Generative and Developmental Systems

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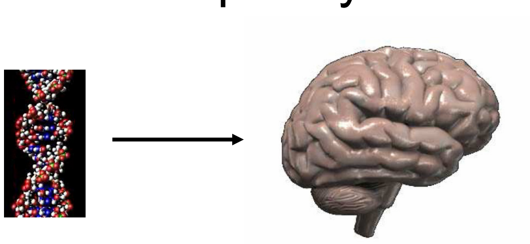
Inspiration vs. Simulation

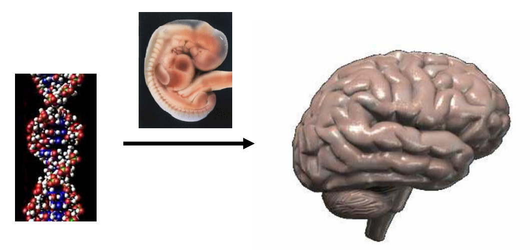
- Often confused in GDS
  - Simulation: Model biology to learn about biology
  - Inspiration: Abstract biology to create new algorithms
- This tutorial's perspective: Looking for inspiration
  - What from biology is *essential* to achieve what we want?
  - What can be ignored?
  - What should we add that is biologically implausible yet works better for our purposes?

Goal: Evolve Systems of Biological Complexity



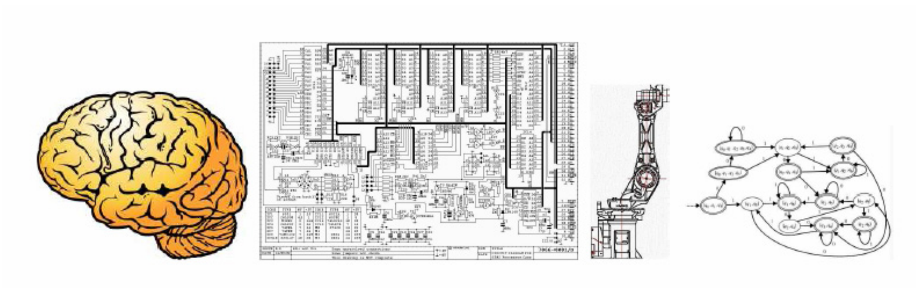
- 100 trillion connections in the human brain
- 30,000 genes in the human genome
- How is this possible?

Development



(embryo image from nobelprize.org)

Solving this Problem Could Solve Many Others



Historical Precedent

- Turing (1952) was interested in morphogenesis
  - Experimented with reaction-diffusion equations in pattern generation
- Lindenmayer (1968) investigated plant growth
  - Developed L-systems, a grammatical rewrite system that abstracts how plants develop

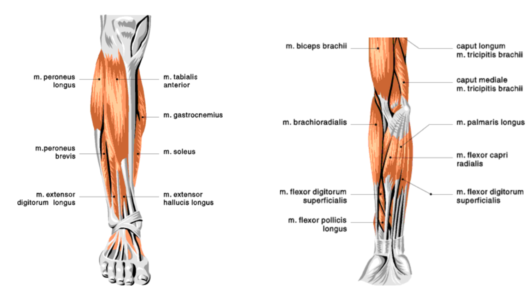
Lindenmayer, A. (1968). Mathematical models for cellular interaction in development: Parts I and II. Journal of Theoretical Biology, 18, 280–299, 300–315.
Turing, A. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society B, 237*, 37–72.

A Field with Many Names

- Generative and Developmental Systems (GECCO track)
- Artificial Embryogeny
- Artificial Ontogeny
- Computational Embryogeny
- Computational Embryology
- Developmental Encoding
- Indirect Encoding
- Generative Encoding
- Generative Mapping
- …

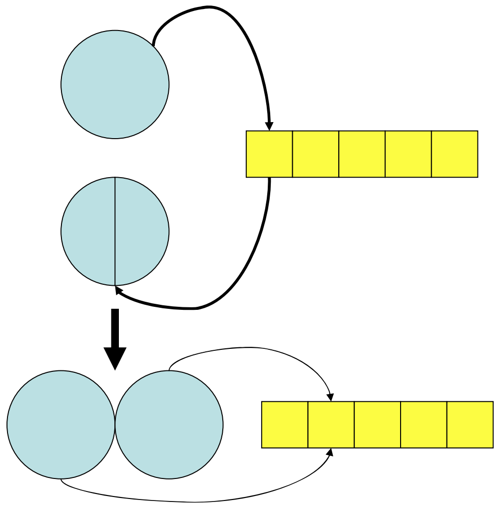
Development is Powerful Because of Reuse

