ISR Institute for Software Research
UNIVERSITY OF CALIFORNIA, IRVINE

Autonomous, Self-Adaptive Software: Architecture-based Tools, Techniques, and Methods

John Georgas, (Eric Dashofy)
Institute for Software Research
University of California, Irvine

May 6, 2004

Outline

- **Software Dynamism**
- Software Architecture
- Architecture-Based Approach
  - Evolution Management
  - Adaptation Management
- Summary

What is dynamism?

- The ability to the change the structure or behavior of a software system at run-time.
  - Generally, in ways not explicitly planned for in the initially deployed system.
- Dynamism is essential for high-availability systems.
  - Medical devices
  - Space probes
  - Emergency response systems
- Dynamism is desirable for all systems.
  - PC security patches, virus updates
  - Service packs and other functionality upgrades
  - MMORPGs
- Dynamism is <u>necessary</u> for self-adaptive systems.

Examples of Dynamic Systems

To this...

- Dynamic load/install plugins in Internet Explorer/Netscape
  - Generally, these work without shutting down the browser.
- Not-so-dynamic systems
  - Windows Update
    - On works without a reboot if resources weren't in use.
  - JPL ce Probe system updates
    - ire restart of many non-core systems.
  - A ion patches
    - not require a full reboot but generally require cation restart.

We would like to move from this...

Techniques for Dynamism

- Plug-in Mechanisms (e.g. Netscape/IE)
  - Generally, specific extensions to a core platform.
  - Core usually remains unchanged.
- Dynamic code loading (e.g. Java ClassLoaders)
  - Handle loading new code and unloading old code.
- Dynamic component instantiation (e.g. CORBA)
  - Generally, handles unloading poorly.
  - Makes understanding and managing changes difficult
    - Little change visibility.

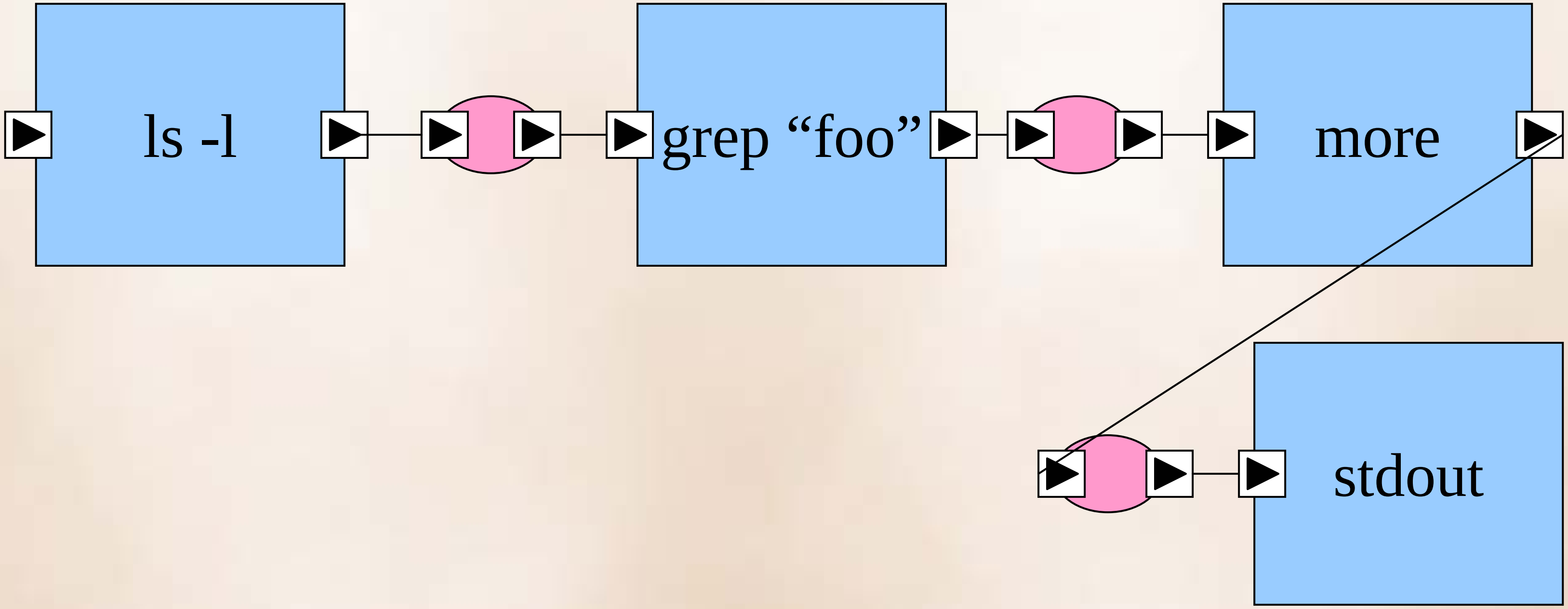
Outline

- Software Dynamism
- **Software Architecture**
- Architecture-Based Approach
  - Evolution Management
  - Adaptation Management
- Summary

