Software Architecture: Past, Present, and Future

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Examples of Architecture Descriptions

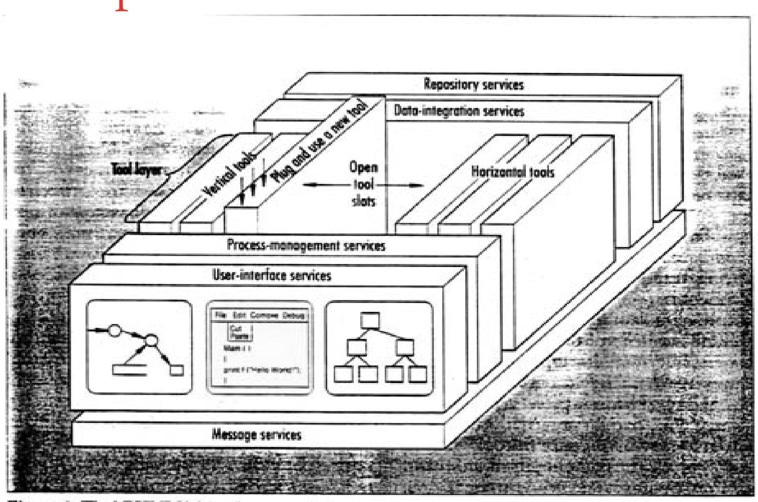

Figure 1. The NIST/ECMA reference model.

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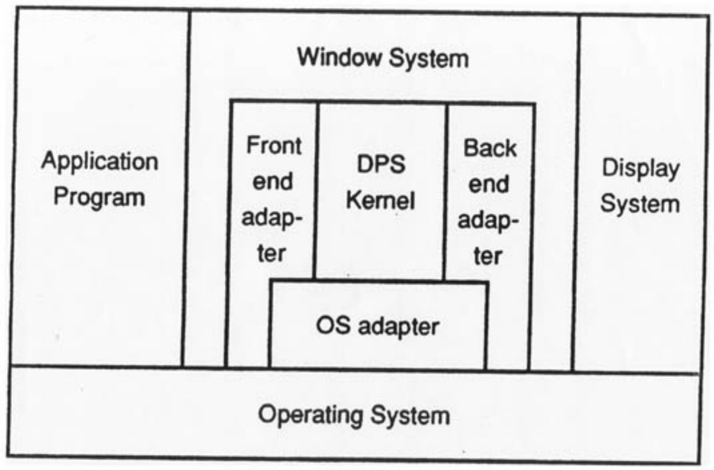

Figure 2. Display PostScript interpreter components.

An Overview of the DISPLAY POSTSCRIPT™ System, Adobe Systems Incorporated, March 16, 1988, P. 10

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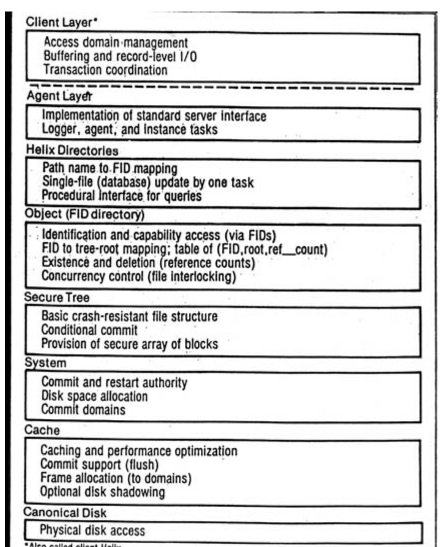

Figure 2. Abstraction layering.

IEEE Software, "Helix: The architecture of the XMS Distributed File System, Marek Fridrich and William Older, May 1985, Vol. 2, No. 3, P. 23

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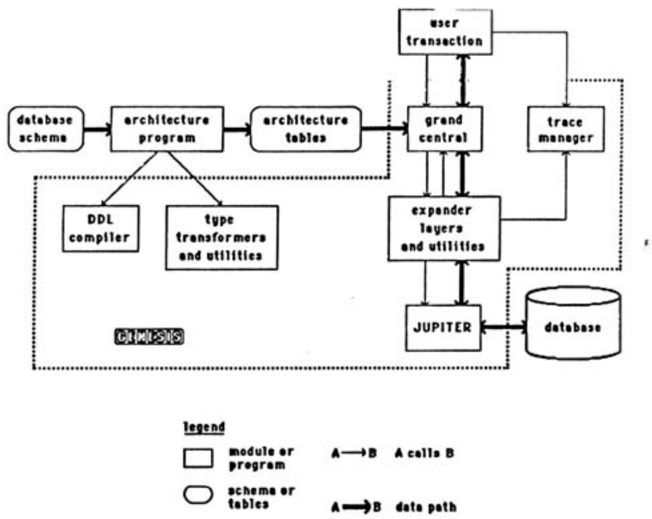

Figure 3.1 The Configuration of the GENESIS Prototype

Genesis: A Reconfiguration Database Management System, D. S. Batory, J.R. Barnett, J.F. Garza, K.P. Smith, K. Tsukuda, B.C. Twichell, T.E. Wise, Department of Computer Sciences, University of Texas at Austin,