- Genetic information is reused during embryo development
- Many structures share information
- Allows enormous complexity to be encoded compactly

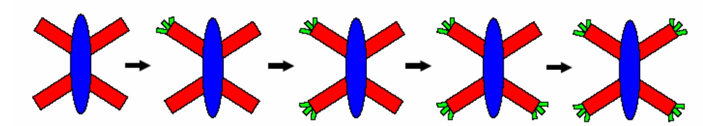


(James Madison University http://orgs.jmu.edu/strength/KIN_425/kin_425_muscles_calves.htm)

The Unfolding of Structure Allows Reuse



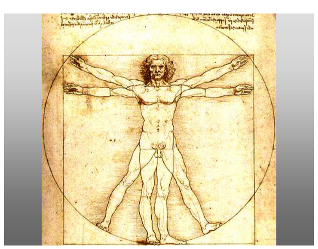
Rediscovery Unnecessary with Reuse



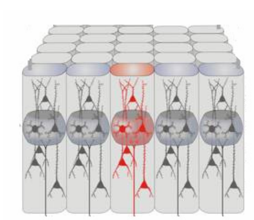
- Repeated substructures should only need to be *represented* once
- Then repeated elaborations do not require rediscovery
- Rediscovery is expensive and improbable
- (Development is powerful for *search* even though it is a property of the *mapping*)

Therefore, GDS

- Indirect encoding: Genes do not map directly to units of structure in phenotype
- Phenotype develops from embryo into mature form
- Genetic material can be reused
- Many existing developmental encoding systems



Symmetry

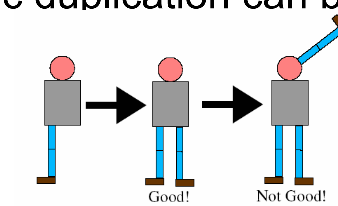


Repetition

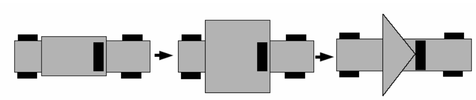
Repetition with variation

Some Major Issues in AE

- Phenotypic duplication can be brittle



- Variation on an established convention is powerful



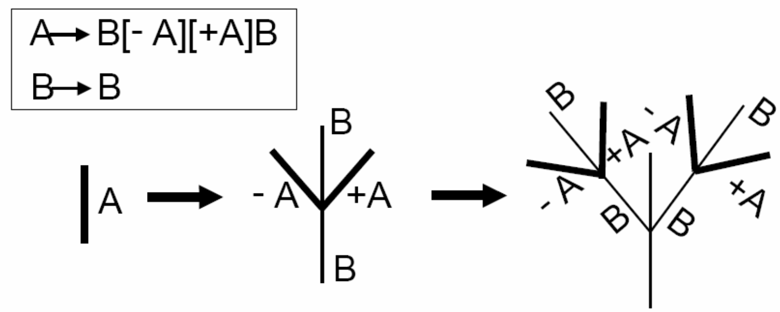
- Reuse with variation is common in nature

Developmental Encodings

- Grammatical (Generative)
  - Utilize properties of grammars and computer languages
  - Subroutines and hierarchy
- Cell chemistry (Development)
  - Simulate low-level chemical and biological properties
  - Diffusion, reaction, growth, signaling, etc.

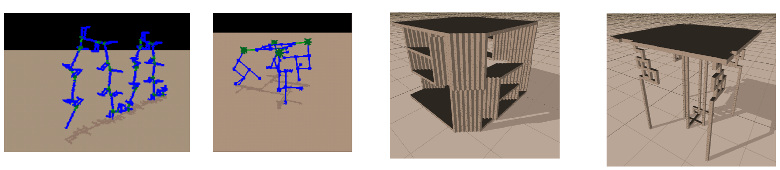
Grammatical Example 1

- L-systems: Good for fractal-like structures, plants, highly regular structures

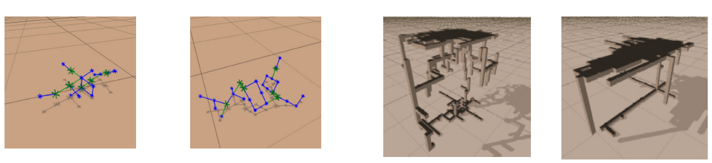


Lindenmayer, A. (1968). Mathematical models for cellular interaction in development: Parts I and II. *Journal of Theoretical Biology, 18*, 280–299, 300–315.
Lindenmayer, A. (1974). Adding continuous components to L-systems. In G. Rozenberg & A. Salomaa (Eds.), *L systems: Lecture notes in computer science 15* (pp. 53–68). Heidelberg, Germany: Springer-Verlag.

