

Fluidic Hysterons and Memory in Flow Networks

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Hysterons provide a minimal description of memory in driven matter: bistable elements with distinct switching thresholds whose collective dynamics generate hysteresis, avalanches, and history-dependent switching. Experimental realizations have so far been dominated by solid-state mechanical systems, where bistability is usually encoded structurally through buckling, snap-through, or geometric incompatibility. Here we realize hysteron physics through a hydrodynamic route. A single elastic fiber anchored in a microfluidic channel becomes bistable through nonlinear elastohydrodynamic feedback: Viscous loading deforms the fiber, deformation reshapes hydraulic resistance, and flow redistribution modifies the loading. This feedback produces a fluidic hysteron whose onset is organized by a cusp catastrophe in geometric control parameters. A parallel bypass channel acts as a geometric load line that reshapes, and can even eliminate, bistability while simultaneously mediating long-ranged hydraulic interactions between fibers. In arrays, varying a single geometric parameter drives a transition from a noninteracting Preisach regime with return-point memory to an interacting regime with configuration-dependent thresholds, mixed-direction switching paths, and projected trajectories that cross the independent-Preisach envelope. These results establish a passive hydrodynamic route to hysteron networks, in which memory emerges from flow-structure feedback and global hydraulic constraints.

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I. INTRODUCTION

Under quasistatic cyclic driving, granular packs, crumpled sheets, amorphous solids, and mechanical metamaterials [1–5] can be trained so that their response depends on loading history rather than instantaneous load. Their deformation is often smooth until interrupted by abrupt, localized rearrangements, such as yield events in disordered solids or snap-through instabilities in architected structures, that reorganize the internal state [6]. Each such rearranging region can be idealized as a bistable switch with distinct up- and down-switching thresholds: a hysteron [7,8]. When many hysterons act independently, their superposition produces classical Preisach hysteresis with ordered nested loops [7,9]. Interactions shift switching thresholds according to the states of other elements, opening non-Preisach pathways, enabling cascades, and, in some systems, breaking the natural componentwise order associated with no passing [10–13]. This viewpoint has elevated hysteresis from a material response to a

design principle: By arranging and coupling hysterons, one can encode counting, memory storage, and reproducible switching sequences as forms of mechanical information processing [12,14–18]. Yet, nearly all experimental realizations remain solid-state systems, where switching is rooted in snap-through, buckling, or geometric incompatibility.

Fluidic networks offer a distinct setting for such questions. Kirchhoff-like hydraulic constraints couple distant elements implicitly, so that a local change in conductance redistributes pressure and flux throughout the network. At the microscale, however, viscous flows obey the linear Stokes equations and are kinematically reversible [19]. History dependence therefore requires additional state variables that do not simply rewind under reversal, for example, viscoelastic stresses, fluid-fluid interfaces, activity, or deformable boundaries [20–28]. Deformable pores and valves can also generate strongly nonlinear and, in some geometries, negative-differential pressure-flow responses for passive flow control [29–32]. Existing microfluidic memory and control strategies have exploited external actuation, membrane valves, or pneumatic control [33–37]. What has remained missing is a passive fluidic counterpart of the hysteron paradigm in which an individual element acquires intrinsic bistability through quasistatic flow-structure feedback and interactions emerge naturally from global hydraulic constraints.

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Here we show that nonlinear elastohydrodynamic feedback between viscous flow and fiber deformation can produce bistability and hysteresis without requiring a structurally bistable element. The minimal realization is a single elastic fiber anchored inside a microfluidic channel under flow-controlled driving: As the imposed flow is ramped quasistatically, the fiber bends and narrows a side gap, redistributing flux between that gap and thin lubrication layers. This closes a feedback loop in which deformation alters the hydraulic resistance, which, in turn, redirects flow and modifies the hydrodynamic loading. We then introduce a parallel bypass channel as a geometric load-line control of width W_2 in parallel with the fiber channel of width W_1 and define the control parameter $\beta \equiv W_2/W_1$. This bypass reshapes, and can suppress, bistability, while simultaneously tuning long-range hydraulic interactions in fiber arrays. By varying this single geometric parameter, we traverse from a noninteracting Preisach regime to an interacting regime with configuration-dependent switching, avalanchelike events, and loss of independent-Preisach monotonicity and projected-envelope confinement [13,38]. The same control parameter therefore reshapes the constitutive response of an individual element and the collective interaction topology of the network.

The long-range interactions in our system parallel those in fluidic memristors [39] and nonlinear resistor networks [40], where coupling is driven by pressure and voltage repartitioning, respectively. Whereas the bistability of the Martínez-Calvo *et al.* memristor arises at the circuit level from compliant volume storage coupled to negative-differential valves and linear hydraulic resistances, each fiber here is already a quasistatic hysteron before network coupling is introduced; its microscale bistability originates directly from fiber geometry via a cusp catastrophe. Altman *et al.* [40] built electronic networks of tunable negative-differential-resistance elements, using both Kirchhoff-mediated effective interactions and programmed neighboring interactions in an electronic analog, whereas our platform provides a direct fluidic analog. Operating in a viscous-dominated flow regime at the microfluidic scale, with characteristic deformation timescales of approximately $\mathcal{O}(10^1 \text{ s})$, our platform enables simultaneous optical state tracking of every element, making it ideal for probing spatiotemporal hysteron interactions.

II. ELASTOHYDRODYNAMIC BISTABILITY

We pattern a single elastic fiber of length L , width b , and height h inside a rigid microfluidic channel of width W and height h_c , anchored at an upstream tilt angle θ_0 against the flow direction [Fig. 1(c)]. As the imposed flow rate Q is ramped quasistatically, we image the fiber deformation and track the tip angle θ . Short fibers ($\lambda = L/W = 0.65$) deform continuously, whereas

long fibers ($\lambda = 1$) undergo a discontinuous snap above a critical flow rate $Q_{\text{cr}}^{\text{up}}$ [Figs. 1(a) and 1(b) and Supplemental Material [41], Sec. 1]. Varying the fiber length L and width b at fixed λ shifts the deformation curves, but preserves the distinction between continuous and discontinuous response, showing that the transition is governed by the geometric ratio λ rather than by absolute size or stiffness.

