Microswimmers from Scalable Galvanic Displacement

Maximilian R. Bailey,* Nico Reichholf, Anne Flechsig, Fabio Grillo, and Lucio Isa*

1. Introduction

Artificial microswimmers are small synthetic particles that transform energy sources, for example, external fields or chemical species, into propulsive motion. As they continuously consume energy, they are intrinsically “out of equilibrium”, displaying a range of collective phenomena not observed in systems at thermodynamic equilibrium. Beyond their fundamental appeal, microswimmers are interesting for a range of autonomous applications ranging from targeted drug delivery to environmental remediation, and even energy conversion, as they enable directed transport of matter at small scales and induce the mixing and pumping of fluids without external agitation. Due to their small size, the Reynolds number of microswimmers is low and viscous forces are dominant, with motion achieved by the asymmetric displacement of the surrounding fluid. Their motion can be fuelled by local or external sources of power, however, in all cases some form of particle asymmetry is required. This asymmetry can be achieved in a number of ways, for example, by applying asymmetric energy fields to a symmetric particle or by using objects that are inherently asymmetric due to their geometry. As an example, micromotors that self-propel via the production of bubbles, such as manganese-based active systems, are particularly promising for fluid mixing and water remediation applications due to their high swimming speeds and low cost. However, for fundamental investigations into active Brownian physics, especially in concentrated systems, large quantities of bubbles are undesirable.

One of the most studied, and arguably the simplest, active colloidal systems are Janus microswimmers. In Janus microswimmers, surface patches with different physicochemical properties induce the self-generation of asymmetric gradients, in turn imparting propulsion. In particular, chemical or catalytic Janus microswimmers exploit the catalytic reaction of a chemical fuel, for example, hydrogen peroxide decomposition catalyzed by a platinum surface, to generate local chemical gradients. However, even these simple microswimmers suffer from a very low throughput, as attaining patchy surfaces for large quantities of catalytically-active particles is synthetically challenging and physical fabrication methods, such as metal deposition, are only able to provide minute particle quantities at the expenses of a large waste of catalytic material. Simmchen et al. first demonstrated the synthesis of large quantities of monodisperse platinum nanoparticles without expensive metals by functionalizing nanoparticles with catalase via the Pickering wax emulsion technique. In a recent advance in the state-of-the-art of Janus microswimmer synthesis, Archer et al. demonstrated the scalable fabrication of catalytic microswimmers by functionalizing particles confined on the surface of Pickering-wax emulsion droplets with a two-step nanoparticle seeding and film-growth protocol. However, this approach involves a poorly controlled reduction of platinum nanoparticles from solution, requiring a significant use of expensive and toxic platinum salt precursor per nm of Pt film, as well as producing undesirable nanoparticle waste. Furthermore, the approach as described is limited to the growth of platinum films.

Here, we combine the Pickering wax-emulsion technique with galvanic electrochemistry to obtain thick Pt metal films from copper nanoparticle seeds rapidly and asymmetrically grown on SiO₂ microparticle supports (Figure 1). In their studies into “galvanophoresis,” utilizing the electromotive force of galvanic exchange reactions for microswimmer motion, the Simmchen group have demonstrated that the galvanic displacement of sputter-coated copper to obtain platinum and gold “hatted” microswimmers is possible. Instead of focusing

M. R. Bailey, N. Reichholf, A. Flechsig, F. Grillo, L. Isa
Laboratory for Soft Materials and Interfaces
Department of Materials
ETH Zürich
Vladimir-Prelog-Weg 5, Zürich 8093, Switzerland
E-mail: maximilian.bailey@mat.ethz.ch; lucio.isa@mat.ethz.ch

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/ppsc.202100200.

