRate = max(coldSideCapacitanceRate,
                                   hotSideCapacitanceRate);

    float heatRate = eff * minCapacitanceRate *
                     (hydraulicHot.T - pneumaticCold.T);

    hydraulicHot.T = hydraulicCold.T - heatRate / (hydraulicCold.mflow * c);
    pneumaticHot.T = pneumaticCold.T + heatRate / (pneumaticCold.mflow * c);
}
```

LYDIA-NG

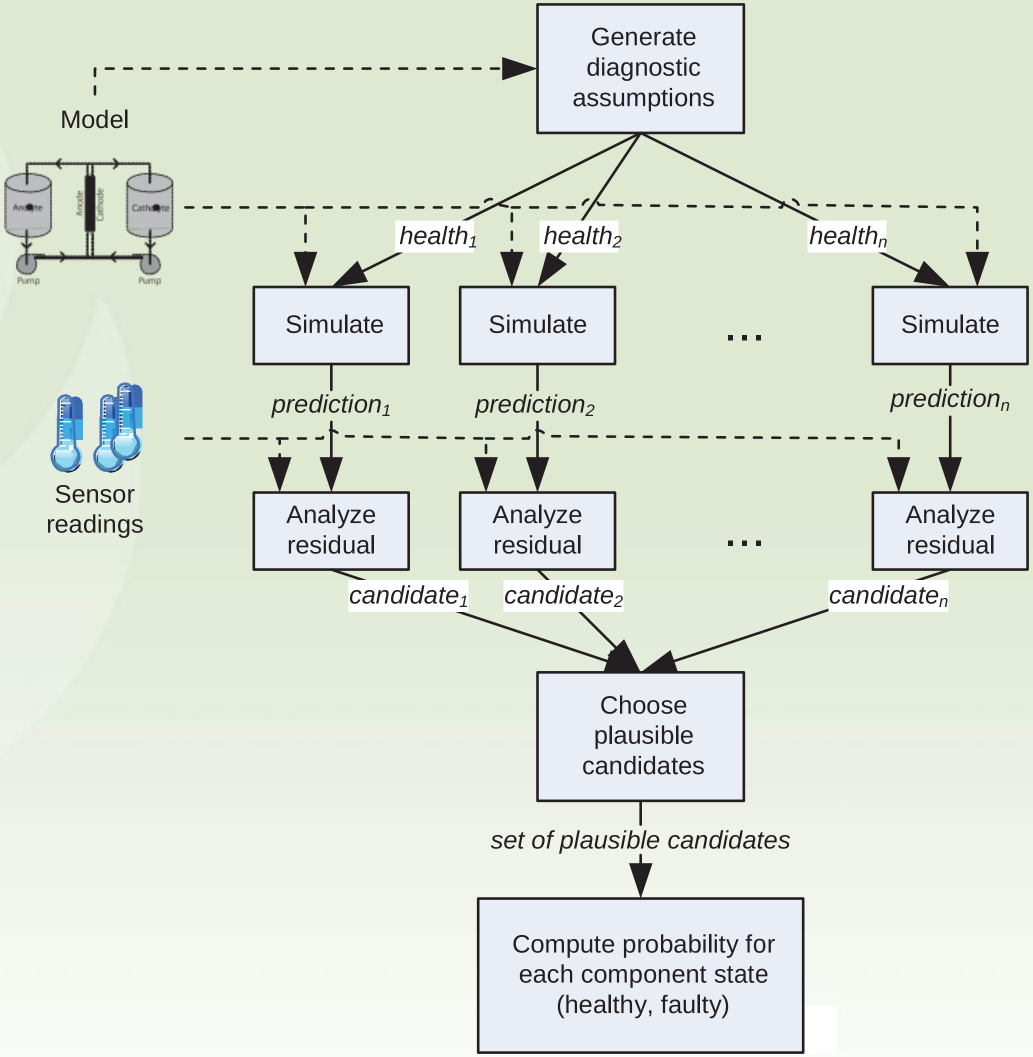
- LYDIA-NG is a diagnostic **framework**
  - Use cases:
    - modeling of diagnostic systems (also an IDE)
    - running of diagnostic scenarios in batch mode (computation of diagnostic metrics)
    - embedding in a SCADA system, e.g., a BMS
- Our view on the development of LYDIA-NG
  - collection of tools (simulators, translators, etc.)
