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Synthesis of Single-Molecule Nanocars

GUILLAUME VIVES AND JAMES M. TOUR*
Departments of Chemistry and Mechanical Engineering and Materials Science,
The Smalley Institute for Nanoscale Science and Technology, Rice University,
MS-222, 6100 Main Street, Houston, Texas 77005

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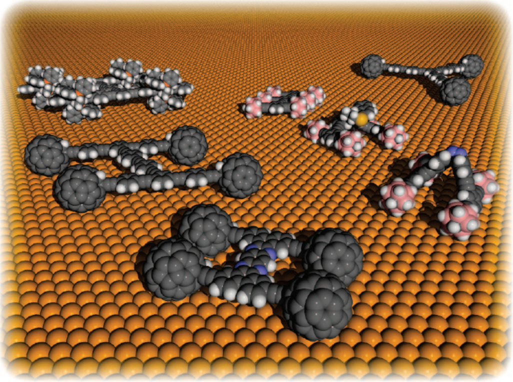

The drive to miniaturize devices has led to a variety of molecular machines inspired by macroscopic counterparts such as molecular motors, switches, shuttles, turnstiles, barrows, elevators, and nanovehicles. Such nanomachines are designed for controlled mechanical motion and the transport of nanocargo. As researchers miniaturize devices, they can consider two complementary approaches: (1) the "top-down" approach, which reduces the size of macroscopic objects to reach an equivalent microscopic entity using photolithography and related techniques and (2) the "bottom-up" approach, which builds functional microscopic or nanoscopic entities from molecular building blocks. The top-down approach, extensively used by the semiconductor industry, is nearing its scaling limits. On the other hand, the bottom-up approach takes advantage of the self-assembly of smaller molecules into larger networks by exploiting typically weak molecular interactions. But self-assembly alone will not permit complex assembly. Using nanomachines, we hope to eventually consider complex, enzyme-like directed assembly. With that ultimate goal, we are currently exploring the control of nanomachines that would provide a basis for the future bottom-up construction of complex systems.

This Account describes the synthesis of a class of molecular machines that resemble macroscopic vehicles. We designed these so-called nanocars for study at the single-molecule level by scanning probe microscopy (SPM). The vehicles have a chassis connected to wheel-terminated axles and convert energy inputs such as heat, electric fields, or light into controlled motion on a surface, ultimately leading to transport of nanocargo. At first, we used C_{60} fullerenes as wheels, which allowed the demonstration of a directional rolling mechanism of a nanocar on a gold surface by STM. However, because of the low solubility of the fullerene nanocars and the incompatibility of fullerenes with photochemical processes, we developed new *p*-carborane- and ruthenium-based wheels with greater solubility in organic solvents. Although fullerene wheels must be attached in the final synthetic step, *p*-carborane- and ruthenium-based wheels do not inhibit organometallic coupling reactions, which allows a more convergent synthesis of molecular machines. We also prepared functional nanotrucks for the transport of atoms and molecules, as well as self-assembling nanocars and nanotrains.

Although engineering challenges such as movement over long distance and non-atomically flat surfaces remain, the greatest current research challenge is imaging. The detailed study of nanocars requires complementary single molecule imaging techniques such as STM, AFM, TEM, or single-molecule fluorescence microscopy. Further developments in engineering and synthesis could lead to enzyme-like manipulation and assembly of atoms and small molecules in nonbiological environments.

Introduction

The drive to miniaturize devices has led to a variety of molecular machines[1−4] inspired by their macroscopic counterparts such as molecular motors,[5−9] switches,[10] shuttles,[11,12] turnstiles,[13] barrows,[14,15] elevators,[16] and nanovehicles.[17] In the current trend of miniaturization of devices, two complementary approaches can be considered. The "top-down" approach consists of reducing the size of macroscopic objects to reach an equivalent microscopic entity using photolithography and related techniques. This approach, extensively

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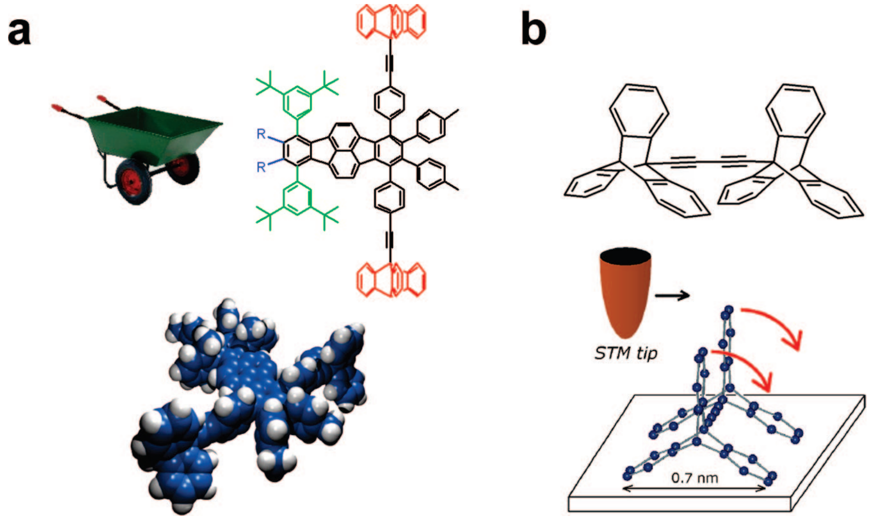


FIGURE 1. (a) Structure of a molecular wheelbarrow and its macroscopic analogue (top) with a side view of the CPK model (bottom) and (b) triptycene dimer axle (top) with a scheme of a manipulation using the STM tip to induce a rolling motion (bottom, arrows indicate the rotation of the wheels). Panel a was reproduced from ref 14 with permission from Elsevier; panel b reproduced from ref 40 with permission from Macmillan Publishers Ltd.

used by the semiconductor industry, is currently nearing its limits in scaling.[18] On the other hand, the "bottom-up" approach consists of building functional micro- or nanoscopic entities from molecular building blocks. This approach, inspired by what natural systems[19,20] are using, holds promise to develop new molecular devices. Among all the molecular machines synthesized by chemists, most of them have been designed to work and to be studied in solution. However, in order to generate useful work for common fabrication, the deposition and study of molecule-sized machines on a surface is an initial crucial step. A few types of surface-mounted molecular machines such as altitudinal[21] and azimuthal[22] rotors, cyclodextrin necklaces,[23] molecular muscles,[24] and molecular shuttles[25] have been prepared and assembled on surfaces. Macroscopic effects have been obtained by molecular machines such as the rotation of a micrometric glass rod on a liquid crystal film doped with a light powered molecular motor.[26] In another example, a millimeter-scale directional transport of a diiodomethane drop across a surface was achieved using a photoresponsive surface based on molecular shuttles.[25] These examples demonstrated that a collective change in a population of molecular motors can be used to move macroscopic-scale objects using some source of energy such as light.

However, the movement of objects at the nanolevel generally remains painstakingly difficult. Nanomanipulators are generally 8−9 orders of magnitude larger than the individual nanoentity that they are intended to manipulate, and they only manipulate one nanosized entity at a time. Following biology's lead, there may be a better way to manipulate nanosized objects by using machines that are close in size to the entities that need manipulation. For example, enzymes can be viewed as nature's nanomachines as they control the transport and placement of molecular-sized entities for the construction of higher order structures. More specifically, the physical transport of oxygen in biological organisms is controlled by nanoscale proteins made specifically for the task. Hemoglobin, the molecule found in red blood cells, efficiently soaks up oxygen in the lungs and deposits it in tissues, then helps to detoxify the tissues by removing CO_2 and protons. Although hemoglobin is part of a passive transport system, biological systems also have self-propelled entities that can transport materials; however, the self-propelled systems are far larger. As nature often propels the nanoscale transporters using gross fields of influence, for example, blood flow made possible by the heart, we too may find that gross fields, such as electric field gradients, are the optimal way to manipulate nanosized cargo carriers. We are also investigating the use of passive transporters that are hemoglobin-like, as well as active transporters that have imbedded nanomotors that could be actuated. These studies may end up suggesting that the nanosized systems are more easily moved and controlled by external fields rather than imbedded motors, but we hope to explore both. In addition, many enzyme molecules function in large groups suggesting that interactions between proteins could strongly affect the dynamic properties of biological nanomachines. The control of biological nanosystems via chemical couplings of individual molecules might be another fundamental principle of their functioning, and that too is being excitingly explored.

