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Colloidal Motors 101: A Beginner's Guide to Colloidal Motor Research

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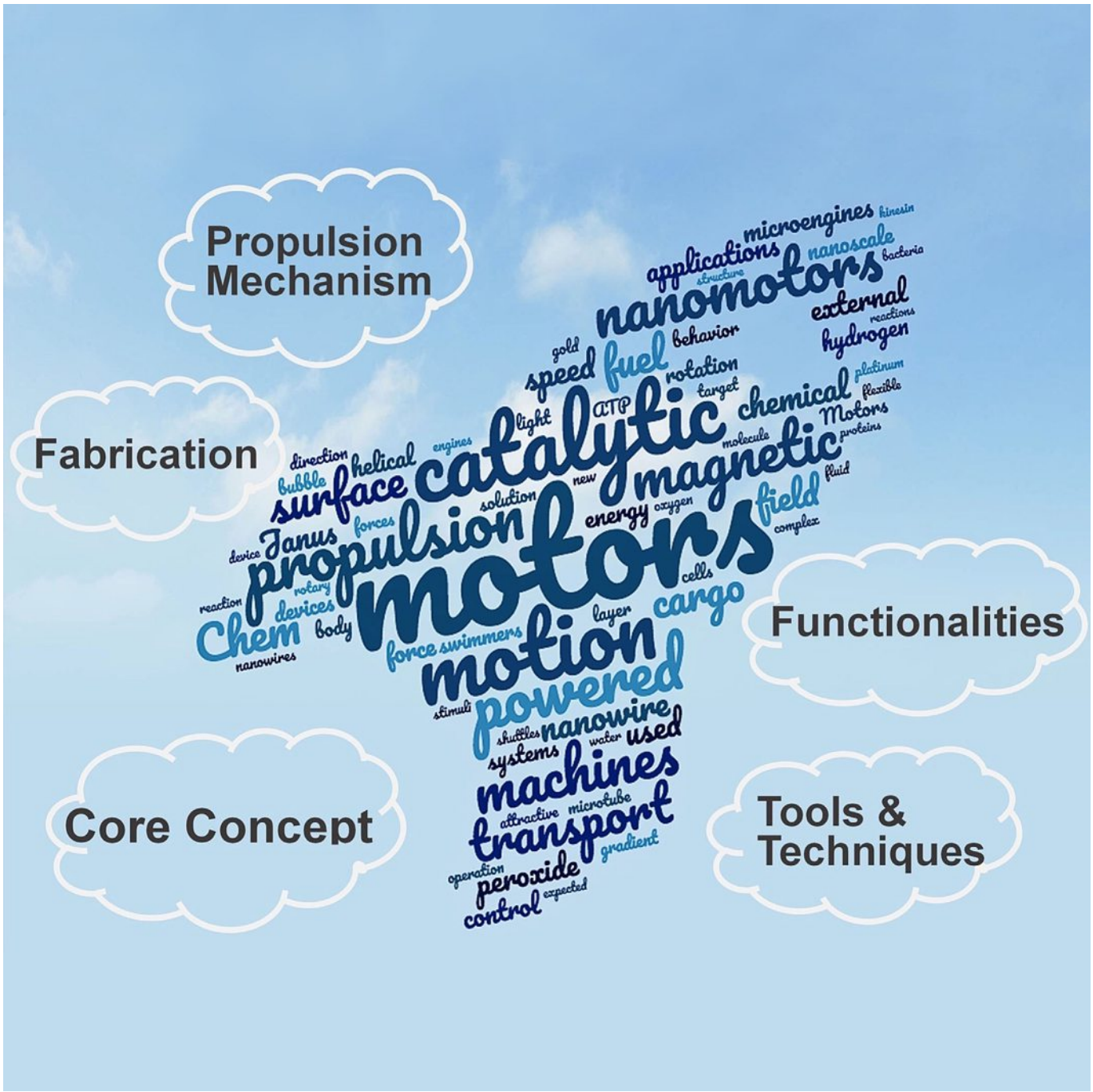

Abstract: The research progress in colloidal motors, synthetic colloids that convert environmental energy and swim in water, has attracted much attention in recent years. Yet, its rapid development and interdisciplinary nature has created a hurdle for beginners, especially students and postdocs. In light of this challenge, this tutorial review gives a bird's eye overview of the research field of colloidal motors, presenting in a beginner-friendly manner subjects including the definition and significance of colloidal motors, physical challenges associated with their motion at the microscale, their fabrication and propulsion mechanisms, functionalities that enable their applications, and essential tools and techniques useful for beginners. Emphasis on each aspect is placed on elucidating and connecting important concepts and ideas, rather than on details and individual references. An appendix of recent review articles grouped by subjects on colloidal motors is given in the Supporting Information. This article equips beginners with a clear big picture and essential knowledge that will facilitate future explorations.

1. Introduction

Colloidal particles are ubiquitous. They are in what we eat and what we breath, they are above us (clouds) and below us (soils), and they exist in many forms, shapes, and compositions. In most cases, they are *passive*, following wind and water flow. But, if powered by energy sources, they suddenly transform into an *active* particle that can swim, sense, carry, and deliver at the microscale. The first discoveries of such colloidal particles, commonly referred to as "colloidal motors" or "micromotors", were made in the beginning of the 21st century.[1] Since then, we have seen an explosion of research activity revolving around this topic, including new propulsion mechanisms, interactions, collective behaviors, proof-of-concept applications, and more. Thus, a new, interdisciplinary research field was born.

The mounting excitement and development of colloidal motors has unfortunately created confusion, an ever-steepening learning curve, and even unfriendliness to students, postdocs, and other researchers who are new to this field. This is why a tutorial review like this one becomes necessary, not to give a comprehensive review of the past, present, or future of colloidal motor research, or to cover everything a colloidal motor researcher needs to know. This formidable task easily takes a full book.[2] Rather, this review attempts to explain, in a way that is accessible and friendly to unfamiliar readers, what colloidal motors are, why they matter, how they can be useful, how to get started in doing research, and what exciting research possibilities await. It is our sincere hope that this article can offer beginners a bird's eye view of the research field of colloidal motors, equip them with core knowledge, and inspire them to explore more, uncharted territories.

This tutorial is organized in the following way. After this Introduction section, section 2 explains what colloidal motors are and are not, and the significance of research is discussed in section 3. Section 4 introduces Brownian motion and low Reynolds number, two important physical concepts that are critical to understanding the features and challenges of motion at small scales. How colloidal motors address these challenges in terms of propulsion mechanisms and fabrication techniques are introduced in sections 5 and 6, respectively, followed by a discussion in section 7 on the four functionalities that enable a wide range of colloidal motor applications. In section 8, we list a few techniques and tools essential for colloidal motor research. Finally, a few cutting-edge research topics are given at the end as examples to inspire. An inexhaustive list of recent review articles is also given in the Supporting Information to direct interested readers to expanded discussions on a particular subject.

(Note: the number "101" in the title is borrowed from the commonly used numbering system of courses offered in universities in countries like the USA and China, where 101 is usually the introductory course of a particular subject, such as in the cases of Physics 101 and Chemistry 101.)

2. What is a Colloidal Motor?

To the best of our knowledge, there is to this day no exact definition of "colloidal motor", or any of its variations that one commonly finds in the literature, such as "nanomotors", "micromotors", "synthetic microswimmers", "microbots", and other less common or more specific terms. All these names refer *loosely* to a type of colloidal particles that are man-made, roughly between 10 nm and 10 μm, and move in a directional manner in an aqueous environment (or at an interface with water being one medium). Although the definition or terminology might be flexible, the following are some unspoken caveats of what a colloidal motor is and isn't, which beginners are recommended to bear in minds.

First, a moving colloidal particle is not necessarily a colloidal motor for two reasons (Figure 1a). The first reason is that all colloids move because of thermal fluctuations (i.e., Brownian motion, discussed in section 4). Therefore, a colloidal motor needs to exhibit motility beyond Brownian motion, and this can be achieved in a number of ways (see section 5 for an ex-

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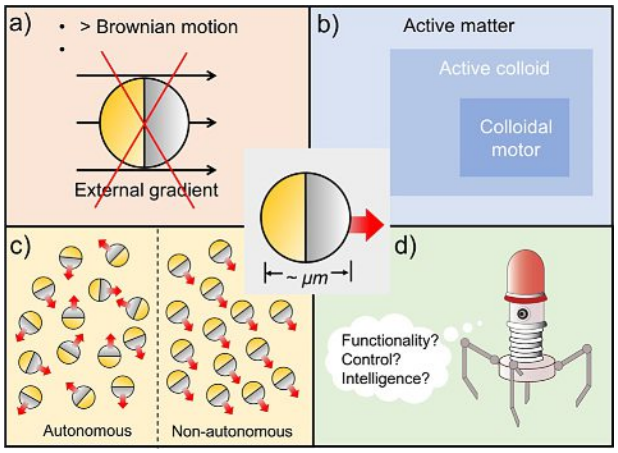

Figure 1. What is (and isn't) a colloidal motor. a) Colloidal motors do not merely respond to an external gradient, or simply undergo Brownian motion. b) Autonomous colloidal motors move independently of each other, whereas non-autonomous motors move in concert. c) "Colloidal motor" is a subset of "active colloid", which is a subset of "active matter". d) Microbots need to be functional, controllable, and intelligent, whereas a colloidal motor may or may not meet these criteria.

panded discussion). The second reason is that a colloidal motor does not just simply follow an external gradient, such as sedimenting colloids, or those undergoing bulk electrophoresis or responding to a magnetic field gradient. Rather, a colloidal motor breaks symmetry locally, often generating a local gradient of some sorts. Combining these two aspects, what makes colloidal motors special is that they convert energy stored in their environment (chemicals, light, electric/magnetic fields, sound, etc.) into mechanical forces locally and in an asymmetric way. In doing so, they dissipate energy and are therefore away from thermodynamic equilibrium.

