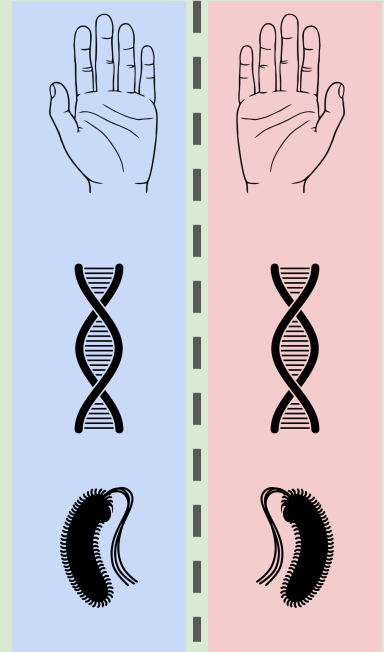


When scientists say “stop”: governing risks from mirror life before they emerge

November 6th, 2025

Dr Jolien Sweere

Mirror Biology Dialogues Fund

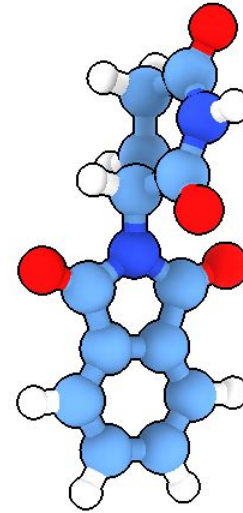
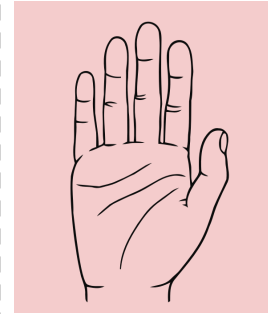
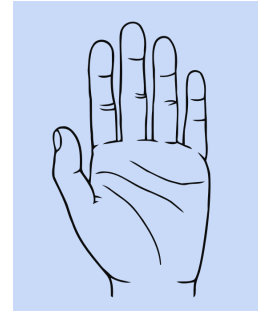


Outline

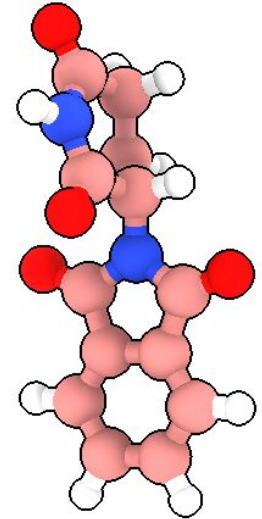
- I. Background
- II. Mirror life: Feasibility and potential benefits
- III. Risks:
 - A. Immune evasion and infections
 - B. Impact on ecosystems
- IV. Containment and countermeasures
- V. Recent progress

Like hands, chiral molecules come in 'mirrored' pairs

- 'Left' and 'right' handed versions have identical physical properties but very different biological properties
- All known life uses key biomolecules with a single handedness, e.g.
 - 'left'-handed L-proteins
 - 'right'-handed D-DNA
- Mirror proteins and DNA are not found in nature but can be chemically synthesized



(R)-Thalidomide
sedative



(S)-Thalidomide
teratogen

Background: Early timeline of mirror life and risks

1848: Louis Pasteur discovers homochirality

1992: A *Science* letter: mirror life *"would have built-in immunity to attack from 'normal' life"* and that *"synthesizers of life... need to consider these matters in detail before getting started."*

2010: A *Wired* article: *"mirror life wouldn't have any predators or diseases to limit its reproduction. They would have to keep an eye on that."*

2012: Church and Regis discuss mirror life in *Regenesys: How Synthetic Biology Will Reinvent Nature and Ourselves*

2014: NSF Grant: *Establishment of a Fully Synthetic, Mirror-Image Biological System*

2019: NSF Grant: *Booting up a mirror cell*

Science

Total Chemical Synthesis of a D-Enzyme: The Enantiomers of HIV-1 Protease Show Demonstration of Reciprocal Chiral Substrate Specificity

R. C. deL. Milton, S. C. F. Milton, S. B. H. Kent*

The D and L forms of the enzyme HIV-1 protease have been prepared by total chemical synthesis. The two proteins had identical covalent structures. However, the folded protein-enzyme enantiomers showed reciprocal chiral specificity on peptide substrates. That is, each enzyme enantiomer cut only the corresponding substrate enantiomer. Reciprocal chiral specificity was also evident in the effect of enantiomeric inhibitors. These data imply that the folded forms of the chemically synthesized D- and L-enzyme molecules are mirror images of one another in all elements of the three-dimensional structure. Enantiomeric proteins are expected to display reciprocal chiral specificity in all aspects of their biochemical interactions.

