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Trends in
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Review

Defying chemical equilibrium with light

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Chemical systems capable of exploiting an energy source to function away from thermodynamic equilibrium are a hallmark of the biological world. The design and operation of artificial versions of such systems constitute a stimulating and highly challenging scientific goal with considerable expectations for application in synthetic chemistry, catalysis, materials science, energy conversion, and medical therapy. In this context, supplying energy in the form of photons has several elements of conceptual interest and practical advantage. Here we present the progress of research over the past 5 years on artificial molecular-based systems that can use light energy to operate away from equilibrium – an emerging field that has just begun to express its innovative potential.

Non-equilibrium states and energy inputs

Equilibrium (see Glossary) is a most familiar concept for chemists, who have been traditionally engaged in studying and creating systems that are thermodynamically stable. However, many transformations occurring in living organisms are enabled by species (e.g., enzymes) that do not operate at their thermodynamic minimum – that is, at equilibrium – but rather in a high-energy state [1–3]. Similarly, structural elements such as microtubules are assembled under non-equilibrium conditions and can exist only as long as the exergonic decomposition of a reactant (e.g., guanosine-5′-triphosphate) can occur [4]. The effective realization of artificial systems capable of operating according to the same principles is a problem of great scientific interest [5,6], with far-reaching consequences [7,8] in the field of synthesis and catalysis [9,10], **molecular motors** [11], materials science [12,13], and energy conversion and storage [14,15]. However, the rational design and preparation of these systems remains an extremely demanding task, mostly because of the difficulties associated with our incomplete understanding of the intricate processes underlying energy transduction at the molecular scale, and with the challenge inherent in the practical realization of the necessary reaction networks [16–19].

For a chemical system to reach an out-of-equilibrium (OEQ) state, the energy provided by a source (e.g., by an exergonic reaction, electricity, or light) must be transferred to a coupled energy-consuming process that can, thus, be driven away from equilibrium (Figure 1, Key figure). The energy input can be either utilized to bring the system into a local minimum (**metastable** or **kinetically trapped** OEQ states) or continuously consumed to sustain an unstable state that does not correspond to a free energy minimum (**dissipative** OEQ state; Box 1). Although different energy sources, such as chemical or electrical, may be used to drive artificial systems away from equilibrium [7–15,20–23], light energy has several advantages [24–26]. Photoirradiation, in fact, can: (i) provide exquisite spatiotemporal and intensity control; (ii) induce clean and reversible transformations; (iii) behave as a ‘traceless stimulus’ (i.e., avoid the formation of waste products); and (iv) represent a non-invasive tool, also for biological matter. Moreover, the interaction between photons and chemical systems can be exploited for analytical purposes (e.g., through spectroscopy). Last but not least, sunlight is an intrinsically renewable form of energy [27,28]. It should also be recalled that, in general, reactions that involve a photoexcitation step are not subjected to **microscopic reversibility** [29].

Highlights

Living organisms rely on processes that occur, and structures that exist, far from thermodynamic equilibrium.

Implementing non-equilibrium regimes within artificial molecular species can lead to systems and materials with unprecedented physical and chemical properties, responsive and adaptive behavior, and the ability to do work on their surroundings.

A chemical process can be driven away from equilibrium by coupling it with another process capable of exploiting energy from a source (chemical reactants, electricity, or light).

Optical excitation allows the non-invasive and clean delivery of controlled amounts of energy to molecules with spatial and temporal precision.

An effective strategy to obtain light-driven non-equilibrium behavior is to combine molecular photoswitches with thermally activated reversible processes such as molecular self-assembly or dynamic covalent bond formation/cleavage.

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Key figure

Idealized free energy curve of a chemical system

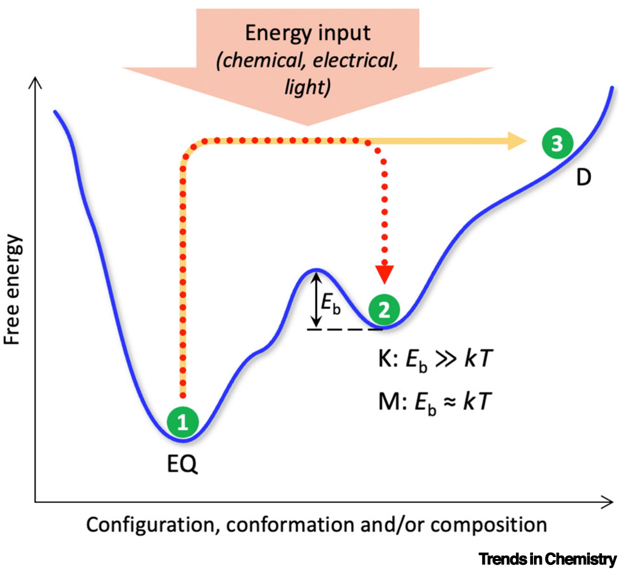

Figure 1. The global thermodynamic minimum (1) corresponds to thermal equilibrium (EQ). Upon application of a chemical, electrical, or photonic energy input to the system in its EQ state, different out-of-equilibrium regimes may be obtained. If the system is brought to a free energy well above the global minimum (2) by a discrete input (dotted red line), it can be either kinetically trapped (K) or metastable (M), depending on whether the activation barrier for escaping the minimum is respectively larger than or comparable with kT (k is the Boltzmann constant). Alternatively (3), the system may reach a dissipative state (D) which is transient and can exist only as long as energy is continuously supplied to the system (yellow line).

