Part B
Ants (Natural and Artificial)

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Real Ants

(especially the black garden ant, *Lasius niger*)

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Adaptive Significance

- Selects most profitable from array of food sources
- Selects shortest route to it
  - longer paths abandoned within 1–2 hours
- Adjusts amount of exploration to quality of identified sources
- Collective decision making can be as accurate and effective as some vertebrate individuals

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Observations on Trail Formation

- Two equal-length paths presented at same time: ants choose one at random
- Sometimes the longer path is initially chosen
- Ants may remain "trapped" on longer path, once established
- Or on path to lower quality source, if it's discovered first
- But there may be advantages to sticking to paths
  - easier to follow
  - easier to protect trail & source
  - safer

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Process of Trail Formation

1. Trail laying
2. Trail following

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Trail Laying

- On discovering food, forager lays chemical trail while returning to nest
  - only ants who have found food deposit pheromone
- Others stimulated to leave nest by:
  - the trail
  - the recruitor exciting nestmates (sometimes)
- In addition to defining trail, pheromone:
  - serves as general orientation signal for ants outside nest
  - serves as arousal signal for ants inside

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Additional Complexities

- Some ants begin marking on return from discovering food
- Others on their first return trip to food
- Others not at all, or variable behavior
- Probability of trail laying decreases with number of trips

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Frequency of Trail Marking

- Ants modulate frequency of trail marking
- May reflect quality of source
  - hence more exploration if source is poor
- May reflect orientation to nest
  - ants keep track of general direction to nest
  - and of general direction to food source
  - trail laying is less intense if the angle to homeward direction is large

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Trail Following

- Ants preferentially follow stronger of two trails
  - show no preference for path they used previously
- Ant may double back, because of:
  - decrease of pheromone concentration
  - unattractive orientation

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Probability of Choosing One of Two Branches

- Let C_L and C_R be units of pheromone deposited on left & right branches
- Let P_L and P_R be probabilities of choosing them
- Then:

$$P_L = \frac{(C_L + 6)^2}{(C_L + 6)^2 + (C_R + 6)^2}$$

- Nonlinearity amplifies probability

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Additional Adaptations

- If a source is crowded, ants may return to nest or explore for other sources
- New food sources are preferred if they are near to existing sources
- Foraging trails may rotate systematically around a nest

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Pheromone Evaporation

- Trails can persist from several hours to several months
- Pheromone has mean lifetime of 30-60 min.
- But remains detectable for many times this
- Long persistence of pheromone prevents switching to shorter trail
- Artificial ant colony systems rely more heavily on evaporation

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Resnick's Ants

Environment

- Nest emits *nest-scent*, which
  - diffuses uniformly
  - decays slowly
  - provides general orientation signal
  - by diffusing around barriers, shows possible paths around barriers
- Trail pheromone
  - emitted by ants carrying food
  - diffuses uniformly
  - decays quickly
- Food detected only by contact

Resnick Ant Behavior

1. Looking for food:
   if trail pheromone weak **then** wander
   else move toward increasing concentration
2. Acquiring food:
   if at food **then**
   pick it up, turn around, & begin depositing pheromone
3. Returning to nest:
   deposit pheromone & decrease amount available
   move toward increasing nest-scent
4. Depositing food:
   if at nest **then**
   deposit food, stop depositing pheromone, & turn around
5. Repeat forever

Demonstration of Resnick Ants

Run Ants.nlogo

Ant Colony Optimization (ACO)

Developed in 1991 by Dorigo (PhD dissertation) in collaboration with Colorni & Maniezzo

Basis of all Ant-Based Algorithms

- Positive feedback
- Negative feedback
- Cooperation

Positive Feedback

- To reinforce portions of good solutions that contribute to their goodness
- To reinforce good solutions directly
- Accomplished by *pheromone accumulation*

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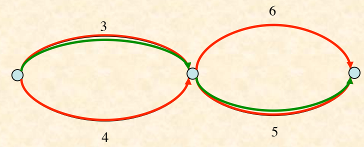
Reinforcement of Solution Components



Parts of good solutions *may* produce better solutions

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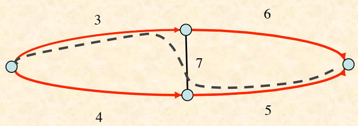
Negative Reinforcement of Non-solution Components



Parts not in good solutions *tend* to be forgotten

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Negative Feedback

- To avoid premature convergence (*stagnation*)
- Accomplished by *pheromone evaporation*

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Cooperation

- For simultaneous exploration of different solutions
- Accomplished by:
  - *multiple ants* exploring solution space
  - *pheromone trail* reflecting multiple perspectives on solution space

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Traveling Salesman Problem

- Given the travel distances between N cities
  - may be symmetric or not
- Find the shortest route visiting each city exactly once and returning to the starting point
- NP-hard
- Typical combinatorial optimization problem

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Ant System for Traveling Salesman Problem (AS-TSP)

- During each iteration, each ant completes a tour
- During each tour, each ant maintains *tabu list* of cities already visited
- Each ant has access to
  - distance of current city to other cities
  - intensity of local pheromone trail
- Probability of next city depends on both

Transition Rule

- Let $\eta_{ij} = 1/d_{ij}$ = "nearness" of city j to current city i
- Let τ_{ij} = strength of trail from i to j
- Let J_i^k = list of cities ant k still has to visit after city i in current tour
- Then transition probability for ant k going from i to $j \in J_i^k$ in tour t is:

$$p_{ij}^k = \frac{\left[\tau_{ij}(t)\right]^\alpha \left[\eta_{ij}\right]^\beta}{\sum_{l \in J_i^k} \left[\tau_{il}(t)\right]^\alpha \left[\eta_{il}\right]^\beta}$$