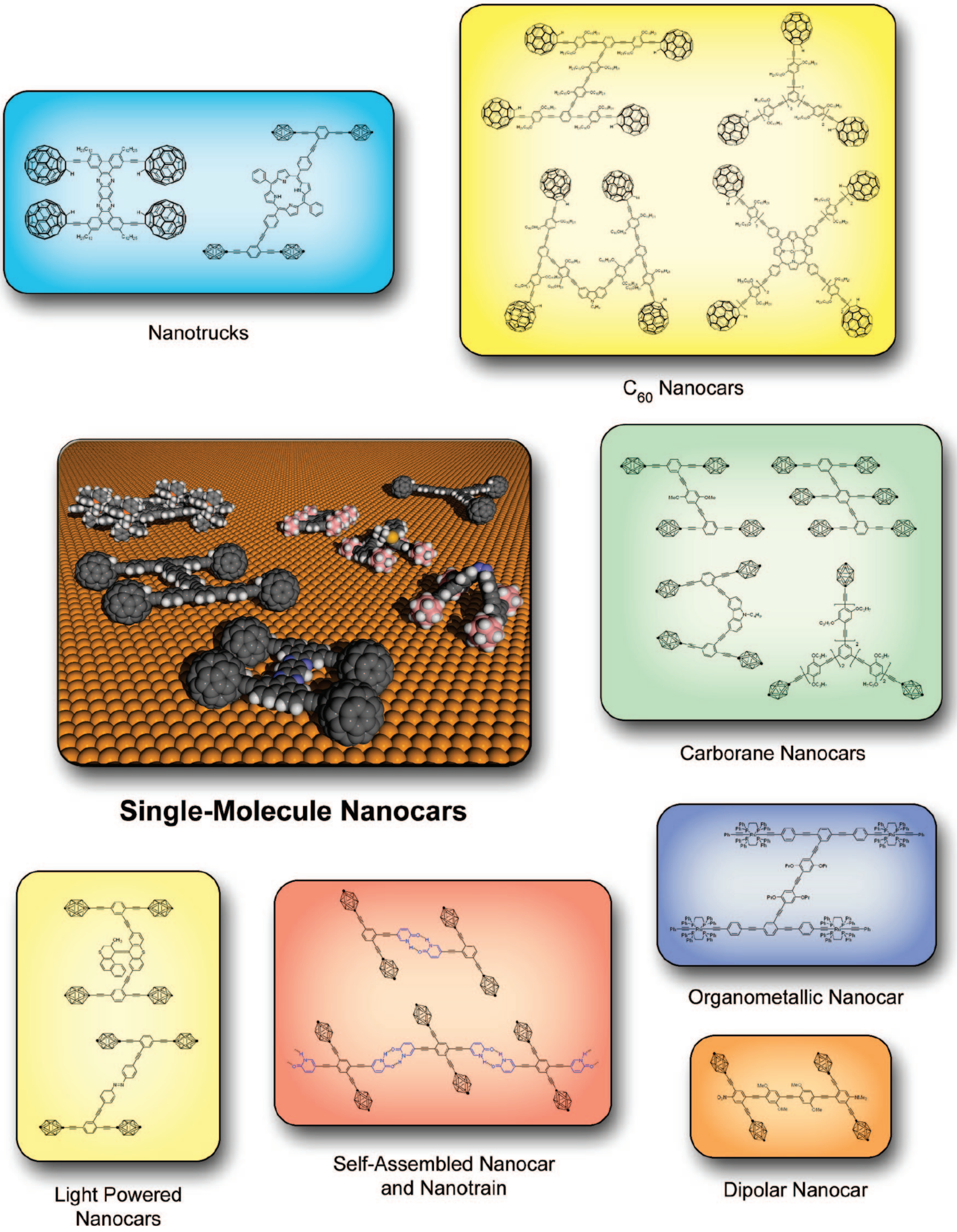


FIGURE 2. Overview of single-molecule nanocars that have been synthesized.

Transport of goods and materials between points is at the heart of all engineering and construction in real-world systems. Just as biological systems survive by nanometer-scale transport using molecular-sized entities, as we delve into the arena of the nanosized world, it beckons that we learn to manipulate and transport nanometer-scale materials in a similar manner. Nanoscale transporters that are truly molecule-sized will be required for the enzyme-like fabrication of sophisticated integrated structures.

We have recently developed a family of nanovehicles designed to operate on surfaces and to be studied at the single-molecule level.[17] The goal of this project is to realize nanomachines that can convert energy inputs (such as heat or electric fields) into controlled motion on a surface, ultimately

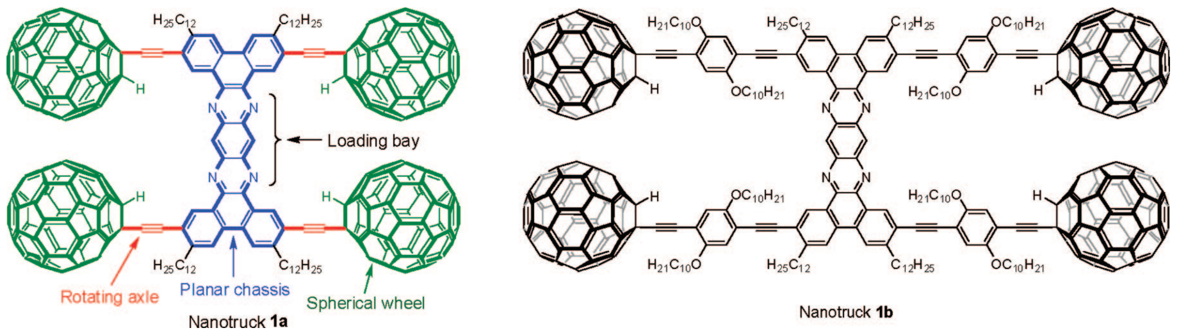
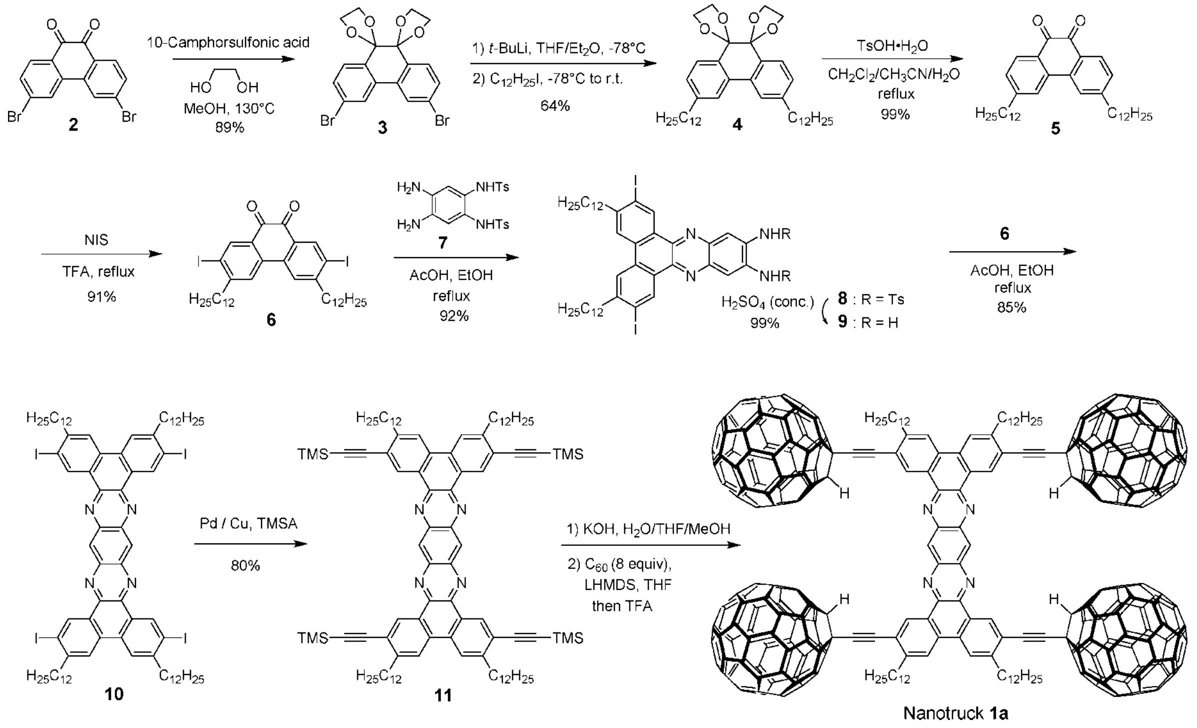


FIGURE 3. Structure of the first generation nanotrucks.[41]