In the vast majority of artificial light-driven OEQ systems, the energy harvesting interface is a **photoswitch**, namely, a molecule that changes its ground-state structural and/or chemical properties upon absorption of photons of a suitable wavelength [30]. This approach requires a judicious integration of photochemical and thermally activated processes, which poses significant

Box 1. Non-equilibrium states of a reactive chemical system

A closed thermodynamic system spontaneously evolves downhill on the **free-energy surface** until it reaches the absolute minimum, which corresponds to the equilibrium state. No external input of energy is needed to maintain this condition and no further macroscopic changes are observed over time. By providing energy from an external source (e.g., in the form of light) some systems can be 'pushed away' from the global minimum. Depending on the characteristics of the system and the experimental conditions, a different relative minimum can be populated. Such a new state can be obtained by providing a discrete amount of energy and can persist for a finite lifetime without further energy supply. If the barrier for escaping the local minimum is high ($E_b >> kT$, where k is the Boltzmann constant), such a lifetime is longer than the experimental time scale and the state is said to be kinetically trapped (K). In the case of a relatively low activation barrier ($E_b \approx kT$), the non-equilibrium state undergoes a transformation into more stable one(s) within an experimentally observable time scale and is therefore defined as metastable (M). Hence, the distinction between kinetically trapped and metastable behavior is not absolute, as it depends on the observation time scale and on the experimental conditions. Alternatively, the energy input can lead to a non-equilibrium state that does not correspond to a clear minimum in the free-energy surface (i.e., $E_b << kT$). When the energy supply stops, the system relaxes very rapidly (on the experimental time scale) towards a local or the global minimum. A state of this kind is said to be dissipative (*D*), because it can only exist as long as the system can consume (i.e., dissipate) energy. If the latter comes from a chemical reactant (fuel), maintaining a dissipative non-equilibrium state requires a constant influx of matter (i.e., the fuel) and removal of waste. In this regard, light is a more convenient energy source because it can be easily provided in a continuous fashion, and there is no need to remove waste products if clean and reversible photoreactions are employed.

Glossary

Autonomous behavior: for a chemical system that is not in equilibrium, the ability to repeat a cyclic process under constant experimental conditions except for the energy input required to drive the transformation.

Azobenzene: a molecular photoswitch, consisting of two phenyl rings connected by a N=N double bond, that can undergo *E-Z* photoisomerization.

Chemical topology: the study of molecular species whose graph, understood as the representation of the set of atoms and bonds, cannot be drawn in a plane without crossing points.

Dissipative self-assembly: association of two or more molecular components to yield unstable complexes or aggregates, enabled by a continuous input of external energy.

Dissipative state: non-equilibrium state that does not correspond to a clear minimum in the free-energy surface and can exist only with a continuous consumption of energy from an external supply, which prevents relaxation to a close energy minimum.

Equilibrium state: configuration that corresponds to the global energy minimum in the free-energy surface accessible to a chemical system. In such a state, the latter undergoes no macroscopic changes.

***E-Z* isomerization:** process involving the transformation between the two geometrical isomers of a compound that contains a double bond.

Free-energy surface: representation of the free energy of a system as a function of parameters that describe its configuration, conformation, and/or composition.

Kinetically trapped state: non-equilibrium state that corresponds to a local minimum in the free-energy surface, separated from the global minimum or from other minima by an energy barrier E_b that cannot be easily overcome at the experimental temperature T ($E_b >> kT$).

Metastable state: non-equilibrium state that corresponds to a local minimum in the free-energy surface, separated from the global minimum or from other minima by an energy barrier E_b that can be overcome at the experimental temperature T ($E_b \approx kT$).

Microscopic reversibility: in a reversible reaction, the mechanism in one direction is the exact reverse of the challenges for any specific molecular design [16,24,31–33]. This article analyzes the progress made over the past 5 years in using light to drive a coupled thermal process/reaction away from its equilibrium to reach a metastable or dissipative state at the molecular or macroscopic scale. The examples described are categorized according to the task accomplished upon irradiation, namely, the influence on: (i) molecular (co)conformations, (ii) **self-assembly**, (iii) reactivity, and (iv) materials properties. A final section will be dedicated to outline unmet challenges and future perspectives in the field.

Photoisomerization-driven directional movements and topological entanglement

Photoisomerization of tailored molecular switches was exploited to achieve directional motion in systems comprising artificial molecular motors. Giuseppone and coworkers [34] reported an overcrowded alkene rotary motor [11] functionalized with two lateral tether loops and arranged in a 'figure-of-eight' shape (Figure 2A). Light irradiation and consequent directionally-biased rotation of the motor induce the progressive entanglement of the tethers and increase the complexity in terms of **chemical topology** [35], until the mechanical strain outmatches the torque delivered by the motor, stopping the rotation. At the most entangled **photostationary states**, the unavailability of the ***E-Z*** **isomerization** pathway triggers a secondary radiative pathway to dissipate the energy provided by irradiation, leading to fluorescence emission. Therefore, light energy is stored in the form of conformational strain, which is released in the dark by causing the reverse rotation of the motor.

The directional rotation of related stilbene switches or motors was also exploited to force ring shuttling in photoresponsive **rotaxane** architectures. The single self-threaded strands of such [1]rotaxanes incorporate a light-driven rotary motor linked to a crown ether [37] or a pillararene [38] ring and two recognition sites of different affinity. The initial stilbene configuration and ring-station interaction are perturbed upon light irradiation, which triggers isomerization, with subsequent rotation, and its translation to linear motion of the ring along the axle toward the secondary, weaker station. Dube and collaborators exploited the unidirectional rotation in a light-activated hemithioindigo rotary motor to drive an epimerization reaction away from equilibrium [39]. Incorporating a sterically encumbered biaryl unit tethered to the motor extremities, the molecular structure enables gearing between the motion of the photoswitch and that of the biphenylene unit about the axially chiral carbon–carbon single bond [40]. The torque delivered by the motor through the tether catalyzes a preferential epimerization of the axial chirality which, being rate limiting, prevents the system from reaching thermodynamic equilibrium between the two atropisomers under operation.

