Co-Evolution in a Flower/Pollinator System

Michael Cusack, Teale Fristoe, Cody Kennedy, Louis Bianchi
The co-evolution between flowers and their pollinators is a game which has been played for at least 100 million years.

The dynamics of this interaction have generated much of the diversity in the flower/pollinator populations that we see today.

In our simplified game we will try to explore this co-evolutionary cycle and examine the forces at work that drive the specialization that we observe in nature.
The Goal of the Game is Sex and Food

Flowers need bees to spread their pollen to other compatible flowers.

Bees want the nectar/pollen reward that flowers offer.

As a result bees and flowers have come up with different strategies to reach their goals.
Three different bee strategies:

-Honesty
   These bees will prefer one flower and try to go to that same flower type consistently.

-Promiscuous
   The promiscuous bees will go to any flower type that is available.

-Cheat
   This bee type will tear an opening at the rear of the flower in order to access its nectar.
Three different flower strategies:

- **Open**
  A typical flower, its pollen and nectar is left exposed for anything to come in and get it.

- **Closed**
  This flower has a certain morphology that only allows for one bee type (Honest in this case) to enter.

- **Protective**
  These flowers have a protective shell that prevents the burrowing caused by cheater bees.
The basic interaction:

Open flowers lack that specificity needed to assure that their pollen gets to its intended destination. As a result closed flowers can emerge.

Closed flowers exclude promiscuous bees from entering but are decimated by an invasion of cheater bees.

Protective flowers can defend against cheater bees but cannot compete as well against closed flowers when there are no cheater bees present.

This might lead to an RPS like dynamic...
Plan B...
Tries to enter...

Bee: 1
Flower: -1

Closed Flower VS Cheater Bee
References


Simulation

- Run a series of steps on a cellular automaton
- Each step, do the following for every flower and every bee:

  Flowers:
  - Spawn if capable
  - Age and die
  - Create nectar

  Bees:
  - Spawn if possible
  - Age and die
  - Decide what to do
  - Either:
    - Move
    - Visit flower

Run a series of steps on a cellular automaton. Each step, do the following for every flower and every bee:

- Flowers:
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- Bees:
  - Spawn if possible
  - Age and die
  - Decide what to do
  - Either:
    - Move
    - Visit flower
Parameters

Simulation driven by several parameters: (red indicates varied, black indicates fixed for our experiment)

- Payoff Matrices
  - Determine payoffs when bees visit flowers
- Maximum Populations
- Starting Populations
- Life Spans
  - Determine how many steps flowers and bees live
- Spawn requirements
  - Determine how much payoff is required to spawn
- Movement Penalty
  - Perceived cost of moving instead of landing for bees
- Flower Refresh Rate
  - How quickly flowers refresh nectar after being visited
Parameterized Payoffs

**Bee payoff:**

<table>
<thead>
<tr>
<th>Open</th>
<th>Specialized</th>
<th>Protective</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Y) Honest</td>
<td>$[b_B - b_H, b_B + b_{Bs}, b_B - b_H - b_{Cp}]$</td>
<td>$[b_B + b_{Bs}, b_B + b_{Bb}, b_B - b_{H} - b_{Cp}]$</td>
</tr>
<tr>
<td>(P) Promiscuous</td>
<td>$[b_B, b_B + b_{Bb}, b_B - b_{Cp}]$</td>
<td>$[b_B - b_{Bb}, b_B - b_{Cp}]$</td>
</tr>
<tr>
<td>(R) Cheating</td>
<td>$[b_B, b_B + b_{Bb}, b_B - b_{Cp}]$</td>
<td>$[b_B, b_B + b_{Bb}, b_B - b_{Cp}]$</td>
</tr>
</tbody>
</table>