  - simple interfaces (our users are not assumed to be expert MBD users)
  - higher coding/documentation/knowledge dissemination standards than typical projects

LYDIA-NG Overview

- Core libraries
  - simulation
    - SPICE
    - symbolic
    - ODEs/DAEs
    - Boolean circuits (old LYDIA heritage)
  - diagnosis
    - forward reasoning (simulation for various health/fault states)
    - backward reasoning (residual analysis)
  - disambiguation
    - entropy-based selection of tests
    - virtual sensors (by-product)

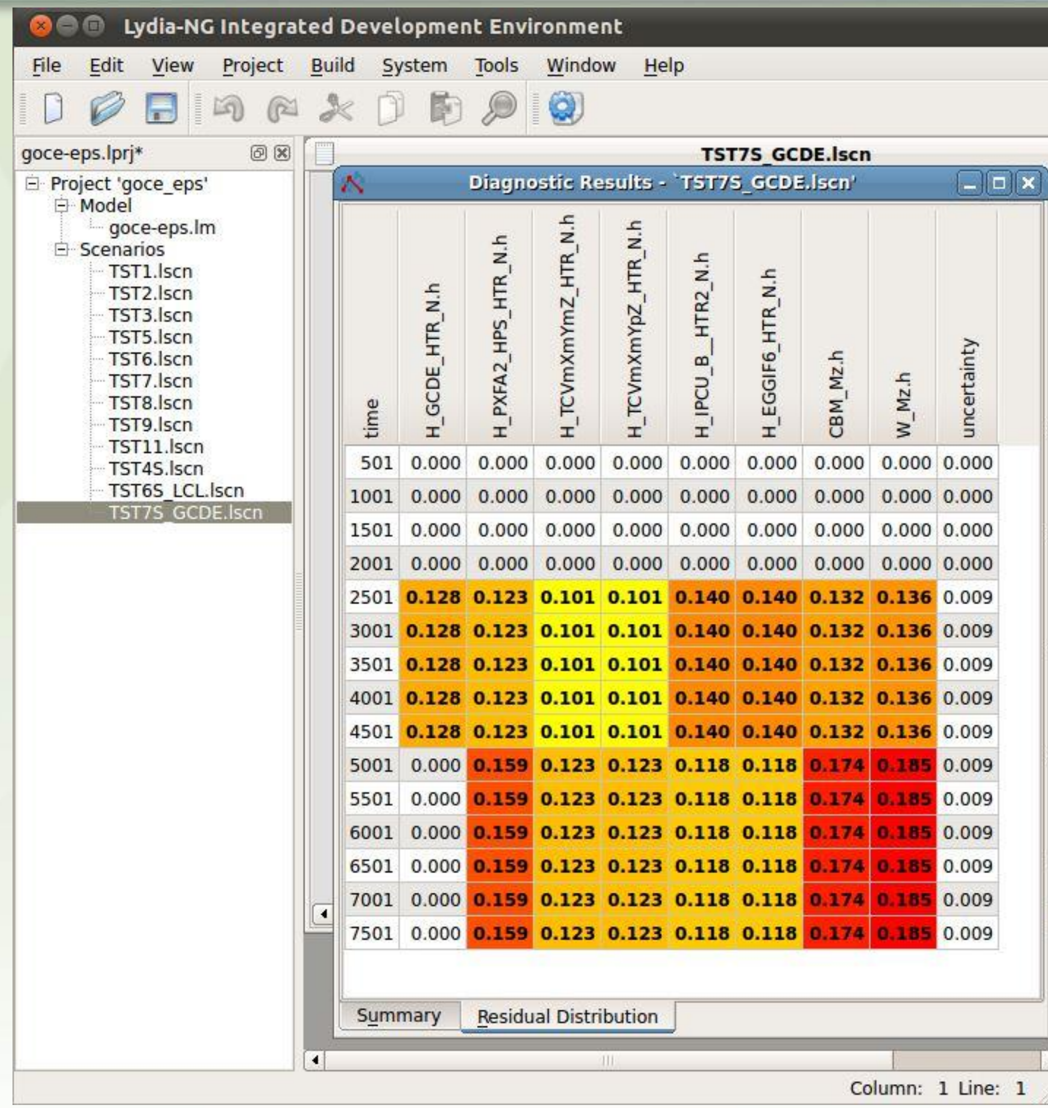
LYDIA-NG Approach to Diagnosis

- The main idea is to run multiple-simulations simultaneously (each simulation reflects different health state)
- Choose those simulations that minimize some residual function
- Report diagnosis as a probability of each component being healthy/faulty



State of LYDIA-NG Development

- LYDIA-NG has reached a milestone in diagnosing an electrical system
  - results show that the software will be useful in practice
  - releasing version 1.0 after fixing some bugs, documentation, and testing
  - preview versions of the software continuously made available to EMWiNS team members for purpose of progress-tracking, collaboration, and planning



time	H_GCDE_HTR_N.h	H_PXFA2_HPS_HTR_N.h	H_TCVmXmYmZ_HTR_N.h	H_TCVmXmYpZ_HTR_N.h	H_IPCU_B__HTR2_N.h	H_EGGIF6_HTR_N.h	CBM_Mz.h	W_Mz.h	uncertainty
501	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1501	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2501	0.128	0.123	0.101	0.101	0.140	0.140	0.132	0.136	0.009
3001	0.128	0.123	0.101	0.101	0.140	0.140	0.132	0.136	0.009
3501	0.128	0.123	0.101	0.101	0.140	0.140	0.132	0.136	0.009
4001	0.128	0.123	0.101	0.101	0.140	0.140	0.132	0.136	0.009
4501	0.128	0.123	0.101	0.101	0.140	0.140	0.132	0.136	0.009
5001	0.000	0.159	0.123	0.123	0.118	0.118	0.174	0.185	0.009
5501	0.000	0.159	0.123	0.123	0.118	0.118	0.174	0.185	0.009
6001	0.000	0.159	0.123	0.123	0.118	0.118	0.174	0.185	0.009
6501	0.000	0.159	0.123	0.123	0.118	0.118	0.174	0.185	0.009
7001	0.000	0.159	0.123	0.123	0.118	0.118	0.174	0.185	0.009
7501	0.000	0.159	0.123	0.123	0.118	0.118	0.174	0.185	0.009

Validation of Diagnostics

- Validation of diagnostics is in general more difficult than that of simulation
  - simulation accuracy metrics such as mean difference from measured values
  - diagnostic accuracy metrics are interrelated (false positives vs. false negatives, classification errors, etc.)
