Centre for the Fourth Industrial Revolution

WORLD ECONOMIC FORUM

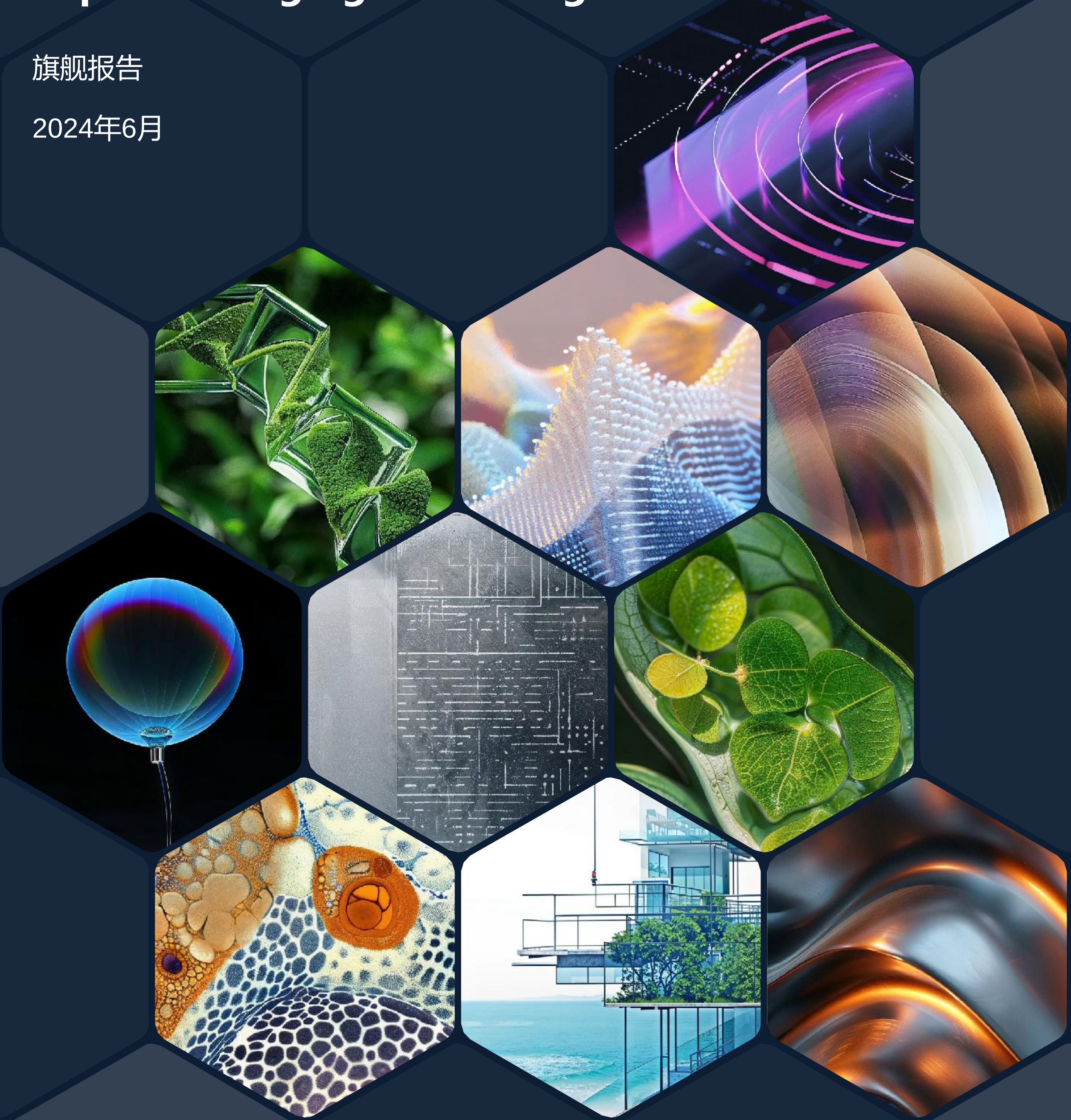
与Frontiers合作

2024年十大新兴技术

Top 10 Emerging Technologies of 2024

旗舰报告

2024年6月



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Top 10 Emerging Technologies of 2024

FLAGSHIP REPORT

JUNE 2024

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Images: Midjourney, Studio Miko. All images in this report have been generated using artificial intelligence.

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弗雷德里克·芬特
（Frederick Fenter）
《Frontiers》首席编辑

杰里米·尤尔根斯 (Jeremy Jurgens) 世界经济论坛执行董事

当组织了解影响未来的因素时，他们会做出更好的选择。自2011年以来，十大新兴技术报告一直是专业人士战略情报的重要来源。该报告借鉴了科学家、研究人员和未来学家的见解，确定了10项有望在三到五年内对社会和经济产生重大影响的技术。

在第12版中，我们扩大了分析的范围和深度。我们从论坛全球未来委员会和Frontiers全球主编网络中汲取了300多名世界领先学者的专业知识，确保了多元化和全面的视角。此外，我们引入了创新的趋势分析方法，涵盖学术文献、融资趋势和专利申请，增强了我们选择过程的严谨性和准确性。

通过这些增强功能，今年的报告重点关注了具有巨大潜力的技术，这些技术可以彻底改变连接、应对气候变化的紧迫挑战并推动各个领域的创新。

从材料科学的进步到医疗保健等领域的变革性技术，该报告展示了一系列旨在塑造未来的解决方案。

如果没有我们的新兴技术指导小组联合主席Mariette DiChristina和Bernard Meyerson，本报告的编写就不可能完成，他们的领导力和专业知识在塑造内容并确保其相关性和影响力方面发挥了重要作用。我们衷心感谢指导小组的所有敬业成员——其中许多人十多年来一直是坚定的合作者——坚定不移地致力于倡导行业领先和社会服务技术。

未来是一个有待研究的领域，也是一个有待塑造的景观。我们希望本报告将成为各部门和各区域专业人员共同建设一个技术改变和丰富全球社会和经济的未来的关键行动呼吁。

Foreword

Frederick Fenter
Chief Executive Editor,
Frontiers

Jeremy Jurgens
Managing Director,
World Economic Forum

Organizations make better choices when they understand the factors shaping the future. Since 2011, the Top 10 Emerging Technologies report has served as a vital source of strategic intelligence for professionals. Drawing on insights from scientists, researchers and futurists, the report identifies 10 technologies poised to significantly influence societies and economies within three to five years.

In this 12th edition, we have broadened the scope and depth of our analysis. We have enlisted the expertise of over 300 world-leading academics from the Forum's Global Future Councils and Frontiers' global network of chief editors, ensuring a diverse and comprehensive perspective. Additionally, we have introduced an innovative trend analysis methodology encompassing academic literature, funding trends and patent filings, bolstering the rigour and accuracy of our selection process.

With these enhancements, this year's report spotlights technologies with immense potential for revolutionizing connectivity, addressing the urgent challenges of climate change and driving innovation across various fields. From advancements in materials science to transformative technologies in healthcare and beyond, the report showcases a diverse array of solutions poised to shape the future.

Producing this report would not have been possible without the Co-Chairs of our Emerging Technologies Steering Group, Mariette DiChristina and Bernard Meyerson, whose leadership and expertise have been instrumental in shaping the content and ensuring its relevance and impact. We extend our heartfelt appreciation to all the dedicated members of the steering group – many of whom have been steadfast collaborators for over a decade – for their unwavering commitment to championing industry-leading and society-serving technologies.

The future is both a realm of study and a landscape to shape. We hope this report will serve as a pivotal call to action for professionals across sectors and regions to collectively build a future where technology transforms and enriches societies and economies worldwide.

引言

十大新兴技术指导小组联合主席致辞。

Mariette DiChristina 波士顿大学传播学院院长

Bernard Meyerson 名誉首席创新官，IBM

世界经济论坛改善世界状况的使命的核心在于相信人类的聪明才智、创业精神、创新与合作的力量。今年的十大新兴技术报告充分展示了这种力量。

深度学习、生成式人工智能和基础模型等人工智能（AI）的突破，使人类创新能力取得显着进展。世界正处于人工智能驱动的科学发现革命的风口浪尖。人工智能的发现具有独特的吸收和组织大量信息的能力，它可能会改善疾病管理、提出新材料并更好地理解我们的身体和心灵。同时，合成数据可以保护个人隐私，同时提供新的全球数据共享和协作机会。

当然，协作依赖于连接，前10大技术中的几个预示着向更具适应性、更高效和更具包容性的连接的转变。可重构智能表面（RIS）动态改变形状以优化无线通信链路；它们结合了超材料、智能算法和先进的信号处理来控制和操纵电磁波。高空平台站通过飞机、飞艇甚至简单的气球，可以为缺乏部署地面系统所需基础设施的偏远地区提供移动网络接入。此类技术可以弥合数字鸿沟，为截至2023年仍缺乏互联网服务的100个国家的超过26亿人提供互联网服务。

随着6G系统的出现，网络现在可以充当传感器，使用无线电信号扫描物理世界，提高通信性能，实现集成传感和通信。

改善世界状况也意味着保护我们的星球和人类。今年，人类健康领域首次将猪的基因工程器官成功植入人体，给等待移植的数百万人带来了希望。沉浸式技术结合了计算能力和虚拟方法，有望快速改进我们日常依赖的系统和物理基础设施。

在环境方面，前十大技术中的许多技术表明，技术如何在应对气候变化方面发挥多方面的作用，包括缓解战略、可持续基础设施发展和促进节能解决方案。弹性热材料在机械应力下释放热量并在松弛时吸收热量，与现有技术相比，其效率更高，能耗更低。同样，另一个积极的环境发展是替代性家畜饲料的出现，减少农产工业废物或残留物、本地作物枯竭和相关资源消耗。此外，为了解决全球变暖问题，将排放物转化为生物燃料等产品的工程生物体为缓解不断增加的二氧化碳水平带来了希望。

以下几页深入探讨了2024年十大新兴技术的规格以及它们如何帮助改善世界状况。我们邀请您参与并欢迎您提供反馈。

Introduction

A message from the Top 10 Emerging Technologies Steering Group Co-Chairs.

Mariette DiChristina
Dean, Boston University
College of Communication

Bernard Meyerson
Chief Innovation Officer
Emeritus, IBM

At the heart of the World Economic Forum's mission of improving the state of the world lies the belief in the power of human ingenuity, entrepreneurship, innovation and cooperation. That power is on full display in this year's edition of the Top 10 Emerging Technologies report.

Breakthroughs in artificial intelligence (AI), such as deep learning, generative AI and foundation models, enable remarkable progress in strengthening human innovation. The world is on the cusp of a science discovery revolution driven by AI. Uniquely able to ingest and organize vast amounts of information, AI-enabled discoveries will likely improve disease management, propose new materials and better our understanding of the body and mind. Meanwhile, synthetic data can protect personal privacy while providing new global data sharing and collaboration opportunities.

Collaboration, of course, relies on connection, and several of the top 10 herald a shift to more adaptive, efficient and inclusive connectivity. Reconfigurable intelligent surfaces (RIS) change shape dynamically to optimize wireless communication links; they combine meta-materials, smart algorithms and advanced signal processing to control and manipulate electromagnetic waves. High-altitude platform stations, through aircraft, blimps or even simple balloons, can bring mobile network access to remote regions lacking the infrastructure required to deploy ground-based systems. Such technology can bridge the digital divide, bringing internet access to over 2.6 billion people in 100 countries that still lack internet service as of 2023. With the emergence of 6G systems, networks can now act as sensors, using radio signals to scan the physical world, improving communication performance and enabling integrated sensing and communication.

Improving the state of the world also means protecting our planet and people. This year, human health saw the first genetically engineered organ from a pig implanted successfully into a human, giving hope to the millions waiting for transplants. Immersive technologies, combining computing power and virtual approaches, promise rapid improvement in the systems and physical infrastructure we rely on daily.

On the environmental front, many of the top 10 demonstrate how technology can play a multifaceted role in addressing climate change, encompassing mitigation strategies, sustainable infrastructure development and promoting energy-efficient solutions. Elastocalorics, releasing heat under mechanical stress and absorbing it upon relaxation, promise much higher efficiency and lower energy use than current technology. Similarly, another positive environmental development is the emergence of alternative livestock feeds, reducing agroindustry waste or residues, native crop depletion and related resource consumption. Additionally, addressing global warming head-on, engineered organisms that convert emissions into products such as biofuels offer hope for mitigating increasing carbon dioxide levels.

The following pages delve into the specifications of the top 10 emerging technologies of 2024 and how they can help improve the state of the world. We invite you to engage and welcome your feedback.

方法

2024年名单的潜在技术是通过世界经济论坛全球未来理事会网络和大学与研究网络进行的一项调查确定的，Frontiers网络由来自全球顶级机构的2000多名主编和十大新兴技术指导小组成员组成。

受访者被要求提供有关他们提出的技术的详细信息，包括技术名称和描述、潜在影响，以及为什么该技术应列入2024年列表的令人信服的理由。

该调查收到了来自29个国家的300多项有效技术提名。为了处理不断增加的回复量，采用了人工智能辅助工具——由Frontiers构建的人工智能趋势分析器——来自动化初始筛选调查答案。该工具根据近年来学术出版物分析确定的趋势主题对回复进行分类和聚类。

随后，指导小组收到了一份包含70项技术的精选清单，并从中选出了最后10项。该小组根据以下标准审查并选择了技术：

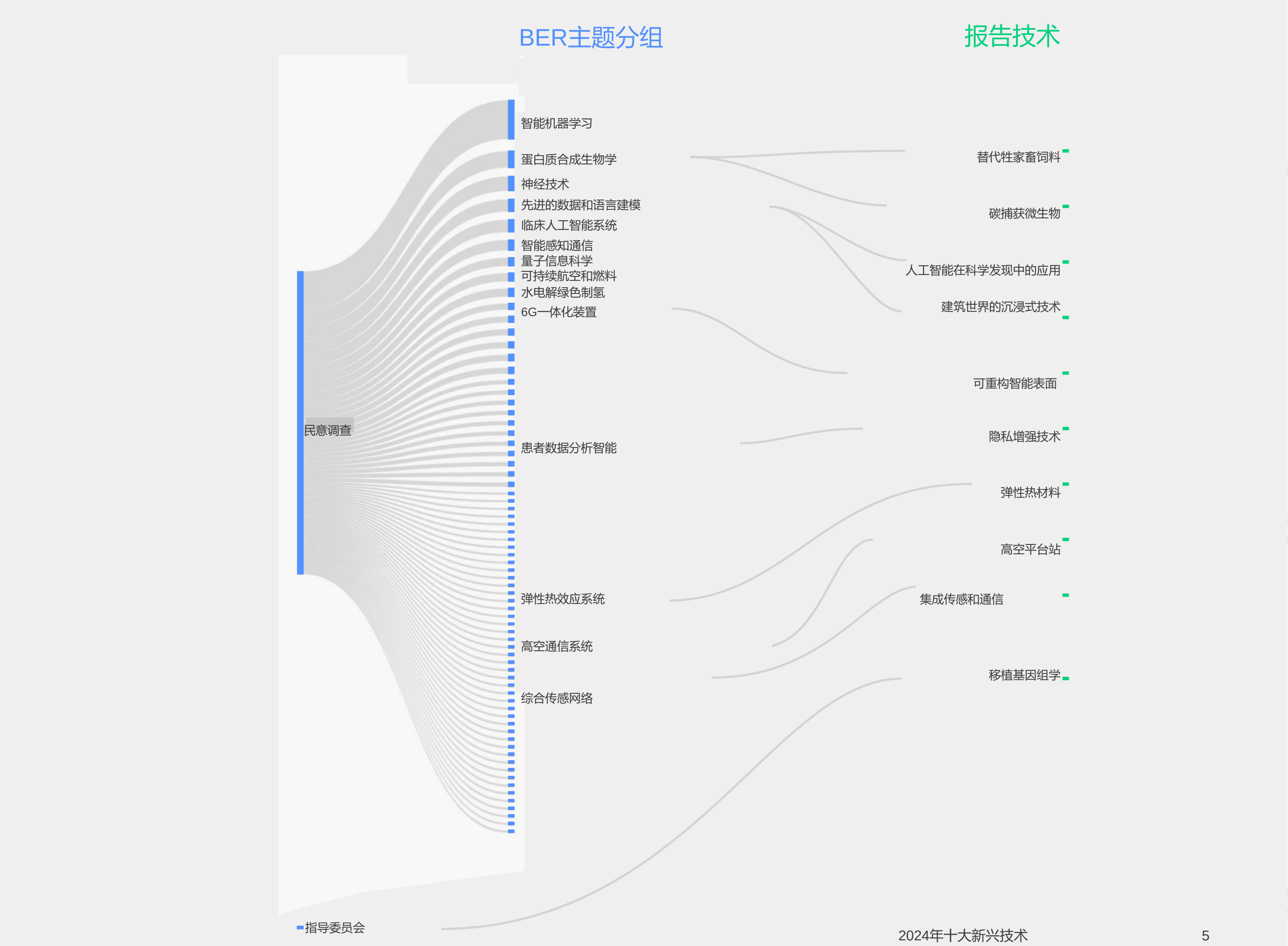
– 新颖性：该技术正在兴起，处于开发的早期阶段，但尚未广泛使用。

– 适用性：该技术可能对社会和经济具有重大用途和益处。

– 深度：该技术正在由多家公司开发，重点是增加投资兴趣和兴奋度。

– 力量：该技术可能会改变既定方式和行业的游戏规则。

图1 前10名评选流程



Methodology

Potential technologies for the 2024 list were identified through a survey distributed across the World Economic Forum's Global Future Councils Network and University and Research Network, the Frontiers network comprising over 2,000 chief editors worldwide from top institutions, and the Top 10 Emerging Technologies Steering Group members.

Respondents were asked to provide detailed information about the technology they put forward, including technology name and description, potential impact, as well as a compelling rationale for why the technology should be on the 2024 list.

The survey received over 300 valid technology nominations from 29 countries. To handle the increased volume of responses, an AI-assisted tool – the AI Trend Analyzer, built by Frontiers – was implemented to automate the initial screening of survey answers. This tool classified and clustered responses based on trending topics identified through an analysis of academic publications in recent years.

The steering group was then presented with a curated list of 70 technologies from which the final 10 were selected. The group reviewed and selected the technologies based on the following criteria:

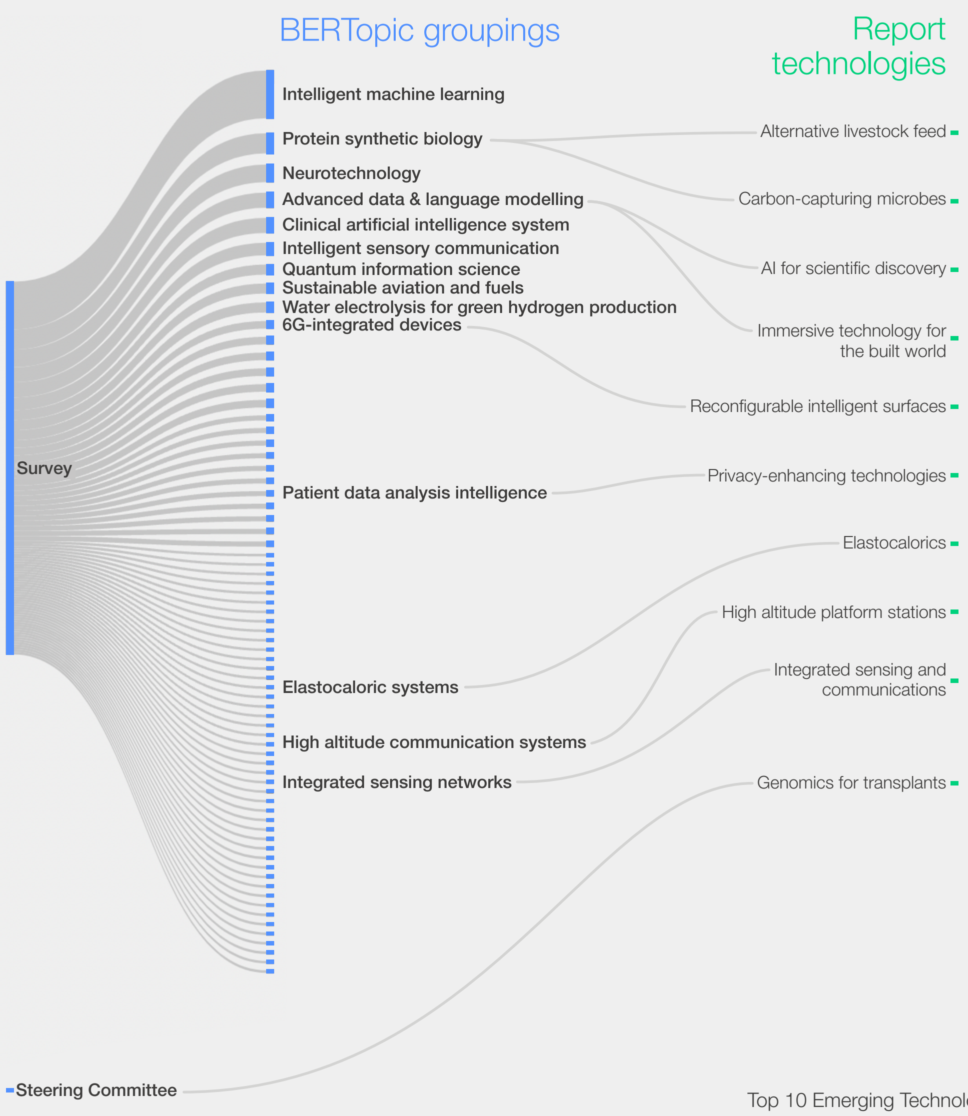
– **Novelty**: The technology is emerging and at an early stage of development but is not yet widely used.

– **Applicability**: The technology is potentially of significant use and benefit to societies and economies.

– **Depth**: The technology is being developed by more than one company, with the focus of increasing investment interest and excitement.

– **Power**: The technology is potentially game-changing to established ways and industries.

FIGURE 1 **Top 10 selection process**



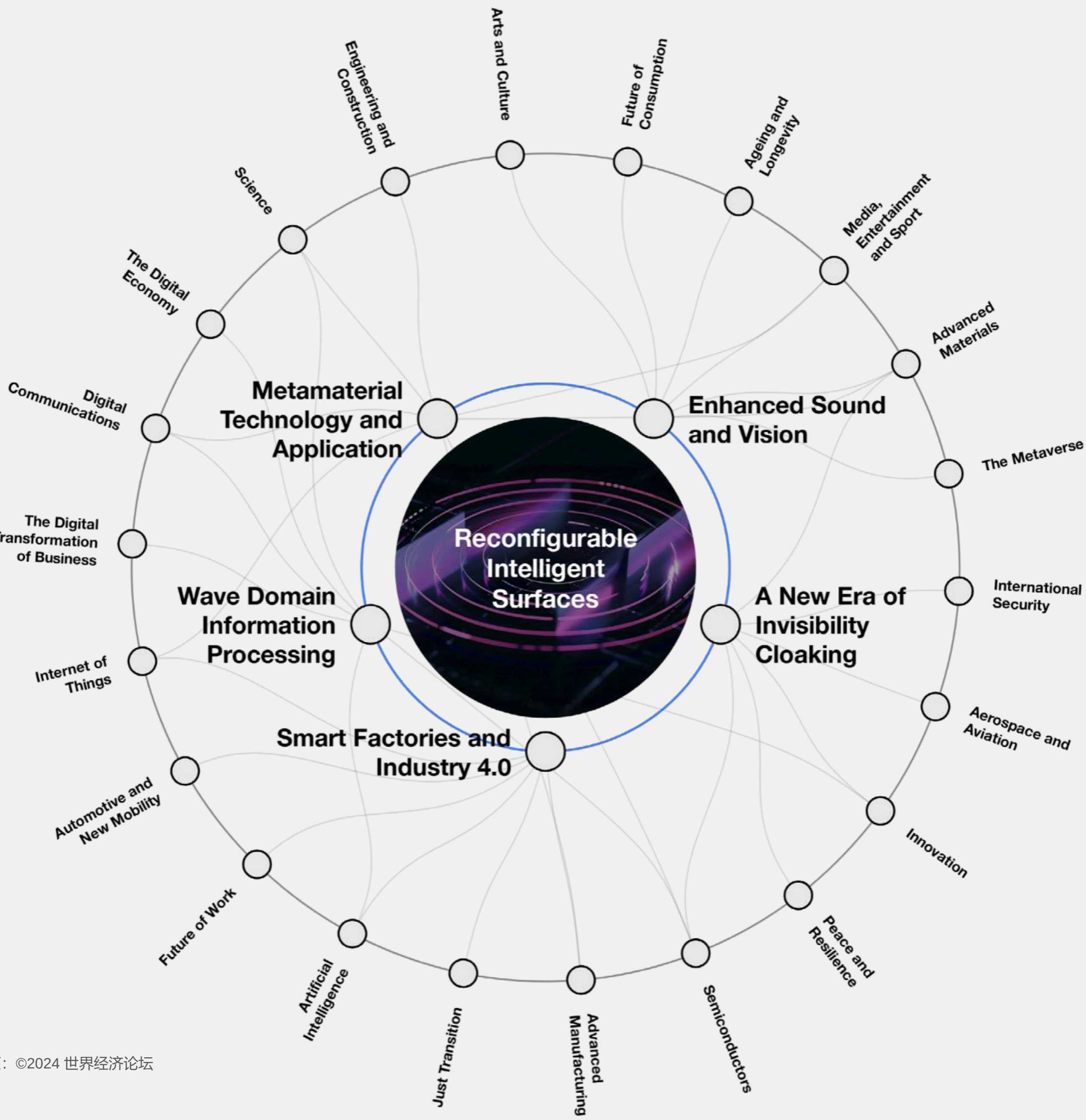
利用专利、资金和地理分布方面的可用数据以及从CB Insights提取的数据，对最后10项技术进行了进一步评估。该报告还使用了来自Dimensions的学术资助数据。

本版深入探讨了技术对各个部门的影响，包括工业、经济、社会、环境、最新进展以及成功扩展所必需的关键要求。为了满足这些新兴技术的活力，Frontiers 为论坛战略情报平台中的每项技术共同制定了转型地图。

读者可以详细了解每种技术的关键问题以及它如何与全球议程上的其他主题联系起来，并从可信来源找到有关该主题的最新文章。

这些描述主要是基于这份报告中的文章。根据指导小组作者的指导和Frontiers编辑的意见，确定了关键问题。这些描述是由Frontiers的编辑研究和撰写的。我们邀请你们继续探索和监测推动经济、行业和全球问题转型变革的技术。点击这里了解更多。

图2 战略情报转型图示例



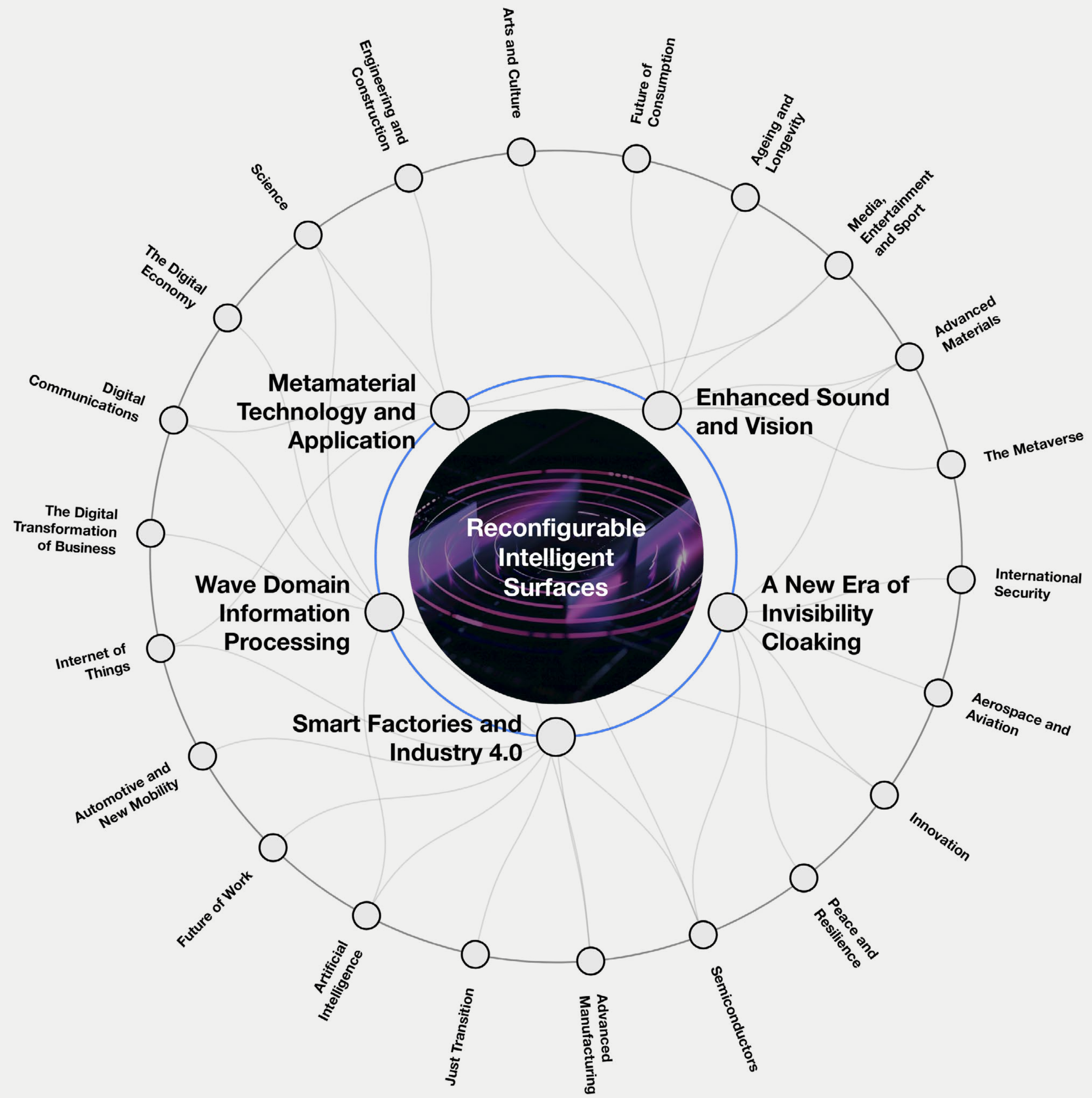
资料来源：©2024 世界经济论坛

These final 10 technologies underwent further evaluation, leveraging available data on patents, funding and geographic distribution, with data pulled from CB Insights. The report also used data on academic grant funding pulled from Dimensions.

