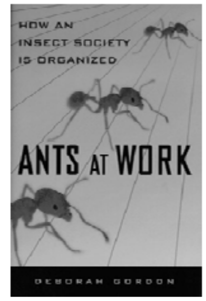
PSYCO 457

Week 9: Collective Intelligence and Embodiment

Intelligent Collectives
Cooperative Transport
Robot Embodiment and Stigmergy
Robots as Insects

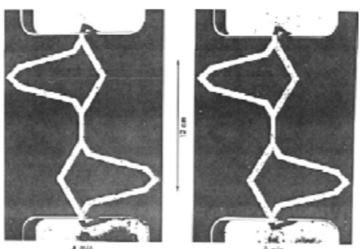
Emergence

- **The world is full of examples of intelligence that emerge from the collective actions of less intelligent components**
- **Classical examples:**
  - **Colony of ants**
  - **Brain of neurons**
- **<u>Here is a video that provides Deborah Gordon's views on emergence</u>**



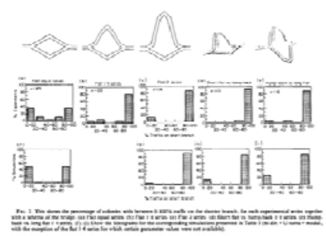
Ants Select Shortest Paths

- **One example of collective computation is related to the travelling salesman problem: over time, a colony of ants will discover the shortest path between the nest and a food source, as shown by Goss et al.**



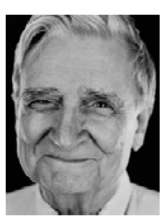
Short Path Sensitivity

- **Ants' choice of the shortest path is very sensitive – Deneubourg and Goss found that even minor discrepancies in distance were detected and exploited, as shown in the graphs below**



Pheromone Signals

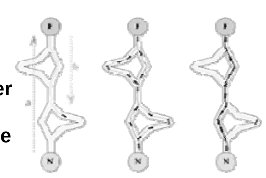
- **How do ants collectively discover the shortest path?**
- **The first answer to this question comes from recognizing that ants can send signals to one another by laying down pheromone trails**
- **<u>E.O. Wilson demonstrates this in this short video</u>**



E. O. Wilson

Natural Computation

- **How do ants compute shortest paths? Naturally!**
- **Ant discovers food, and returns to the nest laying down pheromone trail**
- **Pheromone traces decay over time**
- **Trace will be more likely to be found for short routes, because less likely to have decayed**
- **Trace will be refreshed by new ants**
- **Ultimately, the actions of all the ants will select the shortest trail**



Ant Inspiration

- Collective computation by ants and other insects has inspired work in robotics
- Collective computation can be used to solve problems that individual robots could not solve
- Some of this work is illustrated in a video from the Dorigo robot team

Marco Dorigo

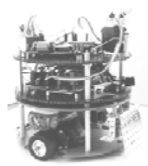
Cooperative Transport

- Ants use cooperative transport to move things that an individual ant could never move
- Video of ant teamwork
- More cooperative transport in this video about ants
- Kube studies cooperative transport amongst robots at the University of Alberta
- Box pushing – weighted box cannot be moved by one robot
- Issue is to create control structure for individuals to accomplish such cooperative tasks

C. Ronald Kube

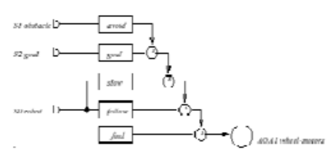
Robot Architecture

- Kube does his research with the CRIPS robot
- Sensors for detecting the goal (the box), obstacles, other robots
- Left and right motors
- Kube programmed 5 behaviors into a robot, with each behaviour under local control of the environment



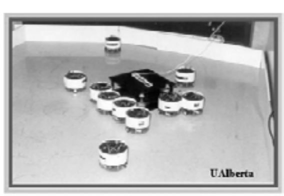
Behaviors And A Subsumption Architecture

- Find: move in a large arc
- Follow: follow another robot
- Slow: slow down to avoid hitting another robot (enables herds to form)
- Goal: turn towards the box
- Avoid: turn away from an obstacle
- These can be arranged in a subsumption architecture as illustrated below



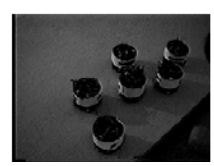
Stigmergy For Cooperative Transport

- This subsumption architecture is designed to control cooperative transport using stigmergy
- "Although it seems intuitive that communication between robots would allow greater cooperation, researchers have begun to investigate cooperative behavior without communication between robots. The advantage of such a noncommunicating system lies in its ability to scale upwards without incurring a communication bottleneck as more robots are added" (Kube & Zhang, 1993)



Stigmergy And Box Pushing

- The five behaviors combine to result in collective intelligence
- If you didn't know how they worked, how would you explain this behavior?
- The robots cooperate to push a box to a goal without direct communication
- All communication is accomplished by moving the box, getting in another robot's way, etc.