Second, the word "autonomous" is often used to describe colloidal motors, but this is not necessarily required (Figure 1 b). Being autonomous in the context of colloidal motor research means that they move independently from each other in completely random directions (unless they are under the influence of inter-particle interactions or an external gradient, such as in the case of chemotaxis). Most, if not all, chemically powered colloidal motors move like this. The opposite case is magnetic colloidal motors, which are magnetized and align and move in the same direction, just like a school of fish (autonomously moving magnetic colloidal motors are rare, but not impossible[3]). Note that not all externally powered colloidal motors move in concert (i.e., all moving in the same direction and turning at the same time). In particular, those powered by electric fields or ultrasound often move in very random trajectories, which are completely independent of each other.[4]

Third, you sometimes hear, especially from physicists, the term "active colloids" and "active matter", which are concepts that are closely related to, but not exactly the same as, colloidal motors. To put it briefly, active colloids[5] are colloidal particles that are powered by an energy source, and show mobility beyond Brownian motion. This includes colloidal motors, but also natural microswimmers such as bacteria, algae, and cells. In fact, much of the inspiration in the field of colloidal motors was drawn from their biological counterparts. Active matter,[6] on the other hand, is an even broader term that also encompasses things like liquid crystals, cellular organelles, and even animals that are driven out of equilibrium by energy input. Colloidal motors are therefore a subset of active colloids, which is itself a subset of active matters (see Figure 1 c). An alternative name that better clarifies the nature of colloidal motors is perhaps *synthetic microswimmers*,[7] but this is not yet a popular term, especially not among chemists or material scientists.

Last but definitely not the least, the word "nano/microbot" is often found in the literature interchangeably with "colloidal motors", implying some sort of intelligence.[8] Whether this is true depends on, among many other things, how one defines robots, how functional a particular type of colloidal motor is, and how well that motor can be controlled (Figure 1 d). Although many exciting possibilities await, and we have in no doubt demonstrated the potential of colloidal motors in quite

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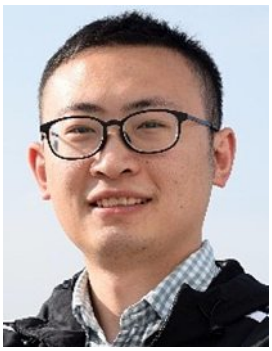

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a few applications, it is not unreasonable to be cautious against overhyped or ungrounded claims. *Buzz words can make or break a research field.*

When stripped away of the halo of functionalities and intelligence, a colloidal motor is very simple: a synthetic colloidal particle that moves by itself beyond Brownian motion. This might sound deceptively simple and lackluster. On the contrary, much of its power and beauty lie in the simplicity in design and concept, as will be discussed in more detail further in this review.

3. Why Should You Care?

Although "colloidal motors" sounds technical and foreign to non-scientists, "nanorobots" is a perfect combination of buzzwords, which reminds us of the tantalizing prospects first proposed in the 1950s and 60s.[9] It is perhaps this popular dream that fuels much of the research on colloidal motors, a dream that one day we can use them as tiny intelligent robots in places and missions in which we and our current technologies fail.[10] And in this dream we see many possibilities: biomedical nanorobots that patrol, sense, deliver, remove, and cure inside human bodies are obviously spearheading the fantasy.[11] Moreover, functional, tolerant, and sensitive nanorobots could prove useful in environmental monitoring and even remediation.[12] In addition, being small, motile, and controllable, nanorobots are the perfect assembly workers in the effort of miniaturizing manufacturing processes,[13] something essential to a slew of functional nanomachines.[14] The list could go on, but you get the idea: colloidal motors could become very useful in many things.

On the other hand, the research on colloidal motors is not necessarily driven by pragmatism, which aims at better, stronger, and smaller machines. Rather, much of the attention has been focused on more fundamental questions such as: what are the materials these colloidal motors are made of, and what properties endow them with the power of autonomously moving around?[15] What happens when two motors meet each other, and what about even more of them, say 100, 1000, or 1 million?[5c, 7a, 16] Can these motors communicate with each other, and how?[17] What if they are moving in very narrow channels, or deep trenches?[18] How efficient are they, and can they beat biological motors, such as motor proteins and enzymes, in energy efficiency?[19] Finding the answers to these questions and many more, ranging from propulsion mechanisms to collective behaviors and dynamics in complex environments, requires close collaborations among researchers across multiple disciplines such as soft matter physicists, biomedical engineers, robotics specialists, and material chemists.

Whether you are enticed by the nanobots fantasies, or interested in more fundamental questions such as active matter and non-equilibrium physics, a great beauty of colloidal motor research lies in this phrase "seeing is believing". It does not take much training for a junior researcher to learn how to fabricate simple colloidal motors, and to watch through a microscope lens how these tiny particles swim, rotate, spin, group, disperse, dash, and stop. It could also be somewhat shocking to see how they interact with each other in seemingly intelligent fashion, chasing each other like sharks after a school of fish, or spontaneously forming intricate patterns that vary over space and time. With clever engineering, one can even use a joystick to manipulate colloidal motors into spelling words and transporting tiny cargos. It is perhaps these exciting, and equally challenging, observations that more directly answer the question of why you should care.

4. Colloidal Motors Move in Tumultuous and Viscous Liquids

Before we move on to the specifics of how colloidal motors are actually made and why they move around, let us first think about what happens to a colloidal particle that tries to move at the nano- and microscale. In this section, two important physical concepts, namely Brownian motion and low Reynolds number, will be introduced. Their relevance to colloidal motors will be discussed in detail, which will help to give you a deeper appreciation of the various techniques and strategies we discuss in the later sections.

4.1. Brownian motion

Although the liquid medium (typically water) that a microswimmer, natural or synthetic, swims in is to us peaceful, it is in fact in a microscopically turmoil state. Water molecules acquire kinetic energy from their environment, and constantly move around in random fashion. Colloids that are suspended among water molecules are therefore bombarded from all directions all the time (Figure 2a). Once in a while, this bombardment nudges the particle slightly in one direction, but the next nudge could move it in a completely different direction. This is known as Brownian motion (another way to see this is thermal noise or fluctuation). When observed for long enough, the net displacement of the suspended particle is zero because of randomness, which could appear harmless. However, for a microswimmer moving in a particular direction, Brownian motion acts on top of its autonomous motion and randomizes it. The end result is a colloidal motor that constantly reorients (Figure 2b), with a reorientation timescale often on the order of seconds or less for motors a few μm in size. This is why colloidal motors exhibit random trajectories over a longer timeframe, and why they are sometimes referred to as active Brownian particles by physicists. Note that, although the single motor dynamics seem random, their ensemble average can be predictably described by considering them as diffusing species with a diffusivity that increases in proportion to the increase in fuel concentration or temperature.

Randomized trajectories are bad news for using these colloidal motors, as many of the desired applications require the motors to move to a destination in a controlled manner. In other words, ideal colloidal motors are often (but not always) expected to behave like cars or bullets, which move in a straight line after being released. Instead, they wander around in crooked trajectories as if they have lost their bearing. Granted, this problem in control can be mitigated by external or

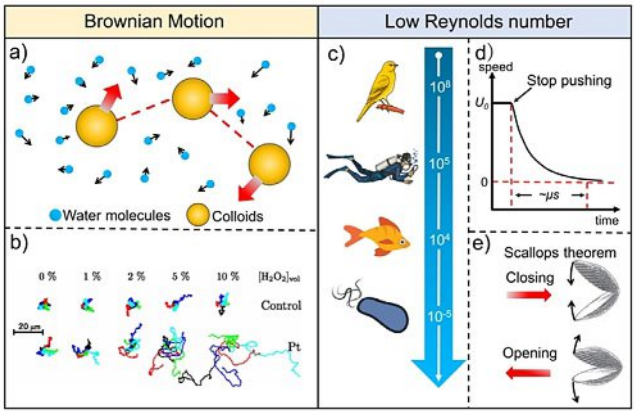

Figure 2. Physical constraints on microswimmers: Brownian motion and low Reynolds number (*Re*). a) A colloidal particle is constantly bombarded by water molecules and therefore exhibits randomized trajectories. b) A colloidal motor's trajectory, although also random, covers a larger area than a Brownian particle. Bottom: Pt-coated Janus motors in various concentrations of H_2O_2; top: particles without Pt in the same fuels. Reprinted with permission from ref. [20]. Copyright: 2007, American Physical Society. c) Various organisms move at vastly different Reynolds numbers. d) Once the propulsive force is stopped, a microswimmer stops its motion almost instantaneously within microseconds. e) The opening and closing of a scallop will not result in net motion at low *Re*.

self-steering strategies (discussed in section 7). Nevertheless, Brownian motion, and the resulting randomization of motor trajectories, poses a serious challenge in particular to controlling colloidal motors. The flip side of the coin is that, although its net displacement over long time is small, a colloidal motor affected by Brownian motion can survey a much larger area over that period of time than purely Brownian particles (another way to put this is that active colloids have larger diffusivity). This feature, illustrated in Figure 2b, could be exploited in sensing and detoxification applications.

