Comb the Honey: Bee Interface Design

by

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Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning
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Abstract:

The overarching goal of the thesis is to understand the mechanisms by which complex forms are created in biological systems and how the external environment and factors can influence generations over different scales of space, time, and materials.

My research focuses on Nature's most celebrated architects — bees — and their architectural masterpiece — the honeycomb. Bee honeycombs are wax-made cellular structures of hexagonal prismatic geometries. Within the comb, bees form their nests, grow their larvae, and store honey and pollen. They operate as a "social womb" informed, at once, by communal (genetic) makeup and environmental forces. Resource sharing, labor division, and unique communication methods all contribute to the magic that is the bee "Utopia." Given that the geometrical, structural, and material make up of honeycombs is informed by the environment, these structures act as environmental footprints, revealing, as a time capsule, the history of its external environment and factors.

In this research, a new installation is designed, enabling the bees to achieve their full potentials as a whole; it enhances the abilities of bees for self-regulation and self-organization so as to promote the resilience of bees in the semi-nature at present.

The novel bee incubator is a detachable installation that can be recycled to bees every Spring while serving as an observational compartment for researchers. It also presents as artwork for display in museums during Winter. This research thrives on a distinctive vision of diverse interactions of technology, design, science, and art, employing an intricate interface that allows us to heal, replenish, augment, and renew the relationship between humans, bees, and nature.

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Chapter 1

Introduction

Bees, one of the most incredible eusocial creatures in nature, are unique species organized into highly structured communities with resource sharing, precise labor division, and refined mechanisms of communication. They demonstrate the most complex and delicate collaboration, nearly unmatched in the eusocial world.

There is no better example of eusocial behavior than the bee, a miracle of natural Utopia, and its honeycomb, a masterpiece of hexagonal perfection.

The architecture of honeycomb — based on elaborate hexagonal prism structures, and the most logical and geometric animal-made habitat in nature — arouses infinite inspiration and interest to artists, designers, scientists, engineers, and researchers. Compared to human dwellings, or other animal architectures, the dwellings of bees are furnished with exquisite inner and outer structures, in terms of ventilation, warmth keeping, food storage, living space, and larva feeding. That is the fruit of the harsh and relentless natural evolution of the bee species for thousands of years in the wild.

However, in a world domesticated by humans for thousands of years, I found that the bee species, especially *Apis mellifera*, could hardly maintain health in bee farms without human interventions. Their survival rate is even worse in the wild, suggesting that the human management pattern has gravely hindered the development and reduced the environmental adaptability of the bee species.

Hence, the urgent question is how can we help the bees to thrive in nature, not merely as one of the domesticated animals in humans' farms. How might we leverage the hive as a designed interface to help the bees proliferate and better adapt to the environment? Would it possible for this design method to encourage the bees to generate more complex honeycomb structures? Could the new structures lead to new social divisions and more jobs in the bee colony?

The research presented in this thesis seeks to address these questions through the development of a novel bee interface design interacting with the natural environment and could provide a new set of insights toward the study of this astonishing organism.

Chapter 2

Hives in History

Honey Hunting

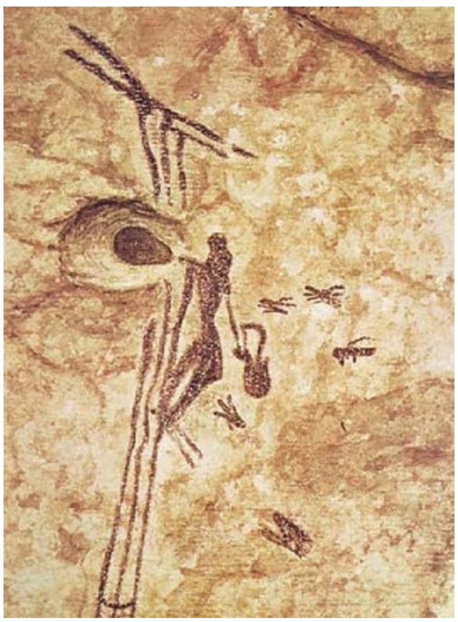


Figure2.1 A rock painting discovered in Arana Cave at Bicorp near Valencia, Spain in Mesolithic period(7,0008,000BP) might be the earliest record of humans interacting with bees.

Bees appeared on earth circa 120 million years ago according to scientists' estimations, much earlier than the appearance of the first humans. The bees have evolved to collect honey and pollen as a social lifestyle in a form of labor division well beyond what we can imagine. Before our ancestors learned to domesticate animals, cooperate with fellow tribe members for foraging, and store food in the field, the bees had already obtained the ability to collect and store food in a colony.

Humans and bees have dramatic differences, as genetically, we are different species. Nevertheless, we do share various similarities in the ways of social organization, hierarchy, and cooperation, to name a few. How ironic that our first interaction probably happened when the human robbed the honey from the bees.

Dating back to the earliest record of human-bee interactions, a rock painting found at Bicorp near Valencia, Spain in the Mesolithic period (7,000–8,000 BP) depicted a man climbing up a ladder while carrying a vessel to raid the bees for honey (Figure 2.1). It was one of the few precious foods our ancestors could access from nature. Since then, the act of hunting for honey has been continued in places like Africa, South America, and Southeastern Asia. Honey hunting is usually performed by a small group of indigenous people, and the skills and rituals are handed down from one generation to the next. It is still one of the major approaches to access the highly concentrated

Figure2.2 Honey hunting in large baobab tree of Hadza in Tanzania.

monosaccharide, one of the purest forms of energy, from nature today. Figure 2.2 shows a young honey hunter of the Hadza tribes in Tanzania.

The activity of honey hunting reveals the most direct motivation for early human-bee interactions, which grew over time into humans designing and building various beehives for the explicit purpose of collecting honey more conveniently — *beekeeping*.

Horizontal Space Utilization

Though we have no way of knowing how the intermediate steps developed between honey hunting and true beekeeping, historical clues lead us to believe that the first acts of beekeeping could date back to ancient Egypt and the first primitive apiary could be traced to the Biblical period.

A large apiary excavated from Beth Shean Valley in the ruined city of Tel Rehov, Israel contained more than 180 hives (Figure 2.3). Dr. Amihai Mazar, Eleazar L. Sukenik Professor of Archaeology at the Hebrew University, revealed that this could be the earliest known apiary, dating from the 10th to early 9th centuries B.C.E. [1]The hives were piled up several tiers high and made of straw, mud, and unbaked clay, each 80 centimeters long and 40 centimeters wide in horizontal cylindrical shapes. They were capped at both ends with a small entrance for the bees to enter and a large opening fitted with a closure (whereby the beekeeper could reach the comb to harvest the honey inside). It would have been very convenient for arrangement and stacking. Those primitive *horizontal hives* revealed the wisdom of ancient ancestors in terms of innovative beehive organization.

Due to little human knowledge about bees, beehive establishment was a demanding job at the time, yet there were also many attempts to initiate beekeeping. The forest mountain lands and hot weather of Lebanon and Israel accounted for local wild bees nesting in the rocks of cliffs or building their combs in underground cavities to keep cool and moist. Here, colonies could forage for sufficient food and grow larger, and split into multiple swarms that would then seek suitable nests for their development. When appropriate nest sites in the rocks and earth cavities were insufficient for a bunch of new colonies to occupy,

Figure2.3 At least 180 hives were found during excavations at the Tel Rehov site in the Jordan Valley.

the bees found empty water pots, broken potteries, or other human utensils as shelters. These objects shared similarities with the bees' natural habitats. Therefore, humans employed their intelligence, slightly modifying their built hives to mimic the wild habitat of bees, from which they derived the unique tube-shaped hives made of a mixture of sun-dried mud, straw, and raw clay.

In the ancient world, people from different territories would adapt their hives to the regional environment. In wooded areas, especially the mountain zone covered by plants, cylindrical hives were usually made of logs, or woven by some plants coated with mud and clay and rolled up together with fennel sticks, depending on the resources of specific regions. In some densely forested European areas like Italy, hives were made out of logs; in southeast Asia, hives were composed of coconut tree leaves and palm tree leaves; in China, straw and mud were used to build hives just like thatched cottages where local people lived.

At the same time, horizontal hives in various shapes were spreading all over the world. Hives were molded horizontally, partially because they were stored in the front or at the back of the house, stacked layer by layer to function as a wall. Besides, the primitive horizontal hive with the tubular structure was favorable in hot climates for the bees to circular airflow back and forth for temperature regulation. Moreover, multiple tube-shaped hives could be stacked on top of each other to provide shade. The hives had one or two openings. One served as the entrance and the other as a vent. Bees entered the hive at the front end so that the beekeepers could cut them off from behind and access the combs full of honey.

The earliest beehives known were made of earth materials and placed horizontally and paralleled. It is noteworthy that most of the horizontal hives were limited to the Mediterranean countries and regions, which is usually accredited to its climate characterized by dry summers and mild, wet winters. So to a certain extent, this kind of spatial arrangement in the early stage directly mirrored the interrelations between the local climate and beehives, concerned with constitution and shapes.

Given the advantages of ventilation and shading, which were compatible with the local climates, earlier horizontal hives were popular in and appropriate for the Mediterranean regions. The Mediterranean beekeepers could manage the beehive from behind, such that they drove the bees out of the front entrance and opened the back lid to harvest the honey. Contrary to this front-to-back horizontal hive, another beehive in the form of up-and-down structure was taking form in northern Europe— the vertical hive.

Beekeeping was introduced into Europe at first with horizontal hives fairly similar to those described above for Mediterranean areas. However, as soon as beekeeping spread to northernmost Europe and other cold regions like England and Russia, a serious problem with the containers came to the surface. During the long and chilly cold season, horizontal hives in those regions lost temperature very fast and could hardly conserve warmth, with the result that a large number of colonies perished every winter. It was the most severe and harsh issue for the apiarists, and almost crushed the whole beekeeping industry.

Figure2.4 Upright hives from the collection of Radomysl Castle, Ukraine, 19th century

Meanwhile, another unique beekeeping method was taking form in northern European forest areas, where the winters were also long and severe. This method was derived from tree beekeeping, the predecessor of which was the tradition of tree hunting. In the dense forest, bee colonies usually nested in trunk cavities so that the thick wood could protect them from harsh winds. Inspired by this, tree beekeeping was quickly adopted throughout Europe, and a large number of trees were cut down for apiculture. This led to an embarrassing situation — suitable tree cavities were nowhere to be found. During successive centuries, hollow logs largely replaced tree beekeeping as kinds of *upright hives* in the north. Beekeeping with either of the two types was still primitive.

To some extent, the upright hive is effectively an updated version of the horizontal hive, allowing the bees to swarm in the upper part of the hive for warm-keeping throughout the winter, identical to the bees' habitat in nature.

Compared with the horizontal hive, the vertical hive (usually made of logs and called "log hives"), with its greater depth, offered better ventilation — the bee colony could swarm into a massive globular cluster in the upper part of the comb to keep warm and healthy since honey was stored at the top part, and also the layer of honey provided extra insulation, serving as protection during the winter. This small step from horizontal to vertical paved the way for overwintering in colder regions and producing brood even in the late winter.

From a scientific point of view, in the shift from horizontal to vertical, the inner structure of the honeycombs changed along with the reorientation of gravity, and the function of the hive changed accordingly. The horizontal hive had a lower center of gravity, a larger bearing area, and a more extensive space for bees to attach comb pieces, which was conducive to stacking and transportation. However, this horizontal cylindrical structure did not allow the bee colony to create extensive combs and reproduce the brood, as they lacked sufficient room in the perpendicular direction. In terms of their biological habits, bees develop along with the longitudinal distribution of gravity, specifically consisting of several distinct regions in the combs — the uppermost honey-storing region, the central brood area, the peripheral pollen rim around the brood, and the bottom drone cells. The horizontal structure compressed the functional space within the hive, which was unfavorable for the development of the whole colony.

In this regard, the approach of restructuring the internal space of the comb by reorientating gravity in consonance with the external environment is a practical and straightforward method for enhancing the bee colony, as evidenced by the history of beehive evolution. Flipping the hive from the horizontal to the vertical orientation and changing the direction of the combs has been validated as beneficial to the bees to some extent.

To address the issue of insufficient room within beehives, people began to investigate more rational solutions for space utilization and came up with the *compound hive*. This hive consisted of two or more upright logs, polished smooth and furnished with a removable flat base and upper board. The interior was divided by a partition but connected with an entrance in order to expand the accessible space for bees. It was the prototype of the detachable beehives that promoted the development of beekeeping technology and presented a preliminary exploration for space utilization. However, the clear disadvantage was that it relied on thick inner walls, which were heavy, material-consuming, and not conducive to beekeeping operations.

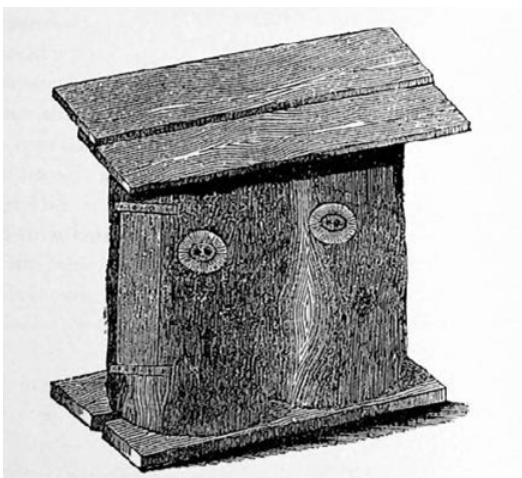


Figure2.5 The Compound Hive, made from two logs and capped with boards (Dzierzon, 1882)

It was at this stage that people commenced expanding the accessible space of the beehive from a single cavity to dual cavities, enabling the bees to expand the range of their internal space.

Material Improvement
Bell-shaped Skep Hive

The bell-shaped skep hive was invented around 0–200 CE in northwest Europe. Large logs used to build horizontal and vertical hives were not normally available west of the deciduous forest zone. Besides, log hives have some innate limitations — they are expensive, heavyweight, material-wasteful, inconvenient for transportation, and restricted by the shape of trees. These hindered the development of large-scale beekeeping activities. An alternative hive version was needed urgently.

The first skep hive was woven from cheap natural materials such as wicker or straw, much lighter than log hives, and easily customizable in size. (Interestingly, it was recorded that bee colonies hid in the piled straw stock over the winter; therefore, this new beehive still reflected the local bee habitat.) It was shaped like an inverted woven basket. For convenient honey access and extraction, the beekeeper needed a large opening, so the opening of the hive was woven widely and placed directly onto a wooden board or rocks that resembled a bell — a so-called *bell-shaped skep hive*.

As the skep hive improved, it became more appropriate for controlling hive weight, transportation, and harvesting honey, even though it has apparent drawbacks. Wicker skeps involved the application of dung and mud to the surface to keep out beetles and moths, but those materials were prone to breaking and peeling. Moreover, straw was a natural habitat for rats and moths, and moisture for any length of time led to the growth of mold. Nonetheless, this material advancement was a crucial milestone in the beekeeping industry.

Hive Exploration: Material and Space

Changes in shapes and materials — from mud to log to straw, from cylindrical to bell-shape — drove hive production toward lighter weight and portability. Since the 1640s, the hive-making industry has also shifted away from inherited traditions and toward rational design and thought.

Octagonal Hives: The Prototype of Modern Hives

Between the 1600s and 1850s, since subdivided sciences had not yet come to be, scientists had broad interests in all newly emerged subjects, and beehive study was no exception. Given that hives had historically been roughly made without any normalized processes, just according to local customs, scientists and beekeeping patrons tried to make rational hives using scientific methods associated with the advancement of apiculture.

It developed a wooden hive made of thin boards with tiers in octagonal shapes. These lightweight wooden tiers could be stacked upon each other, moved from place to place, or put into carts for convenient transportation.

This structure was amended multiple times into a precise mold. The *tiered octagonal hive* was first invented by William Mews in 1649, revised by Christopher Wren in 1654, and later independently designed by Dr. Thomas Brown and John Gedde in 1655 and 1672, respectively.

Octagonal hives represented the ingenuity of *beeology* researchers at that time:

1. The hive was exceptionally exquisite and precision-made, with design sketches in lieu of production by trial-and-error experience.
2. The octagonal design was chosen to approximate the round cross-section of a tree trunk, in the interest of mimicking the natural environment.
3. Various designs and explorations related to optimizing frames for moveability.

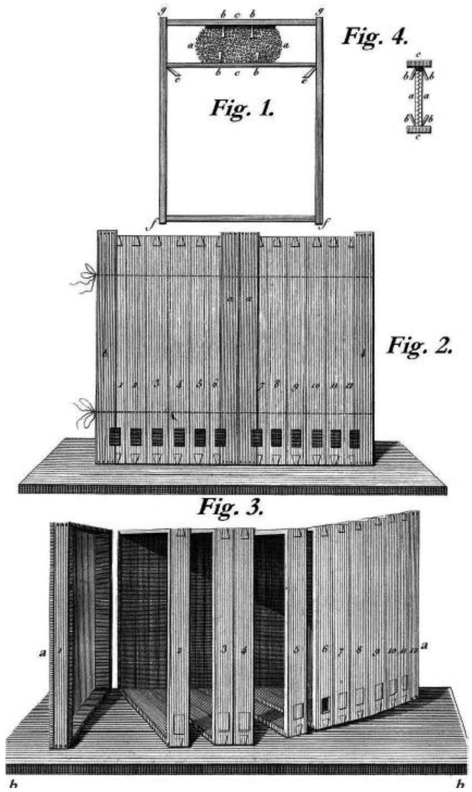


Figure2.6 François Huber's Leaf Hive 1792

Despite their exquisite design and superb improvement, octagonal hives were not the best choice for local beekeepers in light of their costly expenses. These hives were fated to become ornaments for the gardens of noblemen. In most regions, the old-fashioned earthen hives like skeps and log hives were unquestionably much more sensible choices for the apiculture industry.

To extract honey from earthen hives, beekeepers were blind to the exact locations of honey storage, so they usually drove the swarm into an empty hive or simply burned sulfur to kill the whole colony, and then cut all the comb pieces off. This method of harvesting honey was pervasive, and as a result, a large number of bee colonies perished.

Out of these circumstances, François Huber, a Swiss entomologist, invented the *leaf hive* in 1792. He lost his sight at a young age, so he studied bees with the help of an assistant. Previous hives had no way to observe the honeycombs inside, but the *leaf hive* allowed his assistant to open the hives like a book, with each frame separately visible and numbered on the surface. This kind of divided hive served the needs of rational analysis and observation.

Although the *leaf hive* made great progress in harvesting and observation, it had considerable drawbacks as fitting the frames together without crushing any bees was extremely difficult. It was said that Huber's assistant would face attacks by the entire hive just to learn a single fact. Huber's discoveries would not have been possible without the skill and bravery of his assistant, François Burnens, who was fully committed to discovering the truth [2].

Huber’s leaf hive, as the prototype of modern observation hives, served the needs of inspection of the beehive interior. However, it also split the integrity of the nature of the hive, in a sense.

