Adversarial Evolution and Deep Learning for Computational Creativity

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(joint work with Jacob Soderlund and Darwin Vickers)

Artwork of Hercule LeNet

Outline

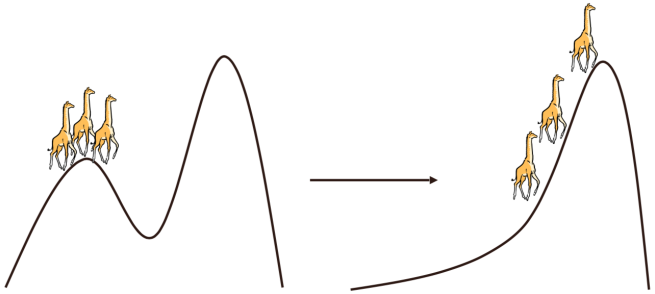
- Adversarial Coevolution in Nature
- Adversarial Coevolution in Computation
- Artist-Critic Co-Evolution
- Interactive Evolution (GP Artist; Human Critic)
- Generative Adversarial Networks (CNN Artist; CNN Critic)
- Evolutonary Art (GP Artist; GP, NN or CNN Critic)
- Artistic Techniques and Styles
- Discussion/Conclusion

Adversarial Coevolution in Nature

- Gazelle adapts to run faster and escape from the Leopard
- Leopard adapts to run faster and catch the Gazelle

Punctuated Equilibria (Eldredge & Gould, 1972)

- Is Evolution gradual? Are there "Gaps" in the fossil record?



- species remain in a meta-stable "niche" for a long time
- external change can lead to rapid adaptation
- environmental change, or a new predator or competitor

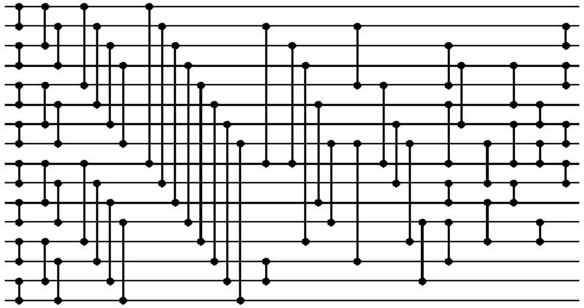
Coevolving Virtual Creatures (Sims, 1994)

- both body and controller of creature evolve
- aim is to get the cube away from opponent

Adversarial Game Learning

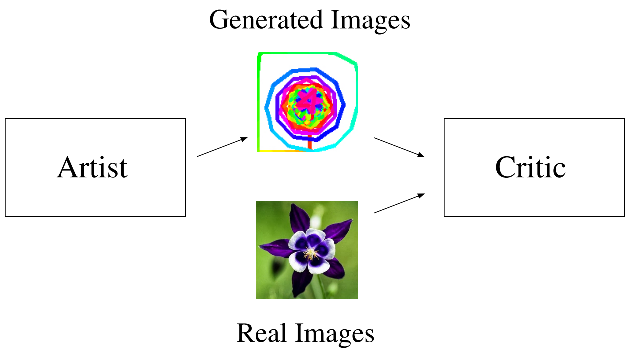
- learning strategic games by self-play
- coevolutionary dynamics
  - can help to improve robustness
  - could also get stuck in oscillation or mode collapse

Coevolution of Sorting Networks (Hillis, 1990)



- coevolution: sorting networks vs. strings to be sorted
- punctuated equilibria, can escape from local optima

Artist-Critic Co-Evolution



Generated Images

Artist

Critic

Real Images

- Critic is rewarded for distinguishing real images from those generated by the Artist
- Artist is rewarded for fooling the Critic into thinking that generated images are real

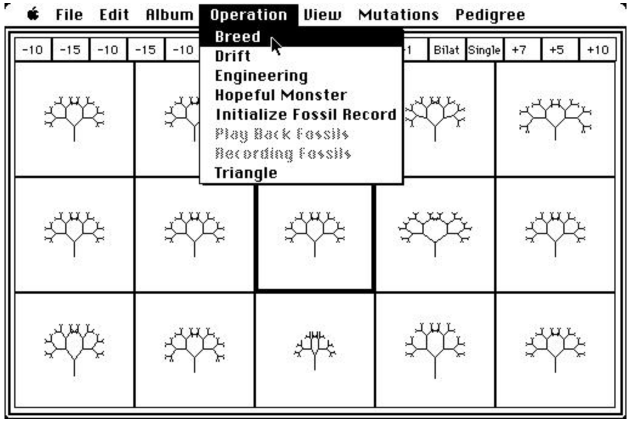
The Creative Act (Marcel Duchamp, 1957)

“All in all the creative act is not performed by the artist alone; the **spectator** brings the work in contact with the external world by deciphering and interpreting its inner qualifications and thus adds his contribution to the creative act.”

Artist-Critic Co-Evolution Paradigms

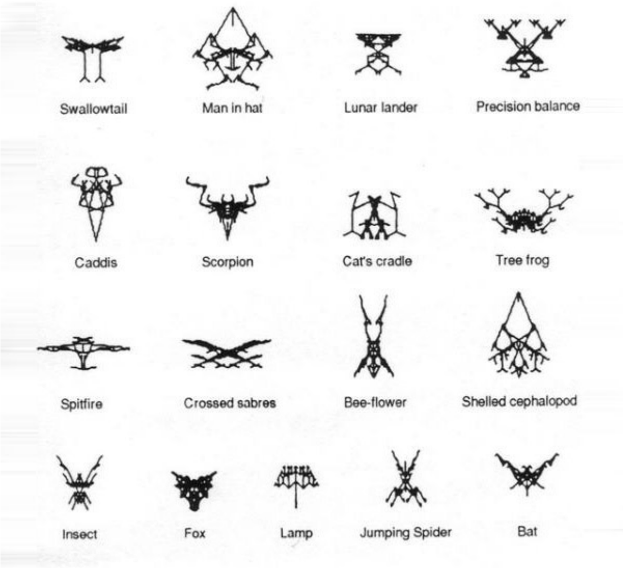
Artist	Critic	Method	Reference
Biomorph	Human	Blind Watchmaker	(Dawkins, 1986)
GP	Human	Blind Watchmaker	(Sims, 1991)
CPPN	Human	PicBreeder	(Secretan, 2011)
CA	Human	EvoEco	(Kowaliw, 2012)
GP	SOM	Artificial Creativity	(Saunders, 2001)
Photo	NN	Computational Aesthetics	(Datta, 2006)
GP	NN	Computational Aesthetics	(Machado, 2008)
Agents	NN	Evolutionary Art	(Greenfield, 2009)
GP	NN	Aesthetic Learning	(Li & Hu, 2010)
HERCL	HERCL	Co-Evolving Line Drawings	(Vickers, 2017)
HERCL	DCNN	HERCL Function/CNN	(Soderlund, 2018)
DCNN	DCNN	Generative Adversarial Nets	(Goodfellow, 2014)
DCNN	DCNN	Plug & Play Generative Nets	(Nguyen, 2016)

Blind Watchmaker (Dawkins, 1986)



- the (Human) user is presented with 15 images
- chosen image(s) are used to breed the next generation

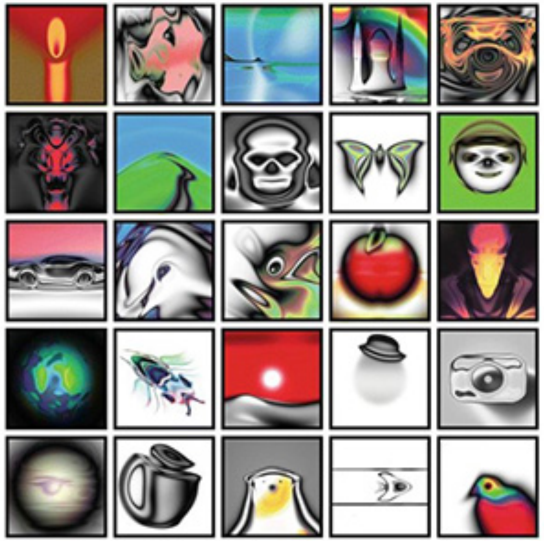
Blind Watchmaker Biomorphs



Interactive Evolution (Sims, 1991)

- Artist = Genetic Program (GP)
  - used as function to compute R,G,B values for each x, y pixel
- Critic = Human

PicBreeder (Secretan, 2011)



PicBreeder (Secretan, 2011)

- Artist = Compositional Pattern Producing Network (CPPN)
- Critic = Human
- interactive Web site (`picbreeder.org`) where you can choose an existing individual and use it for further breeding

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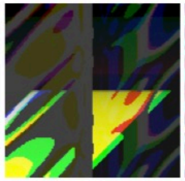
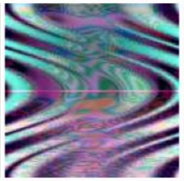
- Interactive Evolution paradigm is cool, but it may require a lot of work from the Human
- Can the Human be replaced by an automated Critic?