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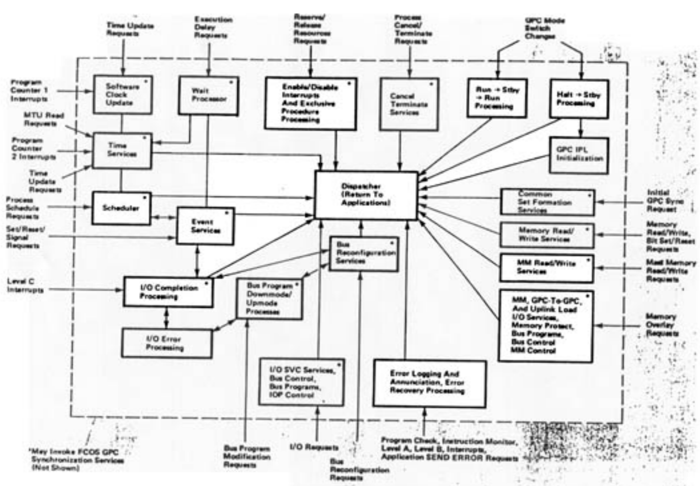

FIGURE 7. Flight Computer Operating System (The FCOS dispatcher coordinates and controls all work performed by the on-board computers.)

Communications of the ACM, "Architecture of the Space Shuttle Primary Avionics Software Systems," Gene D. Carlow, September 1984, Vol. 27, No. 9, P. 933

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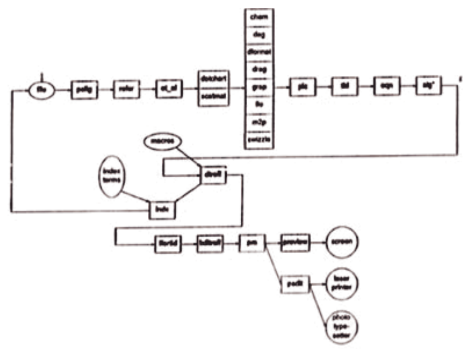

*Thanks to Dan Berry

This Talk

- The Challenge for Software Architecture
  - Today's practice
  - What is needed
- Research Themes (Part 1)
  - Notations and tools for software architecture
  - Architecture-based analysis
- Research Themes (Part 2)
  - Architecture-based dynamic adaptation

Joint Work

- Staff
  - Bradley Schmerl
- Graduate Students
  - Robert Allen
  - Owen Cheng
  - George Fairbanks
  - Vahe Poladian
  - Bob Monroe
  - Bridget Spitznagel

Issues Addressed by an Architectural Design

- Decomposition of a system into interacting components
  - typically hierarchical
  - using rich abstractions for component interaction or system "glue"
- Emergent system properties
  - performance, throughput, latencies
  - reliability, security, fault tolerance, evolvability
- Rationale and assignment of function to components
  - relates requirements and implementations
- Envelope of allowed change
  - "load-bearing walls", limits of scalability and adaptation
  - design idioms and styles

The Challenge

How can we establish intellectual control over this world?

- Express architectural descriptions precisely and intuitively
- Provide soundness criteria & tools to check them
- Analyze architectural designs to determine key properties
- Exploit patterns and styles
- Guarantee conformance between architecture and implementation

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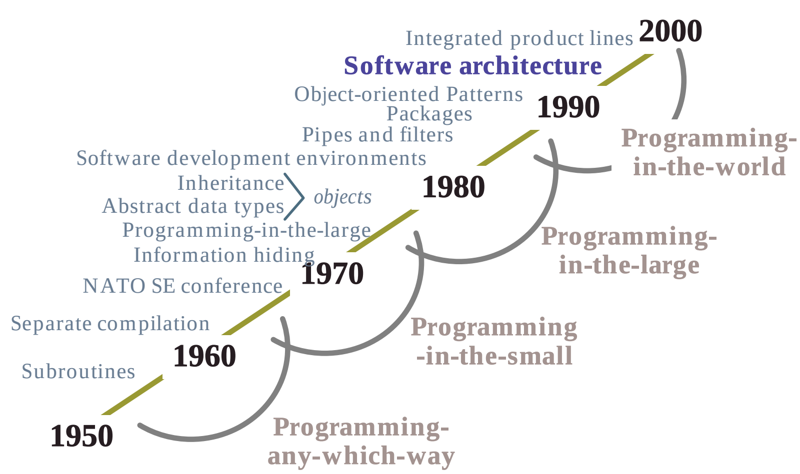
Software Architecture in Context



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Today's Practice

- Growing recognition of role of sw architecture
  - Architect as distinct job title
  - Architectural design reviews part of sw devel processes
  - Investment in product lines and frameworks
  - Courses, textbooks, certificates, conferences
- Standard notations and techniques
  - UML 2.0
    - supporting object-oriented arch modeling
  - "Model-driven architecture,"
    - addressing platform independence
  - Middleware and integration standards
    - enabling component composition

But …

- Notations are largely informal
  - Meager analytical capability
  - No way to check/enforce compatibility with implementation
  - Hard to maintain architectural integrity over time
- There are few tools for the architect
  - Supporting scalability
  - Tailorable to domain and product family
  - Allowing flexible tool integration and analysis
  - Enabling code generation and conformance checking