The Square of Modernism: Langstroth Hive

Honey bees were introduced to America in the early seventeenth century. The first documented evidence of their importation came from a letter of the Council of the Virginia Company, dated December 5, 1621, which listed beehives among the items sent across the Atlantic on one of four ships from the European continent. [3]

Around the year 1850, design and patent applications for beehives were booming. Some of the inventions were based on previous ones with slight and insignificant differences. Nonetheless, people never ceased in the quest for better hives.

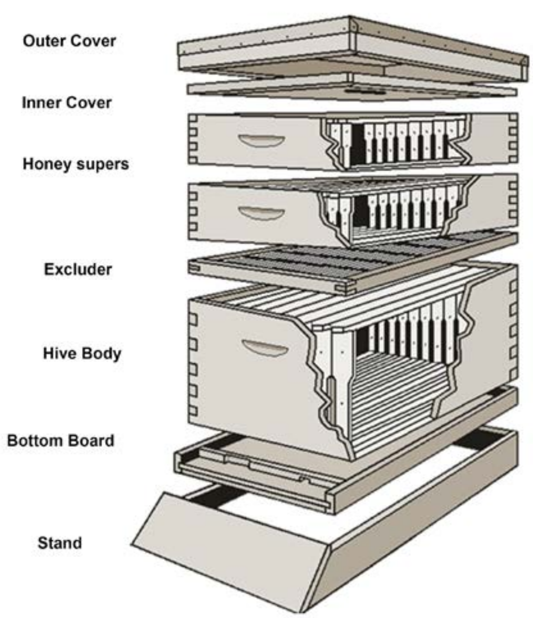


Figure2.7 Structures of Langstroth Hive

Mr. Langstroth in North America started beekeeping in 1827 with several old-fashioned hives, including the leaf hive, skep hive, movable frame box hive, and tiered hive. He studied previous non-movable-frame hives, including octagonal tiered hives and rectangular tiered hive revisions that he described and compared in his publications and writings. He adapted Augustus Munn's *movable-frame hive* [4] in many aspects, including the frame distance (at the time, there were more than 15 ongoing discussions about frame distance), and incorporated the advantages of tiered hives into his design. Previous hives provided myriad inspirations. He borrowed their merits, revised some drawbacks, and combined them into one. In the fall of 1851, he presented his invention of the *Langstroth hive*.

The Langstroth hive is a vertically modular beehive with several detachable boxes (supers) and hive bodies and the key feature of moveable frames that allow the beekeeper to manage the bees at will — a formerly impossible task. The bottom board, used for brooding, and honey supers, used for honey storage, are separated by a queen excluder that confines the queen to the bottom part, nonideally disrupting the connection of the entire colony. Even so, this structure is exceptionally practical, with many outstanding features that improved beekeepers' operations and honey extractions. And today, the Langstroth hive is almost exclusively used for apiculture throughout the world.

These explorations are, in effect, the analyses and understandings of bees and hives, particularly how humans interacted with the bees. From octagonal hives — a transitional mode between the round hives in nature and the rationally designed hives of beekeepers — to the sensible Langstroth hives, the evolutionary history of beehives mirrors the comprehensive process of natural abstraction and rational disciplines of humans. The hive formations — from horizontal to vertical, flat to spatial, cylindrical to cubic — correspond to the further divisions inside the combs and effectiveness of spacial utilization.

The Langstroth beehive was representative of modernist design to some extent. It embraced the characteristic emphasis on predictability, measurability, unified norms, asymmetrical compositions, and minimal ornamentation, pursuing rationality and uniformity to achieve maximum efficiency. At this time, at the peak of Modernism, squares and cubes pervaded every corner of multiple fields. Renowned works like *Composition with Red Blue and Yellow* by Pieter Cornelis Mondriaan [5] in art history, and Bauhaus cube buildings in architecture, demonstrated rationalism as the primary methodology. The dominant beehive design at that time also exemplified the Modernist style — the Langstroth beehive.

Chapter 3

New Hive-Bee Interface Design

Dilemmas

Since the invention of the Langstroth hive, the world has witnessed unprecedented human-induced changes: global warming, deforestation, overexploitation, species extinctions, and resource deficiency. Shifting to fields from natural forests, bees have somehow migrated to semi-natural habitats like backyards and gardens, and even on the roofs of buildings. Although the Langstroth hive has been widely used since its inception in the 19th century, it cannot fulfill the demands of an environment that are constantly changing. It requires a redefinition of apiculture in many aspects like breeding, cultivation, scientific research, and observation of bees.

Bees in Anthropocene

Anthropocene is not an officially approved term, but a proposed geological epoch dating from the onset of significant human-driven impacts on Earth's geology and ecosystems, involving the influence of all living things on Earth, of course including the bees [6].

> *The first use of "the Anthropocene" appears to be in 1922, by the Russian geologist Aleksei Pavlov to designate the present "Anthropogenic system (period) or Anthropocene." The term "Anthropocene" was introduced by atmospheric chemist Paul Crutzen and biologist Eugene Stoermer in 2000 to designate the present era, which for them has overtaken the Holocene that has been in existence for the last 11700 years.* [7]

During the Anthropocene, humans have significantly accelerated changes in physical sedimentation such as erosion and weathering of the earth, carbon cycle perturbation, temperature changes, the extinction of animals and plants, oceanic changes such as ocean acidification, and eustatic fluctuation.

Since bees first appeared on Earth, they have experienced millions of years of evolution through harsh and relentless natural selection. Human beings, as a species that appeared later on the evolutionary tree, have brought about destructive threats to bees since we learned to keep bees as livestock. Habitat loss resulted in the extinction of countless wild bee species. The modern agricultural model, which uses pesticides like neonicotinoids, has caused substantial damages to bees; most notably the trend toward monoculture has been closely coupled with the occurrence of colony collapse disorder in recent years.

Colony Collapse Disorder (CCD)

Colony collapse disorder (CCD) is an unusual phenomenon, first identified in 2006, in which the majority of worker bees in a colony mysteriously disappear, leaving behind a queen, lots of larvae, a few nurse bees, and plenty of honey and pollen.

Agricultural economics can be greatly affected by the health of bees since many crops around the world rely on pollination by *Apis mellifera*. In 2005, the United Nations Food and Agriculture Organization estimated the total global value of crops pollinated by bees at nearly US$200 billion. Between 2007 and 2013, an estimated 10 million bee colonies were lost worldwide to CCD, almost twice the regular loss rate. In the United States, bee shortages have increased the cost of pollination services for farmers by up to 20%, and that higher cost may be passed in part to consumers.[8]

CCD may be linked to a variety of factors including pesticides, fungicides, infections with various pathogens, varroa and acarapis mites, neonicotinoids, loss of habitat, malnutrition, genetic factors, immunodeficiencies, and monoculture. One of the world's largest known monocultures is located at the commercial almond orchards in California. In 2000, almond orchards covered 500,000 acres in the Central Valley. By 2018, that coverage area had more than doubled and was yielding 2.3 billion pounds (1 million tons) of almonds annually. These massive orchards would not be viable without pollination by bees. Paradoxically, the orchards are detrimental to bee health.

Though a diet including almond nectar or apple nectar is healthy for bees ordinarily, being forced to feed on a homogeneous diet for months or years on end leads to malnourishment and imbalanced flora due to lack of comprehensive nutrients and elements. This weakens the bees’ immune systems and makes the colonies very susceptible to diseases.

It is believed that the dwindling diversity of plants could impoverish the bee populations. Bees that pollinate on plants of greater diversity have more robust immune systems than bees that pollinate on mono-crops, even high-protein mono-crops.

Sick bees are frequently treated with antibiotics for bacterial infections. In response, only more antibiotic-resistant bacteria survive in their intestines. This results in a vicious cycle, which is considered to be one of the major causes of CCD.

Other Voices

When confronted with these dilemmas, different voices call for a return to traditions and nature.

Darwinian beekeeping is a brand new concept and approach proposed by Professor Tom Seeley of Cornell University, first in the American Bee Journal in March 2017. It advocates following the laws of natural selection, which is different from the traditional beekeeping method in multiple aspects.

> *Evolution by natural selection is a foundational concept for understanding the biology of honey bees, but it has rarely been used to provide insights into the craft of beekeeping... Adopting an evolutionary perspective on beekeeping may lead to better understanding about the maladies of our bees, and ultimately improve our beekeeping and the pleasure we get from our bees. [9]*

Despite their conveniences, modern beekeeping methods defy the commandments of nature. In particular, mated queens often endure a long-distance shipment — e.g., from humid, warm southern places to dry, cold northern regions — to merge into remote colonies of diverse subspecies, and they might not adapt to the new local climate and flora. Large-scale experiments in Europe also suggest that colonies with local queens have much longer lifespans than those with the non-local queens. Given this, many bee protectors advocate for a movement back to traditional beekeeping methods, using traditional skills and beehives, like tree hives (Figure 3.1).

Tree hive beekeeping, as a traditional method in modern society, is dedicated to arboreal apiculture and rewilding the bees. It involves hollowing out a living tree with a diameter of at least 70 cm and a height of at least several meters to attract indigenous bees. The cavity usually is 20–30 cm in diameter and 70–80 cm in height.

Figure3.1 A tree-hive beekeeper was standing on a scaffold clung to the tree at a high place. Wooden wedges on the trunk next to the hive. A bee smoker was hanging on the wedge for the convenience of operation. Bee smoker calms the bees with smokes fuels including hessian, burlap, pine needles, corrugated cardboard, paper egg cartons, rotten wood, herbs, or anything flammable. A recent experiment that smoke fouls the bees' sensory receptors and causes some to engorge with honey.[10] The evolutionary reason is likely tied to honey bees' survival strategy-their inclination for inhabiting the hollow tree required them to respond to the scent of smoke from a forest fire.[11]

The tree hive is undoubtedly commendable for protecting bees, but it has considerable disadvantages to improve. It is a demanding job, especially for the elderly and nonspecialists, and lacks the efficiency desired by most beekeepers.

Background

Science and technology have developed at an exponential rate in the wake of the Second Industrial Revolution. Cutting-edge technology has enabled research on bees to enter the micro-scale, using gene editing to reinforce the bees. While our comprehension of these living organisms remains limited, an exciting new field redefining bees as macro-integrated life provides a novel perspective for researchers and helps the bees better adapt to the environment.

Figure 3.2 The image was taken at Wuzhi Mountain, Sanya city, the south island of China. The author, Ri Ren was in 2007. Sanya is located in low latitudes and belongs to a tropical maritime monsoon climate zone. The annual average temperature is 25.7°C. The high more than 30°C in June. The 21.4°C. annual sunshine 2534 hours. nnual precipitation 1347.5 mm. Its hot and rainy so the hives were placed in the woods to to block out the intense sun and ultraviolet. There were more than 40 colonies in the Sanya Apiarian Base. The bees were a tropical ecotype of *Apis mellifera ligustica*, which has adapted to the local hot and rainy environment. The author usually wore a T-shirt, half pants, and slippers, with or without a bee hat, during bee operations.

Bees have lived with and under the management of humans for years. They have supported us as semi-domesticated livestock and intertwined with our daily lives through pollinations and honey production. In this context, and given that semi-tamed bees [12] could not survive in the wild, it is imperative to build an efficient and relevant model for establishing respectful relationships between humans, bees, and the environment. It is a requirement that this model assists the bees in adapting to complicated and volatile environments. The research in this thesis seeks to contribute a novel perspective on an optimized mechanism employing a brand new interface reconciling bees, humans with nature.

As a bee protector, beekeeper, researcher, and artist, I have been working with bees for more than a decade. The reason I am so obsessed with bees is that these eusocial insects possess an outstanding social structure, behavior, and nesting mechanism.

Bees are eusocial creatures and the individuals within a colony are intimately connected like a human brain neural network. However, current beehives widely used by the beekeeping industry (e.g., the Langstroth hive) use a set of fully removable frames as the key elements and are designed with the sole purpose of increasing the ease of honey collection, and as such, bluntly cut the connections of the bee community. Mechanical segmentation splits the eusocial structure of the bee colony and hinders self-regulating activities of the population.

Therefore, my overarching goal is to develop a platform that minimizes human interventions, augments bee communications at a holistic level, and enhances their biological properties.

Approaches

Gravity-Informed

Gravity is an omnipresent but little understood physical force. It is a vector with constant intensity and direction throughout geophysical history on Earth. However, this simple definition masks the complexity of gravity as an evolutionary force. In the billions of years since the first life appeared on Earth, gravity has become a critical factor affecting the evolution and development of all living organisms. On the one hand, it represents a factor of physical restriction which compels living beings of all scales, whether early eukaryotes or later mammals, to develop basic means (e.g., actin [13] and skeletons) to counteract the gravitational force and its limits on their shapes and sizes. On the other hand, some organisms have adapted to take advantage of the force to evolve, orient, and develop under conditions of stable pressure and fixed direction. Therefore, gravity is always a key factor and a challenge for all life systems to cope with in the short term and adapt to in the long term.

Gravity has a shaping effect on the size and form of living things. The archeological findings in Natural History Museum of Los Angeles[14] present a 30-million-year-old fossil of a bee in which there is no significant difference in the body shape compared to modern bees. This suggests that the Earth's gravity has not changed for at least millions of years. Contemporary research validates that bees are able to accurately detect the earth's magnetic field and gravity. They can discover the position of honey sources and fly back to their comb using the direction of the earth's magnetic field, gravity, and the angle between the sun and comb, and then share navigational information through *waggle dances*.

Through millions of years of evolution, special receptors have developed in invertebrates and arthropods, enabling them to sense their own positions, postures, equilibriums, and internal conditions. Bees are no exception. Honey bees have those specific receptors in the form of cushions of sensory hairs between the head, thorax, and abdomen, and on all the leg joints, for sensing gravity [15]. Bodily tissues like the club-shaped sensilla of arthropods are weighed down under gravity and stimulate internal mechanoreceptors in a way that depends on and varies with the animal's spatial position [16].

In effect, factors including magnetic field, gravity, and light can influence *Apis mellifera* in various ways. Several research studies have already reported the effects of the magnetic field and light — the observation of De Jong in 1982 [17], Lindauer and Martin in 1972 [18], and Gould in 1978 [19]. Unfortunately, the potential effects of gravity in conjunction with other physical factors on bees have not been well studied yet. Only a handful of experiments can be found about the effects on gravitational changes or related experiments.

It is common sense that human beings construct in an upwards direction — that is, humans confront gravity by building skywards. However, honeycombs forming piece by piece in succession grow downwards, along the direction of gravity. Bees do not challenge gravity but comply with it, aligning with natural rhythms to compile cells. But what if this mono-gravity is changed? Can we decipher a new multifacet prototype of the hive? Might bees generate new and more complex structures by reorienting the comb along with gravity? Will the new structure lead to a set of reformed honeycomb functions? Could the new features induce a new social division of labor in the bee society?

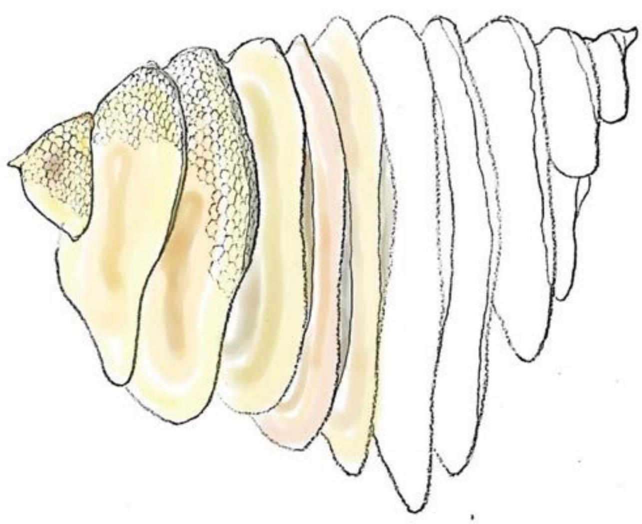


Figure 3.3 Natural Combs Formation – Linear parallel, piece by piece, aligned downward

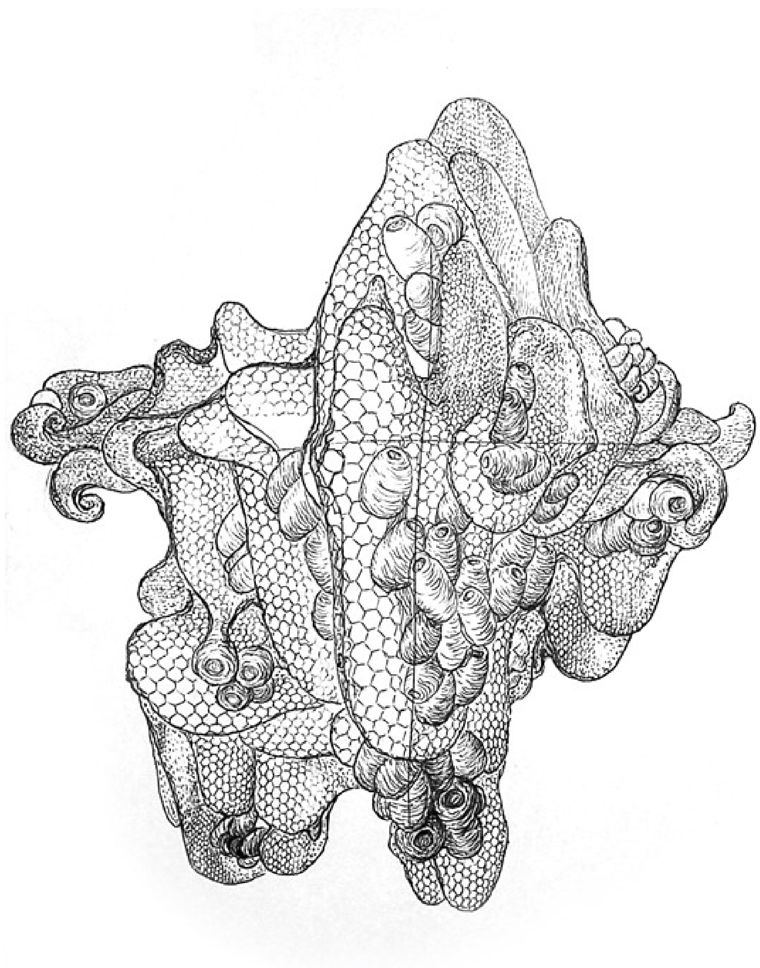


Figure 3.4 Imagined Dynamic Combs – Nonlinear Spiral

Given its pivotal role in shaping life, nothing could affect and alter the adaptability of organisms on Earth more fundamentally than gravity. Hence, the experiments presented here are designed to hinge on the reorientation of gravity, in order to observe and study the changes and effects on bees — including nest alterations, behavior changes, and divisions of labor, to name a few.

Gravity acts on all masses at the Earth's surface. It pulls objects to the ground and defines the weight of each object. Gravity also acts on every individual bee and the hive. Worker bees sense the direction of gravity and their positions in the space through their sensilla, which permit them to delicately balance gravity with all of the traction and other forces to build and connect every single piece of honeycomb correctly as a whole, allowing the complex structure to hang on trees or hive frames without falling.

