Complex Adaptive Systems

Spring 2018

Melanie Moses
Associate Professor UNM Computer Science & Biology
External Faculty, Santa Fe Institute
Complex system: a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution.

Systems in which organized behavior arises without an internal or external controller or leader are sometimes called self-organizing. Since simple rules produce complex behavior in hard-to-predict ways, the macroscopic behavior of such systems is sometimes called emergent.

Here is an alternative definition of a complex system: a system that exhibits nontrivial emergent and self-organizing behaviors. The central question of the sciences of complexity is how this emergent self-organized behavior comes about.
Complex Adaptive Systems

**Interactions**
Systems composed of interacting components

**Emergence**
Structure emerges from interactions among components and between components and their environment

**Scale**
Systems are nested and structure emerges at different scales

**Evolution**
Systems are dynamic and adapt to internal and external conditions
Economies are organic and evolutionary... actions and strategies constantly evolve, structures constantly form and re-form...

individual behaviors react to the pattern they together create
Sensitive dependence on initial conditions

It may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error on the former will produce an enormous error on the latter. Prediction becomes impossible...
It is interesting to contemplate a tangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent upon each other in so complex a manner, have all been produced by laws acting around us.

Charles Darwin
Origin of Species 1859
Interdisciplinary approaches to studying Complex Systems
Andreas Wagner
Arrival of the Fittest

• a phenotype like that of a human body is not just a string of DNA. It is a hierarchy of being that descends from the visible organism, its tissues and cells, to the molecular webs formed by metabolic molecules, signaling molecules, and many others, extending down to the level of individual proteins.

• computers are the microscopes of the twenty-first century. They help us understand molecular webs that Darwin did not even know existed. ...
If a random mutation happens by which some organism can detect and utilize some new source of free energy, and it's advantageous for the organism, natural selection will select it.

The whole biosphere is a vast, linked web of work done to build things so that, stunningly enough, sunlight falls and redwood trees get built and become the homes of things that live in their bark.

The complex web of the biosphere is a linked set of work tasks, constraint construction, and so on. ... necessitating a theory of organization that describes what the biosphere is busy doing...Currently we have no theory of it—none at all.
Complex system: a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution.

Systems in which organized behavior arises without an internal or external controller or leader are sometimes called self-organizing. Since simple rules produce complex behavior in hard-to-predict ways, the macroscopic behavior of such systems is sometimes called emergent.

Here is an alternative definition of a complex system: a system that exhibits nontrivial emergent and self-organizing behaviors. The central question of the sciences of complexity is how this emergent self-organized behavior comes about.
**Traditional Science**
Reductionism: zoom in
Learn more & more about less & less

**Complexity Science**
Look across scales: zoom in & zoom out
Use multiple perspectives
Understand how structure emerges
from interactions within & across levels
Overview of Course Topics

- Chaos & Sensitive Dependence on Initial Conditions
- Information Theory
- Evolution

- Genetic Algorithms
- Cellular Automata
- Swarm Robotics
- Ants & Ant Colony Optimization
- Brains, Neural Nets & Analogies
- Natural and Computational Immunology
- Modeling & the Prisoner’s Dilemma
- Networks, scaling & fractals
The Logistic Map: Chaos from a simple equation

\[ x_{n+1} = rx_n (1 - x_n) \]
Shannon Information

- Entropy
- Mutual Information
- Transfer Entropy

\[ H = - \sum_i p_i \log_2 p_i \]
Evolution by Natural Selection

Variation
Inheritance
Selection
Evolution by Natural Selection

Variation

Diversity
Evolution by Natural Selection

Variation
Diversity
Inheritance
Mutation & Recombination
Evolution by Natural Selection

Variation
Diversity
Inheritance
Mutation & Recombination
Selection
Environment
Genetic Algorithms

Variation
Diversity
Inheritance
Mutation & Recombination
Selection
Environment
FITNESS = # Seeds Collected
Genetic Programming
Cellular Automata
~20,000,000 Ants
Pheromone recruitment: a well-studied emergent behavior

\[ p_{ij}^k(t) = \frac{\tau_{ij}(t)^{\alpha} \cdot \eta_{ij}^{\beta}}{\sum_{l \in N_i^k} \tau_{ij}(t)^{\alpha} \cdot \eta_{ij}^{\beta}} \quad \text{if } j \in N_i^k \]

Ant colony optimization
Swarm Robotics
Brains and Information Processing
Immune systems are really complex.
Modeling Cooperation: The Prisoner’s Dilemma

<table>
<thead>
<tr>
<th></th>
<th>B stays silent (cooperates)</th>
<th>B betrays A (defects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A stays silent (cooperates)</td>
<td>Both serve 1 year</td>
<td>A serves 3 years, B goes free</td>
</tr>
<tr>
<td>A betrays B (defects)</td>
<td>A goes free, B serves 3 years</td>
<td>Both serve 2 years</td>
</tr>
</tbody>
</table>
and 3 modules, respectively. The wire lengths and widths increase as they cross more levels according to the ratio of internal (intra-module) communication per node to external (inter-module) communication per node. Here \( l_i + 1 \) is the length of the wire as level 0, while here the smallest branches, the capillaries, are the length and thickness \( l_i \) and \( D_i \), respectively, in [5] (note that in [5], the aorta or top of the network is labelled \( l_i = 0 \)).