This distinction arises from the coupling between flow and deformation. Viscous loading bends the fiber and progressively narrows the lateral gap between the fiber and the adjacent sidewall, increasing the hydraulic resistance R_g of the gap pathway, which carries flow q_g . At the same time, fluid passes through thin lubrication layers along the sides of the fiber, whose conductance is approximately constant [Fig. 1(c)]. As the fiber deflects, flow repartitions between these two pathways, changing the pressure drop and traction acting on the fiber. We capture this feedback with a reduced elastohydrodynamic model that couples lubrication-based hydraulic resistances for the two flow paths to an inextensible Euler-Bernoulli beam description of the fiber (Methods and Supplemental Material [41], Sec. 2). Although the fiber itself is not intrinsically bistable, the hydraulic loading depends on its instantaneous shape through the resistance of the narrowing gap, and this nonlinear flow-structure feedback is sufficient to generate bistability. This mechanism differs from conventional fluid-driven snap-through devices, where bistability is already embedded in the elastic structure and the flow merely selects between preexisting states [24,43].

Across a wide range of fiber lengths and widths, the measured tip angle θ collapses onto a single master curve when plotted against the elastoviscous number $\text{El} = \Lambda \mu U_m L^3 / D$, where U_m is the mean velocity in the lubrication layers that sets the viscous loading, μ is the fluid viscosity, and $D = EI$ is the flexural rigidity, with $I = hb^3/12$ the second moment of area and E the fiber modulus. Short fibers trace this curve continuously [Fig. 1(d)], whereas long fibers appear to skip an intermediate range of El [Fig. 1(e)]: the data cluster near $\text{El} \lesssim 1$ in the unsnapped state and $\text{El} \gtrsim 10$ in the snapped state. This apparent gap does not reflect a discontinuity in the imposed flow rate Q ; rather, U_m jumps at snapping as the flow repartitions between the lubrication layers and the narrowing gap, and $\text{El} \propto U_m$ jumps with it. The collapse therefore identifies $\text{El} \approx 1$ as the onset criterion for snapping in long fibers. Using this criterion, and assuming that the fiber remains close to θ_0 immediately before snap up, we infer U_m at onset and map it to a predicted critical flow rate $Q_{\text{cr}}^{\text{up}}$ (Supplemental Material [41], Sec. 3.2). The resulting estimate agrees with the measured snap-up thresholds across different fiber dimensions and anchor angles θ_0 for $\lambda \simeq 1$ [Fig. 1(f)].