The presence of Brownian motion poses a challenge to study slow colloidal motors of weak propulsive forces, the activity of which is in large part shadowed by Brownian motion. The typical analysis of taking an average of its instantaneous speeds is no longer meaningful, as the number mostly reflects the contribution of Brownian motion, which typically moves a colloidal particle of a few μm in sizes at a few $\mu m\,s^{-1}$. To compare the relative contribution of a motor's mobility by propulsive force with that by Brownian diffusion, we use a dimensionless Péclet number (*Pe*), which was originally used in fluid mechanics to compare convective transport with diffusive transport. In the context of colloidal motors, however, *Pe* is defined as:[21]

$$Pe = \frac{UL}{D} \tag{1}$$

where *L* is typically the size of the motor, *U* is its moving speed, and *D* is the Brownian diffusivity of this motor in the absence of any propulsion. A large *Pe* therefore means that the active propulsion, no matter what the mechanism is, dominates the motor's activity over Brownian motion, which is fixed for a given particle at a given temperature. A weakly propelled motor, on the other hand, falls into the low *Pe* regime and is mostly dominated by Brownian motion.

Equation (1) also suggests that as motors become smaller, Brownian motion becomes more and more dominant. In fact, the Brownian motion of nanometer-sized motors is so large that, even if they are powered by sufficiently strong forces, they appear to be only wiggling around violently rather than moving in a particular direction. Even magnetic alignment becomes less effective for motors at the nanometer scale. In addition, the increased fluctuation and a limit on optical resolution makes the study and application of colloidal motors at the true nanoscale very challenging.[22] As a result, the quantitative study of the dynamics of a nanomotor relies heavily on mean squared displacement analysis (MSD, see section 8 for more details) and alternative techniques such as florescence correlation microscopy (FCS),[23] dynamic light scattering (DLS),[22b] or even nuclear magnetic resonance (NMR)[24] when the particle is too small to be reliably tracked under an optical microscope.

4.2. Low Reynolds number

Besides Brownian motion, the other critical condition a microswimmer experiences when moving around in water is viscosity. This is somewhat counter-intuitive, as we humans see water as anything but viscous, with a room-temperature viscosity of approximately 0.001 Pa s, which is much smaller than syrup or gels. Things are quite different down at the nano- and microscales. There, even though the viscosity of water is still the same as when looked at macroscopically, particles are much smaller and lighter. So what? Viscosity is really just a measure of how fluid resists shearing, that is, the faster you move, the more you shear the liquid, and therefore the more resistance you experience from the fluid. The shear rate and the drag force are related by viscosity. On the other hand, Newton's law tells us that an object would want to continue to move against drag by inertia. The ratio between these two competing forces, the inertial force that keeps an object moving and the viscous force that tries to stop it, yields an important dimensionless number called the Reynold's number (*Re*):

$$Re = \frac{\rho UL}{\mu} \tag{2}$$

where ρ is the liquid density and μ is the liquid viscosity. A simple order of magnitude estimate shows that for most microswimmers, *Re is extremely small*, on the order of 10^{-4} to 10^{-5}, much smaller than the threshold of low Reynold's number regime ($Re < 2200$). A microswimmer is therefore dominated by viscous forces, whereas its inertia essentially disappears (Figure 2c).

Why does a low *Re* matter? Fluidic dynamics at the low Reynold's number regime is very different from that at high *Re*, and concepts such as lamellar flows and time reversal symmetry become relevant (for readers interested in low *Re* hydrodynamics, see ref. [6a] and [25]). But even without treading deep in the territory of hydrodynamics, a researcher of colloidal motors must know the following two facts. First, as inertia be-

comes negligible at low *Re*, a colloidal motor stops as soon as the propulsion force is removed. More strictly, the time it takes for a colloidal motor to slow down by 99% is on the order of μs (Figure 2d). What this means is that to make a colloidal motor move continuously, which is for most cases required or desired, constant power needs to be applied. In addition, the faster it moves (i.e., the more energy it draws) the larger the fluid drag, which dissipates the driving energy through heat. The fluid drag acting on a spherical colloidal motor is:[25]

$$F_{drag} = 6\pi\mu r U \quad (3)$$

and for a cylindrical motor moving along its long axis it is:[25]

$$F_{drag} = \frac{2\pi\mu L U}{\ln\left(\frac{L}{R}\right) - 0.72} \quad (4)$$

where μ is the dynamic viscosity of water, r is the radius of the spherical motor, L is the length of the cylindrical motor, R is radius of the cylindrical motor, and U is the motor speed. These two equations [especially Eq. (3)] are very commonly used and should be memorized.

Low *Re* swimming makes colloidal motors *intrinsically and terribly inefficient*, and this is very bad news. How inefficient? We have previously estimated the energy conversion efficiency of a few leading examples of colloidal motors, and found the number to vary wildly between 10^{-3} to 10^{-13}.[19] Macroscopic electrical motors, on the other hand, have an energy efficiency close to 50%, whereas bacteria move at approximately 1% energy efficiency.

The silver lining of this low *Re* scenario is that the fluid drag always equals the propulsive force of a colloidal motor (i.e., it moves in an *overdamped* regime). This is because any force imbalance will create acceleration/deceleration, which according to Equations (3) and (4) will change the drag force until it balances with the propulsive force again. As a result, an indirect yet easy to way to estimate the propulsive force, which is often hard to measure directly, is to calculate the drag force from Equations (3) and (4).

Living at low Reynolds number also means completely different ways of moving. At large scales, humans or fish often swim by moving part of their bodies back and forth. This kind of reciprocal motion leads to a net displacement only because of inertia, and in the absence of it the propulsion mechanism fails at low *Re*. This is also known as the "scallop theorem" (Figure 2e), proposed by Purcell,[26] which states that the reciprocal opening and closing of the shells of a scallop will take it nowhere at low *Re* (imagine a microscallop moving forward a little when opening, but returning to the starting point when closing). Therefore, microorganisms and anything that attempts to move at the nano- and microscale have to come up with new ways to overcome this limitation. And they have to do it very efficiently, because swimming at low *Re* is so terribly difficult whereas energy does not come in abundance.

Note that although "small scale" is being emphasized here, the concept of Reynolds number applies to objects at all scales. Everyday objects at large scales, such as a person swimming in a pool, can also experience low *Re* on the order of 1 if the pool is filled with maple syrup. So, all the features and challenges we have discussed in this section applies to this unfortunate person.

To briefly summarize, a colloidal motor, like any other microorganisms moving in water at the nano- and microscale, faces the challenge of Brownian motion, which constantly reorients the particle, and low Reynolds number hydrodynamics, which forbids reciprocal propulsion and severely limits the energy efficiency. In the next section, we examine more closely the various propulsion mechanisms developed to break the shackle of the scallop theorem and power colloidal motors.

5. Propulsion Mechanisms

The scallop theorem forbids reciprocal motion from powering colloidal motors, therefore new designs and new mechanisms unfamiliar to us high *Re* dwellers must be developed instead. There have been numerous review articles that comprehensively discussed these mechanisms (see references in the Supporting Information). Here, we focus on systems powered by chemical reactions or external power sources, with an emphasis on their most fundamental and generic features. Readers are particularly advised to pay close attention to the role of asymmetry. In addition, although these mechanisms differ in many ways, a common feature is an extremely low energy conversion efficiency, often several orders or magnitude lower than unity. Understanding and improving this number represents a major challenge that this research field is currently facing.

5.1. Chemical propulsion

Broadly speaking, there are three major ways chemical reactions can propel colloidal motors: self-electrophoresis, bubble propulsion, and self-diffusiophoresis (Figure 3). One of the earliest examples of colloidal motors was propelled by an asymmetric and catalytic decomposition of H_2O_2 on bimetallic microrods (e.g., Au–Pt, synthesis introduced in section 6).[1a] For this type of colloidal motor, the oxidation and reduction of chemicals occur preferentially on either side of the asymmetric/Janus particle. The asymmetric generation and consumption of ions around the particle establishes a local electric field, which moves the charged particle similar to electrophoresis. This mechanism, illustrated in Figure 3a, was therefore termed *self-electrophoresis* (and less commonly *auto-electrophoresis*),[27] with "self" referring to the fact that the electric field driving the motor is generated by the motor itself. Although the catalytic decomposition of H_2O_2 is a popular choice, redox reactions involving other chemicals such as N_2H_4[28] and Br_2/I_2[29] can also propel Janus particles with self-electrophoresis. This mechanism is arguably the most well understood mechanism for colloidal motors, although other mechanisms could contribute concurrently.[30]

Self-electrophoresis is also responsible for many light-powered colloidal motors,[31] which are typically photo-semiconductor microparticles made into a Janus structure. Unlike bimetal-