Credi and coworkers developed light-driven supramolecular pumps based on rotaxane-type host–guest complexes [41]. Thanks to an energy ratchet mechanism, these devices realize the directionally controlled threading and dethreading of an **azobenzene**-containing axle relatively to a macrocycle [42–44]. During operation, energy dissipation occurs from both photochemical and thermal reactions and the photon energy is exploited to shift the thermal threading–dethreading reactions away from their (local) equilibrium state [45]. The generated dissipative OEQ regime depends on light intensity and was thoroughly investigated [46]. Hence, such pumps can potentially convert light into chemical energy in an **autonomous** fashion. In a successive study, the same group described a rotaxane consisting of crown ether ring interlocked with an axle bearing a pH-sensitive ammonium station and a photoresponsive azoimidazolium secondary station (Figure 2B) [36]. In such a system, the different affinity between the macrocycle and the two geometrical isomers of the azoimidazolium unit affords a photochemical allosteric modulation of acidity at the ammonium site [47], thereby providing a mechanism for ring shuttling. This feature, combined with the different photochemical properties of the encircled and free

mechanism in the other direction. As a consequence, at equilibrium any molecular process and its reverse occur, on average, at the same rate. This principle does not apply to reactions that involve a photoexcitation step.

Molecular motor: molecular-based system capable of performing directionally controlled movements of its parts when powered by energy. In principle, it is capable of converting the supplied energy into mechanical work at the nanometer scale.

Photoisomerization: transformation between geometrical isomers of a compound caused by light irradiation.

Photostationary state: steady state reached by a reactive chemical system in which at least one of the components undergoes a transformation caused by the absorption of light.

Photoswitch: molecular unit that can be interconverted between two or more structurally and chemically different forms by at least one light-induced process. One of such forms is stable, while the other(s) is (are) kinetically trapped or metastable state(s).

Ratcheted synthesis: process in which the thermodynamically unfavorable (endoergonic) synthesis of a compound is enabled by coupling to an energy source.

Rotaxane: mechanically interlocked molecule composed of a dumbbell-shaped component threaded through a macrocycle.

Self-assembly: spontaneous, thermodynamically controlled association of two or more molecular components to yield stable complexes or aggregates.

