HIGHLIGHTS
2023 FROM THE YEARBOOK OF THE MAX PLANCK SOCIETY
Each year, the Max Planck Society submits a scientific research report in the form of a yearbook to render account of the scientific research performed at its Institutes to the public and its funding providers. The central questions addressed are: where do we stand, and where do we want to go? The Max Planck Institutes are asked to select a work or project from their scientific activities that is suitable for presentation in the yearbook, as far as these have reached a certain degree of completion. The yearbook contributions of all Max Planck Institutes are published on our website at www.mpg.de/yearbooks.

For this printed collection, 15 articles were selected and edited in a journalistic manner, which seemed particularly suited for publication from a science communication perspective and especially interesting also for non-experts.

Researchers at the Max Planck Institute for Research on Collective Goods have tested an innovative training programme aimed at enhancing workplace atmosphere and reducing staff turnover. Their findings emphasised the pivotal role of improved relationships between managers and team members in fostering positive outcomes.

Many people who suffer from anorexia struggle with a distorted body image and a strong fear of gaining weight on a daily basis. In a pilot study, a team of researchers at the Max Planck Institute for Intelligent Systems demonstrated that virtual reality body simulations could be a useful addition to existing treatments for anorexia nervosa.

At the Max Planck Institute for Chemical Energy Conversion, researchers are working to develop catalysts and production processes to produce fuels for heavy road transport or shipping using green electricity from water and CO₂ or biological waste. Not all modes of transport will be able to move away from internal combustion engines. Sustainable fuels are therefore needed for these sectors if the energy transition is to succeed.

We hope you find these highlights from our 2023 yearbook both informative and engaging!
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Transition 2.0: Re-establishing the democratic rule of law

The past years have seen a remarkable decline in constitutional democracy in several EU member states. The recent Polish elections demonstrate that such illiberal developments are no one-way street. The new government will now face the challenge to re-establish constitutional democracy. This is a huge task, as the changes are profound. Our project analyses how European law can support this endeavour.

No matter how hard a ruling party tries to consolidate its power, politics and personnel: no government lasts forever. In this spirit, a majority of Polish citizens voted against a further dismantling of constitutional democracy. Reversing the reorganisation of the state carried out by the PiS is a huge task, as the changes of recent years run deep. This reorganisation requires, among other things, re-establishing media pluralism, women’s and LGBTIQ rights and, last but not least, judicial independence. A mere stroke of the legislator’s pen will hardly suffice to restore constitutional democracy and the rule of law in Poland. A kind of transition is required that builds on the transformations of the 1990s: a transition 2.0.

After the fall of the Communist rule, a large-scale political, social, economic, and legal transformation took place that led towards constitutional democracy in many Central and Eastern European countries, culminating in those countries joining the European Union. These states had several conditions to fulfil in order to become EU members. These included the so-called Copenhagen criteria, meaning democracy, the rule of law and fundamental rights. Despite those requirements, however, the transitions of the early 1990s remained unconstrained by international or EU law. Even if naturally seeking inspiration and assistance from abroad, each country exercised a high degree of local choice as to how to deal with its past, how to resolve internal democratic challenges, and how to shape its constitutional and legal future.

European embeddedness

Unlike these processes, a transition 2.0 will be embedded in a much stronger European context. The respective states are members of the European Union and the Council of Europe. Member states form part of one European society, one that is characterised by the common values enshrined in Article 2 of the EU Treaty: democracy, the rule of law and fundamental rights. If those principles come under pressure in some member state, the entire European society is affected. Accordingly, the Union’s law and institutions have a central role to play.

In the past years, EU institutions sought to counter illiberal developments in the member states. Many national measures, such as the overhaul of the Polish judiciary, fell short of their commitments under EU law, in particular the values in Article 2 TEU. In reaction, the EU’s legal toolbox to counter such developments has considerably evolved. In particular, both the Court of Justice of the European Union and the European Court
of Human Rights rendered a series of pathbreaking judgments, in which they found violations of the common values.

However, the EU’s mandate is not limited to taking action against a member state’s disregard for common values. It also has a role to play when a member state decides to change course and restore compliance with these values. On this dimension, there is little scholarship so far.

**Facilitating and constraining transition 2.0**

In collaboration with many academics from Central and Eastern Europe, including the new Polish Minister of Justice, our project provides a first comprehensive assessment how European law and institutions can support and facilitate a member state’s transition 2.0. Various aspects will be addressed. A particular focus is on the reform of the Polish judicial system. In its efforts to dismantle judicial independence, the PiS-led government sent many judges into early retirement. At the same time, it appointed thousands of new, loyal ones in their place. Especially the Constitutional Tribunal is nothing more than a government puppet. These developments did not only violate the Polish Constitution but, importantly, also the European rule of law. Our project demonstrates possible paths to re-establish an independent judiciary.

Yet, European law does not only help facilitate the transition, it also places constraints on it. In particular, the procedures in which the new majority takes action against laws, appointments and measures that are contrary to values must themselves be in line with these values. This requires respect for the principles of legal certainty and legality, which are also an inherent part of the rule of law guaranteed as a common value under Article 2 TEU.

Against this backdrop, it would appear highly problematic if the new majority were to dismiss all judges who were appointed or promoted under the former government. The same applies to opening to appeal the thousands of rulings rendered by these judges. Such a radical move is hardly compatible with the principles of legal certainty and legality. This complicates the transition in two ways. On the one hand, such laws require the signature of the PiS-friendly president. A mere parliamentary resolution without the president’s consent cannot replace a formal legislative process.

On the other hand, reform initiatives can be challenged before the Constitutional Tribunal, which has been packed with supporters of PiS and which has the authority to annul pertinent laws. Replacing the respective judges before the expiration of their regular terms of office is virtually impossible, as the number of judges and their tenure are enshrined in the Polish constitution. These provisions cannot be altered without a majority sufficient to amend the constitution (which the current government does not have). Once judges have been appointed in accordance with the constitution, they cannot be simply dismissed from their positions. As such, any unconstitutional “court packing” would contradict the fundamental value whose protection is at stake: judicial independence.

The full restoration of constitutional democracy does not justify such violations of the domestic law. An elementary principle of the rule of law is that the end does not justify the means. EU law therefore requires that democratic transitions are not pursued in illegal ways.

This is where the project comes in: it provides for many innovative proposals demonstrating how EU law and institutions can support a legal transition. To outline just one possible approach, EU law, and thus, the values enshrined in Article 2 TEU have primacy over the laws of individual member states, including their constitutional laws. If national legislation contradicts Union law, it must be disregarded by all state authorities, such as courts, the executive branch, and the legislature. This principle can also extend to rulings rendered by the Constitutional Tribunal that violate EU law. Due to the primacy of EU law, actions that infringe the values in Article 2 TEU would be inapplicable and would no longer pose an obstacle to the democratic transition.
Can’t live without two

Do we really need both copies of the chromosomes we inherit from our mother and father? According to a fundamental principle in biology, nature does not act without a purpose. For certain genes, having one copy is actually sufficient. In these cases, the duplicate on the second chromosome can be silenced without having any impact on the organism. For other genes, however, a mutation or inactivation in just one of the two copies can trigger a serious disease.

Most vertebrates, including humans, possess two sets of chromosomes in their cells, resulting in what is known as a diploid genome. This implies that each gene has two copies, or alleles, with one inherited from the mother and the other from the father. These alleles each produce messenger RNA (mRNA), which serves as instructions for the cell to produce essential proteins.

The two alleles are believed to act as a redundancy system for each gene. In the event of a mutation or a drop in mRNA production from one allele, the other allele on the second chromosome can serve as a backup. If this backup copy can produce sufficient mRNA, we are largely resistant to the effect of mutations and associated genetic disorders.

One particular class of genes, however, known as haploinsufficient genes, is special. These genes rely on the continuous transcription of two intact alleles. If the expression of even just one allele of these genes is compromised, it will lead to disease. A prime example of this is the MECP2 gene: an excess or deficiency in its expression leads to the neurodevelopmental disorders MECP2 Duplication Syndrome or Rett Syndrome. We therefore suspect that cells have likely developed a specialised “safety” mechanism to safeguard the production of the mRNA from this special class of genes.

mRNA originating from one allele

My team recently discovered exactly such a mechanism. By crossing two genetically distant mouse strains, we were able to determine whether the offspring resulting from the cross produces mRNA of a specific gene from the mother’s chromosome, the father’s chromosome, or both. The majority of haploinsufficient genes produce mRNA from both alleles. However, upon deleting a specific factor, namely the chromatin regulator MSL2, a subset of this class of genes only produced mRNA originating from one allele. Some of these genes are known to cause diseases such as Dias-Logan Syndrome, characterised by severe intellectual impairment. Haploinsufficient genes thus react very sensitively to the amount of mRNA produced. In a healthy organism, both alleles are active and provide the necessary quantity. If this balance is disrupted, however, diseases can manifest. In fact, mice lacking the chromatin regulator MSL2 exhibit various malformations and die either in utero or shortly after birth.
In collaboration with physicians, we have also discovered that mutations in a crucial co-factor of MSL2 result in the neurodevelopmental disorder known as Basilicata-Akhtar syndrome. Patients with this syndrome suffer from developmental delay, intellectual disability, and muscle weakness.

