Modeling the Evolution of Mimicry

Mohiul Islam[1] Peter Grogono[1]

[1]Faculty of Engineering & Computer Science
Concordia University
Montreal, Canada

July 2016

The Inspiration

- Batesian Mimicry
- Mullerian Mimicry
- Evolutionary Dynamics
  - Mimicry Ring

The Model

- Past Work
- FormAL
- Prey
- Predator

Results

- Experiments
- Analysis

Conclusion

The Inspiration: Mimicry

The Inspiration: Mimicry

History

- Henry W. Bates first published in 1862.
    - **Content:** Similarity and dissimilarity between Heliconiinae and Ithomiinae butterflies.
- Bates collected 94 species of butterfly.
- Grouped according to similar appearance.
- **Discovery:** Appearance: similar, Morphological feature: different species.
- 67 of 94: Ithomiinae.
- 27 of 94: Heliconiinae.

The Inspiration: Mimicry

Batesian Mimicry

- Heliconiids are,
  - conspicuously colored
  - extremely abundant
  - slow in mobility.
- Predators, insectivorous birds do not prey on Heliconiids.
  - **Reason:** Inediblity and unpalatability.
- Heliconiids are easily recalled by predators.
  - Reason: Conspicuous coloration.
  - Color acts as warning.
- Ithomiinae and Pieridae are,
  - edible
  - palatable
  - pretend like Heliconiids, enjoy protection.

The Inspiration: Mimicry

Batesian Mimicry

- According to Wilcker:
  - Actor is a mime.
  - False representation of warning pattern: Mimicry.
  - Bates: First to point out, so Batesian Mimicry.
- **Model:** Animal avoided by predator for unpalatable behavior.
- **Mimic:** Imitating animal.

Batesian Mimicry

Plate from Bates (1862)

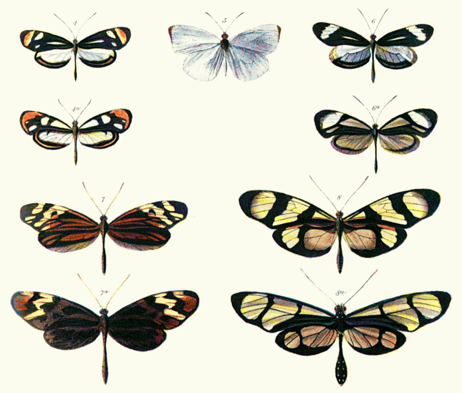


Figure: Plate from Bates (1862) illustrating Batesian mimicry between Dismorphia species (top row, third row) and various Ithomiini (Nymphalidae) (second row, bottom row).

Mullerian Mimicry

- Two inedible unrelated butterfly species have similar appearance.
- Bates: Unable to explain.
- Explanation: from Fitz Muller in 1878.
- Muller's research was also in Brazil.

Explanation:

- Predator's limited memory.
- Inedible species loose number.
- Save loss and survival of species:
  - inedible, different family
  - evolve to have similar appearance.
- Phenomenon: Mullerian mimicry, named after Fritz Muller.

Mullerian Mimicry

Viceroy and Monarch

Figure: A very well-known example of mimicry. Viceroy (top). Unpalatable Monarch (bottom). Image source: Wikipedia

Evolutionary Dynamics

Punctuated Equilibrium

Most sexually reproducing species remain:

- extended state of *stasis*.
- Little evolutionary change in most geological history.

Cladogenesis:

- Process of speciation.
- One split into two distinct species.
- In geological time:
  - Discontinuous change
  - Not gradual transformation

Evolutionary Dynamics

Phyletic Gradualism

- Continued adaptation to new environmental and biological selection pressure.
- Gradually becoming new species.

Phyletic gradualism holds,

- Species population changes gradually.
- No clear demarcation between ancestral and descendant species.
- Gradually changing lineage is divided arbitrarily.
- Evolution is
  - smooth
  - steady
  - incremental
  - but not necessary constant and slow rate in geological time scale.