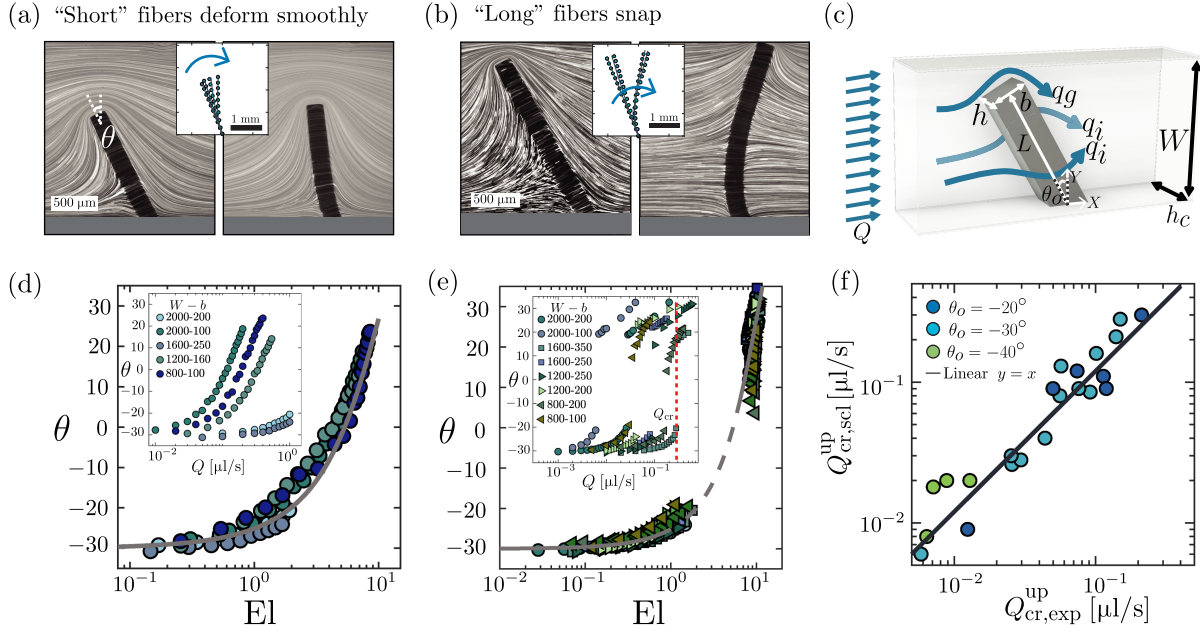


FIG. 1. Elastohydrodynamic snap-through of an anchored fiber. Top-view images: fluorescent tracer streak lines visualize the surrounding flow, while bright-field images are used to extract the fiber centerline and tip angle. (a) A short fiber ($\lambda = L/W = 0.65$, $b = 200 \mu\text{m}$) in a channel of width $W = 2000 \mu\text{m}$ deforms continuously under increasing flow, as characterized by the tip angle θ . (b) A long fiber ($\lambda = 1$, $b = 200 \mu\text{m}$) in the same channel undergoes a discontinuous snap. Insets compare the measured and predicted neutral-axis profiles. (c) Schematic of the device. A fiber of length L and height h is anchored at angle θ_0 in a channel of width W and height h_c . The imposed flow rate Q partitions between the tip gap (flow q_g , gap height h_g) and the thin lubrication layers (flow q_i , layer height h_i). (d),(e) Experimental data collapsed using the elastoviscous number El . Short fibers trace a continuous master curve (d), whereas long fibers split into unsnapped ($El \lesssim 1$) and snapped ($El \gtrsim 10$) branches (e), with the onset of snapping at $El \approx 1$. Symbol color and shape identify the (W, b) combinations listed in the inset legends. Solid curves show the prediction of Eq. (1), and dashed portions denote the unstable branch. Insets show the corresponding dimensional data. (f) Measured snap-up thresholds $Q_{cr,scl}^{up}$ versus the scaling estimate $Q_{cr,exp}^{up}$ for different anchor angles θ_0 and fibers with $\lambda \approx 1$.

The distinction between continuous and discontinuous response follows from the constitutive structure of the elastohydrodynamic coupling. The steady fiber angle obeys the reduced relation

$$\tan \theta = \tan \theta_0 + \frac{El}{6} \tilde{l}_p^3, \quad (1)$$

where $\tilde{l}_p = l_p/L$ is the dimensionless projected fiber length (Supplemental Material [41], Sec. 2). Under flow-controlled driving, solving for the steady response $\theta(Q)$ yields, for long fibers, a discontinuous jump: As Q increases, the lower stable branch terminates at a critical flow rate Q_{cr}^{up} , forcing the system to snap to the upper branch [Fig. 2(a)]. To reveal the full constitutive relation, we invert the problem and compute the flow required to sustain a prescribed configuration, $Q(\theta)$. This uncovers an S-shaped response: two stable branches connected by an intermediate segment with negative slope, $dQ/d\theta < 0$. This negative-differential branch is unstable under flow-controlled driving and therefore inaccessible during

quasistatic ramping; the fiber instead jumps at the two fold points, which define the snap-up and snap-down thresholds, Q_{cr}^{up} and Q_{cr}^{dn} , and hence the hysteresis window $Q_{cr}^{dn} < Q < Q_{cr}^{up}$. This multivalued constitutive law, with two stable branches separated by an unstable negative-slope segment, realizes the constitutive structure of a hysteron under flow-controlled driving [44,45].

The jump amplitude $\Delta\theta$ becomes nonzero only when $\lambda > \lambda_c$, following the scaling $\Delta\theta \sim (\lambda - \lambda_c)^{1/2}$ [Fig. 2(b)]. This square-root onset is the generic scaling of a cusp catastrophe [46,47], in which two fold lines in the (λ, Q) control plane meet at a cusp point (λ_c, Q_{cr}) [Fig. 2(c), inset]. The hysteresis width, $\Delta Q \equiv Q_{cr}^{up} - Q_{cr}^{dn}$, likewise becomes finite only beyond λ_c and grows with increasing λ [Fig. 2(c)]. The critical length ratio λ_c is set by the anchoring angle θ_0 and is essentially independent of the flexural rigidity $D = EI$ over the explored range. Whether a fiber snaps is therefore a geometric question, determined by (λ, θ_0) , whereas the size of the hysteresis window can be tuned by both geometry and stiffness (Supplemental Material [41], Sec. 4).

