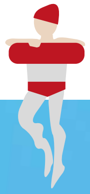


In photochemistry, light delivers the energy for chemical reactions to happen. Photosynthesis is probably the most well-known example of such processes.

Millions **at my Beck and Call!**

Thorsten Bach is in the unusual business of “taming” tiny molecules, teaching them to do exactly as he commands. His aim is to reduce waste. A visionary Italian pioneer is lighting the way – literally!

Claudia Steinert

„Millionen machen, was ich will!“

Licht ist extrem energiereich und kann chemische Reaktionen anstoßen. Dann entstehen neue Stoffe, und was für welche! Lichtenergie ist so stark, dass sie es schafft, Moleküle in herrlich nützliche, aber unglaublich unbequeme Positionen zu zwingen. Deshalb ist die Photochemie oft der einzige Weg, um starre chemische Gerüste herzustellen, wie sie zum Beispiel für Medikamente oder Pflanzenschutzmittel gebraucht werden. Einziger Nachteil: Die Reaktionen sind oft schwer steuerbar. Der Chemiker Prof. Thorsten Bach hat jedoch sehr präzise Vorstellungen davon, was er am Ende einer photochemischen Reaktion in seinem Reagenzglas vorfinden will. Sein Spezialgebiet sind sogenannte chirale Verbindungen.

Das Wort Chiralität kommt vom griechischen cheir, die Hand. Denn Hände sind chiral. Sie bestehen aus denselben Teilen und sind spiegelbildlich aufgebaut. Egal wie man sie dreht und wendet, nie wird es so aussehen, als hätte jemand wirklich zwei linke Hände. Chemiker sagen: Die linke und rechte Hand sind Enantiomere.