© 2021 The Authors. Particle & Particle Systems Characterization published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

DOI: 10.1002/ppsc.202100200

Part. Part. Syst. Charact. 2022, 39, 2100200 2100200 (1 of 6) © 2021 The Authors. Particle & Particle Systems Characterization published by Wiley-VCH GmbH
ports. Copper nanoparticles are thus grown directly on the SiO2 particles via SiO2-wax colloidosomes obtained with the Pickering emulsion technique. After wise to an (3-aminopropyl)triethoxysilane (APTES) modified performing the reduction step, the uncontrolled formation of first complexing the ions onto the microparticle supports before control over nanoparticle growth and minimizing the formation of excess free nanoparticles. Using surface-grown copper as a sacrificial template reduces nanoparticle waste and can potentially minimize the use of expensive and toxic metal precursors. Since the ability of copper to be replaced with a range of metals for the fabrication of microswimmers has already been demonstrated for small quantities of particles,[24,25] combining this electrochemical technique with the well-established Pickering-wax emulsion approach promises a more economical[26] and versatile approach to fabricate microswimmers with different functionalities. In fact, galvanic electrochemistry opens the possibility of obtaining multi-functional micromotors with mixed film compositions by tuning the stoichiometry of salts added during the metal plating step.[27] By tracking the motion of the synthesized Pt Janus microswimmers, we conclude by confirming that a clear asymmetry in the Pt films, obtained here using said emulsions, is a necessary precondition for appreciable microswimmer motion.

2. Results and Discussion

We first develop a protocol for growing platinum films on SiO2 microparticles without asymmetry, that is, under bulk mixing conditions. Our method relies on the rapid complexation of copper ions by amines present on the surface of the SiO2 microparticle supports. Copper nanoparticles are thus grown directly on the SiO2 upon addition of a strong reducing agent, providing greater control over nanoparticle growth and minimizing the formation of excess free nanoparticles. Using surface-grown copper as a sacrificial template reduces nanoparticle waste and can potentially minimize the use of expensive and toxic metal precursors. Since the ability of copper to be replaced with a range of metals for the fabrication of microswimmers has already been demonstrated for small quantities of particles,[24,25] combining this electrochemical technique with the well-established Pickering-wax emulsion approach promises a more economical[26] and versatile approach to fabricate microswimmers with different functionalities. In fact, galvanic electrochemistry opens the possibility of obtaining multi-functional micromotors with mixed film compositions by tuning the stoichiometry of salts added during the metal plating step.[27] By tracking the motion of the synthesized Pt Janus microswimmers, we conclude by confirming that a clear asymmetry in the Pt films, obtained here using said emulsions, is a necessary precondition for appreciable microswimmer motion.

This complexation step, the solution is then washed extensively by centrifugation to remove free Cu(II) ions, ensuring that no free copper nanoparticles are formed in solution upon addition of a strong reductant. The particles retain a light blue color from the complexed copper ions. An aqueous NaBH4 solution is then added dropwise to this mixture, which is left to react under magnetic stirring in an N2 environment. The solution rapidly turns a dark-brown color upon addition of the NaBH4, indicating the formation of Cu0 nanoparticles on the SiO2 particles, which are also visualized by scanning electron microscopy (SEM) (Figure 2b). The resulting Cu-SiO2 particles are then washed in degassed double-distilled water, retaining a brown color from the Cu0 nanoparticles attached onto their surface. We also note that the supernatant during the washing step is always colorless, hinting at the absence of free copper nanoparticles in solution. That the bare SiO2 (not modified with APTES) particles do not turn brown after the same copper seeding steps, and that no nanoparticles are seen when imaging the resultant suspension (neither on the SiO2 particles nor on the SiO2 wafer), is further evidence for a complexed-copper mediated growth of nanoparticles from the APTES-modified SiO2 surface, rather than direct deposition of nanoparticles from solution. We also performed a copper seeding control experiment in the absence of microparticles, and did not observe nanoparticles on the SEM grid substrate, further indicating that the copper seeds observed on the substrate in Figure 2b were likely detached from the SiO2 particles during the drying process, and not formed in solution.

