Systems Biology of Group Decision Making

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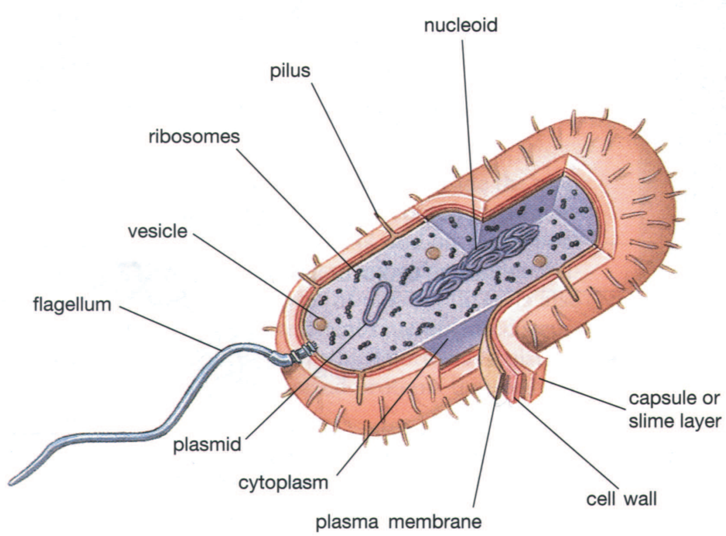
Overview

- Systems biology of decision making
- Group decision making by honey bees
  1. Nest-site selection dynamics
  2. Group choice behavior
  3. Evolutionary adaptation
- Mathematical analysis overview
- Related engineering challenges
- Concluding remarks

Systems biology goals

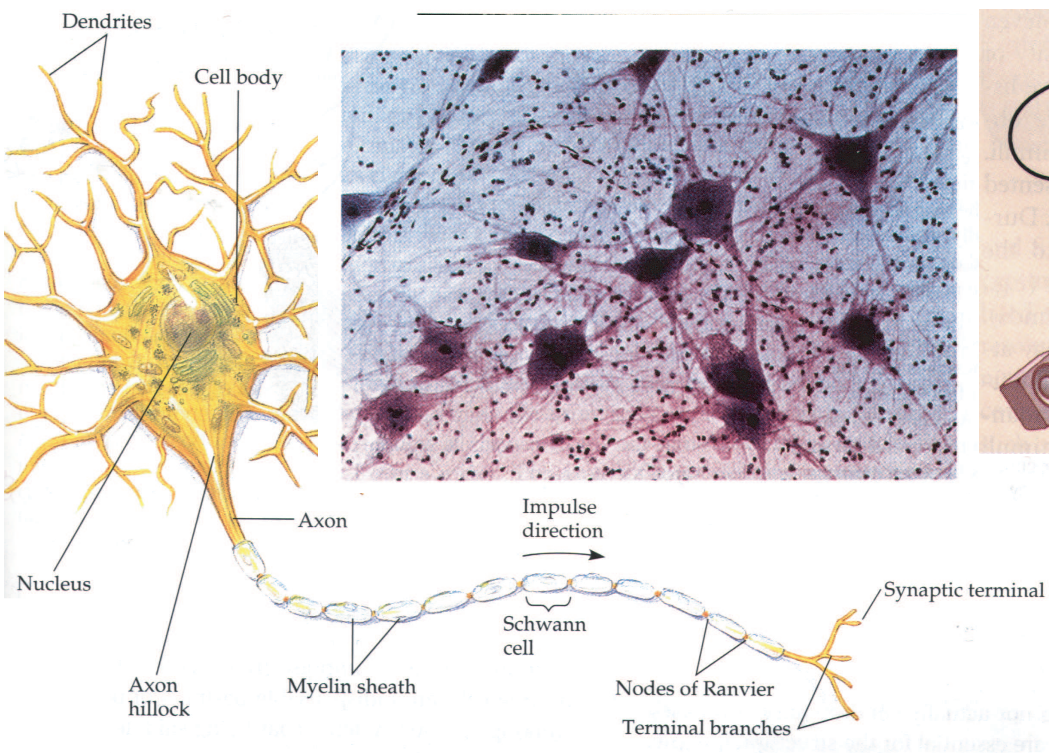
"Whole-(sub)system" understanding of living entities
(e.g., molecular, cellular, organism, ecological)

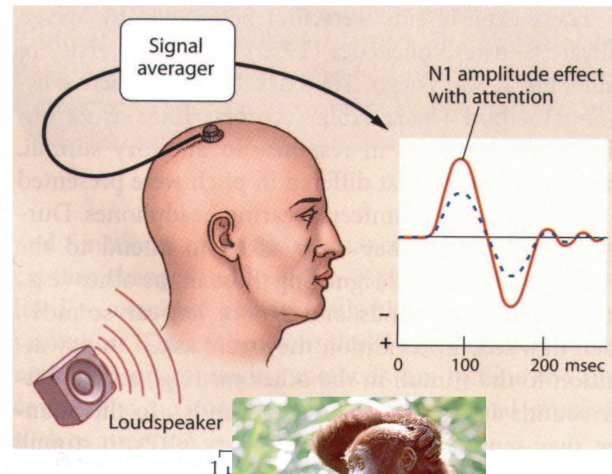


Gray Jay

Systems biology of decision making

Neurobiology, cognitive neuroscience





Current work: Modeling/analysis of perception, attention, choice, learning, optimality,...

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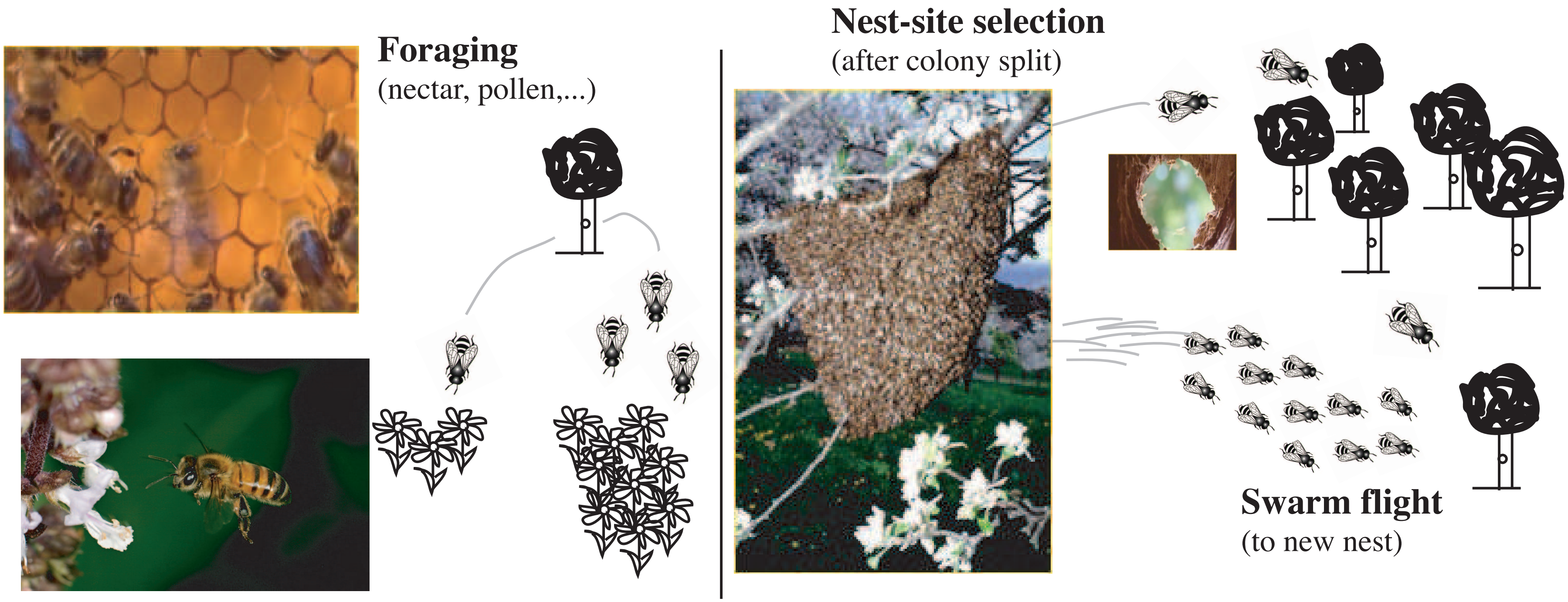
Group decision making, evolution and ecology

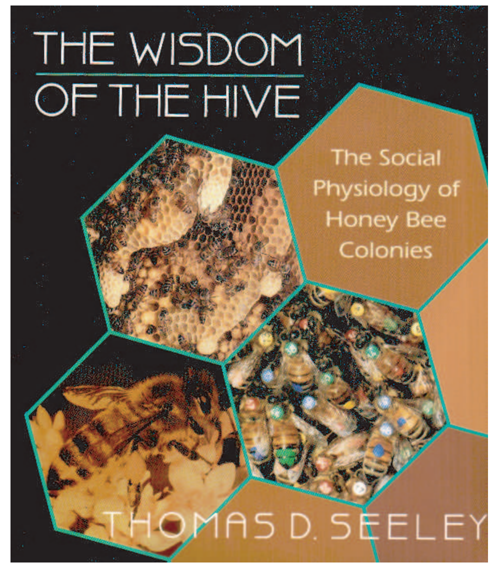
Current work: Modeling/analysis of coordinated motion, foraging, choice, evolutionary stable strategies,...

