Software architecture

- Software architecture: design-based
  - Formal reasoning about properties
  - Static vs. dynamic architectures
- Software architecture: property-based
  - Autonomic systems
  - Relationship to model-based design

Two categories: very soft distinction

- Software architecture: design-oriented
  - Based in software design, in defining taxonomies based on experience, etc.
- Software architecture: property-oriented
  - Based on a desire to design software systems with a particular property — such as autonomic systems, fault-tolerance, privacy, etc.

Design-based software architecture

- Two primary goals
  - Capturing, cataloguing and exploiting experience in software designs
  - Allowing reasoning about classes of designs
- Composition of components and connectors
  - Components are the core computational entities
  - Connectors are the core ways in which components communicate and interact
  - Under constraints — only some combinations are permitted, which is intended to allow demonstration of the presence or absence of key properties
Describing architectures

- There are, roughly, two approaches to describing software architectures
- The first – and the most heavily explored – is to define an ADL – architecture description language
- The second is to extend a programming language with architectural constructs

Partial Comparison

<table>
<thead>
<tr>
<th>ADL</th>
<th>Extend PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Can focus on architectural issues</td>
<td>✓ Provides transition to adopt architecture for existing systems</td>
</tr>
<tr>
<td>✓ Can allow architecture-related analysis</td>
<td>✓ Connects architecture with program, reducing drift</td>
</tr>
<tr>
<td>✓ Separates architectural activities from lower-level activities</td>
<td>✓ Incremental cost to train developers, testers, etc.</td>
</tr>
<tr>
<td>✓ Separates architecture from software, allowing drift</td>
<td>✗ Fuzzier distinction between architecture and program</td>
</tr>
<tr>
<td>✗ Requires additional learning and experience by developers, testers, etc.</td>
<td>✗ May constrain possible analyses</td>
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</tbody>
</table>

First generation ADLs

- ACME (CMU/USC)
- Rapide (Stanford)
- Wright (CMU)
- Unicon (CMU)
- Aesop (CMU)
- MetaH (Honeywell)
- C2 SADL (UCI)
- SADL (SRI)
- Lileanna
- UML
- Modechart

Second generation ADLs

- Changes from MCC list with respect to Wikipedia’s list (1/9/2010)
- Added
  - LePUS3 and Class-Z (University of Essex)
  - ABACUS (UTS)
  - AADL (SAE) - Architecture Analysis & Design Language
- Removed:
  - UML
  - Modechart
ADL +/- 's

**Positives**
- Formal representation of architecture
- Higher level system description than previously possible
- Permit analysis of architectures – completeness, consistency, ambiguity, and performance
- Can support automatic generation of software systems

**Negatives**
- No universal agreement on what ADLs should represent, particularly as regards the behavior of the architecture
- Tend to be very vertically optimized toward a particular kind of analysis

Architecture definition

- Components
- Connectors
- Configurations (topologies)
- Constraints (restrictions)

MCC 1999 Report: ACME

- Developed jointly by Monroe, Garlan (CMU), Wile (ISI/USC)
- A general purpose ADL originally designed to be a lowest common denominator interchange language
- Simple, consistent with interchange objective, allowing only syntactic linguistic analysis

MCC report 1999
simple ACME example (client-server)

```
System simple_cs = {
    component client = {Port send-req}
    component server = {Port receive-req}
    Connector rpc = {Roles {caller, callee}}
    Attachments :
        {client.send-req to rpc.caller;
         server.receive-req to rpc.callee}
}
```

Very much in the flavor of module interconnection languages
1999 MCC: Rapide

- By Luckham at Stanford
- A general purpose ADL designed with an emphasis on simulation yielding partially ordered sets of events
- Fairly sophisticated, including data types and operations
- Analysis tools focus on posets
  - matching simulation results against patterns of allowed/prohibited behaviors
  - some support for timing analysis
  - focus on causality

Rapide

- Components
  - Interface objects
  - Architecture that implements an interface
  - Module that implements an interface
- Connections
  - Connects "sending interfaces" to "receiving interfaces"
  - Components communicate through connections by calling actions or functions in its own interface
  - Events generated by components trigger event pattern connections between their interfaces – basic, pipe, agent