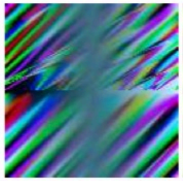
Evolutionary Art (Fully Autonomous)

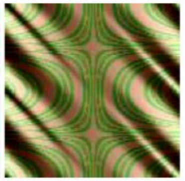
- Artist = Genetic Program (GP or HERCL)
  - artist used as a function to compute R,G,B values for each pixel location x, y
  - alternatively, artist issues a series of drawing instructions
- Critic = GP (evolution) or Neural Network (backpropagation)
- Critic is presented with "real" images from a training set, and "fake" images generated by the Artist
- Critic is trained to produce output close to 1 for real images and close to 0 for generated images (or vice-versa)
- inputs to Critic
  - small number of statistical features extracted from the image
  - more recently, raw image, fed to DCNN

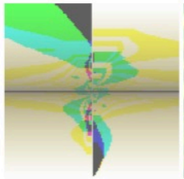
Computational Aesthetics (Machado, 2008)


It.1 Pop.44 Ind.14

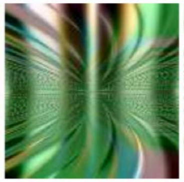

It.9 Pop.43 Ind.15

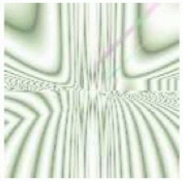

It.9 Pop.20 Ind.32


It.9 Pop.42 Ind.25


It.1 Pop.22 Ind.20

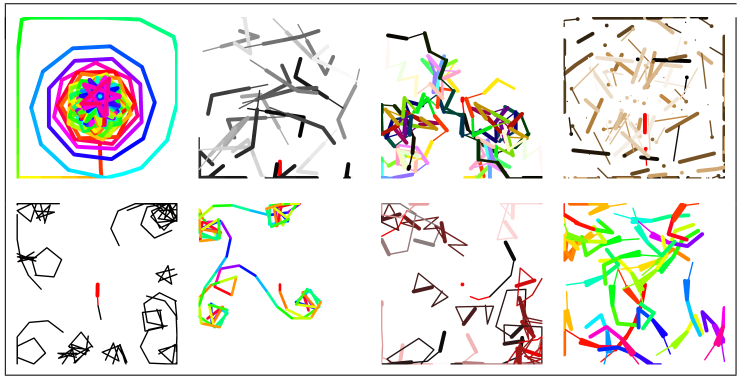
It.9 Pop.44 Ind.23


It.9 Pop.29 Ind.25


It.11 Pop.47 Ind.2

- Generator = Genetic Program
- Critic = 2-layer NN, using statistical features of image

Co-Evolving Line Drawings (Vickers, 2017)



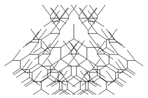
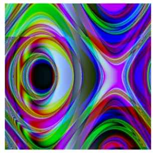
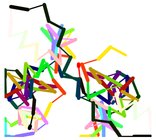
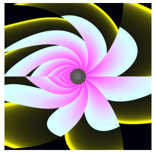
- Generator = Genetic Program (HERCL)
- Critic = GP (HERCL), using statistical features of image

Line Drawing Commands

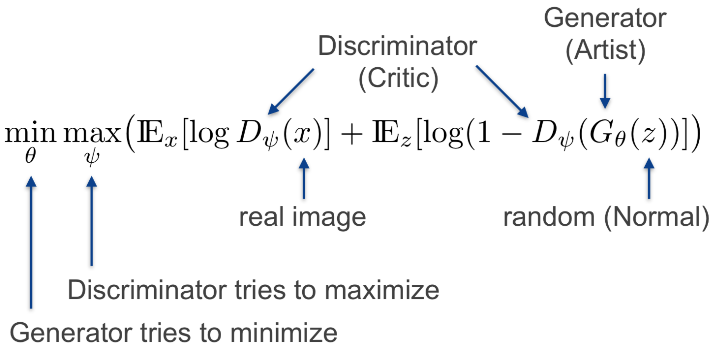
0	TOGGLE		lift pen on/off page
1	MOVE	x	move pen forward by x pixels ($0 \leq x \leq 15$)
2	TURN	x	turn x degrees clockwise
3	SIZE	p	set pen radius to p pixels ($1 \leq p \leq 4$)
4	COLOUR	v	set greyscale value [greyscale mode]
	COLOUR	$l\ h\ s$	set colour in HSV colour space [colour mode]

- the output from the HERCL program is interpreted as a series of line drawing commands
- Critic is also a HERCL program, based on 20 statistical features extracted from the image

Image Generating Paradigms

 Biomorph	 GP	 Picbreeder	 CA
 HERCL(draw)	 HERCL(func)	 HERCL(func)	 GAN

Generative Adversarial Networks (Goodfellow, 2014)



Discriminator (Critic)

Generator (Artist)

$$\min_{\theta}\max_{\psi}\big(\mathbb{E}_x[\log D_\psi(x)] + \mathbb{E}_z[\log(1 - D_\psi(G_\theta(z)))]\big)$$

real image

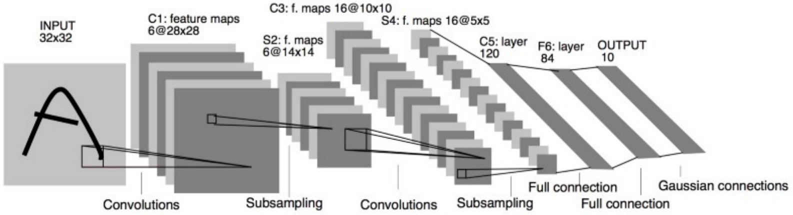
random (Normal)

Discriminator tries to maximize

Generator tries to minimize

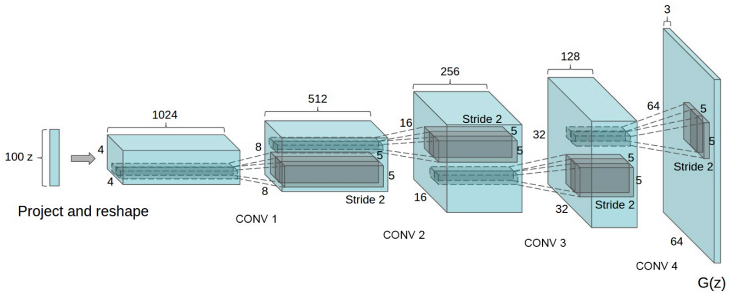
- Artist = Deep CNN
- Critic = Deep CNN

LeNet CNN Discriminator (LeCun, 1998)