Group decision making by honey bees



Today: Nest-site selection...

- Collaborator: Thomas D. Seeley,
  Dept. Neurobiology and Behavior, Cornell University



- Other inputs:
  1. P. Kirk Visscher, Dept. Entomology, Univ. Calif. Riverside
  2. Roger Ratcliff, Dept. Psych., OSU: Cognitive neuroscience, math models; Thomas A. Waite, Dept. Evolution, Ecol., Org. Biology, OSU: Math models of choice by gray jays

Nest-site selection...

- Model and analysis here based on:

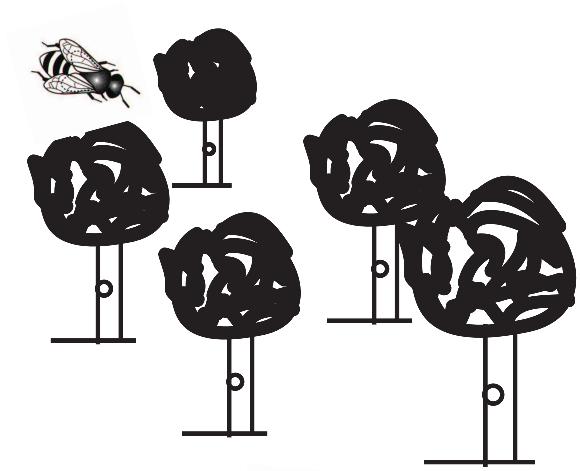
  K.M. Passino and T.D. Seeley, "Modeling and analysis of nest-site selection by honey bee swarms: The speed and accuracy trade-off," *Behavioral Ecology and Sociobiology*, Vol. 59, No. 3, pp. 427-442, Jan. 2006

- Builds on experiments, models, analysis for:

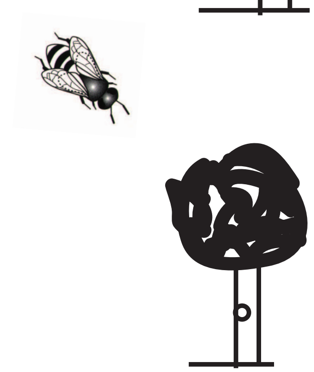
  1. Honey bees: Seeley, Visscher, Buhrman, Myerscough, Britton, Franks, Pratt
  2. Ants: Franks, Pratt, Sumpter, Britton, Mallon, Dornhaus, Fitzsimmons, Stevens

Fast distributed search and selection of best of N nest sites

Weather, energy costs - time pressure!

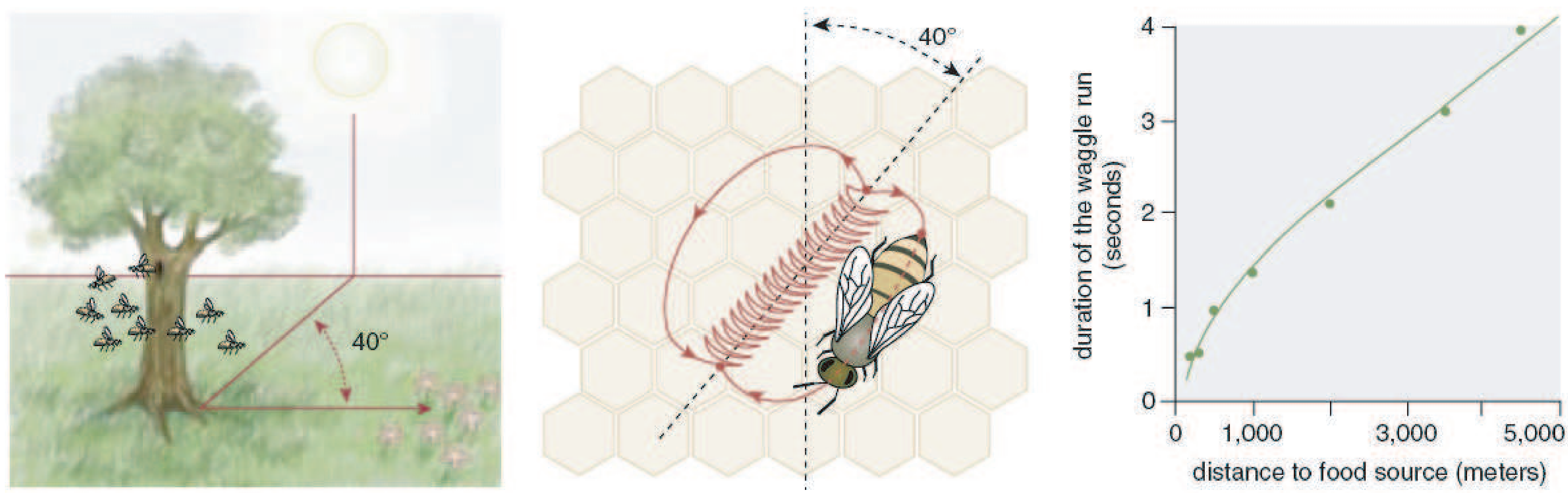


No central decision maker (e.g., queen)

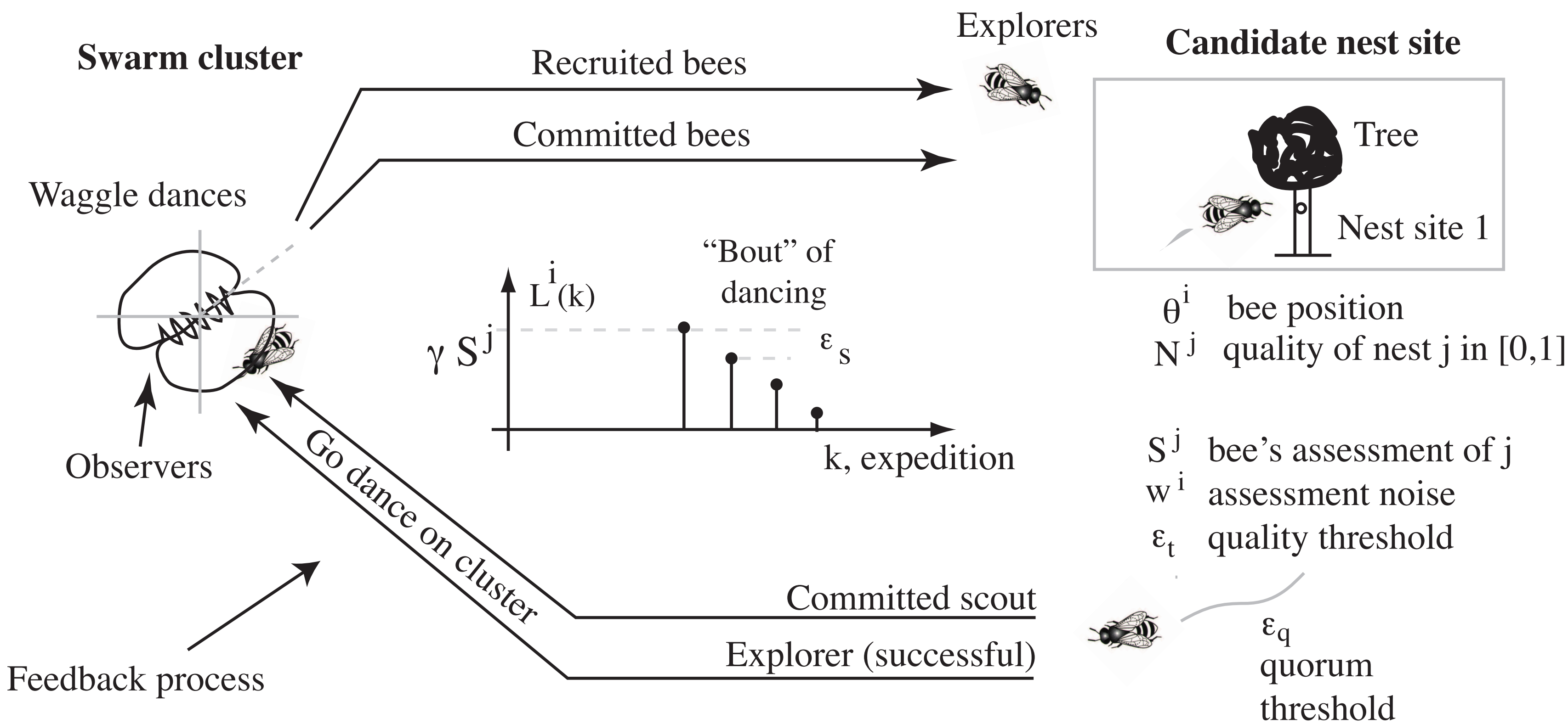


Better nest - better hive success

Bee-to-Bee Communication:
The Waggle Dance



(Images/data taken from: Seeley T.D., Visscher P.K., Passino K.M., "Group Decision Making in Honey Bee Swarms," *American Scientist*, Vol. 94, Issue 3, pp. 220-229, May/June, 2006.)