Rapide constraints

- Pattern
  - Bound execution in terms of event patterns
  - Appear in an interface and/or architecture definition
  - [label] filter_part constraint_body
  - Filter creates context
  - Constraint body constrains computation in context
- Sequential
  - Bound execution in terms of boolean expressions
  - Normally appear in module level behavior
  - Applied to parameters, types, objects and statements

Rapide example

```plaintext
Type Producer (Max : Positive) is interface
  action out Send (N: Integer);
  action in Reply(N : Integer);
behavior
  Start => send(0);
  (?X in Integer) Reply(?X) where ?X<Max => Send(?X+1);
end Producer;

Type Consumer is interface
  action in Receive(N: Integer);
  action out Ack(N : Integer);
behavior
  (?X in Integer) Receive(?X) => Ack(?X);
end Consumer

Architecture ProdCon() return SomeType is
  Prod : Producer(100); Cons : Consumer;
  connect
    (?n in Integer) Prod.Send(?n) => Cons.Receive(?n);
    Cons.Ack(?n) => Prod.Reply(?n);
end architecture ProdCon;
```
Wright: Garlan and Allen (CMU)

- ADL designed with an emphasis on analysis of communication protocols
- Wright uses a variation of CSP to specify the behaviors of components, connectors, and systems
  - CSP: Hoare’s Communicating Sequential Processes
- Syntactically similar to ACME
- Wright analysis focuses on analyzing the CSP behavior specifications

Wright Example

```
Component client = port send- request = \[behavioral spec\]
Component server = port receive-request= \[behavioral spec\]
Connector rpc = role caller = (request!x -> result?x -> caller) * STOP
  role callee = (invoke?x -> return!x -> callee) [] STOP
  glue = (callee.request?x -> callee.invoke!x
        -> callee.return?x -> callee.result!x -> glue) [] STOP
Instances
  s : server; c : client; r : rpc
Connections
  client.send- request as rpc.caller
  server.receive- request as rpc.callee
```

MCC “other” ADLs

- Unicon (Shaw et al. @ CMU)
  - An emphasis on generation of connectors
  - Treatment of connectors as first class objects, which also supports generation of Unicon as a language focusing primarily on the basic ADL
- MetaH (Honeywell)
  - Domain specific ADL aimed at guidance, navigation, and control applications with ControlH
  - Sophisticated tool support available
- C2 SADL (Taylor/Medvidovic @ UCI)
  - Emphasis on dynamism
- SADL (Moriconi/Riemenschneider @ SRI)
  - Emphasis on refinement mappings

MCC: UML as an ADL

- Major positives: lowers entry barrier, enables use of mainstream modeling approaches and tools
- Major negatives
  - Encourages an object connection architecture rather than interface connection architecture
  - Weakly integrated models with inadequate semantics for automated analysis
  - Connectors are not first class objects
  - Visual notation with ambiguity
Communicating Sequential Processes (CSP) is a formal language for describing patterns of interaction in concurrent systems. It is a member of the family of mathematical theories of concurrency known as process algebras, or process calculi.

CSP was first described in a 1978 paper by C. A. R. Hoare... CSP has been practically applied in industry as a tool for specifying and verifying the concurrent aspects of a variety of different systems, such as the T9000 Transputer, as well as a secure ecommerce system.

A process is an entity that engages in communication events.

Events may be primitive or they can have associated data: \( e?x \) and \( e!x \) represent input and output of data, respectively.

The simplest process \( \text{STOP} \) engages in no events.

The "success" event is \( \sqrt{} \).

A process that engages in event \( e \) and then becomes \( P \) is denoted \( e \rightarrow P \).

A process that can behave like \( P \) or \( Q \), where the choice is made by the environment, is \( P \parallel Q \).

A process that can behave like \( P \) or \( Q \), where the choice is made non-deterministically by the process itself, is \( P \parallel Q \).

\( P1 \parallel P2 \) is a process whose behavior is permitted by both \( P1 \) and \( P2 \) and for events that both processes accept.