The copper nanoparticles seeded onto the SiO2 microparticle supports act as a template for the electroless deposition of a platinum film.[18] H2PtCl6 is added to the Cu-SiO2 particle suspension and mixed in an N2 atmosphere. From the respective half-cell potentials of platinum and copper, a spontaneous galvanic replacement reaction between Cu0 and Pt is predicted. After 30 min, formaldehyde is added as a weak reducing agent to assist the autocatalytic film growth of Pt from the Pt-Cu seeds on the SiO2 microparticle support.[22] The (yellow) mixture is left to react overnight in an N2 atmosphere under magnetic stirring. The (now colorless) suspension is then centrifuged with double-distilled water, and the resulting particles are black, indicating a successful exchange with Pt and subsequent film growth (Figure 2c–e). We note that by increasing the Pt concentrations and reaction times used in the film growth step, the functionalized particles possess thicker and more uniform Pt films. Focussed ion beam (FIB)-SEM images show the likely mechanism of film growth, as Pt islands gradually fuse before increasing in thickness (Figure 3).

We finally mention here the importance of following the color changes of the particles and solutions as an indicator for the success of the various reaction steps.

After establishing a protocol for the growth of uniform Pt films on SiO2 microparticles, we extend the method by introducing asymmetry to the APTES surface modification of the SiO2 microparticles via Pickering-wax emulsions, in order to obtain chemical microswimmers.[22] The Pickering-wax emulsion approach used here consists in decorating the surface of molten wax droplets in a hot aqueous medium with SiO2 microparticles. The particles are irreversibly adsorbed at the water–wax interface in the presence of a surfactant, and are immobilized when the wax is solidified. The particle surface immersed in the wax is then protected from chemical
modifications that are subsequently carried out in the aqueous phase. We prepare the Pickering emulsions by adapting the methodology described by Perro et al.\cite{29} SiO$_2$ particles are dispersed in aqueous didodecyldimethylammonium bromide (DDAB) solutions with concentrations selected to provide monolayer coverage of the surfactant on all particles.\cite{30} Solid wax is added to the suspension, heated to 75 °C, and then subjected to a two-step vigorous homogenization protocol.\cite{31} The hot wax–water Pickering emulsion is then rapidly cooled in an ice-bath to obtain solidified SiO$_2$–wax colloidosomes (Figure 2f). The Pickering emulsion is then cleaned by sedimentation with distilled water, a 0.1 m NaCl solution to remove the DDAB cationic surfactant, then water once more to remove the salt.\cite{32} The flexibility of the approach is demonstrated by producing emulsions

![Diagram](image_url)

**Figure 2.** Growth of homogeneous and asymmetric Pt films: a) SiO$_2$ 4.16 µm particles (scale bar 2 µm), b) SiO$_2$ particles after copper complexation and reduction for nanoparticle seeding. We note that many seeds detach during the drying process for SEM sample preparation (scale bar 1 µm). c) Pt-SiO$_2$ bulk-modified particles (scale bar 1 µm), d) SEM image, and e) SEM-energy-dispersive X-ray spectroscopy (EDX) indicating presence of a uniform Pt film (scale bar 2.5 µm). f) SiO$_2$-wax colloidosomes prepared with 4.16 µm particles (scale bar 5 µm), g) (inset) Janus APTES-modified SiO$_2$ particle, further modified with NHS-ester dye after removal of the wax. The dye selectively binds to the APTES groups on the particle (scale bar 0.75 µm). h) False-colored SEM image of patchy Pt-SiO$_2$ particles (scale bar 0.5 µm) i,j) Patchy Pt-SiO$_2$ particles imaged with Pt SEM-EDX. Regions of low Pt signal highlighted with red dashed lines to guide the eye (scale bar 0.75 µm).

![Images](image_url)

**Figure 3.** SEM and FIB-SEM images of various film morphologies and thicknesses observed. Top row: FIB-SEM images of the particles with morphologies similar to those of the bottom row. Approximate film thicknesses (left to right): 130, 160, 210 nm. Scale bars of the top and bottom rows are 0.5 and 2.0 µm respectively.
with various particle sizes (Figure S2 and Table S1, Supporting Information), suggesting an adaptable method to obtain microswimmers with different physical properties.

