

E P L E X

Evolutionary Complexity Research Group at UCF

Generative and Developmental Systems Tutorial

Kenneth O. Stanley

Department of Computer Science
University of Central Florida
Orlando, FL, USA

Email: kstanley@cs.ucf.edu Website: <http://eplex.cs.ucf.edu>

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage, and that copies bear this notice and the full citation on the first page. Copyrights for third-party components of this work must be honored. For all other uses, contact the owner/author(s).

Copyright is held by the author(s).
GECCO'16 Companion, July 20–24, 2016, Denver, CO, USA
ACM 978-1-4503-4323-7/16/07.
<http://dx.doi.org/10.1145/2908961.2926992>



1



Instructor/Presenter

- Ken Stanley's connections to Generative and Developmental Systems (GDS):
 - Co-author of 2003 GDS review paper, *A Taxonomy for Artificial Embryogeny*
 - Co-founder of GECCO GDS Track in 2007 and Co-chair of track from 2007-2009 (now integrated into "Complex Systems" track)
 - Co-inventor of NEAT, CPPN indirect encoding, and the HyperNEAT GDS algorithm
 - At least 20 GDS-related publications

2

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

Course Agenda

- Part 1: Intro to GDS
 - Motivation
 - Classical Encodings
 - Dimensions of Development
- Break
- Part 2: Exploring Abstraction
 - CPPNs
 - HyperNEAT
 - Representations and theoretical issues

3

Objectives of the Tutorial

- At the end, you will know:
 - What GDS is about
 - Motivation for GDS
 - Historical precedent
 - Popular approaches
 - Biological analogies
 - Recent approaches
 - Representational properties
 - Theoretical issues
 - Goals for the field

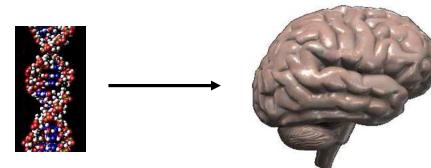
4

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?

5

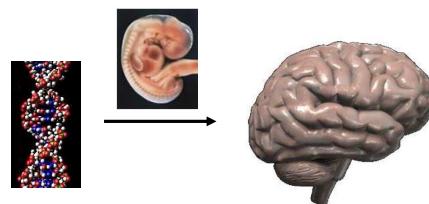
Goal: Evolve Systems of Biological Complexity



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

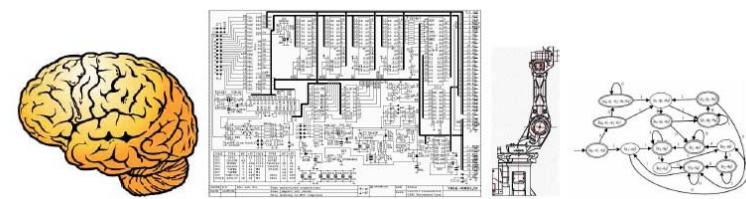
6

Development



7
(embryo image from nobelprize.org)

Solving this Problem Could Solve Many Others



8

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.

9

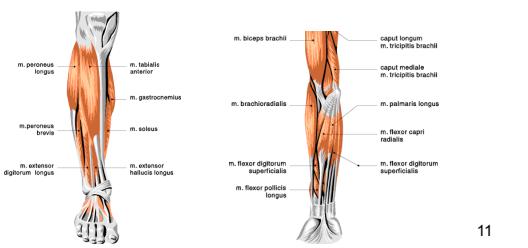
A Field with Many Names

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

10

Development is Powerful Because of Reuse

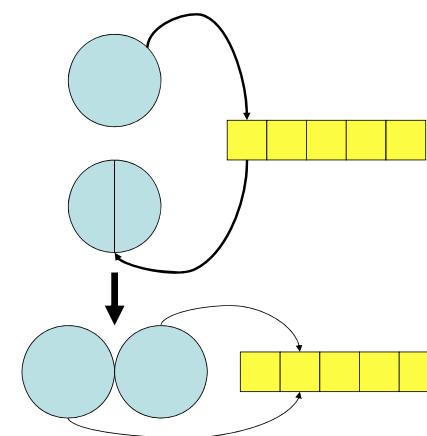
- Genetic information is reused during embryo development
- Many structures share information
- Allows enormous complexity to be encoded compactly



11

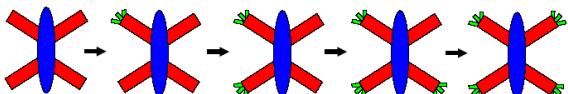
(James Madison University http://orgs.jmu.edu/strength/KIN_425/kin_425_muscles_calves.htm)

The Unfolding of Structure Allows Reuse



12

Rediscovery Unnecessary with Reuse

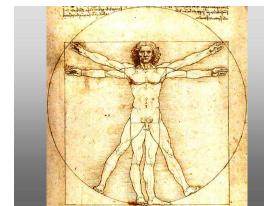


- Repeated substructures should only need to be represented once
- Then repeated elaborations do not require rediscovery
- Rediscovery is expensive and improbable
- (Development is powerful for search even though it is a property of the *mapping*)

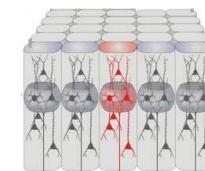
13

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



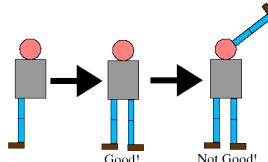
Repetition



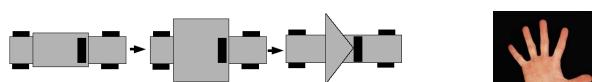
Repetition with variation¹⁴

Some Major Issues in GDS

- Phenotypic duplication can be brittle



- Variation on an established convention is powerful



- Reuse with variation is common in nature¹⁵

612

Classic Developmental Encodings

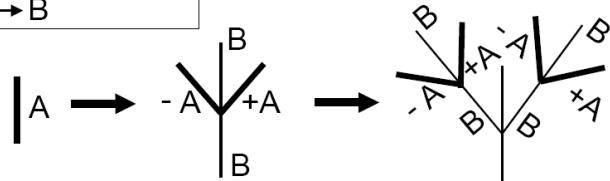
- Grammatical (Generative)
 - Utilize properties of grammars and computer languages
 - Subroutines and hierarchy
- Cell chemistry (Development)
 - Simulate low-level chemical and biological properties
 - Diffusion, reaction, growth, signaling, etc.

16

Grammatical Example 1

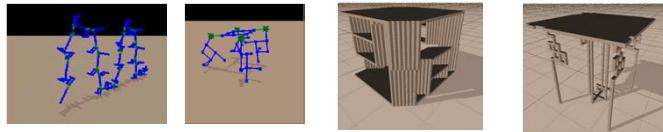
- L-systems: Good for fractal-like structures, plants, highly regular structures

$$\begin{array}{l} A \rightarrow B[-A][+A]B \\ B \rightarrow B \end{array}$$

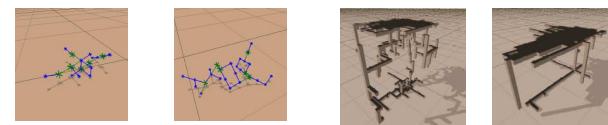


Lindenmayer, A. (1968). Mathematical models for cellular interaction in development: Parts I and II. *Journal of Theoretical Biology*, 18, 280–299, 300–315.
 Lindenmayer, A. (1974). Adding continuous components to L-systems. In G. Rozenberg & A. Salomaa (Eds.), *L systems: 17 Lecture notes in computer science 15* (pp. 53–68). Heidelberg, Germany: Springer-Verlag.

L-System Evolution Successes

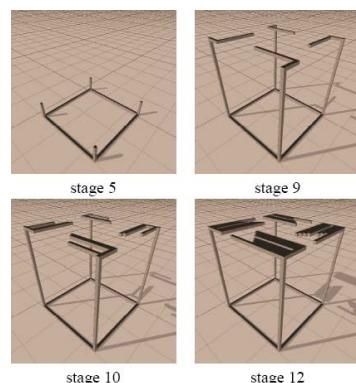


- Greg Hornby's Ph.D. dissertation topic (<http://ic.arc.nasa.gov/people/hornby>)
- Clear advantage over direct encodings



18

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.

19

Grammatical Example 2

- Cellular Encoding (CE; Gruau 1993, 1996)

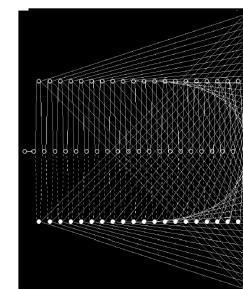
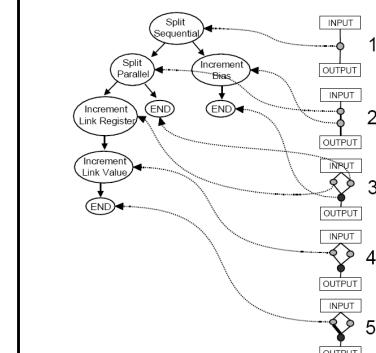
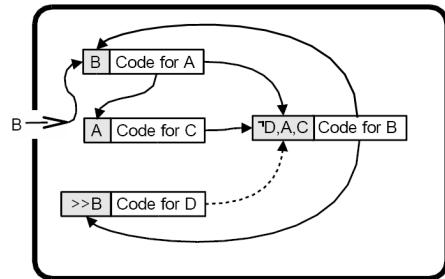
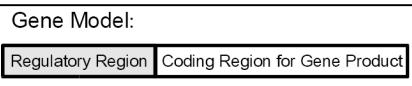


Figure 5.10: A neural network for the symmetry of 40 input units.
 F. Gruau. *Neural network synthesis using cellular encoding and the genetic algorithm*. PhD thesis, Laboratoire de l'informatique du Parallélisme, Ecole Normale Supérieure de Lyon, Lyon, France, 1994.

Cell Chemistry Encodings



21

Cell Chemistry Example: Bongard's Artificial Ontogeny

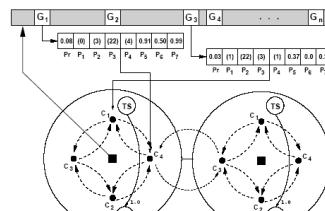


Figure 3: Four agent morphologies The block is not shown in
Bongard, J. C. and R. Pfeifer (2001a) Repeated Structure and Dissociation of Genotypic and Phenotypic Complexity in Artificial Ontogeny, in Spector, L. et al (eds.), *Proceedings of The Genetic and Evolutionary Computation Conference, GECCO-2001*. San Francisco, CA: Morgan Kaufmann publishers, pp. 829-836.

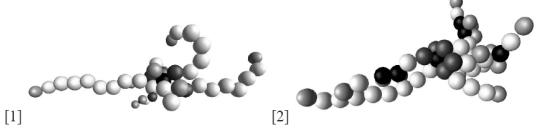
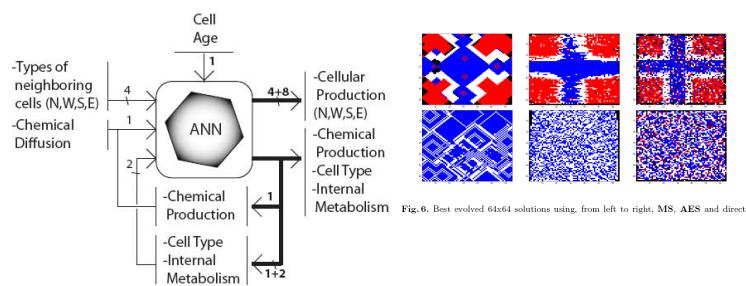


Figure 9: Two agents evolved for block pushing The fittest agents extracted from two independent

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



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).

