ChatGPT

Beehive Summer Simulation Rules (Apis mellifera)

Overview: The following are modular simulation rules for a honeybee colony (species *Apis mellifera*) during the summer season. Each module focuses on a key aspect of hive life – such as foraging, defense, hive maintenance, reproduction, etc. – with simple baseline behaviors that can scale into more complex interactions. The modules are designed to be **clear, independent building blocks** that can be combined and expanded for greater realism. Dependencies between modules are noted, ensuring that interactions (like foraging success feeding into brood care) are accounted for.

Foraging Module

Forager bees collecting nectar from flowers in summer. **Function:** This module governs how worker bees leave the hive to gather resources and share information about those resources. In summer, thousands of workers forage for nectar (to make honey), pollen (for protein), water, and propolis (plant resin for sealing gaps). Foraging is vital to colony survival and reflects both individual bee behavior and colony-level coordination. *Dependencies:* Relies on the presence of flowering plants or water sources in the environment and on communication behaviors within the colony. It provides food and materials that other modules (Brood Care, Hive Maintenance) depend on.

- **F1: Resource Collection (Nectar, Pollen, Water)** – Each day, a portion of the worker bees venture out in search of resources. If a **nectar source** (flowers) is within flight range, foragers collect nectar and return to the hive with a full crop [1]. They deposit nectar into comb cells, where it will gradually evaporate and be ripened into honey. Bees also collect **pollen** in their pollen baskets and unload it into storage cells as “bee bread” for feeding larvae [2]. A smaller contingent of bees are **water foragers** who bring in water to help cool the hive in hot weather [3]. *(Simple -> Complex:* In a basic simulation, foragers can be a fixed percentage of the adult population gathering generic “food.” For more realism, differentiate nectar vs. pollen vs. water foragers and include a search radius and random discovery of resource patches.)* [1] [3]

- **F2: Communication (Waggle Dance)** – When a forager discovers an abundant nectar source, she performs a **waggle dance** on the comb to inform other bees of the location and quality of the find [4]. The dance encodes direction and distance, recruiting additional foragers to the same source. This rule creates a positive feedback: rich sources quickly attract more foragers, boosting efficiency. It depends on F1 (a successful collection trip) to trigger it. Other bees observe the dance and then fly out to the advertised location. *(Simple -> Complex:* An initial model might ignore dances and send foragers out randomly. An advanced model can implement the waggle dance as a communication system that spawns new targeted foraging tasks, increasing yield from known sources.)* [4]

- **F3: Propolis Gathering** – Some foragers collect **propolis** (sticky plant resin) from tree buds and sap. Upon return, this material is used to seal cracks and varnish surfaces inside the hive, strengthening hive structure and preventing drafts or pests. This behavior might be triggered when the hive has small gaps or when pathogen pressure is sensed (since propolis has antimicrobial properties). *(This* *rule can be added in advanced simulations; it's a niche foraging activity and depends on environment availability of resinous plants.)*

- **F4: Foraging Constraints** – Foraging activity is **diurnal** and weather-dependent. Bees leave the hive during daylight and favorable weather (warm, dry conditions). If it's raining heavily or temperatures drop at night, foraging is paused and bees remain in the hive. Each forager has an energy budget – a bee may make multiple trips per day and then tire (in a simple model this can be abstracted). Worker bees typically **wear out** after ~500 miles of flight; summer foragers live only ~30–40 days due to this intense activity [5] [6]. Diminishing returns can be implemented if multiple bees exploit the same flower patch (simulating resource depletion).

Defense Module

Guard bees at the hive entrance on alert. **Function:** This module handles colony defense against predators and intruders. **Guard bees** station themselves at the hive entrance to inspect incoming traffic and react to threats. Summer dangers include wasps or hornets, stray animals, or robber bees from other colonies. The rules here ensure the simulation can model an attack event and the colony's response. *Dependencies:* Relies on having a cohort of workers free to act as guards (which depends on population size from the Brood/Population module). Also ties into environmental events (appearance of predators). Outputs (like alarm signals) affect bee behavior in other modules (e.g. more workers may temporarily shift from other tasks to help in defense).

