Advanced System Architecture
ESD.342/EECS 6.883
2006

• Goals of this course:
• Gain an understanding of system architecture
• Learn existing theoretical and analytical methods
• Compare systems in different domains and understand what influences their architectures
• Apply/extend existing theory in case studies
The Faculty

• Chris Magee
• Joel Moses
• Dan Whitney
ESD’s Domains

Focus of this course
What We Will Do in This Course

• Read the academic literature, including our own notes and papers
• Learn and practice some existing analytical methods, mainly network methods
• Appreciate the wide range of domains where theory and methods have been applied
• Critique existing theory and methods
• Share our knowledge and experience
• Analyze some real systems in detail
• Distil common concepts that emerge from theory and that apply to many kinds of systems
How The Course Will Be Organized

• Class lecture/discussion
• Text: *Six Degrees* by Duncan Watts
• Literature to read before class
• Three homework assignments and exercises to learn to use the software
• Case study project with periodic reports in class
• Class overheads, assigned reading, and optional reading posted on class website.
Grading Formula

• 15% in-class participation (especially reading connections)

• 25% assignments
  – 5% Each for assignments 1 and 2
  – 15% for assignment 3

• 60% Project
  – 20% Final Written Report
  – 15% Final Presentation
  – 15% Modeling Status Presentation
  – 10% 1st Status Presentation
Class Resources

- You!
- Course website
  - Syllabus and schedule
  - Assigned readings
  - Background readings
  - Class overheads
  - Collection of MATLAB routines for doing network analysis
  - Online book on social network analysis methods (subset of what we will be using)
Our Viewpoint

• Importance of data and domain knowledge
• Value of doing case studies with quantitative results
• Understanding of relevant literature in other domains like systems biology, ecology, and economics
• Importance of ideology in framing generic architectures and attitudes toward them
Why We Care

• Lots of things have architectures
  – Physical things - objects, large natural systems
  – Human designed things - products, systems, missions, organizations, projects, infrastructures, software, databases, political and economic systems
  – Natural things - cells, organisms, herds, ecosystems

• Their architectures either determine, strongly influence, or are correlated with their behavior and properties

• Architectural progress and evolution can be observed in both built and natural systems

• There are multiple characteristics of architecture and thus there can appear to be multiple architectures if viewed through these different lenses.
A “Perfect” Theory of Architecture Would Permit Us To:

- Measure
- Characterize
- Understand at a fundamental level
- Design, operate, evaluate, improve
- Predict future behavior
A Definition of Architecture from a Practice Perspective

“An architecture is the conceptualization, description, and design of a system, its components, their interfaces and relationships with internal and external entities, as they evolve over time.”

*John W. Evans*

Source: “Design and Inventive Engineering” Tomasz Arciszewski Fall 2004

• Similar to: “An architecture is a plan for change.”

*Joel Moses*
Two definitions of Architecture from a Fundamental Perspective

• The architecture of a complex system is a description of the structure or regularity of the interactions of the elements of that system (inherently the non-random and longer lived aspects of the system relationships).

• The architecture of a complex system describes the functional character of the elements and the structure of the relationships among the elements.
Baldwin and Clark
(intermediate between practice and fundamental?)

- An architecture declares the modules and defines their functions*
- It also declares and defines the interfaces, including which modules they relate and what relations are supported*
- Finally it declares or embraces standards that define common rules of design, structure, interfaces, or behavior not otherwise declared, including performance evaluation
- * are part of typical system engineering
Instructor Biases

• Magee
• Moses
• Whitney
• Your turn Feb 14 (see assignment 1)
Some Things Do Not Have Architectures with Internal Structure

- Random Networks
- Perfect gases
- Crowds of people
- Their behavior can still be analyzed and often forms a baseline for comparison to things that do have architectures with significant structure
Structural Typology

• Totally regular
  – Grids/crystals
  – Pure Trees
  – Layered trees
  – Star graphs
• Deterministic methods used

• Real things
  – The ones we are interested in
• New methods or adaptations of existing methods needed

• No internal structure
  – Perfect gases
  – Crowds of people
  – Classical economics with invisible hand

• Less regular
  – “Hub and spokes”
  – “Small Worlds”
  – “Grown” including growth models
• Stochastic methods used
Systems Typology I

• Technical Systems
  – Power-oriented (e.g., cars, aircraft, their engines, etc.)
  – Information-oriented
    • Physically realized: e.g., telephone network, Internet
    • Non-physical: e.g., software, mathematical systems (Macsyma, Mathematica)

• Organizations (of humans)
  – Teams
  – Hierarchies
  – Networks

• Social/economic “systems”
  – Markets
  – Social Classes
  – Social networks like coauthors, citation lists, e-mails, terrorists
  – Behaviors: e.g., rumors, diseases, herd mentality

• Biological systems
  – Cells
  – Animal body plans
  – The process and role of evolution