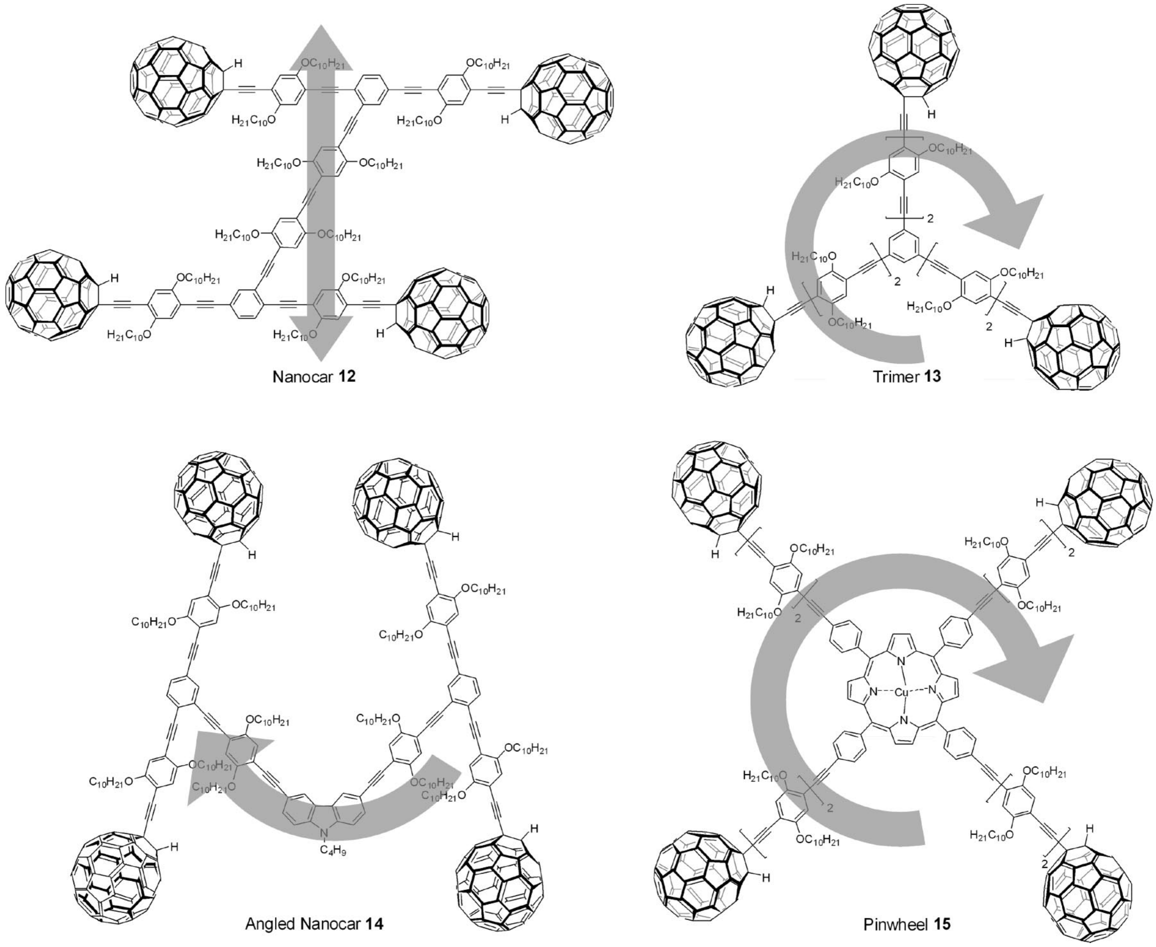
SCHEME 1. Synthesis of the Original Nanotruck **1a**



leading to transport of nanocargo (materials or information) from one place to another. Unlike most molecular machines that are mounted and operated on a surface in a collective manner, the confirmation of the movement of single-molecule machines accomplishing some mechanical task makes the use of scanning probe microscopy (SPM) techniques indispensable. This implies a careful design of the molecules to comply with field microscopy methods.[27] It should be noted that in the nanoworld the rules of physics can differ from those in the macroscopic world where Newtonian physics prevails. It thus makes the prediction of the comportment of molecules counterintuitive because the main interaction at the nanoscale is no longer gravity but electrostatic interactions. Quantum calculation can give some useful information,[28] but an empirical approach remains critical. Thus, for the further development of functional molecular machinery that can move and operate on surfaces, it is essential to try different conditions and accumulate enough results that can lead us to the next step of the rational design of functional molecular devices. Following a brief introduction to the development of surface rolling molecules, recent progress in our laboratory toward the design, synthesis, and testing of several single-molecule nanovehicles is described in this Account.

Surface-Rolling Molecules

The recent development of near-field microscopy techniques and in particular scanning tunneling microscopy (STM) has allowed the manipulation and imaging of individual molecules with atomic-scale precision.[29−31] The controlled lateral manipulation by the STM tip of single molecules on surfaces has been demonstrated with a wide variety of molecules such as Cu(II)-*meso*-tetrakis-(3,5-di-*tert*-butylphenyl) porphyrin (Cu-



Nanocar **12**

Trimer **13**

Angled Nanocar **14**

Pinwheel **15**

FIGURE 4. Second generation nanocars based on a flexible OPE chassis. The arrows indicate expected direction of rolling motion on surfaces.[39,43,44]

TBPP),[32] C_{60},[33,34] the molecular lander,[30] a molecular wheelbarrow,[35] hexa-*tert*-butyl-decacyclene (HB-DC),[36] hexa-*tert*-butyl-hexaphenylbenzene (HB-HPB),[37] a molecular rack and pinion[38] and a nanocar.[39] However only a few studies have been described on the rolling versus sliding motion of what could be called "molecular wheels". The molecular wheelbarrow[15] (Figure 1a) was one of the first molecules that was actually designed to address the mechanics of rolling wheels and motion at the nanoscale. Although the wheelbarrow could be imaged and manipulated by the STM tip in the direction perpendicular to the axles, no actual rolling of the triptycene wheels was initially observed on the studied surface.[35] Later, the STM tip-induced rolling mechanism of an axle equipped with two triptycene-based wheels (Figure 1b) was indeed reported.[40] The study and simulation of the tunneling current during the manipulation demonstrated that a change of conformation corresponding to a rotation of a wheel occurred during the translation of the molecule while being pushed with the STM tip.

Because of the limitations of current nanoscience tools, a detailed single-molecule study on a surface is currently limited to atomically flat surfaces that are suitable for SPM observational techniques. Consequently, the test bed for surface operating molecular machines will be atomically flat surfaces. The most intuitive machinery for controlled translations on such surfaces would be nanovehicles similar to their macroscopic analogue composed of a chassis, axles, and molecular wheels. A panorama of some members of the family of single-molecule surface rolling nanocars designed and synthesized in our laboratory is outlined in Figure 2.

C_{60} Fullerene Wheel Based Nanocars

The first surface-rolling molecule designed in our group (Figure 3) was composed of three basic molecular mechanical parts: C_{60} fullerene-based wheels, a rigid polyaromatic chassis, and alkynyl axles.[41] Nanotruck **1a** has a potential loading bay (acid−base bonding to the nitrogen atoms) to transport atoms on a surface. C_{60} fullerenes were chosen as the wheels because of their near-perfect spherical structure

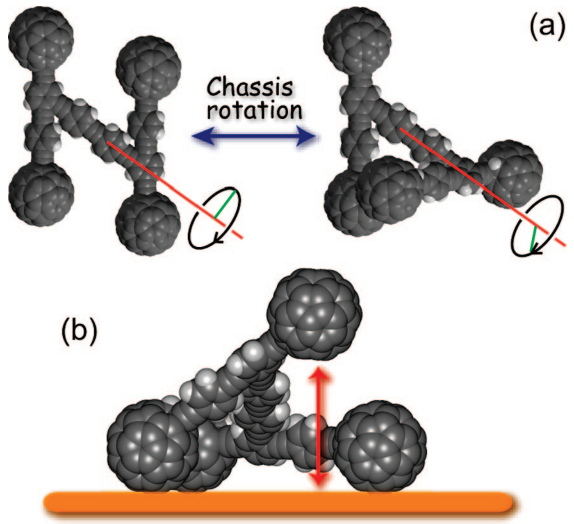


FIGURE 5. Flexibility of the semirigid chassis structure (nanocar derivative,[41] devoid of alkoxy groups for clarity): (a) the triple bonds in the OPE structure can rotate until the fullerene wheels touch one another, which gives the nanocar flexibility orthogonal to the surface plane; (b) one fullerene wheel is elevated while the other wheels remain on the surface to illustrate the suspension concept. Reproduced from ref 41. Copyright 2006 American Chemical Society.

and their robustness, but the connection of the wheels to the chassis proved to be synthetically challenging. A new methodology for an in situ ethynylation of fullerenes was thus developed in order to synthesize the C_{60}-based nanovehicles.

The synthesis of nanotruck **1a** (Scheme 1) uses as a key step a one-pot connection of the four C_{60} wheels to the rigid polyaromatic chassis. The chassis, **11**, was synthesized in nine steps from the dibromo-diketone **2** using standard organic reactions. The development of an in situ ethynylation procedure,[42] in which multiple terminal alkynes are deprotonated in THF using excess lithium hexamethyldisilazide (LHMDS) in the presence of excess fullerenes, was eventually required to achieve the last step. This new reaction was quite effective and was applied to nanotruck **1a**, as well as the family of nanocars and a range of multifullerene molecules. Because **1a** was nearly insoluble, the formation of the product was confirmed by solid-state characterization techniques including MALDI mass spectrometry and NMR.[41] The solubility of the original structure **1a** was later improved by incorporating long alkoxy chains ($-OC_{10}H_{21}$) as solubility enhancers. This modification led to the synthesis of the nanotruck **1b**[41] (Figure 3) whose structure could be determined using common solution-state spectroscopic methods.