The fact that MSL2 can prevent haploinsufficient genes from switching off one of the two gene copies was a fascinating discovery for us. We have thus demonstrated, for the first time, that a protein binding to DNA directly influences the activity of a specific allele. In some haploinsufficient genes, MSL2 ensures that both copies remain active. This challenges the conventional view that the activity of both alleles of a gene is regulated equally.

**Epigenetic modifications**

Next, we investigated how exactly the activity of MSL2 is regulated. It was already known that MSL2 binds to regulatory elements of DNA. Our data show that genes that lose the activity of one allele upon MSL2 depletion are in a unique state. The transcription machinery binds to the active allele, promoting the production of mRNA. The other allele, however, becomes completely inactive. The transcription machinery no longer binds to the DNA and an important regulatory section of the allele is epigenetically modified in such a way that it can no longer be read. All these findings open up a new layer of complexity in our understanding of gene transcription. Not just the total mRNA output matters, but also its origin: does it come from both alleles or one allele, and if so, from which one exactly? What biological outcome could this have?

We hypothesise that there is a whole new unanticipated level of transcription regulation to be discovered once scientists start to consider the role of other chromatin regulators at individual alleles. To explore this further, researchers will need to study animal models in which maternal and paternal alleles can be distinguished. However, most of the laboratory animals currently used are the result of inbreeding of individual mouse strains, making them unsuitable for such studies. Research in this field will therefore have to increasingly focus on analysing hybrid animals originating from the crossing of genetically different lines.

Each of our genes exists in two versions, known as alleles (red, blue), one inherited from each of our parents. Both alleles have the ability to generate messenger RNA (wavy lines). These molecules carry the instructions for the production of proteins.
According to studies conducted by our institute, approximately 800,000 people in Europe die prematurely each year due to air pollution, primarily linked to fine particulate matter. Using advanced modelling techniques, our research group has discovered that particulate matter has a different effect on the body than previously assumed. Our findings should be taken into account in the development of methods to assess the danger of fine particulate matter. Moreover, they could help to effectively reduce the health risks associated with fine particles.

There is no doubt that fine particulate matter poses a significant threat to health, as demonstrated by numerous medical and epidemiological studies. Unlike some other health hazards, such as smoking, particulate matter is difficult to avoid. Particles smaller than 2.5 micrometres, known as PM2.5, are particularly harmful because their small size allows them to penetrate deeply into the lungs. In 2019, researchers from the Max Planck Institute for Chemistry and others reported that air pollution, especially particulate matter, leads to approximately 800,000 premature deaths annually in Europe alone. This indicates that fine particulate matter shortens the average lifespan of Europeans by about two years.

PM2.5 is harmful to health because it triggers and perpetuates a cascade of chemical reactions within the human airways. Reactive oxygen species (ROS) are generated in the fluid film of the pulmonary epithelium lining the airways and alveoli of the human lung. These ROS cause oxidative stress, triggering cellular inflammation, thus promoting cardiovascular disease. Reactive oxygen species encompass a variety of molecules, such as hydrogen peroxide or hydroxyl radicals, which contain oxygen and exhibit high reactivity with other substances. The production of reactive oxygen species in the lungs often serves as a metric in scientific literature to gauge the harmful effects of air pollutants. Nevertheless, reactive oxygen species also occur naturally in the human body. On one hand, they arise as metabolic by-products, while on the other, the body employs them in immune defences against pathogens.

Fine particulate matter promotes the production of hydroxyl radicals

Our research group has employed model calculations to uncover fresh perspectives on the impacts of fine particulate matter within the body. Our findings show that the concentration of reactive oxygen species in the human airways is primarily influenced by hydrogen peroxide produced within the body, which is maintained relatively constant through physiological processes. This means that inhaled particulate matter is less important for the formation of reactive oxygen species than previously assumed. This was initially surprising, considering the wealth of evidence from medical and epidemiological studies linking fine particulate matter to numerous adverse health effects.

Nevertheless, particulate matter heightens oxidative stress within the body. Our calculations demonstrate that the presence of particulate matter causes the generation of hydroxyl radicals. Our findings therefore suggest that the primary effect of particulate matter is the conversion of endogenous peroxides into highly reactive radicals. Unlike hydrogen peroxide, which is already very reactive, hydroxyl radicals are of an even more reactive magnitude, immediately reacting with biological molecules such as proteins and membrane lipids upon formation.

This implies that fine particulate matter serves less as the fuel for generating highly reactive oxygen species, but rather as a catalyst for chemical reactions that ultimately lead to significant damage to cells and tissues. Given that not all components of fine particulate matter
Particulate matter (PM2.5) is generated through air pollution and photochemical reactions in the atmosphere and enters the fluid film of the pulmonary epithelium. Reactive oxygen species such as \( \text{H}_2\text{O}_2 \) and peroxides also accumulate within this environment, stemming from processes inside and outside the body. Individual components of particulate matter such as iron (Fe) and copper (Cu), but also quinones (Q) and secondary organic aerosol (SOA) serve as catalysts for their transformation into hydroxyl radicals, leading to heightened oxidative stress levels.

To search for new markers of oxidative stress, we developed a specialised computer model tailored to simulate the transport of air pollutants into the lungs and the ensuing chemical reactions within the airways. This model enables us to identify the relevant physical, chemical and biological processes and to understand the adverse health effects of various types of air pollutants. In the current version of the model, we have, for the first time, incorporated the production, transport, and chemical transformation of hydrogen peroxide within the cells and blood vessels of the lungs. Expressing these intricate processes in biological tissues through precise mathematical equations presented a significant challenge. Of particular importance in the model is the permeability of the blood-air barrier to hydrogen peroxide, however, we did not know its exact numerical value. To resolve this issue, we constrained the permeability based on known concentrations of hydrogen peroxide and enzymes across different tissues.

At present, cell-free test methods are emerging as potential tools for assessing the health risks associated with fine particulate matter. However, our study reveals that many of these methods may be unsuitable for this purpose, as they often measure the production of all reactive oxygen species, rather than focusing on hydroxyl radicals. As it is difficult to measure short-lived hydroxyl radicals directly, we are also investigating how protein oxidation can serve as a marker of oxidative stress in the lungs, both in terms of measurement and simulation. These markers are more readily detectable in living organisms.

The findings from our studies allow us to draw conclusions on how to effectively and efficiently minimise the health risks posed by fine particulate matter. It is particularly important to target the reduction of particulate matter containing catalytically active components such as iron, copper, and certain organic substances. These pollutants are predominantly emitted by combustion processes, as well as tire and brake abrasion in road traffic. Potential measures to mitigate the adverse health effects of particulate matter could involve reducing the combustion of fossil fuels or developing innovative materials and technologies for tires and brakes. However, before conclusive recommendations can be reached, a deeper understanding of the effects of the various components of particulate matter on the human body is imperative.
Life in transition

We are investigating how great tits and other birds adapt to temperature fluctuations. We hope this information will shed light on whether and how animals are adjusting to climate change and which species might be at risk of extinction.

Many weeks of drought, followed by continuous rainfall – such rapid environmental shifts characterise many habitats across the globe. Most organisms possess adaptations to navigate such changes adeptly. But what happens when it is extremely hot, or stays cold for too long, or the food supply becomes scarce due to weeks of flooding? This is precisely the scenario unfolding with anthropogenic climate change, where weather extremes and temperature fluctuations are intensifying and becoming increasingly unpredictable. In order for an animal species to survive under such altered environmental conditions, it must adapt. We seek to uncover the nature of these adaptations and understand why some animals can thrive in changing environments. By understanding these mechanisms, we can more accurately assess and potentially predict which animals are more resilient and which are more vulnerable to the impacts of climate change.

