

Perpendicular growth of a tip-growing polymer precipitate on parallel line-patterned surfaces

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(Received 29 December 2024; accepted 26 November 2025; published 7 January 2026)

Growth on surfaces with parallel line patterns typically results in longitudinal alignment, whether in living cells or nonliving crystals. However, unlike many other cells, tip-growing fungal germ tubes grow perpendicular to these line patterns. Here, we show that a recently reported artificial system that mimics the tip growth of germ tubes also exhibits similar perpendicular growth on grooved or ridged surfaces. Our experiments using tip-growing polymer precipitates reveal that the soft growing tip can be partially trapped by substrate patterns, and that the tip can change its growing direction when encountering the surface pattern obliquely. We theoretically rationalize this change in growth direction induced by physical interaction between the soft growing system and the substrate topography. Our physical explanation of the unique growth behavior based on material characteristics without external control suggests a way to achieve embedded physical intelligence in soft mechanical systems interacting with the surrounding objects.

DOI: [10.1103/c93s-mpwj](https://doi.org/10.1103/c93s-mpwj)

Surface topography can direct the growth of various systems. From living cells [1–9] to nonliving crystals [10] and self-assembling particles [11], line patterns, such as parallel grooves or ridges, usually induce longitudinal alignment. For instance, various cells, including epithelial cells, embryonic stem cells, fibroblasts, and neurons, tend to grow or migrate along such patterns [1–9]. In contrast, germ tubes of rust fungi, a large group of plant pathogenic fungi, can sense the surface morphology and grow perpendicular to these patterns [12,13]. This unique behavior results from physical interaction between the germ tube and the substrate, as it is also reproduced on chemically inert replicas of leaves [12,14,15] or even on micropatterned artificial surfaces [13,15,16]. Curiously, we observed similar perpendicular growth on line-patterned surfaces in a recently developed artificial system that mimics the tip growth of germ tubes [17]. In this Letter, we show that surface-morphology-induced perpendicular growth can be explained from the physical characteristics of tip growth.

As illustrated in Fig. 1(a), we extruded cellulose acetate-ethyl lactate-acetone solution containing red dye at a flow rate Q via a nozzle in a water-filled bath [17], over which the patterned substrate was horizontally placed. Either groove- or ridge-patterned hydrophilic foam was used as the substrate. The extruded clear solution gradually solidifies as

water-contact time increases, and eventually turns into an opaque solid (see the Supplemental Material S1 [18]). While the outer layer of the precipitate solidifies, the interior remains liquid, allowing the extruded solution to flow toward the tip. Due to this replenishment, the precipitate continuously elongates from the viscoelastic tip. Upon contacting the substrate, the precipitate continues to grow from the tip along the surface. As indicated in Fig. 1(b), the growth zone (clear region), which marks the location of fresh solution, remains identical over time, maintaining a constant advancing contact angle. Particle tracking velocimetry revealed the streamlines within the growing tip [Fig. 1(c)]. Before following the tip morphology, the streamlines are skewed toward the substrate due to buoyancy, causing the growth zone to form near the substrate. When viewed from the bottom, the precipitate grew with the width identical to the tip diameter, which increased with increasing flow rate. We varied the substrate, width and depth (height) of the grooves (ridges), incident angle, size, and growth velocity of the precipitate to investigate the physical interaction-driven growth direction alignment of the tip-growing precipitates.

Perpendicular growth is observed in the tip-growing polymer precipitate when growing on a substrate patterned with either grooves or ridges. Figure 1(d) shows the precipitate encountering multiple parallel grooves during the growth. Although the precipitate first encounters the grooves obliquely, the growing direction gradually turns perpendicular to the grooves, and is maintained throughout the growth (Supplemental Material S1 [18]). The precipitate exhibits a periodic wavy shape along its length (see the Supplemental Material S2 [18]), resembling the pattern observed in germ tubes [19]. Figure 1(e) shows similar oriented growth of the precipitate on a surface with multiple ridges (Supplemental Material S2