Figure 3.5 Honey bees can sense the gravity and the direction so as to coordinate the gravity of each comb piece (light blue arrow represents the gravity of each comb piece, dark blue represents the gravity of the entire honeycomb), and the supporting force from the trunk (red arrow). piece connect into a whole unified honeycomb, the bees have to balance single piece and calculate gravity to make sure that the traction force of the trunk could support the weight of the whole honeycomb without falling down.

For all practical purposes, the internal structure and forces inside the beehive are constantly changing, nonlinear, and self-organizing. It is an intricate dynamic balance.

Gravity is a vector and constant, with gravitational loading in the direction of the center of the Earth. On Earth, standard gravity (equal to 1G) drives many chemical, physical, biological, and ecological processes. If the gravity were reoriented, it would break the balance between the original forces exerted on the object.

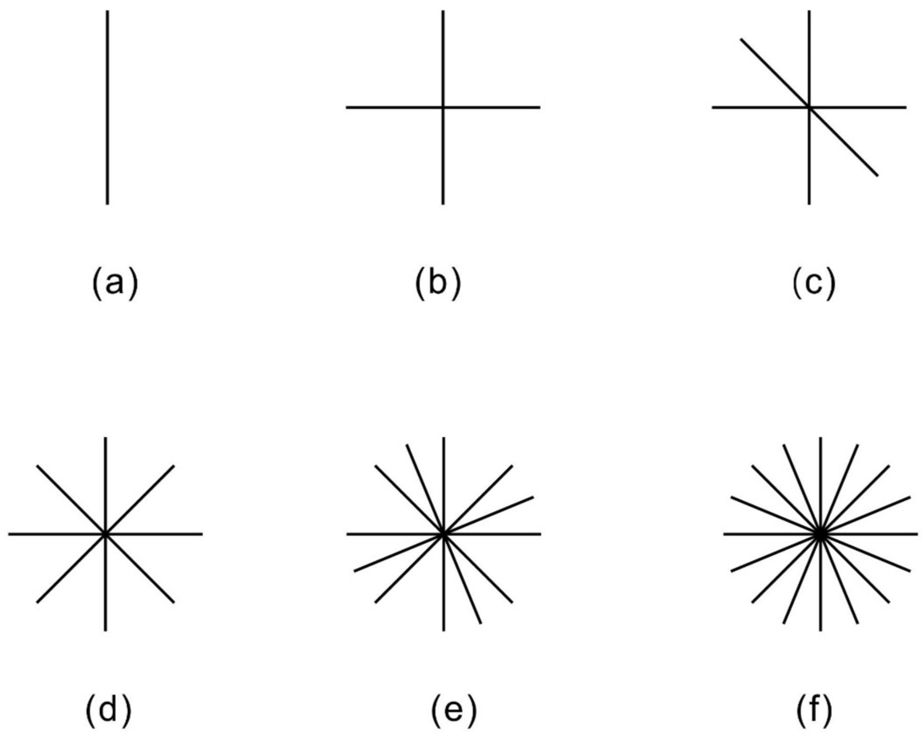


Figure 3.6 he process of gravity changing. (a) he original gravity pointing downwards; (b) through changing the gravity, a cross structure is formed;(c)(e)reorientation will break the balance of the forces exerted on the object so that the object shaped to more complex forms(f)the object grw more complicated through multiple iterations.

In this case, gravity would behave like a catalyst so as to push the resting element/object into an evolving state. This is a simple but highly important factor that has captivated the research interests of scientists, biologists, and artists.

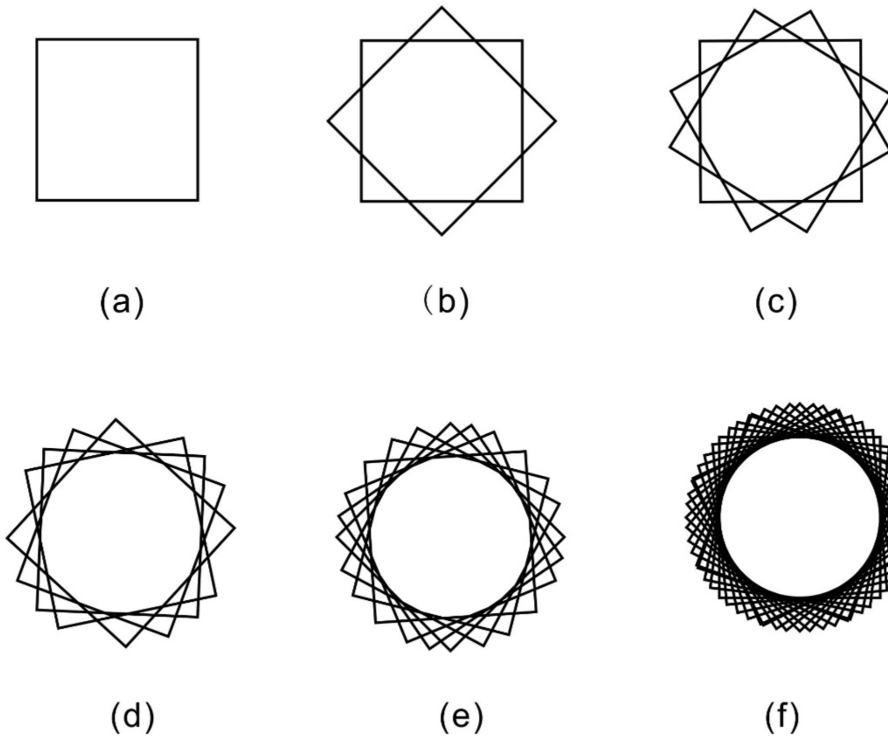


Figure 3.7 Gravity iteration study
(b) after onegravity iteration
(c) after twoiteration
(d)(e) after several iterations, the square has the tendency to be a circle
(f)he square is infinitely close to a circle.

By rotating gravity repeatedly such that the gravity vector is distributed in all directions over time, the samples (combs) are reoriented accordingly. From the point of view of the samples (bees), the gravity vector's trajectory averaged over time shall exert on multiple directions and at last converge toward zero through infinite turnings. However, 1G is always acting on the samples (bees and combs) at any given instant. It is hypothesized that the gravity vector needs to point in a specific direction in order for biological systems like bees to adapt and counteract the disorder created by the reoriented combs. If the gravity vector repeatedly changes direction, the bees will lose their sense of direction and position relative to their combs, and thus experience a state similar to multi-gravity and microgravity.

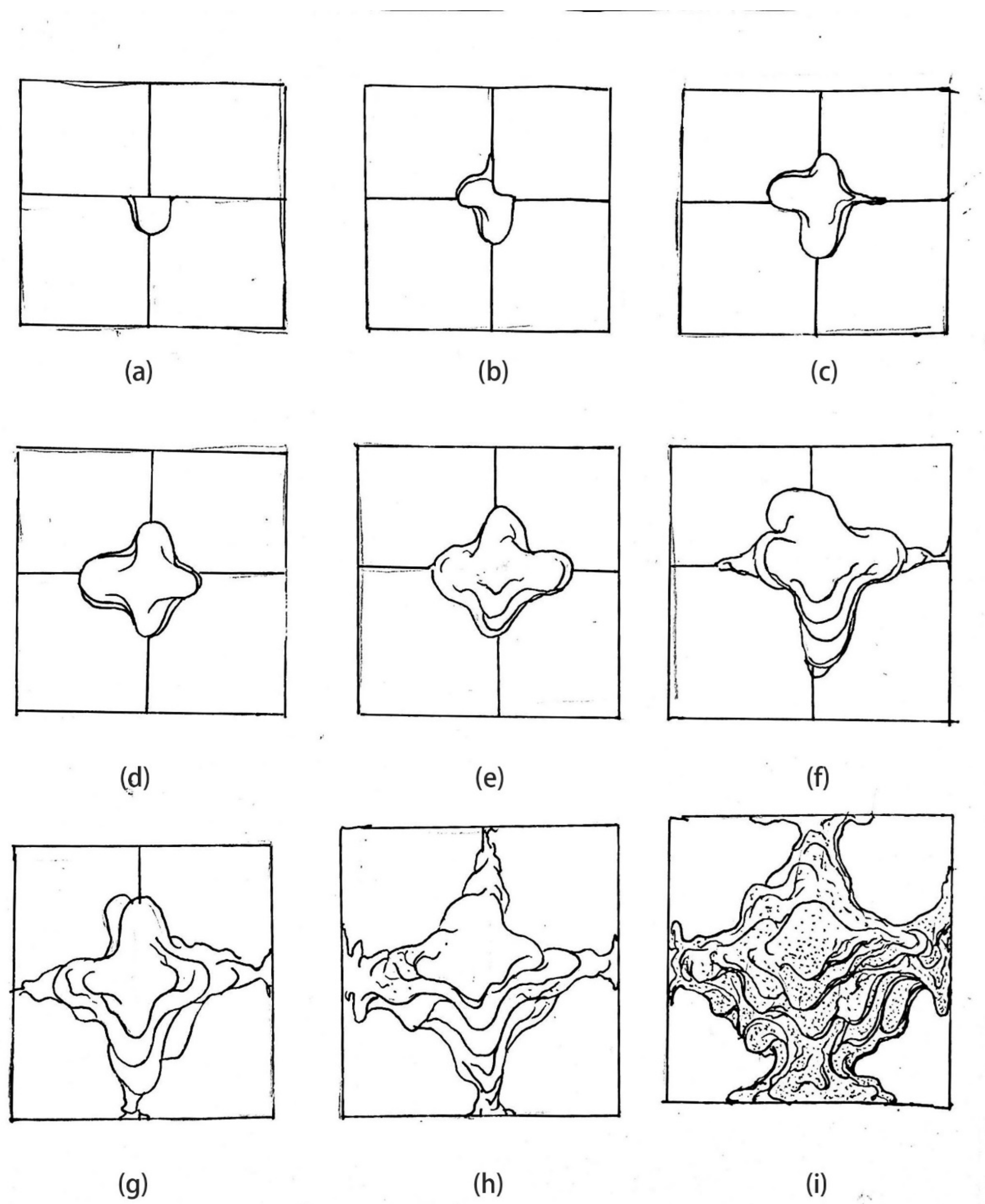


Figure 3.8 Progression sketches of comb generation in the condition of microgravity

The evolution of the bee species has been refined throughout millions of years in a single gravitational direction. Without human intervention, bees have developed a high-level organizational form, the eusocial system. As an alternative to gene editing, I propose a method to apply this fundamental vector of gravity toward the advancement of social frameworks, or even driving a new round of evolution in bees. I grounded my experiments and artwork, the *Yuansu Series*, based on the hypothesis mentioned above.

In order to achieve rational results of gravity reorientation on the bee systems, the experiments were initiated in five regular polyhedron boxes — regular tetrahedron, regular hexahedron (cube), regular octahedron, regular dodecahedron, and sphere. The decision to use regular polyhedrons was to ensure the gravity vector of the hive pivoted at a point after reorienting the gravity; that is to say, no matter how the hive is flipped, its spatial structure was consistently stable (Figure 3.9).

Each regular polyhedron structure had a fixed frame structure connected by diagonal lines such that the bees had a basic structure and bearing points when building their nests. There were ventilation pores at every corner of the polyhedrons and designed openings as entrances, allowing the bees to come in and go out regardless of orientation.

In the spring of 2012 through the spring of 2014, a new series of artworks — *Yuansu II*, a group of experimental works built in acrylic boxes — were created. The author, Ri Ren, cooperated with bees in a highly aligned relationship. The works were effectively hives made of natural beeswax under the force of gravity by turning the direction of the beehive geometry every seven days, whereby the bees would reconstruct the comb autonomously according to the reorientation of gravity.

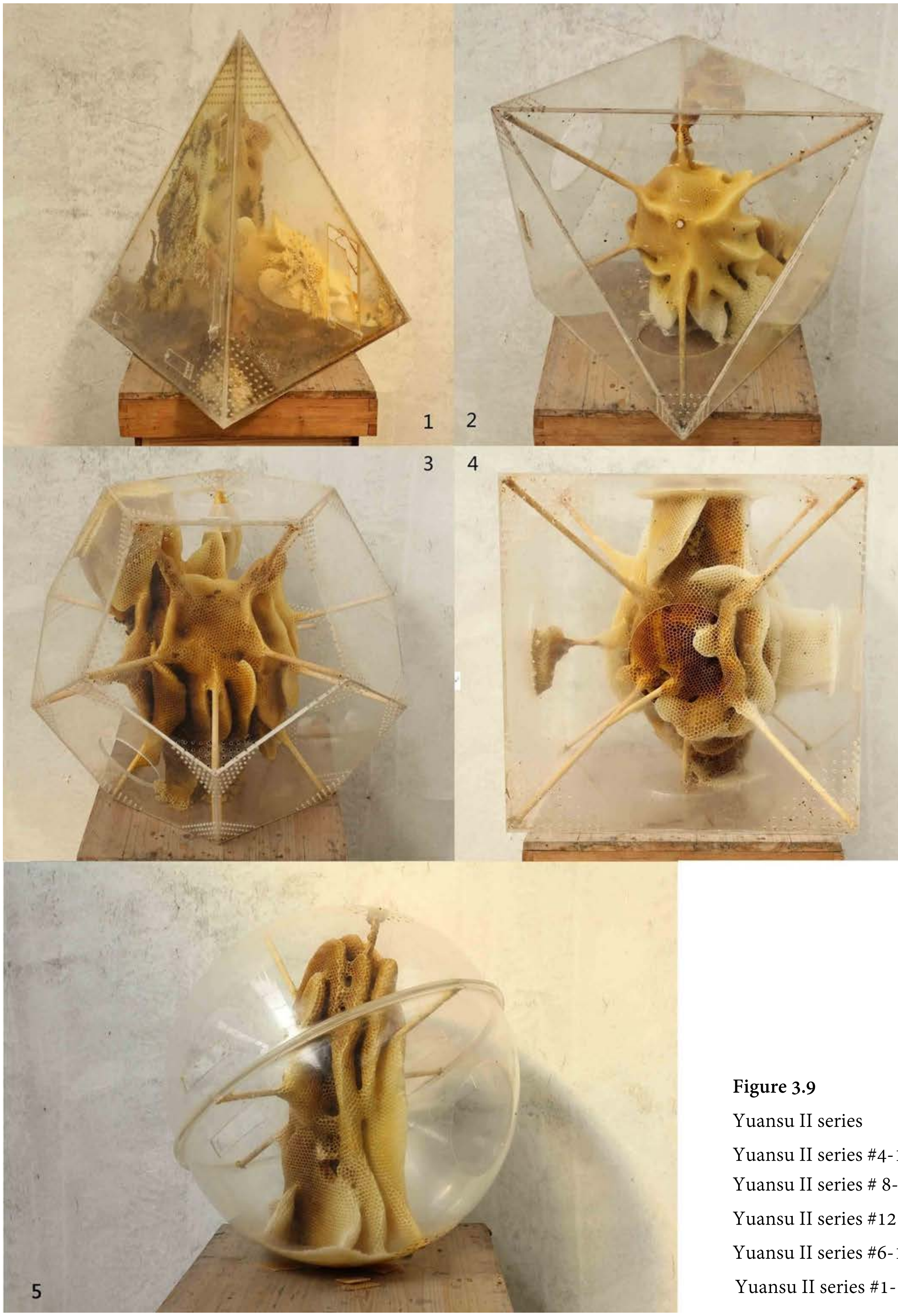


Figure 3.9

Yuansu II series

Yuansu II series #4-1

Yuansu II series # 8-1

Yuansu II series #12-1

Yuansu II series #6-1

Yuansu II series #1-1

The polyhedral structures were carefully designed to have identical volumes so that the bee colony's reactions to gravity could be observed clearly. Taking the cube (regular hexahedron) as an example, every edge was 50 cm long, such that the volume could accommodate a massive swarm of 60,000 bees. In the course of experimentation, nascent combs did not easily take shape in the pyramid (regular tetrahedral) hive and the bees needed a longer time to adjust to every reorientation. The structure of the combs in the pyramid hive was rather chaotic and not able to form into a whole. With the sphere structure, the hive was subject to the external environment like winds and rain, which destabilized it. Moreover, each flip could not perfectly even out the distribution of gravity, so the gravitational effect could not be entirely offset in all directions, and the comb in the spherical hive did not ultimately show growth inclination in all dimensions. The other three hives — the cube, octahedron, and dodecahedron — revealed an equilibrium in every direction, with the result that the combs in these hives presented homogeneous appearances due to the offset effects of numerous gravity reorientations. The bees developed especially strong adaptability in the cube and dodecahedron hives, in which the bees could relatively swiftly figure out the balance and reconstruct the combs to reconcile the chaos with the shifted gravity. Meanwhile, the combs built in the pyramid hive could not reliably form into a stable structure and the scaffold of the comb appeared disordered.

Here, it needs to be understood that the comb is not merely a nest for the bees, but an extension of the bees' life, the matrix. In this perspective, the growth progression of the comb can be regarded as an extension of the evolution of bees.

Considering the adaptability of the bees, their acceptance of the samples, and the similarities to modern hives, apart from destabilizing environmental factors, these five polyhedrons were replaced with several smaller regular hexahedrons (cubes) in the next experiments.