Hormones play a central role in facilitating this adaptive ability. Their concentrations in the bloodstream can rapidly change, providing the energy metabolism with crucial information about environmental fluctuations. One particularly important hormone is corticosterone, belonging to the glucocorticoid group – also known as the stress hormone. Glucocorticoids are produced in greater quantities at low temperatures, stimulating the breakdown of energy reserves to generate heat. Conversely, at milder temperatures, corticosteroid levels decrease, leading to a reduction in the conversion of energy into body heat. These hormones are present in all vertebrates, enabling us to assess the general relevance of our findings and analyse the adaptation of various species to environmental factors.

Great tits and climate change

My team and I are investigating the role of corticosterone in the adaptability of great tits (Parus major). Great tits are widespread throughout Europe in forests and settlements and, as small, warm-blooded animals, they are true masters of temperature adaptation. Over the course of a five-year study, we examined how the
hormone balance of these birds is influenced by climatic conditions. To this end, we regularly collected blood samples from adult wild tits during the breeding season while simultaneously recording air temperatures. By gathering data from the same population over multiple years, we were able to discern natural fluctuations in glucocorticoid levels.

Our findings revealed a significant correlation between glucocorticoids and heat production, with levels increasing notably at lower temperatures. It was noticeable that the level of the increase varied from individual to individual. Some animals react more strongly to the ambient temperature than others in terms of corticosterone release. This diversity within the population could enhance its overall capacity to adapt to a broader range of environmental fluctuations. Interestingly, higher glucocorticoid levels may also confer benefits in higher temperatures by facilitating the release of body heat. If these variations are heritable, populations exhibiting such diversity may be better equipped to cope with the challenges posed by climate change.

**Energy production within the mitochondria**

We also use our measurements to investigate a central site of energy metabolism: the mitochondria. These cellular powerhouses play a crucial role in converting food into energy, a process regulated in part by glucocorticoids. Energy production within the mitochondria is intricately linked to specific regions of the genetic material, the so-called telomeres. Telomeres are regarded as biomarkers for an individual’s health and ability to survive, as they naturally shorten over the course of life, leading to cell death and organismal aging. Our research team was able to show in great tit chicks that individuals experiencing experimentally elevated glucocorticoid levels also exhibit shortened telomeres and compromised energy metabolism in the mitochondria. Apparently, the chicks must navigate a delicate balance between the energy demands of glucocorticoid actions and the effort to preserve telomeres—a challenging dilemma in the era of climate change.

We are currently conducting research aimed at deepening our understanding of the intricate interplay between environmental conditions, corticoids, mitochondria, and telomeres. One aspect of our investigation involves a long-term study on zebra finches to investigate how the birds’ behaviour is linked to their energy metabolism. Zebra finches are ideal subjects for this study due to their remarkable ability to adapt very quickly to unforeseen changes. As they can easily be kept in aviaries, we are able to track the entire lifespan of these birds and gain valuable new insights. This will hopefully enable us to better assess in future whether and how animals adapt to climate change, paving the way for more informed conservation efforts to come.
Water supplies for Earth-like planets

Water is essential for life as we know it on Earth. That is what makes the search for water on other Earth-like planets beyond the solar system so relevant. So far, detecting liquid water on an exoplanet has not been possible. However, new observations with the most powerful space telescope to date space, JWST, suggest that water could already be abundant during the formation of planetary systems: namely, exactly at the distance from the star at which Earth-like planets typically form.

Astronomers are engaged in a debate surrounding the origins of water on Earth and whether similar processes could occur for Earth-like exoplanets orbiting other stars. The prevailing hypothesis suggests that asteroids containing water ice collide with the surface of young planets. However, this concept of water ice from the outer regions of a planetary system enriching terrestrial planets sufficiently to support life as we know it may largely rely on random events. Our recent findings, however, suggest evidence of another process that regularly supplies terrestrial planets with this vital element right from the very beginning of their formation.

Planets form in discs of dust and gas encircling young stars, similar to how the Earth and the other planets in the solar system did around 4.5 billion years ago. Producing images of the dust’s thermal radiation of many such discs is a speciality of the Atacama Large Millimeter/submillimeter Array (ALMA), a powerful ground-based telescope located in the Chilean Andes. These pictures show young discs in various stages of development.

Water in the inner disc of PDS 70

As part of the European research programme MINDS (MIRI mid-Infrared Disc Survey), we closely examined the radiation of the young gas and dust disc surrounding the star PDS 70 using MIRI, the Mid-Infrared Instrument aboard the James Webb Space Telescope (JWST). We focused on breaking down the spectral components of this disc, similar to how a prism disperses sunlight into its constituent colours. The lines in these spectra allow us to identify specific chemical compounds. We were particularly struck by a series of such lines, originating from hot water vapour permeating the disc around PDS 70 at temperatures of approximately 330 degrees Celsius (600 Kelvin). Such temperatures can only occur in the vicinity of the central star, where rocky planets usually form from the disc material. Given the similarities in planet formation across known systems, it is reasonable to speculate that water could have been one of the earliest ingredients for rocky planets, not only around PDS 70, but also elsewhere.

Over time, however, the gas and dust content of planet-forming discs decreases. Either the radiation or wind from the central star removes material such as dust and gas, or the dust grows into larger objects that eventually form planets. With this process in mind and considering the previous failed attempts of finding water in this system, we were expecting a dry inner disc. Hence, the discovery of water in this relatively mature, approximately 5.4-million-year-old disc was surprising to us.
Planet formation is at play in the system: two gas giant planets are currently forming in the outer regions of the disc, PDS 70 b and c. Searching for smaller rocky planets in PDS 70 is much more challenging though, at least for now. Instead, gas giant planets appear much brighter due to their large surface reflecting the light of the central star. That makes them easier to detect in images. Additionally, we want to point out that our observations were not able to look for rocky planets or their precursors in PDS 70. Planetary embryos in the vicinity of the star may take some time before leaving detectable traces. We need to wait until the inner disc loses much of its dusty material to have a clearer view of those inner regions.

What does this discovery mean for life on other planets?

Is it possible that all Earth-like planets have a supply of water early on? If so, this would significantly increase the chances of finding rocky planets with tangible amounts of water, potentially making life as we know it feasible. The MINDS research programme intends to clarify how abundant water is in the rocky planet-forming zones of the discs with ages similar to PDS 70. Researchers are currently analysing the JWST observations of those systems.

But how does the observed water enter the disc? Planet-forming discs around young stars reside in interstellar molecular clouds, giant assemblies of gas and dust. They are characterised by low temperatures (10 K or -260 degrees Celsius) and therefore water there is present in its frozen state surrounding dust grains as thin coatings. When a star such as PDS 70 forms, these water-rich grains became part of the material composing the outer regions of the disc. As time passes, these coated grains drift towards the star and water ice is vaporised.

One side effect created by the star’s ultraviolet light is the breakdown of water molecules into their constituent parts, hydrogen and oxygen atoms. However, the surrounding material located in the inner disc including dust and the water molecules themselves, provides partial shielding against this destructive ultraviolet...
radiation. Thus, the water discovered in the vicinity of PDS 70 could have survived such irradiation. However, some water could also have formed after oxygen gas streamed in from the outer regions of the PDS 70 disc and then combined with hydrogen to produce water. Furthermore, the flow of the incoming gases could sweep ice-rich dust particles along with it. If the ice comes close enough to the central star, water vapour would in turn be produced.

We suspect that one of these mechanisms plays a decisive role in replenishing the water reservoir of the PDS 70 disc. Identifying which mechanism dominates over the others is one of the key research questions under investigation.

Towards a complete picture

JWST is a powerful space telescope and we, at the Max Planck Institute for Astronomy, have played a key role in constructing one of the instruments on board: MIRI. Like a painting that needs many different colours to convey its message, astronomers carry out observations across a broad range of wavelengths to obtain a complete picture of the processes occurring in planet-forming discs. As a result, we have conducted additional observations of PDS 70 with ground-based telescopes and we are currently analysing the data. In addition, we obtained a set of observations of PDS 70 with the other instruments mounted on JWST that provided detailed images of the inner disc regions. Altogether, all these efforts will yield additional insights in the origin of water on rocky planets.

Water everywhere: in this section of the light spectrum, as captured by the MIRI instrument on board the JWST space telescope from the inner region of the planet-forming disc around the star PDS 70 (orange line), a physical model has identified several spectral lines likely originating from hot water vapor (blue line).
Who controls companies today?

The rise of asset managers is reshaping the power dynamics between the wealthy and broader society – encompassing employees, corporations, and the state. Unlike two decades ago, a greater concentration of power now rests in the hands of a select few, predominantly US-based funds and private equity firms. These players wield significant influence not only over corporate governance, but also increasingly over the broader economy.

