New Jun Jie (A0196612B)

Decision Making in a Collective Intelligence: Examining the Honeybee Swarm as a Society of Mind

The honeybee is beautifully social. In a harmonious society, tens of thousands of honeybees cooperate to select a home with near-perfect accuracy. The multitude of bees in a swarm collaborate to achieve a form of collective intelligence, whose abilities far transcend that of an individual honeybee. How can we understand such a complex, collective decision of nest-site selection emerging from the simple, singular bees in a swarm?

Collective intelligence is cognition that emerges from the interaction and collaboration among a group of individuals. The phenomenon of collective intelligence is significant, having been observed and applied in many disciplines, ranging from the design of distributed cognition in artificial intelligence to intelligent swarm behaviour in sociobiology. In the field of artificial intelligence, isolated problem solvers are reaching the limits of their individual capabilities (Kaufman 1). The nature of many challenges is inherently distributed and makes a society of individual agents that form a collective intelligence intuitive as a decentralised solution approach (Kaufman 2). An example is the particle swarm optimization algorithm in computational science (Kennedy and Eberhart 1).

A collective intelligence can be studied through the lens of Society of Mind, a theory of natural intelligence that explains the emergence of decision-making abilities through the interactions in a diverse society of simple, individual agents (Minsky 17). The theory, conceptualised by cognitive scientist Marvin Minsky, views the human mind and any other naturally evolved cognitive systems as a vast society of individually simple processes known as agents (Singh 1). The theory attempts to explain how intelligence could be a product of the interaction of non-intelligent parts. One can draw a deep similarity in the emergence of cognitive intelligence between the agents in the Society of Mind and the bees of the *Apis mellifera* honeybee swarm.

The Society of Mind theory has the potential to shine light on the decision-making mechanisms of the collective intelligence in the honeybee swarm. By examining the honeybee swarm as a Society of Mind, the theory can serve as a useful and effective framework to understand and model the decision-making mechanisms of the *Apis mellifera* honeybee swarm.

Communication in a Collective Intelligence

Communication plays a central role in collective decision making. To collaborate and make a decision in a collective, individuals must communicate between each other (Wagner, Shapiro and Xuan 1), as communication facilitates the sharing of information between agents (Kaufman 2). An examination of the communication mechanism in the *Apis mellifera* honeybee swarm through the Society of Mind theory will enable a better appreciation of the intricacies of communication in a collective.

Communication in the Honeybee Swarm – The "Waggle Dance"

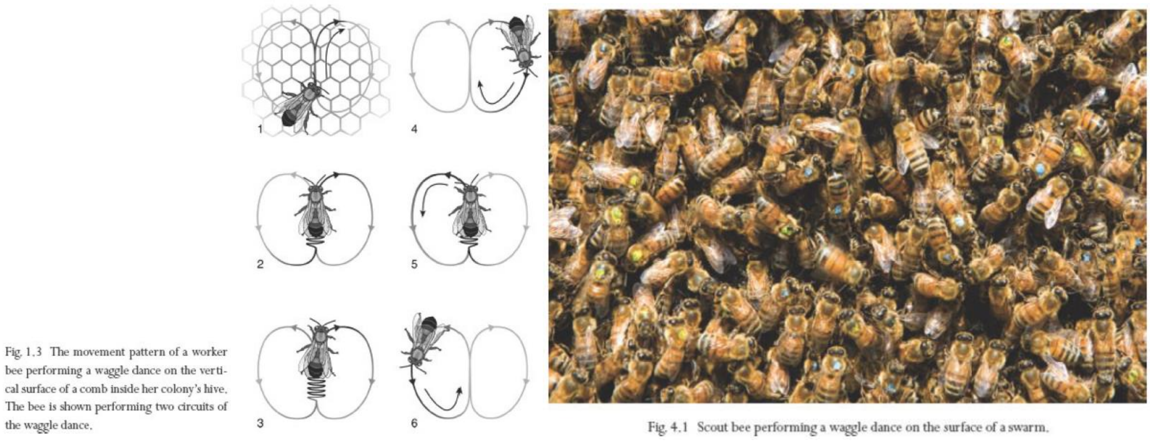

Figure 1. The waggle dance of the honeybee swarm. *Source:* Honeybee Democracy 2010:15

Communication in the *Apis mellifera* honeybee swarm takes place through the propagation of "waggle dances", from one individual forager bee to another, to share information about potential nesting sites within the swarm (Seeley 13). The waggle dance is a figure-eight movement, consisting of a "waggle run" on the surface of the honeycomb while waggling sideways, then stopping to make a semi-circular "return run" back to the starting point, followed by a repetition of the cycle (Figure 1). When a forager bee performs a waggle run, a miniature representation of the flight journey is reproduced, indicating information about the location of interest.