**Flower payoff:**

<table>
<thead>
<tr>
<th>Honest</th>
<th>Promiscuous</th>
<th>Cheating</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W) Open</td>
<td>$[f_B, f_B, -f_{Cb}]$</td>
<td>$[f_B, f_B, -f_{Cd}]$</td>
</tr>
<tr>
<td>(B) Specialized</td>
<td>$[f_B - f_{Cs} + f_{Bs}, f_B - f_{Cs}, -f_{Cb}]$</td>
<td>$[f_B - f_{Cd}, f_B - f_{Cd}, -f_{Cd}]$</td>
</tr>
<tr>
<td>(D) Protective</td>
<td>$[f_B - f_{Cd}, f_B - f_{Cd}, -f_{Cd}]$</td>
<td>$[f_B - f_{Cd}, f_B - f_{Cd}, -f_{Cd}]$</td>
</tr>
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</table>

Parameters:

- $b_B$ = Bee Benefit of Pollinated
- $b_{Bs}$ = Bee Bonus for Specialization
- $b_{Bb}$ = Bee Bonus for Burrowing
- $b_H$ = Bee Honesty Factor
- $b_{Cp}$ = Bee Cost of Visiting a Protective Flower
- $f_B$ = Flower Benefit of Being Visited
- $f_{Cb}$ = Flower Cost of Being Burrowed
- $f_{Cd}$ = Flower Cost of Being Defensive
- $f_{Cs}$ = Flower Cost of Being Specialized
- $f_{Bs}$ = Flower Bonus for Specializing Flower
Permutations

Population maximums:
- 3000 flowers and 1000 bees
- 2000 flowers and 1000 bees
- 2000 flowers and 2000 bees

Cost for bees visiting protective flowers:
- No cost
- Small cost

Bonus for honest bees visiting specialized flowers:
- No bonus
- Small bonus
Understanding the Simulation

Bees:
- Honest (Yellow)
- Promiscuous (Pink)
- Cheater (Red)

Flowers:
- Open (White)
- Closed (Cyan)
- Protective (Blue)

Open Space (Green)
Run simulations
Results:
Baseline. No specialization bonus, protective cost, 1000:3000

Payoff matrix

Bee Payoffs:

<table>
<thead>
<tr>
<th></th>
<th>Open</th>
<th>Specialize</th>
<th>Protect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honest</td>
<td>0.45</td>
<td>0.65</td>
<td>0.40</td>
</tr>
<tr>
<td>Promiscu</td>
<td>0.65</td>
<td>0.00</td>
<td>0.60</td>
</tr>
<tr>
<td>Cheating</td>
<td>0.65</td>
<td>1.65</td>
<td>0.00</td>
</tr>
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Flower Payoffs:

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<tr>
<td>Open</td>
<td>0.60</td>
<td>0.60</td>
<td>0.00</td>
</tr>
<tr>
<td>Specialize</td>
<td>2.50</td>
<td>0.50</td>
<td>-10.00</td>
</tr>
<tr>
<td>Protect</td>
<td>0.55</td>
<td>0.55</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Area Graph

Analytics

Triangle Graphs
Results:

Baseline. No specialization bonus, protective cost, 1000:2000

Payoff matrix

Bee Payoffs:
(Y) Honest [0.45, 0.65, 0.40]
(P) Promiscuous [0.65, 0.00, 0.60]
(R) Cheating [0.65, 1.65, 0.00]

Flower Payoffs:
(W) Open [0.60, 0.60, 0.00]
(B) Specialized [2.50, 0.50, -10.00]
(D) Protected [0.55, 0.55, 0.00]

Analytics

Triangle Graphs
Results:

Baseline. No specialization bonus, protective cost, 2000:2000

Payoff matrix

Bee Payoffs:
- Open: [0.45, 0.65, 1.65]
- Speciali: [0.45, 0.00, 0.65]
- Protecti: [0.40, 0.60, 0.00]

Flower Payoffs:
- Honest: [0.60, 0.60, 0.00]
- Promiscu: [2.50, 0.50, -10.00]
- Cheating: [0.55, 0.55, 0.00]
Results:

Specialization bonus, protective cost, 1000:3000

Payoff matrix

Bee Payoffs:
- Open: [0.45, 0.75, 0.40]
- Honest: [0.65, 0.00, 0.60]
- Cheating: [0.65, 1.65, 0.00]