It has been exactly twenty years since the publication of the book *Wer beherrscht die Unternehmen?* (Who controls companies?). Authored by Martin Höpner of the Max Planck Institute for the Study of Societies, the book focused on the fate of "Deutschland AG" – the network of cross-shareholdings that held together Germany’s largest corporations throughout much of the 20th century. At the heart of this network stood Deutsche Bank and Allianz Insurance at the time.

From the 1990s onwards, the forces of globalisation, financial market liberalisation, and tax incentives spurred German companies to divest their strategic holdings. The "liquidation" of Deutschland AG was expected to result in a more diversified ownership structure among institutional investors with shorter investment, but this expectation was only partially realised. These days, US institutional investors dominate the shareholder landscape, although the shareholder structure is concentrated similarly to how it was in the era of Deutschland AG. Today, it is prominent US asset managers such as BlackRock and Vanguard who dominate the scene. Moreover, the significance of institutional investment firms is also growing among non-listed companies for the first time.

In order to understand this change, a broader historical and theoretical context is essential. Today, capital consists primarily of "institutional" capital, consolidated within pension funds and foundations, which are then channelled to larger capital aggregation hubs, commercial asset managers, or "asset management firms". The historical forerunner of this new asset management capitalism can be traced back to the concept of "finance capital" elucidated by Rudolf Hilferding, the Finance Minister of the Weimar Republic. Towards the
end of the 19th century, an unprecedented demand for capital from industrial companies led to an expansion in the supply of financial securities from the corporate sector, effectively merging two worlds that had previously remained largely separate: industry and the capital markets. The banking sector progressively entrenched itself in industry through extensive credit relationships and direct investments in the equity capital of industrial firms. In Germany and the United States in particular, financiers emerged as the predominant shareholders and creditors of the vast conglomerates and monopolies they played a pivotal role in creating. Despite wielding extensive control, their portfolios were inadequately diversified, rendering them susceptible to the volatilities inherent in capitalism.

These days, the financial sector once again dominates the corporate sector. However, the key players are no longer banks. Instead, the primary actors are asset management companies: private equity firms such as Blackstone, and major fund companies such as BlackRock. They can implement investment strategies that would be too costly for individual shareholders or investors. Asset management companies now make it possible to diversify portfolios broadly and in doing so to hold liquid shares in various types of investment funds. The institutionalisation of capital provides opportunities to control non-financial activities, protect assets, and generate high returns at the same time.

**Private equity: the Blackstone economy**

Private equity firms engage in the acquisition and divestment of shares in companies that are not initially publicly traded on a stock exchange, hence the term 'private.' They see themselves as landscapers in the garden of capitalism, the essence of which is assumed to be a process of displacement and renewal: “unprofitable” companies are acquired with the intention of restructuring them, with the ultimate goal of selling them at a profit (the “buy-out model”).

This description was highly accurate in the US during the 1980s, however, the business model of private equity firms has undergone fundamental changes since then. Instead of focusing on “creative destruction” (as conceptualised by Schumpeter), they are now striving to attain the highest possible returns with the lowest possible risk. Once considered a niche product, private equity has evolved into an indispensable form of investment in the portfolios of pension and sovereign wealth funds. The influx of capital has facilitated the expansion of private equity companies into sectors such as real estate and infrastructure, where steady returns from rental income are tempting. In the area of corporate investments, private equity has developed the “roll-up model”, in which formerly local and family-run companies are bought up and merged into larger units.

Full control over non-financial assets makes it possible to prioritise short-term returns over long-term economic, social and environmental sustainability. And this is also increasingly the case in sectors such as the healthcare and caregiving sectors, which have so far tended to resist commercial mergers.

**Fund companies: the BlackRock economy**

Traditionally, the shareholder structure of listed companies has been categorised into two main types: concentrated structures, which are typically dominated by families and non-financial companies, and dispersed structures, dominated by institutional investors. However, the emergence of index-orientated asset managers is undermining this distinction: today, the shareholder structure is particularly concentrated in the US, for example, primarily due to the presence of the two largest asset managers, BlackRock and Vanguard, within the US market. These two fund companies have now also gained a dominant position in Germany. These “Big 2” asset managers wield considerable influence over future investments and production technologies. However, our research indicates that in practice, they are surprisingly reluctant to use their voting rights to shape the economy. The reason for this is the situation in the US, where the large fund companies are subject
to substantial political pressures: on the one hand, they must appease the Democrats by signalling support for climate policies. On the other hand, they must avoid any actions that might attract the anti-Wall Street wing of the Republicans, which strongly advocates for the promotion and use of fossil fuels. Faced with this rather precarious situation, fund companies are attempting to reduce their control over voting rights by "returning" them to their clients, thus allowing institutional investors to independently determine how their voting rights should be exercised.

The success of asset managers has precipitated a shift in the balance of power between asset owners and other stakeholders, including employees, companies, and the state. In Germany, a small group of primarily US-based fund and private equity companies now wield considerably more influence than they did twenty years ago. In the United States, the roll-up model presents a significant threat to competition, and similar trends are beginning to emerge in Germany, albeit at an early stage. However, it would be erroneous to view this as the revival of "Deutschland AG 2.0," as asset management firms like BlackRock or Blackstone differ fundamentally from traditional German financial institutions. The impact of the internationalisation and institutionalisation of ownership structures on Germany's export-oriented growth model remains an empirical question yet to be fully explored.

Capital linkages in Germany, 2020. The chart shows the network of shareholdings in DAX30 companies that exceed 3 per cent of the equity capital. The width of the arrows corresponds to the size of each investment, the size of the circles to the relative number of investments.
Virtual body models support treatment of anorexia

Many individuals struggling with anorexia face daily challenges stemming from a distorted body image and an intense fear of weight gain. Traditional therapies often encounter limitations, particularly when the anxiety experienced by individuals becomes overwhelming. In a pilot study, we have shown that body simulations in virtual reality could be a meaningful complement to existing treatments.

Simone Behrens, Katrin Giel
Max Planck Institute for Intelligent Systems, Tübingen

Anorexia nervosa, commonly referred to as anorexia, is a serious mental disorder characterised by low body weight, obsessive preoccupations with body weight, and a profound fear of gaining weight. Individuals suffering from anorexia often have a distorted body image, perceiving their underweight state positively despite evident negative consequences. Anorexia can result in life-threatening complications such as malnutrition, organ failure, and various other health issues. Prioritising weight restoration is therefore paramount in the treatment of anorexia. However, many therapeutic interventions are prematurely discontinued due to patients’ intense anxieties regarding weight gain. As a psychotherapist and scientist, I directly observe the significant challenge individuals encounter in navigating this inner conflict.

Novel therapeutic approach via body simulation

Our hypothesis suggests that virtual reality may aid in promoting a healthier, more positive body image. To explore this idea, we utilise the “SMPL model” (Skinned Multi-Person Linear model), which enables the swift generation of digital doppelgangers – or avatars – of individuals. Developed at the Max Planck Institute for Intelligent Systems, this model has been trained on extensive body scan data, accurately capturing a person’s body shape biometrically using minimal parameters, similar to defining a cube by its edge lengths. As a result, it allows for simulation of bodies of varying weights.

Collaborating with computer vision experts at the Max Planck Institute for Intelligent Systems, we have developed an application aimed at immersing individuals in virtual reality, exposing them to representations of their bodies at a healthy, typically higher weight. Therapists have long utilised immersive representations to address anxiety disorders. Virtual reality allows users to immerse themselves in a computer-generated three-dimensional environment, facilitating natural interaction. Equipped with body-mounted sensors, the avatar mirrors users’ movements in real-time as they view it through a virtual reality headset, providing a comprehensive experience from both mirror and first-person perspectives. For instance, if the user desires to see what’s to their left, they can simply turn left.

Virtual simulation as a gateway to self-perception

Current treatment methods face challenges in effectively guiding individuals with anorexia towards embracing the treatment objective of attaining a healthy body weight. Dialogues frequently uncover deeply ingrained avoidance patterns, wherein patients perceive...
Wearing VR goggles, the test person (below) encounters their digital twin (above, displayed on a screen). The avatar replicates real-time movements through sensors attached to the body.

Exploring new avenues in therapy

In a pilot study, we exposed over 40 women to an avatar with a higher body weight than their own, including 20 women with anorexia and 24 women who were clinically healthy, but concerned about their body weight. All participants exhibited increased levels of tension, with the patients experiencing heightened anxiety compared to their counterparts. Our findings indicate a decrease in the fear of weight gain among participants after undergoing four sessions of individualised care. Almost all patients subsequently reported the experience as helpful.