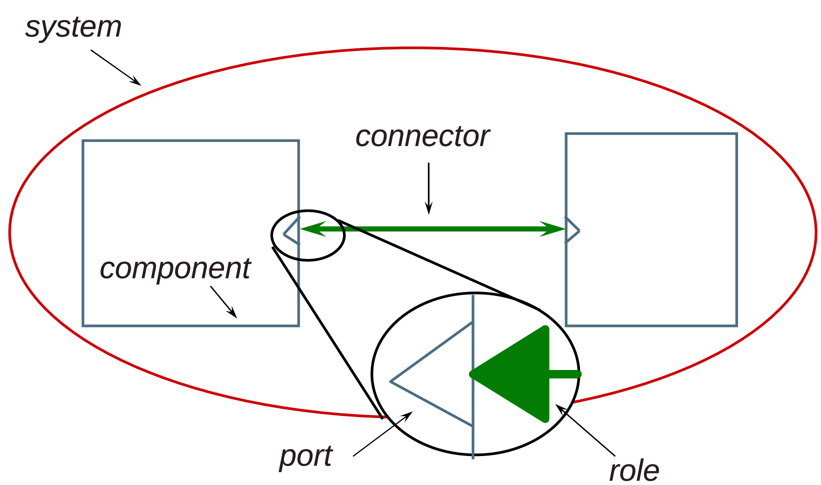
Research Themes (Part 1)

- Formal representation of software architecture
  - Precise definition of high-level system designs
    - Identify design flaws early in lifecycle
    - Specify rules for domain-specific architectural frameworks
  - Architecture-based analyses
    - Reliability, performance, framework conformance,…
- Tools to support software architects
  - Graphical and textual interfaces for creating and maintaining architectures
  - Integration platform for architecture-based analyses and code generation for frameworks

Architectural Views

- There are many possible “views” of software architecture
  - Implementation structures
    - Modules, packages, work units
    - Uses, contains, specializes relations
  - Run-time structures
    - Components, connectors
    - Interactions, quality attributes
  - Deployment structures
    - Hardware, processes, networks
- We focus on Component & Connector (C&C) Views

Representing C&C Views



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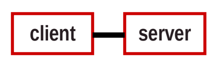
Modeling Structure




```
System simple-cs = {
  Component client = { port call-rpc; };
  Component server = { port rpc-request; };
  Connector rpc = {
     role client-side;
     role server-side;
  };
  Attachments = {
     client.call-rpc to rpc.client-side;
     server.rpc-request to rpc.server-side;
  }
}
```

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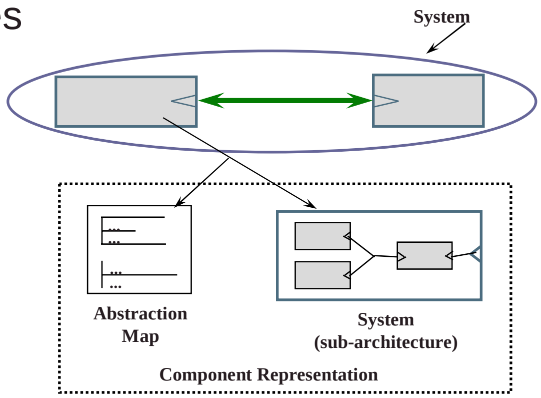
Representations

- Provide hierarchical element abstractions
- Can represent (multiple) sub-architectures



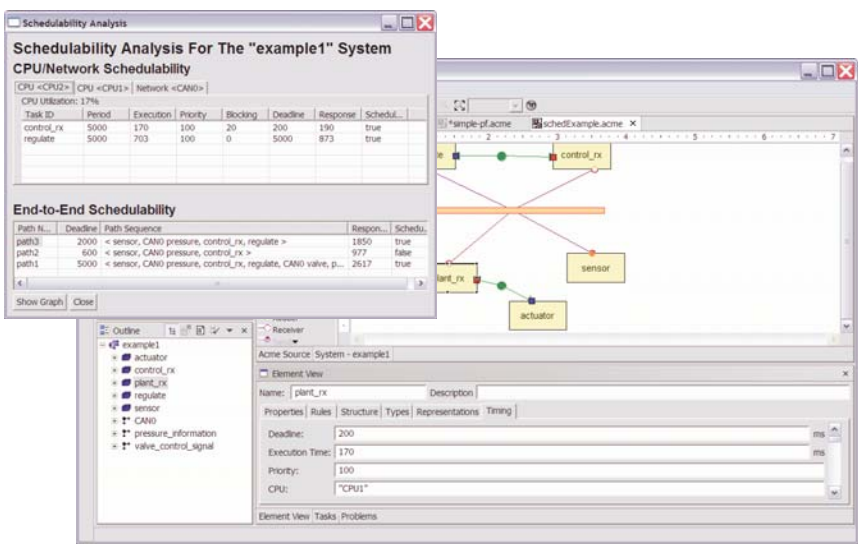
Beyond Structure

- Annotate structure with properties
  - Quality attributes (e.g., performance, reliability)
  - Behavior (e.g., protocols of interaction)
  - Interface details (e.g., required and provided services)
- Properties can then be analyzed by tools
  - Schedulability analysis
  - Reliability analysis
  - Deadlock and race condition detection

Properties

```
System simple-cs = {
  …
  Component server = {
    port rpc-request = {
      Property sync-requests : boolean = true;
    };
    Property max-transactions-per-sec : int = 5;
    Property max-clients-supported : int = 100;
  };
  Connector rpc = { …
    Property protocol : string = "aix-rpc";
  }; …
};
```


Schedulability Analysis



Modeling Architecture Behavior

- Key idea: represent behavior as protocols
  - For connectors define separate protocols for each role and for the "glue" that binds them together
  - For components define protocols for ports and for the overall component behavior
- Can then check (using model checkers)
  - Consistency freedom of connectors
  - Compatibility of component interface to connector interaction protocol
  - Consistency of a component behavior to its interfaces

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Representing Behavior

- Which is the reading/writing end of the pipe?
- Is writing synchronous?
- What if F_2 tries to read and the pipe is empty?
- Can F_1 choose to stop writing?
- Can F_2 choose to stop reading without consuming all of the data?
- If F_1 closes the pipe, can it start writing again?
- If F_2 never reads, can F1 write indefinitely?

