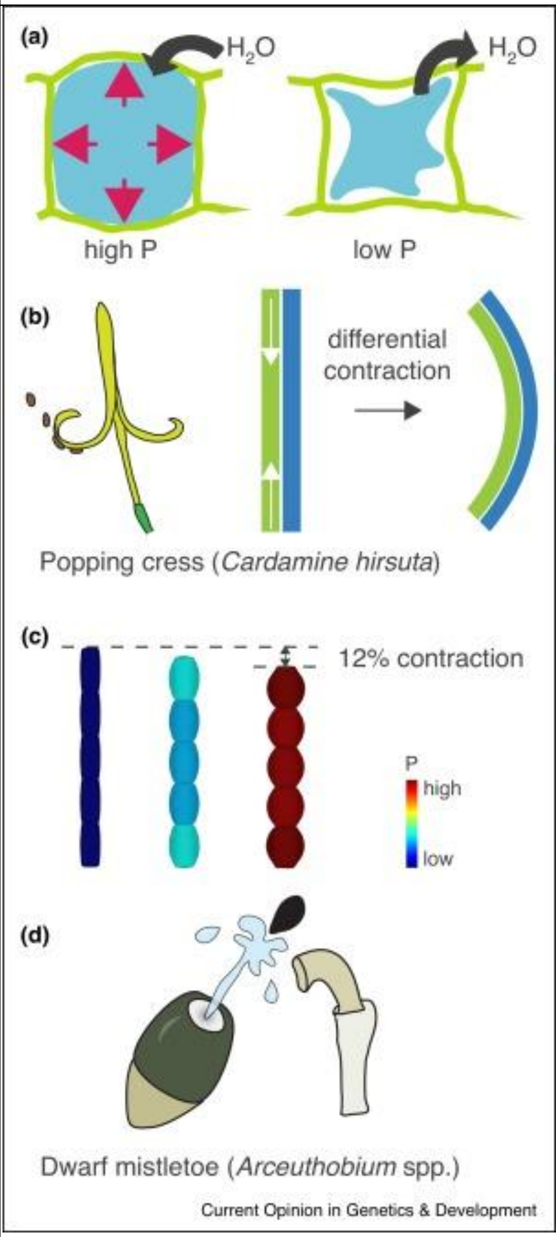
生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	究竟是什麼賦予碎米薺爆炸性彈射力？(What Puts the Explosive Pop in Popping Cress?)
生物系統 LIVING SYSTEM	碎米薺（*Cardamine hirsuta*）
功能類別 FUNCTIONS	#散播種子 #Disperse Seeds
作用機制標題	碎米薺的果莢設計極為複雜，能夠爆裂開啟並將種子遠距離地散播出去。(Popping cress’s fruit pods are complexly designed to explode open and disperse their seeds far and wide.)
生物系統/作用機制示意圖 **(確認版權、註明出處；畫質)**	 出處: https://www.sciencedirect.com/science/article/pii/S0959437X1830011X?via%3Dihub
作用機制摘要說明 (SUMMARY OF FUNCTIONING MECHANISMS)	

導言：

樹木被連根拔起時，其根系錯綜複雜，這些根系不僅為樹木提供養分，還能牢牢固定，使其穩定生長數十年甚至數百年。然而，這些能拯救樹木生命的「錨」同時也限制了樹木（以及所有植物）移動，以主動散播種子。因此，植物發展出各種巧妙的方法來散播種子，以避免與自身後代競爭資源，並擴展其生長範圍。

有些植物透過果實吸引動物來攜帶種子，另一些則依賴風或水來傳播。而一種常見的雜草——碎米薺 (Popping Cress)，則演化出一種能夠以爆炸性方式發射種子的機制，也正因此得名。

碎米薺的種子包裹在細長的橢圓形果莢內。當果莢成熟時，會發出清脆的爆裂聲，隨之迅速裂開，果莢外殼劇烈回縮——就像紙製派對吹笛在停止吹氣時瞬間捲回一樣。在不到半毫秒內，數十顆微小的種子便被猛烈地彈射向四周。這些種子加速至每秒 10 公尺（約每小時 22 英里），最遠可落至 0.3 至 1.25 公尺（1 至 4 英尺）外。

