18. Artificial life

18.1 What is Alife?

- "Life as we know it."
  - Biology = study of carbon-based life
  - Indicators:
    - Self-production
    - Response to stimuli
    - Growth or expansion
    - Ability to die
    - Ability to evolve
- "Life as it could be."
  - Alife = study of dynamics of living systems independent of the substrate.
  - Possible substrates: abstract chemistries, neural networks, cellular automata, ...

18.2 Central concepts

- Emergence
  - Complex global behavior appears from simple local behaviors and interactions.
  - Patterns are unforeseen, not explicitly determined.
  - The global patterns cannot be understood by observing the behavior of individual elements and local interactions.
  - Holistic — whole is more than the sum of its parts.
- Evolution
  - Successful creatures survive and reproduce → pass the genetic material to their offspring.
  - Evolution does not have goal.
  - Population is not "go ing anywhere". i.e., it does not necessarily get better.
  - Evolved virtual creatures by Karl Sims (1994)

- Self-organization
  - A process through which a system increases its complexity without outside guidance or management.
  - Self-organizing systems exhibit emergent behavior.
  - Capacity to generate stable patterns.
  - Positive feedback (amplification, facilitation)
  - Negative feedback (counter-balancing force, stabilizer)
  - Central in biology from single organisms to whole ecosystems.
  - Applied in social sciences.

18.3 Properties of Alife systems

- Bottom-up emergent behavior
- Self-organizing
- Non-linear dynamics
- Self-regulating — no central or global control
- Adaptive — learning or evolving
- Complex — chaotic (or close)
- Analytical methods (mathematical approaches) seldom apply but synthesis (simulations) required to understand the dynamics.

18.4 Why study Alife?

- To gain understanding of emergent phenomena
  - Chaos, complexity, self-organization
- Biological research: conduct controllable and reproducible simulations
- New technologies
  - Genetic engineering
  - Animation
- To design educational toolkits
  - Social systems (SimCity)
  - Ecosystems
  - Economies

18.5 Alife application domains

- Microeconomics
  - Population of byers and sellers
- Evolutionary biology and ecology
  - Emergence of ecosystems
- Social systems
  - Emergence and evolution of societies
  - Traffic flow/jam patterns
  - Segregation in cities
  - Urban sprawl
- Optimization
  - Metaheuristics inspired by simple natural systems
  - Swarm intelligence, e.g., ant colony optimization

18.6 Early example

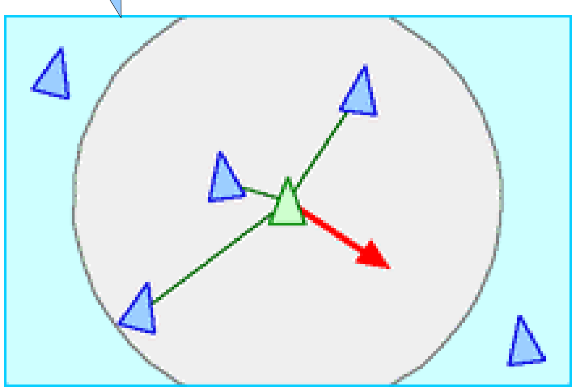
- An excellent example of how complex behavior is generated from simple rules is Craig Raynold's Boids (1987).
- Model of coordinated animal motion, e.g., flocking of bird and fish schools.
- Individual-based model.
- Based on *steering behaviors*:
  - Ability to navigate in a life-like and improvisational manner.
  - Define how an individual moves based on positions and velocities of neighboring individuals.
  - Independent of means of locomotion.
  - Combination of steering behaviors can be used to achieve high level goals.