23

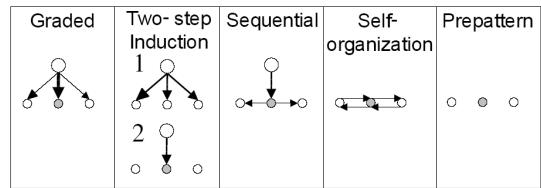
Differences in GDS Implementations

- 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

24

614

Cell Fate

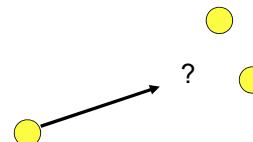


- Many different ways to determine ultimate role of cell
- Cell positioning mechanism can also differ from nature

25

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



26

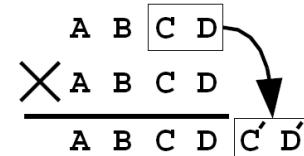
Canalization



- 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*

28

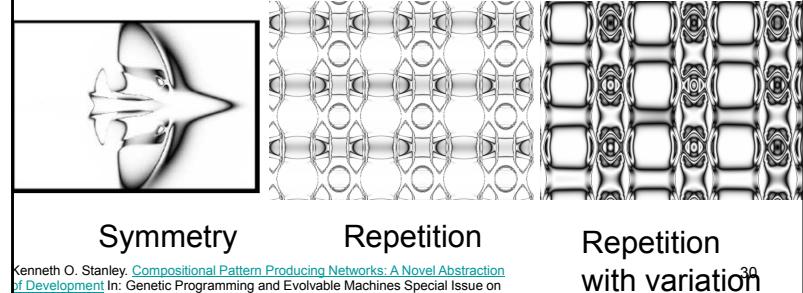
Break

- Take break
- Resume in 10 minutes

29

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

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



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

³⁰

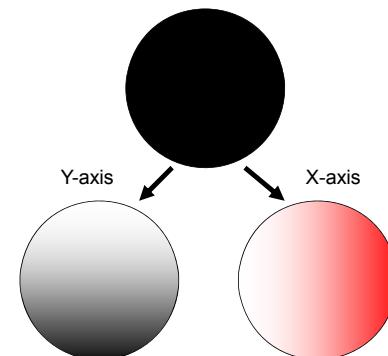
What is Development Really Doing?

- A plan upon a plan upon a plan
- Each layer lays a groundwork for the next
- A structure is built in a coordinate frame
 - First the axes must be defined
 - Then the core structure is situated
 - Then further axes are defined
 - And so on

31

Gradients Define Axes

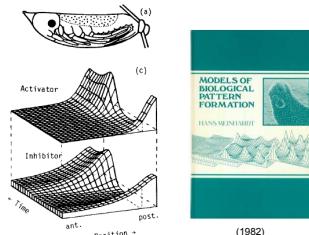
- Chemical gradients tell which direction is which, which axis is which



32

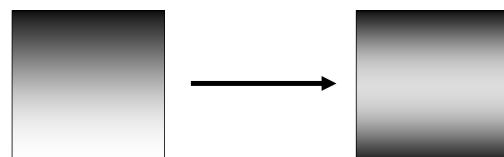
Cells Know Where They Are Through Gradients

- Therefore, they know who needs to do what, and where
- Because *where* is now defined
- Gradients form a *coordinate frame*



33

Higher Coordinate Frames are Functions of Lower Ones

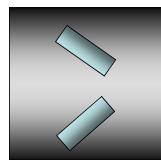


$$f(y) = y$$

$$g(y) = |f(y)|$$

Using g and x as a coordinate space, we can get h :

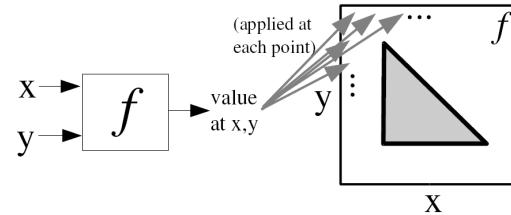
Symmetry from a symmetric gradient



$$h(x, y) = \text{func}[x, g(y)]$$

35

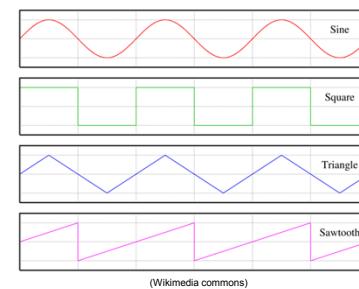
A Novel View: The Phenotype as a Function of Cartesian Space



- Coordinate frames are chemical gradients
- Function is applied at all points

34

Segmentation is a Periodic Gradient

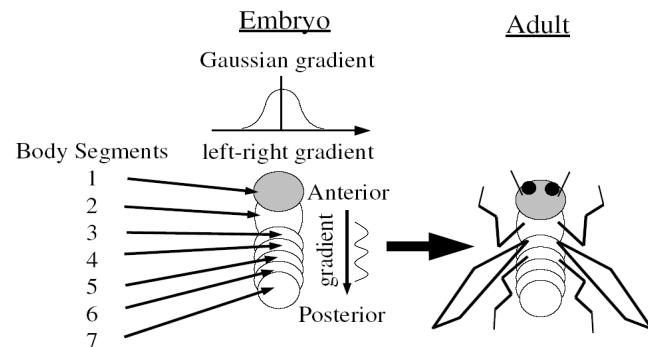


(Wikimedia commons)

- $f(\text{periodic function}) = \text{repeating pattern}$
- Periodic functions mean repeating coordinate frames

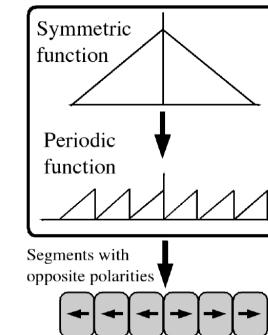
36

Gradients Define the Body Plan



37

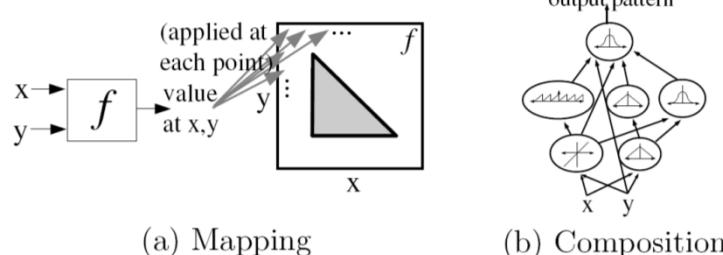
Gradients Can Be Composed



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

38

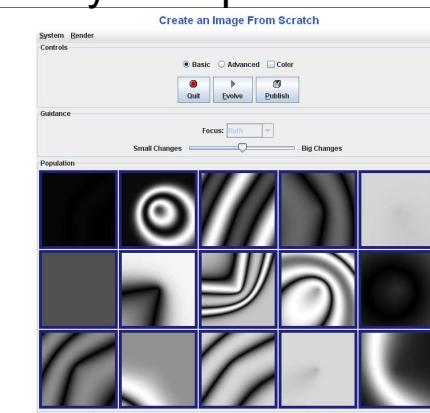
Compositional Pattern Producing Networks (CPPNs)



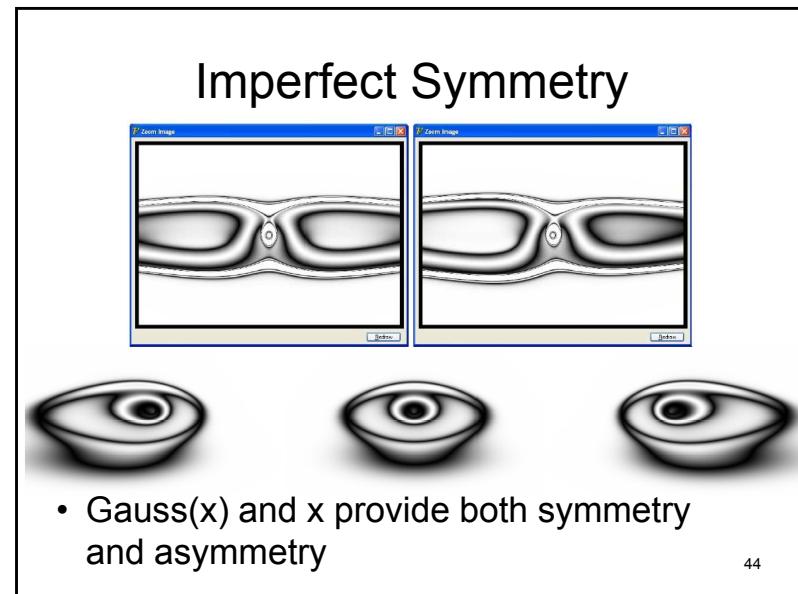
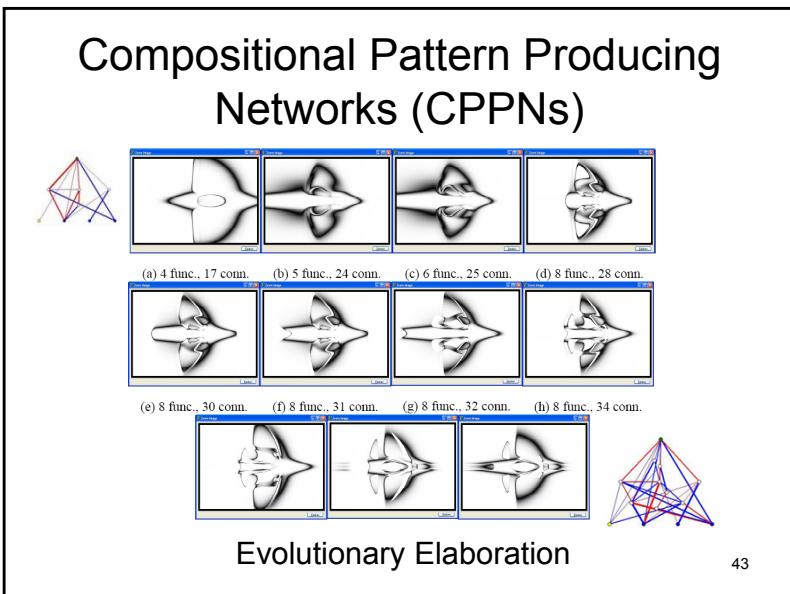
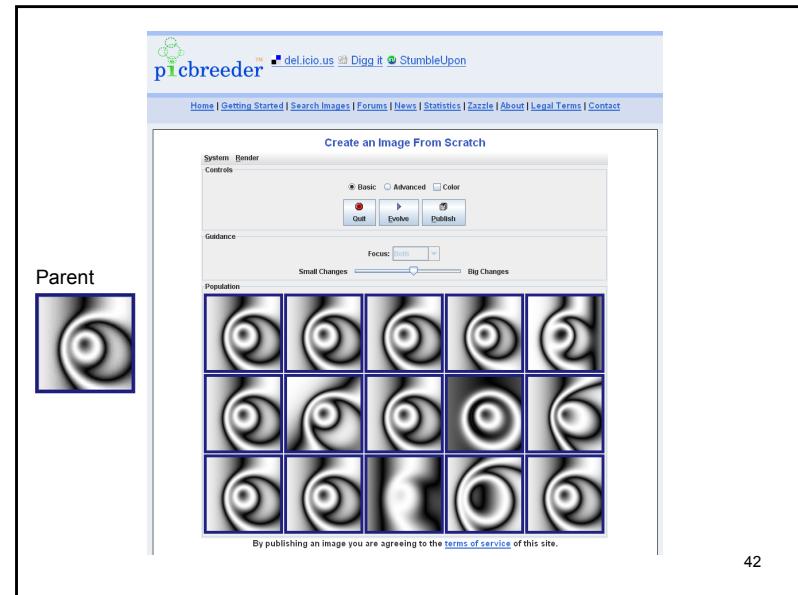
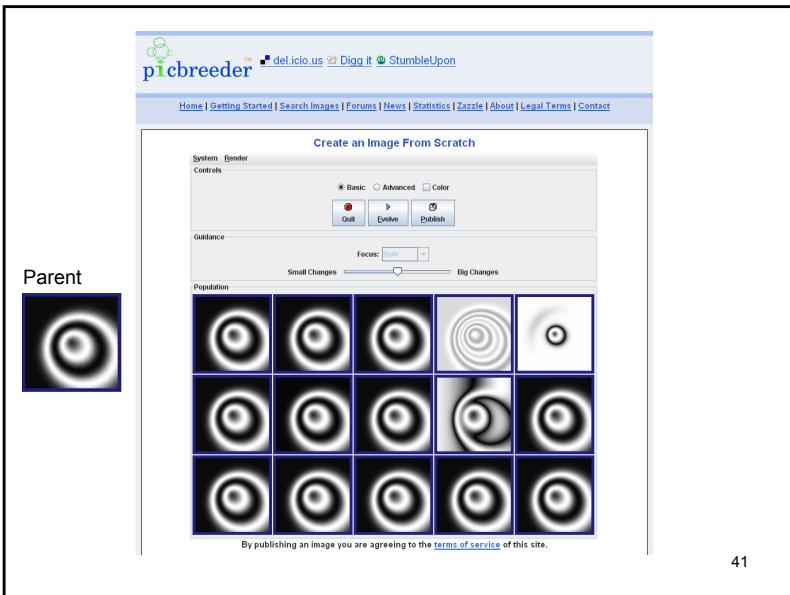
- A connected-graph abstraction of the order of and relationship between developmental events (no growth!)