  - diagnostic metrics are often domain-dependent (e.g., energy)
  - diagnostic world is “less closed”, some metrics can be computed only after, e.g., “repair”

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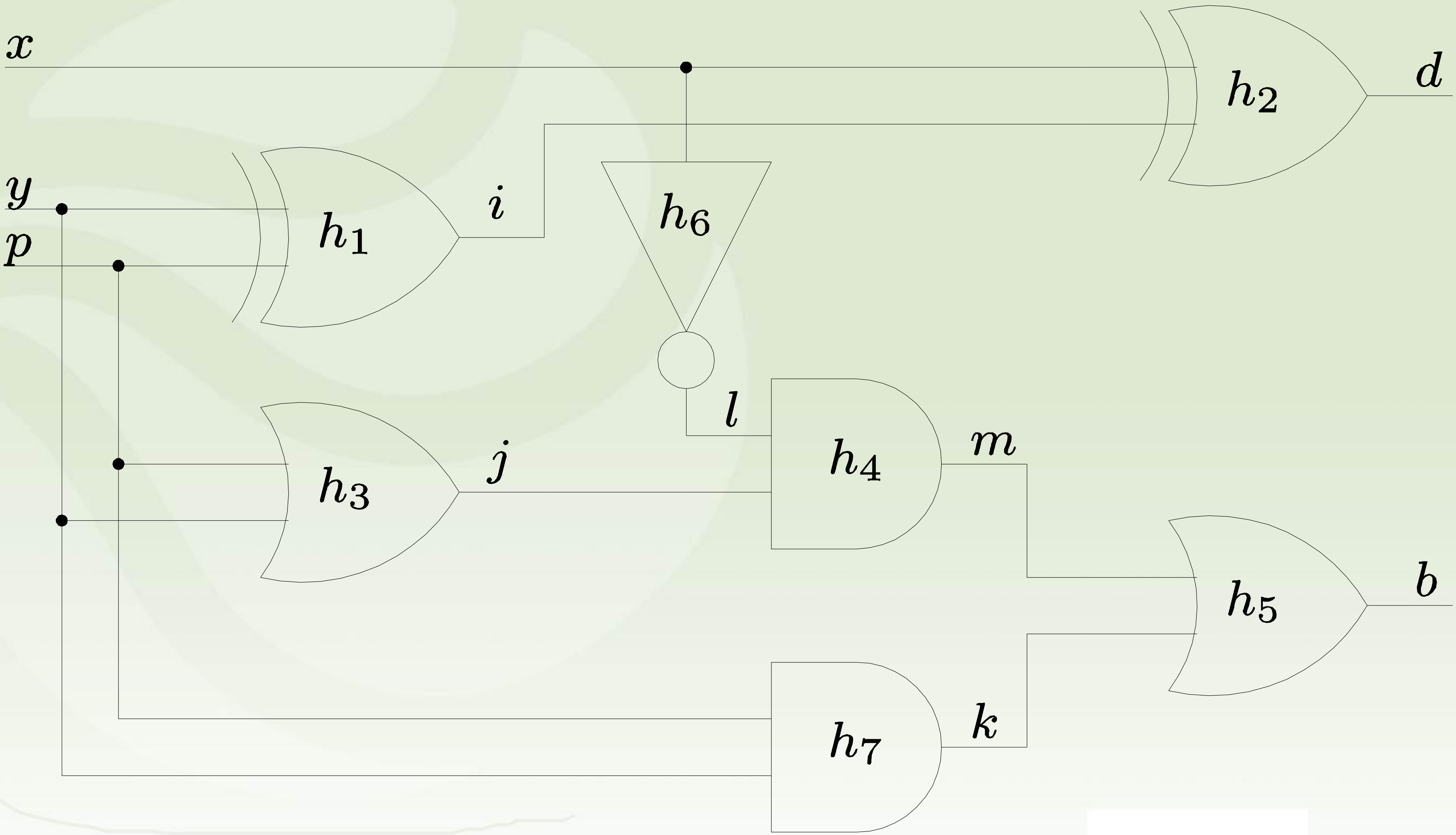
A Small Boolean Circuit



GOCE Electrical Power System

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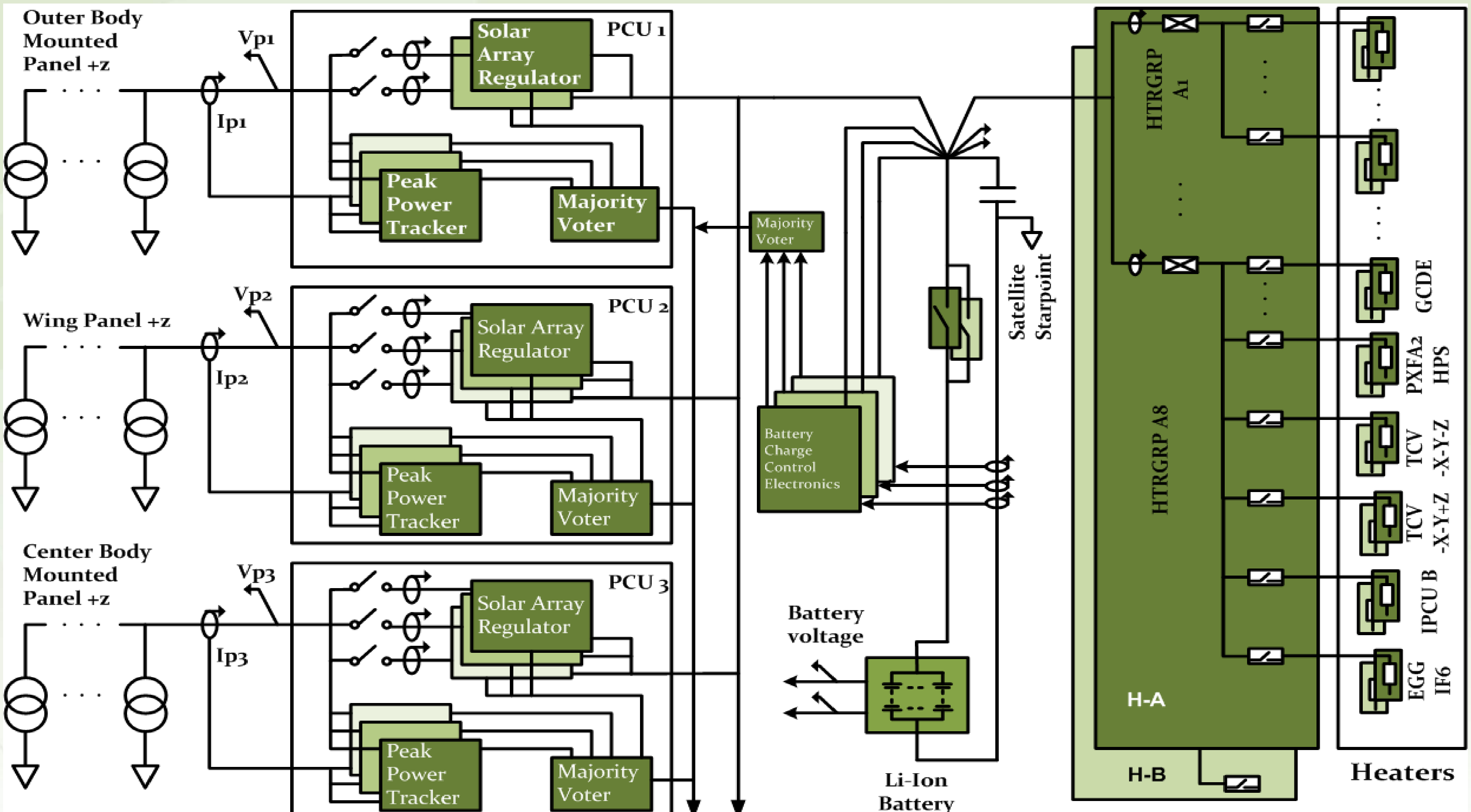

Use-Cases

- Many Boolean circuits (ISCAS-85)
  - show properties of complex systems, easier to analyze complexity
  - check correctness of some diagnostic algorithms
- Analog electrical circuits (GOCE satellite EPS, NASA's ADAPT)
- Thermal-fluid systems (UCC's AHU-9)

Use-Case AHU System

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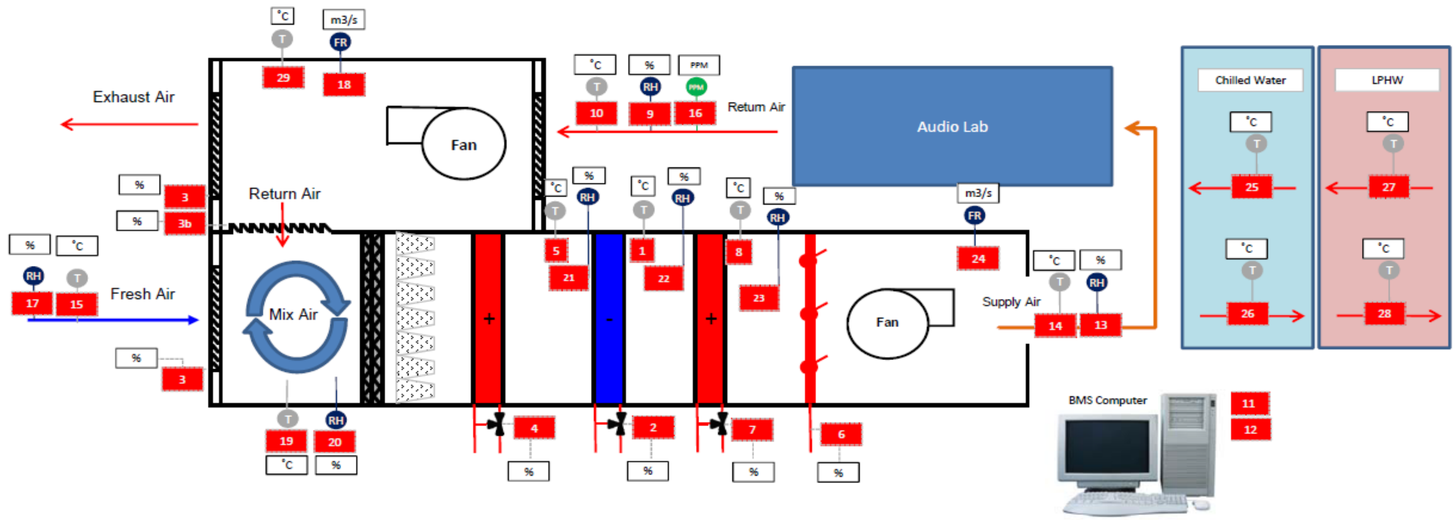
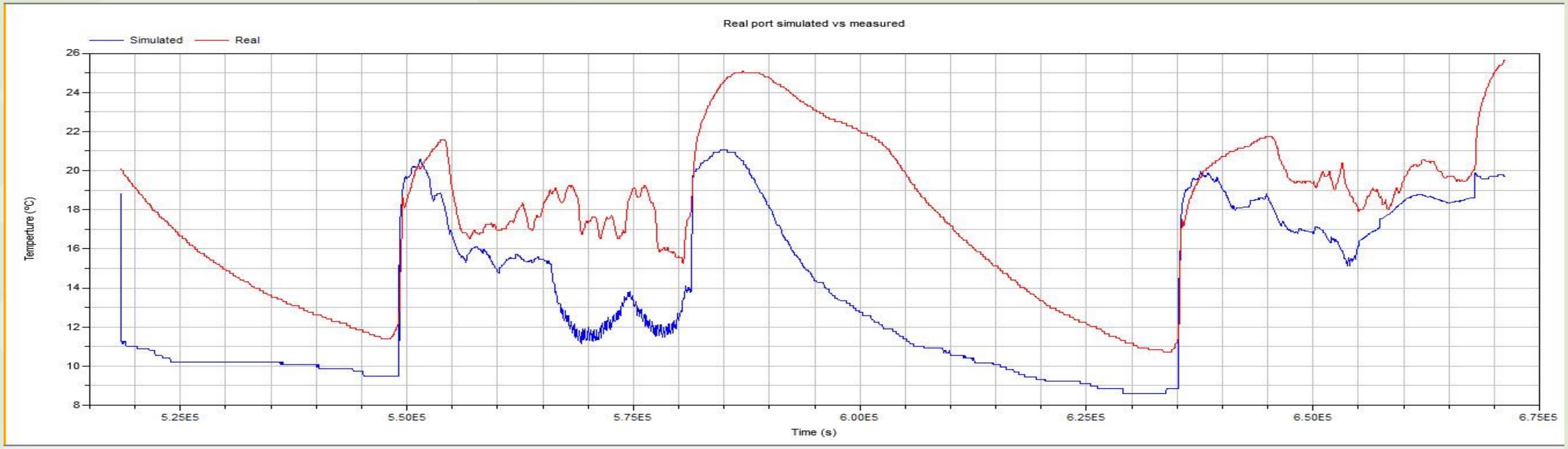