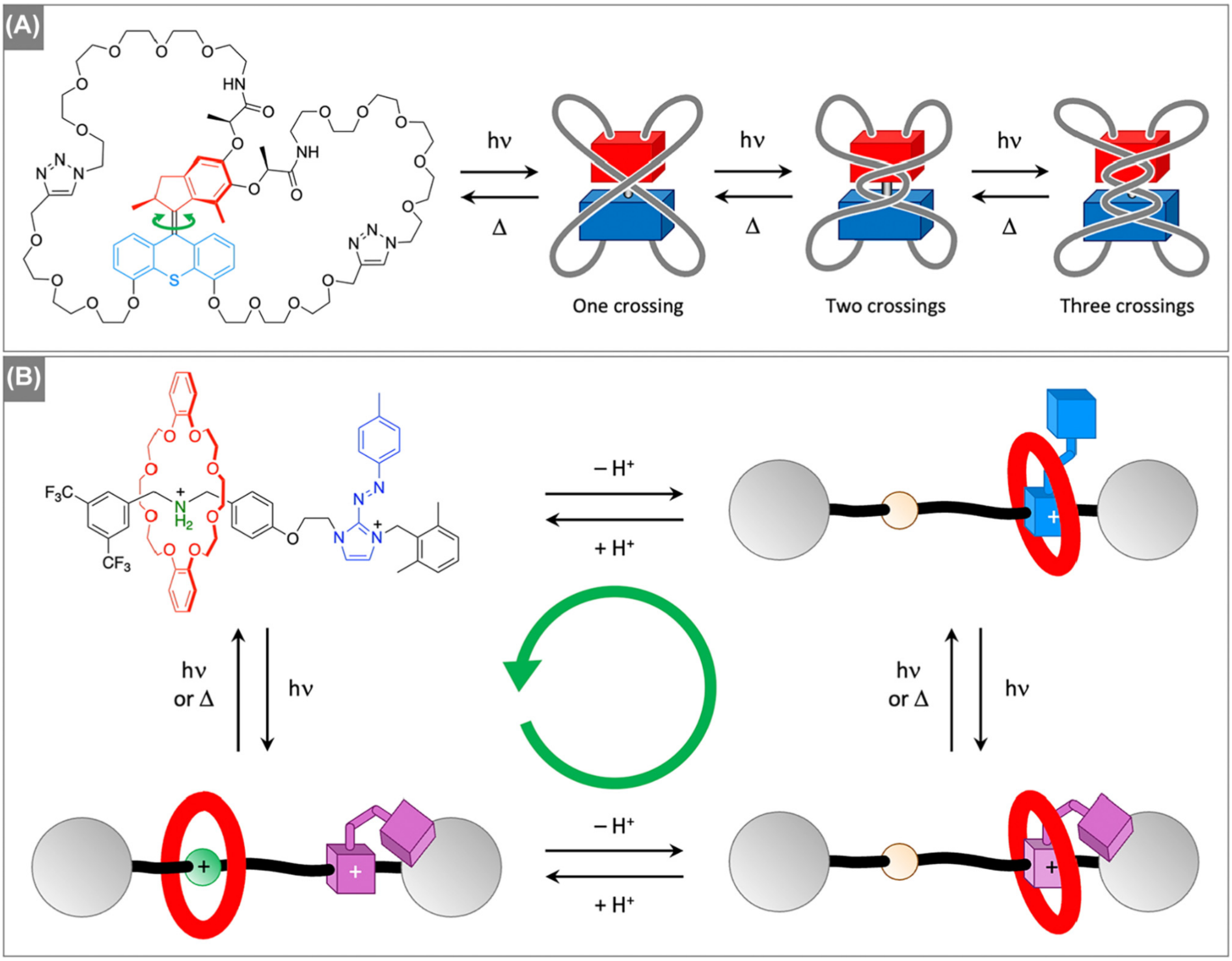

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Figure 2. Light-driven generation of out-of-equilibrium (OEQ) states in intertwined and interlocked molecular structures. (A) Structure of a 'figure-of-eight' macrobicyclic compound consisting of a photochemically driven rotary motor in which the rotor and the stator are connected by two side chains [34]. As shown by the cartoons, the forward and backward stepwise 180° rotations lead to entangled metastable structures with one, two, or three crossings. Δ denotes a thermally activated process that takes place in the dark. (B) Structure of an azoimidazolium-containing rotaxane, and reaction network at the basis of light-induced autonomous ring shuttling, which combines the azoimidazolium *E-Z* photoisomerization, the ammonium protonation-deprotonation, and the ring translation processes [36]. Upon irradiation, the cycle is travelled preferentially anticlockwise (green arrow), leading to a dissipative OEQ behavior.

azoimidazolium moieties, establishes a closed reaction network that can be travelled directionally under stationary illumination, creating dissipative OEQ states.

Non-equilibrium self-assembly fueled by light

Light has been exploited to cause the formation of thermodynamically unfavored assemblies or drive self-assembled states away from thermodynamic equilibrium. One strategy towards light-induced self-assembly exploits photoacids or photoinduced electron transfer (PET) to activate pH- or redox-sensitive building blocks. Inspired by an early study on the self-assembly of a pseudorotaxane complex triggered by PET [48,49], Xu and coworkers reported on the self-assembly of viologen-based supramolecular polymers [50]. PET triggers the formation of ternary complexes between two viologen radical cations and cucurbit[8]uril (CB[8]). Implementation of this strategy with bifunctional monomers bearing two terminal viologen units results in the formation of a supramolecular polymer that reversibly disassembles upon oxidation with air.

Merocyanine photoacids can control the assembly of pH-sensitive building blocks upon photoconversion to the corresponding spiropyran form with release of a proton [51]. Cissé and Kudernac reported on the use of these photoacids to induce the self-assembly of a cyclic peptide into nanotubes [52]. In the dark, thermal conversion to the stable merocyanine form occurs within minutes, leading to nanotube collapse. Yang and Li used a similar strategy to reversibly change the morphology of self-assembled polymeric superstructures by modulating their protonation state [53]. Parquette and coworkers developed merocyanine-functionalized peptides that undergo **dissipative self-assembly** into long fibrils under irradiation due to a variation in the amphiphilicity of the monomers [54,55] (Figure 3A); as a consequence, solvent gelation was