39

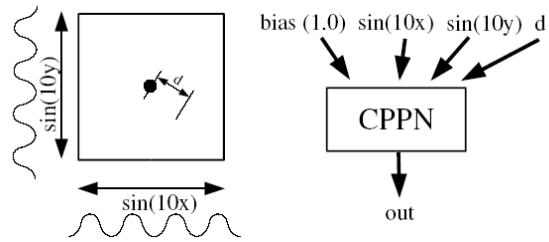
Interactive Evolution: A Way to Explore Encoding



40

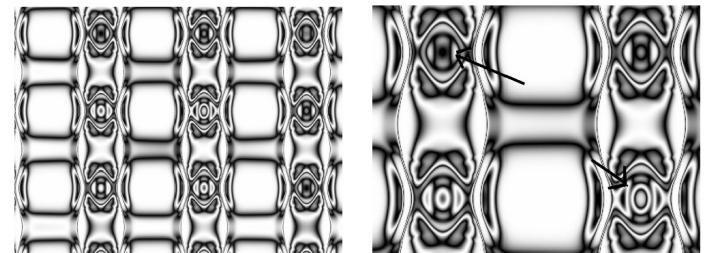


Repetition with Variation



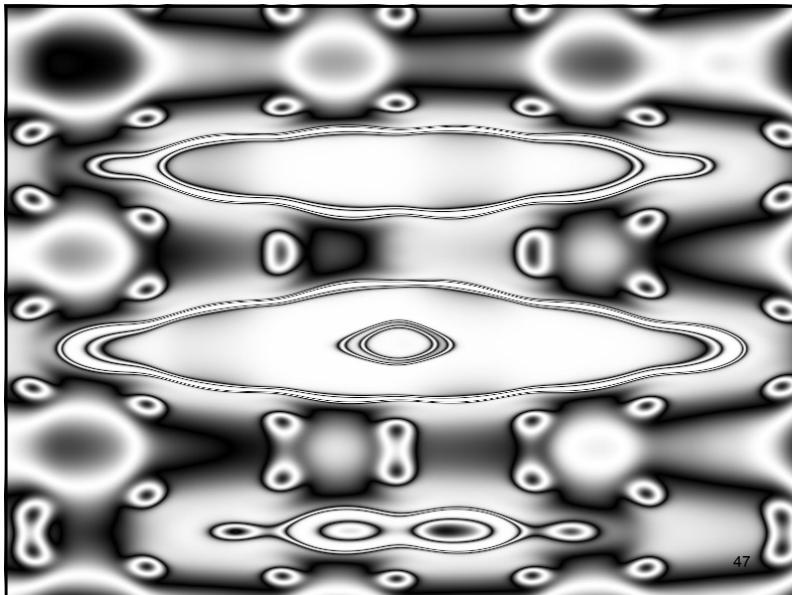
45

CPPNs: Repetition with Variation

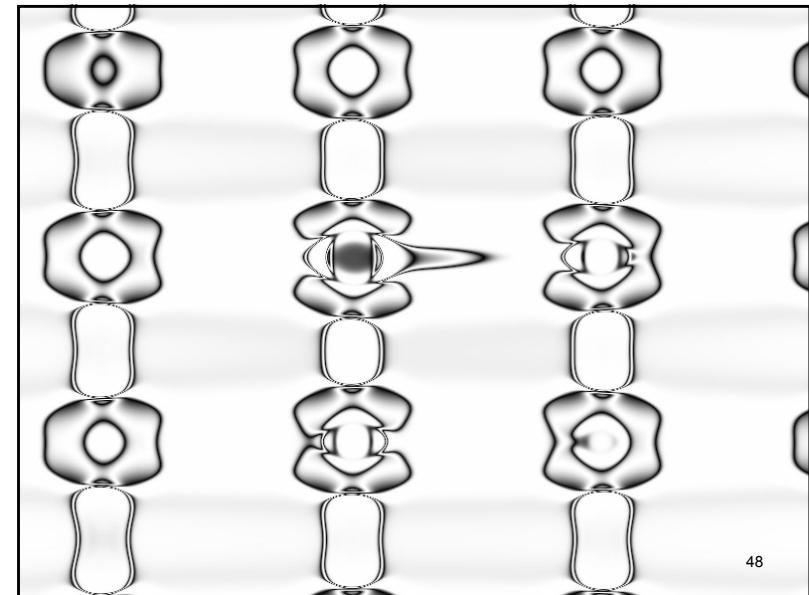


- Seen throughout nature
- A simple combination of periodic and absolute coordinate frames
- A novel view: *not a traditional subroutine*

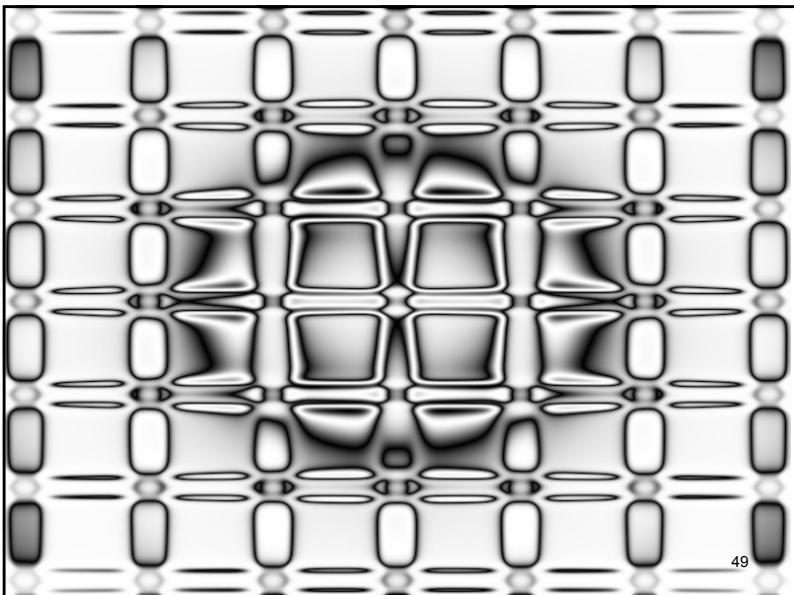
46



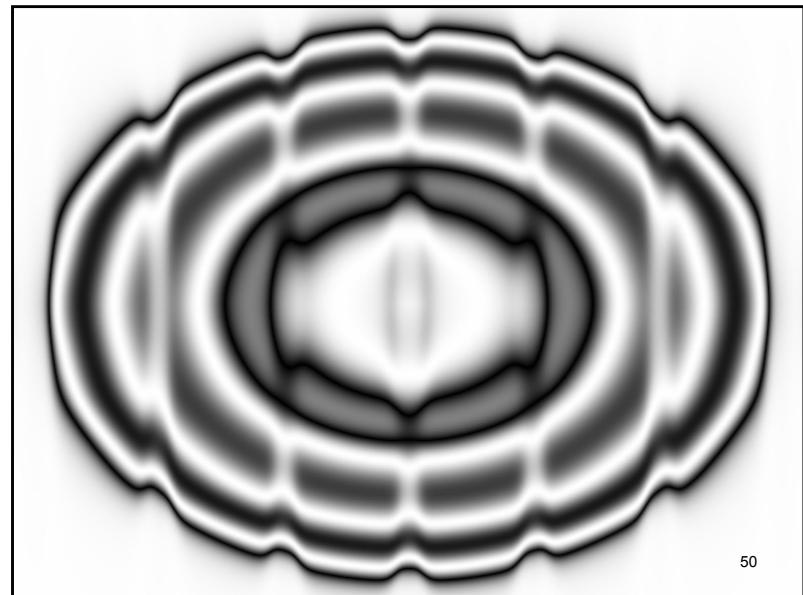
47



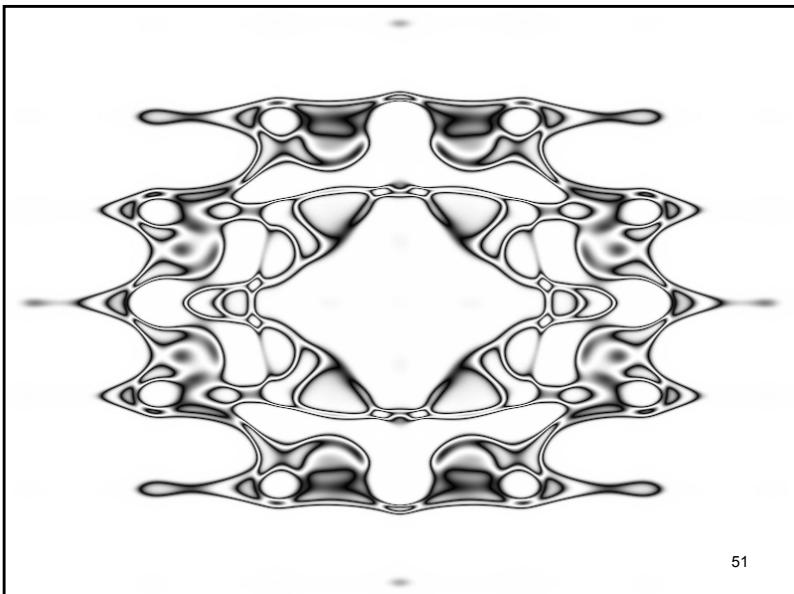
48



49



50



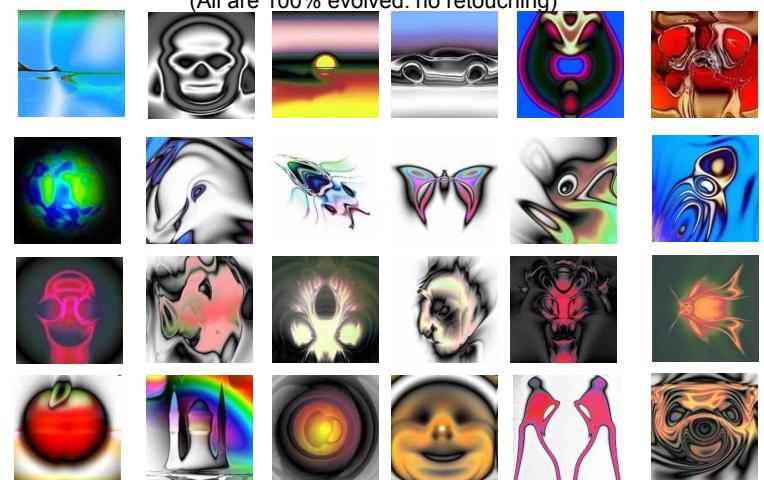
51

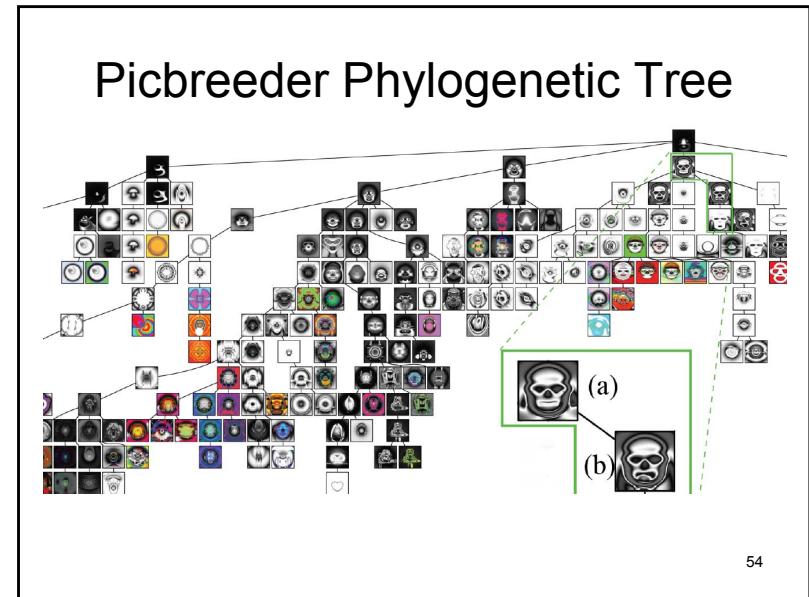
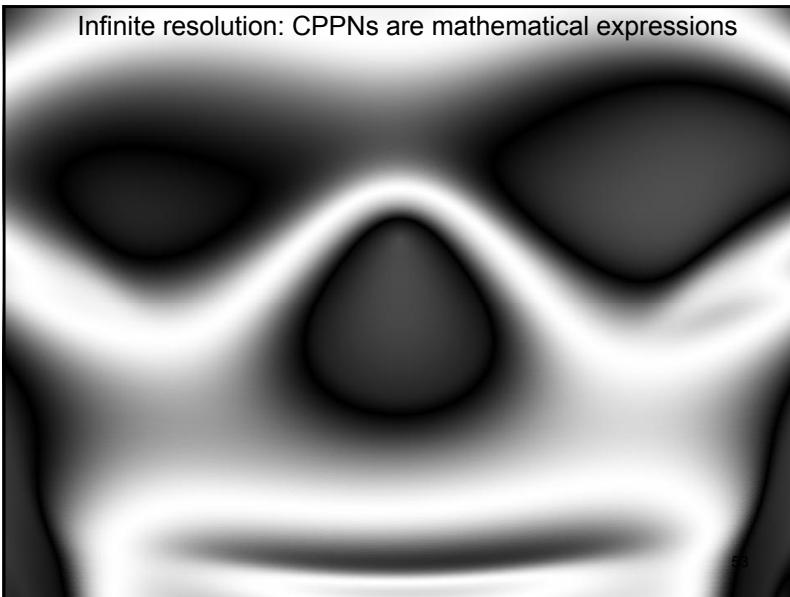
Jimmy Secretan, Nicholas Beato, David B. D'Ambrosio, Adelein Rodriguez, Adam Campbell, Jeremiah T. Folsom-Kovarik, and Kenneth O. Stanley (2011). *Picbreeder: A Computer Game for Evolving Artistic Images*. In *Evolutionary Exploration of Design Space*. *Evolutionary Computation*, 19(3): 345–371, Cambridge, MA: MIT Press

CPPN Patterns

From <http://picbreeder.org>

(All are 100% evolved: no retouching)





CPPNs Abstract Development out of Development!

