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Gallery of Fluid Motion

Hydrodynamics of marbling art

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Marbling is an ancient art form that has evolved across diverse cultures [1–3]. It has historically been used to decorate paper for bookbinding and preventing forgery [4]. Two traditional marbling styles are *ebru*, which uses thickened viscous water, and *suminagashi*, which uses unthickened plain water [5]. A key distinction between the two is that the ebru style is more structured with vibrant colors, while the suminagashi style is more flowing, with minimalist design. Remarkably, both practices have remained relatively unchanged for centuries. We focus on ebru-style marbling (Fig. 1), where marblers float paints on the surface of a viscosified water bath and use various thin tools (e.g., stylus, rake, and comb) to craft one-of-a-kind patterns (Fig. 2). These patterns are then printed onto mordanted paper, which is coated with alum solution for better color adhesion [5]. Modern marblers often use water mixed with carrageenan powder for the bath and diluted fluid acrylics for the paint, in order to marble on paper, fabric, wood, or any other surface imaginable.

Despite its rich historical lineage and aesthetic appeal, the fluid dynamics governing this art form has yet to be studied in detail. We celebrate the *marbelous* hydrodynamics of marbling art through two characteristic behaviors [6]: The physics of spreading, which sets the initial color distribution via a balance between interfacial and inertial/viscous forces, and the physics of mixing, which allows delicate and complex patterns to emerge in response to the dragging of thin tools through the surface. We showcase examples of marbling patterns (Fig. 1) and highlight the role of interfacial tension and viscosity in marbling art.

Interfacial tension underpins the physics of spreading. In marbling, three interfacial tensions are involved: between the paint and air, the paint and bath, and the air and bath [Fig. 3(a)]. Even though the added paint is slightly denser than the bath, these tensions are strong enough to prevent it from sinking. Instead of sinking, the paint spreads across the surface, reducing its gravitational potential energy [Fig. 3(b)]. The surface tension of the paint may be reduced by adding surfactants, promoting

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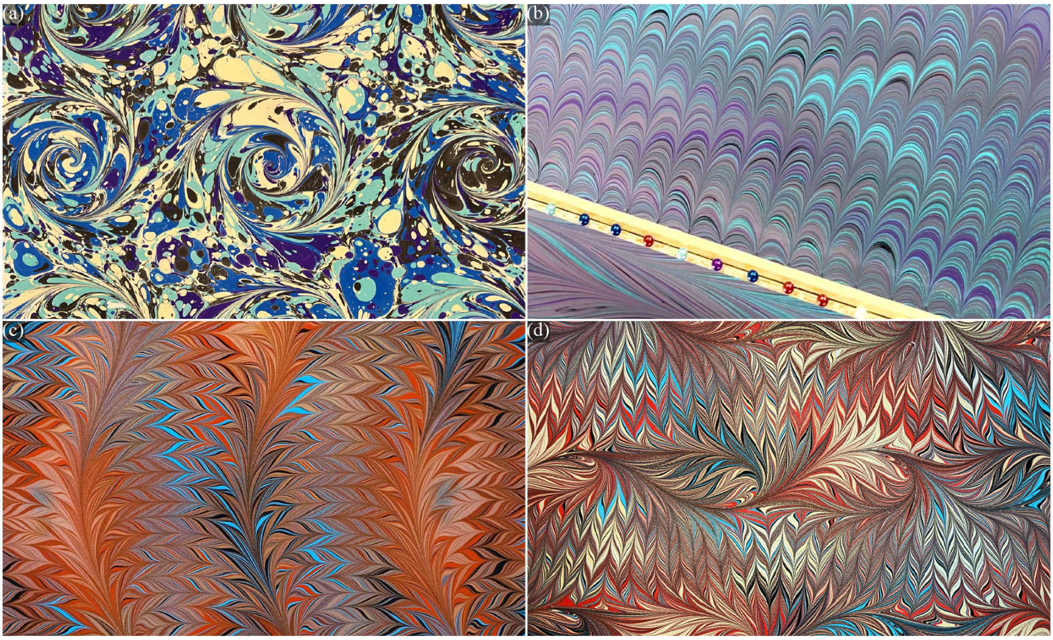

FIG. 1. Four classic marbling patterns. (a) French curl, (b) nonpareil, (c) flame, and (d) octopus.

spreading into relatively thin surface layers. For example, adding a surfactant to the blue paint promotes more spreading, as shown in Fig. 3(c). Because different colored paints may have different surface tensions, marbling is an art of global balance. When new colors are added [Fig. 3(d)],