SCIENCE

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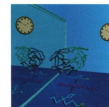
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LETTERS

Left-Handed Comments

We write from the not always equivalent perspectives of organic chemistry and biochemistry to express our mutual dismay that it is considered big news that mirrors appear to work as well in one of our fields as in the other (Cover, 5 June). "Total chemical synthesis of a D-enzyme: The enantiomers of HIV-1 protease show reciprocal chiral substrate specificity," R. C. deL. Milton et al., Reports, 5 June, p. 1445. Corrections and clarifications, 10 July, p. 1477. It was, after all, only this spring that the American Chemical Society celebrated the centenary of the demonstration by Emil Fischer, the father of biochemistry, that the principles of van't Hoff-LeBel stereochemistry could be used to establish the detailed structures of the carbohydrates (1). Perhaps more dismaying is the revelation that there was serious doubt not too long ago about whether enzymes would be subject to rules of symmetry ("On the other hand...," G. A. Baskin, *Pro-*



folding of the "normal" protein would necessarily be wrong-handed when it came to doing the same with the "abnormal" one.

The precision with which this enantio-enzyme has been prepared brings us closer to the day when we must address the viability of enantio-life in the test tube, in the current bio-

sphere, and in the times when life was getting started. Clearly, enantio-life will be as viable as "normal" life in vitro, a claim for de novo biogenesis will be considerably more credible if it is based on building blocks enantiomeric to those found in the biosphere. Although escaped enantio-life would have a built-in immunity to attack from "normal" life, it might have a tough time finding nutriment unless it were achiral or developed racemases and invertases. Would-be synthesizers of life based on amino acids and nucleic acids need to consider these matters in detail before getting started. Such organic or biochemists should therefore not only watch the

2024: Working group on mirror life

Co-chairs:



Jack Szostak



John Glass

Kate Adamala, University of Minnesota

Deepa Agashe, Bangalore Nat. Centre for Biological Sciences

Yasmine Belkaid, Institut Pasteur *

Daniela Bittencourt, EMBRAPA Brazil

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Matthew Chang, National University of Singapore

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George Church, Harvard University *

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Tom Inglesby, Johns Hopkins University *

Farren Isaacs, Yale University

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Craig Venter, J. Craig Venter Institute *

Gregory Winter, Cambridge University *

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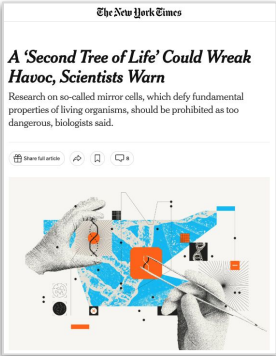
Maria Zuber, Massachusetts Institute of Technology *

** National Academy of Sciences/Medicine member, or equivalent*

Science paper & technical report

In Dec. 2024, 38 scientists from 10 countries published:

- A policy paper on risks of mirror life in *Science*
- An accompanying 300-page technical report

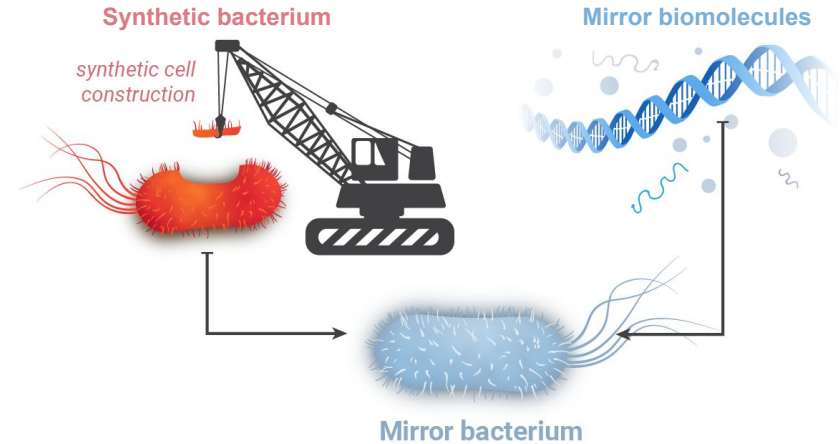


Technical Report on Mirror Bacteria: Feasibility and Risks

The creation of mirror bacteria is increasingly feasible

Most likely pathway towards mirror bacteria:

- Convergence of efforts to produce **mirror biomolecules** with **synthetic cell research** for “bottom-up” assembly
- No known researchers are actively working to make mirror bacteria
- Timelines are highly uncertain:
 - 10–30 years away by default
 - <10 years with a \$500m–\$1b effort
 - AI could accelerate timelines