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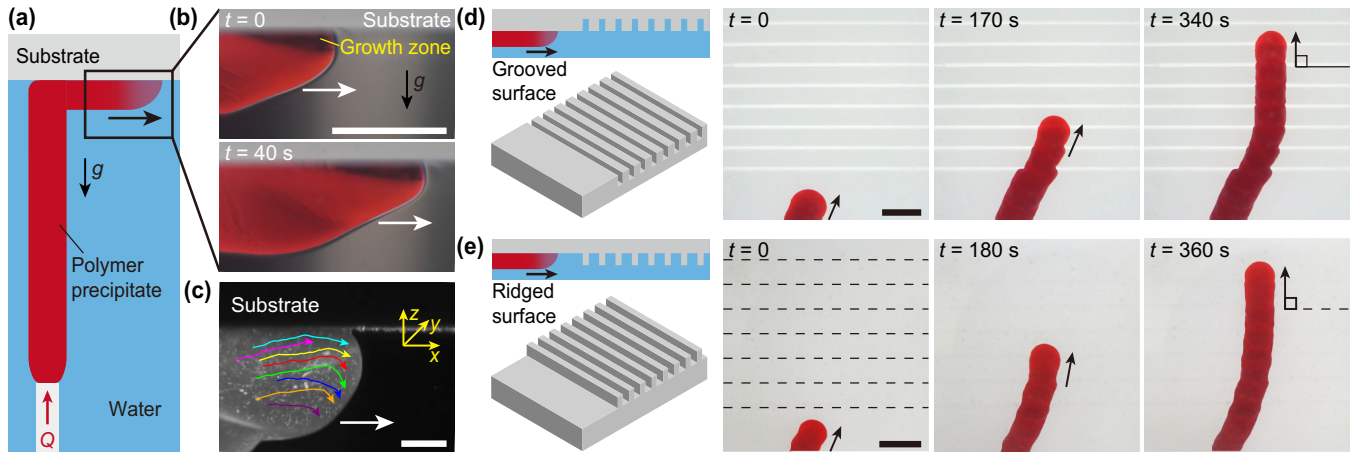


FIG. 1. (a) Schematic that depicts the side view of the experimental setup. (b) Tip growth of the precipitate on an unpatterned melamine foam. (c) Visualized internal flow in the growing tip. Oriented growth of the precipitate on grooved [panel (d)] and ridged [panel (e)] melamine foam. The ridges are denoted with dotted lines in the first image of panel (e). White [panels (b) and (c)] and black [panels (d) and (e)] arrows denote the growing direction of the precipitate. Scale bars: 1 cm [panels (b)–(e)].

[18]). This behavior is observed on two substrates with different stiffness and contact angle, suggesting minimal effect of material properties (see the Supplemental Material S3 and Table S1 [18]). We now rationalize why the growing direction of precipitates becomes aligned perpendicular to the patterns.

We start by experimentally scrutinizing how the growing precipitate interacts with a single line obstacle. The experiment was conducted on a setup similar to Figs. 1(d) and 1(e), but a single groove (ridge) was patterned, and the precipitate encountered the pattern perpendicularly. When the precipitate encountered a single groove, the tip of the precipitate got partially trapped in the groove [Fig. 2(a)]. Specifically, the region near the waist of the tip [blue circle in Fig. 2(a)] is trapped, while the apical region (green circle) crosses the groove. Partially trapped tip results in temporarily reduced width, or necking, but the precipitate continues to grow and recovers its size.

We measured the neck radius R_N varying the groove width w_g , groove depth b , and the precipitate radius R [Fig. 2(a)], to find that R_N decreases with increasing w_g for a given R since the tip gets trapped more in wider grooves [Fig. 2(b)]. Above critical w_g , the precipitate is unable to cross the groove and the whole tip gets trapped (see the Supplemental Material S4 [18]). The effect of b on R_N was found to be small (see the Supplemental Material S5 [18]).

Similar neck formation occurs when the precipitate crosses a ridge [Fig. 2(c)]. The waist of the tip gets trapped in the ridge corner and only the apical part crosses the ridge, and the precipitate recovers its size afterward. The ridge height h exerts pronounced effects on R_N , while the effect of ridge width w_r is small (see the Supplemental Material S6 [18]). The experimental results in Fig. 2(d) show that the neck width decreases with increasing ridge height.

To theoretically determine the trapped portion of the tip, we compare the distance a point in the tip can travel in the direction normal to the pattern with the characteristic length of pattern. During the growth, a material point once at the apex gradually moves along the tip in the meridional direction

before being deposited at the solidifying periphery [17]. We assume that, if the point that has just made contact with the pattern can travel further than the groove width or ridge height before reaching the periphery, this point will pass the pattern. We calculate the travel distance at the growth zone. If a point at the growth zone fails to pass the pattern, the supply of replenishing solution will be cut off and this point will be unable to continue growing in the axial direction. The streamlines within the tip reveal that the velocity components in the xy plane are much greater than the z -directional component at the growth zone [Fig. 1(c)]. Thus, we used the two-dimensional (xy) velocity field in calculating the travel distance.

