Prey Modeling in Predator/Prey Interaction: Risk Avoidance, Group Foraging, and Communication

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Decision, Dynamics and Control in Multi-Agent Systems

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Outline

- Introduction
  - The HUNT Project
  - Why Form A Team?
  - Communication
  - Focus & Motivation
- Risk Avoidance within a Group: Domain of Danger
  - Domain of Danger
  - Limited Domain of Danger
  - Movement Rule Based on Selfish Herd Assumption
  - A Better Movement Rule
  - Greedily Shrink the Domain of Danger
- Trade-off between Risk Avoidance and Foraging
  - Greedy Foraging and De-confliction
  - Different Movement Rules
  - Performance of Different Movement Rules
  - Summary
- Future Work

The HUNT Project

- The **H**eterogeneous **U**nmanned **N**etworked **T**eam (HUNT) project is a multi-university project funded by Office of Naval Research (ONR).
- The goal of the project is to study the mechanism behind cooperative teams in animal kingdom, and apply theses insights on autonomous agent teams in various scenarios.

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ONR
Revolutionary Research . . . Relevant Results

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Why Do Predators Form a Team?

- Group Hunting
  - Teams can be more successful hunting than individuals, e.g. bring down bigger prey
  - Lower risk for each individual
  - Role specialization in some cases

Why Do Prey Form a Team?

- Predator Avoidance
  - Sharing of predation risk
    - Dilution Effect
  - Sharing of vigilance cost
  - Can be among same or different species
- Group Foraging
  - Sharing information
    - Communicate to one another the location of available food
  - Also comes with in-group competition

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Communication

- Communication can take several forms:
  - Audio
  - Visual
  - Chemical
- Within the same species
  - Location of prey and coordinate hunting strategies
  - Location of food
- Among same or different species
  - Presence of predators

Focus & Motivation

- We focus on the following aspects:
  - Predation risk avoidance
  - The trade-off between foraging efficiency and predation risk avoidance
  - The communication mechanism that enables the cooperation
- Good analogy to information gathering mission in risky environment for autonomous agent teams

Lioness hunting warthog, © Peter Blackwell / naturepl.com

A group of wildebeest facing an African wild dog.

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Domain of Danger

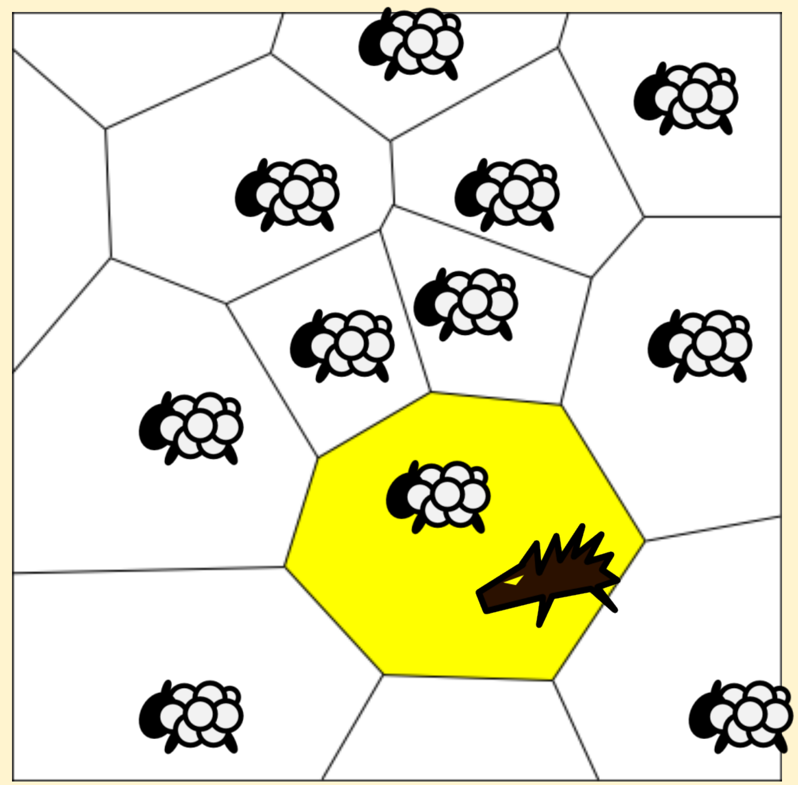
- The domain of danger idea was proposed by W. D. Hamilton in 1971 as a way to explain the gregarious behavior of animals under predation risk.
- Assumptions:
  - There is an undetected predator that can be anywhere.
  - The predator attacks the closest prey.
- Domain of danger defined to be the Voronoi polygon occupied by each agent.[1]

$$P = \{p_i \dots p_n\} \; ; \; p_i \in R^2 \text{ for } i = 1, ..., n$$

$$V(p_i) = \{x | \|x - p_i\|_2 \leq \|x - p_j\|_2, \forall j \neq i\}$$

- Measurement of relative predation risk:

$$\text{Relative Predation Risk} \propto \text{Area}(V(p_i))$$



[1] W. D. Hamilton, 1971, Geometry for the selfish herd

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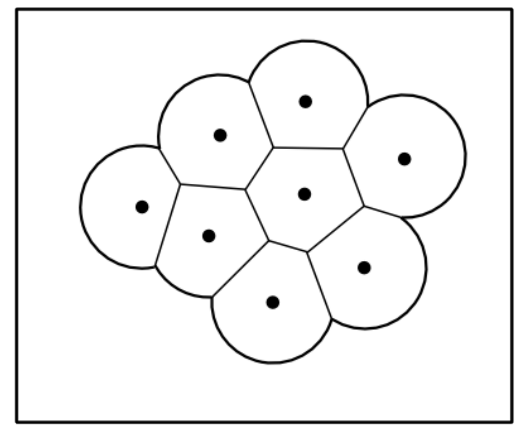
Limited Domain of Danger

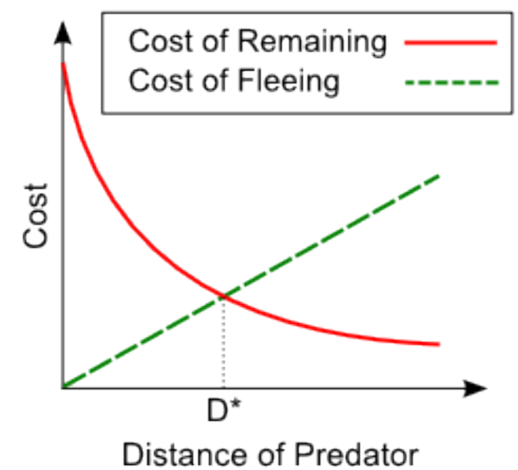
- An agent on the boundary of the group will have domain of danger that extends to infinity.
- Limited domain of danger: [2]

$$L(p_i) = \{x | \|x - p_i\|_2 \leq D^*\}$$

$$V_L(p_i) = V(p_i) \cap L(p_i)$$

- Optimal escape theory: [3]
  - Prey only start fleeing when predators are detected closer than a certain distance.

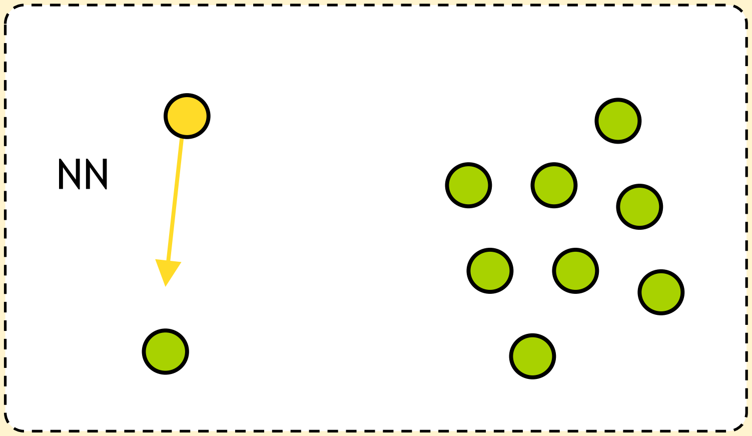


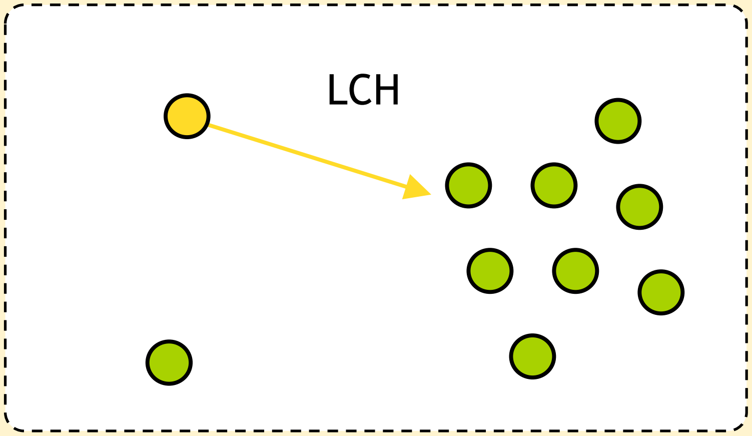


[2] James et al., 2004, Geometry for mutualistic and selfish herds: the limited domain of danger
[3] Ydenberg & Dill, 1986, The Economics of Fleeing from Predators

Movement Rules Based on Selfish Herd Assumption

- Selfish herd assumption:
  Each individual in the group tries to shrink its own domain of danger.
- Movement rules:
  - Nearest Neighbor [4]
  - Local Crowded Horizon [5]
- Resulting behavior matches data gathered from real animal groups such as fiddler crabs under predation risk [6]