This edition delves into the technologies' ramifications across sectors, including industry, economy, society, environment, recent advancements and critical requirements essential for successful scaling. To meet the dynamism of these emerging technologies, Frontiers has co-curated transformation maps for each technology housed on the Forum's Strategic Intelligence Platform. Readers can learn more about the key issues of each technology and how it connects to other topics on the global agenda as well as find the latest articles on the topic from trusted sources.

The descriptions were predominantly based on the articles in this report. Key issues were identified based on guidance from the steering group authors and input from Frontiers' editors. These descriptions were researched and written by the editors at Frontiers. You are invited to continue to explore and monitor the technologies driving transformational change across economies, industries, and global issues. [Explore more here](#).

FIGURE 2 **Example Strategic Intelligence transformation map**



Source: © 2024 World Economic Forum

方框1

构建战略情报：读者指南

新兴技术有可能重塑行业、经济和社会结构，为各种规模和类型的组织带来机遇和挑战。

以下问题旨在帮助您更深入地了解十大新兴技术如何影响您的组织，并确定创新和增长的战略路径。

我们鼓励您以开放的心态解决这些问题，并考虑您组织的独特背景和目标。无论您是企业领导者、技术专家、学者还是政策制定者，该框架都旨在作为组织内战略讨论和决策过程的起点。

- 如果这项技术实现规模化，它将如何影响我组织的运营和目标？
- 该技术在我的组织当前或未来的重点领域有哪些潜在应用？
- 我的组织可以采取哪些步骤将自己定位为有效使用和应用该技术的关键参与者？
- 在这个快速发展的技术环境中，哪些伙伴关系或协作对于成功至关重要？
- 采用这项技术是否意味着我们组织的核心业务、人才结构或运营流程发生重大转变？
- 我的组织如何调整其当前战略，以利用这项新技术的潜力作为创新、增长和/或影响的驱动力？

BOX 1 | Building Strategic Intelligence: a reader's guide

Emerging technologies have the potential to reshape industries, economies and societal structures, presenting both opportunities and challenges for organizations of all sizes and types.

The following questions are designed to facilitate a deeper understanding of how the top 10 emerging technologies may impact your organization and identify strategic pathways for innovation and growth.

You are encouraged to approach these questions with an open mind, considering your organization's unique context and objectives. Whether you are a business leader, technologist, academic or policy-maker, this framework is intended to serve as a starting point for strategic discussions and decision-making processes within your organization.

– If this technology achieves scale, how will it impact my organization's operations and objectives?

– What are the potential applications of this technology in my organization's current or future focus areas?

– What steps can my organization take to position itself as a key player in using and applying this technology effectively?

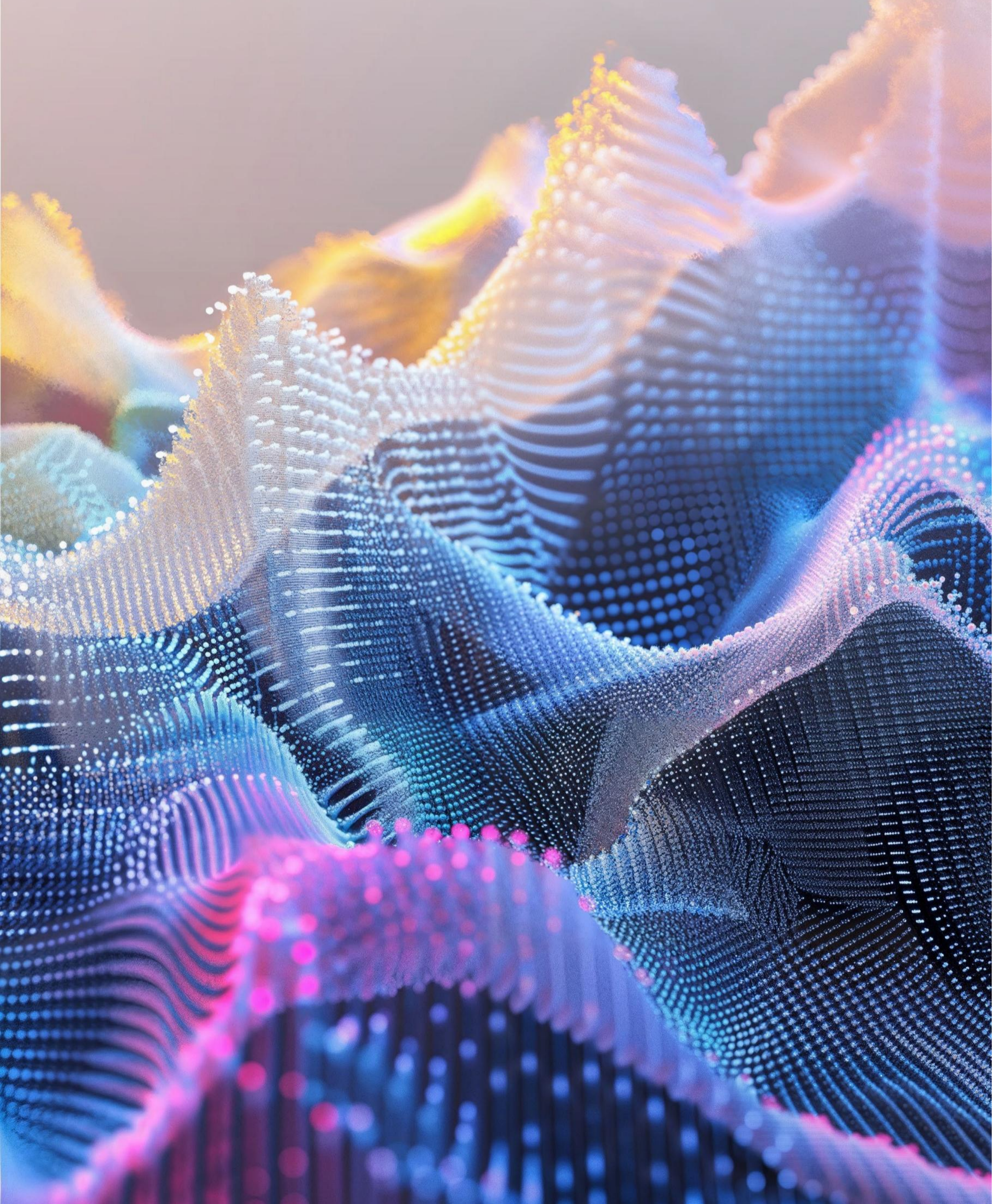
– What partnerships or collaborations are essential for success in this rapidly evolving technological landscape?

– Does the adoption of this technology imply significant shifts in our organization's core business, talent structure or operational processes?

– How can my organization adapt its current strategy to harness the potential of this new technology as a driver of innovation, growth and/or impact?

01　人工智能在科学发现中的应用

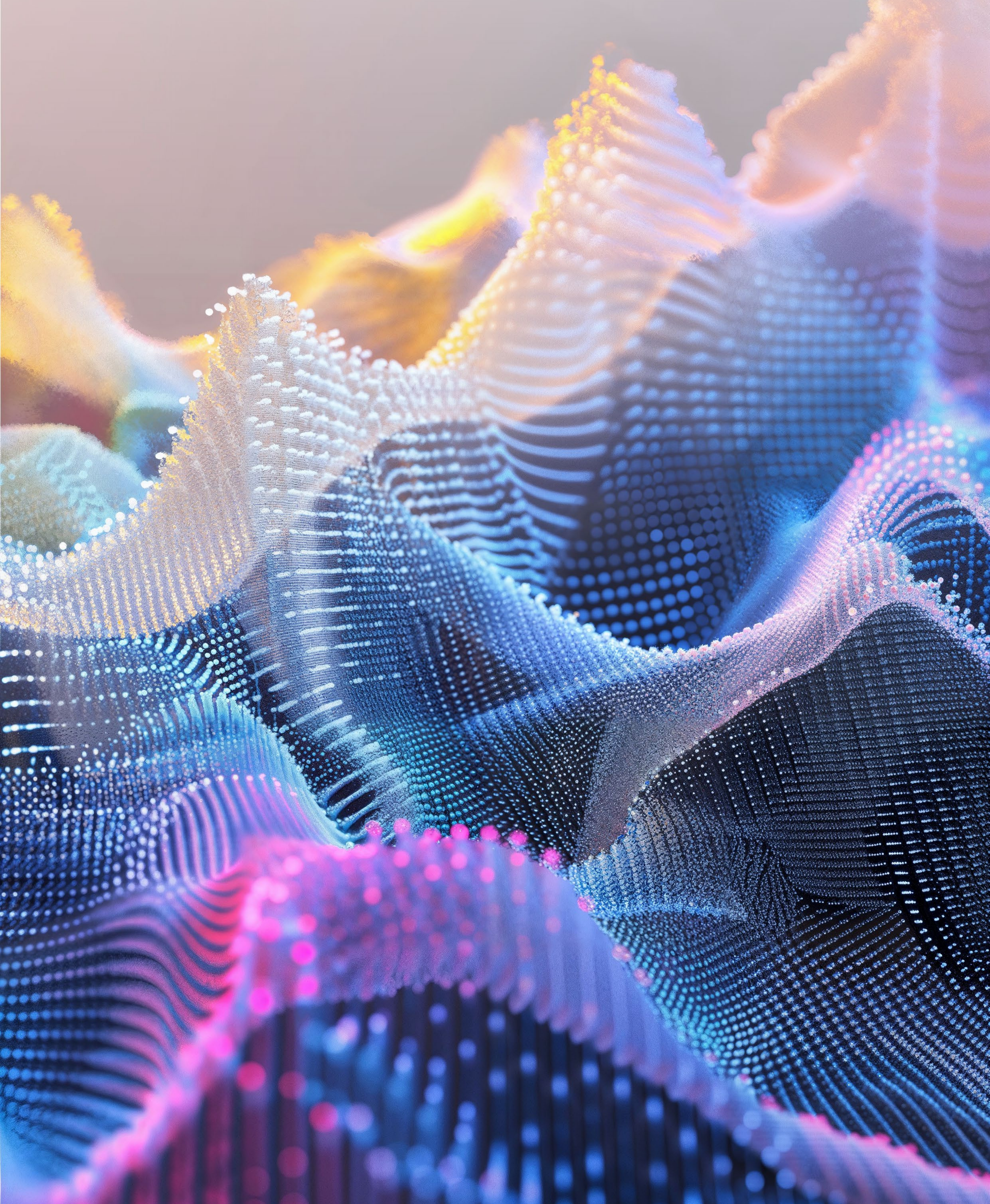
开拓知识新领域



01

AI for scientific discovery

Pioneering new frontiers in knowledge



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人工智能 (AI) 的突破——例如深度学习、生成式人工智能和其他基础模型——使科学家能够做出原本几乎不可能实现的发现，并更广泛地加快科学发现的速度。

在过去的几年里，人工智能在科学发现中的应用方式发生了转变。从Deep Mind的AlphaFold（一种准确预测蛋白质结构3D模型的人工智能系统）到发现新的抗生素家族和用于更高效电池的材料，世界正处于人工智能驱动的新知识发现和使用方式革命的风口浪尖。根据美国总统科学技术顾问委员会最近的一份报告，“人工智能有潜力改变每一个科学学科以及我们进行科学研究的方式的许多方面”。

虽然人工智能已在研究中使用多年，但深度学习、生成式人工智能和基础模型的最新进展具有变革性。科学家们正在构建和使用大型语言模型来挖掘科学文献，与人工智能聊天机器人合作集思广益新假设，创建能够分析大量科学数据的人工智能模型，并使用深度学习来做出发现。他们还在探索如何将人工智能和机器人技术与基于实验室的方法相结合，以创新的方式加速研究。

因此，人工智能正在成为科学研究中一种变革性的通用技术，可以发现原本隐藏的发现。以目前的创新速度，这些可能会导致以下领域的进步：

- 疾病的诊断、治疗和预防。
- 支持下一代绿色技术的新型材料。
- 生命科学领域的突破扩展了当前对生物学的理解。
- 人类思维理解方式的变革性飞跃等等。

科学家预测，通用人工智能将在未来几年内改变科学发现过程的各个部分。研究人员可以利用过去的发现来设想新的可能性——人工智能可以建立联系，并得出超出人类思维能力的推论。

道德考虑和挑战仍然存在——个人隐私、自主权和身份的风险程度以及这些强大技术造成社会破坏的可能性尚未完全清楚。此外，还必须考虑维持人工智能增长所需的能源消耗和资源开采对环境造成的影响。

同样，需要进行更多研究来有效管理该技术的影响。例如，解决数据集中固有的偏差并提高模型生成内容的可靠性对于科学完整性至关重要。确保合乎道德的数据使用和保护研究对象的隐私需要严格的安全措施。驾驭知识产权，特别是模型生成内容的所有权和版权对于协作环境至关重要，必须得到解决。

> “科学家们正在构建和使用大型语言模型来挖掘科学文献，与人工智能聊天机器人一起集思广益，提出新的假设，创建能够分析大量科学数据的人工智能模型，并使用深度学习来进行发现。

↑ 图像：
人工智能在深度学习和生成式模型方面的突破正在改变科学发现。

图片来源：Midjourney和Studio Miko。

提示（简略）：“复杂的数据点汇集在一起并被简化”

阅读更多：
更多专家分析请访问AI for scientific discovery 变换图。

Olga Fink
Assistant Professor, Intelligent Maintenance and Operations Systems, Swiss Federal Institute of Technology in Lausanne

Thomas Hartung
Professor, Bloomberg School of Public Health, Johns Hopkins University

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Breakthroughs in artificial intelligence (AI) – such as deep learning, generative AI and other foundation models – enable scientists to make discoveries that would have been near-impossible otherwise and accelerate the rate of scientific discovery more broadly.

Over the past few years, there has been a transformation in how AI is used in scientific discoveries. From Deep Mind's AlphaFold – an AI system that accurately predicts the 3D models of protein structures – to discovering a new family of antibiotics and materials for more efficient batteries, the world is on the cusp of an AI-driven revolution in how new knowledge is discovered and used.[1,2,3] According to a recent report from the United States President's Council of Advisors on Science and Technology, "AI has the potential to transform every scientific discipline and many aspects of the way we conduct science".[4]

While AI has been used in research for many years, recent advances in deep learning, generative AI and foundation models are transformative. Scientists are building and using large language models to mine scientific literature, working with AI chatbots to brainstorm new hypotheses, creating AI models capable of analysing vast amounts of scientific data, and using deep learning to make discoveries. They are also exploring how AI and robotics can be integrated with lab-based methods to accelerate research in innovative ways.

As a result, AI is emerging as a transformative general-purpose technology in scientific research that can unearth discoveries that would have otherwise remained hidden. With the current rate of innovation, these are likely to lead to advances in the areas of:

– Diagnosis, treatment and prevention of diseases.

– Novel materials that enable next-generation green technologies.

– Breakthroughs in the life sciences that extend current understanding of biology.

– Transformative leaps in how the human mind is understood, and many more.

Scientists predict that general-purpose AI will transform every part of the scientific discovery process over the next few years. Researchers can draw on past findings to envision new possibilities – AI allows connections to be made and inferences to be drawn that lie beyond the capacity of human minds alone.

Ethical considerations and challenges remain – the extent of the risk to individual privacy, autonomy and identity and the possibility of societal disruptions caused by these powerful technologies are not yet fully known.[5] Additionally, environmental impacts resulting from the energy consumption and resource extraction needed to sustain AI growth must also be considered.

Equally, more research is needed to manage the impact of the technology effectively.[6] For example, tackling inherent biases in data sets and enhancing the reliability of model-generated content is crucial to scientific integrity. Ensuring ethical data use and safeguarding research subject privacy require stringent security measures. Navigating intellectual property rights, particularly ownership and copyright of model-generated content is essential to a collaborative environment and must be addressed.

> Scientists are building and using large language models to mine scientific literature, working with AI chatbots to brainstorm new hypotheses, creating AI models capable of analysing vast amounts of scientific data, and using deep learning to make discoveries.

↑ **Image:**
AI breakthroughs in deep learning and generative models are transforming scientific discovery.

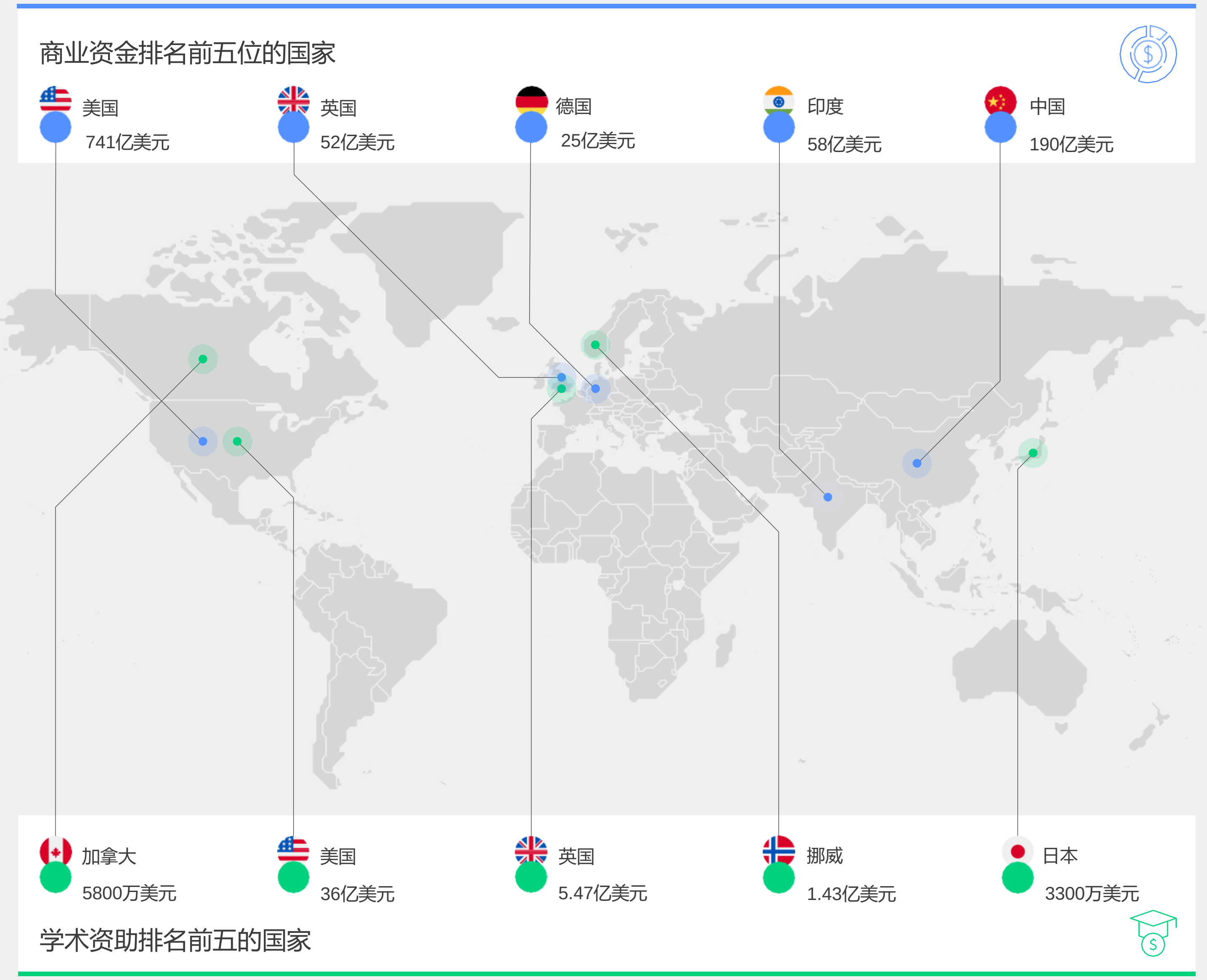
Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Complex data points coming together and being simplified"

Read more:
For more expert analysis, visit the AI for scientific discovery transformation map.

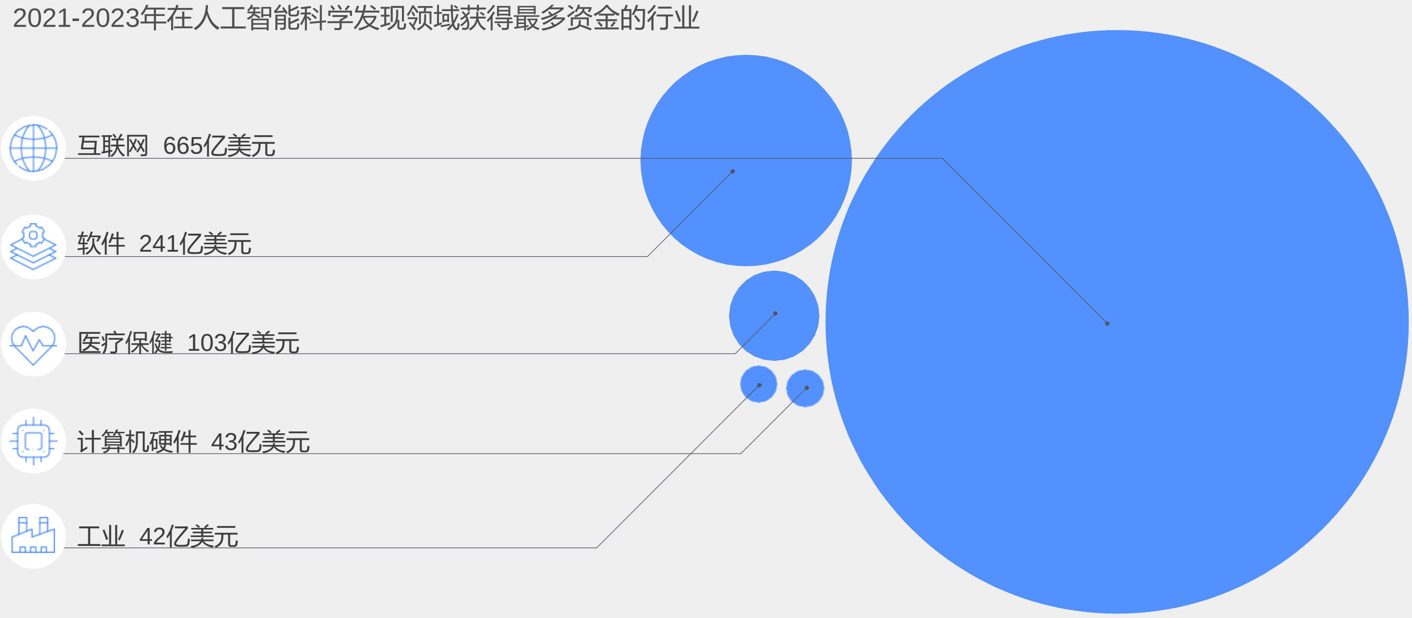
创新领域

2021-2023年人工智能科学发现商业和学术拨款最多的国家



前沿产业

2021-2023年在人工智能科学发现领域获得最多资金的行业

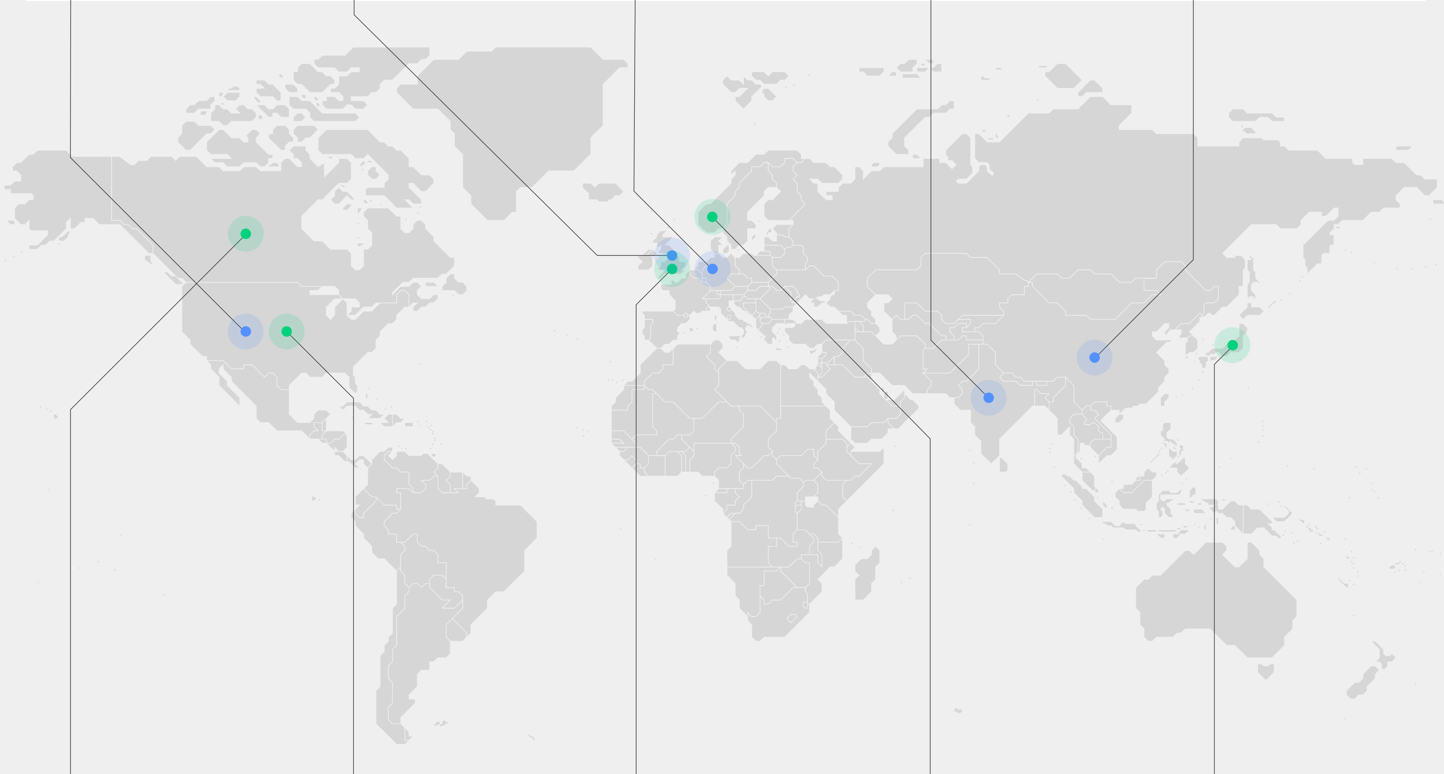


Regions of innovation

Countries with the most business and academic grant funding in AI for scientific discovery from 2021-2023

Top five countries by business funding

- 1 **United States** $74.1 billion
- 4 **United Kingdom** $5.2 billion
- 5 **Germany** $2.5 billion
- 3 **India** $5.8 billion
- 2 **China** $19 billion



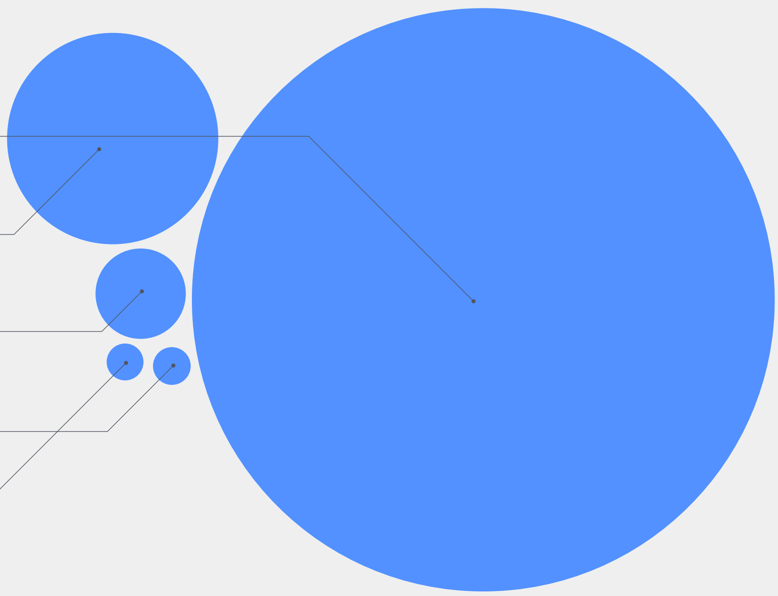
- 2 **Canada** $58 million
- 1 **United States** $3.6 billion
- 4 **United Kingdom** $547 million
- 5 **Norway** $143 million
- 3 **Japan** $33 million

