Multi-Robot Coordination

Chapter 11

Objectives

- To understand some of the problems being studied with multiple robots
- To understand the challenges involved with coordinating robots
- To investigate a simple behaviour-based self-organization strategy for a common application
- To investigate a simple communication strategy

What's In Here

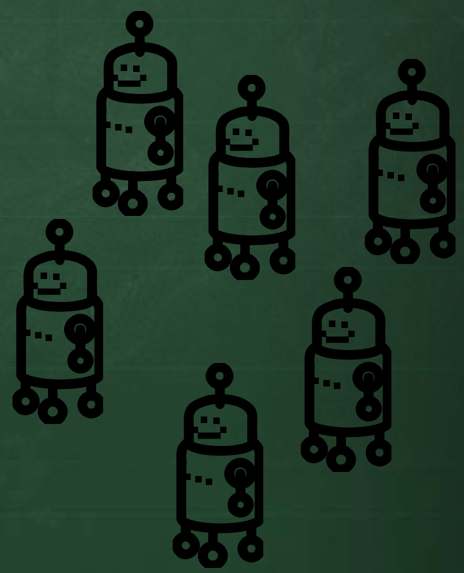
- Multi-Robot Coordination: Purpose and Issues
  - Advantages and Disadvantages of Multiple Robots
  - Types of Research and Disciplines
  - Role of Learning
- The Foraging Problem
  - Explicit Distribution
  - Implicit Distribution
  - Improvement in Distribution
- Hierarchical Communication
  - Various Schemes
    - Random
    - Sequential
    - Vector
    - Focused Averaging

Multi-Robot Coordination

Purpose and Issues

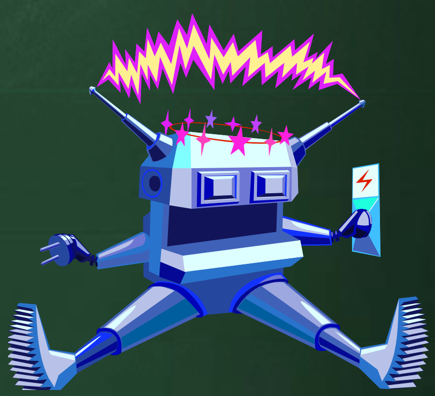
Multiple Robots

- There are advantages when using multiple robots:
  - \+ larger range of task domains
  - \+ greater efficiency
  - \+ improved system performance
  - \+ fault tolerance
  - \+ lower economic cost
  - \+ ease of development ???
  - \+ distributed sensing and action



Multiple Robots

- There are also disadvantages / challenges:
  - performance depends on issues involving interaction between robots
  - interactions complicate development
  - difficult to model group behaviors from top down (i.e., centralized control) when environment is unknown and/or dynamic
  - sensor and/or physical interference
  - need lots of batteries !



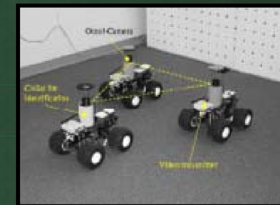
Research

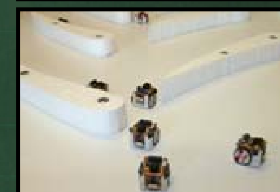
- 5 major themes of robot group research:
  - Group control architecture
    - decentralization and differentiation
  - Resource conflict resolution
    - e.g., space sharing
  - Origin of cooperation
    - i.e, genetically-determined social behavior or interaction-based cooperative behavior
  - Learning
    - e.g., control parameter tuning for desired cooperation
  - Geometric problem solving
    - e.g., geometric pattern formation

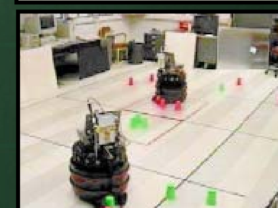
A typical research paper will focus on **only one theme** (or aspect) of group robotics.

Research

- What kinds of problems have been studied:
  - Multi-robot path planning
  - Traffic control
  - Formation generation, keeping and control
  - Target tracking
  - Multi-robot docking
  - Box-pushing
  - Foraging
  - Multi-robot soccer
  - Exploration and localization
  - Transport







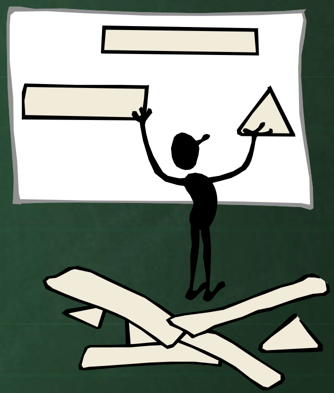
Disciplines

- There are three *disciplines* that are most critical to the development of robotic agents:

  - Distributed Artificial Intelligence
    - distributed Problem Solving or Multi-Agent Systems
    - considers how tasks can be divided among robots
      which share knowledge about problem and evolving solutions.
  - Distributed Systems
    - focus on distributed control addressing deadlock, message-passing, resource allocation etc…
  - Biology
    - bottom-up approach where robots follow simple reactive rules
    - Interaction between robots results in complex emergent behavior

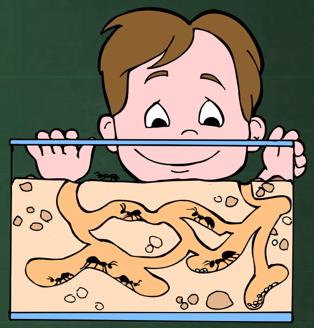
Learning and Adapting

- Robots perform for certain period of time without human supervision in order to solve problem
  - must be able to deal with dynamic changes in environment and their own performance capabilities



- Learning, evolution and adaptation allow robot to improve its likelihood of survival and its task performance in environment:
  - adaptation – how a robot learns by making adjustments
  - learning – helps one robot adapt to environment
  - evolution – helps many robots adapt to environment

Evolution vs. Learning



- **Evolution**:
  - *process of selective reproduction and substitution based on the existence of a distributed population of vehicles*
  - does not perform well when certain environmental changes occur that are different from evolved solutions
- **Learning**:
  - *a set of modifications taking place within each individual during its own lifetime*
  - often takes place during an initial phase when task performance is considered less important
  - control policy used that gives reasonable performance … robot "team" gradually improves over time.

Overview Summary

- There are many aspects of multi-robot coordination
- Robots that perform well together in one kind of environment will perform poorly in others.
- To be useful, multi-robot strategies must:
  - be "designed" and "fine-tuned" for particular applications
  - explicitly / implicitly distribute the work among the robots
  - consider both sensory and environmental interference from other robots
  - be able to operate under unexpected situations
  - be cost-effective

This Course

- Multi-Robot coordination strategies is a huge topic
  – too much to cover in this course
- We will consider:
  – self-organization for simple foraging applications
  – hierarchical communication to focus coverage

- We will look at simulated results:
  – robots will be reactive and use instinctive behaviors
  – analyze the performance over time
  – combine different types of robots

The Foraging Problem

Foraging

- Consider a common problem studied in robotic colonies, *foraging*:
  - gathering/collecting items
    - possibly bringing them to some specific location(s) (e.g., to particular room) or general location(s) (e.g., to outer walls).
  - there are many variations of this problem
- We will consider a specific instance:
  - robots can detect when it finds an item and can push it to some location (or pick it up and drop it off).
  - robots will be encoded with a fixed, instinctive behavior and thus will not learn "how" to forage.

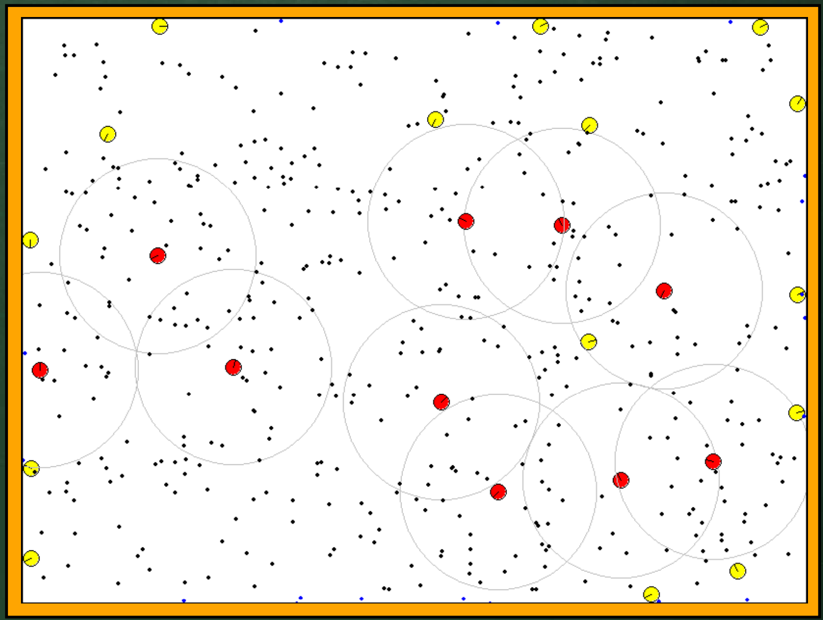
Foraging

- Consider allowing robots to move randomly in an environment with no cooperation.

- Robots must find forage items (e.g., when passing over them) and bring them to the boundaries.

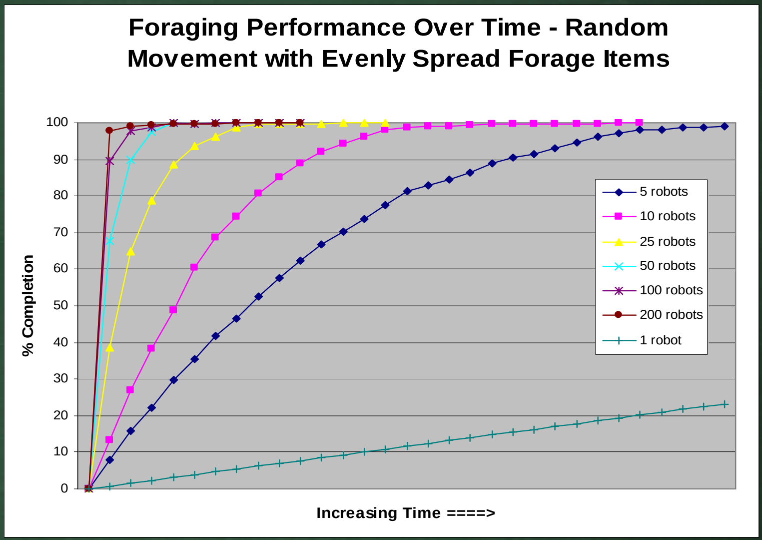
  – Robots may collide, which may interrupt the forage procedure of a robot.