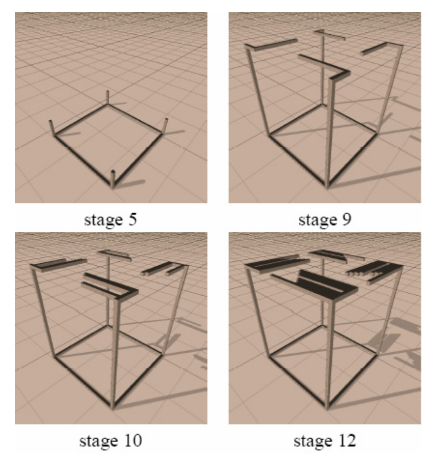
L-System Evolution Successes



- Greg Hornby's Ph.D. dissertation topic (http://ic.arc.nasa.gov/people/hornby)
- Clear advantage over direct encodings



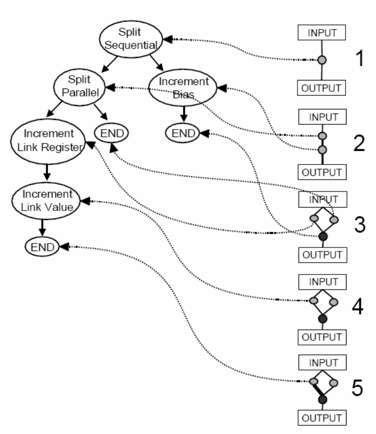
Growth of a Table



Hornby, G.. S. and Pollack, J. B. The Advantages of Generative Grammatical Encodings for Physical Design. *Congress on Evolutionary Computation*. 2001.

Grammatical Example 2

- Cellular Encoding (CE; Gruau 1993, 1996)



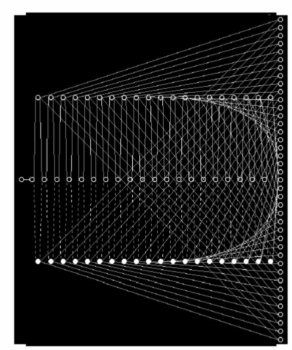
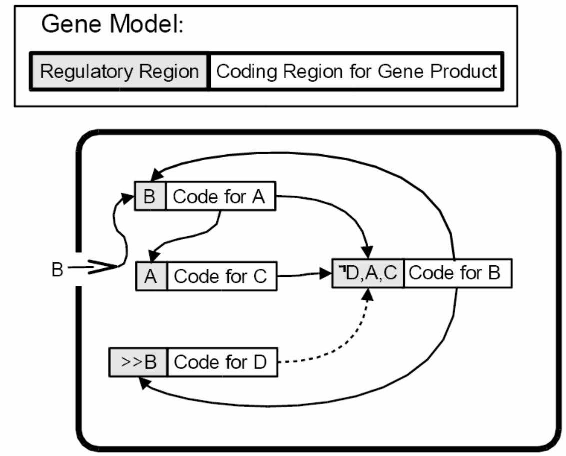


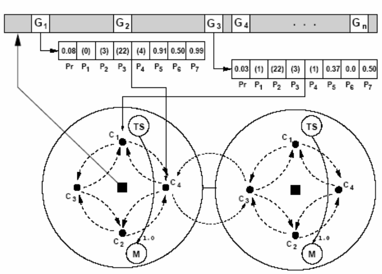
Figure 5.10: A neural network for the symmetry of 40 input units.

F. Gruau. *Neural network synthesis using cellular encoding and the genetic algorithm.* PhD thesis, Laboratoire de L'informatique du Paralllisme, Ecole Normale Supriere de Lyon, Lyon, France, 1994.

Cell Chemistry Encodings



Cell Chemistry Example: Bongard's Artificial Ontogeny



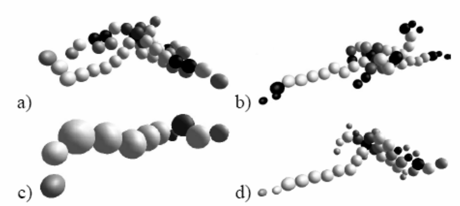


Figure 3: **Four agent morphologies** The block is not shown in

Bongard, J. C. and R. Pfeifer (2001a) Repeated Structure and Dissociation of Genotypic and Phenotypic Complexity in Artificial Ontogeny, in Spector, L. et al (eds.), *Proceedings of The Genetic and Evolutionary Computation Conference, GECCO-2001*. San Francisco, CA: Morgan Kaufmann publishers, pp. 829-836.