Top five countries by academic grant funding

Leading-edge industries

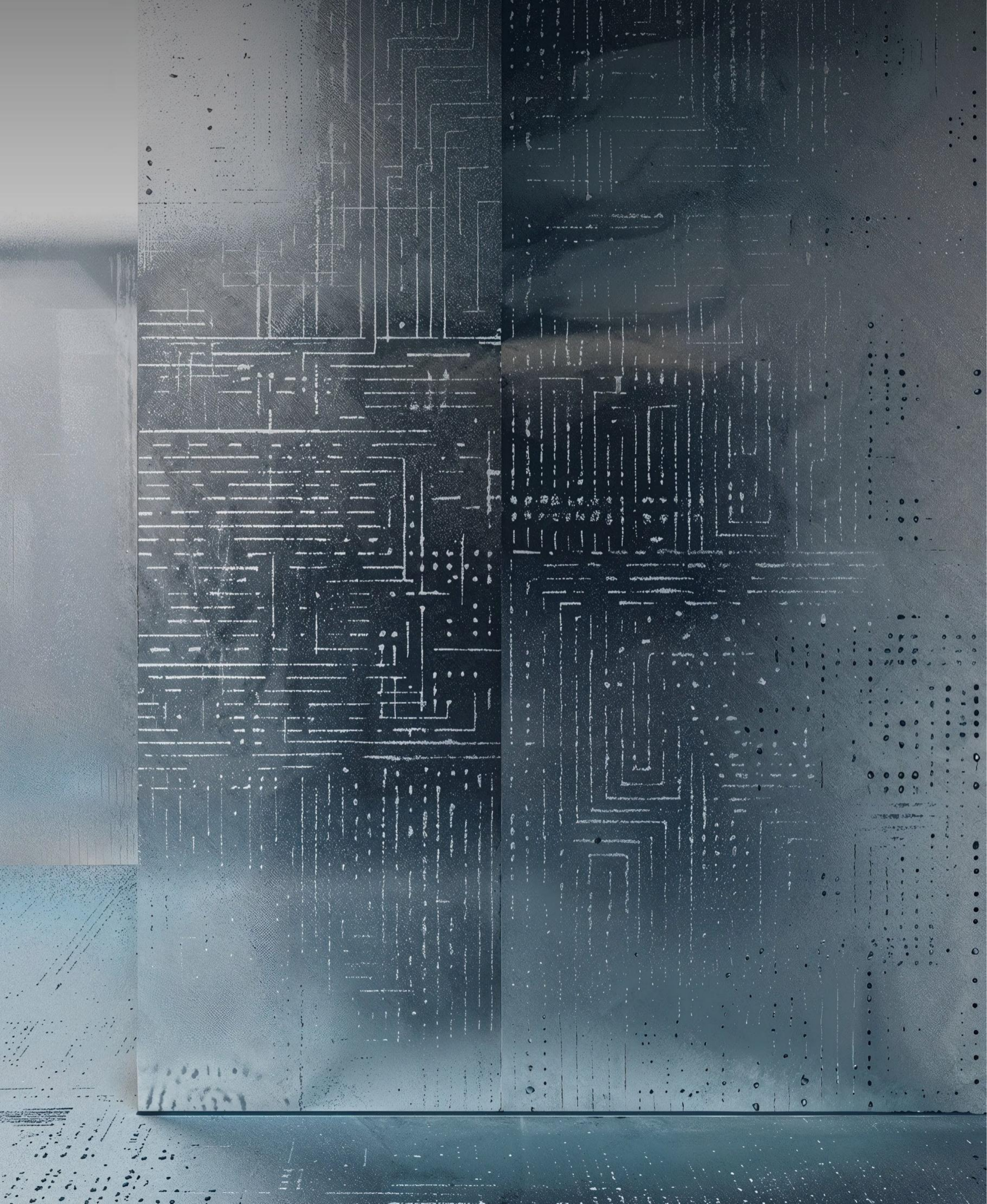
Industries with the most funding in AI for scientific discovery from 2021-2023

- **Internet** $66.5 billion
- **Software** $24.1 billion
- **Healthcare** $10.3 billion
- **Computer hardware** $4.3 billion
- **Industrials** $4.2 billion



02 隐私增强技术

赋能大规模全球协作



02 Privacy-enhancing technologies

Empowering global collaboration at scale

奥尔加·芬克

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亚利桑那州立大学未来社会创新学院教授

巴斯蒂安·范·施恩德尔

ZORGTTP 创新经理

↑ 图像:

隐私增强技术可实现敏感数据的安全共享和使用。

图片来源：Midjourney和Studio Miko。

提示（简略）：“数据点被带有蚀刻的磨砂玻璃遮挡”

阅读更多:

更多专家分析请访问privacy- enhancing technologies变换图。

访问日益庞大的数据集（尤其是在使用人工智能时）会改变研究、发现和创新。然而，对隐私、安全和数据主权的担忧限制了高价值数据在国家和全球范围内共享和使用的程度。一套新兴且强大的技术使得以解决这些问题的方式共享和使用敏感数据成为可能。

近年来，人们对“合成数据”越来越感兴趣。这些数据复制了敏感数据集中的模式和趋势，但不包含可能与个人相关或危害组织或政府的特定信息。在人工智能进步的推动下，合成数据消除了处理敏感数据的许多限制，并为全球数据共享和生物现象协作研究、健康相关研究、训练人工智能模型等开辟了新的可能性。然而，即使出现了国家层面的合成数据，来源国的健康趋势也将暴露出来，并且需要克服此类担忧。

人们对同态加密这一20世纪70年代的技术也重新产生了兴趣。同态加密不是重新创建具有与原始数据相同特征的数据集，而是允许在不直接访问原始数据的情况下分析编码数据。虽然前景光明，但这种加密需要更多的精力和时间才能获得安全的结果。

随着人工智能的进步改变了数据的价值，预计合成数据生成和同态加密等技术将能够实现数据共享和访问，同时确保隐私、安全和数据主权。

特别是在与健康有关的研究中，以不损害个人和社区权利和安全的方式获取数据已经显示出加速疾病检测、治疗和预防进展的希望。

如果要实现人工智能的新兴潜力，保护隐私、安全和数据主权的有效数据共享和利用技术至关重要。然而，尽管合成数据和同态加密具有潜力，但仍存在一些局限性。这些局限性包括，在合成数据的情况下，潜在的重要边缘情况或异常值的表现不佳，以及推断或重建敏感数据的潜在能力，尽管这两种技术都具有固有的去识别性。为了确保其成功，有必要对这些技术及其使用政策进行进一步的研究。

> 在人工智能进步的推动下，合成数据消除了处理敏感数据的许多限制，并为全球数据共享和生物现象协作研究、健康相关研究、训练人工智能模型等开辟了新的可能性。

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Bastiaan van Schijndel

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↑ **Image:**
Privacy-enhancing technologies enable secure sharing and use of sensitive data.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Data points obscured by frosted glass with etchings"

Read more:
For more expert analysis, visit the privacy-enhancing technologies transformation map.

Access to increasingly large datasets – especially when using AI – transforms research, discovery and innovation. However, concerns around privacy, security and data sovereignty limit the degree to which high-value data can be shared and used nationally and globally. An emerging and powerful suite of technologies makes it possible to share and use sensitive data in ways that address these concerns.

In recent years, there has been growing interest in "synthetic data".[7] These data replicate the patterns and trends in sensitive datasets but do not contain specific information that could be linked to individuals or compromise organizations or governments. Powered by advances in AI, synthetic data removes many of the restrictions to working with sensitive data and opens new possibilities in global data sharing and collaborative research on biological phenomena, health-related studies, training AI models and more. However, even with the advent of synthetic data at a national level, health trends in a source nation will be exposed, and such concerns will need to be overcome.

There has also been renewed interest in homomorphic encryption, a technology from the 1970s.[8,9] Rather than recreate datasets with the same characteristics as the raw data, homomorphic encryption allows encoded data to be analysed without the raw data being directly accessible. While promising, such encryption requires significantly more energy and time to achieve a secure result.

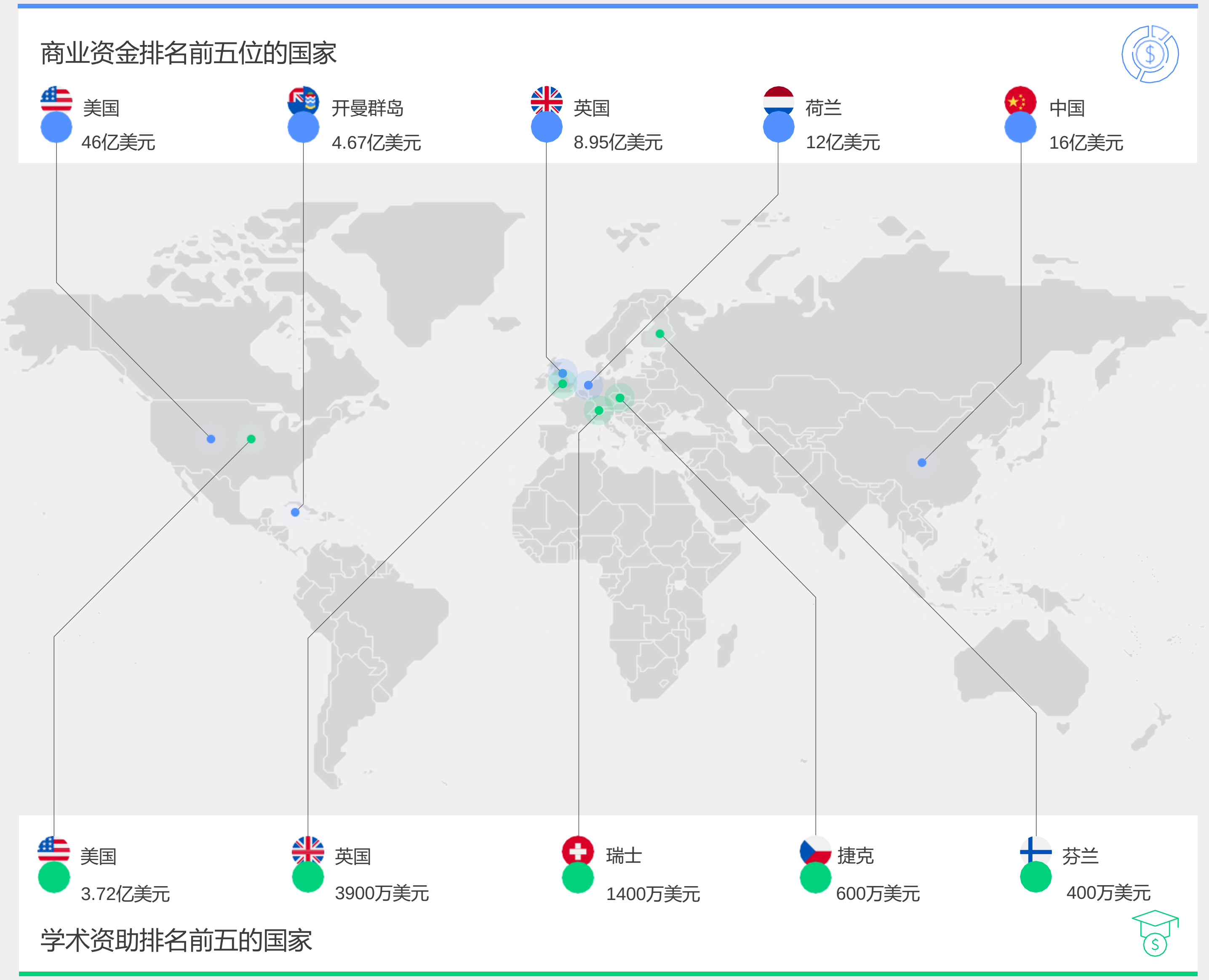
As advances in AI transform the value of data, techniques like synthetic data generation and homomorphic encryption are predicted to enable sharing and access to data while ensuring privacy, security and data sovereignty. Within health-related research, in particular, access to data in ways that don't compromise the rights and safety of individuals and communities is already showing promise for accelerating advances in disease detection, treatment and prevention.[10]

Effective data sharing and utilization technologies that protect privacy, security and data sovereignty are essential if the emerging potential of AI is to be realized. Yet, despite their potential, synthetic data and homomorphic encryption have several limitations. These include poor representation of potentially significant edge cases or outliers in the case of synthetic data and the potential ability to infer or reconstruct sensitive data despite the de-identification inherent in both techniques. Further work on the technologies and the use policies surrounding them will be necessary to ensure their success.[11]

> Powered by advances in AI, synthetic data removes many of the restrictions to working with sensitive data and opens new possibilities in global data sharing and collaborative research on biological phenomena, health-related studies, training AI models and more.

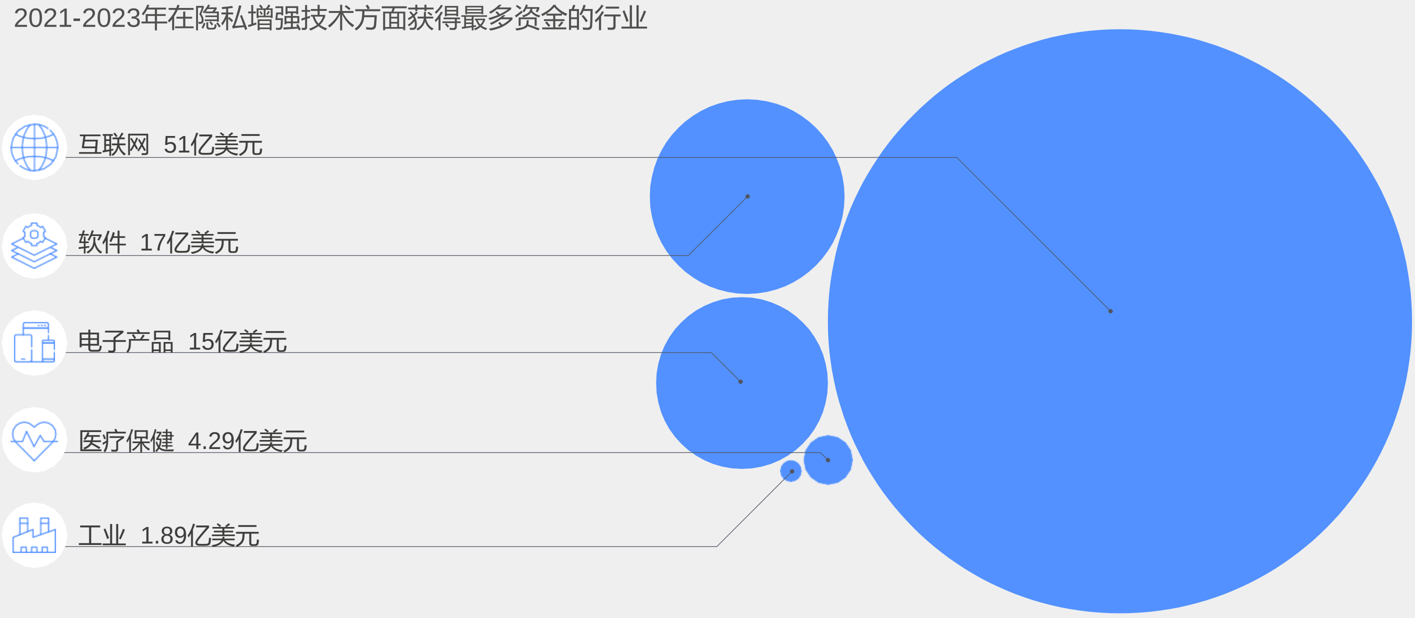
创新领域

2021-2023年隐私增强技术商业和学术拨款最多的国家



前沿产业

2021-2023年在隐私增强技术方面获得最多资金的行业

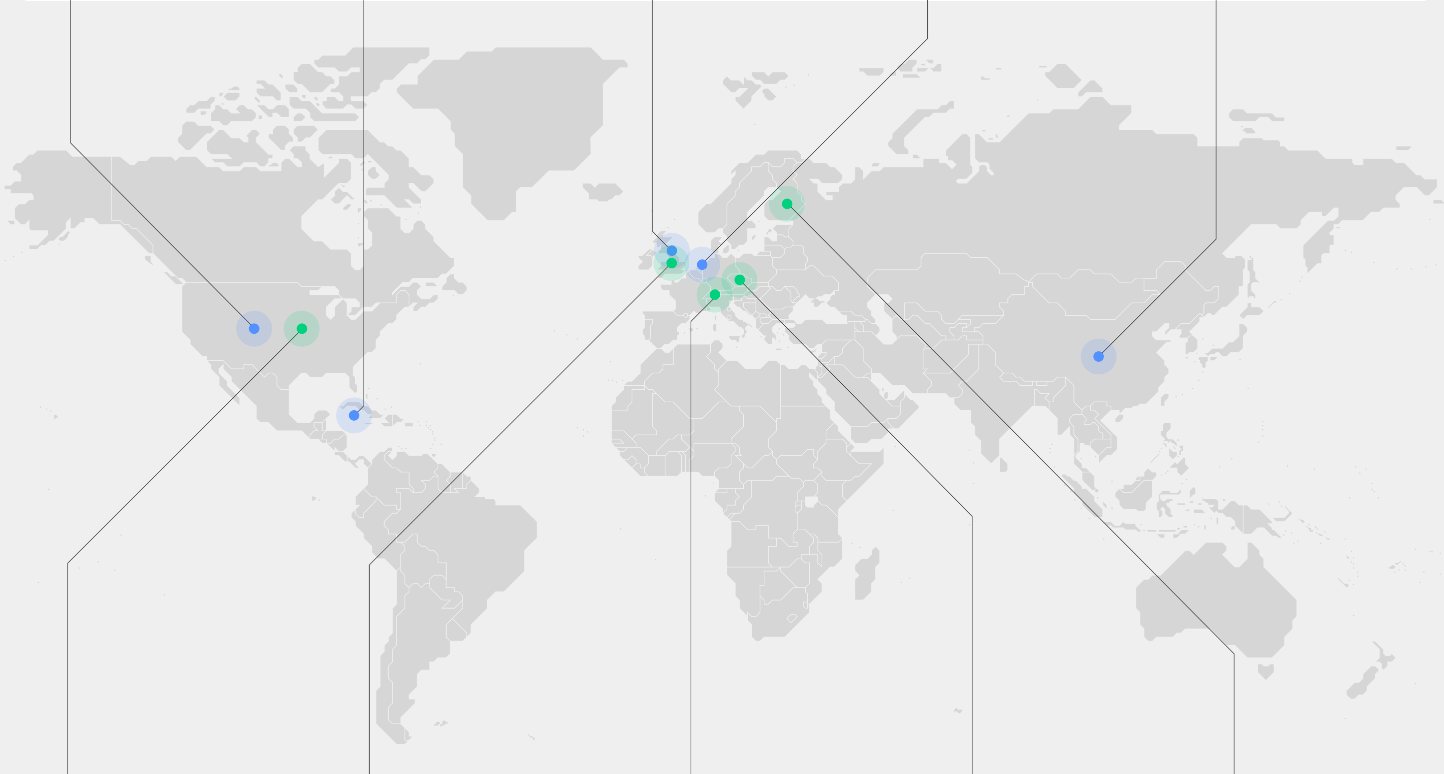


Regions of innovation

Countries with the most business and academic grant funding in privacy-enhancing technologies from 2021-2023

Top five countries by business funding

- **United States** 1 $4.6 billion
- **Cayman Islands** 5 $467 million
- **United Kingdom** 4 $895 million
- **Netherlands** 3 $1.2 billion
- **China** 2 $1.6 billion



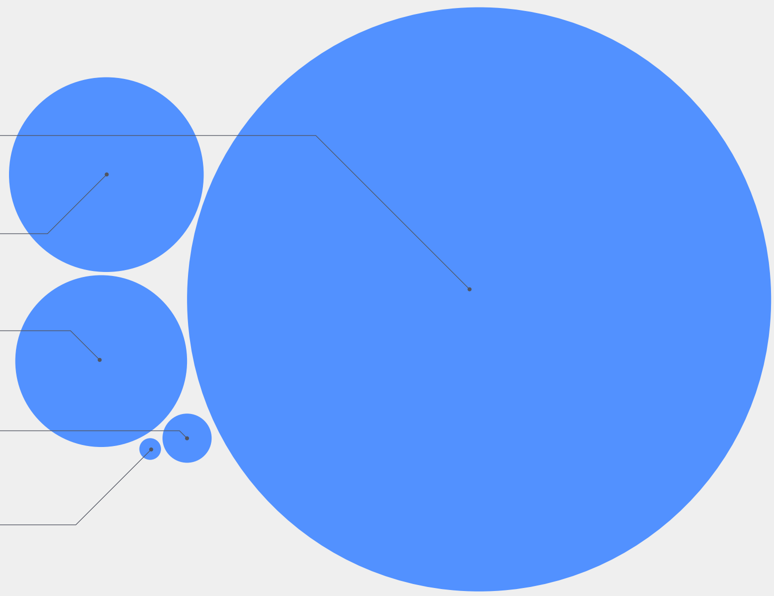
- **United States** 1 $372 million
- **United Kingdom** 2 $39 million
- **Switzerland** 3 $14 million
- **Czechia** 4 $6 million
- **Finland** 5 $4 million

Top five countries by academic grant funding

Leading-edge industries

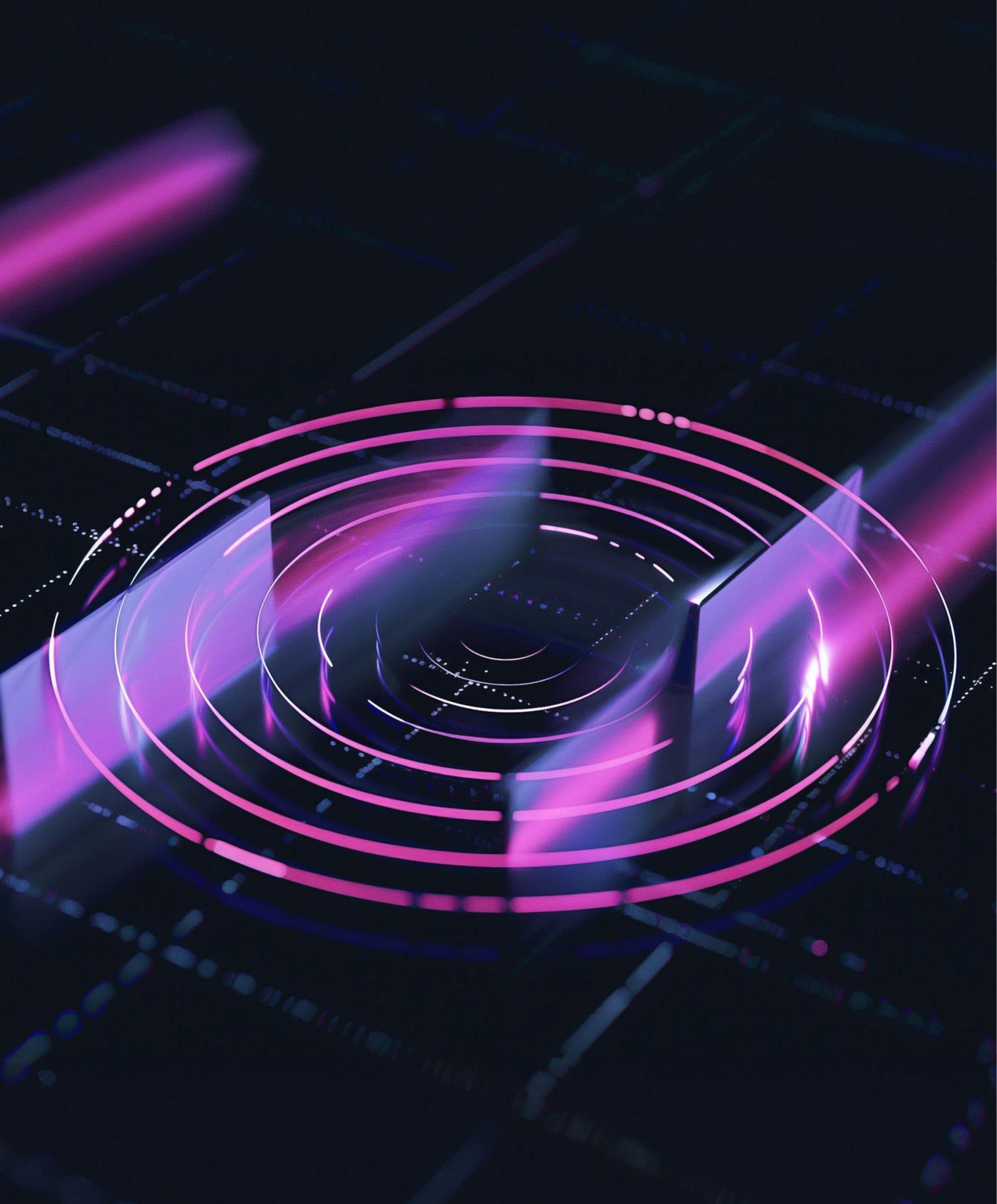
Industries with the most funding in privacy-enhancing technologies from 2021-2023

- **Internet** $5.1 billion
- **Software** $1.7 billion
- **Electronics** $1.5 billion
- **Healthcare** $429 million
- **Industrials** $189 million



03 可重构智能表面

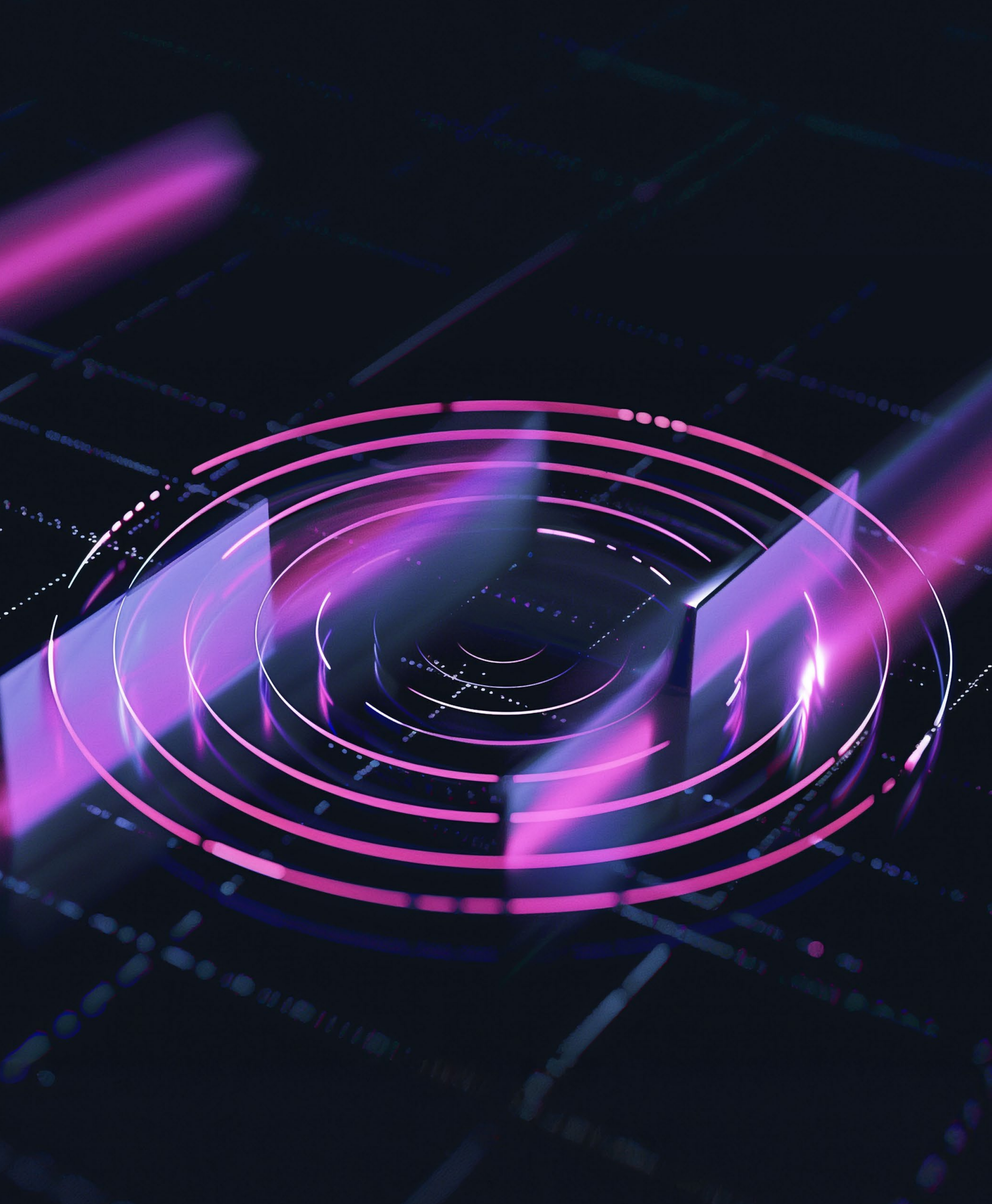
通过智能镜子改变无线连接



03

Reconfigurable intelligent surfaces

Transforming wireless connectivity with smart mirrors



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全球对更高数据速率、更低延迟和节能连接的需求正在飙升。备受期待的6G到2030年推出预计将进一步加剧这一压力。为了应对这些挑战，未来的网络需要进行设计以增强容量和连接性，并重点关注环境的可持续性。输入可重构智能表面（RIS），该平台使用超材料、智能算法和先进的信号处理将普通墙壁和表面转变为用于无线通信的智能组件。

类似于“智能镜子”的理念，RIS能够对电磁波进行精确的聚焦控制，减少干扰和对高传输功率的需求。同样，RIS具有很强的适应性，可以根据实时需求动态调整配置。这种适应性可以有效利用资源并提高无线网络的能源效率。

RIS领域硬件平台的开发和实验举措的激增引起了热衷于探索其下一代无线网络潜力的电信利益相关者的极大兴趣。RIS有效集成到现有无线网络中是一个重要的里程碑。多个RIS平台从硬件角度展示了该技术令人印象深刻的功能。

RIS的发展可能会对多个工业部门产生广泛影响。例如，智能工厂中定制的无线电波传送可以确保高度复杂的环境中的可靠通信。

RIS允许传感器以最小的功率传输数据，用于物联网（IoT），物联网需要大量的能源。对于车载网络，RIS通过实现车辆和基础设施之间的强大通信来提高安全性。为了提高农业环境中的覆盖率，RIS是一种低能耗、高成本效益的有前景的解决方案。

市场情报报告表明RIS正处于指数级采用和增长的风口浪尖。包括Rhode & Schwarz、华为、中兴、英特尔和三星在内的多家公司都在投资RIS，这发出了一个强烈信号：RIS将在未来几年成为电信领域的核心。

然而，在此之前，必须解决几个突出的挑战，包括高昂的硬件成本以及对技术安全和道德使用的明确标准和法规的需求。

> RIS具有很强的适应性，可以根据实时需求动态调整配置。这种适应性可以有效利用资源并提高无线网络的能源效率。

↑ 图像：
RIS提高了数据速率和能源效率，同时减少了干扰，对下一代无线网络至关重要。

图片来源：Midjourney和Studio Miko。

提示（简略）：“模块化无线发射器的特写3D渲染”

阅读更多：
更多专家分析请访问 RIS 变换图。

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Professor, Chemistry and Director, Molecular Nanotechnology Lab, University of Alicante

Global demand for higher data rates, lower latency and energy-efficient connectivity is skyrocketing.[12] The highly anticipated launch of 6G by 2030 is expected to intensify this pressure even further. To meet these challenges, future networks will need to be engineered for enhanced capacity and connectivity and with a strong focus on environmental sustainability. Enter reconfigurable intelligent surfaces (RIS), platforms that use metamaterials, smart algorithms and advanced signal processing to turn ordinary walls and surfaces into intelligent components for wireless communication.

