Generative and Developmental Systems Tutorial

Kenneth O. Stanley
Dept. of EECS, Computer Science Division
University of Central Florida
kstanley@cs.ucf.edu

E P L E X
Evolutionary Complexity Research Group at UCF

http://eplex.cs.ucf.edu

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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
  - Co-inventor of NEAT, CPPN indirect encoding, and the HyperNEAT GDS algorithm
  - At least 20 GDS-related publications

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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

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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

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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?

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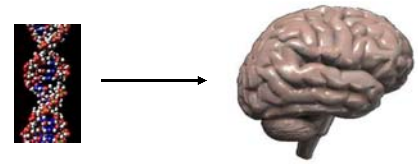
Goal: Evolve Systems of Biological Complexity



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

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Development

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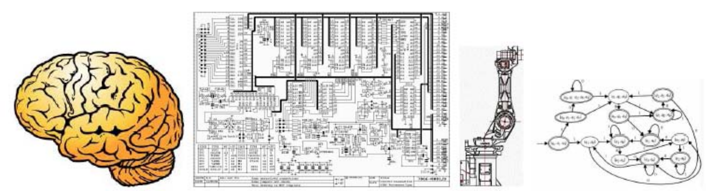
(embryo image from nobelprize.org)

Solving this Problem Could Solve Many Others



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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.

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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
- …

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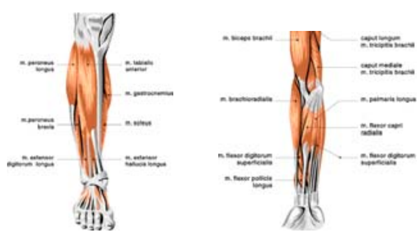
Development is Powerful Because of Reuse

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



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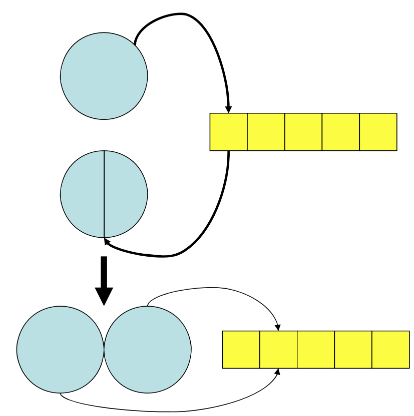
(James Madison University http://orgs.jmu.edu/strength/KIN_425/kin_425_muscles_calves.htm)

The Unfolding of Structure Allows Reuse



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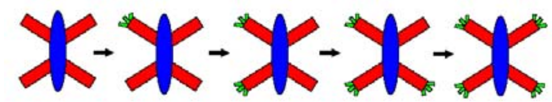
Rediscovery Unnecessary with Reuse



- 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*)

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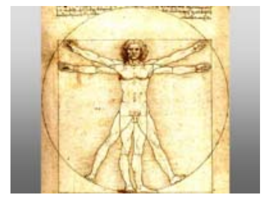
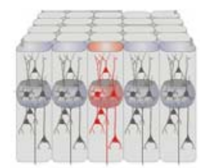
Therefore, GDS

- 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

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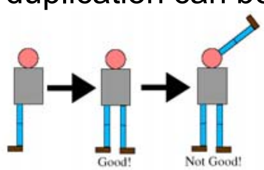
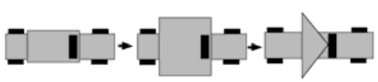
Some Major Issues in GDS

- Phenotypic duplication can be brittle



- Variation on an established convention is powerful



- Reuse with variation is common in nature

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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.

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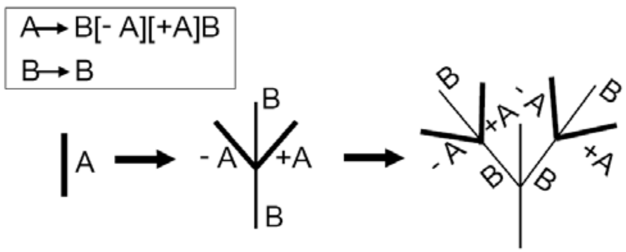
Grammatical Example 1

- 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.

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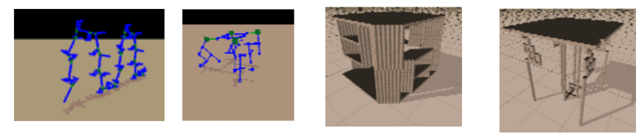
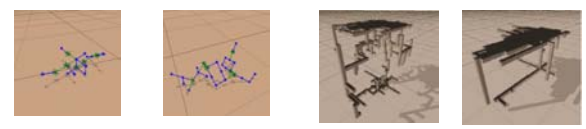
L-System Evolution Successes



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



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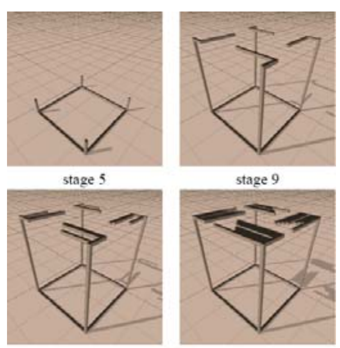
Growth of a Table



stage 5 stage 9

stage 10 stage 12

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

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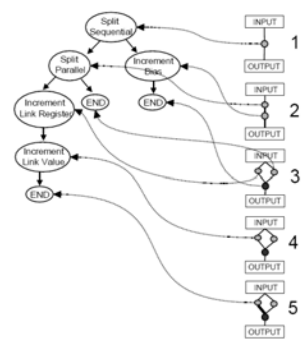
Grammatical Example 2

- Cellular Encoding (CE; Gruau 1993, 1996)



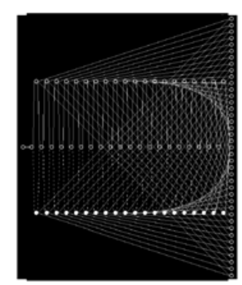


Figure 5.10: A neural network for the symmetry of 40 input units.

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

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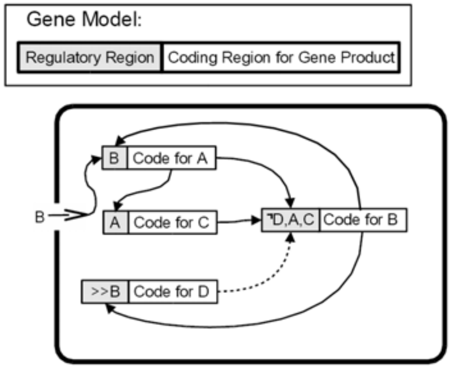
Cell Chemistry Encodings



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Cell Chemistry Example: Bongard's Artificial Ontogeny

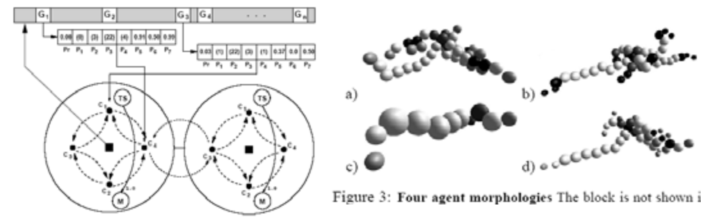

Figure 3: **Four agent morphologies** The block is not shown in

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.

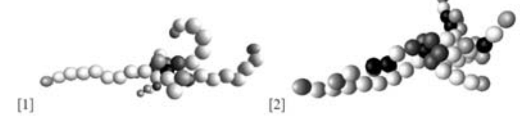

Figure 9: **Two agents evolved for block pushing** The fittest agents extracted from two independent

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.

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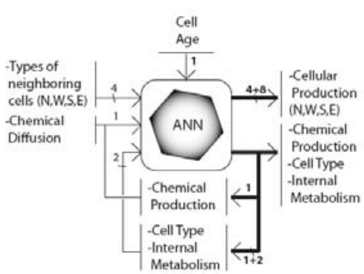
Cell Chemistry Example 2

- Federici 2004: Neural networks inside cells



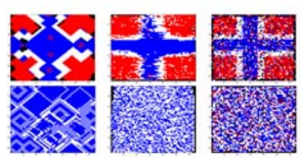


Fig. 6. Best evolved 64x64 solutions using, from left to right, MS, AES and direct

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).