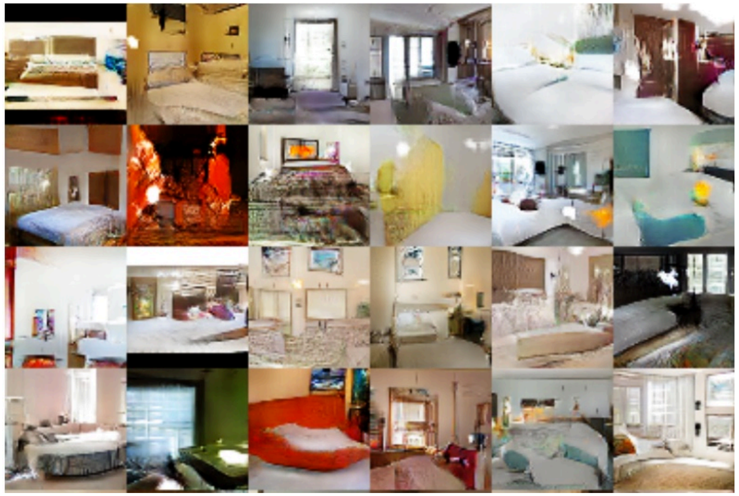
- convolutional layers
- max pooling
- fully connected layers
- for Discriminator, only two outputs

GAN Generator Architecture (Radford, 2016)

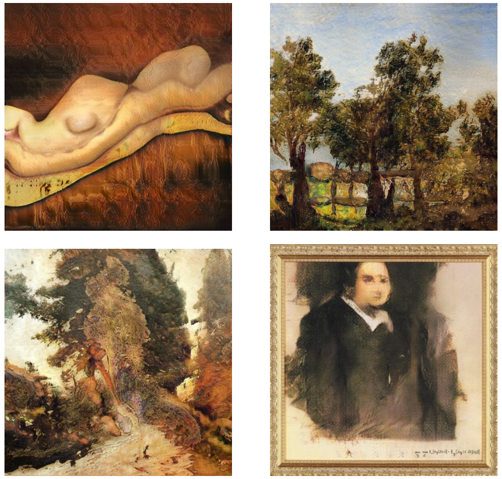


- differentials are backpropagated from Discriminator, through image and into Generator

GAN Generated Images (Radford, 2015)

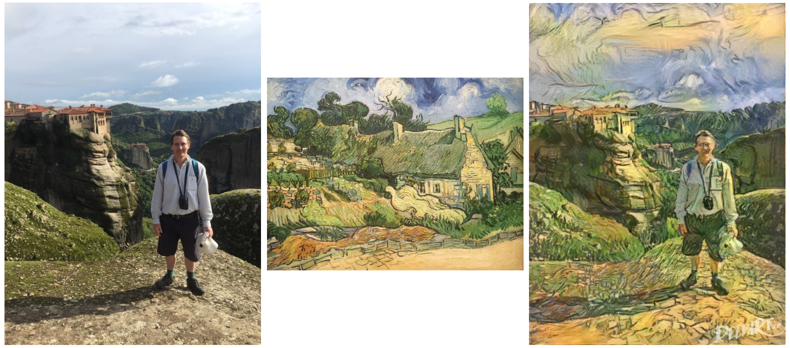


GAN Generated Art (Robbie Barrat; Obvious)



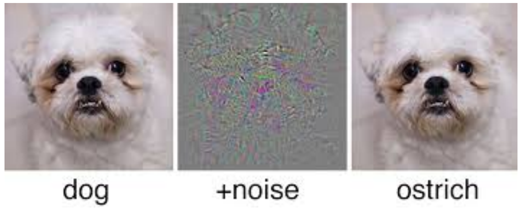
GAN is shown paintings by humans and asked to mimic the style

Neural Style Transfer (Gatys, 2015)



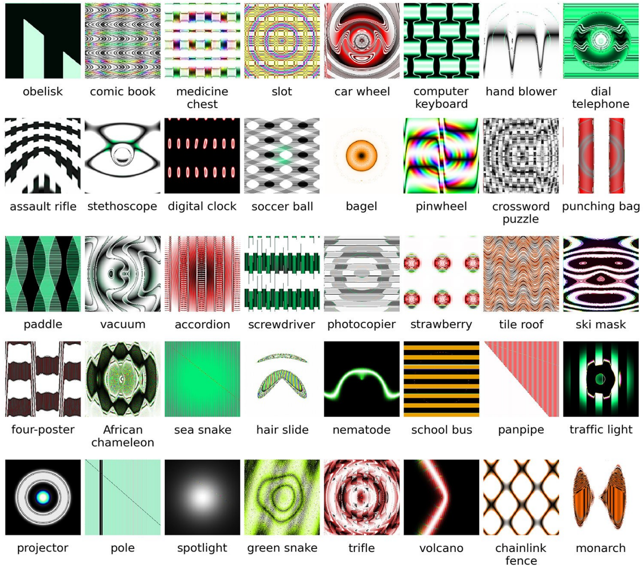
Another method for producing art in the style of a human artist

GANs exhibit Coevolutionary Dynamics

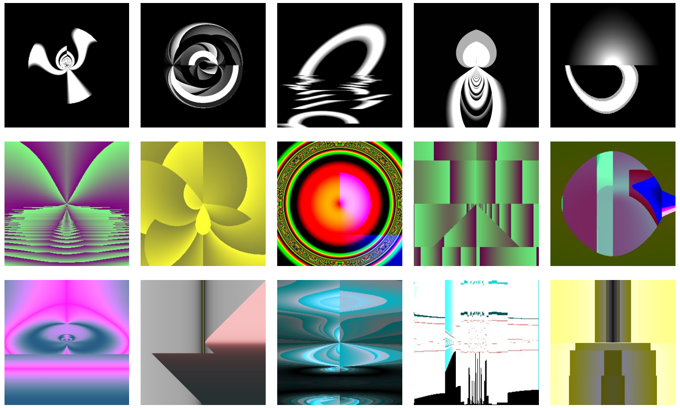


- Deep Networks are easily fooled
- Adversarial training improves quality of images, but can lead to well known problems of coevolutionary dynamics
  - oscillation
  - mode collapse

CPPN vs. Pre-Trained ImageNet (Nguyen, 2015)



Adversarial Evolution and Deep Learning (Soderlund, 2018)



- Artist = HERCL program as a function from x,y to R,G,B
- Critic = Deep Convolutional Neural Network (LeNet)

Adversarial Evolution and Deep Learning

- Generator = HERCL program, as function from x, y to R,G,B
- Critic = LeNet CNN
- in each round, a new Critic is trained to distinguish real images from those previously produced by the Generator
- HERCL Generator is then evolved to produce an image for which the current Critic will assign the best possible score
- each round adds one new image to the gallery
- Generator can re-use code from previous images in gallery
- at the end of the process, Human chooses from the 600-1000 images generated

Hierarchical Evolutionary Re-Combination Language (HERCL)

```
    INPUT:   ickey
   OUTPUT:
   MEMORY:   Minnie..............................
REGISTERS:   .....[6]..[1].  [7]
    STACK:   MM
     CODE:   0[is|.<sy^5>};i|8{^s-~:+7=;wo8|-wo]
                                  ^
```

- combines elements from Linear GP and Stack-based GP.
- programs have access to a stack, registers and memory.
- each instruction is a single character, possibly preceded by a numerical (or dot) argument.