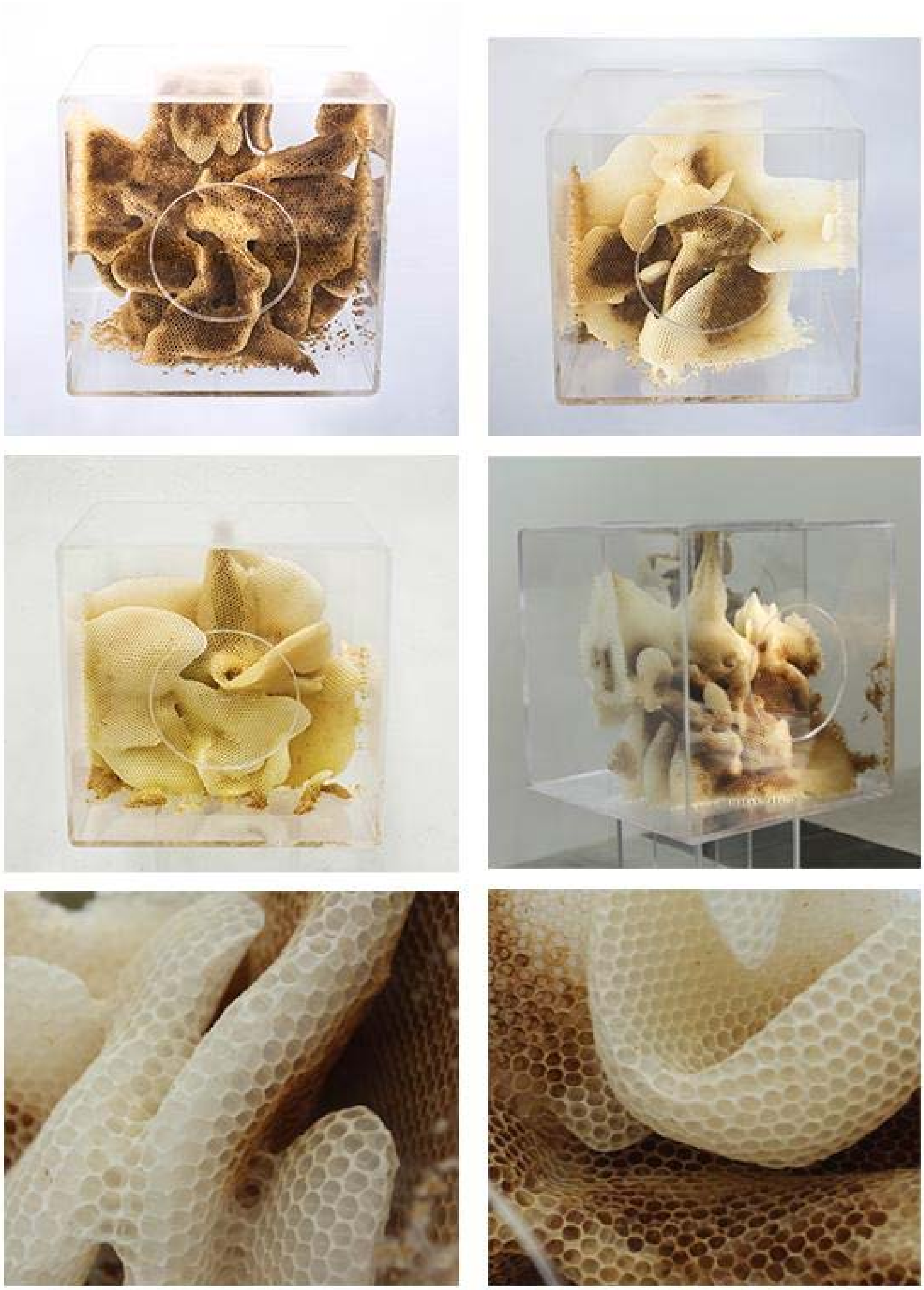


Figure 3.10 Yuansu II SeriesThe Regular Hexahedron Experiments and Details

In the spring of 2014, another series of experiments started in regular hexahedron hives. The goal was to observe the development of and effects on bees under changing gravity conditions and gravity removal via offset. The experiments yielded exciting findings. A majority of the bee colonies adapted to gravity reorientation and made benign interactions with the changes. The comb pieces were no longer parallel to each other but rather formed into various curvatures; besides, the comb extended from the gravitational center toward all directions rather than just downwards. In the following chapter, the same experiments are discussed and detailed explanations will be introduced.

Element-Informed

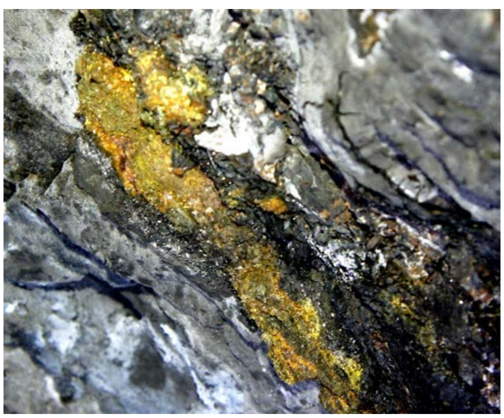


Figure 3.11 Gold in its natural form in rocks.

Gold is a chemical element with the symbol Au, which comes from the Latin word aurum, meaning "shining dawn," and the name of the Roman goddess, Aurora. Ancient Aztecs decorated their temples with gold, believing that gold was "the sweat of the Sun" and would link them to their main deity, Inti, the Sun. Though it is not a reality, their metaphor contains a truth — gold came from the universe. One prominent theory notes that gold, like most of the higher atomic number elements, was forged through nuclear fusion, hundreds of millions of years after the Big Bang kickstarted the nuclear reactions of progressively heavier elements. Another popular theory is that gold formed following the collision of two neutron stars, and exploded outward into the universe. As early as 2.5 billion years ago[20], this chemical element in its native form deposited on Earth, sank toward the core, and was buried in volcanic and sedimentary rocks. Later, humans discovered gold on every continent, even under the ice shell of Antarctica.

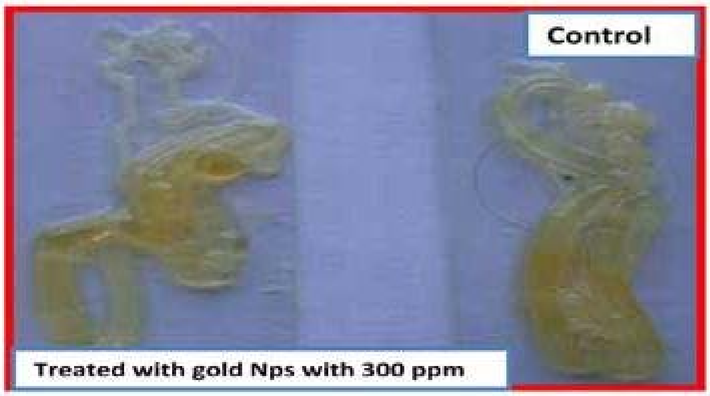
In cultures around the world, gold, with its resplendent luster and lack of tarnishing, is considered precious not only as a means of wealth but also for its spiritual properties. It is viewed as a divine object for its beauty, durability, and apparent perfection. In the Middle Ages, the ancient science and philosophy of alchemy sought to transmute base materials into noble metals, especially gold. It was believed that those who possessed gold had the power to prolong life or even produce immortality. It was thought that gold was the path to eternity.

> *Gold hath these Natures: Greatnesse of Weight; Closeness of Parts; Fixation; Pliantnesse, or softnesse; Immunitie from Rust; Colour or Tincture of Yellow. Therefore the Sure Way, (though most about,) to make Gold, is to know the Causes of the Severall Natures before rehearsed, and the Axiomes concerning the same. For if a man can make a Metall, that hath all these Properties, Let men dispute, whether it be Gold, or no?*
>
> *Francis Bacon* [21]

Whether in the Middle Ages or today, human fondness for gold has never receded. Its atomic number (79) is one of the highest among elements that occur in nature, it is an inert metal, and it does not oxidize at room temperature or even at very high temperatures. Hence, gold is one of the least reactive chemical elements, making it stable and safe for organisms. It is a bright, dense, soft, malleable, and ductile metal, often occurring in free elemental form as nuggets or grains in rocks. Owing to the unique properties, it can be made into thin sheets, gold wires, and even nanoparticles. Due to its attributes of biostability and non-toxicity, gold is safe to consume — for example, added into wine, or decorating meat or coffee. Moreover, some Native American tribes believe that by consuming gold, they would gain power and the ability to levitate. In China, Taoism considered gold to be a restorative element with healing powers.

Modern technology and science have broadened the range of applications for gold. When its eminent electrical conductivity properties came to light, gold started to be used to carry tiny currents without corroding, such that gold is now widely used in sophisticated electronic instruments, including computers, communications equipment, spacecraft, and jet engines. With its excellent biocompatibility, gold is considered to be an ideal carrier for other active components, to enhance absorption at the cellular level, promote cell growth, and hinder bacterial reproduction in tissues. It is applied both in many beauty products as well as in biomedicine, cancer treatments, and vaccine production [22].

(a)



(b)

(c)

Figure 3.12

(a) Effect of gold Nps on matured larval weight.

(b) Effect of gold Nps on silk gland weight.

(c) Effect of gold Nps on cocoon weight.

Atanu Bhattacharyya (2017) Green synthesis of gold nanoparticlests effect on cocoon and silk traits of mulberry silkworm

The biocompatible properties of gold make it appropriate to introduce into bee systems as an agent. Until now, gold has never been introduced into bees systems in any form; therefore, the research in this thesis is significant in helping to solve more mysteries of bees and even decipher some algorithms that biologist, scientists, designers, and artists have long sought to understand.

Bees are fond of collecting various kinds of materials and substances. They are the real collectors in nature. They collect any tree sap, tree bark, and minerals they can find and leverage in the environments. So, what if we provide them with an element that they have never encountered before? Would the bees leverage the element to augment their comb? Would this element be beneficial to their colony? In what direction will the mode develop? After introducing this element, would the social division of the bees change? To explore these questions, we consider the use of gold.

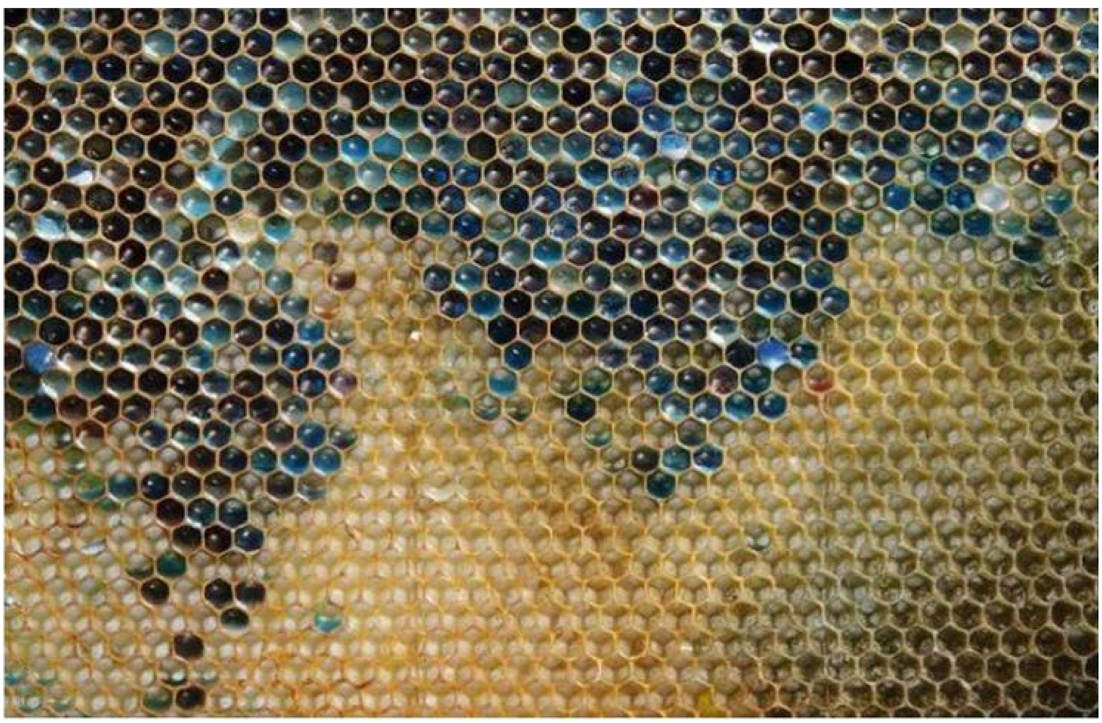


Figure 3.13 A colored honeycomb from a beehive found in Ribeauville near Colmar Eastern France. Bees at a cluster of apiaries in France have producing honey in mysterious shades of blue and green. They were noticed to hives carrying unidentified colorful substances. It was discovered that the bees had collected the materials used to produc M&M's, bite-sized candies in bright red, blue, green, yellow, and brown shells 4km away from their hives.

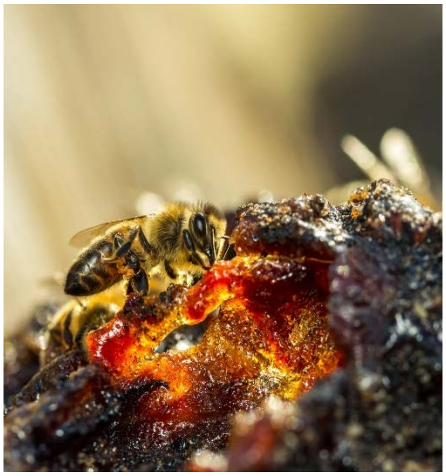


Figure 3.14 Bees are collecting tree sap.

In addition to the biocompatibility and bio-inertness of gold, its extensive application in the aerospace industry is taken into account due to its unique properties, which are compatible with the previous gravity researches.

In the *Maiden Flight* [23] experiment in May 2019, we sent a group comprised of 20 worker bees and a queen to a 100 km micro-gravitational space apogee and back on Blue Origin's suborbital rocket system, New Shepard. We designed two laboratory capsules to support the bees living in the extreme environment of space. In subsequent experiments on the ground, in addition to continuing the simulation of a microgravity environment, I propose to introduce gold into bee systems.

As one of the most malleable metals, gold can be drawn into a monatomic wire and then stretched about twice before it breaks. When light is cast on a semi-transparent gold sheet, it appears greenish-blue since gold strongly reflects yellow and red light [24]. These sheets also strongly reflect infrared light, making them useful as infrared (radiant heat) shields in the visors of heat-resistant suits and the sun-visors of spacesuits [25]. Although it is not the most reflective material under normal light conditions, in the infrared spectrum, gold is the most durable and efficient material for reflecting energy and can be used as a temperature control method to reflect 99% of infrared light [26].

In fact, NASA and its suppliers such as Raytheon, Ball Aerospace and Technologies, and Lockheed have widely used a gold coating on various technical components as reflective protection in order to resist radiant heat and reflect intense light during space explorations. Also, McLaren uses gold foil in the engine compartment of its F1 model as heat shielding in the automobile industry [27].

On the one hand, the high reflectivity of gold of yellow and red light can protect bees against the heat, exposed sunlight, and radiance in extreme environments to avoid excessively high temperatures. On the other hand, as an excellent conductor of heat and electricity, it is convenient for quickly warming up the comb and maintaining the necessary temperature for the whole colony. It also allows the bees to cool down their internal temperature fast in a hot climate. Moreover, gold has a bacteriostatic effect, which can inhibit the growth of microorganisms and bacteria under long-term unmaintained conditions such as in space flight or extreme wild environments. Also, gold has high ductility and can be processed into micron particles, grains, and films, allowing the bees to combine it with the wax cells (normal cell wall thickness is 0.051–0.076 mm).

In this context, I propose a novel experimental approach of incorporating a new element — gold — in conjunction with simulating a microgravity environment through reorientation.

The Au elements used in the experiments are small particles (10–20 um diameter), medium powders (100–200 um diameter), large grains (>250 um diameter), and foil (0.1– 0.2 um thickness), as shown in Figure 3.15. The four ingredients were mixed in a 1:1:1:1 ratio and then provided to the bees collecting independently. A bee counter device was designed for counting the number of collecting bees. Through this method, the bees could collect the gold elements and selectively use the material in their nesting activities.

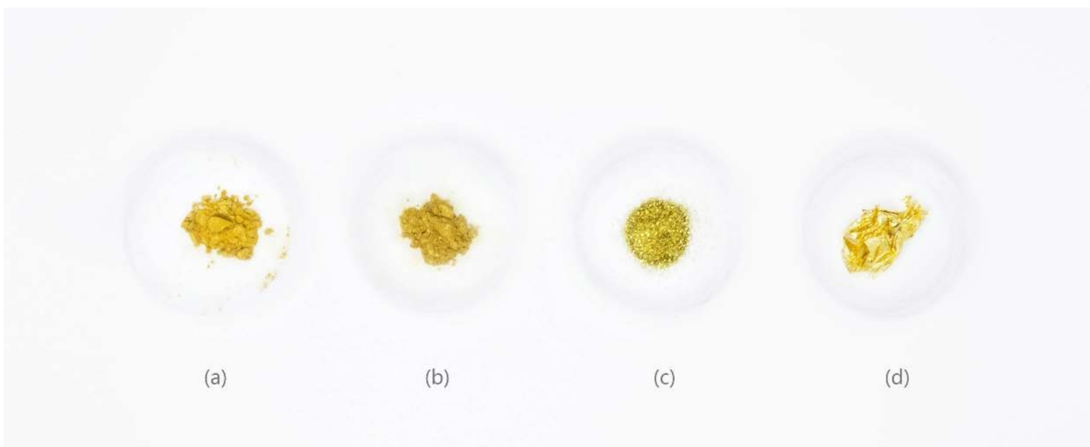


Figure 3.15 Gold elements used in experiments.(a) mall particles: 1020um; (b) medium powder: 100200 um; (c) arge grains: >250um; (d) foil: 0.10.2um; unit: diameter/thickness

It is known that gold elements neither oxidize, change color, nor form compounds with other materials in the hive, which enables us to perceive the arrangement and distributions of the gold element throughout the comb visibly, given this process was independent of self-selection by bees. The aim of the study is to investigate the effect of gold on the behavior of bees. Would it be possible for gold to augment the self-organization of bees? Would the queen lay eggs in these gold cells? Would the distribution of inner structures such as honey and pollen storage change? Would there be a transition of social division among bee colonies? To what extent would the comb and population structure be enhanced, if at all? Moreover, we can explore a new venture in element-informed applications for bee studies, and also for bio-intermediated design and art.

In the experiment, a feeder containing a 60% sugar solution was placed in a fixed position in the beehive, supplying the bees 300–400 g per day to induce collecting behavior and attract collecting bees. A few days later, the sugar feeder was replaced with a bee counter device containing gold elements at the same location to induce continued collection behavior. The bee counter device was designed to record the number of bees passing through the gold container and their consumption of gold elements, to make a comparison with the distribution of the gold elements in the newly made combs.