Evolutionary Dynamics

Punctuated Equilibrium vs. Phyletic Gradualism

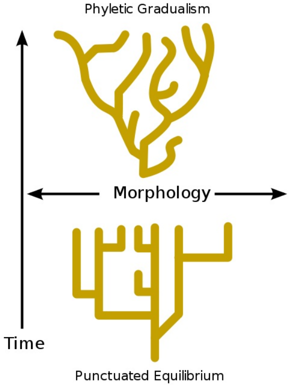


Figure: Punctuated equilibrium (bottom), phyletic gradualism (top). Image source: Wikipedia

Evolutionary Dynamics

Turner's Two Stage Model

- Turner: Synthetic theory.
- Originated from Poulton and Nicholson.
- Mimicry arises in two steps:
  1. A comparatively large mutation achieves a good approximate resemblance.
  2. A gradual evolutionary change refines the resemblance to a higher degree of perfection.
- Theory also applied to Mullerian Mimicry.

Mimicry Ring

- Examine the local butterfly fauna in any area of the world
  - all the aposomatic species
  - limited number of different patterns
  - normally far smaller than the number of species.
- Mullerian mimicry ring:
  - Each cluster of species
  - all sharing a common pattern
- All the rain forest in South and Central America,
  - most of the long winged butterflies (ithomiids, danaids and heliconids)
  - belong to one of only five different rings.

The Model: Evolution of Mimicry

The Model

Evolution of Mimicry

- **Objective:** Build an *agent based* Artificial Life model for simulating the evolution of mimicry.
- Two species of agents:
  1. Prey
     - Model
     - Mimic
  2. Predator
- Prey pattern representation: Cellular Automata.
- Predator pattern recognition: Hopfield Network.
- Environment: Visual representation, 3D, toroidal.

The Model

Past Work

- Turner (1996) and Huheey (1988):
  - **Focus:** Selective pressure on prey, by learning ability of predator.
  - Predator: Simple Monte Carlo learning or mathematical approach.
- Sherratt (2002):
  - Co-evolving predator and prey population.
  - Predators:
    - deterministic
    - cannot learn from experience.
    - attack policy is fixed, either attack or avoid.

Franks and Noble

Working hypothesis

1. *All of the Mullerian mimics in a given ecosystem should eventually converge into one large ring in order to gain maximum protection.*
2. *If the Mullerian mimics do not converge into one large ring, then the presence of Batesian mimics could entice them to do so, by influencing the rings to converge.*

Franks and Noble

Prey and Predator

- Prey:
  - Appearance and palatability.
  - Palatability is fixed, using different level from 0 to 1, where 0.5 is neutrally palatable.
  - Two genes representing external appearance, using values between 1 to 200.
  - Euclidean distance between values represents similarity.
- Predator:
  - Monte Carlo reinforcement learning system.
  - Decision for consumption of prey:
    - Use: set of probability formula.
    - Dependence on phenotype.

Franks and Noble

Result

- Hypothesis 1 of a single large ring did was not established.
- Hypothesis 2 is established.
- **Observation:**
    - Batesian mimics provide pressure on mutants.
    - Batesian pressure on mimicry rings push one into the range of another.

FormAL Framework

- Ideas from Peter Grogono's Formal Artificial Life (FormAL) project.
- **Goal:**
  - Study the emergence of complexity.
  - No variable unless genetically controlled or influenced. *Principal not followed for Hopfield Network.*
- **Agents:**
  - Simulated organism.
  - Reproduce itself using genetic information.
  - Capable of modifying structures of genome between generations.
  - Interaction with other agents.
  - Survive and reproduce in a challenging environment.

FormAL Framework

Environment

Environment is 3D, complete freedom of movement defined from genetic representation.

- **Space:**
  - 3D Lattice of discreet points.
  - $(x, y, z) \in \Sigma^3$, where Σ be the set $\{0, 1, ..., S - 1\}$.
  - S is a universal constant, small positive number. Value is 20, *WorldSize* parameter.
- **Time:**
  - Integer value, increases in discreet steps.
  - Each agent updates itself in each time step.
- **Cell:**
  - Entire environment is divided into multiple cells.
  - A 3D cubical section of the hyperspace.
  - *ISize* parameter kept at 6. Total $ISize^3 = 216$ cells.

FormAL Framework

Environment - Visual representation - Front

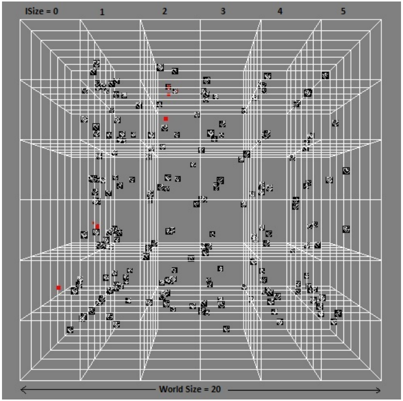


Figure: Three dimensional representation of the environment divided in cells. Presence of different species of agents inside.