HERCL Commands

Input and Output

i	fetch INPUT to input buffer
s	SCAN item from input buffer to stack
w	WRITE item from stack to output buffer
o	flush OUTPUT buffer

Stack Manipulation and Arithmetic

#	PUSH new item to stack	$\ldots\ldots \mapsto \ldots\ldots x$
!	POP top item from stack	$\ldots\ldots x \mapsto \ldots\ldots$
c	COPY top item on stack	$\ldots\ldots x \mapsto \ldots\ldots x, x$
x	SWAP top two items	$\ldots y, x \mapsto \ldots x, y$
y	ROTATE top three items	$z, y, x \mapsto x, z, y$
-	NEGATE top item	$\ldots\ldots x \mapsto \ldots\ldots(-x)$
+	ADD top two items	$\ldots y, x \mapsto \ldots(y+x)$
*	MULTIPLY top two items	$\ldots y, x \mapsto \ldots(y * x)$

HERCL Commands

Mathematical Functions

r	RECIPROCAL	$..x \to ..1/x$
q	SQUARE ROOT	$..x \to ..\sqrt{x}$
e	EXPONENTIAL	$..x \mapsto ..e^x$
n	(natural) LOGARITHM	$..x \mapsto ..\log_e(x)$
a	ARCSINE	$..x \mapsto ..\sin^{-1}(x)$
h	TANH	$..x \mapsto ..\tanh(x)$
z	ROUND to nearest integer	
?	push RANDOM value to stack	

Double-Item Functions

%	DIVIDE/MODULO	$..y, x \mapsto ..(y/x), (y \bmod x)$
t	TRIG functions	$..\theta, r \mapsto ..r\sin\theta, r\cos\theta$
p	POLAR coords	$..y, x \mapsto ..\mathrm{atan2}(y,x), \sqrt{x^2+y^2}$

HERCL Commands

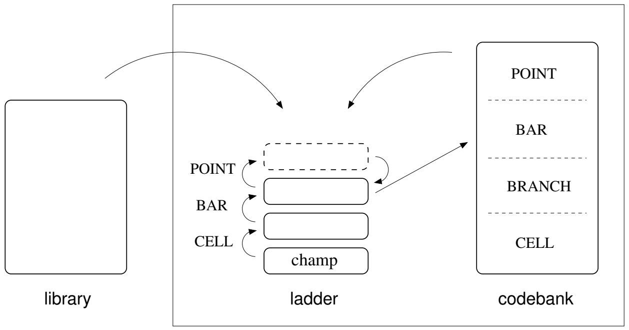
Registers and Memory

<	GET value from register
>	PUT value into register
^	INCREMENT register
v	DECREMENT register
{	LOAD from memory location
}	STORE to memory location

Jump, Test, Branch and Logic

j	JUMP to specified cell (subroutine)
|	BAR line (RETURN on .| HALT on 8|)
=	register is EQUAL to top of stack
g	register is GREATER than top of stack
:	if TRUE, branch FORWARD
;	if TRUE, branch BACK
&	logical AND / logical OR ˜ logical NOT

Hierarchical Evolutionary Re-Combination

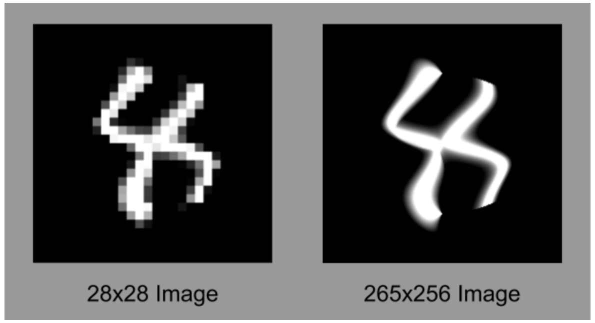


- large crossover/mutation can be followed up by smaller ones.
- if top agent becomes fitter, it moves down to replace the one below it (which is moved to the codebank).
- if top agent exceeds max number of offspring, it is removed.
- good for co-evolution because it keeps the number of competing agents small while preserving diversity.

Previous HERCL Tasks

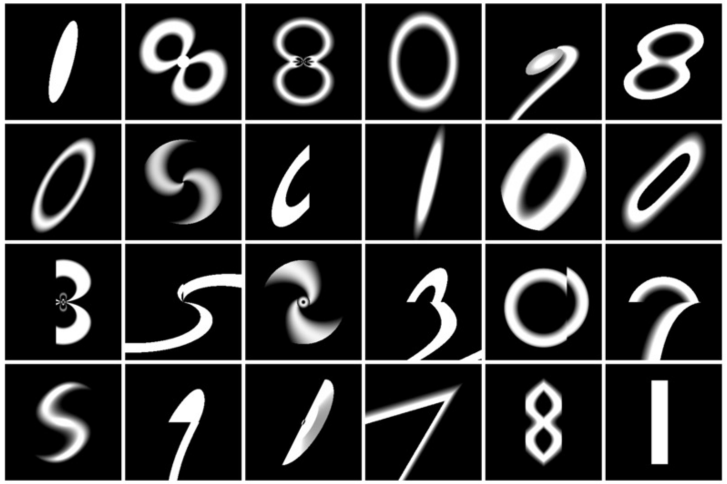
- Classification Tasks
  - sonar
  - ionosphere
  - promoters
  - Australian credit card fraud
  - Pima Diabetes prediction
- Control Tasks
  - double pole balancing
- String Processing Tasks
  - strcat
  - strlen
  - strchr
  - strcmp
- Other Tasks
  - Caesar & Vigenere Cipher
  - Postfix Calculator

Up-Scaling of Images

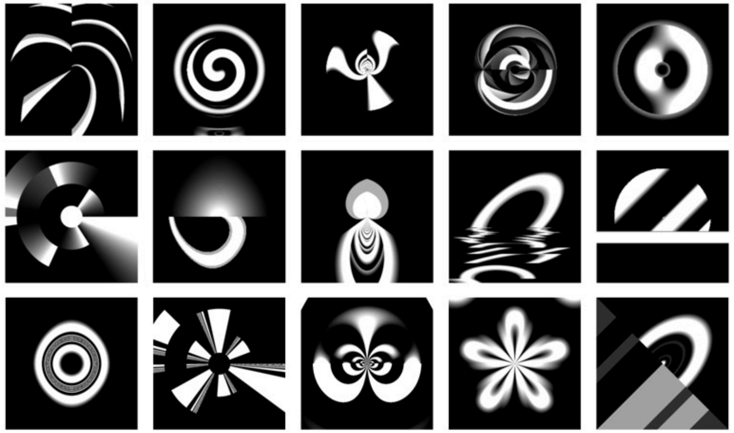


- images are fed to the critic at low resolution
- afterwards, images can be re-generated at high resolution

Images trained with MNIST digits



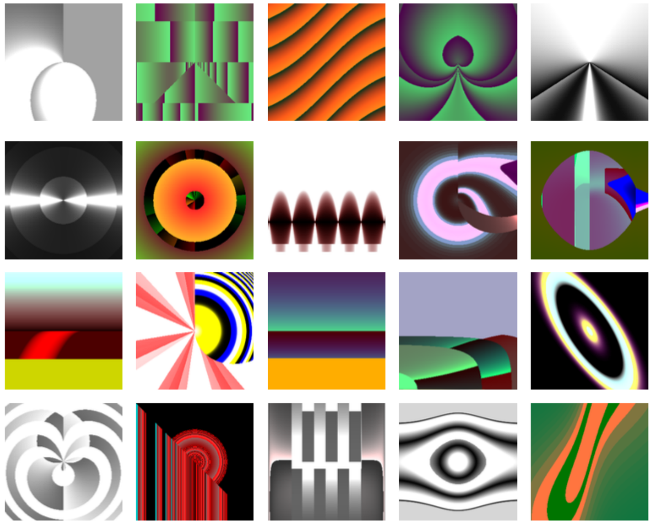
Images trained with MNIST digits



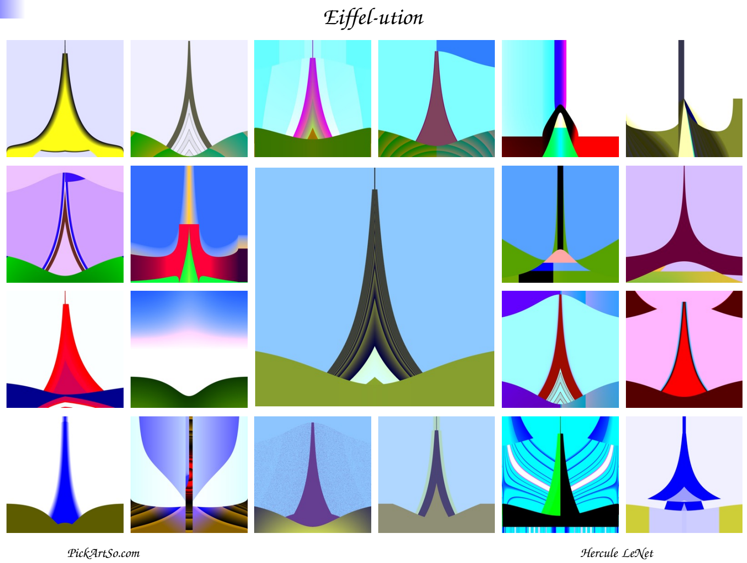
These ones don't look like digits, but may have some artistic merit