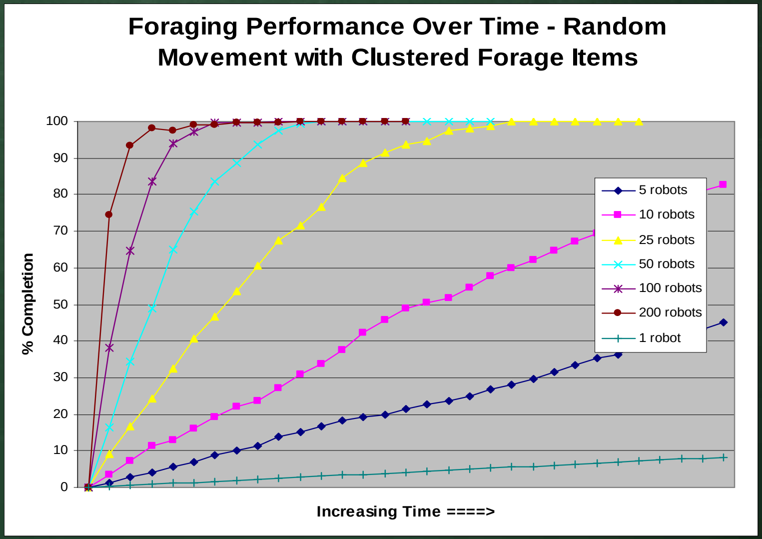
  – Eventually, over time, each forage item will be found by some robot:



Foraging

- As more robots are used, the speed of forage completion increases.
- The performance decreases when the forage items are not evenly distributed.
  - this is because robots are not directed towards forage items, only finding them by chance.





Foraging

- Intuitively, performance can be improved by:
  - reducing collisions (or interference) between robots
  - preventing robots from traveling over the same areas
  - directing robots towards clusters of forage items
- The obvious way of reducing collisions and preventing duplicate travel is to distribute robots by explicitly assigning each one a particular area in the environment in which to forage.
  - environment broken down into "equal-sized" areas which are assigned to individual robots

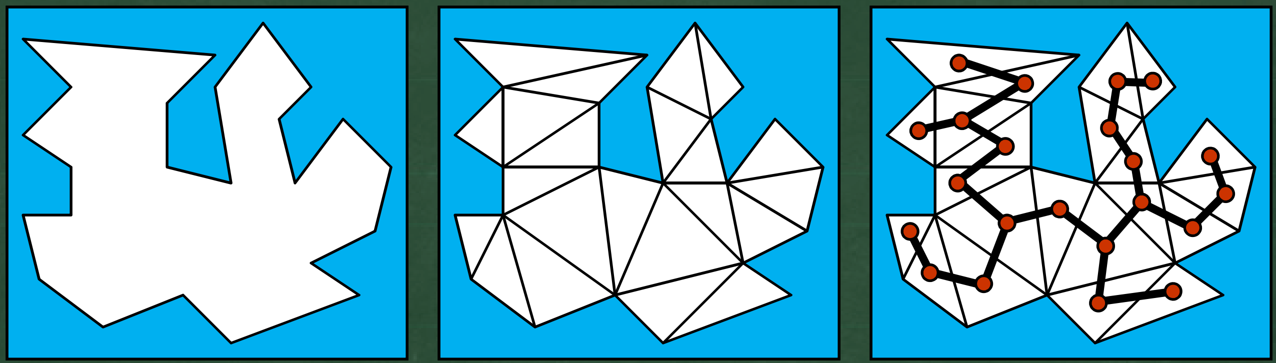
Foraging – Explicit Distribution

- This strategy has advantages:
  + ensure even distribution of robots (good when items to be foraged are evenly distributed randomly)
  + minimizes sensor interference and physical collisions between robots

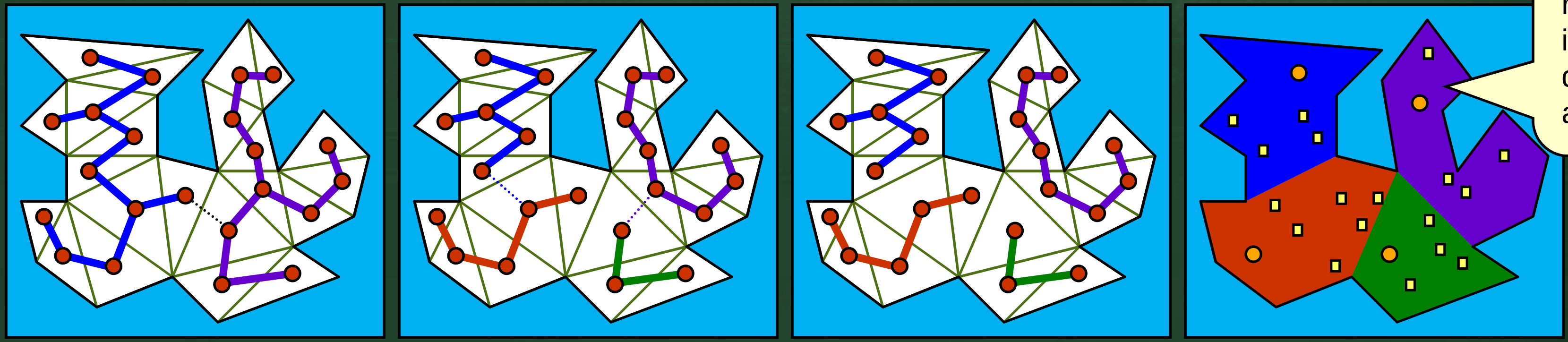
- and disadvantages:
  – requires robots to "know" and maintain specific positions
    - requires knowledge of environment
    - expensive sensors ?? (e.g., GPS)
    - expensive computation (e.g., position estimation)
  – can be inefficient if forage items are clustered

Foraging – Explicit Distribution

- A simple way of determining the foraging areas for each robot is to base the regions on the dual graph:



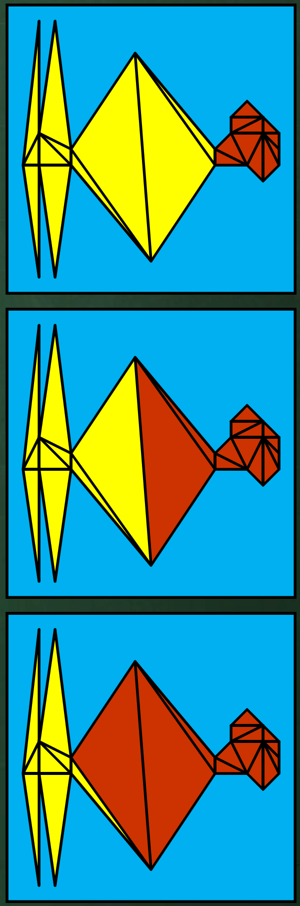
Recursively divide dual graph in "half" until number of regions matches the number of robots:



Each robot remains in its own designated area.

Foraging – Explicit Distribution

- There are multiple ways to split the dual graph by finding an edge that evenly splits:
  - links – # of dual graph links
    - simple and fast, assuming a nice triangulation
  - area – area covered by dual graph triangles
    - best if robots need to perform coverage algorithms or searching with uniform distribution of foraging items.
  - perimeter – perimeters of dual graph triangles
    - good if robots are to patrol outer boundaries of their environment

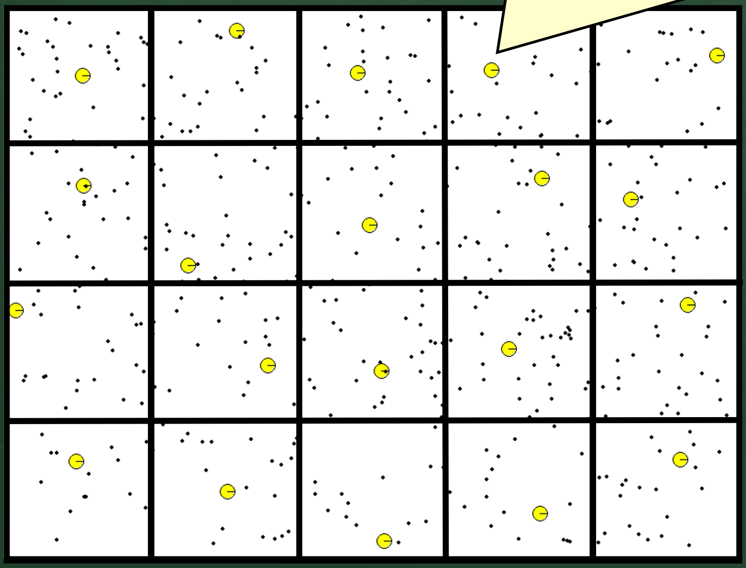


Foraging – Explicit Distribution

- Performance (i.e., speed of forage completion) is highly dependant on shape of environment and location of forage items.

With forage items evenly distributed, robots work effectively in near optimal configuration, provided that robots do not have to leave their environment to complete the task.

With clustered forage items, most robots become useless if forced to remain in a particular area.



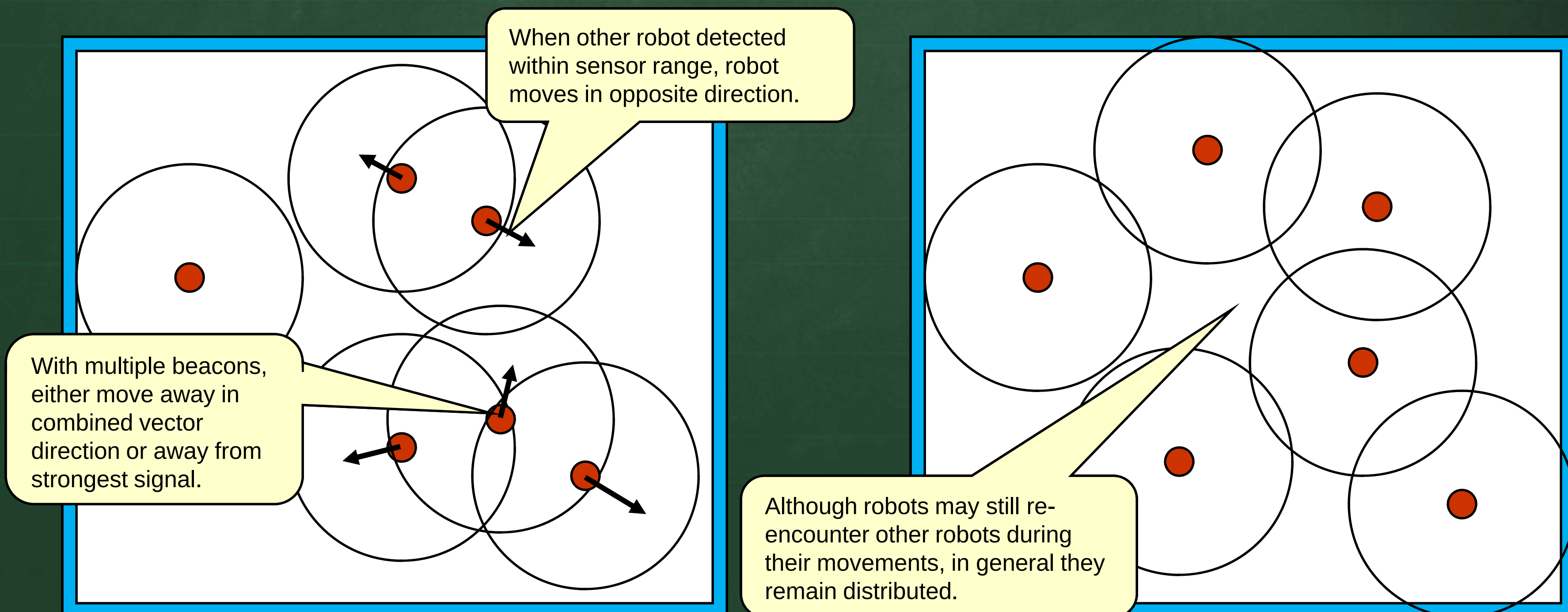
Foraging – Implicit Distribution

- Clearly, fixing the locations of each robot may not be the best choice if:
  - the distribution of forage items is not known to be random and evenly distributed
  - the robots must travel outside their areas to complete the forage task (i.e., to deliver their payload).