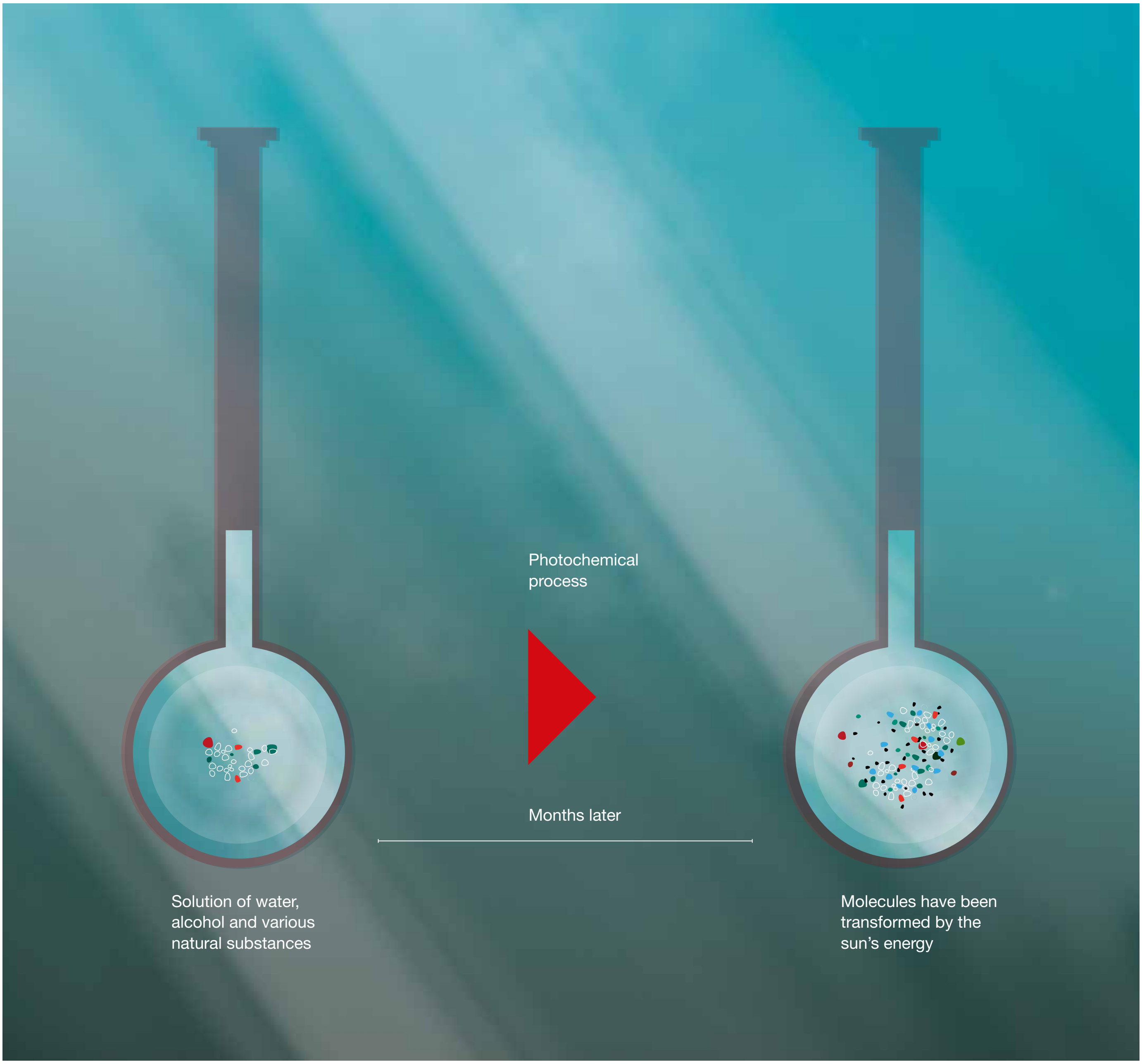
Die Natur liebt Chiralität. Wer mit Medikamenten an Rezeptoren andocken will, wer Enzyme blockieren oder Bakterien attackieren möchte, der braucht jedoch ein ganz bestimmtes Enantiomer. Das andere ist für den Körper mitunter sogar giftig. Heutzutage werden viele chirale Verbindungen trotzdem als Enantiomerengemisch produziert. Erst hinterher wird aufwändig getrennt. Damit gibt Bach sich nicht zufrieden. Er will von Anfang an so präzise konstruieren, dass er am Ende nichts verschwenden muss. Dafür entwickelt er hochkomplexe Katalysatoren, die ebenfalls chiral sind.

Diese Katalysatoren greifen einen der Ausgangsstoffe und positionieren ihn so, dass nur eine Reaktion stattfinden kann. Nur ein Enantiomer entsteht. Chemiker sprechen von asymmetrischer Katalyse.

Ein Drittel von Bachs Mitarbeitern tüftelt zurzeit an diesem Projekt. Sechs bis acht Wochen dauert allein die Herstellung eines Katalysators. Zurzeit arbeitet Bach viel mit Kunstlicht, die wählerischen Katalysatoren mögen nur bestimmte Wellenlängen. Eines Tages möchte Bach jedoch auf Lampen verzichten können. Er will dann die kostenlose Energiequelle Sonnenlicht nutzen. □

> Thorsten Bach will eines Tages das Sonnenlicht als kostenlose Energiequelle für bestimmte Katalysereaktionen nutzen.