- CPPN is decoded by querying each point in space *independently*: no local interaction
- The process of development need not be simulated
- Some Advantages:
 - Patterns stored at infinite resolution
 - Easily biased in fancy ways
 - Perfect regeneration of damaged structure

Is development really the essential property of developmental systems that we've been looking for? Or is there something more fundamental that is simply manifested through development?

55

Are 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?
- Response to CPPNs:
 - Some are arguing that *intermediate information* during development can be exploited by evolution T. Kowaliw and W. Banzhaf, *Augmenting Artificial Development with Local Fitness*, In IEEE CEC 2009
- Still, CPPNs can be iterated over time
 - CPPNs can take environmental inputs

56

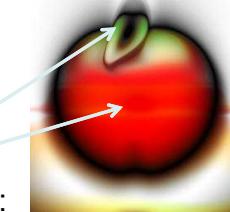
Representational Properties of CPPNs

- Compositionality
 - One pattern can be built upon another (output of one function fed into another)
- Fracture
 - Discontinuous variation of patterns
“fractured problems have a highly discontinuous mapping between states and optimal actions.”
Nate Kohl and Risto Miikkulainen (2009). Evolving Neural Networks for Strategic Decision-Making Problems. *Neural Networks, Special Issue on Goal-Directed Neural Systems.*
 - Define different regions
 - Builds incrementally over evolution



57

The Apple



Stem and Body:
Fractured Regions

58

The Apple



How is it represented?

CPPN has 83 nodes, 264 connections
320 generations

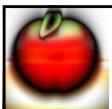
59

Image DNA Tool



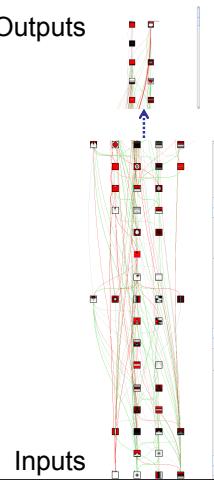
- Allows browsing CPPN

60



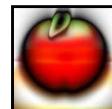
Very Large Apple Network

Outputs



Inputs

61



Starting at the Bottom



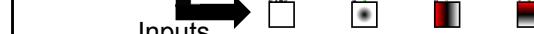
d



x

y

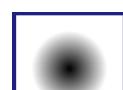
Inputs



62



Starting at the Bottom



d

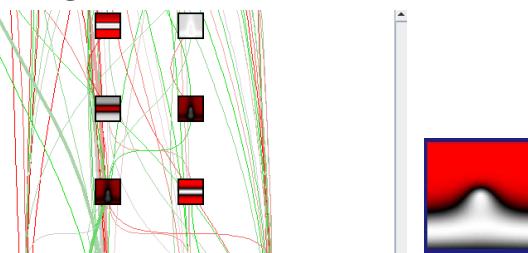


x

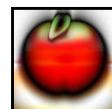


y

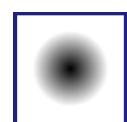
Inputs



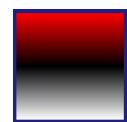
63



Forming Intermediate Patterns



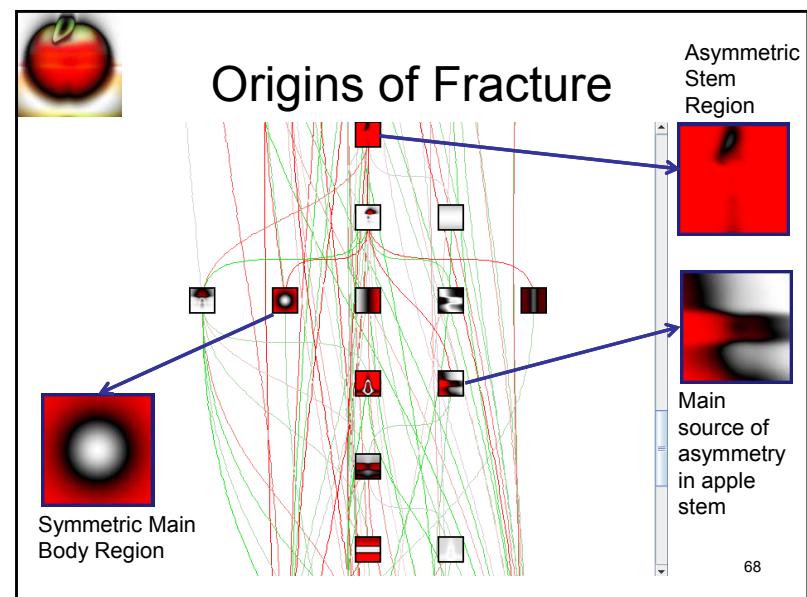
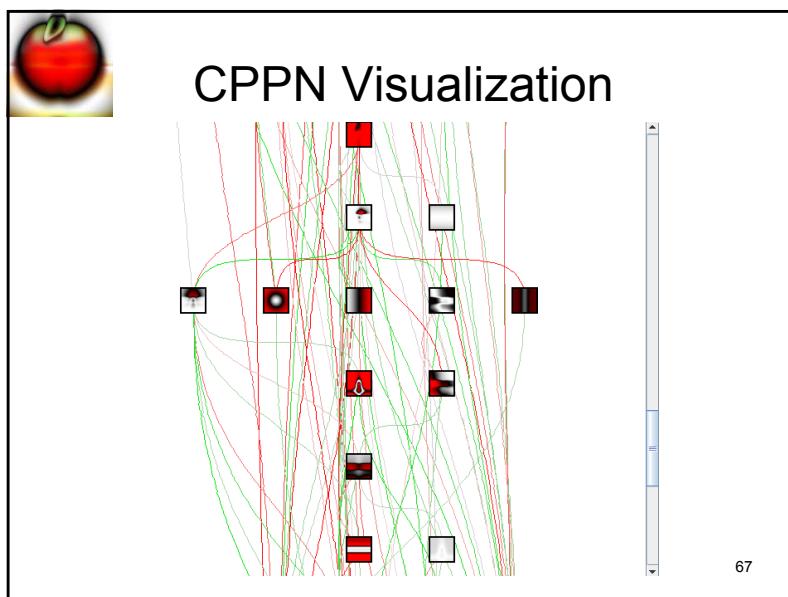
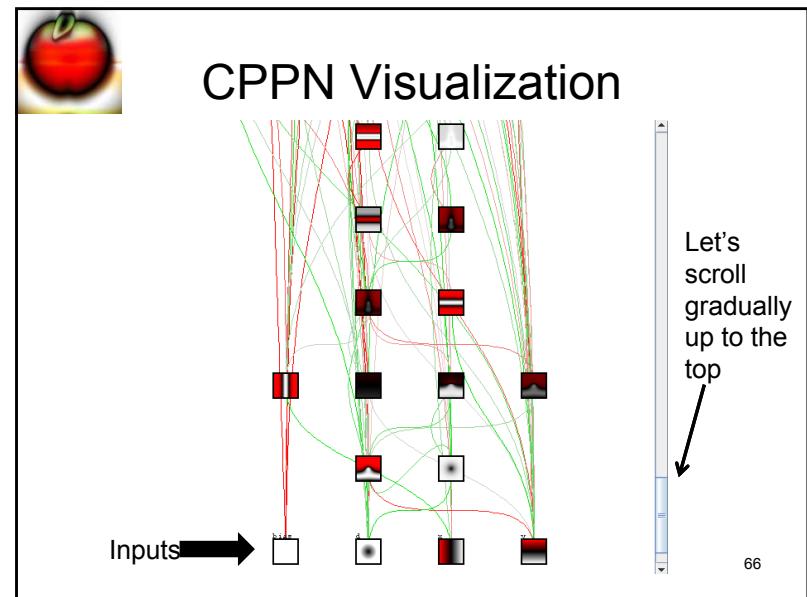
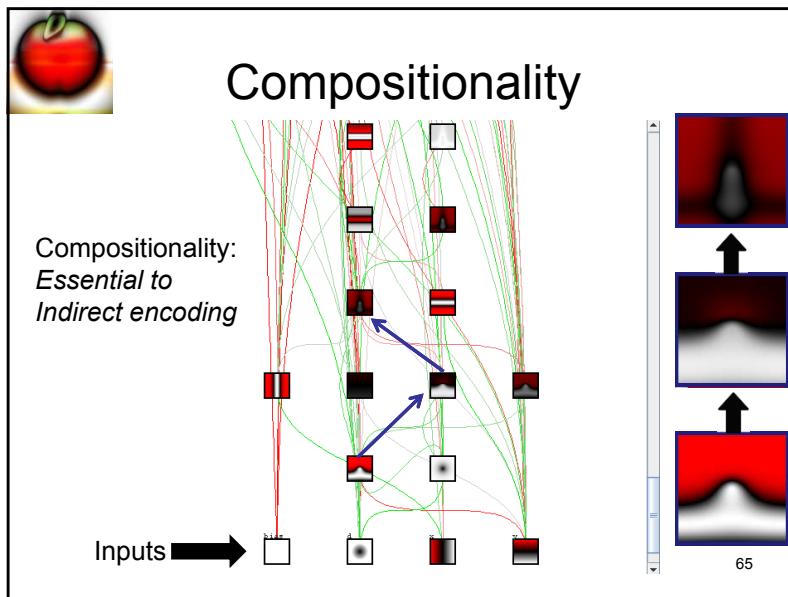
d