- **D1: Guard Post and Inspection** – A small subset of workers (often around the 18–21 day age range) assume the **guard role**, hovering or crawling near the hive entrance [7]. Each incoming bee is inspected by smell; guard bees can detect the colony's unique pheromone on residents. **If a bee carries the hive's scent, it's allowed in; if not, the guards grapple with the intruder and attempt to bar entry [8].** This prevents robber bees from other hives from stealing honey, and keeps out many predators. *(For simplicity, initial simulations can treat all hive members as automatically recognized, and only model obvious intruders. More advanced rules can add a check that occasionally a stranger (robber) bee tries to enter, prompting a guard response.)* [8]

- **D2: Alarm Pheromone & Mobilization** – If a serious threat is detected (e.g. a predatory wasp or hornet at the entrance), the guards release an **alarm pheromone** (isoamyl acetate) to alert the colony [9]. Upon sensing the alarm signal, nearby worker bees rush to the entrance to assist in defense. In the simulation, this rule could be represented by a trigger that spawns additional defenders (temporarily reassigning some idle or internal-task bees to defense). This **depends on D1** (a guard must perceive a threat and trigger the alarm). The result is a rapid increase in defenders at the point of attack. *(In a complex model, the strength of the pheromone signal could scale with threat level, recruiting a proportionate number of bees.)* [9]

- **D3: Threat Neutralization** – Bees respond to intruders with **coordinated aggression**. For small invaders like wasps or robber bees, a few guards can latch on and sting, often at the cost of their own lives (a stinging honeybee dies, but this sacrifice may save the colony) [10]. For large predators such as **hornets**, dozens of bees may swarm the intruder. Honeybees in Asia (e.g. *Apis cerana japonica*) evolved a special **"hot bee ball"** tactic: they engulf the hornet and vibrate their wing muscles to raise its temperature, literally cooking the hornet [11]. European honeybees (*A. mellifera*) are less adept at this, but in a simulation one might allow a similar group response if enough bees pile on a hornet, dealing damage over time [12]. This rule **depends on D2's alarm** to gather sufficient bees. If the defense succeeds, the predator is killed or repelled; if it fails (e.g. too few defenders), the hive can suffer heavy losses. *(The simulation can model a hornet attack as an event where a certain number of defending bees versus the hornet results in either the hornet being killed or the colony taking damage. This adds an external challenge that players must prepare for by maintaining enough guard bees.)* [11]

- **D4: Adaptive Guarding** – Guards adjust their numbers based on threat level and colony size. In a calm period, only a handful of guards patrol. If frequent intrusions occur (e.g. it's late summer and wasps are commonly attacking to steal honey), more workers will be assigned to guard duty (the colony can flexibly reallocate some foragers or house bees to defense roles). This rule can be implicit (handled by increasing guard count after every attack event) or explicit (a percentage of bees become guards when alarm pheromone events per hour exceed a threshold). *This demonstrates scalability:* a simple model might fix a constant number of guard bees, whereas an advanced one dynamically adjusts guard counts and even simulates the **risk** of under-guarding (leading to robbing) or over-guarding (lost opportunity for foraging).

Hive Construction & Maintenance Module

Worker bees building and attending honeycomb structure. **Function:** This module covers the **physical structure** of the hive and its internal environment. It includes **comb building**, repair, resource storage, and climate control inside the hive. Worker bees collectively maintain the wax combs, keep the hive clean, and regulate temperature and humidity to protect the brood and food stores. *Dependencies:* Depends on resources from Foraging (wax is produced from honey consumption; nectar/pollen to store) and on adequate workforce from the Population module. It provides the "infrastructure" for Brood Care (empty comb for the queen to lay eggs and for nurses to raise brood) and is influenced by environmental temperature/humidity.