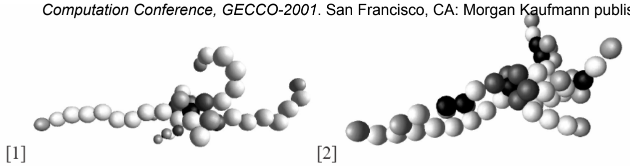
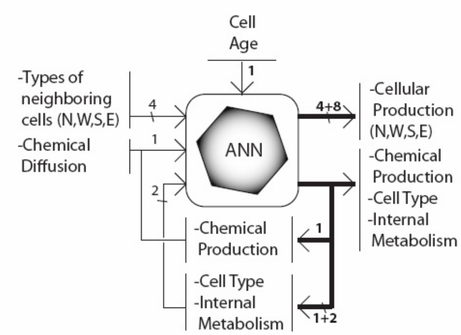


Figure 9: **Two agents evolved for block pushing** The fittest agents extracted from two independent

Bongard, J. C. and R. Pfeifer (2003) Evolving Complete Agents Using Artificial Ontogeny, in Hara, F. and R. Pfeifer, (eds.), *Morpho-functional Machines: The New Species (Designing Embodied Intelligence)* Springer-Verlag, pp. 237-258.

Cell Chemistry Example 2

- Federici 2004: Neural networks inside cells



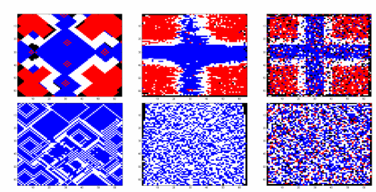


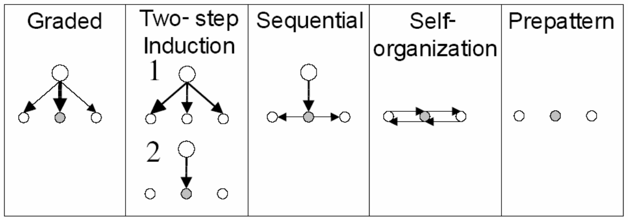
Fig. 6. Best evolved 64x64 solutions using, from left to right, MS, AES and direct

Daniel Roggen and Diego Federici, Multi-cellular development: is there scalability and robustness to gain? In: *Proceedings of PPSN VIII 2004 The 8th International Conference on Parallel Problem Solving from Nature*, Xin Yao and al. ed., pp 391-400, (2004).

Differences in GDS Implementations

- Encoding: Grammatical vs. Cell-chemistry vs. Other (coming later)
- Cell Fate: Final role determined in several ways
- Targeting: Special or relative target specification
- Canalization: Robustness to small disturbances
- Complexification: From fixed-length genomes to expanding genomes

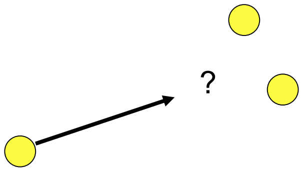
Cell Fate



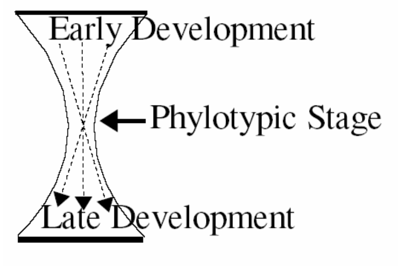
- Many different ways to determine ultimate role of cell
- Cell positioning mechanism can also differ from nature

Targeting

- How do cells become connected such as in a neural network?
- Genes may specify a specific target identity
- Or target may be specified through relative position



Heterochrony



- The order of concurrent events can vary in nature
- When different processes intersect can determine how they coordinate

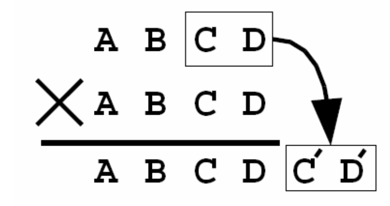
2854 Raff, R. A. (1996). *The shape of life: Genes, development, and the evolution of animal form.* Chicago: The University of Chicago Press.