Flower Payoffs:
- Honest: [0.60, 0.60, 0.00]
- Speciali: [2.50, 0.50, -10.00]
- Protecti: [0.55, 0.55, 0.00]
Results:

Specialization bonus, protective cost, 1000:2000

Payoff matrix

Bee Payoffs:
- Open
- Specialization
- Protection

(Y) Honest: [0.45, 0.75, 0.40]
(P) Promiscuous: [0.65, 0.00, 0.60]
(R) Cheating: [0.65, 1.65, 0.00]

Flower Payoffs:
- Honest
- Promiscuous
- Cheating

(W) Open: [0.60, 0.60, 0.00]
(B) Specialization: [2.50, 0.50, -10.00]
(D) Protection: [0.55, 0.55, 0.00]
Results:
Specialization bonus, protective cost, 2000:2000

Payoff matrix

Bee Payoffs:
- Open \( [0.45, 0.75, 0.40] \)
- Honest \( [0.65, 0.00, 0.60] \)
- Cheating \( [0.65, 1.65, 0.00] \)

Flower Payoffs:
- Honest \( [0.60, 0.60, 0.00] \)
- Speciali \( [2.50, 0.50, -10.00] \)
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Analytics

Triangle Graphs
Results:
No specialization bonus, **no protective cost, 1000:3000**

Payoff matrix

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<tr>
<td>Honest</td>
<td>[0.45, 0.65, 0.45]</td>
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<tr>
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Analytics

Triangle Graphs

Area Graph
Results:
No specialization bonus, no protective cost, 1000:2000

Payoff matrix

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Results:
No specialization bonus, **no protective cost, 2000:2000**

Payoff matrix

### Bee Payoffs:
- **Open**
  - Honest: [0.45, 0.65, 0.45]
  - Promiscuous: [0.65, 0.00, 0.65]
  - Cheating: [0.65, 1.65, 0.00]

### Flower Payoffs:
- **Open**
  - Honest: [0.60, 0.60, 0.00]
  - Specialization: [2.50, 0.50, -10.00]
  - Protection: [0.55, 0.55, 0.00]

### Triangle Graphs
- **Flower Equilibrium**
- **Bee Shares**
- **Flower Shares**
Results:

Specialization bonus, no protective cost, 1000:3000

Payoff matrix

Bee Payoffs:

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<tr>
<td>Honest(Y)</td>
<td>0.45,</td>
<td>0.75,</td>
<td>0.45</td>
</tr>
<tr>
<td>Promiscuous(P)</td>
<td>0.65,</td>
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<td>0.65</td>
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<tr>
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<td>Open(W)</td>
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<td>0.00</td>
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<td>2.50,</td>
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Analytics

Triangle Graphs
Results:

Specialization bonus, no protective cost, 1000:2000

Payoff matrix

Bee Payoffs:

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<th>Protective Cost</th>
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<tr>
<td>Y (Honest)</td>
<td>(0.45, 0.75, 0.45)</td>
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<tr>
<td>P (Promiscuous)</td>
<td>(0.65, 0.00, 0.65)</td>
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<tr>
<td>B (Specialization)</td>
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Area Graph

Triangle Graphs

Analytics
Results:

Specialization bonus, no protective cost, 2000:2000

Payoff matrix

Bee Payoffs:

\begin{tabular}{lccc}
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(Y) Honest & [0.45, 0.75, 0.45] & \ & \\
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\end{tabular}

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\end{tabular}

Analytics

Triangle Graphs
Future work

Improvements for simulation:

- More realistic genetics:
  - Sexual reproduction
  - Diploid genetics
- More genes
  - Especially preferences

- More realistic flower spawning:
  - Simulate bees carrying pollen
- Model bee ignorance:
  - Bees can't see nectar
  - Perhaps add learning
Conclusion

We were able to create a simulation that allows us to explore conditions in which speciation could develop.

In the simulations we ran, Specialization Bonus, Protective Penalty, and 1000:2000 population caps proved to offer the best situation for fluctuations and therefore speciation.