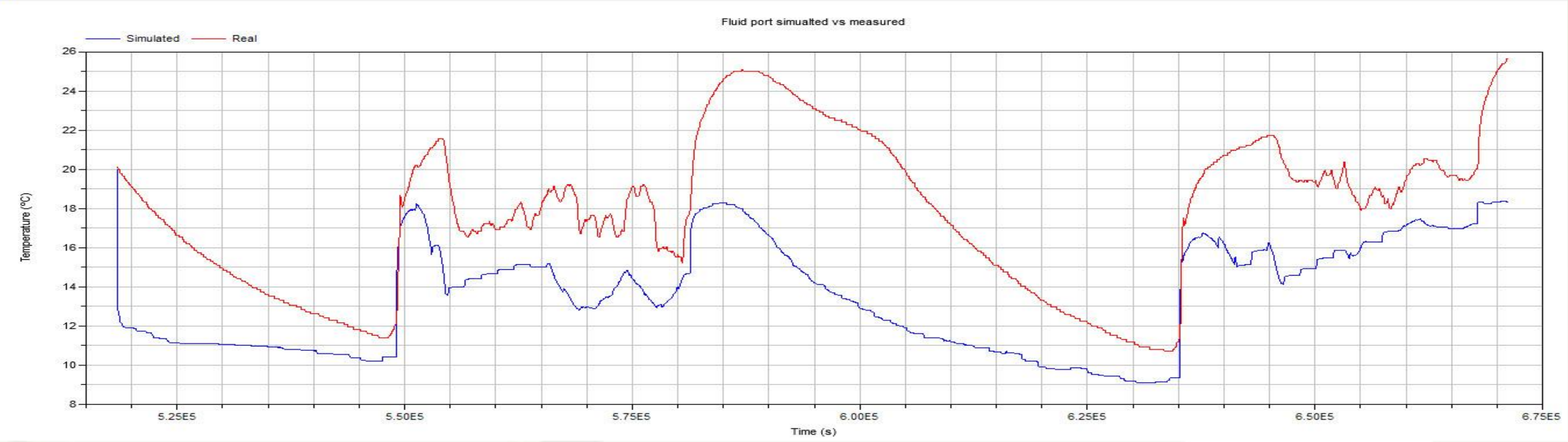


1: AHU9 CHW Offcoil Temperature
2: AHU9 CHW Valve Position
3: AHU9 Fresh Air Damper Position
4: AHU9 Frost Coil Valve Position
5: AHU9 Frost Offcoil Temperature
6: AHU9 Humidity Control Output
7: AHU9 Reheat Coil Valve Position
8: AHU9 Reheat Offcoil Temperature
9: AHU9 Return Air Humidity
10: AHU9 Return Air Temperature
11: AHU9 Space Air Humidity Setpoint
12: AHU9 Space Air Temperature Setpoint
13: AHU9 Supply Air Humidity

15: Outside Air Temperature
16: Now Added - PPM (Parts Per Million)
17: Outside Air Humidity
18: Return Air Flowrate
19: Mix Air Temperature
20: Mix Air Humidity
21: Post Heating Coil Humidity
22: Post Dehum Cooling Coil Humidity
23: Post Reheat Coil Humidity
24: Supply Fan Flowrate
25: Chilled Water Supply Temperature
26: Chilled Water Return Temperature