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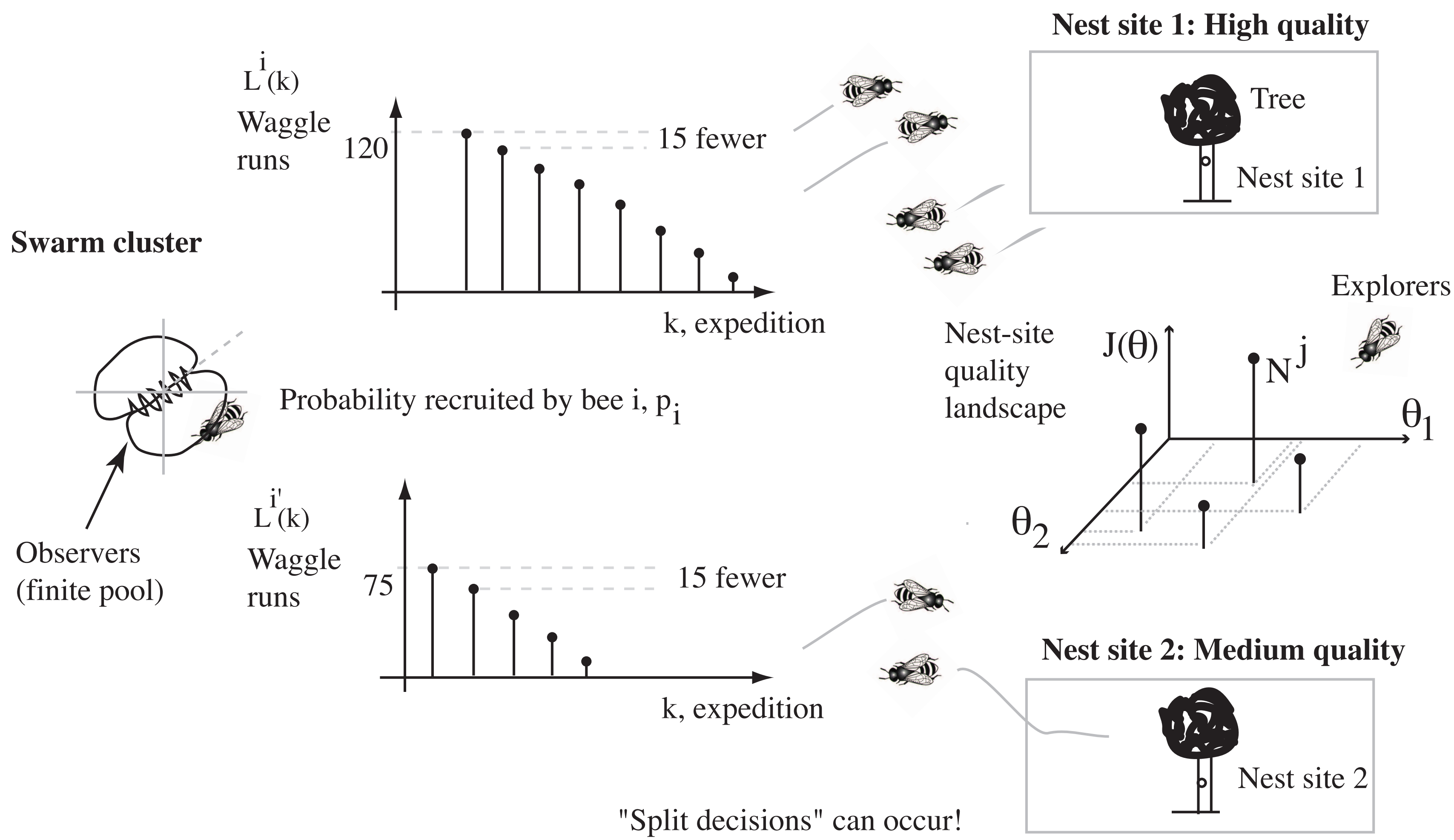
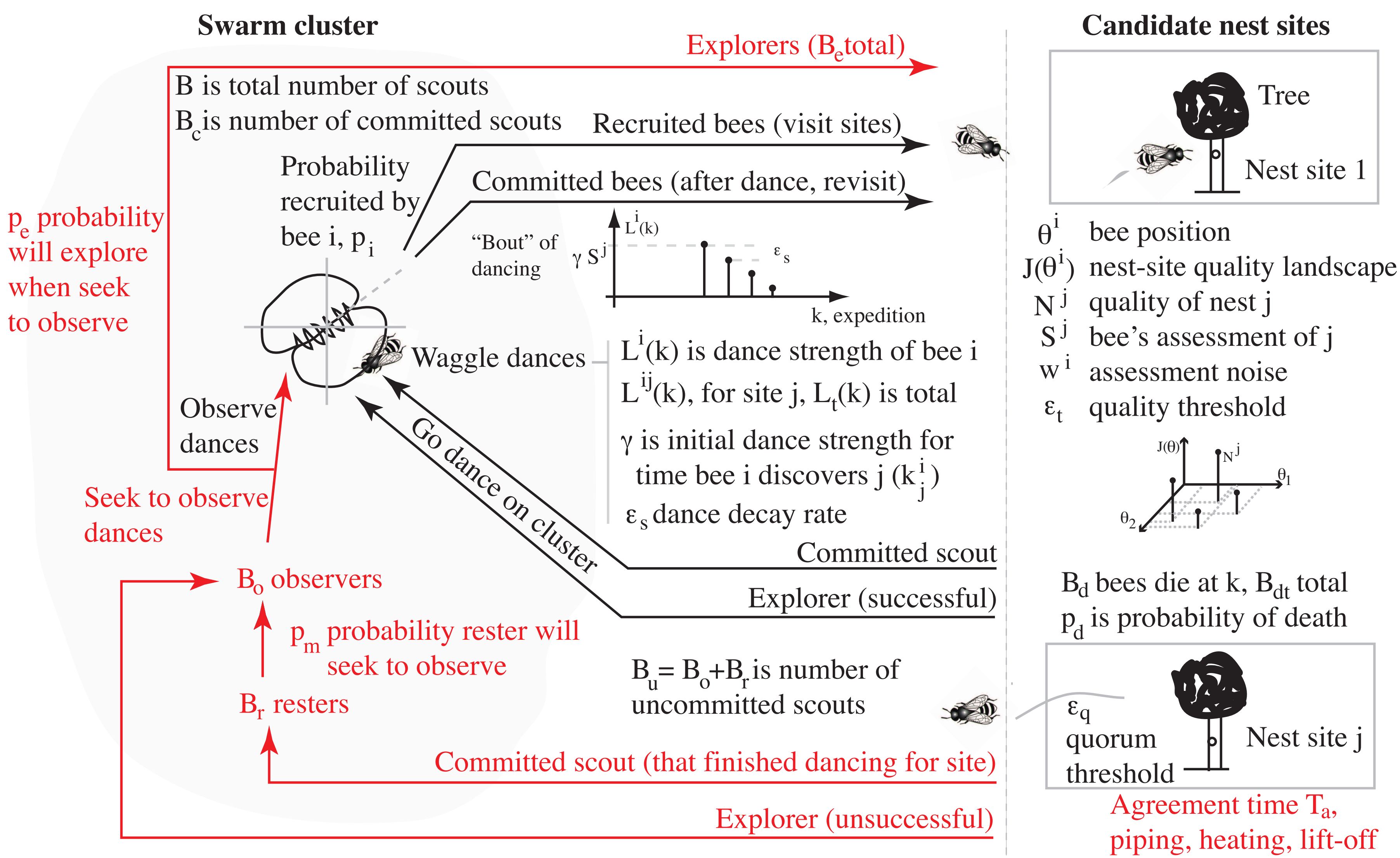


Nest site 1: High quality
Tree
Nest site 1
$L^i(k)$
Waggle runs
120
15 fewer
k, expedition
Swarm cluster
Explorers
Nest-site quality landscape
$J(\theta)$
N^j
θ_1
θ_2
Probability recruited by bee i, p_i
Observers (finite pool)
$L^{i'}(k)$
Waggle runs
75
15 fewer
k, expedition
Nest site 2: Medium quality
Nest site 2
"Split decisions" can occur!