A successfully terminating process is \( \S \), which is the same as \( \sqrt{} \rightarrow \text{STOP} \).
Wright example

- A shared memory connector, with different forms of initialization
- Any of the roles can either get or set the value repeatedly, terminating at any time. The overall communication is complete only when all participants are done with the data
- This version includes no initialization

Style SharedData

Connector SharedData

Role User1 = set → User1 ⌜ get → User1 ⌜ $ ∣
Role User2 = set → User2 ⌜ get → User2 ⌜ $

Glue = User1.set → Glue ⌜ User2.set → Glue ⌜ User1.get → Glue ⌜ User2.get → Glue ⌜ $

End Style

With initialization

- This definition indicates that there is a distinguished role, Initializer, that must supply the initial value.
- The Initializer agrees to set the value before getting it

connector Shared Data2

role Initializer =

let A = set → A ⌜ get → A ⌜ $
in set → A

role User = set → User ⌜ get → User ⌜ $
glue = let Continue = Initializer.set → Continue

User.set → Continue
Initializer.get → Continue
User.get → Continue ⌜ $
in Initializer.set → Continue ⌜ $

§

With lazy initialization

- Does not require that the other participant wait for initialization to proceed

connector Shared Data3

role Initializer =

let A = set → A ⌜ get → A ⌜ $
in set → A

role User = set → User ⌜ get → User ⌜ $
glue = let Continue = Initializer.set → Continue

User.set → Continue
Initializer.get → Continue
User.get → Continue ⌜ $
in Initializer.set → Continue ⌜ $

§

Looks good but...

connector Bogus

role User1 = set → User1 ⌜ get → User1 ⌜ $

role User2 = set → User2 ⌜ get → User2 ⌜ $

glue = let Continue = User1.set → Continue

User2.set → Continue

User1.get → Continue ⌜ $
in User1.set → Continue ⌜ $

User2.set → Continue ⌜ $

§
Analysis

- An analysis of a well-formed system should be able to show that it is deadlock-free.
- For architectural connectors, the means avoiding the situation in which two components can wait in the middle of an interaction, each port expecting the other to take some action that will never happen.
- A connector process is free from deadlock if whenever it cannot make progress, then the last event to have taken place must have been √.
- In other words, the roles and glue work in such a way that if the overall connector process stops, it will be in a situation that is a success state for all the parties.

Wright tools

- Allow you to assert deadlock-freedom and to have it automatically checked.
- It converts Wright descriptions into FDR, a commercial model-checker that offers the choice of verification using CSP Traces Refinement, Failures Refinement, and Failures-Divergences Refinement models.
- Asserts might be, for the shared data example:
  - ? DFA [FD=User1]
  - ? DFA [FD=SharedData1]
- DFA means DeadlockFree Process.
- FD means Failures-Divergences Refinement model.
- Returns true if proven, false with counterexample otherwise.

Counterexample example

- √ DFA [FD=User1]
- √ DFA [FD=User2]
- X DFA [FD=Bogus]
- The connector glue requires that User1 or User2 initialize the variable, but does not specify which one.
- If either begins with a set, then that event will occur first and all is OK.
- But if User1 and User2 both attempt to perform an initial get — which is entirely legal — then the connector will deadlock.
- The tool identifies a counterexample.
  - The Glue process is ready to accept √, User1.set, User2.set while both the User1 and User2 processes will only accept get.
Wright: pipe connector

```plaintext
constructor Pipe =
  role Writer = write—Writer Close 
    role Reader = let ExitOnly = close — 
    role Reader = let Reader = Reader Read — Reader Read — Reader = Writer Write — Writer Close 
  role Reader = Writer Write — Writer Close 
  role Reader = Writer Close — Writer Close 
  role Reader = Writer Close — Writer Close

Fig. 5. A pipe connector.
```

With trace specification

```plaintext
constructor Pipe =
  role Writer = write—Writer Close 
    role Reader = let ExitOnly = close — 
    role Reader = let Reader = Reader Read — Reader Read — Reader = Writer Write — Writer Close 
  role Reader = Writer Write — Writer Close 
  role Reader = Writer Close — Writer Close 
  role Reader = Writer Close — Writer Close

For every trace in which Reader.read-eof occurs, there must also be an occurrence of the event Reader.close, and the number of times that Reader.read has occurred equals the number of occurrences of Writer.write. That is, before eof is signaled, all data have been read, and the pipe is closed.
```

ArchJava: PL++ rather than ADL

- **ArchJava**: Jonathan Aldrich, UW⇒CMU (much more since the material here)
- Combine architectural description with programming language
  - Ensure implementation code obeys architectural constraints.
  - Doesn't preclude common programming idioms.
  - Allow easier traceability between architecture and implementation.
- ArchJava uses a type system to guarantee communication integrity between an architecture and its implementation.