The travel distance normal to the pattern is the product of the velocity normal to the pattern and the growing time. We first calculate the velocity at each material point of the tip. Every point on the tip moves in the direction normal to the surface [17,20–22]. Knowing the growth direction, the growth velocity of every point at the tip can be obtained from self-similarity. As shown in Fig. 2(e), the growth velocity $u(\phi)$, where ϕ denotes the central angle, is obtained by numerically calculating the distance between the material point positions at two time steps, t_0 and t_1 (see the Supplemental Material S7 [18]). When the tip grows straight, the apex ($\phi = 0$) exhibits the maximum growth velocity U and $u(\phi)$ decreases in the meridional direction, or $u(\phi) = Uf(\phi)$, where $f(\phi) = 0.0547\phi^4 - 0.553\phi^2 + 1$ is a fitted function [Fig. 2(f)] [22,23]. Knowing U and ϕ , we can calculate the normal (u_n) and tangential (u_t) components of the growth velocity with respect to the pattern. For instance, when the tip encounters the pattern perpendicularly [Fig. 2(e)], $u_n(\phi) = u(\phi) \cos \phi = Uf(\phi) \cos \phi$ and $u_t(\phi) = u(\phi) \sin \phi = Uf(\phi) \sin \phi$. For the timescale, we used a characteristic time of tip growth, $\tau = R/U$ (see the Supplemental Material S8 [18]) [17]. This allows us to calculate travel distance $u_n(\phi) \times \tau = Rf(\phi) \cos \phi$ (see the Supplemental Material S9 [18]). According to our model, a portion near the apex has large travel distance and therefore can cross the pattern for a given