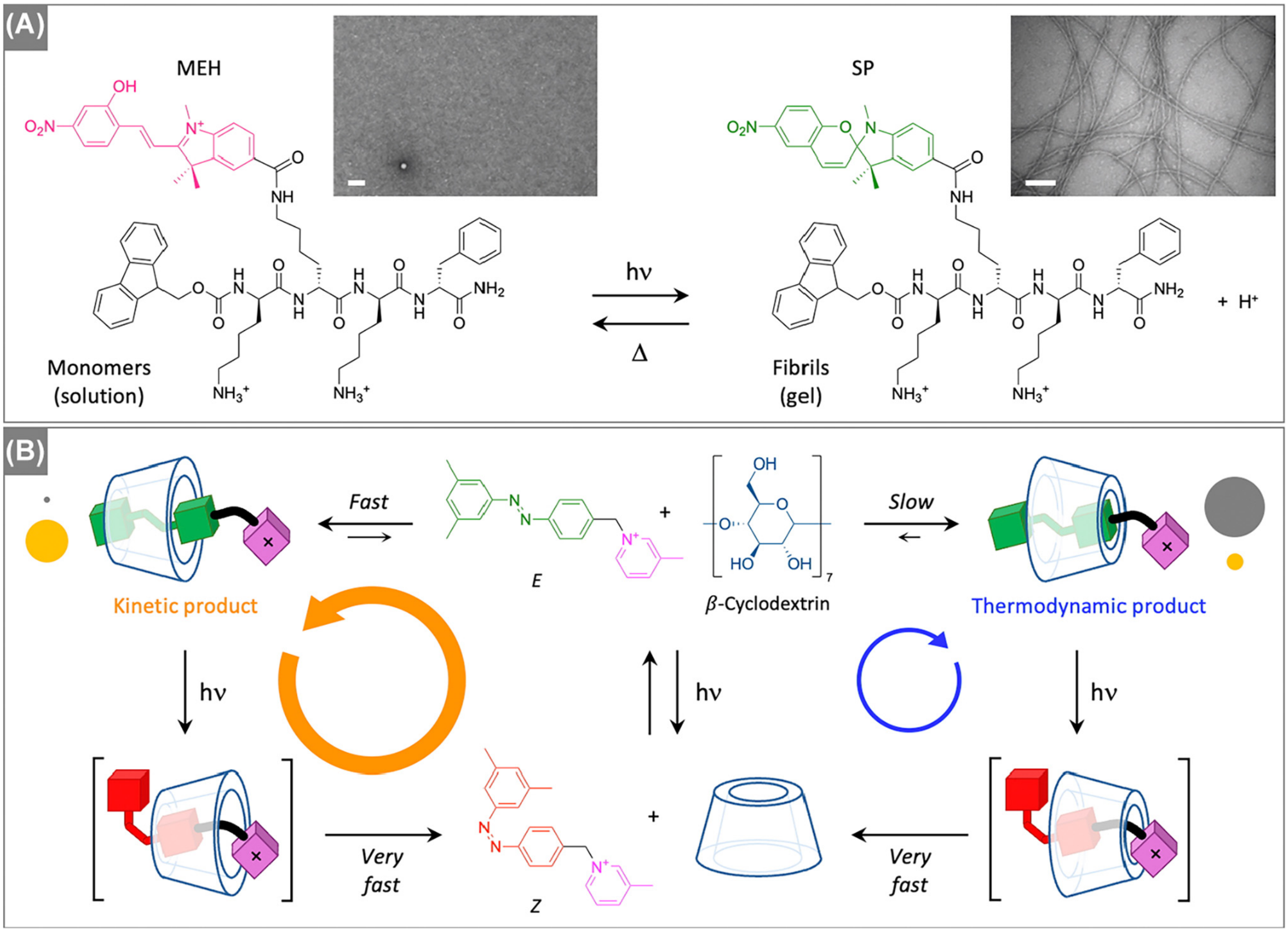

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Figure 3. Photoinduced non-equilibrium self-assembled structures. (A) Light-induced self-assembly and thermal disassembly of oligopeptide nanofibers in water, relying on a polarity change brought about by the interconversion between the merocyanine (MEH) and spiropyran (SP) forms of a photochromic substituent [54]. Δ denotes a thermally activated process occurring in the dark. The photographs show the transmission electron microscopy (TEM) images of the sol and gel states (scale bars, 100 nm). Reproduced from [54] with permission from the Royal Society of Chemistry. (B) Schematic diagram of the self-assembly of cyclodextrin-azobenzene complexes in the dark (top line) and under the action of light (full scheme), in water at room temperature [59]. The circles next to the cartoons of the complexes represent the relative abundance of each complex in the dark (equilibrium distribution, in grey) and under visible light irradiation (λ = 453 nm, in yellow). Both systems are of potential interest for biological applications as they operate in an aqueous environment under visible-light irradiation.

observed. Spiropyran-merocyanine photoacids were also employed to control the pH-dependent folding of DNA-based nanodevices into double or triple helix. Different OEQ states with distinct folding geometries can become favored with respect to the dark conditions. This strategy was exploited to displace cargo sequences loaded as a duplex-forming strand [56], self-assemble DNA duplexes into higher order fiber-like superstructures [57], or to induce supramolecular polymerization of nanoscopic building blocks formed by DNA origami [58].

An alternative approach, described by Otto and coworkers, involves the use of porphyrin-mediated photooxidation to induce the self-assembly of new members in a mixture of replicators [60]. The favored replicator strongly binds the photocatalyst and is dismantled by singlet oxygen, promoting the emergence of smaller replicators that are weaker porphyrin binders.

Only a handful of examples are reported that use light to directly induce the assembly through photo-modification of the building blocks. Pioneering work was performed by Sleiman and coworkers [61] and by Grzybowski and Klajn [62]. Zhang and coworkers exploited azobenzene isomerization to induce the OEQ self-assembly of a ureidopyrimidinone-based quadruple H-bonding motif [63]. Irradiation switches the available H-bond sites from one to four, enabling the interaction with a 2,7-diamino-1,8-naphthyridine derivative, thereby inducing recognition of the two units. Recently, Credi and coworkers described azobenzene-cyclodextrin complexes that can exist in two orientationally isomeric forms which exhibit different stabilities and assembly kinetics (Figure 3B) [59]. Photoirradiation populates an OEQ state in which the less stable and kinetically favored isomer is accumulated at the expenses of the thermodynamically stable, slower-forming one.

Other interesting examples were reported by the groups of Clever and Beves, who demonstrated the light-induced encapsulation of a guest in a diazocine-functionalized cage [64], and the control on the morphology of a metal-coordination cage [65,66], respectively. Di Stefano and coworkers showed that light can be used to control complexation equilibria of metal ions by crown ether-type macrocycles in a dissipative fashion [67]. Specifically, they utilized simultaneous light and chemical stimuli to achieve a time-dependent modulation of the amount of potassium ions complexed by different crown ethers in a mixture. Very recently, the groups of Nitschke [68] and Aprahamian [69] elegantly showed that macroscopic concentration gradients can be established by coupling photochemical reactions with complexation equilibria; in these cases, however, the asymmetry required to achieve directed transport is determined by irradiating solutions in the two arms of a U-tube (separated by a bulk liquid membrane) with different wavelengths.

Light-controlled non-equilibrium formation of covalent species

This section will focus on systems that exploit light to control the outcome of a covalent bond breaking/forming process, yielding high-energy products and generating an OEQ speciation. In most cases the molecular design requires the light-harvesting portion of the molecule be irreversibly connected (covalently or mechanically) to the reactive moiety [31]; it is also possible, however, that the two roles are fulfilled by the same molecular moiety [70].

Herder and Lehn reported on photodynamic covalent bonds as a strategy to alter the composition of a dynamic covalent library of alkoxyamines, in which the N–O bond can undergo homolytic cleavage after energy transfer from a covalently linked photosensitizer [71]. Upon photoirradiation of an equilibrated library of photosensitized and non-photosensitized alkoxyamines, only those lacking the sensitizer are stable and can be accumulated. Exploiting this information ratchet mechanism, the composition of the library moves toward the self-sorting of the doubly sensitized and doubly non-sensitized members.

Extensive work on the modulation of reactivity using light has been performed by Hecht and Branda, who exploited photoswitches (mostly diarylethenes) functionalized with a diene or an aldehyde, to control their reactivity in Diels-Alder or imine exchange reactions, respectively [31,72,73]. Building upon these results, systems to photocontrol the composition of dynamic covalent libraries of azobenzene-based imine macrocycles (Figure 4A) [74] or to catalyze transimination reactions to convert an azobenzene-based cage into a non-photoactive cage [75] were developed by the groups of Schmidt and Feringa, respectively. Hecht and coworkers described the use of light to drive uphill an imine-formation equilibrium, appending a ketone electrophile within a closed diarylethene-like structure [76] Upon photoinduced ring-opening the ketone is converted into a phenol, which is unreactive towards imine exchange. A similar cycle can be devised for the ring-opened imine, which is converted into a stable aniline upon ring closing. Owing to the distinct absorption spectra of the two forms (ketone and imine), careful alternation of the irradiation wavelength shifts the equilibrium towards the unfavored imine product by capturing its ring-closed aniline and depleting the unreacted ketone.