- A compromise is to hard-code specific behavioral rules into the robots that minimize their collisions and attempt to keep them distributed.

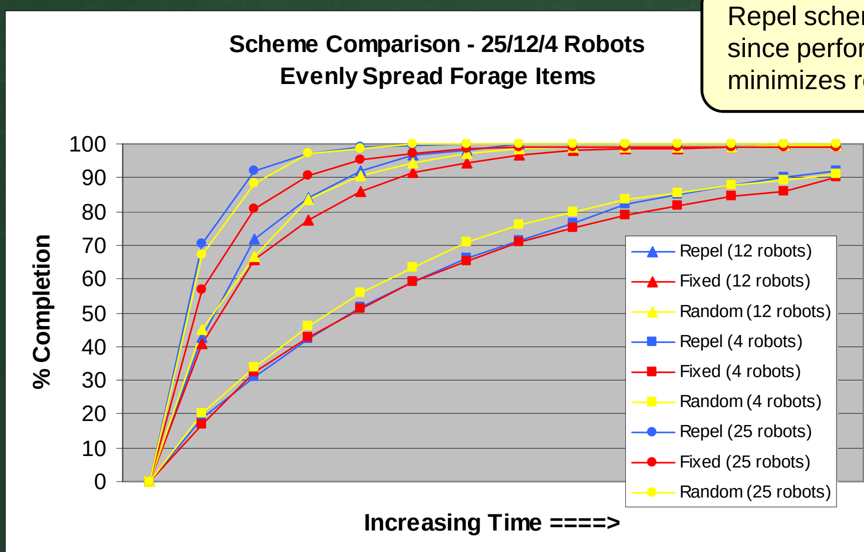
Foraging – Implicit Distribution

- Consider robots with omni-directional beacons which are detectable from other nearby robots:
  – robots avoid moving towards nearby beacons
  – intuitively, robots should remain separated/distributed

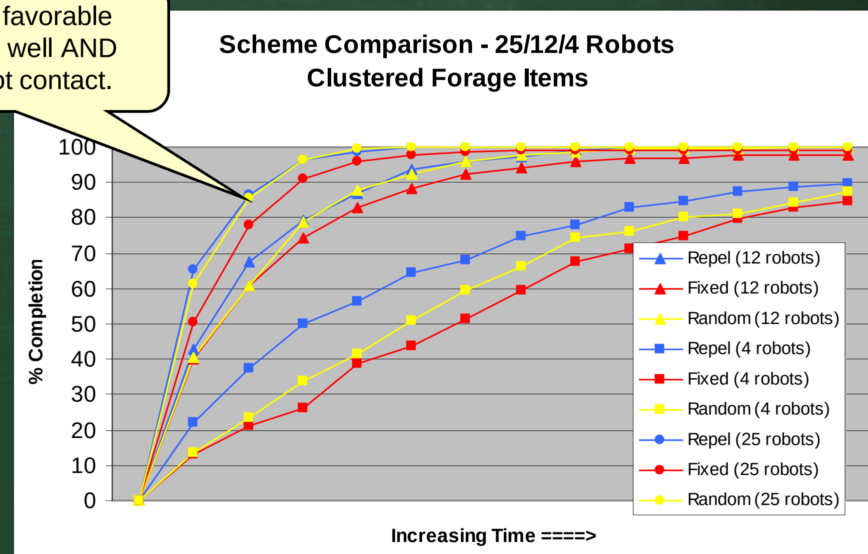


Foraging – Comparison

- A comparison of these schemes shows that:
  - for evenly spread forage items there is no significant advantage of either scheme in terms of forage completion time and the simple random movement seems to do well.
  - for clustered forage items the fixed area scheme performs poorly with few robots and the repel scheme performs better

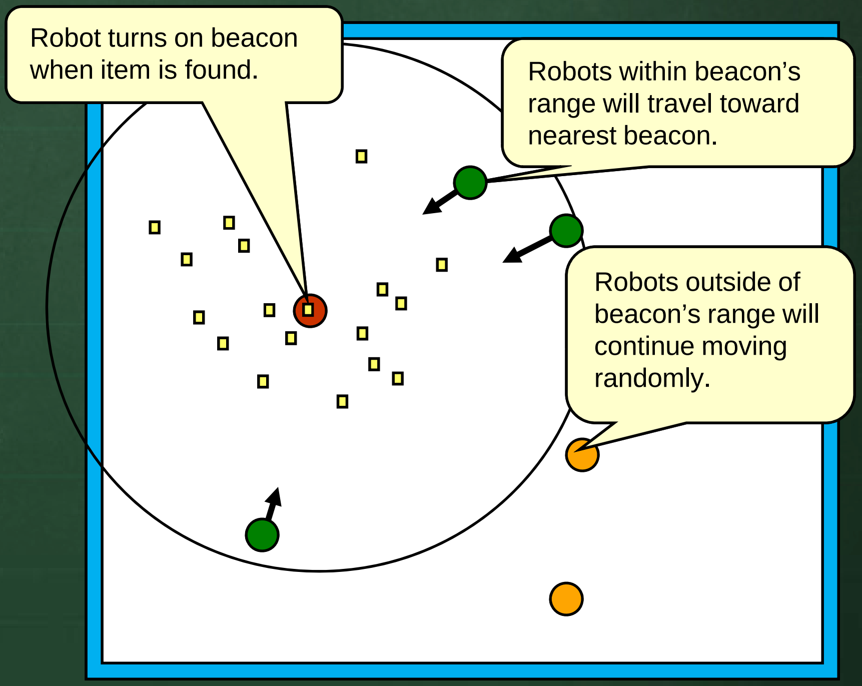


Repel scheme favorable since performs well AND minimizes robot contact.



Foraging – Improvement

- A more significant improvement can be made if something is known about the forage items (e.g., they are clustered).
  - can "signal" other robots when item is encountered
  - leave signal on until:
    - fixed amount of time elapses
    - other robots come nearby
  - can either wait stationary or continue moving



Foraging – Improvement

- Consider five "beacon attraction" schemes:
  - **Always On** – beacon is always on, robot keeps moving
  - **Timed Out Stationary** – beacon on for fixed time, robot waits stationary until beacon timeout
  - **Timed Out Moving** – beacon on for fixed time, robot keeps moving
  - **Until Near** – beacon on until robot nearby, robot waits stationary until another robot comes nearby
  - **Until Near or Timed Out** – beacon on for fixed time, robot waits stationary until beacon timeout or until another robot comes nearby

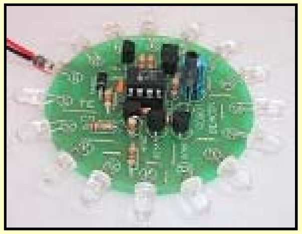
Robots may get into a deadlock situation.

Foraging – Improvement

- *Here is the basic idea behind the attraction code:*

```
REPEAT {
  int desiredDirection = direction of closest/strongest beacon signal;
  IF (desiredDirection != null) {
    boolean collisionDetected = read front collision sensors;
    IF (collsionDetected) {
      Turn away from obstacle;
    }
    Turn towards desiredDirection
  }
  ELSE {
    wander (i.e., move forward or turn randomly)
  }
}
```

Depends on sensor. The desired direction may be that of the strongest signal (if many beacons sensors are mounted in a circular fashion), or may be a direction representing a combination of multiple signals. Usually, the direction will be one of 8 to 16 fixed directions around the robot.



```
IF (a forage item is found) {
    Turn on my beacon;
    Wait for XXX seconds;
    Turn off my beacon;
}
```

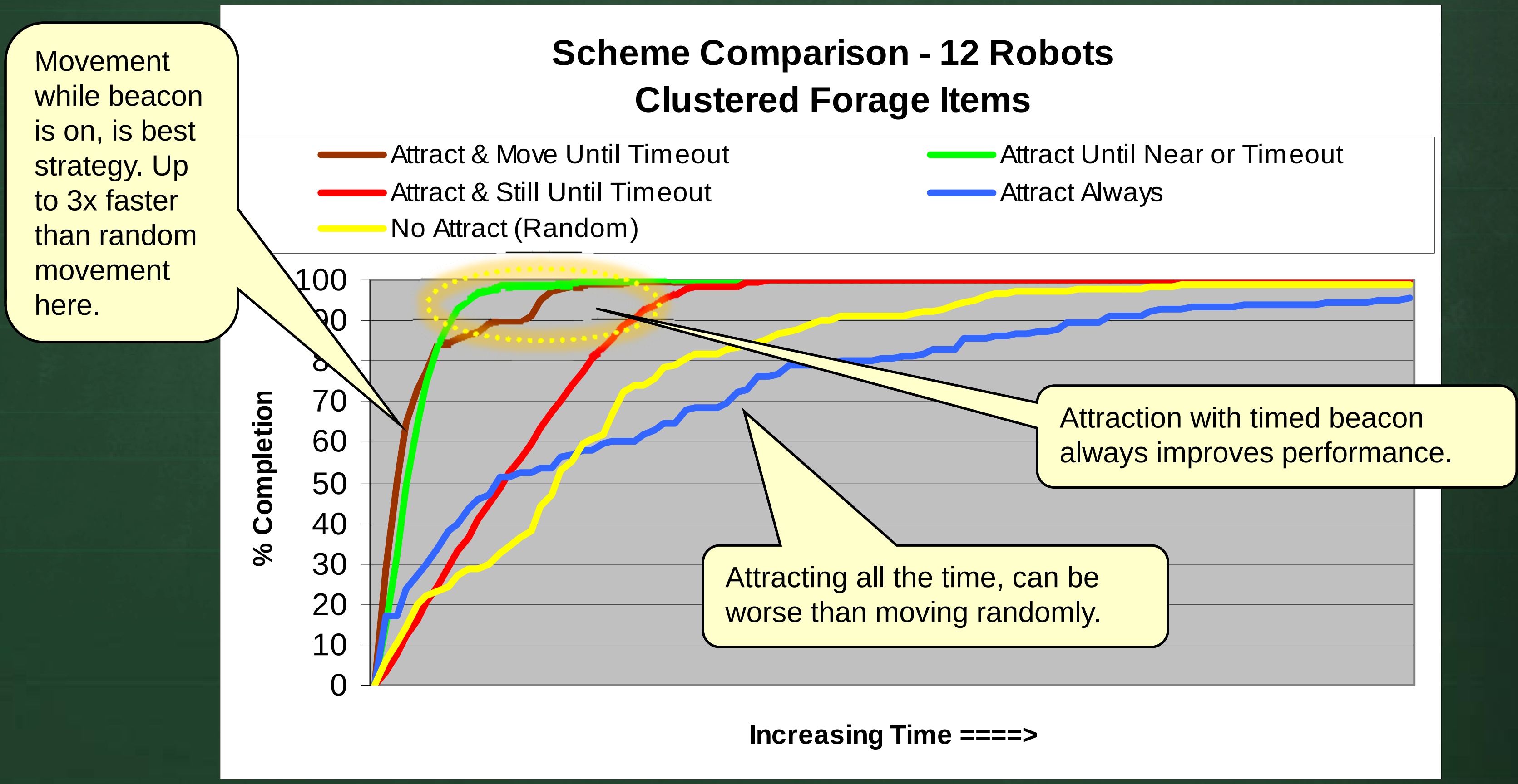
Add this code for the **TimedOutStationary** scheme

```
IF (a forage item is found) {
    Turn on beacon;
    counter = 5000;     //msec
}
IF (--counter == 0) {
  Turn off beacon;
}
```

