Quorum Sensing in Multi-Agent Systems

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As used by current researchers, the term *quorum sensing* (QS) denotes a means for a group of independent agents to reach common decision, and then to take collective action. Although the independence of each of the agents leads to the strength of the collective action, this independence also leads to a non-deterministic outcome, since a quorum may not be reached even when appropriate. A quorum could be prevented by various causes, such as insufficient density of agents, interfering communication noise, adversarial interference in the inter-agent communications, or adverse environmental conditions. If and when the tipping point of a quorum for decision-making is reached, then the independent behavior of the individuals changes, and the group begins to act as a unified entity.

Quorum Sensing in Nature

Two well-researched examples of quorum sensing in the literature of the natural sciences include bacteria and honeybees, revealing common QS-pattern characteristics as well as some differences. Here we will use a set of six characteristics drawn from Dove (2010) to discuss this QS pattern. These are the SAREPH characteristics: self-organization (S), adaptive tactics (A), reactive resilience (R), evolving strategy (E), proactive innovative (P), and harmonious operation (H).

Bacteria

To ground the quorum-sensing pattern, one bacterial example will be discussed in terms of its SAREPH characteristics. The abilities of bacteria were once believed to be very simplistic and lacking in one of the main capabilities that differentiate higher organisms, the ability to communicate and act as a group. This thinking was challenged by the research of Bassler (2002) on the bacterium *V. harveyi*. Bassler identified the methods by which individual *V. harveyi* bacteria not only communicate but also make collective changes in their behavior based upon the concentration of the group in the immediate area.

Self Organizing. The bacteria secrete molecules, which are sensed by the nearby bacteria and serve both to identify members of the same species and to determine the relative concentration of peers in the immediate area. Once the concentration reaches a tipping point, all of the bacteria react collectively. Initially all bacteria function as individuals and exist in a benign state, but when quorum is sensed they all change behavior and self-organize into a unified entity to achieve a goal, such as luminescence or releasing toxins.

Adaptive Tactics. The bacteria communicate with other bacteria species, sensing and communicating with the other bacteria species. They adapt their tactics to an adversarial or cooperative environmental situation.

Reactive Resilience. Bacteria exhibit reactive resilience to cope with attacks on the underlying communication mechanisms. Defoirdt, Boon, and Bossier (2010) found variability in the signal-molecule concentration, and the same species would show variability in the number of receptors present. They theorized this variability to be a natural reaction of the bacteria to stave off attack of the receptors by quorum-sensing antagonists that compete with the natural signals of the bacteria. In another example by Henke and Bassler (2004), the *V. cholerae* bacteria showed that deactivation of either or both of two main quorum-sensing circuits did not stop the bacteria from action expression (bioluminescence) during quorum. A third sensing circuit was discovered that provided complete redundancy for the failure of the primary sensing circuits.

Evolving Strategy. A variety of experiments (Defoirdt, Boon, Bossier 2010; Wei 2006) indicate that quorum sensing in a given population of bacteria is capable of evolving, as the population grows, to overcome ineffectiveness (for whatever reason) in quorum-sensing mechanisms. These studies also suggest that this evolution occurs through selectively favored mutations in signal generators, signal sensors, and quorum triggers.

Proactive Innovation. We define the proactively innovative characteristic as acting preemptively, perhaps unpredictably, to gain advantage. This is the typical purpose of QS in bacteria: individual bacteria wait in quiet until the time when their population has grown large enough to succeed at a goal that would be unlikely in smaller number, and at the tipping point, the individual behavior changes throughout the entire population into collective action.

Harmonious Operation. The behavior of *V. harveyi* to detect the concentration of its species and react through bioluminescence reveals the ultimate collective purpose of the microorganism colony—to work together in harmony to accomplish a common task as a large multicellular organism would in a similar situation.

Honeybees

Honeybees use quorum sensing to find and establish a new nesting site (Seeley, Visscher, Passino 2006). Here we will forego the SAREPH analysis of the honeybees, and refer the interested reader to a fuller treatment of their quorum-sensing pattern in Hamar and Dove (2012). Bee colonies reproduce through budding, where the queen leaves the hive with a portion of the workers to form a new nest elsewhere. After leaving the old nest, the workers form a swarm that persists throughout the decision-making phase. Communication is accomplished through a bee "dance." Bee scouts that have found a good site dance with more intensity and for longer periods than do scouts that have found a less desirable site. As a result, more scouts travel to the better sites for confirmation. These new scouts explore the advertised nest sites, return to the swarm and dance their findings. Continued confirmation skews the dancing in favor of better sites, until a group decision is made. However, a group decision by quorum may be not be acted upon if environment conditions such as adverse weather preclude successful action.

The Quorum-Sensing Pattern

A formal description of the reusable pattern includes seven elements:

1) the context in which the generic pattern is applicable,
2) the generic problem to be addressed,
3) the generic tradeoffs and contradicting forces to consider when applying the pattern,
4) the generic nature of the solution,
5) a grounded example of the pattern being employed in a four-panel graphic of pattern dynamics,
6) the agility of the pattern exhibited as SAREPH characteristics of the grounded example (discussed earlier),
7) examples in the literature of the pattern employed in multiple domains.

Context. A multi-agent system with a goal that requires a sufficient number or density of agents to accomplish.

Problem. A need to ascertain when a sufficient number or density of agents exists to carry out a common goal that cannot be accomplished individually.

Forces. A desired individual action vs. the quantity or density of agents required to succeed; true signal recognition vs. false signals from noise and competing agents; sufficient quorum vs. inappropriate environmental conditions; high signal concentration in small environments vs. sufficient signal concentration in large environments; resource allocation to QS-driven goal achievement vs. resources needed in companion goal achievement; individual QS cost vs. collective benefit of QS goal achievement; resilience of non-deterministic distributed control vs. efficiency of deterministic centralized control.