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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

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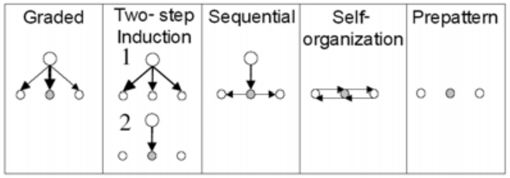
Cell Fate



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

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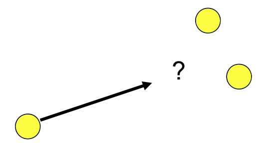
Targeting

- 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



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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.

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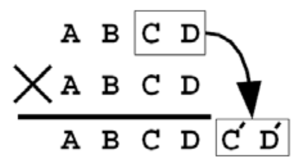
Complexification through Gene Duplication



- *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*

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Break

- Take break
- Resume in 10 minutes

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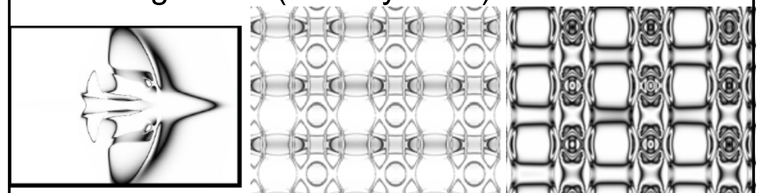
High-Level Abstraction: Compositional Pattern Producing Networks (CPPNs)

- 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

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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

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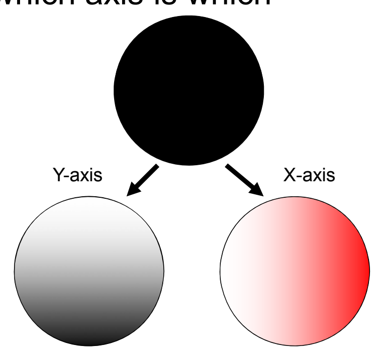
Gradients Define Axes

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



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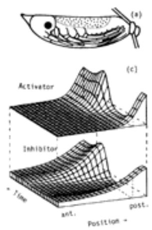
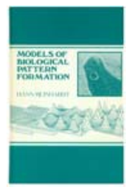
Cells Know Where They Are Through Gradients

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





(1982)

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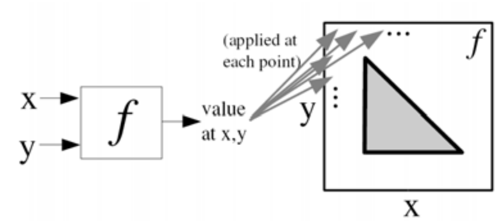
A Novel View: The Phenotype as a Function of Cartesian Space



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

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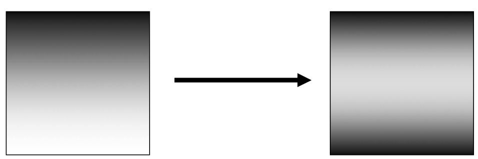
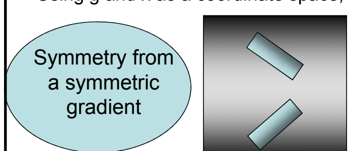
Higher Coordinate Frames are Functions of Lower Ones



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

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



$$h(x, y) = func[x, g(y)]$$

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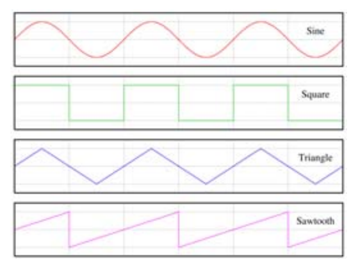
Segmentation is a Periodic Gradient



(Wikimedia commons)

- *f*(periodic function) = repeating pattern
- Periodic functions mean repeating coordinate frames

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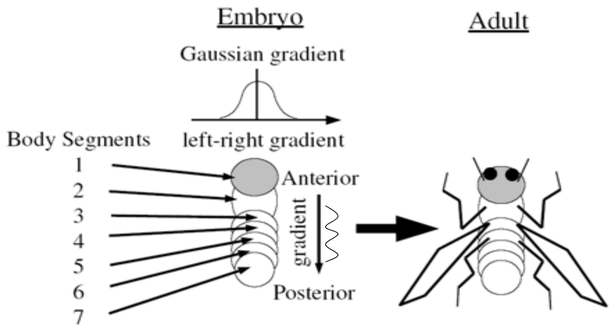
Gradients Define the Body Plan



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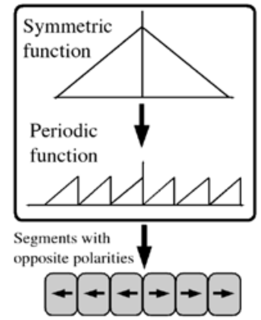
Gradients Can Be Composed



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

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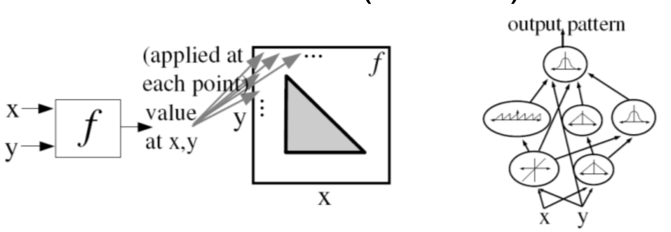
Compositional Pattern Producing Networks (CPPNs)



(a) Mapping (b) Composition

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

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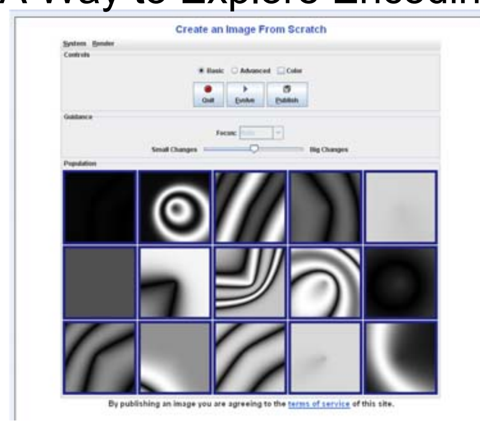
Interactive Evolution: A Way to Explore Encoding



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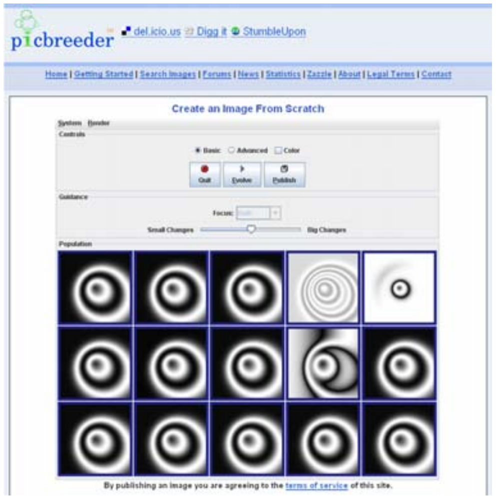

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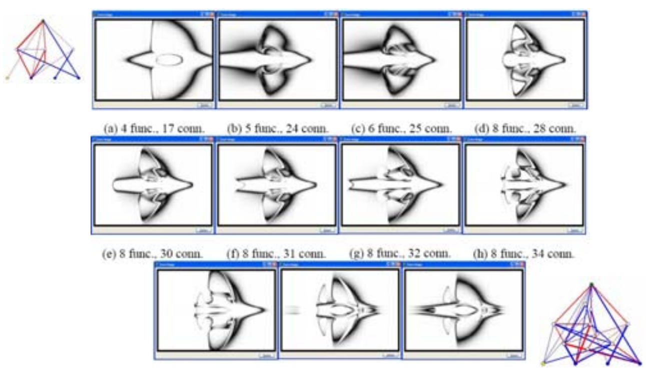
Compositional Pattern Producing Networks (CPPNs)