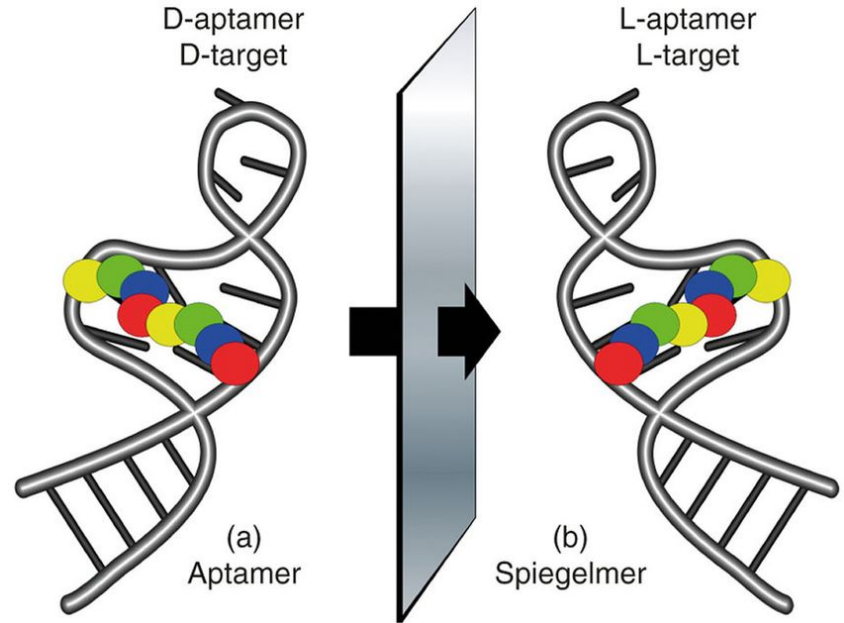
Chapter 2: Pathways to Mirror Life

2.1 Advances in chemistry permit the synthesis of mirror biomolecules with diverse applications	26
2.2 Progress in synthetic biology could allow the assembly of a mirror bacterium from non-living mirror components	28
2.3 A natural-chirality bacterium might be converted into a mirror bacterium in a stepwise fashion	33
2.4 Other approaches to creating mirror bacteria are plausible	41
2.5 The feasibility of mirror life will increase as related technologies advance	50

Why make mirror life? Limited foreseeable benefits

Motivation to create mirror bacteria:

- Overcome the technical challenge and satisfy scientific curiosity
- Primary proposed application is to produce **mirror biomolecules**, more cheaply and at greater scale.



Source: Maier & Levy, 2016)

Achiral nutrients could support mirror bacteria growth

Achiral Nutrients that Support *E. coli* growth

Sole carbon sources	
Central metabolites	Citrate, fumarate, glycolate, glyoxylate, α -ketoglutarate, pyruvate, succinate
Fatty acids	Acetate, acetoacetate, butyrate, propionate, valerate Medium-chain (C_6 – C_{10}) fatty acids Long-chain ($\geq C_{12}$) fatty acids
Alcohols	Butanol, ethanol, propanol
Sugars and polyols	Dihydroxyacetone, ethylene glycol, galactitol, glycerol, mucate
Aromatic acids	Benzoate, m-coumarate, 2-furoate, 3-hydroxyphenylacetate, phenylacetate, phenylpropionate, phenylethylamine
Amines	γ -aminobutyrate, putrescine
Misc.	γ -hydroxybutyric acid, methyl pyruvate, m-tartaric acid
Sole nitrogen sources	
Amino acids	Glycine
Amines	Agmatine, γ -aminobutyrate, dopamine, phenylethylamine, putrescine, spermidine, tyramine
Nucleobases	Adenine, cytidine, thymine, uracil

Typical concentration of accessible nutrients:

- Natural waters: 1–1000 $\mu\text{g/L}$
- Soil: 0.8–8 mg / L**
- Gut lumen: 0.1–150 mg/L
- Blood: 0.1–180 mg/L

Estimated minimum required concentrations for *E. coli* growth:

~ 100s of $\mu\text{g/L}$

**Data from soil with plant growth

Key references: Clark & Cronan (1996); Gunina & Kuzyakov, *Soil Biol. Biochem.* (2015); Lin (1996); Thurman (2014); Tong et al, *mBio* (2020); The Human Metabolome Database (2022)

Many immune mechanisms would likely fail during mirror bacteria infection

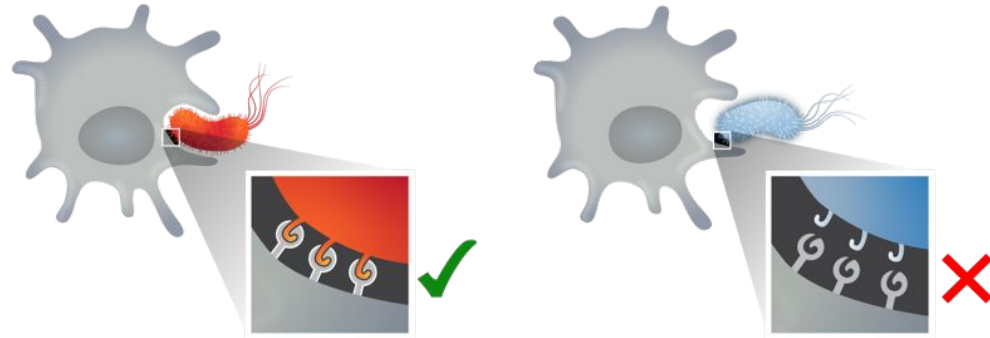
Across multicellular life, immunity depends on **chiral molecular interactions** that could be impossible with mirror bacteria.