Solution. Develop an inter-agent signaling mechanism that generates and receives signals of goal interest that employs multiple strategies to guard against signal-interfering and false influences.

Grounded Pattern Example

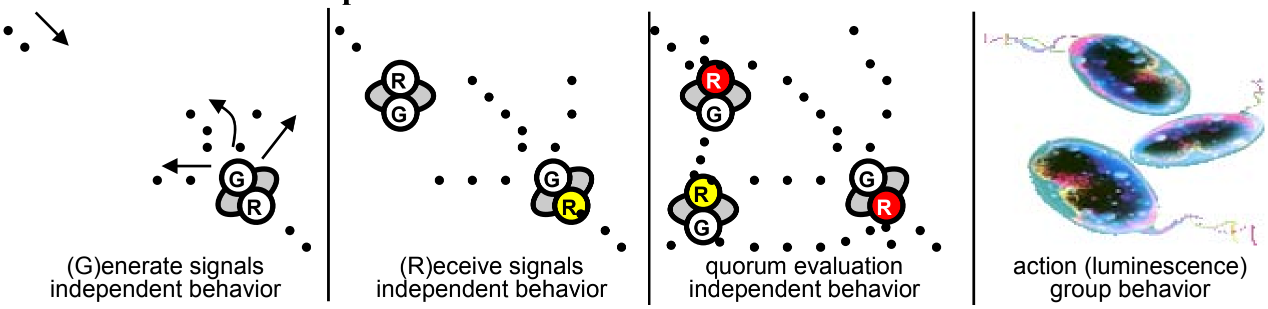

Figure 1: Bacteria in the light-generating organ of night-feeding bobtail squid create light when the density of the bacteria indicates sufficient population.

Agility of Pattern Example. Group members participate in a self-organized collective action when a signaled quorum is sensed (S); individual signaling and sensing methods adapt to both environment and intraspecies density conditions (A); redundant methods for individual signaling and sensing provide resilience to adversarial and environmental threats (R); selective pressure causes signaling-ineffective individuals to evolve over successive generations toward signaling-effectiveness (E); achieving a quorum decision causes a collective, proactive behavior change (P); signaling and sensing processes enable decision-making in harmony with collective purpose (H).

Examples in the Literature. Bacteria employ quorum sensingto identify the local concentration of the species and act with a single outcome (Bassler 2002; Wei et al. 2006). Honeybee scouts survey prospective nest sites and "report" in competition to the swarm until they reach a quorum on the quality of the site (Seeley, Visscher, and Passino 2006; Seeley et al. 2006). In an analogous manner to these biological organisms, "cyber worms" lay quiet until the number of infected hosts is sufficient to trigger a collective attack (Vogt, Aycock, Jacobson 2007).

Application

In quorum sensing systems, the resilience and robustness of actions by the group appear to stem from at least three characteristics observed in natural systems: agent independence, broadcast signaling, and adaptable signaling mechanisms. There is no vulnerable central control over agent behavior—no decision issued by a queen, no bacteria boss exists—but rather a non-deterministic collective behavior that trades off determinism for resilience. Quorum signaling is not targeted at a narrow agent-to-agent channel, but rather is broadcast with non-deterministic effect. Bacteria use redundant but diverse signaling mechanisms at the individual agent level, and these mechanisms guard against various kinds of interference. Honeybees proactively inhibit signaling from bees with competing site-selections, in order to break deadlocks. These examples may provide important guiding principles that could be transferred to human-made systems, especially if those systems become targets of intelligent adversaries.

The application of the quorum-sensing method for group decision-making and action-taking in communities of practice can lead to some innovative approaches. The Internet Storm Center (http://isc.sans.edu/about.html) practices a form of QS. We can see the core elements of quorum sensing at work in the events that led to the center's creation (as described on their website):

> On March 22, 2001, intrusion detection sensors around the globe logged an increase in the number of probes to port 53, the port that supports the Domain Name Service. [. . .] Within an hour of the first report, several analysts, all of whom were fully qualified as SANS GIAC certified intrusion detection experts, agreed that a global security incident was underway. They immediately sent a notice to a global community of technically savvy security practitioners asking them to check their systems to see whether they had experienced an attack. Within three hours a system administrator in the Netherlands responded that some of his machines had been infected, and he sent the first copy of the worm code to the analysts. The analysts determined what damage the worm did and how it did it, and then they developed a computer program to determine which computers had been infected. [. . .] Just fourteen hours after the spike in port 53 traffic was first noticed, the analysts were able to send an alert to 200,000 people warning them of the attack in progress, telling them where to get the program to check their machines, and advising what to do to avoid the worm.

The Internet Storm Center uses a centralized distribution mechanism for system evolution: speculative sensors are distributed to globally disbursed agents, followed by a distribution of new action capability if quorum is reached. Individual agents retaining new sensor and action capabilities evolve self-sufficiency at the local level.

Centralized distribution of capability evolution is one way to coevolve in a rapidly changing predator-prey balance. Another way would mimic nature's horizontal gene transfer, with peer-to-peer distributions that reduce the threat to signal channel vulnerability.

Promising application areas for quorum sensing in engineered systems include autonomous robotic swarms, situational sense-making, mobile network nodes that monitor the behavior of neighbor nodes, anomaly detection leading to intrusion conclusions, and detected features in so-called "big data" that identify a pattern. Non-determinism arising from signal interference and environmental conditions will be an area that needs careful attention.

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