Picture credits: Jooss



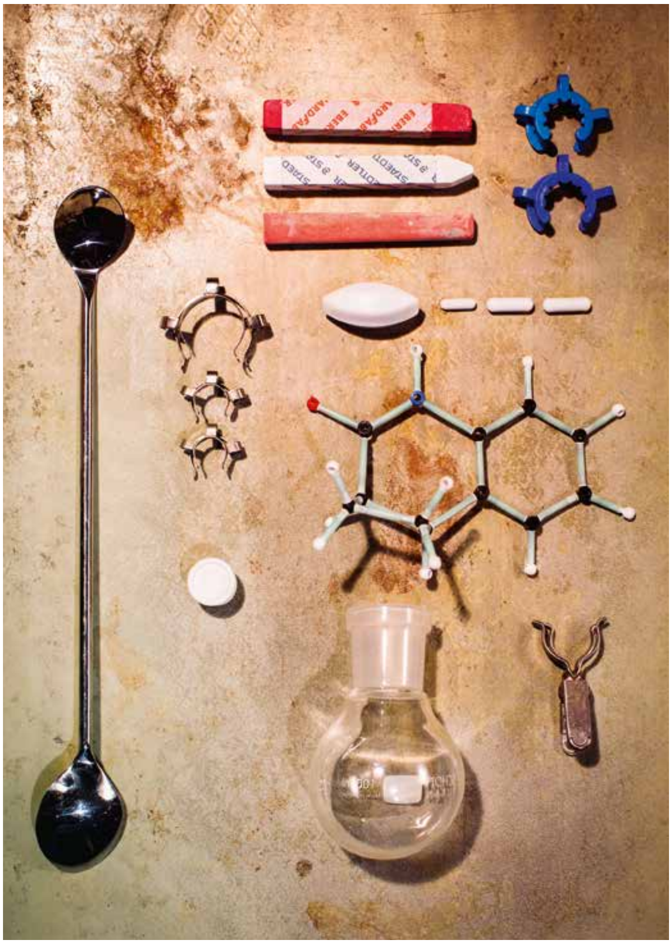
More than a hundred years ago, Italian chemist Giacomo Ciamician discovered that light could help transform molecules into new forms. Back then, Ciamician already said that someday we might no longer need fossil fuels.

Link
www.oc1.ch.tum.de

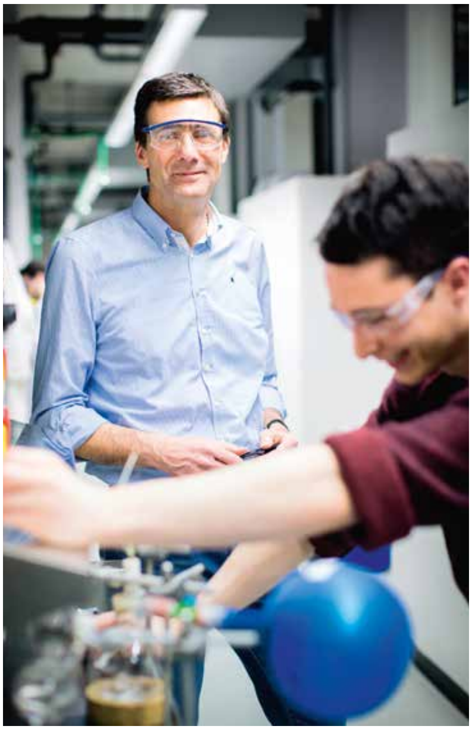
Sometimes it takes more than just a good idea – you also need to be in the right place at the right time. For chemist Giacomo Ciamician, that place was Bologna – around 1910. Summers there are hot and bright, flooding the Italian city with nine or ten hours of blazing sunlight each day. Having already passed the fifty-year mark, Ciamician was considered an old man by the standards of the time – but an active one. Along with his assistant, he hauled numerous flasks onto the balcony of the institute where he was teaching and researching. The two men balanced them on shelves, ledges and balcony railings, filling every available space. Long necks stretched to the sky, the glass bulbs sat and waited. Solutions of water, alcohol and various natural substances lay dormant inside.

