Lecture 3

From Life to CAs in General

- What gives Life this very rich behavior?
- Is there some simple, general way of characterizing CAs with rich behavior?
- It belongs to Wolfram's Class IV

The four classes of feedback behaviour

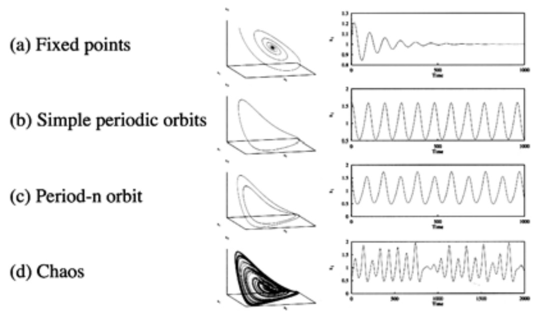

fig. from Flake via EVALife

Wolfram's Classification

- Class I: evolve to fixed, homogeneous state
  - ~ limit point
- Class II: evolve to simple separated periodic structures
  - ~ limit cycle
- Class III: yield chaotic aperiodic patterns
  - ~ strange attractor (chaotic behavior)
- Class IV: complex patterns of localized structure
  - ~ long transients, no analog in dynamical systems

Langton's Investigation

Under what conditions can we expect a complex dynamics of information to emerge spontaneously and come to dominate the behavior of a CA?

Approach

- Investigate 1D CAs with:
  - random transition rules
  - starting in random initial states
- Systematically vary a simple parameter characterizing the rule
- Evaluate qualitative behavior (Wolfram class)

Why a Random Initial State?

- How can we characterize typical behavior of CA?
- Special initial conditions may lead to special (atypical) behavior
- Random initial condition effectively runs CA in parallel on a sample of initial states
- Addresses emergence of order from randomness

Assumptions

- Periodic boundary conditions
  - no special place
- Strong quiescence:
  - if all the states in the neighborhood are the same, then the new state will be the same
  - persistence of uniformity
- Spatial isotropy:
  - all rotations of neighborhood state result in same new state
  - no special direction
- Totalistic [not used by Langton]:
  - depend only on sum of states in neighborhood
  - implies spatial isotropy

Langton's Lambda

- Designate one state to be quiescent state
- Let K = number of states
- Let $N = 2r + 1$ = size of neighborhood
- Let $T = K^N$ = number of entries in table
- Let n_q = number mapping to quiescent state
- Then

$$\lambda = \frac{T - n_q}{T}$$

Range of Lambda Parameter

- If *all* configurations map to quiescent state: $\lambda = 0$
- If *no* configurations map to quiescent state: $\lambda = 1$
  - If every state is represented *equally*: $\lambda = 1 - 1/K$
    - A sort of measure of "excitability"

Example

- States: $K = 5$
- Radius: $r = 1$
- Initial state: random
- Transition function: random (given λ)

Demonstration of 1D Totalistic CA

Run NetLogo 1D CA General Totalistic

or

<www.cs.utk.edu/~mclennan/Classes/420/NetLogo/CA-1D-General-Totalistic.html>

Go to CBN
Online Experimentation Center

<mitpress.mit.edu/books/FLAOH/cbnhtml/java.html>

Class I (λ = 0.2)

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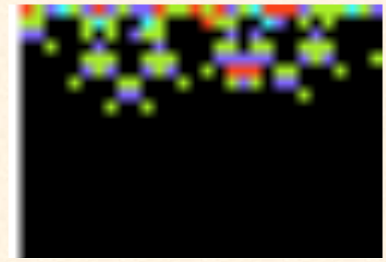
Class I (λ = 0.2) Closeup



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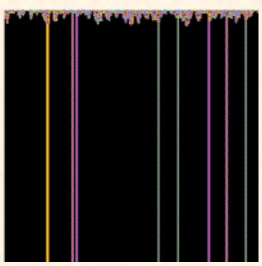
Class II (λ = 0.4)



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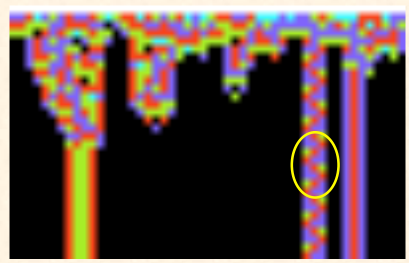
Class II (λ = 0.4) Closeup



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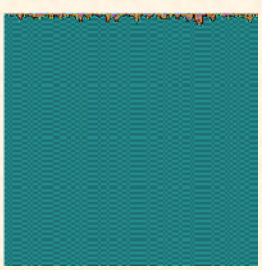
Class II (λ = 0.31)