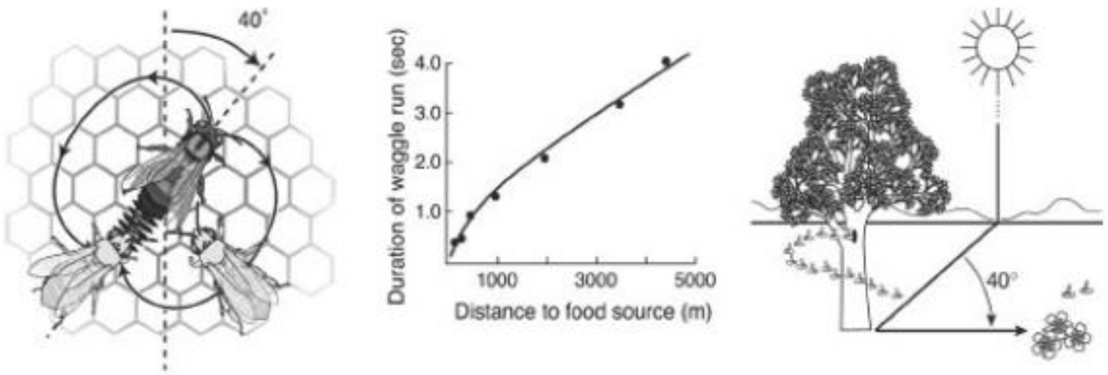

Figure 2. Information encoded in the waggle dance. *Source:* Honeybee Democracy 2010:15

The waggle dance allows an individual forager bee to share information about the potential nesting site to the rest of the swarm (Seeley 15). The waggle dance encodes distance and angle from the hive to the location of interest, represented by the waggle run duration and angle relative to the comb's vertical respectively (Figure 2). A forager bee dances from seconds to minutes, trailed by unemployed forager bees that "take part in each part of her manoeuvrings" (Seeley 14). The dance-follower bees then search only where the dancer bee had previously foraged, even at remote spots. The dance-followers' behaviour is evidence that information about location was acquired through the foragers' dance. Returning dance-followers will then advertise the sites upon returning through another series of waggle dances, trailed by even more unemployed forager bees that will then searched for the potential nest-site.

Communication in the Society of Mind – The "K-line"

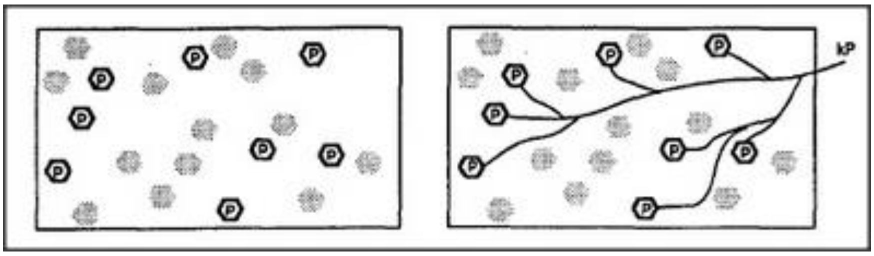

Figure 3. The K-line. *Source:* Society of Mind 1986:83

Communication in the Society of Mind takes place through a type of agent called a "knowledge line", or "K-line" (Minsky 81). The K-line attaches to other agents that are active when information is processed, forming a specific collection of agents unique to the context. As a result, the K-line develops into a wire-like structure attached to many different agents (Figure 3).

