Teach Cellular Automata

as a gateway to understand *Life, the Universe, and Everything*

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ALIFE ARTIFICIAL LIFE INSTITUTE

Artificial Life Institute

Non-profit research institute based in Kyoto

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Cooking new realistic ALife system

https://alife.institute/

Characteristics of Cellular Automata

- Inherently visual experience
- Easy to program
- Hard to understand
- Gateway to various topics in mathematics, computer science, biology...

The Teaching Plan

1. Show stunning visuals
2. Explain the rules (e.g. Game of Life)
3. Hands on coding!
4. Break the rules
5. Explain concepts (e.g. emergence)
6. Introduce algorithms (e.g. evolutionary algorithm)

Topics

Substrates:

- Elementary CA, Game of Life, Lenia, Neural CA...

Studies:

- Maths, ALife concepts, compare to biology...

Algorithms:

- Machine learning, evolutionary algorithms...

The Substrates

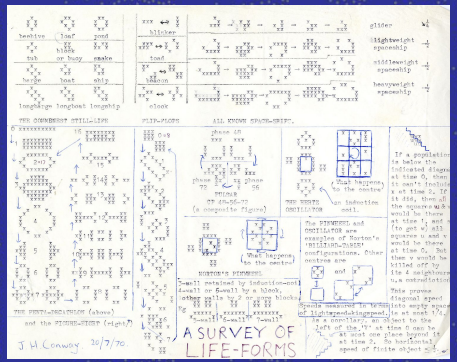
Conway's Game of Life

Most intuitive rules + most stunning results

- Example videos: e.g. Life in Life (OTCA metapixel)
- Start by hand calculation on a grid paper!
- Program in your favorite language (vibe code ok)
- History of CA → John Conway, John von Neumann…
- Types of patterns → oscillators, limit cycles, gliders, symmetries (translation, reflection, rotation invariant)

https://oimo.io/works/life/

Open Q: What crazy patterns can you find?



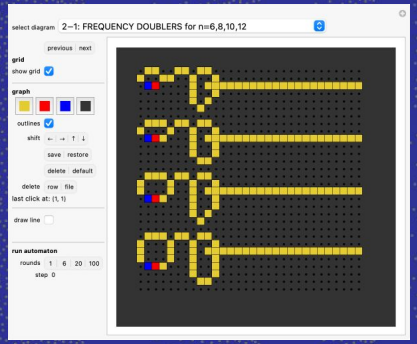
Other Cellular Automata

What if we change the rules?

- Different logic: Brian's Brain
- More states: Wireworld
- Higher dimensions: 3D / 4D
- Larger neighborhoods: Larger-than-Life

software: Golly

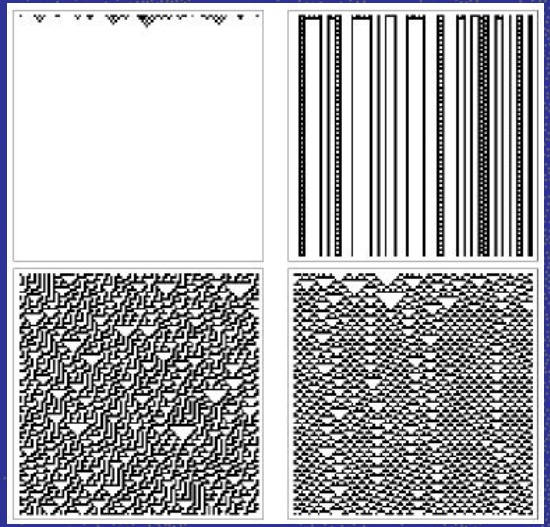
Open Q: What rules produce interesting patterns?

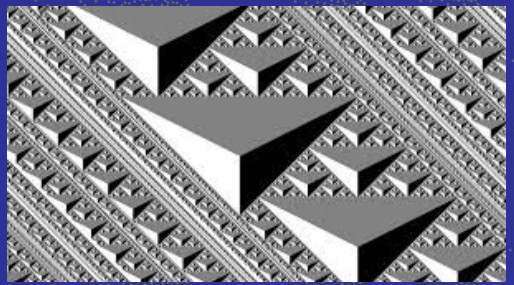


Elementary Cellular Automata

- Wolfram's study on ECA rules
- Book: A New Kind of Science
- Classification & statistical analysis
  - Class 1: uniform
  - Class 2: repetitive
  - Class 3: total chaos
  - Class 4: complex patterns
- Rule 110 → universal computation, Turing complete

Open Q: Best way to classify rules?