27: LPHW Supply Temperature
28: LPHW Return Temperature

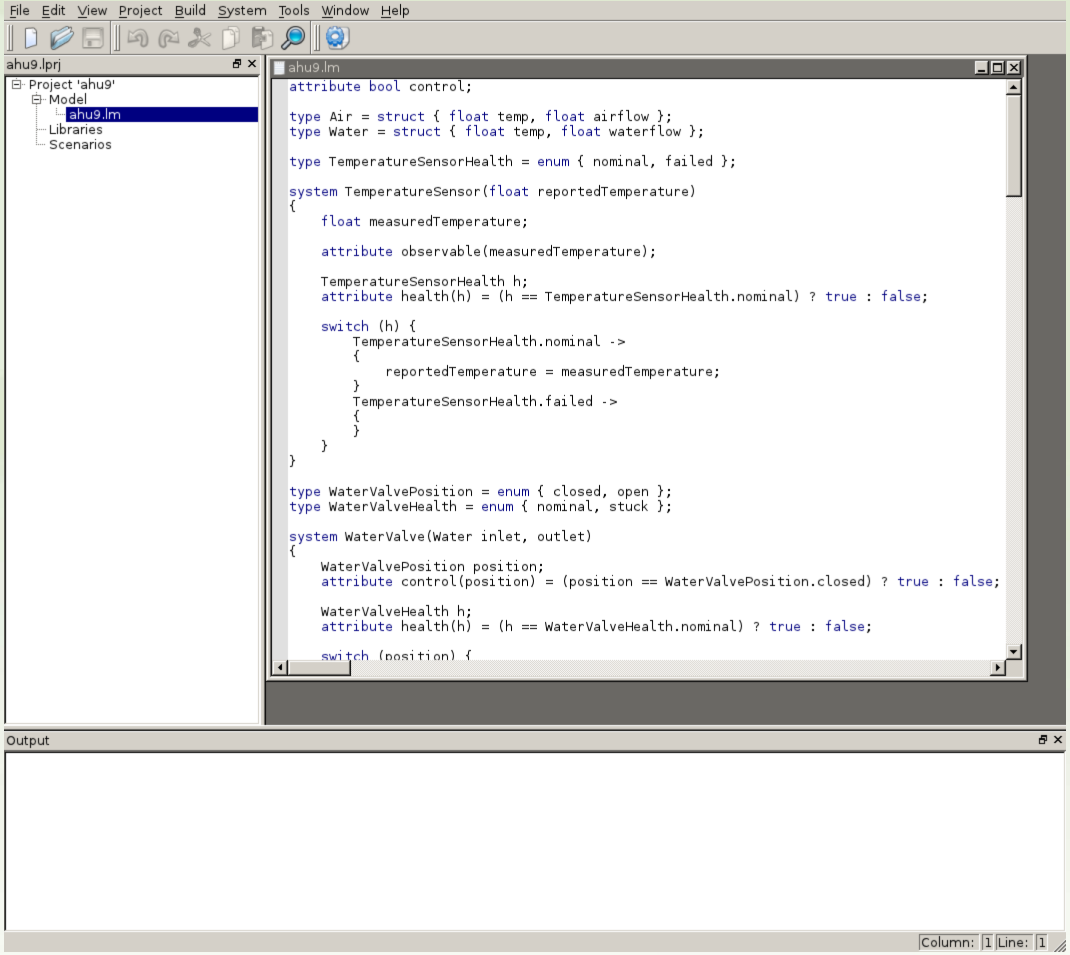
AHU Modeling





LYDIA-NG and AHU-9

- Modeling effort includes the following:
  - Top-level topology (100%)
  - Component fault-modes and user commands (100%)
  - Component equations (0%)
- Model parametrization and calibration



AHU Simulation

- ODE
  - not stiff
  - RK4 will do the job
  - error is function of the step-size
- We need to maintain multiple simulations that can be stopped/continued whenever sensor data arrives
- Some ODEs reduce to algebraic equations – we also saw from GOCE that fault simulations are cheaper in terms of CPU time, memory

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Summary

- Lydia-NG: MBD framework
  - Accepts multiple equation types
  - Generalises Modelica
    - mode-based equations