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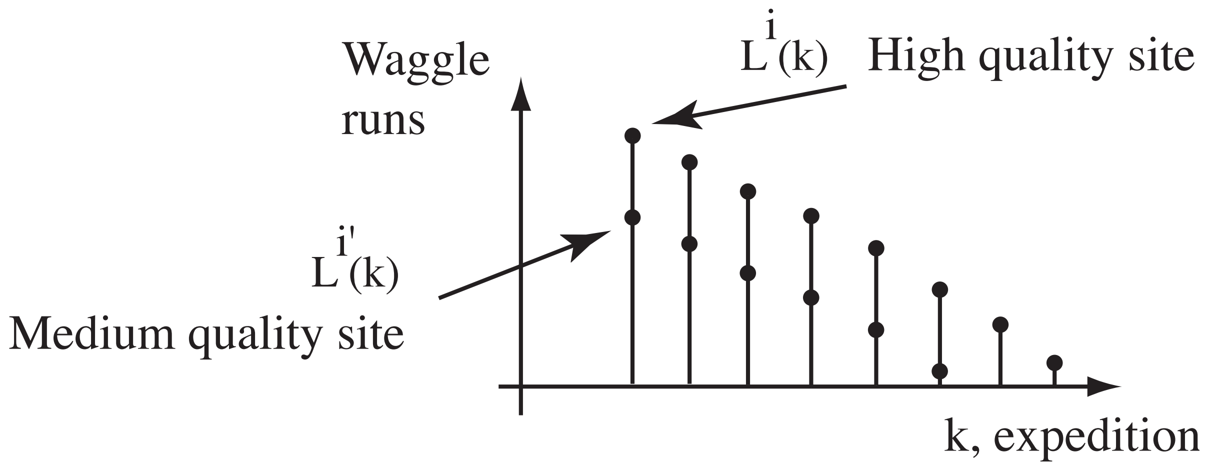
Mechanism for discrimination

➔ Discriminating between two different quality sites?



★ Site quality differences → (nonlinear) differential increase in # dances (recruits, positive feedback)

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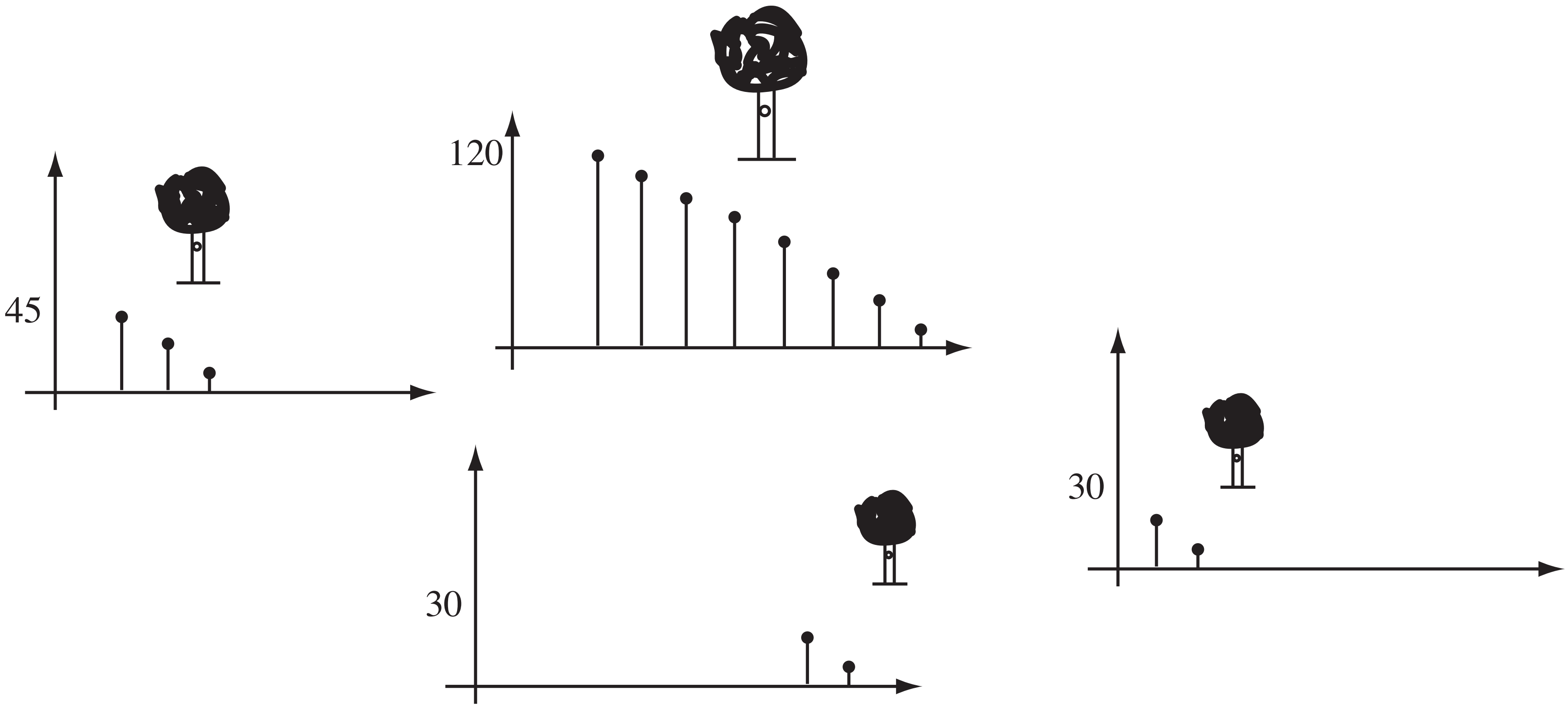
➔ Depends on absolute quality, example:

$N^j - N^{j'} = 0.2$ (assume no noise or pool-size effects)

1. Two high-quality sites:
   - $N^{j'} = 0.8 \longrightarrow$ bout total $= 540$
   - $N^j = 1.0 \longrightarrow$ bout total $= 825$
   - Percent increase: $\frac{285}{540} \times 100 = 53\%$
2. Two low-quality sites:
   - $N^{j'} = 0.2 \longrightarrow$ bout total $= 45$
   - $N^j = 0.4 \longrightarrow$ bout total $= 150$
   - Percent increase: $\frac{105}{45} \times 100 = 233\%$

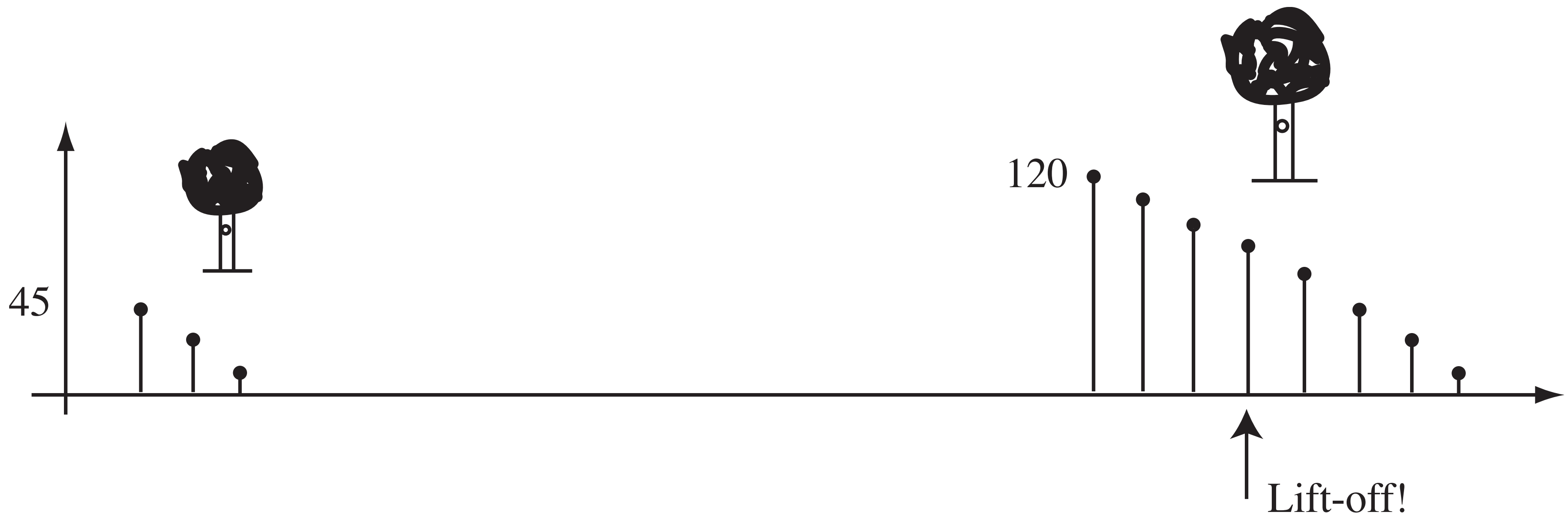
★ Discrimination best when it matters most!