Evolutionary Elaboration

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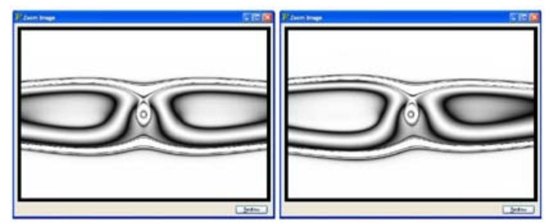
Imperfect Symmetry



- Gauss(x) and x provide both symmetry and asymmetry

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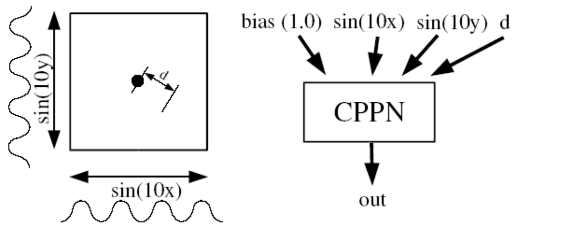
Repetition with Variation



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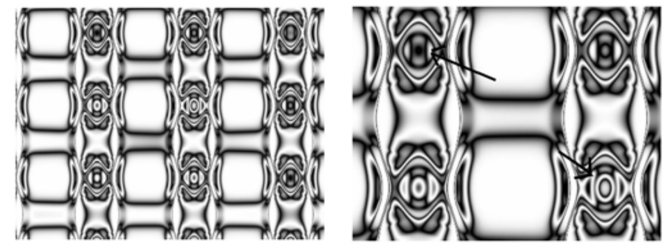
CPPNs:Repetition with Variation



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

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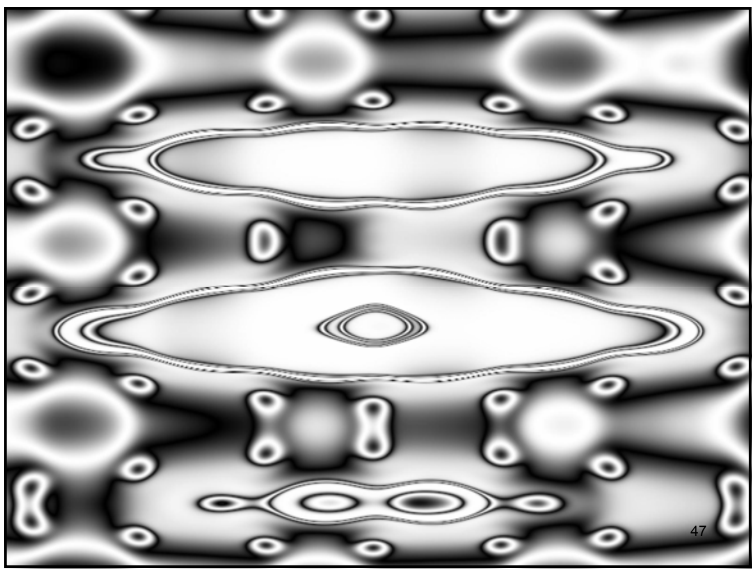

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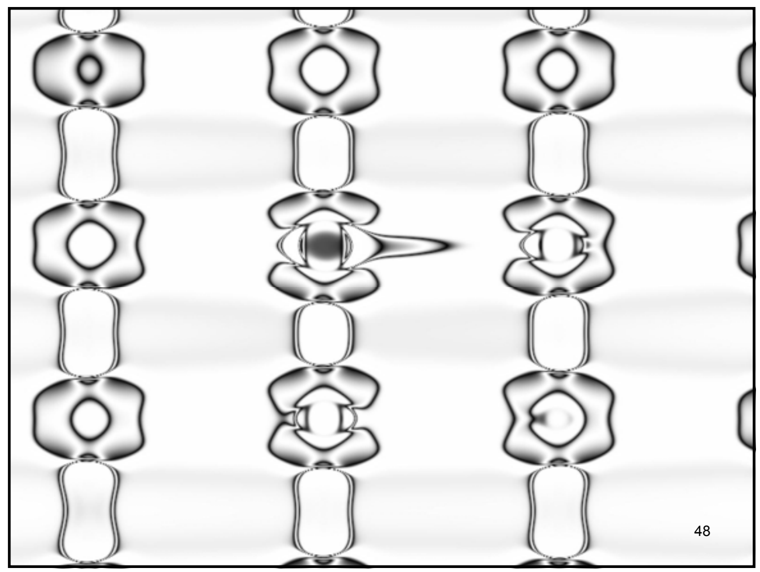

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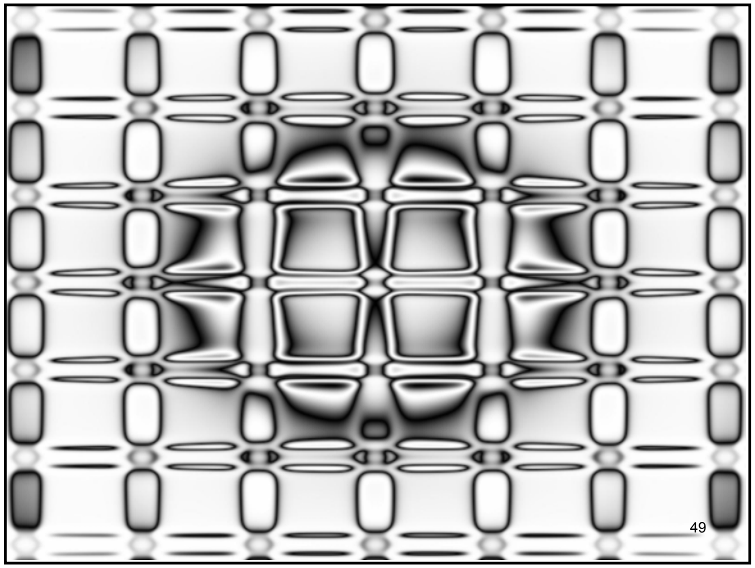
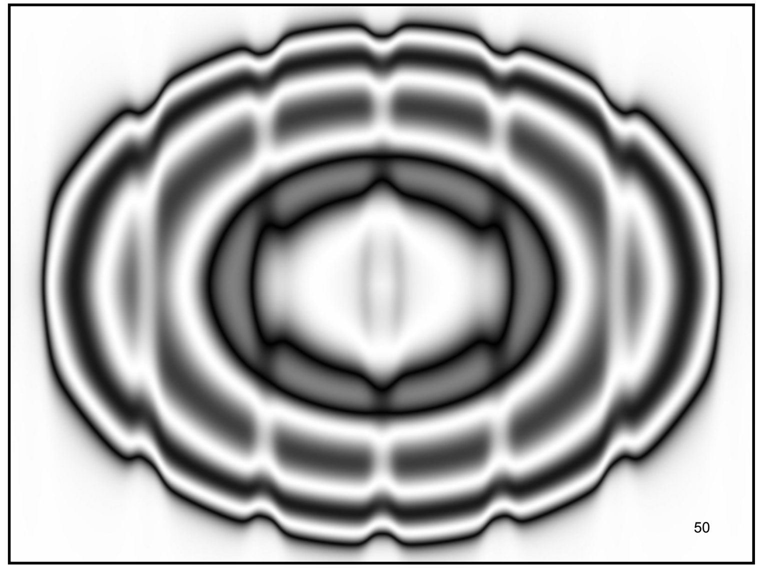
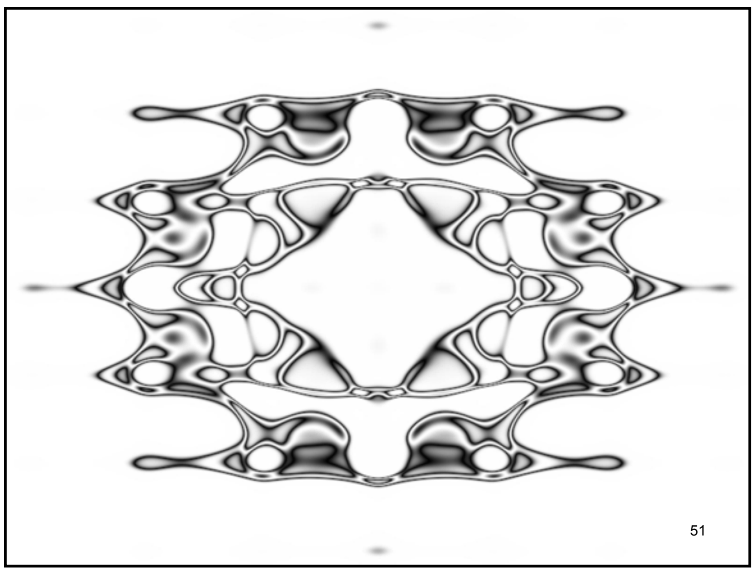