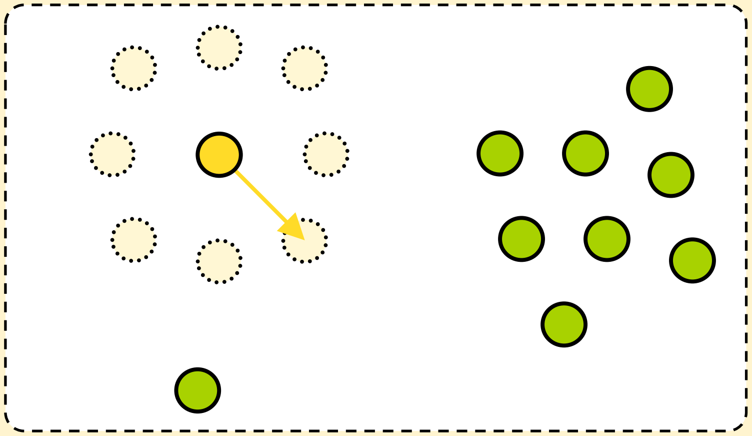


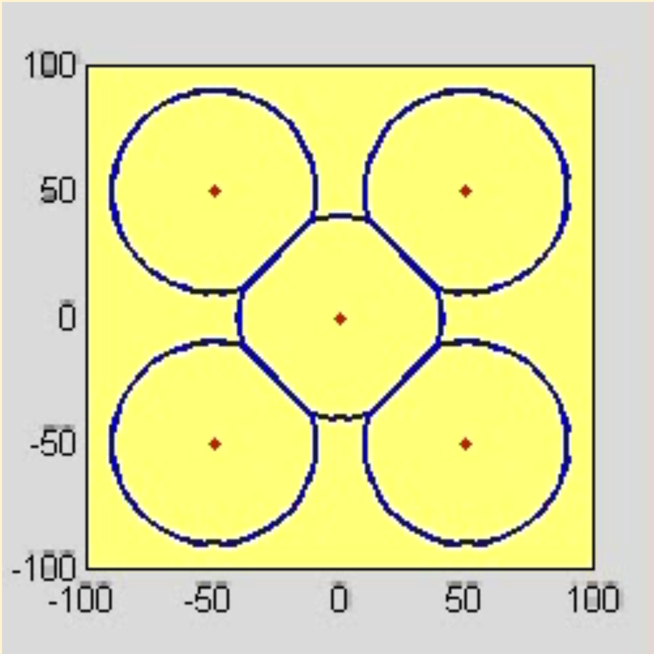


[4] W. D. Hamilton, 1971, Geometry for the selfish herd
[5] Viscido, et al., 2002, The Dilemma of the Selfish Herd: The Search for a Realistic Movement Rule
[6]STEVEN V. VISCIDO, M. MILLER, and D. S. WETHEY, "The Response of a Selfish Herd to an Attack from Outside the Group Perimeter," *Journal of Theoretical Biology*, vol. 208, no. 3, pp. 315-328, 2001.

Greedily Shrink the Domain of Danger

- We propose a movement rule to shrink the domain of danger in a greedy manner
  - Assume all other agents are stationary
  - Calculate domain of danger at some possible locations it can be at next time step
  - Move to the one with smallest domain of danger
- Agents gather together to shrink their domain of danger





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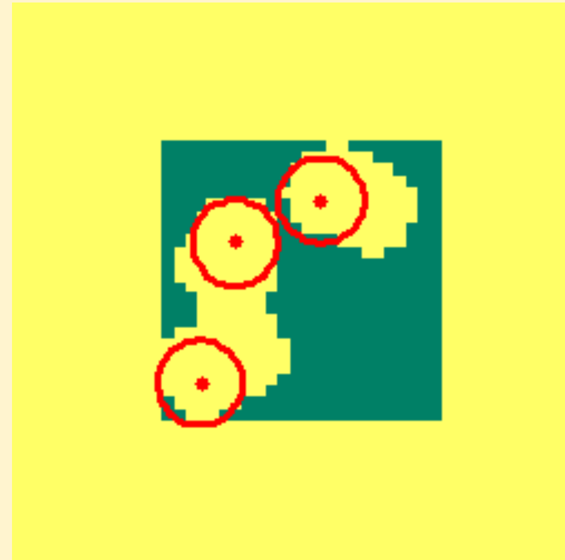
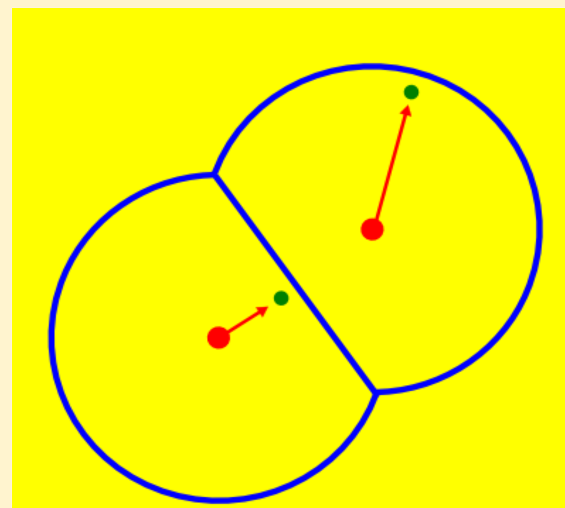
Greedy Foraging and De-confliction

- Foraging model:
  - Foraging area is divided into discrete cells
  - Each cell contains unit amount of food
  - Agents can gather all food within its foraging radius
- Greedy Approach with De-confliction
  - Agents consider all possible locations they can be at the next time step
  - Move to the location that will give the most food income
  - Using Voronoi polygon as de-confliction mechanism





With De-confliction

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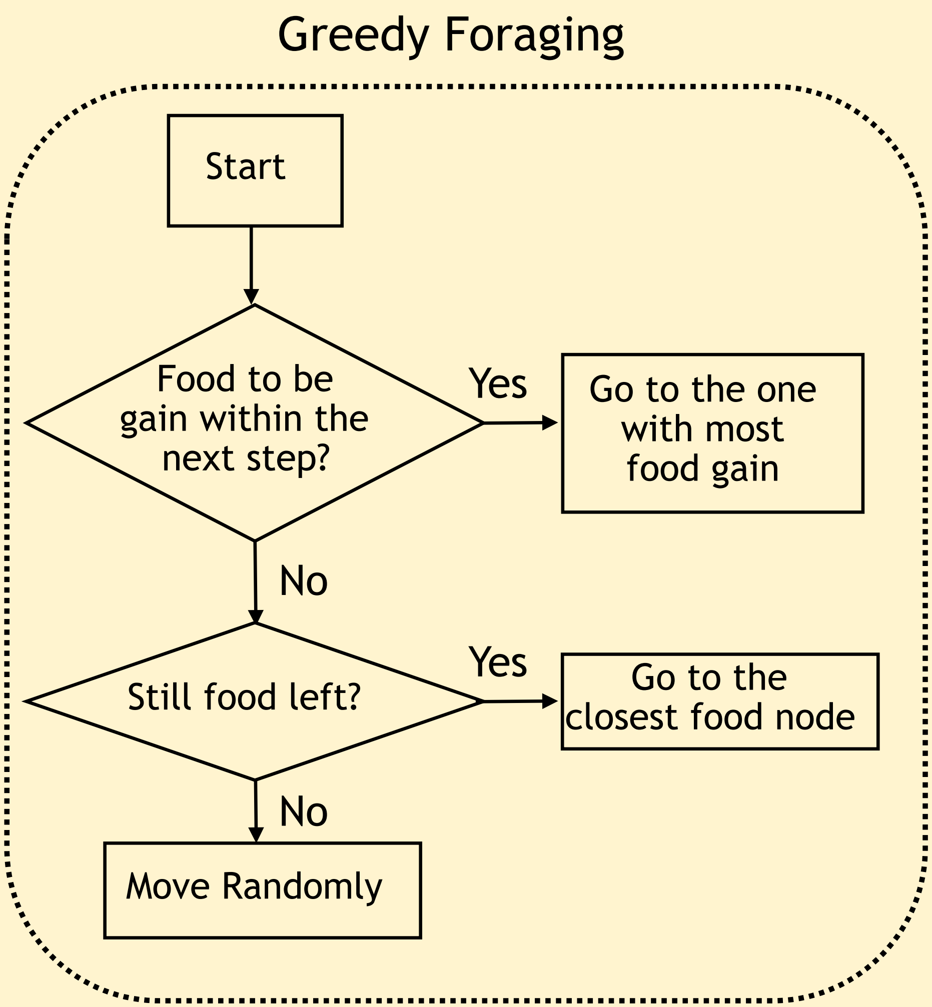
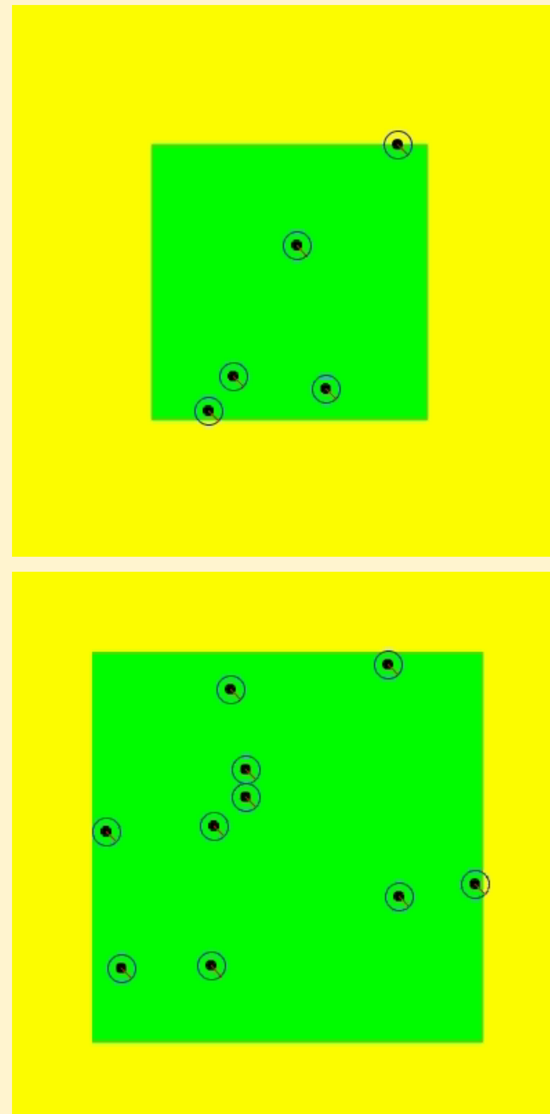
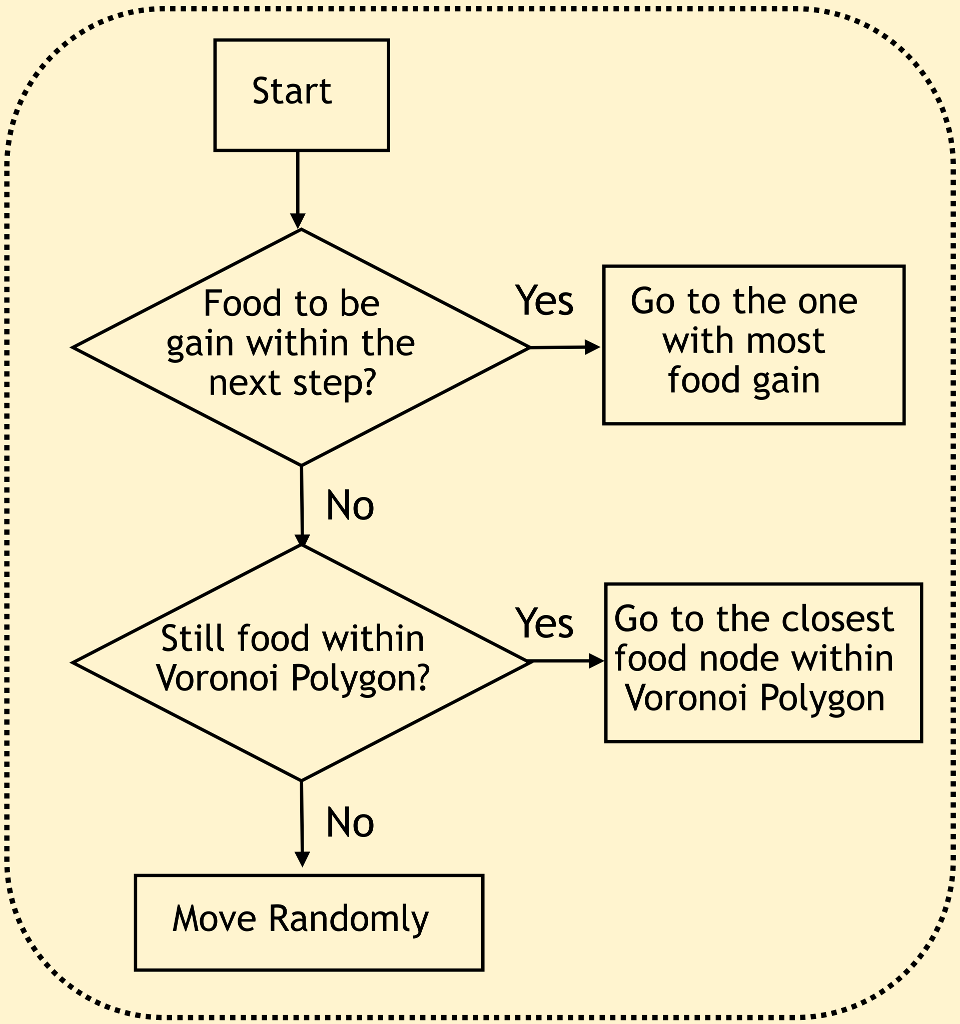
Movement Rule A: Greedy Foraging