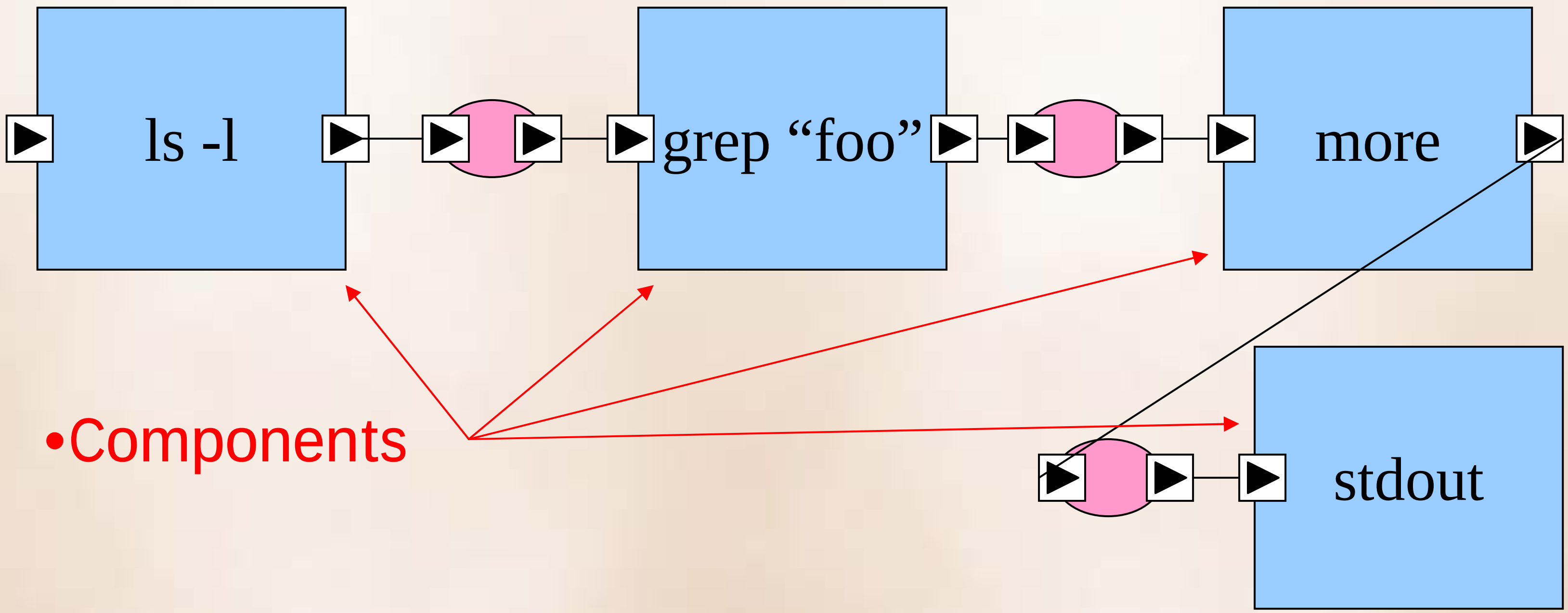
Architecture: A New Perspective

- Architecture views software systems at the level of components and connectors.
  - Not lines-of-code or modules.
  - Not objects.
- Architecture generally leverages explicit software models that depict at least:
  - Software Components
    - Including provided and required interfaces.
  - Explicit (generally) Software Connectors
    - Provided and required interfaces.
  - Explicit links between the two.
    - Links form various system configurations.

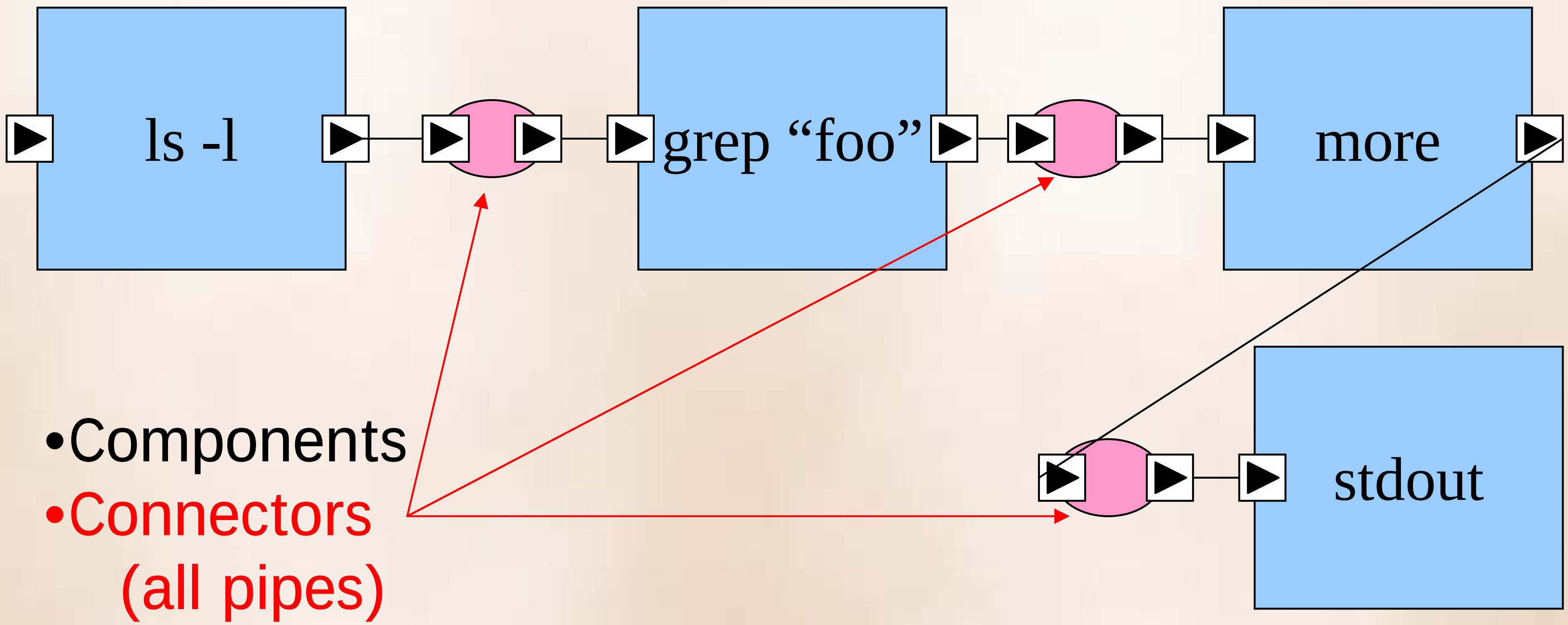
Example of an Architecture-level Depiction:



Example of an Architecture-level Depiction:

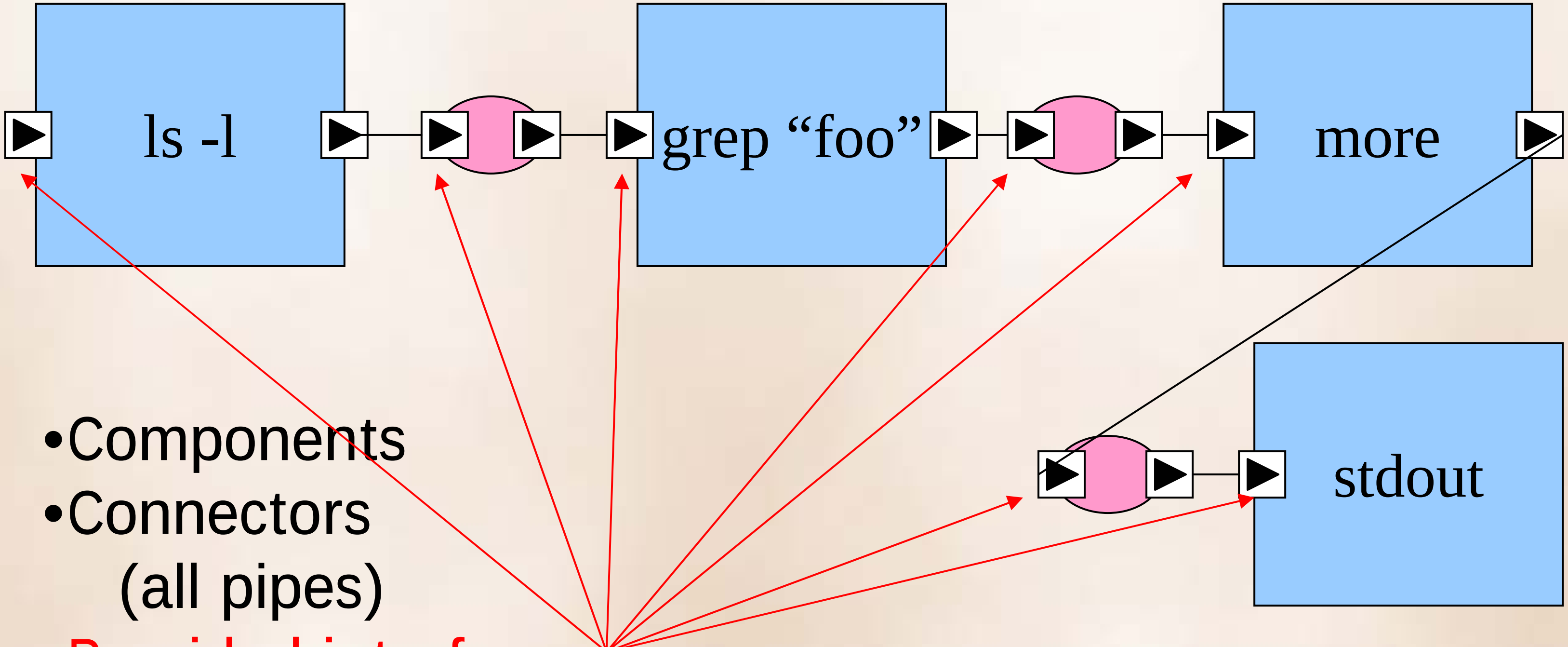


Example of an Architecture-level Depiction:



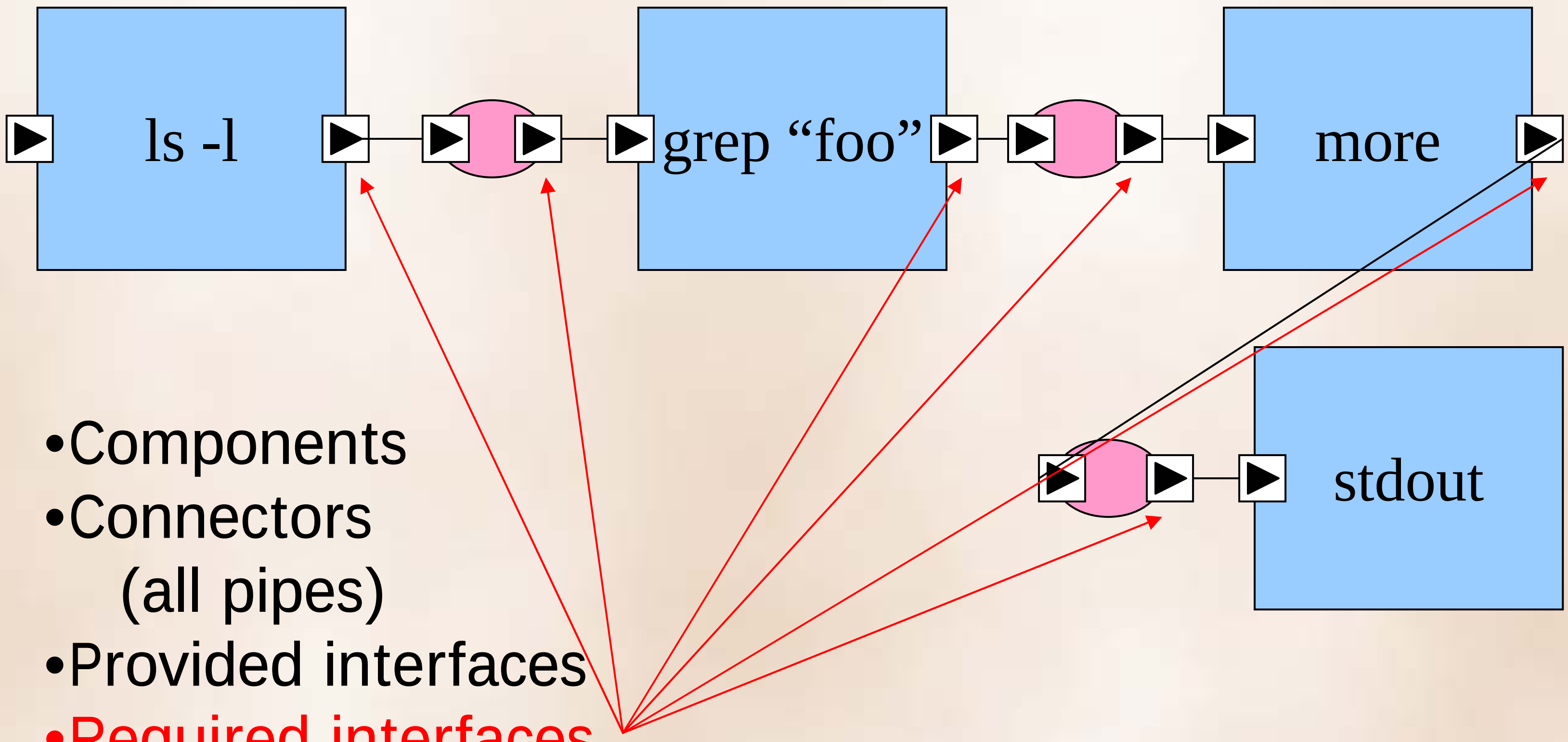
- Components
- Connectors (all pipes)

Example of an Architecture-level Depiction:



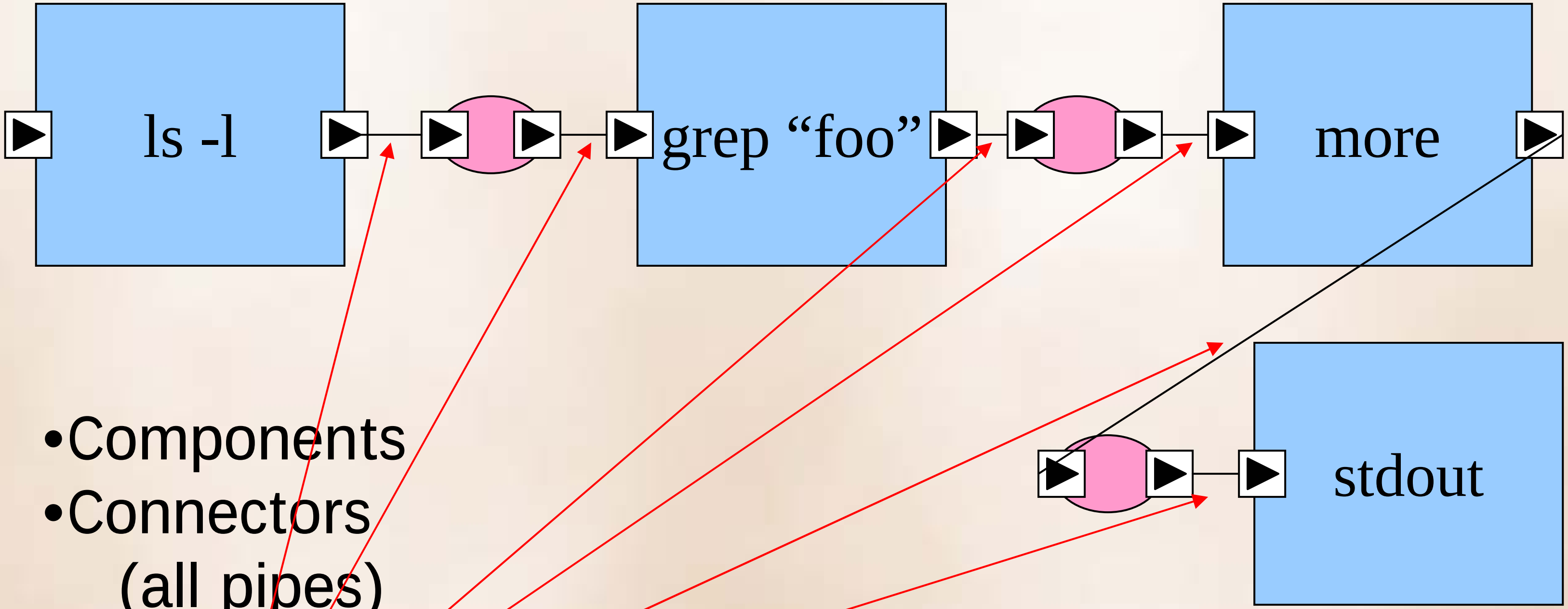
- Components
- Connectors (all pipes)
- Provided interfaces

Example of an Architecture-level Depiction:



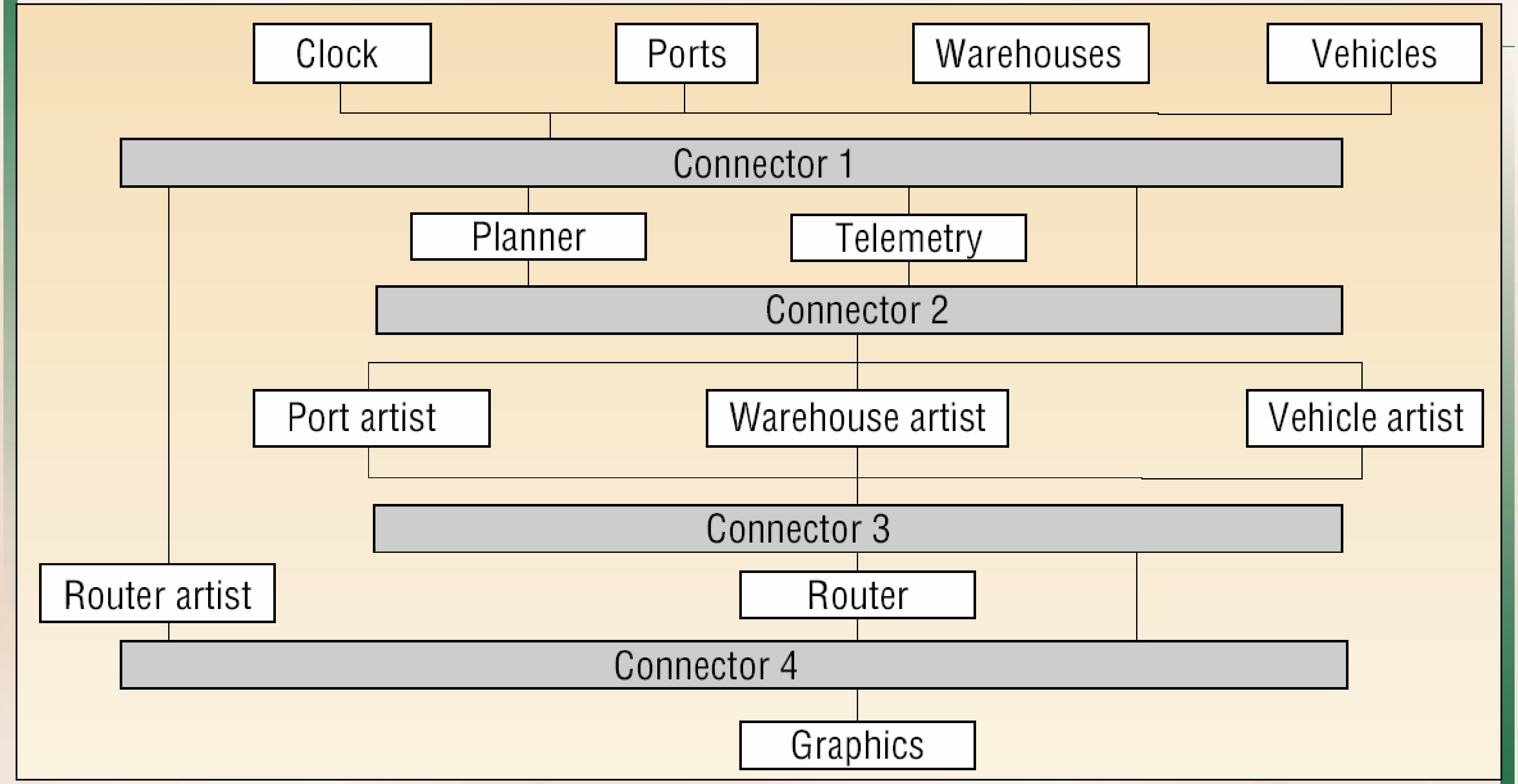
- Components
- Connectors
  (all pipes)
- Provided interfaces
- Required interfaces