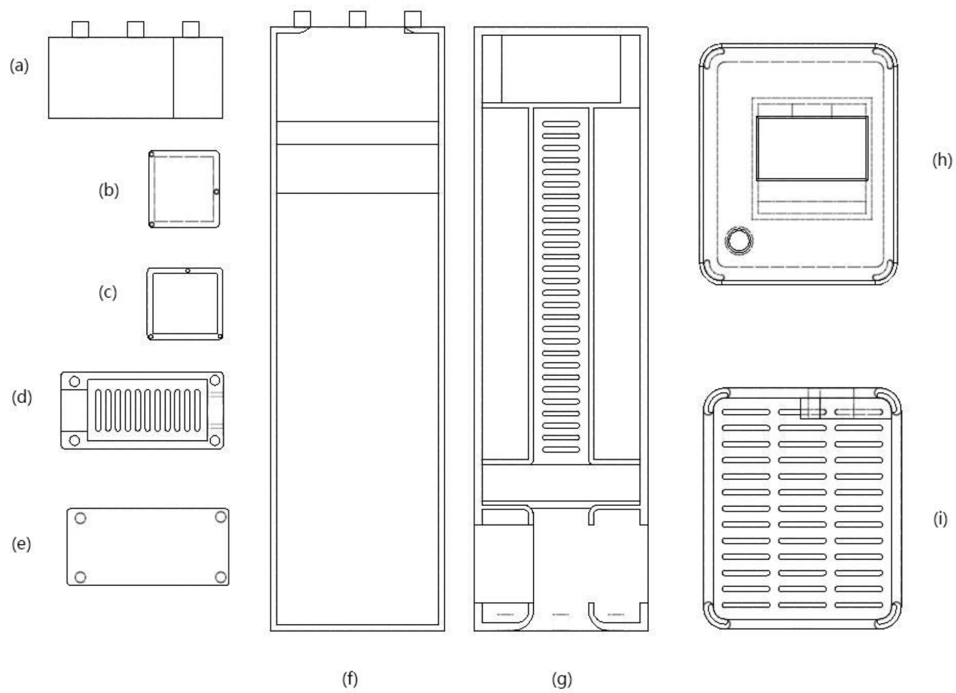


Figure 3.16 Front view of Bee Counter Device Design

The bee counter device (Figure 3.16, Figure 3.19) was designed with a liquid-crystal display (LCD) module and an infrared obstacle avoidance sensor module, combined with a light-emitting diode (LED) as the reference of obstacle presence. It displayed and counted the number of bees as they passed through the gold-collecting compartment. [28]

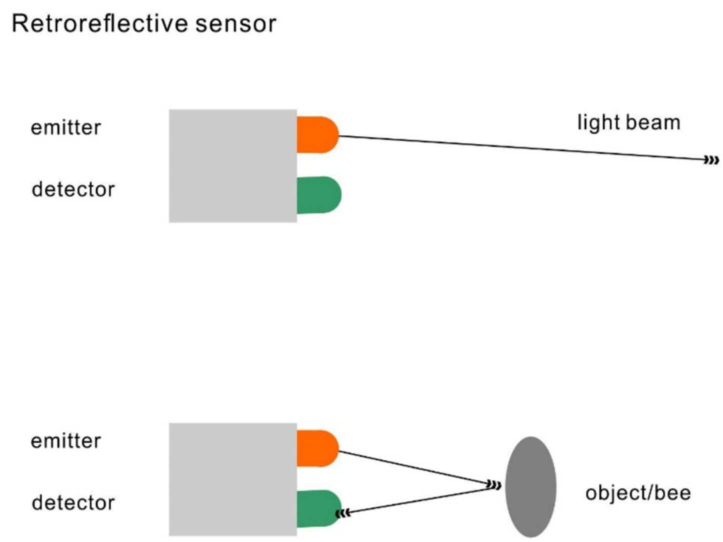


Figure 3.17 Configurations of Optically Activated Object

The device, equipped with an infrared sensor module, could verify the presence or absence of an object within a predetermined range (Figure 3.17). It consisted of a light emitter and a light detector placed adjacent to each other, facing in the same direction. When no object was present, light from the emitter would not reflect the light off of anything and back to the detector, suggesting nothing would be received by the detector. When an object was present, the light beam would be reflected to the detector and the infrared sensor module would detect the object.

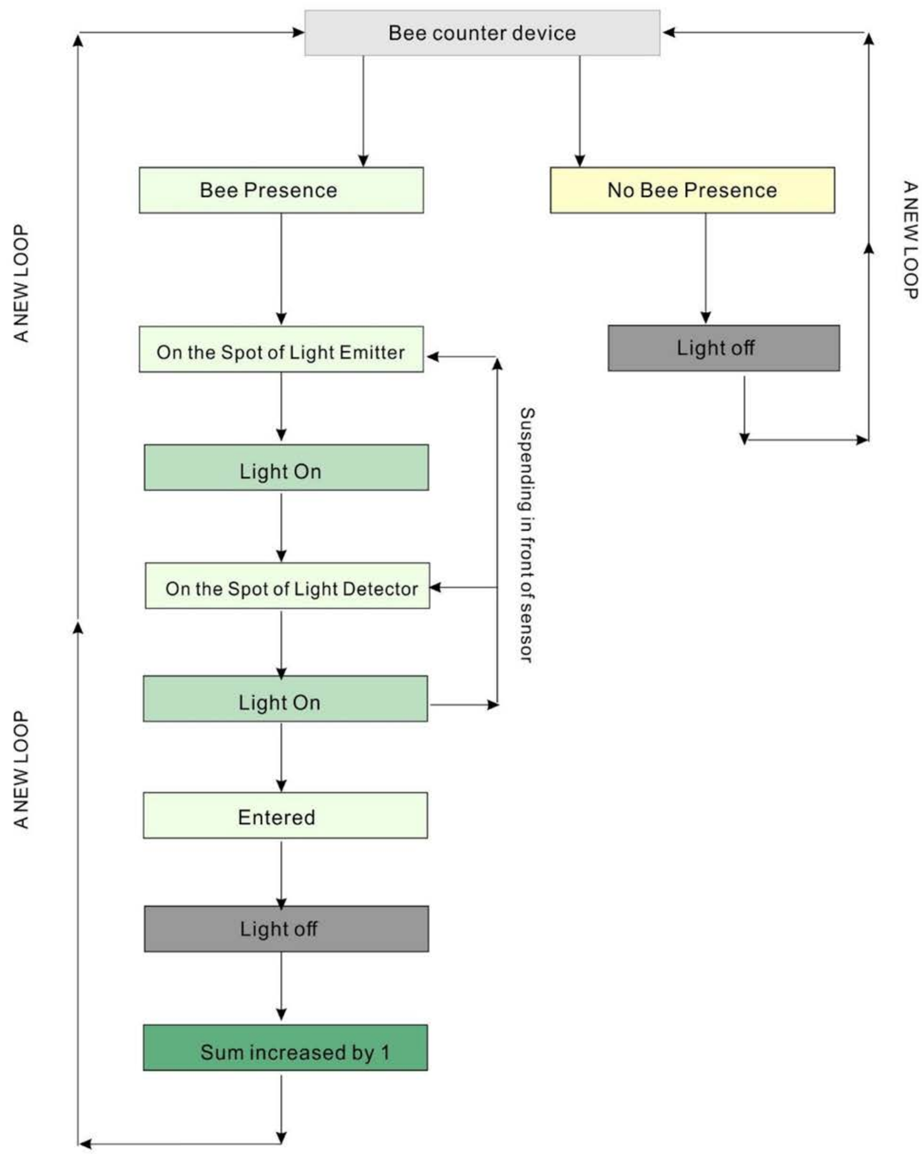


Figure 3.18 Design Principle Flowchart

In the "no bee present" condition, the programming statement was circulated in the outer-shell loop; in the "bee present" condition, the loop was interrupted by the LED turning on (Figure 3.18, Figure 3.19).

The statement was set to check the status every 0.5 seconds. If the status had changed (due to the bee leaving the presence of the sensor), the statement would jump out of the loop into another code line and increase the counter reading by one. This whole process would repeat until receiving the command to reset.(Figure 3.18)

Figure 3.19 Bee counter device in the Beehive

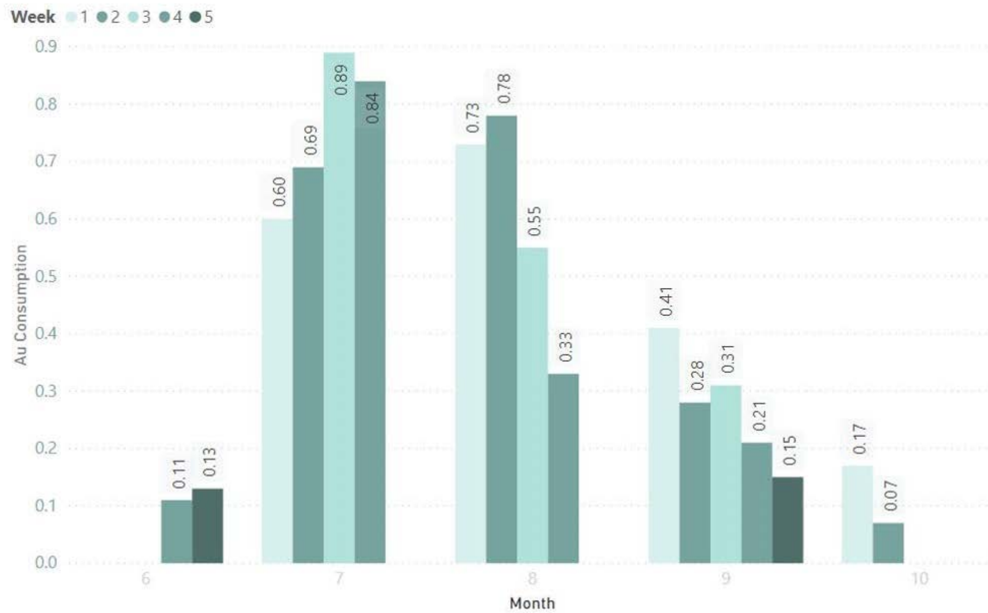


Figure 3.20 Au consumption timeline month /week of 2019

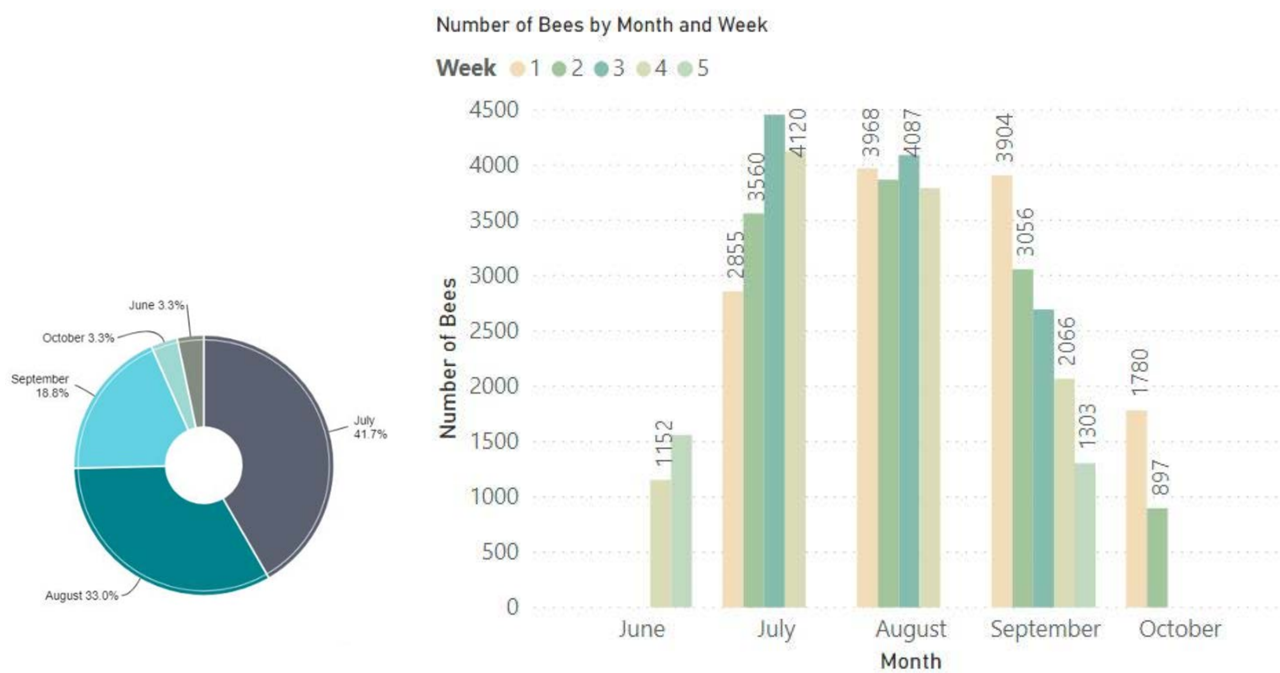


Figure 3.21 Left: Au consumption percentage of 2019; Right: Number of oldcollecting ees

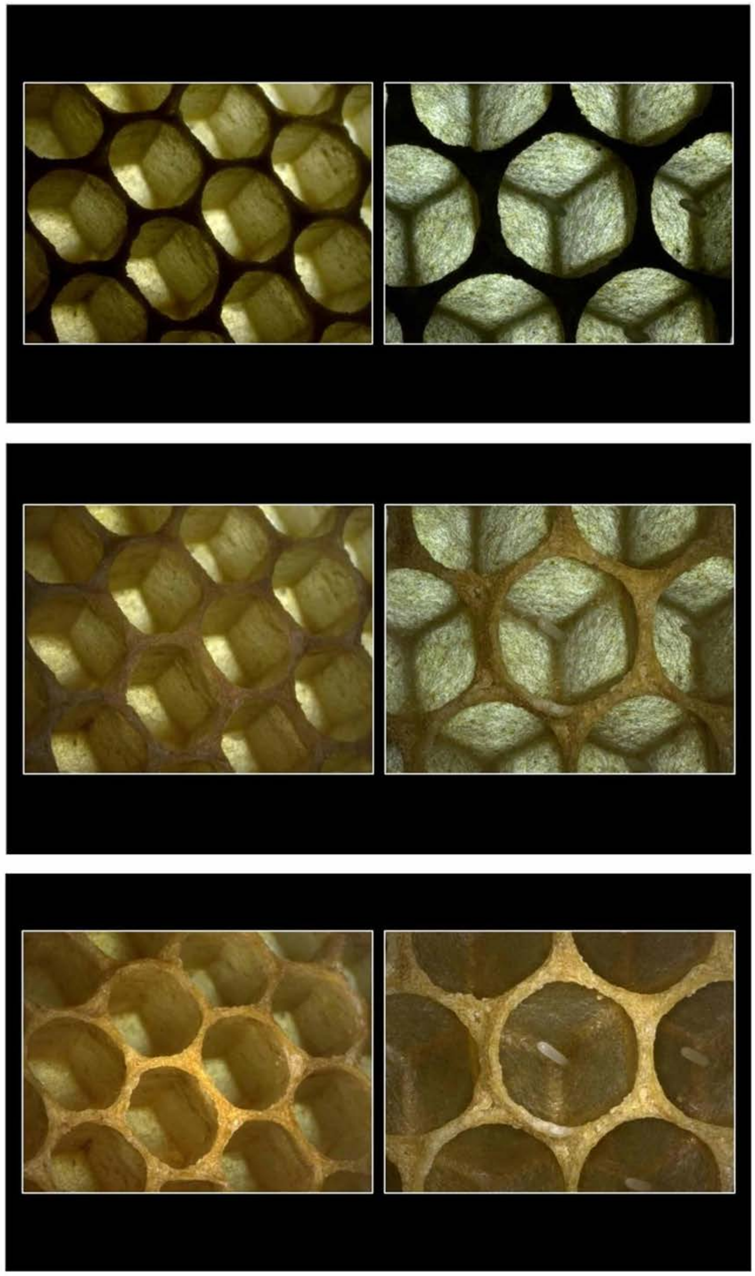


Figure 3.22 Microscope image revealed that eggs developed well in gold cells

Nesting bees applied the gold elements into the honeycomb substrate as needed. Whenever the comb unit was reconfigured, gold consumption would ramp up in the next two days, and then fall back to normal levels gradually. In terms of mechanical distribution, the internal scaffold changed according to the reorientation of gravity as the bees applied gold to adjust and strengthen the comb structure.

Compared with other no-gold colonies in subsequent observations, these applied-gold colonies were not plagued by parasites like varroa mites and wax moths in the experiment unit, even without using bee medicines to treat them[29].

Through gold element incorporation, coupled with gravity reorientation, the experiment comb revealed anisotropy as a result of the new mechanism for ventilation — several nested structures with connecting channels wrapped inside and various sizes of holes and cavities linking to the channels. The organic hybrid structure is more conducive to the ventilation and humidity adjustment of the whole system. The malleability of gold meant that the comb pieces with gold elements incorporated could withstand larger physical curvatures and more significant impacts than ever. Entirely new folds and channel structures emerged. Combs extended from relatively two-dimensional plates to three-dimensional space, composing more complex and dynamic spatial structures. This optimized energy utilization and resource allocation throughout the colony.

Figure 3.23 Multi-structure appeared in Curved Space

Figure 3.24 Large and Small Holes Linking Together with Bees Guarded the Entrances

Figure 3.25 Nurse bees are taking care of larvae and eggs

It was observed that the queen laid eggs in the gold cells and eggs and larvae incubated well. Due to the thermally conductive nature of gold, the insulation of gold combs is better than that of pure wax combs. It was observed that the number of nurse bees was significantly less than that of a typical colony, which suggests that the hybrid structure enhanced the labor division of the bee society. The inner channels connected all the partitioned sections of the hive so that the bees could commute from the food storage area to the brood area through shortcuts. With fewer bees needed to fulfill the same amount of nurse work, the bees could evolve more efficient configurations for other jobs.

Based on the favorable feedback of the above experiments, it is interesting to further investigate helping bees self-organize and adapt to their environment. I propose a new functional hive design — the novel bee incubator — aimed at providing an interface between bees, humans, and nature.

Bee Incubator Installation

As of now, recent centuries have witnessed unprecedented human-induced changes, in the wake of global warming, deforestation, overexploitation, species extinctions, and resource deficiency since the Langstroth hive was invented in 1851. Shifting fields, from natural forests, bees have somehow migrated, to semi-natural habitats like backyards and gardens, even on the roof of buildings. Even though Langstroth hive has been widely used since its inception from the 19th century, it could not fulfill the demand of the environment that is constantly changing. It requires a redefinition of apiculture in many aspects like breeding, cultivation, scientific researches, and observations of the bees.

Since the appearance of *Homo sapiens*, humans have represented only a minority of the ecosystem, and likewise, bee hunting was merely one snippet of the numerous links among the food chains. However, the correlation between humans and bees has been evolving relentlessly since the first encounter. In the wake of the onset of the Anthropocene, the relationships between humans and nature have changed. Owing to the rapid development of science and technology such as gene editing, human beings are able to transform and reorganize nature, such that man-made nature has replaced parts of the organic nature into a *semi-nature*. As some organisms have been genetically modified, the linear course of natural evolution has been broken and we cannot simply return to the past. This complex interdependent relationship exists between humans and bees. We are highly dependent on bee pollination for agriculture. However, our fertilizers and pesticides have menaced the life of bees, making it so that the bees can no longer live in this semi-nature environment in an uncultivated way. Interestingly, bee research today has delved into the genetic level, whereas beekeeping tools and operations are stuck in the mid-19th century. It can be perceived that the apiculture industry is extremely outdated compared to other fields at present. Thus, it is imperative to establish a mutual benefit mechanism that helps the bees mitigate the omnipresent threats conditioned by the complicated and volatile environment.

A bee incubator design based on this concept implements technologies and scientific methods as a medium to replenish the relationships between bees, humans, and nature.