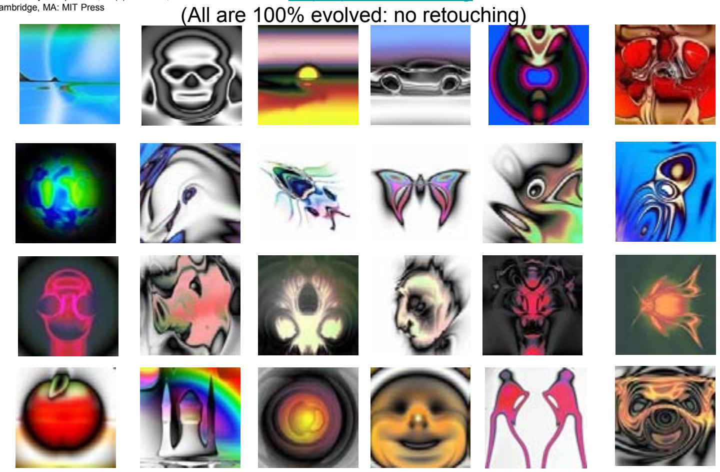


Jimmy Secretan, Nicholas Beato, David B. D.Ambrosio, Adelein Rodriguez, Adam Campbell, Jeremiah T. Folsom-Kovarik, and Kenneth O. Stanley (2011). Picbreeder: A Case Study in Collaborative Evolutionary Exploration of Design Space. *Evolutionary Computation*, 19(3): 345–371, Cambridge, MA: MIT Press

CPPN Patterns

From http://picbreeder.org

(All are 100% evolved: no retouching)



Infinite resolution: CPPNs are mathematical expressions

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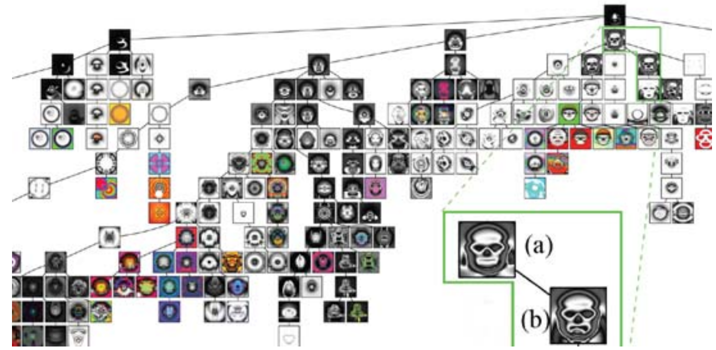
Picbreeder Phylogenetic Tree



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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?

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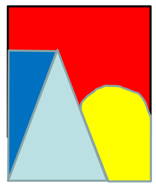
Are Unfolding Over Time and Local Interaction Essential to Development?

- 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

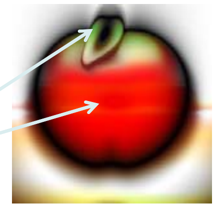
Representational Properties of CPPNs

- 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

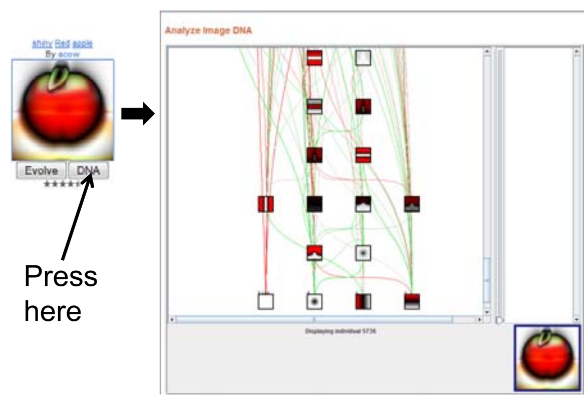
The Apple

How is it represented?