Example of an Architecture-level Depiction:



- Components
- Connectors
  (all pipes)
- Provided interfaces
- Required interfaces
- Links

A slightly larger example



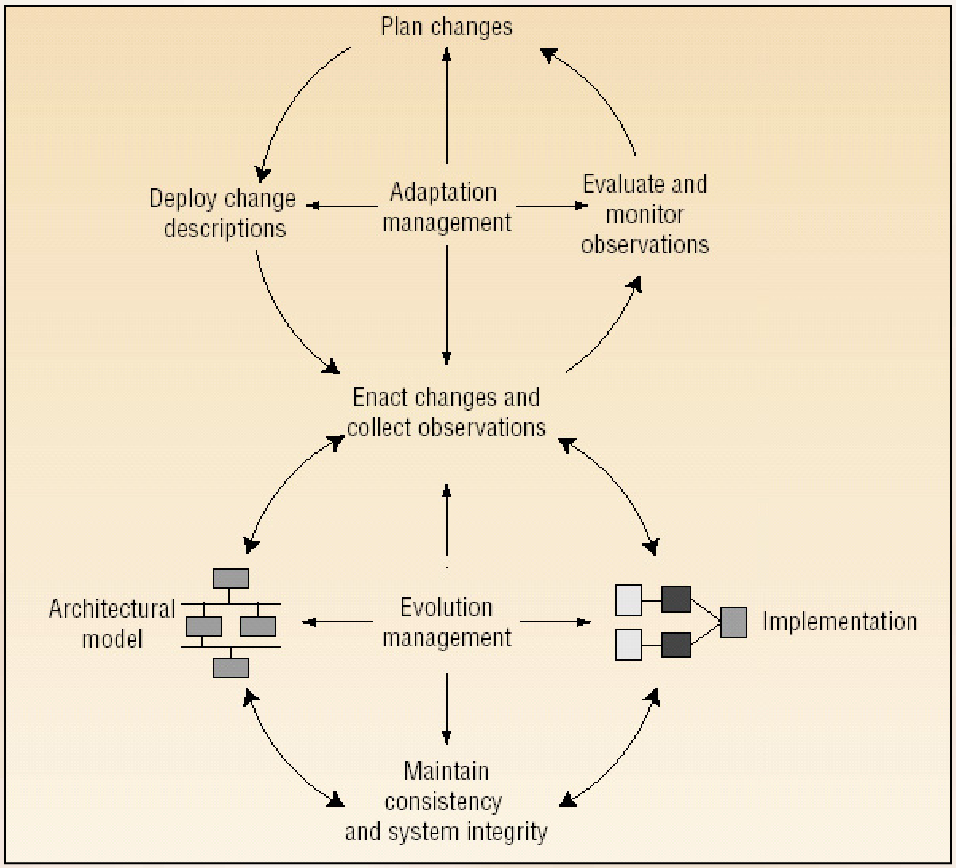
Outline

- Software Dynamism
- Software Architecture
- **Architecture-Based Approach**
  - Evolution Management
  - Adaptation Management
- Summary

Can we use architecture to manage and enact dynamism?

- Leverage architecture-level models to:
  - Understand and visualize the structure of the system.
  - Depict, visualize, and understand changes to that structure.
  - Guide automated tools in making changes to modeled components.
- Leverage the above concepts to:
  - Serve as the basis for self-healing/self-adaptive systems that make decisions and changes based on architecture-level models.

A Vision for Architecture-based Adaptation: The Figure-8 Diagram



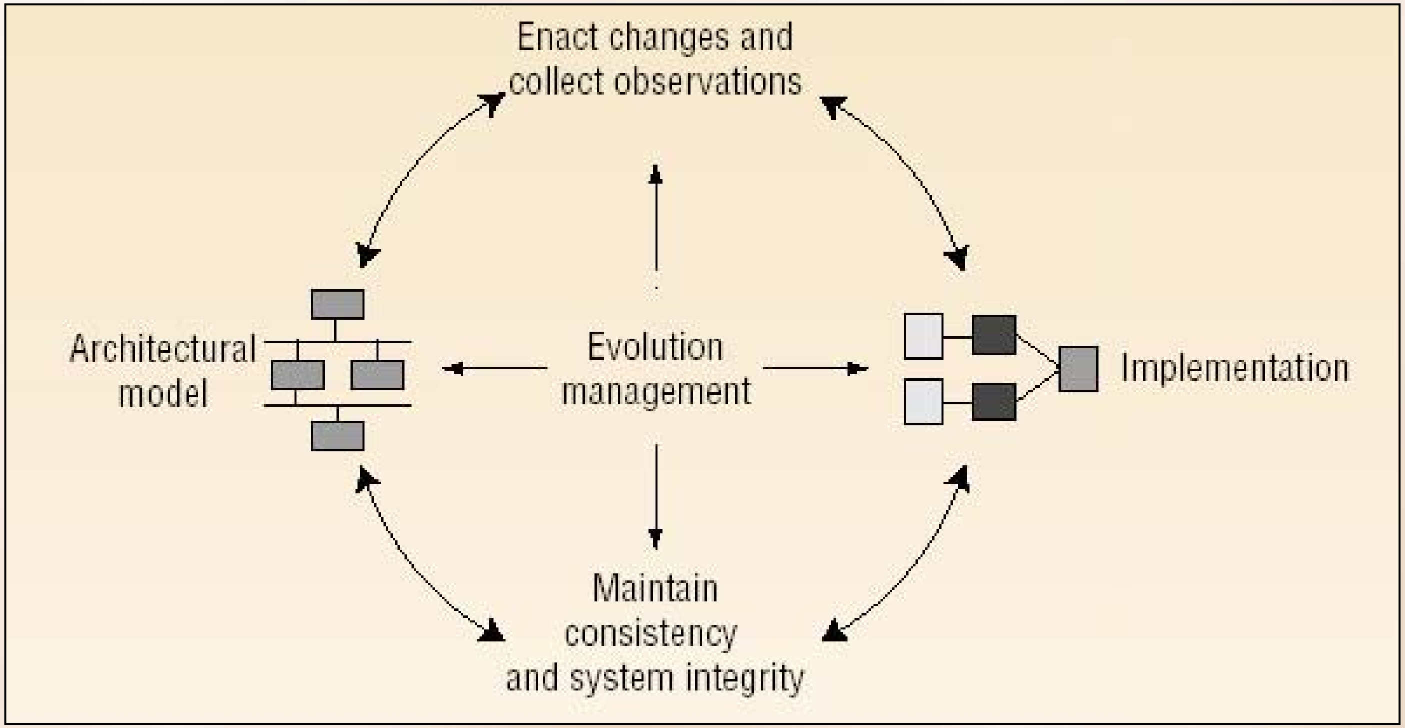
Feedback and Planning

Implementation Issues

Outline

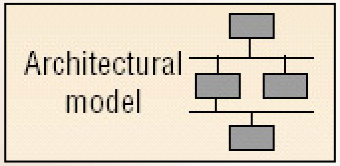
- Software Dynamism
- Software Architecture
- **Architecture-Based Approach**
  - **Evolution Management**
  - Adaptation Management
- Summary

First Focus: Bottom Half



Key Insight: Keep the model and the implementation in-sync: a change to one automatically results in a change to the other.