The very first photochemical experiment

What happened next took what seemed like an eternity and was utterly unexciting to watch. Hours, days and weeks went by with no sign of anything at all. Nothing that you could see, hear or otherwise perceive in any way. Inside the flasks, though, change was afoot. Very gradually, the sun's glare was transforming the molecules – splitting compounds and forming new ones. Months later, when Ciamician came to analyze the contents of the flasks, he found different substances to the ones he had originally mixed into them. So with this experiment he was able to prove to the world that we can harness energy from sunlight. And that, he said, might someday mean that we would no longer need fossil fuels. At a time well before any talk of crude oil shortages or climate change, Ciamician was already predicting artificial photosynthesis. He was a ▷



Picture credit: Jooss, Graphics: ediundsepp



> *“It’s great when you’re heading into entirely new territory and come up with the very first ideas.”* *Thorsten Bach*

Prof. Thorsten Bach

A pioneer in photochemistry

Thorsten Bach's involvement with photochemistry began more by accident than design. During his doctorate at the University of Marburg, he was working with metal complexes that could only be photochemically generated. "That meant I had the right equipment, so then I gradually built up my knowledge," he explains. At that point, at the start of the 1990s, nobody else was pursuing similar concepts. Was he worried about barking up the wrong tree? On the contrary: "It's great when you're heading into entirely new territory and come up with the very first ideas," counters Bach.

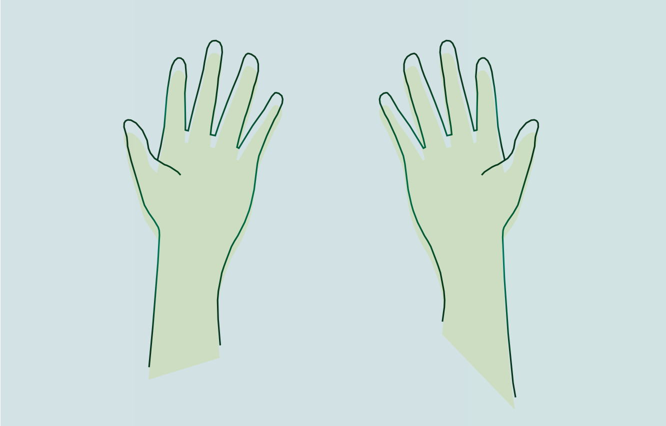
Following a period of research in Harvard, he returned to Germany, qualifying as a lecturer in Münster before taking up his first professorship at the University of Marburg. In 2000, Bach went on to join TUM as Professor of Organic Chemistry. His wife, also a chemist, teaches at the Weihenstephan-Triesdorf University of Applied Sciences. As far as Bach is concerned, the best thing about his job is the level of autonomy he enjoys. "When it comes to research, I'm given free rein," he confirms. At the same time, he sees himself as having a social responsibility, feeling that artificial photosynthesis is something chemists like him are now called upon to develop. Ciamician would have been thrilled.

Picture credits: Jooss

visionary in the realm of photochemical research. Around a hundred years later, Prof. Thorsten Bach stands in his office at TUM's Garching campus on a gray winter's day. Looking up at the cloudy sky, he notes: "Ciamician's experiments wouldn't have worked here at all." Way too overcast; nowhere near enough light. Definitely not the right place.

Focus on chiral compounds

Meanwhile, though, things have moved on in this field and today's photochemists are no longer dependent on sunshine. Bach's lab is equipped with lamps that cast rays of all wavelengths within cylindrical mirrors. The spectrum ranges from longwave, low-energy green light through blue beams to shortwave, high-energy ultraviolet – the UV light that is invisible to the human eye but sometimes makes itself felt as sunburn after a day at the beach. Bach needs all these different lamps because molecules are very particular – they only accept light energy at specific wavelengths. So depending on the reaction Bach sets out to test, he switches on different lights.
Light is full of energy, and molecules can absorb this and move into an excited state. However, they do not stay at this elevated energy level for long. They either emit their excess energy in the form of light or store it in one or more chemical bonds. This creates new substances, and that is where things get interesting! The light energy is so strong that it forces the molecules into exceptionally useful but astonishingly awkward positions.
Unlike Ciamician, Bach is not just trying to generate any old molecules, however. On the contrary, he has a very precise idea of what he hopes to find in his test tube at the end of a photochemical reaction. His particular focus is on chiral compounds. ▷



Chiral molecules exhibit the same symmetry as our hands: They consist of the same elements and mirror each other. No matter how you rotate them, they can never be converted into each other.