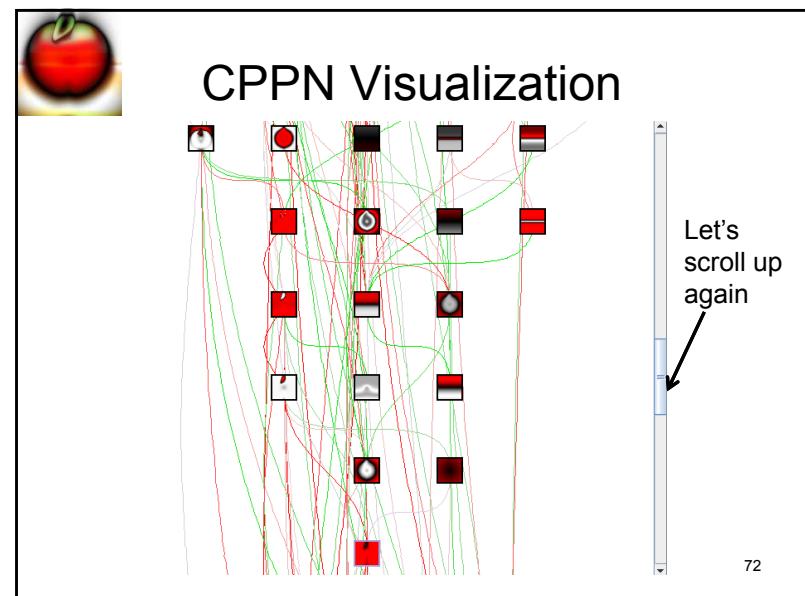
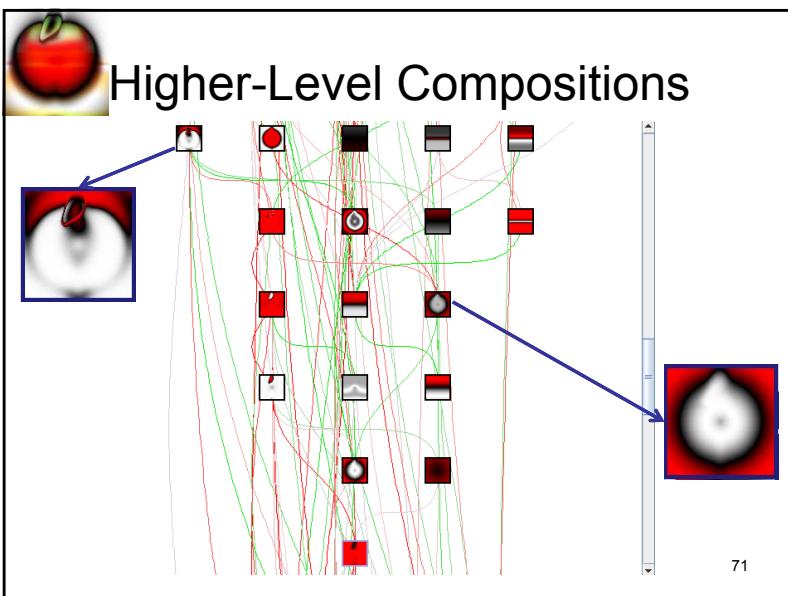
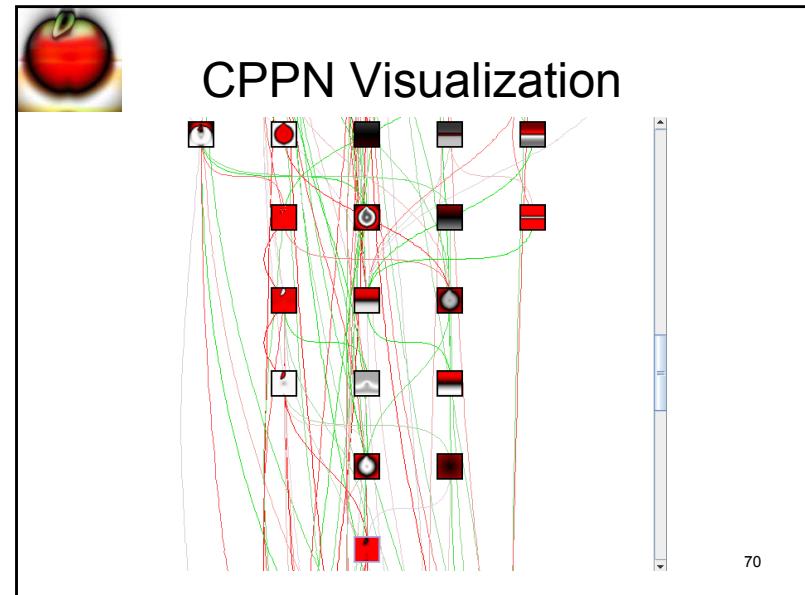
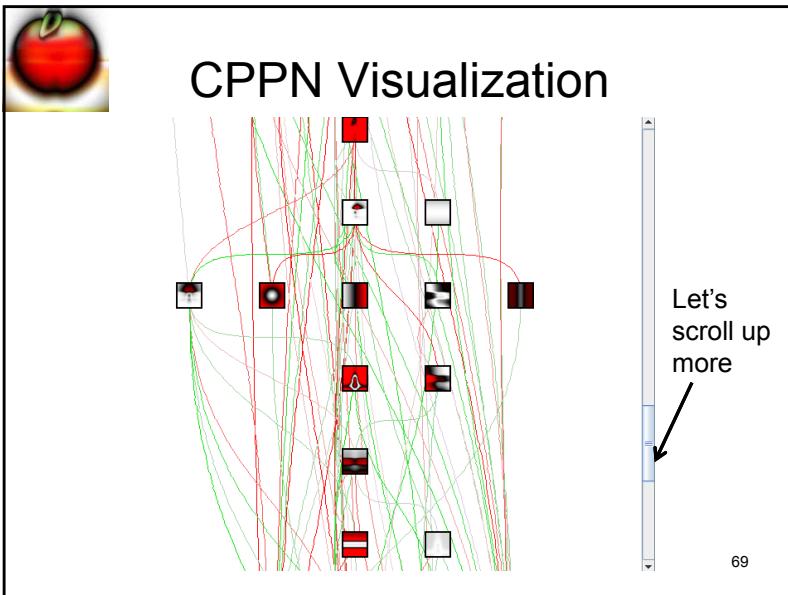


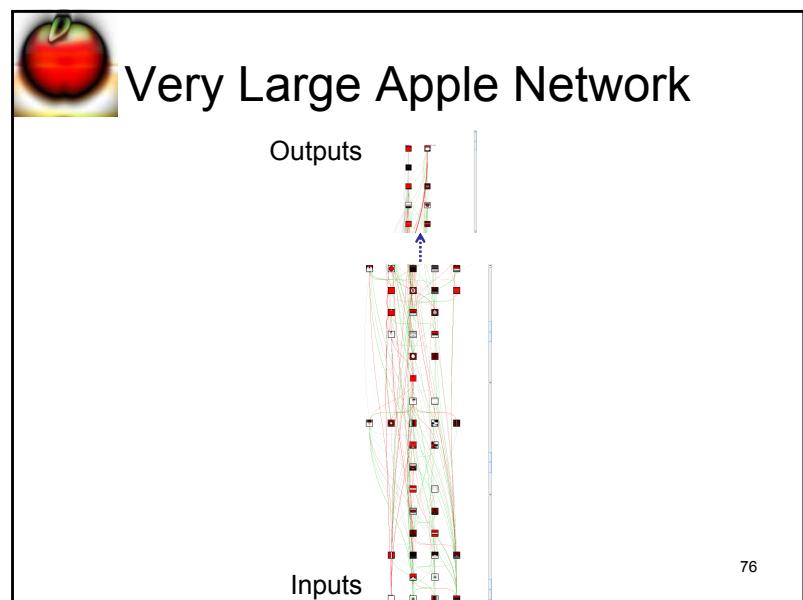
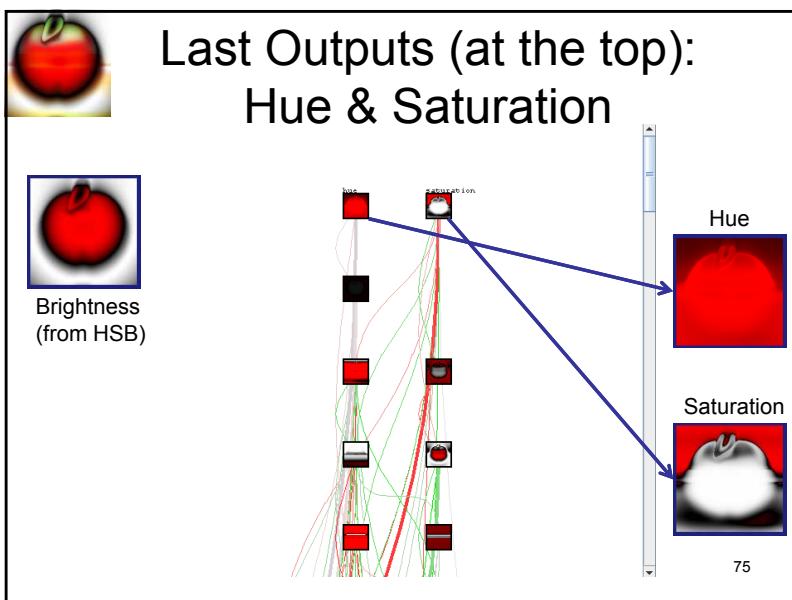
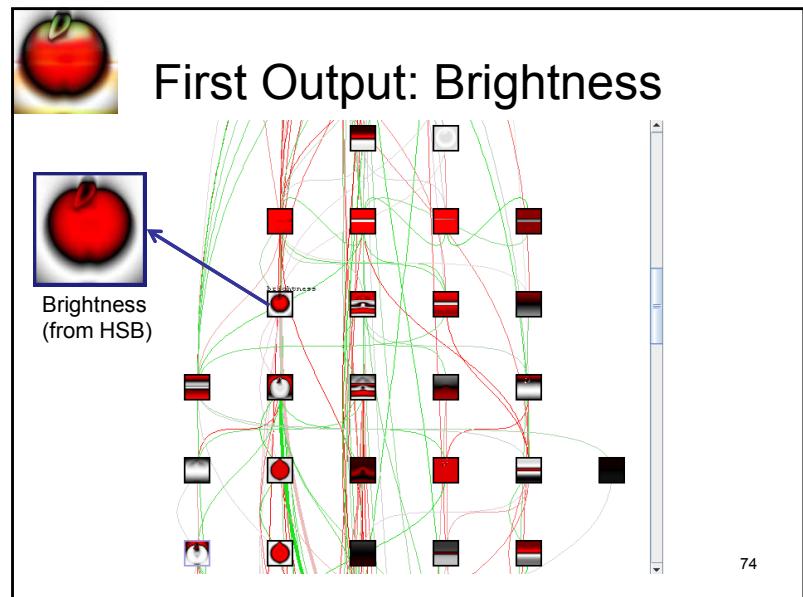
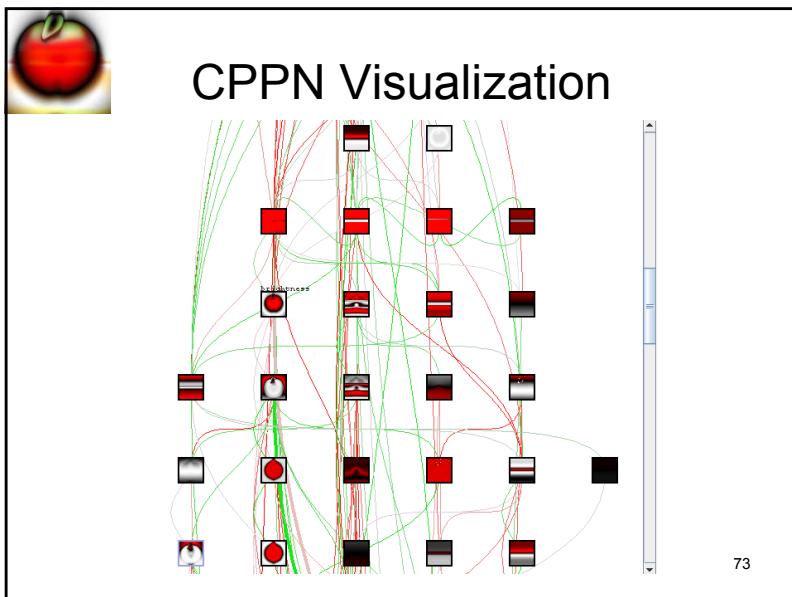
y

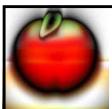
Gaussian Function of inputs

64



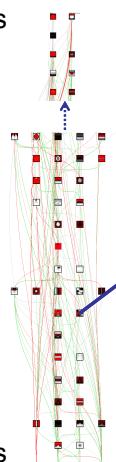






Gene Knockout Experiment

Outputs



Remember this node?
(the source of stem
asymmetry)

What happens if we
delete it?
(gene knockout
experiment)

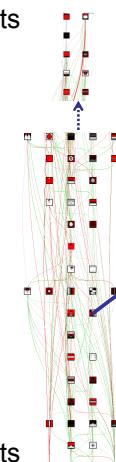
Inputs

77



Gene Knockout Experiment

Outputs



Watch here!