As clear and encouraging as these preliminary findings are, individual reactions to the simulated healthy body varied significantly. Measurable physiological responses (increased heart rate, sweating, stress hormones) indicated an intense and highly emotional experience for all patients. However, the majority reported a reduction in tension during treatment, while others asserted that they did not perceive the experience negatively. This divergence in reactions may arise from variations in patients' capacity to articulate their emotions. For example, the state of being underweight could lead to bodily reactions that are not expected, or individuals with anorexia might interpret their physiological responses differently.

These aspects will be examined in greater depth in a larger clinical-experimental study. Our aim is to uncover the reasons behind the heightened anxiety experienced by individuals when confronted with their virtual image displaying a healthy but increased weight, and to provide comprehensive support on their journey towards recovery. Additionally, we are extending our focus to a second target group: individuals with severe obesity. Utilising the simulation, our goal is to assist them in gradually attaining a healthy body weight.

their underweight condition as “normal” and harbour a profound fear of gaining weight, equating it with becoming “fat” as a result of regular eating.

Before investigating the clinical utility of our virtual reality application, we were aiming to understand, through several smaller studies – initially focusing on women – how individuals with anorexia emotionally respond to their avatars and whether the confrontation alleviates distress. Results indicate that despite their distorted body image, patients are capable of accurately assessing the weight of their digital representations. Moreover, they appear to confine the distorted perception of underweight as an “ideal weight” solely to their own bodies. This finding was surprising to us because it challenges the common assumption that individuals with anorexia misperceive their weight. Additionally, it was observed that patients experienced significant anxiety prior to being confronted with various weight variations of their bodies during the study. Nevertheless, they described the experience of engaging with a healthier body as beneficial and intriguing.
The roots of the Anthropocene

Understanding how tropical land use and deforestation affects the dynamics of the global Earth system and identifying potential tipping points are key to the future of our species on this planet. By exploring the long history of human societies in tropical forests and bringing together natural and social systems in interdisciplinary models, we can evaluate the repercussions of early human interaction with tropical environments. This historical interaction has left irreversible imprints on the Earth, with consequences that will reverberate far beyond the 21st century.

Human activity has so profoundly transformed the Earth that debates have arisen regarding the potential onset of a new geological epoch: the Anthropocene. While the exact beginning of this ‘human age’ has not yet been conclusively determined, it is hard to deny that the impacts of human activities on the Earth’s natural systems are rapidly increasing. There is a risk that critical tipping points will soon be reached, such as the potential loss of the Amazon rainforest – which, in the worst-case scenario, could lead to irreversible alterations in the Earth’s ecosystems.

The Anthropocene concept can also be described as the emergence of a new functional part of the Earth’s vast metabolic system: the so-called technosphere. In terms of its physical composition, it encompasses all artefacts, buildings, land-use patterns and energy systems of human origin, which alone weigh an estimated 30 trillion tonnes. The historical appearance and expansion of the technosphere is complex and has taken place over a long period of time. Although the rate of human impact on the planet has surged since the mid-20th century due to industrialisation and rapid technological advancement, the social, economic, technological, and environmental origins of the Anthropocene extend much further into the past. From the dawn of agriculture to the invasion of the Americas by Europeans and the global exchange of goods that followed – early societies laid the groundwork for the profound upheaval that the Earth system is currently experiencing.

Taking a look at the tropics

Tropical forests serve as a particularly crucial example in this context. Given the ecological importance of the tropics and their projected rise in population and urban expansion, it is becoming increasingly important to understand how technologies, socio-economic systems, land use, and the Earth system have interacted in these regions over time. Recent archaeological, historical and palaeoecological research findings illustrate how past
human land use – from slash-and-burn agriculture to urbanisation – has affected plants, animals, soils, and even the climate. In an interdisciplinary project at the Max Planck Institute of Geoanthropology, researchers from different departments have investigated the impact of early human activities on the natural functioning of tropical forests and analysed the tropical belt within the broader context of the global challenges posed by the Anthropocene.

**Thresholds for tropical land use**

The scientists have identified three key thresholds in human land use in tropical rainforests over the last 10,000 years. The first two mark the beginning of food production and the emergence of new forms of settlement. Many foods that we take for granted around the world today – such as maize, chicken, and chocolate – have their origins in the tropics. The spread of rice and water buffalo in tropical forests was often accompanied by heightened levels of deforestation, soil erosion, and greenhouse gas emissions. It can also be assumed that the onset of urbanisation in the tropics around 1,000 to 2,000 years ago, and their associated exchange networks and resource demands, introduced new pressures on these ecosystems. New information and technologies were brought into circulation and invasive species spread.

The third threshold refers to the expansion of European and, later, US colonialism and imperialism around the tropics. Whereas Europe and the Americas had previously been isolated from each other, the arrival of the Iberian colonial powers directly connected them and integrated them into a global system of economic exploitation. As a result, wild and domesticated animal and plant species were traded and introduced on a large scale.
scale, permanently changing landscapes around the world. Moreover, the spread of disease and the slave trade and violence practised by the colonial powers had a drastic impact on the Indigenous population and their land use.

It is possible that feedback mechanisms of the Earth system were already permanently altered at this time. The marginalisation of Indigenous land-use practices and the spread of the colonial system, based on land clearance for profit, as well as forced and slave labour, continued into the 20th century. The effects this had on global inequalities and tropical sustainability can still be felt today.

Rice is a staple food for much of the world’s population. In the past, large areas of land were cleared to create rice terraces. Growing rice requires a lot of water and causes methane emissions that harm the climate.

From the past into the future

The Max Planck Institute of Geoanthropology looks into the past to gain insights into present and future challenges. Using a transdisciplinary approach and innovative methods, it is possible to trace the emergence of socio-economic inequalities back hundreds of years and analyse their relationship with the emerging technosphere. By investigating human impacts on tropical regions, we seek a deeper understanding of the enduring consequences of consumption patterns, particularly those originating from Western Europe and North America. This approach also helps us to support Indigenous peoples and other vulnerable populations in their efforts to combat climate change. Furthermore, our research sheds light on the regional and global interconnections between technologies, socio-economic trends, soil quality, climate, and biodiversity. These fresh perspectives not only provide a better understanding of our current and future Earth system, but also lay the groundwork for potential actions to be undertaken by society and policymakers.
Crowding in the cell nucleus

EUGENE KIM
Max Planck Institute of Biophysics, Frankfurt am Main

Every nucleus in our cells contains a two-metre-long molecular thread: DNA. Despite the confined space, its information must be consistently accessible. Fortunately, nature has devised a solution: proteins that securely package DNA while simultaneously regulating its activity. My team and I are investigating how they do this.

Many people will remember a common problem from back in the days of the cassette recorder: the tangled tape! While this chaos may seem like an almost unsolvable challenge, nature has a solution for such disorder. But how do you manage to achieve order when you have to house a two-metre-long DNA molecule within a cell nucleus that is only a few thousandths of a millimetre in size? Imagine trying to squeeze a 20 kilometre-long thread of wool into a table tennis ball. This illustrates the challenge cells have to face with their genetic material. The solution lies in the DNA molecule becoming highly folded and twisted.

My team and I want to find out how DNA is folded and how the resulting spatial structures impact the genetic material’s functions. To find the answers to these questions, we are using a wide range of cutting-edge microscopic techniques. Our goal is to unravel the underlying principles governing genome organisation.

Packaging DNA to save space is one thing – but it must also be accessible, for example during cell division or gene expression. Order is imperative because securely storing and passing on genetic information is essential for life. So what prevents a chaotic tangle of DNA?

Nature’s solution lies in SMC protein complexes—the abbreviation SMC stands for Structural Maintenance of Chromosomes. These protein complexes loop the DNA. They are ring-shaped and can encircle the DNA molecule. Until recently, however, the exact mode of action of one representative of such proteins, Smc5/6, was merely speculation.

DNA forms loops

To address this conundrum, we labelled the DNA and Smc 5/6 proteins with fluorescent dyes. Through real-time observation, we discovered that Smc5/6 also loops the DNA similarly to other SMC proteins. Each red-labelled Smc 5/6 protein consistently travels in one
direction along the turquoise-coloured DNA, similar to wagons on a roller-coaster. In order to extrude DNA loops, two Smc 5/6 proteins must assemble and form a dimer.