Images trained with CIFAR-10 photographs

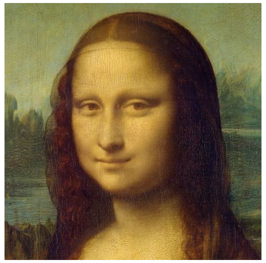
Images trained with CIFAR-10 photographs

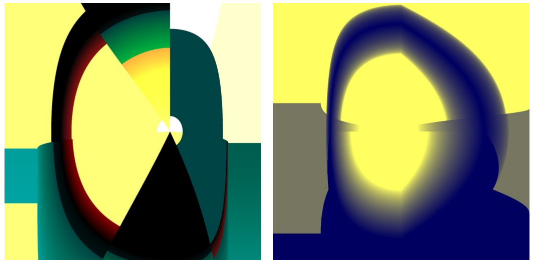


Eiffel-ution



Mona Lisa



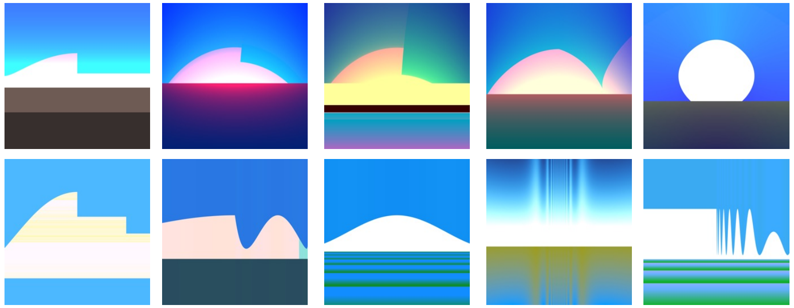


Experiments with Landmarks

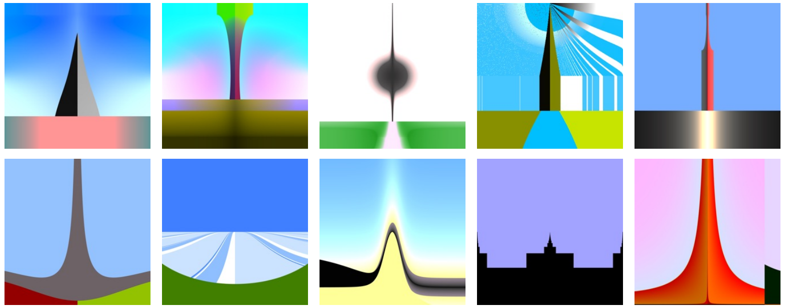
- collected photographs of 10 famous landmarks
- HERCL artist acting as function from x, y to R,G,B
- LeNet CNN critic with 16 filters in conv1, 24 in conv2
- data augmentation, by cropping
- two different resolutions (48×48 and 64×64)
- selected 5 best images from each run