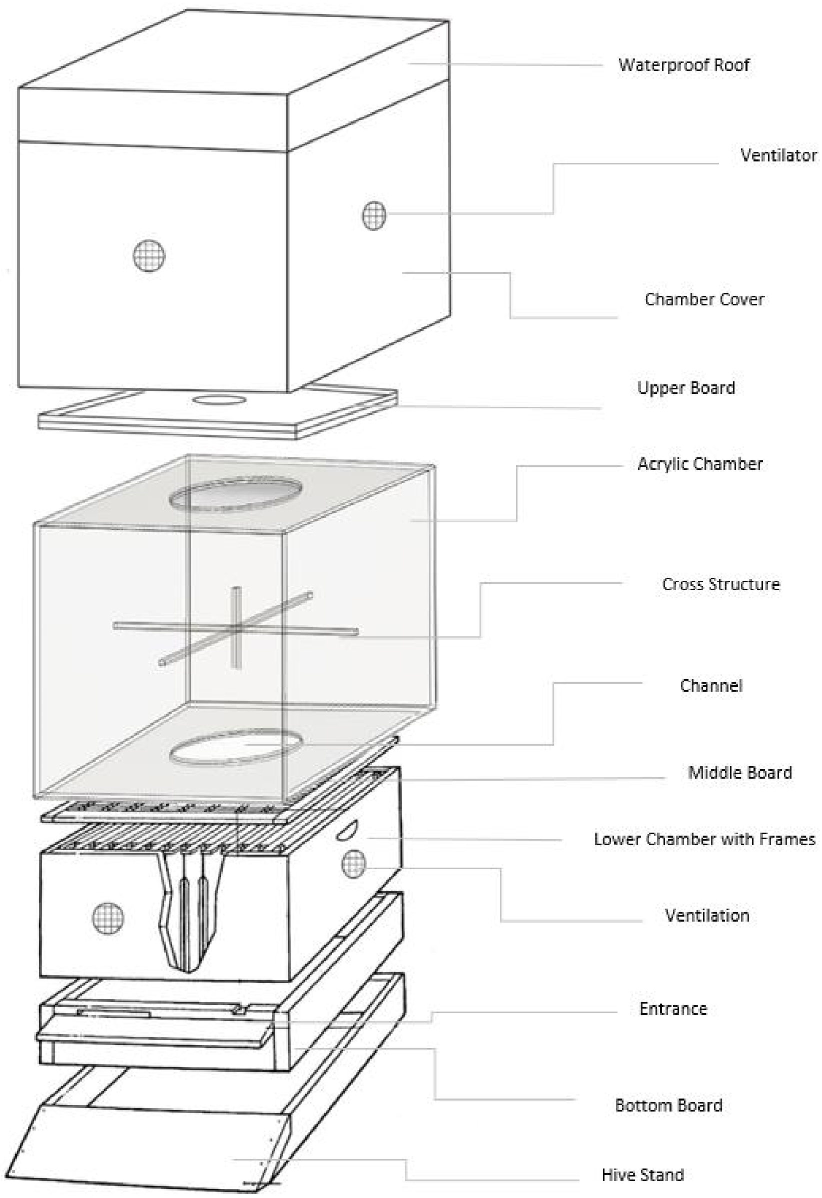


Figure 3.26 Prototype of bee incubator

As illustrated in Figure 3.26, the bee incubator prototype comprised an acrylic chamber with round openings symmetrical on the top and bottom, allowing bees to crawl through, back and forth, up and down between it and the lower chamber. The simplified cross-frame situated in the middle provided the fundamental support for the self-organizing constructions, without any partitions and redundant parts, enabling the bees to generate comb pieces according to their own algorithms.

Each opening was a diameter of 22 cm, designed with the appropriate needs for ventilation (Appendix A). We can compare this with the polyhedron hives of previous gravity experiments, which used ventilation holes of 3 mm diameter in each corner. It was perceived that the bees did not need these small holes for ventilation at all, and in fact sealed all of the small openings with propolis, but kept the large openings as the entrances to the hive. This suggests that bees adjust the airflow automatically according to the conditions of the internal hive. Extra vents would increase the possibility of other insects entering the hives and overload the work of guard bees. The symmetrical openings in this new prototype were designed to be favorable for airflow circulation, and supported by previous research that determined two large openings to be sufficient.

In terms of material selection, transparent acrylic was used to facilitate experiment observation in order to clearly decipher the collective behavior and comb the structure of bees. Since the bees would secrete wax and build combs in a dark environment naturally, a waterproof shading cap was added as a chamber cover. It also served as heat and sunshine insulation, protecting the bees from intense sunlight in summer. The opening on the upper board performed as an extra adjustable vent to assist the bees in controlling temperature and humidity of the combs, a stand was embedded in the acrylic installation to support the device counter, and a recycling tray[30] on the bottom for collecting the dropped gold residue for reuse.

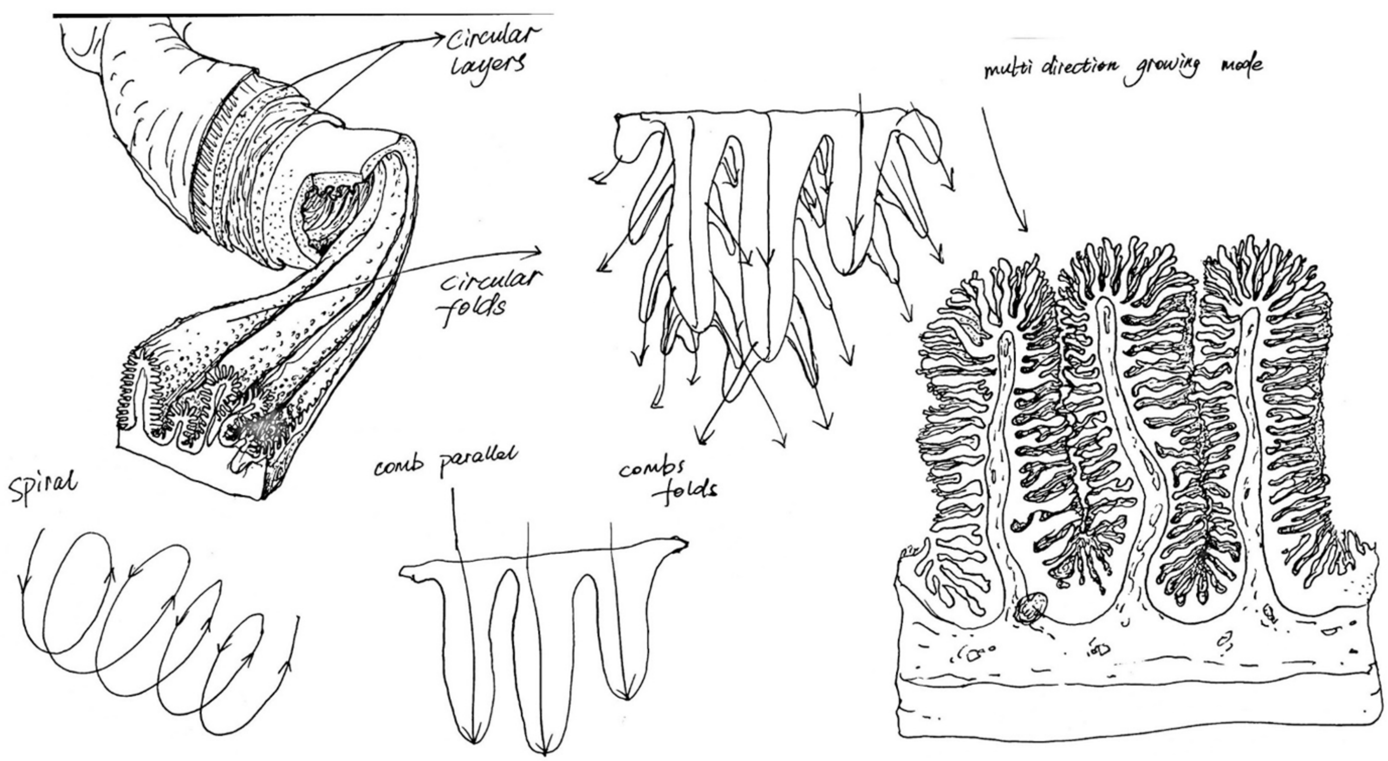


Figure 3.27 Comb folds resemble intestinal folds structure.

Self-Regulating Bee Space

When frames are added to the bottom or super, the space between the frames and hive walls as well as between adjacent comb structures is called *bee space*. There have been many attempts to understand the needs of bee space since people noticed that some specified dimensions of bee space could prevent the bees from constructing redundant comb pieces to some extent. This dimension, frame-to-frame and frame-to-wall, has a strictly defined scale according to the body length of the worker bee. Specifying the bee space is one of the crucial notions considered when building modern beehives.

It needs to be understood that the interior of combs constructed with intricate hexagonal structures would be reframed and revised. Bees rebuild and alter the functional constructions, the internal framings, and the mechanical structures according to external environment factors like temperature and humidity in order to achieve a rational and maximized utilization of space and materials.

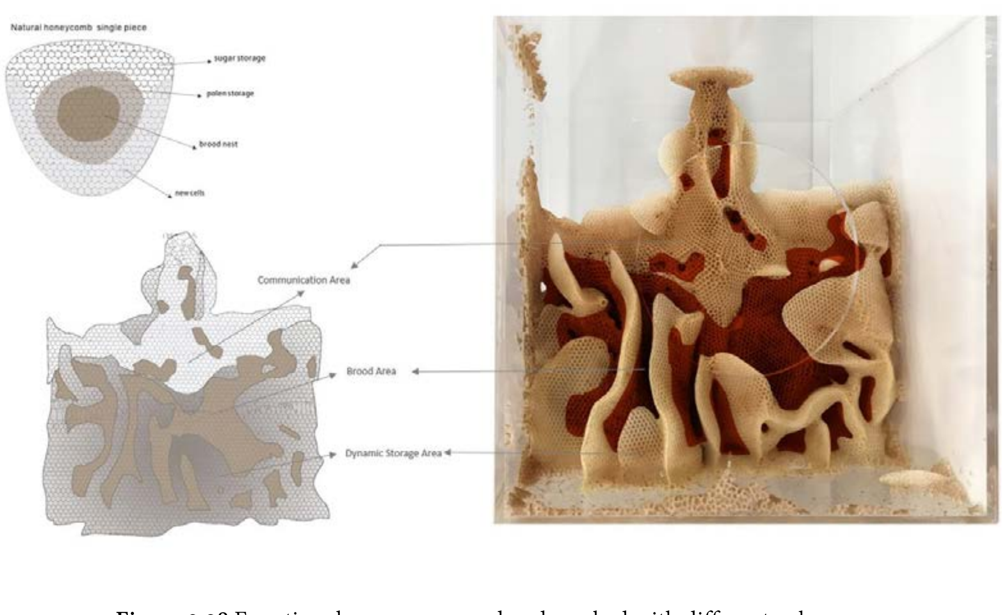


Figure 3.28 Functional areas compared and marked with different colors

Modern beehive mechanically specifies the distance of bee space to a certain limit to be parallel, unchangeable, and equal-divided. It cannot be proved by any scientific researches that this fixed distance benefits the bees most, but minimize their pathway for the good of our daily management and honey extractions.

Brace comb and bridge comb

Some redundant comb pieces attaching frames to frames, combs to combs, and combs to frames have little value for beekeepers since they do not hold any significant amount of honey or brood. They are quite annoying and often ignored and then removed by beekeepers. Those redundant parts are called *brace comb* and *bridge comb*. Just like circular folds of intestine, they are seemingly useless but are actually needed for certain functions. Brace comb serves as an important platform for bees to effectively communicate and share the information of honey and pollen. These unimpressive pieces connect the entire comb and bees as a living body. For easier production, modern beehives cut off this communication mechanism of the bees, weakening their adaptability to the environment.

The Balance — Workers and Drones

A colony comprises a queen, hundreds of thousands of female worker bees, and several hundred male drones, making up a balance. They all experience the same ontogenetic development phases: egg stage, larva, prepupa, pupa, and adult. The three castes of bees only vary a bit in development time: 24 days for drones, 21 days for workers, and 16 days for queens. The workers take all the responsibility of the proper operations for the entire colony, except for laying eggs. A healthy queen lays up to thousands of eggs. In preparation, worker bees build cells and perform hygienic tasks, then wait for the queen to lay eggs in the cells. During their first instar, the eggs depend on the worker bees to produce heat, keeping them at the appropriate temperature. After three days, the eggs hatch into a worm-like form, larvae. Workers feed them a rich diet of honey, pollen, and the mixture of the microbiome from the worker's guts and saliva. This process is extremely critical since newly-hatched bees are free of bacteria and microbiome, so they need it to be transferred from the elder bees to gain immunity to the environment. As a result, maintaining the worker bees healthy and strong is crucial for the entire colony. Five days later, the workers seal the cell with the newly-hatched larvae inside. Elder larvae and pupae spit bee silk, encasing themselves like a cocoon through the remaining stages of maturation. During this period, the worker bees act as nurses and warmth keepers to balance the heat and airflow in the brood area. On the 21st day, pre-adult bees use their mandibles to chew their way out of the cocoons and the wax seal, and emerge into a grown adult. Straightaway, the bee starts its busy life.

New adult worker bees clean the cell at the very beginning because their glands have not fully developed to secrete wax or feed pupae. Eventually, they grow to take on these jobs, in order to feed the larvae and pupae, nourish the queen and drones, cap the cell, patrol the comb, measure the comb, revise and rebuild the comb.

Drones are the male bees in the colony and one of their essential roles is to mate with the queen. At the normal ratio in nature, drones comprise 20% of the bee population on average. However, they do not work, collect honey, or even sting intruders. Since the queen mates once in her entire life with no more than fifteen drones, most of the drones have no chance to even fulfill their roles. They are free to access any other colony of the same species, consuming honey and pollen as they wish, but the workers keep them around in case a new queen needs mating.

A drone devours much more honey than a worker bee but contributes so little that it seems useless to beekeepers. Hence, modern hive designs neglect drone cells and try to minimize the space of drones.

However, besides mating with a queen, drones play another important role in the bee colony. As known, workers have no access to others colonies, but drones are the exception. Healthy drones usually stroll around in adjacent hives and make accommodations at will, acting as agents and exchangers, transferring guts bacteria and passing the microbiome from their original colony to the others, through honey consumption and mouth-feeding by the workers. The workers feed not only the drones but also the baby larvae so that different guts microbiota and bacteria are passed on to the next generations by mouth-feeding.[31]These activities enrich the microbiota of all the adjacent colonies, and group immunity becomes optimized in a certain sense. However, these are beyond the reach of modern beehives.

Hence, my experimental design attempts to imitate the process of natural evolution, using the most basic natural factors such as gravity and natural elements to promote the adaptation and development of bee populations in a semi-artificial environment and nature. As a prototype, I propose this novel bee incubator, which allows bees to develop in an intact space as a supplementary mechanism to restore their resilience, rather than in a specified space with split modes.

The Emergence of Inclusive Channels

The original hive structure was a parallel sheet-like structure, primarily functioning as a heat dissipation mode. By means of gravity reorientation and gold incorporation, interconnected tunnels were organically created and served as more sophisticated and efficient functional systems for heat dissipation.

Insulation requires a significant number of bees to clump together into a spherical shape. The new hive requires far fewer bees to maintain temperature, which reduces the number of heat-producing worker bees required, so that the spare ones can shift to other labor forms. It is an efficient and complex building system that is more conducive to the ventilation and humidity adjustment of the whole structure. Every large and small hole connects with channels that all guarded by temperature-regulated bees (Figure 3.24).

Thermal Imaging

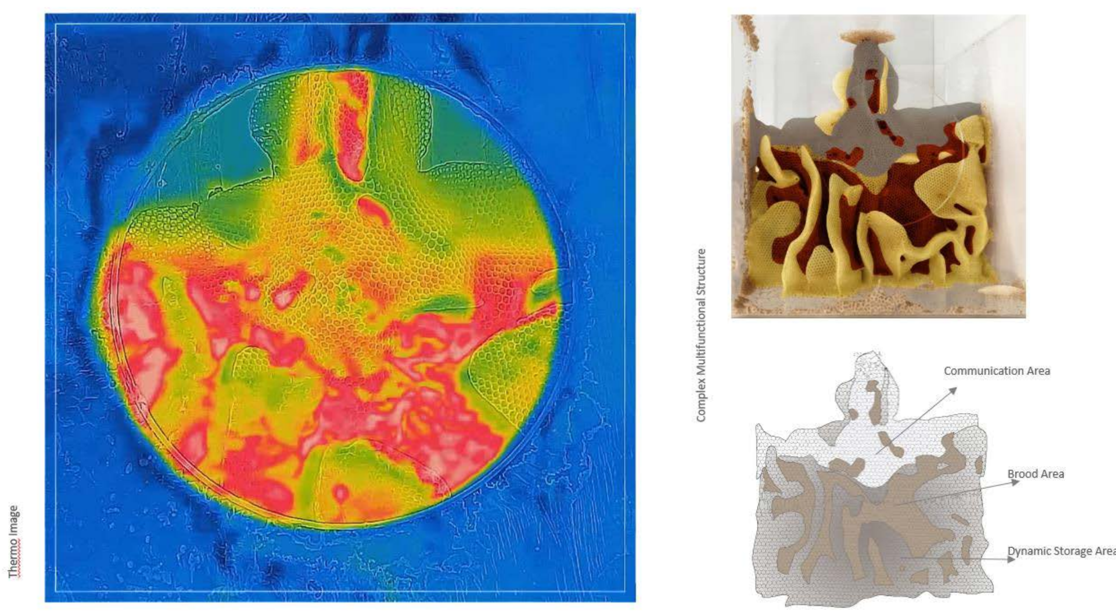


Figure 3.29 The left is a thermal image of the experimental unit; the two images on the right are marked with functional areas in different colors.

Thermal imaging was used to capture heat distribution and map the moving trajectory of the bees underneath the surface, which enriched the understanding of social interactions within the bee society under the conditions of gravity and gold incorporation.

The dark blue square (Figure 3.29, Figure3.30) depicts the shell of the acrylic installation, which has the lowest temperature since the heat radiation could not penetrate through acrylic. The red area represents a high-temperature range around 37°C. The dots of white-pink target the tunnels underneath the surface of the comb, which reach the maximum temperature of over 37°C. The blue arrows in Figure 3.30 reveal the trajectory of the bees moving back and forth through the tunnels in the thermal imaging video. These channels constructed by the bees connect all the functional sections of the beehive. Brood, honey, pollen, and communication areas are composed of a dynamic system that enables the bees to effectively control temperature, ventilation, and humidity and act as connections that shortened the distance of food transportation. Requiring a more stable temperature environment for the development of the larvae and pupae, the brood area presents as red in the thermal image. The yellow area shows a relatively low temperature for regions of food storage. Workers ripen the nectar stored in the yellow area by energetically flapping their wings at full speed to evaporate the moisture to less than 17%. The gray area, used to exchange information, shows the lowest temperature.