策略：
碎米薺果莢的彈射機制兼具精妙與複雜。果莢由不同層組成，外層細胞柔軟，易於彎曲，而內層細胞則含有堅硬的木質素，使果莢保持筆直。
木質素的「U」形結構支撐內層細胞的底部，當施加足夠的力時，木質素達到臨界點，瞬間克服其剛性，「U」形兩側猛然向下翻轉，導致內層細胞劇烈回縮，果莢瞬間裂開，並以強大彈力將種子拋射出去。這種雙穩態結構類似於玩具彈力手環或金屬捲尺，在外力作用下，能從一種穩定狀態迅速轉變為另一種。
水分在該機制中扮演關鍵角色。隨著果莢生長，外層細胞吸收水分，導致細胞壁膨脹，對內層木質素施加越來越大的壓力，最終達到崩解臨界點，並在 3 毫秒內釋放所有蓄積的彈性能，使果莢猛烈爆開，種子如煙火般被彈射至四周。
潛力：
碎米薺所展現的彈射機制，為高效能彈射裝置及機械結構的設計提供了重要啟發。例如，可應用於仿生機器人抓取系統、微型彈射裝置，甚至在太空探索領域，用於極端環境中的高效物質傳輸。
此外，該機制還啟發了對環境條件的即時監測與回應系統的設計，這對於能源收集及遠程探索（包括外太空任務）具有極大的應用潛力。

Introduction:
The intricate root systems visible at the base of uprooted trees didn't provide those trees only with nutrients. They held them in place, keeping them stable and upright for decades or even centuries. But those life-saving anchors also prevent trees (or any plants) from moving to spread their seeds. So plants have devised inventive ways to disperse seeds—to avoid competing with their own offspring for resources and to expand their range.
Some plants produce fruits to entice animals to carry away seeds. Others rely on winds and water to do the same. One common weed, the popping cress, has evolved a way to launch its seeds in an explosive burst that gives the plant its name.
Its seeds are encased in a slender oblong pod. With a loud pop, the pod splits open and its sheaths curl back rapidly—like a coiled paper party horn when you stop blowing into it. Within half a millisecond, scores of tiny seeds are violently ejected outward in all directions. They accelerate to speeds of 22 miles per hour (10 meters per second) and land 1 to 4 feet (0.3 to 1.25 meters) away.

The Strategy:
The mechanism that accomplishes this effective outburst is as fascinating as it is complex.
The pods have different layers. The outer layer has soft, pliable cells that curl easily. But an inner layer of cells contains a strong, stiff compound called lignin. It resists curling, and the pod stays straight.
The lignin is shaped like a "U" cupping the bottom of the inner-layer cells. But if you apply enough

force on lignin, it reaches a threshold that instantly overcomes its resistance. The two sides of the "U" slap downward and the inner layer suddenly curls open. The structure is called "bistable," because it has two stable states and rapidly shifts between them. It works like a toy snap bracelet or a thin metal tape measure, which can maintain its rigidity until you snap it—and then it bends immediately.

In the case of popping cress, water is the key to building up tension. As the pod grows, water fills the cells in the flexible outer layer causing their cell walls to expand. That substantially builds up tension against the lignin in the inner-layer. In this way, the system builds up potential elastic energy slowly but can release it rapidly.

When the tension on the lignin finally flattens its rigid U-shape, all that pent-up tension is released in just 3 milliseconds and the pod splits open. Pod sheaths curl back with a powerful snap that hurls the seeds with ballistic force up and outward like exploding fireworks.

The Potential:

The popping cress has evolved an effective system to build up potential elastic energy and instantly convert it into strong kinetic energy. Understanding its structural components and the physics underlying how they work together offers lessons on how to design robotic manipulators and ballistic systems.