A second generation of nanocars based on a "Z shaped" oligo(phenylene ethynlene) (OPE) chassis was then developed. The key improvement in the molecular structure over the nanotrucks **1a** and **1b** was the introduction of a semirigid chassis as depicted in Figure 4. The better flexibility of the OPE chassis combined with the increased number of alkoxy units ($OC_{10}H_{21}$) dramatically increased the solubility while easing the purification and characterization of the massive fullerene-wheeled structures compared with the first generation nanotrucks (Figure 3). The possibility of carrying a molecular cargo was lost due to the absence of nitrogen atoms for docking carrier molecules, but more flexibility was gained due to the possibility of rotation around the alkyne connections between the chassis and axle portions in the OPE system (Figure 5). Similar to an automobile suspension, the chassis flexibility gives the nanocar degrees of freedom orthogonal to the surface plane and thereby permits it to climb one-atom-step high gold islands.

The OPE-based chassis was synthesized stepwise using multiple Sonogashira coupling reactions (Scheme 2). The four fullerene wheels were successfully coupled via the in situ ethynylation method to complete the synthesis of the nanocar **12**.

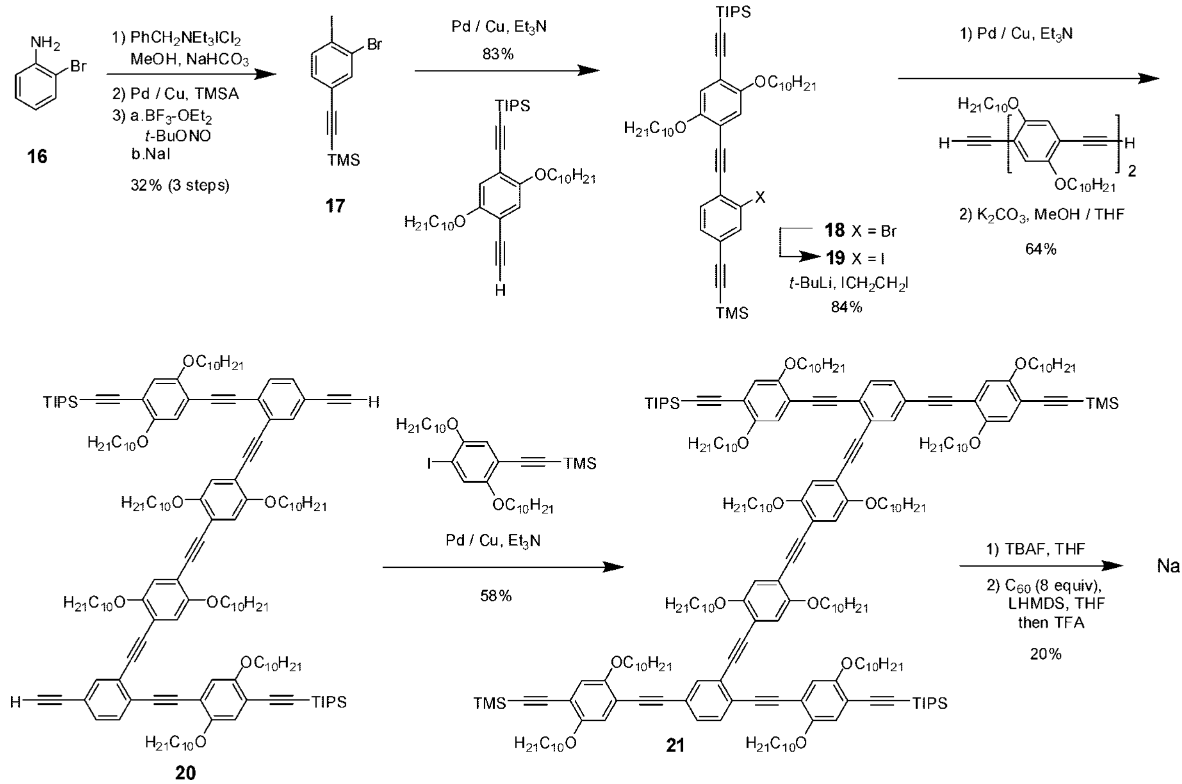
With nanocar **12** and the three-wheeler trimer analogue **13**, we have been able to demonstrate the action of the fullerene-wheel architecture at the single-molecule level.[39] The evidence for the fullerene-wheel-assisted rolling motion of the nanocars **12** on the gold surface was obtained by the comparison of two different modes of thermally induced translation and pivoting, respectively, for nanocar **12** and trimer **13** (Figure 6). Furthermore, electric field gradient induced motion could be observed by placing the STM tip in front of the nanocar, which would induce rolling motion toward the tip as the tip was moved across the surface.[39]

A modified chassis was also incorporated into the nanocar family to improve our understanding of the interactions between the fullerene wheels and metal surfaces as well as the directional control and surface-rolling versus pivoting capabilities of nanocars. To combine the translational movement of nanocar **12** and the rotational motion of the trimer **13**, an angled nanocar **14**[43] (Figure 4) was designed. The angled chassis created by the carbazole moiety provides a rigid angle, which could lead to circular motion on surfaces. A porphyrin—fullerene pinwheel **15** (Figure 4), with a square planar rigid structure that might lead to spiraling motion on surfaces, was also synthesized.[44] Both molecules have been imaged by STM on gold surfaces,[43,44] and directional motion studies are still underway.

Carborane Wheel Based Nanocars

C_{60} fullerene wheel based nanocars proved to be useful for STM imaging of rolling motion. However, the electronic nature of fullerene makes it unsuitable for the development of more

SCHEME 2. Synthesis of nanocar **12**[39]



complex nanomachines using light as the power input due to rapid energy transfer to the fullerenes.[45] In the quest for new wheels, the *p*-carborane moiety was a good candidate for the potential development of rolling molecules because of its spherical shape and its aromatic nature[46,47] that allows easy substitution reactions at one or both of the carbon atoms positioned *para* to each other. Moreover, the *p*-carboranes are robust and, unlike fullerenes, are very soluble in common organic solvents and do not inhibit organometallic coupling reactions, thus allowing a more convergent synthesis of molecular machines.

A variety of carborane-wheeled nanocars and three-wheeled analogues were synthesized, inspired by the C_{60}-based nanocars (Figure 7).[45] Our smallest model, nanocooper **22**, was easily synthesized in seven steps (Scheme 3) from a common starting material in an overall yield of 50%. Because only the wheels are imaged by STM and the axle size is similar to the interaxle distance, **22** is recorded as four bright dots arranged in a square shape, making it impossible to determine the directionality of motion for the molecule by the STM images. Thus, the 3 × 2 arrangements of nanocaterpillar **23** wheels would make it possible to determine both molecular direction and diffusion direction by STM. Furthermore, the difference in the number of wheels will assist in the dimensional analysis of the molecules sliding or rolling on the surface by STM. As shown in Figure 7, molecules **22**–**25** are designed to move in specific patterns on the surface. Nanocooper **22** and nanocaterpillar **23** are expected to translate in a one-dimensional fashion since the axles are parallel to each other. Similarly, the angled nanocar **24** is expected to make small circles on a surface if the molecule is indeed rolling, and the trimer **25** can be imaged to only pivot in the same manner as the fullerene trimer **13**.