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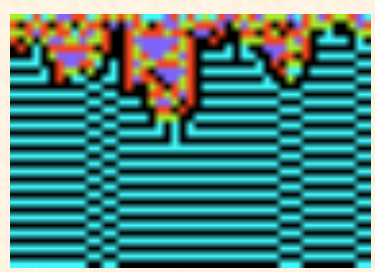
Class II (λ = 0.31) Closeup



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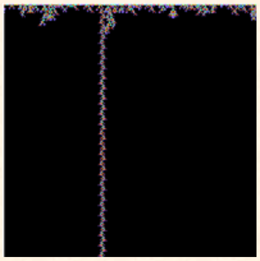
Class II ($\lambda = 0.37$)



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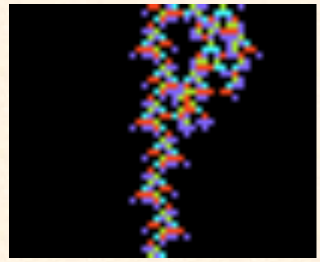
Class II ($\lambda = 0.37$) Closeup



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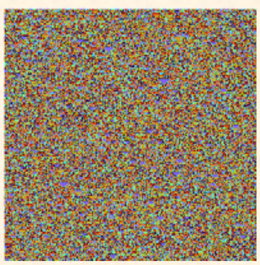
Class III ($\lambda = 0.5$)



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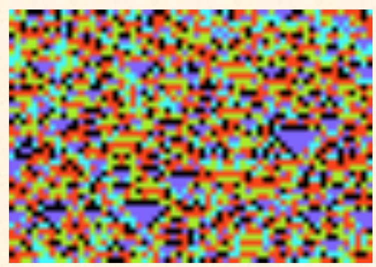
Class III ($\lambda = 0.5$) Closeup



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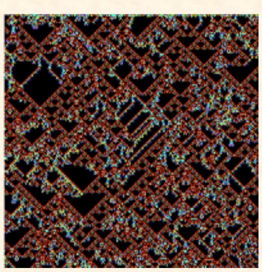
Class IV ($\lambda = 0.35$)



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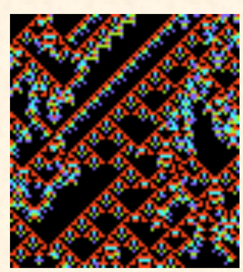
Class IV ($\lambda = 0.35$) Closeup



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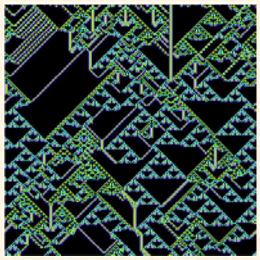
Class IV (λ = 0.34)



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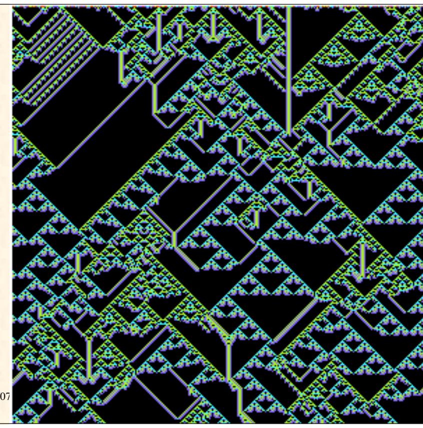

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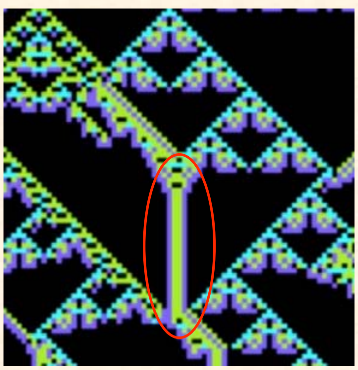

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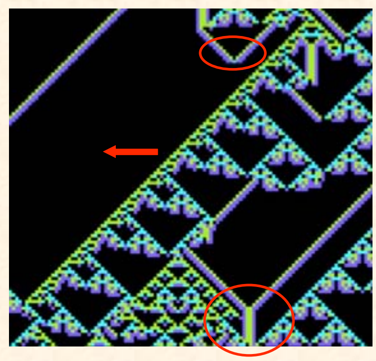

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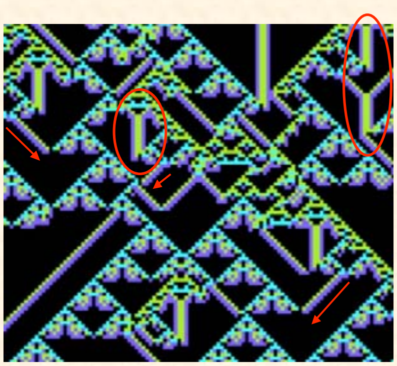