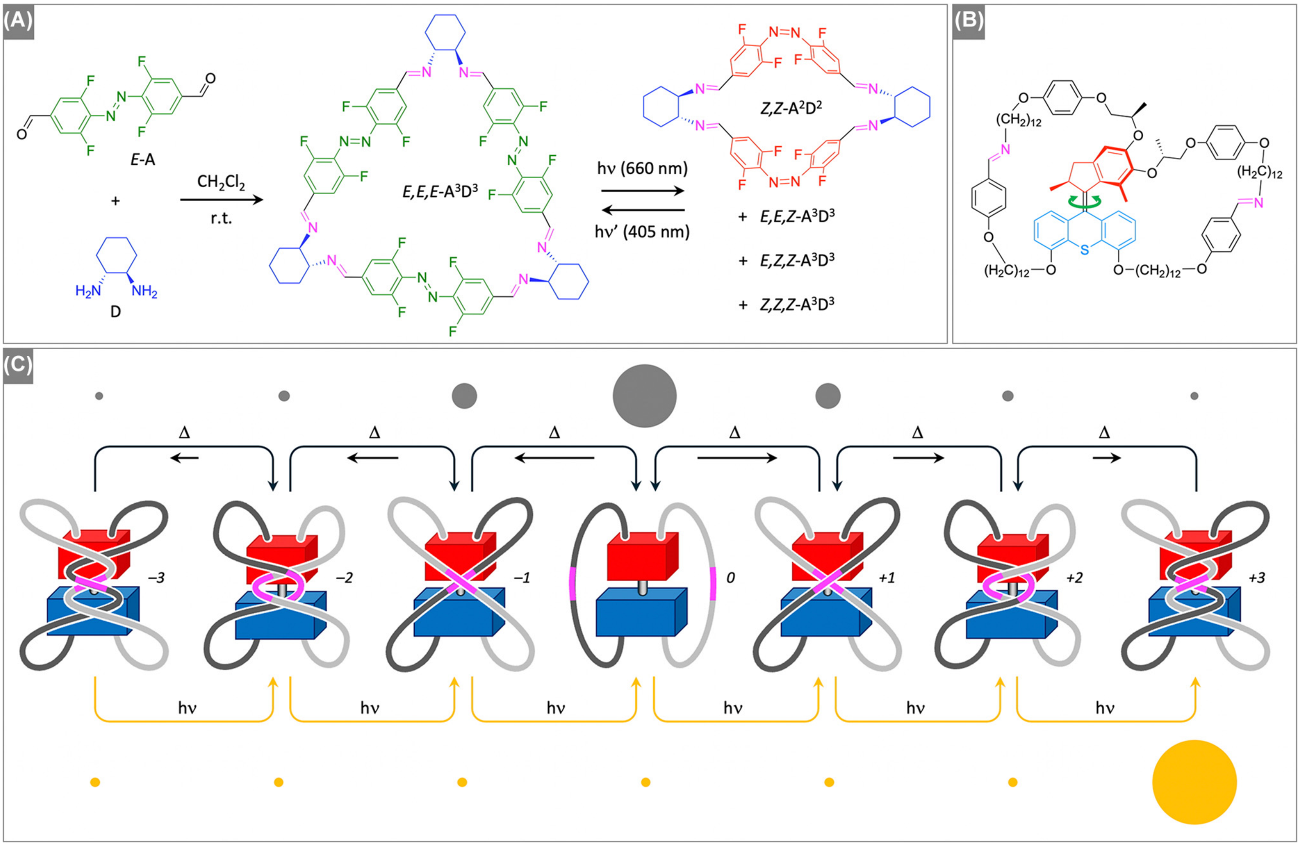

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Figure 4. Photochemical non-equilibrium control of imine bonds. (A) The reaction of an azobenzene bis-aldehyde derivative (A) in its *E* configuration with *R*,*R*-1,2-diaminodicyclohexane (D) in CH_2Cl_2 at room temperature yields selectively the macrocycle *E*,*E*,*E*-A^3D^3 [74]. Irradiation of the macrocycle with red light causes the *E* → *Z* isomerization of the A units and shifts the equilibrium towards the smaller *Z*,*Z*-A^2D^2 ring, which was observed by ^{19}F-NMR and mass spectroscopy besides the mixed configurational isomers of the A^3D^3 macrocycle. Successive irradiation with blue light triggers the *Z* → *E* isomerization of the A moieties and the stable macrocycle *E*,*E*,*E*-A^3D^3 is restored. (B,C) A 'figure-of-eight' species consisting of two imine-containing macrocycles bridged by a photoactivated molecular rotary motor (B) [77]. In such a molecule, crossings can be created (C) by either thermal nucleophile exchange of the imines (black arrows) or by light-driven unidirectional rotation of the overcrowded alkene moiety (yellow arrows). The labels ±*n* indicate the chirality of the crossing and the number of twists. Irradiation winds up the bicyclic species unidirectionally, generating a distribution of species (yellow circles; the size of the circle is proportional to the relative abundance of the species) with increasing number of crossings that is markedly different from its equilibrium value (grey circles). After three 180° turns, mechanical strain prevents further rotation.

