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## A sound approach to self-assembly

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## SYSTEMS CHEMISTRY

## A sound approach to self-assembly

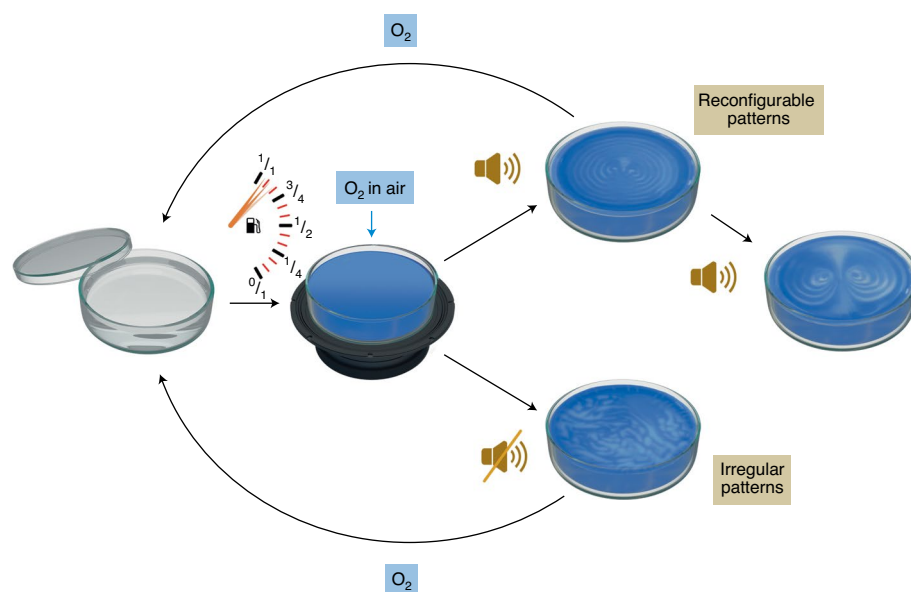
Controlling the formation of ordered and predictable patterns in dissipative reaction-diffusion processes is challenging. Now, liquid vibrations induced by audible sound have been shown to direct the formation of spatiotemporal patterns in switchable chemical systems and assemblies.

Charalampos G. Pappas

The majority of chemical processes conducted in the laboratory involve a 'closed' system that proceeds downhill in thermodynamic terms: the products of the reaction have a lower Gibbs free energy than the starting materials and they can be isolated and stored. In contrast, the chemistry of life operates in a very different way — most molecules from which living systems are built are turned over continuously and are not necessarily thermodynamically stable. Such homeostatic ('open') systems operate far from equilibrium and they are dissipative, which means that they need a constant energy input to maintain themselves<sup>1</sup>. Such far-from-equilibrium systems are also associated with the formation of active patterns<sup>2</sup>, not just in chemical reactions<sup>3</sup>, but also in macroscopic systems such as sand ripples and slime-mould aggregation.

Patterns in chemical reactions are typically controlled through chemical and mechanical triggers. Sound waves have also been used to influence molecular and macromolecular events<sup>4</sup>, but this typically involves ultrasound — high-energy oscillating pressure waves of various frequencies (>20 kHz). These processes often require such high frequencies because they occur through acoustic cavitation — the formation and collapse of high-energy bubbles — which leads to local increases in temperature and pressure that can affect chemical reactions. This high-frequency constraint of ultrasound has mostly led to the formation of static chemical shapes.

Now, writing in *Nature Chemistry*, Hwang, Mukhopadhyay, Kim and co-workers have merged these two concepts — dissipative self-assembly and the effect of sound on chemical processes — to produce temporary and reconfigurable macroscopic patterns in liquids, similar to what is observed in oscillating reactions<sup>5</sup>. Their approach relies on low-frequency audible sound (25–90 Hz) in contrast with the majority of sound-responsive systems reported to date, in which ultrasonic vibrations are



**Fig. 1 | Audible sound-controlled transient spatiotemporal patterns in chemically fueled systems.**

A schematic representation of the use of audible sound to facilitate the dissolution and diffusion of atmospheric gases (such as O<sub>2</sub> in this example) in water, giving rise to the fabrication of dissipative systems based on redox chemistry. Reconfigurable patterns were temporarily observed as a result of switching on the sound at different frequencies; in some cases, a pattern of concentric circles evolves into a double-vortex feature. Irregular patterns were generated in the absence of liquid vibrations. Credit: Ella Maru Studio.

ordinarily used to overcome kinetic barriers associated with assembly and gelation<sup>3</sup> or with rare anisotropy changes emerging from audible waves in organic media<sup>6</sup>. The audible-sound approach developed by this team of researchers gives access to precisely positioned transient supramolecular structures in solution — a longstanding challenge in fully synthetic systems.