The plant also inspires design systems that can monitor and respond to environmental conditions and take advantage of the circumstances in exotic locales to produce energy. Such innovations could lead to biomimetic solutions for challenges to remote exploration in unknown locales, including space missions.

文獻引用 (REFERENCES)

「通過結合不同尺度的分析，我們識別出導致爆炸性散播的組織層面力學中的特定細胞特徵。我們證明，在維持膨壓的活細胞因非各向性變形而產生的張力中，*C. hirsuta* 果實積極產生張力。這一異常機制依賴於果實表皮的三維細胞幾何與各向異性細胞壁性質的結合。此外，我們展示了促使組織張力產生的儲存彈性能是通過果瓣捲曲以爆炸性方式釋放的。這一捲曲機制需要在單一細胞層中實現木質素的不對稱分布，並代表了與 Cardamine 屬爆炸性種子散播相關的進化新穎性。」(Hofhuis, H.et al 2016)

「幾何形狀同樣是*C. hirsuta*中迅速釋放儲存能量的關鍵——不僅關乎果瓣的幾何形狀，最終更在於果瓣單一細胞層中細胞壁的幾何結構。果瓣內層（內果皮b）的細胞在其內側因木質化的次生細胞壁而呈現不對稱加厚。木質素在這些細胞中精確沉積，形成由極細鉸鏈連接的三根僵硬杆狀結構。果瓣必須沿其長度捲曲才能達到放鬆狀態，但其橫向曲率卻阻礙了這一過程。打開這些鉸鏈式細胞壁會使果瓣的橫截面變平，從而移除能量屏障，促使彈性能的突然釋放。例如，玩具彈力手環便是依據類似原理運作。」
(Galstyan, A., & Hay, A. 2018)

「詳細了解植物如何控制種子發育、構造散播所需的結構組件、建立分子機械以使種子在適當時刻保持休眠，並監測環境以在最佳時機釋放種子，可能為當前太空任務設計帶來多種解決方案。這可促進設備小型化、更高整合與打包效率、能源效率以及更高的自主性與穩健性。」(Pandolfi, C., & Izzo, D. 2013)

"By combining analyses at different scales of magnitude, we identify specific cellular features that cause the tissue level mechanics underpinning explosive dispersal. We demonstrate that

tension is actively generated in C. hirsuta fruit by the anisotropic deformation of living cells that sustain turgor pressure. This unusual mechanism relies on a combination of three-dimensional cellular geometry and anisotropic cell wall properties of the fruit epidermis. Moreover, we show that the stored potential energy giving rise to tissue tension is released explosively via coiling of the fruit valves. This coiling mechanism requires the asymmetric localization of lignin in a single cell layer of the valve and represents an evolutionary novelty associated with explosive seed dispersal across the genus Cardamine."

"Geometry is also key to the rapid release of stored energy in C. hirsuta — geometry of the fruit valve, but ultimately the geometry of a cell wall in a single cell layer of the valve. Cells in the inner (endocarp b) layer of the valve are asymmetrically thickened by a lignified secondary cell wall on their inner face. Lignin is precisely deposited in these cells to form three stiff rods connected by very thin hinges. The fruit valve needs to coil along its length to reach its relaxed state, but its transverse curvature prevents this. Opening these hinged cell walls flattens the cross-section of the valve, which removes this energy barrier, allowing the sudden release of elastic energy. Toy slap bracelets, for example, work by a similar principle."

"Understanding in detail how plants control the development of seeds, fabricate structural components for their dispersal, build molecular machineries to keep seeds dormant up to the right moment and monitor the environment to release them at the right time could provide several solutions impacting current space mission design practices. It can lead to miniaturization, higher integration and packing efficiency, energy efficiency and higher autonomy and robustness."