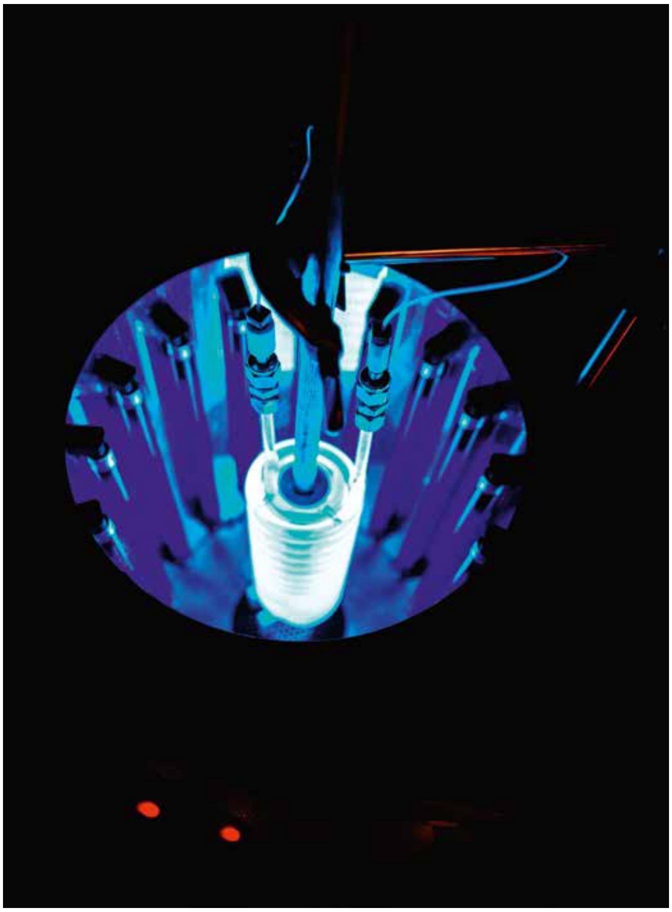
The word chirality is derived from the Greek cheir, or hand. And looking at your own two hands is a good starting point when considering this concept. Our hands themselves are chiral. There are two reasons for this. Firstly, they consist of the same elements and secondly, they mirror each other. No matter how you turn or rotate them, you can never make it appear as though you truly have two left hands. Chemists refer to enantiomers when talking about chiral molecules that mirror each other. A mixture of corresponding enantiomers is known as a racemic mixture or racemate.

But no matter how similar enantiomers may appear, they can work in deceptively different ways. The drug penicillamine is a good example. Its active agent is a chiral compound. One enantiomer, D-penicillamine, is an antibiotic, whereas its mirror enantiomer, L-penicillamine, is toxic. Only one of the two possible enantiomers in this type of compound can be successfully used as medication.

Designing new catalysts for efficient production

Many chiral compounds are still produced as racemic mixtures, which then require effort to separate. “You can separate almost anything, but it is certainly costly,” confirms Bach. It also means throwing away half of what you produce – much to Bach’s discontent. His aim is to increase production precision to such an extent that there is no waste at the end.

When Thorsten Bach is pondering a new reaction, he turns to plastic balls the size of cherry stones and sticks the size of matches, which he crafts into molecular models. He bonds nitrogen and oxygen, forms a ring of black carbon spheres and then adds enough hydrogen atoms to occupy all available ▷



Light with different wavelengths delivers the energy the molecules need to undergo certain photochemical reactions.