The first system demonstrated by Hwang, Mukhopadhyay, Kim and co-workers uses a bipyridinium derivative (methyl viologen) whose colour depends on its oxidation state — intense blue when reduced and colourless when oxidized — that can be reversibly switched between the two forms. In the experiments reported here, reduction is fuelled by sodium

dithionite (Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub>) and subsequent oxidation is mediated by atmospheric oxygen. Upon exposure to audible sound (40 Hz), a deep-blue solution containing the reduced methyl viologen reconfigures into a regular pattern of dark blue/light blue concentric rings, gradually becoming colourless as the system is reoxidized through exposure to the air (Fig. 1).

Reproducible patterns were obtained through several refuelling cycles (by addition of Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub>); in the absence of sound, random maze-like patterns were formed and no pattern formation was observed under oxygen-free conditions. Furthermore, irregular patterns were produced when alternative methods of gas dissolution, such as vortexing or stirring, were used. This experiment suggests

that the regular spatiotemporal patterns result from oxygen-rich and oxygen-poor regions in solution which, in turn, controls the redox state of the viologens in those regions. Although sound waves of various frequencies have been used previously to generate oscillation cycles, those lasted only for short periods of time and suffered from cavitation effects, resulting in poorly understood acoustic mechanisms<sup>7</sup>.

Having demonstrated the sound-controlled generation of redox domains in solution, the team set about investigating the mechanism of pattern formation further. Safranin, a commercially available dye, appeared to be an ideal candidate for the mechanistic studies because it becomes reddish-orange when oxidized — this is essentially a reverse colour change to the methyl viologen system, which becomes coloured when it is reduced. With safranin, the coloured pattern featured a red/orange spot at the centre accompanied with the formation of concentric red/orange rings. The system evolves to give a double-vortex motif, which is attributed to a combination of vertical vibrations of the liquid surface and lateral streaming flows. It is suggested that, because the nodes in the generated waves do not vibrate as much as other parts of the liquid surface, there is lower dissolution of oxygen at these points. In contrast, the lateral flows of dissolved gases are much more complex and will require further study. As would be expected, the patterns are highly dependent on the size and shape of the dish in which these solutions are exposed to audible sound.

Hwang, Mukhopadhyay, Kim and co-workers were able to extend the generality of their approach beyond redox switching by applying it to pH-responsive systems. Sound-driven dissolution of CO<sub>2</sub> into a solution containing a pH-sensitive

acid–base indicator (bromothymol blue) resulted in the formation of different colour domains, again in a pattern of concentric rings. As previously observed, chaotic patterns were generated in the absence of sound waves.

The influence of audible sound was then investigated in the context of dissipative self-assembling systems. A redox-responsive system was engineered based on a molecular receptor (cucurbit[8]uril) capable of forming a stable charge-transfer complex with a cationic bis-bipyridinium-based guest. Upon the addition of a chemical fuel, which partially reduces the bipyridinium groups, the host–guest complex rearranges and forms nanoscale aggregates that are purple. These assemblies fall apart as the system reoxidizes on exposure to air and reverts to being colourless. In another system, a pH-sensitive perylene analogue formed dynamically unstable fibrillar architectures upon bubbling CO<sub>2</sub> through the solution at a high pH. The non-equilibrium pathway was supported by UV–vis and fluorescence spectroscopy, dynamic light scattering and electron microscopy techniques. In both of these systems described above, predictable spatiotemporal patterns of dissipative self-assembling structures were visualized upon switching on the sound.

Given the importance and the complexity of dynamic motifs in biological systems, this report of reconfigurable patterns induced by audible sound waves at different frequencies is particularly striking. It would be interesting to investigate whether by fine tuning the acoustic properties (for example, intensity, pressure, time exposure) and the molecular systems themselves, the relatively narrow frequency window could be expanded and more complex patterns formed. The combination of audible-sound-induced liquid vibrations and dissipative self-assembly opens up exciting perspectives in systems chemistry

more generally and life-like chemical systems in particular. Moreover, these low-frequency sound vibrations could perhaps be used to explore the effect of controlled frequencies on cell differentiation because it is increasingly clear that cells are highly sensitive to a multitude of physical and mechanical cues presented by their environment.

These impressive discoveries establish a straightforward method for producing pH- or redox-specific domains, which is in stark contrast to the difficulties usually encountered in designing and controlling pattern formation in far-from-equilibrium systems. The future of this field may focus on more complex and dynamic chemical networks, where different compound classes (for example, peptides and nucleotides) co-exist and compete for various energy sources. In systems such as these, audible sound waves combined with chemical messengers may give rise to the emergence of switchable and complex patterns, imposing order into disordered systems. □

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#### Competing interests

The authors declare no competing interests.

## MAIN-GROUP CHEMISTRY

# A convenient P<sup>-</sup> source

White phosphorus is a prominent source of P atoms but has remained difficult to activate without using transition metals. Now, a bidentate ligand based on silicon(II) donors has successfully stabilized a P<sub>2</sub> moiety, and the resulting complex acts as a transfer reagent for P<sup>-</sup> anions.

David Scheschkewitz

In typical chemical reactions, two components react with one another to yield a new species featuring

fragments of both starting materials. Very often, however, the product will be more complex than needed. For

instance, the reduction of ketones to alcohols formally involves the addition of H<sub>2</sub> to the C=O double bond. In

