Questions and answers on mirror biology and mirror life[1]

What is mirror biology?

Many biomolecules, such as DNA with its double helix, are asymmetrical, meaning they do not look the same if reflected in a mirror. Just as your left hand is a reflection of your right hand – if you put one hand facing up on top of another, they do not overlap – a "mirror" molecule is a reflection of an asymmetrical molecule. This property of asymmetrical molecules is known as chirality. Many biomolecules, such as amino acids and sugars, exist in only one chiral form: amino acids in natural life are almost exclusively left-handed (L-form) and sugars are right-handed (D-form). This specific handedness affects how molecules interact, fit into enzymes, and carry out biological functions. Even small changes in chirality can lead to significant differences in biological activity, which is why chirality is a central concept in biochemistry, pharmacology, and synthetic biology.

Mirror biology refers to the study of biological systems that use molecules with reversed chirality compared to those found in naturally occurring life on Earth. Scientists are increasingly able to synthesize mirror-image biomolecules. Recent advances have enabled the chemical synthesis of mirror-image kilobase-length nucleic acids and large functional proteins. These mirror-image biomolecules have scientific and potential therapeutic applications. For example, mirror-image biomolecules can enhance drug specificity, reduce side effects, and increase resistance to enzymatic degradation, leading to longer-lasting and more effective treatments. Mirror-image molecules can also avoid immune system detection, enabling stealth therapeutics for chronic or autoimmune conditions and because of their stability, mirror-image molecules could be well suited for long-term treatments for chronic therapies. Mirror-image biomolecules are not a focus of concern.

What is mirror life?

Mirror life, on the other hand, raises significant concerns. It would consist of lifeforms composed entirely of mirror-image biomolecules. At present, mirror life is a hypothetical scientific creation, and no reproducing mirror organisms have been reported. Mirror life cannot arise from existing life. The incremental steps through which evolution proceeds would be unable to invert the chirality, or handedness, of complex biomolecules, let alone all biomolecules in an organism simultaneously. But, with scientific advances, a mirror organism might be created in a laboratory and scientists have begun early work towards creating mirror bacteria. The creation of mirror genomes, mirror proteomes, or other enabling technologies could be key

[1] WHO thanks the WHO Technical Advisory Group on the Responsible Use of the Life Sciences and Dual-Use Research (TAG-RULS DUR) for their valuable input and advice, and expresses special gratitude to its Chair for her leadership in shaping this Q&As.

precursors to the ultimate creation of mirror life. For some scientists, the development of mirror ribosomes is considered as a red line that should not be crossed and therefore should be prevented.

In short, **mirror biology** covers mirror life, as well as synthetic mirror-image biomolecules, which are not a focus of concern, although they may not be without risks. **Mirror life** is focused on self-replicating organisms. **Mirror bacteria** are one type of self-replicating organism.

Are there potential benefits of mirror life?

The creation of mirror life appears to offer few foreseeable benefits beyond satisfying scientific curiosity and technical ambitions. The primary potential benefit that has been pointed to in terms of mirror bacteria is the provision of scalable biomanufacturing of mirror biomolecules. In other words, mirror bacteria could serve as biological factories for producing mirror-image nucleic acids and proteins for therapeutic and research applications, similar to current approaches with natural bacteria. By evading immune recognition and degradation, mirror bacteria could also speculatively serve as a chassis for targeted cell-based therapies and other cell-based interventions.

However, creating mirror bacteria would not be necessary to achieve these benefits. Advances in chemical synthesis methods could provide sufficient mirror biomolecule production capacity for therapeutic needs. Moreover, given current limitations of manufacturing cell-based therapies using natural bacteria, it is unclear whether mirror bacteria could be effectively used in this manner in the future.

What are the risks of mirror life?