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Specifying Connector Behavior

Wright: a variant of CSP (Hoare 85)

- Events: e, request, read?y, write!5
- Processes: P, Reader, Writer, Client, §
  - Sequence: e → P, P ; Q
  - Choice: P ⊓ Q, P [] Q
  - Composition: P || Q

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Example: A Pipe Connector

Connector Pipe
Role Writer = (write!x → Writer) ⊓ (close → §)
Role Reader = Read ⊓ Exit
where Read = (read?x → Reader) [] (eof → Exit)
Exit = close → §
Glue = Writer.write?x → Glue []
Reader.read!y → Glue []
Writer.close → ReadOnly []
Reader.close → WriteOnly
where ...

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Architectural Styles

- Architectural styles represent families of systems
  - Vocabulary of component and connector types (clients&servers, pipes&filters, …)
  - Properties of interest and shared analyses
  - Constraints on topology and properties
- Most systems are instances of styles
  - Sometimes generic (3-tired client-server, …)
  - Often domain-specific (power-train controllers, …)

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Representing Styles

- Augment notation with
  - Component, connector, and property types
  - Constraints
- Constraints
  - First-order predicates over architecture structure and properties
  - Augmented with architectural primitives to simplify expressions

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Styles/Families

```
Family PipeFilterFam = {
     Component Type filterT = {
        Ports {In,Out};
        …};
     Connector Type pipeT = {
        Role Reader = {Property datatype = …};
        Role Writer = {Property datatype = …};
        Invariant
          self.Reader.datatype =
               self.Writer.datatype;
        …}
 System myPF-System : PipeFilterFam = {…}
```

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Example: MDS

- MDS defines an architectural framework for a family of NASA space systems
  - System of architectural component types
  - Rules on how they can be connected
  - Run-time infrastructure for executing MDS systems
  - Reusable code base
- Checking/ensuring conformance to MDS is an important and hard problem
  - Many rules, many components, complex topology
  - Mapping between architectural design and code is non-trivial

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Formal Modeling of MDS

- Acme used to specify the MDS style
  - 8 Component types (sensor, actuator, estimator …)
  - 12 Connector types (measurement query, command submit, state update)
- MDS rules defined using Acme constraints
  - Ten "rules" from MDS designers become 38 checkable predicates
- AcmeStudio for tool support
  - Eclipse-based graphical editor, constraint checker, tool plug-ins

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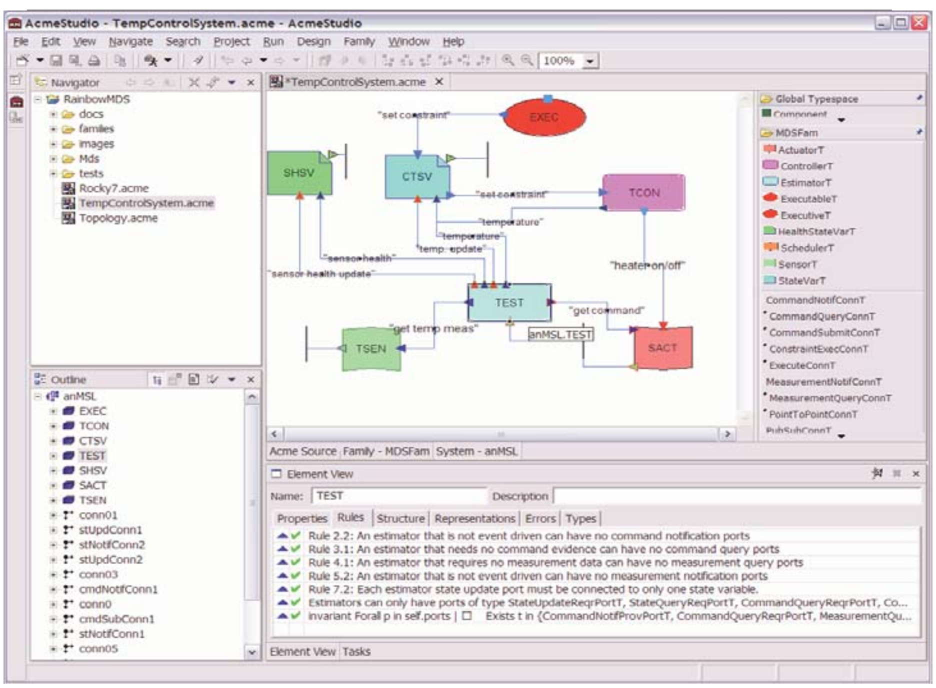
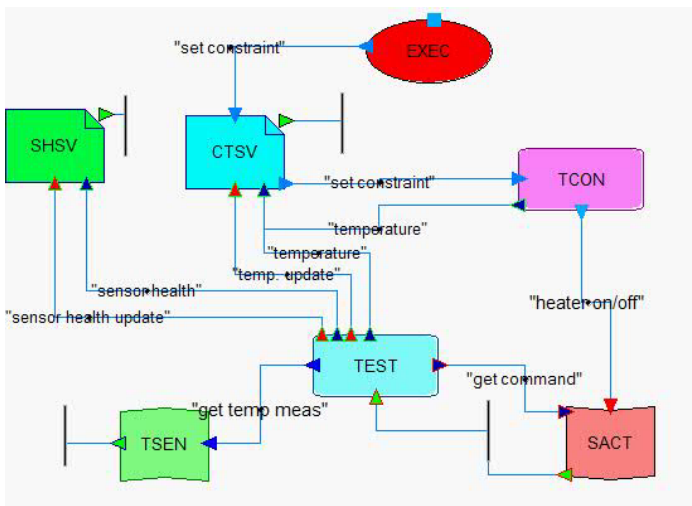