Canalization

- Crucial pathways become entrenched in development
  - Stochasticity
  - Resource Allocation
  - Overproduction

Nijhout, H. F., & Emlen, D. J. (1998). Competition among body parts in the development and evolution of insect morphology. *Proceedings of the National Academy of Sciences of the USA, 95*, 3685–3689.
Waddington, C. H. (1942). Canalization of Development and the Inheritance of Acquired Characters. *Nature, 150*, 563.

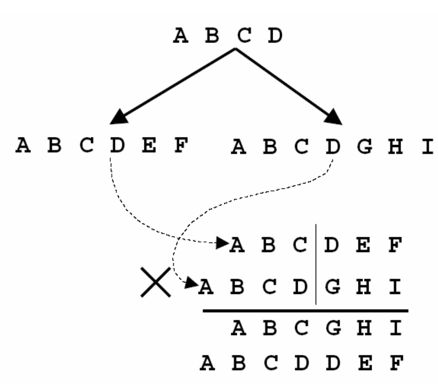
Complexification through Gene Duplication



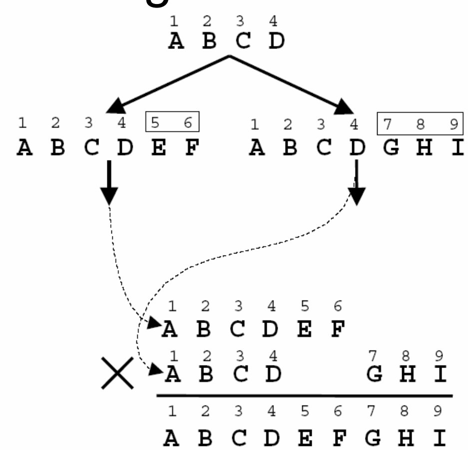
- *Gene Duplication* can add new genes in *any* indirect encoding
- Major gene duplication event as vertebrates appeared
- New *HOX* genes elaborated overall developmental pattern
- Initially redundant regulatory roles are *partitioned*

General Alignment Problem

- Variable length genomes are difficult to align



Historical Markings (NEAT) Solve the Alignment Problem

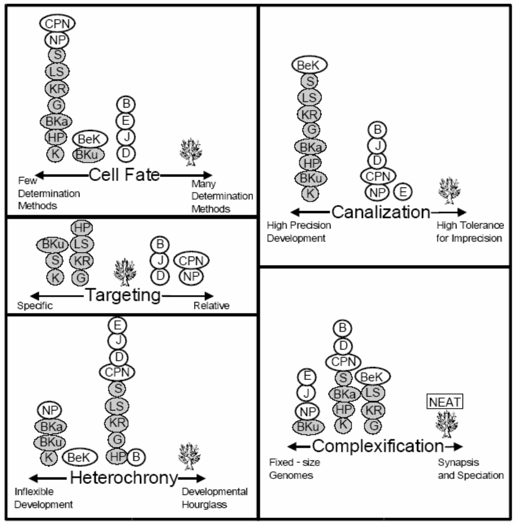


NEAT: NeuroEvolution of Augmenting Topologies

K. O. Stanley and R. Miikkulainen. Evolving neural networks through augmenting topologies. Evolutionary Computation, 10:99–127, 2002.

K. O. Stanley and R. Miikkulainen. Competitive coevolution through evolutionary complexification. Journal of Artificial Intelligence Research, 21:63–100, 2004.

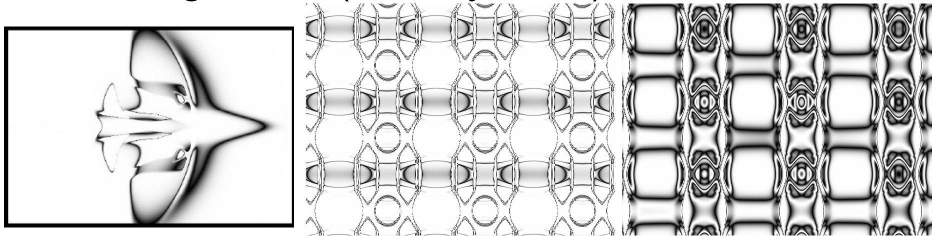
Exploring the Space of GDS (2003)



K. O. Stanley and R. Miikkulainen. A taxonomy for artificial embryogeny. Artificial Life, 9(2):93–130, 2003.

High-Level Abstraction: Compositional Pattern Producing Networks (CPPNs)