Add this code instead for the **TimedOutMoving** scheme

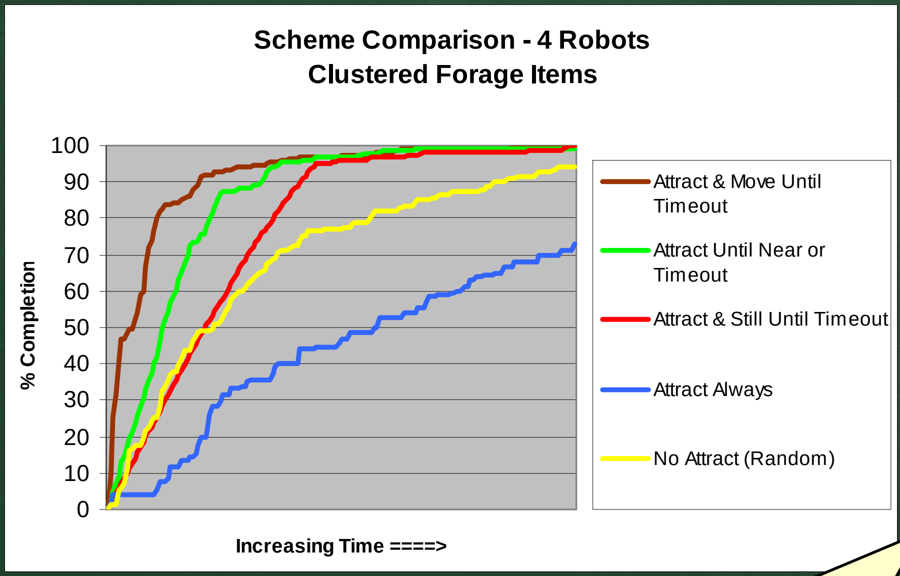
Foraging – Improvement

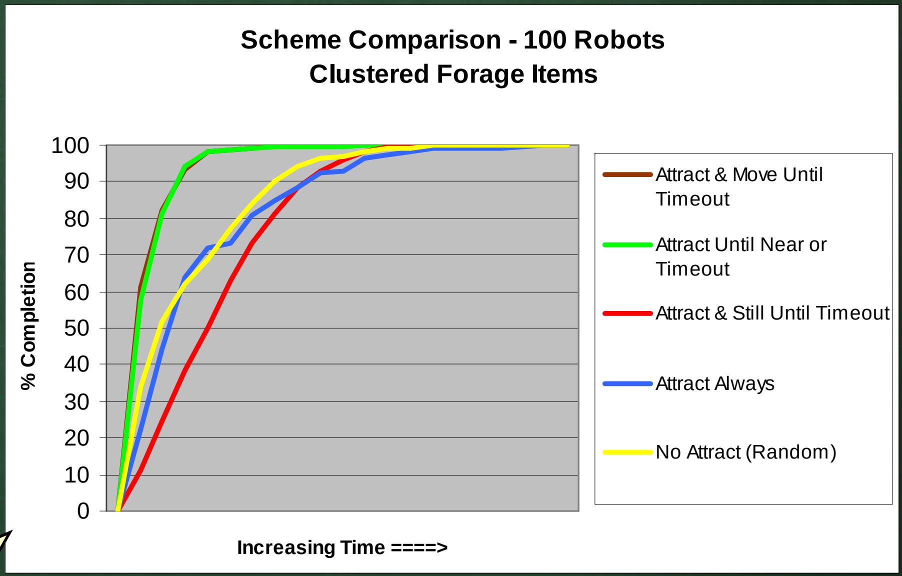
- What about performance ?



Foraging – Improvement

- Even when varying the number of robots, the attraction scheme performs well:

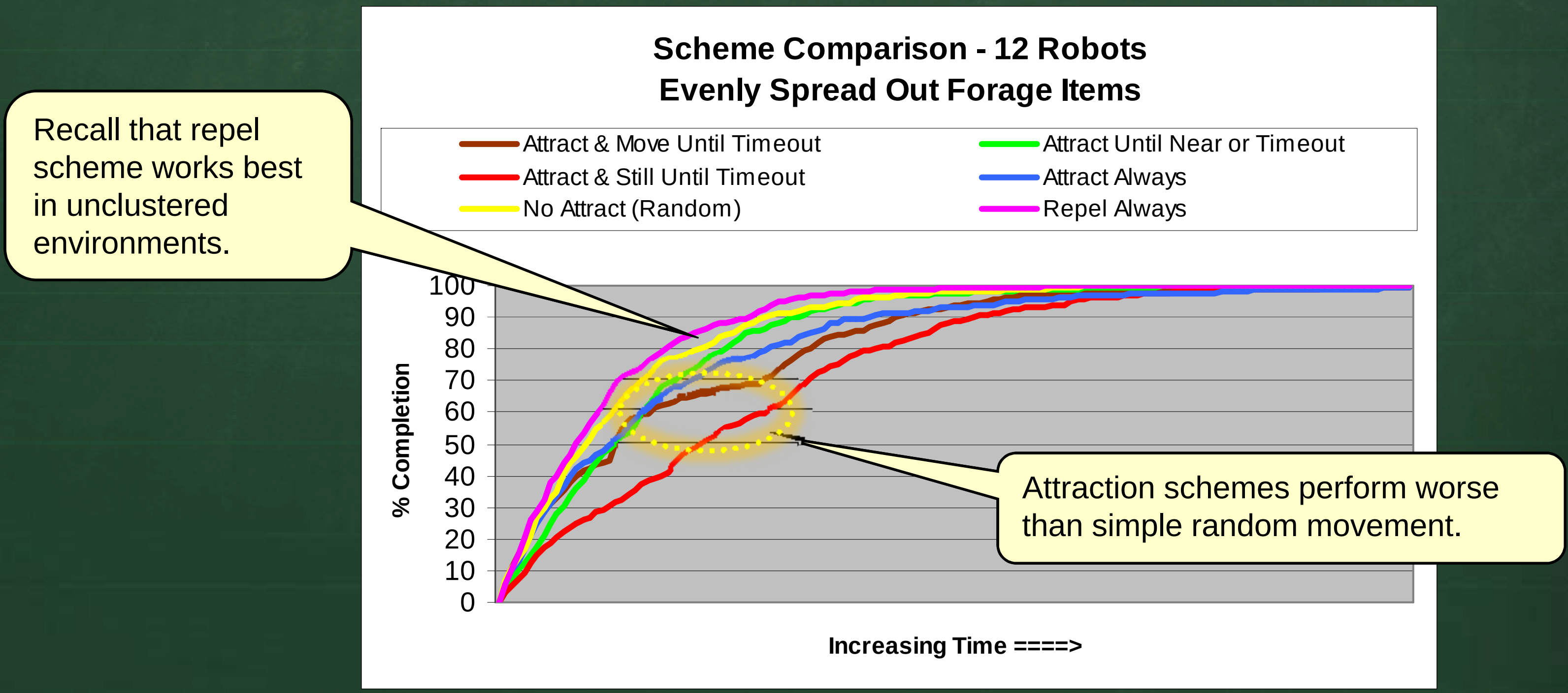




The time scales between the graphs is different, in order to accentuate the differences in the schemes.

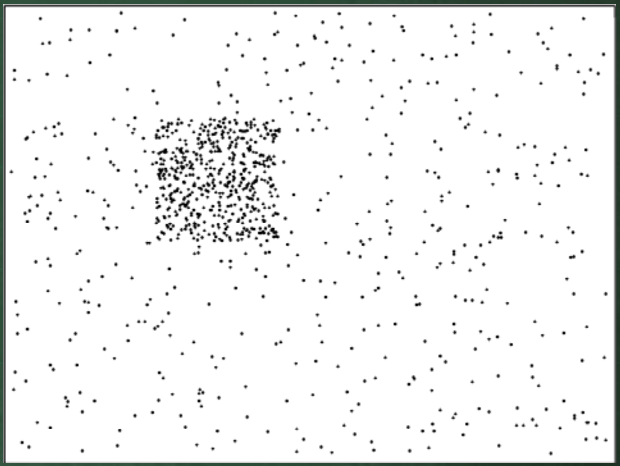
Foraging – Improvement

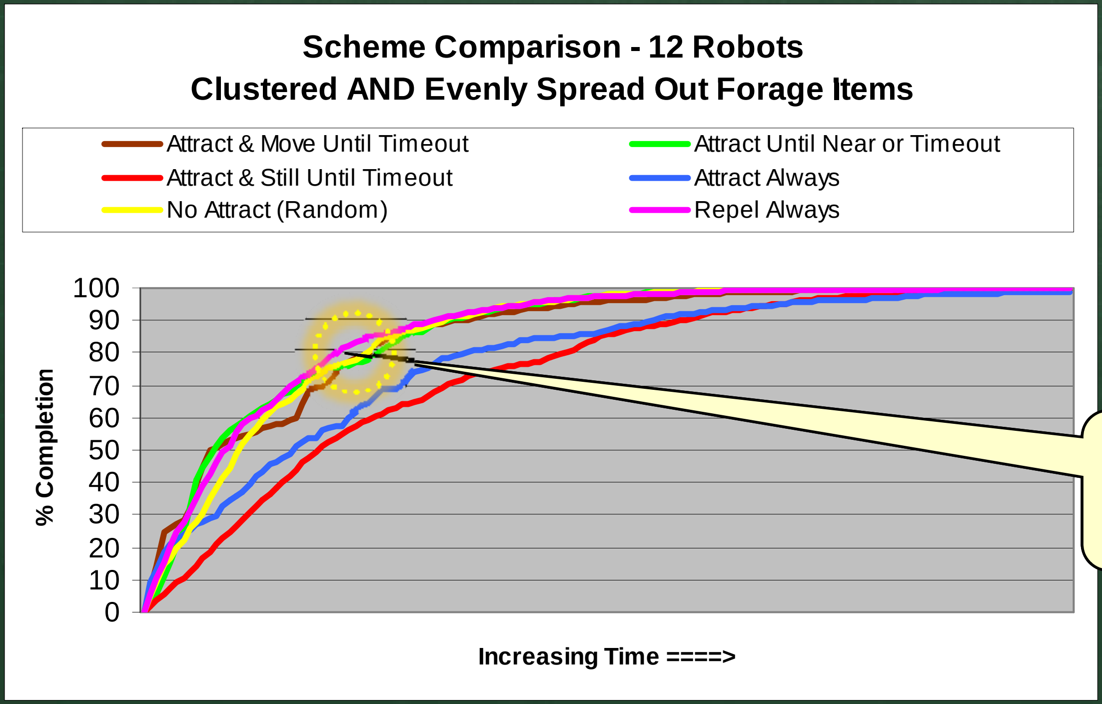
- Of course, in non-clustered environments, the attraction scheme performance degrades and actually reduces efficiency over random scheme:



Foraging – Improvement

- What about environments with both clustered items AND spread out items ?