Mechanism for distractors



★ Swarm can simultaneously consider *many* distractors

Mechanism for early/late discoveries



★ Group-level coupling can be good (dance decrease and finite pool effect)

Mechanism for ignoring individual errors

- Filtering:
  - Cluster: Averaging of multiple dancing bees
  - Nests: Quorum threshold → "balanced assessment"
- Swarm combines information from *many* bees

Search-select phases and dynamic internal coupling

- ➔ Internal *phase-dependent* coupling:
  - Amount of search regulated by # discoveries, N
  - Dance completion (coupling biased to higher quality sites)
  - Cross-inhibition (high quality inhibits lower quality)

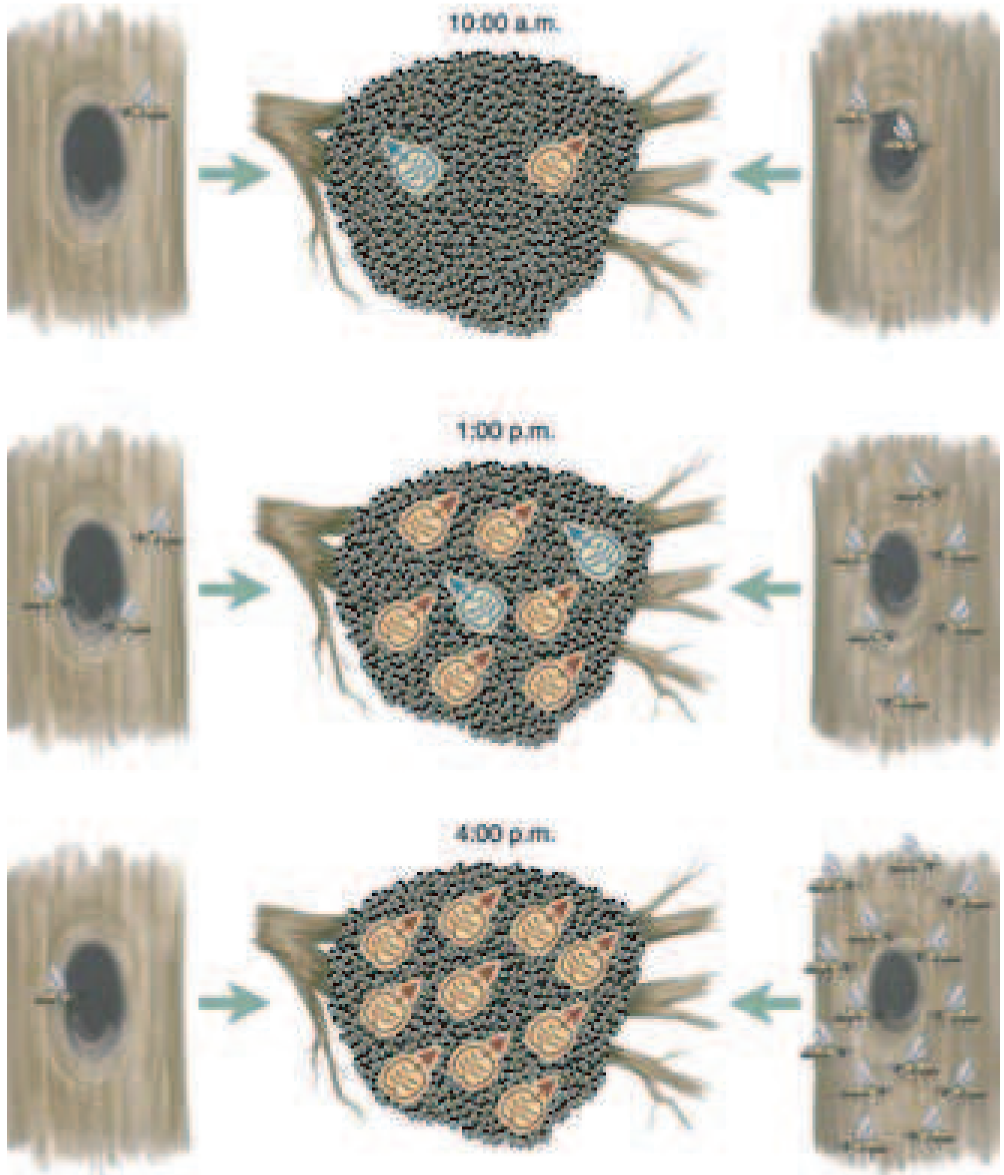
★ Swarm allocates bees to search or select to come to a fast/good decision.

Speed-accuracy trade-off

- More accurate choices cost more time T_a or $\sum L_t$
- Mechanisms for speed-up/slow down:
  - Positive feedback speeds up the process (for site of sufficient quality)
  - Distractors cause delays $\rightarrow$ extra time for search
  - Close-quality sites cause delays $\rightarrow$ "deliberation"

Swarm "cognition"

- Unit of cognition = bee (neuron)
  - Signals
  - Network
- "Internal model" of problem domain
  - Neural image
  - Group memory?



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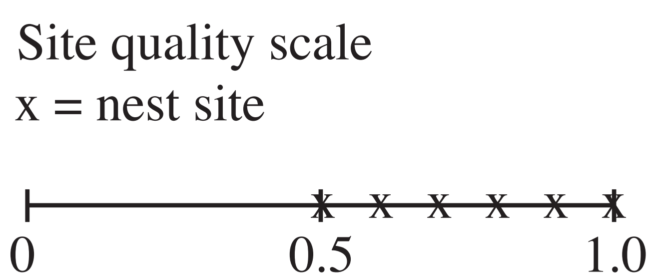
Using group memory

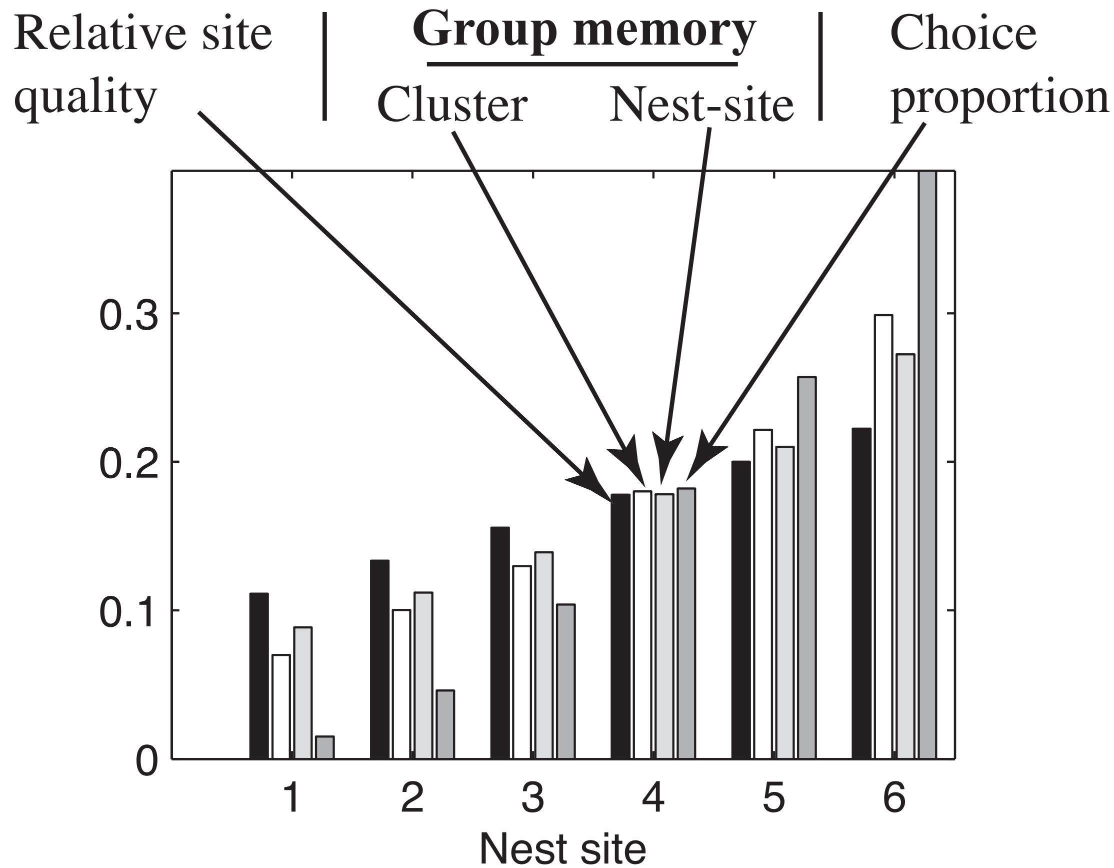
- ➜ Individual samples of group memory are inaccurate
- ➜ Distributed *multipurpose* group memory:
  1. Explore/recruit decision based on *total* amount of dancing
  2. Proportion of recruits to each site = proportion of dances for site
  3. *Self-referential* quorum sensing (estimates)
- ★ Group sampling of group memory is accurate!