Sydney Opera House

© Bernard Gagnon

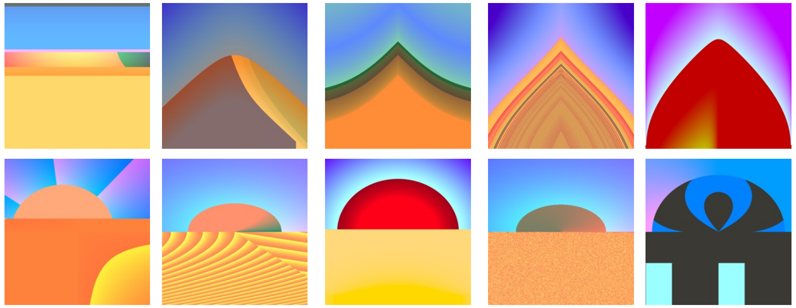


Eiffel Tower



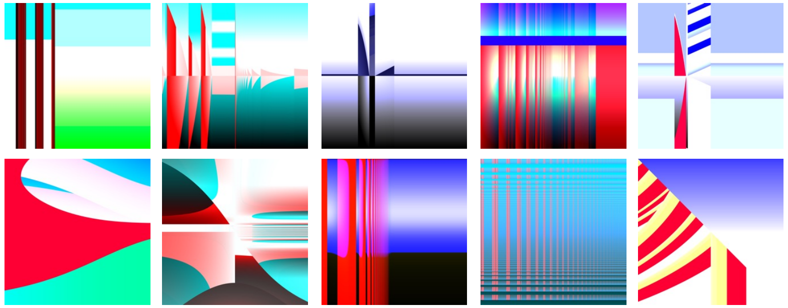
Pyramids

© Ricardo Liberato



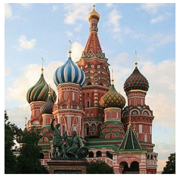
Golden Gate Bridge

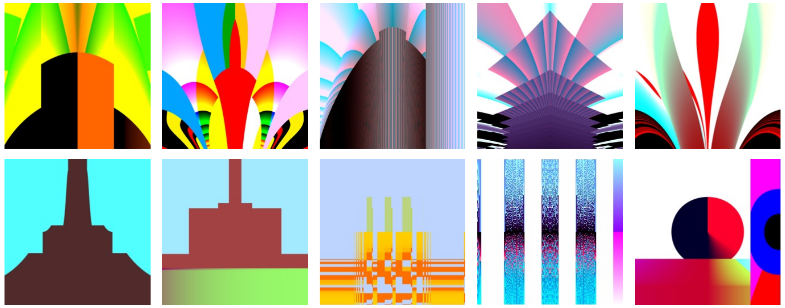
© Rich Niewiroski



Saint Basil's Cathedral

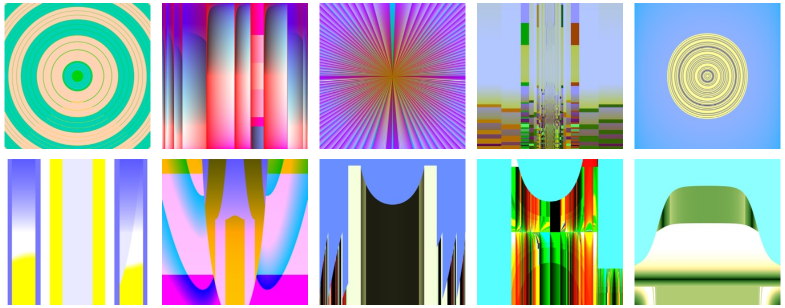
© A.Savin





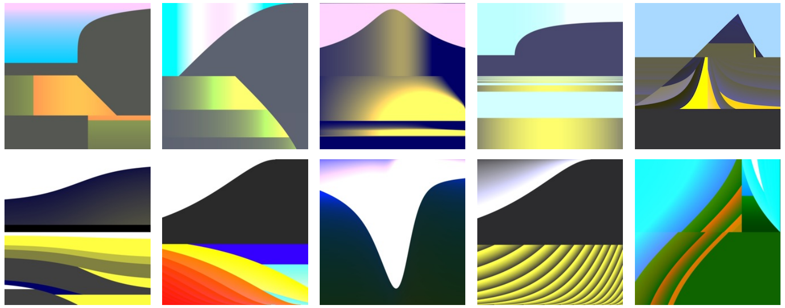
Notre Dame de Paris

© Jérôme Blum

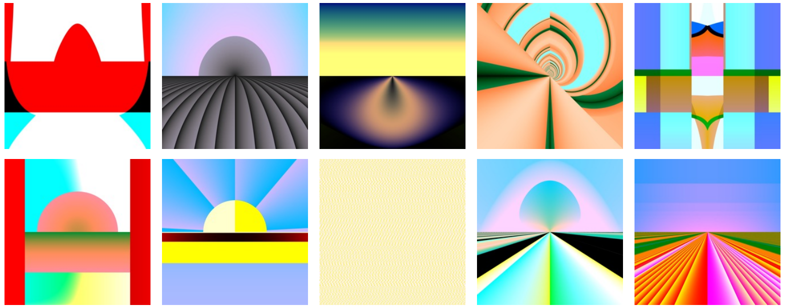


Machu Picchu

© Allard Schmidt

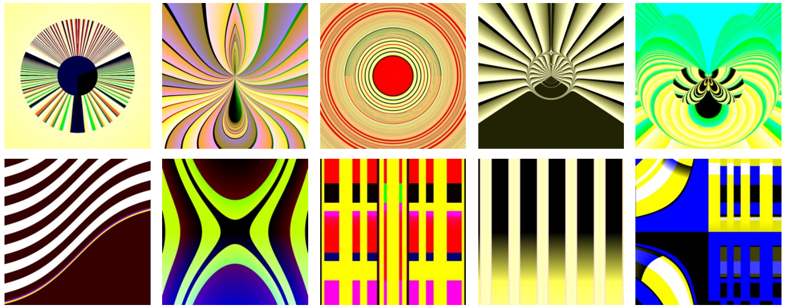


Taj Mahal



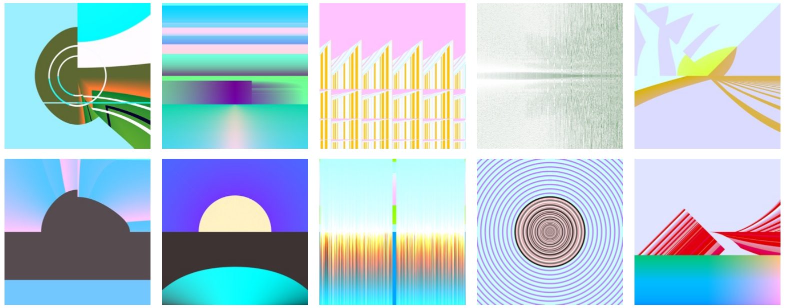
Angel Oak Tree

© DannyBoy7783

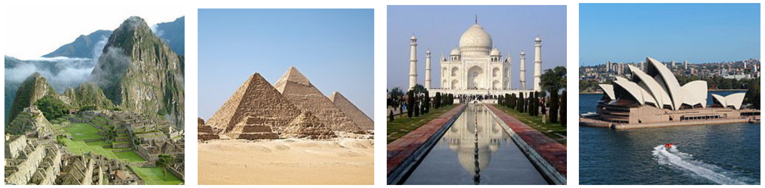


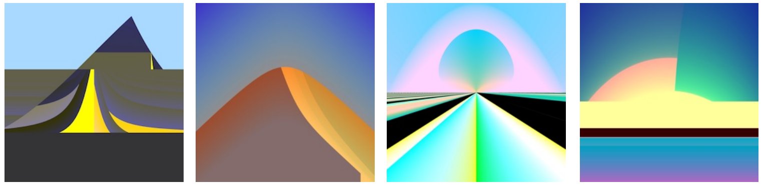
Grand Canal in Venice

© Hans Peter Schaefer



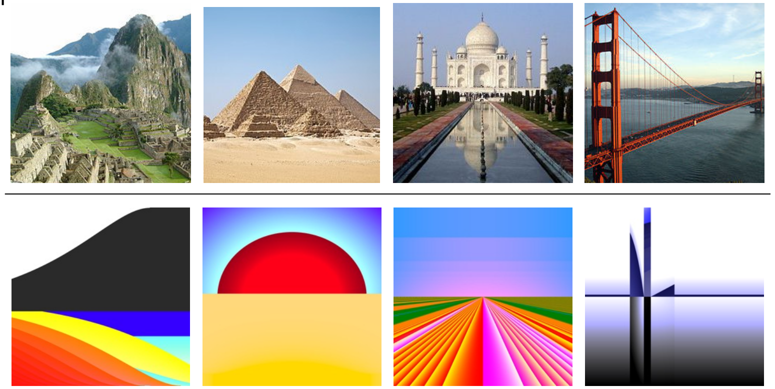
Minimalism





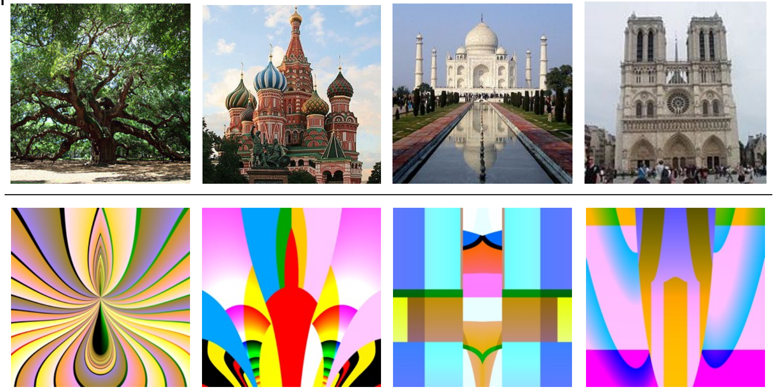
- the object is suggested by simple lines and shapes

Colors and Shading



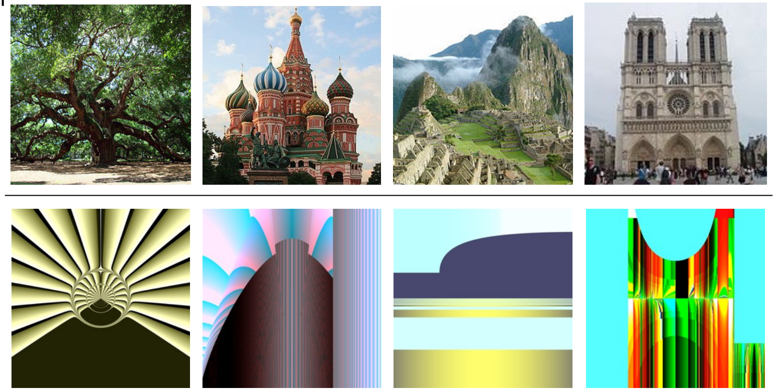
- vibrant, fauvist colors; or sometimes near black-and-white
- enhanced contrast, halo effect

Abstraction



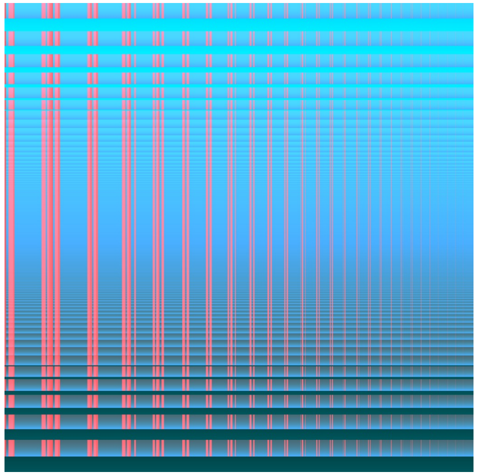
- abstract, rather than figurative rendition of the subject
- colors and shapes recombined in different patterns

Fractals



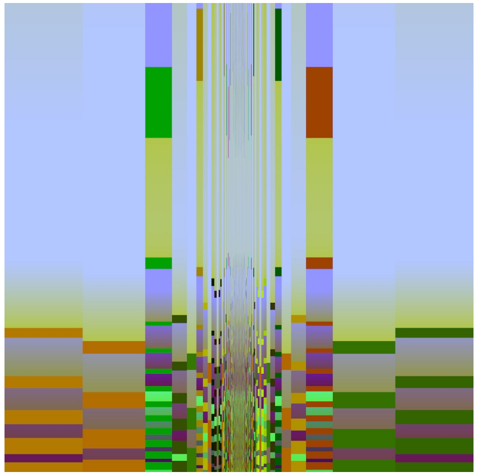
- low algorithmic complexity achieved through self-similarity
- fractal art, psychedelic art, stained glass or glass art

M.C. Escher?