In humans and other vertebrates, mirror bacteria could likely:

- Passively translocate across barrier tissues
- Avoid many mechanisms of recognition and killing by innate and adaptive immunity

This could potentially lead to systemic infections that could be fatal.

Many invertebrates and possibly plants could also be vulnerable.



Chapter 4: Risks to Human Health

- 4.1 Innate immune detection of mirror bacteria could be significant!
- 4.2 Mirror bacteria would likely be resistant to most innate
- 4.3 Adaptive immunity to mirror bacteria would likely
- 4.4 Mirror bacteria could plausibly pass bacteria into the bloodstream and tissues
- 4.5 Mirror bacteria could plausibly

Chapter 6: Animal Infection

- 6.1 Vertebrate susceptibility to mirror bacterial infection would likely be similar to that of humans
- 6.2 Many invertebrates would likely be susceptible to mirror bacteria

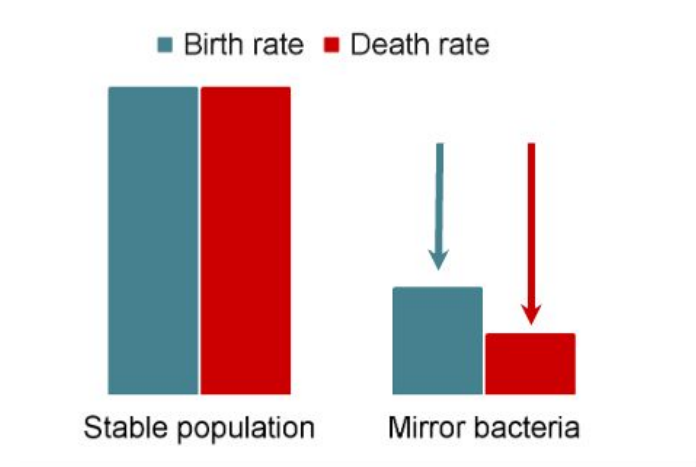
Chapter 7: Plant Infection

- 7.1 Mirror bacteria are likely to evade plant innate immunity
- 7.2 Mirror bacteria could plausibly establish chronic local infections within leaves and roots
- 7.3 The extent to which mirror bacteria could spread through and colonize agricultural plants

Mirror bacteria could evade biological controls and disrupt global ecosystems

Natural-chirality bacteria in the environment are kept in check by ecological controls

- Mirror bacteria would likely be highly resistant to bacterial predators due to mismatched chirality
- Without these ecological controls, mirror bacteria could invade many diverse environments
- Potential result: **great ecological harm** (e.g., effects on nutrient or geochemical cycling, degradation of habitats, exposure to animals and humans)
- Mirror bacteria would not have to outcompete all other life forms to be dangerous



Chapter 8: Environmental Survival and Spread

8.1 Mirror bacteria would be inherently resistant to many biological controls	156
8.2 Mirror bacteria could colonize natural environments outside of multicellular hosts	157
8.3 Invasive mirror bacteria could rapidly disperse through the environment	165
8.4 Invasive mirror bacteria could rapidly evolve and diversify	175
8.5 Invasive mirror bacteria could cause irreversible ecological harm	178
8.6 Countermeasures to invasive mirror bacteria might lessen but would not halt the ecological damage	181
	187

Containment that is robust to misuse is not feasible

Even the most robust containment and biosafety measures cannot eliminate all risk

- Biocontainment is plausible but could be deliberately undone
- Physical containment is vulnerable to human error or malicious action
- Malicious actors could replicate methods to construct mirror bacteria and likely make them more robust



Chapter 3: Engineering, Biosafety, and Biosecurity of Mirror Bacteria

54

3.1 The creation of any mirror bacterium could enable the generation of diverse mirror bacterial strains and species and their modification by routine genetic engineering

55

3.2 Biocontainment approaches might reduce accident risk, but they would face challenges

60

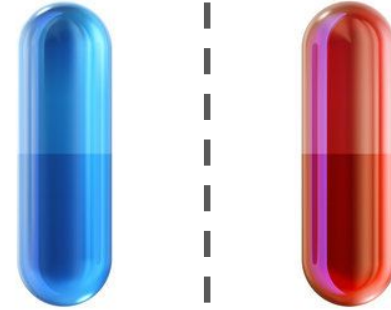
3.3 Creating robustly biosecure mirror bacteria is not feasible