Communication integrity

- Each component in the implementation may only communicate directly with the components to which it is connected in the architecture (Ludkham & Vera).
- If “out of band” communication can take place, most properties are hard to guarantee.
- Related to some degree to The Law of Demeter (Lieberherr et al.)
  - A can call B, but A cannot use B to allow A to call C — this would allow A to have knowledge of B’s internal structure — a form of representation exposure.
  - B can be modified (if needed) to handle this for A, or A can obtain a direct reference to C.
- Wikipedia ([1/10/2010]): “In particular, an object should avoid invoking methods of a member object returned by another method. For many modern object oriented languages that use a dot as field identifier, the law can be stated simply as ‘use only one dot’. That is, the code ‘a.b.Method()’ breaks the law where ‘a.Method()’ does not.”
Component example

```java
public component class Parser {
    public port in {
        provides void setInfo(Token symbol, SymTabEntry e);
        requires Token nextToken() throws ScanException;
    }
    public port out {
        provides SymTabEntry getInfo(Token t);
        requires void compile(AST ast);
    }
    public void parse() {
        Token tok = in.nextToken();
        AST ast = parseFile(tok);
        out.compile(ast);
    }
    AST parseFile(Token lookahead) { ... }
    void setInfo(Token t, SymTabEntry e) {...}
    SymTabEntry getInfo(Token t) { ... }
}
```

```java
Component example