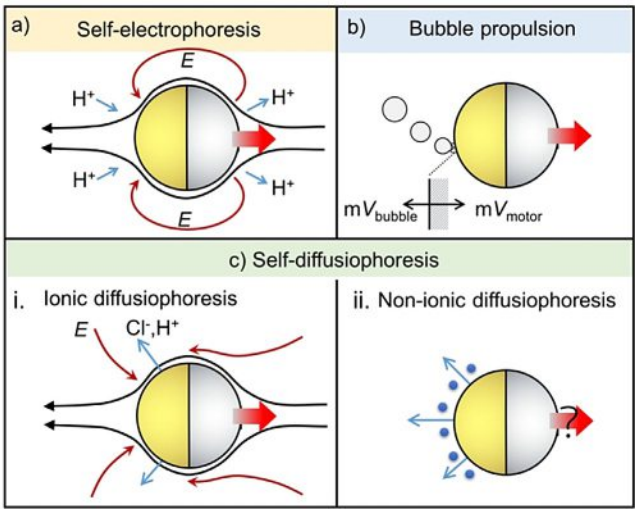

Figure 3. Mechanisms for chemical propulsion. Flow lines (black arrows), the flux of chemicals (blue arrows), and electric field lines (red arrows) are for illustrative purpose only. Large red arrows indicate the moving direction of a motor. Inset in b) illustrates the momentum transfer between a bubble and the motor.

lic rods, which spontaneously split a redox reaction into two half reactions occurring on each side, a photo-semiconductor produces electron–hole pairs when irradiated with light of proper wavelength. Electrons and holes then migrate to different parts of the particle where reduction and oxidation half reactions occur. Ions are then asymmetrically produced, and the electric field drives the colloids in the same way as bimetallic rods. For example, TiO_2 microspheres half-coated with SiO_2 (serves as the inert hemisphere) move in water away from the SiO_2 side when irradiated with UV light.[32] Its motility significantly increases upon replacing SiO_2 with metal (gold or platinum), which facilitates the electron–hole separation and collects the electrons efficiently.[33] Adding oxidative (e.g., H_2O_2) or reductive (e.g., methanol) chemicals into the solution also speeds up the motors.

The decomposition of H_2O_2 can lead to a completely different propulsion mechanism, which is often referred to as bubble propulsion or bubble recoil (Figure 3b).[34] To elaborate, H_2O_2 decomposes into O_2, and oxygen bubbles are produced when the amount of O_2 exceeds the local solubility limit. When a bubble detaches from the surface of a microparticle (or the inside surface of a microtube, see section 6 for details), its momentum is transferred to the particle and pushes it in the opposite direction (Figure 3b, inset). A number of papers have studied the mechanism theoretically,[34b,35] and usually a tube structure or a relatively large catalytic surface (such as a 5 μm SiO_2 microsphere half-coated with Pt) is needed for bubbles to form.[36] Furthermore, any chemical reaction that produces bubbles can enable bubble propulsion, including recent examples of the reaction of Al with alkaline[37] or Mg/Zn with water.[38]

A third mechanism by which chemical reactions can power colloidal motors is self-diffusiophoresis.[39] As the name suggests, this mechanism is a result of the asymmetric diffusion of chemical species produced from a particle surface. As nearly all chemical reactions involve diffusion of some species, this mechanism applies to most, if not all, of chemically powered colloidal motors. Having a basic understanding of what it is and is not therefore carries significant value.

To begin with, there are two types of diffusiophoresis, namely ionic (also called electrolyte) diffusiophoresis (Figure 3c, i), and non-ionic (also called non-electrolyte or neutral) diffusiophoresis (Figure 3c, ii), arising from the diffusion of ionic and non-ionic/neutral chemical species, respectively. A colloidal particle with a surface chemical reaction that produces ions is affected by ionic diffusiophoresis, and its speed is governed by:[40]

$$U = \underbrace{\frac{\nabla c}{c_0}\left[\left(\frac{D^+ - D^-}{D^+ + D^-}\right)\left(\frac{k_B T}{Ze}\right)\frac{\varepsilon\zeta_p}{\eta}\right]}_{\text{Electrophoretic Term}} - \underbrace{\frac{\nabla c}{c_0}\left[\left(\frac{2\varepsilon k_B^2 T^2}{\eta Z^2 e^2}\right)\ln\left(1-\tanh^2\left(\frac{Ze\zeta_p}{4kT}\right)\right)\right]}_{\text{Chemiphoretic Term}} \quad (5)$$

where ∇c is the electrolyte gradient, c_0 is the electrolyte concentration, D^+ and D^- are the diffusion constants of the cation and anions, k_B is the Boltzmann constant, T is the temperature, Z is the valence of the electrolyte, e is the elementary charge, ε is the solution permittivity, η is the dynamic viscosity of the solution, and ζ_p is the zeta potential of the particle.

To briefly and qualitatively explain Equation (5), let us use AgCl particles as an example,[41] which under light decompose into Ag and release H^+ and Cl^- of different diffusion coefficients. To maintain the charge neutrality in the bulk solution, an electric field pointing toward the particle is spontaneously formed, which speeds up the slower ion (Cl^-) and slows down the faster one (H^+). This local and self-generated electric field then moves the charged particle in a way similar to self-electrophoresis (see ref. [41] for a mechanistic study of how exactly this propulsion occurs). The electrophoretic term in Equation (5), which we just described, is highly dependent on the difference in diffusivity between the cation and anion. Moreover, besides inducing individual propulsion, this self-generated electric field also pushes and pulls nearby particles (inert and active alike) and induces collective behavior such as schooling and predator–prey dynamics, a topic discussed in numerous other review articles.[5c,16,42] The chemiphoretic term in Equation (5), on the other hand, considers the electrostatic interaction between the released ions and the particle surface,[39b] and is often much weaker than the electrophoretic term.

What if the reaction only produces neutral molecules? In this case, there will be no electric field, but the molecules interact with the particle through forces beyond electrostatics, such as van der Waals forces, excluded volume effects, etc. The particle speed is governed in this case by Equation (6):[39b]

$$U = \frac{k_B T}{\eta} K L \nabla C \quad (6)$$

where *K* and *L* together determine the way and strength of the solute–particle interaction. Although this equation appears much easier than that of electrolytes [Eq. (5)], *it is actually much harder to use* because neither the sign nor the magnitude of *K* or *L* are easy to predict or measure. Most studies on colloidal motors driven by non-ionic self-diffusiophoresis are theoretical, and we are not aware of any experimental measurement of the solute–particle interactions. In fact, to the best of our knowledge, there is no experimental report of colloidal motors driven undeniably and solely by non-ionic self-diffusiophoresis, as it is often challenging to rule out the possible existence of charged intermediates or the contributions from electrokinetics. Therefore, although it is often tempting and convenient to point to non-ionic diffusiophoresis to predict or explain experimental observations, **great caution** is advised because it is often challenging to prove or disprove this mechanism.

For readers interested in more in-depth discussions on diffusiophoresis, an expanded and excellent introduction to ionic self-diffusiophoresis can be found in ref. [39d], whereas the review article by Moran and Posner did a great job elucidating non-ionic self-diffusiophoresis.[43]

The various chemical mechanisms discussed in this section can be a bit confusing to beginners. They are summarized in a flow chart in Figure 4 to help you identify what the operating

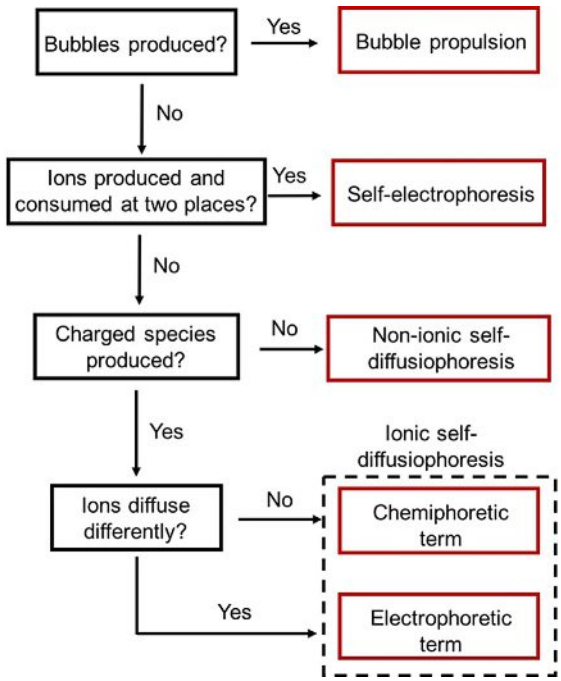

Figure 4. Identifying the mechanism for a colloidal motor.

mechanism is for a particular colloidal motor. Please keep in mind, however, that this chart should only be used as a general guidance rather than strict criteria, as exceptions do exist (and that's usually the fun part of the game).

Before we close this section, we touch upon one particular colloidal motor system to showcase the coexistence of simplicity and complexity often encountered in this research field. Owing to their simple fabrication, easy visualization, and seemingly straightforward mechanism, Pt-coated dielectric microspheres have become arguably THE most popular model system of colloidal motors, especially among physicists. For a long time, people regarded it as being driving by non-ionic self-diffusiophoresis, as Pt catalyzes the decomposition of H_2O_2 into O_2 yet no bubbles are seen locally. However, a few recent studies have revealed hidden layers of complexity. In particular, experiments show that these motors slow down in solutions of added salt.[44] Such a decrease in speeds at high ionic strength is commonly regarded as a hallmark of an electrokinetic propulsion, and strongly suggest that Pt Janus motors are driven by a self-generated electric field, rather than by non-ionic diffusiophoresis. Alternative mechanisms similar to self-electrophoresis have therefore been proposed that consider factors such as the non-uniformity of the coating thickness,[44b] charged intermediates,[44] and bulk association and dissociation of chemical species.[45] Details of these studies could appear intimidating to beginners, but you are advised, above all, to be aware of the electrokinetic effect and related controversy/complexity when using and discussing this particular motor system.