Temperature Control System



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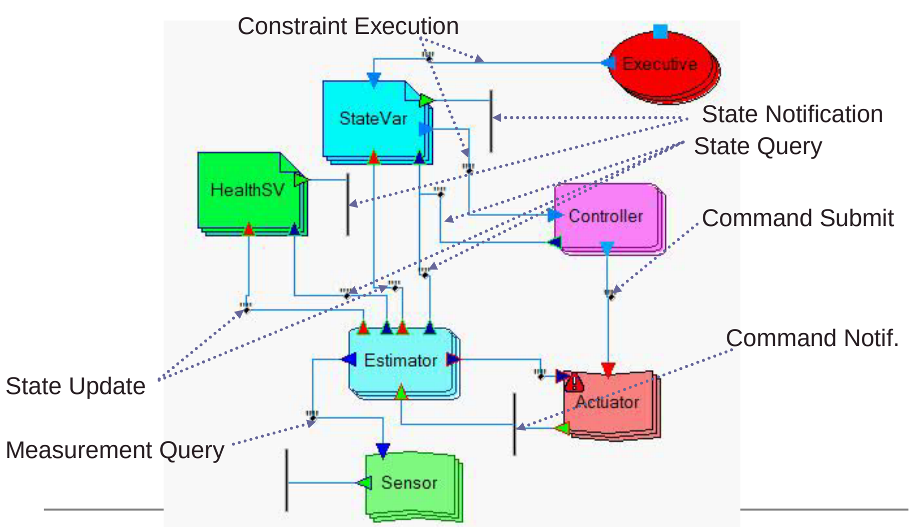
The MDS Style



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MDS Rules

- As specified by MDS designers:

  "For any given Sensor, the number of Measurement Notification ports must be equal to the number of Measurement Query ports (rule R5A)."

- Acme rule (associated with the sensor component type)

  numberOfPorts (self, MeasurementNotifReqrPortT) ==
  numberOfPorts (self, MeasurementQueryProvPortT)

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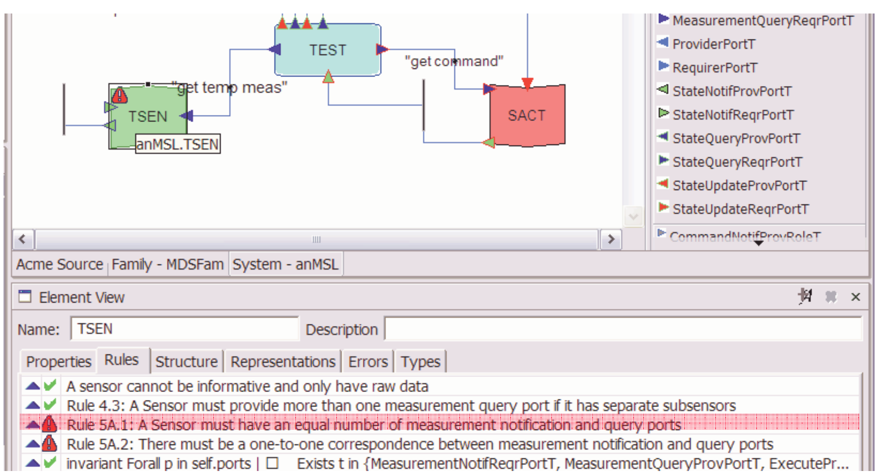

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More MDS Rules

- Rule 4:"Every estimator requires 0 or more Measurement Query ports. It can be 0 if estimator does not need/use measurements to make estimates, as in the case of estimation based solely on commands submitted and/or other states. Every sensor provides one or more Measurement Query ports. *It can be more than one if the sensor has separate sub-sensors and there is a desire to manage the measurement histories separately.* For each sensor provided port there can be zero or more estimators connected to it. It can be zero if the measurement is simply raw data to be transported such as a science image. It can be more than one if the measurements are informative in the estimation of more than one state variable."

More MDS Rules

- As specified by MDS designers:

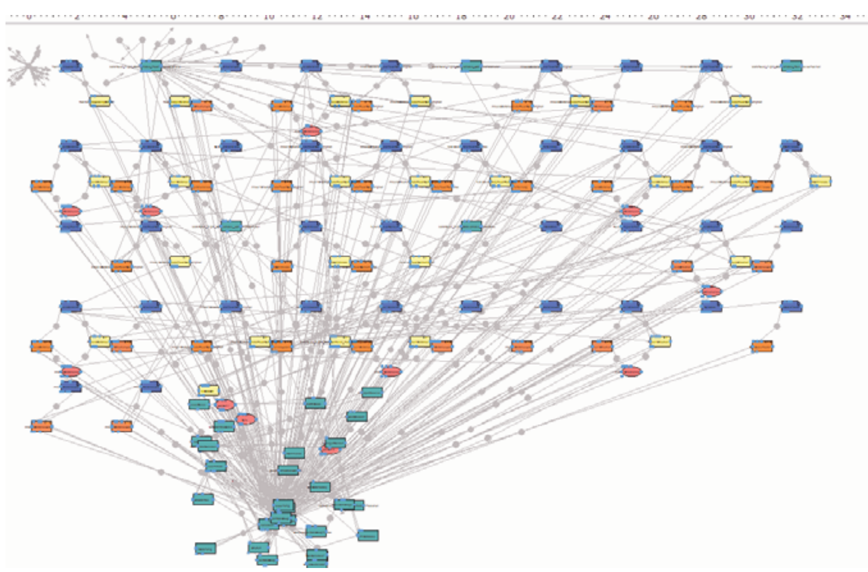
  "…It can be more than one if the sensor has separate sub-sensors and there is a desire to manage the measurement histories separately…."
- Acme rule (associated with the sensor component type):