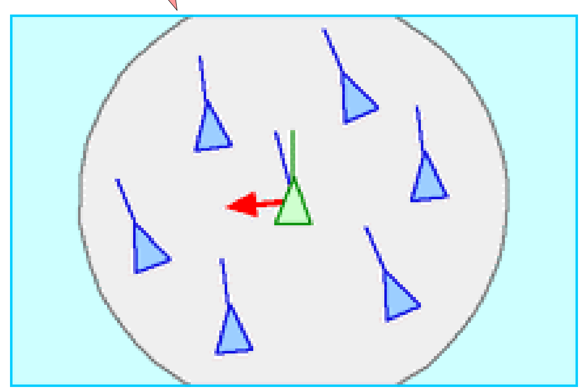
18.7 Examples of steering behaviors

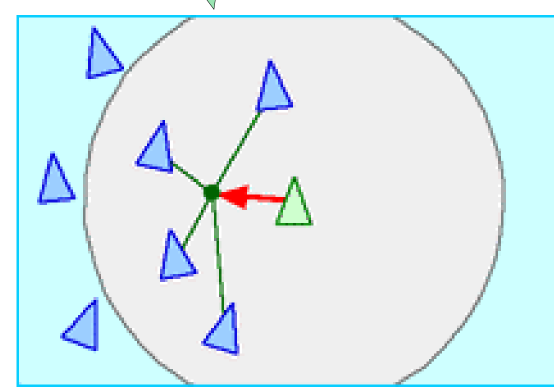
Separation:
Steer to avoid crowding the local flockmates.

Alignment:
Steer towards the average heading of local flockmates.

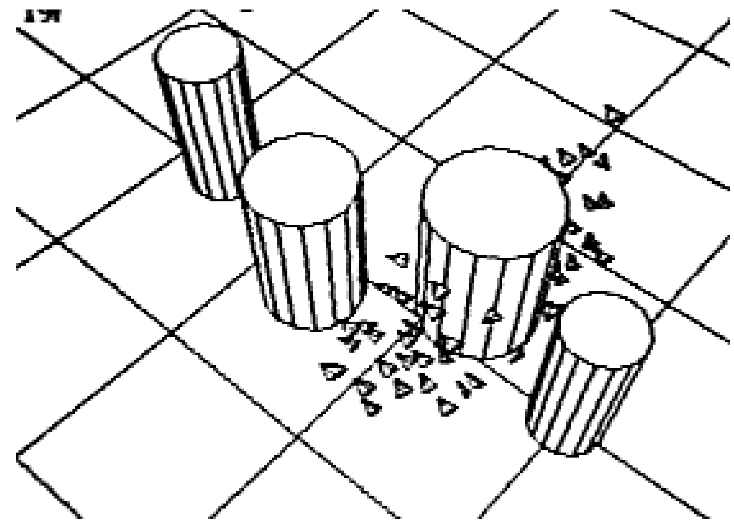
Cohesion:
Steer to move towards the average position of local flockmates.







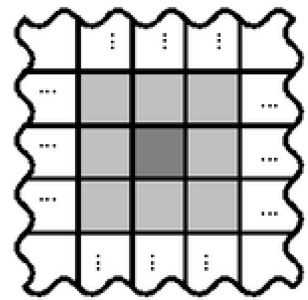
- Each boid has access to the whole flock, but only reacts to flockmates within some small neighborhood around it, characterized by distance and angle (e.g., visual field).
- Simple behaviors for individuals and pairs:
  - Seek and flee
  - Pursue and evade
  - Wander
  - Obstacle avoidance
  - Path/wall following
  - Flow field following
- Combined behaviors and groups
  - Leader following
  - Queuing
  - Collision avoidance, etc.



- Behavioral animations
  - Stanley and Stella in Breaking the ice (1987)
  - Bat swarms and penguin flocks in Batman Returns (1992).