CPPN has 83 nodes, 264 connections
320 generations

59

Image DNA Tool

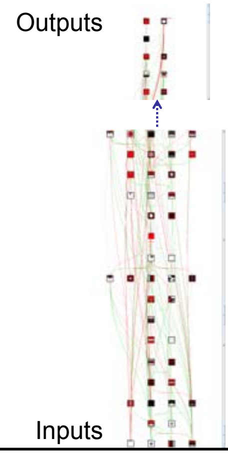


Press here

- Allows browsing CPPN

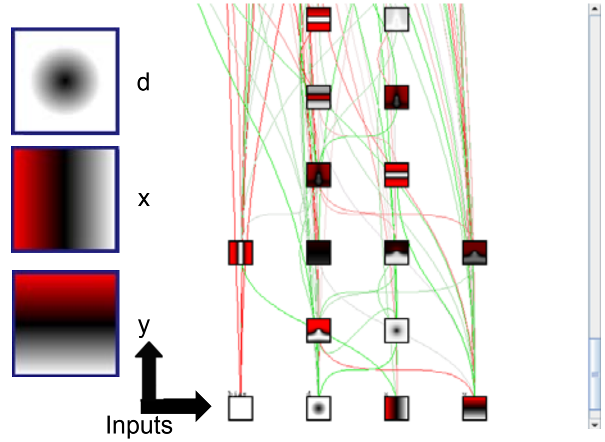
60

Very Large Apple Network



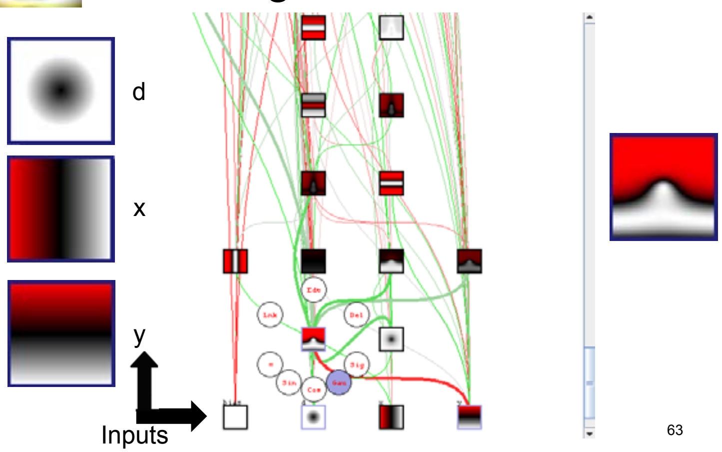
61

Starting at the Bottom



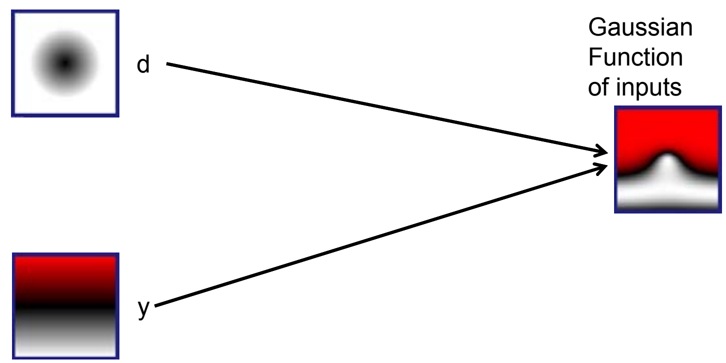
62

Starting at the Bottom

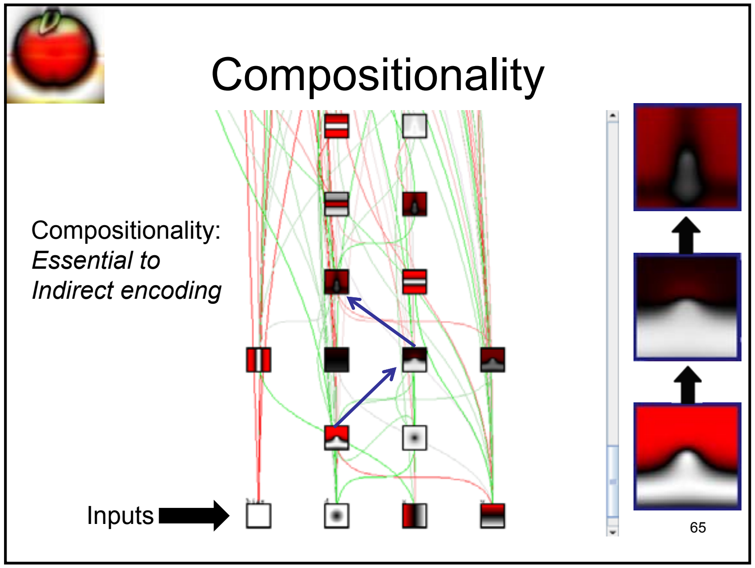


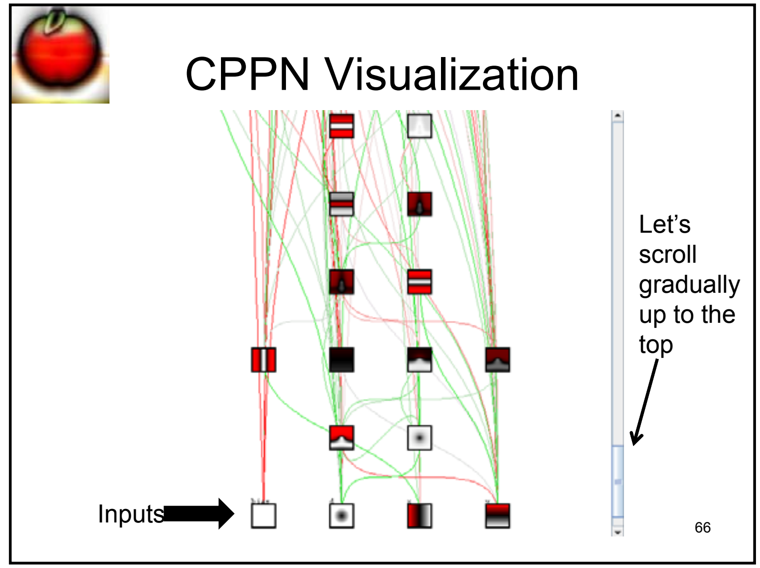
63

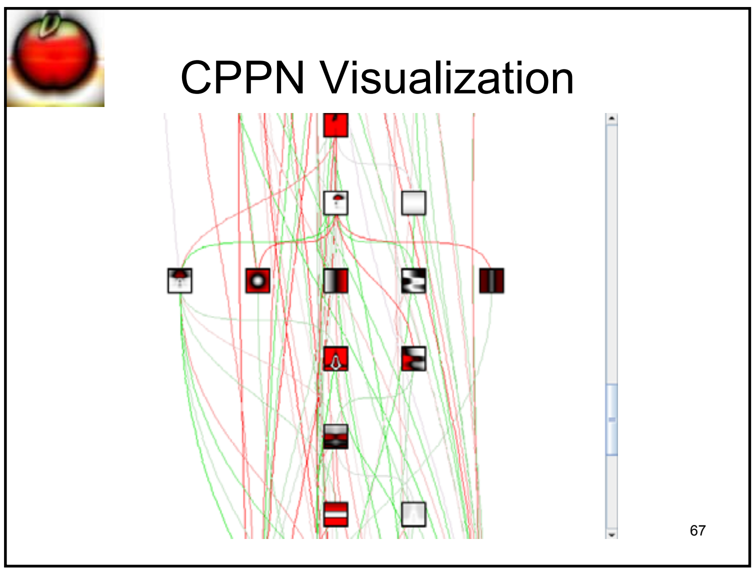
Forming Intermediate Patterns

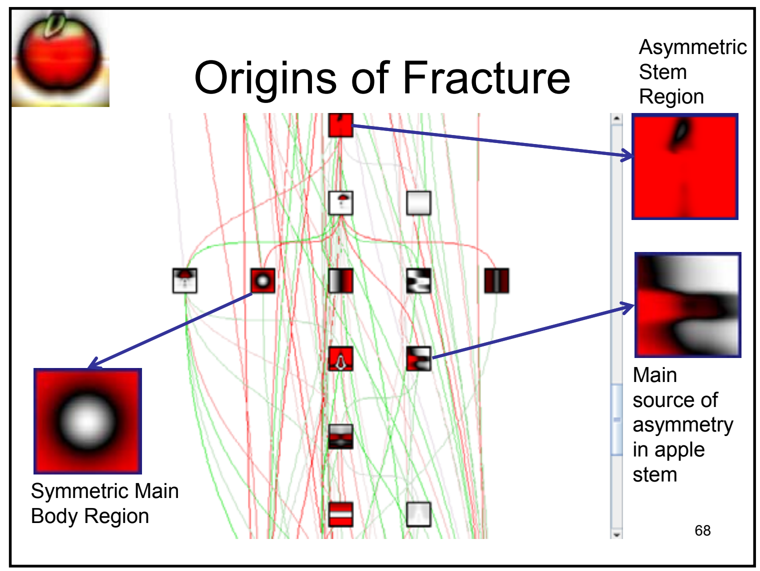


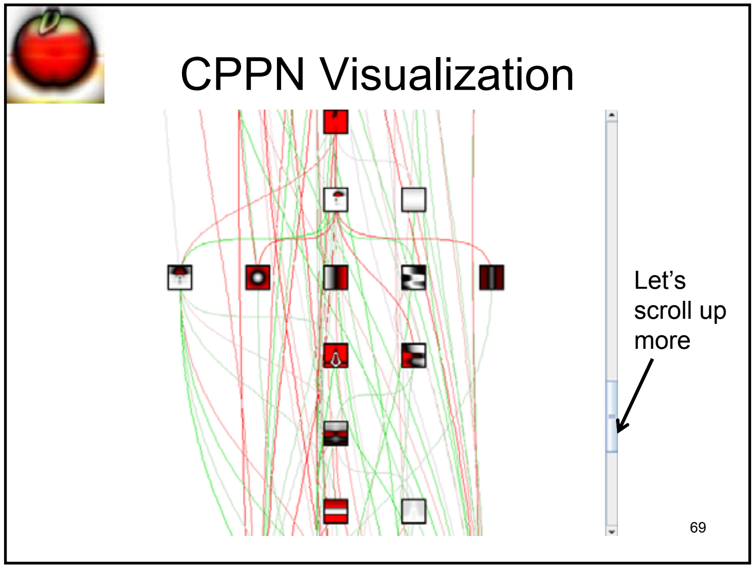
64

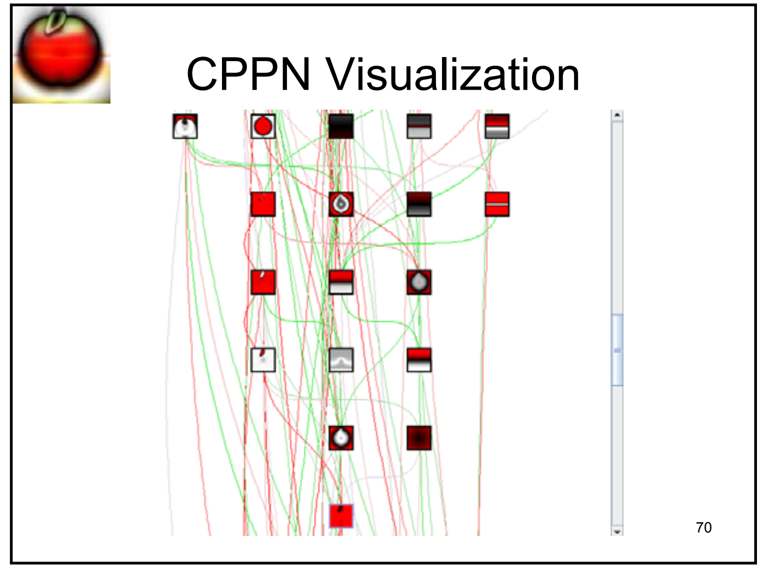

Compositionality
Compositionality:
Essential to
Indirect encoding
Inputs
65

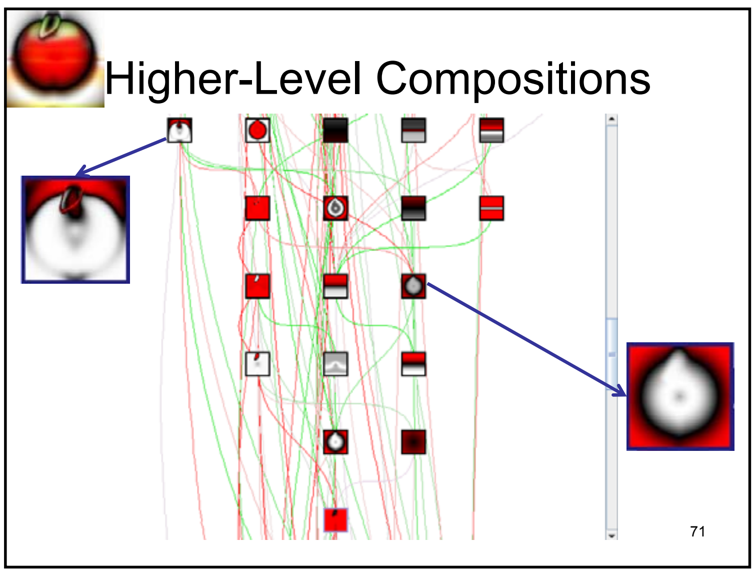

CPPN Visualization
Let's
scroll
gradually
up to the
top
Inputs
66

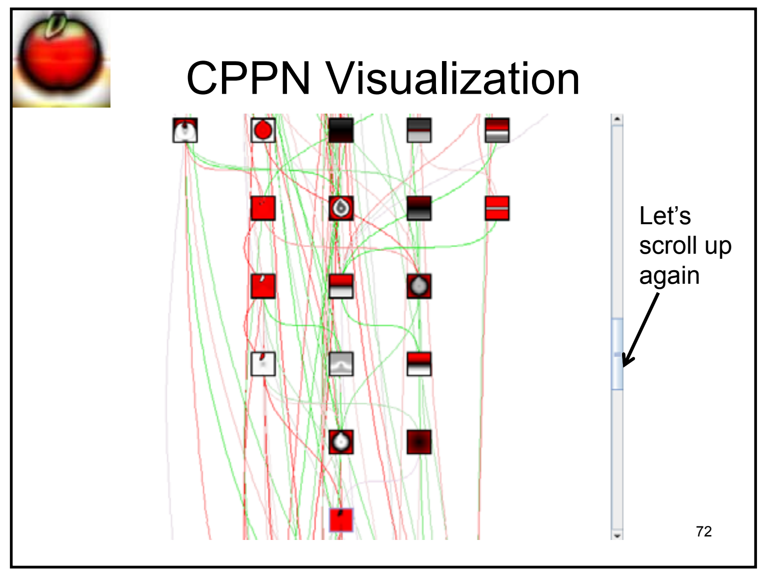

CPPN Visualization
67


Origins of Fracture
Asymmetric
Stem
Region
Symmetric Main
Body Region
Main
source of
asymmetry
in apple
stem
68

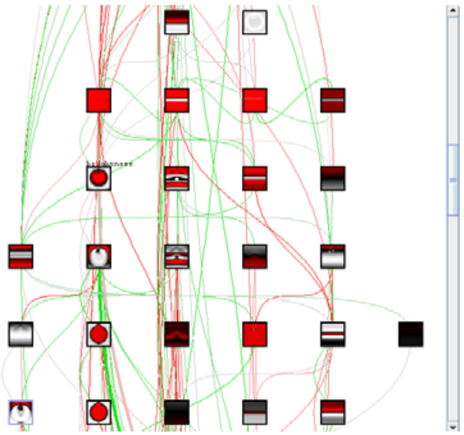

CPPN Visualization
Let's scroll up more
69


CPPN Visualization
70


Higher-Level Compositions
71


CPPN Visualization
Let's scroll up again
72

CPPN Visualization



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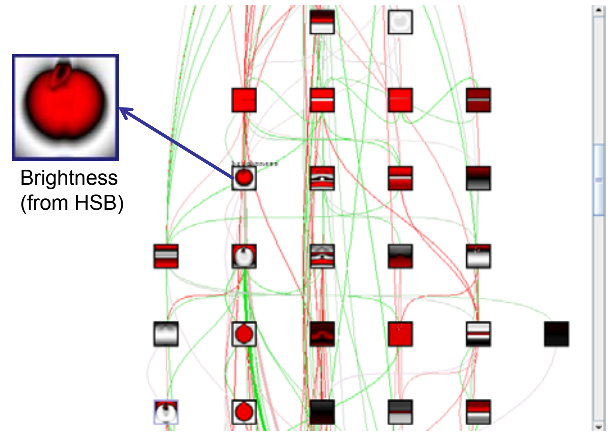
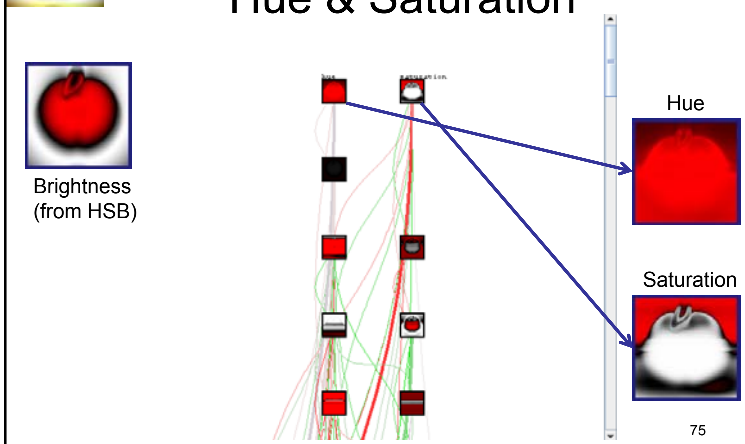
First Output: Brightness