Organometallic Wheel Based Nanocar

In the ongoing quest for efficient molecular wheels, octahedral 18-electron *trans*-alkynylbis(1,2-bis-(diphenylphosphino)-ethane)ruthenium(II) complexes (Figure 8) appeared to be candidates, since the low rotation barrier around the alkyne bond would allow a free rotation, while the bulky phosphine ligands might act as a tire to interact with metallic surfaces.[48] Good physisorption on metallic surfaces, which has been demonstrated to be crucial for a rolling motion of the wheels,[49] should be provided by the diphenylphosphine groups. With an overall wheel size of ~1.2 nm, the wheels should be clearly imaged by STM. Moreover, the large *Z* value of the ruthenium atoms should allow high-resolution TEM as a complementary imaging technique. Nanocar **28** (Figure 9) with organometallic wheels based on a

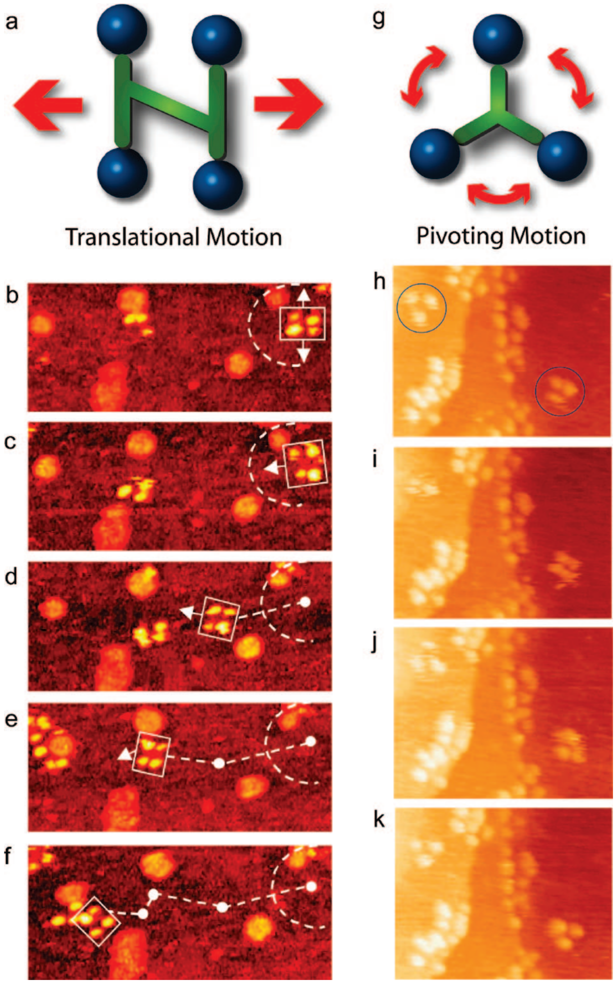


FIGURE 6. Comparison of thermally induced motions of (a) four-wheeled **12** with (b−f) its STM-imaged motions and (g) three-wheeled **13** with (h−k) its STM-imaged motions. (b−f) Sequence images were taken during annealing at ~200 °C (bias voltage, $V_b = -0.95$ V; tunneling current, $I_t = 200$ pA. Image size is 51 × 23 nm^2). The orientation of the nanocar **12** is easily determined by the fullerene wheel separation, with motion occurring perpendicular to the axles.[39] Acquisition time for each image is approximately 1 min, with images b−f selected from a series spanning 10 min, which shows an ~80° pivot (b) followed by translation interrupted by small-angle pivot perturbations (c−f). (h−k) A sequence of STM images acquired approximately 1 min apart during annealing at ~225 °C shows the pivoting motion of **13** (both circled molecules) and lack of translation of any molecules ($V_b = -0.7$ V; $I_t = 200$ pA. Image size is 34 × 27 nm^2). For video files of nanocar motions, see Supporting information. This data was obtained in the laboratory of K. Kelly, our collaborator.[39,41] Reproduced from ref 41. Copyright 2006 American Chemical Society.

trans-alkynyl ruthenium complex and its trimer analogue **29** were subsequently synthesized to be studied by STM.

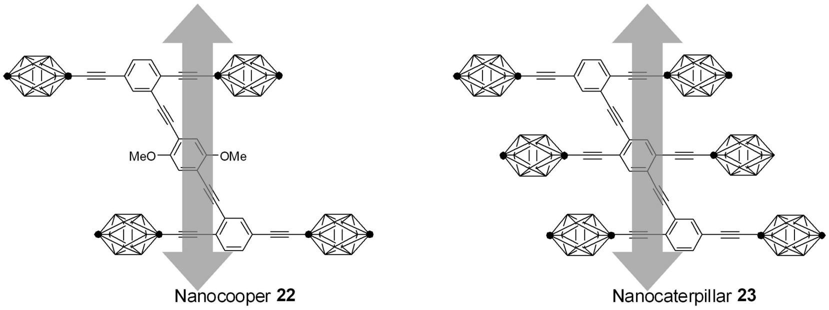
Functionalized Nanocars

The next goal of our project was to realize a nanomachine that can convert energy inputs into controlled motion on a surface. Nanocar **12** delivered a partial answer to the question of how to obtain directional motion on a surface using thermal energy as the energy input. However because thermal motion leads to less controlled motion, using some integral "motor" would constitute a higher level of control. The electric field of the STM tip was successfully used to pull the nanocars in a forward rolling motion.[39] Other sources of energy such as light, electrostatic or chemical energy can also be considered.

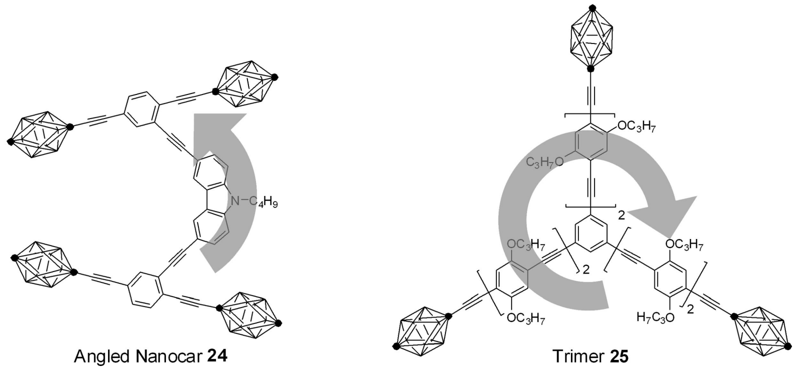
Light-Induced Paddlewheel-like Driven Motion: A Motorized Nanocar

A motorized nanocar[50] was designed to achieve a unidirectional rolling motion on surfaces. The motorized nanocar was designed bearing a light-powered molecular motor in its central portion for an eventual paddlewheel-like propulsion action along a substrate surface (Figure 10). We opted for the unidirectional molecular rotary motor developed by Feringa and coworkers as the motor for our motorized nanocar because it can precisely perform unidirectional rotation using only light and mild heating (35−65 °C) as the power input. Moreover it can operate even when assembled atop metal surfaces[51] and be functionalized without disturbing the rotation of the motor, allowing the motor substructure to be introduced into more complex structures.

Unfortunately, the fullerene wheels proved to be incompatible with the light-powered motor developed by Feringa due to a rapid intramolecular quenching of the photoexcited state of the motor moiety by the fullerenes.[50] However by using the *p*-carborane wheels, a fully functional motorized nanocar **30** (Figure 11 and Scheme 4) could be synthesized in 12 steps with an overall yield of 5%.[50] Thermodynamic and kinetic parameters (in solution) of the thermal conversion of the unstable to stable isomer were determined at different temperatures by ^{1}H NMR.[50] All the values were similar to those obtained by Feringa for the motor bearing methoxy moieties (rather than alkynes) at the 2,7-positions.[52] Encouragingly, we found that the presence of the relatively bulky *p*-carborane wheels does not alter the rotation of the motor, implying that the chassis and axle-bearing alkynyl moieties are long enough to prevent steric interactions. Finally, whether the motor will have sufficient power to rotate and thus propel the nanocar on a surface and whether an energy transfer to the metallic surface during photolysis will be problematic remain to be determined.



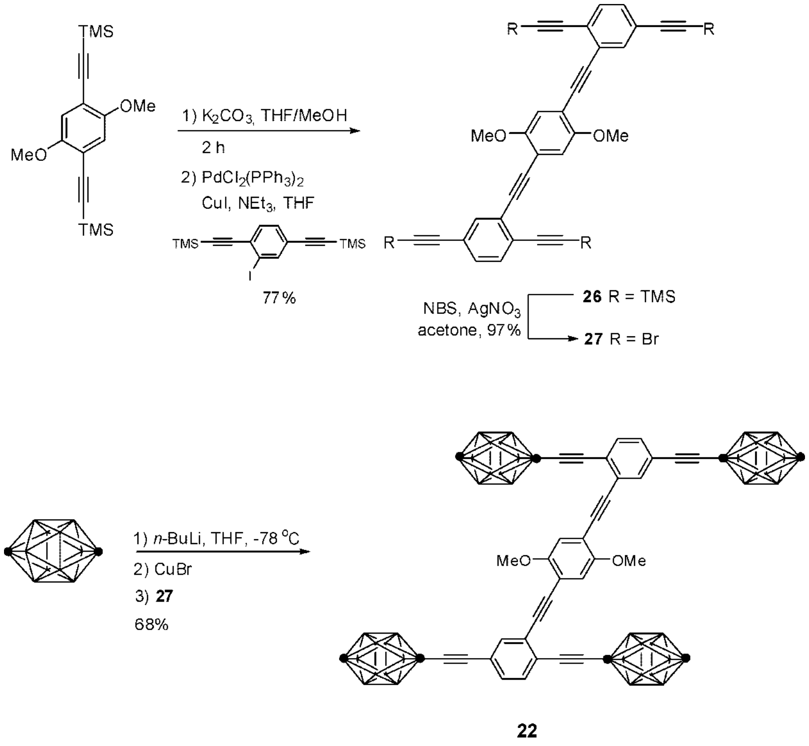
Nanocooper **22** Nanocaterpillar **23**



Angled Nanocar **24** Trimer **25**

FIGURE 7. Molecular structure of *p*-carborane nanocars. The arrows indicate expected direction of rolling motion on surfaces. The *p*-carborane wheels have BH at every vertex except at the darkened (●) vertices, which represent C and CH positions, *ipso* and *para*, respectively, relative to the alkynes. Adapted from ref 45. Copyright 2007 American Chemical Society.