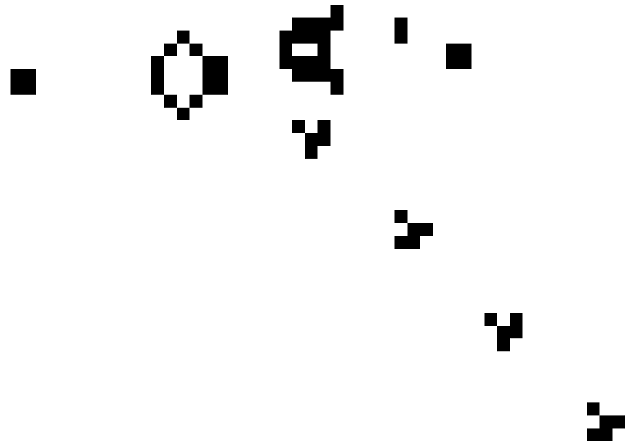
18.8 Game of Life

- Created by John Conway 1970.
- Two-state, two-dimensional cellular automaton.
- The state of a cell — dead or live —at time t depends on its nearest neighbors' states at time t-1.



- Moore neighborhood
- Three simple rules:
  - If a cell, dead or alive, has exactly three of its neighbors live, it will be live at next time step.
  - If a live cell has exactly two of its neighbors live, it will stay live at the next time step.
  - In all other cases, the cell will die at the next time step for overcrowding or loneliness.

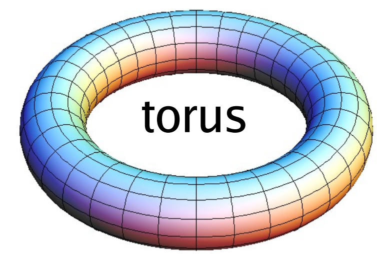
Gosper's glider gun



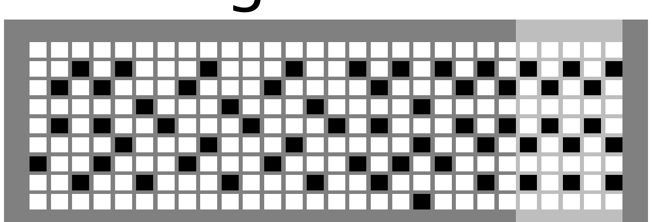
- Outcome patterns:
  - Stable state
  - All cells die
  - Oscillation between few states
  - Gliders
- How to interpret these patterns?
  - For instance, what is the meaning of two gliders merging?

18.9 Cellular automaton (CA)

- von Neumann and Ulam in 1940's
- Infinite, regular grid of cells, often represented as a torus, i.e., the rectangular grid “wra ps over” from top to bottom (and vice versa) and right to left (and vice versa).

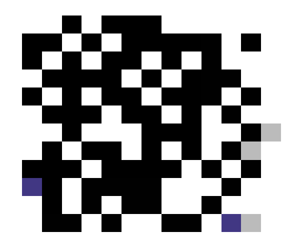


- Cells can be in any finite number of states.
- Every cell has the same update rule.
- CA is reversible if for every current configuration there is exactly one past configuration.
- Garden of Eden patterns — patterns that cannot be reached from any initial configuration, so they can only appear as initial configurations.



The first found by Banks, 1971.

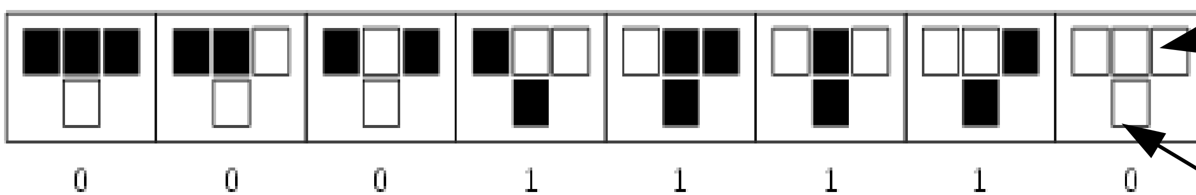
Currently the smallest found by Beluchenko, 2006