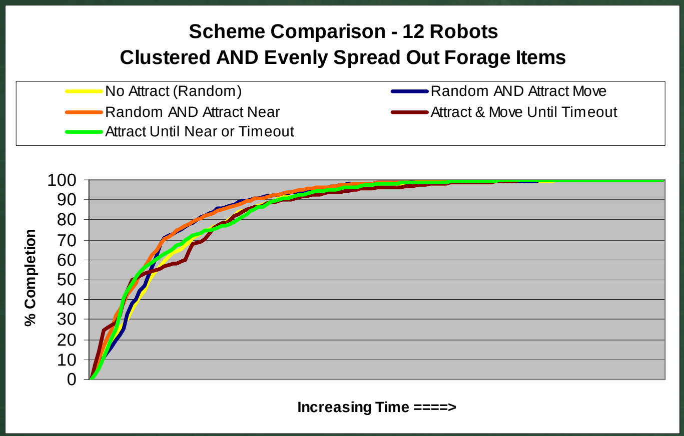




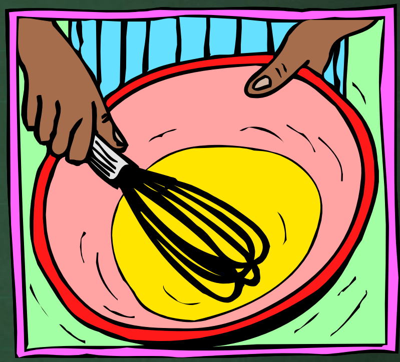
Performance is near to random … but provides only a small improvement.

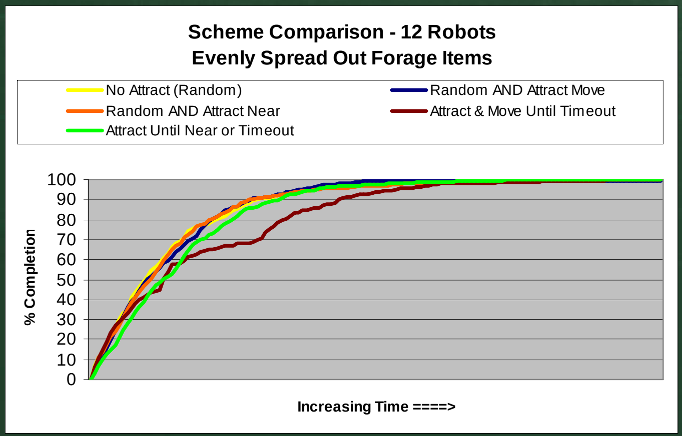
Foraging – Improvement

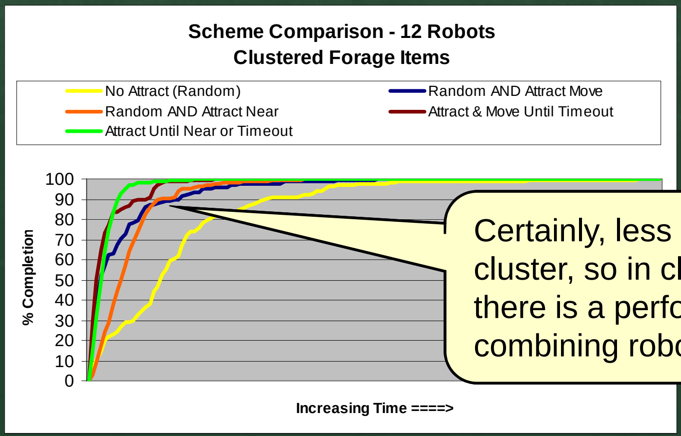
- Can mix various kinds of robots:
  - e.g., some attract, some repel



Combining 6 random with 6 attract robots performs best despite type of environment !!







Certainly, less robots are attracted to cluster, so in clustered environment, there is a performance tradeoff when combining robot types.

Other Similar Problems

- Similar attraction/repel strategies can be implemented for other problem scenarios such as coordinated mapping, searching, patrolling, floor cleaning etc.
  - same principles apply, but results may differ.

- As seen, using heterogeneous groups (i.e., mixing different kinds of robots) may prove to be the most robust and efficient solution overall.
- Experimentation helps to tweak solutions:
  - wanna do an honours project or a Master's thesis ?

Hierarchical Communication

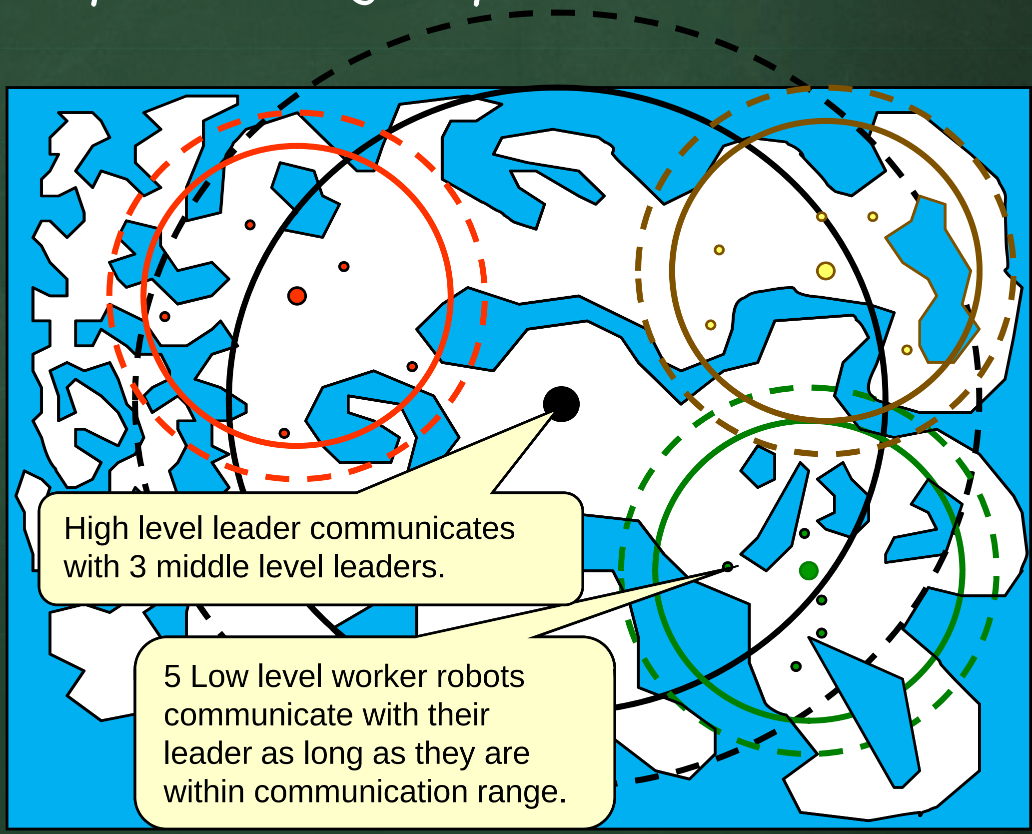
Communication

- Another important issue with respect to multi-robot algorithms has to deal with communications:
  - do the robots need to communicate (e.g., send data) ?
  - is there any advantage to doing so ?
  - how often should they communicate ?
  - should there be unlimited communication between robots or should there be restrictions (i.e., groups) ?

- We will look here at one aspect of using ***hierarchical communication.***

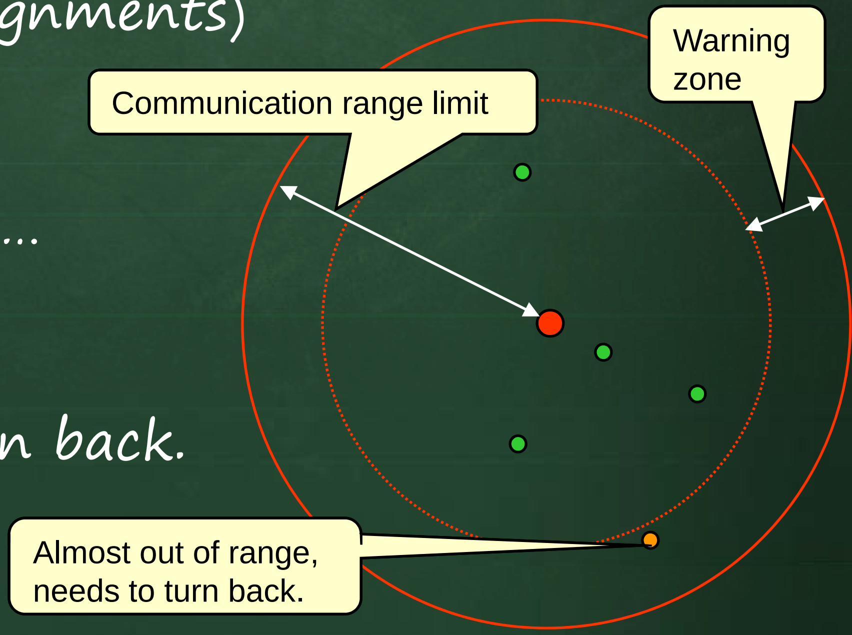
Hierarchical Communication

- Consider robots organized into a hierarchy:
  - Each robot belongs to a group and all group members can communicate to a group "leader" via wireless communication.
  - The leaders are also grouped together with a higher level leader to which they communicate.



Hierarchical Communication

- Within a hierarchy, worker robots must always remain within communication range:
  - allows data to be transmitted to leader (e.g., map data)
  - allows leader to send commands at any time (e.g., new directions and updated task assignments)
  - allows quick docking for battery recharging, working in shifts etc…
  - a warning buffer zone should be used to inform worker to turn back.