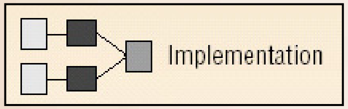
Assumptions Implicit in the Figure-8 Diagram



- There is a modeling language.
- It can be accessed programmatically.

Deploy change descriptions

- Change descriptions can be expressed and deployed to (multiple?) sites.

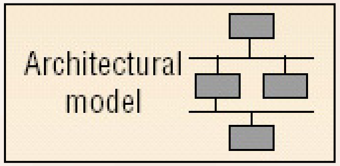


- There is an implementation framework that supports dynamic changes.

Maintain consistency and system integrity

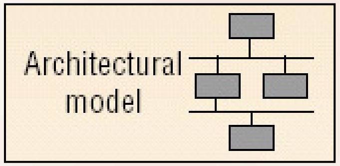
- There is a tool that can maintain model←→implementation consistency.

A Modeling Language



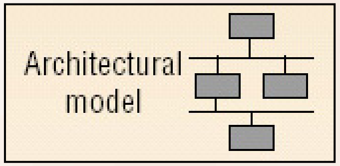
- Traditionally architectures are expressed in an Architecture Description Language (ADL):
  - A formalism that allows you to ‘write down’ architectures.
    - At minimum, must support:
      - Components
      - Connectors
      - Interfaces
      - Links
    - For our purposes, must also support some mapping to implementation.
  - Ideally, flexible enough to support many domains.

Problems with current ADLs

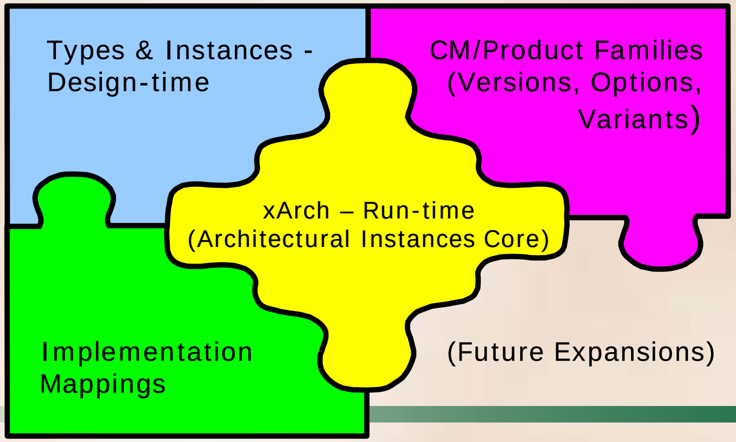


- Too broad.
  - Example: Acme
  - Supports arbitrary properties on elements, but only basic support for these properties
- Too narrowly-focused.
  - Examples: Rapide, Wright, Darwin, Meta-H, etc.
  - Support one domain or set of concerns well, others poorly.
  - Often lack implementation mappings.
- Not extensible.
  - Too hard to extend existing ADLs (and their tool-sets) to add information.

Our Solution: xADL 2.0



- An extensible, XML-based ADL.
  - Modeling features all expressed in language modules (XML schemas).
  - A composition of XML schemas make up an ADL.
  - Schemas available from UCI to support:
    - Design-time & run-time structural modeling.
    - Implementation mappings.
    - Product-line architectures (allows managing model evolution over time).



Change Descriptions

Deploy change descriptions

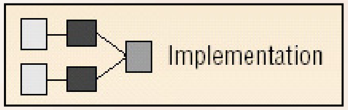
- Required to express and understand architectural changes.
- Different levels of change to consider:
  - Basic ‘diffs’
    - Describe changes between Model1 and Model2.
  - Product-Line ‘diffs’
    - Describe changes between Product-Line1 and Product-Line2.
  - Pattern-based ‘diffs’
    - Describe changes to patterns found in Model1 and and patterns found in Model2.

Our Change Descriptions

Deploy change descriptions

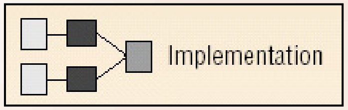
- We currently support:
  - Basic ‘diffs’
  - Product-line ‘diffs’
- Both implemented as extensions to xADL 2.0.
- Accompanied by automated tools:
  - Automatically generate diff documents from two architectures or product lines.
    - (the architecture equivalent of ‘diff’ on UNIX)
  - Automatically merge a diff into an architecture or product line.
    - (the architecture equivalent of ‘patch’ on UNIX)

Architecture Frameworks



- Bridge the gap between elements found in architectural styles
  - (components, connectors)
- ...and programming languages.
  - (classes, objects, procedure calls)
- Often support a particular architectural style or family of styles.
- For our purposes, should support run-time dynamism primitives (add/remove component, add/remove link, etc.).
- Potential candidates:
  - Component frameworks like COM, EJB, CORBA...

c2.fw: One such framework



- Architectural style(s):
  - Component- and message-based styles.
  - Special support for C2 style.
- Programming languages:
  - Java
  - (Other frameworks available for other languages)
    - C++, Embedded C++, Ada95, etc.
- Dynamism Primitives
  - Exposes a single, unified interface for adding/removing components, connectors, links, interfaces, etc.

Maintain Consistency

Maintain consistency and system integrity

- Tool must monitor both architectural model and running system:
  - When model changes (e.g. due to patching a diff), must modify the implementation to match.
  - When application changes (e.g. due to component failure or shutdown) must modify the model to match.
- Algorithms to accomplish this with different kinds of models and dynamism primitives are still being researched.