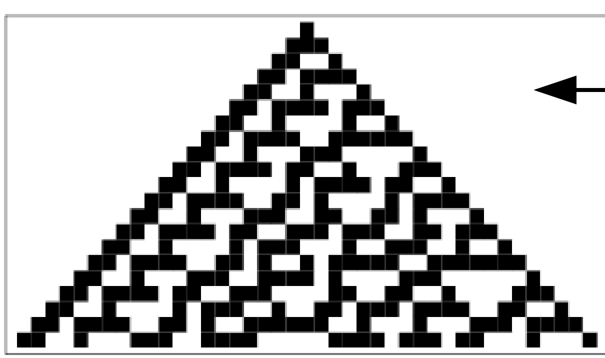
18.10 Elementary CA

- Stephen Wolfram's “New Kind of Science”(2002)
- Traditionally computation has been
  - Engineering to build practical systems using computation
  - Mathematics to prove theorems about computation
- NKS: Systematic empirical study of computational systems for their own sake.

rule:



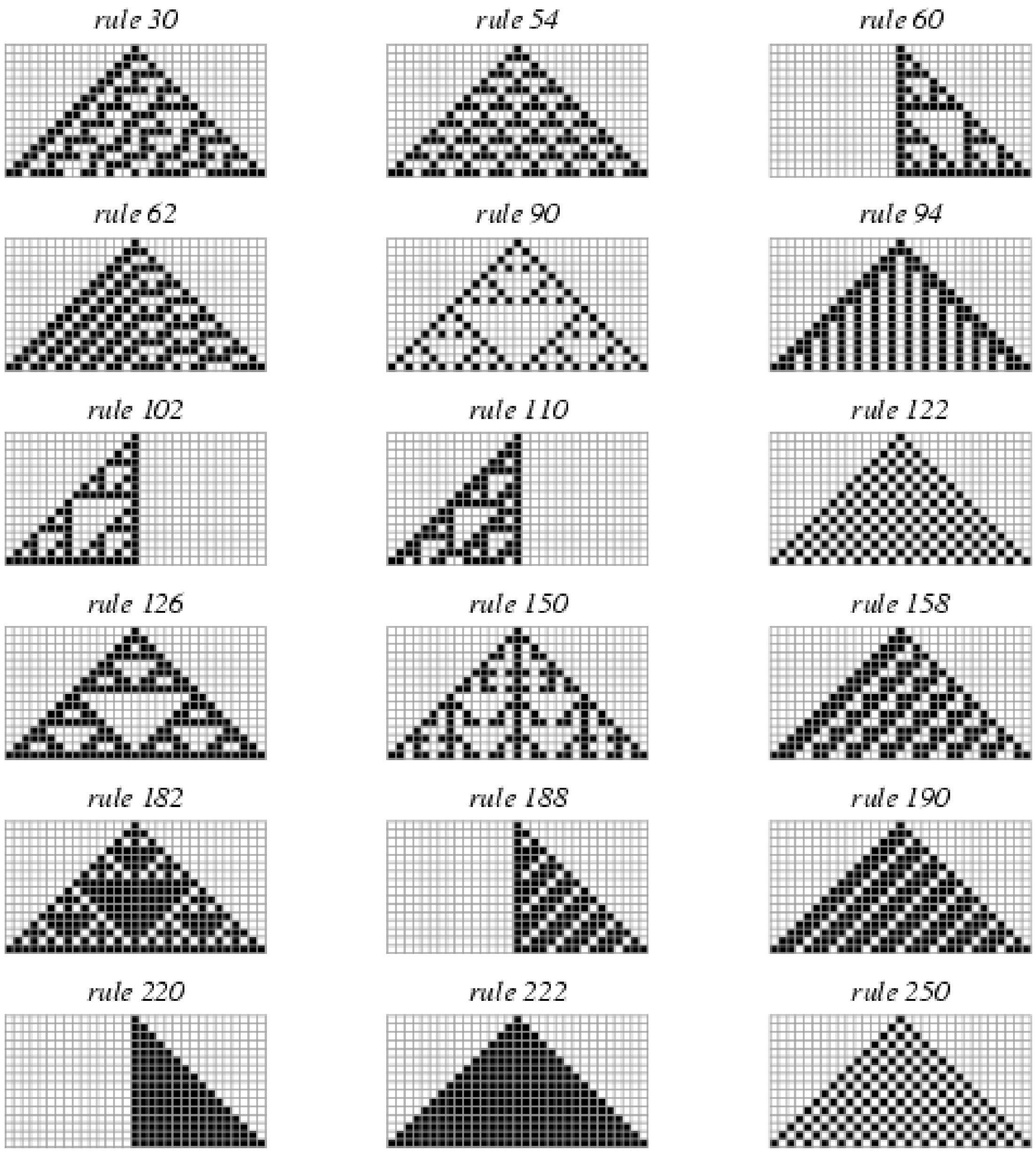
$2^3 = 8$ possible neighborhood patterns