62

Medical countermeasures are unlikely to be sufficient

While some existing and/or novel medical countermeasures (MCMs) may be effective:

- Antibiotics typically require a functional immune response to be effective
- Novel MCMs could be developed, but development, testing, and scaling could be difficult during an outbreak
- Equitably distributing these MCMs around the world during a pandemic would be extremely difficult
- MCMs cannot plausibly prevent harms across plants, animals, and ecosystems



Chapter 5: Medical Countermeasures

107

5.1 New antimirror compounds could be developed to target mirror bacteria, but most existing antibiotics would not function

108

5.2 Conjugate vaccines could plausibly be developed against mirror bacteria

113

5.3 The efficacy of other countermeasures against mirror bacterial infection is unclear

116

2024: Working group recommendations (Science)

Global conversation needed to chart a path forward

Starting point for discussion:

- Research on mirror biomolecules is safe and should continue, as should work with natural-chirality cells
- Mirror bacteria should not be created and funders should not fund work to make them, given current understanding
- Research should be done transparently to better understand risks from mirror bacteria without advancing toward their creation
- Consider governance of precursor technologies on way to mirror life needed that protects benefits

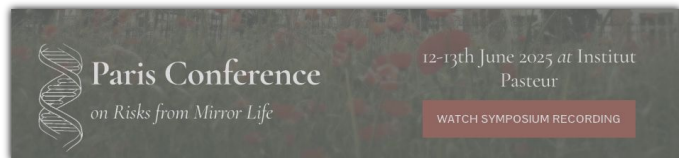
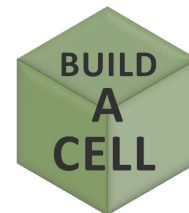


What has happened since the
publication?

Broadening scientific discussion in 2025



GAMRIC
Global AMR Innovators Conference



BROWN

Scientific discourse

FEB. 25, 2025

Remember The Glycans: Consideration of Glycans in Evaluating the Threat of Mirror-Image Life Forms.

RATMIR DERDA Department of Chemistry, University of Alberta, Edmonton, AB T6G 2G2, Canada

[...]

A recent analysis of the potential threat posed by mirror-image life forms (1) presented an important topic for the scientific community. Major concerns were raised by the authors, who argued that many aspects of the immune response to mirror bacteria could be deficient. However, there was limited consideration of the crucial roles of the third pillar of biomolecules, namely carbohydrates (comprising oligo- and polysaccharides, a.k.a. glycans), in con-

DEC. 23, 2024

In response to "Confronting risks of mirror life".

DAVID PERRIN Professor, UBC Chemistry Department

In the December 12th issue of *Science*, Adamala *et al.* in "Confronting risks of mirror life" raise the specter of "mirror-life" organisms—bacteria whose molecular components are the enantiomers of those found in natural life—warning of the "unprecedented risks" such organisms might pose to human health. Yet a number of critical aspects were not fully discussed. These include the immune system's capacity to respond, the complex nature of bac-

JAN. 24, 2025

Response to Perrin

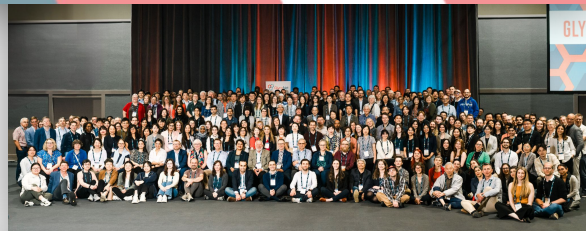
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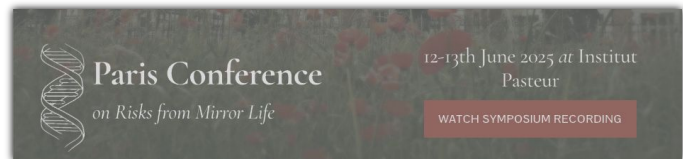
Global
Challenges

www.global-challenges.com

Computational Perspectives on Amoxicillin and Staphylococcus Aureus in Mirror Life

