EndlessForms.com: Collaboratively Evolving Objects and 3D Printing Them

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Abstract

This abstract introduces EndlessForms.com, the first website to allow users to interactively evolve three-dimensional (3D) shapes online. Visitors are able to evolve objects that resemble natural organisms and engineered designs because the site utilizes a relatively new generative encoding inspired by concepts from developmental biology (Figure 1). This Compositional Pattern Producing Network (CPPN) encoding abstracts how natural organisms grow from a single cell to complex morphologies. Once evolved, visitors can click a button and have their evolved design 3D printed in materials ranging from plastic to silver. The site takes advantage of a recently released Web technology technology called WebGL that enables the visualization of 3D objects in Internet browsers. EndlessForms.com thus brings together recent innovations in evolutionary computation, Web technologies, and 3D printing to create a powerful collaborative interactive evolution experience that was not possible as recently as a year ago. In the first year of its release, nearly 3 million objects have been evaluated on the site during 190,000 generations of interactive evolution. A sizable community of citizen scientist participated: there were over 40,000 unique visitors from 150 countries and all 50 US states. In addition to its scientific mission of fueling intuitions regarding generative encodings for evolutionary algorithms, EndlessForms serves an educational outreach goal: visitors learn about evolution and developmental biology in a fun virtual setting and can transfer the 3D objects they create to the physical world (Figure 2).

View a video tour of EndlessForms at http://goo.gl/YvoBw

Compositional Pattern Producing Networks (CPPNs) abstract the process of natural development without simulating the low-level chemical dynamics involved in developmental biology (Stanley, 2007). Cells (and higher-level modules) in natural organisms often differentiate into their possible types (e.g. heart or spleen) as a function of where they are situated in geometric space (Wolpert and Tickle, 2010). With CPPNs, phenotypic elements are similarly specified as a function of their geometric location (Stanley, 2007). Each CPPN is a directed graph in which every node is itself a single function, such as sine or Gaussian. The nature of the functions can create a wide variety of desirable properties, such as symmetry (e.g. a Gaussian function) and repetition (e.g. a sine function) that evolution can exploit (Figure 1).

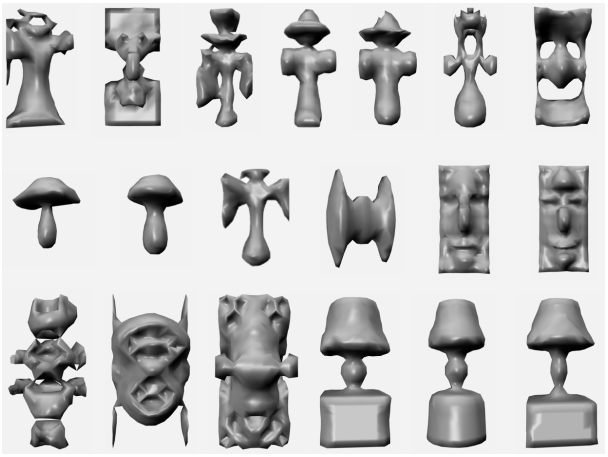

Figure 1: Example objects evolved on EndlessForms.com. Because they are evolved with a generative encoding based on developmental biology, the objects exhibit important properties seen in natural and engineered designs, such as symmetry and repetition, with and without variation.

To evolve 3D objects, inputs for the x, y, and z dimensions, and the distance from center, are provided to a CPPN. A *workspace* (maximum object size) is defined with a *resolution*, which determines the number of voxels in each dimension. On EndlessForms.com there are 10 voxels in the x and z dimensions and 20 in the y (vertical) dimension. These four values are iteratively input to a CPPN, and voxels are considered full if the CPPN output is greater than a threshold (here set to 0.1), otherwise the voxel is considered empty. The 3D voxel array is then processed by the surface-smoothing Marching Cubes algorithm. A normal is provided for each vertex when visualizing the objects in WebGL, which allows the renderer to further smooth the surface. These two smoothing steps enable high-resolution CPPN objects to be visualized without prohibitive computational costs.