Rule 30

$2^8 = 256$ possible rules, i.e., finite automata that can be indexed with a 8-bit number.

Examples of rules:



Some living things operate like CA, example *conus textile*.

- Wolfram's thesis is that CAs can be used to reveal unknown aspects of natural phenomena.
- For instance, rule 110 has been applied to
  - Computation of natural logarithm
  - Solutions of differential equations
- NKS has been heavily criticized for
  - Failing to provide evidence
  - Not following scientific methodology
  - Lack of predictive power of established theories
  - Not being rigorous enough (a lot is based on visual inspection of CAs)
  - Not being original or important.
  - Failing to recognize the contribution of others.

18.11 Self-replicating systems

- John von Neumann (1949)
  - What is the level of organizational complexity required for self-replication?
  - Tried to **build** a universal self-reproducing automaton.
  - Designed a 2-dimensional cellular arrangement that consisted of a large number (> 40000) of 29-state automata (never built).
  - Had the functionality of a Universal Turing Machine.
  - The state of the automaton was a function of its own state and four of its neighbors.
- Later approaches with reduced number of states (29 $\rightarrow$ 8), but requiring a huge number of cells (100 million) to achieve computational universality (Codd, 1968).

- Langton's loops (1970's)
  - Defined a minimal cellular automaton capable of self-replication with no computational universality.
  - Loop has 49 cells, eight states and 29 rules.
  - Cells in state 2 form a sheath, the inner cells have information for reproduction.
  - Self-replication carried out by the tail; cells grow to produce a new loop, which breaks off when fully formed.

	2	2	2	2	2	2	2	2					
2	1	7	0	1	4	0	1	4	2				
2	0	2	2	2	2	2	2	0	2				
2	7	2					2	1	2				
2	1	2					2	1	2				
2	0	2					2	1	2				
2	7	2					2	1	2				
2	1	2	2	2	2	2	2	1	2	2	2	2	2
2	0	7	1	0	7	1	0	7	1	1	1	1	1
	2	2	2	2	2	2	2	2	2	2	2	2	2