Group memory, simulations/evaluation

- Relative site quality: $N^j / \sum_j N^j$
- Cluster: $E[\sum_k \sum_i L^{ij}(k)]$ for j, relative mean
- Nest sites: $E[\max_k B(j,k)]$ for site j, relative mean
- Choice proportion

Choice test pattern



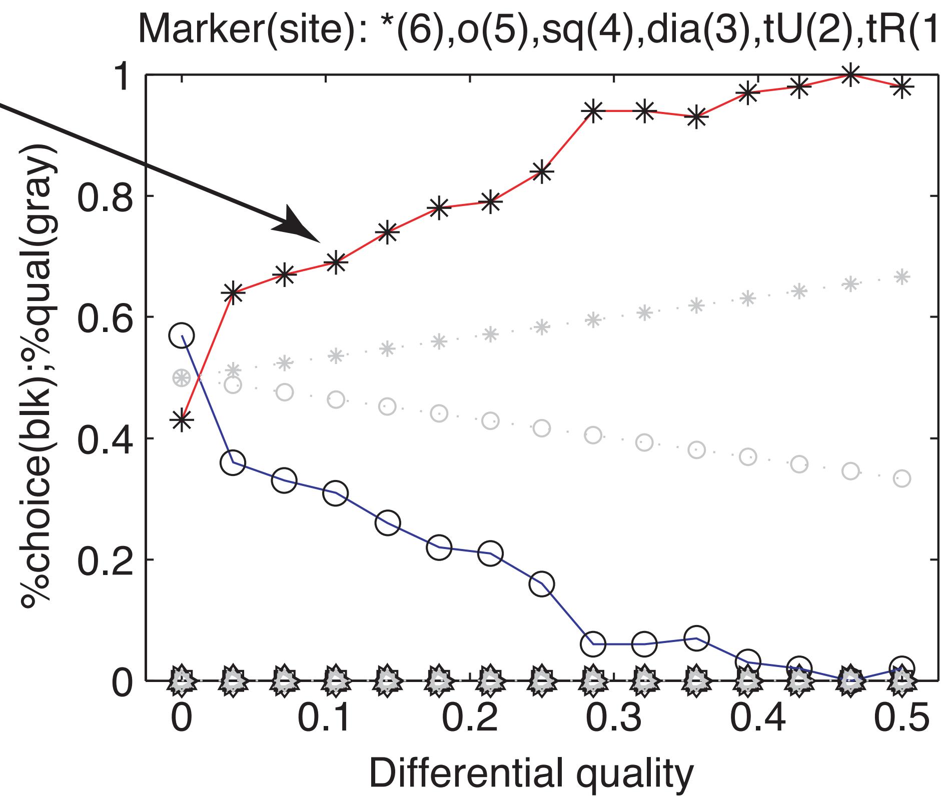


Emergence

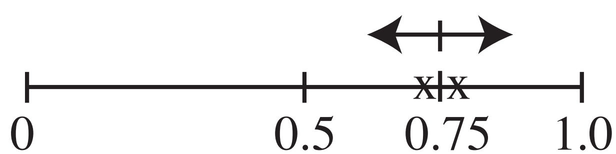
- Swarm knowledge = $\sum$ bee knowledge + $\sum$ bee locations/actions
- Individual bees do not know the emergent dynamics or choice