  (numberOfPorts(self, MeasurementQueryPort) > 1)
  →
  self.manageHistoriesSeparately AND
  hasCommandableSubunits(self));

  where hasCommandableSubunits = …

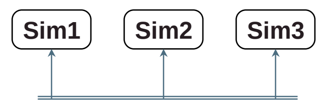
On-going Work

- Scaling up to realistic systems
  - Thousands of components
- Tools to refine architectures to code
  - Ensure implementation conforms to architecture
  - Reuse large body of framework code
- Analyses
  - Schedulability, power consumption, footprint
  - Requirements coverage



Example: Distributed Simulation

- Distributed simulation
  - simulation is a multi-billion $ industry
  - critical problem for DoD (and others) is multi-vendor interoperability
  - envision ~1000 cooperating simulations
- The "High-Level Architecture" (HLA)
  - Defense Modeling and Simulation Office (DMSO)
  - standard -- about 250 pages
  - http://www.dmso.mil/docslib/hla
  - each page defines 1 API call



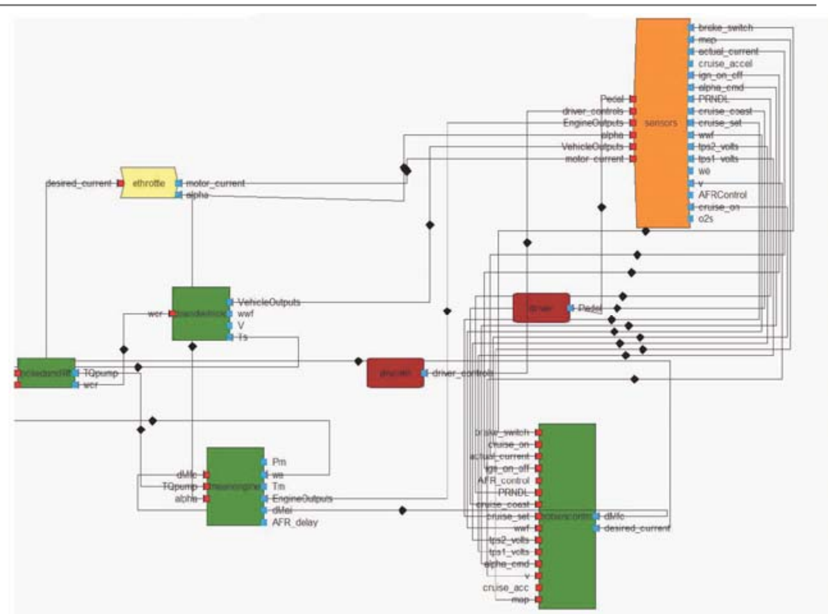
Classification of Findings

- Ambiguity/imprecise wording 28
  - critical reading, Wright, other
- Inadequate pre-/post-conditions 12
  - critical reading
- Missing information 20
  - critical reading, Wright, FDR
- Race conditions 5
  - FDR, Wright
- Errors (invariant violation, unexpected conseqs) 11
  - critical reading, Wright, other
- Misc (typos, impl warnings, doc^n inconsistencies) 11
  - critical reading ,Wright, FDR

87 issues

Example: Ford Model-based Design

- Worked with Ford Motor Company to develop tools for design of automotive control systems
- Two layered model
  - abstract, platform-independent
  - concrete, component model
- Tools to map between them
  - Component selection
  - Automatic “hook-up”
  - Creation of composite Simulink models
- Estimated savings
  - “what used to take 6 months now takes a week”



Beyond Static Analysis

- We are making great progress in design-time techniques for improving traditional systems
- But … increasingly, systems
  - are composed of parts built by many organizations
  - must run continuously
  - operate in environments where resources change frequently
- For such systems, traditional methods break down
  - Exhaustive verification and testing not possible
  - Manual reconfiguration does not scale
  - Off-line repair and enhancement is not an option

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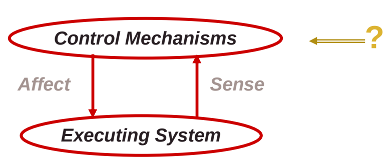
Research Themes (Part 2)

- Goal: systems automatically and optimally adapt to handle
  - changes in user needs
  - variable resources
  - faults
  - mobility

But how?