The cleaned colloidosomes are then dispersed in an aqueous NH\textsubscript{4}OH solution, to which APTES is added dropwise. The solution is then gently agitated using an orbital mixer. APTES modification is conventionally carried out in alcohols for greater control over the silanization process; however, we find that the produced colloidosomes degrade when placed in organic solvents (see Section S2 and Figure S4, Supporting Information). We therefore carry out the asymmetric APTES modification of the SiO\textsubscript{2} microparticles in water,[39] and use a large excess of APTES to account for losses from self-condensation reactions. We note that the primary objective here is the presence of amine groups for copper complexation on the SiO\textsubscript{2} surface, and thus a smooth monolayer coverage of APTES molecules is of lesser import. To remove excess APTES, weakly attached particles, and any potential side-products from the APTES modification process, the APTES modified colloidosomes are then filtered and washed extensively with twice-distilled water. The colloidosomes are then dispersed in chloroform before filtration to remove the protecting wax masks. Asymmetric modification of the particles with APTES is visualized using an NHS-ester dye (Figure 2g). Finally, the asymmetrically APTES-modified SiO\textsubscript{2} particles are plated with Pt as described previously to obtain Pt-SiO\textsubscript{2} Janus particles (Figure 2h–j).

A Janus distribution of Pt, which catalyzes the decomposition of H\textsubscript{2}O\textsubscript{2}, on the surface of the microparticles creates asymmetric gradients around the Pt-SiO\textsubscript{2} particles. These in turn develop asymmetric flow fields, which result in the self-phoresis of the particles.[40] (Figure 4a). We note that the particles are mostly plated by the Pt film, which reduces swimming speeds compared to a true Janus hemispherical coverage,[41] due to the limited penetration of the particles into the wax phase. To achieve higher swimming speeds, the degree of surface modification could be tuned by adjusting the three-phase contact angle, for example, via surfactants[39] or pH.[40] To evaluate our galvanic approach to microswimmer fabrication, we perform particle tracking experiments in fuel-rich environments. We track the trajectories of the bulk-Pt-functionalized and Janus-Pt-functionalized microparticles and quantify their short-time mean squared displacements (MSD, Figure 4b). We then evaluate the particle velocities from their short-time MSDs using \( \langle \Delta x^2 \rangle = 4D_T\Delta t + V^2\Delta t^2 \). This analysis requires that rotational diffusion does not influence the motion of the microswimmers, that is, that \( \tau < \tau_R \), where \( \tau_R \) is the characteristic time of rotation.[37,38] (see Section S4, Supporting Information for discussion). We therefore compute the MSD over 2s (20 data points at 10 FPS to fit two variables), noting that \( \tau_R \approx 50 \text{ s} \). We also find that for the particles where the asymmetry can be clearly seen, their motion is similar to that of the “sliding states” characteristic of Pt-based microswimmers,[18] with the Pt cap to the back of the microswimmer (see Movie S1, Supporting Information).

To determine the efficacy of our synthetic protocols to obtain microswimmers, we evaluate the active Péclet numbers (\( Pe \)) of the unfunctionalized SiO\textsubscript{2}, bulk Pt-functionalized SiO\textsubscript{2}, and the Janus Pt-functionalized SiO\textsubscript{2}.

\[ Pe = \frac{V}{\sqrt{D_T D_R}} \]

Determines the ratio of the ballistic (\( V \) is the propulsion speed) and diffusive (with \( D_T \) and \( D_R \) the translational and rotational diffusivities, respectively) components of motion, and provides a measure of the relative importance of directed motion, ergo, the proportion of active particles. Setting a threshold \( Pe > 20 \), we find that 68% of the Janus Pt-functionalized particles are active, providing an indirect measure of the yield of our microswimmer fabrication protocol (Figure 4c). We note that even without the asymmetric functionalization provided by the Pickering wax-emulsions, 34% of the bulk Pt-functionalized particles surpass the \( Pe > 20 \) threshold. Spontaneous symmetry breaking of a concentration field and swimming behavior has also been theorized for symmetric particles at \( Pe = 4 \).[40,41] However, in our case, the bulk-grown films possess inherent asymmetries, which we hypothesize are sufficient to induce minor gradients and thus particle motion. Nonetheless, the doubling in the proportion of