Pheromone Deposition

- Let $T^k(t)$ be tour t of ant k
- Let $L^k(t)$ be the length of this tour
- After completion of a tour, each ant k contributes:

$$\Delta\tau_{ij}^k = \begin{cases} Q/L^k(t) & \text{if } (i,j) \in T^k(t) \\ 0 & \text{if } (i,j) \notin T^k(t) \end{cases}$$

Pheromone Decay

- Define total pheromone deposition for tour t:

$$\Delta\tau_{ij}(t) = \sum_{k=1}^m \Delta\tau_{ij}^k(t)$$

- Let ρ be decay coefficient
- Define trail intensity for next round of tours:

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t)$$

Number of Ants is Critical

- Too many:
  - suboptimal trails quickly reinforced
  - ∴ early convergence to suboptimal solution
- Too few:
  - don't get cooperation before pheromone decays
- Good tradeoff:
  number of ants = number of cities
  ($m = n$)

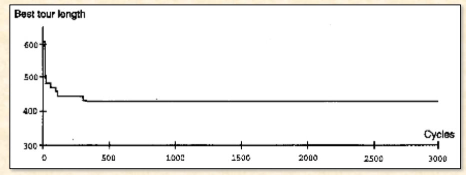
Improvement: "Elitist" Ants

- Add a few ($e \approx 5$) "elitist" ants to population
- Let T^+ be best tour so far
- Let L^+ be its length
- Each "elitist" ant reinforces edges in T^+ by Q/L^+
- Add e more "elitist" ants
- This applies accelerating positive feedback to best tour

Time Complexity

- Let t be number of tours
- Time is $\mathcal{O}(tn^2m)$
- If $m = n$ then $\mathcal{O}(tn^3)$
  - that is, cubic in number of cities

Convergence



- 30 cities ("Oliver30")
- Best tour length
- Converged to optimum in 300 cycles

fig. < Dorigo et al. (1996)

Evaluation

- Both "very interesting and disappointing"
- For 30-cities:
  - beat genetic algorithm
  - matched or beat tabu search & simulated annealing
- For 50 & 75 cities and 3000 iterations
  - did not achieve optimum
  - but quickly found good solutions
- I.e., does not scale up well
- Like all general-purpose algorithms, it is out-performed by special purpose algorithms

Improving Network Routing

1. Nodes periodically send *forward ants* to some recently recorded destinations
2. Collect information on way
3. Die if reach already visited node
4. When reaches destination, estimates time and turns into *backward ant*
5. Returns by same route, updating routing tables

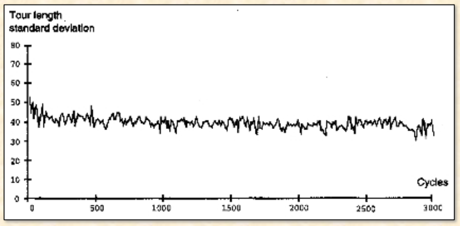
Some Applications of ACO

- Routing in telephone networks
- Vehicle routing
- Job-shop scheduling
- Constructing evolutionary trees from nucleotide sequences
- Various classic NP-hard problems
  - shortest common supersequence, graph coloring, quadratic assignment, …

Improvements as Optimizer

- Can be improved in many ways
- E.g., combine local search with ant-based methods
- As method of stochastic combinatorial optimization, performance is promising, comparable with best heuristic methods
- Much ongoing research in ACO
- But optimization is not a principal topic of this course

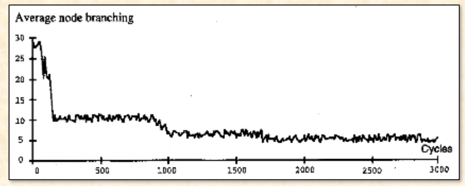
Nonconvergence



- Standard deviation of tour lengths
- Optimum = 420

fig. < Dorigo et al. (1996)

Average Node Branching Number



- Branching number = number of edges leaving a node with pheromone > threshold
- Branching number = 2 for fully converged solution

fig. < Dorigo et al. (1996)

The Nonconvergence Issue

- AS often does not converge to single solution
- Population maintains high diversity
- A bug or a feature?
- Potential advantages of nonconvergence:
  - avoids getting trapped in local optima
  - promising for dynamic applications
- Flexibility & robustness are more important than optimality in natural computation

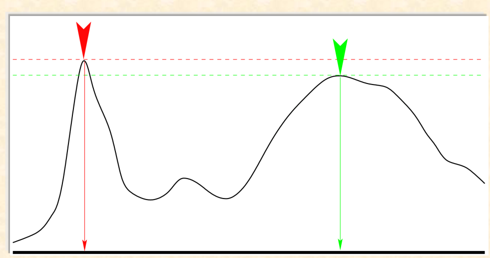
Natural Computation

Natural computation is computation that occurs in nature or is inspired by computation occurring in nature

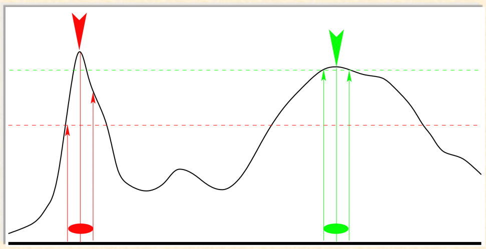
Optimization in Natural Computation

- Good, but suboptimal solutions may be preferable to optima if:
  - suboptima can be obtained more quickly
  - suboptima can be adapted more quickly
  - suboptima are more robust
  - an ill-defined suboptimum may be better than a sharp optimum
- "The best is the enemy of the good"
  (*Le mieux est l'ennemi du bien*. – Voltaire)

Robust Optima



Effect of Error/Noise



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