The creation of mirror life would constitute a radical departure from known life and could plausibly result in catastrophic harm to humans, animals, plants, and the environment. Human, animal and plant immune systems, as well as phages and other predators, have evolved to recognize and interact with natural bacteria. The key concern is that mirror bacteria, and mirror life more generally, might therefore evade immune systems and natural predators. This could leave much multicellular life on Earth vulnerable to potentially life-threatening infections. It could also enable mirror bacteria to act like an invasive species, colonizing some external environments, and potentially causing irreversible ecological disruption and threatening agriculture and the food supply. These considerations also present security concerns, including potential misuse. Research intended to produce beneficial enzymes, for example, could also enable the development of mirror pathogens or invasive species that could harm the health of humans, animals, plants, or the environments.

Would medical countermeasures work against mirror bacteria?

Treatment options would be limited. Most antibiotics interact stereospecifically (in a way that is specifically 'handed') with their microbial targets, so existing countermeasures would be restricted to a few achiral or racemic antibiotics (those that would recognise mirror targets). As an emerging infectious disease, there would be no pre-existing vaccine. It should be possible to develop novel anti-mirror compounds and conjugate vaccines, but, as with a new pandemic, the practical challenges to developing such measures quickly, manufacturing them at scale, and distributing them equitably around the world would be considerable. Importantly, there are no guarantees that mirror bacteria would not develop resistance to any potential treatments. While developing and deploying medical countermeasures for humans would be extremely difficult, developing and deploying countermeasures for all potentially affected species and the environment would likely not be possible.

Why is this being discussed now?

The scientific community had informally been discussing potential risks from mirror life for decades, but until the possibility of building mirror life came into view more recently, nobody had undertaken a thorough risk assessment. In December 2024, a group of 38 leading scientists working in Brazil, China, France, Germany, India, Japan, Singapore, the UK and the US published an analysis in *Science* describing potentially severe risks of mirror life. The paper was accompanied by a detailed technical report that carefully outlined the problem and provided the first in-depth assessment of the potential risks.

Weighing up potential risks and potential benefits, the group of authors urged that "Unless compelling evidence emerges that mirror life would not pose extraordinary dangers…mirror bacteria and other mirror organisms, even those with engineered biocontainment measures, should not be created." Ongoing discussions continue to explore which, if any, enabling technologies should be avoided in order to prevent creation of mirror life.

How can the Global guidance framework for the responsible use of the life sciences support states?

The WHO Global guidance framework for the responsible use of the life sciences: mitigating biorisks and governing dual-use research offers a structured basis for anticipating and governing the exceptional risks posed by mirror life. It promotes early identification of emerging technologies through foresight and provides values, principles and practical tools to guide decisions before risks materialise. It integrates biosafety, biosecurity and dual-use oversight into a coherent biorisk management approach, helping stakeholders assess whether proposed work − such as creating mirror organisms – falls within acceptable risk boundaries. The Framework also encourages multi-stakeholder engagement to mitigate biorisks, recognizing that decisions around the balancing of scientific risks and benefits require input from and affect many diverse stakeholders.

The Framework also equips governments and institutions with adaptable mechanisms for research review, funding oversight and responsible publication, supporting consistent responses to high-consequence advances. In parallel, it strengthens global preparedness by fostering awareness, education and cross-sector engagement, ensuring that diverse actors can collectively evaluate and manage the potential impacts of mirror life.

What is the path forward?

It is estimated that capacities to create mirror life are likely to be at least a decade away, and they would require large investments and major technical advances. There is, therefore, a window of opportunity to consider and to pre-empt the risks before they are realised. To seize this window, the authors of the December 2024 *Science* article encouraged all relevant expert communities to critically engage with the analysis in the paper and in the technical report. They noted, in particular, that they "welcomed arguments and evidence about mirror life that they had not yet considered."

The *Science* article called on the global community, including scientists, governments, ethicists, security experts, industry and civil society groups, and particularly low- and middle-income countries, as mirror bacteria could have potentially disproportionate impacts on them, to collaboratively consider the risks from mirror life and to appropriate governance mechanisms.

WHO, other international organizations and entities, including the Secretary-General's Scientific Advisory Board, are following the science carefully and engaging in broad stakeholder conversations to ensure that risks are identified, considered and pre-empted.