Lorenzo Pedroni, Chiara Dall'Asta, Gianni Galaverna, and Luca Dellafora*

Initial policy & governance discussions

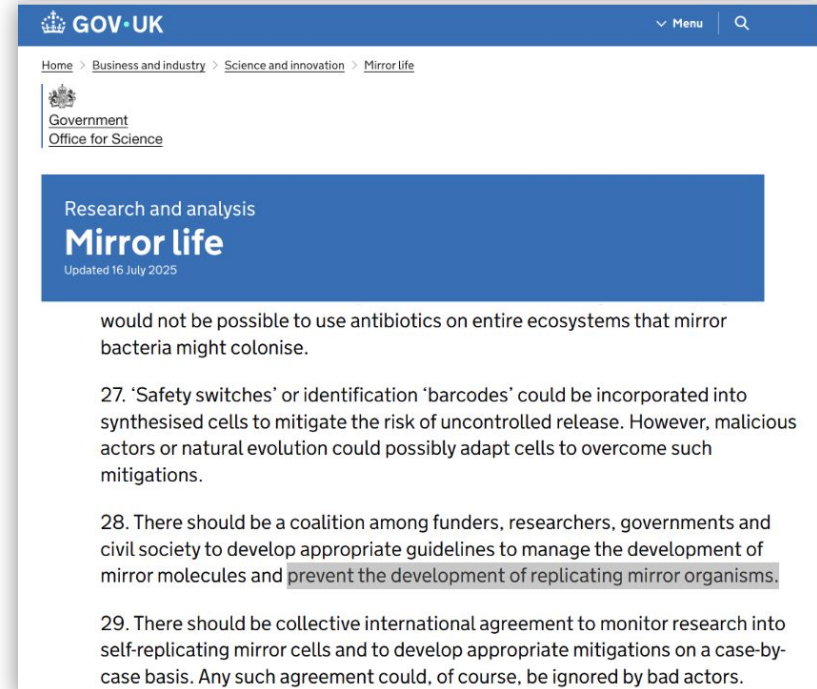


UK Govt Office for Science Expert Roundtable– Jan 2025

“28. There should be a **coalition among funders, researchers, governments and civil society** to develop appropriate guidelines to manage the development of mirror molecules and **prevent the development of replicating mirror organisms**.

29. There should be **collective international agreement to monitor research** into self-replicating mirror cells and to develop appropriate mitigations on a case-by-case basis. Any such agreement could, of course, be ignored by **bad actors**.

30. Stopping all research into mirror life would compromise the UK's ability to manage risks and benefit from opportunities.”



The screenshot shows a web page from the UK Government Office for Science. The header includes the GOV.UK logo and navigation links. The breadcrumb trail is: Home > Business and industry > Science and innovation > Mirror life. The page title is 'Mirror life' with a subtitle 'Research and analysis' and a date 'Updated 16 July 2025'. The main content area contains three paragraphs of text, with the last two paragraphs highlighted in grey. The first paragraph discusses the use of antibiotics on ecosystems. The second paragraph discusses 'safety switches' or 'barcodes' for synthesised cells. The third paragraph discusses the need for a coalition among funders, researchers, governments, and civil society to manage the development of mirror molecules and prevent the development of replicating mirror organisms. The fourth paragraph discusses the need for collective international agreement to monitor research into self-replicating mirror cells and to develop appropriate mitigations on a case-by-case basis.

Home > Business and industry > Science and innovation > Mirror life

Government
Office for Science

Research and analysis
Mirror life
Updated 16 July 2025

would not be possible to use antibiotics on entire ecosystems that mirror bacteria might colonise.

27. 'Safety switches' or identification 'barcodes' could be incorporated into synthesised cells to mitigate the risk of uncontrolled release. However, malicious actors or natural evolution could possibly adapt cells to overcome such mitigations.

28. There should be a coalition among funders, researchers, governments and civil society to develop appropriate guidelines to manage the development of mirror molecules and **prevent the development of replicating mirror organisms**.

29. There should be collective international agreement to monitor research into self-replicating mirror cells and to develop appropriate mitigations on a case-by-case basis. Any such agreement could, of course, be ignored by bad actors.

Spirit of Asilomar Summit Entreaty– February 2025

“3. We believe that **mirror life should not be created** unless future research convincingly demonstrates that it would not pose severe risks.

4. Current technical barriers to the creation of mirror life provide a **valuable window of opportunity to further evaluate and address its risks.**

5. We call on the global community—including scientists, governments, ethicists, industry, and civil society groups—to **establish governance mechanisms capable of preventing the creation of mirror life.** This should include governance of key technologies that, if not properly controlled, could facilitate the creation of mirror life. We also **encourage further research to evaluate the risks of mirror life,** as long as this research does not itself facilitate the creation of mirror life.”



SPIRIT OF ASILOMAR ENTREATY 2025.4.4

Risks from Mirror Life

ENDORSERS:

Zack Abbott, Kate Adamala, Adedotun Adefolalu, Tessa Alexanian, Rafael Anta, Lawrence Banks, Yuhao Bao, Tarsh Bates, Françoise Baylis, Kenneth Bernard, Linda van Blijsterveldt, Daniela Matias de Carvalho Bittencourt, Nadine Bongers, Tanner Braman, Patrick Cai, Cong Cao, Alex Capron, Matthew Chang, Maria Chavez, Yonatan Chemla, Liyam Chitayat, Matthew Cobb, Sebastian Cocioba, Mariano-Florentino Cuéllar, James Diggs, Gerald Epstein, Kevin Esvelt, Fernan Federici, Alonso Flores, Anemone Franz, Paul Freemont, Paul Friedrichs, Lu Gao, Dalton George, John Glass, Ernest Glover, Stephanie Guerra, Michael Imperiale, Tom Inglesby, Wilmot James, Roudiul Jannah, Adam Jones, Lennart Justen, Jukka Kantola, Sebyunya Emmanuel Kato, Faisal Khan, Cholisit Kiattisewee, Katharine Ku, Ruipeng Lei, Filippa Lentzos, Poh Lian Lim, Ariel Lindner, Walter Ian Lipkin, Marc Lipsitch, Robin Lovell-Badge, Becky Mackelprang, Janet Mertz, Piers Millett, Aishwarya Mitra, Kutubuddin Molla, Felix Moronta-Barrios, Ben Novak, Jassi Pannu, Christine Parthemore, Rolando Perez, Juan Perez-Mercader, Octavio Ramirez, Shrestha Rath, David Relman, Philip Ross, Larisa Rudenko, Wasim Sajjad, Yousif Shamoo, James Smith, Andrew Snyder-Beattie, Robert Speight, Shankar Sundaram, Bong Hyun Sung, Kassahun Tesfaye, Jirapat Thawecheun, Todd Treangen, J. Craig Venter, Justin Vigar, James Wagstaff, Sophia Wang, Guoyu Wang, Andy Weber, Joshua Wentzel, Ping Yan, Jaime Yassif, Doogab Yi, Weiwen Zhang, Joy Zhang, Xinguang Zhu, Laurie Zoloth, Maria Zuber

UNIDIR Advisory Board on Disarmament Matters Report- July 2025

“The Board also acknowledged specific biotechnology-related risks, including the eventual **creation of “mirror organisms”**. Advances in this field raise concerns about the potential development of novel biological agents, including convergence with chemical agents, as well as potentially catastrophic ecological consequences. These developments **could present unprecedented, perhaps existential, risks.**”



Carnegie Endowment Workshop- May 2025

Sloan Foundation Commitment- Aug 2025

"Public and private funders should commit to not funding research with the goal of creating mirror bacteria"



"The program will not support...research with the goal of creating mirror organisms."

UNESCO International Bioethics Committee (IBC) Report- Sept 2025

“V.2.3 Impose Precautions on “Mirror” replicating cells

201. Enact a **precautionary global moratorium** on creating mirror cells (living, dividing organisms made of DNA, proteins, sugars and lipids with reversed chirality). **International authorities (e.g. via the UN Biological Weapons Convention) should explicitly include these in emerging biohazard oversight.** Researchers should be encouraged to find alternative routes towards synthesis of beneficial mirror molecules and to further study the risks of mirror cells via simulations or non-living experiments.”



Germany's Zentrale Kommission für die Biologische Sicherheit (ZKBS) Statement- Sept 2025

Synthetic Biology Working Group:

"The ZKBS has examined the [Science paper & Technical Report] authors' arguments and **shares their key assessments**. In particular, the ZKBS recognizes the potential, albeit currently difficult to assess, danger posed by self-replicating mirror bacteria to humans, animals, plants, and the environment. **The call for a broad scientifically and socially oriented debate is explicitly supported.**"

(Translation)



Consortium for Science, Policy and Outcomes – Oct 2025

“Some points of consensus emerged. Research on mirror biomolecules should proceed.

Efforts to create self-replicating mirror organisms should not. Intermediate steps require special oversight, with evidence gates guiding progress. Public engagement must be ongoing and inclusive. **Biosafety professionals need resources and support.** And governance must operate at both local and global levels.”



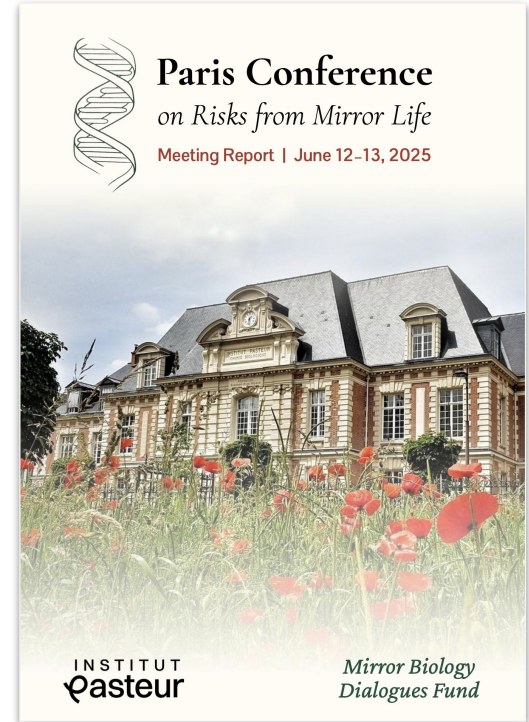
**Consortium for Science,
Policy & Outcomes**
at Arizona State University

What is next?