The speed at which SMC proteins operate is remarkable: a single protein complex can channel up to 1,000 DNA building blocks per second.

In this way, the DNA thread is packaged in a space-saving manner without creating chaos. The loop configuration assists the cell in controlling which proteins to produce: genes located in the outer area of the loop are more easily accessible and can therefore be read more easily. At the base of the loops, DNA segments that are typically far apart draw closer, allowing them to influence each other. This flexibility enables the cell to upregulate gene activity during growth or division, or to suppress it when the corresponding proteins are present in sufficient quantities.

We also discovered that two specific protein subunits control the activity of Smc5/6. In their absence, an increasing number of loops is formed. Our next goal is to gain a deeper understanding of how these two subunits are activated and deactivated to regulate both loop extrusion and gene transcription. These findings hold medical significance because errors in SMC protein function can result in genetic material damage, leading to hereditary diseases, developmental disorders, or cancer.

Understanding the mechanisms behind these defects can pave the way for developing methods to repair or prevent such damage.
A programme for improved workplace climate

Toxic workplace relationships characterised by antisocial and unethical behaviour can have profound negative impacts on employee well-being. We present a field experiment in which we were able to contribute to improving the work environment and reducing employee turnover through implementing an innovative training programme. The positive outcomes of the programme are primarily attributed to the enhanced relationships between leaders and team members.

A positive working atmosphere is crucial for fostering employee motivation, engagement, and retention within a company. While this correlation may seem intuitive, workplaces with toxic relationships are unfortunately widespread. In many companies, toxic relationships have emerged as the primary driver of burnout and employee turnover. Employees predominantly resign due to issues with their immediate supervisors, rather than with the company as a whole.

Toxicity in the workplace manifests through antisocial behaviours such as bullying, gossip, and the frequent use of disrespectful and condescending language. When leaders engage in such behaviour, it can quickly become the norm within the workplace culture.

In a study published in 2023, we evaluated the effectiveness of an innovative training programme aimed at eliminating toxic relationship dynamics within companies. The programme was offered to 3,000 employees across 20 large companies in Turkey, spanning six major industries: energy, chemistry, defence, finance, construction, and textiles. Half of these companies were randomly selected to participate in the training before the others, allowing us to evaluate the causal effects of the programme on the relationship atmosphere within the companies.

In evaluating the work environment, we relied on four measurement instruments. Firstly, we analysed personnel data on employee turnover. Secondly, we measured pro- and antisocial behaviour's through laboratory experiments, including tendencies toward toxic competition. Thirdly, we evaluated workplace satisfaction, perception of company values, collegiality, behavioural norms, and prescriptive norms through workplace atmosphere surveys. Fourthly, we identified professional networks within the company by asking employees to name up to three colleagues from whom they receive professional support. This information allows us to measure social networks and attachment to supervisors.

Training for improved collaboration

To implement the training programme, we partnered with a consulting firm founded by former industry professionals dedicated to combating toxic workplace environments. The content of the training programme focused on the benefits of social behaviour in the workplace and the importance of professional communication. While the programme was open to all employees, particular emphasis was placed on encouraging leaders to participate.

The training consisted of two phases: the first phase involved a series of workshops, primarily focusing on respectful communication, understanding colleagues’ perspectives, and tolerance for differing opinions. These sessions were highly interactive and utilised
Managers play a pivotal role in shaping the workplace relationship culture.

innovative methods such as creative theatre and role-playing. In the second phase, participants were tasked with developing projects to improve communication and relationship culture within their companies. After eight weeks of teamwork, participating teams presented their projects to senior management and implemented them into practice.

Reduced toxic competition

The training programme had significant positive effects on most of the areas we examined: employee turnover, especially at the leadership level, was lower in companies that offered the programme compared to the control group. Additionally, employees in these companies exhibited fewer antisocial tendencies in the workplace, showing reduced inclination towards toxic competition and displaying more generosity in trusting their colleagues compared to employees in control companies.

The positive effects on prosocial behaviour were accompanied by increased workplace satisfaction, a stronger perception of company values, and improved collegiality within departments. Moreover, the training programme benefited social networks within the company, with a significant decrease from 13% to 8% in employees in control companies reporting a lack of professional support from any of their colleagues.

Strong social networks

Leadership plays a key role in shaping workplace relationship culture. We could primarily attribute the positive effects of the training programme to the improvement in leaders’ attitudes towards their team members. The latter reported experiencing higher-quality leadership within their organisations, particularly perceiving their supervisors as more professional and empathetic.

Our study demonstrates that an innovative training programme can effectively reduce toxic competition, increase prosocial behaviour, strengthen social networks, and reduce employee turnover within companies. These findings emphasise the importance of promoting prosociality for cultivating a healthy work environment in large companies, impacting both daily interactions and professional relationships between leaders and team members.
Mysterious meiosis

There is still a widespread misconception that when people are unable to have children, it is usually due to female infertility. In fact, infertility is about equally common in men and women into middle age. My research group is dedicated to understanding the process of sperm formation. Our work has the potential to pave the way for forthcoming fertility treatments and contraceptives specifically tailored to men.

**LINDA ODENTHAL-HESSE**

Max Planck Institute for Evolutionary Biology, Plön

Sperm develop from precursor cells undergoing a specialised form of cell division known as meiosis. During meiosis, the parental chromosomes are rearranged and the genetic material is mixed, before chromosomes are evenly distributed among sperm cells. Thus each sperm is genetically unique. This process, referred to as recombination, enhances the genetic diversity of a species. Recombination errors can massively impair the health and development of an organism. Male meiosis has an inbuild quality control mechanism where individual defective cells can be eliminated. However, if crucial proteins governing meiosis are not produced, all precursor cells eventually die and infertility is the result.

My team and I are focused on unravelling the molecules that control meiosis and recombination. A key player in this process is the protein PRDM9. It places the signalling molecules, thereby epigenetically determining the locations where recombination and the reshuffling of genetic material can take place. It ensures that recombination does not interfere with gene expression happening at the same time. This form of epigenetics therefore does not govern gene activity at all, but instead the recombination of genetic material – a previously unknown feat of epigenetic regulation. Additionally, PRDM9 also orchestrates several other proteins that together are responsible for initiating the exchange of chromosomal segments.

Our primary interest lies in understanding where exactly recombination occurs most frequently, the so-called "hotspots" of recombination. The location of hotspots vary greatly between species. For example, although 98.8 percent of the genetic material of chimpanzees and humans is the same, their recombination hotspots are in completely different places. Moreover, hotspots differ even among individuals within the same population – like you and me – largely due to the high rate of evolution of the PRDM9 protein. There are numerous PRDM9 variants in humans, and across other species in the animal kingdom. In house mice for example there are hundreds of different PRDM9 proteins found in mice. This diversity between mouse subspecies has curious consequences – if house mice from different subspecies that harbour disparate PRDM9 variants interbreed, the resulting male offspring are infertile. Reminiscent of the better-known sterility of mules – a hybrid between horse and donkey.

**Fertile hybrids**

In contrast, some mammals can produce fertile offspring even if they lack PRDM9. Despite losing this protein approximately 14 million years ago, the ancestors of domestic dogs, wolves, and foxes are all fertile, and can also produce hybrids that are capable of reproduction – unlike mules. Examples include the
Faulty meiosis in a mouse progenitor cell unable to produce healthy sperm. Instead of clearly separated pairs of homologous chromosomes (green), complex patterns of several non-homologous chromosomes have formed, which erroneously attempt to recombine with each other. This also results in wrongly joined sections (yellow).

Czechoslovakian wolfhound, a cross between the German Shepherd and the Carpathian wolf, and coy-wolves in the USA (coyote-wolf hybrids). Many fish and amphibian species as well as crocodiles and birds can also thrive without PRDM9. This suggests the existence of alternative mechanisms for controlling recombination during meiosis.

Regulating fertility

We are currently investigating the recombination patterns observed in sperm cells from animals lacking PRDM9, such as dogs and songbirds, and compare them with those of PRDM9-regulated hotspots in mice – including of different subspecies of mice. We are investigating another regulator of fertility and recombination – present on a previously unmapped section of the mouse X chromosome. We have pinpointed the chromosomal segment, that interacts with PRDM9, and can either inhibit or facilitate the process of chromosome pairing based on the variation in the number of tiny regulatory molecules.