```java
public component class Compiler {
    private final Scanner scanner = ...;
    private final Parser parser = ...;
    private final CodeGen codegen = ...;
    connect scanner.out, parser.in;
    connect parser.out, codegen.in;
    public static void main(String[] args) {
        new Compiler().compile(args);
    }
    public void compile(String[] args) {
        // for each file in args do:
        ...parser.parse();
        ...
```
More…

Data sharing

- ArchJava extensions to describe architectural constraints on data sharing (using alias control analysis)
- Can describe data that is confined within a component, passed linearly from one component to another, or shared temporarily or persistently between components.
- Careful use of sophisticated language/type constructs like uniqueness, lending, mutability, etc.

Quick recap

- Architectural description via specially designed languages (ADLs) and via programming language extensions
- Reasoning about architectural properties
  - ADLs (like Wright) allow the definition of properties to check within the scope of the language and analysis tools
  - PL++ (like ArchJava) define the properties to always be checked
- Other tradeoffs with respect to adoption, to implementation issues, etc.

Static vs. dynamic architectures

- ACME, WRIGHT, etc. define static architectures – essentially, all processes need to be known statically (and thus not created during execution of the implementation)
- The need for dynamic architectures – creation and management of processes at run-time – has been a hot topic for at least a decade (in the software architecture research area, that is)
- Lots of work on this, but I'll focus on
  - Peyman Oreizy, Nenad Medvidovic, Richard N. Taylor.
    "Architecture-Based Runtime Software Evolution".
    International Conference on Software Engineering (April 1998)
ICSE N-10 award paper

- This paper received the ICSE 2008 Most Influential Paper Award, which recognizes the paper with the most influence on theory or practice during the 10 years since its publication.
- The following (partial set of) slides are stolen from the retrospective talk at ICSE 2008 by Peyman, Neno and Dick (http://www.ics.uci.edu/~peymano/dynamic-arch/).

Change during runtime?

- Critical systems require “continuous availability”
- Power grid, financial systems, ...
- Increasingly important in everyday systems

State of the Practice

- Redundant and fault-tolerant hardware
- “Hot pluggable” drives and memory
- System virtualization (ala VMware and Xen)
- Binary code patching
- Programming language facilities for dynamic loading, linking, and patching of code
- Software designed for fault tolerance (architectural styles and patterns)
Towards a Unifying Framework

All approaches:
1. Use a “model” to highlight some system details while hiding others.
2. Grapple with 5 aspects of runtime change:
   a. evolve behavior
d. asynchronous change
e. probe running system
b. evolve state
c. adjust execution context

Dynamic Adaptation Models I

- Prior to our ICSE 1998 paper
- Style-based models: CHAM, graph-grammars
- ADL-based models: Darwin, Dynamic Wright, Rapide
- Did not gain wide adoption
- Lack of system-level facilities
- Constrained notion of dynamism

Dynamic Adaptation Models II

- Subsequent to our ICSE 1998 paper
- “Figure 8” model: system adaptation driven by architecture

Dynamic Adaptation Models III

- Rainbow: similar to “Figure 8”
- Self-managed systems: dynamic plan generation
Research Projects

- Aura: QoS-driven system reconfiguration
- MobilePulse: QoS optimization via dynamic reconfiguration
- Siena: Client-server, and network-level dynamic
- Grid computing: Dynamic addition and removal of computing resources

Commercial Solutions

- Roll your own: predefined dynamic adaptations via options
- Skype
- Promotion/demotion of nodes
- P2P-based adaptations
- MapReduce automatic data routing from failed to live nodes

Promising Directions

- A simple message: if you want or need adaptable applications you can either:
  - Make no constraints on developers
  - ... and then work like crazy to try to obtain adaptation
- Constrain development to make adaptation easier and predictable
- This should not be news: the message is styles

How Do You Make Adaptation Easier?

- Make the elements subject to change identifiable
- Make interaction controllable
- Provide for management of state

Lots of Successful Examples

- Pipe-and-filter
- Dynamic pipe-and-filter: Weaves
- Event-based systems: Field & pub-sub
- Event-based components and connectors: C2
- REST
Checklists: an aside

- Last night my wife and I attended the Town Hall talk by Dr. Atul Gawande on his new book, The Checklist Manifesto.
- Excerpts from Malcolm Gladwell’s review [amazon.com]
- “He is really interested in a problem that afflicts virtually every aspect of the modern world—and that is how professionals deal with the increasing complexity of their responsibilities.
- “… a distinction between errors of ignorance (mistakes we make because we don’t know enough), and errors of ineptitude (mistakes we made because we don’t make proper use of what we know). Failure in the modern world… is really about the second of these errors…”

More from Gladwell

- “He walks us through a series of examples from medicine showing how the routine tasks of surgeons have now become so incredibly complicated that mistakes of one kind or another are virtually inevitable: it’s just too easy for an otherwise competent doctor to miss a step, or forget to ask a key question or, in the stress and pressure of the moment, to fail to plan properly for every eventuality.
- Gawande then visits with pilots and the people who build skyscrapers and comes back with a solution. Experts need checklists—literally—written guides that walk them through the key steps in any complex procedure. He shows how his research team has taken this idea, developed a safe surgery checklist, and applied it around the world, with staggering success.”

So, role of checklists in software engineering?

- Based on a desire to design software systems with a particular property—such as autonomic systems, fault-tolerance, privacy, etc.
- But weren’t properties checked by ADLs, etc.?
- Absolutely.
- The difference in property-oriented (remember, I made that term up) is that the properties are described and the systems are produced—at least to the first order
  - In contrast to producing an architecture and ensuring it has properties
  - Perhaps this is at least as much an issue of generation as property-orientation

Software architecture: property-oriented

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  - In contrast to producing an architecture and ensuring it has properties
  - Perhaps this is at least as much an issue of generation as property-orientation
**Model-based design**

- **Wikipedia (1/11/10):** “... is a mathematical and visual method of addressing problems associated with designing complex control systems. ... Model-based design is a methodology applied in designing embedded software.”

