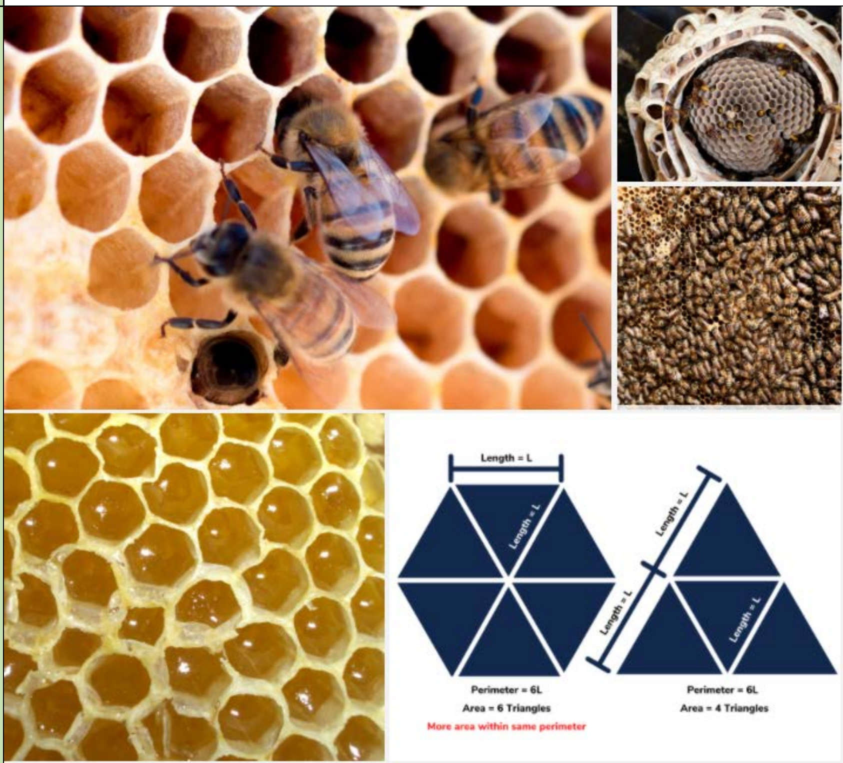
生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	蜂巢結構節省空間而堅固 (Honeycomb structure is space-efficient and strong)
生物系統 LIVING SYSTEM	蜜蜂 *Apis*、馬蜂亞科 Polistinae、胡蜂亞科 Vespinae (Honeybees, polistinae, vespinae)
功能類別 FUNCTIONS	#應付擠壓 #形狀/材料最佳化 #防止溶化 #貯存液體 #Manage compression #Optimize shape/materials #Preventing melting #Store liquids
作用機制標題	蜜蜂與胡蜂採用六角形隔間建造節省空間而堅固的巢室 (Bees and wasps build space-efficient and strong nests using hexagonal cells)
生物系統/作用機制示意圖	

作用機制摘要說明 (SUMMARY OF FUNCTIONING MECHANISMS)

蜜蜂為何適應於以六角形隔間來築巢的這個問題已受爭論長達數世紀之久。在《物種起源》(On the Origin of Species) 一書中，達爾文提出的理論是天擇 (natural selection) 所導致的「蠟質節約」 (an economy of wax)。節儉用蠟對蜜蜂而言是明智之舉，因為牠們需要消耗大約八磅的蜂蜜才能產生一磅的蜂蠟。

但是，數學家花了很多時間研究六角形，才直抵真相。在公元前 36 年左右，一位名喚 Marcus Terentius Varro 的學者首先寫了這個特殊的數學問題，之後被稱作「蜂窩猜想」(honeycomb conjecture)，其指出相比於其他形狀（例如三角形或正方形），「一個六角形能在圓形圖樣中佔據最大空間」。

在 2019 年的一場訪談中，終於證明出蜂窩猜想的數學家 Thomas Hales 說：最終，「六角形蜂窩是以最短周長來貼合最大空間的方法」。從蜜蜂的角度來看，這意味這個結構具有更大容量來存放更多蜂蜜，但卻花費較少能量便得以建造而成。換句話說，達爾文是對的。