An ingenious approach to affect the formation of imine bonds by exploiting a photoinduced molecular motion was reported by Kathan, Schalley, Feringa, and coworkers (Figure 4B,C) [77]. In a 'figure-of-eight' molecule incorporating an overcrowded alkene motor (Figure 4B), terminal loops wind up progressively as a consequence of photoinduced unidirectional rotation, thereby increasing the topological complexity of the system (i.e., the number of crossing points between the loops; see also Figure 2A). However, the presence of an aldimine bond in the loops, which becomes dynamic in the presence of a nucleophile, can allow relaxation of the topologically entangled, high-energy structures to their equilibrium distribution (Figure 4C). Thus, irradiation leads to a non-equilibrium speciation of the various topological states and, for the highly entangled ones, the imine exchange reaction is largely shifted towards the unstrained reagents (aldehyde and amine).

Very recently, Greenfield and coworkers introduced aryliminopyrazoles as a new class of photoswitchable imines [78,79]. By combining *E-Z* photoisomerization and transimination process, it was shown that light irradiation generates non-equilibrium dissipative states for the imine exchange reaction [70]. The amount of energy stored in the non-equilibrium state was estimated, considering both the contributions of the photoisomerization (distribution of the *E/Z* isomers) and the constitutional change (distribution of the imine products). The originality of this approach stems from the fact that the light-fueled 'driving' reaction (namely, photoswitching) and the thermally-activated 'driven' reaction (namely, transimination) take place on the same site of the molecule.

All the aforementioned studies are relevant examples of **ratcheted synthesis** because they exploit light energy to shift a reactive system away from its equilibrium distribution (i.e., to bring a thermally activated process energetically uphill) [9,10].

Light driven non-equilibrium in soft materials

The incorporation of photoswitchable dynamic behavior in polymer-based soft materials can be exploited to induce physical and mechanical non-equilibrium properties at the macroscale. By introducing light-driven rotary motors as crosslinking points in polymer gels, Giuseppone and collaborators exploited the work generated by the unidirectional rotation to increase entanglement of the matrix and cause the macroscopic contraction of the gel [80]. The rotary motor operation caused the OEQ winding of the polymer strands; when the unwinding was allowed by employing dithienylethene-based photoswitchable 'modulators' as crosslinkers together with the motors, it was possible to reversibly contract and expand the system with alternate cycles of UV and visible light [81]. Later, self-standing gels were developed that could operate as bending actuators, generating a force able to lift weights up to hundreds of times the mass of incorporated rotary motors [82,83].

A different approach to soft materials that can do mechanical work was reported by Stevens and collaborators. Their system relies on a sophisticated oscillating reaction network, based on pH modulation controlled by light gated feedback loops, that was introduced in a swellable hydrogel, demonstrating the possibility to translate the OEQ pH gradient into chemomechanical work [84].

Recently, Baretta and Frasconi exploited the balance between a PET-mediated disulfide reduction and electrochemically-induced disulfide formation in a crosslinked hydrogel, to achieve dissipative gel softening and realize a photoresponsive delivery system [85].

Alternative systems use light to achieve localized and reversible sol-gel transitions that could be applied in 3D printing and patterning. An example is the 'light-stabilized dynamic materials

(LSDM)' approach developed by Barner-Kowollik and coworkers, who exploited the photoreaction between appropriate side substituents of polymer chains and bifunctional linkers to create networks under irradiation (Figure 5A) [86]. The visible light-induced cycloaddition of a bis-triazolinedione linker to the naphthalene pendant units of the macromolecules (Figure 5B) forms a crosslinked gel-like polymer network which persists during irradiation and reverts to a viscous liquid in the dark, owing to dissociation of the cyclic adduct (Figure 5C). The LSDM was applied as a self-destructive photoresist in 3D direct laser writing to produce selectively erasable multi-material scaffolds at the micro scale [87,88].

As discussed in previous sections, merocyanine photoacids can be exploited to control the assembly of pH responsive DNA units with light. Li and coworkers applied such a strategy to the