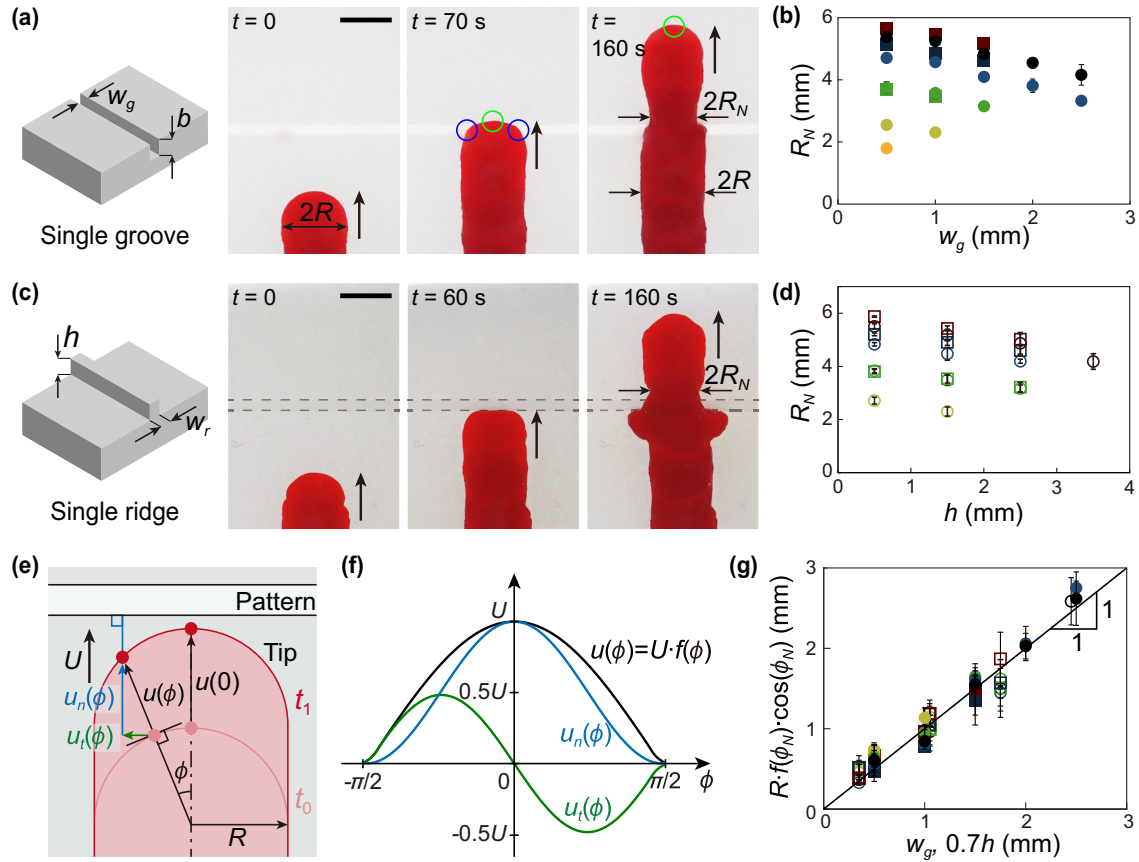


FIG. 2. (a) Tip-growing precipitate passing a single groove. (b) Neck radius R_N vs groove width w_g for precipitates with different sizes. (c) Tip-growing precipitate passing a single ridge. The ridge is denoted with dotted lines. Black arrows denote the growing direction of the precipitate [panels (a) and (c)]. Melamine foam is used as a substrate [panels (a) and (c)]. (d) Neck radius R_N vs ridge height h for precipitates with different sizes. (e) Growth velocities and growing directions at various points in the tip. (f) Calculated $u(\phi)$, $u_n(\phi)$, and $u_t(\phi)$ of a tip-growing system growing perpendicular to the pattern as shown in panel (e). (g) Experimental results shown in panels (b) and (d) are collapsed onto a single line when plotted according to our model. The symbols for different conditions are listed in Table S2 of the Supplemental Material [18] [panels (b), (d), and (e)]. Scale bars: 5 mm [panels (a) and (c)].

precipitate stream, which is consistent with the experimental finding.

We compared the travel distance in the direction normal to the pattern at the neck, $Rf(\phi_N)\cos\phi_N$, with the characteristic length scale of the pattern, where ϕ_N is the central angle at the neck. It is because the neck has the shortest normal travel distance among the points that have crossed the pattern. For the characteristic length scale of the pattern, we used the width w_g for the groove and height h for the ridge. As shown in Fig. 2(g), we found that for precipitates encountering either a groove or a ridge, the experimental results collapse onto a single line with reasonable prefactors, 1 (groove) and 0.7 (ridge).

Now we discuss how the partial trapping of tip by the pattern leads to growth direction change. Although every material point in the tip has different growth direction and velocity, the tip appears to grow in a single direction that cancels out the transverse velocity components, or $\int_{-\pi/2}^{\pi/2} u(\phi)\sin\phi d\phi = 0$. Hence, we assume that a partial blockage of the growing tip causes redistribution of velocity vectors at every material point in the still-expanding region, which chooses a new growth direction that cancels out the transverse velocity components.

Figure 3(a) uses a simple vertical wall that allows us to grasp an essential physics behind such refraction of the growing tip partially blocked by an obstacle. When the growing precipitate partially contacts the obstacle, the part that has not been blocked [white solid line in the rightmost image of Fig. 3(a)] changes the growth direction (see the Supplemental Material S3 [18]). We measured the refraction angle θ_r versus the blocked meridional angle α [Fig. 3(b)]. Our assumption predicts that θ_r satisfies

$$\int_{-\pi/2+\alpha}^{\pi/2} u(\phi)\sin(\phi-\theta_r)d\phi = 0, \quad (1)$$

which well matches the experimental results [Fig. 3(b); see the Supplemental Material S10 [18]].

Based on this model, we rationalize surface-morphology-induced oriented growth of tip-growing systems. When a tip is partially trapped by an obstacle, the growth direction after passing the pattern is determined by the part that is not trapped, which we can calculate using the previously described model. As shown in Figs. 3(c) and 3(d), when the tip encounters the pattern with an incident angle θ_i , if the points with a central angle ranging from $-\pi/2 + \alpha$ to $\pi/2 - \beta$ pass