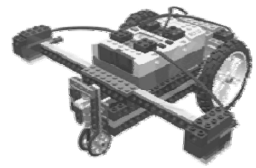


Control Problems Still Exist

- **Problems can still exist in this control structure**
  - **Stagnation occurs when a number of robots distribute themselves equally about the box**
  - **Cyclic behavior is another form of stagnation**
- **<u>But such problems occur in nature too…collective activity emerges from antagonistic actions from individuals as can be seen in this video</u>**
- **“As workers stream outward carrying eggs, larvae, and pupae in their mandibles, other workers are busy carrying them back again. Still other workers run back and forth carrying nothing” (Wilson’s description of ants moving a nest)**

Degrees of Embodiment

- **“Embodiment is grounded in the relationship between a system and its environment. The more a robot can perturb an environment, and be perturbed by it, the more it is embodied” (Fong et al., 2003)**
- **Stigmergy requires a high degree of embodiment, because agents must be able to alter the environment to be under its stigmergic control**
- **Our robots to date have not exhibited this kind of embodiment**

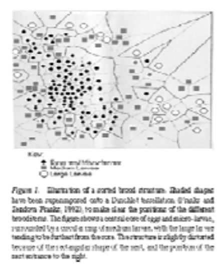


The Lemming

- **The Lemming is an attempt to explore a higher degree of embodiment in our LEGO robots**
- **Its behavior is affected by the color of bricks that it detects**
- **It moves bricks to a different location**
- **This permits colonial interactions, because bricks moved by one Lemming can affect the behavior of other robots**

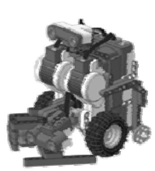
Brood Sorting By Ants

- **The Lemming was inspired by research on brood sorting in ants, which has in turn inspired sorting algorithms for robot collectives**
- **Our general goal was for Lemmings to keep dark bricks in the middle of the arena, and to push light bricks away**



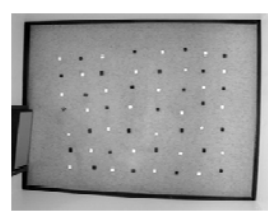
Lemming Subsumption Architecture

- **The Lemming was programmed with a subsumption architecture**
- **Level 0**
  - **Move forward**
- **Level 1**
  - **Use upper sonar to detect and avoid obstacles**
  - **Spin away, but spin direction is affected by brick color if a brick is carried**
- **Level 2**
  - **Use lower sonar to detect and approach bricks on the floor**
- **Level 3**
  - **Process brick color**
    - **White – blind bulldoze to edge**
    - **Black – leave near another brick**



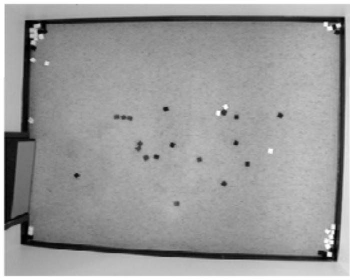
The Lemming World

- **The Lemming is placed in a testing arena bounded by walls, and starting with a “checkerboard” array of white and black bricks**
- **<u>Let’s watch a video to see how this world is transformed</u>**
- **Note that this problem can be faced by more than one Lemming, who can “communicate” with one another using the bricks**



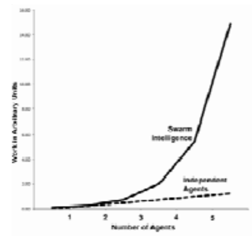
One Lemming's work

- After 70 minutes, a single Lemming has sorted the bricks. Notice that the white bricks are in the corners – even though corners are not part of the Lemming program!