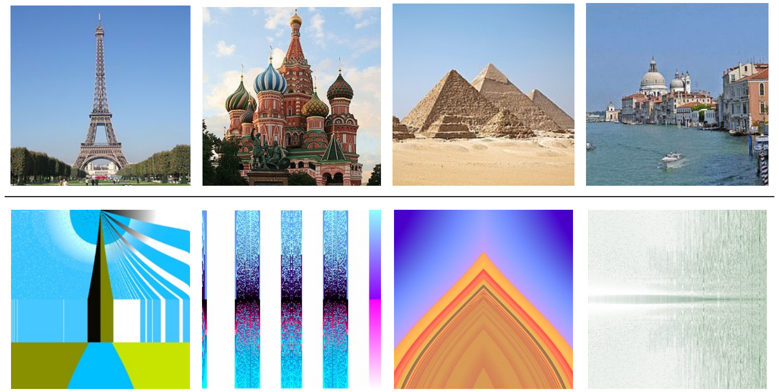
- where does the real beam end and the reflection begin?

Notre Dame



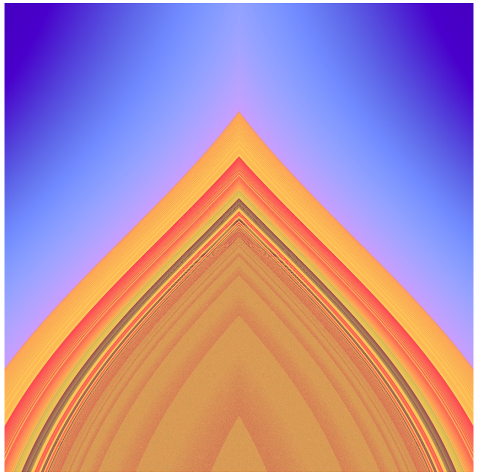
- this image has a distinctive rectangular fractal structure

Pointillism



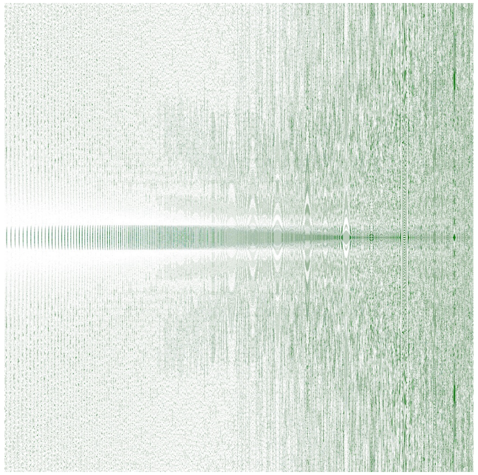
- sensitive function from x, y to R,G,B creates a pattern of dots

Great Pyramid



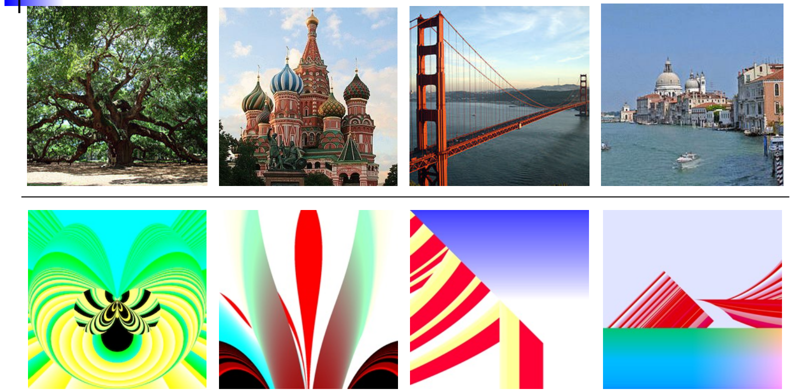
- can we see the individual grains of sand in the desert?

Grand Canal



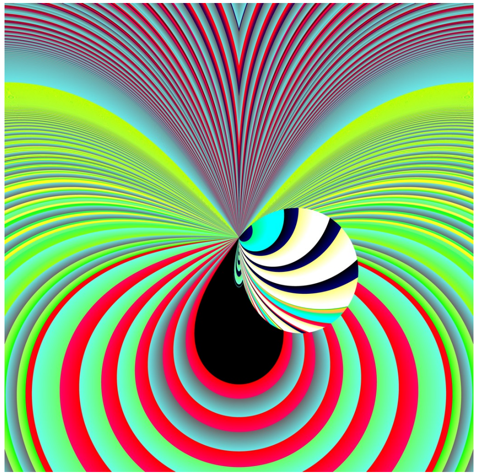
- is there some kind of structure, reflected in the water?

Metaphor

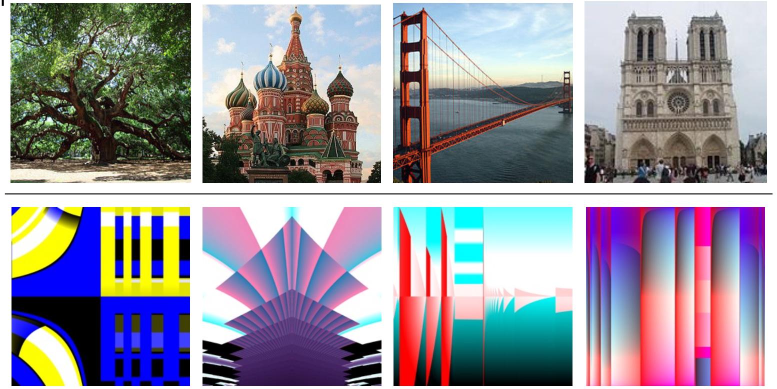


- images evolved to resemble one thing may end up looking like something else

Tree or Insect?

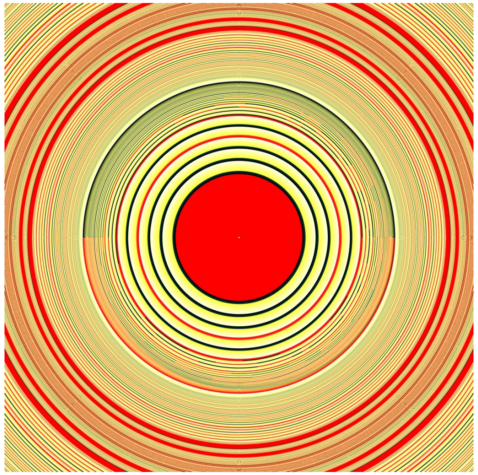


Repeated Substructures, with Variations



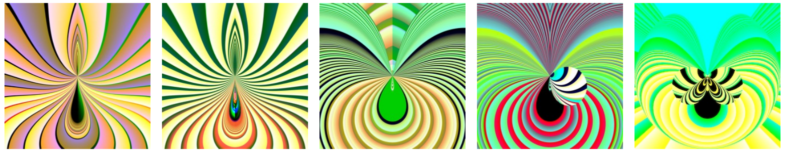
- imperfectly repeated substructures give the impression of having arisen from some natural process

Tree Rings



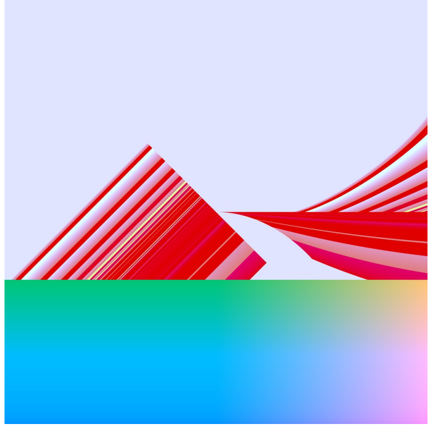
- the tree rings are so real, we can almost smell the sawdust!