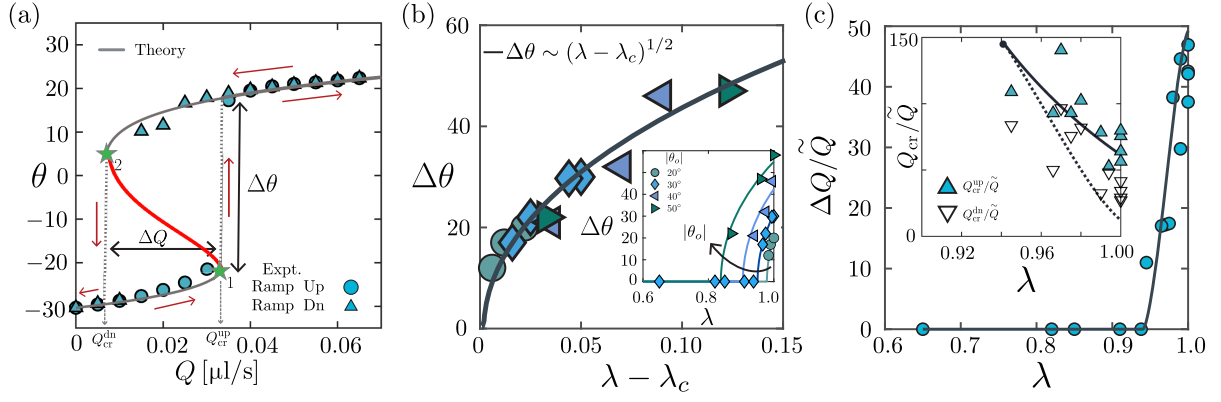


FIG. 2. Constitutive bistability and cusp scaling of a fluidic hysteron. (a) Full constitutive response of a snapping fiber with $\lambda = 1$ and $b = 200 \mu\text{m}$. Under flow-controlled driving, the fiber follows the lower stable branch until the snap-up threshold $Q_{\text{cr}}^{\text{up}}$, then jumps to the upper branch; on ramp down it remains snapped until the lower threshold $Q_{\text{cr}}^{\text{dn}}$, producing hysteresis. The jump amplitude $\Delta\theta$ and hysteresis width $\Delta Q = Q_{\text{cr}}^{\text{up}} - Q_{\text{cr}}^{\text{dn}}$ quantify the bistable response. Circles and triangles distinguish the ramp-up and ramp-down branches. (b) Jump amplitude $\Delta\theta$ as a function of distance from threshold. Data for different θ_0 collapse when plotted against $\lambda - \lambda_c$, following the square-root scaling predicted by the cusp catastrophe analysis. Inset: $\Delta\theta$ vanishes for $\lambda < \lambda_c$ and becomes finite for $\lambda > \lambda_c$. Symbol shape and color denote the anchor angle $|\theta_0| = 20^\circ, 30^\circ, 40^\circ, 50^\circ$. (c) Dimensionless hysteresis width $\Delta Q/\tilde{Q}$ (Methods) as a function of λ . The hysteresis width vanishes below threshold and becomes finite in the snapping regime. Inset: the critical flow rates $Q_{\text{cr}}^{\text{up}}$ and $Q_{\text{cr}}^{\text{dn}}$ form the two fold lines that emerge beyond the cusp point. Filled up triangles and open down triangles denote $Q_{\text{cr}}^{\text{up}}/\tilde{Q}$ and $Q_{\text{cr}}^{\text{dn}}/\tilde{Q}$. Throughout, lines are theoretical model predictions and symbols are experimental data.

III. GEOMETRIC LOAD-LINE CONTROL

To turn the single fluidic hysteron into a tunable circuit element, we add a linear bypass channel of width W_2 in parallel with the fiber channel of width W_1 and define the control parameter $\beta \equiv W_2/W_1$. The limit $\beta = 0$ recovers the isolated hysteron [Fig. 3(a)]. As β increases, an increasing fraction of the imposed flow is diverted through the bypass. Snapping is shifted to larger imposed flow

rates, while both the jump amplitude $\Delta\theta$ and the hysteresis width ΔQ decrease; beyond a critical value of β , snapping is completely suppressed [Fig. 3(a), inset; Supplemental Material [41], Sec. 5]. This behavior follows from the shared pressure drop across the two branches. The total flow satisfies $Q = Q_{\text{NL}}(\Delta P, \text{state}) + Q_L(\Delta P)$, where Q_{NL} is the flow through the fiber channel and depends on both the pressure drop ΔP and the instantaneous fiber state

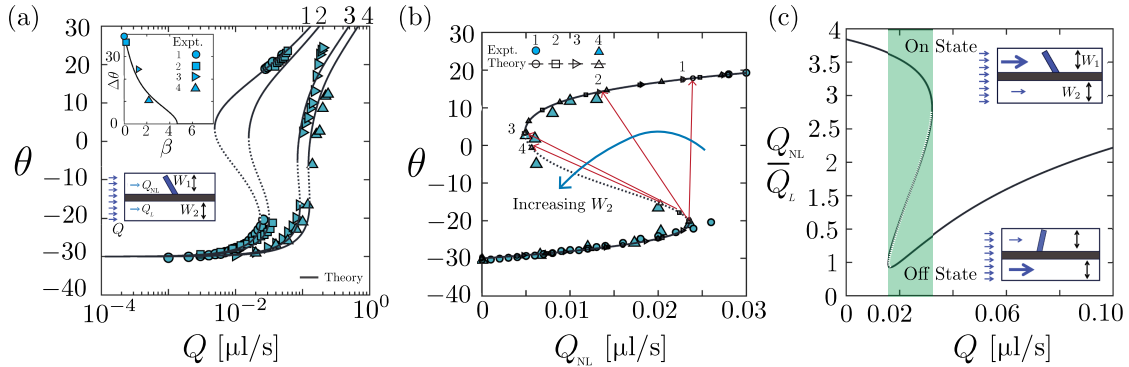


FIG. 3. A geometric load line tunes and suppresses the fluidic hysteron. (a) Flow-deformation curves for increasing bypass width ratio $\beta = W_2/W_1$, for cases 1–4 with $\beta = 0, 0.17, 1.45$, and 3.13 , respectively. Increasing β shifts snapping to larger imposed flow rates and reduces the jump amplitude $\Delta\theta$. Inset: $\Delta\theta$ decreases monotonically with β and vanishes beyond a critical bypass width. (b) Constitutive response plotted against the flow through the fiber channel, Q_{NL} . Solid lines show the theoretical prediction, illustrating how the bypass load line allows the system to traverse the negative-differential branch that is inaccessible in the single-channel limit. Symbols are particle-tracking-velocimetry measurements confirming the reduction of flow through the fiber channel with increasing deformation. (c) Passive flow routing for case 2. Snapping switches the preferred flow path from the fiber channel to the bypass, so that the fiber channel is relatively open (on) before snapping and relatively closed (off) afterward. The green band marks the imposed-flow interval over which both routing states are stable and the flow split is history dependent; the upper and lower schematics show the un-snapped (open) and snapped (closed) states, and arrow thickness indicates relative flow.

(snapped or unsnapped), while the bypass flow is linear $Q_L = \Delta P/R_b(\beta)$. The bypass therefore provides a tunable load line: Its linear flow-pressure relation intersects the nonlinear constitutive response of the fiber channel and selects the operating point. Decreasing the bypass resistance flattens the load line, progressively reducing the jump amplitude; beyond a critical β , the load line intersects the constitutive curve only once, eliminating bistability entirely [Fig. 3(b)].

Functionally, the bypass converts the anchored fiber into a passive flow router. Before snapping, most of the flow passes through the fiber channel; after snapping, the large increase in its hydraulic resistance diverts the flow into the bypass [Fig. 3(c)]. The device therefore switches between relatively open and relatively closed flow states without requiring intrinsic elastic multistability, external actuation, or membrane-based valving [24,27]. As a modular element, it could add passive, history-dependent switching to a larger microfluidic circuit.