Akin to the idea of "smart mirrors", RIS enable the precision focusing control of electromagnetic waves, reducing interference and the need for high transmission power. Equally, RIS are highly adaptive and can dynamically adjust configurations according to real-time demands. This adaptability enables efficient use of resources and enhances energy efficiency in wireless networks.[13,14,15]

The development of hardware platforms and a surge in experimental initiatives in the field of RIS have drawn considerable interest from telecommunication stakeholders keen on exploring its potential for next-generation wireless networks. A significant milestone was the effective integration of RIS into existing wireless networks. Several RIS platforms have showcased the technology's impressive capabilities from a hardware perspective.[16]

The growth of RIS is likely to impact several industrial sectors broadly.[17] For example, tailored radio wave propagation in smart factories can ensure reliable communication in a highly complex environment. RIS allow sensors to transmit data with minimal power for the internet of things (IoT), which demands considerable energy. For vehicular networks, RIS enhance safety by enabling robust communications between vehicles and infrastructure. To improve coverage in agricultural settings, RIS are a promising solution with low energy consumption and high-cost efficiency.[18]

Market intelligence reports suggest RIS are on the cusp of exponential adoption and growth. Several companies, including Rhode & Schwarz, Huawei, ZTE, Intel and Samsung, are all investing in RIS, sending a strong signal that RIS will be central to the telecommunications landscape in the coming years.[19]

Before this happens, however, several outstanding challenges will have to be addressed, including high hardware costs and the need for clear standards and regulations on the secure and ethical use of the technology.[20]

> RIS are highly adaptive and can dynamically adjust configurations according to real-time demands. This adaptability enables efficient use of resources and enhances energy efficiency in wireless networks.

↑ **Image:**
RIS enhance data rates and energy efficiency while reducing interference and are critical to next-generation wireless networks.

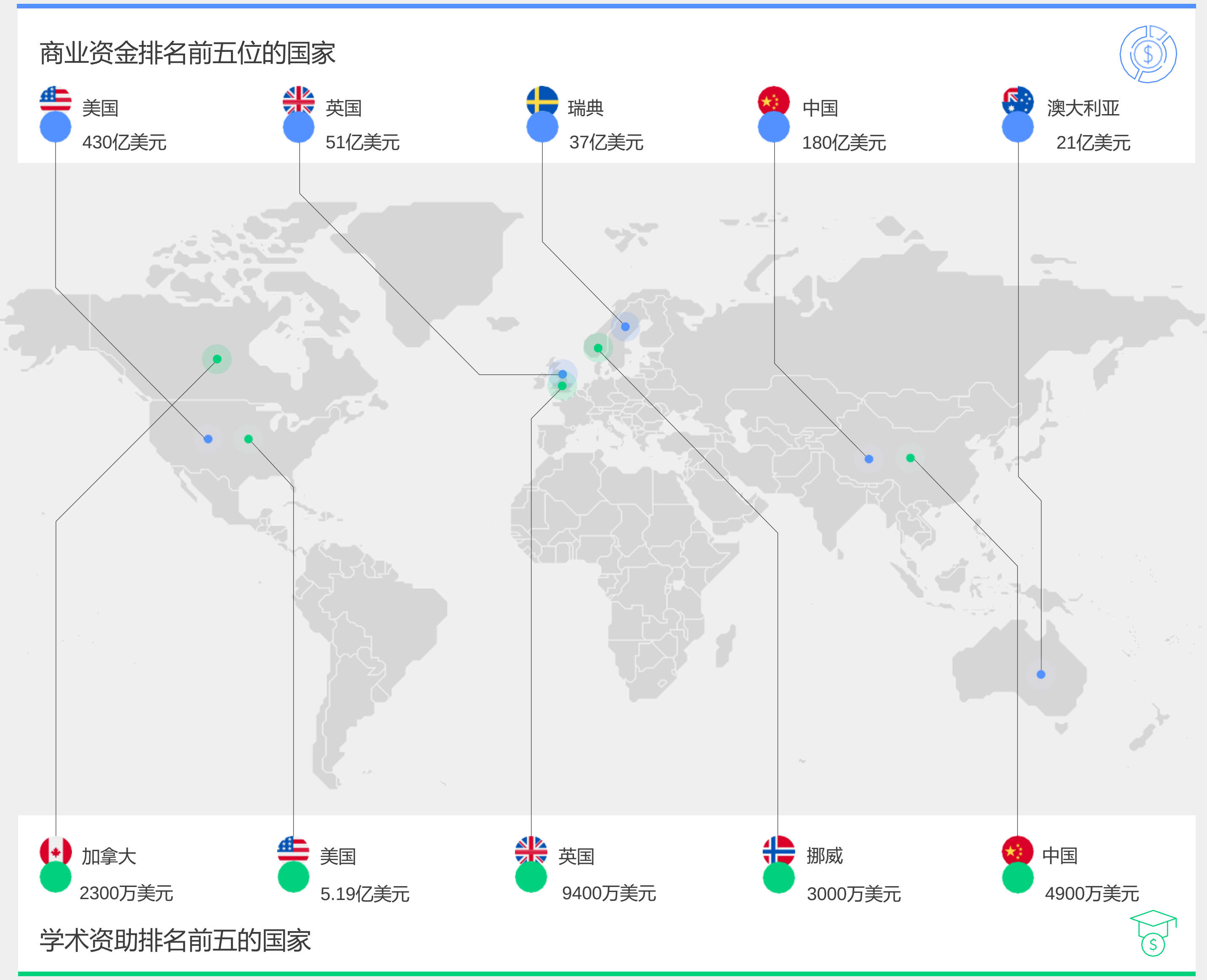
Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Close up 3D render of modular wireless transmitter"

Read more:
For more expert analysis, visit the RIS transformation map.

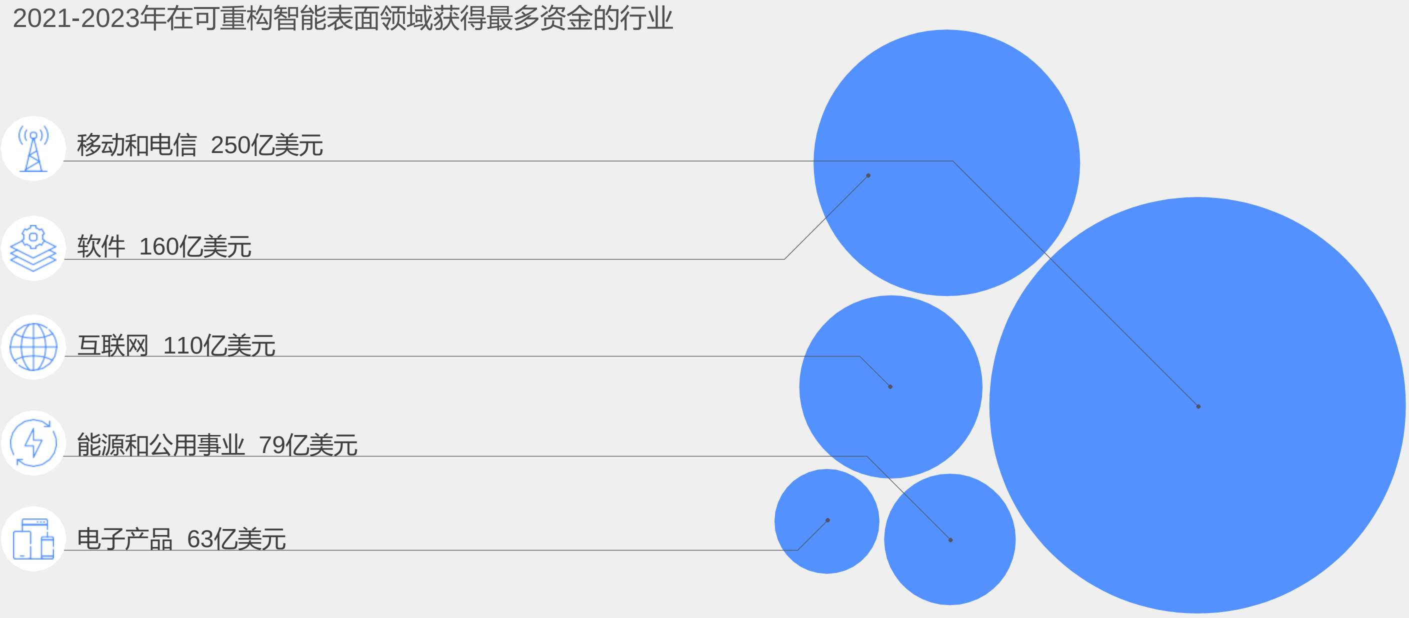
创新领域

2021-2023年可重构智能表面商业和学术拨款最多的国家



前沿产业

2021-2023年在可重构智能表面领域获得最多资金的行业



Regions of innovation

Countries with the most business and academic grant funding in reconfigurable intelligent surfaces from 2021-2023

Top five countries by business funding

1. **United States** $43 billion
2. **China** $18 billion
3. **United Kingdom** $5.1 billion
4. **Sweden** $3.7 billion
5. **Australia** $2.1 billion

1. **United States** $519 million
2. **United Kingdom** $94 million
3. **China** $49 million
4. **Norway** $30 million
5. **Canada** $23 million

Top five countries by academic grant funding

Leading-edge industries

Industries with the most funding in reconfigurable intelligent surfaces from 2021-2023

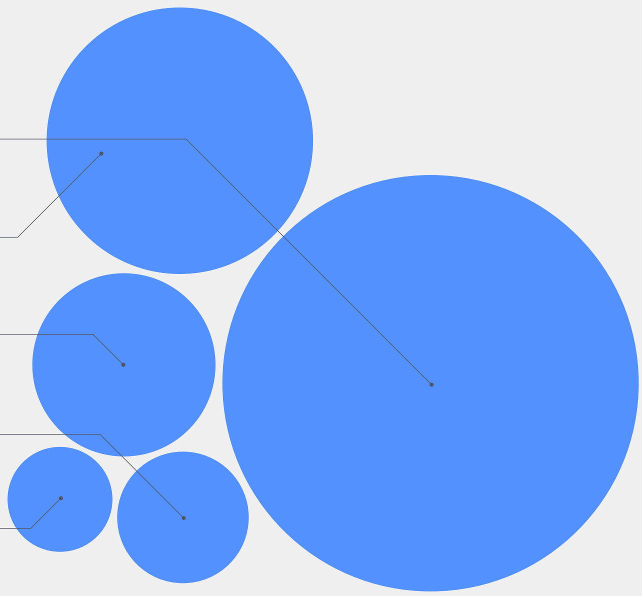
Mobile and telecommunications $25 billion

Software $16 billion

Internet $11 billion

Energy and utilities $7.9 billion

Electronics $6.3 billion



04

高空平台站

弥合平流层之间的互联网鸿沟

04

High altitude platform stations

Bridging the internet divide from the stratosphere

穆罕默德·斯利姆·阿鲁伊尼

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玛丽埃特·迪克里斯蒂娜

波士顿大学传播学院新闻实践系主任兼教授

高空平台站（HAPS）在距地球约20公里的平流层高度运行。它们通常采用气球、飞艇或固定翼飞机的形式，为观察和通信提供了一个稳定的平台，可以运行数月。太阳能电池板效率、电池能量密度、轻质复合材料、自主航空电子设备和天线的进步，加上频带的扩展和新的航空标准，使HAPS在短期内可行。HAPS可以提供卫星和地面发射塔无法比拟的连通性、覆盖范围和性能增强，特别是在山区、丛林或沙漠等地形复杂的地区。

进入互联世界是通向未来的桥梁，创造繁荣之路和新的教育可能性，并加强社会互联互通的结构。然而，根据国际电信联盟 (ITU) 的数据，全球约有三分之一的人仍处于离线状态。妇女和老年人受到的影响尤为严重。应对这一挑战的一个关键因素是更好的基础设施。

HAPS可以改善传统通信基础设施服务不足的社区的连通性，特别是在偏远地区。COVID-19大流行凸显了互联网接入的重要性，揭示了连通性的差异如何使社会经济不平等长期存在。通过弥合这一数字鸿沟，HAPS技术可以让人们获得教育、医疗保健和经济机会。

除了提供互联网接入外，这些适应性强的平台还可以在各种关键应用中发挥重要作用，从支持灾害管理到增强宽带覆盖和环境监测。HAPS快速部署和适应不断变化的条件的能力可能使其成为管理紧急情况的宝贵工具，在紧急情况下，及时的信息和通信可以挽救生命。

航空航天工程领导者对HAPS的投资已经在材料、推进系统和太阳能电池技术方面取得了进步。HAPS现在在商业和实际应用中具有经济可行性。在开发可靠、长寿命HAPS方面拥有丰富知识和资源的组织已经帮助其发展并在未来的通信基础设施中发挥作用。

业界的例子包括空中客车Zephyr、泰雷兹公司的Stratobus和波音公司的Aurora项目。更低的延迟、更低的成本、更高的容量、容易的硬件升级和更快的部署都是有吸引力的商业主张。2023年市场规模为7.833亿美元，预计从2023年到2033年将以10.4%的复合年增长率增长。

然而HAPS在平流层高度运行的时间非常长，在几个方面与传统的有人驾驶飞机不同，目前的监管框架不适合这一目的。国际民用航空组织（ICAO）等组织正在积极讨论新的政策和指导，以便负责任地部署HAPS。

> “HAPS可以提供卫星和地面发射塔无法比拟的连通性、覆盖范围和性能增强，特别是在山区、丛林或沙漠等地形复杂的地区。

↑ 图像：
HAPS在偏远和服务欠缺的地区提供增强的长期连接和通信。

图片来源：Midjourney和Studio Miko。

提示（简略）：“高空科学航天气球。数字信号连接”

阅读更多：
更多专家分析请访问 HAPS 变换图。

Mohamed-Slim Alouini

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Mariette DiChristina

Dean and Professor, Practice in Journalism, Boston University College of Communication

High altitude platform stations (HAPS) operate at stratospheric altitudes, approximately 20 kilometres above Earth. Typically taking the form of balloons, airships, or fixed-wing aircraft, they offer a stable platform for observation and communication and can operate for months. Advances in solar panel efficiency, battery energy density, lightweight composite materials, autonomous avionics and antennas, coupled with the expansion of frequency bands and new aviation standards, make HAPS viable in the near term. HAPS can deliver connectivity, coverage and performance enhancements that neither satellites nor terrestrial towers can match, particularly in areas with difficult terrains such as mountains, jungles or deserts.[21]

Access to the connected world serves as a bridge to the future, creating pathways to prosperity and new educational possibilities as well as strengthening the fabric of social connectivity. Yet, according to the International Telecommunication Union (ITU), about one-third of people worldwide remain offline. Women and older adults are disproportionally affected.[22] A key component in addressing this challenge is better infrastructure.

HAPS could improve connectivity for communities underserved by traditional communications infrastructure, particularly in remote areas. The COVID-19 pandemic highlighted the critical nature of internet access, revealing how disparities in connectivity perpetuate socioeconomic inequalities. By bridging this digital divide, HAPS technology could enable access to educational, healthcare and economic opportunities.

In addition to providing internet access, these adaptable platforms can play an important role in various critical applications, from supporting disaster management to enhancing broadband coverage and environmental monitoring. The ability of HAPS to quickly deploy and adapt to changing conditions could make them an invaluable tool in managing emergencies, where timely information and communication can save lives.[23]

Investment in HAPS from aerospace engineering leaders has created advancements in materials, propulsion systems and solar cell technology.[24] HAPS are now economically viable for commercial and real-world deployment. Organizations with extensive knowledge in and resources for developing reliable, long-endurance HAPS have aided its evolution and role in the future of communications infrastructure.

Industry examples include the Airbus Zephyr, Thales' Stratobus and Boeing Aurora projects. Lower latency, reduced costs, higher capacity, easy hardware upgrades and faster deployment are attractive commercial propositions. The market size was valued at $783.3 million in 2023 and is expected to grow at a compound annual growth rate of 10.4% from 2023 to 2033.[25]

However, HAPS, operating at stratospheric altitudes for extremely long durations, are different from traditional crewed aircraft in several ways, and current regulatory frameworks are not fit for purpose. Organizations such as the International Civil Aviation Organization (ICAO) are actively discussing new policies and guidance to enable the responsible deployment of HAPS.[26]

> HAPS can deliver connectivity, coverage and performance enhancements that neither satellites nor terrestrial towers can match, particularly in areas with difficult terrains such as mountains, jungles or deserts.

↑ Image:
HAPS provide enhanced, long-term connectivity and communication in remote and underserved areas.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "High altitude scientific aerospace balloon. Digital signal connectivity"

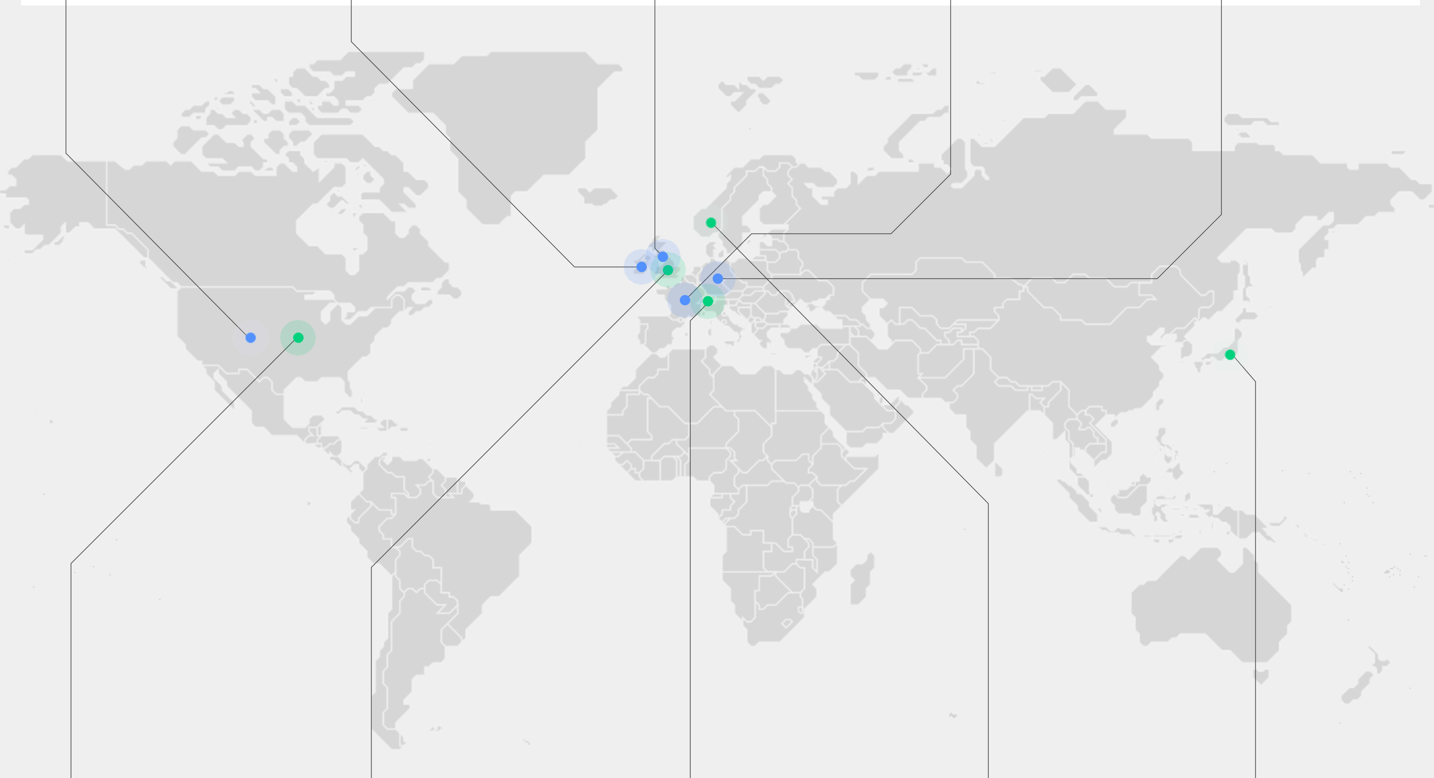
Read more:
For more expert analysis, visit the HAPS transformation map.

创新领域

2021-2023年高空平台站商业和学术资助最多的国家

企业资金排名前五位的国家

美国	4.47亿美元
爱尔兰	1.9亿美元
英国	2.51亿美元
法国	2.22亿美元
德国	6.36亿美元



美国	7800万美元
英国	1400万美元
瑞士	500万美元
挪威	400万美元
日本	300万美元

学术资助排名前五的国家

前沿产业

2021-2023年高空平台站资金投入最多的行业

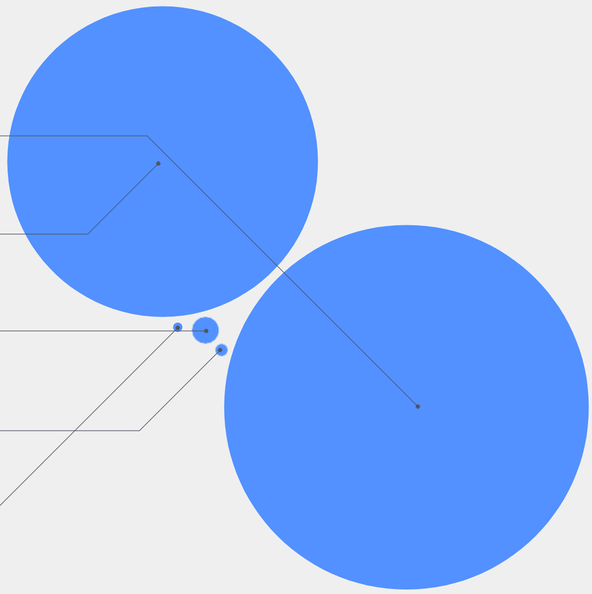
汽车和运输 10亿美元

工业 8.87亿美元

软件 7600万美元

商业产品和服务 3500万美元

移动和电信 2700万美元

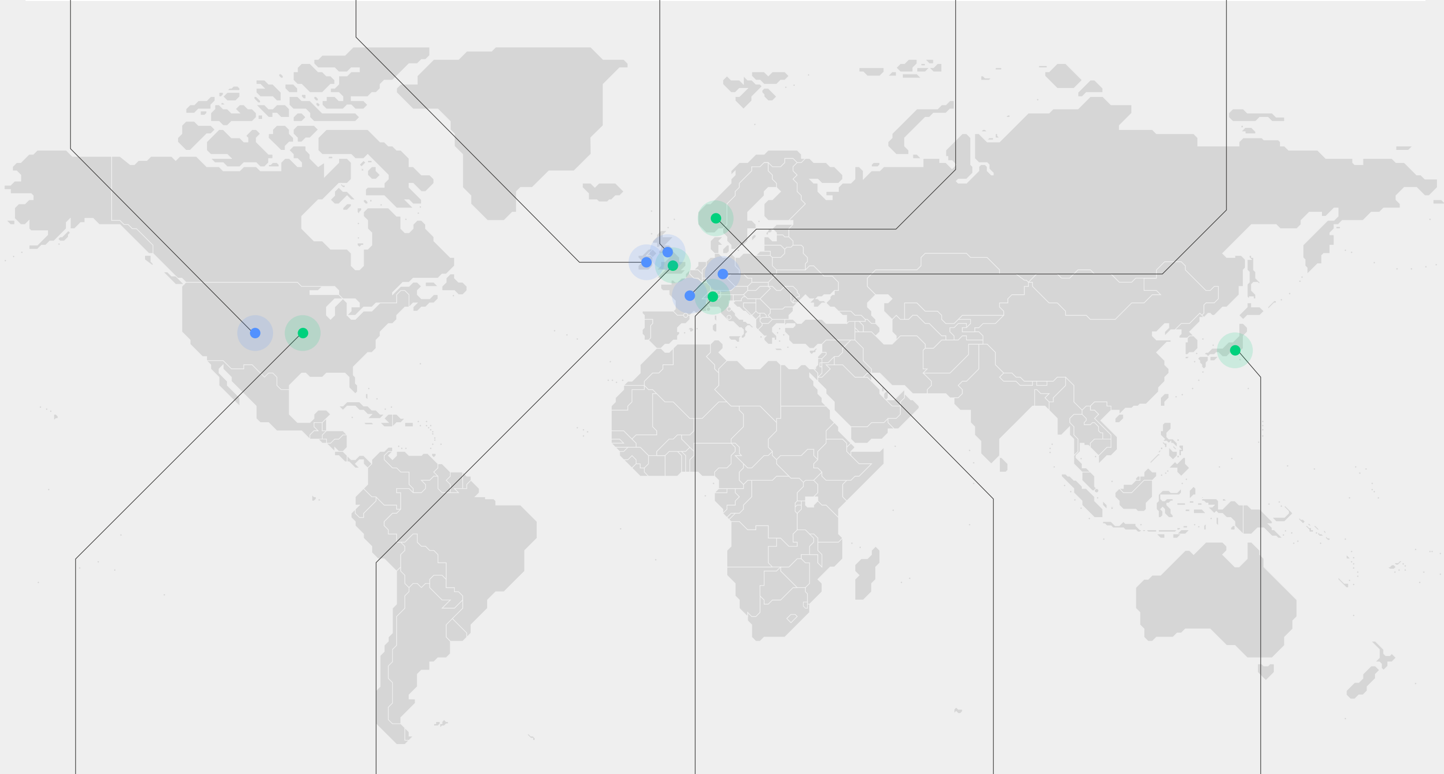


Regions of innovation

Countries with the most business and academic grant funding in high altitude platform stations from 2021-2023

Top five countries by business funding

- 2 United States $447 million
- 5 Ireland $190 million
- 3 United Kingdom $251 million
- 4 France $222 million
- 1 Germany $636 million



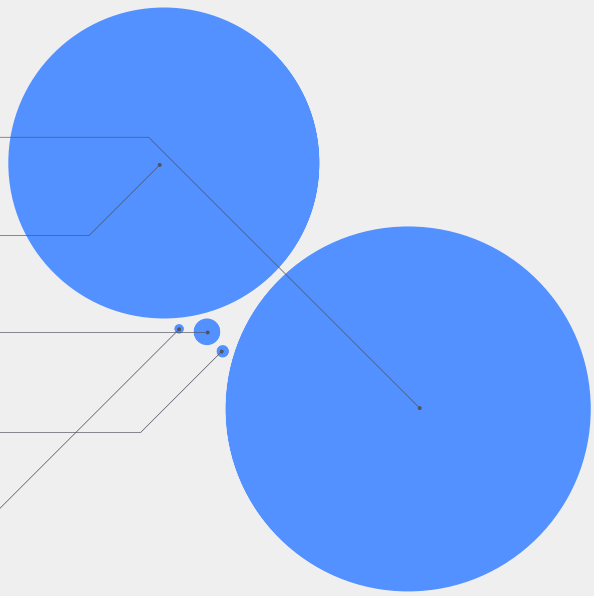
- 1 United States $78 million
- 2 United Kingdom $14 million
- 3 Switzerland $5 million
- 4 Norway $4 million
- 5 Japan $3 million

Top five countries by academic grant funding

Leading-edge industries

Industries with the most funding in high altitude platform stations from 2021-2023

- **Automotive and transport** $1 billion
- **Industrials** $887 million
- **Software** $76 million
- **Business products and services** $35 million
- **Mobile and telecommunications** $27 million



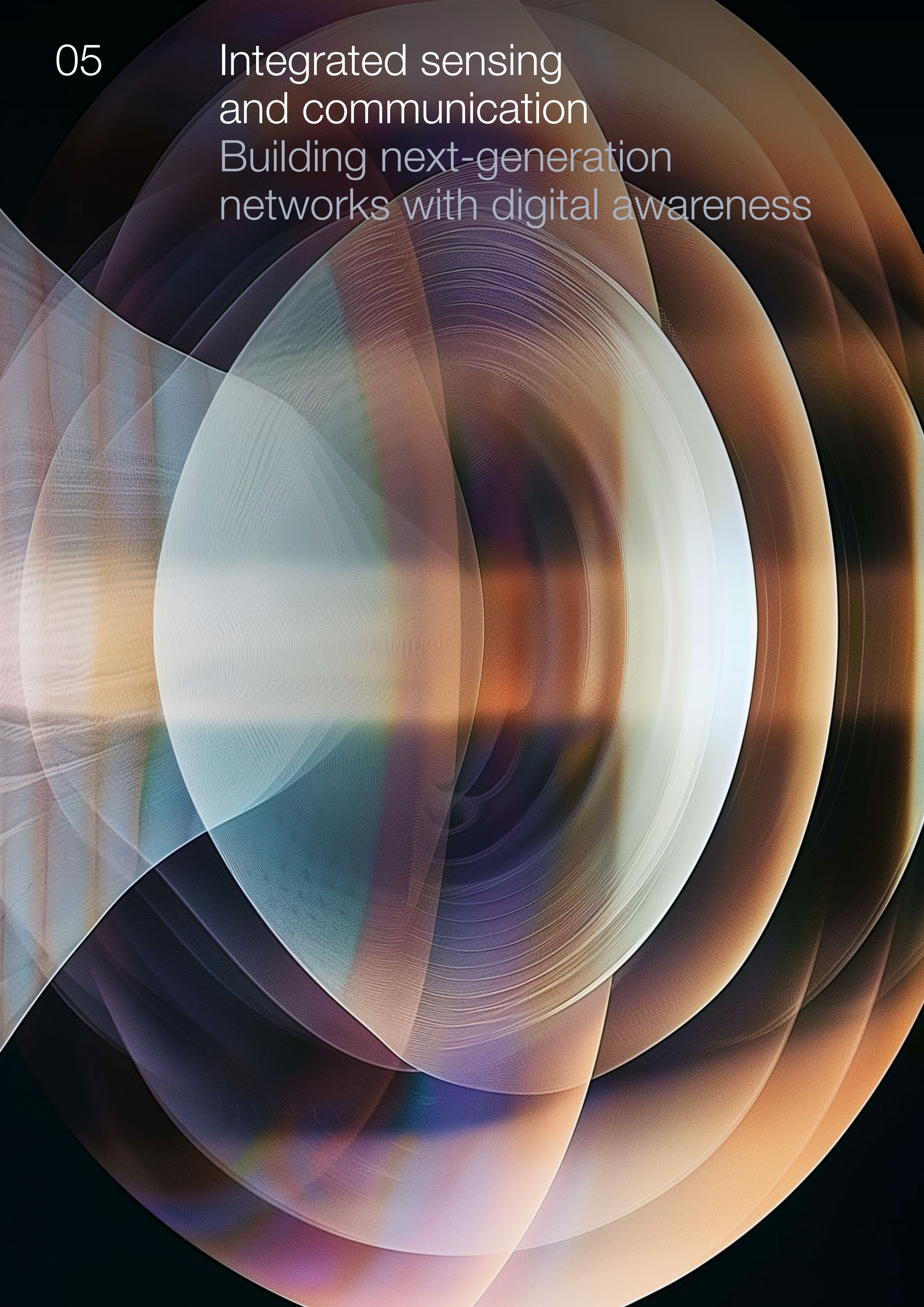
05

集成传感和通信

构建具有数字意识的下一代网络

05 Integrated sensing and communication

Building next-generation networks with digital awareness



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伦敦大学学院信号处理和无线通信教授

↑ 图像：
ISAC 将数据收集和传输整合到一个系统中，优化效率并实现创新应用。

图片来源：
Midjourney 和 Studio Miko。

提示（简略）："重叠、脉动的声波"

阅读更多：
更多专家分析请访问 ISAC 变换图。

几十年来，传感和通信技术的单独发展导致了功能重叠的设备过剩，导致设备拥塞、频谱效率低下和经济损失。集成传感和通信(ISAC)解决了这一问题，将传感和通信能力纳入单一系统，促进数据的同时收集和传输。这种集成优化了硬件、能源和成本效率，同时也实现了超越传统通信范例的新应用。

ISAC使无线网络具有环境感知能力，从而实现本地化、环境测绘和基础设施监控等功能。这方面的例子包括使用传感器和数据分析来监测空气和水质、土壤湿度和天气状况的环境监测系统。这些系统有助于智能农业、环境保护和城市规划。此外，智能电网将传感器和通信技术集成到电网中，提高了效率和可靠性，同时能够监控电力消耗和发电。

ISAC的采用还有望使设备利用更加可持续。潜在的好处包括减少能源和硅消耗，以及改进设备再使用、回收或再利用的选择。

光无线ISAC技术代表了一项特别令人兴奋的进步。通过集成传感和通信功能，照明和显示系统可以无缝地成为无线生态系统的一部分。发光表面可以作为网络节点，在没有电磁干扰的情况下促进通信和传感。这在智能医疗和工业制造等敏感环境中尤其有利。

然而，ISAC潜力的实现取决于克服技术障碍、建立通信标准并确保网络级协调。它的成功将通过其在从联网汽车到电子医疗等各个行业的采用来衡量。这强调了该领域持续创新和协作的必要性。

> ISAC使无线网络具有环境感知能力，从而实现本地化、环境测绘和基础设施监控等功能。

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Decades of separate development in sensing and communications technologies have resulted in a surplus of devices with overlapping functions, leading to device congestion, spectrum inefficiency and financial loss.[27] Integrated sensing and communications (ISAC) addresses this by bringing sensing and communication capabilities into a single system, facilitating simultaneous data collection and transmission. This integration optimizes hardware, energy and cost efficiency while also enabling novel applications beyond conventional communication paradigms.[28]

ISAC makes wireless networks environment-aware, enabling capabilities like localization, environment mapping and infrastructure monitoring. Examples of this include environmental monitoring systems that use sensors and data analytics to monitor air and water quality, soil moisture and weather conditions. These systems help in smart agriculture, environmental conservation and urban planning. Additionally, smart grids integrate sensors and communication technologies into power grids, enhancing efficiency and reliability while enabling the monitoring of electricity consumption and generation.[29,30]

The adoption of ISAC also promises to render device utilization more sustainable. Potential benefits include reduced energy and silicon consumption alongside improved options for device reuse, recycling or repurposing.[31]

Optical-wireless ISAC technology represents a particularly exciting advancement. By integrating sensing and communication capabilities, lighting and display systems can seamlessly become part of the wireless ecosystem. Illuminated surfaces can serve as network nodes, facilitating communication and sensing without electromagnetic interference. This is especially advantageous in sensitive environments such as smart healthcare and industrial manufacturing.[32]

However, the realization of ISAC's potential hinges on surmounting technical hurdles, establishing communication standards and ensuring network-level coordination. Its success will be gauged by its adoption across various industries, from connected cars to e-health.[33] This underscores the imperative for ongoing innovation and collaboration in this field.