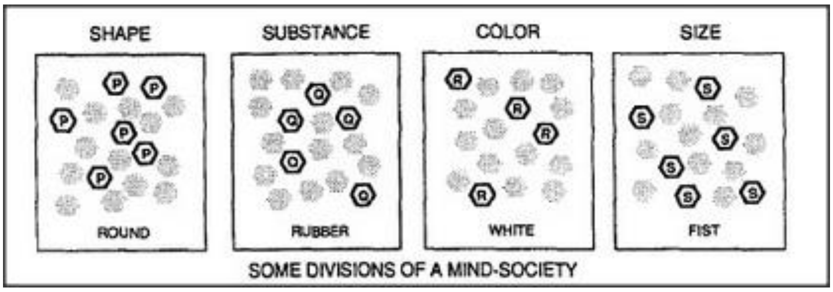

Figure 4. Divisions in the Society of Mind. *Source:* Society of Mind 1986:85

The attachment of K-lines to different agents allows knowledge to be represented and shared with other agents in the Society of Mind. A K-line first attaches to agents containing related bits of information to form an "agency". Agencies that represent related "concepts" then form a "division" to represent knowledge. For instance, a division representing knowledge of "shapes" can consist of agencies such as "round" and "square" (Figure 4).

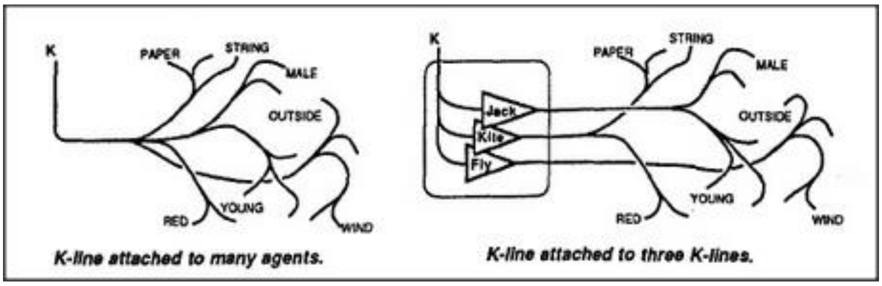

Figure 5. K-line attached to other K-lines. *Source:* Society of Mind 1986:89

When the need arises for the retrieval of information, the relevant K-line is activated, which activates other agents attached to it, triggering agents downstream of the K-line. The next time similar information is processed, the system activates similar K-lines formed in the past and all agents attached to it. When K-lines are repeatedly activated in different contexts, a new K-line is formed and attached to the past K-line related by context, forming a mental state of K-lines in a web-like structure, and all agents can be activated. The activated agents can then be used if they are relevant in the given context (Figure 5). When those K-lines are activated, each K-line activates hundreds or thousands of other agents.

Insights into Communication in a Collective Intelligence

The Society of Mind theory highlights that the mode of communication in the *Apis mellifera* honeybee swarm is through the propagation of information from one honeybee to another. Like the K-lines that propagate activations downstream of the K-line, the bees propagate waggle dances about a nest-site to other bees in the swarm. Through a relative examination of the Society of Mind and the honeybee swarm, a series of insights into the mechanism of communication in a collective intelligence can be realised.

The distribution of communication among individual agents allows for a democratic decision-making process in a collective intelligence. One individual agent’s contribution is made up of a collective contribution prior to the agent, like how one honeybee’s waggle dance is inspired by the previous honeybee’s advertisement to search for the potential nest-site. Thus, the eventual collective information about all potential nesting sites is contributed by all individuals in the collective. Due to the honeybee swarm’s decentralised nature of exploring homesites, honeybee swarms are very efficient in exploiting the best location sites in terms of distance and quality. As each bee has limited knowledge locality, each bee makes an independent, individual evaluation of a site, preventing an error from being propagated throughout the swarm. As a result, the outcome of the collective decision, its responsibility and stake, is distributed among many members, facilitating a democratic decision-making process in a collective intelligence.

Therefore, the Society of Mind theory serves as a useful and effective framework to understand and model the decision-making mechanism of communication in the *Apis mellifera* honeybee swarm.

Conflict Resolution in a Collective Intelligence

A democratic decision-making process in a collective can cause conflict among the agents. As individuals have access to only a limited span of information, the knowledge contained in each agent might be incomplete, resulting in disagreement (Alshabi, Ramaswamy and Itmi). To make a collective decision, agents must communicate with each other, share information and resolve conflicts.