As a side note, although useful for producing thrust, oxygen bubbles are often a reoccurring nightmare for colloidal motors powered by H_2O_2, regardless of whether the mechanism is electrophoresis or diffusiophoresis, as the bubbles often obstruct the field of view, creating trouble for visualizing and tracking motors, and their growth and burst move particles uncontrollably. This is a practical issue that is hardly solved (see ref. [46] for a workaround), and puts a particularly serious constraint on studies of chemical motors in dense populations.

5.2. External powers

The other large category of colloidal motors is those powered by external power sources, including electric fields, magnetic fields, heat, ultrasound, and light. Although in most cases the underlying principle is always to break the symmetry, exactly how this is achieved can be vastly different in each case.

Electric fields have historically been known to drive the motion of colloidal particles through electrophoresis. However, to electrically power individual colloids into independent motion requires special designs. The literature presents four major ways to do this, and both direct and indirect current (DC/AC) electric fields can be used. First, DC electric fields can induce chemical reactions, which further induce motion by electrophoresis, diffusiophoresis, or bubble propulsion. A typical example is bubble-propelled conducting microobjects undergoing bipolar electrochemistry between two electrodes (Figure 5a).[48] Second, a DC electric field can also induce an electrokinetic effect called Quincke rotation (Figure 5b), and dielectric microspheres immersed in liquid of low conductivity can, as a result, rotate and move forward.[49] Third, a diode can rectify an alternating electric field into direct current, inducing electrokinetic flows and therefore self-propel (Figure 5c). This has been demonstrated with diodes of millimeter sizes,[50] and rod diodes a few micrometers long.[51] Finally, the two sides of

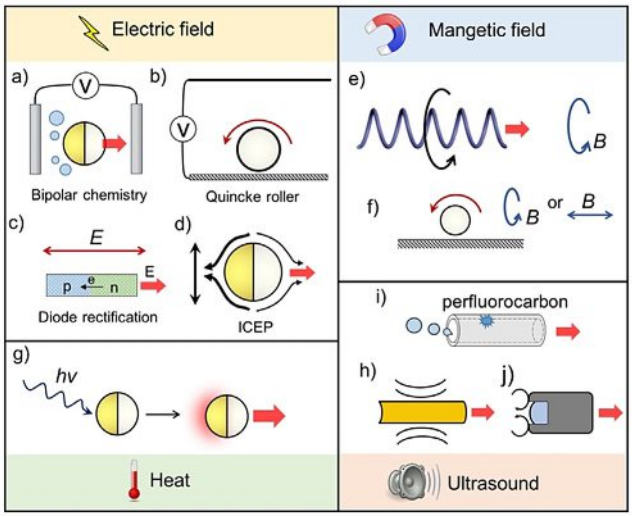

Figure 5. Mechanisms for externally powered colloidal motors (see main text for detailed descriptions). a)–d) Motors powered by electric fields through various mechanisms. e) A helical microparticle rotates along its long axis and moves forward in a rotating magnetic field. Reprinted with permission from ref. [47]. Copyright: 2014, Royal Society of Chemistry. f) A magnetic particle rolls near a surface in a rotating or oscillating magnetic field. g) A Janus particle undergoes thermophoresis by a light-induced temperature gradient. h–j) Ultrasound powered motors, including an asymmetric microrod moving owing to local microstreaming (h), a microtube ejecting bubbles as perfluorocarbon vaporizes under ultrasound (i), and a microparticle moving away from an oscillating bubble trapped at a cavity (j).

a metal-dielectric Janus microparticle polarize differently under AC electric fields, leading to asymmetric electroosmotic flows, which propel the particle away from the metal hemisphere (Figure 5 d). Colloid motors powered by this so-called induced charge electrophoresis (IECP) effect have become a popular model system in soft matter research in recent years.[4a, 52]

Magnetic fields have also become a popular choice for powering colloidal motors, mostly because the ease of use and relatively straightforward mechanisms.[53] Primarily, there are two ways magnetic fields can propel colloidal motors. First, a magnetic colloid can move in low Reynolds number fluid by deforming its body in a non-reciprocal way (i.e., not just simply back and forth) in response to a rotating or oscillating magnetic field (Figure 5 e). Prominent examples include microhelices (described in section 6 and Figure 6 e) and either flexible chains of magnetic beads[54] or flexible metal/polymer segments in a microrod.[55] The second way magnetic fields drive colloidal motors relies on a surface, where a rotating magnetic colloid experiences a larger hydrodynamic drag closer to the surface than the side further away from it (Figure 5 f). This asymmetry gives rise to a class of magnetic colloidal motors called "surface walkers" (see ref. [56] and references therein), which can be rods, spheres, dimers, chains, and many other configurations. Note that although magnetic field gradients can certainly exert a force on a magnetic particle and pull it, this is rarely considered as self-propulsion as a colloidal motor does not simply respond to an external gradient, as we discussed in section 2.

Heat powers colloidal motors by self-thermophoresis,[57] which relies on an asymmetric distribution of fluid temperature around a particle. This is commonly achieved by illuminating a Janus particle half-coated with a material with a large extinction coefficient, which releases a large amount of heat when illuminated with light of proper wavelengths (Figure 5 g). Typical examples are dielectric microspheres half-coated with a thin layer of gold or carbon, which under infrared light heats up and produces a temperature difference of a few degrees K between the two hemispheres, large enough to propel the particle.[57d] Note that in a special design such a temperature difference can lead to de-mixing of local binary mixtures,[58] and thus move the particle by diffusiophoresis. Besides the photothermal effect described above, other endo- or exothermic processes such as chemical reactions and magnetic hysteresis can also be exploited to drive a Janus particle, yet experimental examples are rare.[57c]

Motors powered by ultrasound have recently appeared in the spotlight,[59] because the wide expectation of colloidal motors being applied in biomedical settings requires a power source that is biocompatible and easily accessible in hospitals. For example, surprising experimental discoveries in 2012 that metallic microrods can be propelled into fast motion and rotation by resonating megahertz ultrasound raised widespread interest (Figure 5 h). Around the same time, microtubes filled with perfluorocarbon were shown to move like bullets as perfluorocarbon vaporizes under ultrasound (Figure 5 i).[60] The third type of examples are microstructures that trap air bubbles when immersed in water, which upon ultrasound radiation produce acoustic streaming, which propels the particle (Figure 5 j).[61] Over the last five years or so, through a collaborative effort around the globe, we now stand in a much better position to understand and control the dynamics of colloidal motors with ultrasound.[62] Applications have also emerged in drug and gene delivery,[63] intracellular transport,[64] sensing,[65] and many other fronts. The three examples introduced here represent three fundamentally different mechanisms of how ultrasound can propel a colloidal motor, each with their unique features and disadvantages, and perhaps only good for a particular type of application.

Finally, light as an abundant and tunable energy source offers tantalizing possibilities to power colloidal motors.[31a–c, e, 66] Indeed, numerous reports have studied using light of various wavelengths to power and steer colloidal motors. However, light itself is rarely the energy source, except in a handful studies involving photon-nudging.[67] Rather, it is often a secondary effect originated from illumination, be it photothermal effect from metal plasmonics, or photochemical reactions and the resulting phoresis, that ultimately moves the particle.

5.3. Other mechanisms

A few less common propulsion mechanisms fall outside the realm of either chemical or external propulsion. Among them, colloidal motors driven by the Marangoni effect and biohybrid motors are particularly worth mentioning. A colloidal motor powered by the Marangoni effect changes the surface tension

of its environment by releasing or consuming certain chemicals.[68] The resulting surface tension gradient along its body pulls the particle towards where the surface tension is higher. The most typical example is perhaps a camphor particle floating on the surface of water.[69] It is pulled forward by releasing camphor at its rear, which lowers the surface tension of water upon dissolving. An interesting and useful feature with camphor boats and Marangoni colloidal motors in general is the emergence of collective behaviors[70] or even oscillation,[71] enabled by an interaction among each other's gradients and hydrodynamics.

Although the concept of bionic robots has been around for some time, combining living microorganisms and synthetic colloids into a functional biohybrid microbot is a relatively new idea.[72] Recent examples include spermbots, a sperm cell trapped in a magnetic microtube,[73] as well as bacteria in conjunction with microtubes, beads, or red blood cells.[74] The benefit of biohybrid colloidal motors is quite straightforward, as it combines the versatility of synthesis and functionalization of synthetic materials with the inherent motility and sensing capability of bacteria or sperm cells. However, interesting prospects for collective behavior or emergent intelligence, hallmarks of many living systems, have not been explored with these biohybrids.

To briefly summarize, we have in this section highlighted the various mechanisms by which a colloidal motor can self-propel. A central theme is asymmetry, either in the distribution of chemicals, or in the acquisition of external energy, which gives the motor its directionality. In addition, propulsion mechanisms require special materials that are either chemically active or responsive to other environmental stimuli (heat, light, electromagnetic waves, or sound). Both the asymmetry and materials thus become key factors to consider when fabricating colloidal motors, which will be discussed in the following section.