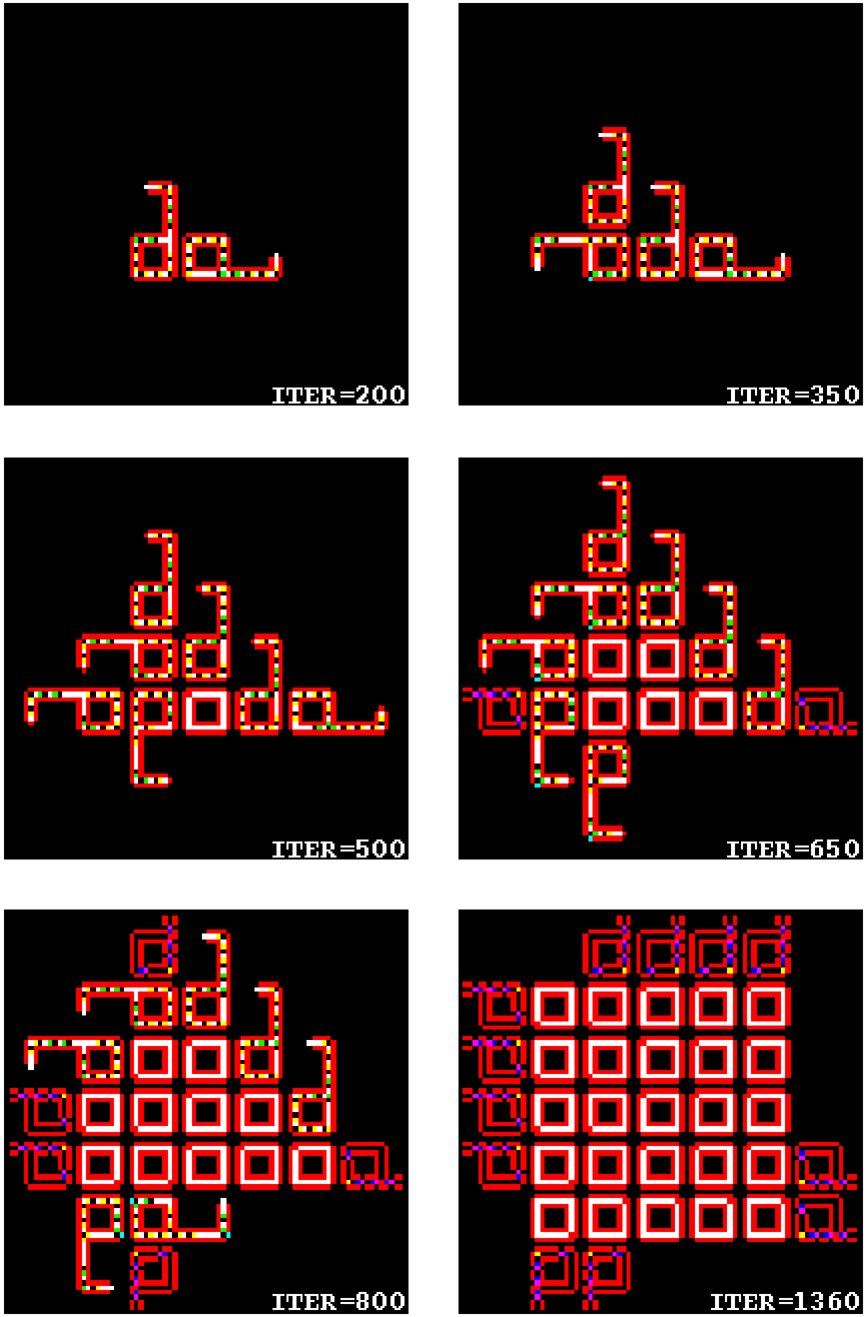


Figure 3-10: Propagation pattern of Langton's loop.