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Class IV Shows Some of the Characteristics of Computation

- Persistent, but not perpetual storage
- Terminating cyclic activity
- Global transfer of control/information

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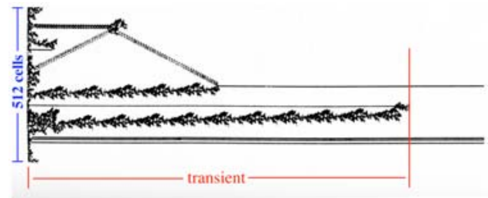
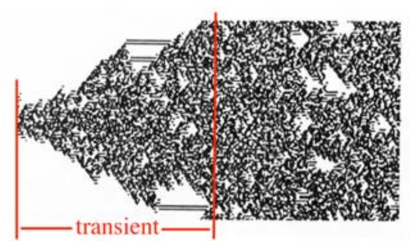
λ of Life

- For Life, $\lambda \approx 0.273$
- which is near the critical region for CAs with:
  $K = 2$
  $N = 9$

Transient Length (I, II)



Transient Length (III)



Shannon Information
(very briefly!)

- Information varies directly with surprise
- Information varies inversely with probability
- Information is additive
- ∴The information content of a message is proportional to the negative log of its probability

$$I\{s\} = -\lg \Pr\{s\}$$

Entropy

- Suppose have source S of symbols from ensemble $\{s_1, s_2, \ldots, s_N\}$
- Average information per symbol:

$$\sum_{k=1}^{N} \Pr\{s_k\} I\{s_k\} = \sum_{k=1}^{N} \Pr\{s_k\}\left(-\lg \Pr\{s_k\}\right)$$

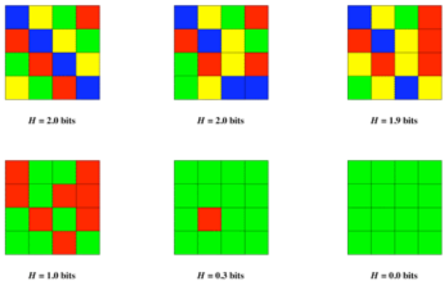
- This is the *entropy* of the source:

$$H\{S\} = -\sum_{k=1}^{N} \Pr\{s_k\} \lg \Pr\{s_k\}$$

Maximum and Minimum Entropy

- Maximum entropy is achieved when all signals are equally likely
  No ability to guess; maximum surprise
  $H_{max} = \lg N$
- Minimum entropy occurs when one symbol is certain and the others are impossible
  No uncertainty; no surprise
  $H_{min} = 0$

Entropy Examples



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Entropy of Transition Rules

- Among other things, a way to measure the uniformity of a distribution

$$H = -\sum_i p_i \lg p_i$$

- Distinction of quiescent state is arbitrary
- Let n_k = number mapping into state k
- Then $p_k = n_k / T$

$$H = \lg T - \frac{1}{T}\sum_{k=1}^{K} n_k \lg n_k$$

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Entropy Range

- Maximum entropy ($\lambda = 1 - 1/K$):
  uniform as possible
  all $n_k = T/K$
  $H_{\max} = \lg K$
- Minimum entropy ($\lambda = 0$ or $\lambda = 1$):
  non-uniform as possible
  one $n_s = T$
  all other $n_r = 0$ ($r \neq s$)
  $H_{\min} = 0$

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Further Investigations by Langton

- 2-D CAs
- $K = 8$
- $N = 5$
- 64×64 lattice
- periodic boundary conditions

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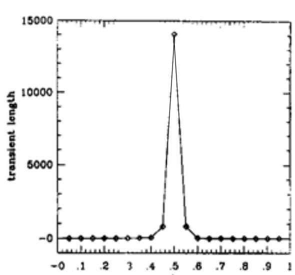
Avg. Transient Length vs. λ (K=4, N=5)



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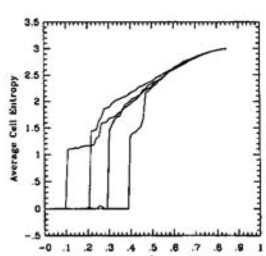
Avg. Cell Entropy vs. λ (K=8, N=5)



$$H(A) = \sum_{k=1}^{K} p_k \lg p_k$$

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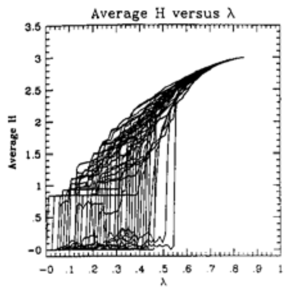
Avg. Cell Entropy vs. λ (K=8, N=5)