6. Making Colloidal Motors of Various Structures

Having familiarized ourselves with the various ways colloidal motors move, we now describe how colloidal motors are made. Although motors of a wide range of structures, compositions, and shapes have been fabricated, the general principle is to make an *asymmetric particle made of active materials*, as mentioned at the end of the last section. In this section, we are going to focus on the fabrication strategies of the most common and important types of colloidal motors: bimetallic microrods, Janus microspheres, microtubes, and microhelices. A comprehensive summary of how colloidal motors of these types and beyond are fabricated can be found in ref. [15].

The earliest colloidal motors, bimetallic microrods moving in H_2O_2, were first discovered around 2004.[1] A typical example is gold–platinum (Au-Pt) rods, made by electrodepositing metal segments in porous templates, a technique called template-assisted electrodeposition (Figure 6a).[79] Rods of different metal combinations can be easily made by this technique, with tunable lengths and diameters. Empirically, the longer the rods, the more slowly they move in H_2O_2.[80] Sometimes ruthenium (Ru) or rhodium (Rh) segments are grown instead of platinum to reduce the amount of oxygen bubbles (Pt is one of the best catalyst for H_2O_2, whereas Ru and Rh are less active[81]).

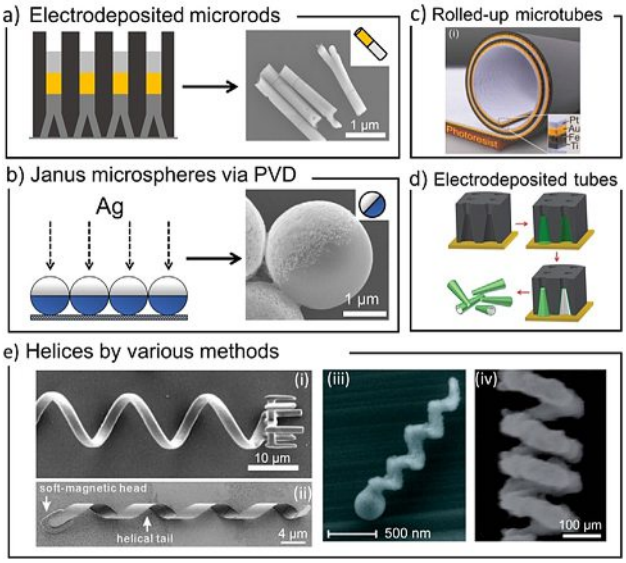

Figure 6. Typical structures of colloidal motors. a) Electrodeposited microrods. Left: cartoon illustration of the deposition process in anodized aluminum oxide (AAO) membranes. Right: A scanning electron microscope (SEM) image of fabricated microrods. b) Janus microspheres fabricated by physical vapor deposition (PVD). Left: a layer of microspheres is coated with a thin layer of silver. Right: a SEM image of fabricated Janus microspheres. c) Reprinted with permission from ref. [75]. Copyright: 2009, John Wiley and Sons. d) Reprinted with permission from ref. [33a]. Copyright: 2011, American Chemical Society. e) Helical micromotors fabricated by two photon lithography (i, reprinted with permission from ref. [76]. Copyright 2012, John Wiley and Sons), self-rolling/strain engineering (ii, reprinted with permission from ref. [77]. Copyright: 2009, AIP Publishing), glancing-angle deposition (iii, reprinted with permission from ref. [78]. Copyright: 2009, American Chemical Society), and dealloying of Cu-Pd nanorods (iv, reprinted with permission from ref. [47]. Copyright: 2014, Royal Society of Chemistry).

Around the same time as the discovery of rod motors, Janus microspheres were discovered to move in H_2O_2, too.[20] These particles are typically silicon dioxide or polymer (e.g., polystyrene) microspheres half-coated with a thin layer ($\approx$10 nm or less) of platinum. The coating is often made through physical processes such as thermal/e-beam evaporation or sputtering (Figure 6b). The term "Janus" is derived from the Roman god Janus, and refers to the particle asymmetry.[82] Microspheres are commercially available, uniform in size, and the physical fabrication of Janus particles is robust and straightforward. These benefits have therefore made Pt-Janus motors one the most popular active colloid systems, especially among physicists. Titanium oxide or other photosemiconductors can also be coated on the microspheres or used as the core, and the resulting Janus particle becomes photo-active (see section 5.1 for more details of their operations).[32,33b,83] Other variations of Janus motors, such as dimers and patchy particles,[84] can also be fabricated to break symmetry.

Microtubes have become a popular structure for bubble-propelled colloidal motors in recent years.[36a,85] Bubbles are

often produced inside the tube by catalytic reactions and ejected from one end of the tube, propelling it forward in a recoil mechanism discussed in section 5.1. Microtubes can be fabricated in a number of ways, and the most popular methods are 1) metal (or semiconductor) thin films spontaneously rolling into tubes when peeling off a substrate[86] (Figure 6c), and 2) electrodepositing metals or polymers preferentially on the inside of a porous membrane[33a,75,87] (Figure 6d). Both methods offer many possibilities to tailor the structure, composition, and functionalization of these tubes. Other methods, such as assembly of polyelectrolyte,[88] have also been developed. In addition, fabricating tubes with one opening smaller than the other so bubbles can eject more directionally, as well as functionalizing its inner surface with proper catalysts both require special techniques and skills. The major advantage of microtubular motors is the relatively straightforward propulsion mechanism, which is tolerant to salt and many contaminants, and produces a large propulsive force. This type of colloidal motor is therefore heavily studied for applications.

Another notable class of colloidal motors have twisted bodies (Figure 6e). For example, microhelices can be made by strain-engineering a thin strip of metal by microfabrication techniques,[77] glancing-angle deposition of materials on top of a monolayer of microspheres,[78,89] dealloying of microrods from electrodeposition,[47] or by two photon lithography (basically ultra-fine 3D printing).[76] An interesting alternative is inspired by nature, where helical structures such as vascular plants[90] or algae[91] can serve as templates. Colloidal motors with twisted bodies move by converting rotation about their long axes into a directional motion along this axis, and this can be done by magnetic fields or chemical reactions.

Finally, we touch upon a few other notable types of colloidal motors. Motors don't have to be solid. Liquid metal droplets can move,[92] and so do droplets of other liquids[93] such as liquid crystals,[94] ionic liquids,[95] and emulsion droplets.[37,68,96] Gel microparticles can move too, but examples are few.[97] In a different sense, non-solid particles can have holes or pores, and these porous particles move by enzymes or catalytic nanoparticles that are hosted on their surfaces, facilitated by the greatly expanded surface areas.[98] Stomatocyte motors fabricated by clever self-assembly of macromolecules have an interesting bowl-shape, where embedded active species such as enzymes or Pt nanoparticles catalyze reactions and produce bubbles.[99] Furthermore, in some cases, a group of particles are assembled through various mechanisms and become motile, whereas an individual particle is unable to do so or moves in different ways.[100]

To summarize, we have mainly introduced in this section the fabrication of colloidal motors of rod, tubular, spherical, and helical shapes. Both chemical and physical methods can be used, but with their own advantages. For example, chemical methods are useful for producing motors in large quantities but suffer from lower polydispersity, whereas physical methods are better in precision and uniformity (think about a layer of uniformly distributed Janus microspheres, or an array of microhelicies by two photon lithography), but yields are limited.

7. Using Colloidal Motors

As was briefly discussed earlier, much of the academic and popular interest in colloidal motors stems from the possibility of using them as nanorobots in various scenarios. The core functionalities of colloidal motors in these applications can be roughly categorized into sensing (Figure 7a), cargo loading/unloading and transport (Figure 7b), mechanical forces (Figure 7c), and navigation (Figure 7d), and the principles for realizing each functionality will be briefly discussed in this section.

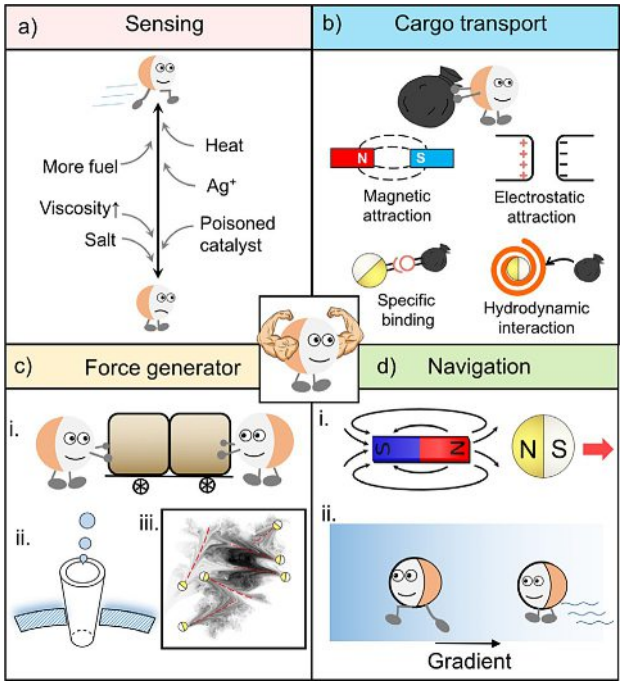

Figure 7. Core functionalities of colloidal motors. a) Sensing. A colloidal motor can sense the local environment by changing its speed in response to various cues present in the medium. b) Cargo transport. A colloidal motor can pick up cargos by a number of strategies. c) Force generator. i: Colloidal motors assemble two pieces of cargo by mechanical forces. ii: A microtube with a sharp tip penetrates into a membrane. iii: Moving colloidal motors stir and mix inhomogeneous solutions. d) Navigation. Two popular ways to steer a colloidal motor is by i) magnetic fields and ii) chemotaxis/phototaxis from a gradient.