Conflict resolution is a fundamental process for collaboration between individuals (Wagner, Shapiro and Xuan 1). All forms of communication and interaction between individuals are motivated by the need to resolve conflict and the need to deal with interdependence between one another (Wagner, Shapiro and Xuan 1). Individuals must be able to resolve conflicts that arise from collaboration, such as choosing among alternatives, in the process of achieving their goals (Kai, Zhonghua and Zheng 1). A close examination of the conflict resolution mechanism in the *Apis mellifera* honeybee swarm through the Society of Mind theory will unravel the complexities of conflict resolution in a collective.

<u>Conflict Resolution in a Bee Swarm – The Recruitment-Leakage Model</u>

To decide on a future nest-site, the *Apis mellifera* honeybee swarm must resolve the conflict among many competing choices of possible homesites suggested by many individual honeybees through a vigorous debate.

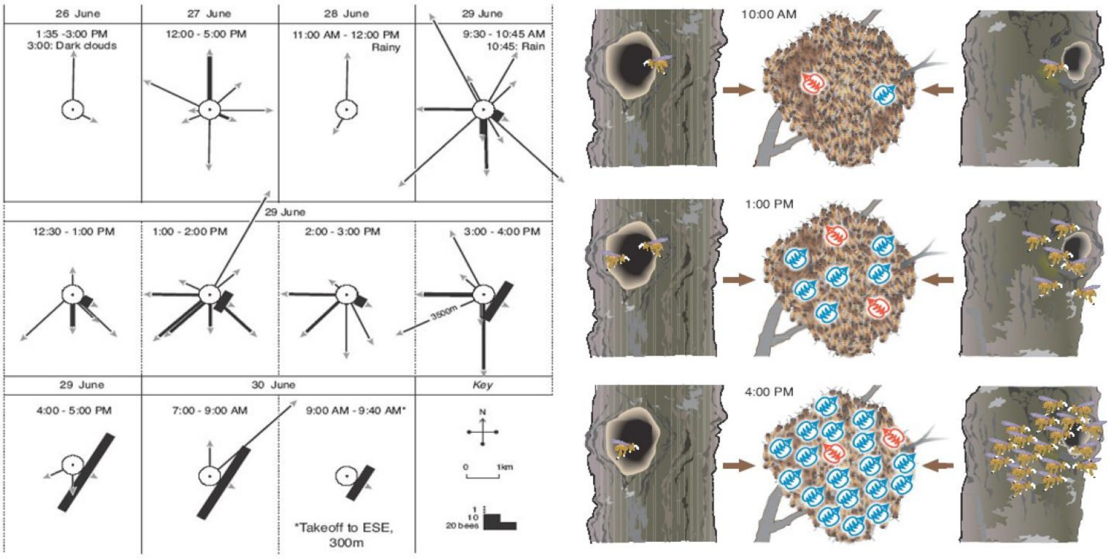

Figure 6. Collective decision of bees to choose a future homesite. *Source:* Honeybee Democracy 2010:128

In one honeybee colony observed by Seeley, different candidate homesites were advertised over a few days (Figure 6). On day 1 and 2, 13 bees advertised a site 1,500 metres to the north of the honeycomb and a site 300 metres to the southeast. Day 3 was mostly rainy, and no new sites were advertised. On day 4, more than 20 new sites were advertised. The site 1,500 metres to the north had no new dancer bees while the site 300 metres to the southeast had new dancer bees advertising for it every hour. On the final hour of dance activity between 4:00pm and 5:00pm, the recruitment of forager bees to the southeast site overwhelmed that of other sites, with 61 new dancer bees and only two recruiting to alternative sites. On the morning of day 5, the swarm launched into flight to the southeast and settled in residence in the wall of a bomb-damaged building.

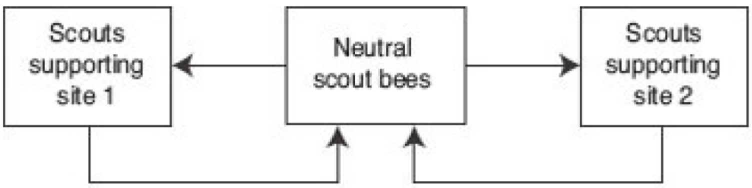

Figure 7. The Recruitment-Leakage model of conflict resolution. *Source:* Honeybee Democracy

When a forager bee performs a waggle dance to support a site, the dance can recruit neutral bees into supporters for that site. Conversely, dancer bees currently supporting a site can also re-join, or “leak” into the pool of neutral bees. The conflict-resolution mechanism in a honeybee swarm thus consists of two processes of recruitment and leakage of supporters for an advertised site (Figure 7).