Swarm choice test #1: Discrimination

Low absolute quality amplifies effect
Overcomes individual assessment noise

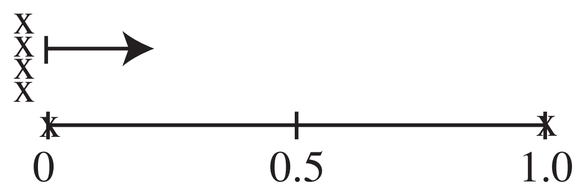


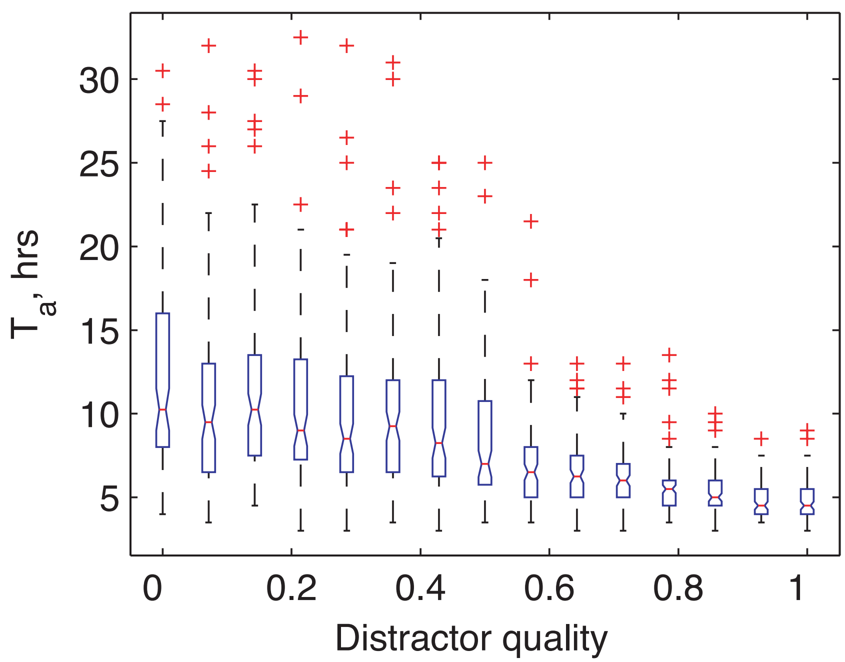
Site quality pattern

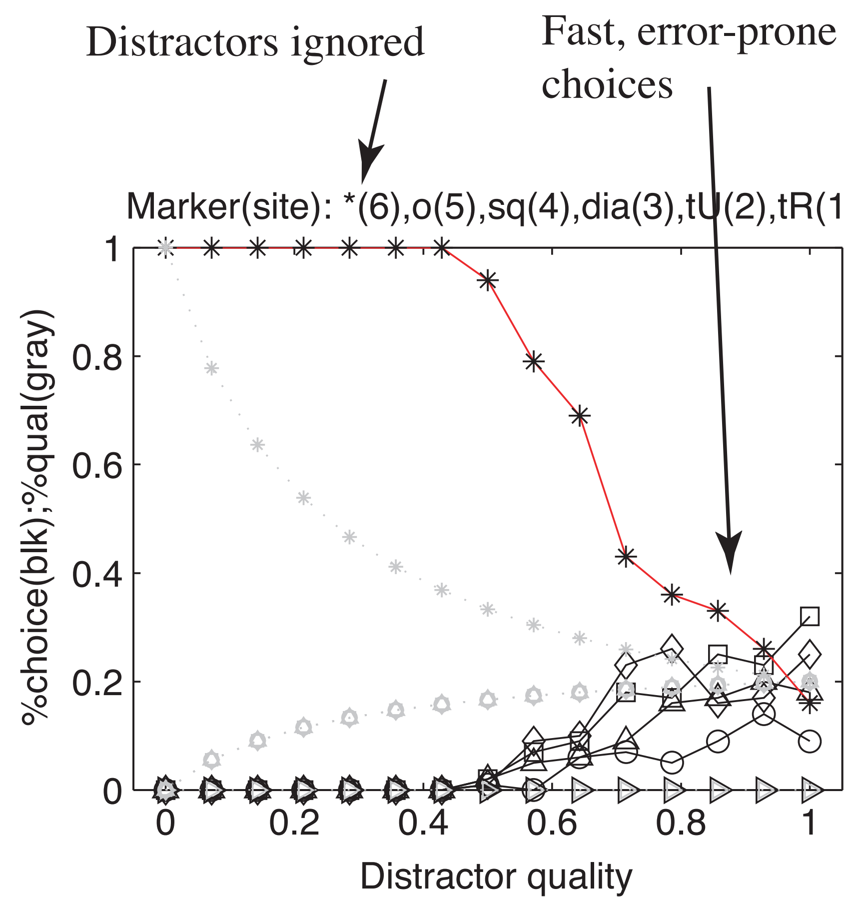


Swarm choice test #2: Distraction

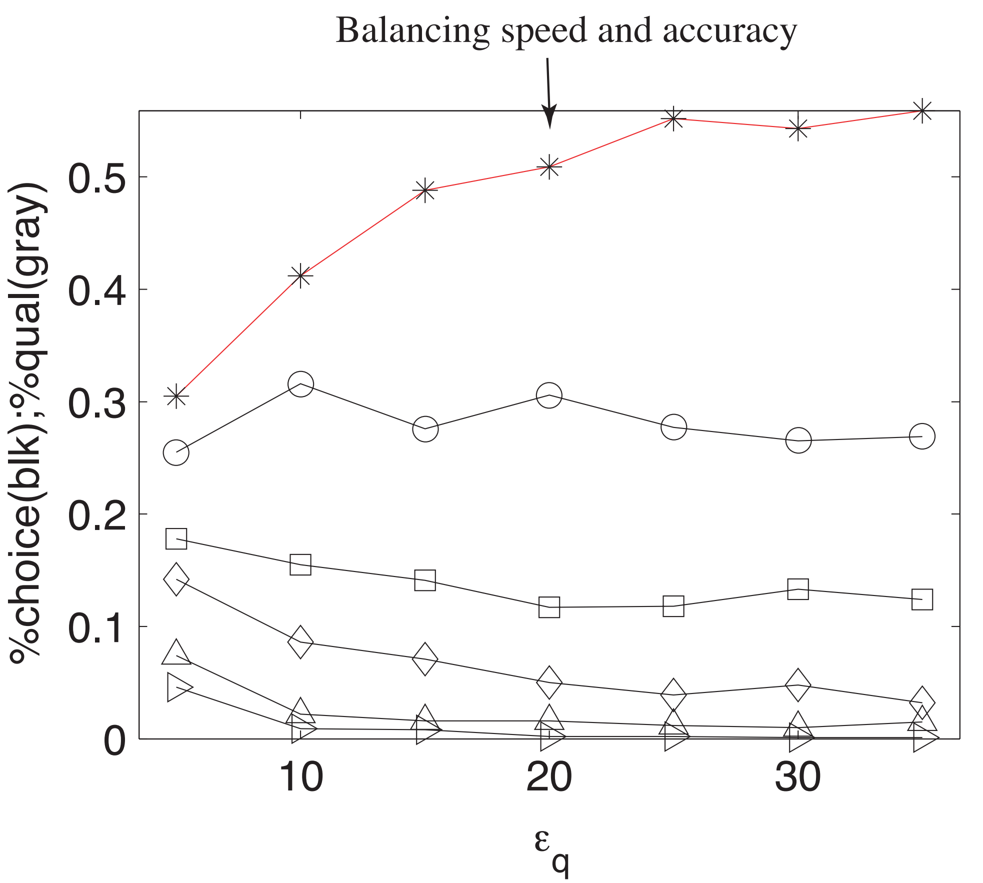
Site quality pattern

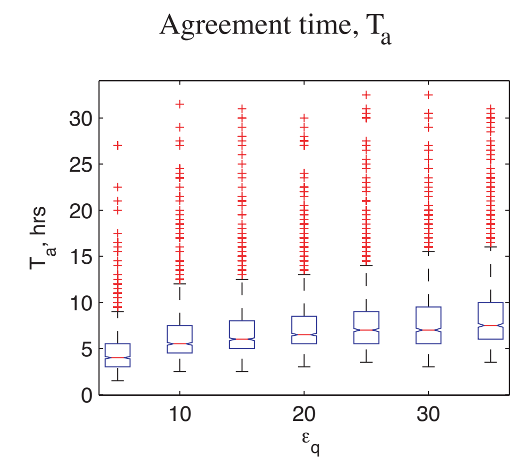


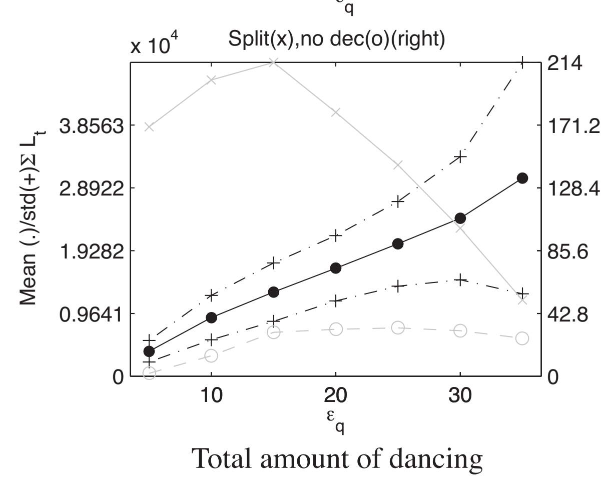




Adaptation: Quorum threshold ϵ_q



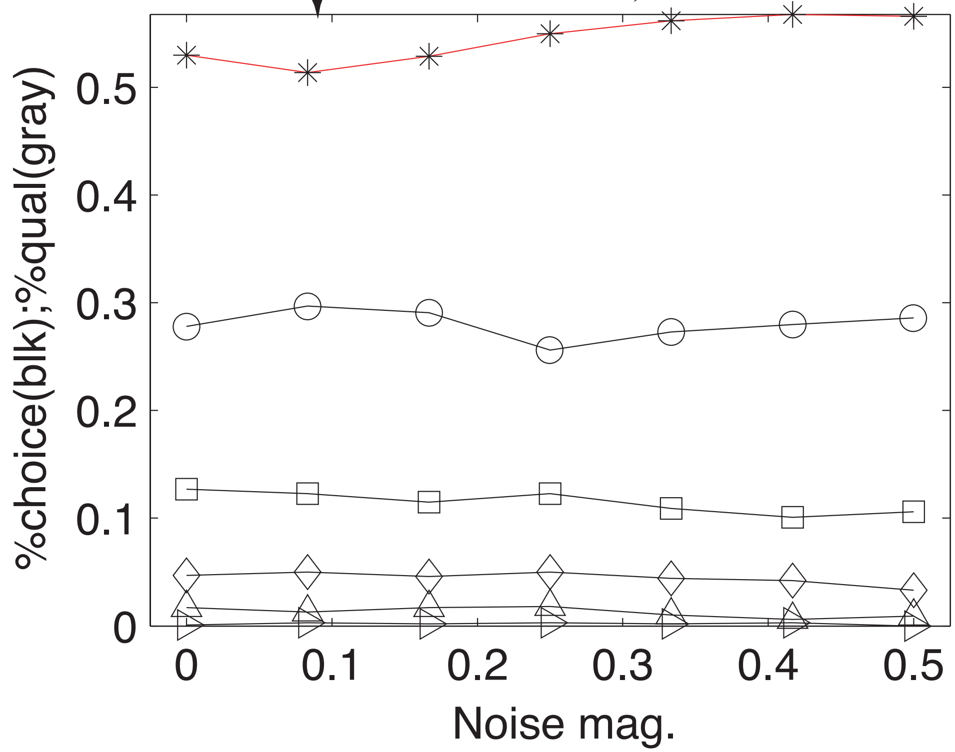




Bee assessment noise magnitude

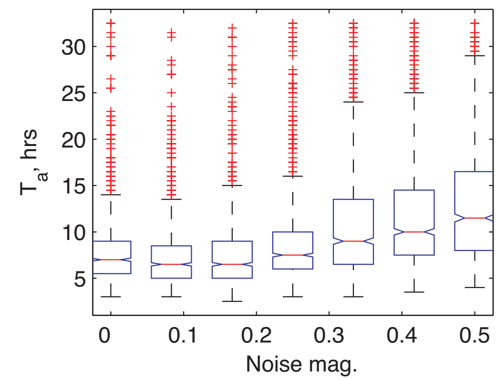
Swarm choice performance largely unaffected!