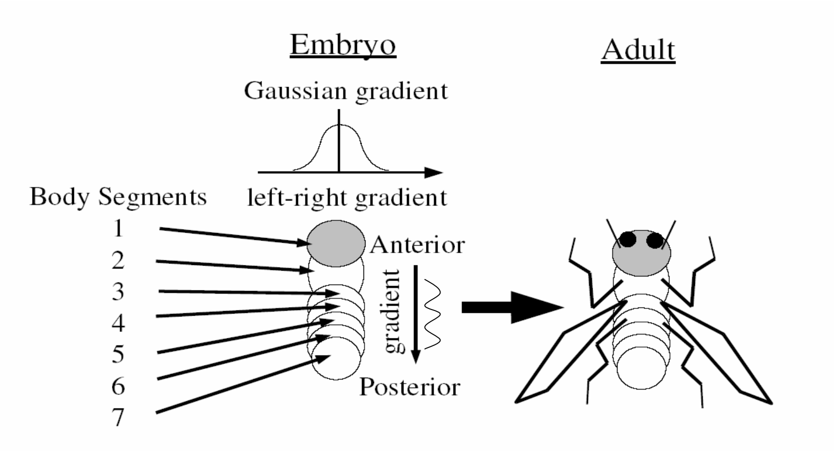
- An artificial indirect encoding designed to abstract how embryos are encoded through DNA (Stanley 2007)



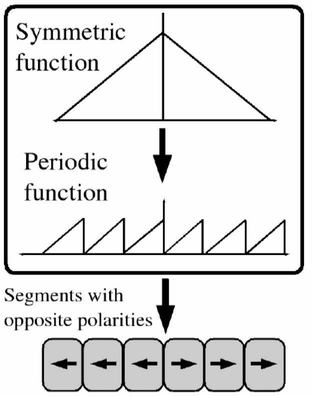
Symmetry Repetition Repetition with variation

Kenneth O. Stanley. Compositional Pattern Producing Networks: A Novel Abstraction of Development In: Genetic Programming and Evolvable Machines Special Issue on Developmental Systems 8(2): 131-162. New York, NY: Springer, 2007

Gradients Define the Body Plan

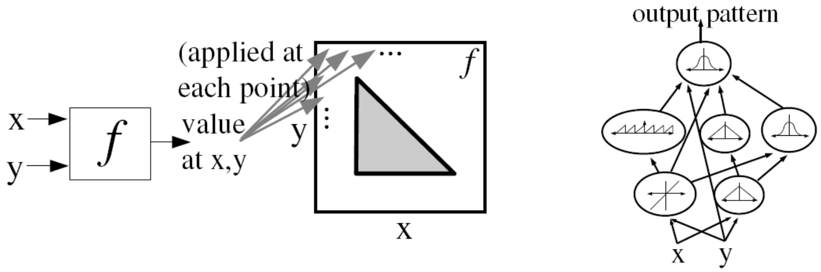


Gradients Can Be Composed



- Is there a general abstraction of composing gradients that we can evolve?

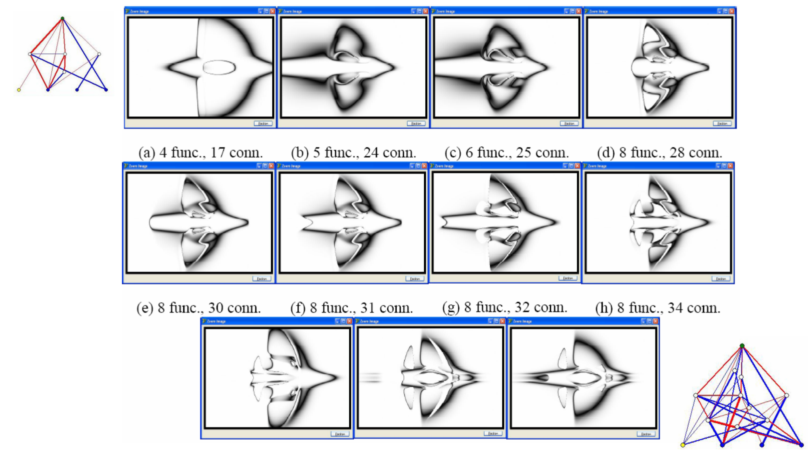
CPPNs



(a) Mapping (b) Composition

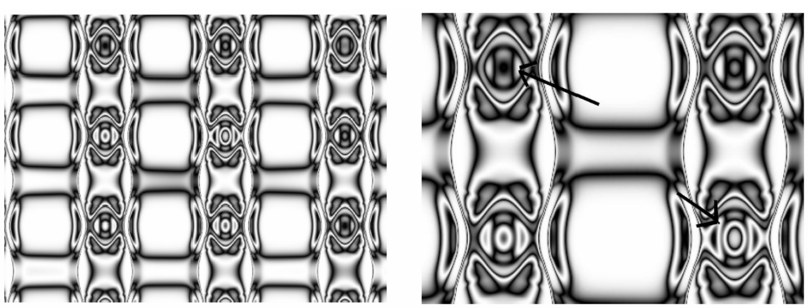
- A connected-graph abstraction of the order of and relationship between developmental events