Architecture Evolution Manager

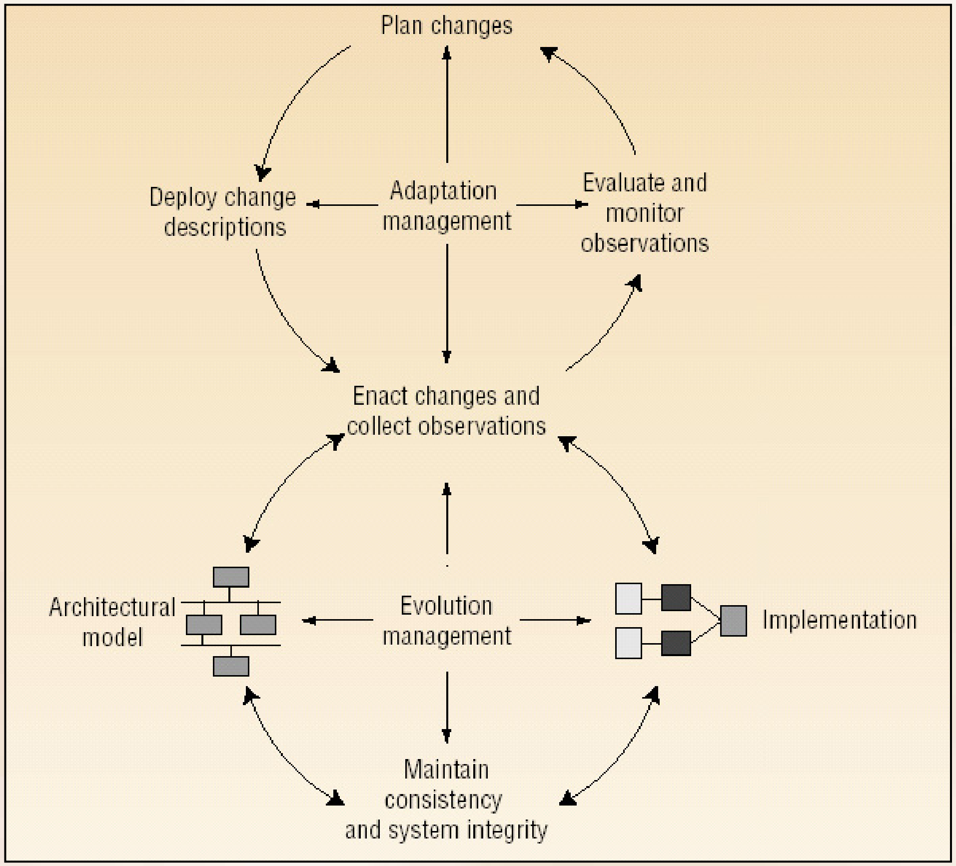
Maintain consistency and system integrity

- A component of our architecture-based development environment that performs this function.
- Currently supports local changes, will evolve to support distributed changes and things like maintaining component state across replacements/upgrades.

Open Dynamism Research Issues

- Distributed systems
  - Encounter many new types of failures—network failure, host failure, etc.
- Infrastructure adaptation
  - Can be partially addressed with a multi-level approach (AEMs running inside other AEMs).
  - We have a proof of concept in our current infrastructure.
- Maintaining state across component upgrade/replacement.
- Assessing/maintaining reliability.

A Vision for Architecture-based Adaptation: The Figure-8 Diagram



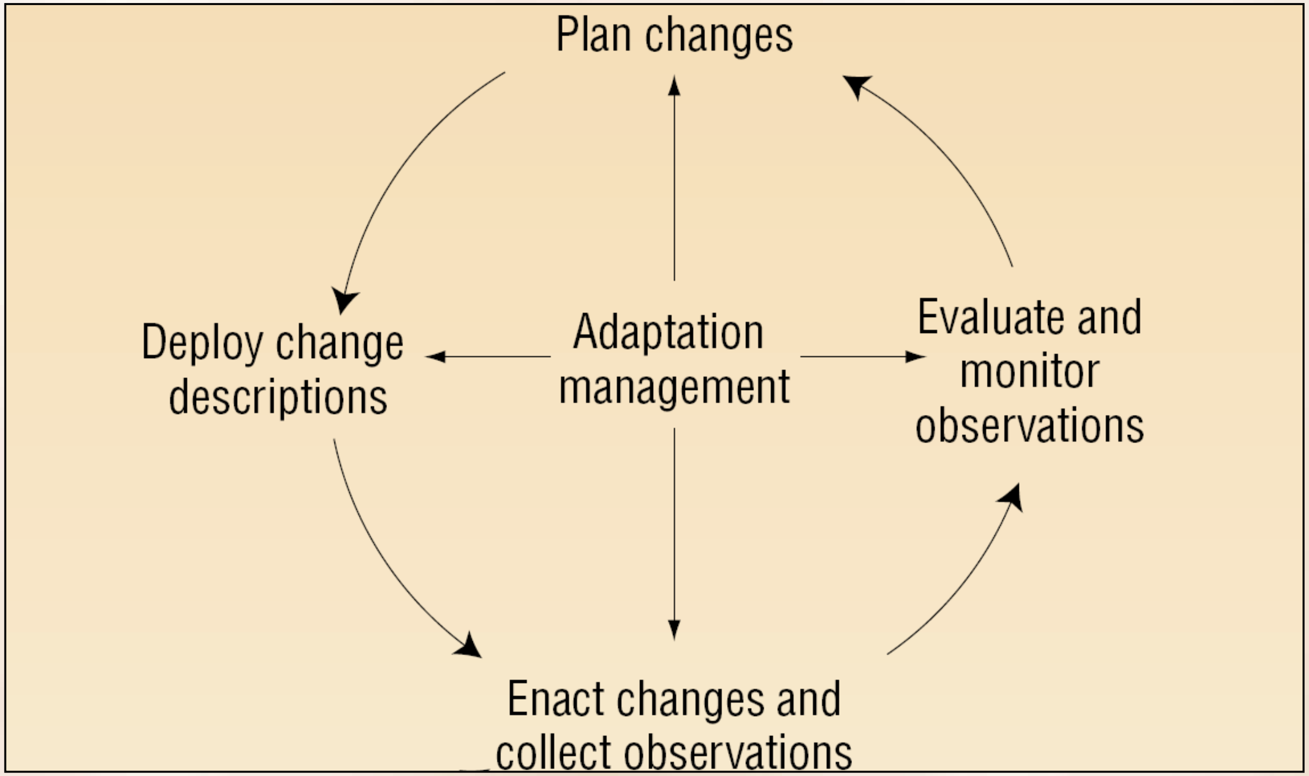
Feedback and Planning

Implementation Issues

Outline

- Software Dynamism
- Software Architecture
- **Architecture-Based Approach**
  - Evolution Management
  - **Adaptation Management**
- Summary

Second Focus: Top Half



Key Insight: Managing and planning adaptations is done at the architectural level, independent of the application semantics.