74

Last Outputs (at the top): Hue & Saturation



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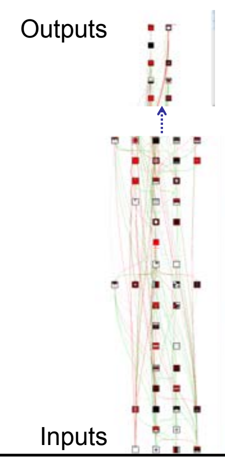
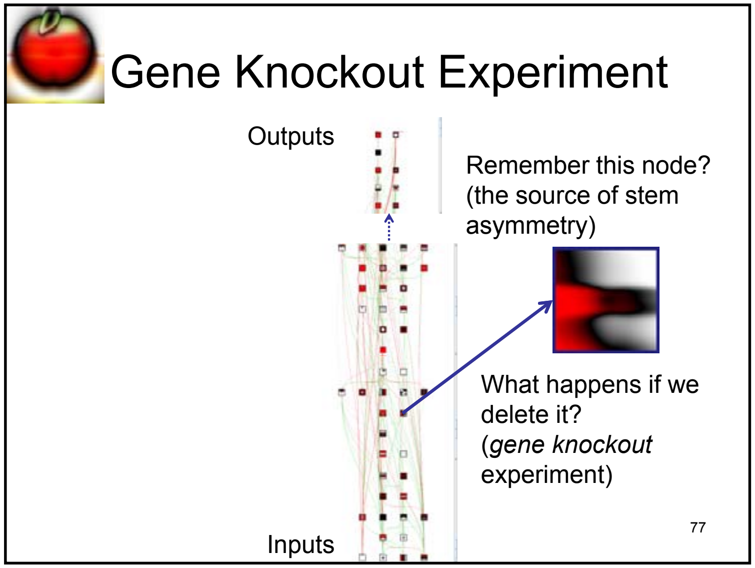
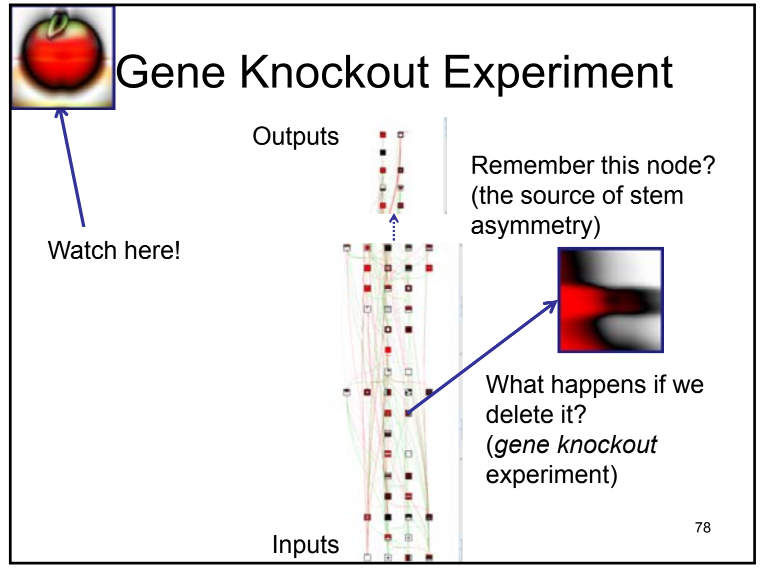
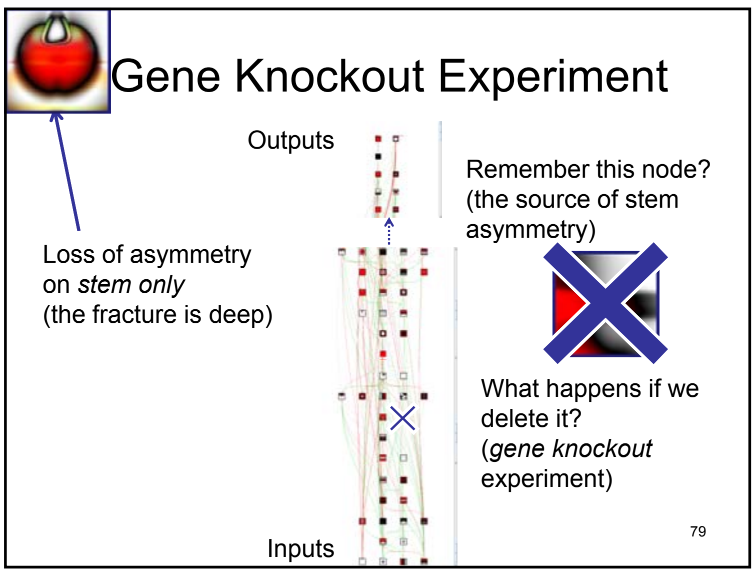
Very Large Apple Network

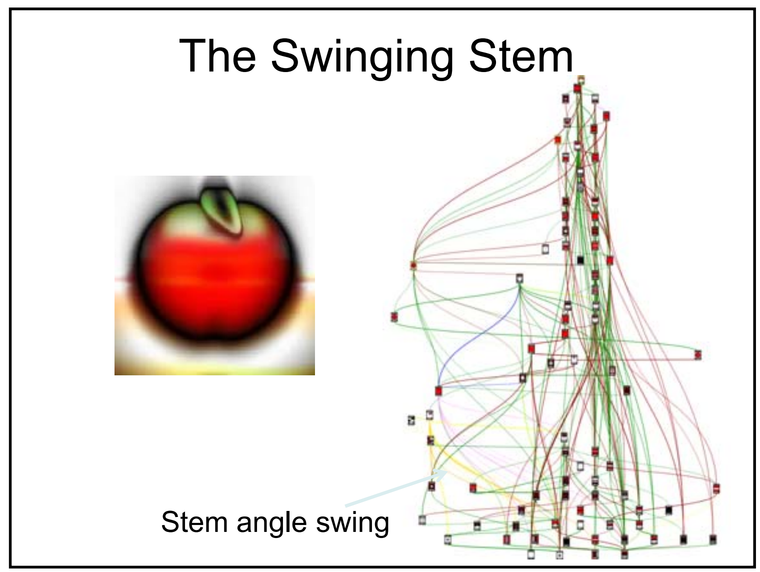


76


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
Loss of asymmetry
on *stem only*
(the fracture is deep)
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

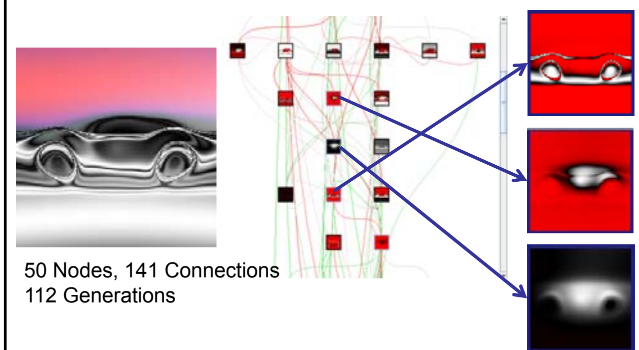
- Where would you split this image?

50 Nodes, 141 Connections
112 Generations

81

Other Notable Fracture

- Masks for different parts inside the CPPN

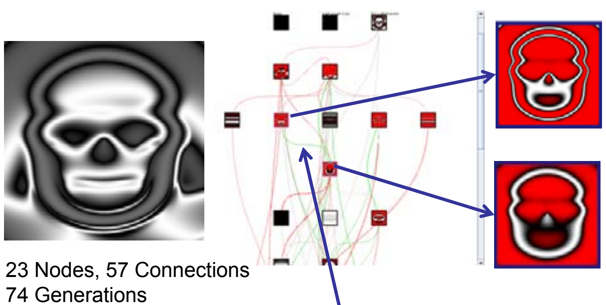


50 Nodes, 141 Connections
112 Generations

82

The Mouth of the Skull

- Fracture is often surprisingly intuitive

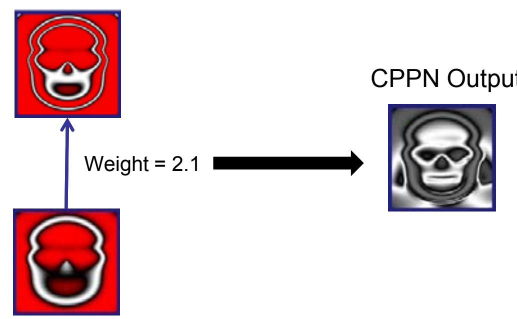


23 Nodes, 57 Connections
74 Generations

83

Scaling the Mouth

- Single gene controls the mouth aperture



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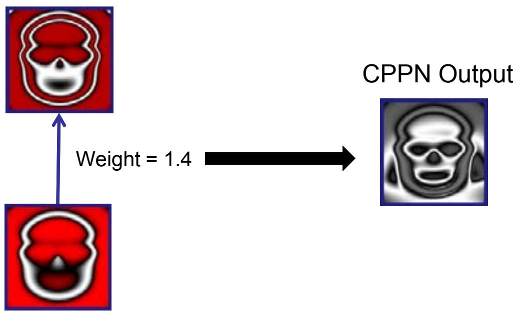
Scaling the Mouth

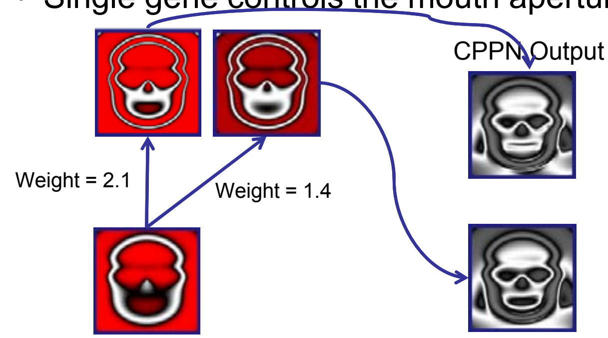
- Single gene controls the mouth aperture