Compositional Pattern Producing Networks (CPPNs)



Evolutionary Elaboration

CPPNs:Repetition with Variation



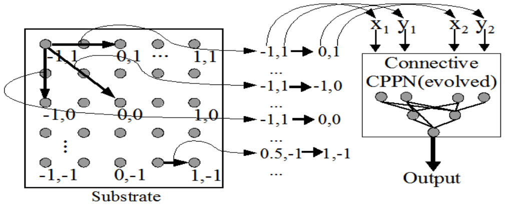
- Seen throughout nature
- A simple combination of periodic and absolute coordinate frames
- A novel view: *not a traditional subroutine*

Is Unfolding Over Time and Local Interaction Essential to Development?

- What is lost if they are abstracted away?
- What is the role of local interaction?
  - “Where am I?”
  - If I know where I am, do I need it?
- What about adaptation/change over life?
  - CPPNs can be iterated over time
  - CPPNs can take environmental inputs

Hypercube-based NeuroEvolution of Augmenting Topologies (HyperNEAT)

- Evolving neural networks with CPPNs
- Insight: A connectivity pattern in 2-D is isomorphic to a spatial pattern in 4-D
- Result: Large-scale connectivity patterns



Jason J. Gauci and Kenneth O. Stanley. Generating Large-Scale Neural Networks Through Discovering Geometric Regularities. In: *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2007)*. New York, NY: ACM, 2007

Jason J. Gauci and Kenneth O. Stanley. A Case Study on the Critical Role of Geometric Regularity in Machine Learning. Proceedings of the Twenty-Third AAAI Conference on Artificial Intelligence (AAAI-2008). Menlo Park, CA: AAAI Press, 2008.

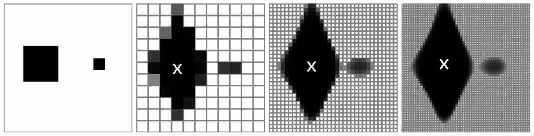
David B. D'Ambrosio and Kenneth O. Stanley. A Novel Generative Encoding for Exploiting Neural Network Sensor and Output Geometry. In: *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2007)*. New York, NY: ACM, 2007

At this GECCO:: David B. D'Ambrosio and Kenneth O. Stanley. Generative Encoding for Multiagent Learning. In: *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2008)*. New York, NY: ACM, 2007

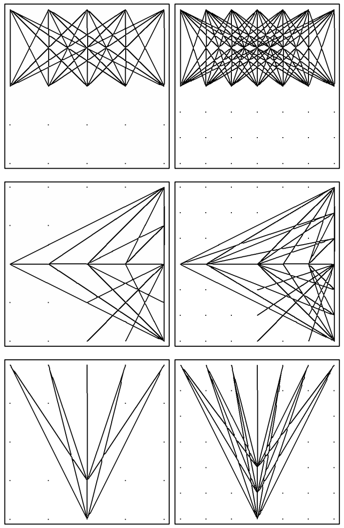
To appear: Kenneth O. Stanley, David B. D'Ambrosio, and Jason Gauci. A Hypercube-based Encoding for Evolving Large Scale Neural Networks. *Artificial Life*, 2008.

HyperNEAT

- Infinite-resolution connectivity patterns
- Massive working multimillion connection networks



(a) Sensor Field (object placement) (b) 11x11 Target Field (12,827 connections) (c) 33x33 Target Field (1,033,603 connections) (d) 55x55 Target Field (7,970,395 connections)



Another Biological Abstraction: Implicit Encoding

- Idea: Let the *interaction* of genes in a GRN define connections in a network
  - Mattiussi and Floreano's Analog Genetic Encoding (AGE)
  - Reisinger and Miikkulainen's (2007) Implicit Encoding
- No explicit growth: The interaction is among genes
  - Similar products leads to stronger connections
- Advantages: Compact encoding, one-to-many interaction, allows gene duplication

Mattiussi, C., and Floreano, D. 2004. Evolution of Analog Networks using Local String Alignment on Highly Reorganizable Genomes. In: *Proceedings of the 2004 NASA/DoD Conference on Evolvable Hardware* (EH' 2004).