Implicit Assumptions

Enact changes and collect observations

- Changes can be enacted and observations collected.

Evaluate and monitor observations

- Observations can be evaluated for their meaning.

Plan changes

- Modifications can be planned according to some criteria.

Planning Changes

Plan changes

- Interesting questions:
  - *Who* is responsible?
    - System designers, administrators, users.
  - *When* should changes be enacted?
    - Pre-planned situations, user discretion.
  - *What* are the specifics?
    - Pre-planned change scripts, user-defined modifications.

Self-Adaptive Software

Plan changes

- Software that can modify itself in response to:
  - Software faults.
  - Changing deployment conditions.
  - New behavioral requirements.
- Modifications do not need human intervention.
- The system itself decides...
  - ...when changes need to take place.
  - ...what the specifics of these changes are.

Various Approaches

Plan changes

- Changes are pre-programmed into software components.
  - Little visibility, close coupling with implementations.
- Pre-planned change scripts.
  - Static responses for a non-static world.
  - Limited to the foresight of the system designer.
- Adaptive algorithms
  - Domain-specific solutions in a constrained environment.

The challenge lies in developing an approach that ensures high visibility, strict decoupling, and dynamic evolution.

A Knowledge-Based Approach: Overview

Plan changes

- An architecture-centric, knowledge-based approach which reasons about change based on *observations* and *policies*.
  - Observations comprise known information.
  - Policies define when modifications should take place and what the *responses* should be.
- Features:
  - High visibility
    - Knowledge and policies are specified as part of the system's architectural description.
  - Decoupled
    - Policies are strongly-decoupled from component implementations.
    - Components need not have any knowledge of adaptation.
  - Dynamic
    - Observations may be transient.
    - Policies may be added, removed, and composed.

Knowledge-based Adaptation Policies

Plan changes

- Policies determine the timing and specifics of adaptations.
- Knowledge-based policy structure:
  - Observation+ ➡ Response+
- Adaptation policies are specified at the architectural level, and can be dynamically modified at run-time.
- Representational support using xADL 2.0, and expert system implementation using the Java Expert System Shell (JESS). Again, fully extensible.

Adaptation Observations

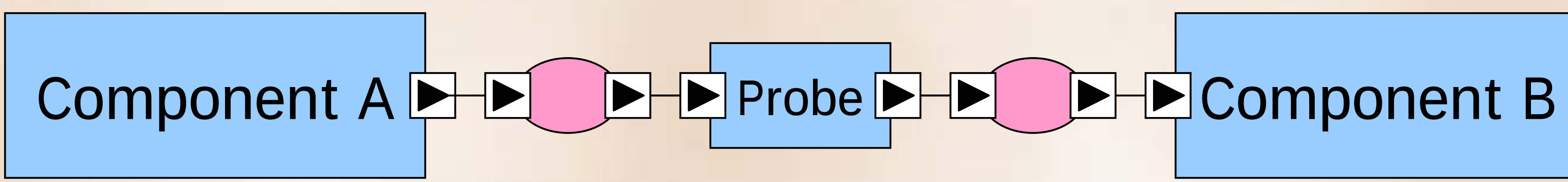
Evaluate and monitor observations

- Observations express architectural knowledge.
  - Events indicating non-nominal operation.
    - Component or connector failure.
  - Events indicating the structure of the architecture has changed.
    - Components and connector addition, link removal, etc.
  - Events which may indicate composition errors.
    - Requests and notifications go unanswered or ignored.
- These observations are supported by:
  - xADL 2.0 modeling extensions.
  - c2.fw implementation framework.
- But, they are easily extended to accommodate domain-specific information.

Collecting Observations

Evaluate and monitor observations

- May be emitted by components themselves.
- Collected using independent software probes.
  - May be dynamically inserted into the running system.
  - Primarily observe communication patterns.



Adaptation Responses

Enact changes and collect observations

- Responses indicate architectural modifications.
  - Addition of architectural elements (components, connectors, or links).
  - Removal of architectural elements.
  - Addition and removal of observations or adaptation policies.
  - Composite operations.
- Using these responses, the system can modify both:
  - Its structure, and therefore its behavior.
  - The policies guiding adaptations themselves.
- Again, supported by xADL 2.0 extensions and the c2.fw framework but also fully extensible.

Enacting adaptations

Enact changes and collect observations

- Modifications due to adaptation responses are not directly enacted. May need to...
  - Maintain architectural constraints.
  - Log and publish modifications.
- Architecture Adaptation Manager (AAM)
  - Point of coordination for these “value add” services.
- AAM (to be) included in the ArchStudio 3.0 toolkit.
  - Currently, coordinates constraint maintenance facilities.

A short example

Plan changes

- Unmanned Air Vehicle (UAV) with limited on-board resources.
- Operates software components supporting various tasks.
  - Nominal navigation.
  - Threat avoidance navigation.
  - Image processing.
  - Inter-networking management.
- In certain situations, some of these tasks take precedence.

An example policy

Plan changes

- Policy giving threat avoidance precedence.

```
<AdaptationPolicy id="Avoid_threats">
        <Description>Replace normal navigation.</Description>
        <Observation id="Threat_Detected" />
        <Response id="Replace_Component"
          old="Nominal_Nav" new="Threat_Avoidance_Nav"/>
</AdaptationPolicy>
```

- Observations
  - Domain specific: Threat Detected.
- Responses
  - Composite operation:
    - Remove Nominal navigation component.
    - Adding Threat Avoidance component in its place.

Open Research Issues

- Distributed systems
  - Can local adaptation decisions give rise to global adaptive behavior?
- Expressiveness
  - Is this knowledge-based approach expressive enough?
- Safety and Predictability
  - Given the non-deterministic nature of the approach, can guarantees about the system’s architecture be made?
  - Are constraints sufficient for this?

Outline

- Software Dynamism
- Software Architecture
- Architecture-Based Approach
  - Evolution Management
  - Adaptation Management
- **Summary**

Summary

- *Architectural* models are central not only to software development but also evolution.
- Architecture provides a promising approach for:
  - Dynamic, run-time system evolution.
  - Developing self-adaptive capabilities.
- "Proof of concept" techniques and tools:
  - xADL 2.0 architecture description language.
  - ArchStudio 3 environment.
  - Knowledge-Based Architecture Adaptation Management (KBAAM).