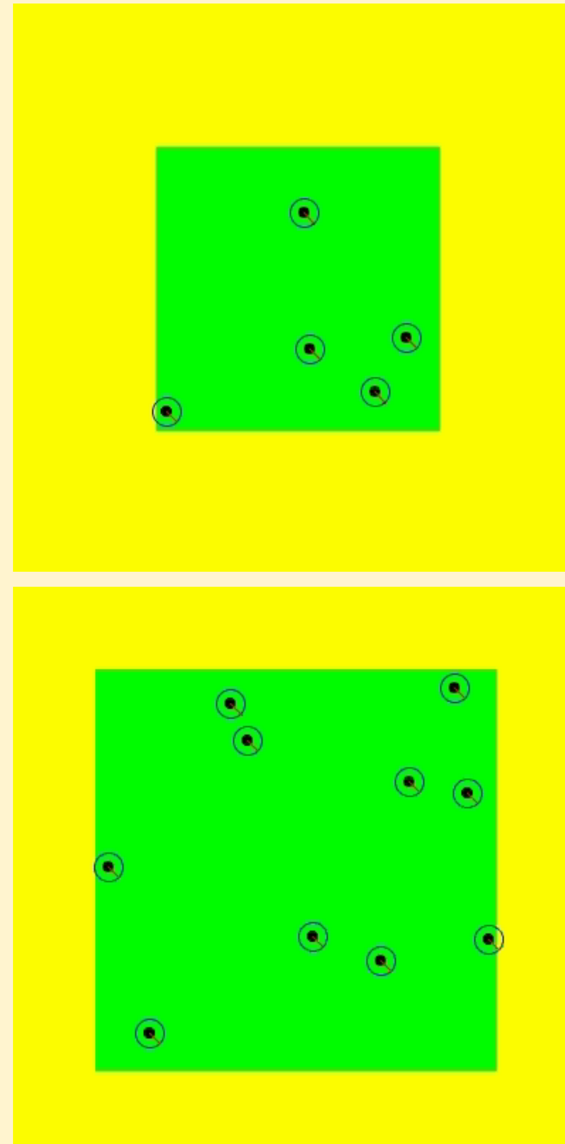




Movement Rule B:
Greedy Foraging with De-confliction

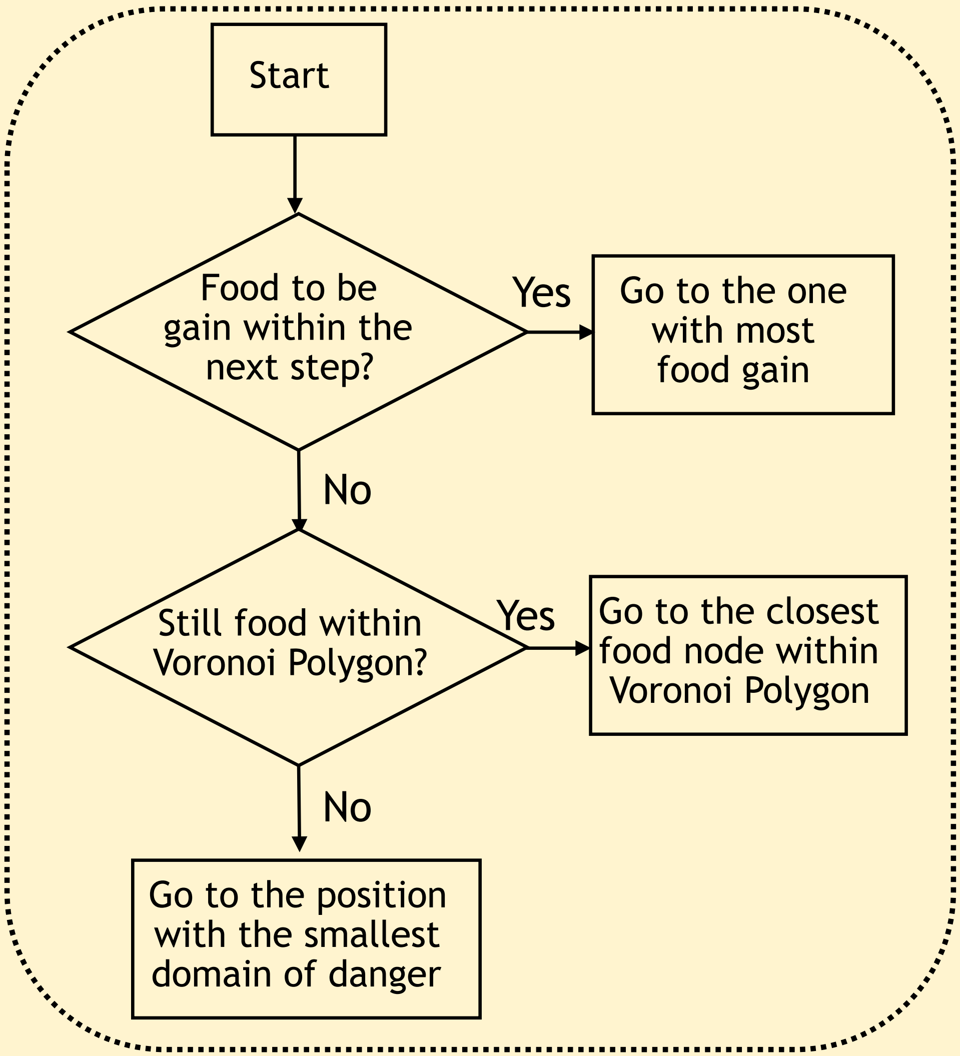
Greedy Foraging with De-confliction

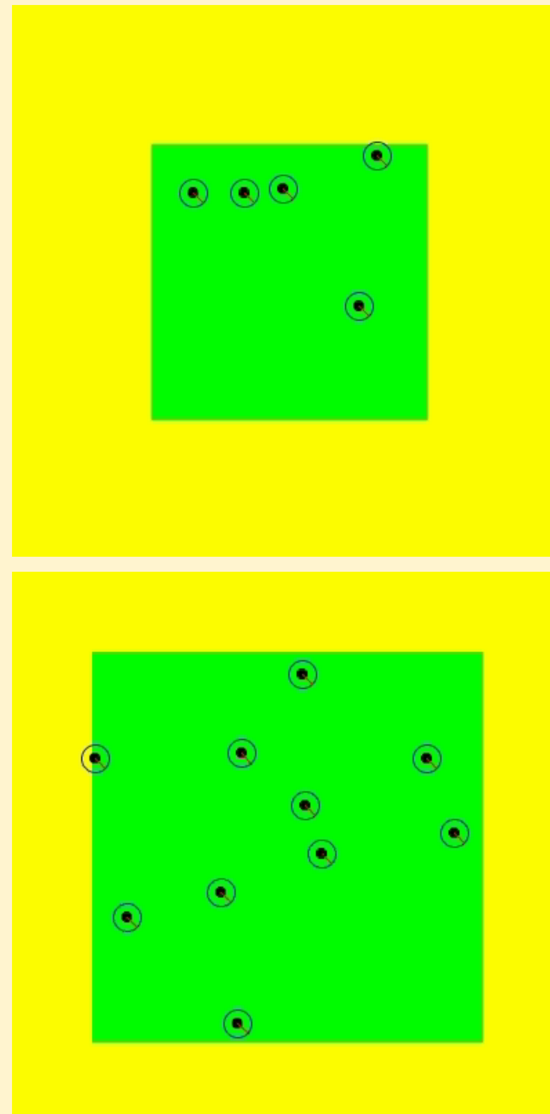




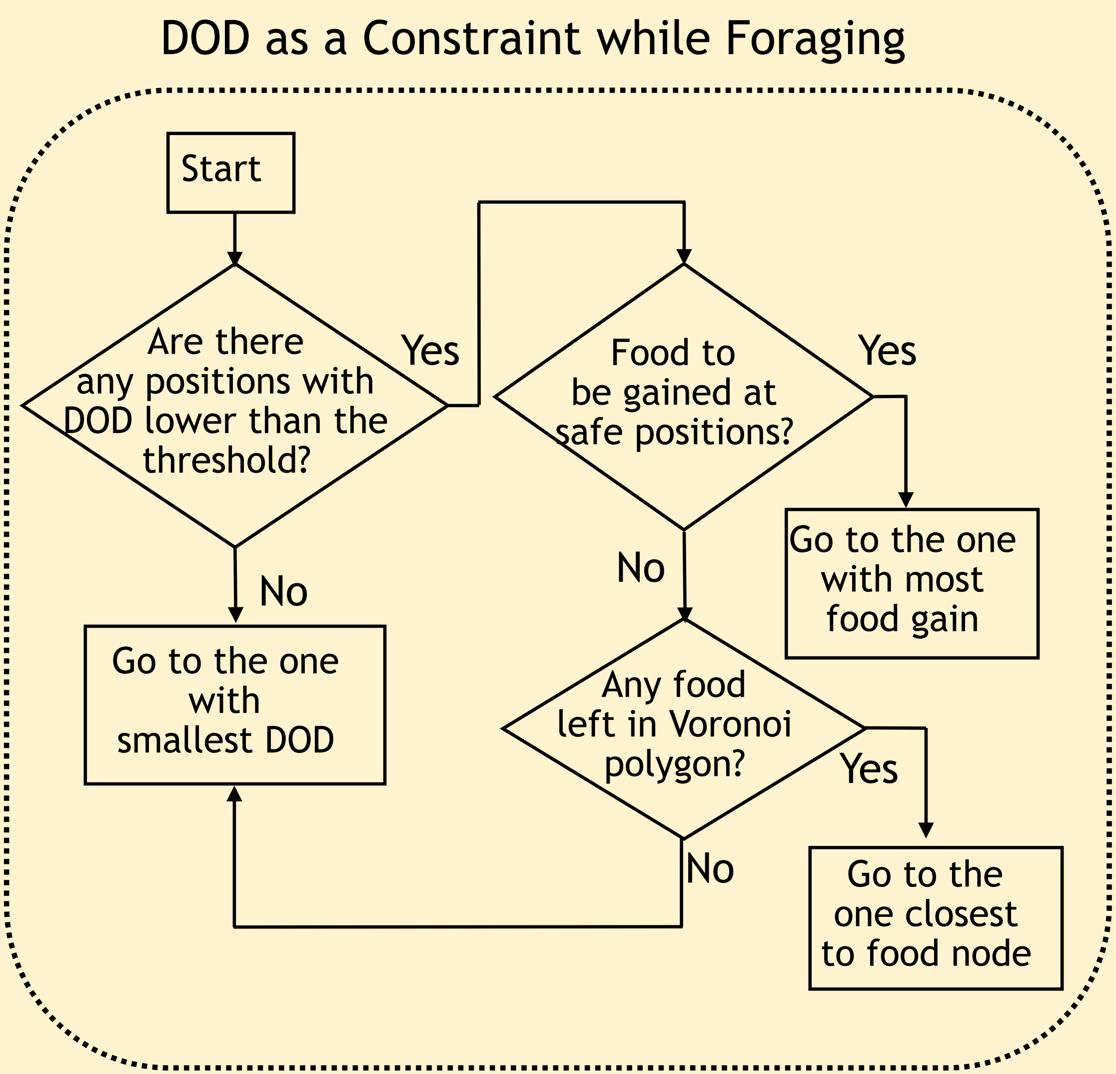
Movement Rule C: Greedy Foraging then Domain of Danger

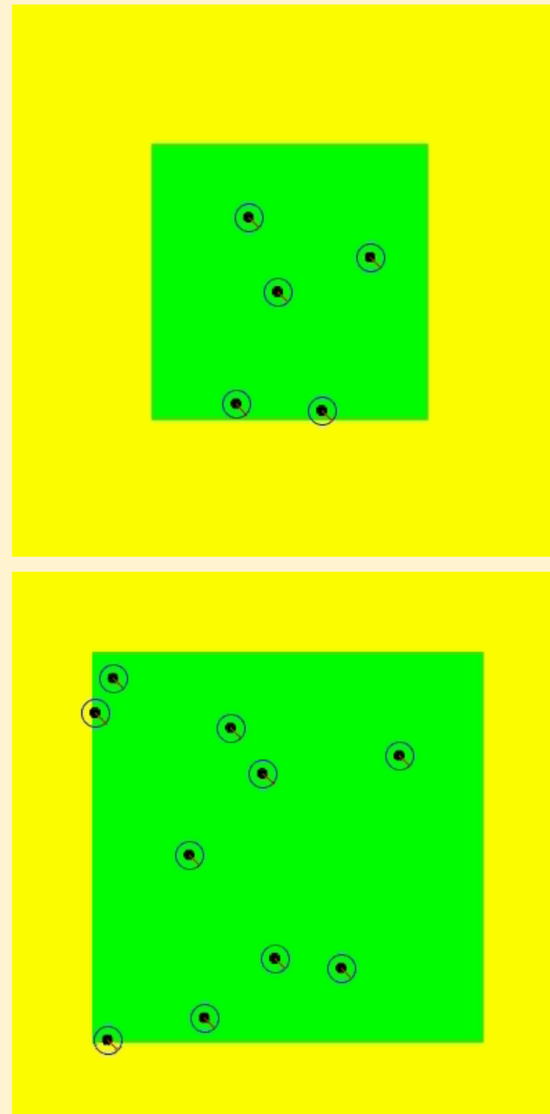
Greedy Foraging then DOD





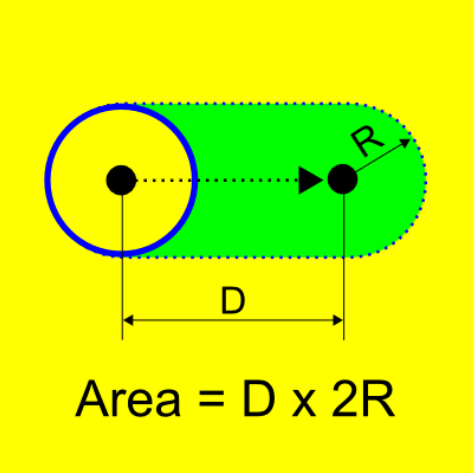
Movement Rule D:
DOD as a Constraint while Foraging



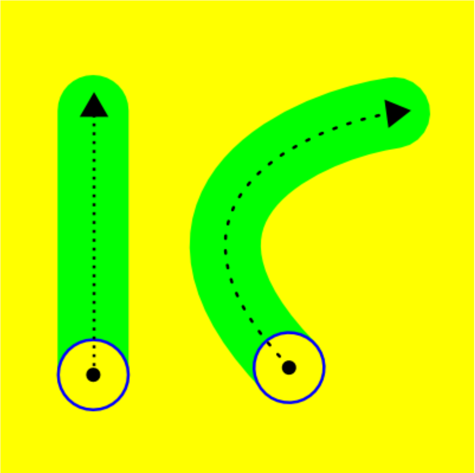


Performance of Different Movement Rules

- Ideal Optimal:
  Assuming that every agent gets the highest foraging gain at every time step
- 4 Different movement rules:
  - A: Greedy Foraging
  - B: Greedy Foraging with De-confliction
  - C: Greedy Foraging then domain of danger
  - D: Domain of Danger as a constraint while Foraging
- Performance Index:
  - Percentage of food left in the field
  - Ratio of team domain of danger to maximum possible team domain of danger