---

**Figure 4.**

a) Optical micrograph of two particles in motion overlaid with their trajectory (duration: 120 s). We note that the film asymmetry is clearly apparent for only one of the microswimmers. We attribute this to the thick Pt films grown and the relatively limited asymmetry arising from a small three-phase contact angle. b) Short-time mean squared displacements (MSD). Unfunctionalized SiO\textsubscript{2} (black triangles), bulk-functionalized Pt-SiO\textsubscript{2} (red diamonds), and Janus Pt-SiO\textsubscript{2} (\( Pe>20 \), blue circles). The inset shows the MSD on a log-log scale. Error bars are the standard error c) Active particle yields (\( Pe>20 \)) from different synthetic routes (colors as in (b)). The error bars correspond to 95% confidence intervals, which were obtained with bootstrapping. All particle tracking investigations were performed using 0.5v/v% H\textsubscript{2}O\textsubscript{2} fuel concentration, and statistics were gathered from at least 130 particle trajectories.
microswimmers obtained by purposely introducing asymmetry as well as the higher overall fitted velocities (unfunctionalized SiO$_2$ = [0.077; 0.096] $\mu$m$^{-1}$, bulk Pt = [0.63; 0.81] $\mu$m$^{-1}$, Janus Pt = [1.2; 1.6] $\mu$m$^{-1}$—95% confidence intervals from bootstrapping) highlight the importance of the anisotropy obtained from using Pickering-wax emulsions.

3. Conclusion

In summary, we have demonstrated galvanic electrochemistry as a viable approach to fabricate Pt-based microswimmers in a scalable fashion by combination with the Pickering-wax emulsion technique. Interestingly, we find that the inherent asymmetry of the produced films also leads to motion of some particles functionalized isotropically by bulk stirring. Nonetheless, introducing asymmetry into the platinum films with Pickering wax emulsions doubles the proportion of microswimmers obtained, and leads to a twofold increase of the propulsion velocity. By using copper as a sacrificial template, the method can potentially minimize the use of expensive and toxic noble metal precursors, and the rapid complexation of copper by amine groups reduces synthesis time. Complexing first the metal ions before addition of a strong reducing agent also prevents the uncontrolled formation of nanoparticles in solution, providing a further handle on the synthesis of the metal films as well as minimizing nanoparticle emissions. By exploiting galvanic electrochemistry, the method presented here can be extended to various metals or even combinations thereof, providing a versatile approach to obtain large quantities of a range of functional Janus particles. However, we note that the variability in patch sizes obtained via Pickering-wax emulsions currently limits the proposed synthetic procedure to applications where particle uniformity is of lesser import. Strategies building on previous work to achieve finer control over particle penetration into the wax-phase therefore warrant further investigation. The recent emergence of galvanophoresis as an alternative, highly efficient propulsion mechanism for microswimmers suggests further uses for a synthetic route producing large quantities of microparticles with asymmetric copper films. Our proposed approach also lends itself to templating with more oxidation-resistant metals such as palladium, which may be a more durable material for this specific application.