Paris Conference on Risks from Mirror Life

Recommendations based on conference discussions:

1. Researchers should **refrain from pursuing the creation of mirror organisms**, and public/private **fundors should make clear that they will not support research aimed at this goal**.
2. Work should start now to **develop frameworks for governing key technical milestones on the pathways to mirror life**, with input from a wide range of global stakeholders.
3. Efforts to mitigate the risks of mirror organisms should **preserve scientific freedom and the potential benefits of life-science research** to the maximum extent possible.
4. **Further research should be conducted** into the risks of mirror life, as long as this research does not itself advance their creation and is performed in an open and transparent fashion.



Examples of governance in life sciences

- Funding prohibitions (e.g., Horizon Europe Article 18)
- Norms (e.g., against human cloning)
- Voluntary self-regulation (e.g., 2012 H5N1 moratorium)
- Materials access controls (e.g., radioactive materials license)
- National laws & regulations (e.g., US DURC/PEPP)
- International agreements (e.g., BWC)

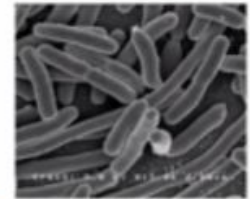
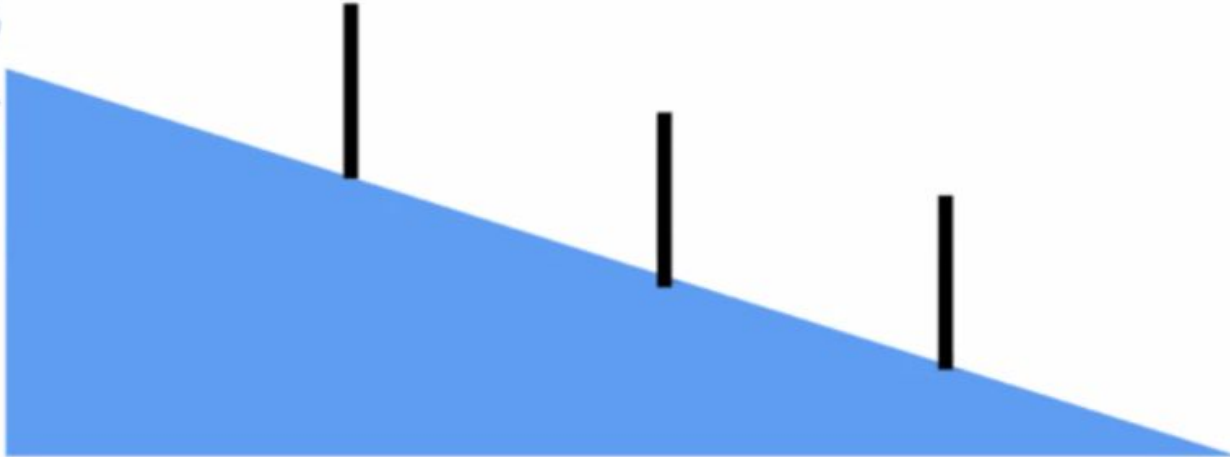
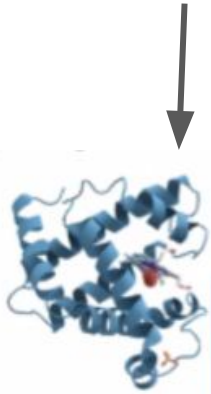


Identifying the right barriers / stopping points

Acceptable research (mirror molecules for therapeutics)

**The right barriers allow
beneficial research to
continue without concern**

What we need to avoid
(mirror bacteria)



The RIVM Dual-Use Quickscan: mirror bacteria and their precursor technologies could be vulnerable to misuse

Dual-Use Quickscan

15 of 15 questions answered

Themes

- High-risk biological agent
- Host range and tropism
- Virulence
- Stability
- Transmissibility
- Absorption and toxicokinetics

Vragenlijst

To obtain a complete overview, all questions must be completed. For each question you will find a short explanation and some literature examples. [Click here for more explanation.](#)

High-risk biological agent

1. Are you working with a biological agent, or parts of it, that can be considered a high-risk pathogen?

☒ Yes ☐ No ☐ Unknown

∨ Explanation

The questions around potential for misuse of the knowledge around, or the products of this research itself, could plausibly be answered with “yes”

If you walk away with anything...

Key points

1. Mirror life could pose unprecedented risks while yielding potentially few benefits
2. We have an unusual (but not indefinite) opportunity to *prevent* a threat
3. Urgency to act due to decreasing barriers; community aiming to define appropriate stopping points

Other takeaways

1. No strategic advantage in developing mirror life
2. Research should proceed, but without creating safety or security concerns
3. International coordination on policy is important but unilateral action can still reduce risks