IV. INTERACTING FLUIDIC HYSTERONS AND AVALANCHES

Equipped with a tunable fluidic hysteron, we now move from single-element bistability to the collective switching of coupled hysterons [8]. In the no-bypass limit ($\beta = 0$), the two fibers experience the same imposed flow, but do not interact, and therefore behave as independent hysterons [Figs. 4(a) and 4(b)]. Labeling the unsnapped state by 0 and the snapped state by 1, two fibers with nested hysteresis loops (fiber 1 nested within fiber 2) traverse the sequence $00 \rightarrow 01 \rightarrow 11 \rightarrow 10 \rightarrow 00$ under a

full ramp-up–ramp-down cycle, as shown by the transition graph in Fig. 4(b) [48]. The θ_1 – θ_2 phase space reflects this independence: the system visits four well-separated clusters corresponding to the four binary states, and transitions occur along the coordinate axes, indicating that only one fiber switches at a time.

Introducing a bypass channel produces implicit hydraulic coupling through a shared global constraint rather than through explicit mechanical contact. The two fibers remain spatially separated, but the state of either fiber changes the effective resistance of the nonlinear branch and thereby the flow seen by the other. The interaction is long ranged and effectively all to all within the fiber branch, with strength controlled by the geometric parameter $\beta = W_2/W_1$.

For small β , the coupling already produces qualitatively new behavior. When one fiber snaps, $00 \rightarrow 01$, the resistance of the fiber branch increases, diverting flow into the bypass and reducing the flow through the remaining unsnapped fiber. The second fiber therefore snaps only at a larger imposed flow. When it eventually does so, the additional increase in branch resistance reroutes enough flow to unsnap the first fiber, producing an avalanche-like transition $01 \rightarrow 10$; as the flow rate increases further, the first fiber snaps up again arriving at the 11 state [Fig. 4(c)]. In the θ_1 – θ_2 phase space, this appears as a diagonal jump rather than a sequence of axis-aligned transitions. We denote by n the number of such avalanches, with $n = 0$ for the noninteracting limit and $n = 1$ for this weakly coupled regime.

At larger β , corresponding to stronger coupling, a second avalanche appears on ramp down. The unsnapping order

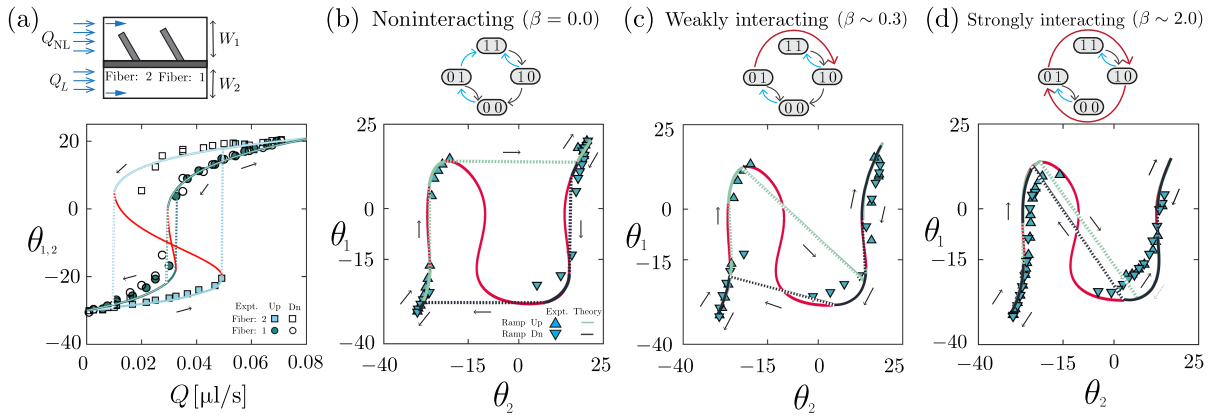


FIG. 4. Transition pathways in a two-hysteron fluidic network. (a) Schematic of two fibers coupled through a parallel bypass channel with width ratio $\beta = W_2/W_1$. The individual constitutive curves are nested: fiber 1 has $L_1/W_1 = 0.96$ and $b_1 = 150 \mu\text{m}$, and its switching thresholds lie inside those of fiber 2, for which $L_2/W_1 = 1$ and $b_2 = 240 \mu\text{m}$. In (b)–(d), states are written s_2s_1 , with $s_i = 0$ unsnapped and $s_i = 1$ snapped; the right digit denotes fiber 1 and the left digit fiber 2. (b) Noninteracting limit ($\beta = 0$). The transition graph follows the classical Preisach sequence $00 \rightarrow 01 \rightarrow 11 \rightarrow 10 \rightarrow 00$, and the θ_1 – θ_2 phase space contains four discrete clusters connected by only axis-aligned transitions. (c) Weakly interacting regime. A single avalanche appears during ramp up, producing the mixed-direction exchange $01 \rightarrow 10$ and a diagonal jump in phase space ($n = 1$). (d) Strongly interacting regime. Avalanches occur on both ramp up and ramp down, producing two diagonal jumps and reversing the unsnapping order relative to the snapping order ($n = 2$). Lines represent the theoretical model and symbols represent experimental data.

is now reversed relative to the snapping order, $11 \rightarrow 10 \rightarrow 01 \rightarrow 00$, and the phase space shows two diagonal jumps [Fig. 4(d)]. In hysteron language, this is an “antiferromagneticlike” interaction: The snapped state of one fiber favors the unsnapped state of the other, producing avalanche-mediated pathways that are forbidden in the noninteracting Preisach limit [13,17,49].