Picture credits: Jooss, Graphics: ediundsepp

connection points. This handicraft is not strictly necessary, since molecules can now be simulated by computer. But that is just not the same, in Bach's book – he needs something tangible for inspiration. So there he sits, model in hand, and considers how best to produce it. Chemists like Bach are architects that seldom set eyes on their elaborate constructions. A great deal exists only as theory, in formulas and abstract concepts. Or, indeed, as plastic models. Bach, however, does not find this frustrating – on the contrary, it fascinates him. Without even seeing the molecules, he can control them precisely. "Millions of molecules at my beck and call!"

A general difficulty is that many molecules are far more similar to us humans than we might think. They are not actually all that keen on changing themselves and creating something new. They prefer to mooch about lethargically in corners. They could be breaking bonds, forming new ones, combining to form completely different molecules – in theory. But they actually prefer not to.

To get things moving, energy must be applied to the molecules – activation energy, as chemists call it. Heat is very simple and effective in this respect, but light works sometimes too.

Light energy and catalysts in combination

Another possibility is to accelerate the reaction by using catalysts. Catalyst molecules are only added to the reacting solution in tiny amounts, since the catalyst itself is not expended during a reaction. So at the end, when all the starting substances have turned into new products, the catalyst remains unchanged. Bach is using both methods at once: light energy and catalysts. But accelerating reactions is not the primary purpose of his catalysts – they are intended to increase precision. Highly complex, chiral catalysts engage one of the initial substances, position it and thus ensure that new bonds can only occur at precisely defined points. This means that only one of the two possible enantiomers is formed in the reaction. The more selective the reaction, the better. Researchers consider it a positive outcome if at least 95 percent of the desired enantiomer is present at the end.

Like photochemistry, asymmetric catalysis is still a very new research field. It was in the 1970s that scientists were first able to apply this method to large-scale pharmaceutical production, manufacturing L-DOPA for the treatment of Parkinson's disease. And in 2001, the Royal Swedish Academy of Sciences awarded a Nobel Prize for advances in asymmetric catalysis. So Bach is linking the two emerging fields of photochemistry and asymmetric catalysis. Funding from the European Research Council is lending momentum to his project, and he has allocated a third of his team to developing chiral photocatalysts.