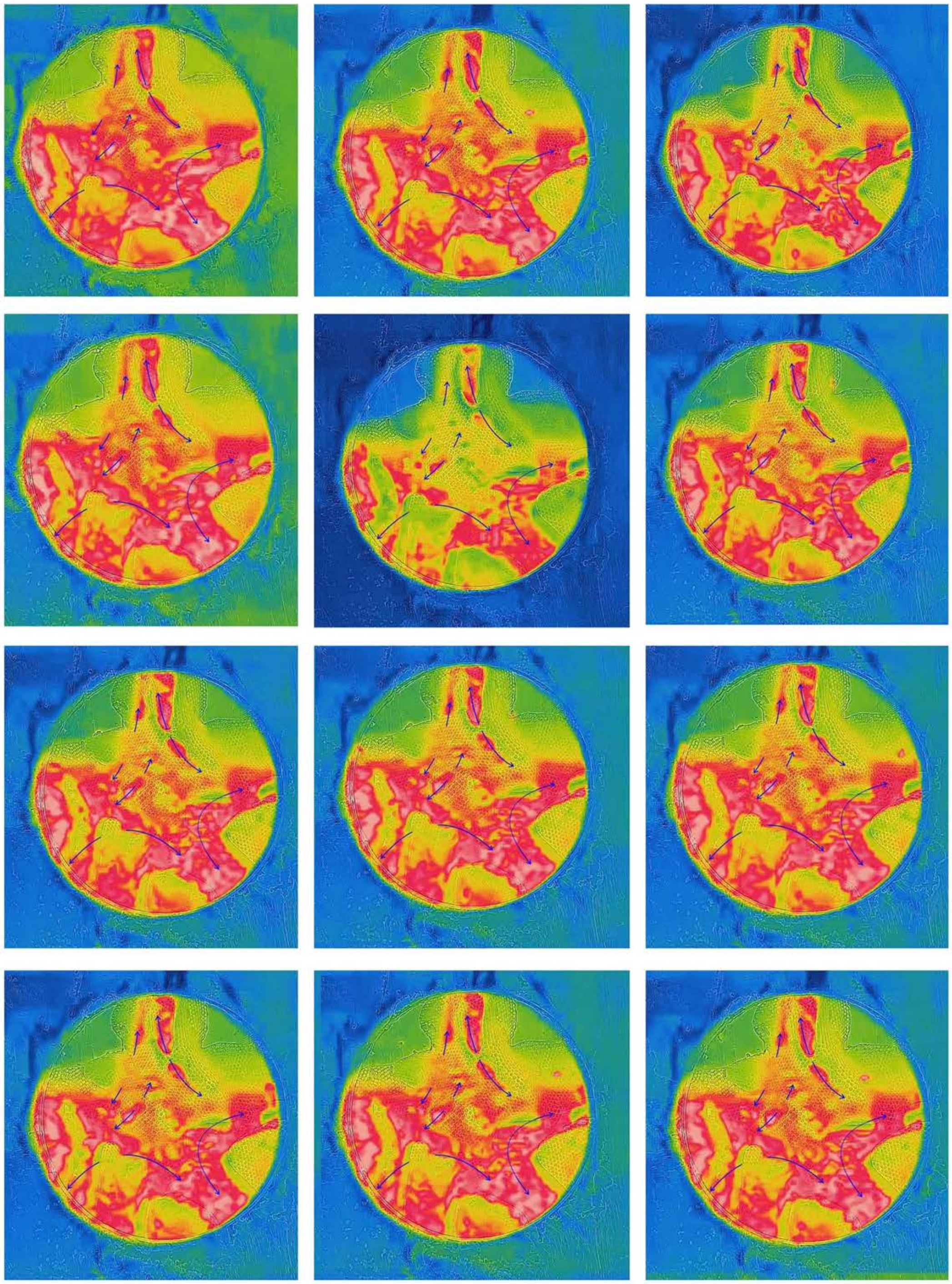


Figure 3.30 Stills from thermal video of the bee incubator

The Emergence of Folds

The strength of honeycomb was enhanced by the incorporated gold, due to the malleability and toughness of gold. The complexity of honeycomb evolved. The food storage areas extended just like intestinal folds and shared similar functions with it; the increased surface area of the comb folds developed by the bees increased the honey storage capacity per space unit in the hive (Figure 3.27). The dendritic structure of spiral folds forming from divergent comb sheets embraced the brood area in the center, with honey and pollen encircled in extending space. These folds structures achieved full potentials with optimal and maximal resource utilization.

The Curvature of the Comb Pieces

The curve-comb pieces intertwined such that one arc surface fused with another, forming into a multi-regional interconnected entity. As shown in the stills from the thermal video (Figure 3.30), the intersected surfaces permitted the bees to travel quickly within these areas, from one functional area to another. At the same time, these intertwined arcs enhanced the toughness and stiffness of honeycomb sheets, serving an identical function to the cross-frame support in architecture. With every reorientation, the bees reconstructed the honeycomb according to the change in gravity vector combined with the mechanical balance of the original honeycomb, and calculated iterations to the original one.

Compared with honeycombs in the previous experiment (introduced to gravity reorientation but not gold elements), the honeycombs incorporated with gold have greater curvatures. This phenomenon suggests that bees have the ability to identify the properties of different materials, including those they never encountered, and wild bees at an autonomous status could gain considerable adaptations to the intervention of external factors. The collective mechanism endows the bees with super coordinations to form the unique bee algorithm, so that the bees have extraordinary abilities to leverage external substances to ameliorate and enhance their comb. Compared with the pure wax comb, the gold honeycomb is able to withstand more extreme environmental conditions — e.g., space exploration with more than 15 times the atmospheric pressure of standard G.

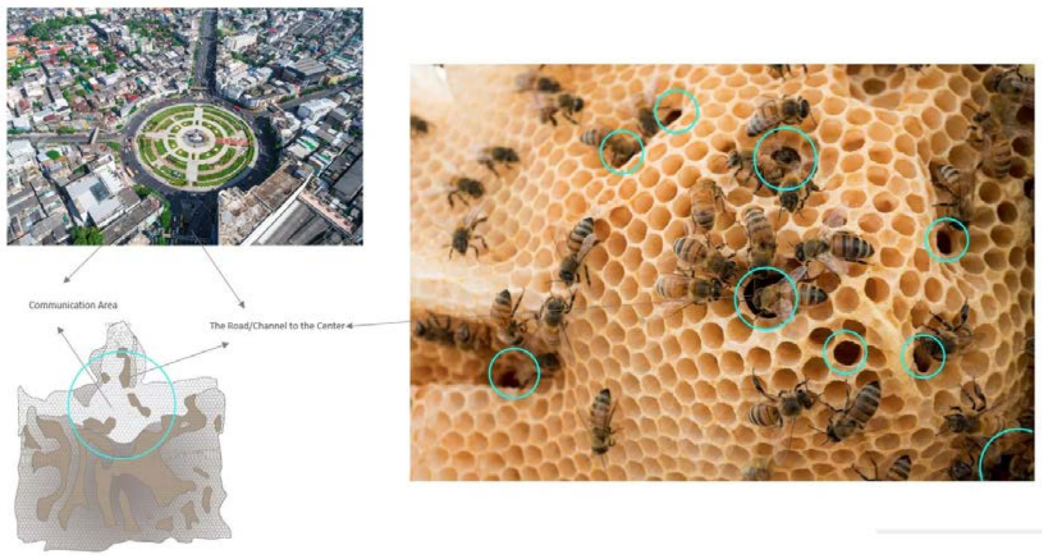


Figure 3.31 The central ball-shaped area is just like the plaza in human society,providing a platform for communications.

The center was constructed as a globular structure, which is quite different from the conventional parallel sheet combs. The downward parallel formation acts to dissipate heat, whereas the spherical shape encases heat within internal spaces. When a foraging bee performs the waggle dance on a single piece of comb, the recruiting information cannot be passed all the way to the bees situated on different combs since all the pieces are paralleled and separated. Quite the opposite, the spherical comb structure provides a space corresponding to the city square (Figure 3.31), where the bees can receive the information from every direction, which is conducive to information transmission. There are holes embedded in the spherical structures, connecting with the tunnels beneath the surface and linking to other functional areas. This structure accelerates the speed of information delivery, contributing to a synergy of global communications.

Worker bees contribute to almost all of the functions in the bee colony except egg laying. The labor system is differentiated into nurse bees, collecting bees, heat-production bees, ventilating bees, guard bees, feeding bees, builder bees, etc. There are still more subdivisions within these jobs. Collecting bees can be divided into nectar-collecting bees, pollen-collecting bees, water-collecting bees, and propolis-collecting bees. Moreover, cleaning bees comprise cell-cleaning bees, debris-removing bees, hive-cleaning bees, and dead-brood-cleaning bees.

Figure 3.32 The author observing the conditions in the bee incubator.

From the first day of birth, the worker bees get straight to work, performing their duties until the last days of their lives. However, the inflexible structures of modern beehives lead to considerable useless and repetitive works. For instance, if one bee wanted to access the 10th frame from the 1st frame, it would need to circumvent all the frames in a zigzag path, which significantly decreases its work efficiency. In contrast, the newly emerged functional structures described in the research presented this thesis — no matter the channels, curvatures, or the spherical center — have been validated to improve the efficiency of the bees. It is perceived that due to the enhancement of heat insulation and flow ventilation, the number of heat-producing bees decreased. The bees could feed more larvae and pupae per unit time, thanks to the formation of the interconnected structures like tunnels and curves. As a result, the bees that used to engage in these jobs could shift to other labor divisions, such as flapping wings at the opening of the tunnels, and guarding the entrances. Unprecedentedly, incorporation of the gold element also led to the emergence of another new division — the gold-collecting bee. The novel bee incubator brought about transformation and diversification of the traditional honeycomb, while gravity reorientation and gold incorporation prompted a series of new divisions among bee society.

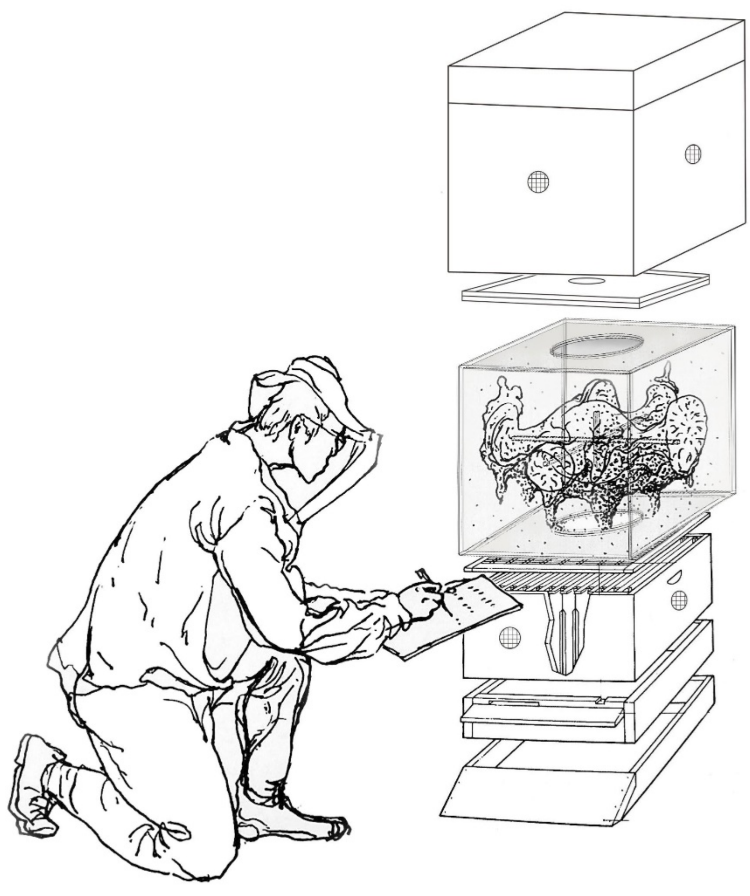


Figure 3.33 The transparent installation facilitates scientific observation and data recording.

Recyclability

The novel bee incubator can be returned to the bee colony during the Spring season when the bees massively proliferate, collected in Summer and Fall, and displayed as an art piece for exhibition in Winter when the bees no longer need it. Moreover, as a recyclable installation, it can be given back to the bees in the next Springs for reuse. It is an interface, a novel hive, a bee incubator, a research installation, a recycling device, and also an artwork that intertwines art and science within.

Contributions

From the perspective of art and design, the novel honeycombs place a greater emphasis on the contributions of the bees than those of the beekeeper. Since the honeycomb structure gradually changes with the environment, this honeycomb design can be understood as a time-resolved embodiment of the natural environment around the organic hive, with a rapid increase in honeycomb production directly linked to the blossoming period of the surrounding plants. The comb structure sculpted by bees is highly dependent on the surrounding resources, and directly influences the timeline required for the bees to build their nests. In terms of the two crucial artistic concepts, in which time and space are incorporated into the comb generating process, this unique biological material growing system can be viewed as a significant achievement in both of these areas.

The bee incubator is designed to achieve the function of renewing and recycling comb structures. The traditional beekeeping method and beehive structure divide the bee colony, which reduces the adaptability of bees to environmental changes. Also, the wax recycling efficiency in traditional hives is relatively low. Therefore, the novel bee incubator described here, with a separate honeycomb building module that can be reused more efficiently by the colonies, is incredibly valuable from a bee energetics perspective.

From a scientific perspective, a visible interface provides convenience for researchers to directly observe the bee colony and perform experiments. In modern beekeeping, there are two basic types of beehives: one is a totally enclosed traditional wooden beehive, and the other is a fully exposed transparent beehive for display purposes (as is commonly found in museums). Neither design, however, is optimal. To address these limitations, I designed a semi-exposed and semi-hidden prototype incubator, which enables the bees to self-organize the space in which they live and freely transfer food and energy as they need or desire. In two novel approaches — a gravity-reoriented approach and an element-informed approach — the original system was reiterated and replenished with a dynamic system established by bees. It helped the bees to enhance and augment their biological nature, while simultaneously opening up a vision to achieve bioart inspired by collective organisms. Meanwhile, it also explored the possibilities of how to extend the bee reproduction system for environmental extremes and the bee settlement to outer space for future applications.

Out of this research, the avant-garde incubator and the collection of honeycombs generated will lead to a series of new insights regarding the relationship between science, design, and art with respect to the biology of bees. These insights will not only lead to a set of guidelines that enable scientists, designers, and artists to leverage combs as designable interfaces, but also help bees better adapt to the changing environment, thus, tightening the relationship between human, bees, and nature.

Chapter 4

Art Works and Projects Related

The Fat Chair

Joseph Beuys, one of the most emblematic artists of the postwar period, began participating in the interdisciplinary art performances of the international Fluxus movement in the early 1960s, while he was struggling with artistic concepts inspired by German philosopher Rudolf Steiner and derived in his distinctive fashion from such anthroposophical sources as his "Nine Lectures on the Nature of Bees." In his lectures, Rudolf Steiner sees the bees as a holistic living body, including workers, drones and a queen, revealing the parallels of the bee colony and the human circulatory system and, while also developing a distinctive epistemology to articulate social and spiritual ideals. Thus, Beuys found the prototype of an ideal social sculpture running through his career as an artist and Utopian.

During World War II, the artist was wounded and rescued by Tartar tribesmen in a wrap of animal fat and felt that came to symbolize warmth and healing energy, which was often used in his works afterward.

Materials like butter, grease, honey, blood, felt, and beeswax, all point to a *state of warmth*, or temperature. As the fundamental factor of life maintenance in living organisms, it controls the circulation and dissipation of energy within the body to balance the temperature. Beeswax and honey are firmly related to the temperature of bees. Also, bees are organisms susceptible to temperature, and they adjust the temperature through aggregation and ventilation. When building honeycomb, the bees soften the wax into formable shapes by producing heat through all their labors like brewing honey and feeding larvae. Beuys' interest in this theme of heat and temperature led him to make use of these warm materials in his works (Figure 4.1).

Beuys used wax, honey, and grease in artistic creation as he sought to find the primary energetic material forms. He understood it as a "prelinguistic," a non-verbal narrative and a more intrinsic language of perception.

Figure 4.1 The fat chair
Artist: Joseph Beuys 1921–1986
Originl Title: Fettstuhl
Medium: Wood, glass, metal, fabric, paint, fat and thermometer
Dimensionisplayed: 1830 × 1550 × 640 mm

Live-in Hive

The artist Mark Thomson planned to live with bees for three weeks, placing his head into a specialized frame inside the installation to hold him still, being fed with a system of tubes directly to his mouth, and perceiving a private series of interaction with the bees — a meditation of the bees around him (Figure 4.2). It was planned around the time of the beginning of a new city, the fusing of the two Berlins, just before the fall of the Berlin Wall. However, this activity is extremely dangerous in that the bees will expel any intruder (usually a rat or moth) by stinging them to death and burying them with propolis, and Thomson failed to work it out. Yet, it was a bold attempt to interact with bees up close.

Figure 4.2
Mark Thompson inside the beehive installation: Live-in Hive (1979)

Yuansu VII-Beehand

The artist Ri Ren spent seven days with the bees, placing his right hand still into the beehive, from the initial rejection to the final adoption. The bees ultimately perceived the hand of the artist as a part of the beehive, so as to extend their honeycombs on it (Figure 4.3).

Ren cleaned his right hand with the bees' most intimate substances, honey and pollen, which helped the bees get familiar with it day by day. As a result, the bees turned it into a part of the beehive and built nest pieces on it. As they continued developing deeper communications and experiencing the interactions further during the seven days and nights, the bees and the artist both achieved interdependent relationships as organisms in nature.

Figure 4.3 Stills from Video Yuansu VII-Beehand, 2015, Ri Ren

Masked Ball

The artist Aganetha Dyck combined everyday objects with bees, wrapping the objects (e.g., books, toys, and ceramic statues) with beeswaxes. She simply desired to experience the process of working with bees.

> *"All the things I've told you about bees are really not important, it's more about opening up the hive . . . seeing all of them . . . putting my hand down just above them and feeling their warmth, their energy. It's not their wax . . .it's them I'm drawn to." (Ramírez, J. A. 2000)*

Figure 4.4
Name: Masked Ball
Size: Life size
Artist: Aganetha Dyck
Photo Credits: Peter Dyck

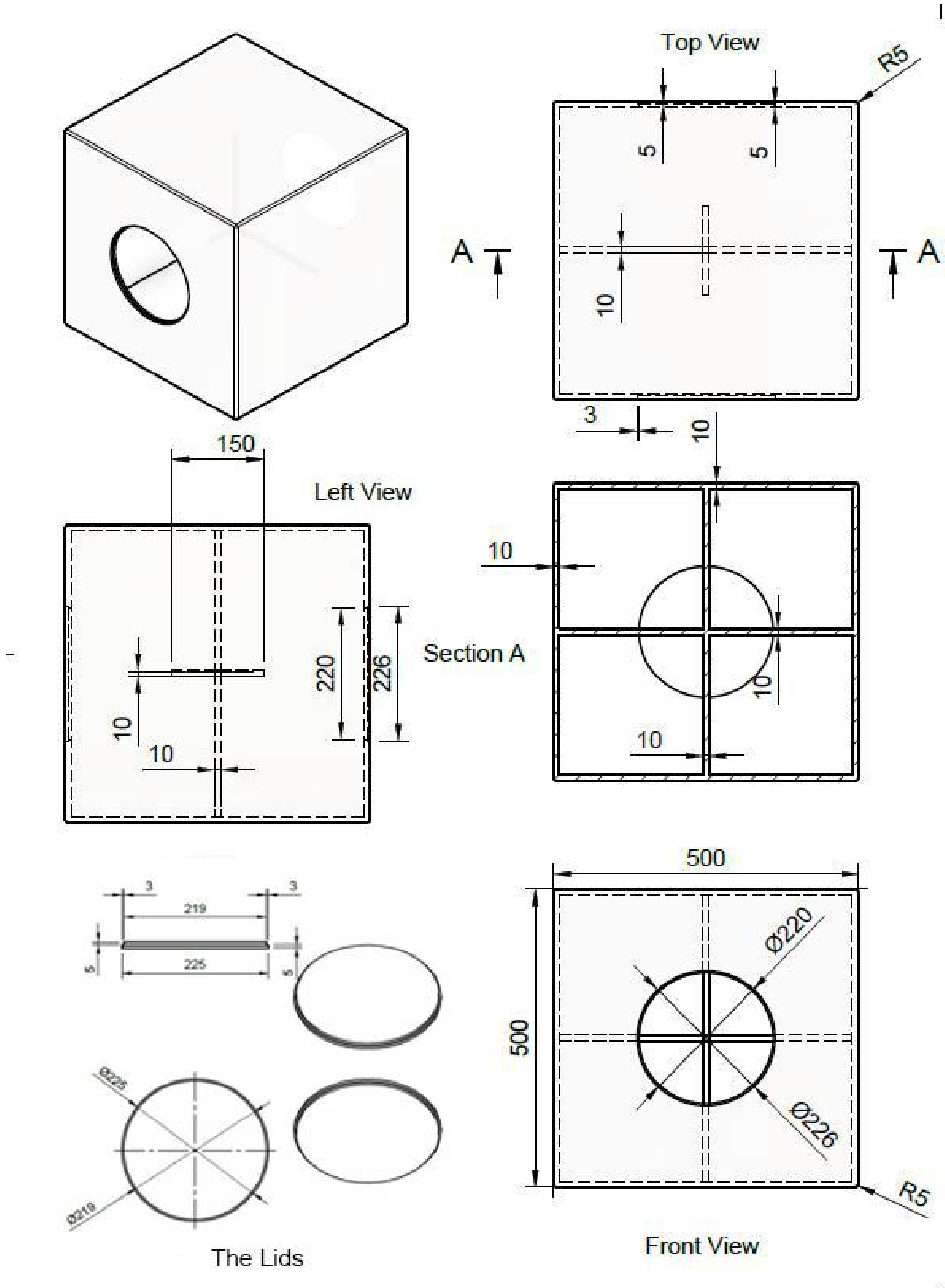
Maiden Flight

Maiden Flight is an autonomous biological laboratory environment designed for studying the impact of space flight on a bee colony. In this project, the MIT Mediated Matter Group sent two queen bees with 20 nurse bees to space under zero gravity, to explore the effects of extreme environments on dynamic hive structure and behavior change of honeybees.

