

CAPTURE & FILTER

Micro-Scale Fluid Control Without Moving Parts

How biology routes and processes fluids using surface geometry alone

5	3	3–5	5
convergent strategies	principle clusters	TRL range	featured strategies

PROBLEM FRAMING

Lab-on-chip devices require fluid control at the microscale. Biological systems — plant vascular networks, insect tracheae, kidney nephrons — route, filter, and concentrate fluids without pumps or valves, using surface energy, osmotic gradients, and geometric constrictions.

Application domains: medicine, water_management, materials

Principle cluster: microfluidics, capillary action, wettability gradient

Physics & Mechanism

Underlying physics

[DRAFT] Fluid transport at the microscale is governed by the balance between surface tension forces and viscous resistance. In a cylindrical capillary of radius r , capillary pressure $\Delta P = 2\gamma \cos \theta / r$ (Young-Laplace equation). For $r = 10 \mu\text{m}$ and $\gamma = 72 \text{ mN/m}$ (water-air), $\Delta P \approx 14 \text{ kPa}$ — driving flow without external pressure. Biological vascular networks exploit this: plant pit membranes ($0.1\text{--}10 \mu\text{m}$ pores) generate capillary driving pressures sufficient to lift water 100+ m. Passive valving uses surface-energy barriers: a hydrophobic patch at a channel junction prevents aqueous fluid from advancing until sufficient pressure accumulates. Constrictions create flow-dependent pressure drops (Hagen-Poiseuille: $\Delta P = 8\eta LQ / \pi r^4$) — acting as flow resistors that balance multi-channel networks. Lotus leaf-inspired wettability gradients drive droplet transport without enclosure in microchannels. Spider silk fiber-knot arrays implement gradient-driven droplet transport at open surfaces. [END DRAFT]

Biological Strategies

Capture, Absorb, or Filter Liquids *Cotula fallax* (buttonweed plant) · TRL 3/9 · 36 genera

Cotula fallax, a fog-harvesting plant, utilizes fine hair fibers covering its leaves and stems to passively collect water droplets from fog. These trichomes are extremely thin biological filaments that protrude from the leaf epidermis, creating a hierarchical surface structure. When fog passes through the plant canopy, water droplets contact these hair fibers and coalesce due to capillary forces a...

Design principle: Engineer fog collection structures using arrays of extremely fine synthetic fibers (hair-like elements) arranged in harp or grid configurations with optimized spacing and orientation. Prioritize fiber

Capture, Absorb, or Filter Liquids Hummingbirds

This hummingbird tongue operates through a passive mechanical trap mechanism fundamentally different from capillary tube dynamics. As the forked tongue tip enters nectar, the structure expands and opens, allowing fluid to be drawn into grooves along the tongue surface. Upon withdrawal from the flower, the tongue tip contracts and closes, trapping the captured liquid within the channel structure. T...

Design principle: The hummingbird tongue demonstrates a passive fluid-capture system that could inspire engineered solutions for handling low-viscosity liquids without active pumping mechanisms. The key design principl

Capture, Absorb, or Filter Liquids Pitcher plant (*Nepenthes* species) and similar carnivorous plants with directional wettability gradients · TRL 5/9 · 36 genera

Pitcher plants (*Nepenthes*) feature specialized inner pitcher wall tissues with microscopic wax crystal structures arranged to create spatially graded wettability—superhydrophobic near the rim transitioning to superhydrophilic lower regions. This gradient in the epicuticular wax layer of the pitcher walls exploits molecular-scale asymmetry to generate capillary-driven, unidirectional liquid transpo...

Design principle: Engineer surfaces using graded wettability inspired by pitcher plant tissue architecture: combine superhydrophobic outer layers with superhydrophilic inner cores, mimicking the wax-to-mucilage transit

Capture, Absorb, or Filter Liquids *Welwitschia*

Welwitschia mirabilis inhabits one of Earth's driest regions and has evolved leaf morphology and surface characteristics which function as a moisture-harvesting system. This plant's two long leaves develop grooved or channeled surfaces that capture water droplets from fog, dew, and occasional mist. Such structural features create pathways along the leaf surface that guide accumulated moisture towa...

Design principle: Engineers designing water-harvesting systems in arid regions can apply *Welwitschia*'s leaf-channeling strategy by incorporating grooved or ribbed surfaces that guide condensation and moisture toward co

Distribute Solids Wood ferns

Wood ferns generate spores within sporangia, specialized capsules containing a ring of cells that control spore dispersal. As water within these cup-shaped cells gradually evaporates, the remaining liquid occupies an increasingly curved meniscus. That curvature generates mounting surface tension forces that pull inward on the cell walls. This cells can sustain this tension only to a critical thres...

Design principle: This system demonstrates how phase change and surface tension can be engineered as a passive energy storage and release mechanism. Water acts as both the working fluid and energy source, with evaporat

EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

<https://atlasofnature.org/challenge/microfluidics-passive-control>

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