7.1. Sensing

The speed of a colloidal motor is often sensitive to its surroundings. For a chemically powered colloidal motor undergoing self-electrophoresis, for example, its speed decreases as the fuel concentration (e.g., H_2O_2)[1a] or the solution temperature (i.e., decreasing reaction rate) decreases,[101] or as the solution conductivity (i.e., ionic strength) increases.[27b] In addition, silver ions are found to significantly increase the speed of bimetallic rods and Pt-coated Janus particles in H_2O_2 by enhancing their catalytic performance.[17b,102] Moreover, bubble-propelled micromotors move slower at higher viscosity[34b] or in the presence of chemicals that poison the surface catalyst (Pt).[103] Therefore, a moving colloidal motor senses the local environ-

ment and responds with an increase or decrease in its speed, which becomes the output signals (Figure 7a). Depending on the nature of the analytes, the motor could serve as a viscometer,[104] pH meter, pollution sensor, or biochemical sensor.

7.2. Controlled cargo loading/unloading and transport

Developing micromachines that cruise inside human bodies and treat disease is perhaps the holy grail of microrobotics research, and this ambition has fueled a large body of research on using colloidal motors as cargo carriers. Depending on the choice of motors and cargos, and their functionalization, cargos can be attached to the motors by electrostatic forces (i.e., binding between oppositely charged particles),[105] magnetic forces (i.e., both the motor and cargo are magnetized and attract to each other),[105b,106] or specific bindings (e.g., streptavidin–biotin interactions, receptors, etc.; Figure 7b).[107] Even hydrodynamic interactions can be used. For example, a microbead can be towed by the hydrodynamic vortex behind a rotating colloidal motor,[108] or by suction from a microtube.[109] A porous colloid particle, such as mesoporous silica,[110] nanoporous metal,[63a] or a polymer network[111] is often required to load smaller cargos such as drug molecules. A motor towing cargoes is known to move slower than a free motor, as the more cargo it carries the larger the moving assembly is, and the slower it moves, following the simple Stoke's drag argument [Eq. (3) and (4)].[109,112] Once the cargo-carrying motor reaches its destination, the cargo can be released in a number of ways, which correspond to the loading strategies. However, a strong binding strategy usually means difficult unloading, and satisfying both needs is still a major challenge today.

7.3. Force generator (mixer)

A moving colloidal motor exerts forces to its surroundings in two ways: propulsive force and fluid flows (Figure 7c). For rod-shaped motors, such as metallic microrods moving in ultrasound and microtubular motors moving by bubble recoils, a typical propulsive force is on the order of 1–10 pN (assuming speeds on the order of $\approx 10\ \mu m\ s^{-1}$), whereas their relatively sharp tip means pressure on the order of 10 Pa. Forces and pressures of such magnitudes can be used to push or pull microscopic cargos (Figure 7c, panel i), or could even penetrate into soft tissues or polymer particles (panel ii),[108,113] although cell membranes (elastic modulus on the order of 1000 Pa) are probably too rigid to be penetrated. Recent advances in faster and stronger colloidal motors could very likely break this record, and smash microscale structures and even tissues like a bullet.[113,114] On the other hand, moving colloidal motors are often considered as micromixers, inducing strong local convective flows as they move through liquid (panel iii). In this way, they greatly accelerate mass transport, which is otherwise slow by pure diffusion, and chemicals such as dye molecules, organic pollutants, or drugs can be dispersed, collected, or neutralized much faster.[115]

7.4. Navigation

Many of the proposed applications for colloidal motors require control over their directionality, but this can be a challenging task given that Brownian motion constantly nudges the motors away from their original path, as well as that imperfect fabrication often leads to circular trajectories. The most popular way to steer a moving colloidal motor is perhaps by magnetic fields (Figure 7d, panel i),[116] and this naturally requires the motor to be magnetic, which can be done by incorporating magnetic segments, coatings, or nanoparticles (Ni, Fe, or Fe_3O_4) into the design of motors. The downside of magnetic steering is that it requires a somewhat sophisticated setup (e.g., Helmholtz coils), and all motors are steered in the same direction (i.e., moving non-autonomously). A second method to impart directionality to random colloidal motors is taxis, for example, phototaxis or chemotaxis (Figure 7d, panel ii).[117] This biomimetic approach, as employed by many bacteria, algae, and other microorganisms, uses a gradient of environmental signals (light in phototaxis and chemicals in chemotaxis), and colloidal motors respond by moving up (positive taxis) or down (negative) the gradient. Although taxis is potentially useful in guiding motors to move autonomously and independently towards their target (such as tumor sites), it is a very weak driving force. Additionally, we are only in the early days of understanding how different types of colloidal motors move in gradients. These challenges limit the usefulness of this steering mechanism.

7.5. A few other notes

Although a moving motor can do many things, fixing it to a surface converts a motor to a pump, which has many unique advantages and applications and has been reviewed elsewhere.[118] In addition, being fixed and often larger, a micropump is an easier target than colloidal motors for mapping out distributions of chemical gradients, electric fields,[119] and flow profiles. It therefore serves as a convenient model for fundamental studies of motors operating with the same mechanisms.[120]

We have intentionally left out a detailed presentation of exactly what these motors can be used for. Importantly, focusing on these four major functionalities rather than countless examples of how they are applied saves a beginner from the labor of combing through the vast amount of literature, which, for interested readers and more specific applications, have been very nicely reviewed (biological applications,[11a,c–k,121] environmental applications,[12a,d–g,122] and security/defense applications[123]).

Finally, we offer a quick comment on selecting the right type of colloidal motors for a particular purpose. On the fundamental side, a clean, simple motor system is desired as a model system to study non-equilibrium thermodynamics and active matter. As a result, motors that produce bubbles are generally considered a bad choice (typically any motor that relies on H_2O_2). Motors powered by electrophoresis/diffusiophoresis are sometimes considered tricky and "not clean" by

physicists, as these motors introduce complicated interactions (electrostatic, electrokinetics, hydrodynamics, dipolar, steric, to name a few) among each other and with their environments. But it is often this complication that leads to collective behavior and unusual dynamics in complex environments. Nevertheless, electrically powered colloidal motors, such as Quincke rollers and ICEP swimmers (introduced in section 5.2), have recently gained more popularity in the physics community over classic Pt-coated motors in H_2O_2 especially for the study of collective and emergent behaviors.

On the application side, it is often the proper selection and compromise of the four functionalities in this section that determine the usefulness of a colloidal motor. For example, biomedical applications of colloidal motors require a propulsion mechanism that is controllable, tolerant of high salt concentrations (phoretic motors are no good), and biocompatible (motors powered by toxic fuels such as H_2O_2 are no good). Motors powered by magnetic fields or ultrasound are the more promising candidates for this purpose, whereas infrared light driven phoretic motors, although suffering from a few limitations, have the unique possibility of chemotactic targeting capability. Environmental applications and in vitro biosensing are more lenient in the choice of motors, with perhaps a different emphasis on proper surface functionalization, which enables cargo delivery or surface reactions.

8. Tools and Techniques

This section introduces a number of common techniques and tools useful for the research of colloidal motors, which also serves as vivid testimony to the interdisciplinary nature of this field. Be mindful of this nature, as perhaps no two groups in the world share exactly the same set of visions and skills. Therefore, although you are advised to learn broadly, pay attention to the unique pros and cons of each technique, and assemble a toolbox that is the best for you and your group.

Most often, motor experiments start with sample preparation (Figure 8a). This includes making colloidal motors through any of the methods we have introduced in section 6, which often involve physical or chemical synthesis. Then, depending on how these motors are powered, introduced in section 5, a proper experiment setup is needed, which could include an experimental chamber filled with aqueous colloidal suspension, Helmholtz coils for magnetic manipulation, or light sources of particular wavelengths. Experiment setups are connected to a microscope (Figure 8b), arguably the most important piece of equipment for colloidal research. Both upright or inverted microscope configurations, and both bright field or dark field microscopy, can be used, each with unique advantages. Sometimes, more advanced microscopy techniques, such as confocal scanning laser microscopy (CSLM) or super-resolution microscopy, are needed for specific purposes. The choice of microscopes, lens (with various magnification and immersion techniques), optical filters, and light sources is an art, which greatly affects the outcome of your experiments. And like any other art form, it takes practice to perfect.