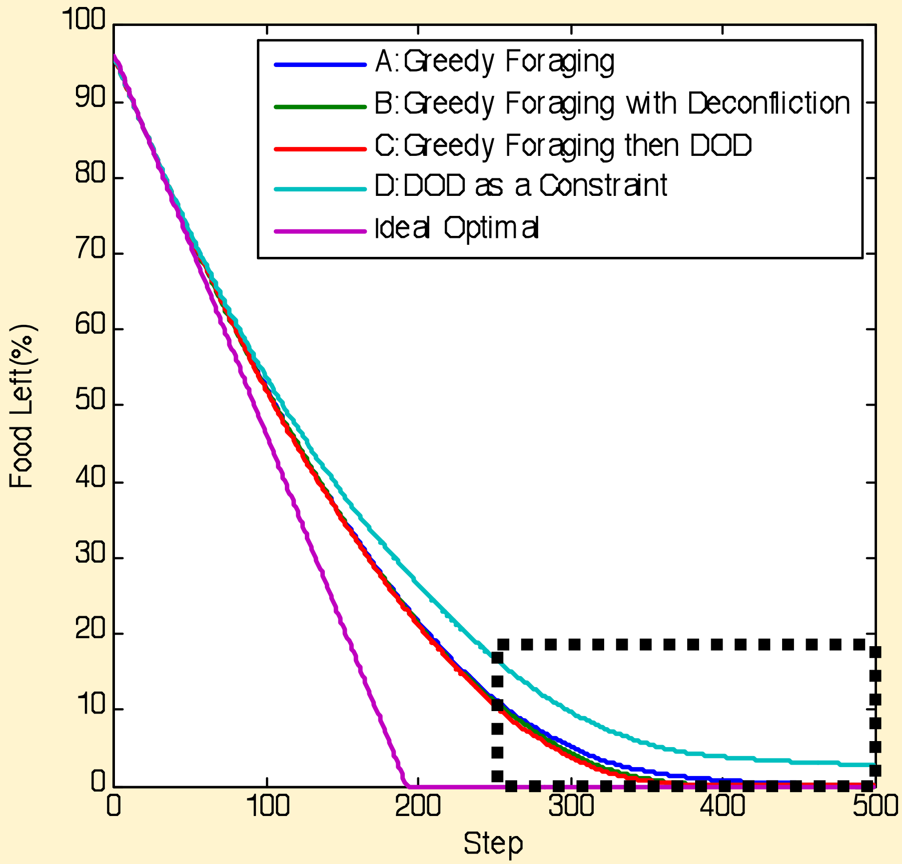


Computation of Ideal Rate

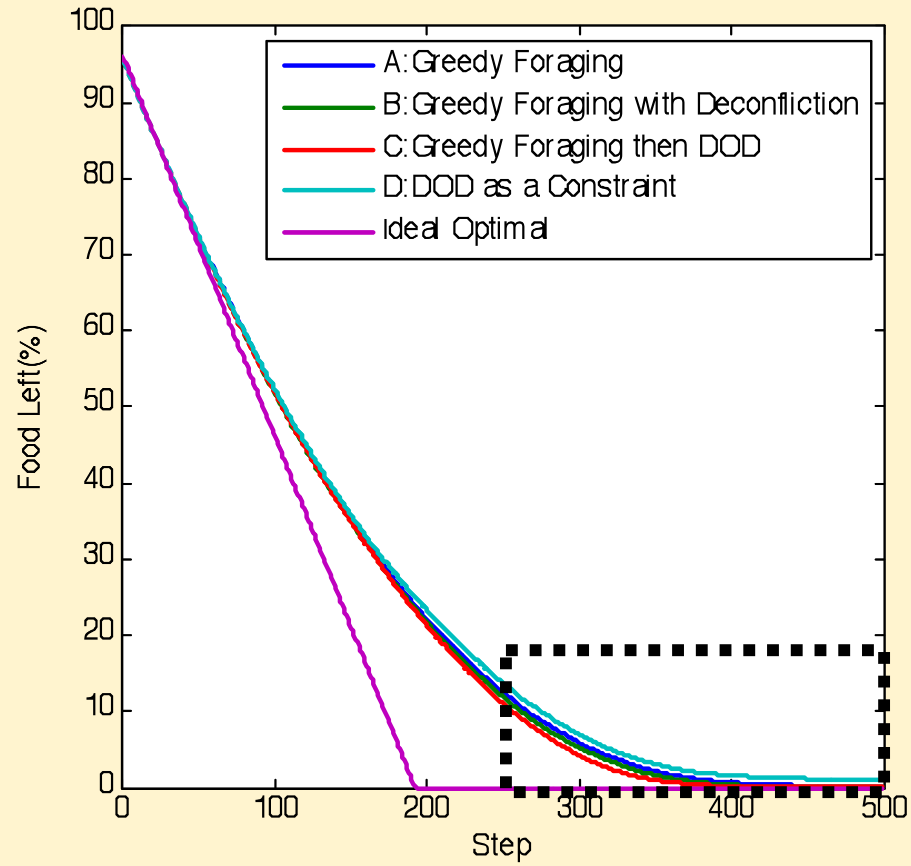


Examples where ideal optimal is possible

Foraging Efficiency

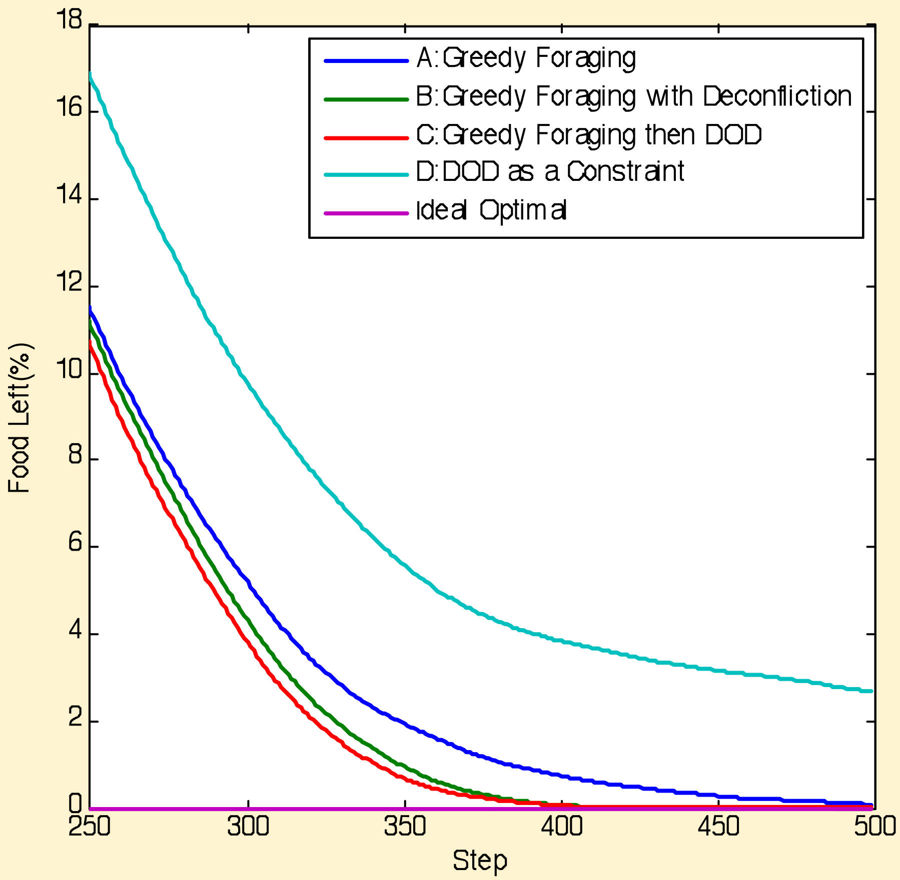


Foraging Efficiency with 5 agents
100 x 100 food nodes

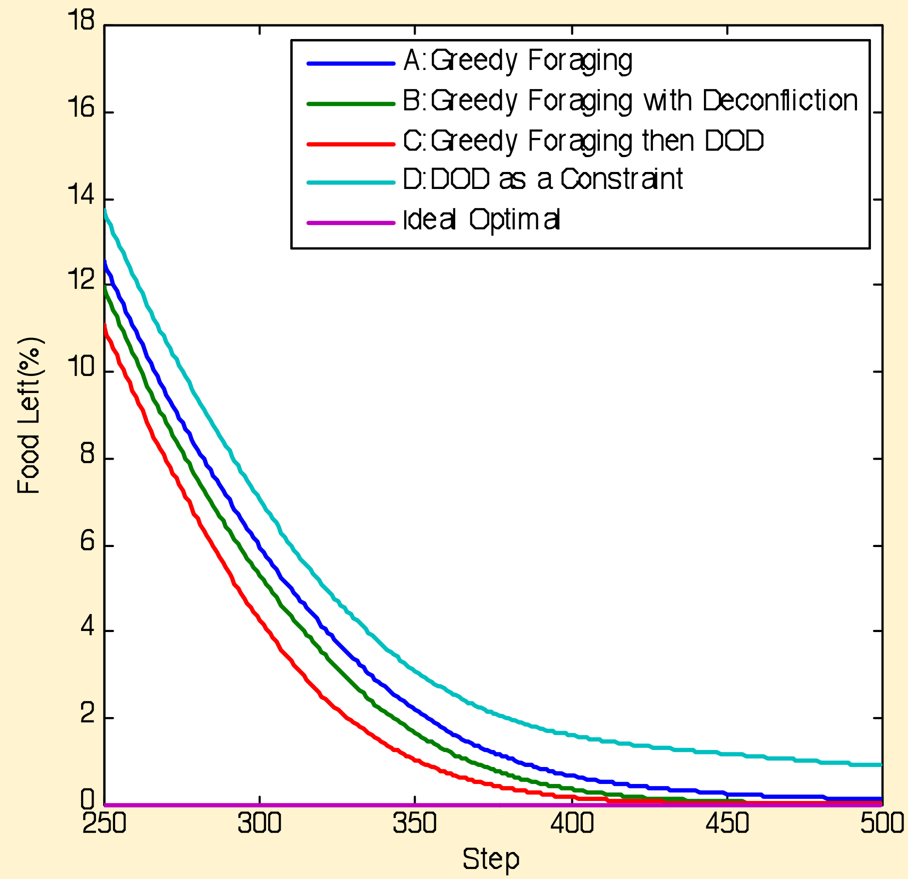


Foraging Efficiency with 10 agents
141 x 141 food nodes (twice the amount of food)

Foraging Efficiency (Zoomed In)