    - Wider range of inference algorithms

Future Work

- Integrate control
- Extend language to wider range of dynamical systems
- Examine other real-world applications
  - thermal systems
  - Mechanical systems (drive trains)
- DXC-2013

Call for Participation

- Want to play with/test/develop LYDIA-NG?
  - LYDIA-NG is free for academic use/open-source
  - send an email to `alex@general-diagnostics.com`
- Want to apply LYDIA-NG to your research/write a paper?
- Want to extend LYDIA-NG to solve #@! equations?

Come to DX-2013

- Come to DX-2013, Oct 1-4, Dan Panorama Hotel, Jerusalem (http://dx-2013.org/)
- DXC-2013
    - synthetic track (ISCAS)
    - electrical system (ADAPT)
    - thermal fluid system (AHU-9)
    - software track

Future (Present) Work

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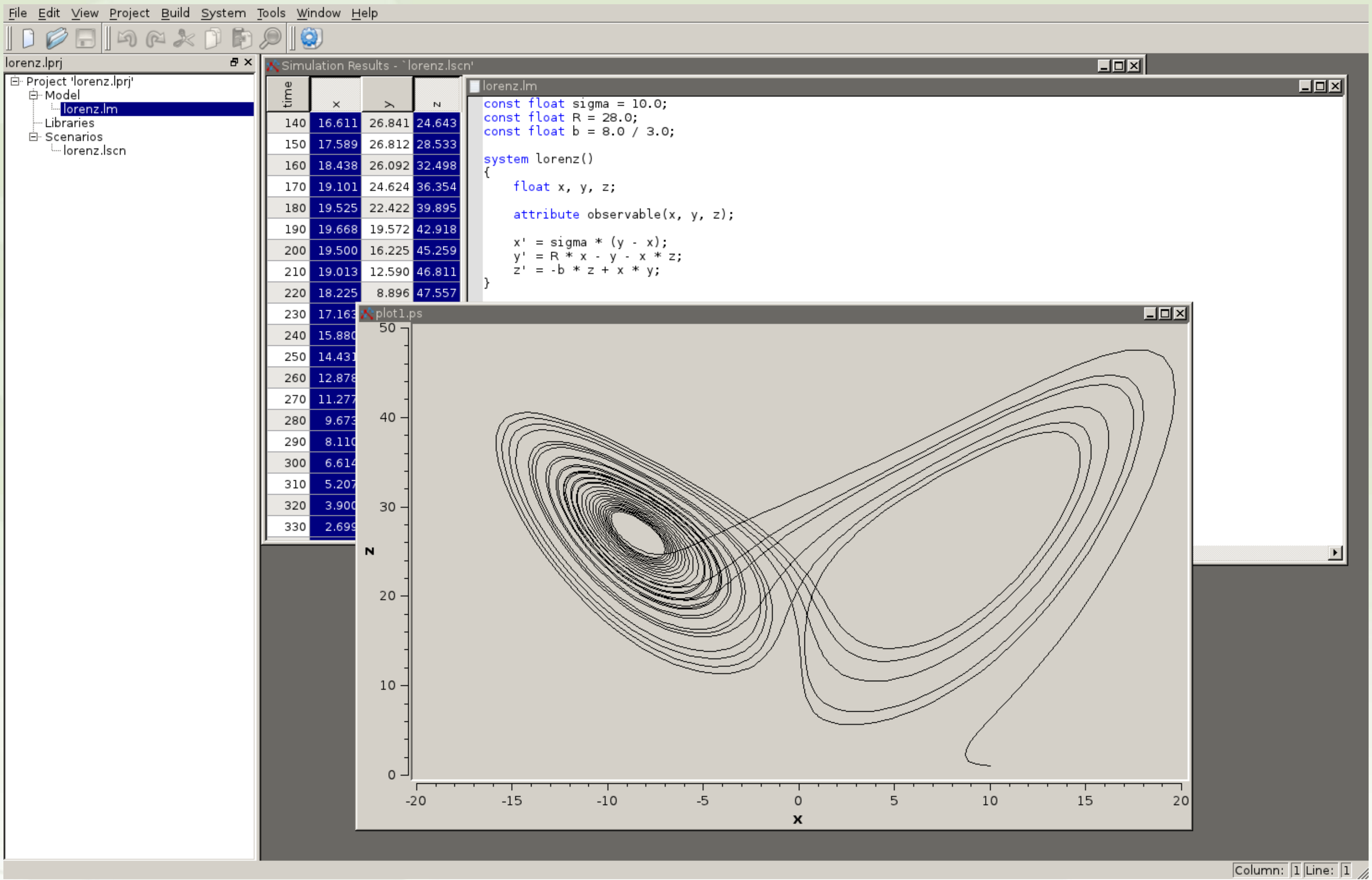