4. Experimental Section

Copper Seeding Onto SiO$_2$ Microparticles: SiO$_2$ microparticles were modified in water for reasons outlined in Supporting Information (Section S3, Supporting Information). Briefly, 125 mg of 4.16 $\mu$m SiO$_2$ microparticles (SD = 0.19 $\mu$m, microparticles GmbH) were dispersed in 49 mL double-distilled water, and then 1 mL of NH$_4$OH was added under stirring (1000 RPM). After 5 min, 90 $\mu$L of APTES was added dropwise, and the suspension was left to stir for further 1 h. The APTES-modified particles were then washed four times by centrifugation (1300 RPM, 1 min) with double-distilled water (50 mL). The suspension was then made up to 45 mL with double-distilled water, and 5 mL of an aqueous 2mg mL$^{-1}$ CuSO$_4$ solution was added dropwise under stirring (1000 RPM) and left for 1 h. The Cu(II)-APTES SiO$_2$ microparticles were then washed four times with double-distilled water (50 mL) by centrifugation (1300 RPM, 1 min). The solution was then made up to 22.5 mL with double-distilled water, and degassed for 30 min with N$_2$ under stirring (1000 RPM). 2.5 mL of a 1 M aqueous NaBH$_4$ solution was then added dropwise, and the reaction proceeded for 30 min under continuous degassing. The resulting brown Cu$_5$SiO$_2$ particles were then washed 3x in degassed, double-distilled water (50 mL), before making up the suspension to 150 mL with degassed, double-distilled water.

Platinum Film Growth from Copper Seeds: 50 mL of an aqueous 0.33 mm (34 mg) H$_2$PtCl$_6$-6H$_2$O solution was added to the stirred 150 mL Cu-SiO$_2$ particle suspension (1000 RPM) under continuous degassing. The galvanic exchange proceeded for 30 min, before dropwise addition of 1.35 mL formaldehyde to the suspension to initiate the auto-catalytic growth of the Pt films. The vessel was then degassed vigorously for a further 5 min, then left to react overnight in a sealed vessel. The resulting Pt-SiO$_2$ microparticles were then washed 4x with double-distilled water.

Preparation of SiO$_2$-Wax Colloidosomes: 250 mg of SiO$_2$ particles were dispersed in DDAB solutions with concentrations corresponding to an approximate surfactant monolayer coverage on all particles (5 mL, 0.0054 mg mL$^{-1}$).[26] Wax (230 mg) was added to the suspension, and then placed in an silicone oil bath at 75 °C, and first stirred at 3000 RPM for 15 min after the wax had melted with a T-25 digital ULTRA-TURRAX. After this initial dispersion step, the suspension was then homogenized under vigorous stirring for 160 s (11000 RPM). After homogenization, the hot, wax-in-water SiO$_2$ particle-stabilized Pickering emulsion was then rapidly cooled in an ice-bath to obtain solidified SiO$_2$-wax colloidosomes. The colloidosomes were then washed consecutively by gravitational sedimentation with distilled water to remove excess wax and unattached particles (two times, 50 mL), a 0.1 M NaCl solution to remove the DDAB cationic surfactant (2x, 50 mL), then distilled water (3x, 50 mL) to remove any salt.

Asymmetric Platinum Film Growth on SiO$_2$ Microparticles: The washed SiO$_2$-wax colloidosomes were dispersed in an aqueous NH$_4$OH solution (100 mL, 0.6 v/v%) under gentle agitation using an orbital shaker. 360 $\mu$L of APTES was then added dropwise to this suspension, and left for 1 h under continued shaking (350 RPM). The APTES-modified SiO$_2$-wax colloidosomes were then collected by vacuum filtration on ashless filter paper and washed with copious amounts of distilled water (300 mL). The collected colloidosomes were then left to dry in a vacuum oven at 40 °C, weighed, then dispersed in 50 mL CHCl$_3$ and left stirring for 1 h to dissolve the wax. The Janus-modified APTES-SiO$_2$ microparticles were then collected by vacuum filtration on a PTFE filter membrane (pore size 1.5 µm) by copious washing first by CHCl$_3$ (150 mL) then EIOH (50 mL). The particles were again dried in a vacuum oven and weighed. The yield of Janus particles was typically on the order of 50% (125 mg). Pt films were then asymmetrically grown on the Janus APTES-SiO$_2$ microparticles as described above.