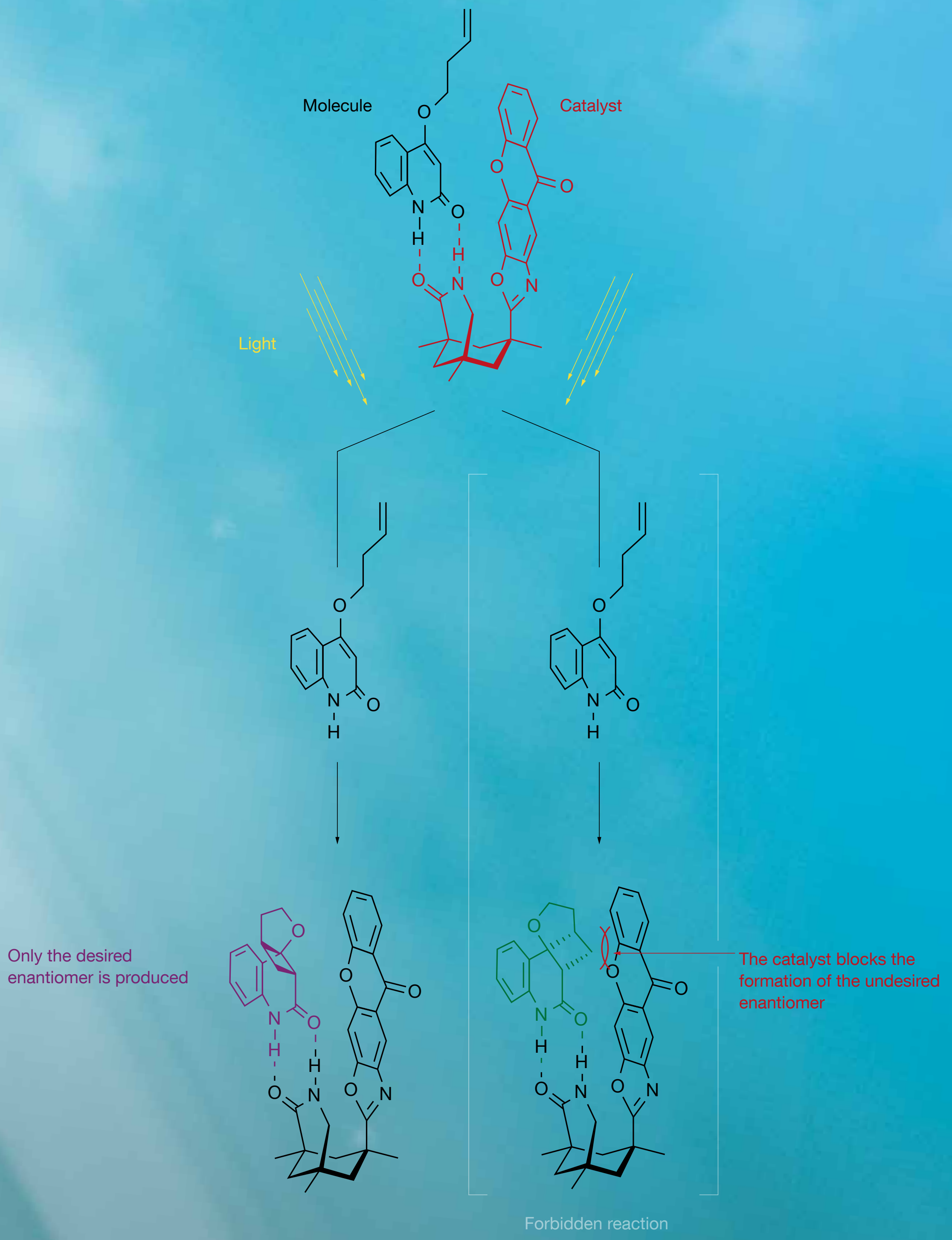
Asymmetric catalysts enable selective production of enantiomers

First, the chemists consider which molecule they intend to produce. From there they can work out what a catalyst would need to look like to force the initial substances into the right geometry. Generating the catalyst alone takes six to eight weeks, and then the scientists place a solution consisting of initial substance, catalyst and solvent into a test tube. This they position inside a circle of lamps and switch on the cooling system – the lower the temperature, the less the molecules move. Light shines through the glass from all sides. But no-one can see what exactly is happening inside. Whether the team's work over the past weeks has paid off only becomes evident when they test the substances in the test tube.

At that point, Bach and his researchers gather around the analyzer – and wait. At some point, a number pops up on the display – a sign from the first enantiomer. Deep breaths and another wait. If no second number appears, the reaction is a success. The light and the catalyst have worked with the precision Bach envisaged.

The team is currently focusing on reactions known as [2+2] cycloadditions. Here, two functional groups each consisting of two carbon atoms bond to form a four-membered ring. This scaffold is extremely taut and robust. Chemists can attach all kinds of side groups to its edges to produce substances with widely varying effects. Rigid is good, as far as Bach is concerned. As long as nothing wobbles, the side groups can latch onto the possible receptors in precisely defined positions and the outcome is better than with molecules that move. However, rigid is also chemically challenging. The energy input required to force the atoms into this shape is particularly high, so photochemistry – i.e. light – is essential. Bach's working group has already developed a few promising potential catalysts. The only drawback is that most of them are very fond of artificial light, finding the sun's longer wavelength problematic. Someday, though, Bach hopes to abandon his lamps and get right back to where Ciamician started a good hundred years ago – free energy in the form of sunlight.

Claudia Steinert



Bach's research subject are photochemical reactions that produce chiral molecules, i.e. molecules exhibiting two enantiomers. He designs catalysts that make these reactions more precise by ensuring that only the desired enantiomer is produced.

Graphics: ediundsepp (source: TUM)