18.12 Swarm intelligence

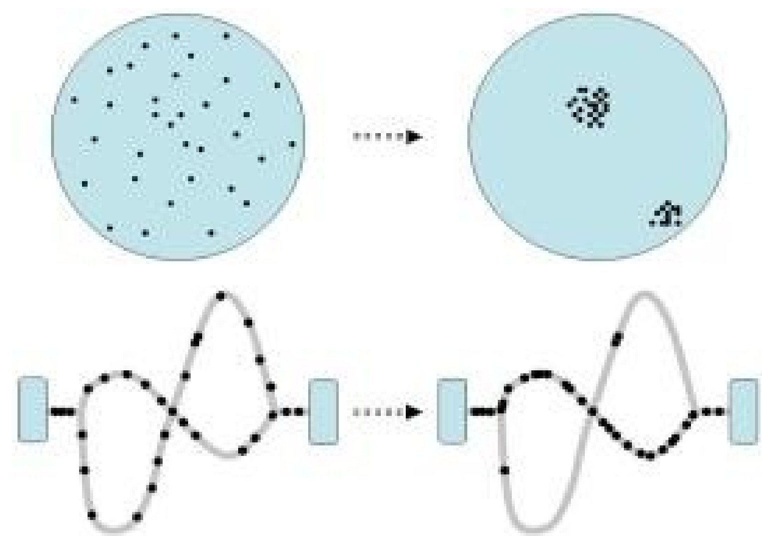
- "The property of a system whereby collective behaviors of unsophisticated agents interacting locally with their environment cause coherent global patterns to emerge."
- Utilizes observable patterns in biological systems.
- Inspiration from nature to solve hard problems (e.g., TSP)
  - Well-defined but computationally hard
  - Fuzzy problems
  - Non-predictable and dynamic problems

- Analogies to computational systems
  - Distributed system of autonomous agents
  - Self-organized control and decentralized cooperation.
  - Division of labor and distributed task allocation.
  - Indirect interactions.

- Characteristics:
  - Coordination without evident communication: indirect communication via interaction with the environment.
  - Perception of environment and ability to change the environment, but no explicit model of the environment.
  - Autonomous with no central control.

18.13 Ant colony optimization

- Inspired by social insect colonies
  - Individual ants are behaviorally unsophisticated, but collectively perform complex tasks.
  - Division of labor
  - Cooperative transportation
- Group foraging and nest building



- Flexible — can respond to internal or external challenges.
- Robust — task can be completed even if an individual fails.

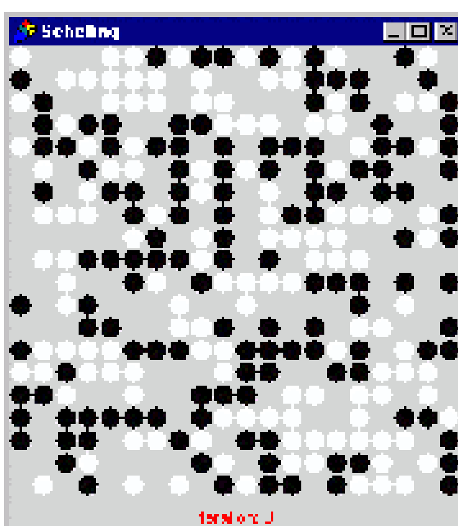
- Stigmergy
  - Form of communication by means of modification of the environment.
  - “Indirect social interaction”
  - Information exchange by means of a current task: Pheromone trails to mark the way
    - Deposit pheromones on the ground
    - Detect pheromones deposited by others.
    - Evaporation
- Dense heterarchy
  - Opposite to hierarchy
  - Global properties influence the local level properties, and vice versa.
  - Each individual can exchange information with any other.

18.14 CA model of segregation

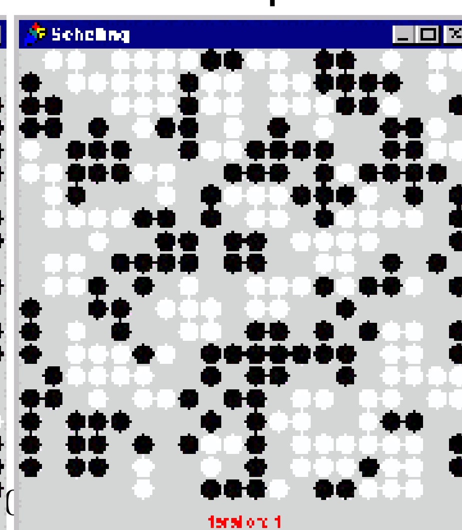
- Schelling's segregation model (1971):
  - Slight differences in preferences can lead to distinct patterns of segregation between any two groups:
    - Two racial or ethnic groups in the city
    - Smoker and non-smokers
    - Young and old
  - People care more about their own group.
  - No single factor can explain the segregation patterns in the city:
    - Economic differences between ethnic groups
    - Housing affordability
    - Preference for neighborhood's ethnic composition
    - Nature of urban structure (e.g., job locations, school districts)