Re-Combination, Variations on a Theme



- code for previous images in the gallery is made available for genetic re-combination, allowing the artist to revisit and further develop earlier themes

Genetype to Phenotype Mapping



HERCL code:

```
0[!qatcz]
1[capwwwo.]
2[%]
3[is.32#>sg:1j|c>xg:hp2j|+a{>cpa%.4338#p>g~<:0j|xww.88#wo]
```

Pseudocode

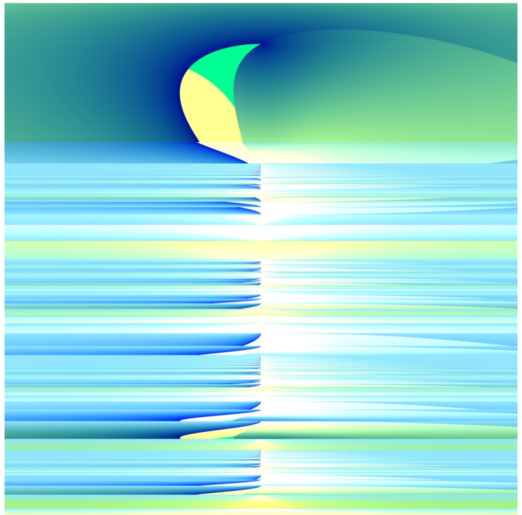
```
scan $(x, y)$                // $-1 \leq x \leq 1$,   (upper) $-1 \leq y \leq 1$ (lower)
if $y \geq 0.32$                                              // water
    return $(\sqrt{y^2 + (\sin^{-1} y)^2},\ \mathrm{atan2}(y, \sin^{-1} y),\ x)$
else
    if $y > x$                                                // obstacle
        $u = \sin^{-1}(x + y)$
    else                                                      // ship
        $r = \sqrt{y^2 + \tanh(x)^2}$,  $\theta = \mathrm{atan2}(y, \tanh(x))$
        $u = \sin^{-1}(\lfloor \theta / r \rfloor + (\theta \bmod r))$
    end
    $\phi = \frac{\pi}{4}(-1 + 2\,\mathrm{sgn}(u))$,   $\rho = \sin^{-1}(\sqrt{2}u)$
    $z = \mathrm{atan2}((\phi \bmod \rho), 0.4338)$,  $s = \sqrt{(\phi \bmod \rho)^2 + 0.4338^2}$
    if $s \leq z$                                             // sails
        return $(z, s, 0.88)$
    else                                                      // hull
        $v = \sin^{-1}(\sqrt{z}) \cos(\lfloor \phi / \rho \rfloor)$
        return $(v, \lfloor v \rceil, 0.88)$                  // (blue, green, red)
    end
end
```

Discussion

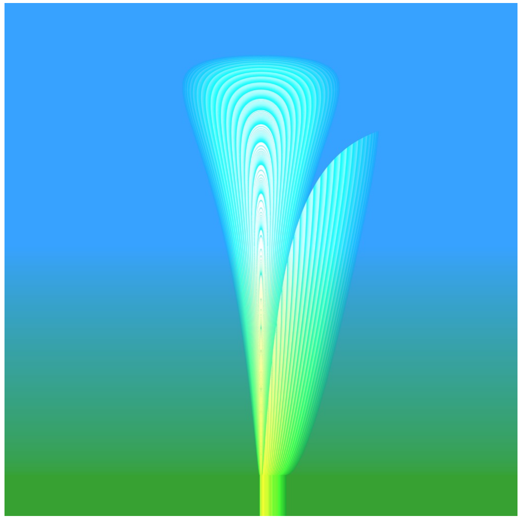
- interplay between evolution and deep learning
- enhanced contrast, variations in color
- minimalism, abstraction, fauvism, fractals, pointillism, metaphor
- ability to surprise
- recombination of previous elements
- low algorithmic complexity, but realistic enough to fool the critic

> "Imagination is a good servant, and a bad master.
> The simplest explanation is always the most likely."
>
> - Hercule Poirot

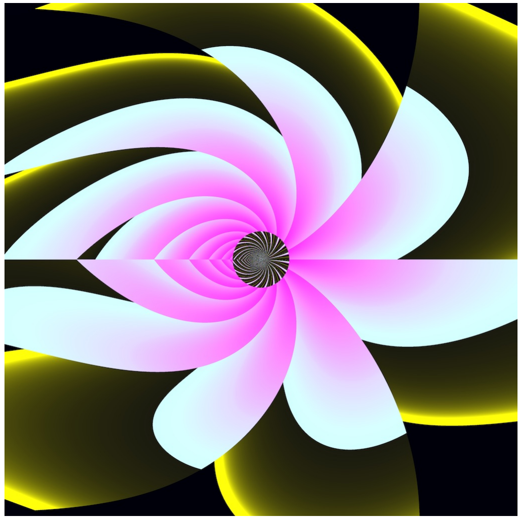
Burj al Arab



Cosmic Flower

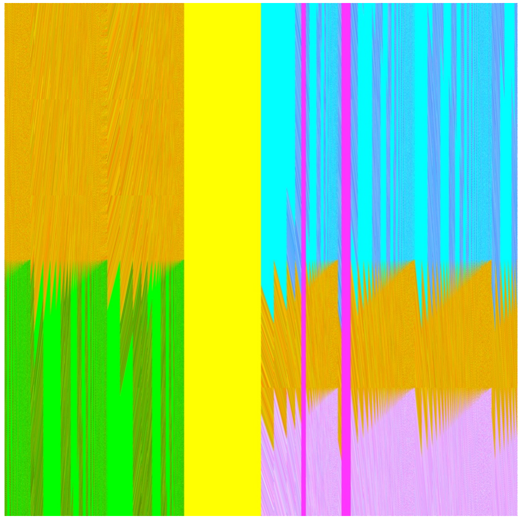


Water Lily Flowers

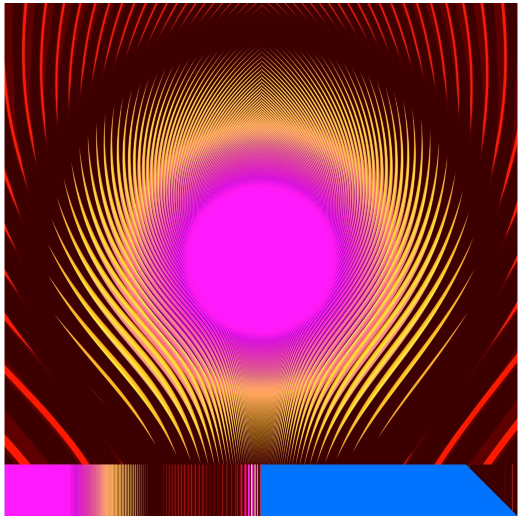


Water Lily Flowers

Abstraction / Details



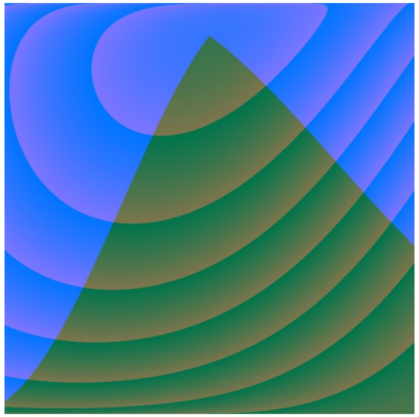
Self-Portrait of AI Artist



Conclusion

- adversarial training / coevolution is a powerful technique
- coevolutionary dynamics observed in biology, evolutionary computation, game learning, sorting networks, GANs and evolutionary art
- deep neural network is a good choice for discriminator, but it is fruitful to try different kinds of generator
- possible future applications to areas such as text generation, cybersecurity, deception, modular evolving systems, credit assignment

Questions



Questions ?