Answer: Move from open-loop to closed-loop systems



Architecture-based Self-repair

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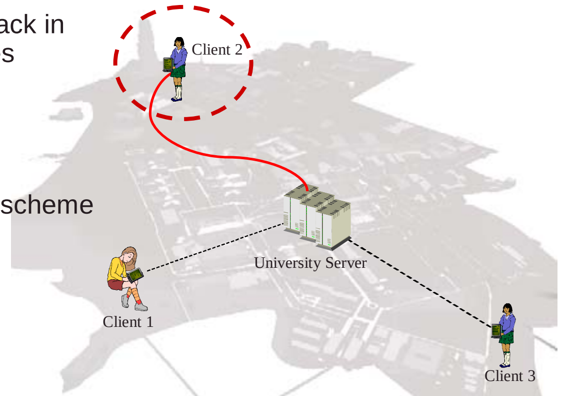
Example: University Grade System

- Students using University web
  - University aims to provide timely and ubiquitous access
  - One student tries to hack in and change her grades
- Possible (escalating) responses:
  - Turn on auditing
  - Switch authentication scheme
  - Sandboxing
  - Move grades data
  - Close off connections
  - Partition network
  - Turn off services



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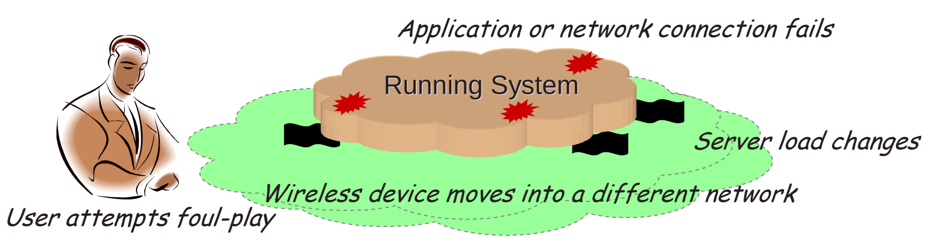
Many Things Can Go Wrong

- Resource variability
- Changing environments
- Shifting user needs and intents
- System faults



The system should dynamically adapt to these problems.

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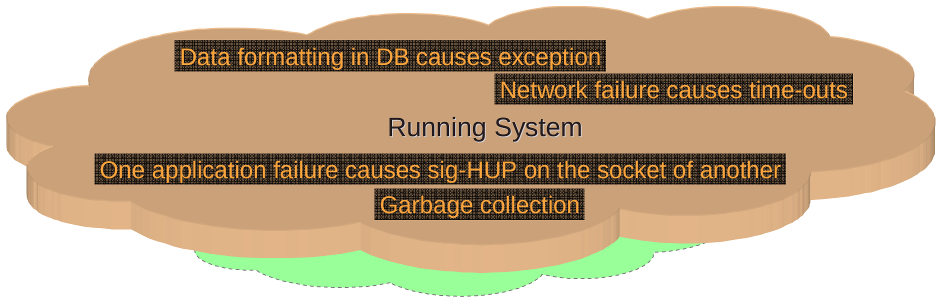
Traditional, Internal Mechanisms

Limitations
- Detection limited to localized view of system
- Outcome difficult to reason about
- Costly or infeasible to modify existing system
- Difficult to reuse logic for new system

- Exception handling
- Network time-outs
- Signal and interrupt
- Memory management



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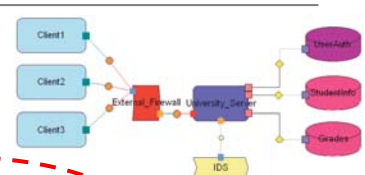
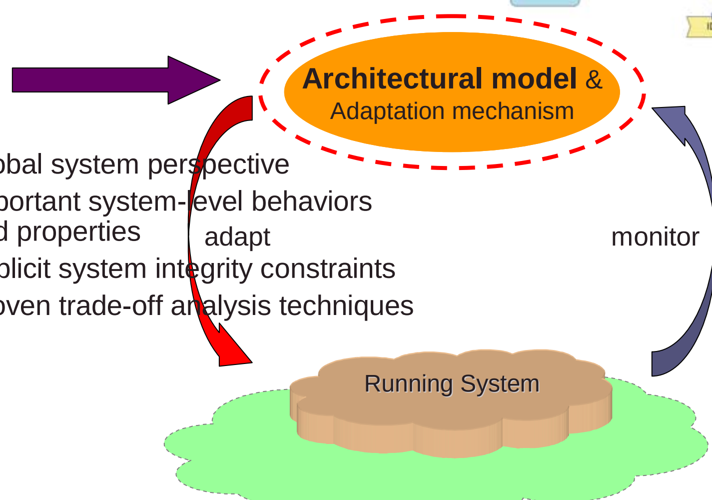
External Adaptation





- Global system perspective
- Important system-level behaviors and properties
- Explicit system integrity constraints
- Proven trade-off analysis techniques

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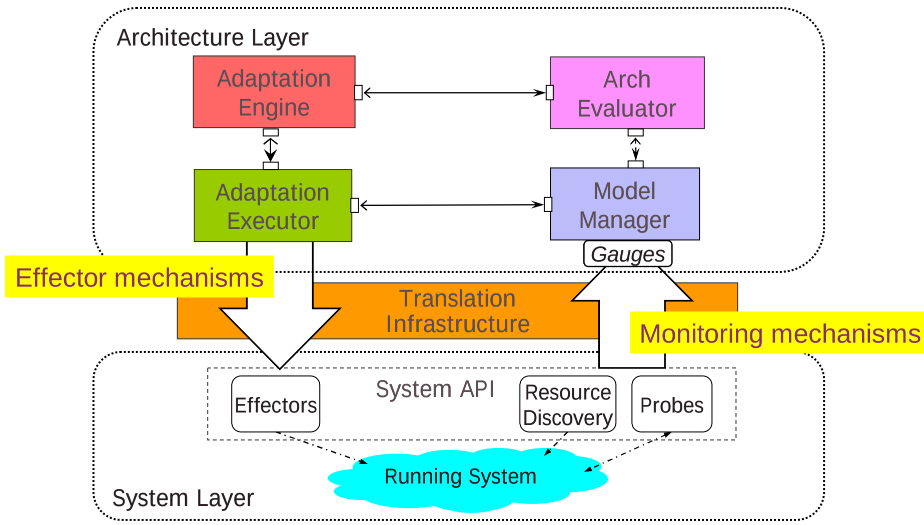
Rainbow