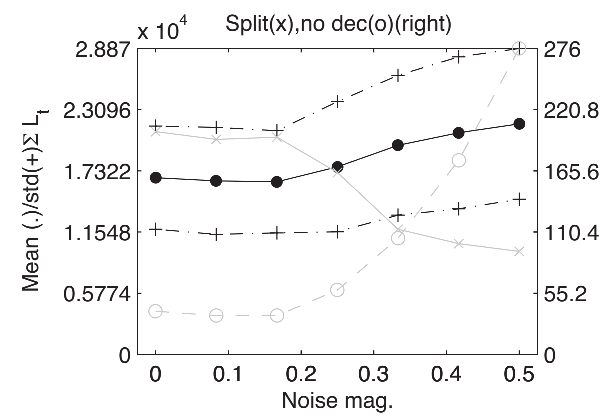
Balancing speed and accuracy



Noise - deliberation...

Agreement time, T_a





Total amount of dancing

Mathematical analysis:
Overview of in-progress work

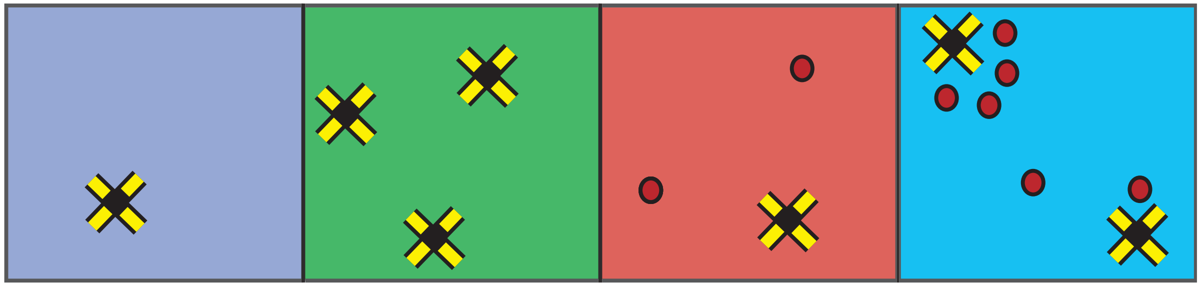
- Modeling approaches:
  1. Ordinary differential equations
  2. Distributed/asynchronous discrete event systems

Analytical challenges (Nevai)

1. One site: Minimum site quality level to achieve quorum? $E[T_a]$?
2. Two sites: Site quality & discovery time difference impact on $P(Correct\,choice)$ and $E[T_a]$?
3. Multiple sites: Number of distractors impact on $P(Correct\,choice)$ and $E[T_a]$?
4. *Optimal* search/selection strategy?

Related engineering challenge (Moore, Schumacher)

➔ Cooperative search and selection: Low/poor information, speed/accuracy trade-offs



✔ Modeling/analysis: Related to the bees!

- Financial support: AFOSR/AFRL OSU "Collaborative Center of Control Science" (CCCS)

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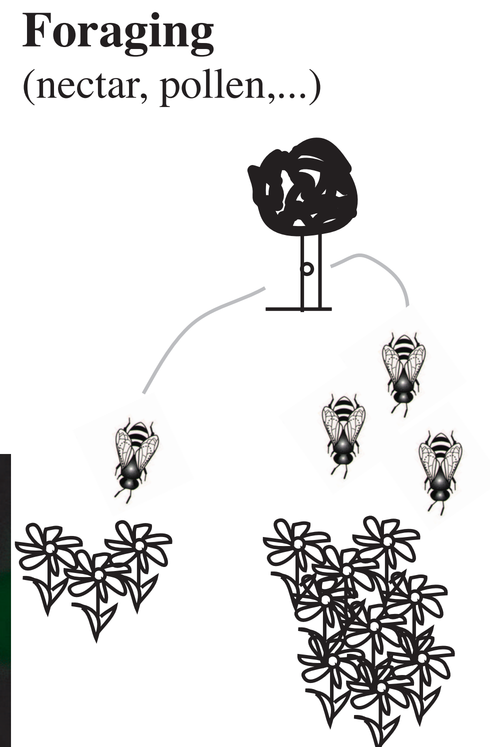
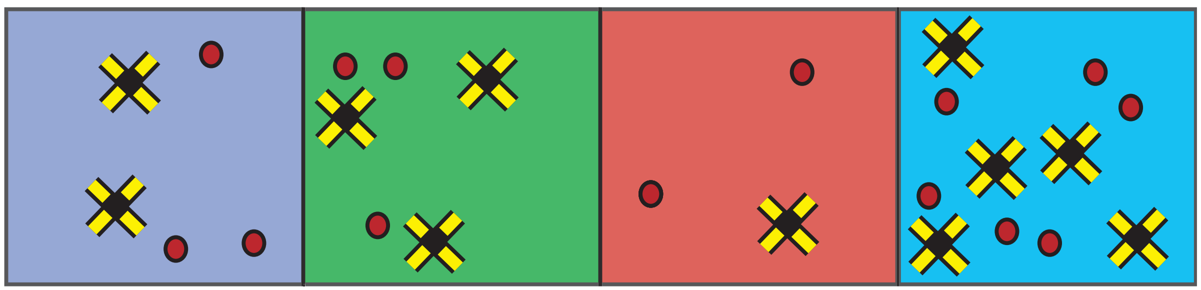
Other challenges, social foraging (Seeley)



- ➜ Modeling/analysis: Stable, optimal distribution

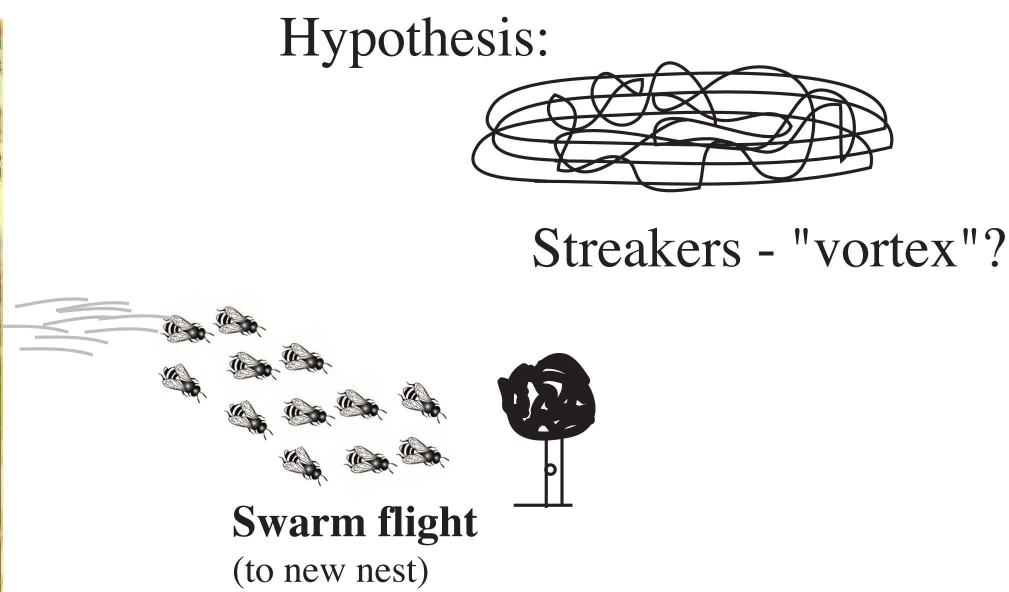
Related engineering challenge (Finke)

- ➔ Cooperative prioritized surveillance: Low/poor information, fast/optimal vehicle distributions



- ✔ Modeling/analysis: Stability of vehicle distribution, design

Other challenges, flying bee swarms (Schultz/Seeley)



- Modeling/analysis: Cohesiveness, regulation
- Relevance to coordinated vehicle group motion?
  Weak/doubtful!

Concluding remarks

- ✔ New challenges of systems biology of decision making
- ✔ Honey bee swarm "group cognition"
  1. Distributed decision making dynamics
  2. Behavioral tests, adaptation
- ✔ Mathematical analysis overview
- ✔ Related problems in biology and engineering

Biological problems & solutions =

Technological problems & solutions?

Absolutely not!

But, general mathematical modeling and analysis can apply to both.

Learn from nature?

Richard Feynman, physicist:

"The imagination of nature is far, far greater than the imagination of man."

Enriching distributed decision-making...

- ✔ Examples of what is possible
- ✔ Principles of robust/optimal design
- ✔ **Glimpses of beautiful (optimal/robust) complex system "designs"**