> ISAC makes wireless networks environment-aware, enabling capabilities like localization, environment mapping and infrastructure monitoring.

↑ Image:
ISAC combine data collection and transmission into a single system, optimizing efficiency and enabling innovative applications.

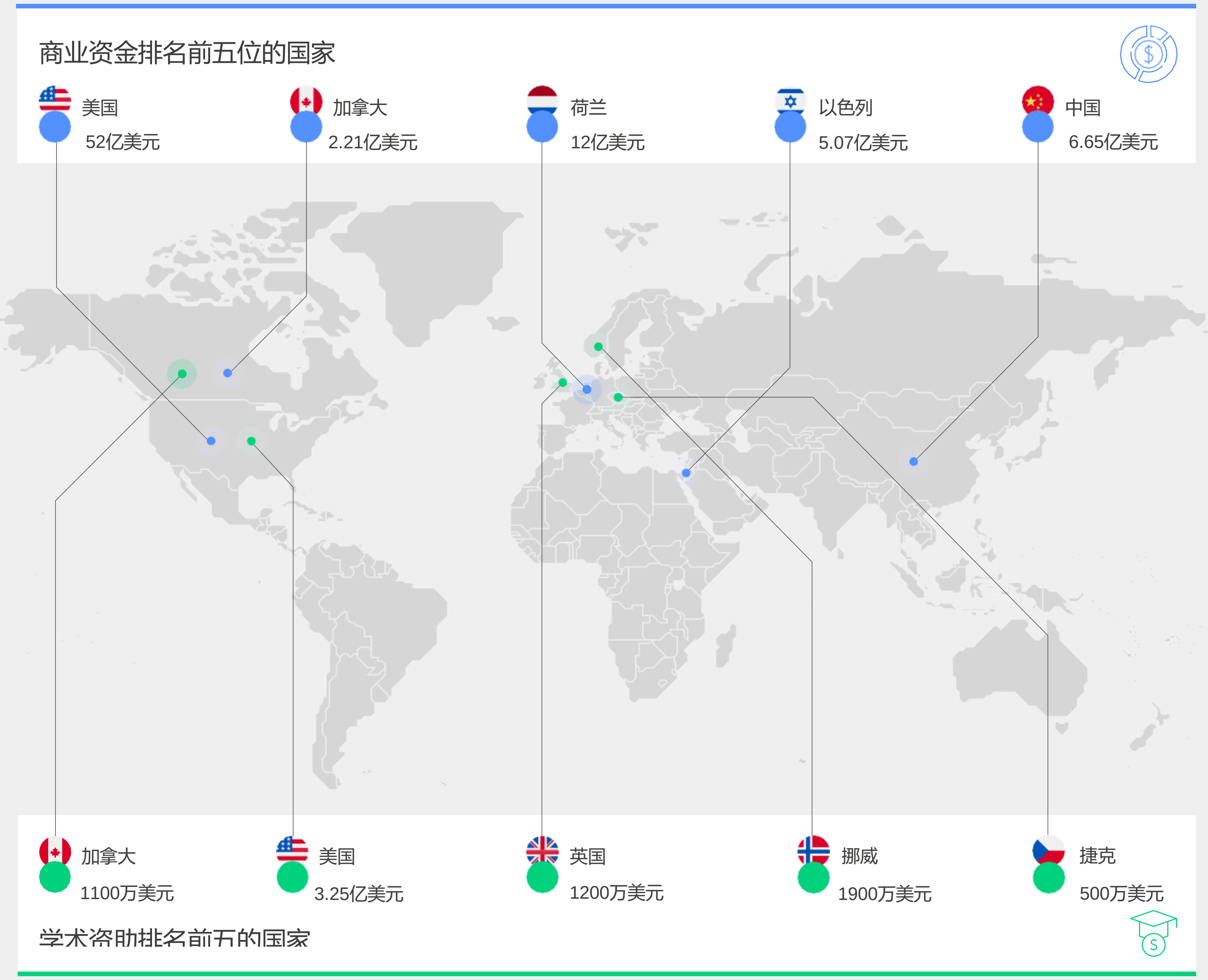
Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Overlapping, pulsing sound waves"

Read more:
For more expert analysis, visit the ISAC transformation map.

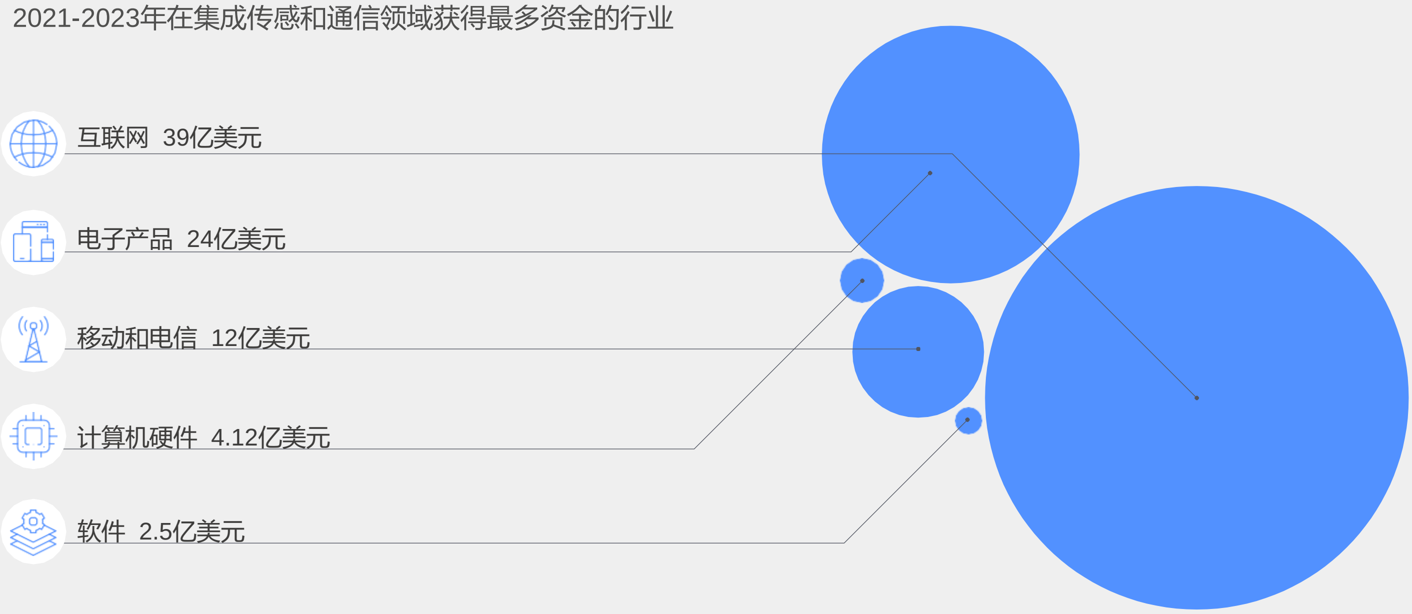
创新领域

2021-2023年在综合传感和通信领域拥有最多商业和学术拨款的国家



前沿产业

2021-2023年在集成传感和通信领域获得最多资金的行业

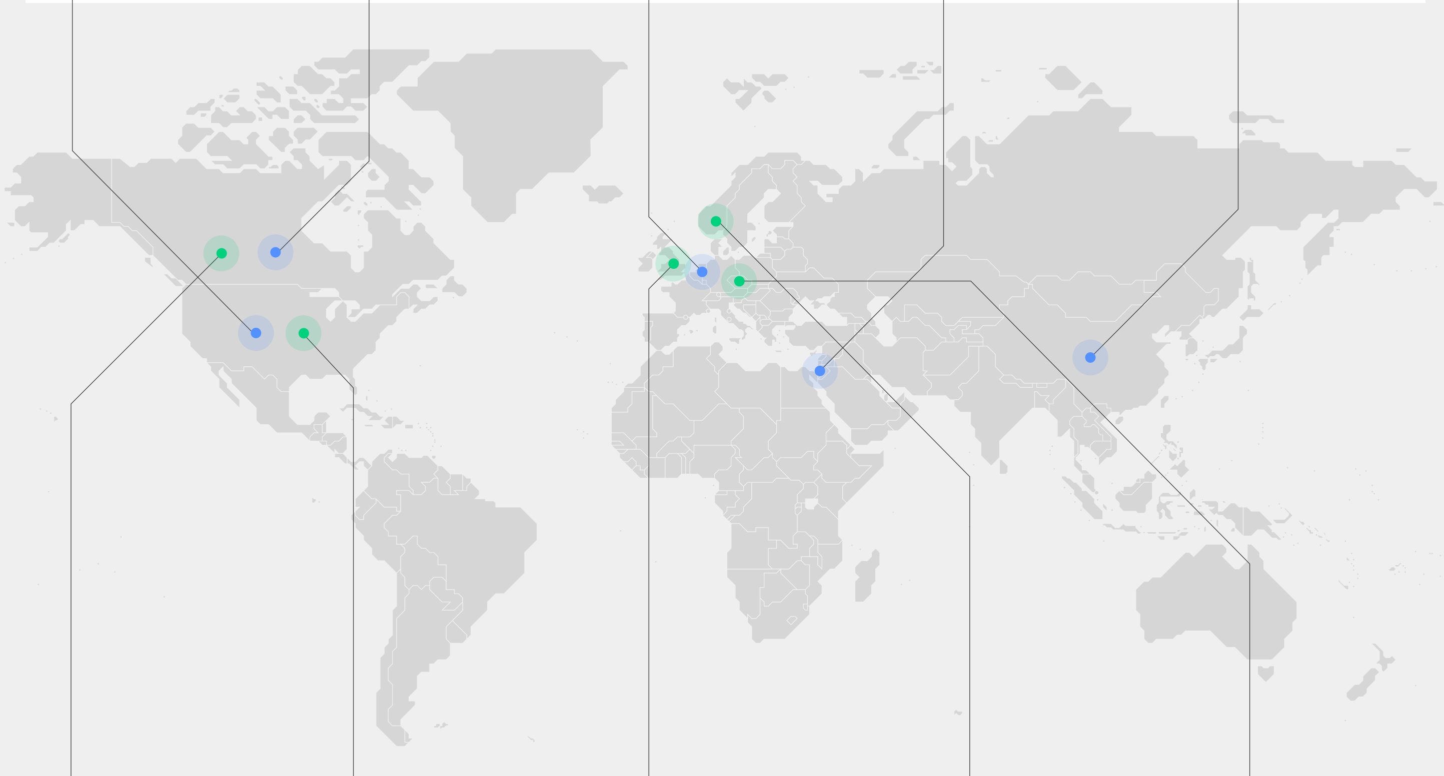


Regions of innovation

Countries with the most business and academic grant funding in integrated sensing and communication from 2021-2023

Top five countries by business funding

- 1 United States $5.2 billion
- 5 Canada $221 million
- 2 Netherlands $1.2 billion
- 4 Isreal $507 million
- 3 China $665 million



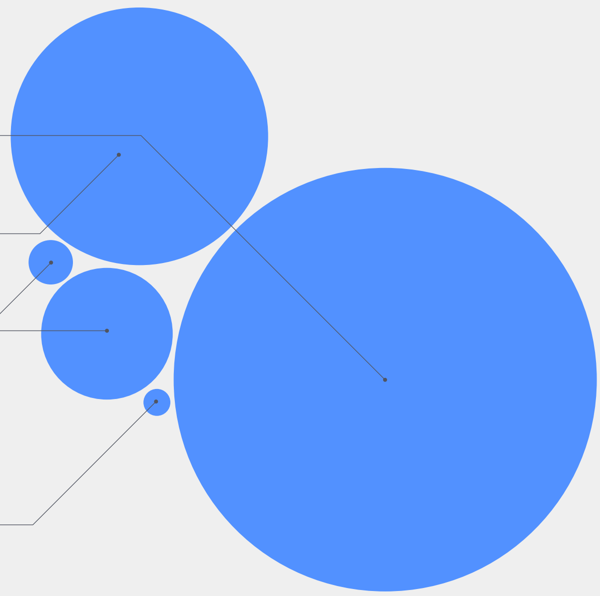
- 4 Canada $11 million
- 1 United States $325 million
- 3 United Kingdom $12 million
- 2 Norway $19 million
- 5 Czechia $5 million

Top five countries by academic grant funding

Leading-edge industries

Industries with the most funding in integrated sensing and communication from 2021-2023

- **Internet** $3.9 billion
- **Electronics** $2.4 billion
- **Mobile and telecommunications** $1.2 billion
- **Computer hardware** $412 million
- **Software** $250 million



06

建筑世界的沉浸式技术
为建设和维护奠定新的基础

06

Immersive technology for the built world

Laying new foundations for construction and maintenance

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随着主要科技平台在虚拟世界中寻求实用性，一个行业即将迎来转型：建筑业。用于建筑世界的沉浸式和人工智能驱动的沉浸式现实工具使设计师和建筑专业人员能够检查物理和数字之间的一致性，确保准确性和安全性并促进可持续性。

建筑业是世界上规模最大、最具影响力的行业之一，占全球二氧化碳 (CO_2) 排放量的40%。尽管其足迹巨大，但该行业在拥抱数字革命方面进展缓慢。然而，沉浸式技术有望改变这一现状。

沉浸式设计体验通过在施工开始前测试假设、识别潜在错误并提供解决方案，帮助预测施工过程中可能出现的挑战。虚拟原型和实验提高了准确性。数字孪生已经在工业中广泛使用，可用于模拟更为复杂的城市发展项目提案的结果，更好地开发基础设施和服务选民，并提高效率和效力。至关重要的是，这将简化从设计到实施的施工流程，识别和消除浪费，提高效率和可持续性。

同样，对于一个正在蓬勃发展的行业来说，技能和劳动力短缺正在出现，目前供应严重不足。仅在美国，全国建筑商和承包商协会估计，到2025年，该行业在正常招聘的基础上将需要引进近454,000名新工人，以满足行业需求。通过为建筑、工程和建筑行业的专业人士创造沉浸式学习和培训环境，无论地点如何，虚拟世界都有可能缓解技能和劳动力短缺的问题。

虚拟世界还可以提高维护和检查的效率。例如，一家日本建筑公司估计，在全国范围内，光是去检查就花费了100万个小时。如果元宇宙提供强大而可靠的远程检查功能，则可以将数百万小时重新分配给其他关键工作。

可以说，这一领域的下一个飞跃将是生成式人工智能的结合，文本到建筑的信息建模可能会将文本提示直接转换为详细的三维建筑模型，包括建筑规范、安全信息和其他元数据。

尽管风险可能包括隐私和能源获取，特别是在发展中国家，但积极主动和合作的方式将鼓励创新，同时使其具有包容性和安全性。缩小概念化和实施之间差距的承诺最终可能会导致设计领域中一些最具技术性的专业人士被淘汰，从而需要新颖的培训路径和技能提升计划。

> “至关重要的是，这将简化从设计到实施的施工流程，识别和消除浪费，提高效率和可持续性。

↑ 图像：
沉浸式技术通过整合数字世界和物理世界来改变建筑，提高准确性、安全性和可持续性。

图片来源：Midjourney 和Studio Miko。

提示（简略）：“摩天大楼的亮蓝色横截面”

阅读更多：
更多专家分析请访问沉浸式技术 变换图。

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University Professor Emeritus of Architectural
Engineering, Kyoto University

As major tech platforms search for utility in the metaverse, one industry stands poised for transformation: construction. Immersive and AI-driven immersive reality tools for the built world allow designers and construction professionals to check the congruence between the physical and digital, ensuring accuracy and safety and advancing sustainability.

Construction is one of the world's largest and most impactful industries, contributing 40% of global carbon dioxide (CO_2) emissions.[34] Despite its immense footprint, the industry has been slow to embrace the digital revolution. However, immersive technology holds the promise of transforming this landscape.

Immersive design experiences help anticipate the challenges that could evolve during construction by testing hypotheses, identifying potential errors and providing solutions before construction starts. Virtual prototyping and experimentation increase accuracy. Digital twins, already in widespread industrial use, could be used to simulate outcomes of far more complex proposals for urban development projects, better develop infrastructure and serve constituents, and allow greater efficiency and effectiveness. Crucially, this would streamline the construction process from design to implementation, allowing waste to be identified and eliminated, improving both efficiency and sustainability.[35]

Equally, for an industry that is booming, a skill and labour shortage is emerging to the point where supply is now critically low. In the US alone, the national trade association Associated Builders and Contractors estimates that in 2025, the industry will need to bring in nearly 454,000 new workers on top of normal hiring to meet industry demand.[36] The metaverse has the potential to mitigate skill and labour shortages through the creation of immersive learning and training environments, regardless of location, for professionals in the architecture, engineering and construction industries.[37]

The metaverse also stands to improve efficiencies in upkeep and inspection. A Japanese construction company, for example, estimates that nationwide, one million hours are spent simply travelling to inspections.[38] If the metaverse provides robust and reliable remote inspection capabilities, these million hours could be reallocated towards other critical work.

Arguably, the next leap forward in this field will be the incorporation of generative AI, with text-to-building information modelling possibly converting textual prompts directly into detailed, three-dimensional building models, encompassing construction specifications, safety information and other metadata.[39]

Although risks may include privacy and access to energy, especially in the developing world, a proactive and collaborative approach will encourage innovation while making it inclusive and safe. The promise to reduce the gap between conceptualization and implementation might end up rendering obsolete some of the most technical professional figures in the design field, calling for novel training paths and upskilling programmes.

> Crucially, this would streamline the construction process from design to implementation, allowing waste to be identified and eliminated, improving both efficiency and sustainability.

↑ **Image:**
Immersive technology transforms construction by integrating digital and physical worlds, enhancing accuracy, safety and sustainability.

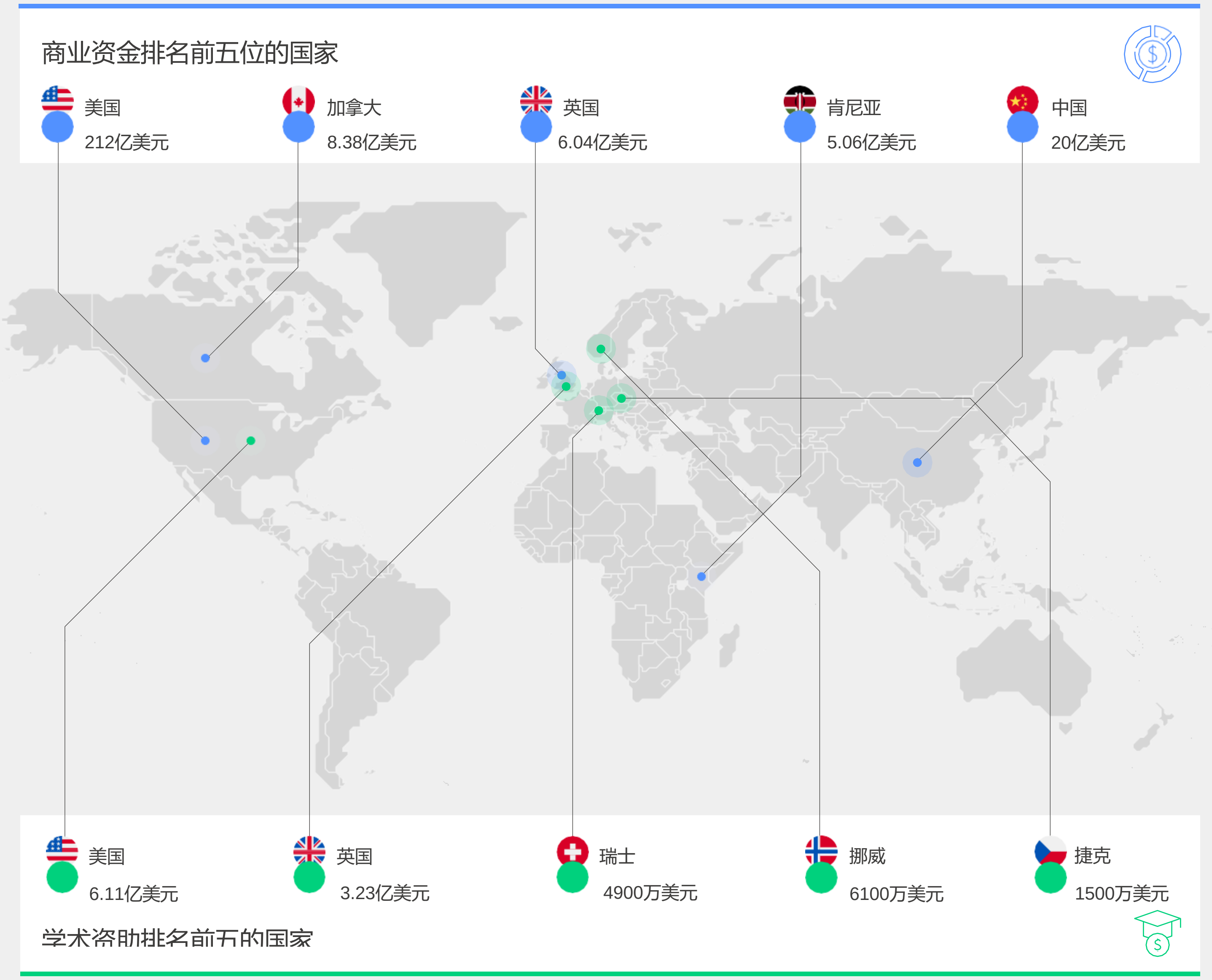
Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Brightly blue coloured cross section of a skyscraper"

Read more:
For more expert analysis, visit the immersive technology transformation map.

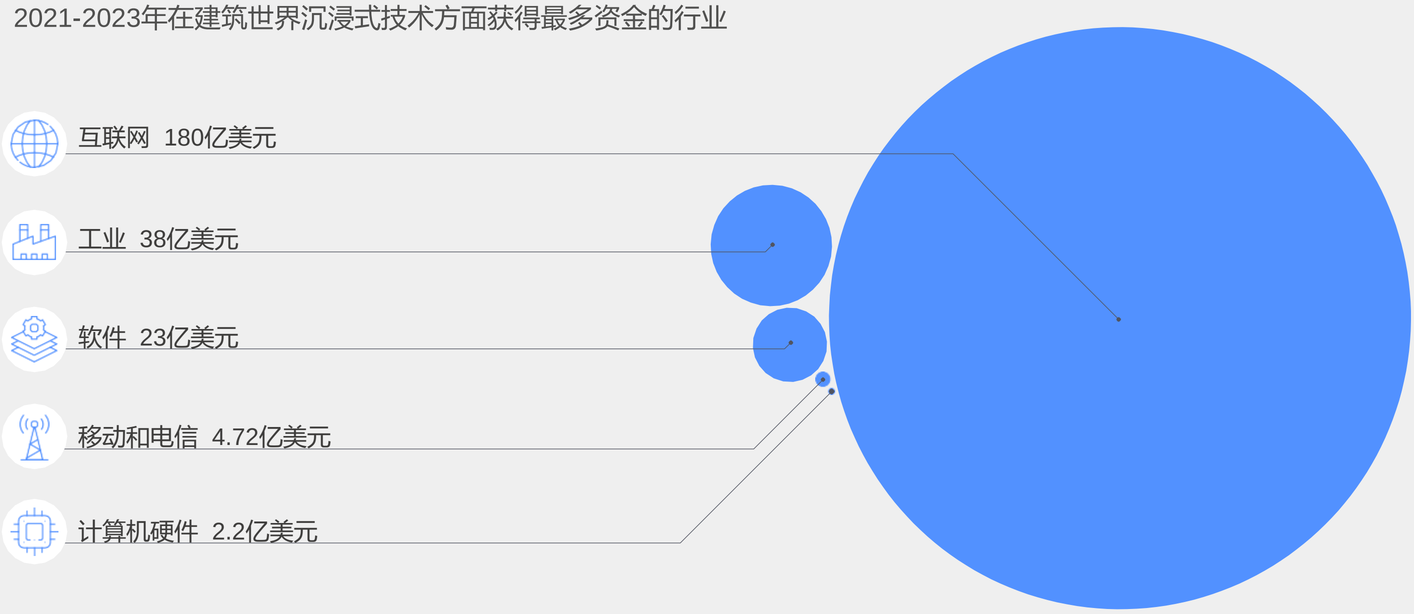
创新领域

2021-2023年建筑世界沉浸式技术商业和学术拨款最多的国家



前沿产业

2021-2023年在建筑世界沉浸式技术方面获得最多资金的行业

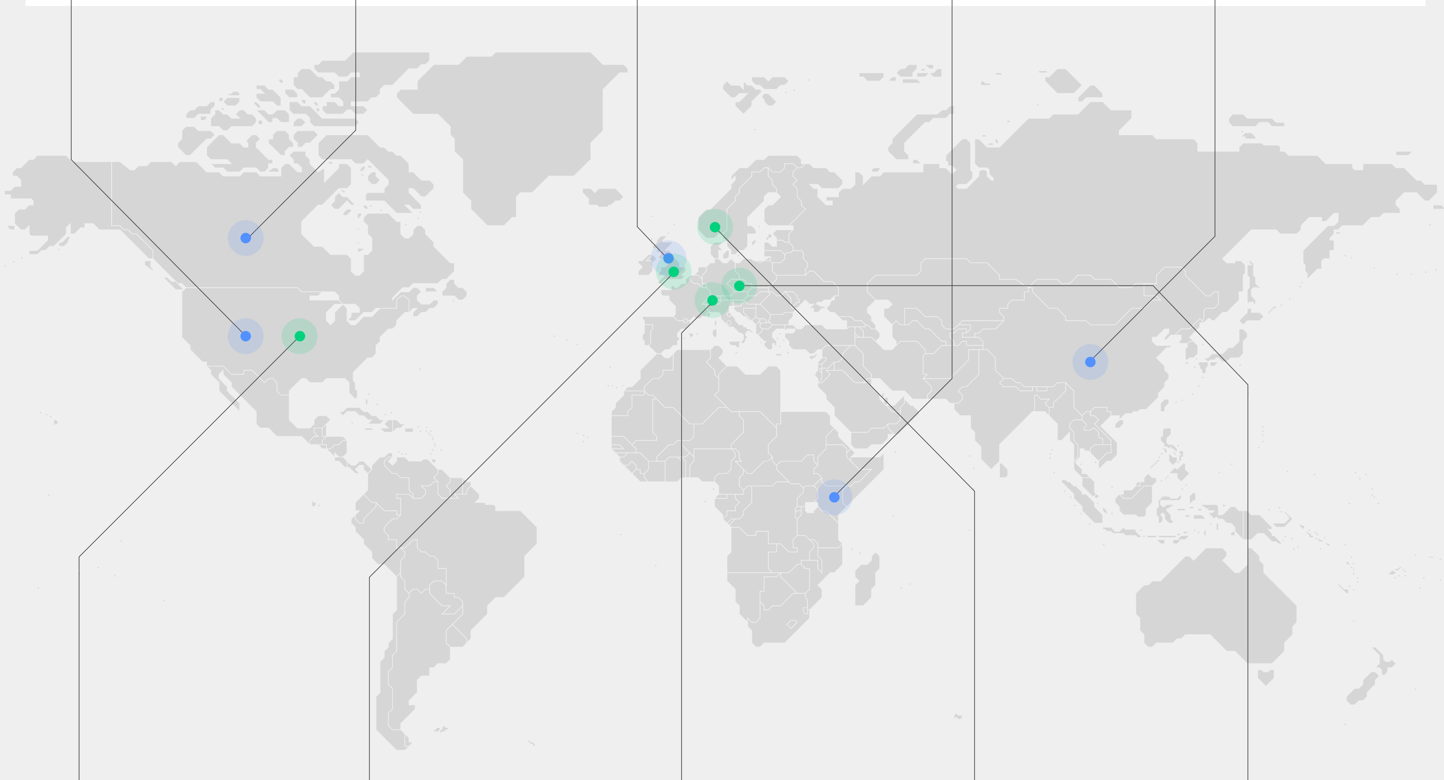


Regions of innovation

Countries with the most business and academic grant funding in immersive technology for the built world from 2021-2023