参考文獻清單與連結 (REFERENCE LIST) **Harvard 或 APA 格式**

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https://www.youtube.com/watch?v=Fzgmh9jUbyg https://www.inaturalist.org/taxa/55829-Cardamine-hirsuta 以上非 AskNature 的相關連結，屬相關資訊網址
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碎米薺（*Cardamine hirsuta*）擁有細長的橢圓形果莢，當成熟時會劇烈爆裂開啟。果莢的外殼會迅速回縮，並將種子以強大動能向四周拋射出去。

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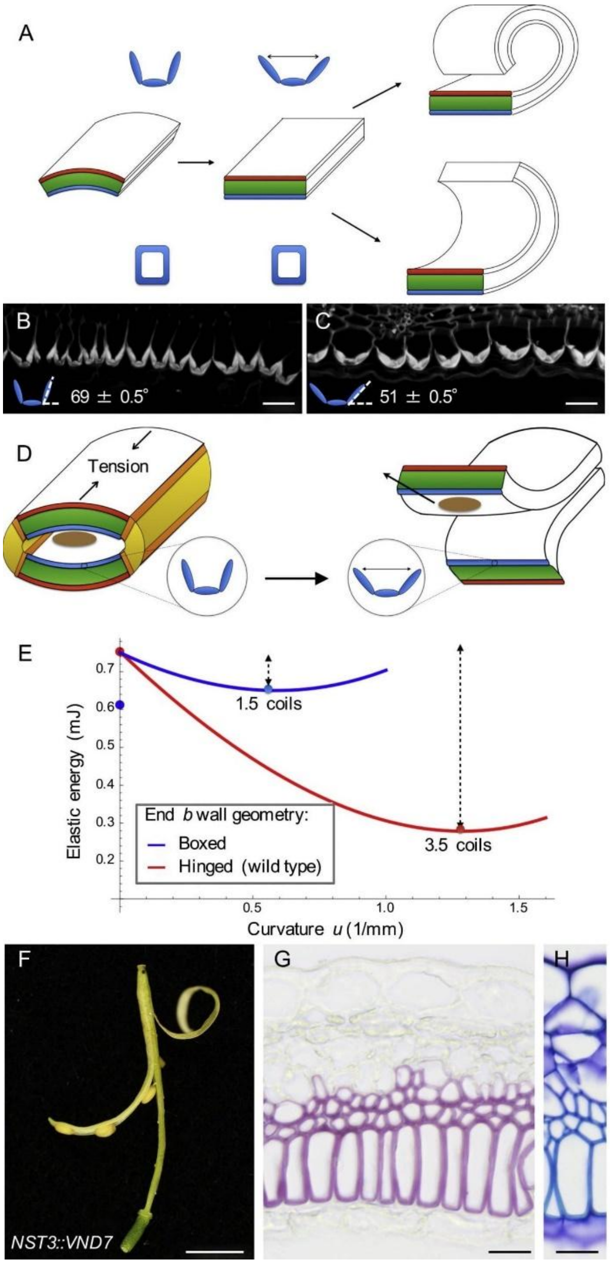

A) 碎米薺的果莢由兩層細胞組成：外層（紅色）由柔軟、有彈性的細胞構成，容易彎曲；內層（藍色）則含有剛硬的木質素，能夠抵抗彎曲，使果莢保持筆直。

B) 木質素（藍色）呈「U」形，環抱著內層細胞的底部。

C) 當木質素承受足夠的壓力時，它會達到臨界點，瞬間克服其剛性，「U」形結構的兩側猛然向下翻轉，內層細胞隨即劇烈捲曲打開。

D) 這種結構被稱為「雙穩態」，因為它具有兩種穩定狀態，並能在兩者之間迅速切換。隨著果莢生長，外層柔韌細胞吸收水分並膨脹，使其細胞壁擴張，對內層木質素施加越來越大的壓力。

E) 這種機制能夠逐步累積潛在的彈性能量，並在關鍵時刻瞬間釋放。

F) 當這一過程發生時，果莢外殼會劇烈爆裂開啟，將種子強力拋射至四周。G 和 H 顯示的是木質素在細胞內的受力影像。比例尺 = 5 毫米。

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