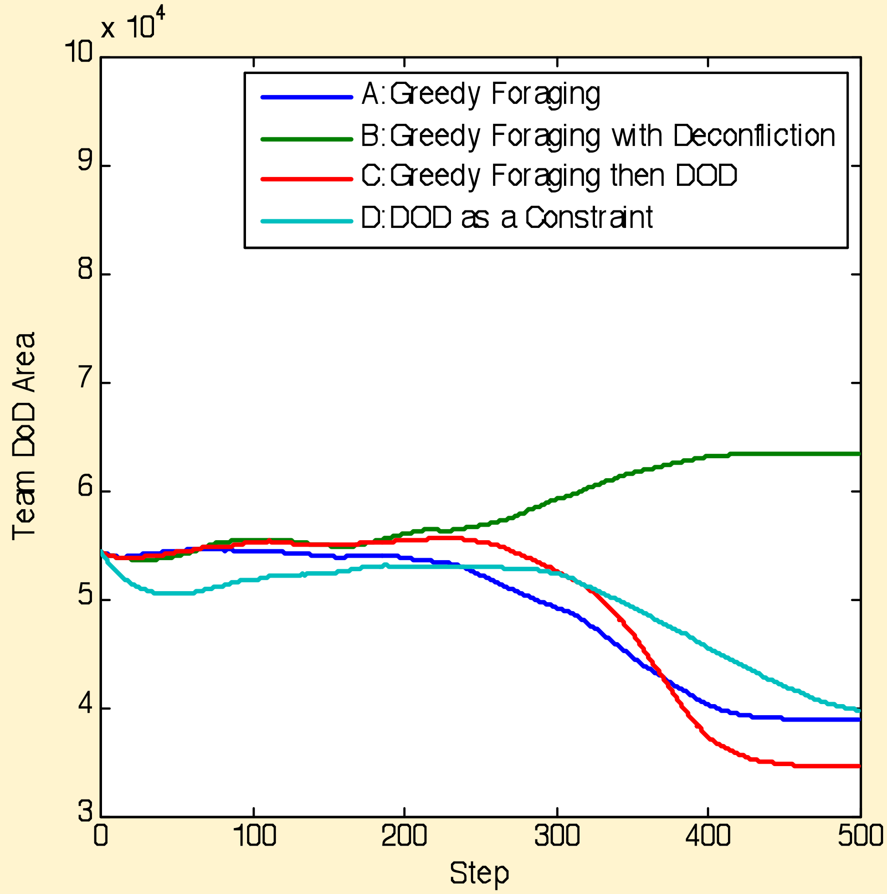


Foraging Efficiency with 5 agents
100 x 100 food nodes

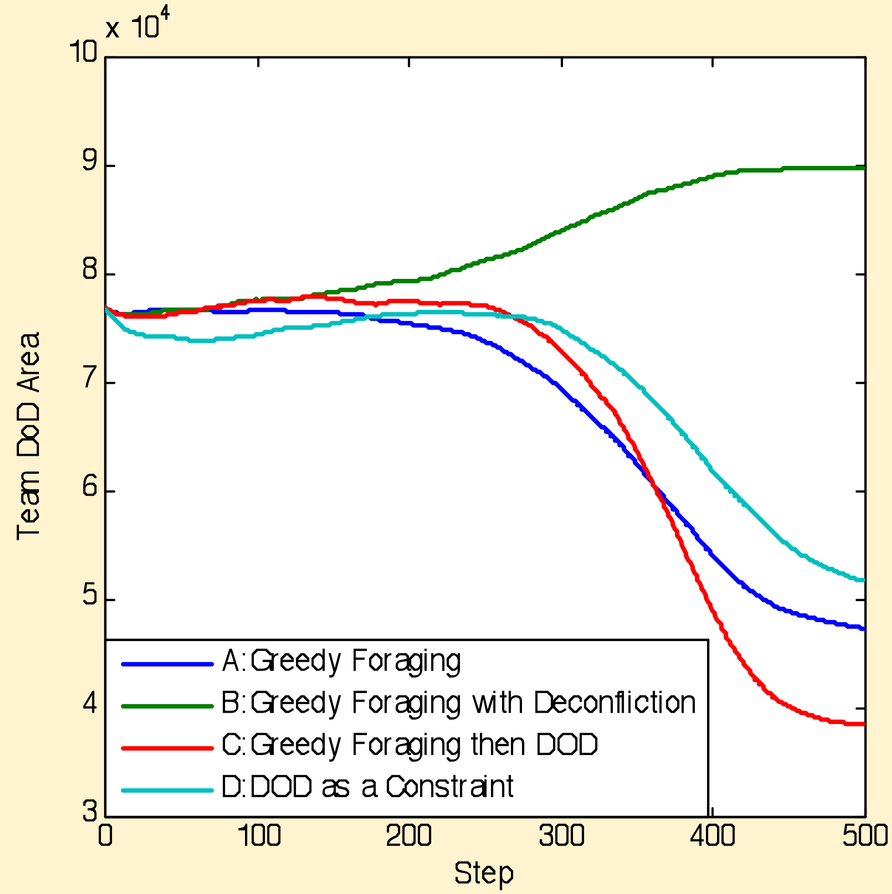


Foraging Efficiency with 10 agents
141 x 141 food nodes (twice the amount of food)

Team Domain of Danger Performance



Team DOD with 5 agents
100 x 100 food nodes



Team DOD with 10 agents
141 x 141 food nodes
(twice the amount of food)

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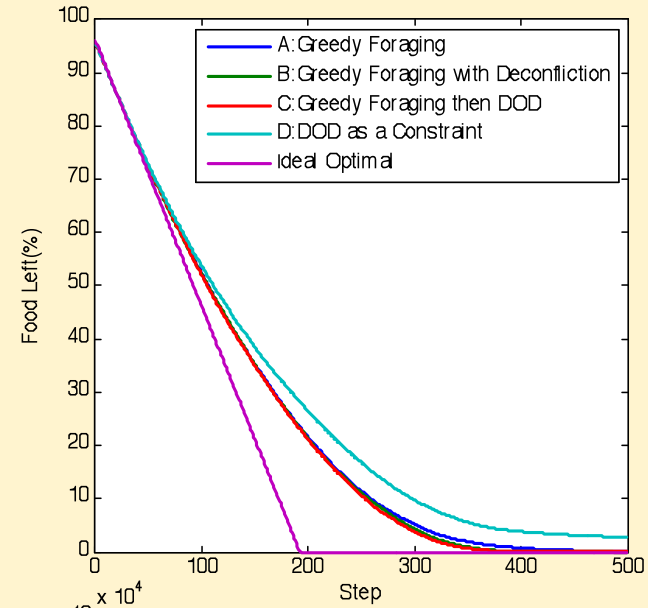
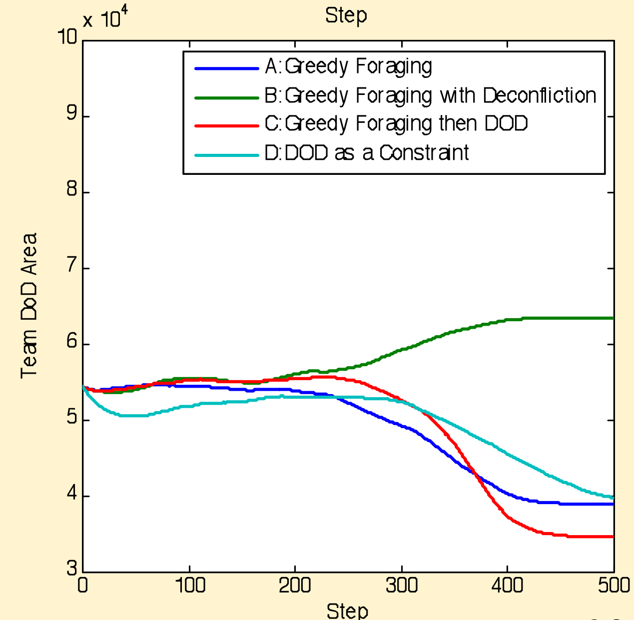
Summary of Performance Comparison

- Adding de-confliction enhances the foraging performance but causes the team to spread
- Adding the DoD shrinking mechanism prevents over-spreading and further enhances foraging performance
- Foraging under the constraint of domain of danger size greatly degrades the foraging performance
- The effect on foraging efficiency of the domain of danger constraint is smaller when there are more agents





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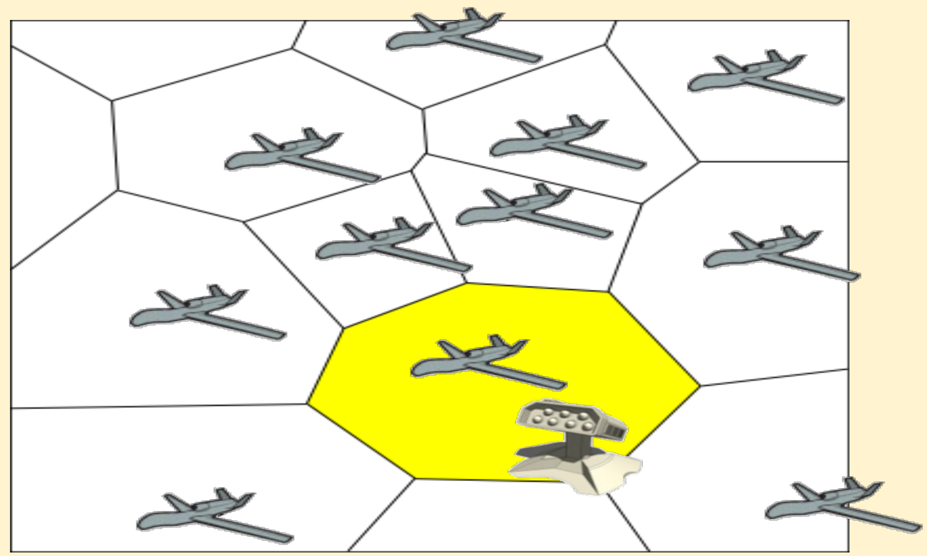
Possible Applications in Autonomous Agent Team

- Analogy between food gathering for animals and information gathering for autonomous agents:
- Foraging-like behavior especially suitable for exploration scenarios where the goal is to explore an unexplored region of interest
- Domain of danger concept
  - Fits nicely into scenarios where undetected threat is expected in the region of interest
    - e.g. SAM sites or hostile enemy units.



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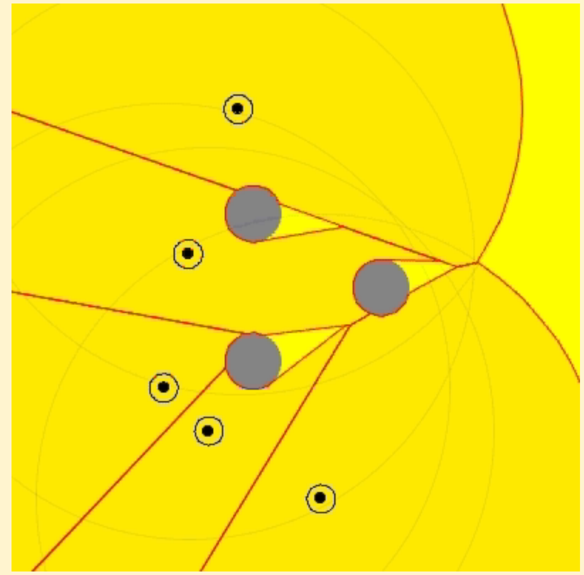
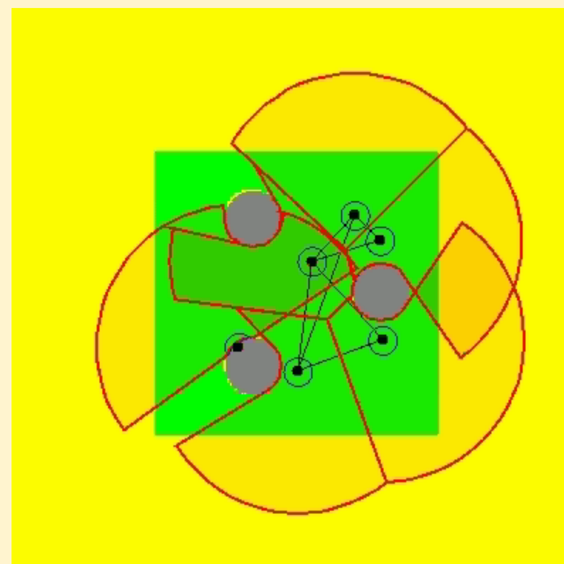
Future Work

- Sparse patches of food
- Estimation of foraging gain for longer horizon
- More explicit trade-off tuning between risk avoidance and foraging gain
- Domain of danger with obstacles
- Limited Communication
  - Obstacles
  - Range
- Trade-off with communication
  - Agents determine whether to forage by themselves or to communicate food location to others





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Thank you

Predator-Prey Interaction

- Predator-prey interaction: one of the most important factors affecting behavior of animals
  - Especially true for prey: have to constantly be aware of predation risk
- Prey animals living in a group
  - Benefit of reduced predation risk,
  - Decreased foraging efficiency due to foraging competition from groupmates
- Trade-off between predation risk and foraging gain: Information gathering missions in risky environments have similar characteristics

Lioness hunting warthog, © Peter Blackwell / naturepl.com

A group of wildebeest facing an African wild dog.