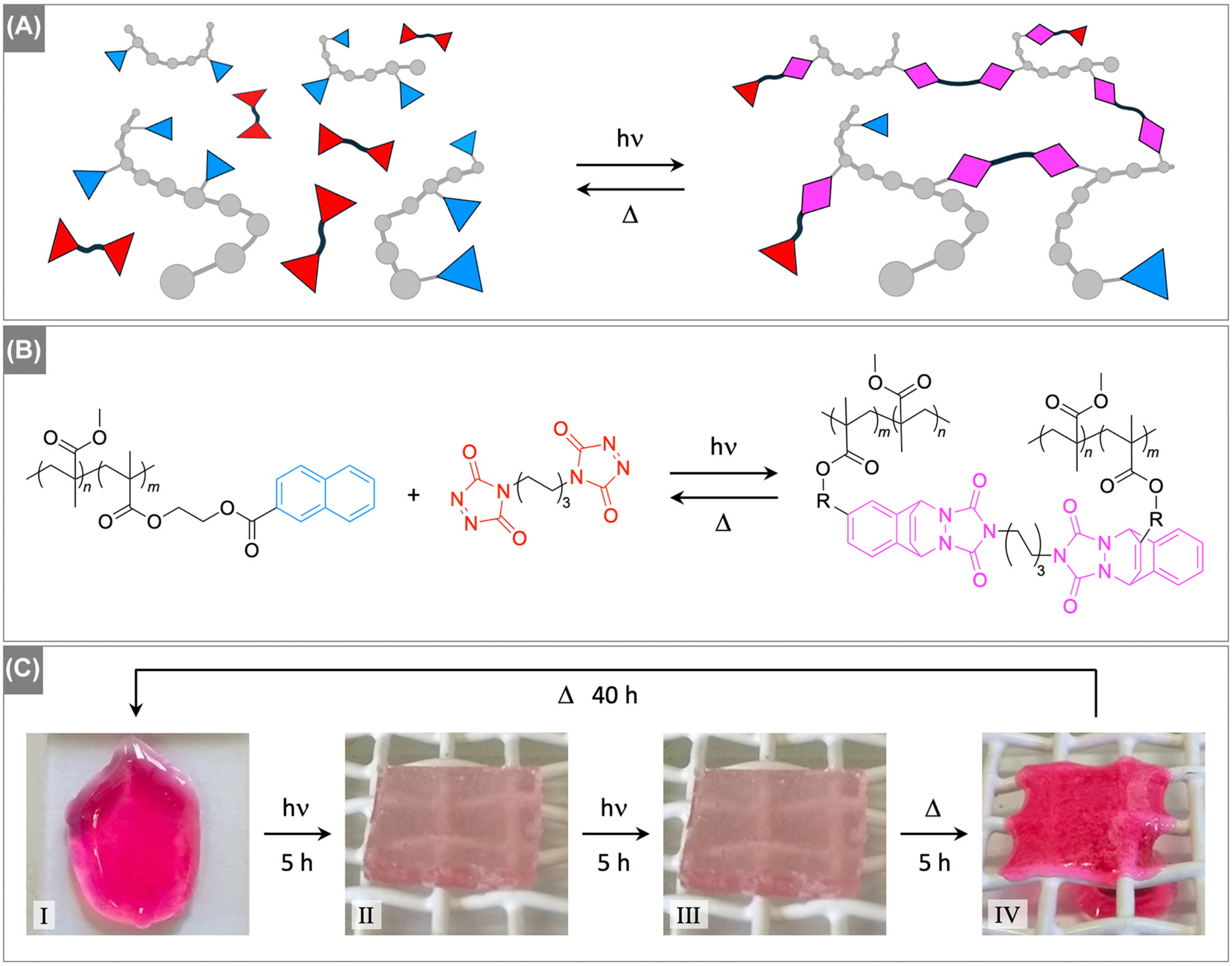

Figure 5. Light-stabilized dynamic materials. Schematic representation (A) and structure formulas (B) of a dynamic polymer in which a covalently crosslinked network is generated through a visible light-driven cycloaddition [86]. Δ denotes a thermally activated process occurring in the dark. (C) Demonstration of the light-stabilized dynamic behavior. By curing a propylene carbonate solution of the components (I) with green light, a crosslinked material is obtained (II). The resulting network remains intact under irradiation (III), whereas turning off the light initiates a spontaneous cycloreversion at room temperature (IV), leading to the dissociation of the crosslinks and the collapse of the material (I). The solution can be recovered and cured again upon irradiation, thereby repeating the cycle. Reproduced from [86] with permission from the American Chemical Society.

creation of reversible hydrogels under irradiation and used them for reprogrammable photopatterning of simple structures [89].

Hamachi and collaborators reported on the formation of OEQ patterns induced by irradiation followed by diffusion processes, in self-sorting supramolecular double network (SDN) hydrogels. The network is composed by a combination of lipid- and peptide-type nanofibers, the latter functionalized with a photoactive acylhydrazone. UV irradiation of the SDN using a photomask triggers the local *E* → *Z* isomerization of the photoswitch with fragmentation of the peptide-type nanofibers and migration of the monomers to neighboring regions. Subsequent *Z* → *E* thermal conversion and the following assembly-diffusion processes result in the formation of fibrillar patterns in the illuminated area [90].

Concluding remarks and future perspectives

The use of light makes it possible to bypass microscopic reversibility and access unconventional reactive pathways for complex systems in high-energy states. Although this general principle is clear, its practical implementation with synthetic species to achieve predetermined goals remains challenging (see Outstanding questions). The previous sections highlighted the substantial advancements of the field in the past few years and their impact in diverse areas of chemical research. The energy gathered by irradiation can be used to trigger unfavored secondary processes such as self-assembly, topological entanglement, controlled chemical reactivity, and specific functions in materials. Most of these systems, though, exploit light to become kinetically trapped in high-energy states, for example, by temporarily modifying molecular properties (e.g., shape, polarity, redox potential) and/or the medium conditions (e.g., pH); because the energy consumption pathway remains limited to the photochemical reaction – the coupled equilibrium merely adapts to new conditions imposed by irradiation – it is difficult to achieve a truly dissipative behavior. However, the fundamental and often overlooked advantage of using light lies in its potential to continuously drive dissipative cyclic processes, which can do work in a clean and controlled way. To date, only a limited selection of systems has provided a preliminary glimpse into the potential of such asset. It can thus be envisioned that in the upcoming decade research efforts in the field will be directed to the understanding of the principles that govern dissipative light-to-work transduction and the subsequent development of appropriate molecular tools to effectively harness and exploit them. Indeed, (sun)light is a valuable and renewable resource, and photochemically driven non-equilibrium processes can have a primary role in the technological advancements that will shape our future.

Outstanding questions

What are the key principles to effectively couple a photochemical process with a thermal reaction so that the light energy harvested by the former can drive the latter away from equilibrium?

How should a reaction network be designed in order to obtain a light-induced dissipative behavior?

What characteristics should a molecular photoswitch possess in order to transduce light energy for an out-of-equilibrium chemical system? Are there other viable options among the plethora of known photochemical reactions?

Molecular self-assembly and imine exchange are a most common choice for the role of the thermally activated reaction to be shifted away from equilibrium. Are there other possibilities?

How can the energy stored in a photoinduced non-equilibrium state be measured or estimated and compared with the incoming energy input? How can these figures be optimized by design?

What are the pros and cons of integrating the 'driving' photoreaction and the 'driven' equilibrium in the same reactive site? How does this strategy compare with a more modular approach, in which the two processes take place at well distinct sites?

What kind of new materials and functionalities can be achieved by light-driven dissipative self-assembly?

Can photon-fueled artificial chemical systems open novel and unconventional ways to convert and store solar energy?

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Declaration of interests

The authors declare no competing interests.

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