The rate of recruitment of neutral bees to support a site is affected by the liveliness of the waggle dance. The more profitable a homesite evaluated by a forager bee is, the livelier the bee will be, and the number of cycles of waggle dance circuits it will perform on the honeycomb increases. Neutral bees become supporters for any site strictly in proportion to the amount of dancing relative to other sites. The better the potential homesite, the stronger the dancing of the forager bees supporting it, and the greater the effectiveness in recruiting additional supporters for the homesite.

The rate of leakage of dancer bees re-joining the pool of neutral bees can be explained by the "Retire-and-Rest" concept, where every bee incurs a steady motivation decay, an internal neurophysiological process, until it no longer has any motivation left for the dance (Seeley 117). The steady motivation decay is observed as each bee reduces the strength of her dancing over consecutive trips back to the swarm, regardless of the quality of the chosen site. A bee that advertises a high-quality site tends to start her reporting by performing a large number of waggle dance circuits, while one that advertises a low-quality site tends to start her reporting with a smaller number of waggle dance circuits.

A bee from a high-quality site will advertise her site over many consecutive trips back to the swarm, and therefore in sum will produce a strong advertisement with many dance circuits. Eventually, the conflict among the many competing choices of potential nest-sites is resolved when the dances of one nest-site remains, and the *Apis mellifera* honeybee swarm takes off toward the nesting site.

Conflict Resolution in the Society of Mind – The Principle of Non-Compromise

Conflict can arise in the Society of Mind when two agents have any form of conflicting interests. Take Minsky's example of agents involved in play in the minds of children. Children enjoy both building things and knocking things down. The two agents responsible would be the "Wrecker", whose specialty is knocking down blocks, and "Builder", whose specialty is making towers from blocks (Figure 8).

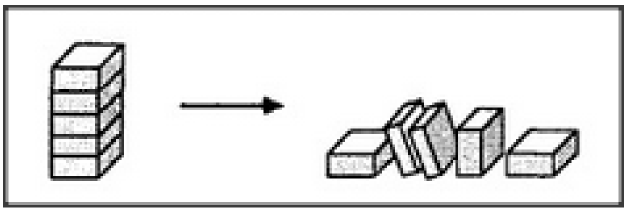

Figure 8. Builder and Wrecker agents. *Source:* Society of Mind 1986:32

At some point in the middle of play, conflicting interests may arise between the two agents. Wrecker may consider the tower to be sufficiently tall to smash, while Builder may want to continue making the tower taller. Builder and Wrecker disagrees on whether the tower is high enough, and whether to smash or continue building the tower.

One mechanism of conflict resolution in the Society of Mind is through the "Principle of Non-Compromise" (Minsky 33), by which conflicting agencies are ignored and control is yielded to another independent agency. The longer an internal conflict persists among an agent's subordinates, the weaker becomes that agent's status among its own competitors. If such internal problems aren't settled soon, other agents will take control and agents formerly involved will be "dismissed".