Top five countries by business funding

1 United States $21.2 billion
3 Canada $838 million
4 United Kingdom $604 million
5 Kenya $506 million
2 China $2 billion

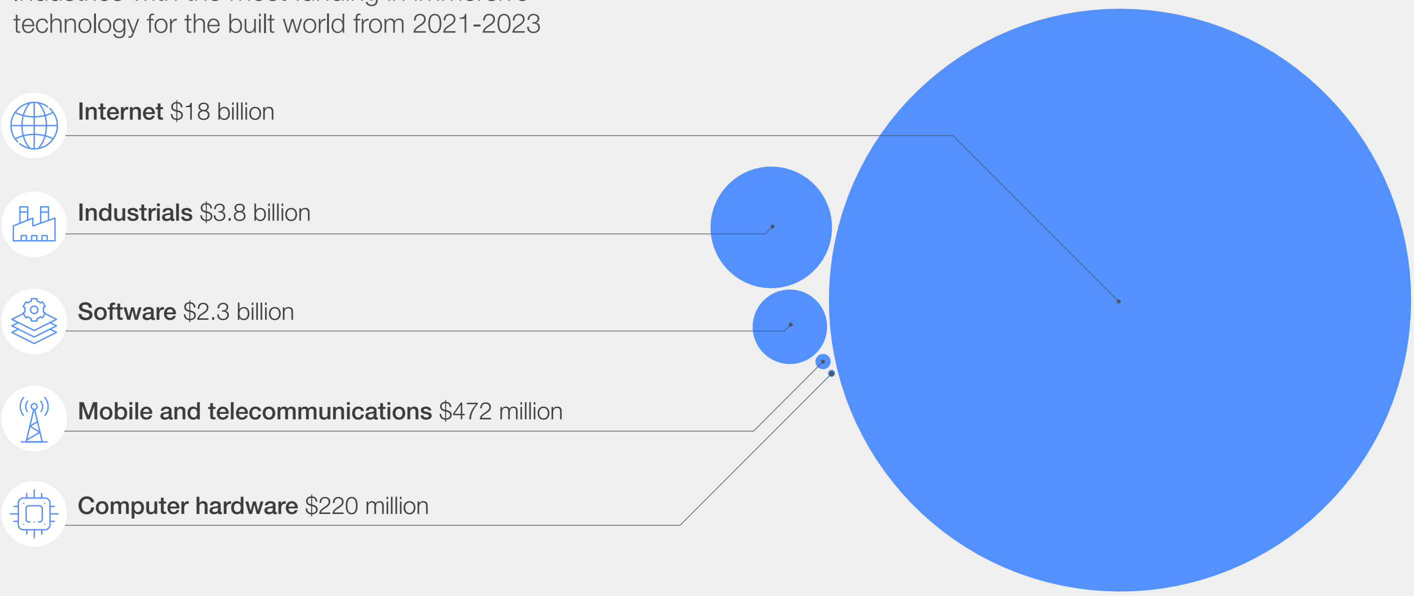


1 United States $611 million
2 United Kingdom $323 million
4 Switzerland $49 million
3 Norway $61 million
5 Czechia $15 million

Top five countries by academic grant funding

Leading-edge industries

Industries with the most funding in immersive technology for the built world from 2021-2023



07

弹性热材料

让热系统像肌肉一样工作

07

Elastocalorics

Powering heat systems to work like muscles

Mine Orlu

伦敦大学学院药剂学教授

威尔弗里德-韦伯

莱布尼茨新材料研究所科学主任

↑ 图片：弹性热材料提供突破性的冷却解决方案，在不使用有害制冷剂的情况下大幅减少能源使用。

图片来源：Midjourney和Studio Miko。

提示（略）：“金属弯曲的特写3D渲染。释放热量”

阅读更多：

更多专家分析请访问弹性热材料变换图。

随着全球气温上升，对冷却解决方案的需求将会激增。国际能源署 (IEA) 估计，未来30年全球空间制冷能源需求将增长到原来的三倍以上，到2050年约占全球电力需求增长的37%。弹性热材料是一项创新技术，可以大幅减少加热和冷却所需的能量。

弹热热泵的潜在影响，特别是在对冷气需求增加的背景下，是巨大的。美国能源部的一项研究将它们列为当前系统最有希望的替代方案。这项技术的核心是弹性热材料，它在受到机械应力时发出热量，在应力放松时冷却。这使得他们在连续的压力和放松循环中运作。弹性热泵的另一个好处是，它们不依赖于对环境有潜在危害的制冷剂气体。相反，它们利用了镍和钛等广泛可用的金属。

综上所述，弹性热技术可以显著降低满足新兴的温度控制能源需求对环境的影响。从社会角度来看，这项技术可以增强电网电力有限或无电网地区的冷却能力，从而提高生活质量并解决气候变化影响的一个关键方面。

该领域的研究和开发进展迅速，科学出版物的速度为每22个月翻一番。以汽车和冷却行业为主导的专利申请激增，凸显了人们对这项技术日益增长的商业兴趣。技术方面，材料和器件设计不断改进；新原型能够展示弹热热泵可以实现什么。

同样，大学和企业也推出了多种功能性弹热热泵模型，探索互补材料和创新生产技术的使用。

扩展弹热热泵需要克服一些重大障碍。这些泵需要能够承受数百万次拉伸和松弛循环而不会损坏的材料——这一过程正在通过尝试不同的金属合金和制造技术来解决。工程师正在研究能够利用液压有效地移动能量的系统，以帮助挤压或拉伸材料，从而触发加热或冷却。

此外，为了使这些热泵得到广泛应用，这些材料的生产需要大幅扩大，以满足全球变暖带来的不断增长的冷却需求。然而，随着商业兴趣的增长和技术创新，弹热热泵的广泛采用前景广阔，开创了高效、环保的冷却解决方案的新时代。

> 弹性热技术可以显著降低满足新兴的温度控制能源需求对环境的影响。

Mine Orlu
Professor, Pharmaceutics, University College London

Wilfried Weber
Scientific Director, Leibniz Institute for New Materials

As global temperatures rise, the need for cooling solutions is set to soar. The International Energy Agency (IEA) estimates that the global energy demand for space cooling will more than triple over the next 30 years, accounting for about 37% of global electricity demand growth by 2050.[40] Elastocaloric heat pumps are an innovative technology that can drastically reduce the energy required for heating and cooling several times over.[41]

The potential impact of elastocaloric heat pumps, particularly in the context of heightening demand for cool air, is substantial. A US Department of Energy study ranks them as the most promising alternative to current systems.[42] The heart of this technology is elastocaloric materials, which emit heat when subjected to mechanical stress and cool down when the stress is relaxed. This allows them to operate on a continuous stress and relaxation cycle. The added benefit of elastocaloric heat pumps is that they do not rely on refrigerant gases, which are potentially damaging to the environment. Instead, they make use of widely available metals like nickel and titanium.

Taken together, the environmental impact of catering to emerging energy requirements for temperate control can be significantly reduced by elastocaloric technology. Socially, this technology can enhance access to cooling in regions with limited or no grid-based electricity, thereby improving quality of life and addressing a key aspect of climate change impact.[43]

Research and development in the field is advancing quickly, with the rate of scientific publications doubling every 22 months. The surge in patent applications, with automotive and cooling industries taking the lead, underscores the growing commercial interest in this technology. On the technological side, there has been steady improvement in materials and device designs; new prototypes are able to demonstrate what elastocaloric heat pumps can achieve. Similarly, universities and businesses have introduced several functional elastocaloric heat pump models, exploring the use of complementary materials and innovative production techniques.[44]

Scaling elastocaloric heat pumps involves overcoming some big hurdles. These pumps need materials that can last through millions of cycles of being stretched and relaxed without breaking down – a process that's being tackled by experimenting with different metal alloys and manufacturing techniques. Engineers are working on systems that can efficiently move energy using hydraulics to help squeeze or stretch materials, which can trigger heating or cooling.[45]

Additionally, for these heat pumps to become widely available, the production of these materials needs to scale up significantly to align with the constantly increasing demand for cooling that has been forecast in the face of global warming. However, with growing commercial interest and technological innovation, the future looks promising for the widespread adoption of elastocaloric heat pumps, ushering in a new era of efficient and environmentally friendly cooling solutions.

> “The environmental impact of catering to emerging energy requirements for temperature control can be significantly reduced by elastocaloric technology.

↑ **Image:**
Elastocalorics offer a groundbreaking cooling solution, drastically reducing energy use without harmful refrigerants.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): “Close up 3D render of metal bending. Releasing heat”

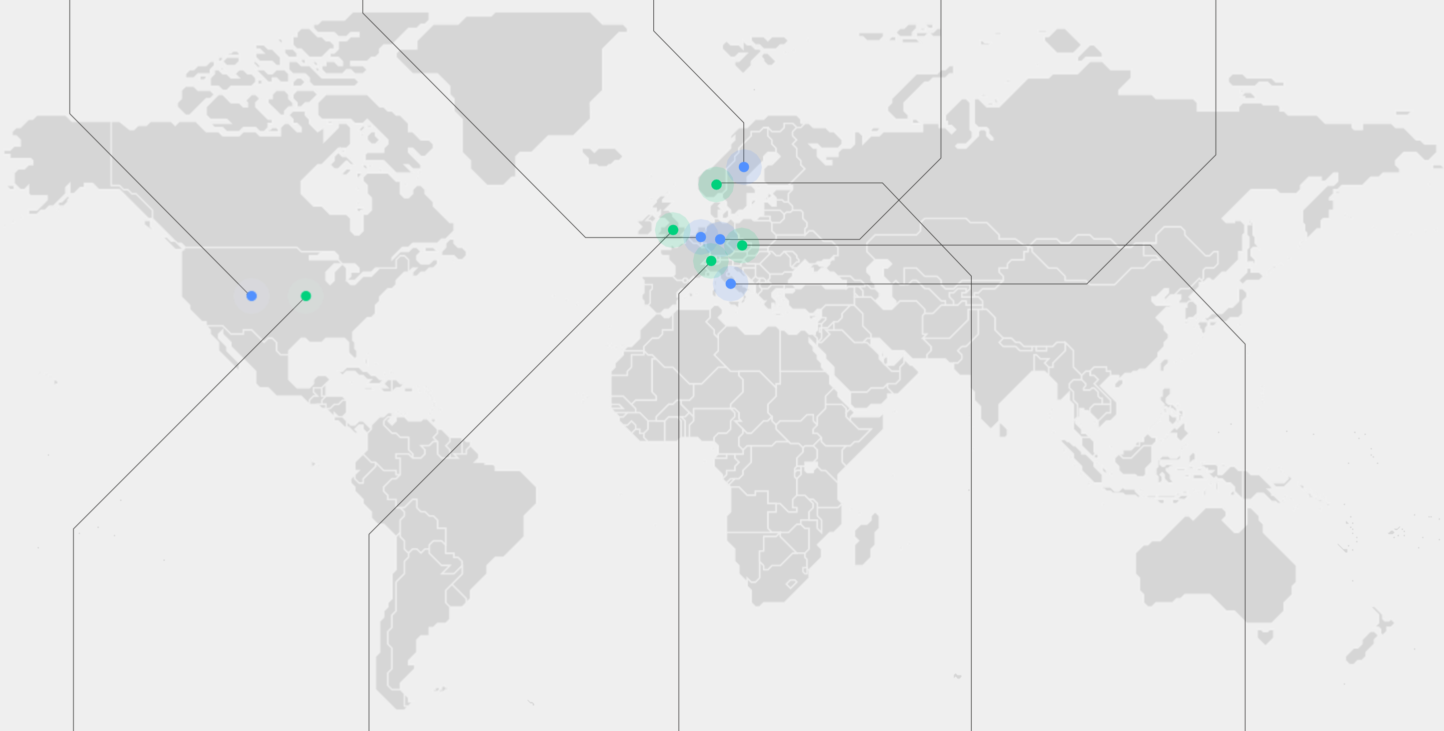
Read more:
For more expert analysis, visit the elastocalorics transformation map.

创新领域

2021-2023年弹性热材料商业和学术拨款最多的国家

商业资金排名前五位的国家

美国 11亿美元
荷兰 4.75亿美元
瑞典 37亿美元
德国 4.43亿美元
意大利 5.55亿美元

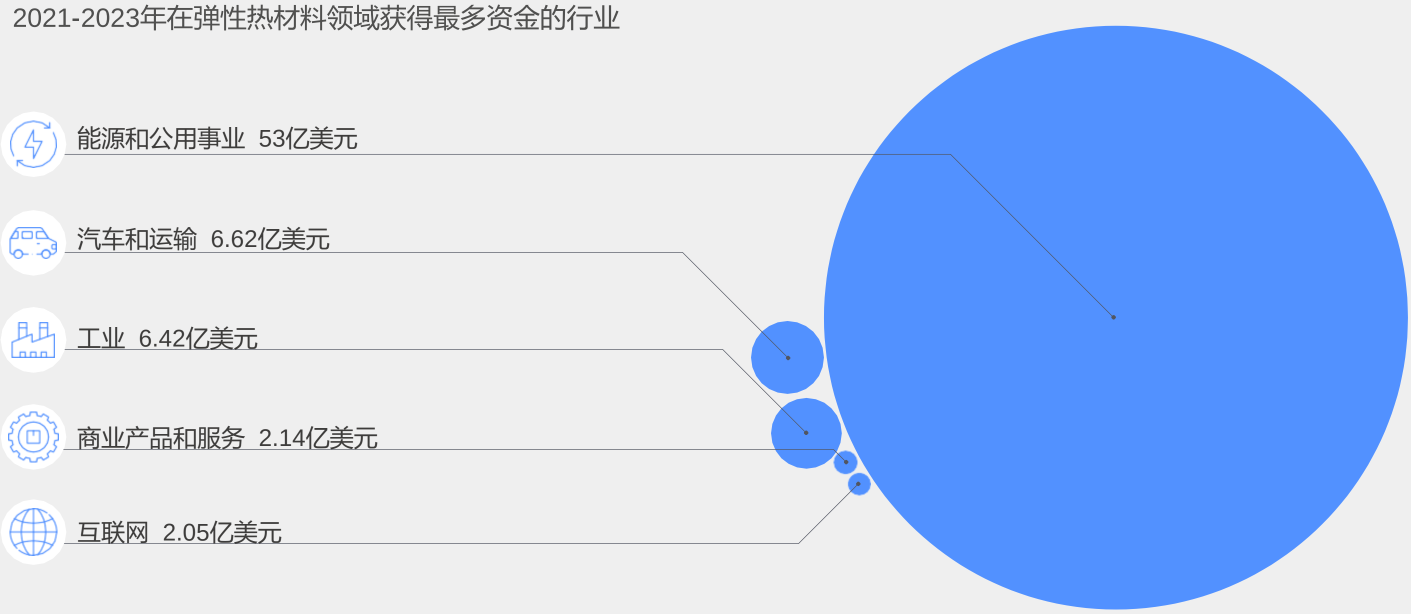


美国 2.95亿美元
英国 1.71亿美元
瑞士 1100万美元
挪威 1200万美元
捷克 800万美元

学术资助排名前五的国家

前沿产业

2021-2023年在弹性热材料领域获得最多资金的行业

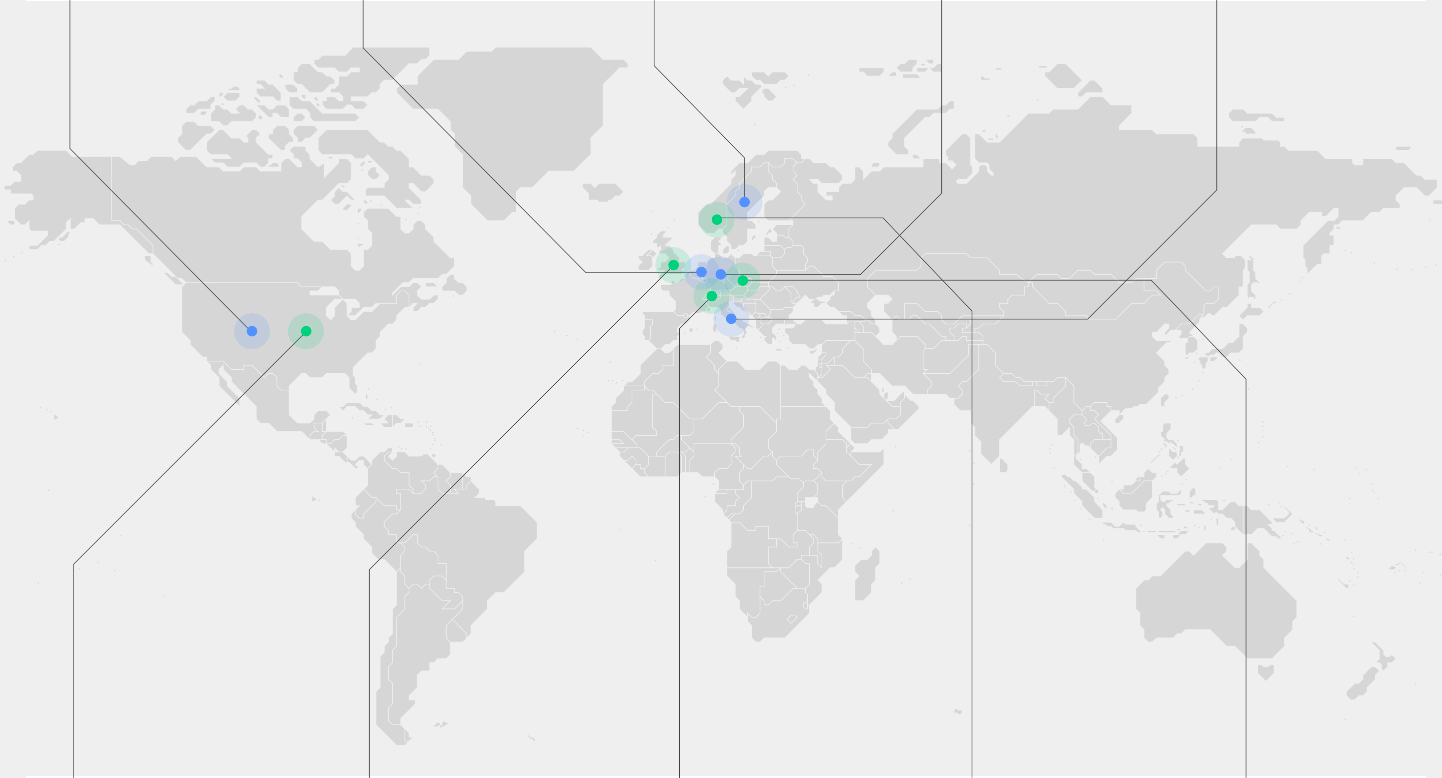


Regions of innovation

Countries with the most business and academic grant funding in elastocalorics from 2021-2023

Top five countries by business funding

- 2 United States $1.1 billion
- 4 Netherlands $475 million
- 1 Sweden $3.7 billion
- 5 Germany $443 million
- 3 Italy $555 million



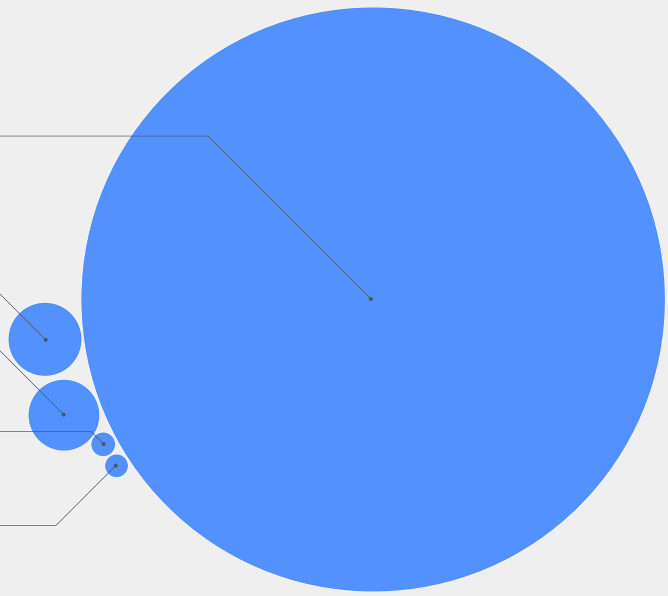
- 1 United States $295 million
- 2 United Kingdom $171 million
- 4 Switzerland $11 million
- 3 Norway $12 million
- 5 Czechia $8 million

Top five countries by academic grant funding

Leading-edge industries

Industries with the most funding in elastocalorics from 2021-2023

- **Energy and utlities** $5.3 billion
- **Automotive and transport** $662 million
- **Industrials** $642 million
- **Business product and services** $214 million
- **Internet** $205 million



08 碳捕获微生物

改造微生物，将排放物转化为有价值的产品

08 Carbon-capturing microbes

Engineering organisms to convert emissions into valuable products

Sang Yup Lee

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杨泽群

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在气候变化的紧迫性下，一场无声的革命正在酝酿：微生物被用来捕获空气或废气中的温室气体，并将其转化为高价值产品。为了驱动这个过程，生物体利用阳光或氢等化学能。对生物体进行工程设计有望提供广泛的可持续产品，同时减少全球变暖。

微生物碳捕获正在成为控制大气二氧化碳和缓解全球变暖的一种有前途的策略。同时，它可以生产具有巨大市场潜力的各种产品，例如燃料、肥料和动物饲料。为了实现这一目标，研究人员正在开发微生物（包括细菌和微藻），它们利用阳光或可持续化学能来吸收和转化气体。

微生物碳捕获有两种主要设计。第一种是光生物反应器，利用像蓝藻和微藻这样的光合生物来捕获二氧化碳，利用阳光来处理富含二氧化碳的气体，这些气体从含有这些生物的池子中冒出来。第二种是当微生物利用氢、有机废物流或使用可再生能源从CO_2衍生的其他化学品等来源捕获CO_2时。无论它们使用阳光还是化学品作为能源，这两种系统改造生物体，将CO_2转化为新产品，例如生物柴油或富含蛋白质的动物饲料。每个系统的产品价值差异很大；选择使用哪个系统取决于实施公司的具体需求和能力，例如可用资源。这也意味着，一旦实施，公司可以为市场生产新产品，而不是为每吨CO_2支付50至100美元来抵消其排放。

该技术由专门从事细胞修正以促进特定物质生产的组织推动。

经过一系列成功的演示和概念验证，微生物碳捕获现已准备好从试点过渡到大规模生产。到2022年，全球对该技术的投资已达到64亿美元，凸显其已做好上市准备。以色列的Seambiotic、西班牙的Alga Energy和美国的Bio Process Algae等公司已经部署了中试规模的设施，以探索微生物碳捕获系统的商业可行性。

尽管取得了重大进展，微生物碳捕获系统仍然面临着阻碍其广泛采用和商业化的挑战。首先，微生物大多适应低温条件，在从热工业废气中捕获二氧化碳方面效果较差。需要额外的耗能冷却设施。优化需要研究如何提高微生物对工业废气热量水平的抵抗力，以及对酸性杂质的抵抗力。其次，现有的微生物碳捕获系统仍然非常昂贵。然而，产品的高价值可以至少抵消部分成本。最后，生产场地需要充足的阳光和可再生或清洁能源，但这在全球所有地区都无法得到保证。只有克服这些挑战，才能在全球努力中充分发挥该技术的潜力实现净零排放世界。

> “一旦实施，公司可以为市场生产新产品，而不是为每吨CO2支付50至100美元来抵消其排放。

↑ 图片：旨在捕获碳的微生物可以将温室气体转化为燃料和肥料等有价值的产品。

图片来源：Midjourney和Studio Miko。

提示（简略）："明亮的个体绿色DNA包裹在方形网格中。

阅读更多：
更多专家分析请访问[微生物碳捕获](#) 变换图。

Sang Yup Lee

Senior Vice-President, Research; Distinguished Professor, Korea Advanced Institute of Science and Technology

Hailong Li

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Amid the urgency of climate change, a silent revolution brews: microorganisms are being used to capture greenhouse gases from air or exhaust gases and convert them into high-value products. To drive this process, the organisms use sunlight or chemical energy such as hydrogen. Engineering the organisms promises a wide palette of sustainable products while simultaneously reducing global warming.

Microbial carbon capture is emerging as a promising strategy to control atmospheric CO_2 and mitigate global warming.[46] Simultaneously, it can produce various products with significant market potential, such as fuels, fertilizers and animal feed. To achieve this, researchers are developing microorganisms – including bacteria and microalgae – that use sunlight or sustainable chemical energy to absorb and transform gases.

There are two main designs for microbial carbon capture. The first, photobioreactors, use photosynthetic organisms like cyanobacteria and microalgae to capture CO_2, employing sunlight to process CO_2-laden gas bubbled through a bath containing such organisms. The second is when microorganisms capture CO_2 by using energy from sources like hydrogen, organic waste streams or other chemicals derived from CO_2 using renewable energy.[47] Regardless of whether they use sunlight or chemicals for energy, both systems modify organisms to convert CO_2 into new products, such as biodiesel or protein-rich animal feed.[48] The product value of each system varies significantly; the choice between which system to use depends on the specific needs and capabilities of the implementing company, such as available resources. This also means that companies could, once implemented, generate new products for the market instead of paying between $50 and $100 per tonne of CO_2 to offset their emissions.

The technology is driven by organizations specializing in cell modification to boost specific substance production.[49] Following a series of successful demonstrations and proofs-of-concept, microbial carbon capture is now ready to transition from pilot to full-scale production. By 2022, global investment in the technology had already reached $6.4 billion, highlighting its readiness to be brought to market.[50] Companies such as Seambiotic in Israel, Alga Energy in Spain and Bio Process Algae in the US have deployed pilot-scale facilities to explore the commercial viability of microbial carbon capture systems.

Despite significant progress, microbial carbon capture systems still face challenges that hinder their widespread adoption and commercialization. Firstly, microorganisms are mostly adapted to low-temperature conditions and are less effective in capturing CO_2 from hot industrial exhaust gases. Additional energy consuming cooling facilities are needed. Optimization requires investigating how to improve microbial resistance to industrial exhaust levels of heat, as well as resistance against acidic impurities.[51] Secondly, existing microbial carbon capture systems are still very expensive.[52] However, the high value of the products could offset at least part of this cost. Lastly, production sites need an abundance of sunlight and access to renewable or clean energy, which is not guaranteed across all global regions.[53] Only when these challenges are overcome will the full potential of the technology be realized as part of the global effort to achieve a net-zero emission world.

> “Companies could, once implemented, generate new products for the market instead of paying between $50 and $100 per tonne of CO_2 to offset their emissions.

↑ **Image:** Microorganisms engineered to capture carbon can convert greenhouse gases into valuable products like fuels and fertilizers.