FormAL Framework

Agent Mobility

- Position is calculated in each step in time.
- Vector components: *position*, *force*, *acceleration* and *velocity*.
- *force* is calculated from the mobility genes.
- Newton's law of motion, used to calculate *acceleration* when *force* is not zero.
- *acceleration* is integrated to obtain *velocity* and new *position*.

The Prey

Mimics and Models

- Agent in the FormAL environment.
- Genetic representation of pattern with Cellular Automata.
- Creates diversity of species.
- Pattern evolution is in the process of punctuated equilibrium.
- Mobility and reproduction capability controlled genetically.

The Prey: Mimics and Models

Pattern Representation

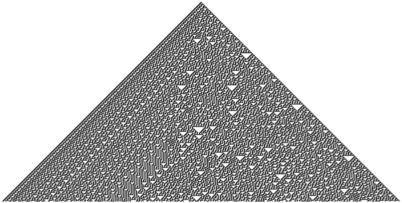


Figure: Cellular Automata Rule 30. Image source: Wikipedia

Current Pattern	111	110	101	100	011	010	001	000
New state of center cell	0	0	0	1	1	1	1	0

Table: Cellular Automata rule

The Prey: Mimics and Models

Species Diversity

- Pattern genome is 8 bit binary. Decimal range 0 to 255.
- 256 unique CA pattern.
- Linear representation of pattern stored in Hopfield Network.
- Pattern similarity: Hamming distance between linear representation.
- Single species: group of prey with a specific pattern.
- Inter species reproduction: restricted to control diversity of patterns.
- “Pattern Mutation Rate”: control diversity of new species.

Prey Pattern

Genotype vs. Phenotype

- Genetic bit difference of one.
- Vastly different phenotype.

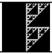
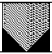
CA Rule	$60 \equiv 00111100$	$61 \equiv 00111101$	$62 \equiv 00111110$
Pattern			

Table: Difference in prey pattern genotype and phenotype

The Prey: Mimics and Models

Genome

- 17 bit prey Genome

Pattern(8)	Palatability(2)	Mobility(6)	Reproduction(1)
10101101	01	110001	1

Table: Distribution and purpose of each gene of the 17 bit prey genome.

The Prey: Mimics and Models
Punctuated Equilibrium

- Punctuated Equilibrium:
  - inclined to cladogenesis instead of gradualism.
  - Turner's emphasis on punctuated equilibrium to explain evolution of mimicry.
  - CA pattern evolution: single mutation in the pattern genome.
  - Change of pattern:
    - not gradual
    - arbitrary discontinuous

The Prey: Mimics and Models
Mobility

- Mobility gene: 6 bits.
- Use: calculate the magnitude of force for mobility.
- Direction:
  - Towards collection of maximum prey species in a cell.
  - Away from concentration of predators.
  - Move towards the selected cell with the magnitude of force calculated.

The Prey: Mimics and Models

Reproduction

- Begins at "Reproductive Age"
- Capability is decided on 17th bit gene.
- Mate selection is random, but within same cell.
- Mate needs to be
  - similar species
  - genetically capable to reproduce
  - reached maturity
- Reproduction process:
  - Single point crossover.
  - Two point mutation: different rates
    - *Pattern Mutation Rate*
    - *Genome Mutation Rate*

The Predator

- Agent in the FormAL environment.
- Provide selection pressure for the evolution of mimicry.
- Equipped with Hopfield Network Memory.
- Mobility and reproduction capability controlled genetically.
- Unable to represent pattern recognition capability with genome.
- New predators are born with zero memory, as memory is not inherited.

The Predator
Learning

- Predator's interaction objective with prey is consumption.
- Consumption is based on palatability.
- If unable to consume prey is thrown back into environment.
- Store prey pattern into memory with the associated palatability.
- New pattern learned with Hebbian Learning.

The Predator

Design of Memory

- Input to Memory:
  - Each prey has an evolving CA represented by a binary Genome.
  - 2D pattern is serialized to a 1D binary array.
  - Binary representation converted to bipolar representation.
- Pattern Recognition with Hopfield Network:
  - Learning: Apply Hebbian learning to calculate weights.
  - Initialization: Input to network initialized with input vector.
  - Iterate Until Convergence: Asynchronous update of each neuron. Input: previous state.
  - Output: Finally a pattern is set as output when the network reaches convergence.