The same circuit balance extends directly from two fibers to an array. Let Q_{NL} denote the common flow through the series fiber branch, R_b the bypass resistance, and $\Delta P_i(Q_{\text{NL}}, s_i)$ the pressure drop across fiber element i , where $s_i = 0$ and 1 are the unsnapped and snapped states. Including the state-independent pressure drop $\Delta P_l(Q_{\text{NL}})$ of the remaining fiber-channel segments, flow and pressure continuity give

$$R_b(Q - Q_{\text{NL}}) = \Delta P_l(Q_{\text{NL}}) + \sum_{i=1}^N \Delta P_i(Q_{\text{NL}}, s_i). \quad (2)$$

When $\beta = 0$, equivalently, $R_b \rightarrow \infty$, the imposed flow passes through the fiber branch, $Q_{\text{NL}} = Q$, and the effective switching points in Q are independent. For finite β , switching any fiber changes the right-hand side of

Eq. (2); the network then rebalances Q_{NL} for every fiber, making the effective switching points in the imposed total flow configuration dependent. The mixed-direction, counterswitching transition $01 \rightarrow 10$ is the minimal two-element instance of this mechanism. Experiments and calculations for larger arrays are reported below and in Supplemental Material [41], Sec. 6.

V. COLLECTIVE SWITCHING AND NON-PREISACH PATHWAYS

To probe how hydraulic coupling reorganizes collective switching, we study arrays of $N = 10$ fibers in series under nested write-read protocols [Figs. 5(a) and 5(b)]. We denote the full measured fiber-state configuration by $\mathbf{s} = (s_N, \dots, s_1)$, with $s_i = 0$ and 1 for the unsnapped and snapped branches. The averages $\langle \theta \rangle$ and $\langle s \rangle = N^{-1} \sum_i s_i$ provide compact collective readouts, while the five- and ten-fiber transition graphs in Supplemental Material [41], Figs. S12 and S14 resolve the complete binary configurations.

In the independent-Preisach limit, increasing Q switches individual bits from 0 to 1, so successive configurations remain ordered componentwise and projected nested

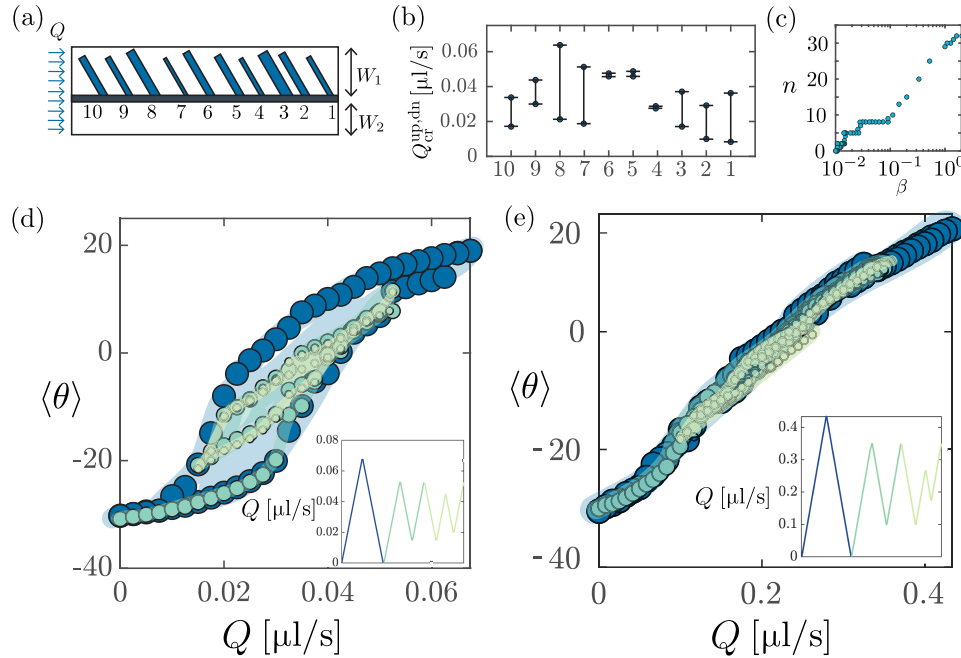


FIG. 5. Collective memory in arrays of fluidic hysterons. (a) Schematic of an array of $N = 10$ fibers connected in series with a parallel bypass channel. (b) Measured snap-up and snap-down thresholds, $Q_{\text{cr}}^{\text{up}}$ and $Q_{\text{cr}}^{\text{dn}}$, for each of the ten fibers, showing the spread of individual switching flow rates. (c) Calculated number of avalanches n as a function of the bypass width ratio β . Stronger interactions produce progressively more avalanches. (d),(e) Symbol color denotes the drive cycle: cycle 1 (dark blue) traces the outer major loop, and cycles 2 (teal) and 3 (light green) are successively nested minor loops driven between the turning points shown in the corresponding inset. The insets show the imposed quasistatic flow protocol $Q(t)$ in the same cycle colors. (d) Measured mean fiber angle $\langle \theta \rangle$ under nested write-read protocols in the noninteracting limit ($\beta = 0$). Minor loops remain enclosed within the major loop. (e) Measured mean fiber angle $\langle \theta \rangle$ for an interacting network ($\beta \approx 0.3$). The projected trajectory crosses the cycle-1 envelope, demonstrating loss of independent-Preisach envelope confinement. Supplemental Material [41], Fig. S14 gives the corresponding state-resolved ten-bit path and reveals avalanchelike, mixed-direction multibit events.

trajectories remain confined within the outer envelope. Writing $\mathbf{s} \leq \mathbf{s}'$ when $s_i \leq s'_i$ for every fiber, this is the natural componentwise order associated with no passing in the noninteracting system. Bypass coupling removes this simple ordering. In the five-fiber experiment, the avalanchelike up-ramp event $00011 \rightarrow 00100$ is mixed direction and net dissonant: Fibers 1 and 2 release, while fiber 3 snaps, so the number of snapped fibers decreases from two to one as Q increases. The interacting ten-fiber path contains the up-ramp changes $0000001000 \rightarrow 0100000001$ and $1110101111 \rightarrow 1111001111$ and the down-ramp sequence $1100000001 \rightarrow 1000001001 \rightarrow 0100001001$. These are avalanchelike, mixed-direction multibit events between successive steady configurations under quasistatic driving. Each ten-fiber event contains counterswitching and connects configurations that are incomparable under the componentwise order, but none are net dissonant: the snapped-fiber count either follows the drive or remains unchanged. Together with the cycle-1 projected-envelope crossing in Fig. 5(e), these state-resolved paths demonstrate configuration-dependent thresholds, counterswitching, and loss of the monotone path and envelope confinement of independent-Preisach hysterons.