- **H1: Comb Building & Wax Production** – **Comb construction** is carried out by young "architect" worker bees (around 12–18 days old) that can produce **beeswax** from special glands on their abdomen [13] [14]. When new space is needed (e.g. an empty frame or cavity in a hive), these builders consume large amounts of honey and metabolize it into wax flakes. They then chew and mold the wax to form the hexagonal cells of honeycomb [13]. The comb is built in sheets, forming the familiar vertical panels of hexagonal cells. This rule is **triggered** when the colony's storage or brood space is nearly full or a new swarm has arrived in an empty nest. Bees will form "chains" or festoons when building extensive new comb, ensuring proper thickness and respecting the ~3/8 inch **bee space** between combs [15]. *(In a simple simulator, comb capacity can be a numeric limit; if reached and if space allows, spawn new comb at a resource cost. Advanced models could simulate incremental cell construction requiring X wax units per cell, produced by builder bees.)* [13] [16]

- **H2: Comb Utilization & Storage** – Different areas of the comb are designated for specific uses (this can be implicitly managed or explicitly tracked in the simulation). **Honey storage** typically occurs in the upper sections of comb: bees deposit nectar and then fan it to evaporate moisture, eventually capping the filled cells with wax when it becomes honey [17]. **Pollen storage** (bee bread) is often in cells near brood areas, providing easy access for feeding larvae [2]. **Brood cells** are usually in the central and lower comb areas where the queen lays eggs [18]. Bees maintain this organized layout as they build. *(A simple simulation might not distinguish cell types, treating the hive as having total "storage* *capacity" and "brood capacity." A more detailed one could map out a grid of cells with states: empty, honey, pollen, egg, etc., and have rules to fill or empty them.)* This rule interacts with **Foraging (F1)** – incoming nectar/pollen goes into storage – and with **Brood (B1/B2)** – empty cells are needed for eggs and for storing food for larvae.

- **H3: Temperature Regulation (Cooling)** – Honeybees work collectively to keep the brood nest around **33–36°C** for ideal development [19]. In hot summer conditions, worker bees fan their wings to circulate air and cool the hive. **Ventilator bees** position themselves at the hive entrance and throughout warm areas, fanning in unison to create airflow [20]. Additionally, bees spread out droplets of water (brought in by water foragers, see F1) on the comb and then fan, promoting evaporation that cools the hive [3]. This **cooling rule** activates when internal hive temperature rises above the comfortable range (due to hot weather or heat from many bees). It depends on water availability (from F1) and sufficient workers that can engage in fanning. *(Basic model:* assume the hive has an ideal temperature and implement a simple check: if external temp > X, bees consume some water and reduce internal temp by fanning. *Advanced:* simulate a hive temperature variable that responds to outside temperature, bee fanning effort, and internal heat production, with a feedback loop where more bees fan if too hot.)* [21] [3]

- **H4: Temperature Regulation (Heating)** – On cool nights or if a sudden chill occurs (summer storms, etc.), bees must also **warm the brood**. Workers act as **"heater bees"**, vibrating their flight muscles to generate heat (similar to shivering) [22] [23]. Some heater bees press their bellies against brood cells or even enter empty cells in the brood nest to act as little radiators, warming the surrounding brood comb [24]. This rule kicks in when internal sensors or bee feedback detect brood temperature dropping below ~33°C. It requires that some bees disengage from other tasks to produce heat. They consume extra honey for energy when doing this. *(In a simulation, one might simply ensure that if temperature < threshold, a number of bees equivalent to "heater bees" are allocated and hive temperature increases. More complex models could have dedicated heater bee roles and track their energy use.)* [23] [24]

- **H5: Hygiene & Comb Maintenance** – **Housekeeper bees** keep the hive clean and orderly. They remove debris and carry out any dead bees (a specialized "undertaker" role) to prevent disease [25]. They also detect and remove parasites (like pulling out larvae that might be infested by varroa mites, although that's advanced). For the simulation, this can be a simple rule that if debris or dead bee events are generated, a house bee will clear them after some time. **Comb repair** is also part of this: if cells are damaged (through heavy use or pest damage), wax-working bees will patch and rebuild them as needed (using the same wax production mechanism as H1). Hygiene has dependencies on colony health events (e.g., if an illness or die-off occurs, more debris to clean). In a basic model this may be glossed over, but it's mentioned for completeness and future scalability (could tie into disease dynamics if simulated).