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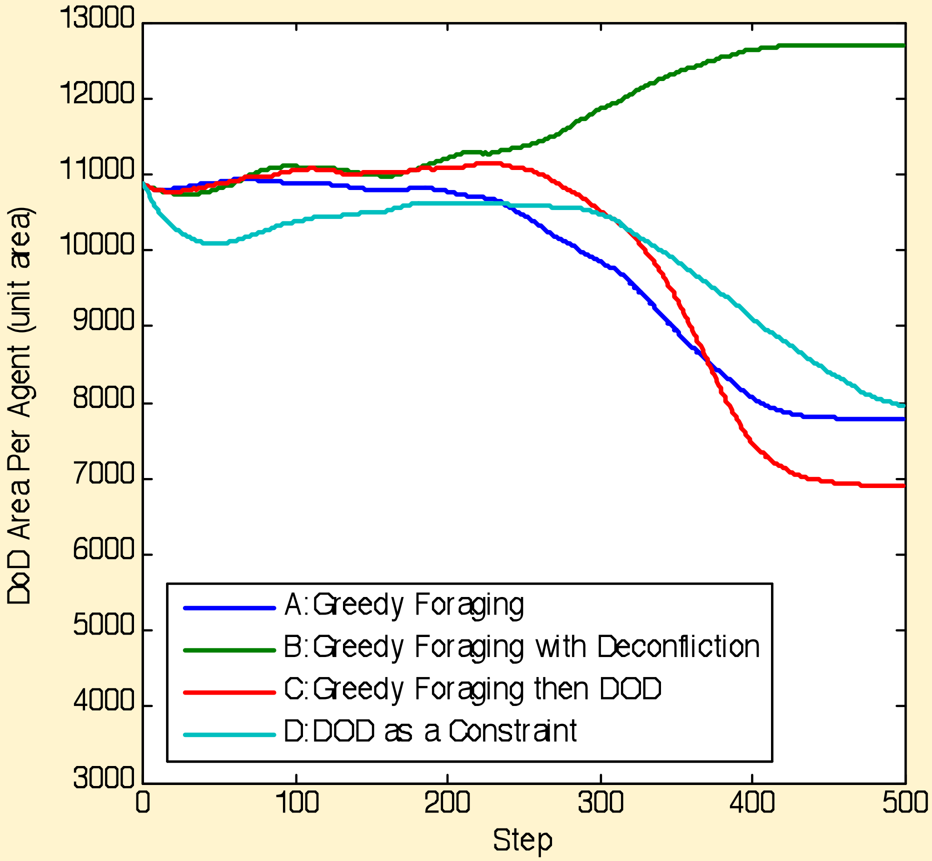
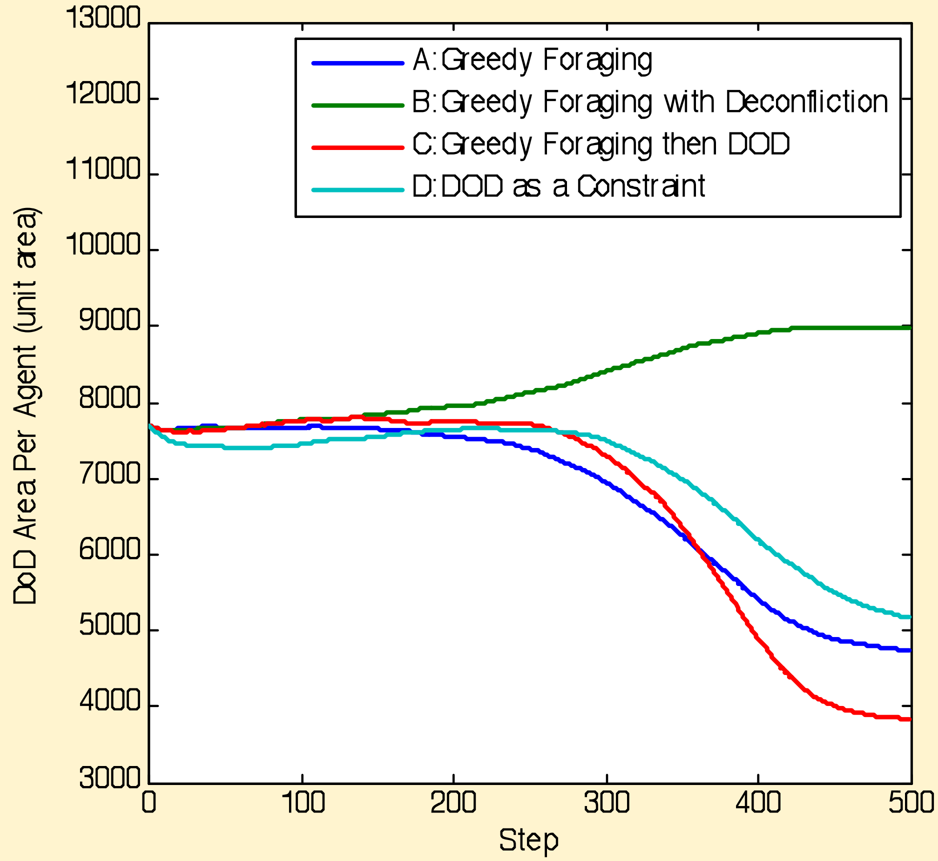
Team Domain of Danger Performance (Actual Area)



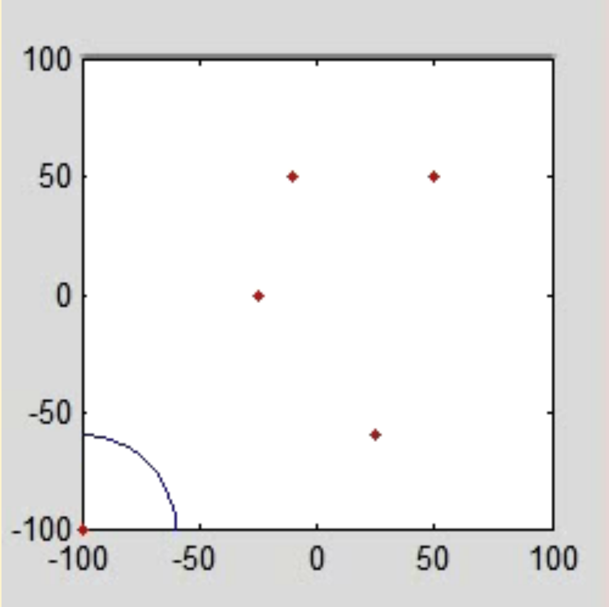
Team DOD with 5 agents
100 x 100 food nodes

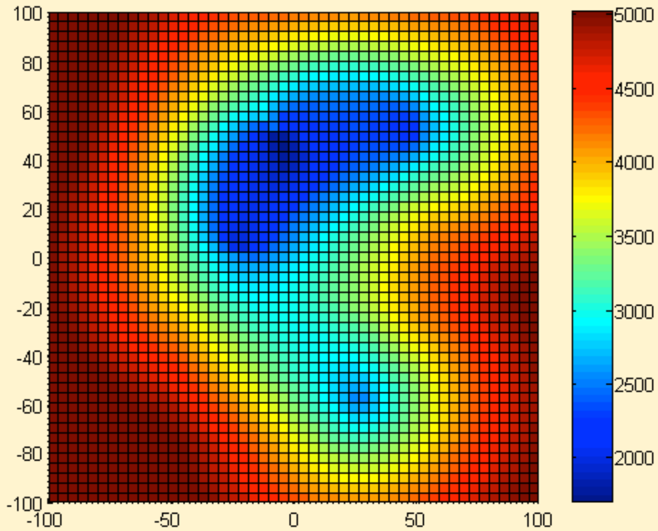


Team DOD with 10 agents
141 x 141 food nodes (twice the amount of food)

A Better Movement Rule

- Assuming all other agents are stationary, an agent can calculates its domain of danger at any location
- With a domain of danger map, the agent can aim for the safest location in the field
- However
  - Other agents are not stationary
  - Sampling domain of danger at every location is computationally expensive
- Instead of planning for a long time horizon, an agent can just plan one step ahead





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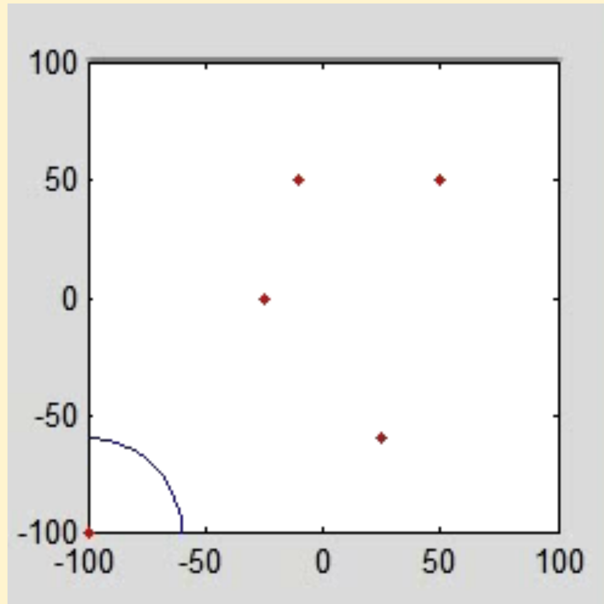
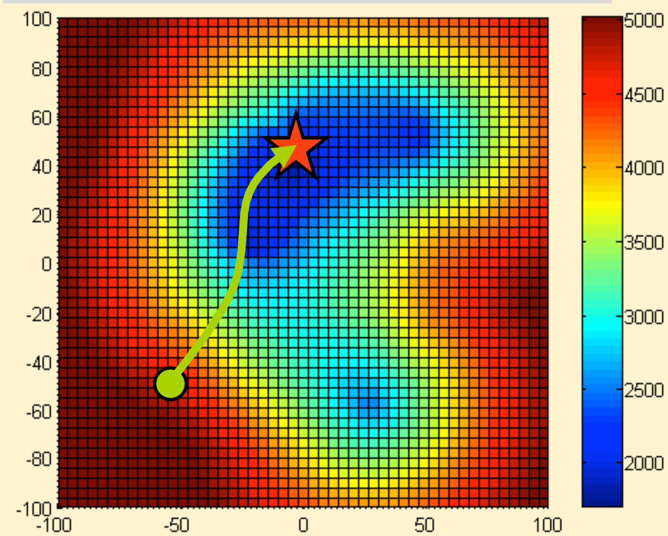
Plan a Path to the Global Min