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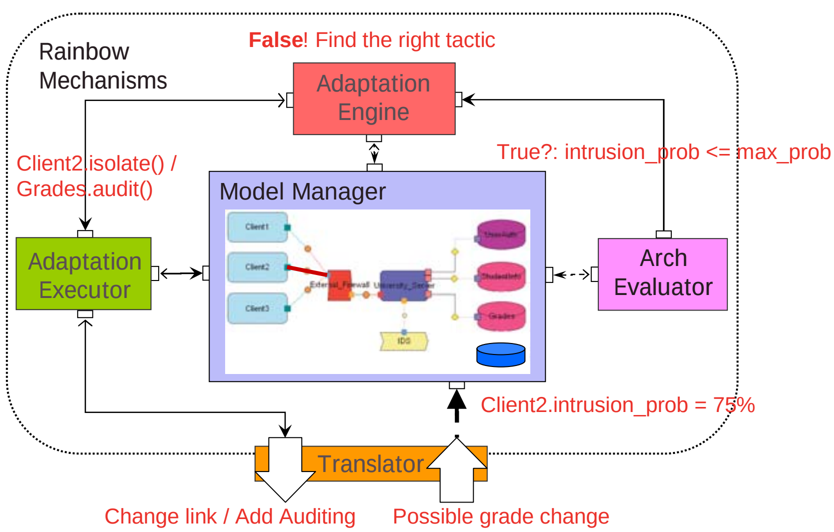
Rainbow Illustrated – Intrusion Detection



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Research Challenges

- One size does not fit all
- Ideally the approach should
  - apply to many architecture and implementation styles
    - Generality
  - facilitate adding self-adaptation capabilities to existing software systems at low cost
    - Cost-effectiveness
  - support run-time trade-off between multiple adaptation goals
    - Composablity

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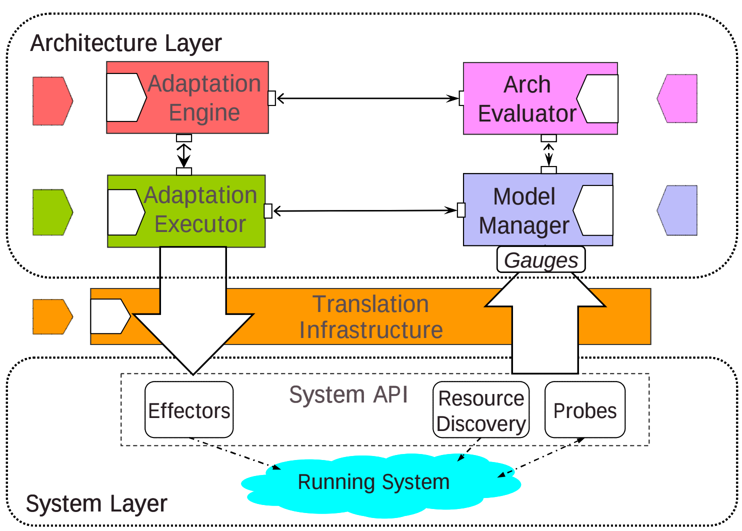
Our *Rainbow* Approach (2)



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Rainbow as a Tailorable Framework

- General framework with
  - *Reusable* infrastructure + *tailorable* mechanisms

  ⇩

  Specialized to targeted
  - system + adaptation goals
- Main components
  - Monitoring mechanisms
  - Model manager
  - Architectural evaluator
  - Adaptation engine
  - Effector mechanisms
  - Translation infrastructure

What's tailored

- Properties, probes & gauges
- Vocabulary of model
- Architectural constraints
- Strategies & tactics
- System change operators
- Arch-system mappings

Progress To Date

- Rainbow prototype
  - Developed and integrated mechanisms
  - Tested control cycle
  - Demonstrated usefulness for specific adaptation scenarios
- Case studies
  - Three styles of system
    - Client-server, service-coalition, data repository
  - Three kinds of adaptation goals
    - Performance + security + cost
- Adaptation language under development

Some Research Challenges

- Modeling
  - Architectural “recovery” at run time
  - Environment modeling and scoping
  - Handling multiple models and dimensions of concern
- Capabilities of the adaptation infrastructure
  - Efficient, scalable constraint evaluation
  - Timing issues (non-deterministic arrival of system observations, change latencies)
  - Avoiding thrashing
- Advanced features
  - Reasoning about the correctness of adaptation
  - Adapting the adaptation strategies

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Other Software Architecture Research

- Architectures for emerging systems
  - *Pervasive computing* – thousands of heterogeneous computing elements
  - *Service oriented computing* – highly dynamic, highly distributed
- Architecture conformance and discovery
  - How can we ensure that a system has its advertised architecture?
- Methods and processes
  - Architecture-centric development

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The END

Software architecture has come a long way.

There remain many challenges.

We examined two research threads

- Modeling architectures:
  - Representation and Analysis
  - Practical tools
- Run-time adaptation:
  - The reusable, tailorable **Rainbow** framework

Many more exist!

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