Brood Care & Population Dynamics Module

Function: This module simulates how the colony grows and sustains its population. It includes the **care of brood (eggs, larvae, pupae)** by nurse bees and tracks the life cycle and roles of bees. Key behaviors are feeding and tending the young, and regulating the amount of brood rearing based on resources. Population dynamics cover birth of new bees (from the queen's egg laying) and death of old bees, maintaining a roughly stable workforce in summer (until growth triggers swarming). *Dependencies:* Requires stored food (honey, pollen) from Foraging to feed larvae. Needs comb space from Hive Construction for new eggs. Influences other modules by providing new workers (for foraging, guarding, etc.) and can trigger Swarming if population gets too large.

- **B1: Egg Laying & Brood Cycle** – The queen bee lays eggs continuously in summer, up to ~2,000 eggs per day during peak season [26]. Each egg is deposited in an empty brood cell. After 3 days, an egg hatches into a **larva**. Worker **nurse bees** then feed these larvae intensively with royal jelly and pollen/honey mix. Larvae grow for ~6 days, then are capped with wax by the bees and enter the **pupal stage** in their cells. After about 12 more days (for worker brood), a new adult bee emerges, chewing her way out of the capped cell. This 21-day cycle (queen's egg to emerging worker) drives colony population growth. *(A simple simulation can implement a timer or counters for eggs -> larvae -> pupae -> new bee, to spawn new adult bees at the end of the cycle. More complex rules can differentiate castes: worker vs. drone vs. new queen brood have different timings – 24 days for drones, 16 for queens.)* This rule depends on **H2** having open brood cells and on the presence of a healthy queen (see Queen module). It feeds into population count and the age structure used in task allocation. [26]

- **B2: Nurse Bee Care** – **Nurse bees** (typically young workers ~4–12 days old) are responsible for feeding and caring for all brood. They produce nutrient-rich secretions (royal jelly from glands in their head) and feed larvae up to **1,300 meals per day per nurse** in total effort [27]. They also keep the brood warm (often huddling over the brood nest as part of H4 heating) and clean the cells around brood. In the simulation, this can be represented by a general rule that a certain number of nurses are required per amount of open brood; if there is a shortage of nurses relative to larvae, brood growth might slow or some larvae could die (advanced outcome). **Dependencies:** draws on **stored pollen/honey** (converting them into brood food), so strong foraging (F1) is needed to support heavy brood rearing. It also links to **Queen's laying rate** – if the queen lays more eggs than nurses can feed, some larvae might starve. *(One can start simple: assume infinite nursing capacity so long as some number of workers exist. To scale up realism, introduce a nurse-to-larva ratio and check that enough food is in storage. This adds challenge to balance foraging and brood rearing in the game.)* [27] [28]

- **B3: Population Tracking & Demographics** – The simulation should keep track of the **number of bees in each stage** (eggs, larvae, pupae, adults) and caste (workers, drones, queen). In summer a healthy colony might have 40,000–60,000 **adult workers**, a few hundred **drones**, and many brood in progress [29] [30]. Worker bees live ~6 weeks in summer on average [31], so a portion of the oldest workers die off daily (the simulation can implement a rolling attrition of a certain percentage of adults). Meanwhile, new adults emerge daily from the brood cycle (B1) to replace them, keeping population roughly steady or slowly increasing. **Drones** (male bees) are also produced in late spring and summer when the colony is large and resources abundant [32]. A few hundred drones may be present at a time [30]. Drones do not work in the hive or forage; they consume food and simply await opportunities to fly out and mate (see Queen & Drone module). The model can treat drones as part of population count with negative impact on stores (they eat but don't contribute) – in a simple model, drones might be omitted initially, then added later for complexity. *(Key dependency:* population growth depends on **Queen egg-laying (B1)** and enough resources/nurses (B2). Population decline could happen if resources run out (for instance, if famine, the queen may slow egg laying and some adults may die early). This module provides input to all other modules: e.g., number of available foragers (F1) or guards (D1) comes from the current adult population.)