Remember this node?
(the source of stem
asymmetry)

What happens if we
delete it?
(gene knockout
experiment)

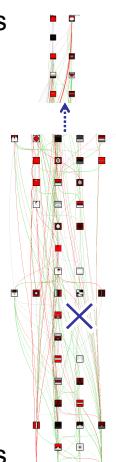
Inputs

78



Gene Knockout Experiment

Outputs



Remember this node?
(the source of stem
asymmetry)



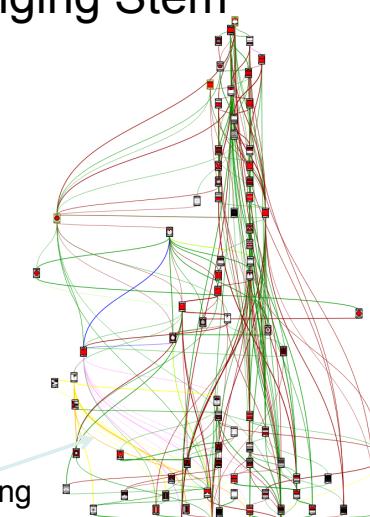
What happens if we
delete it?
(gene knockout
experiment)

Inputs

79



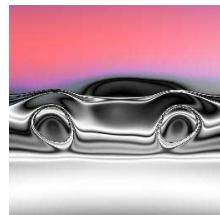
The Swinging Stem



Stem angle swing

Other Notable Fracture

- Where would you split this image?

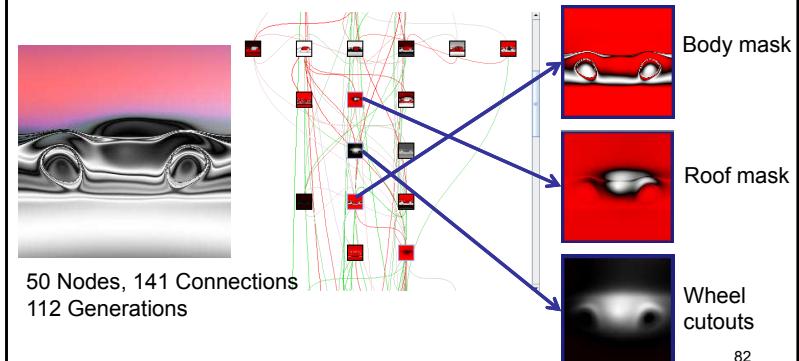


50 Nodes, 141 Connections
112 Generations

81

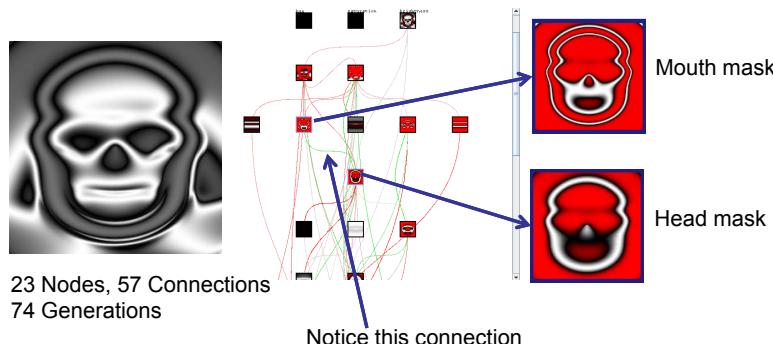
Other Notable Fracture

- Masks for different parts inside the CPPN



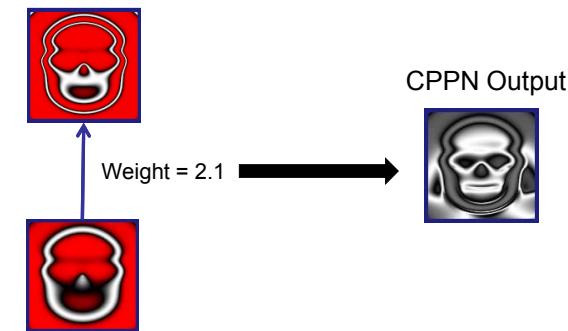
The Mouth of the Skull

- Fracture is often surprisingly intuitive



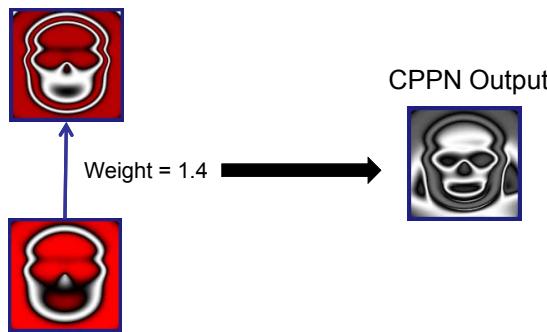
Scaling the Mouth

- Single gene controls the mouth aperture



Scaling the Mouth

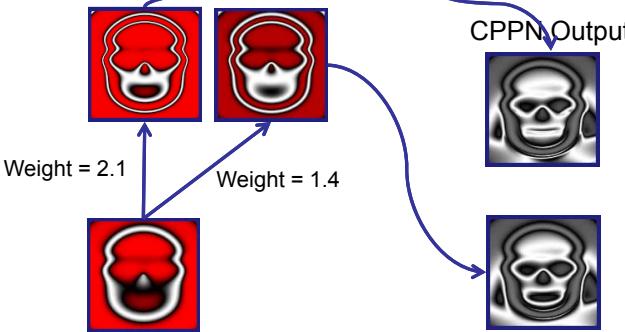
- Single gene controls the mouth aperture



85

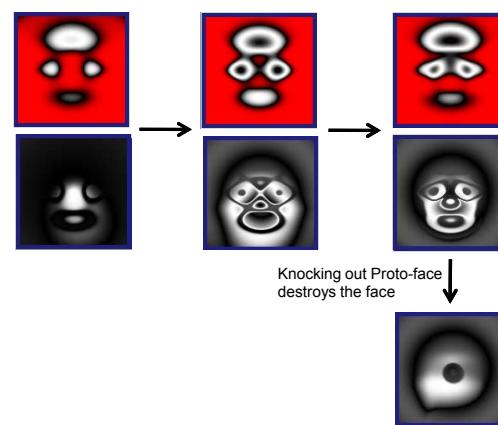
Scaling the Mouth

- Single gene controls the mouth aperture



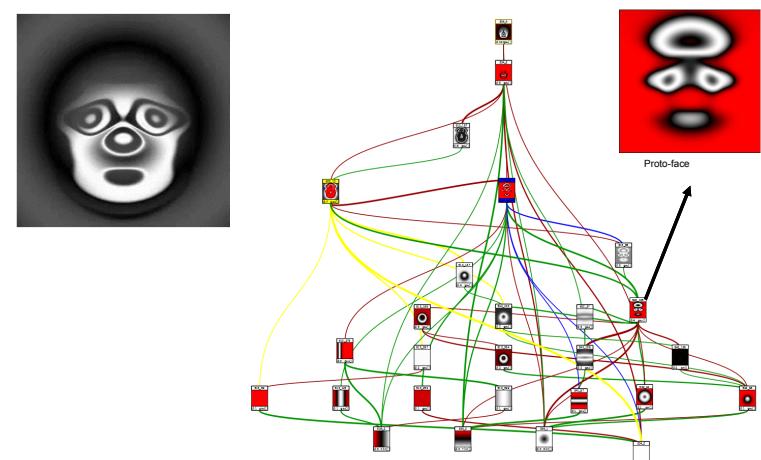
86

Many Faces “Conserve” the Same Proto-face Mask



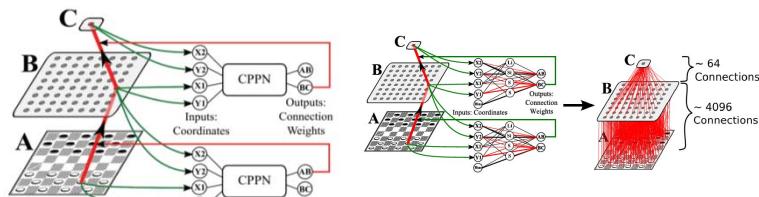
87

Cartoon Face



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

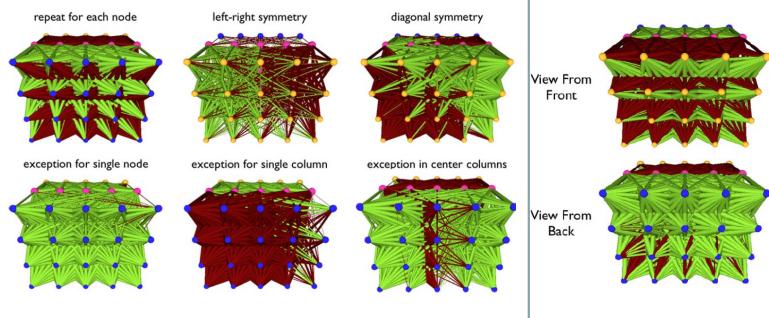


- See <http://eplex.cs.ucf.edu/hyperNEATpage/HyperNEAT.html> for more information and publication links

Kenneth O. Stanley, David B. D'Ambrosio, and Jason Gaudi. [A Hypercube-Based Indirect Encoding for Evolving Large-Scale Neural Networks](#). *Artificial Life* journal 15(2), 2009.
This GECCO: Several HyperNEAT papers in GDS and Alife tracks

Similar Regularity and Fracture in HyperNEAT

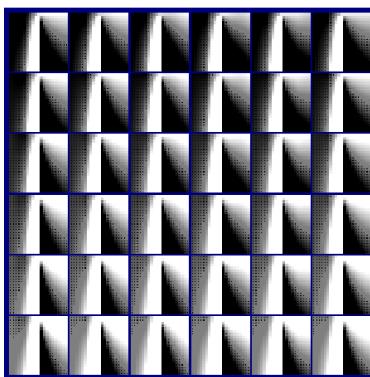
- Just 4-D instead of 2-D



90

Clune J, Stanley KO, Pennock RT, Ofria C (2011) On the performance of indirect encoding across the continuum of regularity. *IEEE Transactions on Evolutionary Computation*. 15(3): 346-367.

Fractured Neural Receptive Fields in HyperNEAT

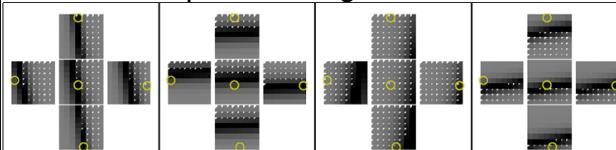


Oliver J. Coleman, Evolving Neural Networks for Visual Processing. Undergraduate Honours Thesis (Bachelor of Computer Science, University of New South Wales School of Computer Science and Engineering), 2010.

91

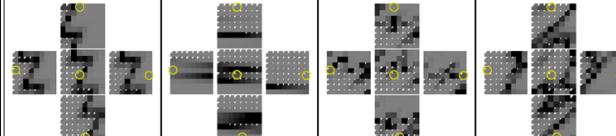
Geometric Patterns Inside Evolved HyperNEAT ANNs

Influence Maps of *more general* solutions



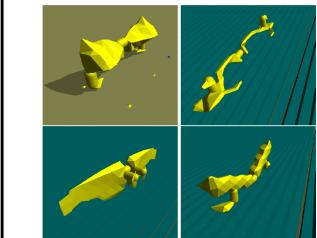
We can see the difference

Influence Maps of *less general* solutions

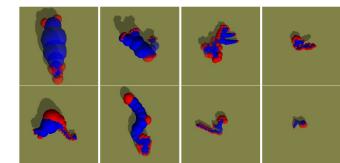


Jason Gaudi and Kenneth O. Stanley (2010). Autonomous Evolution of Topographic Regularities in Artificial Neural Networks. In: *Neural Computation* journal 22(7), pages 1860-1898. Cambridge, MA: MIT Press.

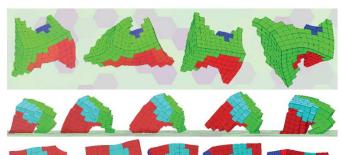
CPPN-encoded Creatures



Joshua E. Auerbach and Josh C. Bongard
On the Relationship Between Environmental and Mechanical Complexity in Evolved Robots
13th International Conference on the Synthesis and Simulation of Living Systems (ALife XIII).
East Lansing, MI, July, 2012.



Joshua E. Auerbach and Josh C. Bongard
Evolving Complete Robots with CPPN-NEAT: The Utility of Recurrent Connections. 2011 Genetic and Evolutionary Computation Conference (GECCO 2011). Dublin, Ireland, July, 2011.



Sebastian Risi, Daniel Cellucci, Hod Lipson (2013). Ribosomal Robots: Evolved Designs Inspired by Protein Folding.
To appear in: Proceedings of the Genetic and Evolutionary Computation Conference (GECCO-2013). New York, NY: ACM.