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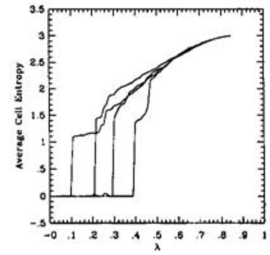
Avg. Cell Entropy vs. λ (K=8, N=5)



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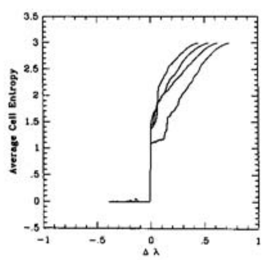
Avg. Cell Entropy vs. Δλ (K=8, N=5)



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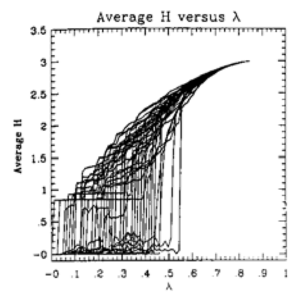
Avg. Cell Entropy vs. λ (K=8, N=5)



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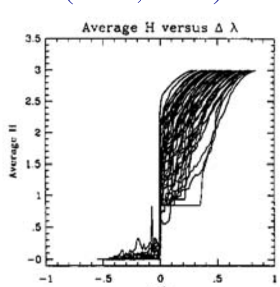
Avg. Cell Entropy vs. Δλ (K=8, N=5)



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Entropy of Independent Systems

- Suppose sources A and B are independent
- Let $p_j = \Pr\{a_j\}$ and $q_k = \Pr\{b_k\}$
- Then $\Pr\{a_j, b_k\} = \Pr\{a_j\} \Pr\{b_k\} = p_j q_k$

$$H(A,B) = \sum_{j,k} \Pr(a_j, b_k) \lg \Pr(a_j, b_k)$$
$$= \sum_{j,k} p_j q_k \lg(p_j q_k) = \sum_{j,k} p_j q_k (\lg p_j + \lg q_k)$$
$$= \sum_j p_j \lg p_j + \sum_k q_k \lg q_k = H(A) + H(B)$$

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Mutual Information

- *Mutual information* measures the degree to which two sources are not independent
- A measure of their correlation

$$I(A,B) = H(A) + H(B) - H(A,B)$$

- $I(A,B) = 0$ for completely independent sources
- $I(A,B) = H(A) = H(B)$ for completely correlated sources

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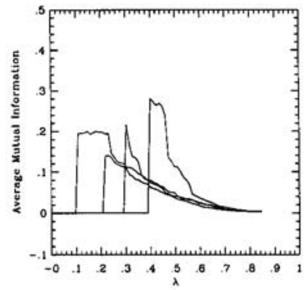
Avg. Mutual Info vs. λ (*K*=4, *N*=5)



$I(A,B) =$
$H(A) + H(B)$
$- H(A,B)$

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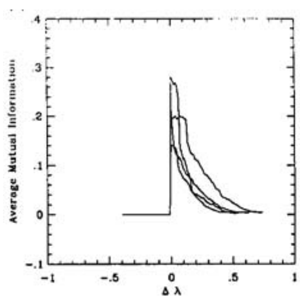
Avg. Mutual Info vs. Δλ (*K*=4, *N*=5)



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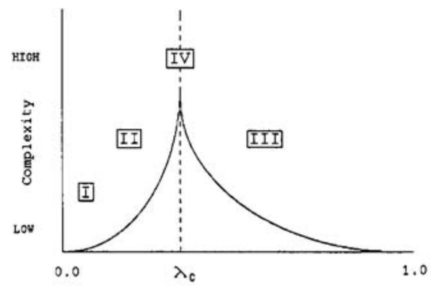
Complexity vs. λ



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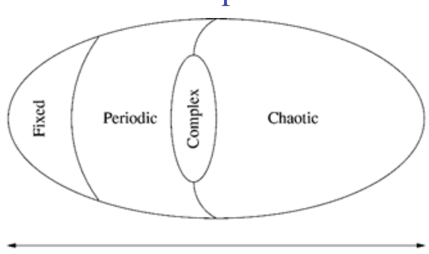
Schematic of CA Rule Space vs. λ



8/29/07 Fig. from Langton, "Life at Edge of Chaos" 53

Additional Bibliography

1. Langton, Christopher G. "Computation at the Edge of Chaos: Phase Transitions and Emergent Computation," in *Emergent Computation*, ed. Stephanie Forrest. North-Holland, 1990.
2. Langton, Christopher G. "Life at the Edge of Chaos," in *Artificial Life II*, ed. Langton et al. Addison-Wesley, 1992.
3. Emmeche, Claus. *The Garden in the Machine: The Emerging Science of Artificial Life*. Princeton, 1994.

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