Thank You

Backup

Introduction

- History
  - LYDIA – diagnosis of Boolean circuits
    - SAFARI – stochastic diagnosis
    - FRACTAL – disambiguation of diagnoses (reduce diagnostic uncertainty – entropy based methods)
    - Beyond diagnosis – worst case sensor data – diagnosability (MIRANDA)
  - A resistor network can be modeled with Boolean variables but that is very difficult – e.g., 4-bit multiplication tables
  - LYDIA-NG – generalization to continuous variables
    - SAFARI-NG – greedy stochastic reasoning, but also other candidate generation policies
    - FRACTAL-NG – disambiguation
- The insight that allows generalization of Lydia to Lydia-NG is that simulation is a key-component in model-based diagnosis
  - What is the simulation step in the MBD circuit problem shown in the next slide?

LYDIA-NG Disambiguation

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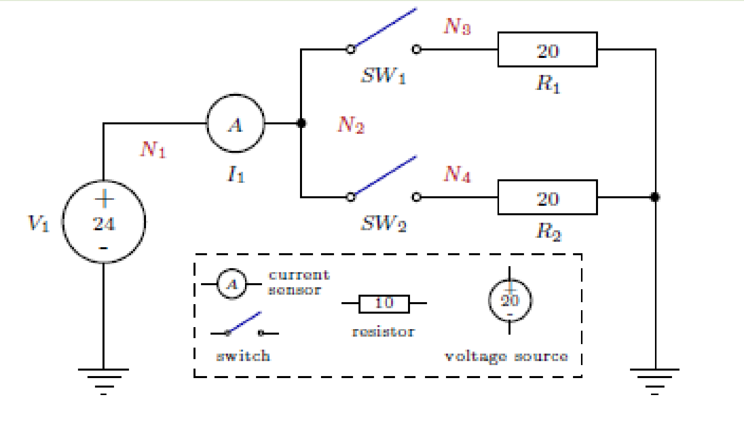
- Entropy-based methods for computing uncertainty of a component:

$$U(C) = \sum_{x \in C^*} -\Pr(C = x) \lg_{|C^*|} \Pr(C = x)$$

- Per system:

$$\overline{U} = \frac{1}{|COMPS|} \sum_{C \in COMPS} U(C)$$



LYDIA-NG Approach to Disambiguation

- AHU systems are typically sensor-lean to reduce cost
- AHU models are imprecise due to:
  - fine-grained CFD modeling is too complex
  - the AHU model cannot include a model of the local weather
- Sensors may drift/fail
- As a result diagnosis may be inaccurate
- We propose an algorithm that can increase the diagnostic accuracy by "playing" with the system
  - for example the system can reconfigure the mixing box to confirm/disprove a hypothesis about a failing heating coil