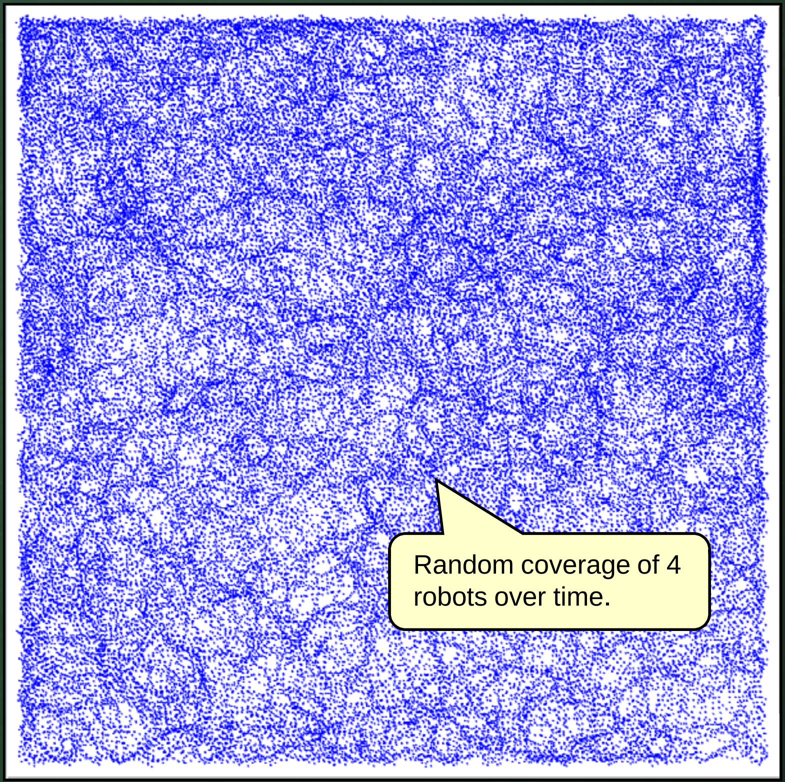
Hierarchical Communication

- A main issue with bottom-up behavior-based programming is that only *local information* (i.e., information from a robot's own sensors) is usually available.

- With such a hierarchical scheme, lower level robots can be given global knowledge of the environment and/or of task completion.
  - should provide benefit over no-communication schemes for more complex problems
  - can allow "steering" of robots to accomplish task more efficiently.

Hierarchical Schemes

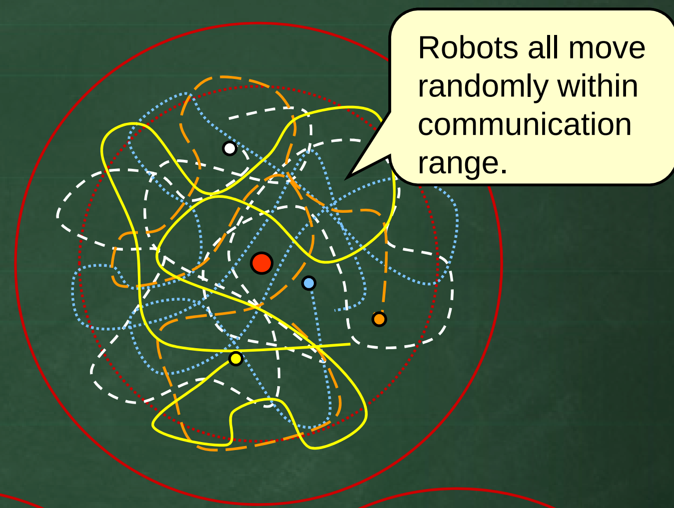
- Consider robots moving randomly to cover a simple environment:
  - good enough to investigate the general problem of robot coverage under various communication schemes.
  - more efficient schemes can be used to cover environment and techniques can be "tweaked" to each application.



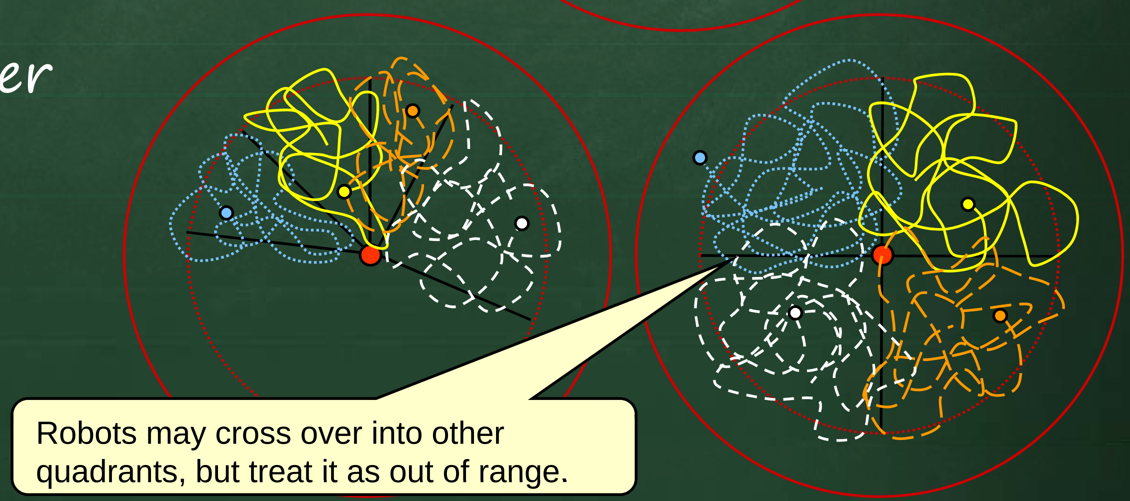
  - random coverage actually performs well over time.

Hierarchical Schemes

- Now consider a leader with 4 worker robots:
  - worker robots move randomly within leader's communication range:



  - we can restrict worker movements to fixed or variable-sized wedges/quadrants:



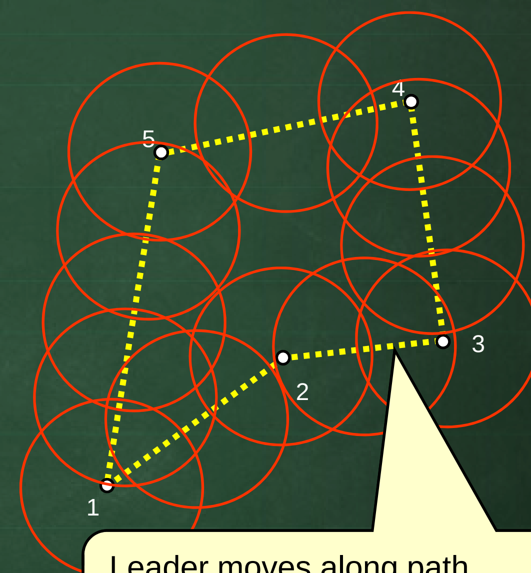
Hierarchical Schemes

- Leader must also move in order to cover whole environment properly.

- Consider various leader movement schemes:
  - Random: move in random direction
  - Sequential: move along a fixed path in sequence
  - Vector: move in direction towards quadrant that had most "out of safe zone" occurrences
  - Toward Average: vector scheme with added "pull" towards leader's average location
  - Away From Average: vector scheme with added "push" away from leader's average location

Hierarchical Scheme – Sequential

- The basic sequential scheme works as follows:
  - Leader moves slower than workers (e.g., 1/10th of speed)
  - Leader heads towards next location in some sequence (e.g., along a predetermined path)
  - Leader may remain at each location for a while or leave immediately.
  - Timeout may be used if location is not reached within certain time limit



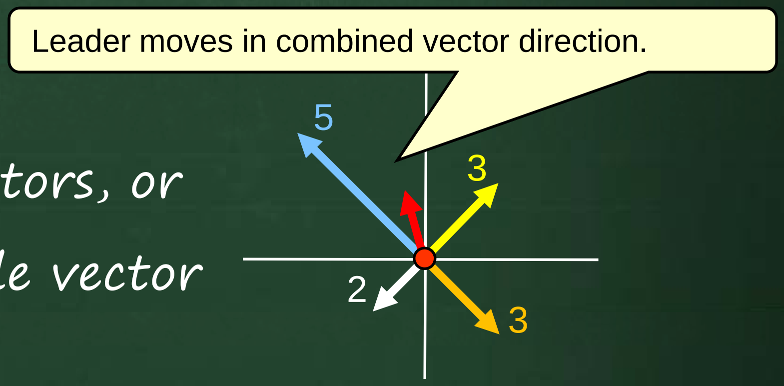
Leader moves along path, while workers move randomly within the “safe” range.

Good if need to unload workers, then reload and transport to new site.

Necessary in order to avoid getting stuck behind obstacles.

Hierarchical Scheme – Vector

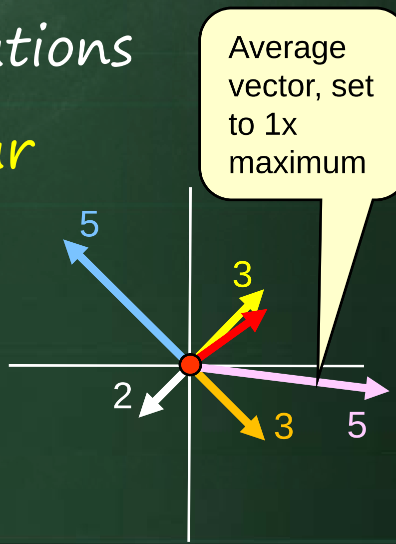
- The basic vector scheme works as follows:
  - Leader moves slower than workers (e.g., 1/10th of speed)
  - Each time worker leaves "safe" range, a counter is incremented
  - Leader computes 4 vectors facing 4 quadrants with magnitudes equal to these counters
  - Leader moves:
    - in combined direction of these vectors, or
    - in direction of strongest magnitude vector



Hierarchical Scheme – Avg. Vector

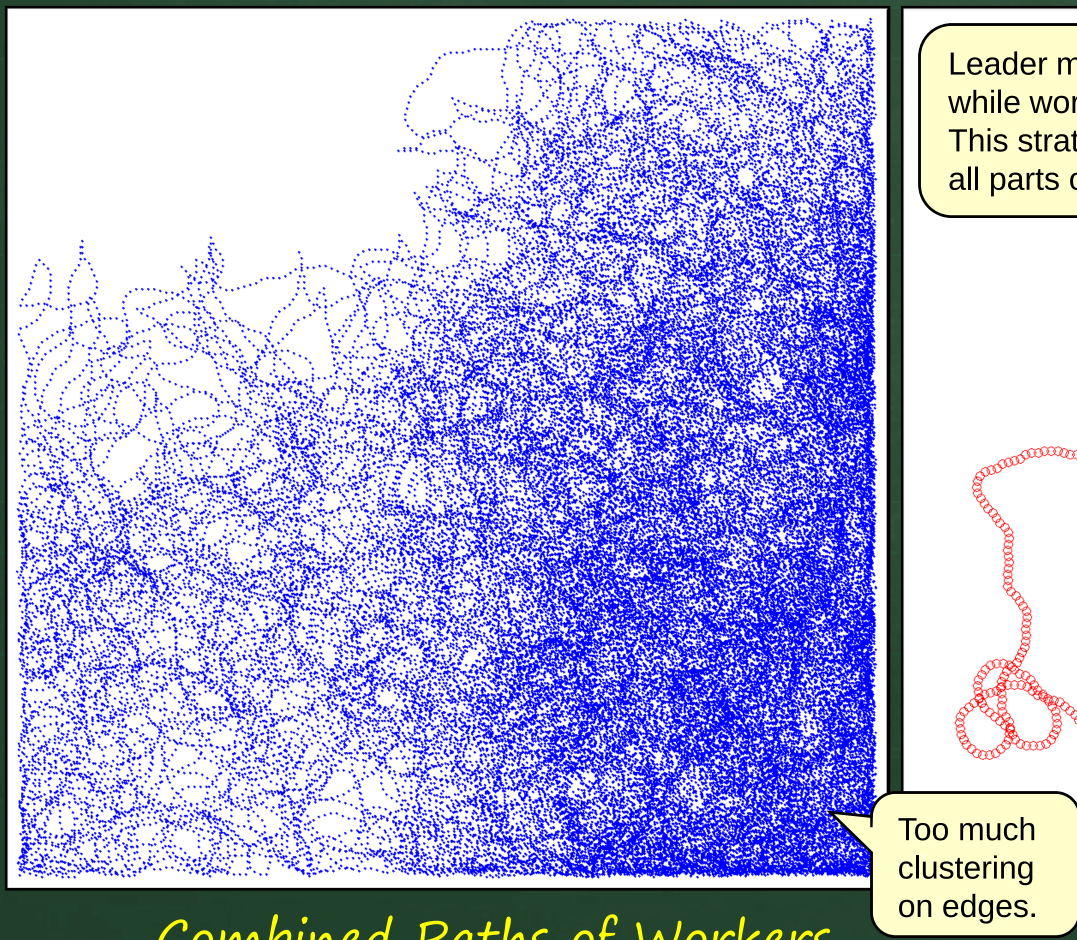
- The average vector scheme works as follows:
  - Same 4 vectors as Vector scheme are used.