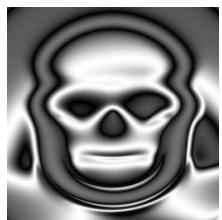
93

A Word of Caution: The Objective Paradox

- *The full potential of an indirect encoding may not be revealed by testing whether it can evolve to satisfy a particular objective*
- Reason: Fundamental discoveries (like symmetry) that are essential for further progress may yield no objective improvement on task fitness (like “walk far”)

94

Example: Evolve a Skull and a Butterfly with CPPNs



Target Image 1



Target Image 2

Results Are Terrible

Brian G. Woolley and Kenneth O. Stanley (2011). On the Deteriorous Effects of A Priori Objectives on Evolution and Representation. In: Proceedings of the Genetic and Evolutionary Computation Conference (GECCO-2011).

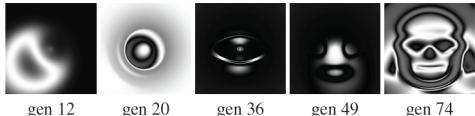
- Typical best results given 30,000 generations (only odd runs shown)

Skull	Run 1	Run 3	Run 5	Run 7	Run 9	Run 11	Run 13	Run 15	Run 17	Run 19
	20f, 24c failed	20f, 29c failed	19f, 24c failed	22f, 28c failed	21f, 28c failed	16f, 22c failed	21f, 27c failed	23f, 29c failed	18f, 25c failed	25f, 28c failed
Butterfly	Run 1	Run 3	Run 5	Run 7	Run 9	Run 11	Run 13	Run 15	Run 17	Run 19
	22f, 27c failed	21f, 27c failed	22f, 25c failed	20f, 28c failed	18f, 23c failed	21f, 27c failed	27f, 34c failed	22f, 25c failed	24f, 29c failed	20f, 28c failed

- Question: *Was it a bad fitness function?*

No: The Problem is the Stepping Stones

- Stepping stones in GDS are complex
- Stepping stones to a skull do not look like a skull:



- The objective-based experiment did not reveal the potential of CPPN-based encoding
- Moral: *Methods that aim for diversity (like novelty search or behavioral diversity) will be essential for GDS (even with DNA!)*

Joel Lehman and Kenneth O. Stanley (2011).
Abandoning Objectives: Evolution Through the Search for Novelty Alone
In: Evolutionary Computation journal (19)2, pages 189-223, Cambridge, MA: MIT Press.

97
Mouret, J. B., & Doncieux, S. (2012). Encouraging behavioral diversity in evolutionary robotics: An empirical study. *Evolutionary computation*, 20(1), 91-133.

Where is GDS Useful?

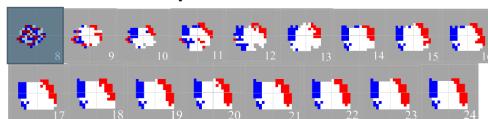
- Problems with regularities
 - Board games
 - Visual processing/image recognition
 - Pictures
 - Music
 - Puzzles
 - Architectures/morphologies
 - Brains
 - Bodies
- Problems requiring high complexity
 - High-level cognition
 - Strategic thinking
 - Tactical thinking
- Regeneration and self-repair

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.

98

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

99

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)

100

Long Term Issues

- What are the ultimate encodings?
- What are the ultimate applications?
- What application requires a structure of 100 million parts and actually utilizes the structure?
 - How can we formalize the problem?
- How can GDS combine with *plasticity*?
- How can we make progress despite the objective paradox?

101

More information

- My Homepage: <http://www.cs.ucf.edu/~kstanley>
- NEAT Users Group: <http://groups.yahoo.com/group/neat>
- Evolutionary Complexity Research Group: <http://eplex.cs.ucf.edu>
- Picbreeder: <http://picbreeder.org>
- HyperNEAT Information: <http://eplex.cs.ucf.edu/hyperNEATpage/HyperNEAT.html>
- Email: kstanley@eeecs.ucf.edu

102

References from Slides

- Joshua E. Auerbach and Josh C. Bongard. *On the Relationship Between Environmental and Mechanical Complexity in Evolved Robots*. Proceedings of the 13th International Conference on the Synthesis and Simulation of Living Systems (ALife XIII). East Lansing, MI, July, 2012.
- Joshua E. Auerbach and Josh C. Bongard. *Evolving Complete Robots with CPPN-NEAT: The Utility of Recurrent Connections*. Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2011). Dublin, Ireland, July, 2011.
- 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.
- Cheney N, MacCurdy R, Clune J, Lipson H. *Unshackling evolution: evolving soft robots with multiple materials and a powerful generative encoding*. Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2013). Amsterdam, July 2013.
- Clune J, Pennock RT, and Ofria C. *The sensitivity of HyperNEAT to different geometric representations of a problem*. Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2009). New York, NY: ACM, 2009
- Clune J, Stanley KO, Pennock RT, Ofria C (2011) *On the performance of indirect encoding across the continuum of regularity*. IEEE Transactions on Evolutionary Computation. 15(3): 346-367.
- Oliver J. Coleman, *Evolving Neural Networks for Visual Processing*. Undergraduate Honours Thesis (Bachelor of Computer Science, University of New South Wales School of Computer Science and Engineering), 2010
- D'Ambrosio, D. B. and Stanley, K. O. *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
- D'Ambrosio, D. B. and Stanley, K. O. *Generative Encoding for Multiagent Learning*. In: *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2008)*. New York, NY: ACM, 2007

103

References from Slides

- Dawkins, R.: *The Blind Watchmaker*. Longman, Essex, U.K. (1986)
- Gauci, J. and Stanley, K. O. *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
- Gauci, J. and Stanley, K. O. *A Case Study on the Critical Role of Geometric Regularity in Machine Learning*. In: *Proceedings of the Twenty-Third AAAI Conference on Artificial Intelligence (AAAI-2008)*. Menlo Park, CA: AAAI Press, 2008.
- Gauci, J. and Stanley, K. O. *Autonomous Evolution of Topographic Regularities in Artificial Neural Networks*. In: *Neural Computation journal 22(7)*, pages 1860-1898. Cambridge, MA: MIT Press, 2010.
- Gruau, F. *Neural network synthesis using cellular encoding and the genetic algorithm*. PhD thesis, Laboratoire de L'informatique du Parallélisme, Ecole Normale Supière de Lyon, Lyon, France, 1994.
- Hornby, G. S. and Pollack, J. B. *The Advantages of Generative Grammatical Encodings for Physical Design*. In: *Congress on Evolutionary Computation*. 2001.
- Nate Kohl and Risto Miikkulainen (2009). *Evolving Neural Networks for Strategic Decision-Making Problems*. *Neural Networks, Special issue on Goal-Directed Neural Systems*.
- T. Kowaliw and W. Banzhaf, *Augmenting Artificial Development with Local Fitness*, In IEEE CEC 2009
- 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.
- Mattiussi, C., and Floreano, D. 2004. *Evolution of Analog Networks using Local String Alignment on Highly Reorganized Genomes*. In: *Proceedings of the 2004 NASA/DoD Conference on Evolvable Hardware (EH' 2004)*.

References from Slides

- Miller J. F. Evolving a self-repairing, self-regulating, French flag organism. In: *Proceedings of Genetic and Evolutionary Computation Conference (GECCO 2004)*, Springer LNCS 3102 (2004) 129-139.
- 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.
- Raff, R. A. (1996). *The shape of life: Genes, development, and the evolution of animal form*. Chicago: The University of Chicago Press.
- Reisinger, J. and Miikkulainen, R. Acquiring Evolvability through Adaptive Representations. In: *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2007)*. New York, NY: ACM, 2007
- Sebastian Risi, Daniel Cellucci, Hod Lipson (2013). Ribosomal Robots: Evolved Designs Inspired by Protein Folding. *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO 2013)*. New York, NY: ACM.
- Roggen, D. and Federici, D. 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).
- Jimmy Secretan, Nicholas Beato, David B. D'Ambrosio, Adelein Rodriguez, Adam Campbell, Jeremiah T. Folsom-Kovarik, and Kenneth O. Stanley (2011). Picbreeder: A Case Study in Collaborative Evolutionary Exploration of Design Space. *Evolutionary Computation*, 19(3): 345–371, Cambridge, MA: MIT Press
- Stanley, K. O. and Miikkulainen, R. Evolving neural networks through augmenting topologies. *Evolutionary Computation*, 10:99–127, 2002.
- Stanley, K. O. and Miikkulainen, R. Competitive coevolution through evolutionary complexification. *Journal of Artificial Intelligence Research*, 21:63–100, 2004.
- Stanley, K. O. and Miikkulainen, R. A taxonomy for artificial embryogeny. *Artificial Life*, 9(2):93–130, 2003.

105

References from Slides

- Stanley, K. O. 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
- Stanley, K. O., D'Ambrosio, D.B., and Gauci, J. A Hypercube-Based Indirect Encoding for Evolving Large-Scale Neural Networks. *Artificial Life journal* 15(2), 2009.
- Turing, A. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society B*, 237, 37–72.
- Waddington, C. H. (1942). Canalization of Development and the Inheritance of Acquired Characters. *Nature*, 150, 563.

106

Additional References

- Alberch, P. (1987). Evolution of a developmental process: Irreversibility and redundancy in amphibian metamorphosis. In R. A. Raff & E. C. Raff (Eds.), *Development as an evolutionary process* (pp. 23–40). New York: Alan R. Liss.
- Ambros, V. (2002). A hierarchy of regulatory genes controls a larva-to-adult developmental switch in *C. elegans*. *Cell*, 57, 40–57.
- Amores, A., Force, A., Yan, Y.-L., Joly, L., Amemiya, C., Fritz, A., Ho, R. K., Langeland, J., Prince, V., Wang, Y.-L., Westerfield, M., Ekker, M., & Postlethwait, J. H. (1998). Zebrafish HOX clusters and vertebrate genome evolution. *Science*, 282, 1711–1784.
- Angeline, P. J. (1995). Morphogenic evolutionary computations: Introduction, issues and examples. In J. R. McDonnell, R. G. Reynolds, & D. B. Fogel (Eds.), *Evolutionary Programming IV: The Fourth Annual Conference on Evolutionary Programming* (pp. 387–401). Cambridge, MA: MIT Press.
- Astor, J. S., & Adami, C. (2000). A developmental model for the evolution of artificial neural networks. *Artificial Life*, 6(3), 189–218.
- Belew, R. K., & Kammerer, T. E. (1993). Evolving aesthetic sorting networks using developmental grammars. In S. Forrest (Ed.), *Proceedings of the Fifth International Conference on Genetic Algorithms*. San Francisco, CA: Morgan Kaufmann.

107

Additional References

- Bentley, P. J., & Kumar, S. (1999). The ways to grow designs: A comparison of embryogenies for an evolutionary design problem. In *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO-1999)* (pp. 35–43). San Francisco, CA: Morgan Kaufmann.
- Boers, E. J., & Kuiper, H. (1992). *Biological metaphors and the design of modular artificial neural networks*. Master's thesis, Departments of Computer Science and Experimental and Theoretical Psychology, Leiden University, The Netherlands.
- Bongard, J. C. (2002). Evolving modular genetic regulatory networks. In *Proceedings of the 2002 Congress on Evolutionary Computation*. Piscataway, NJ: IEEE Press.
- Bongard, J. C., & Paul, C. (2000). Investigating morphological symmetry and locomotive efficiency using virtual embodied evolution. In *Proceedings of the Sixth International Conference on Simulation of Adaptive Behavior* (pp. 420–429). Cambridge, MA: MIT Press.
- Bongard, J. C., & Pfeifer, R. (2001). Repeated structure and dissociation of genotypic and phenotypic complexity in artificial ontogeny. In L. Spector, E. D. Goodman, A. Wu, W. B. Langdon, H.-M. Voigt, M. Gen, S. Sen, M. Dorigo, S. Pezeshk, M. H. Garzon, & E. Burke (Eds.), *Proceedings of the Genetic and Evolutionary Computation Conference* (pp. 829–836). San Francisco, CA: Morgan Kaufmann.
- Calabretta, R., Nolfi, S., Parisi, D., & Wagner, G. P. (2000). Duplication of modules facilitates the evolution of functional specialization. *Artificial Life*, 6(1), 69–84.
- Cangelosi, A., Parisi, D., & Nolfi, S. (1993). *Cell division and migration in a genotype for neural networks* (Tech. Rep. PCIA-93). Rome: Institute of Psychology, C.N.R.