- **B4: Division of Labor (Role Allocation)** – In a more advanced simulation, **not all workers are identical**; their tasks can shift with age or colony needs (a phenomenon called age polyethism). Early in life a worker tends to do inside duties (cleaning, nursing, comb building), later she transitions to outside duties (guarding, then foraging) [5] [33]. For simplicity, an initial model can assume any worker can do any job as needed. A scalable rule, however, is to **assign roles** based on age groups or in response to demand. For example, if the colony is overheating, many mid-aged bees become fan ventilators (H3) regardless of their usual role [34]. If an attack occurs, even foragers might rush to help the guards (per D2). Implementing this dynamic role allocation means each tick, the simulation assesses colony needs: e.g., "We need X nurses for Y larvae, and Y foragers for available flowers, etc." and **reassigns workers** to tasks accordingly. This ensures critical needs are met (brood feeding, defense) at slight expense of less critical ones. *(This is an area to scale complexity: a basic version might have fixed proportions of bees in each role, whereas an advanced version has an algorithm for task switching. Ultimately, this leads to very realistic colony behavior where the colony self-balances its workforce.)* [6] [34]

Queen & Drone Module

Function: This module addresses the special roles of the **queen** (the sole fertile female who lays all eggs) and **drones** (males whose only function is to mate with queens). It covers queen-driven colony regulation (through egg-laying and pheromones) and how drones are produced and behave. These rules often act as triggers for colony-wide events like swarming or shifts in brood production. *Dependencies:* Relies on hive conditions from other modules (the queen's laying rate might depend on food availability; drone rearing depends on colony strength). In turn, it influences population (by egg output in Brood module) and genetics (through mating in Swarm events).

- **Q1: Queen's Egg Laying & Pheromones** – The queen is the **reproductive heart** of the colony. She can lay fertilized eggs (which become female workers or new queens) and unfertilized eggs (which become male drones) [35]. In summer, a healthy, well-fed queen lays eggs relentlessly to maintain the population [26]. The simulation can model the queen as having an egg-laying rate (e.g., eggs per day) that may be adjusted based on colony needs (some games make this a parameter players can observe or influence by feeding). Alongside egg-laying, the queen emits a suite of **pheromones (queen's scent)** that provide cohesion to the colony. One important pheromone (QMP, queen mandibular pheromone) **suppresses workers from rearing new queens** and keeps the workers focused and cooperative. As long as the queen is present and strong, the colony will not attempt to raise a replacement. *(In the simulation, one can assume a binary state: queen-present = no new queens reared, unless a special Swarm trigger occurs. Loss or weakening of the queen leads to rule Q3 below.)* The queen's pheromone also acts as a signal of her presence throughout the hive – if the hive grows too large or the queen gets old and her pheromone levels drop, the **colony may prepare to either swarm or supersede the queen** [36] [37] (see Swarm module). [26] [37]

- **Q2: Drone Production & Behavior** – Drones (male bees) are reared from unfertilized eggs when the colony is heading into reproduction mode (late spring and summer). **Hundreds of drone brood** may be raised, typically placed at the edges of the brood nest or in larger drone-sized comb cells if available [38]. The rule for drone rearing can be: *if* the colony population is high and nectar flow is strong (plentiful food), *then* the queen lays some unfertilized eggs to develop as drones. **Drone bees** take 24 days from egg to adult (slightly longer than workers). Once mature, drones do very little inside the hive – **they do not forage, defend, or help** [39]. They beg for food from workers or help themselves to honey, and spend afternoons flying out in search of queens. A simulation can represent drones as consumers of resources that periodically take “flight” events. **Drone congregation flight:** on warm sunny days, drones leave the hive around midday and fly to specific areas where drones from many hives gather (the simulation can simplify this by not needing to locate the area – just mark drones as out flying for a period) [40]. If a virgin queen from any colony is in the area, drones attempt to mate. In our single-colony simulation context, mating would occur during a Swarm event when a new queen is out. After a mating flight (whether they mate or not), drones that survive return to the hive to repeat the next day. Importantly, **drones die immediately upon mating** – a successful drone perishes as his endophallus detaches during mating [41]. *(If simulating multiple colonies or wild populations, drones from this hive could mate with queens from others. In a single-colony game, drone behavior might be abstracted unless the player also manages mating of their queen.)* [39] [40]