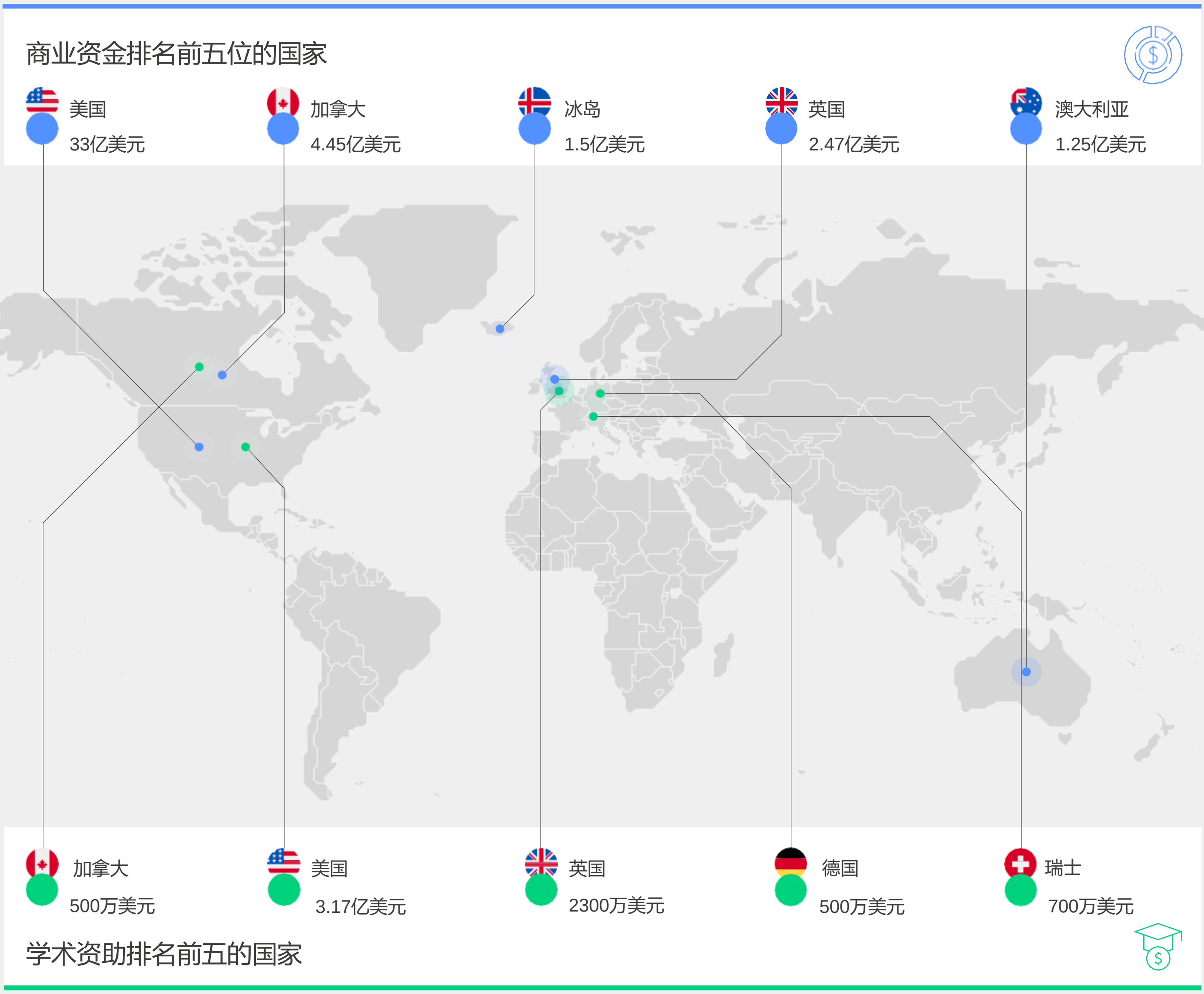
Credit: Midjourney and Studio Miko.

Prompt (abbreviated): “Bright individual green DNA encased in a square grid.

Read more: For more expert analysis, visit the microbial carbon capture transformation map.

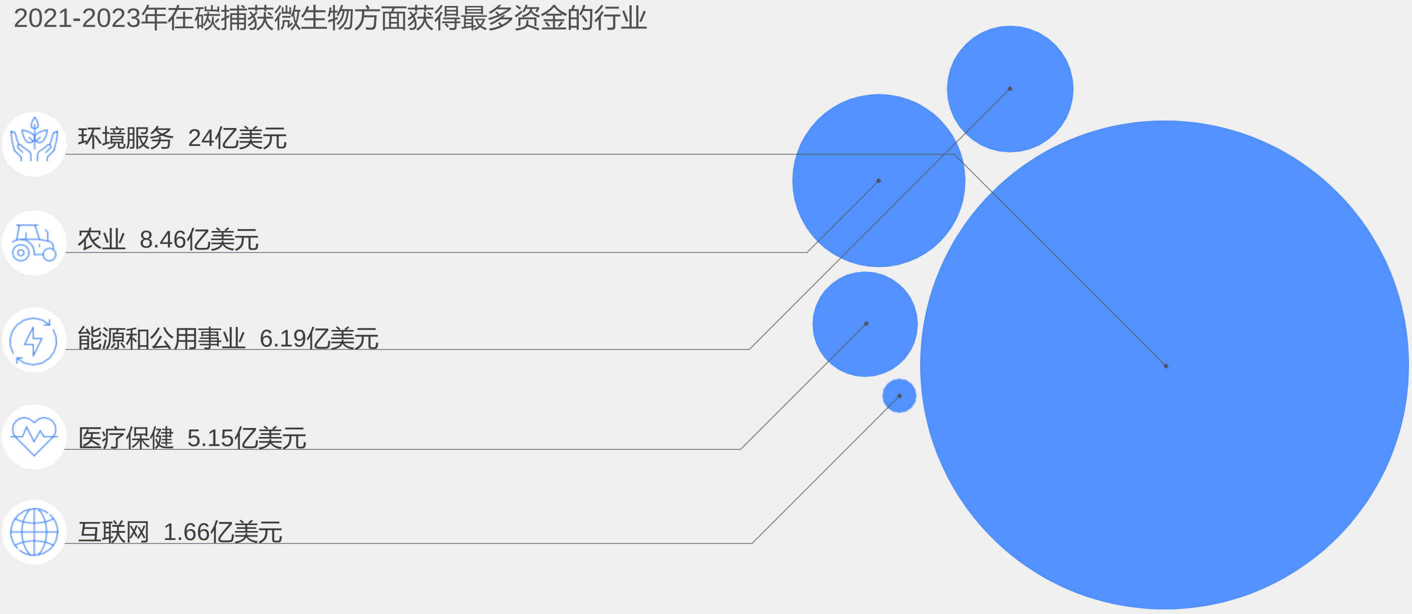
创新领域

2021-2023年碳捕获微生物商业和学术拨款最多的国家



前沿产业

2021-2023年在碳捕获微生物方面获得最多资金的行业

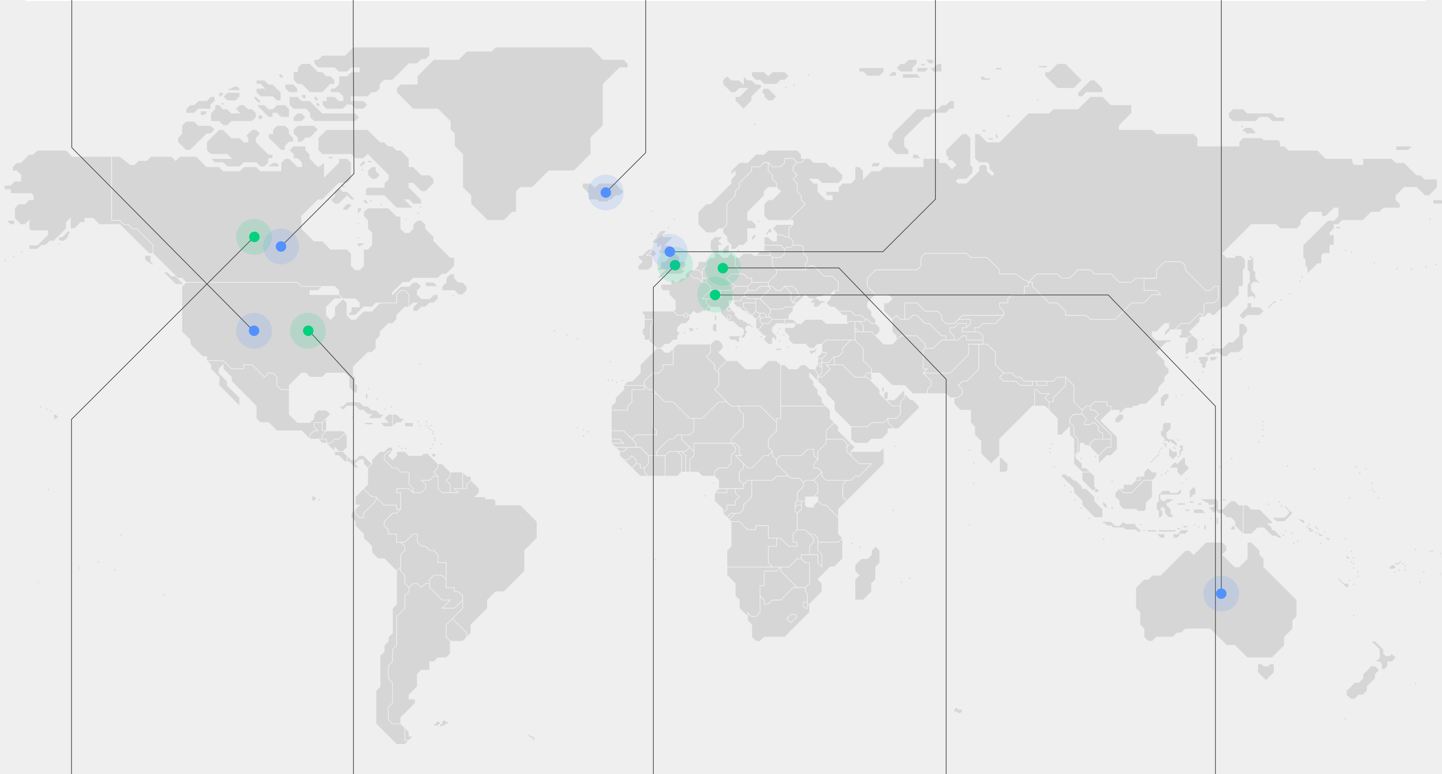


Regions of innovation

Countries with the most business and academic grant funding in carbon-capturing microbes from 2021-2023

Top five countries by business funding

1. United States $3.3 billion
2. Canada $445 million
3. United Kingdom $247 million
4. Iceland $150 million
5. Australia $125 million



1. United States $317 million
2. United Kingdom $23 million
3. Switzerland $7 million
4. Germany $5 million
5. Canada $5 million

Top five countries by academic grant funding

Leading-edge industries

Industries with the most funding in carbon-capturing microbes from 2021-2023

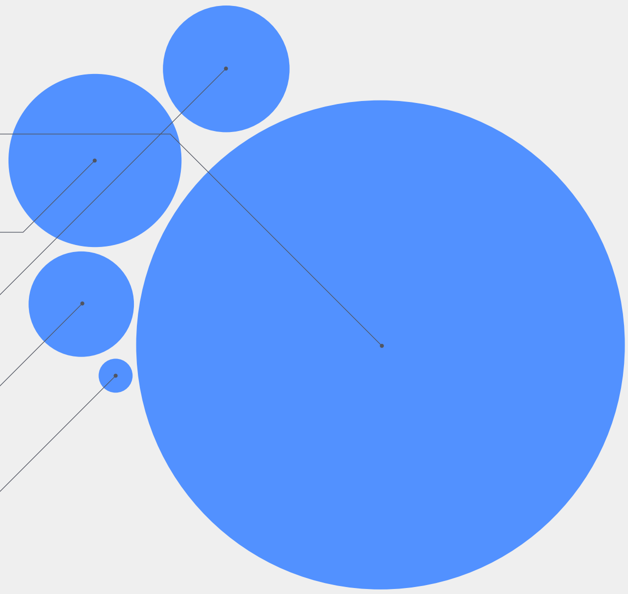
Environmental services $2.4 billion

Agriculture $846 million

Energy and utilities $619 million

Healthcare $515 million

Internet $166 million



09 替代性家畜饲料

彻底改变动物营养以实现可持续发展

09

Alternative livestock feeds

Revolutionizing animal nutrition for sustainability

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替代性家畜饲料提供可持续的解决方案，以满足畜牧业对蛋白质日益增长的需求。这些饲料源自昆虫、单细胞蛋白质、藻类和食物垃圾，为大豆、玉米和小麦等传统原料提供了可行的替代品。

饲料替代品可显着改善可持续性。目前，近80%的大豆产量被用作动物饲料，对环境造成了严重的负面影响。这种需求导致了土地利用变化导致的森林砍伐、生物多样性丧失、过度施肥以及温室气体排放。转向替代性家畜饲料可以缓解这些挑战，并促进畜牧业中更加环境可持续的做法。

替代动物饲料的另一个优势是它增加的多样性和营养价值，这可以在保护动物福利方面发挥关键作用。它可以提供比传统饲料更广泛的营养成分，改善动物健康和福祉，并有可能改善产品本身的质量。例如，可以工业规模生产昆虫，以产生高质量的蛋白质，而单细胞蛋白质或藻类可以为多种动物提供必需的蛋白质和脂肪。此外，捕获人类食物垃圾或使用藻类、满江红、鹰嘴豆和橙子果肉等成分正在成为有前途的替代品。

这些替代来源的成本效益也是一个关键因素。它们的生产和获取通常更便宜。使用黑水虻幼虫（BSFL）是一个例子；研究表明，在动物饲料中添加BSFL可以降低饲料相关成本。这主要是因为BSFL可以从有机废物中培养，从而减少对传统的、更昂贵的饲料原料的需求，如鱼粉或豆粕。

牲畜饲料替代原料市场充满活力，全球多家公司现已成功推出优质替代选择。2023年，全球动物饲料替代蛋白市场价值39.6亿美元。预计未来十年其价值将大幅增长，到2033年将增至82亿美元。

然而，替代动物饲料不仅仅是万能的解决方案。其可行性因当地可用性、制造成本以及环境和社会条件而异。其他挑战，包括环境法规、道德问题和竞争仍然存在。例如，可持续饲料资源与可持续燃料生产之间的竞争日益激烈。这种竞争可能会限制牲畜饲料的供应，可能会推高价格并阻碍广泛采用。替代动物饲料行业未来的成功取决于其应对这些挑战并适应对更可持续和更高效的饲料选择的需求的能力。

> 转向替代性家畜饲料可以促进畜牧业中更加环境可持续的做法。

↑ 图像：

替代性家畜饲料为传统动物饲料提供了可持续和营养的替代品，并减少了对环境的影响。

图片来源：Midjourney和Studio Miko。

提示（简略）：“单细胞，藻类”

阅读更多：

更多专家分析请访问替代性家畜饲料变换图。

Mariette DiChristina
Dean, Boston University College of Communication

Javier Garcia-Martinez
Professor, Chemistry and Director, Molecular Nanotechnology Lab, University of Alicante

Alternative livestock feeds offer sustainable solutions to address the growing demand for protein in animal agriculture. These feeds, sourced from insects, single-cell proteins, algae and food waste, provide viable alternatives to traditional ingredients like soy, maize and wheat.[54]

Feed alternatives offer substantial sustainability improvements. Currently, nearly 80% of soy production is used as animal feed, leading to significant negative environmental consequences.[55] This demand drives deforestation, biodiversity loss, over-fertilization and greenhouse gas emissions from land-use changes. Transitioning to alternative livestock feeds could mitigate these challenges and promote more environmentally sustainable practices in animal agriculture.

A further advantage of alternative animal feed is the diversity and nutritional value it adds, which can play a critical role in protecting animal welfare. It can offer a broader range of nutrients than conventional feeds, improving animal health and well-being and, potentially, the quality of the produce itself.[56] For instance, insects can be produced on an industrial scale to yield high-quality protein, while single-cell proteins or algae can supply essential proteins and fats for several species of animals. Additionally, capturing human food waste or using ingredients like algae, azolla, chickpeas and orange pulp are emerging as promising alternatives.[57]

The cost-benefit of these alternative sources is also a key factor. They are often cheaper to produce and obtain. The use of black soldier fly larvae (BSFL) is an example; studies show that adding BSFL into animal diets can reduce the costs associated with feed. This is primarily because BSFL can be cultivated from organic waste, reducing the need for traditional, more expensive feed ingredients like fish meal or soybean meal.[58]

The market for alternative ingredients to feed livestock is vibrant, and multiple companies worldwide have now successfully introduced quality alternative options.[59] In 2023, the global animal feed alternative protein market was valued at $3.96 billion. It is projected to significantly grow in value over the next decade, increasing to $8.2 billion by 2033.[60]

Alternative animal feed is, however, more than a one-size-fits-all solution. Its feasibility varies based on local availability, manufacturing costs and environmental and social conditions. Other challenges, including environmental regulations, ethical concerns and competition, remain. Sustainable feed resources are increasingly competing with sustainable fuel production, for example. This competition could limit the availability of livestock feeds, potentially driving up prices and hindering widespread adoption. The future success of the alternative animal feed industry depends on its ability to navigate these challenges and adapt to the demand for more sustainable and efficient feed options.

> “Transitioning to alternative livestock feeds could promote more environmentally sustainable practices in animal agriculture.

↑ **Image:**
Alternative livestock feeds provide sustainable and nutritious alternatives to traditional animal feed, and reduce environmental impact.

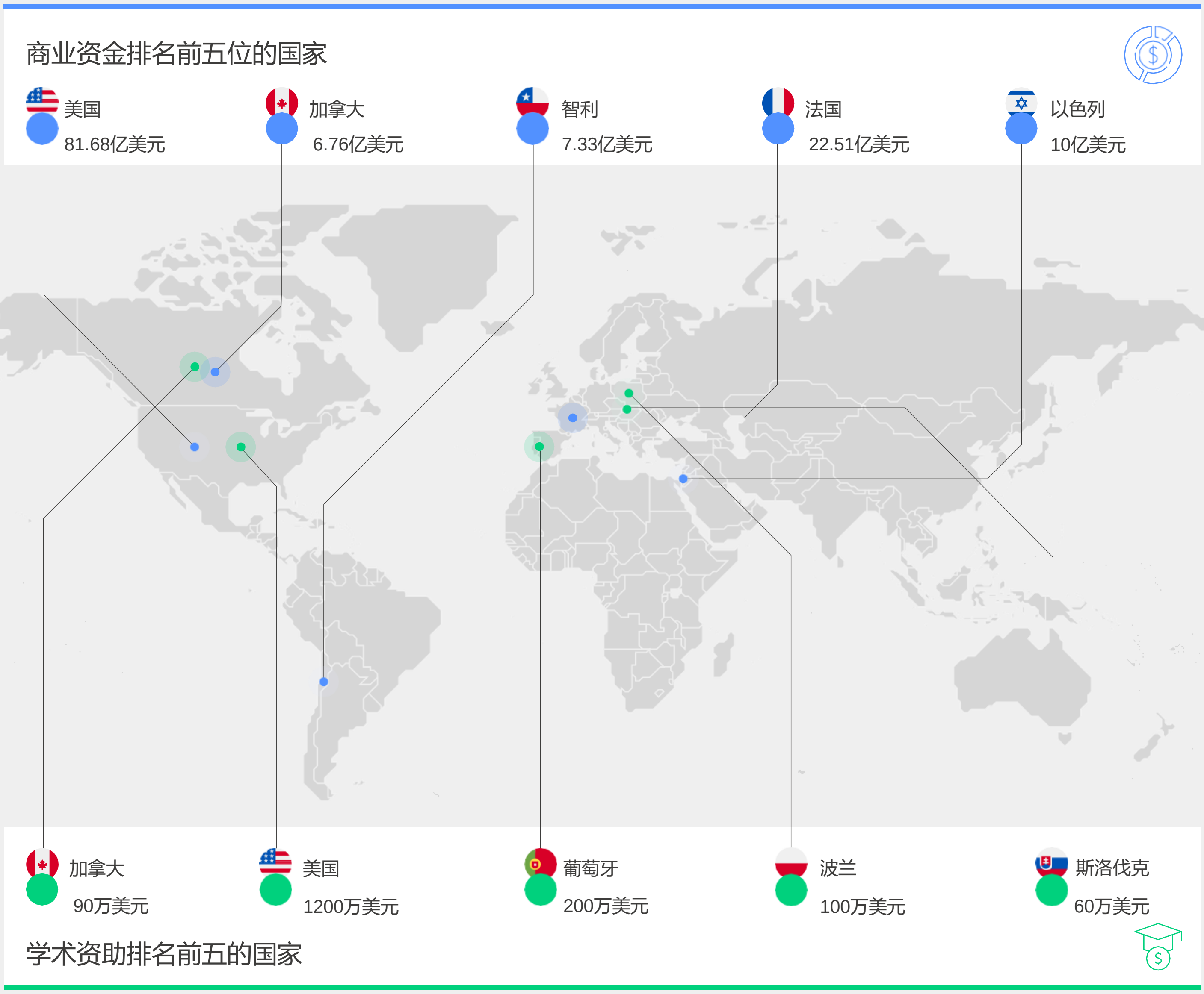
Credit: Midjourney and Studio Miko.

Prompt (abbreviated): “Single-cell, algae”

Read more:
For more expert analysis, visit the alternative livestock feeds transformation map.

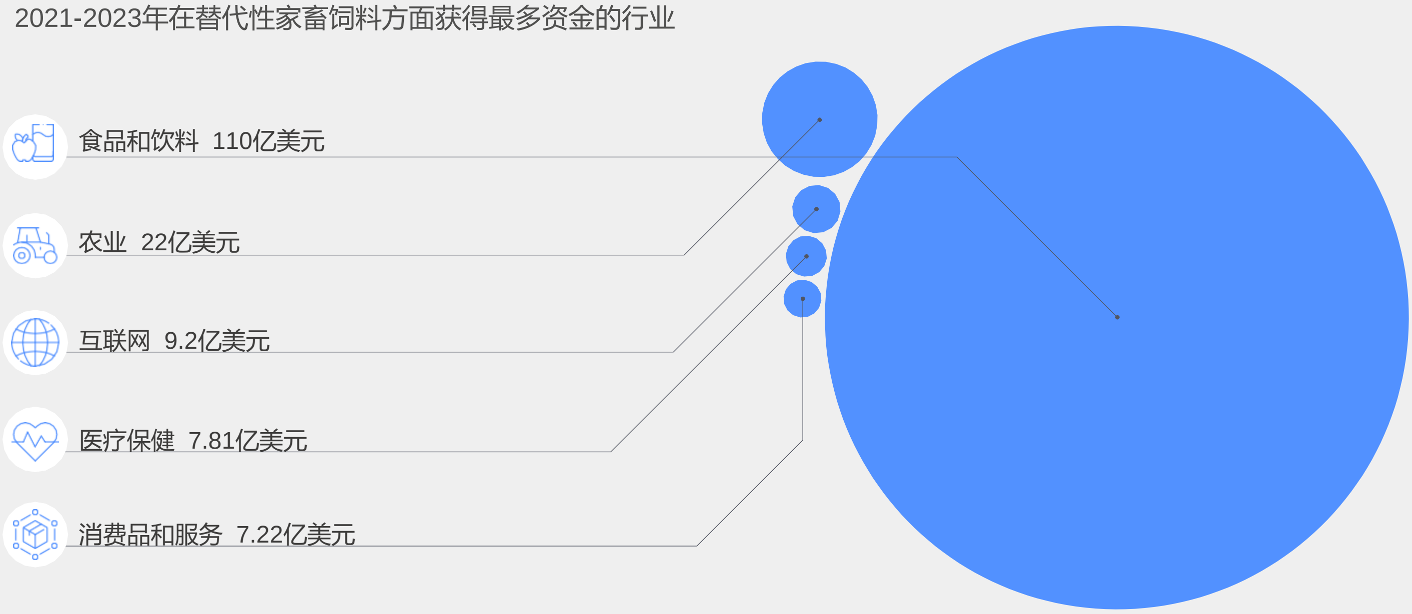
创新领域

2021-2023年替代性家畜饲料商业和学术拨款最多的国家



前沿产业

2021-2023年在替代性家畜饲料方面获得最多资金的行业

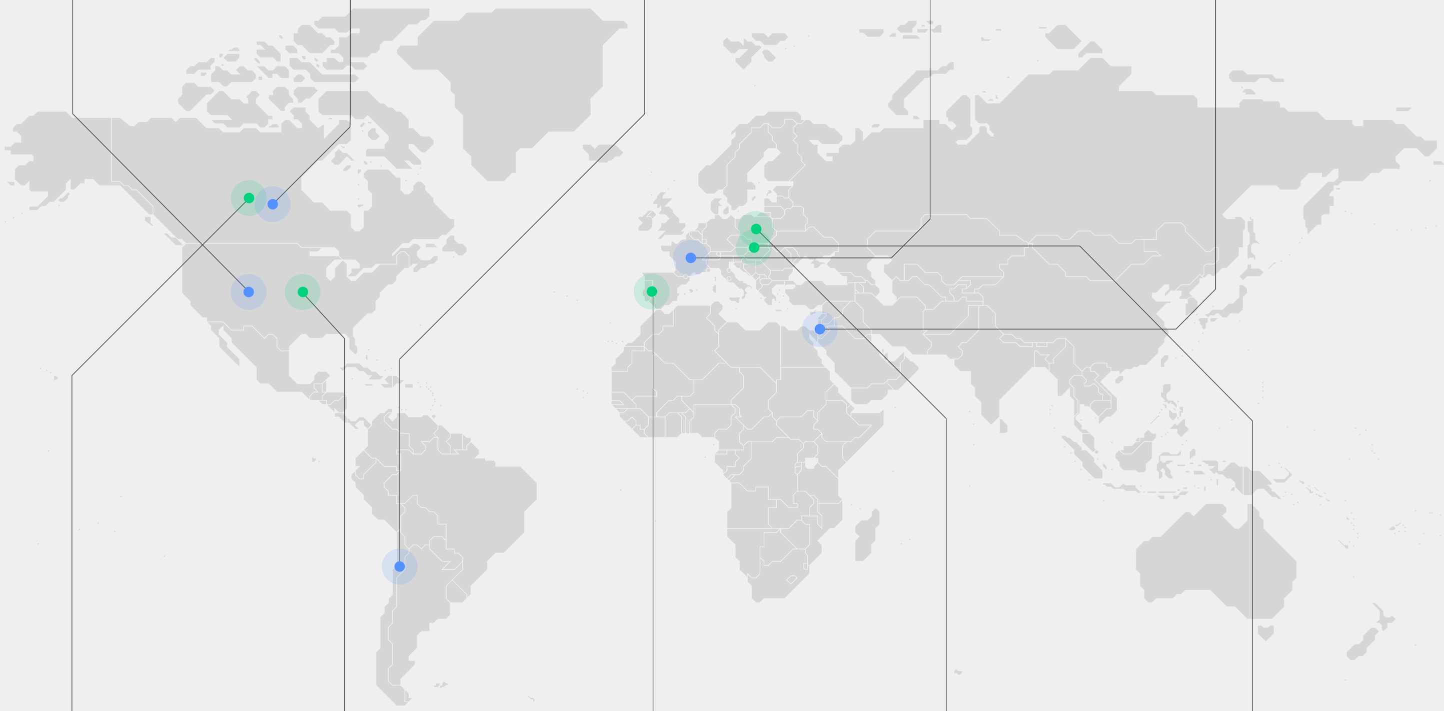


Regions of innovation

Countries with the most business and academic grant funding in alternative livestock feeds from 2021-2023

Top five countries by business funding

- **United States** 1 — $8,168 million
- **Canada** 5 — $676 million
- **Chile** 4 — $733 million
- **France** 2 — $2,251 million
- **Israel** 3 — $1,000 million



- **Canada** 4 — $0.9 million
- **United States** 1 — $12 million
- **Portugal** 2 — $2 million
- **Poland** 3 — $1 million
- **Slovakia** 5 — $0.6 million