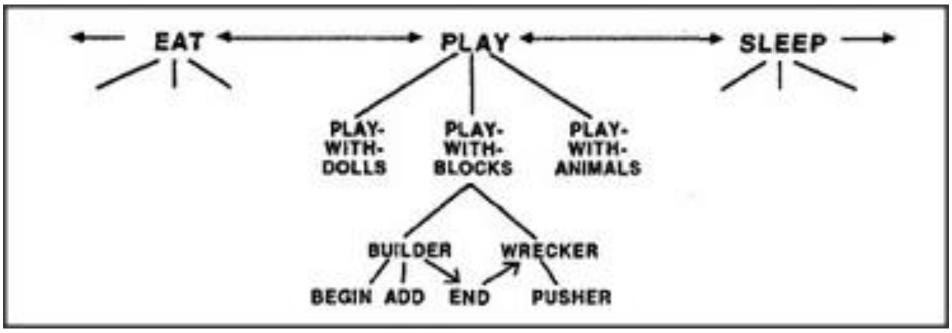

Figure 9. Hierarchy of agents. *Source:* The Society of Mind 1986:32

The Society of Mind tends to migrate conflict between agents to a mutual superior, or "mental managers" (Singh 10) at a higher level in the hierarchy of agents (Figure 9). With different kinds of knowledge in disagreement, the Principle of Non-Compromise is employed to utilise other agencies to resolve the conflict. New mental managers are recruited to group related sets of lower-level skills together. When two agents disagree, mental managers can instead use the conflict as a sign that they need to reformulate the problem by bringing in some third agent with a different perspective, one that can see the problem and its potential solution with greater clarity (Singh 10). The job of the manager is not so much to directly resolve the conflict, but rather to find other points of view that cause the conflict simply to disappear from the new vantage point (Singh 10).

The longer a conflict between agents is prolonged, the weaker their mutual superior becomes, and tends to cause a loss of control to other agencies. For example, Builder and Wrecker were originally activated by a higher-level agent in the hierarchy, Play-with-Blocks (Figure 9). Any prolonged conflict between Builder and Wrecker is likely to weaken their mutual superior, Play-with-Blocks, reducing Play-with-Block's ability to suppress its possible rivals, Play-with-Dolls and Play-with-Animals. If the prolonged conflict is not settled quickly, it could weaken Play at the next-higher level, and rival agencies, Eat or Sleep, might seize control.

Insights into Conflict Resolution in a Collective Intelligence

At first glance, the Society of Mind theory does not seem to effectively model conflict resolution in a bee swarm, due to a seemingly fundamental difference in the conflict resolution structures between the bee swarm and the Society of Mind. The conflict resolution structures can be described as horizontal versus vertical architectures (Bond and Grasser). The bee swarm has a horizontal conflict resolution architecture, where individual bees work toward the goal without needing any direct one-to-one conflict resolution; all bees are on the same level with equal importance, represented through their waggle dances. The Society of Mind has a vertical conflict-resolution architecture, where agents are structured in a hierarchical order of importance, from higher-level superiors to lower-level agents. Therefore, the Society of Mind theory seems ineffective in modelling conflict resolution in the bee swarm.

However, upon thorough investigation, the Society of Mind's vertical conflict-resolution architecture actually builds on the relatively simpler horizontal architecture in the bee swarm. Consequently, the Society of Mind has the capacity to not only model the bee swarm, but model more complex collective intelligences. The Society of Mind theory explains that the conflicts in the honeybee swarm are resolved through an automatic weakening of individual agents with as conflict persists. Like the weakening of Play-with-Blocks caused by the conflict between Builder and Wrecker, the waggle dances of lower quality nest-sites loses liveliness relative to that of other higher quality nest-sites.

Furthermore, the Society of Mind theory’s mode of conflict resolution allows for the modelling of a more complex collective intelligence and its decision-making mechanisms. An instance of a more complex decision-making mechanism is one that enables cooperation among self-interested individuals with different goals. Bees are a relatively simple collective and have only one common interest—to ensure their Queen survives (Seeley 116). As a result, the simple collective decision-making entity of the bees need not have a highly sophisticated mechanism of conflict-resolution.

Therefore, the expressivity of Society of Mind theory to model both simple and complex collective intelligences makes the theory all the more useful and effective as a framework to understand and model the decision-making mechanisms of a collective intelligence in the *Apis mellifera* honeybee swarm.

The Emergence of a Collective Intelligence

The Society of Mind, a theory explaining the emergence of natural intelligence in an individual from a society of simple agents, is surprisingly effective as a framework to examine the decision-making mechanisms of a collective intelligence in the *Apis mellifera* honeybee swarm.

The theory proves useful to examine the mechanisms of communication and conflict resolution in the honeybee swarm, and one can only wonder at the potential of the Society of Mind theory to model other mechanisms of a collective intelligence, such as the specialisation of abilities or the learnability of individual agents in a collective. The theory brings to light the inner workings of the collective intelligence of a honeybee swarm, and has the potential to examine a range of other forms of collective intelligences, such as the foraging behaviour in ant colonies, flocking behaviour in birds, schooling behaviour in fish and collaborative behaviour in swarm robotics.

The Society of Mind theory greatly improves our appreciation of the emergence of collective intelligence, that the sum is greater than its parts, and inspires our imagination of the complexity and elegance of the emergence of intelligence in any collective.

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