SCHEME 3. Detailed Synthesis of the *p*-Carborane Wheeled Nanocar **22**[45]



Light-Induced Crawling Motion: A Nanoworm

Another type of light induced motion was considered by incorporating an azobenzene moiety in the chassis of two photoactive nanovehicles[53](Figure 12). The *cis*−*trans* photoisomerization of the azobenzene chromophores could potentially generate an inchworm-like motion on a surface. It is widely accepted that the photoirradiation step from *trans* to *cis* configuration has a rota-

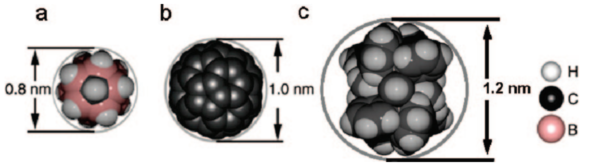


FIGURE 8. Relative size and space-filling of (a) *p*-carborane, (b) C_{60} fullerene and (c) *trans*-[Ru(C≡CH)$_2$(dppe)$_2$] wheels. Reproduced from ref 48, Copyright 2009, with permission from Elsevier.

tional pathway, whereas the thermal step from *cis* to *trans* has an inversion pathway.[54] The combination of these dissimilar pathways might help to propel the nanoworm (Figure 13). Preliminary solution-based photoisomerization showed isomerization from *trans* to *cis* in the *p*-carborane-wheeled nanoworm **38**.[53] Suprisingly little switching effect was observed for nanoworm **37**. Usually, fullerenes attached via alkynes on conjugated systems induce a weak electronic interaction called periconjugation,[55] which causes disruption in the electronic communication of the chromophore and has produced $\sim$0% conversions in systems with two fullerenes in prior work.[50,56] However, despite having four fullerene wheels, **37** showed slight conversion, suggesting that the distances between the azobenzene and fullerene moieties might play an important role in the efficiency of the quenching effect. Studies are underway to image these nanoworms by microscopy and thereby study the photoactivated motion on surfaces. Like the motorized nanocar **30**, nonconductive surfaces and or a switch to AFM or confocal microscopies might be necessary.

Electric Field Gradient Induced Motion: Dipolar Nanocar

Apart from light, electric field gradients have also been used to induce a rotary motion in molecular machines such as surface-bound molecular motors incorporating a dipolar rotor.[21,22] While the early nanocar **12** showed thermal and electric field gradient induced rolling motion, the dipolar nanocar **39**[57] (Figure 14) was designed to enhance electric field induced motion by incorporating a strong net dipole along its chassis. By introduction of a push−pull system composed of a dimethylamino moiety as the potent electron-donating end and a nitro group as the efficient electron-withdrawing end, AM-1 calculations suggested that the chassis would display a significant dipole moment of $\sim 8\mu_b$ where there is surface-restricted rotation of the substituted aromatic units on the chassis.[57]

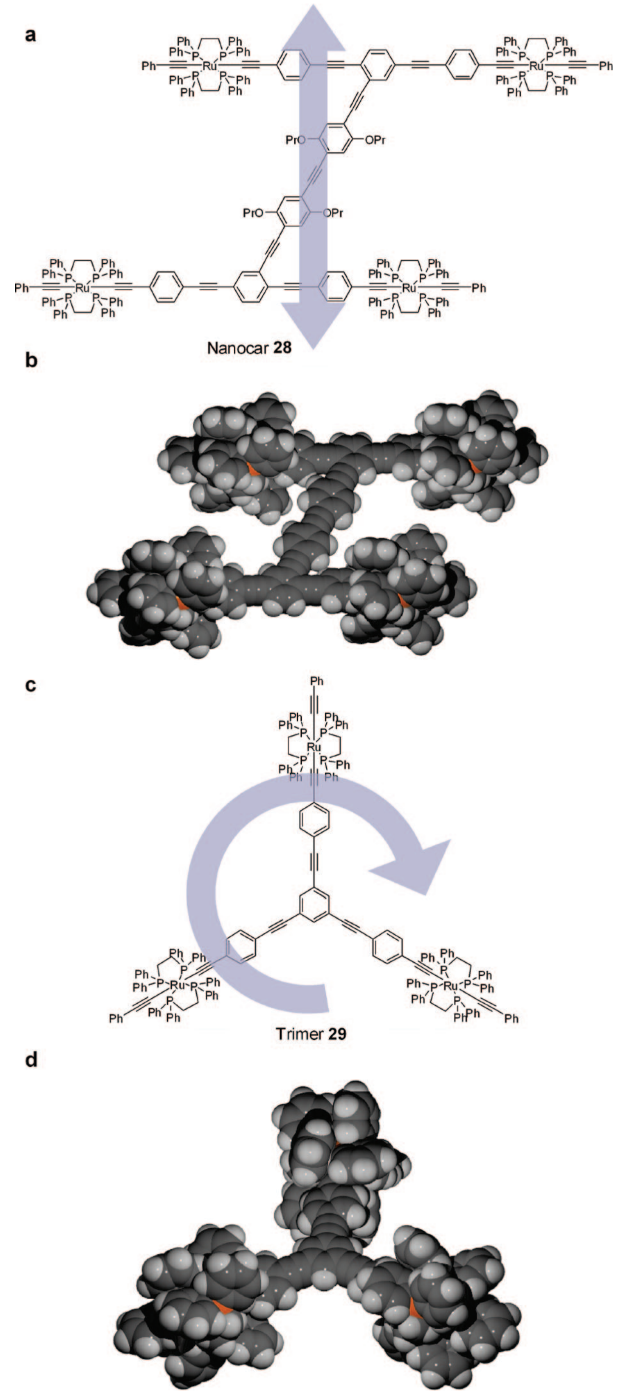


FIGURE 9. Nanocar **28** (a, b) and trimer **29** (c, d) with ruthenium wheels and their CPK model geometry optimized with SPARTAN. The arrows indicate expected direction of rolling motion on surfaces. Reproduced from ref 48, Copyright 2009, with permission from Elsevier.

Transport: Porphyrin-Based Nanotruck

Controlling the transport of atoms or molecules at the molecular level is crucial for the "bottom-up" building of nanomachines. While the original chassis of nanotrucks **1a** and **1b** incorporated nitrogen atoms, which could act as ligands for atom transport, this ability was lost in the second generation OPE-based chassis. To enable molecular transport on a surface, a porphyrin inner core was added to the chassis of the *p*-carborane based nanotruck **40** (Figure 15).[58] Porphyrins and

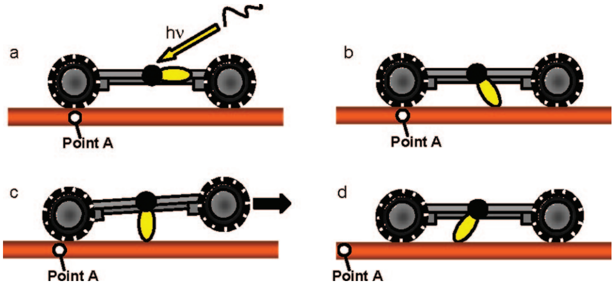


FIGURE 10. Propulsion scheme for the motorized nanocar where (a) 365 nm light would impinge upon the motor, which (b) affords motor rotation and (c) sweeping across the surface to (d) propel the nanocar forward. Reproduced from ref 50. Copyright 2006 American Chemical Society.