• Categorizations and taxonomies of these systems also have architectures…
  – Linnean and other categorizations of “the tree of life”
Systems Typology II

- **Overtly designed**
  - Can be an architect
  - A design strategy is practical
  - Products, product families
  - Cars, airplanes
  - Bell System
  - Organizations
  - Centrally-planned economies

- **Infrastructures**
  - Architect not common
  - Protocols and standards are crucial
  - Design strategy may or may not be practical
  - May be designed when small
  - Usually grow with less direction from a common strategy when large
  - Regional electric grids
  - City streets
  - Federal highway system

- **Natural systems**
  - No architect
  - Follow laws of physics
  - Respond to context
  - Change, develop
  - Differentiate or speciate
  - Interact hierarchically, synergistically, exploitatively
  - Cells, organisms, food webs, ecological systems

In all cases, there is legacy, possibly a dominant influence
### Systems Typology III: Complex Systems Functional Classification Matrix from Magee and de Weck

<table>
<thead>
<tr>
<th>Process/Operand</th>
<th>Matter (M)</th>
<th>Energy (E)</th>
<th>Information (I)</th>
<th>Value (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transform or Process</td>
<td>GE Polycarbonate Manufacturing Plant</td>
<td>Pilgrim Nuclear Power Plant</td>
<td>Intel Pentium V</td>
<td>N/A</td>
</tr>
<tr>
<td>Transport or Distribute</td>
<td>FedEx Package Delivery</td>
<td>US Power Grid System</td>
<td>AT&amp;T Telecommunication Network</td>
<td>Intl Banking System</td>
</tr>
<tr>
<td>Store or House</td>
<td>Three Gorge Dam</td>
<td>Three Gorge Dam</td>
<td>Boston Public Library (T)</td>
<td>Banking Systems</td>
</tr>
<tr>
<td>Exchange or Trade</td>
<td>eBay Trading System (T)</td>
<td>Energy Markets</td>
<td>Reuters News Agency (T)</td>
<td>NASDAQ Trading System (T)</td>
</tr>
<tr>
<td>Control or Regulate</td>
<td>Health Care System of France</td>
<td>Atomic Energy Commission</td>
<td>International Standards Organization</td>
<td>US Federal Reserve (T)</td>
</tr>
</tbody>
</table>
Comments on Typologies: Attributes of Effective Classification

- Standards for Taxonomy
  - *Collectively Exhaustive and Mutually Exclusive*
  - *Internally Homogeneous*
  - Stability
  - Understandable Representation and Naming

- None of the approaches really fulfill these criteria. Interestingly (more later in course), *no categorizations* of man made systems have ever been found that fulfill these criteria. *Natural systems categorizations have been found that do fulfill* these criteria (Linnaeus and Mendeleyev) and these have even been the basis of future successful predictions.
How to Learn

• We will learn more about such architecture/structure by examining a wide variety of systems such as biological, sociological, economic at a variety of levels in addition to the technological and organizational systems of most direct interest to us, because

• These systems are similar in many ways, perhaps more than we think

• Since we want to influence structure (not just accept it as we are interested in design), we will also explore how structure is determined by looking at system typologies and constraints that influence or determine the structure

• We will use network methods - a choice of level of abstraction
Important topics at the “Research Front”

- How useful are the metrics that exist for architectural or structural attributes in the case of Engineering Systems (high complexity and heterogeneity)?
- Can we invent metrics for heterogeneous systems that are more useful indicators of important “properties of real systems”?
- Can we quantify important properties such as flexibility and find analytical relationships to some structural metrics?
More Research Front Topics

• To what extent are intuitively important aspects of architecture quantifiable and measurable?
• Are there useful paradigms, patterns, principles or other lessons from natural systems that researchers on real system architectures can use - and how can they be used?
• Assuming we know what functions, performance, and abilities we want, what methods can be used to create a suitable architecture?
• Assuming we know what architecture we want, what are the most effective ways of influencing the architecture of complex, evolving engineering systems?
Terms and Definitions

- System
- Function
- Performance
- Cost
- Properties or characteristics
  - Complexity, uncertainty, emergence
- Ilities - often have life-cycle importance
  - Flexibility
  - Robustness
  - Sustainability
  - Others?
Form and Function

• Function
  – (narrow) what the system does, as opposed to Performance and Ilities
  – (broad) combines function, performance and ilities

• What is the relationship between Form and Function?
Other System Characteristics

- Complexity
- Uncertainty
- Emergence
- Various definitions have been proposed

What are the relationships, especially trade-offs, between forms, functions,ilities, performance and these characteristics?
Other Words That We Will Use and Need to Understand

• Element, module, component, agent
• Pattern (repeating)
• Interface, boundary
• Integrality, modularity, dependence, independence, central control, distributed control, autonomy
• Relationship, interaction, path
• Hierarchy, layer, platform
• Decomposition, integration
• Cluster, clique