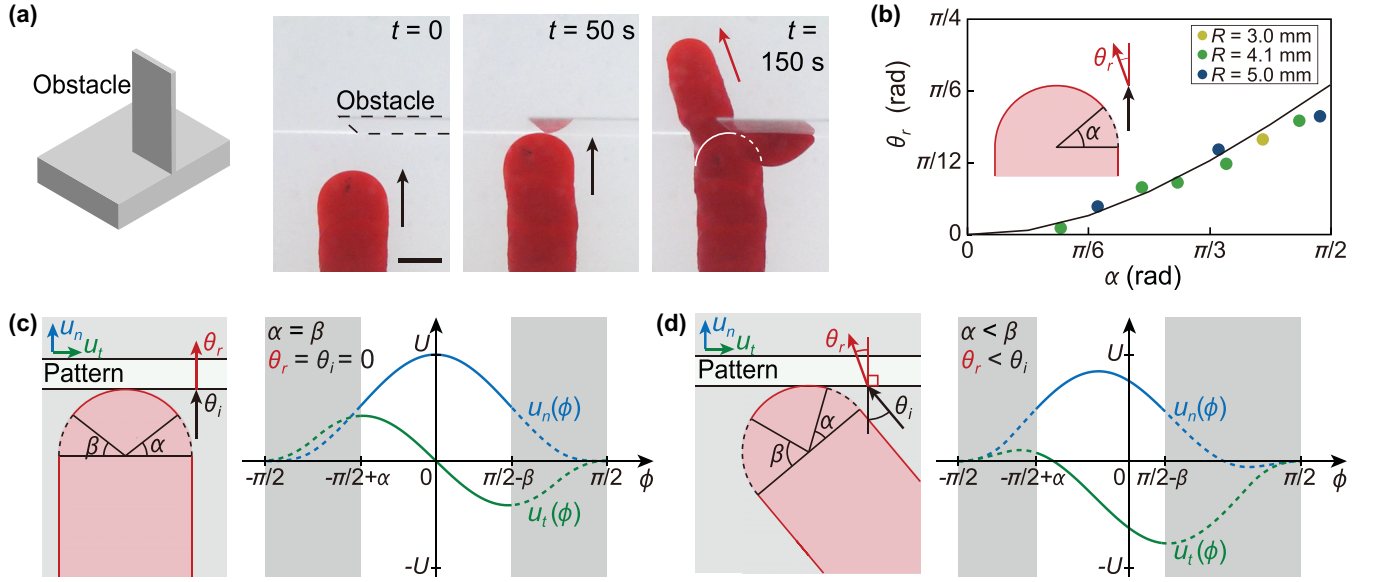


FIG. 3. (a) The growing precipitate changes the growth direction when partially blocked by a vertical wall. Black arrows and red arrow, respectively, denote the growth direction of the precipitates before and after contacting the obstacle. The outline of the obstacle is denoted by black dotted line. Scale bar: 5 mm. (b) Refraction angle after passing the obstacle. Solid line denotes theoretical prediction. Schematic of tip-growing system encountering a pattern perpendicularly [panel (c)] or obliquely [panel (d)], with corresponding growth velocity distributions. Solid lines and dotted lines, respectively, denote the nontrapped and trapped parts [panels (c) and (d)].

the pattern, the refraction angle θ_r is the angle that satisfies the following:

$$\int_{-\pi/2+\alpha}^{\pi/2-\beta} u(\phi) \sin(\phi + \theta_i - \theta_r) d\phi = 0. \quad (2)$$

We consider two cases: the precipitate encountering the pattern perpendicularly or obliquely (see the Supplemental Material S11 [18]).

As shown in Fig. 3(c), when the precipitate perpendicularly encounters the pattern ($\theta_i = 0$), distribution of u_n and u_t is symmetric and the tip gets symmetrically trapped by the pattern ($\alpha = \beta$; see the Supplemental Material S12 [18]). Thus, we get $\theta_r = 0$ in Eq. (2). Therefore, when the tip-growing system perpendicularly encounters the pattern, the interaction between the pattern does not result in growth direction change ($\theta_r = 0$ when $\theta_i = 0$).

Figure 3(d) depicts a tip-growing system obliquely encountering the pattern ($\theta_i \neq 0$). In contrast to when $\theta_i = 0$, velocity distribution is not symmetric as $u_n(\phi) = u(\phi) \cos(\phi + \theta_i)$ and $u_t(\phi) = u(\phi) \sin(\phi + \theta_i)$, which results in asymmetrically trapped residue by the pattern ($\alpha < \beta$; see the Supplemental Material, S12 [18]). Due to this asymmetry, Eq. (2) yields the growth direction change after passing the pattern. Intriguingly, this asymmetry always results in the refraction angle that is smaller than the incident angle ($\theta_r < \theta_i$), since the normal velocity distribution is skewed toward $\phi = -\pi/2$.

