Outline

1. Introduction
2. Evolutionary Design
3. Morphogenesis and Design
4. Cellular Automata
5. Generative Representations
6. Morphogenic Evolutionary Design
7. Emergent Designer DEMO
Introduction

- Two important engineering design objectives:
  - Development of novel designs
  - Optimization of engineering designs
- Inspiration from Nature
- Complex systems as models of phenomena occurring in nature
  - Simplicity of mechanisms and potential richness of generated behaviors
Evolutionary Algorithms

- Uses a population of individuals
- Individuals are points in search space
- Individuals are evaluated for their “fitness”
- Population dynamics:
  - New individuals (samples) are created from existing high fitness parents using operators like:
    - Crossover
    - Mutation
  - Existing low fitness individuals are deleted
Evolutionary Design
Evolutionary Design
Can We Do Better?
Morphogenesis

- How about going a step further in imitating the nature?
  - Morphogenesis - an embryological development of the structure of an organism or a part.
Morphogenetic Design
Cellular Automata

- **Cellular automata** as generative representations of engineering systems
Cellular Automata: Mechanism
Cellular Automata: Dynamical Behavior

- Homogeneous states (fixed-points) (rule 100)
Cellular Automata: Dynamical Behavior

- Periodic states (periodic orbits) (rule 1)
Cellular Automata: Dynamical Behavior

- Eventually periodic states (rule 123)
Cellular Automata: Dynamical Behavior

- Chaotic states (rule 30)
Cellular Automata: Dynamical Behavior

- Self-similar structures (fractal structures) (rule 90)
Cellular Automata: Dynamical Behavior

- Complex, localized propagating structures (rule 110)
Design Representations

- **Parameterized** representations (optimality):
  - Focus restricted to a particular design concept or at most several concepts
  - Attributes encoded directly as genes

- **Generative** representations (creativity):
  - More general and usually more complex representations
  - Do not encode solutions but rather rules on how to build these solutions
Generative Representations

Consist of two parts:

- encoding of the ‘design embryo’
- encoding of a ‘design rule’ which is applied to the design embryo to develop a design concept from it
Generative Representations

Design embryo:

- an ordered set of cell values
- represents an initial configuration (usually one-, or two-dimensional) of structural members (e.g. types of wind bracing, beams, columns)
- forms a seed from which a design concept is developed
Generative Representations

Design rule:

- a formal description of a transformation that changes the current configuration of structural members into a new configuration
- this transformation defines a unit time step.
Generative Representations

Generative representation of a wind bracing system

Developmental process of constructing a wind bracing system from its generative representation
Design Evaluation: Multi-stage Process

- Generative representation
- Developmental process
- Design concept
- Application of loads
  - Structural analysis and sizing optimization
- Detailed design
  - Assign fitness
  - Total weight

SODA
Generative Representations

<table>
<thead>
<tr>
<th>Rule 85</th>
<th>Rule 105</th>
<th>Rule 155</th>
<th>Rule 173</th>
<th>Rule 15</th>
<th>Rule 37</th>
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<tbody>
<tr>
<td><img src="image1" alt="Rule 85 Diagram" /></td>
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<td><img src="image3" alt="Rule 155 Diagram" /></td>
<td><img src="image4" alt="Rule 173 Diagram" /></td>
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<table>
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<tr>
<th>Rule 131</th>
<th>Rule 195</th>
<th>Rule 153</th>
<th>Rule 54</th>
<th>Rule 124</th>
<th>Rule 182</th>
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<tr>
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<td>581,961</td>
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<td>637,123</td>
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</table>
How to Find Good Embryos and Rules?

- Again, look at nature
  - Use evolution!!!

Morphogenic Evolutionary Design

<table>
<thead>
<tr>
<th>design embryo</th>
<th>design rule (1D CA rule)</th>
</tr>
</thead>
<tbody>
<tr>
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Morphogenetic Evolutionary Design

Typical average best-so-far curves (design of wind bracing system with 2 types of elements):

- **Totalistic CA rules** outperformed parameterized representations
- Also, …
- They found ‘optimal’ solution very fast (in less than 100 evaluations)
Morphogenetic Evolutionary Design
Morphogenic Evolutionary Design

Morphogenic

Optimization Only

<table>
<thead>
<tr>
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<th>Standard CA</th>
<th>Totalistic CA</th>
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<tbody>
<tr>
<td>Radius = 1</td>
<td>547,428</td>
<td>563,865</td>
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<tr>
<td></td>
<td>556,177</td>
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<td></td>
<td>4.4727</td>
<td>6.6963</td>
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<td></td>
<td>559,982</td>
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<tr>
<td></td>
<td>4.8465</td>
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</table>

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<thead>
<tr>
<th></th>
<th>Standard CA</th>
<th>Totalistic CA</th>
</tr>
</thead>
<tbody>
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<tr>
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<td>485,175</td>
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Morphogenetic Evolutionary Design

Even simplest CA rules produced diverse dynamical behavior and generated interesting structural shaping patterns.

<table>
<thead>
<tr>
<th>Fixed-point Behavior</th>
<th>Periodic Behavior</th>
<th>Apparently Chaotic Behavior</th>
<th>Localized Propagating Structures</th>
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<tbody>
<tr>
<td>Rule 0, 8, 32, 40, 64, 72, 96, 104, 128, 136, 160, 168, 192, 200, 224, 232</td>
<td>Rule 1, 33, 129, 161</td>
<td>Rule 23, 31, 55, 63, 87, 95, 119, 127</td>
<td>Rule 14, 46, 142, 174</td>
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<tr>
<td>Rule 4, 12, 36, 44, 68, 76, 100, 108, 132, 140, 164, 172, 196, 204, 228, 236</td>
<td>Rule 23</td>
<td>Rule 82, 210</td>
<td>Rule 102</td>
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<tr>
<td>Rule 23</td>
<td>Rule 102</td>
<td>Rule 57</td>
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Emergent Designer

A design support tool based on models of complex adaptive systems

version 1.0
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Integrated research and design support tool:

<table>
<thead>
<tr>
<th>Unified Evolutionary Computation Engine (De Jong)</th>
<th>Cellular automata computation using Mathematica (Wolfram Research)</th>
<th>Design evaluation conducted by SODA (Grierson)</th>
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<td>Automatic report generation using OpenOffice.org</td>
<td>Visualization (Mathematica &amp; PtPlot)</td>
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Emergent Designer

DEMO
Design Evaluation: Multi-stage Process

- Generative representation
- Developmental process
- Design concept
- Application of loads
- Structural analysis and sizing optimization
- Assign fitnesses
- Detailed design
- Total weight AND Max. Displacement
Emergent Designer

- New version 2.0

<table>
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<th>ECJ</th>
<th>Cellular automata computation using Mathematica (Wolfram Research)</th>
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<tr>
<td>(Sean Luke) George Mason University</td>
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Emergent Designer

- Multiobjective Evolutionary Algorithm implemented: SPEA2
- Several simple multiobjective optimization problems added
- Single- and Multiobjective design of steel structural systems in tall buildings