Understanding which genes are responsible for initiating meiosis could pave the way for temporarily preventing this process and thereby halting sperm formation – a putative male contraceptive approach. Male meiosis is continuous, so after discontinuation of the active substance, the processes should resume rapidly, allowing fertility to be restored at any time.
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According to estimates, global shipping alone is responsible for three percent of global greenhouse gas emissions. It also generates emissions of particulate matter and nitrogen oxide. Clean-burning alternatives to marine diesel, produced from renewable raw materials, hold significant potential for enhancing sustainability in this sector.

At RWTH Aachen University, the “Fuel Science Centre” (FSC) is working on such alternative fuels. While sustainable synthesis routes are important, it is equally important that these fuels burn as cleanly and with as few emissions as possible. Mixtures of saturated hydrocarbons and long-chain alcohols are considered particularly attractive fuel candidates. The latter contain oxygen atoms, which ensure that the mixtures generally burn more cleanly and produce less soot than conventional marine diesel, for example. The inclusion of alcohols in the combustion mixture also leads to a decrease in nitrogen oxides (NOx) emissions. This is another important factor for shipping in particular, because unlike our vehicle fleet, ships typically lack exhaust catalytic converter for NOx reduction.

The Max Planck Institute for Chemical Energy Conversion is involved in the FSC. Our task is to develop a potentially CO₂-neutral synthesis route for fuels that can also be realised on an industrial scale. That second condition is not a matter of course, because not everything that works in small laboratory vessels also works in larger reactors.

Long-chain alcohols without petroils

A particular focus of this work has so far been on the long-chain alcohols mentioned above, which usually contain six or more carbon atoms. Traditionally, these alcohols are synthesised through reductive
hydroformylation of alkenes. These are hydrocarbons featuring a double bond between two of their carbon atoms. Such alkenes are usually obtained from petroleum fractions.

In our research, we were looking for a synthesis route that eliminates the need for fossil raw materials and can be accomplished using renewable energy. To achieve this goal, we combined Fischer-Tropsch synthesis (FTS) with the aforementioned hydroformylation (HF). One practical aspect of this approach is that both reactions utilise hydrogen (H$_2$) and carbon monoxide (CO) as starting materials. Hydrogen can be obtained by the electrolytic splitting of water, while CO can be generated either electrochemically from CO$_2$ or by gasification of biomass or plastic waste. Both raw materials can therefore be produced in a climate-neutral, resource-saving, and sustainable manner if the electricity required for electrolysis is sourced from renewable energies.

Effective synthesis in a reactor

The Fischer-Tropsch synthesis, developed nearly a century ago at a predecessor institute of the neighbouring Max-Planck-Institut für Kohlenforschung here in Mülheim, involves linking carbon atoms from CO molecules to form carbon chains on a suitable catalyst surface while separating oxygen in the form of water. At the end of this synthesis, a mixture of alkanes – hydrocarbons without double bonds – and alkenes is typically obtained. The ratio of alkanes to alkenes can be controlled by the choice of catalyst. We aim for a high proportion of alkenes, as they serve as precursors for the desired alcohols. We can also to some extent influence the length of the resulting chain via the process control. The hydroformylation of the resulting alkenes then takes place on another catalyst, where the double bond reacts with H$_2$ and CO to produce the desired alcohol.

The individual steps FTS and HF have long been known and established in industry. We subsequently had the idea of conducting both steps sequentially in the same reactor system in order to make the sustainable synthesis of alcohols particularly effective and therefore cost-effective. But this is more difficult than it sounds because the catalysts involved are fundamentally different in nature and thus exhibit their optimal performance under different operating conditions. Metals such as cobalt or iron are suitable for FTS, while catalysts for hydroformylation typically consist of complexes in which a metal atom is surrounded by various molecular residues. It is precisely the nature and positioning of these molecular residues on the metal atom that control catalysis. Because this is a molecular catalyst – in contrast to the metallic FTS catalyst – we need a solvent for it. There is another difference: while the metallic FTS catalytic converter works better at higher temperatures, the molecular HF catalytic converter decomposes above a certain temperature.
To produce long-chain alcohols with low CO\textsubscript{2} content in a single reactor, a research team from Mülheim has developed a porous aluminum oxide material with cobalt (Co) nanoparticles. Initially, alkenes — hydrocarbons with a double bond — are generated from carbon monoxide (CO) and hydrogen (H\textsubscript{2}), both dissolved in the reaction medium within the pores. These alkenes undergo hydroformylation to form alcohols using a dissolved molecular catalyst, which also includes cobalt.
No additional energy input

We carry out this tandem reaction at around 200 degrees Celsius. On the one hand, this is sufficiently high for the cobalt metal to catalyse the FTS and, on the other hand, not so high as to chemically alter the molecular cobalt catalyst. Incidentally, no additional energy input is required to maintain this temperature of 200 degrees because once the reactions are underway, they sustain themselves due to the heat released. Cooling, however, may be crucial to maintain optimal conditions.

In the end, this approach gave us product mixtures containing up to 50 per cent alcohols, an unprecedented proportion. The remaining components are alkanes, which are also found in classic diesel fuel. Incorporating some pure hydrocarbons into future fuels is necessary to fulfil certain property standards. It would therefore be ideal if this portion of the fuel could also be produced sustainably. Despite these successes, it would still be premature to transition the entire process to industrial production. We are currently working on scaling up our double reaction from laboratory scale to a larger plant as part of the EU E-Tandem project. This also involves finding practicable solutions separating the molecular catalyst from the resulting products and facilitating its reuse. If the E-Tandem project proves successful, we may eventually have the capability to produce clean-burning, diesel-like fuels entirely from renewable raw materials and energy sources. This, in turn, could significantly reduce the CO₂ footprint of industries such as global shipping and heavy goods transport — an inspiring vision for a more sustainable future!

Two steps in the same reactor system make the sustainable synthesis of alcohols particularly effective.

Pores with two catalysts

Furthermore, there is another challenge: once a formed alkene detaches from the surface of the FTS catalyst, the existing C-C double bond can react with the hydrogen also present. This leads to hydrogenation instead of hydroformylation, which is a competitive reaction that we naturally want to suppress on the way to the alcohols. We therefore needed an arrangement that would allow the HF reaction to take place immediately after the alkenes are released from the metal surface. Unfortunately, the catalysts that promote high alkene contents in the FTS products, which would be advantageous for our purposes, also promote hydrogenation.

In order to take all requirements into account, we have collaborated with colleagues in Spain to develop a suitable reactor and catalyst concept. We use a metallic cobalt layer as the FTS catalyst, which we apply to a highly porous carrier material with a defined pore size. This assembly is suspended in a liquid in which our molecular catalyst, a cobalt complex, is also dissolved. The porous character ensures a large contact surface area for the FTS to occur. The size of the pores is carefully selected so that the catalyst molecules also fit into them. When the CO and H₂ mixture is introduced into this liquid, the FTS takes place within the pores on the cobalt surface. As the formed alkenes dissolve, a significant portion is captured directly by the cobalt complexes, where they undergo hydroformylation and are subsequently reduced to alcohols. This is only possible because the complexes, as mentioned above, also enter the pores. If this were not the case, the hydrogenation of the double bonds would very probably start immediately and reduce our alcohol yield.
At first glance, bones may appear dry and dead. However, they are remarkably alive and, much like other organs in the body, undergo constant remodelling. Two cell types keep the build-up and breakdown in balance: osteoblasts, responsible for forming new bone cells, and osteoclasts, which break down bone tissue. As we age, this delicate balance tilts in favour of osteoclasts, leading to a breakdown in bone substance. If bone density declines too much, it can result in osteoporosis, a condition characterised by increased risk of bone fractures, diminished mobility, and chronic pain. Around ten percent of people in the European Union are affected by osteoporosis, with the majority being older individuals.

There are currently two treatment approaches for osteoporosis: inhibiting bone-degrading osteoclasts or stimulating bone-building osteoblasts. However, both approaches only work to a limited extent and can lead to unwanted side effects. Consequently, there is a pressing need for novel treatment options.

### Blood vessels promote bone formation

The extensive vascular network, spanning kilometres, supplies all the cells in the body with oxygen and nutrients. The vascular cells also release signals that have an effect on other cells. Together with my colleagues, I am investigating how this transportation network impacts bone growth, structure, and healing, utilising a wide range of different methods. Our research indicates that in older mice the smallest vessels, known as capillaries, which promote bone formation, have largely disappeared. If we administer specific signalling substances to the animals to stimulate the formation of new capillaries, new bone material is generated. The question now is: can we translate these findings into developing treatments for bone loss in humans?