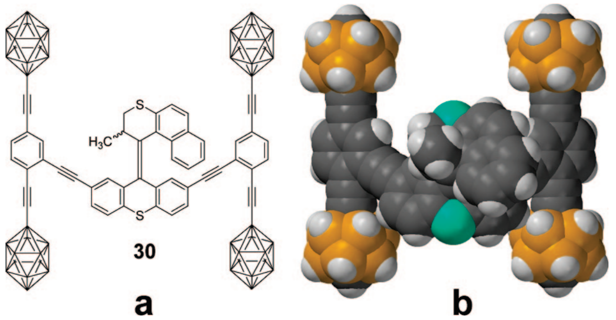


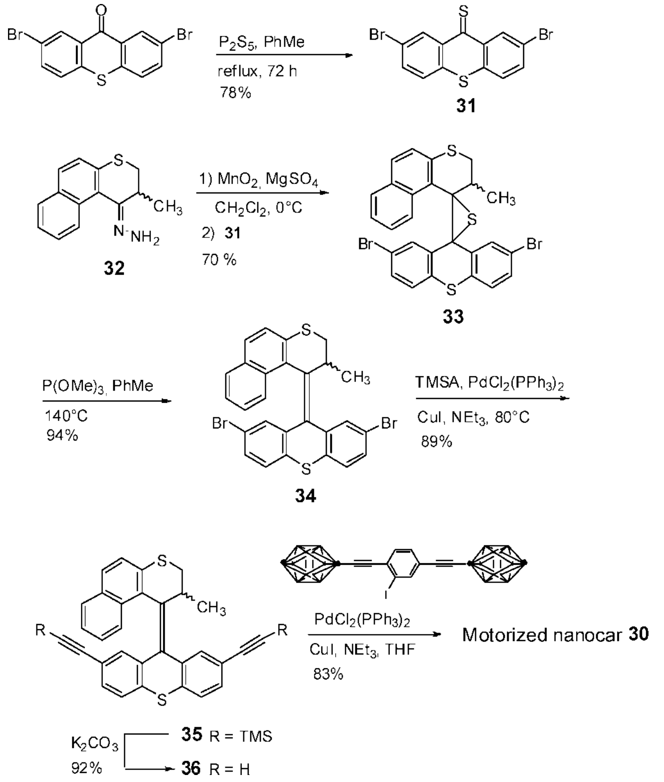
FIGURE 11. (a) The structure of motorized nanocar **30** and (b) the space-filling model of **30**. Reproduced from ref 50. Copyright 2006 American Chemical Society.

metal-complexed porphyrins have been observed using STM,[59] making them suitable to incorporate into features for better imaging and to provide the requisite transport "loading bay". Thus, nanotruck **40** bears a porphyrin inner core that should allow for the incorporation of metals and then the subsequent transportation of other small molecules across the surface with STM monitoring.

Self-Assembling Nanocars

Inspired by natural systems, we have integrated the concepts of assembly lines and self-assembly to construct new nanocar models in an automated mass production protocol. Among all the weak noncovalent interactions used in supramolecular assemblies, hydrogen-bond interactions were first chosen due to their efficiency in yielding well-defined structures with their strong spatial directionality.[60] The half-nanocar **41** (Figure 16) with a 2-pyridone moiety was synthesized and showed a spontaneous self-association in solution to selectively yield the corresponding hydrogen-bonded nanocar **41a**.[60] The ability for self-association of the 2-pyridone moiety was further exploited to build a nanotrain on a surface. Specifically, monomer **42** (Figure 17) bearing two 2-pyridone moieties connected in opposite directions to a carborane axle was synthesized. Linear structures were obtained by self-assembly of **42** on a SiO_2 surface.[61] AFM images showed lengths as long as ~5 μm and heights in the range of 0.7−1.6 nm, which are within the range of the molecular height of carboranes or carboranes with axles.

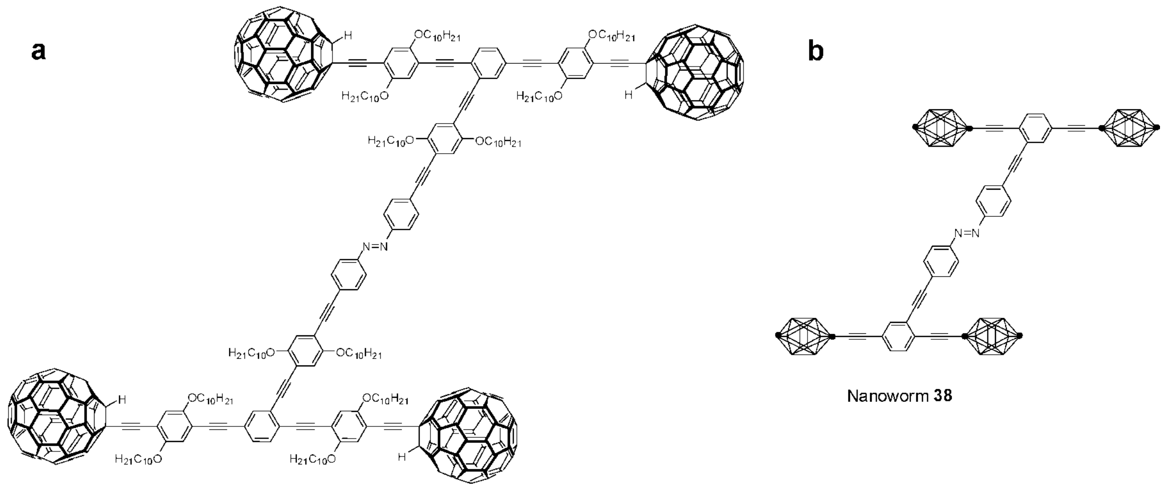
SCHEME 4. Synthesis of Motorized Nanocar **30**[50]



Self-assembly using metallic complexes was also explored with the half-nanocar **43** where a carborane axle is connected to a terpyridine ligand.[60] Nanocars were assembled in solution by complexation with iron(II) or ruthenium(II) (Scheme 5) to yield the corresponding octahedral complexes **44a** and **44b**.

Conclusion

In this Account, we have outlined our approach in the design and synthesis of surface-rolling molecules constructed to convert energy inputs into controlled motion on a surface and to transport nanosized cargo. The fullerene wheel based nanocars provided a first example of a thermally induced or electric field gradient induced directional motion on a surface. The use of new *p*-carborane or ruthenium-based wheels allowed the development of functionalized nanocars able to potentially use light or electric field gradient induced motion, transport atoms, and self-assemble in solution or on surfaces. However, challenges still remain in the synthesis of new molecular wheels for long distance motion on non-atomically flat surfaces as well as



Nanoworm **37**

Nanoworm **38**

FIGURE 12. (a) C_{60}-wheeled nanoworm **37**—extended dodecyl-substituted axles were added to ensure solubility; (b) *p*-carborane-wheeled nanoworm **38**.[53]

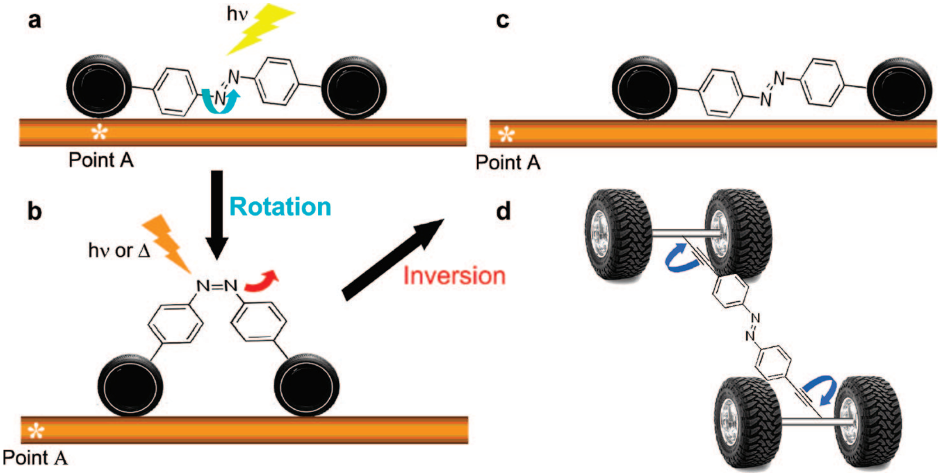
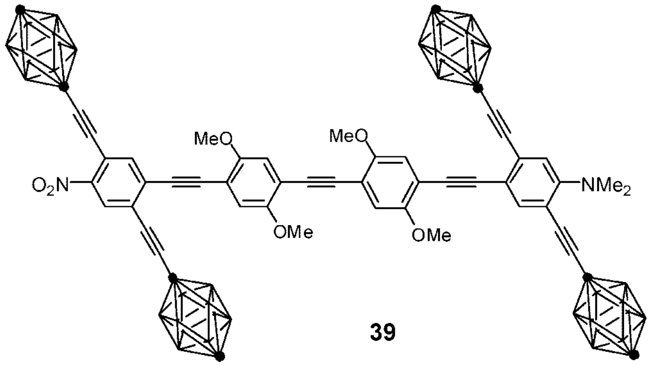
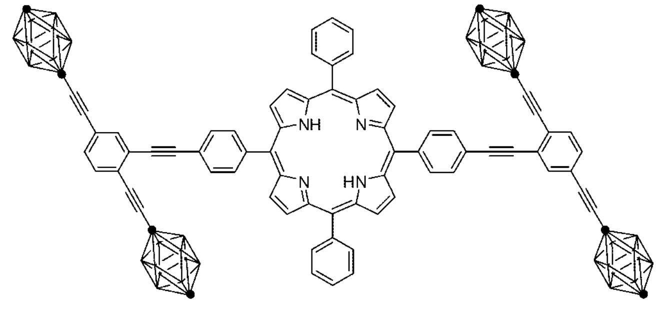


FIGURE 13. (a) Side view model of the nanoworm. The proposed photoactivated rotational pathway on a surface away from the reference point (noted by the star) by irradiating at 365 or 435 nm to convert a to b (*trans* to *cis* isomerization) by rotation. (b) Model of the nanoworm (*cis*) irradiated at >495 nm (or heated) to induce the inversion pathway to c, which constitutes a *cis* to *trans* conversion, thus further propelling the nanoworm from the starred reference location. (c) The nanoworm again in the *trans* conformation, after completing the cycle of *trans* to *cis* to *trans* conversion, that is further displaced from the starred reference point. (d) Top view; rotation about the alkyne bonds is possible in order to achieve favorable conformations. Reproduced from ref 53. Copyright 2008 American Chemical Society.