- Bounded neighborhood model
  - Composition of neighborhood of significance; one composition that everyone prefers to alternatives.
  - Relative neighborhood homogeneity appreciated, but small number of minority households accepted.
  - Household stays until the composition changes so much it exceeds a threshold.

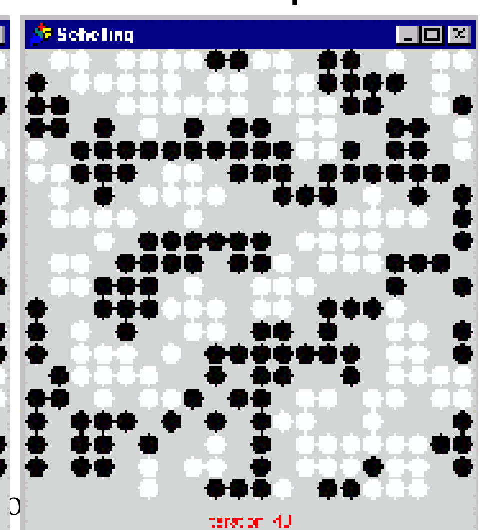
Start



After 4 steps

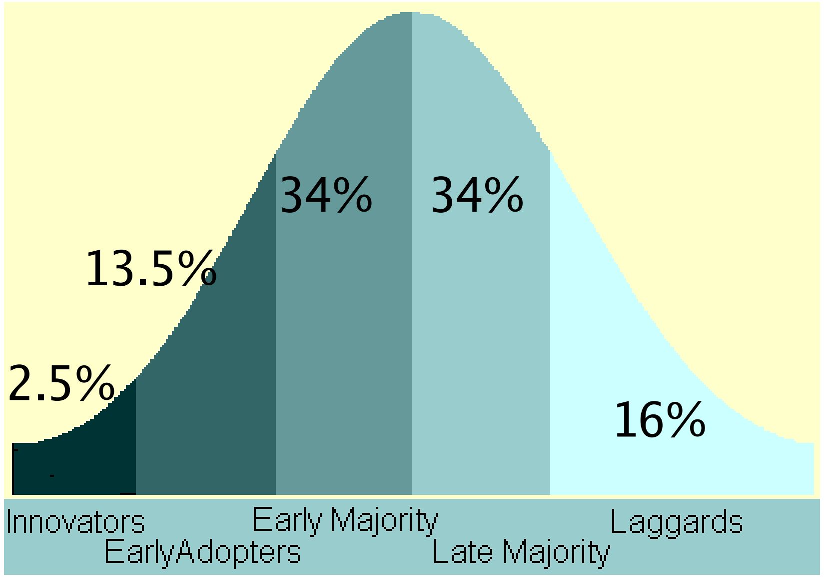


After 40 steps



18.15 Other cellular models

- Urban sprawl
  - City represented as a two-dimensional grid of locations.
  - Each location is either developed (there is a building or other urban structure) or undeveloped.
  - The probability of being developed at the next time step depends on the number of developed cells in the neighborhood.
- Innovation diffusion
  - How, why and at what rate new ideas and technology spread in a community.
  - Communication process over time through certain channels among people in some social system.



- Effectiveness of greenbelts
  - How parks and other green sections of the city hinder the spread of urban development.
  - Greenbelts cannot be developed.
  - Two kinds of agents: households and service centers.
  - Households relocate based on
    - Aesthetic quality of the location, i.e., the distance to greenbelt
    - Available services, i.e., the distance to the closest service center.
  - New service center are established if enough new development (households) in the area.