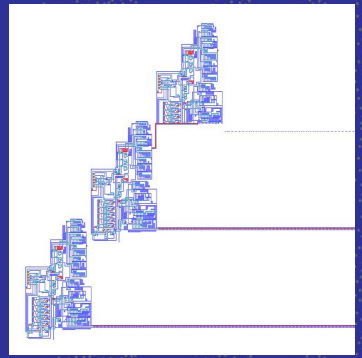


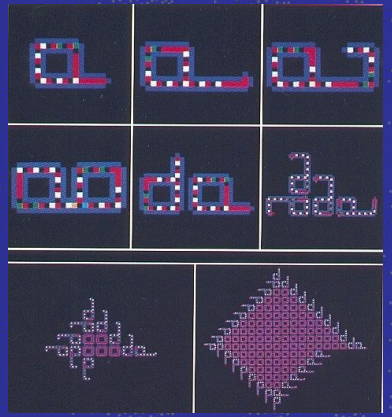
Self-Replicating Machines

What's the simplest CA with a self-replicating pattern?

- Not just splitting, but a machine that read a data tape
- Like ribosome – ALife try to mimic real life
- Self-replication, Turing machines
- Versions:
  - von Neumann's universal constructor
  - Codd's Cellular Automata
  - Langton's Loop
  - Sayama's Evoloop

Open Q: How can we design evolvable self-replicators?





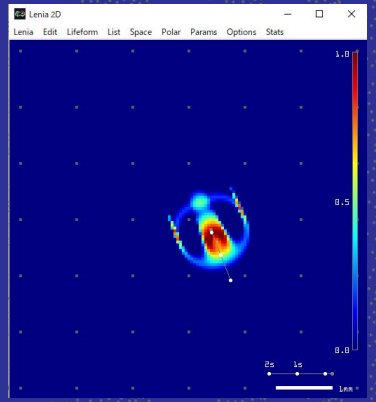
Lenia

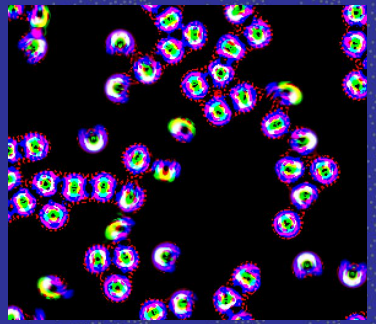
What if we change everything to continuous?

- Totally different dynamics
  - patterns move in any direction
  - can repair themselves (to some extent)
- Simple evolutionary algo → mutate and select
- Variants: multiply components,
  mass conservation, particle system