The Predator

Attack Algorithm

- Agent reaches ‘Minimum Attack Age’ it starts hunting.
- Select a random prey within vicinity (same cell).
- Involves recognition of prey pattern.
- Pattern memorization and recognition process: computationally expensive.
- Two parameters to limit
  - Hopfield Minimum Memory Size (value 2 to 6)
  - Hopfield Maximum Memory Size (value 10)
- New predator attacks without caution.
- Attacks everyone and in the process store pattern and palatability.
- When memory reaches ‘Hopfield Minimum Memory Size’: intelligent selection.

The Predator

Genome

Mobility(4)	Reproduction(1)
1101	1

Table: Distribution and purpose of each gene of the 5 bit predator genome.

The Predator
Mobility

- Magnitude of force of movement: 4 bits of genome.
- Direction: number of prey species present in a neighboring cell.
- Move towards the cell with least number of predator and most number of prey.
- Result: Predators are distributed all over the environment.
- Increases agent's predatory behavior.

The Predator

Reproduction process

- Reproduction age: begins.
- Reproduction age interval: which is difference in time between two reproduction activity.
- Capability: 5th gene.
- Selection: another predator from same cell which satisfy above conditions.
- Perform genome crossover and mutation: create new predator.
- New predator initialized with zero memory.

The Results

Results

- **Objective**: Evaluate evolution of mimicry.
- **Evaluation process**:
  - Calculate number of mimicry rings.
  - Calculate size of mimicry rings:
    - Population of *palatable* species.
    - Population of *unpalatable* species.
- **Report parameters**:

Parameter	Value
Mimicry Ring hamming distance	10 % of the Pattern Size
Number of Rings to report	8

Table: Parameters to mimicry ring report.

Two Prey Species

Initial Configuration

	Prey configuration			Predator configuration
Population	Rule110 (Palatable)		108	10
	Rule30 (Unpalatable)		108	
Reproduction	Age Limit	100		500
	Interval	1000		1200
Mutation Rate	Pattern	0.05		0.3
	Genome	0.5		
Demise Age	2000			2500
Minimum Attack Age				500
Memory Configuration				Minimum: 2
				Maximum: 10

Table: Agent configuration of 2 prey species

Two Prey Species

Population vs. Time (10k)

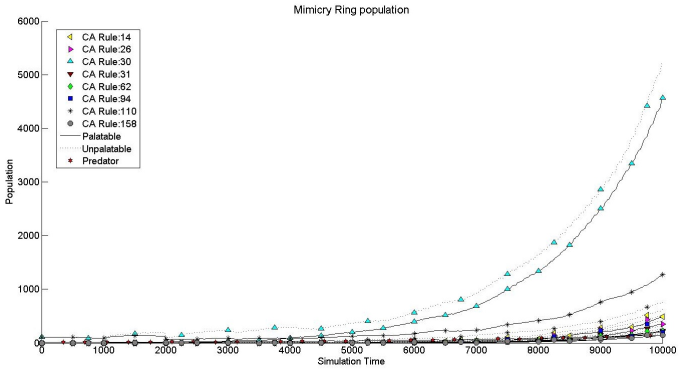


Figure: Population distribution of mimicry rings, initialized with 2 prey species, 10k iterations

Two Prey Species

Population vs. Time (5k)

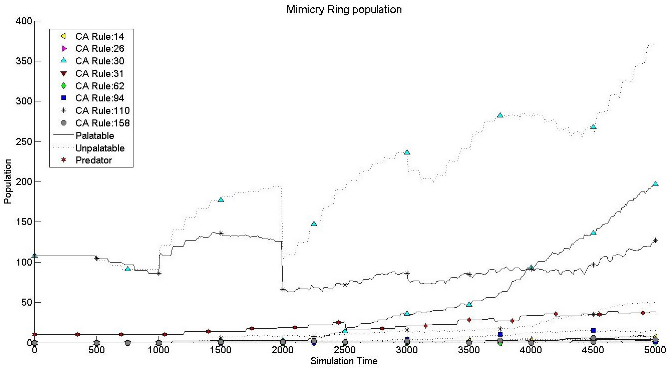


Figure: Population distribution of mimicry rings (2 prey species, 5k iterations)

Two Prey Species

Number of Mimicry Rings

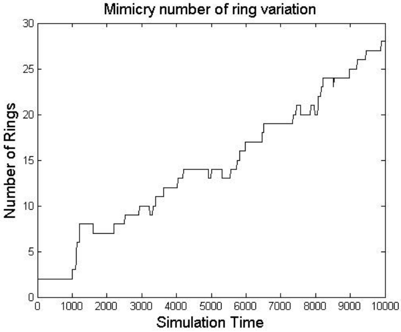


Figure: Number of mimicry rings, initialized with 2 prey species.