- **Q3: Queen Succession (Supersedure)** – If the queen dies unexpectedly (e.g. simulation event, or old age) or her egg-laying significantly dwindles, the colony will attempt to **raise a new queen** from the existing brood. Nurse bees select a few young female larvae (less than 3 days old) and begin feeding them copious royal jelly, enlarging their cells into **queen cells** (vertical, peanut-shaped cells). After ~16 days from the egg’s laying, a virgin queen will emerge. Usually the first virgin to emerge will seek out and eliminate rival queen cells or fight other virgins until only one remains as the new queen. Workers may also **supersede** (replace) a queen that is failing – sometimes they rear a new queen while the old one is still present, then the two queens might coexist briefly or the old one is killed by the workers once the new one mates and starts laying [37]. In the simulation, queen loss could be a random event or result of aging. The rule would be: if no queen present (or queen pheromone below threshold), and the colony has larvae, then initiate queen-rearing. This results (after the queen development time) in a new queen taking over, during which time eggs are not laid. *(This is an advanced scenario for long-term simulations; a simpler model might assume the queen is immortal or replaced externally. Including it adds depth and realism, especially if combined with events like the queen being lost during a swarm or dying of old age.)*

- **Q4: Mating and Genetic Refresh** – A virgin queen, either after swarming or supersedure, must **mate** to be a productive queen. About a week after emerging, she takes one or several mating flights and mates with a number of drones (often 10–15) in mid-air [41]. After mating, she stores the sperm and returns to the hive to begin or resume laying fertile eggs. In a simulation focused on a single hive, this mating can be assumed to succeed if drones exist in the environment. If the simulation doesn’t track external colonies, one might simplistically assume enough drones from wild sources are present for the queen to mate. If mating fails (queen doesn’t mate due to bad weather or no drones), the queen will only lay unfertilized eggs (which become drones) – leading to colony failure if not corrected. This can be an edge-case rule for added challenge. *(For an entertainment simulator, this detail might be optional, but it provides completeness: players might need to ensure a new queen gets mated by having drones around or timing swarms to the drone season.)*

Swarming Module

Function: Swarming is the colony’s natural method of reproduction (creating a new colony) and typically occurs in late spring or early summer. This module governs the conditions and processes of swarming. It’s a **culmination of other behaviors**: high population, ample resources, and internal signals prompt the hive to split. In a simulation game, swarming could be a dramatic event where the player “loses” some bees that leave to form a new hive (unless managed). *Dependencies:* Depends strongly on Population (needs overcrowding or large numbers), on Queen & Drone dynamics (queen condition, presence of drones/new queen), and uses behaviors from Foraging (scouts) and Hive Construction (quick comb building by swarm). Swarming can be disabled or rare in a simple model, and introduced as a complex event in advanced play.

- **S1: Swarm Trigger Conditions** – As the colony reaches a peak population (often 50,000+ bees) and **the brood nest becomes congested with bees and food** and perhaps the queen's pheromone becomes diluted in the large population, a **swarm impulse** is initiated [42] [36]. In the simulation, this could be checked by: if population exceeds X and a high percentage of brood cells are filled, then the hive enters "swarm preparation" state. Additional cues: an aging queen or the presence of older brood that can be turned into new queens. Once triggered, workers start raising **new queen cells** (usually at the bottom of comb frames) by feeding selected larvae royal jelly (as per Q3). The old queen is put on a diet by the workers – they feed her less so she slims down to fly [43]. This trigger rule has **dependencies:** it needs a strong colony (Brood/Population module) and a queen present (Queen module). *(Basic vs. advanced:* a basic simulator might simply trigger a swarm when a fixed population threshold is hit. A more advanced one might require multiple conditions – high population, high brood, abundant nectar flow – to reduce false swarms and to make timing more realistic.)