The full-state comparison provides a complementary result: every repeated extremum in the state-resolved five- and ten-fiber experiments recovers the same binary configuration (no differing bits, equivalently, zero Hamming distance, $d_H = 0$; Supplemental Material [41], Figs. S12 and S14). The bypass ratio β therefore tunes the topology of collective switching paths while retaining reproducible end point recovery in the protocols tested.

Supplemental Material [41] extends this comparison across system size. Five-fiber experiments and calculations provide an intermediate state-resolved bridge between the two-fiber mechanism and the ten-fiber experiment, while a structured $N = 100$ calculation shows that the same circuit balance and incremental quasistatic procedure remain tractable in dense arrays and maps the resulting projected collective response.

VI. DISCUSSION

Together, these results establish a fluidic realization of the hysteron framework developed in solid-state mechanical systems [5,8]. Earlier studies of deformable pores and membrane valves established passive nonlinear flow control, including negative-differential pressure-flow responses, but did not develop these elements as reproducible quasistatic memory networks [29–32]. More recently, Altman *et al.* [40] realized collective memory states and avalanches in an electronic analog of bistable flow networks, while Martínez-Calvo *et al.* [39] developed fluidic memristors in which hysteresis emerges at the circuit level from compliant volume storage coupled to nonlinear and linear hydraulic resistances. By contrast, in

our system, a single fiber already acts as a hysteron. Its bistability is geometric in origin: The snapping transition has the structure of a cusp catastrophe, controlled by the length ratio λ and anchor angle θ_0 , while stiffness sets the flow scale and tunes the width of the hysteresis window. Cusp catastrophes are generic organizing structures for the onset of bistability in nonlinear systems, from mean-field first-order transitions to optical bistability [46,50]; here, this structure emerges from the coupling between viscous flow and elastic deformation rather than from an intrinsic elastic energy landscape.

The fluidic setting also changes the nature of interactions between hysterons. In solid-state systems, coupling is typically mediated by short-ranged elastic stresses or contact forces. Here, a local change in resistance redistributes pressure and flux throughout the network through Kirchhoff-like hydraulic constraints. In the presence of a bypass, this leads to an all-to-all coupling within the fiber branch, with interaction strength controlled by the single geometric parameter $\beta = W_2/W_1$. The resulting antiferromagneticlike interaction, in which snapping of one fiber disfavors snapping of the others, generates state-dependent thresholds, avalanchelike events, and mixed-direction switching paths that are forbidden in the independent-Preisach limit. The measured return points nevertheless recover exactly in every five- and ten-fiber protocol tested. The interactions therefore alter switching-path topology and projected-envelope geometry without establishing failure of strict return-point memory. This coexistence is consistent with interacting-hysteron systems in which complex pathways and avalanches can occur while return-point recovery remains robust [11–13,38].

Our fluidic setting therefore provides a tunable, optically resolved realization of interacting-hysteron physics, in which interaction strength is set by geometry rather than by local contact mechanics or material disorder. The coupling further depends on the driving mode: changing the control variable alters the single-fiber load line and stability problem, so pressure-controlled switching thresholds and accessible branches cannot, in general, be inferred unchanged from the flow-controlled response. Under the imposed-flow protocol used here, series elements carry the same prescribed flow and become independent when the bypass is removed. Under imposed total pressure, a state change alters the common flow through all series elements and therefore couples them even as $\beta \rightarrow 0$. An uncoupled pressure-driven reference would instead place the elements in parallel, so each branch retains the same prescribed pressure drop. This control-mode dependence is analogous to that reported for arrays of inflatable elements [44].

The ability to tune both the local constitutive response and the interaction strength using geometry suggests a broader design principle for memory-bearing flow networks. Embedding fluidic hysterons in networks beyond a simple linear series, such as loops, trees, or disordered

graphs, would introduce topology-dependent interactions and provide experimental access to questions about how network architecture shapes transition pathways, frustration, and memory capacity [51–53]. In this sense, fluidic hysteron networks provide a complementary experimental setting for the statistical physics of interacting hysterons, with interactions mediated by conservation laws rather than elastic contact or stress redistribution.

Finally, this system provides a minimal physical analog of living flow networks, which couple local mechanical adaptation, such as compliance and shear-dependent remodeling, to global hydraulic constraints [54–57]. Real biological networks are far richer, involving active remodeling, growth, and biochemical signaling [58,59] and, in some cases, store history directly in their architecture, as in the encoding of past stimuli in the tube-diameter hierarchy of *Physarum* [60]. Yet, our results show that passive ingredients alone suffice to generate history-dependent collective response, identifying flow-structure feedback as a sufficient mechanism for memory in fluidic networks. A central open question is, therefore, which aspects of memory and adaptation in living and soft adaptive flow networks genuinely require active control, and which are already latent in the passive mechanics of coupled deformable elements under global constraints.

VII. METHODS

A. Device fabrication

Experiments were performed in polydimethylsiloxane (PDMS) microfluidic devices fabricated by standard soft lithography. Channel molds were patterned on silicon wafers using a laser writer. A PDMS prepolymer and curing agent mixture (10:1 by weight) was poured onto the mold and cured for 4 h at 65 °C. The cured PDMS slab was then bonded to a glass slide spin-coated with a thin layer of uncured PDMS mixture. The channels used in this study had widths $W = 800, 1200, 1600$, and $2000 \mu\text{m}$ and a height $h_c = 80 \mu\text{m}$ [Fig. 1(c)].