3D objects are evolved with interactive evolution (see Secretan et al. 2011 for review). The website user views

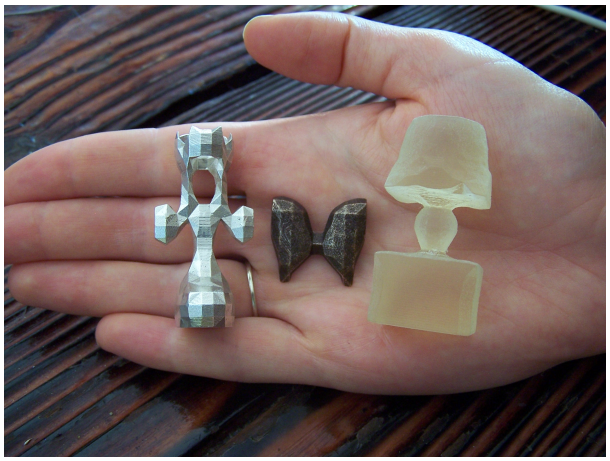

Figure 2: Objects evolved on EndlessForms printed in plastic, silver, and bronze. A "3D Print" button on the page for each object sends the design to our 3D printing partner Shapeways.com.

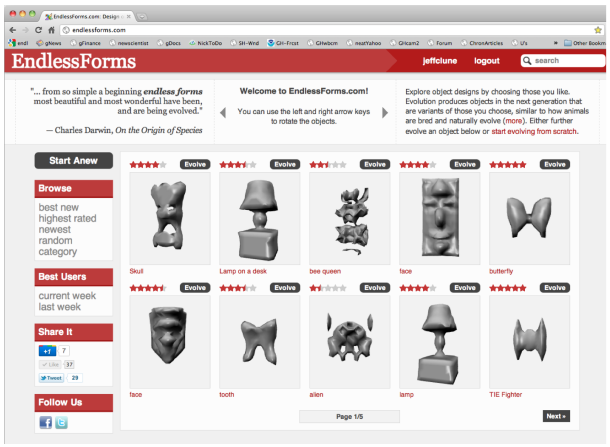

Figure 3: The EndlessForms.com homepage, including objects that users have evolved and rated highly.

15 rotating objects and selects one or more to serve as the parents of the next generation. The algorithm and its parameters are described in Clune and Lipson (2011).

Crowdsourced evolution has been previously implemented by websites like Picbreeder.org, which allows users to evolve 2D images with CPPNs (Secretan et al., 2011). The complexity and natural appearance of the resulting images often support claims regarding the legitimacy of CPPNs as an abstraction of biological development (Stanley, 2007). It is possible that CPPNs are unable frequently to make sensible forms with the added difficulty of another dimension, and when objects must be one contiguous unit (which aids in transfers to reality). Thus, a demonstration in 3D significantly strengthens these claims of legitimacy, because the natural world is three-dimensional. Evolving CPPN objects in the natural 3D setting demonstrates that generative encodings based on *geometric* abstractions of development capture some of the complexity-generating power of natural morphological development. Doing so also provides a visually intuitive testbed for studying how variants of such generative encodings behave. It also reveals the utility of CPPNs as a representation for 3D object design (Clune and Lipson, 2011).

We previously described how to evolve 3D shapes with CPPNs on a personal computer (Clune and Lipson, 2011). However, crowdsourcing represents a fundamentally different way of exploring a design space (Secretan et al., 2011). By allowing visitors to share designs and further evolve them, innovations discovered by one user can be built upon by the crowds that follow. For example, when one user finds a mushroom or lamp design, other users generate many interesting variants on that theme (Figure 1). There are currently over 60 lamps and 20 mushrooms descendent from those two discoveries. To catalyze such crowdsourced efforts we enabled users to share their discoveries via Facebook and Twitter (Figure 3). Collaborative evolution also means that no individual has to perform all the evaluations between generation 0 and a new discovery, facilitating deep searches into promising areas of the search space. Users can further evolve objects published by others, or start anew from randomly generated genomes, which increases diversity in the search. Evolved objects can be brought into the physical world via 3D printing (Figure 2), which creates a fun incentive for users to keep evolving.