The spiral structure in the compartment I designed (on the right of Figure 4.5) was built by bees under simulated gravity-free environments on Earth, as an accommodation. Compared to a typical comb structure, it contributed to reducing the impact during flight conditions up to 15 G and vertical velocities up to 1 km/s.

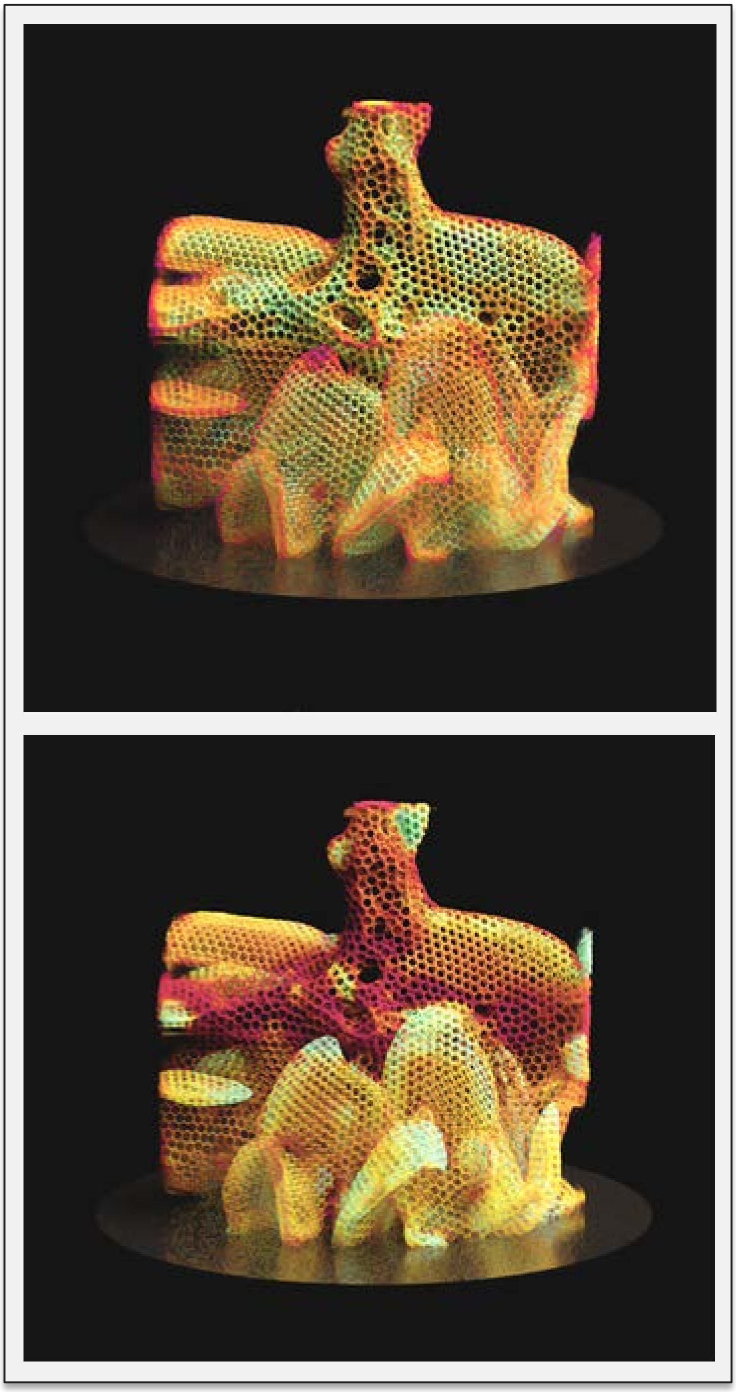
Figure 4.5 Maiden Flight, by Mediated Matter Group, Media Lab, MIT, April of 2019

Appendix A



Prototype Design of the Bee Incubator Used in the Experiement[32]

Appendix B



Upper image: Curvature of Gold-incorporated Comb

Lower Image: Thickness of Gold- incorporated Comb[33]

Appendix C

Computed Tomography(CT)Scanning Images of Gold-Incorporated Comb in Varous angles[34]

Appendix D

The Author Ri Ren with Gold-Incorporated Comb

List of Illustrations

that the traction force of the trunk could support the weight of the whole honeycomb without falling down. Beehive Image credit: Joe Dempsey photo.Com The diagram is made by Ri Ren.

13. **Figure 3.6** represents the process of gravity changing. (a) is the original gravity pointing downwards; (b) through changing the gravity, a cross structure is formed;(c)(d)(e)Through reorientation the gravity of the object repeatedly, it will break the balance of the forces exerted on the object so that the object was shaped to more complex forms.(f)the object grew into more complicated through multiple iterations. Image credit: Ri Ren

14. **Figure 3.7** Gravity iteration study

(b) after one-time gravity iteration
(c) after two-times gravity iteration
(d)(e) after several times gravity iterations, the square has the tendency to be a circle.
(f) The square is infinitely close to a circle without ends.
Image credit: Ri Ren

15. **Figure 3.8** Progression sketches of comb generation in the condition of microgravity. Image credit: Ri Ren

16. **Figure 3.9** Yuansu II series

1. Yuansu II series #4-1
2. Yuansu II series # 8-1
3. Yuansu II series #12-1
4. Yuansu II series #6-1
5. Yuansu II series #1-1

Image credit: Ri Ren

17**. Figure 3.10** Yuansu II Series-The Regular Hexahedron Experimentations and Details. Image credit: Ri Ren

18. **Figure 3.11** Gold in its natural form in rocks. Retrieved from webcomicms.net

19. **Figure 3.12**

(a) Effect of gold Nps on matured larval weight.
(b) Effect of gold Nps on silk gland weight.
(c) Effect of gold Nps on cocoon weight.

Image credit: R. R. Patil, H. Raja Naika, S. G. Rayar, N. Balashanmugam, Vivek Uppar & Atanu Bhattacharyya (2017) Green synthesis of gold nanoparticles: Its effect on cocoon and silk traits of mulberry silkworm (Bombyx mori L.), Particulate Science and Technology, 35:3, 291-297, DOI: 10.1080/02726351.2016.1154121

20. **Figure 3.13** A colored honeycomb from a beehive has been found in Ribeauville near Colmar Eastern France.— Bees at a cluster of apiaries in France have producing honey in mysterious shades of blue and green. They were noticed back to hives carrying unidentified colorful substances. It was discovered afterward that the bees had collected the materials used to producing M&M's, bite-sized candies in bright red, blue, green, yellow, and brown shells 4km away from their hives. Image retrieved from https://www.nydailynews.com/news/world/french-bees-making-colored-honey-article-1.1175991

21. **Figure3.14** Bees are collecting tree sap. Image retrieved from https://twitter.com/markhortonphoto/status/1030816445419212800

22. **Figure3.15** Gold elements used in experiments. (a) small particles: 10-20um; (b) medium powder: 100-200 um; (c) Large grains: >250um; (d) foil: 0.1-0.2um; unit: diameter/thickness

43. **Figure 4.3** Stills from Video *Yuansu VII-Beehand*, 2015, Ri Ren

Name: Yuansu VII-Beehand
Artist: Ri Ren
Year: 2015
Video: 11'26"

44. **Figure 4.4**

Name: Masked Ball
Size: Lifesize
Artist: Aganetha Dyck
Photo Credits: Peter Dyck

45. **Figure 4.5** Maiden Flight, by Mediated Matter Group, Media Lab, MIT, April of 2019

Copyright: Mediated Matter https://www.media.mit.edu/projects/maiden-flight/overview/

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[1] See the article: Excavations reveal first beehives in ancient Near East from The Hebrew University of Jerusalem, Public Release on 3-SEP-2007, https://www.eurekalert.org/pub_releases/2007-09/thuo-erf090307.php

[2] See the descriptions: The Life and Writings of Francis Huberby A. P. De Candolle. - Edinburgh New Philosophical Journal - October 1832 to April 1833 - Volume 14 - Pages 283 - 296 https://books.google.com/books?id=WmQ7AQAAIAAJ&pg=PA283

[3] See the description: Kritsky. G., 2010. The Quest for the Perfect Hive. Oxford University Press, Inc. New York

[4] Munn's hive was also called 'a true hanging bar-frame hive' by Herrod –Hempsall, patented in France in 1838. Munn described the hive in the first edition of his book A Description of the Bar-and-Frame-Hive (1844)

> *When the hive is filled with honey, two or three, or more of the bars may be, at any time, removed, or exchanged for unoccupied bars, without much disturbing the brood combs…these hives can be applied to many of the systems of bee-management, and prove equally profitable, and more manageable than some of the newly-invented hives.*
>
> *The frames with their contents can be drawn out …whenever it is wished to examine the bees, &c., as the 1-1/8 of an inch spaces between the grooves will allow of a sufficient distance to be preserved, between the lateral surfaces of the perpendicular combs formed in the "bee-frames," and thus permit them to slide by each other with facility*

[5] Dutch artist Pieter Cornelis Mondriaan (1872-1944) is one of the representatives of modernism. In the 1920s, Mondrian began to create the definitive abstract paintings for which he is best known. He limited his palette to white, black, gray, and the three primary colors, with the composition constructed from thick, black horizontal and vertical lines that delineated the outlines of the various rectangles of color or reserve. The simplification of the pictorial elements was essential for Mondrian's creation of new abstract art, distinct from Cubism and Futurism. The assorted blocks of color and lines of differing width create rhythms that ebb and flow across the surface of the canvas, echoing the varied rhythm of modern life. The composition is asymmetrical, as in all of his mature paintings, with one large dominant block of color, here red, balanced by the distribution of the smaller blocks of yellow, blue-gray, and white around it. This style has been quoted by many artists and designers in all aspects of culture since the 1920s. https://www.theartstory.org/artist/mondrian-piet/artworks/#pnt_4

[6] It is generally considered Anthropocenelocating locates a possible beginning of the first atomic bomb in 1945, or the Partial Nuclear Test Ban Treaty in 1963.

[7] See the explanations in Against the Anthropocene: visual culture and environment today, Demos, T. J., 2017, P9-10

[8] CCD, Colony collapse disorder, is a syndrome specifically defined as a dead colony with no adult bees and with no dead bee bodies but with a live queen, and usually honey and immature bees, still present. It was conjunction with a drastic rise in reports of disappearances of Western honey bee (Apis mellifera) colonies in North America. Beekeepers in most European countries have observed a similar phenomenon since 1998, especially in Southern and Western Europe; the Northern Ireland Assembly received reports of a decline greater than 50%. The phenomenon became more global when it affected some Asian and African countries as well. In the six years leading up to 2013, more than 10 million bee colonies across the world were lost, due to CCD, nearly twice the normal rate of loss. https://en.wikipedia.org/wiki/Colony_collapse_disorder

[9] Professor Tom Seeley discussed this method in his article about Darwinian Beekeeping. Bees for Development Journal 122, March 2017

[10] See the research of Shimanuki et al. 2007 and the narration from The Quest for the Perfect Hive by Kritsky. 2010.

[11] See the note from *The Quest for the Perfect Hive* by Kritsky. 2010

[12] The bee species studied in this thesis specifically refers to the Italian bee, Apis mellifera ligustica, shortened as bees in the content below.

[13] Actin is a family of globular multi-functional proteins that form microfilaments. It is found in essentially all eukaryotic cells (the only known exception being nematode sperm), where it may be present at a concentration of over 100 μM; its mass is roughly 42-kDa, with a diameter of 4 to 7 nm. Actin participates in many important cellular processes, including muscle contraction, cell motility, cell division and cytokinesis, vesicle and organelle movement, cell signaling, and the establishment and maintenance of cell junctions and cell shape. Many of these processes are mediated by extensive and intimate interactions of actin with cellular membranes. In vertebrates, three main groups of actin isoforms, alpha, beta, and gamma have been identified. The alpha actins, found in muscle tissues, are a major constituent of the contractile apparatus. The beta and gamma actins coexist in most cell types as components of the cytoskeleton, and as mediators of internal cell motility. It is believed that the diverse range of structures formed by actin enabling it to fulfill such a large range of functions is regulated through the binding of tropomyosin along the filaments. Wikipedia.org/wiki/Actin

[14] See the fossil of honeybee worker of Natural History Museum of Los Angeles.

Fossil: a 30-million-year-old honeybee worker

Species: Apis henshawi
Geological range:Late Oligocene
Geographic distribution: Germany (Rott Formation)
Type of specimen: Apis (Synapis) henshawi. Its type locality is Rott (MCZ coll), which is in a MP 30 lacustrine - large lignite in the Rott Formation of Germany
Specimen size: 1cm.
Collection: Natural History Museum of Los Angeles

[15] See the researches: Tautz, J. 2008. *The Buzz About Bees: Biology of a Superorganism*. Berlin: Springer.

[16] See the researches: Anken R.H., Rahmann H. 2002. *Gravitational Zoology: How Animals Use and Cope with Gravity. In: Horneck G.*, Baumstark-Khan C. (eds) Astrobiology. Springer, Berlin, Heidelberg

[17] See the experiments: De Jong, D., 1982, The orientation of comb-building by honeybees, J. Comp. Physiol.

[18] See the experiments: Lindauer, M., and Martin, H., 1972, Magnetic effects on dancing bees, in: Animal Orientation and Navigation (S. R. Galler, K. Schmidt-Koenig, G. J. Jacobs, and R. E. Belleville, eds.), NASA SP- 262, U. S. Government Printing Office, Washington, D. C.

[19] See the experiments: Gould, J. L., Kirschvink, J. L., and Deffeyes, K. S., 1978, Bees have magnetic remanence, Science 202: 1026–1028.

[20] See the narrations: Venable, Shannon L., 2011, Gold, A Cultural Encyclopedia, ABC-Clio,LLC, US.

[21] This description on the making of gold was included in *Experiment Solitary, touching the Making of Gold*, Century IV of Francis Bacon's Sylva Sylvarum, or a Naturall Historie in ten Centuries... London, 1627, which was part of Bacon's unfinished Instauratio Magna.

[22] In May 2010, scientists at the University at Buffalo and the U.S. Center for Disease Control published the results of their research on drug delivery dilemmas in vaccines targeting potential viral pandemics in the Proceedings of the National Academy of Sciences. In this study, gold nanorods were successfully used as the delivery agent to inject a single strand RNA molecule proven to trigger an immune response in the body.

"To Attack H1N1, Other Flu Viruses, Gold Nanorods Deliver Potent Payloads." Press release, University at Buffalo, May 24. http://www.buffalo. edu/news/11387

[23] Maiden Flight is a project of Mediated Matter Group, Media Lab, MIT, April of 2019. The description of this project is in Chapter 4.

[24] Gold: causes of color. June 2009.http://www.webexhibits.org/causesofcolor/9.html

[25] See the explanations: Mallan, Lloyd (1971). Suiting up for space: the evolution of the spacesuit. John Day Co. p. 216. ISBN 978-0-381-98150-1.

[26] See the narrations of gold from https://en.wikipedia.org/wiki/Gold

[27] Paul Hardiman, 1997 McLaren F1, Sports Car Market magazine - January 2009， P42-43

[28] Component (a) is a platform, which can be articulated and used to broaden the entrance of the chamber (g), which was designed 13 mm in width. (b) and (c) are the assembled modules, which are used to narrow down the entrance according to the circumstances. It ensured that the bees could find the entrance quickly and that only one bee passed through at a time. Part (d) is the infrared sensor holder with vents on the bottom and the cap (e).

Component (f) shared the same appearance and entrance with the gold container (g) and was used to familiarize the bees with the subsequent experiment in which the feeder (containing sugar solution) was substituted in at the same spot in the beehive. Compartment (g) is the project box, covered by a transparent acrylic cap. Three cavities distributed in the corners of the chamber (g) were used to contain gold elements with ventilating slots in the center. (h) and (i) is the enclosure box and the cover used to embed the Arduino board, LCD, wires, and DC input. An LED wais mounted on the structure to add reference light for better inspection of the bees passing through.

[29] Generally, bee colonies require the use of medicines to treat parasites and other diseases in spring, summer, and autumn. For the purpose of comparison, the applied-gold colony did not use any bee medicine like formic acid fumigant or solution. The experimental bee colony stays in good health.

[30] There was a tray placed on the bottom board(Figure3.29) to collect the dropped gold for recycling use.

[31] The worker bees may have contacts with drones from various colonies, carrying divergent bacteria and guts microbiota and then transferred through the workers to the larvae.

[32] Prototype Design of the Bee Incubator Used in the Experiment. Image Credit: Ri Ren

[33] Upper image: Curvature of Gold-incorporated Comb—the highest curvature presents as red-pink and the lowest as green-blue.

Lower Image: Thickness of Gold- incorporated Comb—the thickest presents as red-pink, and the thinnest as green-blue. Image Copyright: MediatedMatter Group, MIT Media Lab.

[34] Computed Tomography(CT)Scanning Images of Gold-Incorporated Comb in Various angles. Image Copyright: MediatedMatter Group, MIT Media Lab.

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