Vascular systems are hierarchical branching networks where pipes and wires are described as level 0, while here the smallest branches, the capillaries, process oxygen delivered via a hierarchical vascular system. Similarly, microprocessors are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases. In the rest of the paper, we present the unified energy–time–scaling model for mammals (§3a,b) and then for microprocessors (§3c).

We model mammals as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. Here, we model mammals as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. We first derive energy and time-scaling relations from physical principles, and we model microprocessors as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. We then use the model to derive a series of predictions about how time and energy scale with system size, first for mammals (§3a,b) and then for microprocessors (§3c). We model the scaling of length \( l_i \), width \( w_i \), radius \( r_i \), and thickness \( D_i \) according to the relative length of pipe or wire between successive hierarchical levels. The relative radius \( \frac{r_i}{r_j} \) and relative thickness \( \frac{D_i}{D_j} \) define the relative dimensions, respectively. This model resembles the hierarchical branching model of vascular systems proposed in [5], where core computer chips are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases.

Core computer chips are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases. Here, we model mammals as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. Obviously, the smallest branches, the capillaries, are the length and thickness \( l_i \) and \( D_i \), respectively, in [5] (note that in [5], the aorta or top of the network is labelled \( l_i = 0 \)).

Vascular systems are hierarchical branching networks where pipes and wires are described as level 0, while here the smallest branches, the capillaries, process oxygen delivered via a hierarchical vascular system. Similarly, microprocessors are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases. In the rest of the paper, we present the unified energy–time–scaling model for mammals (§3a,b) and then for microprocessors (§3c). We model mammals as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. We first derive energy and time-scaling relations from physical principles, and we model microprocessors as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. We then use the model to derive a series of predictions about how time and energy scale with system size, first for mammals (§3a,b) and then for microprocessors (§3c). We model the scaling of length \( l_i \), width \( w_i \), radius \( r_i \), and thickness \( D_i \) according to the relative length of pipe or wire between successive hierarchical levels. The relative radius \( \frac{r_i}{r_j} \) and relative thickness \( \frac{D_i}{D_j} \) define the relative dimensions, respectively. This model resembles the hierarchical branching model of vascular systems proposed in [5], where core computer chips are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases.

Core computer chips are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases. Here, we model mammals as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. Obviously, the smallest branches, the capillaries, are the length and thickness \( l_i \) and \( D_i \), respectively, in [5] (note that in [5], the aorta or top of the network is labelled \( l_i = 0 \)).

Vascular systems are hierarchical branching networks where pipes and wires are described as level 0, while here the smallest branches, the capillaries, process oxygen delivered via a hierarchical vascular system. Similarly, microprocessors are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases. In the rest of the paper, we present the unified energy–time–scaling model for mammals (§3a,b) and then for microprocessors (§3c). We model mammals as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. We first derive energy and time-scaling relations from physical principles, and we model microprocessors as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. We then use the model to derive a series of predictions about how time and energy scale with system size, first for mammals (§3a,b) and then for microprocessors (§3c). We model the scaling of length \( l_i \), width \( w_i \), radius \( r_i \), and thickness \( D_i \) according to the relative length of pipe or wire between successive hierarchical levels. The relative radius \( \frac{r_i}{r_j} \) and relative thickness \( \frac{D_i}{D_j} \) define the relative dimensions, respectively. This model resembles the hierarchical branching model of vascular systems proposed in [5], where core computer chips are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases.

Core computer chips are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases. Here, we model mammals as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. Obviously, the smallest branches, the capillaries, are the length and thickness \( l_i \) and \( D_i \), respectively, in [5] (note that in [5], the aorta or top of the network is labelled \( l_i = 0 \)).

Vascular systems are hierarchical branching networks where pipes and wires are described as level 0, while here the smallest branches, the capillaries, process oxygen delivered via a hierarchical vascular system. Similarly, microprocessors are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases. In the rest of the paper, we present the unified energy–time–scaling model for mammals (§3a,b) and then for microprocessors (§3c). We model mammals as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. We first derive energy and time-scaling relations from physical principles, and we model microprocessors as composed of nodes (regions of tissue) that process oxygen delivered via a hierarchical vascular system. We then use the model to derive a series of predictions about how time and energy scale with system size, first for mammals (§3a,b) and then for microprocessors (§3c). We model the scaling of length \( l_i \), width \( w_i \), radius \( r_i \), and thickness \( D_i \) according to the relative length of pipe or wire between successive hierarchical levels. The relative radius \( \frac{r_i}{r_j} \) and relative thickness \( \frac{D_i}{D_j} \) define the relative dimensions, respectively. This model resembles the hierarchical branching model of vascular systems proposed in [5], where core computer chips are organized hierarchically into a nested structure of modules and submodules, where wires become longer and thicker as the hierarchical level of a module increases.