In our presentation we will describe the results of this experiment in collaborative object design, including the types of objects evolved and the effect that crowdsourced evolution had on the exploration of the design space. We will also discuss future directions for harnessing crowds to facilitate research in interactive evolution, generative encodings, and automated object design.

References

Clune, J. and Lipson, H. (2011). Evolving three-dimensional objects with a generative encoding inspired by developmental biology. In *Proceedings of the European Conference on Artificial Life*, pages 144–148.

Secretan, J., Beato, N., D'Ambrosio, D., Rodriguez, A., Campbell, A., Folsom-Kovarik, J., and Stanley, K. (2011). Picbreeder: A Case Study in Collaborative Evolutionary Exploration of Design Space. *Evolutionary Computation*, To appear.

Stanley, K. (2007). Compositional pattern producing networks: A novel abstraction of development. *Genetic Programming and Evolvable Machines*, 8(2):131–162.

Wolpert, L. and Tickle, C. (2010). *Principles of Development*. Oxford University Press, 4th edition.

EndlessForms.com

A demonstration of easy to use crowdsourced design

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Abstract

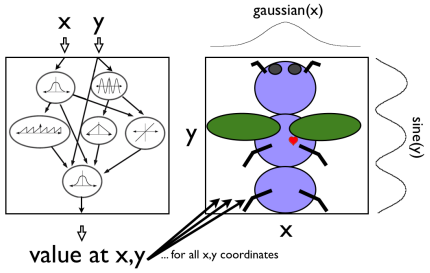
Typical methods of producing 3D designs involve an expert using a Computer Aided Design (CAD) program to created a desired shape. However, **many users are not CAD experts, so smarter, more automated design tools are needed**. Here we present EndlessForms.com, a proof of concept design tool for allowing extremely **simple, crowdsourced design in a web browser**.

In the first year of its release, **3 million objects** have been evaluated on the site during 200,000 generations of interactive evolution. A sizable community of citizen scientists have participated: there have been over 50,000 unique visitors from 150+ countries and all 50 US states.

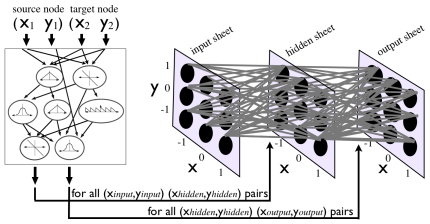
View a video tour of EndlessForms.com at `http://goo.gl/YvoBw`.

Generating Shapes

Objects resemble natural organisms and engineered designs because we use an encoding inspired by developmental biology called a Compositional Pattern Producing Network (CPPN). This encoding abstracts natural growth from a single cell to complex morphologies.

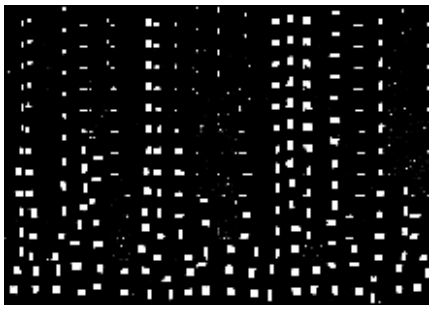


CPPNs combine mathematical functions to create regularities, such as symmetries and repeated modules.