108

Additional References

- Carroll, S. B. (1995). Homeotic genes and the evolution of arthropods and chordates. *Nature*, 376, 479–485.
- Cohn, M. J., Patel, K., Krumlauf, R., Wilkinson, D. G., Clarke, J. D. W., & Tickle, C. (1997). HOX9 genes and vertebrate limb specification. *Nature*, 387, 97–101.
- Curtis, D., Apfeld, J., & Lehmann, R. (1995). Nanos is an evolutionarily conserved organizer of anterior-posterior polarity. *Development*, 121, 1899–1910.
- Dellaert, F. (1995). *Toward a biologically defensible model of development*. Master's thesis, Case Western Reserve University, Cleveland, OH.
- Dellaert, F., & Beer, R. D. (1994). Co-evolving body and brain in autonomous agents using a developmental model (Tech. Rep. CES-94-16). Cleveland, OH: Dept. of Computer Engineering and Science, Case Western Reserve University.
- Dellaert, F., & Beer, R. D. (1994). Toward an evolvable model of development for autonomous agent synthesis. In R. A. Brooks & P. Maes (Eds.), *Proceedings of the Fourth International Workshop on the Synthesis and Simulation of Living Systems (Artificial Life IV)*. Cambridge, MA: MIT Press.
- Dellaert, F., & Beer, R. D. (1996). A developmental model for the evolution of complete autonomous agents. In P. Maes, M. J. Matarić, J.-A. Meyer, J. Pollack, & S. W. Wilson (Eds.), *From animals to animats 4: Proceedings of the Fourth International Conference on Simulation of Adaptive Behavior*. Cambridge, MA: MIT Press.
- Deloukas, P., Schuler, G. D., Gyapay, G., Beasley, E. M., Soderlund, C., Rodriguez-Tome, P., Hui, L., Matise, T. C., McKusick, K. B., Beckmann, J. S., Bentolia, S., Bioreau, M., Birren, B. B., Browne, J., Butler, A., Castle, A. B., Chinnikulchai, N., Cleo, C., Day, P. J., Deheja, A., Dibling, T., Drouot, N., Duprat, S., Fizames, C., & Bentley, D. R. (1998). A physical map of 30,000 human genes. *Science*, 282(5389), 744–746.

109

Additional References

- Gruau, F. (1994). *Neural network synthesis using cellular encoding and the genetic algorithm*. Doctoral dissertation, Ecole Normale Supérieure de Lyon, France.
- Gruau, F., Whitley, D., & Pyeatt, L. (1996). A comparison between cellular encoding and direct encoding for genetic neural networks. In J. R. Koza, D. E. Goldberg, D. B. Fogel, & R. L. Riolo (Eds.), *Genetic Programming 1996: Proceedings of the First Annual Conference* (pp. 81–89). Cambridge, MA: MIT Press.
- Hart, W. E., Kammerer, T. E., & Belew, R. K. (1994). *The role of development in genetic algorithms* (Tech. Rep. CS94-394). San Diego, CA: University of California.
- Hornby, G. S., & Pollack, J. B. (2001). The advantages of generative grammatical encodings for physical design. In *Proceedings of the 2002 Congress on Evolutionary Computation*. Piscataway, NJ: IEEE Press.
- Hornby, G. S., & Pollack, J. B. (2001). Body-brain co-evolution using L-systems as a generative encoding. In L. Spector, E. D. Goodman, A. Wu, W. B. Langdon, H.-M. Voigt, M. Gen, S. Sen, M. Dorigo, S. Pezeshk, M. H. Garzon, & E. Burke (Eds.), *Proceedings of the Genetic and Evolutionary Computation Conference*. San Francisco, CA: Morgan Kaufmann.
- Hornby, G. S., & Pollack, J. B. (2002). Creating high-level components with a generative representation for body-brain evolution. *Artificial Life*, 8(3).
- Hubel, D. H., & Wiesel, T. N. (1965). Receptive fields and functional architecture in two nonstriate visual areas (18 and 19) of the cat. *Journal of Neurophysiology*, 28, 229–289.
- Jakobi, N. (1995). Harnessing morphogenesis. In *Proceedings of Information Processing in Cells and Tissues* (pp. 29–41). Liverpool, UK: University of Liverpool.

111

Additional References

- Eggenberger, P. (1997). Evolving morphologies of simulated 3D organisms based on differential gene expression. In P. Husbands & I. Harvey (Eds.), *Proceedings of the Fourth European Conference on Artificial Life* (pp. 205–213). Cambridge, MA: MIT Press.
- Ellinson, R. P. (1987). Change in developmental patterns: Embryos of amphibians with large eggs. In R. A. Raff & E. C. Raff (Eds.), *Development as an evolutionary process* (pp. 1–21). New York: Alan R. Liss.
- Fleischer, K., & Barr, A. H. (1993). A simulation testbed for the study of multicellular development: The multiple mechanisms of morphogenesis. In C. G. Langton (Ed.), *Artificial life III* (pp. 389–416). Reading, MA: Addison-Wesley.
- Force, A., Lynch, M., Pickett, F. B., Amores, A., Lin Yan, Y., & Postlethwait, J. (1999). Preservation of duplicate genes by complementary, degenerative mutations. *Genetics*, 151, 1531–1545.
- Gans, C., & Northcutt, R. G. (1983). Neural crest and the origin of vertebrates: A new head. *Science*, 220(4594), 268–274.
- Gilbert, C. D., & Wiesel, T. N. (1992). Receptive field dynamics in adult primary visual cortex. *Nature*, 356, 150–152.
- Gilbert, S. F. (Ed.) (2000). *Developmental biology* (6th ed.). Sunderland, MA: Sinauer Associates.
- Gruau, F. (1993). Genetic synthesis of modular neural networks. In S. Forrest (Ed.), *Proceedings of the Fifth International Conference on Genetic Algorithms* (pp. 318–325). San Francisco, CA: Morgan Kaufmann.

110

Additional References

- Kaneko, K., & Furusawa, C. (1998). Emergence of multicellular organisms with dynamic differentiation and spatial pattern. *Artificial Life*, 4(1).
- Kauffman, S. A. (1993). *The origins of order*. New York: Oxford University Press.
- Kitano, H. (1990). Designing neural networks using genetic algorithms with graph generation system. *Complex Systems*, 4, 461–476.
- Komosinski, M., & Rotaru-Varga, A. (2001). Comparison of different genotype encodings for simulated 3D agents. *Artificial Life*, 7(4), 409–418.
- Koza, J. R. (1992). *Genetic programming: On the programming of computers by means of natural selection*. Cambridge, MA: MIT Press.
- Lall, S., & Patel, N. (2001). Conservation and divergence in molecular mechanisms of axis formation. *Annual Review of Genetics*, 35, 407–447.
- Lawrence, P. (1992). *The making of a fly*. Oxford, UK: Blackwell Science Publishing.
- 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.
- Lipson, H., & Pollack, J. B. (2000). Automatic design and manufacture of robotic lifeforms. *Nature*, 406, 974–978.

112

Additional References

- Luke, S., & Spector, L. (1996). Evolving graphs and networks with edge encoding: Preliminary report. In J. R. Koza (Ed.), *Late-breaking papers of genetic programming 1996*. Stanford, CA: Stanford Bookstore.
- Marin, E., Jeffries, G. S. X. E., Komiya, T., Zhu, H., & Luo, L. (2002). Representation of the glomerular olfactory map in the *Drosophila* brain. *Cell*, 109(2), 243–255.
- Martin, A. P. (1999). Increasing genomic complexity by gene duplication and the origin of vertebrates. *The American Naturalist*, 154(2), 111–128.
- Mjolsness, E., Sharp, D. H., & Reinitz, J. (1991). A connectionist model of development. *Journal of Theoretical Biology*, 152, 429–453.
- 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.
- Nolfi, S., & Parisi, D. (1991). *Growing neural networks* (Tech. Rep. PCIA-91-15). Rome: Institute of Psychology, C.N.R.
- O'Reilly, U.-M. (2000). Emergent design: Artificial life for architecture design. In *7th International Conference on Artificial Life (ALIFE-00)*. Cambridge, MA: MIT Press.
- Prusinkiewicz, P., & Lindenmayer, A. (1990). *The algorithmic beauty of plants*. Heidelberg, Germany: Springer-Verlag.
- Radding, C. M. (1982). Homologous pairing and strand exchange in genetic recombination. *Annual Review of Genetics*, 16, 405–437.

113

Additional References

- Raff, E. C., Popodi, E. M., Sly, B. J., Turner, F. R., Villinski, J. T., & Raff, R. A. (1999). A novel ontogenetic pathway in hybrid embryos between species with different modes of development. *Development*, 126, 1937–1945.
- Raff, R. A. (1996). *The shape of life: Genes, development, and the evolution of animal form*. Chicago: The University of Chicago Press.
- Reinhart, B. J., Slack, F. J., Basson, M., Pasquinielli, A. E., Bettinger, J. C., Rougvie, A. E., Horvitz, H. R., & Ruvkun, G. (2000). The 21-nucleotide let-7 RNA regulates developmental timing in *Caenorhabditis elegans*. *Nature*, 403, 901–905.
- Schnier, T. (1998). *Evolved representations and their use in computational creativity*. Doctoral dissertation, Department of Architectural and Design Science, University of Sydney, Australia.
- Siddiqi, A. A., & Lucas, S. M. (1999). A comparison of matrix rewriting versus direct encoding for evolving neural networks. In *Proceedings of the 1998 IEEE International Conference on Evolutionary Computation (ICEC'98)* (pp. 392–397). Piscataway, NJ: IEEE Press.
- Sigal, N., & Alberts, B. (1972). Genetic recombination: The nature of a crossed strand-exchange between two homologous DNA molecules. *Journal of Molecular Biology*, 71(3), 789–793.
- Sigrist, C. B., & Sommer, R. J. (1999). Vulva formation in *Pristionchus pacificus* relies on continuous gonadal induction. *Development Genes and Evolution*, 209, 451–459.
- Sims, K. (1994). Evolving 3D morphology and behavior by competition. In R. A. Brooks & P. Maes (Eds.), *Proceedings of the Fourth International Workshop on the Synthesis and Simulation of Living Systems (Artificial Life IV)* (pp. 28–39). Cambridge, MA: MIT Press.

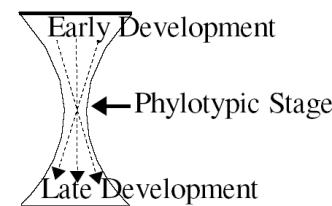
114

Additional References

- Slijper, E. J. (1962). *Whales*. New York: Basic Books.
- Turing, A. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society B*, 237, 37–72.
- Vario, J. (1994). From evolutionary computation to computational evolution. *Informatica*, 18(4), 417–434.
- Voss, S. R., & Shaffer, H. B. (1997). Adaptive evolution via a major gene effect: Paedomorphism in the Mexican axolotl. *Proceedings of the National Academy of Sciences of the USA*, 94, 14185–14189.
- Waddington, C. H. (1942). Canalization of development and the inheritance of acquired characters. *Nature*, 150, 563.
- Wilkins, A. (2002). *The evolution of developmental pathways*. Sunderland, MA: Sinauer Associates.
- Williams, R., Bastiani, M., Lia, B., & Chulupa, L. (1986). Growth cones, dying axons, developmental fluctuations in the fiber population of the cat's optic nerve. *Journal of Computational Neurology*, 246, 32–69.
- Williams, R., Cavada, C., & Reinoso-Saurez, F. (1993). Rapid evolution of the visual system: A cellular assay of the retina and dorsal lateral geniculate nucleus of the Spanish wildcat and the domestic cat. *Journal of Neuroscience*, 13(1), 208–228.
- Wolpert, L. (1987). Constancy and change in the development and evolution of pattern. In B. C. Goodwin, N. Holder, & C. C. Wylie (Eds.), *Development and Evolution* (pp. 47–57).
- Zigmund, M. J., Bloom, F. E., Landis, S. C., Roberts, J. L., & Squire, L. R. (Eds.). (1999). *Fundamental neuroscience*. London: Academic Press.

115

Extra: Heterochrony

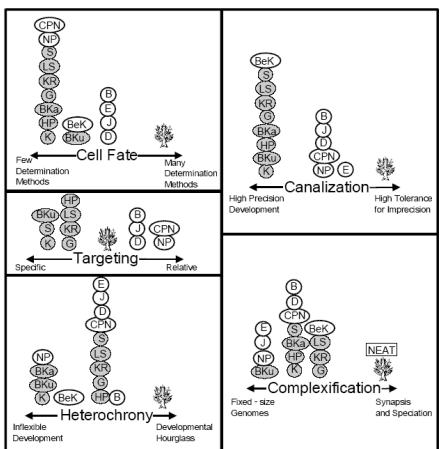


- The order of concurrent events can vary in nature
- When different processes intersect can determine how they coordinate

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

116

Extra: Exploring the Space of GDS (2003)



117

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