Generated Prey Species

Population vs. Time (10k)

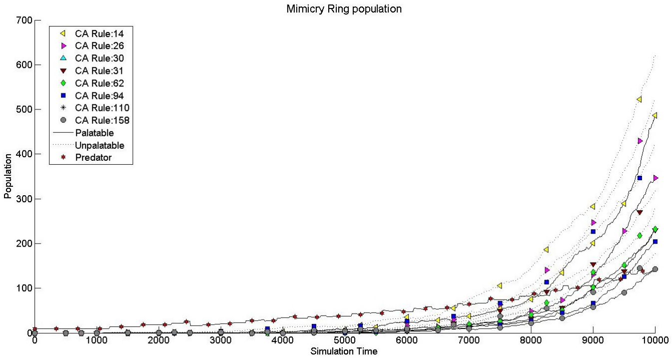


Figure: Population distribution of generated mimicry rings (2 prey species)

Four Prey Species

Increased Population

	Prey configuration			Predator configuration	
Population	Rule110 (Palatable)		**150** ↑	**20** ↑	
	Rule30 (Palatable)		**150** ↑		
	Rule55 (Unpalatable)		**150** ↑		
	Rule190 (Unpalatable)		**150** ↑		
Reproduction	Age Limit	100		500	
	Interval	1000		**2500** ↑	
Mutation Rate	Pattern	0.05		0.3	
	Genome	0.5			
Demise Age	2000			**7000** ↑	
Minimum Attack Age				500	
Memory Configuration				Minimum	4
				Maximum	10

Table: Agent configuration of 4 prey species with increased population

Four Prey Species

Increased Population

Population vs. Time (10k)

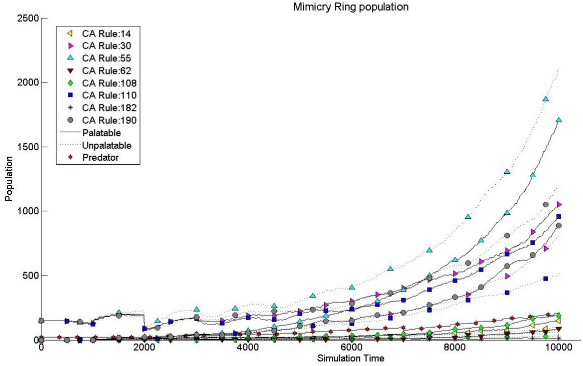


Figure: Population distribution of mimicry rings (4 prey species, increased population)

Only Unpalatable Species

Initial Configuration

	Prey configuration			Predator configuration
Population	Rule110 (Unpalatable)		150	**20** ↓
	Rule30 (Unpalatable)		150	
	Rule55 (Unpalatable)		150	
	Rule190 (Unpalatable)		150	
Reproduction	Age Limit	100		500
	Interval	1000		2000
Mutation Rate	Pattern	0.05		0.3
	Genome	0.5		
Demise Age	2000			**5000** ↓
Minimum Attack Age				500
Memory Configuration				Minimum: **4** ↓
				Maximum: 10

Table: Agent configuration of 4 prey species all unpalatable.

Only Unpalatable Species

Population vs. Time (10k)

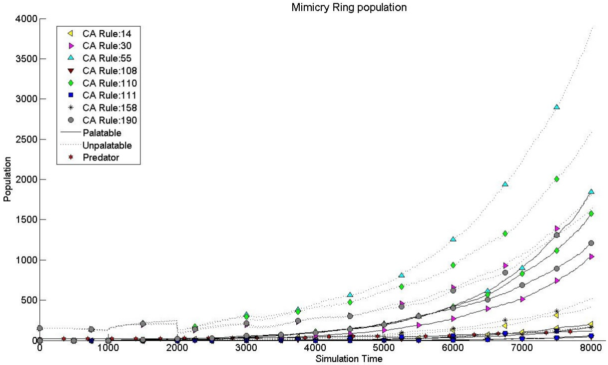


Figure: Population distribution of mimicry rings(4 prey species all unpalatable)

Only Unpalatable Species

Reduced Predator Memory
Population vs. Time (10k)