Until recently, observing processes within dense, highly calcified bones was almost impossible. However, our team has developed a method that allows us to prepare bone material in such a way that we can
analyse it using high-resolution microscopes. Through this, we have discovered that the formation of new blood vessels in bones differs fundamentally from that in other organs. Specifically, we have identified two distinct types of capillaries with different functions in the different bone regions. The type H capillaries are surrounded by precursor cells for osteoblasts. By releasing growth factors and other signals, they induce the transformation of areas containing cartilage cells into solid bone substance. These capillaries play a vital role in bone growth during early development and in the healing of bone fractures.

Type R capillaries, on the other hand, influence the precursor cells of osteoblasts, thereby strengthening the formation of bone trabeculae, a network of tissue within the bone. Some therapies for osteoporosis therefore rely on activating these capillaries. However, they are also involved in processes that contribute to the loss of bone mass. This complex interplay between blood vessels, osteoclasts, and osteoblasts within the bone must be taken into account in new therapeutic approaches. Our bones all contain bone marrow and hematopoietic cells, but vary significantly in form and function. While the long bones of the limbs support the body’s weight, the skull protects the brain and other head structures. Our studies on mice reveal that the bone marrow of the skullcap actively expands – i.e. increases in size – throughout adult life and into old age, which involves continuous growth of the vascular system. In contrast, bone marrow formation in the long bones of the limbs concludes by adulthood.

**Blood vessels (red) in the skull of an adult mouse. (blue: cell nuclei)**

**Distinct bone marrow within the skull**

The skull is also special in another respect: it is shielded from certain ageing processes. While long skeletal bones have more inflammatory factors and more fat cells as they age, and their blood vessels become more permeable, the skull remains unaffected by these changes. Research has shown that the bone marrow in the skull of middle-aged and older mice contains fewer inflammatory factors and fewer permeable blood vessels. It also plays a more significant role in blood cell formation compared to the long bones. In humans, too, the bone marrow within the skull appears fundamentally distinct from that of the long bones and expands throughout life.

By unravelling these and other secrets of the skeletal system, we may one day be able to treat bone fractures and bone loss more effectively. Additionally, our discoveries provide valuable insights into the processes of aging and offer potential strategies for preventing and curing age-related illnesses.
Genes and the environment

With modern technology, it is now possible to identify the genes that control a trait such as longevity. The question, however, is whether the same genes regulate longevity under different environmental conditions and, if so, whether they have the same effect in every environment. Only when we answer these questions will we know how organisms adapt to new environments and why, for example, some individuals but not others develop certain diseases when they eat or behave unhealthily. In a large-scale experiment, we wanted to answer the question whether an individual’s diet influences the genes that govern their life expectancy.

The fruit fly serves as an ideal model organism for this purpose: just like humans, they become obese on a high-sugar diet, develop insulin insensitivity, and die earlier. Additionally, we can keep hundreds of thousands of them under controlled conditions in the laboratory and analyse the genome of each individual fly. Our objective was to identify the genes that control the lifespan of fruit flies under varying nutritional conditions.

In our experiment, we divided tens of thousands of fruit flies into two groups, feeding one a healthy, low-sugar diet and the other a diet high on sugar. Next, we analysed the genome of thousands of young (one to two-day-old) and old (one to two-month-old) flies. A gene that is more common in old animals should have a life-prolonging effect; one that is common in young flies, but rare in old ones, on the other hand, appears to shorten life.

We have discovered around 2,000 positions in the genome that impact lifespan. Two thirds of these play a role in both low-sugar and high-sugar diets. However, 600 of these genes only exert their effects on lifespan in the presence of a high-sugar diet. This suggests that the influence of these genes may first have to be triggered or “awakened” by the composition of the diet. If the flies have a healthy diet, these genes are irrelevant...
for determining how long or short the lifespan of an individual is. But if placed in a stressful environment – for example, a high-sugar diet – they become important for longevity. Our findings once again refute the inaccurate, yet still widespread assumption, that genetic effects are inherently static: that a gene controls a trait, and that differences between individuals in a population can be explained by a single or a few genes. We now understand that most complex traits are actually regulated by hundreds or thousands of genes or genomic segments, and that natural variation can be explained by the joint effect of all those pieces of the genome. Our research supports the idea that the effects of the genes controlling longevity are not static, but dynamic, and modified by the environment. This suggests that genes that are critical for our own health are also susceptible to environmental factors. Going forward, this dynamic interplay should be taken into account in the search for the causes of a whole range of non-communicable diseases.
Green steel from toxic red mud

The production of aluminium generates around 180 million tonnes of toxic red mud every year. At the Max Planck Institute for Sustainable Materials, previously called the Max-Planck-Institut für Eisenforschung, we have now shown how green steel can be produced from aluminium production waste in a relatively simple way. In an electric arc furnace similar to those used in the steel industry for decades, we convert the iron oxide contained in the red mud into iron using hydrogen plasma. We also demonstrate how this process would be economically viable.

According to forecasts, the demand for steel and aluminium is anticipated to increase by up to 60 percent by 2050. However, the conventional methods of producing these metals exact a significant toll on the environment. Eight percent of global CO₂ emissions come from the steel industry, making it the sector with the highest greenhouse gas emissions. Meanwhile, the aluminium industry produces around 180 million tonnes of red mud every year, a highly alkaline waste containing traces of heavy metals such as chromium. In countries like Australia, Brazil, and China, among others, this waste is typically dried and disposed of in vast landfill sites, resulting in high processing costs. During periods of heavy rainfall, the red mud is often washed out of the landfills, while during dry spells, the wind can blow it into the environment as dust. In addition, the highly alkaline red mud corrodes the concrete walls of the landfills, resulting in red mud leaks that have already triggered environmental disasters on multiple occasions, such as those witnessed in China in 2012 and in Hungary in 2010. In addition, large quantities of red mud are also simply disposed of in nature.

One solution for two problems

Our process could simultaneously solve the waste problem of aluminium production and improve the steel industry’s carbon footprint. In a study published in the science journal Nature, we show how red mud can be utilised as a raw material in the steel industry. This is possible because the waste generated from aluminium production consists of up to 60 percent iron oxide. We melt the red mud in an electric arc furnace and simultaneously reduce the contained iron oxide present to iron using a plasma that contains ten percent hydrogen. This transformation, known in technical jargon as plasma reduction, takes just ten minutes, during which the liquid iron separates from the liquid oxides and can then be extracted easily. The iron is so pure that it can be processed directly into steel.
Toxic red mud, one of the largest environmentally hazardous waste products of the aluminium industry, can be converted into carbon dioxide-free steel through plasma reduction using green hydrogen plasma.
Producing iron directly from red mud with hydrogen is also economically feasible, as cost analysis indicates.

The remaining metal oxides are no longer corrosive and solidify on cooling to form a glass-like material that holds potential for various applications in the construction industry, such as filling material. Other research groups have produced iron from red mud using a similar approach with coke, but this produces highly contaminated iron and large quantities of CO\textsubscript{2}. By employing green hydrogen as a reducing agent, our approach eliminates these greenhouse gas emissions. This corresponds to one-third of the world’s annual steel production. By adopting green hydrogen as the reducing agent, the steel industry could prevent the release of almost 1.5 billion tonnes of CO\textsubscript{2} emissions.

Neutralised heavy metals

The presence of heavy metals in the red mud can also be effectively neutralised through our process. Following reduction, we have identified chromium within the iron. Other heavy and precious metals are also likely to become integrated into the iron or segregate into distinct areas. This is something we intend to explore in further studies. Valuable metals could subsequently be extracted and recycled. And heavy metals that persist in the metal oxides become firmly bound within them and can no longer be washed out with water, as commonly occurs with red mud. Producing iron from red mud directly using hydrogen not only provides dual environmental benefits, it also pays off economically too, as we have demonstrated in our cost analysis. This economic viability is a crucial aspect when it comes to transferring the process into industrial practice. Utilising hydrogen and an electricity mix for the electric arc furnace sourced from partially renewable sources, the process becomes economically feasible when the red mud contains 50 percent or more iron oxide. If the costs for the disposal of the red mud are also considered, a mere 35 percent iron oxide content is sufficient to make the process economical. With the utilisation of green hydrogen and electricity, factoring in today’s costs – including the expense of landfilling the red mud – a proportion of 30 to 40 percent iron oxide is required for the resulting iron to remain competitive in the market. These are conservative estimates because the costs for the disposal of the red mud are probably calculated rather low. And there is another advantage from a practical point of view: electric arc furnaces are widely used in the metal industry – including in aluminium smelters – as they are used to melt down scrap metal. In many instances, the industry would therefore only need to make minimal investments to become more sustainable.
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