空間使用效率 (space efficiency) 並非六角形建築的唯一好處。當六角形堆疊在一起時，它以偏移的方式填充跨度，因此每根「管子」的周圍具有六面短壁，從而使該結構具有很高的抗壓強度 (compression strength)。蜂窩也散熱良好，可防止蠟質結構在炎熱天候下融化。儘管只有少數物種的胡蜂會儲存蜂蜜，但牠們也採用六角形隔間所具有的優勢來築巢。空間效率、強度、以及受控制的熱損失對人類建築亦同樣重要，因此蜂窩毫無疑問地啟發了人類的設計。

科學家與工程師已經將六角形設計融入看似無止盡的應用中，包括輕量建築材料、用於橋樑建構的可撓性面板、吸音 (sound absorption)、光擴散 (light diffusion)、催化劑 (catalyst) 設計、磁屏蔽 (magnetic shielding)、組織工程 (tissue engineering)、甚至製造更好的衝浪板。

達爾文寫道：「只有無趣愚鈍的人，才會在觀察蜂巢精緻的結構及其美麗如一的適應性時，不會產生熱烈的讚賞。」。在研究這些結構超過一個半世紀之後的今日，我們依然有新的發現並欣賞與仿效之。

The question of why honey bees adapted to building their nests from hexagonal cells has been debated for centuries. In On the Origin of Species, Darwin theorized that natural selection led to “an economy of wax.” Being frugal with wax is wise work for a honey bee given they need to consume approximately eight pounds of honey to produce one pound of wax.

But it took mathematicians studying the hexagon shape to make a beeline to the truth. Around 36 B.C., a scholar by the name of Marcus Terentius Varro first wrote about this particular math problem, later dubbed the “the honeycomb conjecture,” by stating that, compared to other shapes such as a triangle or a square, a “hexagon inscribed in a circular figure encloses the greatest amount of space.”

In a 2019 interview, Thomas Hales—the mathematician who finally proved the conjecture—said that ultimately, “A hexagonal honeycomb is the way to fit the most area with the least perimeter.” From a bee’s perspective, that means storing more honey in a larger volume while spending less energy building a structure to contain it. In other words, Darwin was right.

And space-efficiency isn’t the only benefit of building with hexagons. Stacked together, hexagons fill spans in an offset arrangement with six short walls around each “tube,” giving structures a high compression strength. Beehives also dissipate heat well, preventing the waxy structure from melting on hot days. Though few species of wasps store honey, they too build nests using hexagonal cells, taking advantage of these same benefits. Efficiency, strength, and controlled heat loss are all important for human structures as well, so it's no wonder that honeycombs inspire human design.

Scientists and engineers have incorporated hexagonal designs into seemingly endless applications, including light-weight building materials, flexible panels for bridge construction, sound absorption, light diffusion, catalyst design, magnetic shielding, tissue engineering, and even building better surfboards.

"He must be a dull man who can examine the exquisite structure of a comb, so beautifully adapted to its end, without enthusiastic admiration," wrote Darwin. As we examine these structures more than a century and a half later, we're still finding new things to admire and emulate.

文獻引用 (REFERENCES)

「經過數千年的探究，我們已經超越傳統上將超高機械強度作為蜂巢結構唯一特徵的認知，並逐漸加深我們對蜂窩結構多功能設計原理的理解。」

「部分是因為蜂窩的等周 (isoperimetric) 特性，在數個世紀以來，有大量的文獻將蜜蜂稱為幾何學者 (geometer)… 在 18 世紀，蜂窩的數學結構 (mathematical architecture) 被視作天地萬物中偉大的目的論趨勢 (teleological tendency) 之證據。」

"Through thousands of years of exploration, we have gone beyond the traditional awareness of the exceptionally high mechanical strength as the only characteristic of honeycomb structures, and have gradually deepened our understanding of multifunctional design principles for honeycomb structures."

"In part because of the isoperimetric property of the honeycomb, there is a vast literature through the centuries mentioning the bee as a geometer. . . During the 18th century, the mathematical architecture of the honeycomb was viewed as evidence of a great teleological tendency of the universe."

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延伸閱讀

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生物系統延伸資訊連結 (LEARN MORE ABOUT THE LIVING SYSTEM/S)

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https://asknature.org/strategy/honeycomb-structure-is-space-efficient-and-strong/