- **S2: Swarm Departure** – Just before the new queens emerge, the **old queen and a large portion of the workers leave** the hive in a swarm [42]. Typically **about half** the bees (including all ages of workers and some drones) gorge on honey, then rush out of the hive following the queen in a mass exodus [44] [45]. In the simulation, this could be an event that instantly reduces the original colony's adult population by a certain percentage (e.g. 50%). Those bees are now a "swarm cluster" in the environment. The swarm often **temporarily gathers** on a nearby tree branch or structure while scout bees search for a new home [46]. The departure rule would create a new entity (the swarm) separate from the original hive. If the simulator is only managing one hive, you might either (a) treat the swarm as a loss (bees gone), or (b) allow the player to recapture it or follow it as a new hive. *(From an entertainment perspective, swarming could be a failure state to avoid by proper management, or an opportunity to expand to a second hive.)*

- **S3: Swarm Resettlement** – **Scout bees** (experienced foragers within the swarm) fly out from the clustered swarm to seek a suitable new nest site [47]. This could be a hollow tree or any cavity. They then return and use waggle dances to advertise locations; through a collective decision process, the swarm selects the best site (per Thomas Seeley's research) [47]. In the simulation, this process can be simplified: after a fixed duration (say a few hours or a day), the swarm will choose a new home automatically. The swarm then takes off again and moves into the chosen cavity. **Comb construction begins immediately** in the new location – with no brood to care for in the first days, the swarmed bees can dedicate effort to building fresh comb and storing incoming nectar [48]. The old queen in the swarm will start laying eggs in the new comb as soon as cells are available. *(For the simulation, once a swarm has moved, you could spawn a new hive with that population at a new location. If the game supports multi-hive management, this becomes a second colony to manage. Otherwise, it might simply be an event where the original hive's population is cut and, after some time, returns to normal if the swarm is recaptured.)* [48]

- **S4: Post-swarm Parent Hive** – Back at the original hive, a **virgin queen emerges** from one of the queen cells (the first one out usually). She may kill the other rival queens or the workers might let more emerge and then the queens fight until one remains [49]. The new queen then takes a mating flight (see Q4) and, after mating, starts laying eggs, restoring the brood cycle. The parent colony now has far fewer workers (since half left), and it may take time to rebuild. They might also still have a good amount of honey and pollen stored (less mouths to feed initially). In the simulation, the immediate effect of swarming is a big drop in population and a pause in brood production until the new queen is mated and active. This could be a risky period where the colony is weaker (vulnerable to threats, cannot forage as much). If the new queen fails to mate or dies, the colony could collapse – an advanced outcome to include for realism. *(In a straightforward model, assume the new queen always succeeds and the hive slowly recovers. In a high-complexity model, simulate the possibility of queen failure requiring another emergency queen rearing or the hive dwindling.)*

- **S5: Swarm Prevention/Management (Optional)** – For players or simulation parameters, it might be useful to have ways to prevent swarming (as real beekeepers do). This could include **spreading out brood frames** or adding extra empty hive boxes (supers) to relieve congestion, thereby nullifying the S1 trigger conditions. Another method is doing a **split** (artificial swarm): the simulation could allow an action to divide the colony manually, similar to a swarm but controlled. While not a "natural" rule, including this as an option would increase the strategic aspect of the simulator. *(This highlights how the rules can be made interactive for an entertainment-focused sim: the user might be able to intervene in what is otherwise an automatic biological process.)*

Module Dependencies Summary: Each of the above modules can be developed and tested in isolation, but they interlock to create a complete colony simulation. For example, **foraging success (Module F)** increases food stores, enabling **brood rearing (Module B)** to produce more workers; a larger population then risks **swarming (Module S)** or needs more **comb building (Module H)** to expand. A **hornet attack (Module D)** might temporarily pull bees away from foraging or cause losses that affect population. The queen's state (Module Q) underpins everything – if she falters, brood rearing slows and the colony may initiate swarming or supersedure. By keeping these rules modular and **scalable**, the simulation can start simple (e.g. just basic foraging and brood growth in a static hive) and progressively add layers (complex defense behaviors, nuanced climate control, swarming events, etc.) for a richer, realistic beehive experience.

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