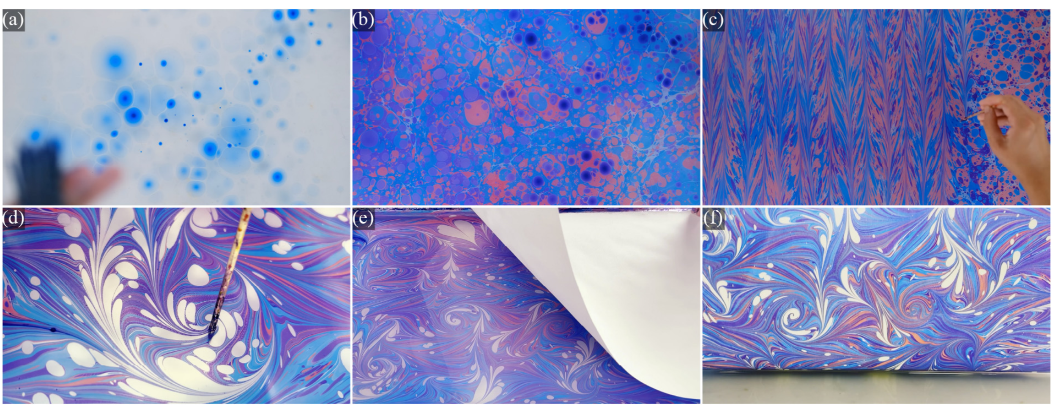

FIG. 2. The steps of marbling. (a) Apply paint onto the viscosified bath (b) until the paint covers the surface. (c), (d) Use thin tools to create patterns. (e) Gently place mordanted paper onto the bath and (f) remove the printed paper for rinsing and drying. We marbled in an 18 in $\times$ 24 in $\times$ $1\frac{1}{3}$ in clear tray. For preparation, we made the marbling bath at least 24 h in advance, using approximately two tablespoons of Jacquard carrageenan powder per gallon of water. We diluted the Golden fluid acrylic paint with distilled water in a 1:2 ratio. For the papers, we used Masa paper and Hahnemühle Ingres paper, mordanted with a solution of alum and water (one cup alum per gallon of warm water). After marbling [step (f)], we rinsed the papers to remove excess bath and then dried them on a drying rack. Once dry, we pressed them for a few days to flatten. For more detailed marbling instruction manuals, we refer the reader to Maurer-Mathison [5]. Additional details about these experiments are provided by Sun [6] (§4.2).

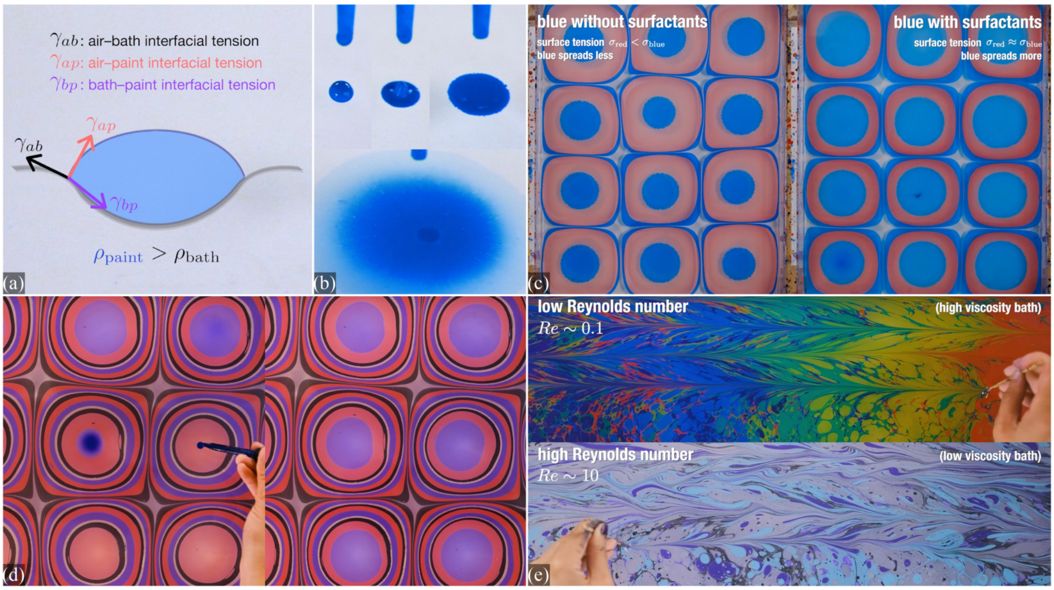

FIG. 3. Physics of spreading and (not) mixing. (a) The balance of interfacial tensions supports the weight of the paint. (b) Snapshots of a droplet spreading. (c) Blue paint without surfactant spreads less than with surfactant. (d) Altering surface tensions leads to surface pattern rearrangement. (e) Comparison of high and low viscosity baths.

the resulting Marangoni stresses—differences in surface tension across the bath's surface—cause rearrangement of the surface pattern.

After setting the initial color distribution, thin tools are used to create patterns. The main reason these patterns remain unmixed is due to the high viscosity of the bath. The appropriate Reynolds number is generally less than one, suggesting that inertia plays a relatively small role, and the fluid motion is dictated by the motion of the thin tool. Higher viscosity baths thus give marblers greater control over the final patterns. At lower viscosity, inertial effects may become significant, leading to an unstable wake behind the thin tool [Fig. 3(e)]. In either case, diffusion acts on a longer timescale than the time it takes to marble, so detailed patterns tend to be stable with sharp interfaces.

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