- Assuming all other agents stay where they are, we can calculate the size of domain of danger at every position
- Convert the DOD area to log of probability of being targeted.

$$R(s) = \log(\varepsilon \times \frac{\text{area of Voronoi polygon}}{\text{area of the whole field}})$$

- Obtain a DOD area map
  - Given initial position of agent, we can identify position with the smallest domain of danger and move our agent towards it
- The log of probability of being targeted while traveling a path indicated by a series of points: s_0, s_1, …, s_n can be represented by $\sum_{i=0}^{n} R(s_i)$





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Gradient Decent on Volume of DOD

- Definition of Voronoi Partition

$P = \{p_i \dots p_n\}$

$V(p_i) = \{x | \|x - p_i\|_2 \leq \|x - p_j\|_2, \forall j \neq i, j \leq n\}$

- Limit Domain of Danger (LDOD)

$B(p) = \{x | \|x - p\|_2 < R\}$

$D(p) = V(p) \cap B(p)$

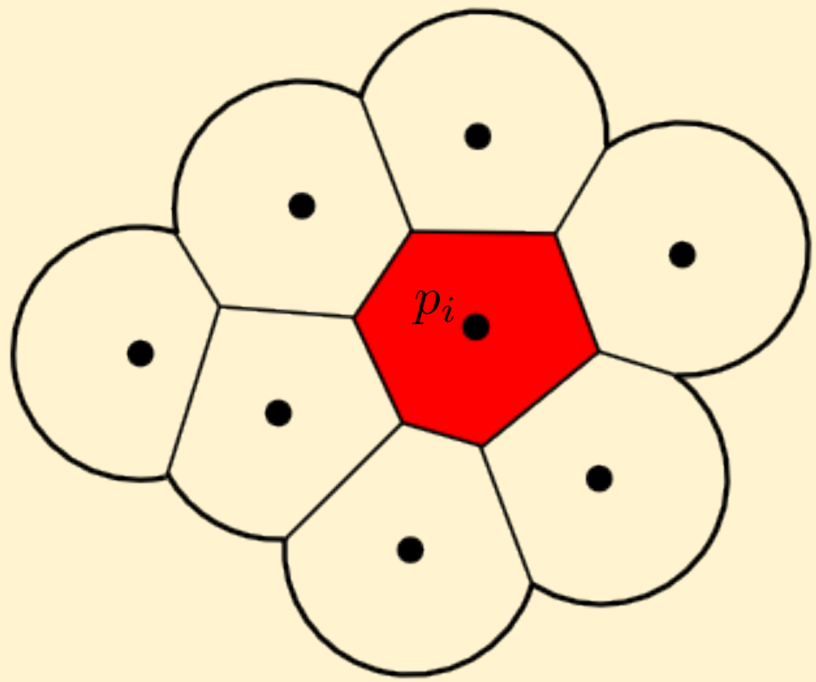
- Volume of LDOD

$H(p) = \int_{D(p)} \phi(\tau) d\tau$

ϕ: the density function

- Gradient Decent

$p_{next} = p + d\nabla H(p)$



Consider Selfish Vigilance with DOD

- Center of mass and the gradient

$$P = \{p_i \dots p_n\}$$

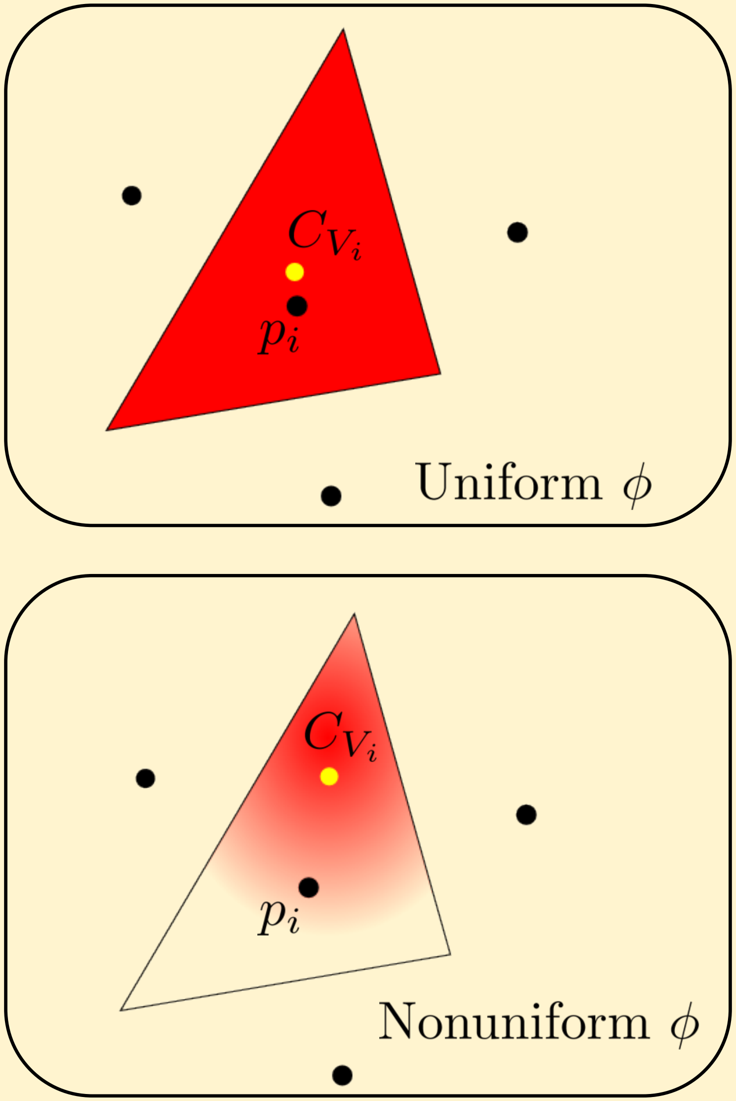
$$H_V(P) = \int_Q \min_i \|q - p_i\|^2 d\phi(q)$$

$$= \sum_i \int_{V_i} \|q - p_i\|^2 d\phi(q)$$

$$\frac{\partial H_V(P)}{\partial p_i} = 2M_{V_i}(p_i - C_{V_i})$$

$$M_{V_i} = \int_{V_i} \phi(q)dq \,; C_{V_i} = \frac{1}{M_{V_i}} \int_{V_i} q\phi(q)dq$$

$$C_{V^*} = \underset{p_i}{\operatorname{argmin}}\, H_V(P)$$



[1]M. Lindhe, P. Ogren, and K. Johansson, "Flocking with Obstacle Avoidance: A New Distributed Coordination Algorithm Based on Voronoi Partitions," *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, 2005, pp. 1785-1790.

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Consider Selfish Vigilance with DOD

- Modified Threat Coverage

$$H_V(P) = \sum_i \int_{V_i} \frac{\|q - p_i\|^2}{R^2} d\phi(q)$$

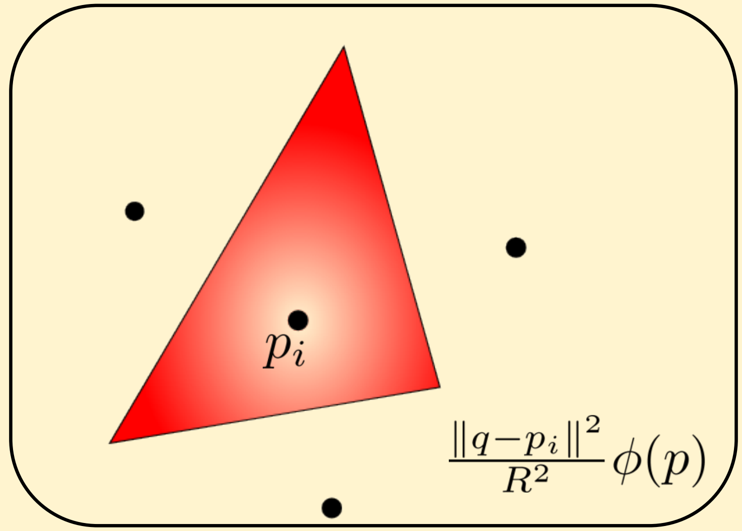
$$H_{V_i}(p_i) = \int_{V_i} \frac{\|q - p_i\|^2}{R^2} d\phi(q)$$

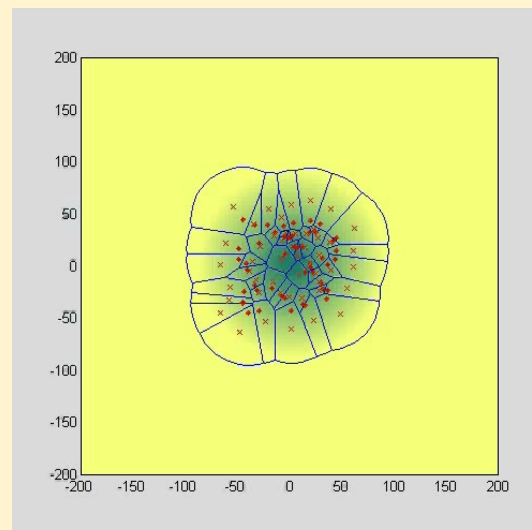
R : DOD Radius

$\frac{\|q-p_i\|^2}{R^2}$: Vigilance discount for position q

$\phi(q)$: How likely that a predator is at q

- Each agent moves toward its Cv to minimize it's modified threat coverage (Lloyd Algorithm)
- Explains the tendency for prey to "spread" evenly by moving toward the center of its DOD in safe situation





However

- The partial gradient formula is derived when Vi is consider fixed.

$$H_{V_i}(p_i) = \int_{V_i} \frac{\|q-p_i\|^2}{R^2} d\phi(q)$$

$$\frac{\partial H_{V_i}(p_i)}{\partial p_i} = 2M_{V_i}(p_i - C_{V_i})$$

- Doesn’t take into account that Vi changes as agent move.
- In fact the direction to shrink the threat value within DOD is usually the opposite direction.
- How to derive exactly?

$$H(p_i) = \int_{V(p_i)} \|p_i - q\|^2 \phi(q) dq$$

$$\frac{\partial H(p_i)}{\partial p_i} = ?$$