- “The automotive industry has embraced model-based approaches mostly for the following reasons: (i) These graphical functional models visualize both the underlying mathematics (i.e. the differential equations) and the software that later on implements the functions on a specific processor. ... (ii) The models can be simulated ... very early in the development process. ... (iii) The models can be used as a basis for automatic code generation. This not only saves the efforts for the manual coding of the algorithms but also prevents transcription errors from the models to the code.”

- Also related to domain specific modeling

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**Principle of Alternatives [via E. Jackson]**

- A high-level specification defines a design space.
- The design space is complex, so some refinements are dead-ends and require backtracking through the design space.
- Model-based design (or model integrated computing), provides tool support to simultaneously explore multiple alternatives.

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**How to describe the design space?**

- UML, UML variants (e.g., Executable UML), etc.
- Matlab/Simulink
- Design-time approximations of embedded system models
- Abstract state machines (E. Jackson et al.)
- Security policies as complex data + invariants
- Model transformations for semantic anchoring and code generation.
- Many more!

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**E. Jackson: FORMULA (sketch!)**

A Simple Example

We define a domain via term algebra equipped with a set of invariants written in a non-monotonic extension of Horn logic.

- Constraint: Every graph must have a 3-colored 4-clique.
- Domain Signature
- With formation rules

Break-down of encoding: Representation of domain in FORMULA syntax.
Autonomic computing

- IBM's term for self-managing and self-adaptive software systems
- Systems get more complex, increasing the difficulty and cost of building larger systems in new domains, etc.
- Autonomic computing systems are intended to adapt to unpredictable changes in the environment to remove the need for explicit adaption from the users and developers
Related to architecture how?

- Dependent on some of the kinds of mechanisms used in model based design
- Dependent on dynamic architectures
- Disciplined creation and adaptation of architectures that exhibit the self-manageability characteristic

IBM’s vision

- Kephart and Chess focused on the increasing “nightmare of pervasive computing” in which the complexity of the interactions leads us to a situation where the designers are deeply hampered
- The essence of autonomic computing is to have the systems manage themselves, to deliver better system behavior while offloading tedious and error-prone system administrative activities from people.

IBM: four dimensions

- Self-Configuration: Automatic configuration of components
- Self-Healing: Automatic discovery and correction of faults
- Self-Optimization: Automatic monitoring and control of resources to ensure the optimal functioning with respect to the defined requirements
- Self-Protection: Proactive identification and protection from arbitrary attacks

IBM Autonomic Systems: 8 defining characteristics

- An autonomic computing system needs to “know itself” - its components must also possess a system identity. Since a “system” can exist at many levels, an autonomic system will need detailed knowledge of its components, current status, ultimate capacity, and all connections to other systems to govern itself. …
- An autonomic computing system must configure and reconfigure itself under varying (and in the future, even unpredictable) conditions. System configuration or “setup” must occur automatically, as well as dynamic adjustments to that configuration to best handle changing environments.
- An autonomic computing system never settles for the status quo - it always looks for ways to optimize its workings. It will monitor its constituent parts and fine-tune workflow to achieve predetermined system goals.
An autonomic computing system must perform something akin to healing - it must be able to recover from routine and extraordinary events that might cause some of its parts to malfunction. It must be able to discover problems or potential problems, then find an alternate way of using resources or reconfiguring the system to keep functioning smoothly.

A virtual world is no less dangerous than the physical one, so an autonomic computing system must be an expert in self-protection. It must detect, identify and protect itself against various types of attacks to maintain overall system security and integrity.

An autonomic computing system must know its environment and the context surrounding its activity, and act accordingly. It will find and generate rules for how best to interact with neighboring systems. It will tap available resources, even negotiate the use by other systems of its underutilized elements, changing both itself and its environment in the process -- in a word, adapting.

An autonomic computing system cannot exist in a hermetic environment. While independent in its ability to manage itself, it must function in a heterogeneous world and implement open standards -- in other words, an autonomic computing system cannot, by definition, be a proprietary solution.

An autonomic computing system will anticipate the optimized resources needed while keeping its complexity hidden. It must marshal I/T resources to shrink the gap between the business or personal goals of the user, and the I/T implementation necessary to achieve those goals -- without involving the user in that implementation.

Great thoughts, but…

- How to achieve these characteristics?
  - One key mechanism is closed control loops – from control theory
  - That is, the system needs to be able to monitor itself and to adapt itself – without diverging into unexpected and unacceptable behaviors
  - This requires explicit representations of many aspects of the system, so they can be accessed and modified at run-time
  - At some level connected to mechanisms such as run-time code-generation, reflection, the meta-object protocol, open implementations, etc.

Key mechanism

- Closed control loops – control theory
- That is, the system needs to be able to monitor itself and to adapt itself – without diverging into unexpected and unacceptable behaviors
- This requires explicit representations of many aspects of the system, so they can be accessed and modified at run-time
- At some level connected to mechanisms such as run-time code-generation, reflection, the meta-object protocol, open implementations, etc.
Cheng et al. 2009: Roadmap

Alternative mechanisms

- Biologically-inspired... stay tuned

Suggestions for third topic...

- ...after architecture and tools?

Questions?