When combined, these results rationalize the oriented growth. When a tip-growing system passes multiple line patterns, although the initial incident angle may be nonzero, the refraction angle, which is the incident angle for the next pattern, will gradually converge to zero. Once the incident

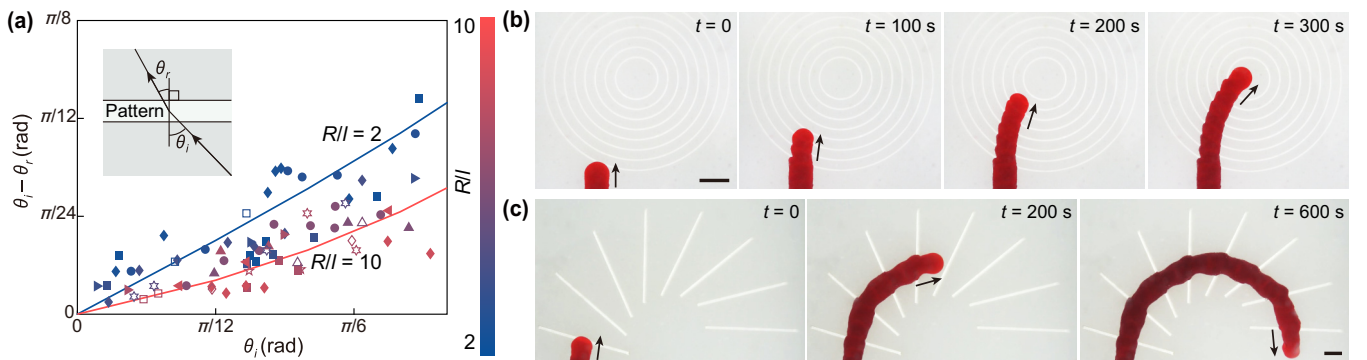


FIG. 4. (a) Growing direction change ($\theta_i - \theta_r$) of a tip-growing precipitate upon passing a line pattern. Filled and empty symbols denote precipitates encountering grooves and ridges, respectively. The symbols for different conditions are listed in Table S2 of the Supplemental Material [18]. (b) Growing precipitate grows toward the center of the bull's-eye pattern. Scale bar: 1 cm. (c) Guiding the growth of precipitate using prepatterned substrate. Scale bar: 5 mm. Black arrows denote the growing direction of the precipitate [panels (b) and (c)].

angle becomes zero, there will be no growth direction change upon passing the patterns.

Now we validate our model by comparing the theoretically predicted growth direction change ($\theta_i - \theta_r$) with the experimental results. We find that two nondimensional variables, R/l and θ_i , determine the growth direction change in the model. The growth direction change is significant when the asymmetry (difference between α and β) is large—when either R/l is small or θ_i is large. Supporting the idea that a partially blocked tip alters growth direction, both groove depth and ridge width, which minimally affect tip trapping, had little effect on the change in growth direction (see the Supplemental Material S13 [18]). As shown in Fig. 4(a), the results from the theoretical model well describe the experimental results.

Exploiting the oriented growth, we can preprogram the growth of precipitate using substrates with specific patterns. First, the growing precipitate can autonomously sense the bull's-eye pattern and change the growing direction to advance toward the pattern's center [Fig. 4(b); Supplemental Material S4 [18]]. In addition, we can precisely control the growth

direction of the precipitate. For example, a substrate patterned with grooves with a specific angular arrangement can guide the precipitate to grow in a U shape [Fig. 4(c)].

Here, we demonstrated the perpendicular growth of tip-growing precipitates on surfaces with line patterns, a behavior reminiscent of tip-growing fungal germ tubes. We also rationalized how the purely physical nature of tip growth can lead to this unique behavior. While our system does not fully replicate the complex features of germ tubes, such as endocytosis or exocytosis [24], it suggests that certain behaviors of systems may emerge from the physical aspects of their growth.

We thank Professor J. Ha for critically reading the manuscript. This work was supported by National Research Foundation of Korea (Grants No. 2018-052541 and No. 2021-017476) via SNU SOFT Foundry Institute. H.-Y.K. acknowledges administrative support from SNU Institute of Engineering Research.

Data availability. The data supporting this study's findings are available within the article.

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