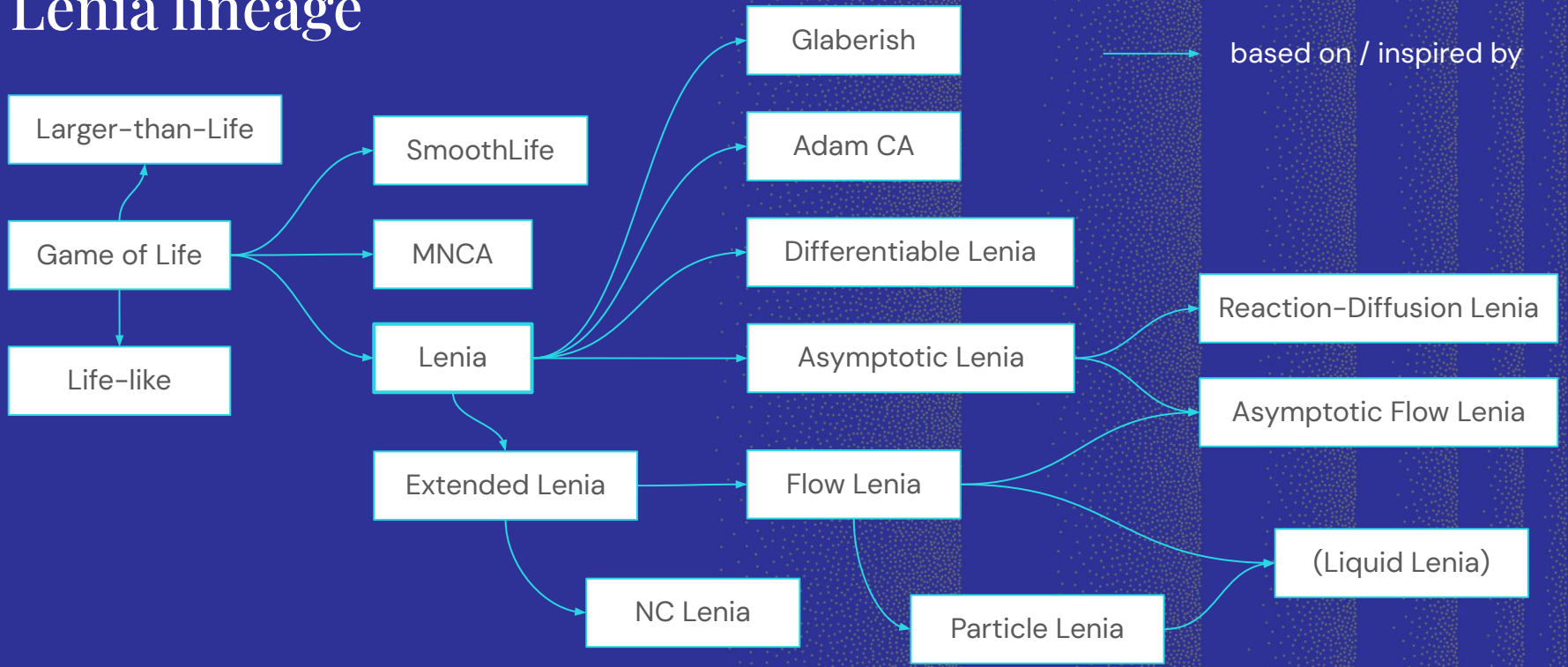
http://lenia.org/

Open Q: How to detect a pattern from noisy background?





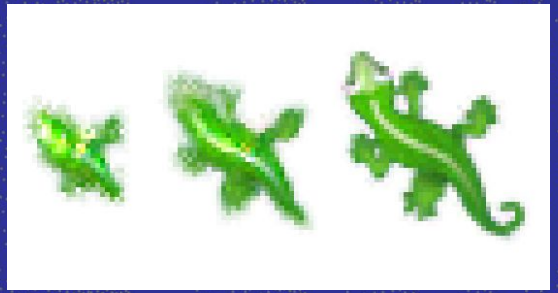
Lenia lineage



Neural Cellular Automata

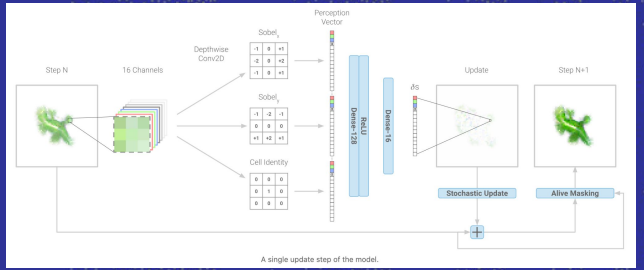
What if we train CA like a neural network?

- Parameters trained with gradient descent
- Patterns grow and self-heal!
- Relate to neural networks → CNN, L2 loss, SGD...



https://distill.pub/2020/growing-ca/

Open Q: How can we use NCA?
e.g. solve ARC-AGI?



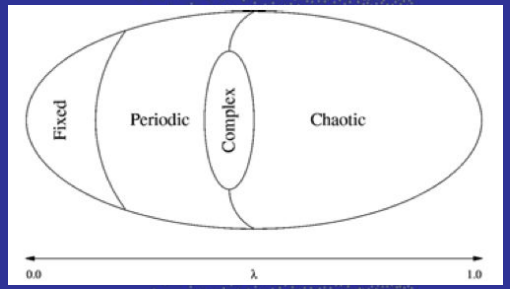
The Studies

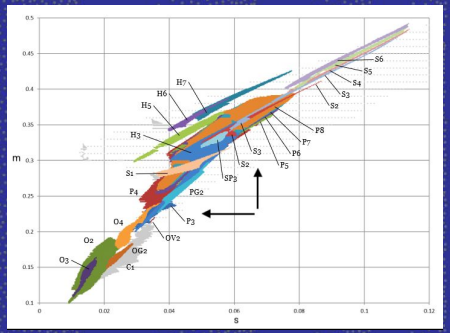
Complexity & Edge-of-Chaos

Why some CA patterns look boring but some complex & interesting?

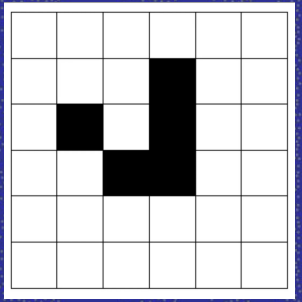
- Simple rules produce complex patterns
- Complexity thrive between boring order and total chaos
- But what exactly is “complexing” & “interesting”? Can we measure them?

Open Q: A good metric to measure complexity (of a CA)?



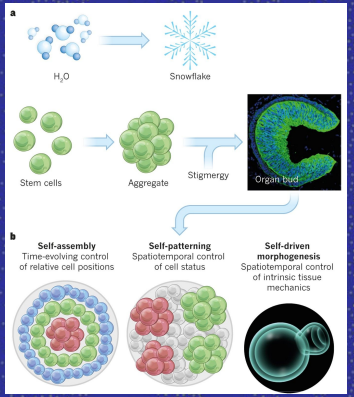


Emergence & Self-Organization



How CA patterns come into existence?