Particle Tracking Experiments: Particle tracking experiments were performed on a Nikon Upright LV150N microscope (20x). Stock H$_2$O$_2$ (30 v/v%, Acros Organics) was added to dilute particle suspensions of the Pt-functionalized microswimmers to obtain 300 µL of a fuel rich (0.5 v/v% H$_2$O$_2$ solution. 280 µL thereof was then pipetted into a flow-through cell (cell 157–QS; Hellma Analytics) with a light path length of 1 mm. Videos were taken at 10 fps on a Hamamatsu C1440–20UP digital camera. Particle trajectories were then analyzed using the MATLAB implementation of the Crocker and Grier IDL particle tracking method[45] and in-house MATLAB scripts.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors thank David Häberlin and Aaron Iten for their exploratory investigations at the beginning of the project. The authors are also
grateful to S. van Kesteren and Dr. G. A. Filonenko for their various suggestions pertaining to the synthesis at the beginning of this investigation. The authors also thank Dr. M. Hu for his assistance with the FIB-SEM imaging, and the Scientific Center for Optical and Electron Microscopy (ScoPeM) of ETH Zurich for access to their instrumentation. Open access funding provided by Eidgenössische Technische Hochschule Zurich.

Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
Author contributions are defined based on the CRediT (Contributor Roles Taxonomy). M.R.B. and L.I. contributed to the conceptualization. M.R.B. and F.G. carried out the formal analysis. F.G., L.I. contributed to the validation. M.R.B., N.R. and A.F. contributed to the methodology. M.R.B. and N.R. contributed to the investigation. M.R.B. and F.G. carried out the formal analysis. F.G., L.I. contributed to the supervision. M.R.B., N.R., and A.F. contributed to the methodology. M.R.B. and F.G. contributed to the writing—original draft and M.R.B., N.R., F.G., and L.I. contributed to the editing and reviewing of the manuscript.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
catalysts, galvanic exchange, microswimmers, scalable, synthesis, versatility

Received: September 3, 2021
Revised: December 8, 2021
Published online: December 23, 2021