39

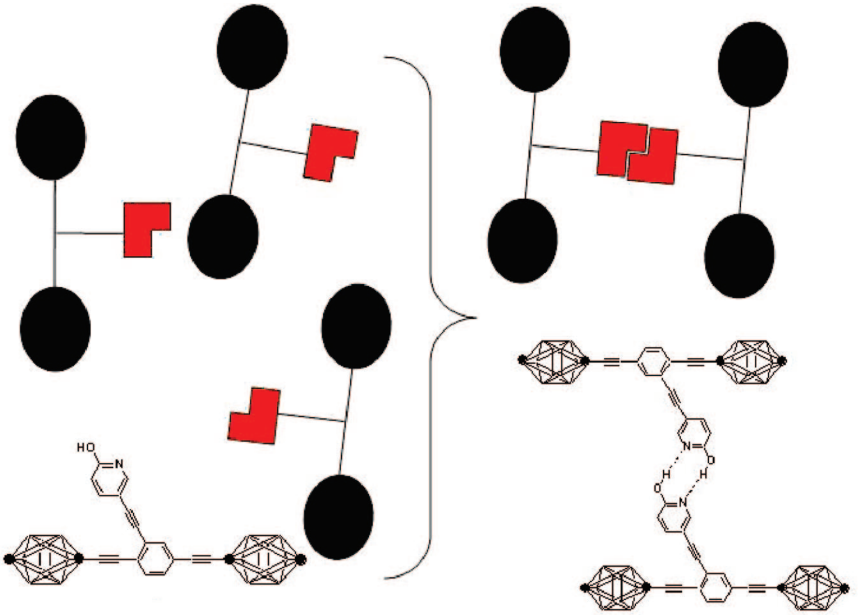
FIGURE 14. Dipolar nanocar **39** with carborane wheels.[57]



Nanotruck **40**

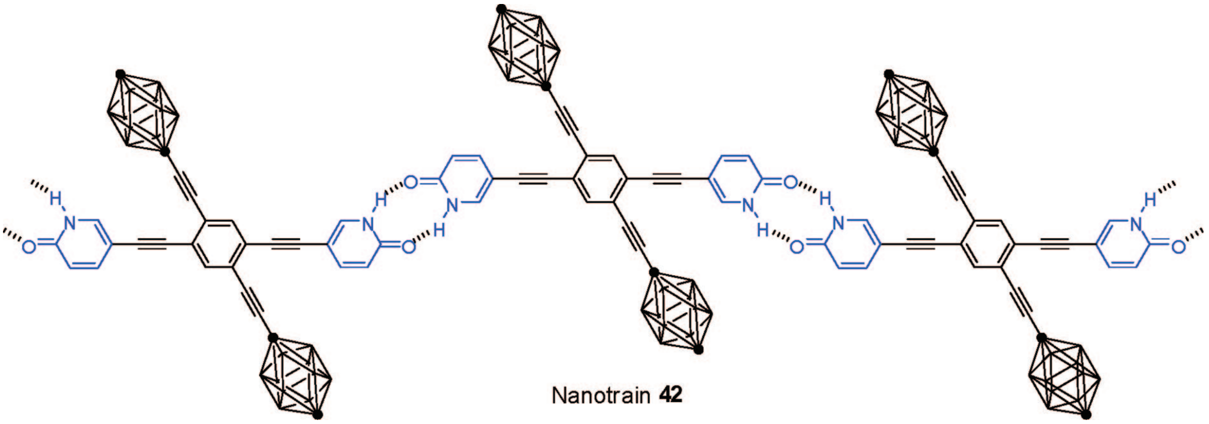
FIGURE 15. Porphyrin-based nanotruck **40** with carborane wheels.[58]

the synthetic challenges of preparing nanovehicles with accurate motion and directional control. The bottleneck of our research is currently not synthesis but imaging. Therefore, the development of new techniques for single-molecule studies, such as single-molecule fluorescence



Half-nanocar **41** Self-assembled nanocar **41a**

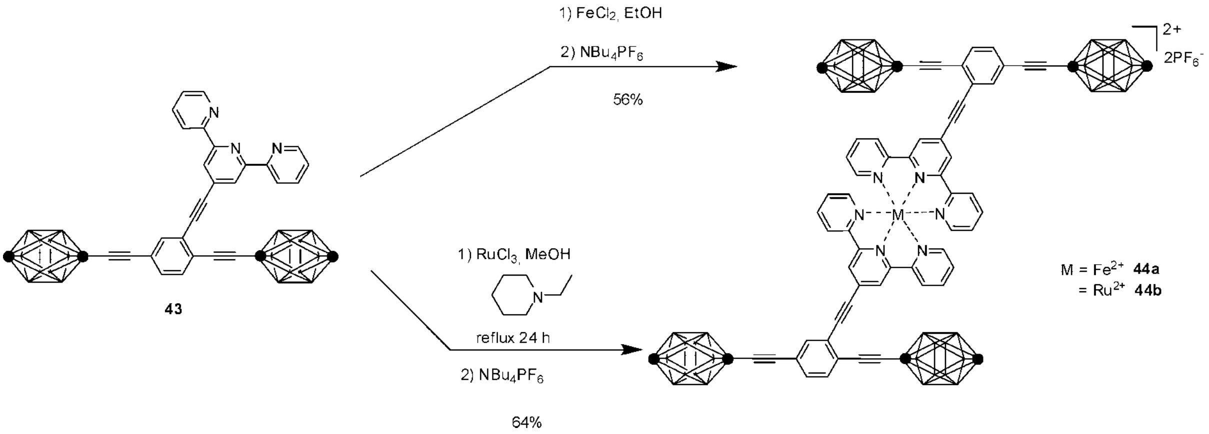
FIGURE 16. Illustration of the self-assembled hydrogen-bonding nanocar **41**. Reproduced from ref 60, Copyright 2008, with permission from Elsevier.



Nanotrain **42**

FIGURE 17. Schematic representation of hydrogen-bonded self-assembled linear structures, nanotrains, obtained from **42** on a surface.[61]

SCHEME 5. Synthesis of metal-assembled nanocars **44a** and **44b**[60]



microscopy, is critical for the widespread development of surface operating nanomachines. Exploration of that technique is underway in our laboratory,[62] but complementary and simpler imaging methods are critical to propel the study of nanomachines. Finally, it is our hope that these very early stage studies in nanocars will aid in underpinning future techniques for the enzyme-like manipulation and assembly of atoms and small molecules to build higher level structures in nonbiological environments; a truly bottom-up approach to fabrication in years to come.

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Supporting Information Available. Two videos of nanocar motions. This material is available free of charge via the Internet at http://pubs.acs.org.

BIOGRAPHICAL INFORMATION

Guillaume Vives graduated from the Ecole Normale Supérieure of Lyon where he obtained the agrégation of chemistry. He obtained his Ph.D. in 2007 from the University Paul Sabatier of Toulouse working on the introduction of organic and organometallic insulating fragments in molecular motors under the supervision of Gwénaël Rapenne and Jean-Pierre Launay. Since 2007, he has been a postdoctoral fellow at Rice University working with James M. Tour on the development of functionalized nanovehicles.

James M. Tour, a synthetic organic chemist, received his Bachelor of Science degree in chemistry from Syracuse University, his Ph.D. in synthetic organic and organometallic chemistry from Purdue University with Ei-ichi Negishi, and postdoctoral training in synthetic organic chemistry at the University of Wisconsin and Stanford University with Barry Trost. After spending 11 years on the faculty of the Department of Chemistry and Biochemistry at the University of South Carolina, he joined Rice University in 1999, where he is presently the Chao Professor of Chemistry, Professor of Computer Science, and Professor of Mechanical Engineering and Materials Science in the Smalley Institute for Nanoscale Science and Technology. Tour's scientific research areas include the application of organic chemistry to materials science.

FOOTNOTES

*To whom correspondence should be addressed. E-mail: tour@rice.edu.

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