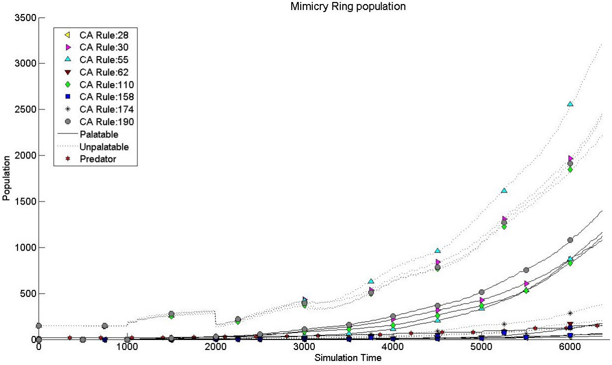


Figure: Population distribution of mimicry rings. 4 prey, all unpalatable but reduced predator memory

Only Palatable Species

Initial Configuration

	Prey configuration			Predator configuration	
Population	Rule110 (Palatable)		150	20	
	Rule30 (Palatable)		150		
	Rule55 (Palatable)		150		
	Rule190 (Palatable)		150		
Reproduction	Age Limit	100		500	
	Interval	1000		2000	
Mutation Rate	Pattern	0.05		0.3	
	Genome	0.5			
Demise Age	2000			5000	
Minimum Attack Age				500	
Memory Configuration				Minimum	4
				Maximum	10

Table: Agent configuration of 4 prey species all palatable.

Only Palatable Species

Population vs. Time (7k)

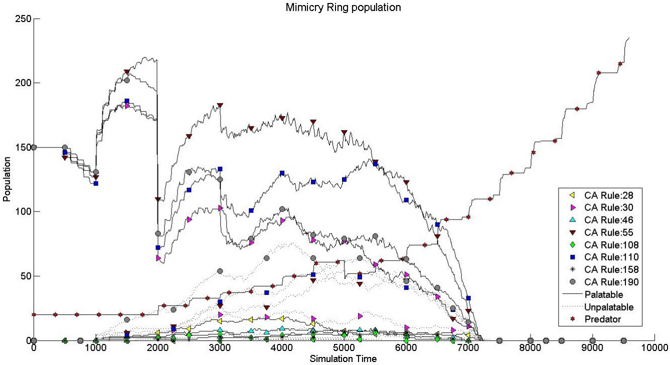


Figure: Population distribution of mimicry rings (4 prey species all palatable)

Only Palatable Species

Number of Mimicry Rings

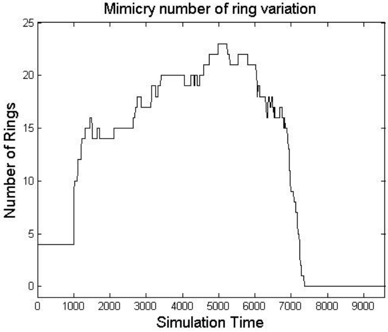


Figure: Number of mimicry rings (4 prey species all palatable)

Analysis
Batesian Mimicry

- Batesian Mimicry has taken effect, for all possible initial conditions.
  - Every ring of unpalatable species there is a palatable ring.
- Start with palatable population, prey reaches extinction. **Reason:** No models to mimic for palatable species.
- **Conclusion:** This model can simulate evolution of Batesian Mimicry.

Analysis

Mullerian Mimicry

"Mullerian mimics converge into one large ring."

- Initialize simulation with 4 unpalatable species. No palatable ones.
- After 10k iteration all unpalatable species survive with dominance.
- **Reason:** Predator minimum memory configuration set to 4.

New experiment:

- Reduce predator memory to 1.
- **Observation:** Single large ring do not occur.
- **Conclusion:** Similar to Franks and Noble.
  Multiple Mullerian mimics do not converge into one large ring.

Analysis
Conclusion

- Successful simulation of evolution of mimicry.
- Accurate simulation of mimicry ring.
  Diverse new rings and shift in their population.
- Proof of the theory of Turner: evolution of mimicry with punctuated equilibrium.

Conclusion

Conclusion

Artificial Life:

- Tool for biological inquiry
  - Success: Proof of Turner's punctuated equilibrium
  - Proof of Franks and Noble's converge of one large ring.
- Nature inspired computer science
  - Success: Appropriate emulation of Batesian and Mullerian mimicry.
- Solve problem in computer science
  - Not successful: unable to find the appropriate problem solving scenario.