[1] S. Ramaswamy, Annu. Rev. Condens. Matter Phys. 2010, 1, 323.
[2] M. E. Cates, J. Tailleur, Annu. Rev. Condens. Matter Phys. 2015, 6, 219.
[3] S. J. Ebbens, Curr. Opin. Colloid Interface Sci. 2016, 21, 14.
[4] P. Diez, E. Lucena-Sánchez, A. Escudero, A. Llopis-Lorente, R. Villalonga, R. Martínez-Máñez, ACS Nano 2021, 15, 4467.
[5] L. Wang, A. Kaeppler, D. Fischer, J. Simmchen, ACS Appl. Mater. Interfaces 2019, 11, 32937.
[6] V. V. Singh, F. Soto, K. Kaufmann, J. Wang, Angew. Chem., Int. Ed. 2015, 54, 6896.
[7] Y. Alapan, B. Yigit, O. Beker, A. F. Demirörs, M. Sitti, Nat. Mater. 2019, 18, 1244.
[8] K. Yuan, M. Pacheco, B. Jurado-Sánchez, A. Escarpa, Adv. Intell. Syst. 2021, 2100002.
[9] J. J. Abbott, K. E. Peyer, M. C. Lagomarsino, L. Zhang, L. Dong, I. K. Kaliakatsos, B. J. Nelson, Int. J. Rob. Res. 2009, 28, 1434.
[10] E. M. Purcell, Am. J. Phys. 1977, 45, 3.
[11] C. W. Shields, O. D. Velev, Chem 2017, 3, 539.
[12] F. Mou, J. Zhang, Z. Wu, S. Du, Z. Zhang, L. Xu, J. Guan, iScience 2019, 19, 415.
[13] F. Cichos, M. Fränzl, S. Muinos-Landin, V. Holubec, ACS Nano 2021, 15, 3434.
[14] S. Heckel, J. Grauer, M. Semmler, T. Gemming, H. Löwen, B. Liebchen, J. Simmchen, Langmuir 2020, 36, 12473.
[15] H. Ye, Y. Wang, X. Liu, D. Xu, H. Yuan, H. Sun, S. Wang, X. Ma, J. Colloid Interface Sci. 2021, 588, 510.
[16] J. Hu, S. Zhou, Y. Sun, X. Fang, L. Wu, Chem. Soc. Rev. 2012, 41, 4356.
[17] M. N. Popescu, Langmuir 2020, 36, 6861.
[18] K. K. Dey, F. Wong, A. Altemose, A. Sen, Curr. Opin. Colloid Interface Sci. 2016, 21, 4.
[19] J. Zhang, F. Mou, Z. Wu, S. Tang, H. Xie, M. You, X. Liang, L. Xu, J. Guan, ACS Appl. Mater. Interfaces 2019, 11, 16639.
[20] A. B. Pawar, I. Kretzschmar, Langmuir 2008, 24, 355.
[21] J. Simmchen, A. Baesa, D. Ruiz, M. J. Esplandieu, M. Vallet-Regi, Small 2012, 8, 2053.
[22] R. J. Archer, A. J. Parnell, A. I. Campbell, J. R. Howse, S. J. Ebbens, Adv. Sci. 2018, 5, 1700528.
[23] G. Bystrzejewska-Piotrowska, J. Golimowski, P. L. Urban, Waste Manage. 2009, 29, 2587.
[24] J. Bastos-Arrieta, C. Bauer, A. Eychmüller, J. Simmchen, J. Chem. Phys. 2019, 150, 14.
[25] L. Feuerstein, C. G. Biermann, Z. Xiao, C. Holm, J. Simmchen, J. Am. Chem. Soc. 2021, 143, 17015.
[26] A. Sarkar, A. Manthiram, J. Phys. Chem. C 2010, 114, 4725.
[27] X. Xia, Y. Wang, A. Ruditskiy, Y. Xia, Adv. Mater. 2013, 25, 6313.
[28] B. Modec, N. Podjed, N. Lah, Molecules 2020, 25, 7.
[29] A. Perro, F. Meunier, V. Schmitt, S. Ravaine, Colloids Surf. A 2009, 332, 57.
[30] S. Kord Daroun Kalai, Dissertation, Freie Universität Berlin, Berlin 2019.
[31] K. Lebdioua, A. Aimable, M. Cerbelaud, A. Videcoq, C. Peyratout, J. Colloid Interface Sci. 2018, 520, 127.
[32] M. R. Bailey, F. Grillo, N. D. Spencer, L. Isa, Adv. Funct. Mater. 2021, 2100175.
[33] J. Anderson, Annu. Rev. Fluid Mech. 1989, 21, 61.
[34] M. N. Popescu, S. Dietrich, M. Tasinkevych, J. Ralston, Eur. Phys. J. E 2010, 31, 351.
[35] S. Jiang, S. Granick, Langmuir 2008, 24, 2438.
[36] A. Synytska, A. Kirillova, L. Isa, ChemPlusChem 2014, 79, 656.
[37] C. Bechinger, R. Di Leonardo, H. Löwen, C. Reichhardt, G. Volpe, G. Volpe, Rev. Mod. Phys. 2016, 88, 4.
[38] H. Löwen, J. Chem. Phys. 2020, 152, 40901.
[39] W. E. Uspal, M. N. Popescu, S. Dietrich, M. Tasinkevych, Soft Matter 2015, 11, 434.
[40] R. Golestanian, Phys. Rev. Lett. 2009, 102, 188305.
[41] S. Michelin, E. Lauga, D. Bartolo, Phys. Fluids 2013, 25, 6.
[42] M. Bundschuh, J. Füser, S. Lüderwald, M. S. McKee, G. Metreveli, G. E. Schaumann, R. Schulz, S. Wagner, Environ. Sci. Eur. 2018, 30, 1.
[43] J. C. Crocker, D. G. Grier, J. Colloid Interface Sci. 1996, 179, 298.