- “The whole is ~~more than~~ different from the sum of parts”
- The process: self-organization = interaction of parts
- The result: emergence = properties that cannot be reduced to parts
- More ex: sports team, traffic, free market, ecosystem
- Multi-level: molecule → cell → organism → society



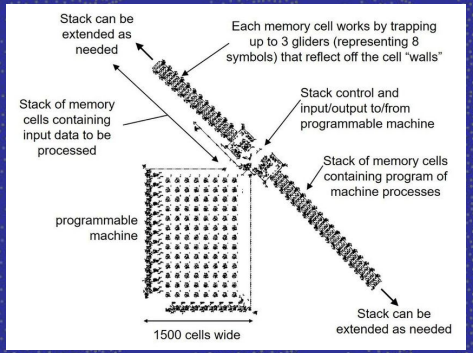
Open Q: How does emergence work? How to design an emergent system?

Universal Computation

Can CA do computation?

- Some CAs are Turing complete, i.e. can (theoretically) perform any computation of a universal Turing machine
- Example: Run Windows inside Game of Life!
- ECA Rule 110, Game of Life, von Neumann CA...
- Others: Minecraft, MS Excel, Magic: the Gathering..

Open Q: Is Lenia (or other CAs) Turing complete?

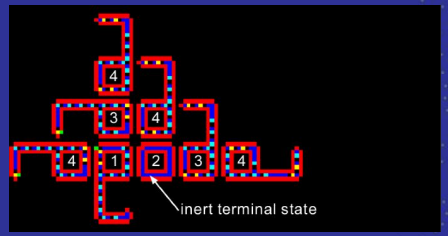


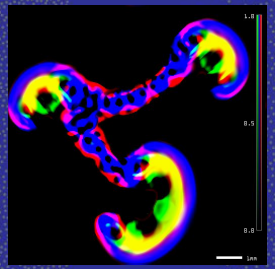
Autopoiesis & Self-Replication

How CA resembles real life?

- A pattern that constantly produces its own parts (vs a factory)
- Maintains own boundary & individuality
- Levels: self-maintain (fragile), self-repair (robust), self-replicate (repair from fragment), self-assemble (emerge from parts)
- Types of self-replication: simple fission, bag-like, machine with tape

Open Q: More machine-with-tape like ribosome or von Neumann machine?

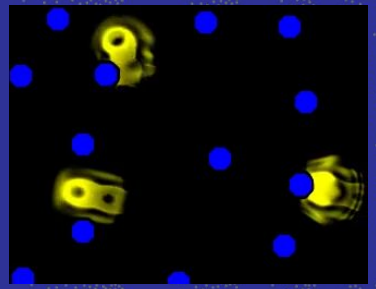




Advanced Topics

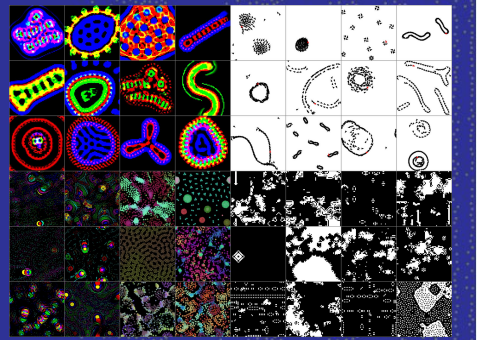
Sensori-motor agency:

- Usually CA patterns just move blindly
- Can we train or evolve a CA pattern to sense the world and act accordingly?



Open-endedness:

- Usually interestingness of CA will plateau
- Can we keep evolving a CA world with infinite novelty?



The Algorithms

Parallel Computing

How to run CA efficiently?

- CAs are simulations / games, repeated simple rules
- Best to parallelize using GPU
- Program frameworks e.g. JAX

Open Q: How to parallelize CA using multiple GPUs?

Machine Learning

How can we train CA patterns?

- CA can be parameterized (rule + pattern)
- Define loss (e.g. target pattern / behavior)
- Use gradient descent to optimize parameters
- ALife x AI

Evolutionary & Genetic Algorithms

How can we evolve CA patterns?

- CA not always have gradient (not differentiable)
- Define fitness (e.g. moving speed)
- Use evolutionary algorithm:
  - mutute, select, crossover, reproduce
- Use genetic algorithm:
  - compress rule + pattern into genome
- “Intrinsic evolution” = evolve without fitness

Novelty Search & Quality Diversity

How to get more diverse patterns?

- Not just optimizing, need diversity
- Define diversity descriptor (e.g. size)
- Quality diversity: both optimize and diversify

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Thank you!