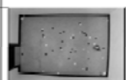
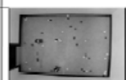
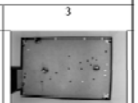
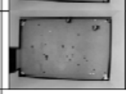
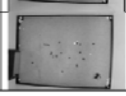


Collective Intelligence

- Is a collective intelligent?
- One measure of collective intelligence is to consider the efficiency of work as a function of number of workers
- If the relationship is linear, there is no collective intelligence
- However, if there is a nonlinear increase in efficiency, collective intelligence is revealed

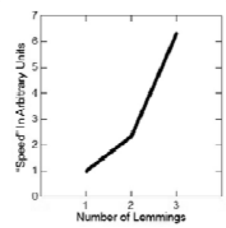


Lemming Collective Intelligence

Table 8-1			
	Number of Lemmings		
Duration of Activity	1	2	3
11 Minutes			
30 Minutes			Done
70 Minutes		Done	Done

Explaining Collective Intelligence

- Why are the Lemmings collectively intelligent?
  - Individuals encounter others, which increase the likelihood of turning to the center to deposit black bricks and solve the task
- Why do white bricks go into corners
  - The bricks are automatically pushed there because of room geometry, and then cannot be removed
- Note that collective intelligence, and pushing white bricks into corners, were surprises that emerged from this project!



Robot Explorations of Insects

- In the previous examples, information about insects has been used to inspire robot design
- Robots can also be used as models to study insect phenomena
- Mike Wilson has developed the robot on the right to study theories of quorum-based decision making that could be applied to insects

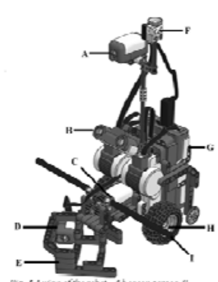
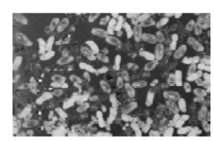


Fig. 4 A view of the robot. A beacon sensor, B ultrasonic sensor, C touch sensor, D brick colour sensor, E plough/brick catch/bumper, F debug light, G NXT brick, H drive wheel, I whiskers.

Choosing A New Home

- The "rock ant" temnothorax albipennis has to move nests frequently because it lives in fragile cracks in rocks
- If a colony has the choice of a poor nest near by, or a better nest much further away, then it will usually choose the better nest
- However, this is done without the ants making detailed, direct comparisons between the two sites
- How does the colony choose the better site?



Choice By Quorum

- Scout ants find a potential new nest
- They recruit another ant to visit the new site (top figure)
- The likelihood of an ant staying at the new site is a function of some judgement about nest site quality
- When enough ants have selected a site, a quorum is detected, and the old nest is moved to the new – ants aren't recruited, they are carried (bottom figure)
- How is such a quorum computed?

Wilson's Robot Behavior

- Capable of detecting beacons that broadcast different signals, and moving to them
- Capable, like the Lemming, of capturing bricks and recognizing their color
- Capable of detecting and avoiding obstacles, and of distinguishing a wall obstacle from a robot obstacle
- A colony of robots was started with beacons in some corners of an arena and a checkerboard pattern of bricks on the floor

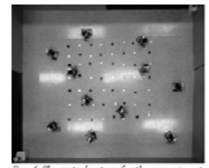


Fig. 5 The initial set up for the experiment runs. The arena measures 260 x 305 cm. The robots are placed randomly around the arena. White and black bricks are arranged in a grid alternating between white and black.

Quorum Computing By Robots

- Wilson's robots computed a quorum by using touch sensors to detect when another robot was encountered
- Such encounters affected the likelihood of staying at a beacon that attracted robots
- When enough encounters had occurred, the beacon was selected and bricks were transported to it

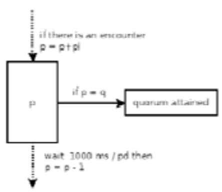
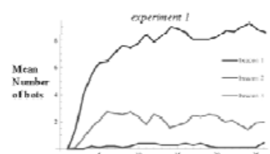


Fig. 2. The threshold response model. p increase by p_i = 50 at each encounter and drains by p_d = 10/second. The quorum threshold is q = 550. This means the robot must have 11 encounters in less than 55 seconds in order to trigger the quorum response. The drain and fill rates of p were determined experimentally after levels 1-7 had been created. I guessed a drain and fill rate for p and then ran the robots in an arena with a beacon 1 and a beacon 3. I logged the rate of encounters for each robot throughout the run and determined p_i, p_d and q from these values.

Robot Beacon Selection

- Over time, the robots would choose one beacon over another, and a quorum could be achieved
- The graph below illustrates the number of robots near each of three beacons at different times



Quorum Decision and Brick Sorting

- When enough encounters were made at a beacon, a quorum was achieved. Black bricks would be moved to it, while white bricks were pushed away

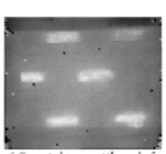


Fig. 6 Corrected image at the end of a run. Beacon 1 is located in the top-right corner and beacon 2 is in the bottom-left corner.

Difference in probability of final positions of the two kinds of bricks (Black - White)