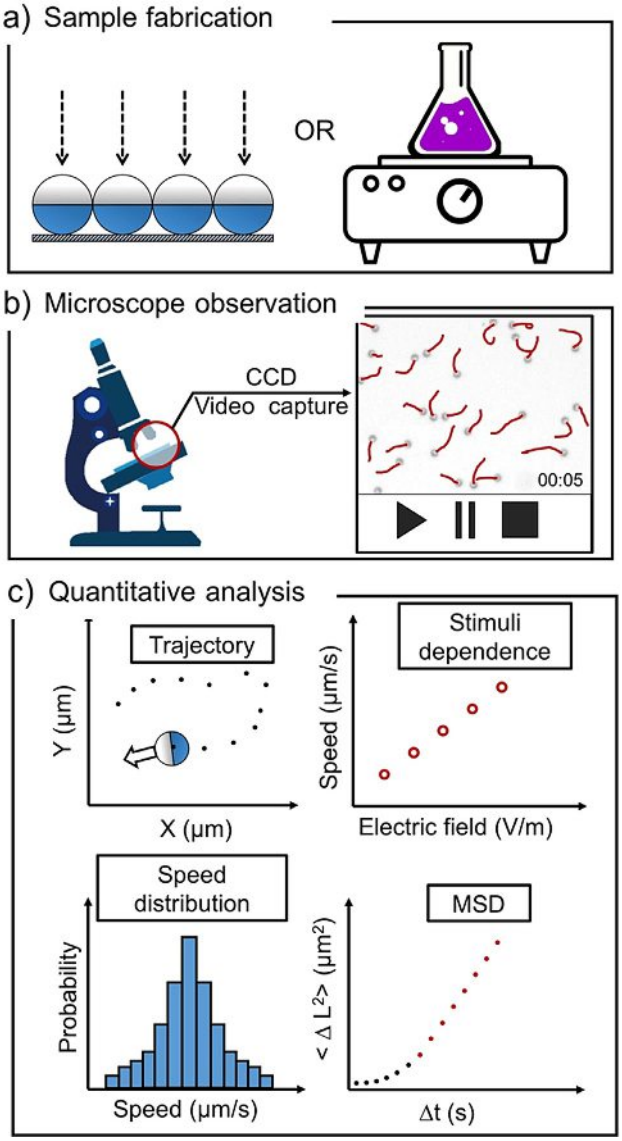

Figure 8. Schematics for the basic tools and techniques for colloidal motor research. a) Motors are commonly fabricated by physical (left) or chemical (right) methods. b) Motors are observed by a microscope, and cameras are used to record videos for further analysis. Left: an upright microscope is given as an example. Right: a real optical micrograph of many Janus microspheres moving under AC electric field, with arbitrary red lines to indicate trajectories. c) A few common techniques for analyzing the dynamics of moving colloidal motors. Top left: trajectory of a motor; top right: how the average speeds of the entire motor population change with the strength of the stimuli (e.g., electric field or concentrations of chemicals); bottom left: distribution of speeds of a population of motors is often Gaussian-like; bottom right: mean squared displacement (MSD) analysis of motors, with red and black data points indicating the diffusive and ballistic regimes, respectively.

What you see under a microscope needs to be stored in a medium suitable for analysis and sharing (Figure 8b). This is done with cameras mounted on microscopes, typically of COMS or CCD technologies. Videos are then saved to computers, where the color, frame rate, length, size, and format of these videos can be processed by software programs such as imageJ.[124] The processed videos are then loaded by computer programs that, based on image processing algorithms, calcu-

late and output the *xy* coordinates of moving colloids. Sometimes other information is extracted, including the orientation of a colloidal motor (for rods as well as for Janus particles with a clear distinction between two hemispheres). Such information extraction can be done by a number of programs, some are proprietary and charge money (such as those from camera manufacturers), some are open source (e.g., Video Spot Tracker,[125] imageJ plugins, and Physmo[126]), and others are homemade (e.g., MATLAB codes). Needless to say, the quality of particle tracking of the chosen program propagates throughout all the following analysis, and thus greatly affects the results you obtain in the end. Tweaking parameters in the program is therefore a common task for getting high quality data.

Once the tracking data (most commonly the 2D coordinates of moving particles) are ready, quantitative analysis become possible (Figure 8c). The most common analysis performed by the majority of researchers include plotting particle trajectories (the line you get by connecting their coordinates over time), calculating motor speeds under various experimental conditions, and calculating the particle directionality (commonly extracted from how straight their trajectories are). Sometimes the distribution of speeds, either among different particles within one frame, or over a period of time for one particle, is plotted to yield more information. In addition, the relative distance and speeds of two or more particles (either motors or passive particles nearby) can often give valuable information on their interactions, whereas more advanced analysis such as correlation in space and time is particularly useful as far as collective behaviors are concerned.

Although instantaneous speeds are a straightforward figure of merit for colloidal motor research, it is less meaningful for slower moving motors where Brownian motion dominates, as well as for nanomotors that do not show significant directionality (discussed in section 4.1). In these cases, mean squared displacements (MSD, see bottom right of Figure 8c) analysis is a better quantification tool, which yields the true, active speed on top of the contribution from Brownian motion. In addition to extracting speeds, MSD analysis is also a powerful tool for dissecting the dynamics of an active particle, and distinguishing it from a Brownian particle. This is done by plotting MSD over different time intervals and examining the power scaling of the curves (i.e., whether the *y* axis scales to the first or second order of the *x* axis). A characteristic MSD plot of colloidal motors shows a smooth transition of power scaling from 2 ("ballistic regime") to 1 ("Brownian regime") at a timescale associated with its rotational diffusion, whereas that of a Brownian particle only shows a straight line. The exact way MSD is calculated and analyzed can be found in the literature.[20,127] Another important tool for colloidal motor research is computer simulation. This is often used in conjunction with experimental investigations to predict and explain, although studies solely focused on simulations are also common, especially in the physics community. Popular simulation methods include molecular dynamics,[74a,128] Brownian dynamics,[129] Lattice Boltzmann,[130] and numerical simulation with programs such as COMSOL,[19,27c] all with their own strengths and limitations, and typically only good for a particular set of problems. The numerous branches of computer simulations and their applications in the study of colloidal motors is a broad subject beyond the scope of this review (and the capability of the authors). A lack of a review article on this specific topic is therefore very unfortunate.

9. Concluding Remarks

By completing this introductory *Colloidal Motors 101* course, you have learned the most basic and important aspects of colloidal motor research, including their scientific nature and significance, fabrication techniques, various propulsion mechanisms, the four major features that enable their application, and various frequently used tools and techniques. The door now opens for you to face some of the most exciting challenges at the forefront of current colloidal motor research, which include (but not limited to) the following:

New fuels for chemical propulsion. The use of H_2O_2 and many other existing chemical fuels is not biocompatible, and phoretic mechanisms are inherently inefficient, especially at high salt concentrations. Alternative fuels for colloidal motors that break these limitations may hold the key for their biomedical applications, and bubble-free chemical motors are highly desired for studies of collective behavior.

Motor–motor interactions and collective behaviors. As colloidal motors almost never move alone (especially true when applications are considered), it is important to understand how they interact with each other and possible collective behaviors. This is also where motor dynamics in a group quickly become complex and even non-linear.

Motors in complex environments. Real environments are never simple, and confinements in multiple dimensions can both pose a serious challenge for the operation of colloidal motors, and significantly alter their dynamics.[18,131] This is particularly relevant to biomedical applications, as human bodies are a naturally complex environment.

Precise control over the dynamics of individual motors through structural design. Many reports have suggested that motor dynamics can be modulated by their shapes and sizes,[132] yet exactly how these features are correlated still remains largely unexplored. In addition, although the art of precise synthesis of large quantities of colloidal particles of specific shapes and sizes is a well-studied subject, this knowledge has not permeated the colloidal motor community.

What is truly required for motors to operate as cancer-fighting microrobots in human bodies? Recent studies[133] have begun to seriously examine the qualities needed to combat the associated scientific and engineering challenges (biocompatibility, steering, cargo loading and unloading strategy, removal after use, etc.), but we could still be far from seeing the whole picture, let alone solving all the issues. This is where a closer collaboration with biomedical engineers and medical doctors is critical.

How to produce a large quantity of colloidal motors in a financially competitive fashion?[134] This is likely required for environmental applications such as removal of pollutants. This question is closely related to another question of whether col-

loidal motors can beat existing technologies for solving practical challenges in either cost effectiveness or energy efficiency. We have so far seen very few studies of head-to-head comparisons, and the common claim that "colloidal motors are faster, stronger, more powerful, and more efficient and therefore useful" simply needs more data to support it.

Is there a killer application? In the possible event that colloidal motors prove to be more expensive or less effective than existing technologies, we need to envision new practical challenges that simply do not have any existing solutions. The *fantastic voyage* vision of microrobots roaming in blood streams is certainly a good start, yet there is a long way to go on this road. The emergence of novel applications that only colloidal motors excel at requires ingenious ideas of every researcher, senior and junior.

Finally, to advance from a beginner to a full-fledged researcher, you are expected to 1) familiarize yourself with past literature; 2) keep yourself updated on recent developments in the field and be aware of the research trends; 3) constantly improve yourself in both skills and knowledge, which could cover material sciences, biology, soft matter physics, hydrodynamics, non-linear sciences and engineering; 4) generate new ideas that are challenging yet feasible, as well as impactful and enticing to a broad audience.

Like in any other field, there are no shortcuts from apprentice to master, and the journey is bound to be rough. But you are warmly invited to join us in this colorful, exciting, and flourishing field of research, and brace yourself for the adventure of your lifetime!

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Conflict of interest

The authors declare no conflict of interest.

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