    Leader also keeps track of its overall average position
  - Leader computes 1 new vector facing either towards or away from the global average according to its current location
  - Leader includes this new vector in its computations
  - Magnitude of global average vector set to scalar multiple of maximum of other vectors (e.g., 2x, 1x, ½x, etc…)

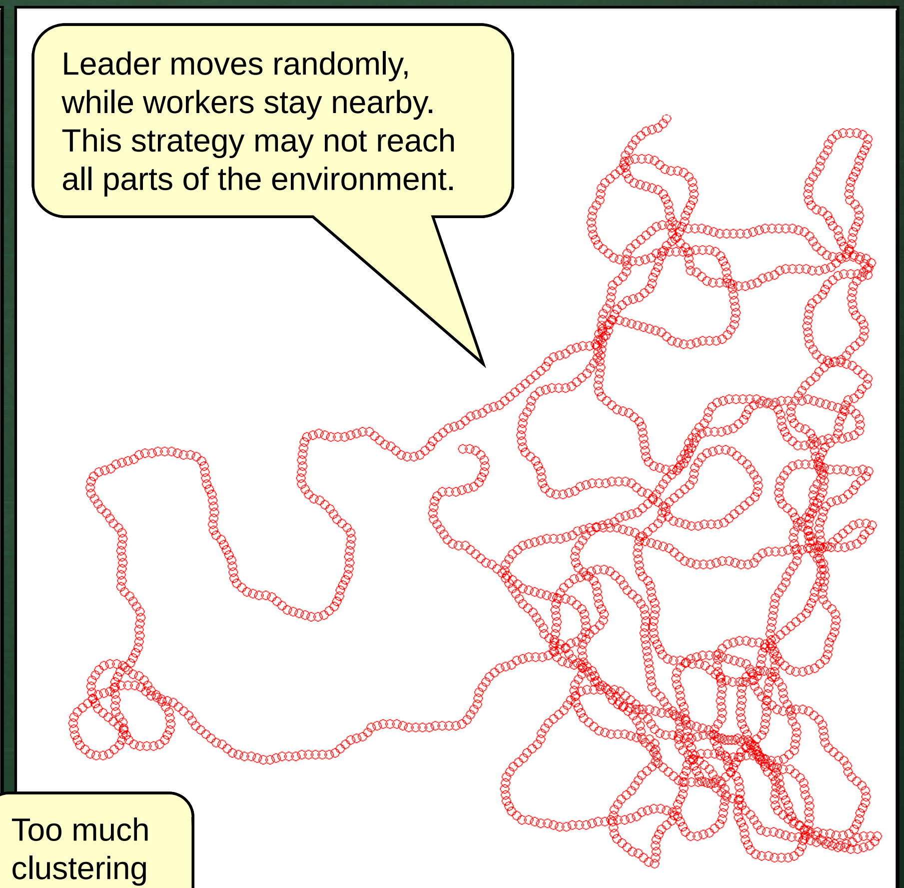


Hierarchical Results

- Results from the Random movement scheme:



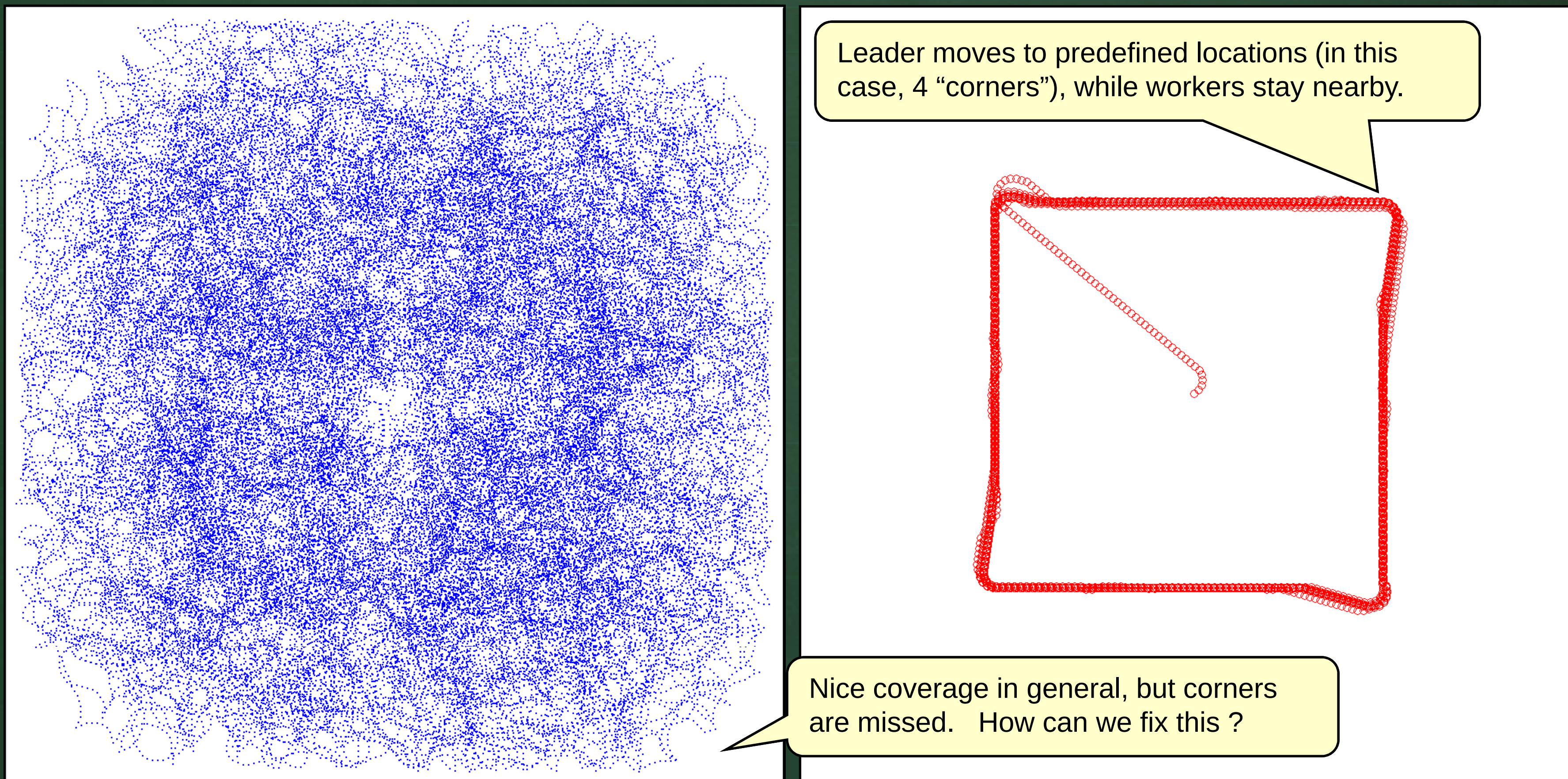
Combined Paths of Workers



Leader's Path

Hierarchical Results

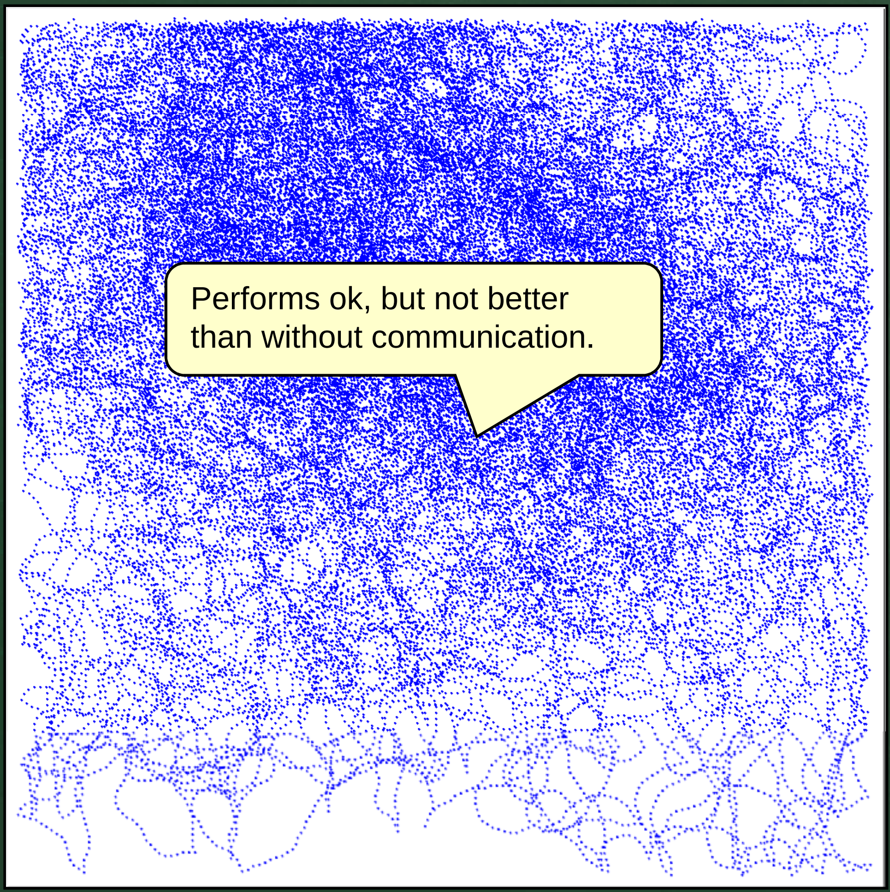
- Results from the 4-Point *Sequential* scheme:



Combined Paths of Workers Leader’s Path

Hierarchical Results

- Results from the Vector scheme:

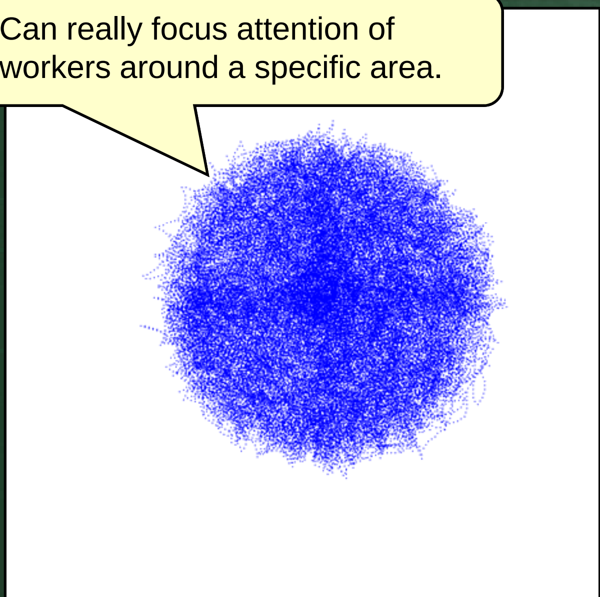


Combined Paths of Workers

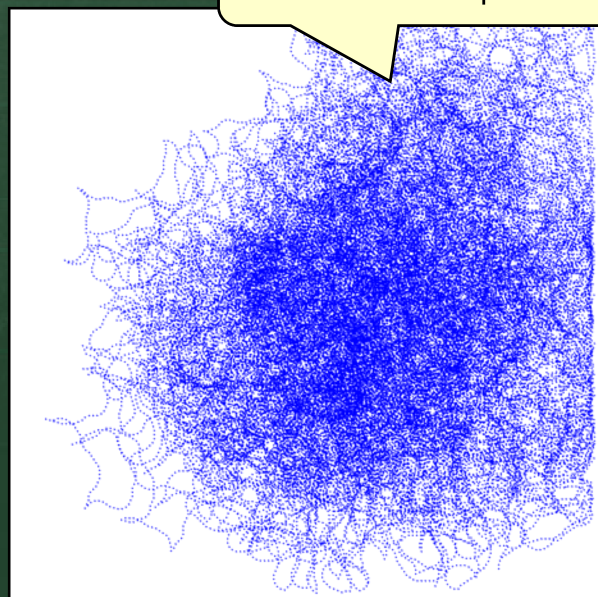
Leader's Path

Hierarchical Results

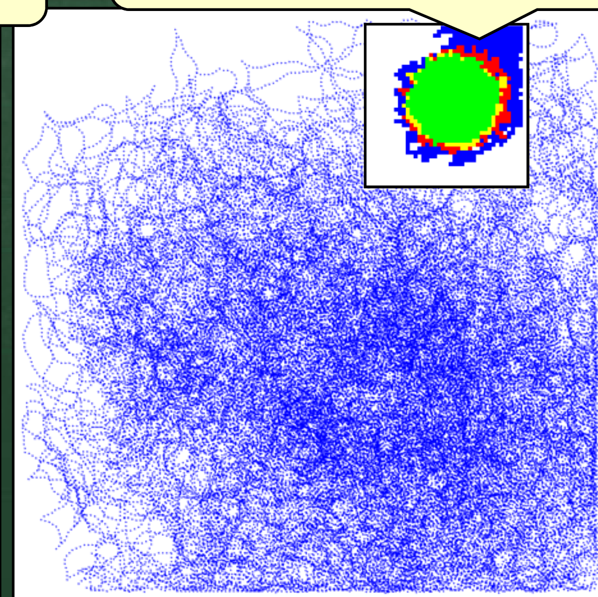
- Results from the Toward Average Vector scheme:
  - good for applications such as focused searching in which the likelihood of success is localized about some known location.



2x Attraction Magnitude



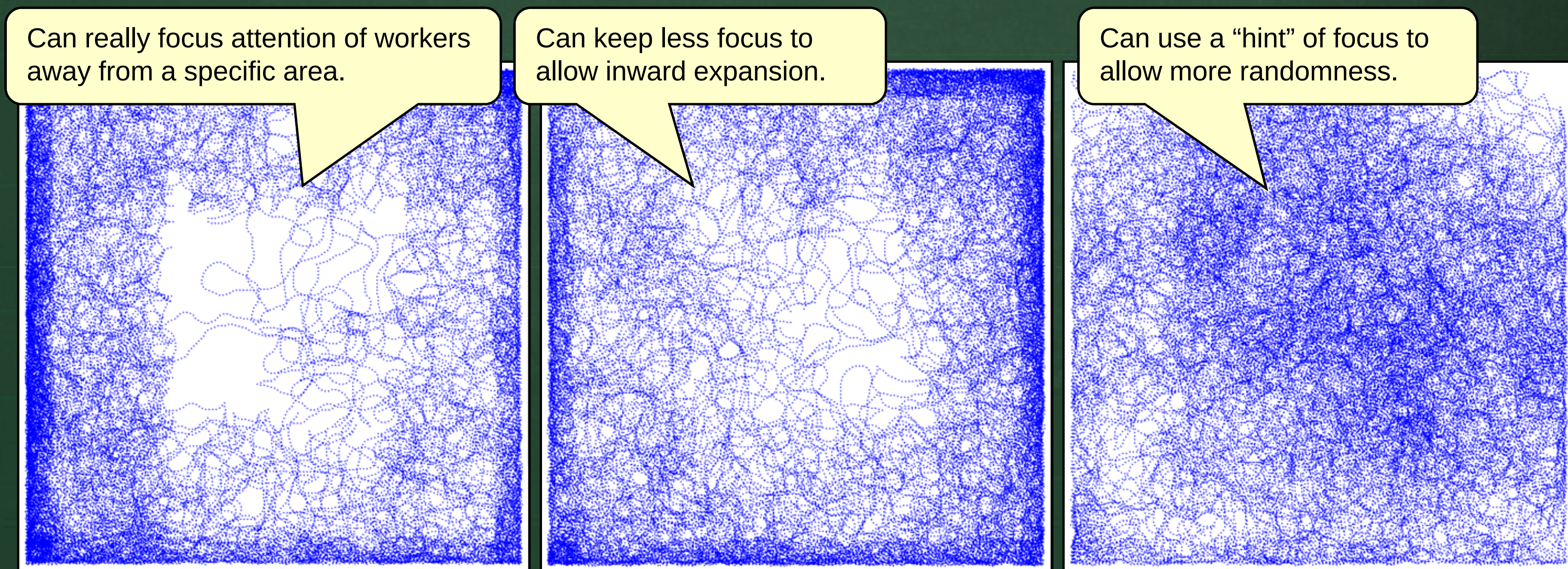
1x Attraction Magnitude



½ x Attraction Magnitude

Hierarchical Results

- Results from Away From Average Vector scheme:
  - good for applications such as mapping to "force" exploration away from previously mapped areas.



2x Repel Magnitude　　1x Repel Magnitude　　½ x Repel Magnitude

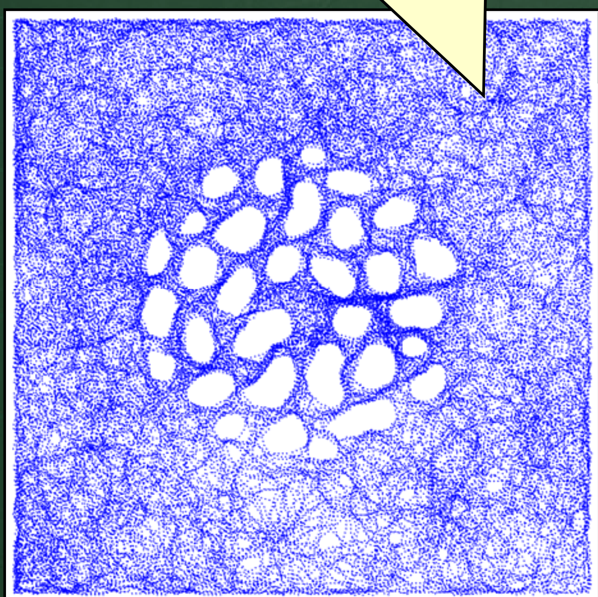
Hierarchical Results

- Results in environments with obstacles:

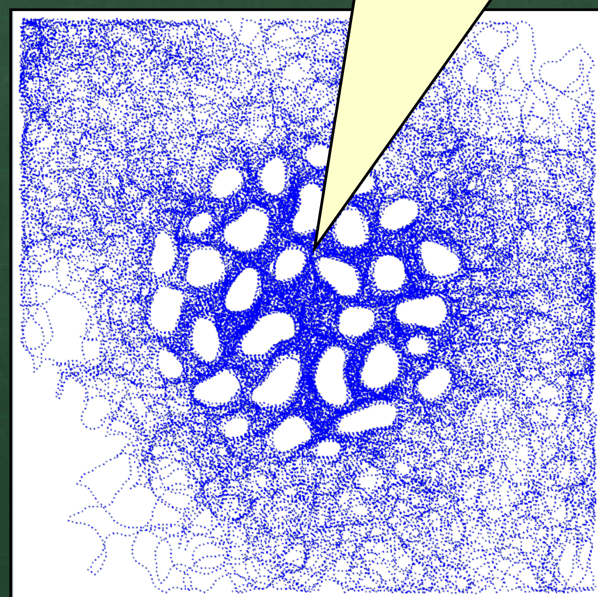
Good overall coverage, but does not focus on obstacles as being more/less important.

Can provide a better coverage around obstacles resulting in more accurate mapping.

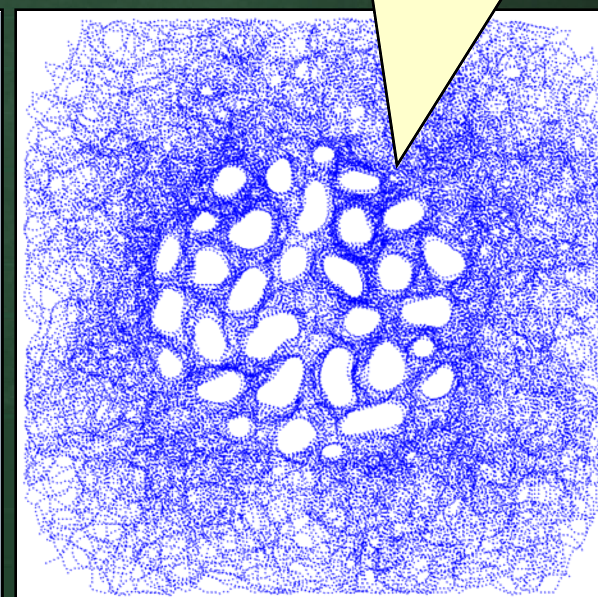
Can provide a coverage more focused along path (in this case around outer obstacle cluster).



No Communication



Vector Scheme



Sequential Scheme

Summary

- You should now understand:
  - The issues involved with coordinating multiple robots
  - How to produce self-organization using simple behaviors
  - The simple foraging problem and how to improve performance in various ways
  - How to provide simple hierarchical communication to focus multi-robot coverage.