Deformable hydrogel fibers were fabricated *in situ* using stop-flow lithography [61]. One wall of each channel contained PDMS microposts that served as anchors for the fibers. A photosensitive solution of polyethylene glycol diacrylate, Milli-Q water, and photoinitiator was injected into the channel using a syringe pump. The flow was then stopped and the solution exposed to masked ultraviolet light, photopolymerizing the hydrogel structures. This procedure yielded fibers with Young's modulus $E = 0.30 \pm 0.04 \text{ MPa}$, height $h = 70 \mu\text{m}$, width $b \in [100, 400] \mu\text{m}$, and length ratio $\lambda = L/W \in [0.65, 1.00]$. Fibers were anchored at upstream tilt angles $\theta_0 \in \{-50^\circ, -40^\circ, -30^\circ, -20^\circ\}$. Some devices additionally contained a parallel bypass channel of width W_2 alongside the fiber channel of width W_1 , characterized by the width ratio $\beta = W_2/W_1$ [inset of Fig. 3(a)].

B. Flow control and imaging

The volumetric flow rate Q was imposed using a Harvard Apparatus syringe pump. The prescribed path was followed sequentially as one uninterrupted increasing-decreasing protocol: Successive set points were approached from the preceding point, without resetting the device between measurements, and a reset occurred only when the programmed protocol itself returned to $Q = 0$. At each set point, the system was allowed to reach steady state before θ was recorded. Quasistatic ramps in the range $Q \in [10^{-3}, 10^0] \mu\text{L s}^{-1}$ ensured $\text{Re} \ll 1$. The memory therefore resides in the occupied stable branch rather than in fluid inertia or a transient flow state. Fiber deformation was imaged in top view at 1 Hz using bright-field microscopy. The tip angle θ was extracted from binary masks of the fiber centerline using custom image-analysis code based on intensity thresholding. Uncertainty was estimated from repeated segmentation and calibration.

C. Reduced elastohydrodynamic model

The fiber was modeled as an inextensible Euler-Bernoulli beam with linear constitutive law $M = EI\kappa$, clamped at the anchor and free at the tip. The surrounding flow was decomposed into parallel pathways: a variable-height tip-gap pathway with hydraulic resistance $R_g(\theta)$ and constant-thickness lubrication-layer pathways with resistance R_l . Each pathway was described using lubrication approximations appropriate for slender gaps (Supplemental Material [41], Sec. 2). Flow partitioning between these pathways determined the pressure and shear tractions acting on the fiber, which were projected onto an effective distributed load in the beam equation. Steady states were obtained by solving the coupled nonlinear elastohydrodynamic system for the tip angle θ and, when needed, the full fiber shape. Stability was assessed by identifying segments of the constitutive curve with $dQ/d\theta < 0$.

D. Quasistatic array calculation

For an N -fiber array, the stable single-fiber constitutive branches were assembled through Eq. (2). The imposed flow rate was advanced quasistatically in small increments along the prescribed ramp-up–ramp-down or nested protocol. At each step, the circuit equation was solved self-consistently for Q_{NL} and the stable branch occupied by each fiber, using the configuration at the preceding step to retain the loading history. Once the steady configuration was obtained, the full state vector, switching direction, and imposed Q were recorded. Abrupt changes involving multiple fibers between successive steady configurations were counted as avalanches. This incremental quasistatic procedure generated the 2-, 5-, and 100-fiber calculations. Full equations and parameter ranges are given in Supplemental Material [41], Sec. 6.

E. Elastoviscous number and geometric parameters

The length ratio is $\lambda = L/W$. A geometric prefactor $\Lambda = [3b(h_c + h)]/h_i^2$ collects the remaining geometric parameters. The elastoviscous number is defined using the mean velocity in the lubrication layers, U_m , as $El = (\Lambda\mu U_m L^3)/D$, where $D = EI$ is the flexural rigidity. For long fibers, U_m was inferred from the hydraulic partition model using the measured flow rate Q and device geometry. A corresponding characteristic flow scale, $\tilde{Q} := (6q_i)/El = 3Dh_i/\Lambda\mu L^2$, combines the elastic and viscous contributions into a single control scale used to nondimensionalize the hysteresis width in Fig. 2(c) (Supplemental Material [41], Sec. 2).

F. Transition graphs and state labels

Each fiber was assigned a binary state $s_i \in \{0, 1\}$ according to whether θ_i lay on the lower (unsnapped) or upper (snapped) branch. Experimental states were assigned by following branch continuity and each fiber's measured switching events rather than by imposing a universal 0° angle cutoff; this accounts for shorter fibers that snap down slightly below vertical. The switching thresholds Q_{cr}^{up} and Q_{cr}^{dn} were determined from ramp-up and ramp-down experiments. The diagrams in Supplemental Material [41], Figs. S12 and S14 were constructed by listing the stable configurations visited along the programmed protocols and the directed changes under increasing or decreasing Q . Arrows that contain several bit changes connect successive steady configurations at finite increments of imposed flow and are described as avalanchelike multibit events. At each repeated reversal value Q_r , the first and return configurations were compared by counting the fiber states that differ, quantified by the Hamming distance $d_H(\mathbf{s}, \mathbf{s}') = \sum_i |s_i - s'_i|$. The mean angle $\langle \theta \rangle = N^{-1} \sum_i \theta_i$ and mean binary state $\langle s \rangle = N^{-1} \sum_i s_i$ were used as collective readouts, and projected-envelope crossing was assessed from the mean-angle response.

Note added. Recently, Stinissen *et al.* reported two intrinsically bistable inflatable membranes coupled by an equal-volume-change constraint, with preset volume selecting the pair's state-diagram topology and whether avalanches occur [62]. By contrast, the hysterons here are elastic fibers that are not intrinsically bistable: Bistability arises from through-flow elastohydrodynamic feedback and interactions from bypass-mediated hydraulic redistribution in a flow network.

DATA AVAILABILITY

The data and analysis code underlying this study are available in a public repository [63].

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