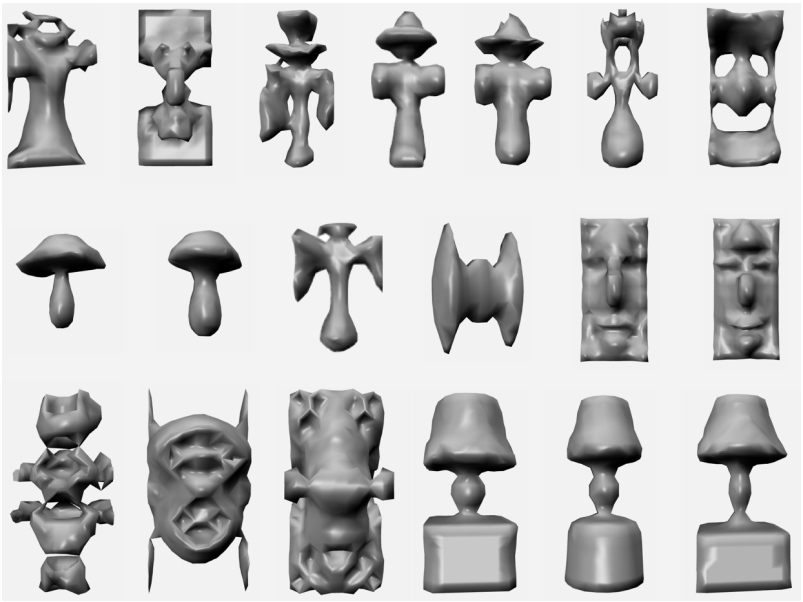
HyperNEAT produces ANNs from CPPNs [1, 2].

We are also investigating new generative models for creating designs, such as these produced by deep learning (below).

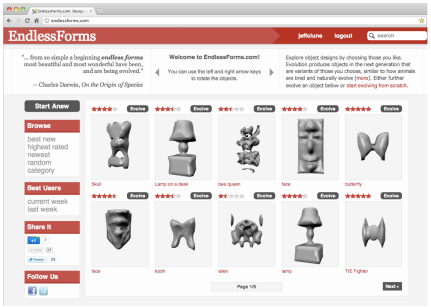


Preliminary 2D shapes produced by a Restricted Boltzmann Machine (RBM).

Example shapes evolved on EndlessForms.com



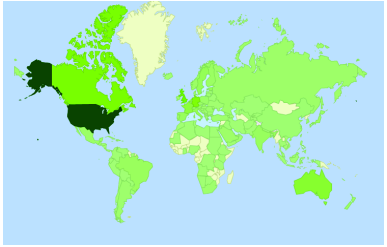
EndlessForms.com Website



- **3 million** objects evaluated by users
- **200,000** evolutionary generations
- **50,000** visitors from 150+ countries

Slashdot · COMMUNICATIONS OF THE ACM · Technology Review · Hacker News · KURZWEIL ACCELERATING INTELLIGENCE · msnbc.com · CHRONICLE ONLINE · NewScientist

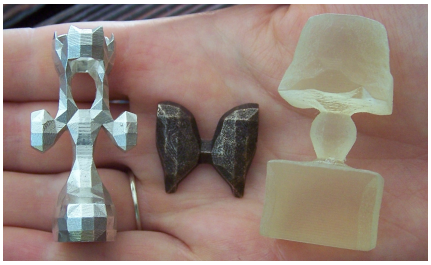
EndlessForms has received a variety of favorable press.



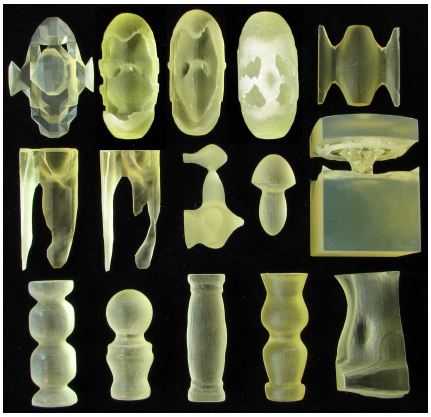
Visitors from all over the world have used EndlessForms.com

3D printed objects

Once objects are evolved, visitors can click a button to have their design 3D printed in materials ranging from plastic to silver.



Objects evolved on EndlessForms.com and 3D printed in silver, bronze, and plastic.



Objects evolved and printed in plastic on an Objet Connex500.

Abbreviated References

[1] J. Clune, K.O. Stanley, R.T. Pennock, and C. Ofria. On the performance of indirect encoding across the continuum of regularity. *IEEE Transactions on Evolutionary Computation. To appear.*, 2011.

[2] K.O. Stanley, D.B. D'Ambrosio, and J. Gauci. A hypercube-based encoding for evolving large-scale neural networks. *Artificial Life*, 15(2):185–212, 2009.