Joseph Reisinger and Risto Miikkulainen. Acquiring Evolvability through Adaptive Representations. In: *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2007)*. New York, NY: ACM, 2007

Some GDS Theoretical Issues

- Expressive power of different encodings
- Chomsky hierarchy: Generative grammars of different expressive power
  - Is a CPPN comparable?
- Key consideration: Does the development process halt?
  - Yes (when phenotype complete): Then the issue is *universal function approximation*
  - No (continues indefinitely over lifetime): Then the issue is Turing completeness
- A CPPN can be a universal function approximator
  - An *iterated CPPN* may be more
- What is more important: Theoretical equivalence or *bias* in practice?
  - What *can* happen is not necessarily what *will* happen

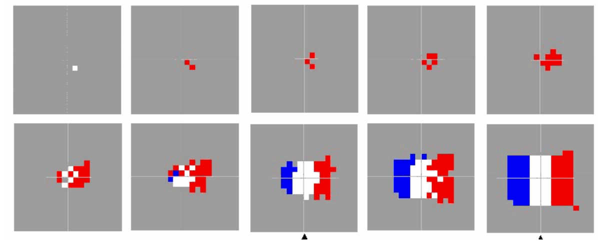
How Can We Learn How Well GDS Works?

- Benchmarks
  - Evolution of pure symmetry
  - Evolving a specific shape
  - Evolving a specific connectivity pattern
  - Flags
  - Problems with repetition and/or variation
- Interactive evolution
  - Allow human to explore the space of a dev. encoding (like Dawkin's Biomorphs, 1986)
  - Learn principles by seeing how things change, become canalized, etc..
  - Example: See http://picbreeder.org for CPPN exploration
- Major application?

Dawkins, R.: The Blind Watchmaker. Longman, Essex, U.K. (1986)

Progress through Benchmarks

- Visualization is most revealing
  - Observe growth and final product



Julian Miller's French Flags http://www.elec.york.ac.uk/intsys/users/jfm7/french-flag/sld018.htm

Miller J. F. Evolving a self-repairing, self-regulating, French flag organism. Proceedings of Genetic and Evolutionary Computation Conference (GECCO 2004), Springer LNCS 3102 (2004) 129-139.

  - Shapes and pictures are easy to analyze

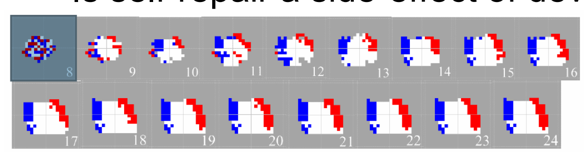
Where is GDS Useful?

- Problems with regularities
  - Board games
  - Visual processing/image recognition
  - Pictures
  - Music
  - Puzzles
  - Architectures/morphologies
  - Brains
  - Bodies
- Problems requiring high complexity
  - High-level cognition
  - Strategic thinking
  - Tactical thinking
- Regeneration and self-repair

Miller J. F. Evolving a self-repairing, self-regulating, French flag organism. Proceedings of Genetic and Evolutionary Computation Conference (GECCO 2004), Springer LNCS 3102 (2004) 129-139.

Regeneration and Self-Repair

- A major interest in much GDS research
- Is self-repair a side-effect of development?



Miller J. F. Evolving a self-repairing, self-regulating, French flag organism. Proceedings of Genetic and Evolutionary Computation Conference (GECCO 2004), Springer LNCS 3102 (2004) 129-139.

Fig. 8. Autonomous recovery of French flag from randomly rearranged cells (French flag at iteration 8 - see Fig. 4). There is no further change after iteration 24

- In some encodings self-repair is not needed
  - In CPPNs every cell knows its role instantaneously from its position
  - However, some applications may not provide positional information

Where is GDS not Useful?

- Problems without regularity
- Simple high-precision domains
  - Very small picture reproduction
- Simple control tasks
  - Go to the food
  - Balance the pole (5-connection solution)

GDS Testing Paradox

- GDS is a mismatch for simple problems
- Hard problems are too hard to just get started
- Where do we begin?
  - Somewhere in the middle
  - Example: Board games with ANNs

Long Term Issues

- What are the ultimate encodings?
- What are the ultimate applications?
- What application requires a strucutre of 100 million parts and actually utilizes the structure?

More information

- My Homepage: http://www.cs.ucf.edu/~kstanley
- NEAT Users Group: http://groups.yahoo.com/group/neat
- Evolutionary Complexity Research Group:
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