85

Scaling the Mouth

- Single gene controls the mouth aperture



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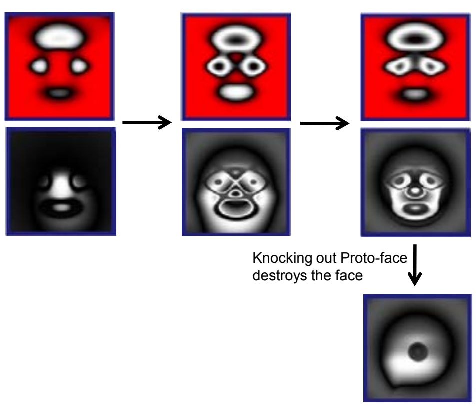
Many Faces "Conserve" the Same Proto-face Mask



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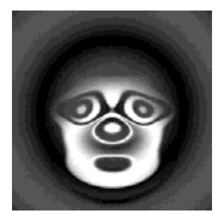
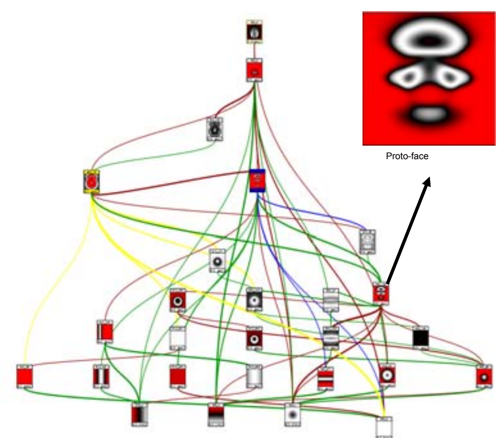
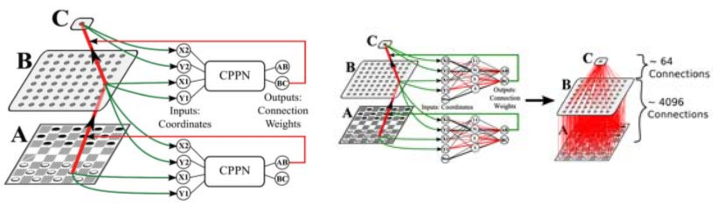
Cartoon Face





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 Gauci 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

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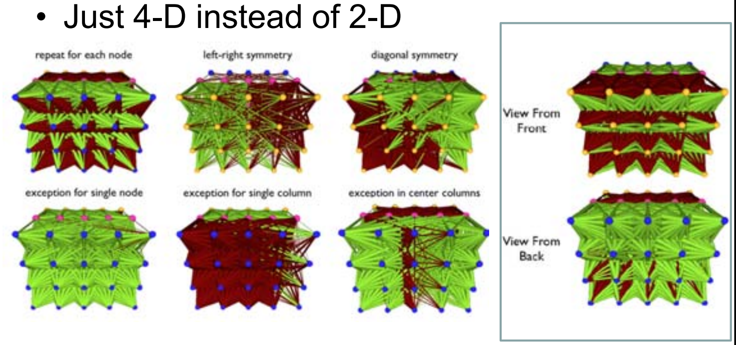
Similar Regularity and Fracture in HyperNEAT

- Just 4-D instead of 2-D



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.

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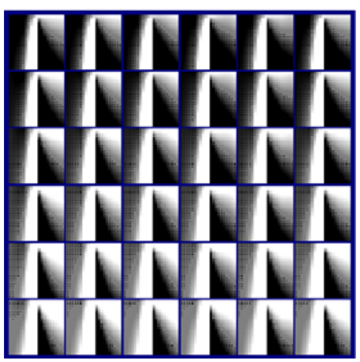
Fractured Neural Receptive Fields in HyperNEAT



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.

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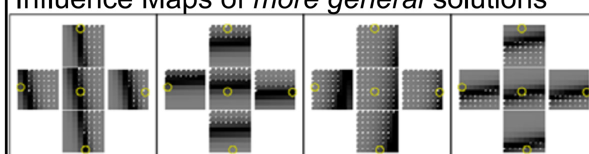
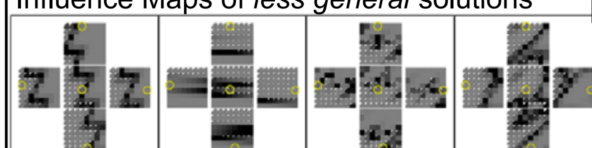
Geometric Patterns Inside Evolved HyperNEAT ANNs

Influence Maps of *more general* solutions



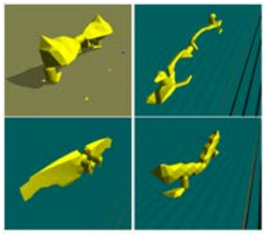
We can see the difference

Influence Maps of *less general* solutions

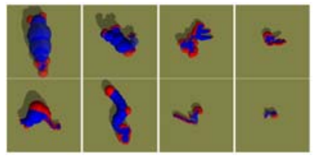


Jason Gauci and Kenneth O. Stanley (2010). Autonomous Evolution of Topographic Regularities in Artificial Neural Networks. In: Neural Computation journal 22(7), pages 1860-1898. Cambridge, MA: MIT Press.

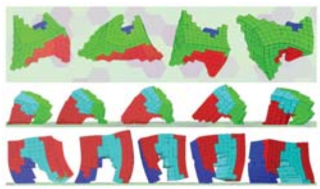
CPPN-encoded Creatures

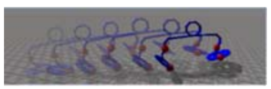


Joshua E. Auerbach and Josh C. Bongard
On the Relationship Between Environmental and Mechanical Complexity in Evolved Robots
13th International Conference on the Synthesis and Simulation of Living Systems (ALife XIII).
East Lansing, MI, July, 2012.



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.

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.

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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")

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Example: Evolve a Skull and a Butterfly with CPPNs

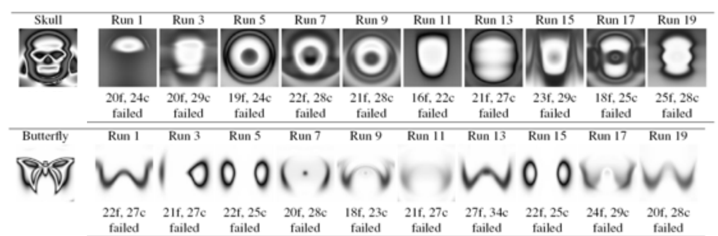
Target Image 1

Target Image 2

Results Are Terrible

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

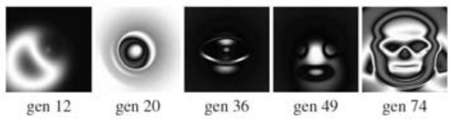
- Typical best results given 30,000 generations (only odd runs shown)



- 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.

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

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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.

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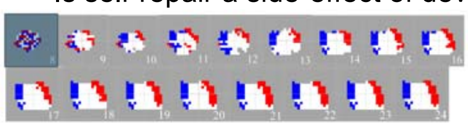
Regeneration and Self-Repair

- 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

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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)

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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?

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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@eecs.ucf.edu

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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.

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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

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

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T. Kowaliw and W. Banzhaf, Augmenting Artificial Development with Local Fitness, In IEEE CEC 2009

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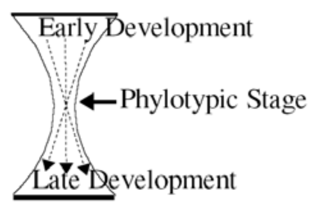
Extra: Heterochrony



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

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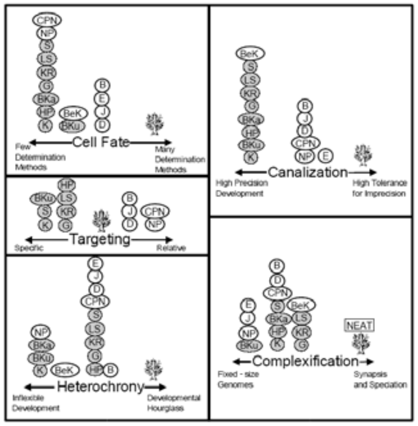
Extra: Exploring the Space of GDS (2003)



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