Top five countries by academic grant funding

Leading-edge industries

Industries with the most funding in alternative livestock feeds from 2021-2023

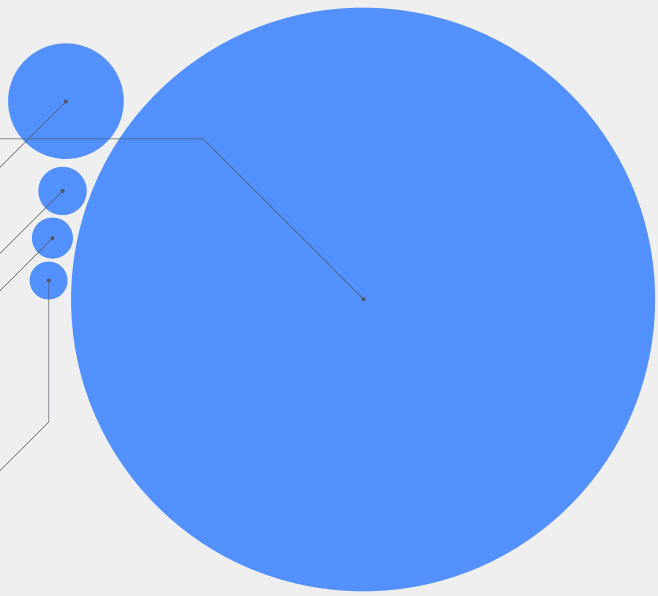
Food and beverage $11 billion

Agriculture $2.2 billion

Internet $920 million

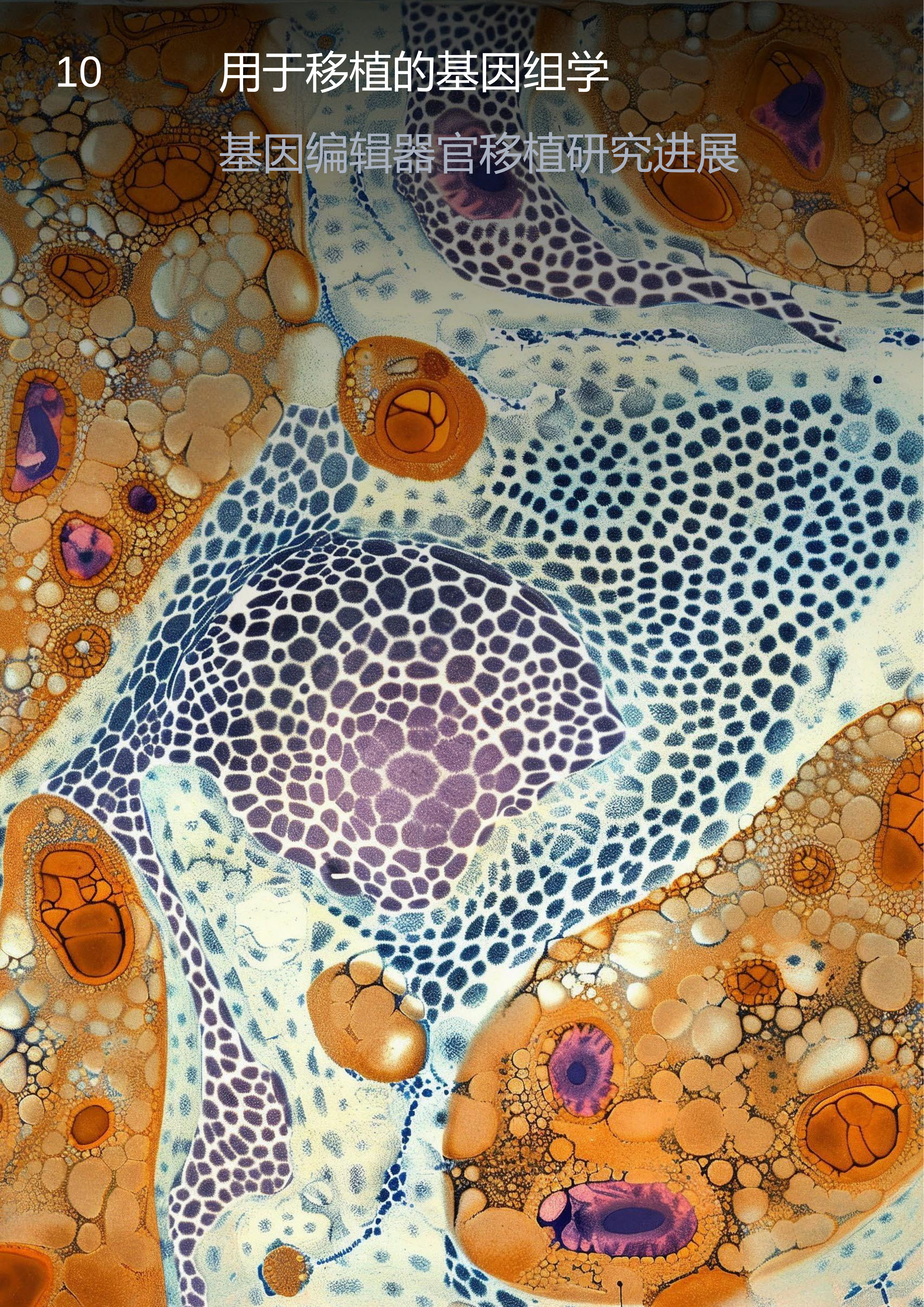
Healthcare $781 million

Consumer products and services $722 million



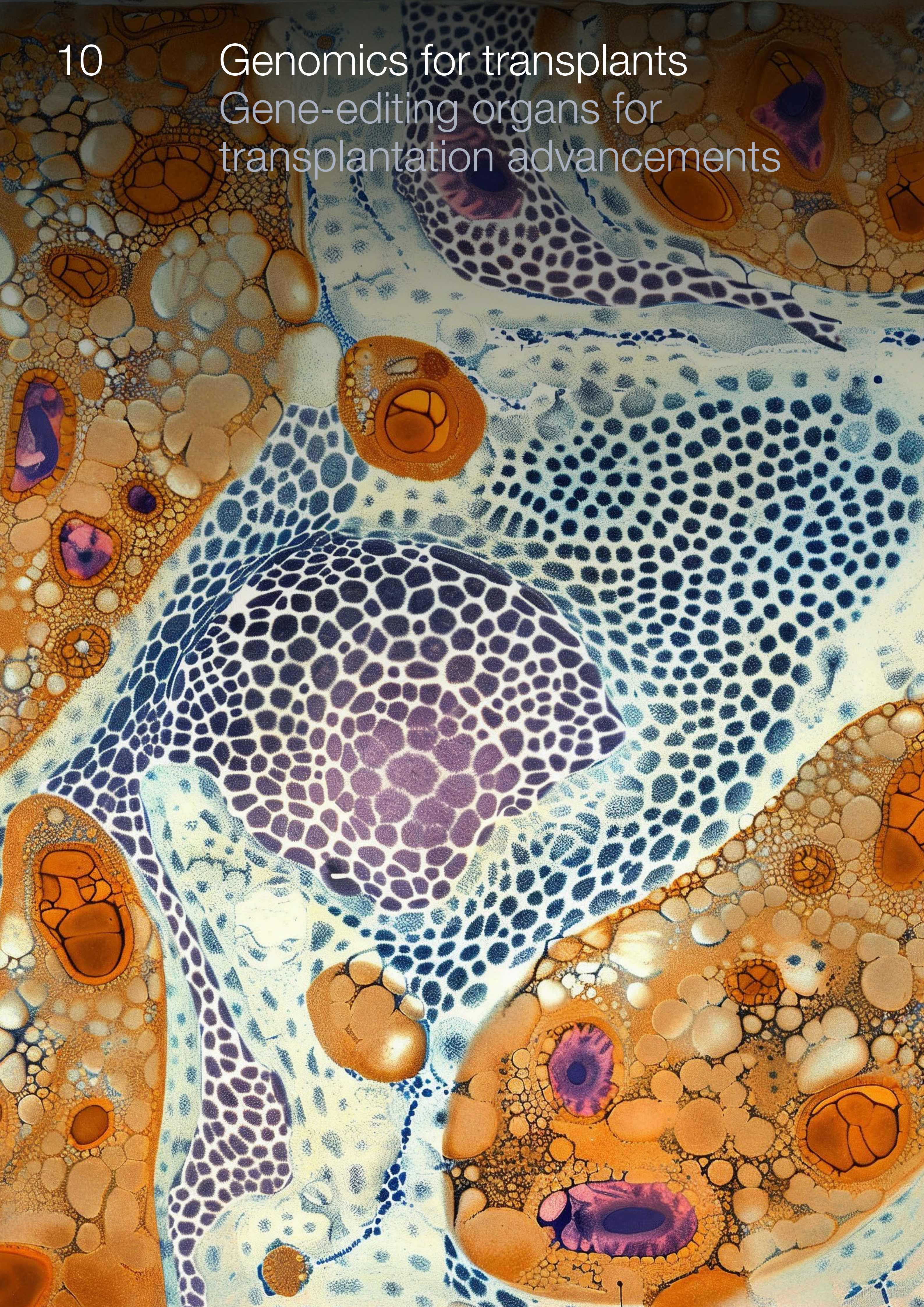
10 用于移植的基因组学

基因编辑器官移植研究进展



10 Genomics for transplants

Gene-editing organs for transplantation advancements



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器官移植是20世纪下半叶医学上的一项重大进步，并继续取得进展。2024年3月的一个显着里程碑强调了这一持续的发展：首次成功将非人类（猪）肾脏移植到活体人类受体中。这种进步是由一些基本因素推动的，比如我们理解和精确编辑基因组的能力。

器官移植可以挽救生命，但需求远远超出了可用的捐赠者库。仅在美国，就有超过100,000名患者正在等待器官移植，但今年只有大约30,000个器官可供使用。

为了满足这一需求，三十多年来，将动物器官移植到人体的科学取得了稳步进展。借助CRISPR-Cas9等技术，现在可以在一头猪中进行多种基因操作，以克服免疫（排斥）屏障。其中包括插入可能影响移植猪器官功能的基因，以及删除可能感染接受猪移植物的患者的病毒基因。虽然有些猪经历了多达69次基因编辑，但大多数猪只进行了大约10次基因编辑。

这种理解和精确编辑基因组的能力，加上新的免疫抑制药物治疗方案，使得拥有维持生命的猪肾脏或心脏的非人类灵长类动物的生存期现在可以延长数月甚至数年（在肾移植的情况下）。

此外，了解基因组提供的不仅仅是用于移植的器官。美国有超过100万患者患有1型糖尿病（青少年糖尿病），估计有3000万患者患有2型糖尿病，可以通过移植猪胰岛细胞（产生胰岛素）来治愈。美国有100万帕金森病患者；植入特殊的猪细胞可以改善它们的状况。

如果"异种移植"，即从动物身上移植器官到人类身上，成为一种常见的治疗形式，它不仅会影响数百万患者的生活质量，还会带来医疗保健经济的变化。

例如，参与透析方案的工作人员可能会大幅减少，而参与器官和细胞移植各个方面的工作人员，包括养猪工作人员可能会增加。尽管异种器官移植一开始会很昂贵，但可能很快就会证明，它比维持长期透析的病人或需要经常紧急入院的心力衰竭病人更便宜。

实验室的进展令人鼓舞，美国食品和药物管理局（FDA）批准对两名活体患者进行猪心脏移植（2022年和2023年），以及对一名患者进行猪肾移植（2024年）。虽然这三例移植手术的接受者都不幸在手术后去世，但人类器官捐赠的轨迹表明，随着研究的进展和技术的进步，存活率将显著提高。

异种移植引起了道德方面的考虑，需要进一步探索，最好是由政策、商业和社会领域的各个领导人进行探索。此外，仍需要从最初的患者试验中获取大量数据，以确保治疗效果最大化。然而，从现有移植技术中获得的可靠经验，再加上基因编辑技术能力的提高和成本的下降，表明我们有充分的理由对种间移植的未来持乐观态度，以防止每年成千上万的人类生命不必要的损失。医疗保健和工业领域的这些变化发生的速度有多快还将取决于监管机构和社会如何应对这一新的治疗领域。

> 这种理解和精确编辑基因组的能力，加上新的免疫抑制药物治疗方案，使得拥有维持生命的猪肾脏或心脏的非人类灵长类动物的生存期现在可以延长数月甚至数年。

↑ 图片：移植基因组学可以可能会彻底改变移植并解决器官短缺问题。

图片来源：Midjourney和Studio Miko。

提示（简略）："细胞"

阅读更多：

更多专家分析请访问移植基因组学 变换图。

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Organ transplantation, a significant advancement in medicine during the latter half of the 20th century, has continued to progress. This ongoing evolution was underscored by a remarkable milestone in March 2024: the first successful transplantation of a non-human (pig) kidney into a living human recipient.[61] This progress is driven by fundamental enablers such as our ability to understand and precisely edit the genome.

Organ transplants save lives – but the need far outstrips the available donor pool. In the US alone, more than 100,000 patients are awaiting an organ transplant, and yet only approximately 30,000 organs will become available this year.[62]

To meet this need, for more than three decades, steady progress has been made in the science dealing with the transplantation of organs from animals into humans. Thanks to technology like CRISPR-Cas9, it is now possible to create multiple genetic manipulations in a single pig to overcome the immunological (rejection) barrier. These include inserting genes that may impact the function of the transplanted pig organ and deleting genes for viruses that might infect the patient who receives a pig graft. While some pigs have undergone as many as 69 gene edits, the majority have approximately 10 gene edits.[63]

This ability to understand and precisely edit the genome, coupled with novel immunosuppressive drug regimens, has enabled the survival of non-human primates with life-supporting pig kidneys or hearts for periods now extending months or even years in the case of kidney transplantation.

Furthermore, understanding genomes offers much more than organs for transplantation. Over one million patients in the US have type 1 diabetes (juvenile diabetes), and an estimated 30 million have type 2 diabetes, which could be cured by the transplantation of pig pancreatic islet cells (which produce insulin).[64] There are over one million patients in the US with debilitating Parkinson's disease; implanting specialized pig cells could improve their condition.[65]

If "xenotransplantation", or the transplantation of organs from animals into humans, becomes a common form of therapy, it would impact not only the quality of life of millions of patients but could also bring about changes in the healthcare economy. For example, there could be significant reductions in the number of staff involved in dialysis programmes and an increase in those involved in all aspects of organ and cell transplantation, including pig breeding. Although xenotransplantation will initially be expensive, it might soon prove less costly than maintaining a patient on long-term dialysis or a patient with heart failure who requires frequent emergency admissions to the hospital.

Progress in the laboratory has been sufficiently encouraging, enabling the US Food and Drug Administration (FDA) to approve pig heart transplants in two living patients (in 2022 and 2023) and a pig kidney transplant in one patient (in 2024).[66,67,68] Although the recipients of all three transplants sadly passed away after the procedures, the trajectory of human organ donations indicates that survival rates will significantly improve as research progresses and techniques advance.

Xenotransplantation raises ethical considerations that need further exploration, ideally by various leaders in policy, business and societal spaces. In addition, a vast amount of data still needs to be acquired from initial patient trials to ensure the efficacy of treatments is maximized. However, solid prior learnings from established transplant technology, combined with the increasing capability and dropping costs of gene-editing techniques, indicate good reasons to be optimistic regarding the future of interspecies transplants to prevent the needless loss of hundreds of thousands of human lives each year. How quickly these changes in healthcare and industry occur will also depend on how regulatory authorities and society respond to this new therapy field.

> "This ability to understand and precisely edit the genome, coupled with novel immunosuppressive drug regimens, has enabled the survival of nonhuman primates with life-supporting pig kidneys or hearts for periods now extending months or even years.

↑ **Image:** Genomics for transplants can potentially revolutionize transplantation and address organ shortages.

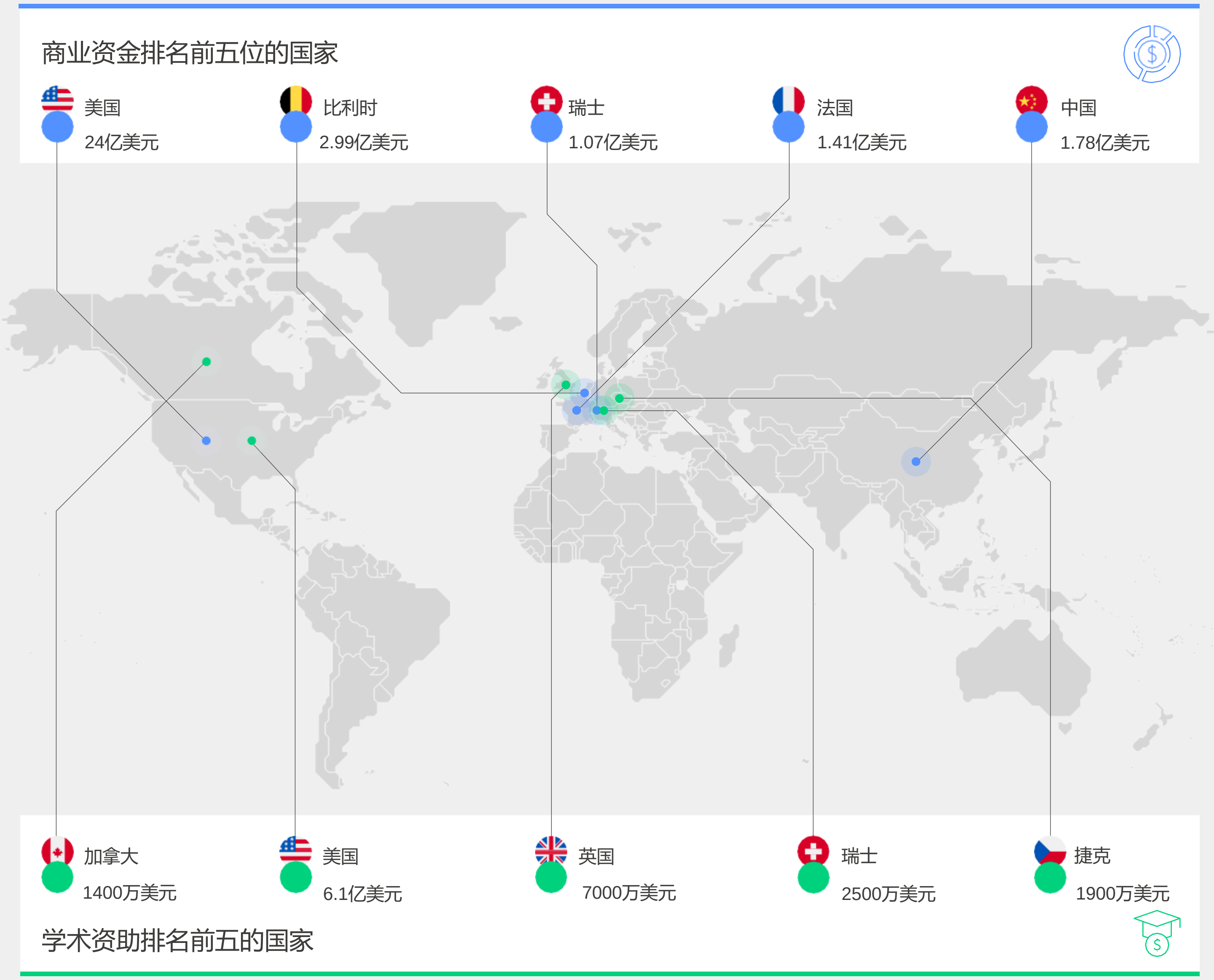
Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Cells"

Read more: For more expert analysis, visit the genomics for transplants transformation map.

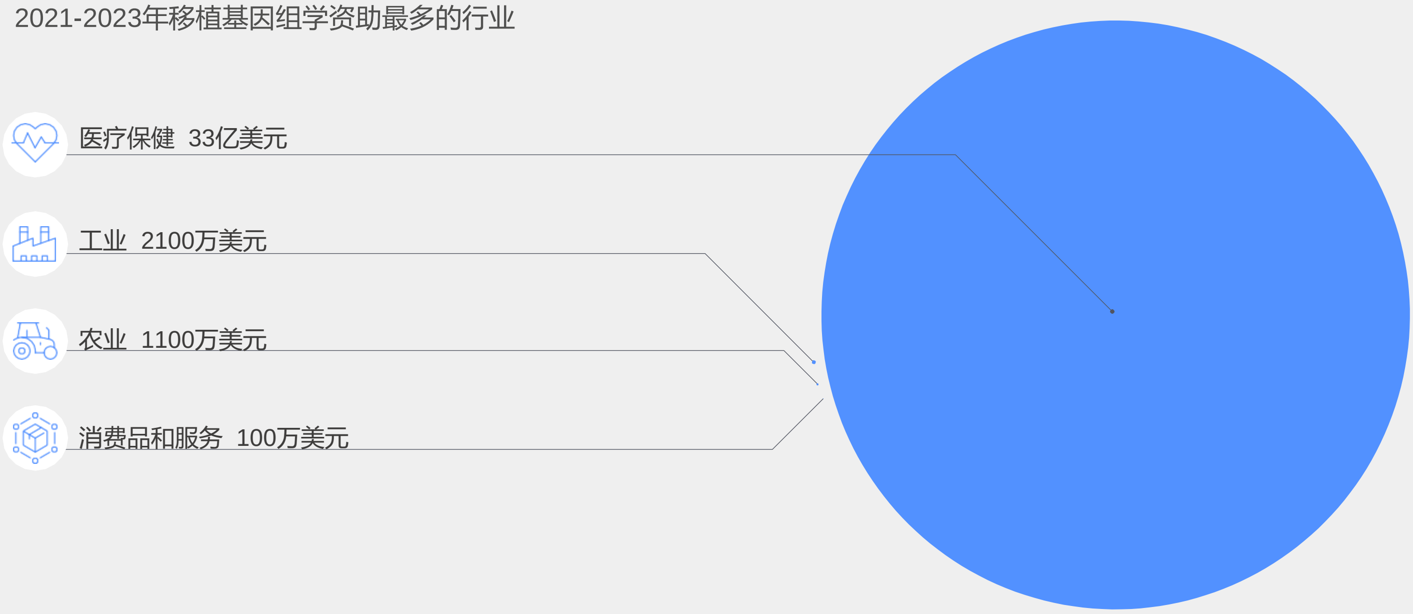
创新领域

2021-2023年移植基因组学商业和学术拨款最多的国家



前沿产业

2021-2023年移植基因组学资助最多的行业

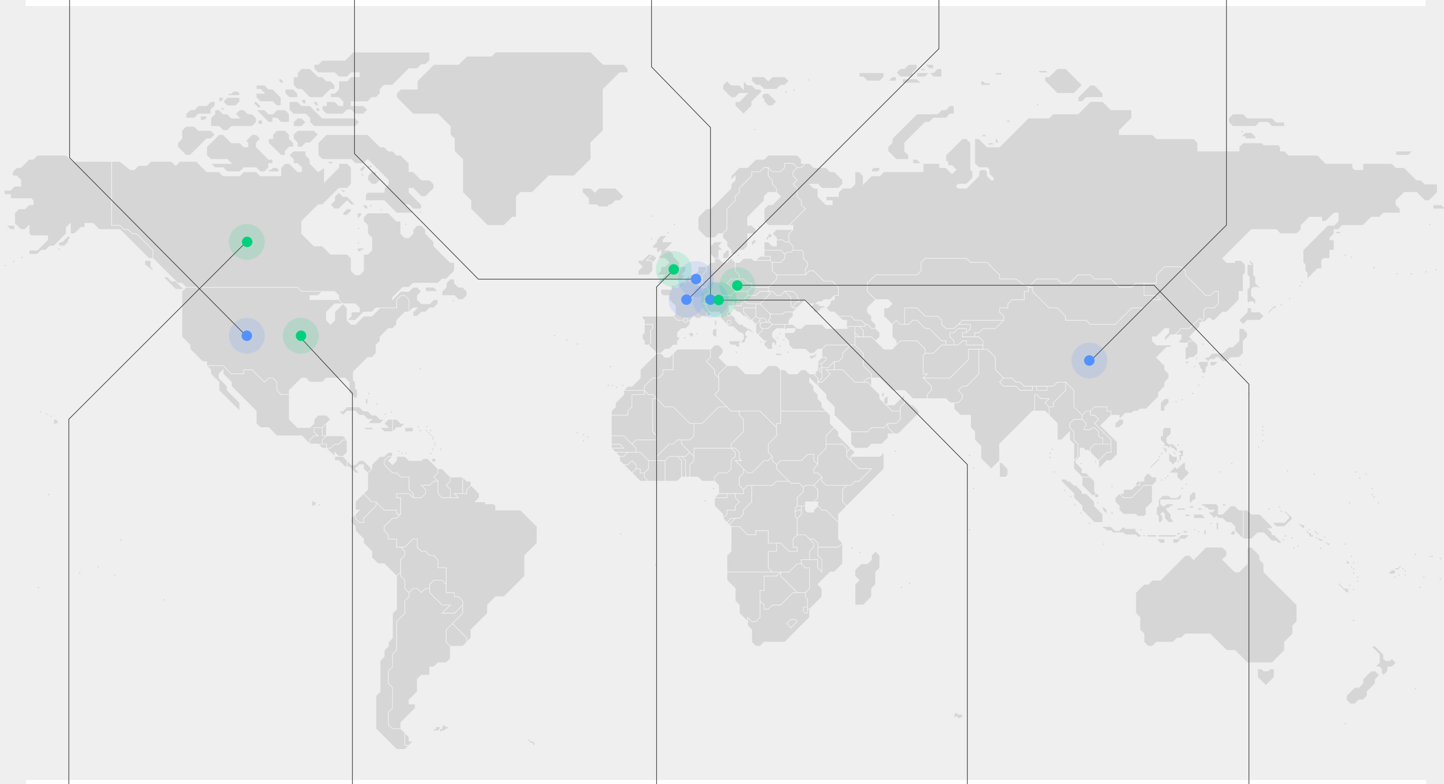


Regions of innovation

Countries with the most business and academic grant funding in genomics for transplants from 2021-2023

Top five countries by business funding

1. United States $2.4 billion
2. Belgium $299 million
5. Switzerland $107 million
4. France $141 million
3. China $178 million



5. Canada $14 million
1. United States $610 million
2. United Kingdom $70 million
3. Switzerland $25 million
4. Czechia $19 million

Top five countries by academic grant funding

Leading-edge industries

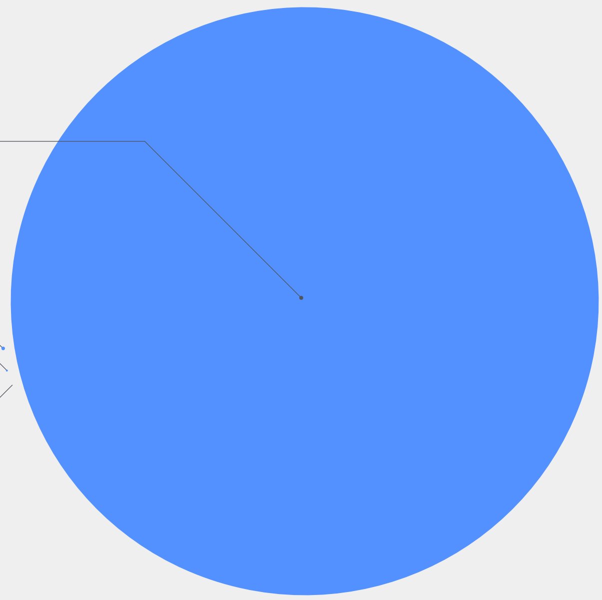
Industries with the most funding in genomics for transplants from 2021-2023

Healthcare $3.3 billion

Industrials $21 million

Agriculture $11 million

Consumer products and services $1 million



Appendix: Data methodology

A1 Introduction

This appendix provides a detailed overview of the data sources, collection methods, processing steps, analytical techniques, assumptions and limitations used in this report. This information is crucial for understanding the context and reliability of the data presented in the graphics.

A2 Data sources

– **Academic grant funding:** Data was sourced from Dimensions for all grants starting between 2021 and 2023.

– **Business funding:** Data was sourced from CB Insights for total funding from 2021 to 2023.

A3 Data collection methods

Data was collected based on the following criteria:

– **Geographical scope:** For academic grant funding, the location of the primary affiliated institutions of the grantees was used. For funding data, the location of the companies that received funding was considered.

– **Time period:** Data was collected for the period from January 2021 to December 2023.

– **Industry scope:** Specific technology sectors were analysed using key phrase matches against titles and abstracts of grants and funding records.

A4 Data processing

The following steps were taken to process the data:

– **Cleaning and preparation:** Grants with no funding amounts were excluded from the counts and sums. Similarly, data entries without relevant funding amounts were excluded from the analysis.

– **Transformation:** Key phrase matching was performed against titles and abstracts to identify relevant records.

– **Software and tools:** Data processing was conducted using software tools such as Python for data cleaning and transformation.

A5 Analytical techniques

The following analytical techniques and methodologies were employed:

– **Statistical methods:** Analysis of the number of grants and total funding amounts by region and industry.

– **Visualization tools:** Visualizations were created using CB Insights to illustrate funding trends by geography and industry.

A6 Assumptions and limitations

– **Assumptions:** It was assumed that the data provided by Dimensions and CB Insights is accurate and up-to-date as of the run date.

– **Limitations:** Potential biases exist due to the exclusion of grants and funding records with no funding amounts. The availability and granularity of data may vary across different regions and industries.

A7 References

Dimensions Database, 2024. Data retrieved on 24/04/24.
CB Insights Database, 2024. Data retrieved on 24/04/24.

TABLE 1 **Key phrase matches for tech sectors**

Technology	Key phrases
AI for scientific discovery	(Artificial intelligence OR large language models) AND (scientific discovery OR research OR science)
Privacy-enhancing technologies	Synthetic data OR data simulation OR data generation OR data anonymization OR privacy-enhancing data
Reconfigurable intelligent surfaces	Reconfigurable intelligent surfaces OR 6G OR wireless communication OR smart cities
Integrated sensing and communications	Integrated sensing OR communications integration OR sensor fusion OR telemetry OR wireless sensor network OR multi-sensor systems
High altitude platform stations	High altitude platform system OR aeronautical engineering OR high-altitude platforms OR stratospheric OR high-altitude OR airship technology
Immersive technology for the built world	Assistive reality OR built environment OR building information modelling OR design complexity OR construction technology OR digital twin OR spatial computing
Elastocalorics	Elastocaloric OR heat pumps OR cooling system OR thermal management
Carbon-capturing microbes	Microbial systems OR microbial carbon capture OR bioremediation OR microbial consortia OR microbial metabolism
Alternative livestock feeds	Alternative animal feed OR animal nutrition OR plant-based feed OR insect-based feed
Genomics for transplants	Genetically engineered organs OR genetic engineering OR organ engineering OR transgenic organs OR organ transplantation OR tissue engineering

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Frontiers in Big Data
Frontiers in Built Environment
Frontiers in Communications and Networks
Frontiers in Digital Health
Frontiers in Energy Research
Frontiers in Materials
Frontiers in Signal Processing
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Endnotes

1. *Google*. (n.d.). *DeepMind AlphaFold*. https://deepmind.google/technologies/alphafold/.
2. Wong, F., E. J. Zheng, J. A. Valeri, N. M. Donghia, et al. (2024). Discovery of a structural class of antibiotics with explainable deep learning. *Nature*, vol. 626, no. 7997, pp. 177-185. https://doi.org/10.1038/s41586-023-06887-8.
3. Conover, E. (2024). *Artificial intelligence helped scientists create a new type of battery*. Science News. https://www.sciencenews.org/article/artificial-intelligence-new-battery.
4. President's Council of Advisors on Science and Technology. (2024). *Supercharging Research: Harnessing Artificial Intelligence to Meet Global Challenges.*
5. Ibid.
6. Maynard, A.D. & S. M. Dudley. (2023). Navigating Advanced Technology Transitions Using Lessons from Nanotechnology. *Nature Nanotechnology*, vol. 18, pp. 1118-1120.
7. Jordon, J., L. Szpruch, F. Houssiau, M. Bottarelli, et al. (2022). Synthetic Data -- what, why and how? *arXiv*. https://arxiv.org/abs/2205.03257.
8. Williams, E.A. (2024). *From Promising to Practical: The Transformative Impact of Homomorphic Encryption*. Techspective. https://techspective.net/2024/04/04/from-promising-to-practical-the-transformative-impact-of-homomorphic-encryption/#google_vignette.
9. R. L. Rivest, L. Adleman, M. L. Dertouzos, et al. (1978). On data banks and privacy homomorphisms. *Foundations of Secure Computation*, vol. 4, no. 11, pp. 169-180.
10. Gonzales, A., G. Guruswamy & S.R. Smith. (2023). Synthetic data in health care: A narrative review. *PLOS digital health*, vol. 2, issue 1, e0000082. https://doi.org/10.1371/journal.pdig.0000082.
11. Bartell, J. A., S.B. Valentin, A. Krogh, H. Langberg & M. Bøgsted. (2024). A primer on synthetic health data. *arXiv*. https://arxiv.org/abs/2401.17653.
12. *International Energy Agency*. (n.d.). *Data Centres and Data Transmission Networks*. https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks.
13. Basar, E., M. Di Renzo, J. De Rosny, M. Debbah, et al. (2019). Wireless communications through reconfigurable intelligent surfaces. *IEEE Access*, vol. 7, pp. 116753-116773.
14. Di Renzo, M., A. Zappone, M. Debbah, M-S. Alouini, et al. (2020). Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and road ahead. *IEEE Journal of Selected Areas in Communications*, vol. 38, no. 11, pp. 2450-2525.
15. Abdelhady, A., A. Salem, O. Amin, B. Shihada, & M-S. Alouini, VLC via intelligent reflecting surfaces: Metasurfaces vs mirror arrays. *IEEE Open Journal of Communication Society*, vol. 2, pp. 1-20, January 2021.
16. Feng, Y., Q. Hu, K. Qu, W. Yang, et al. (2023). Reconfigurable Intelligent Surfaces: Design, Implementation, and Practical Demonstration. *Electromagnetic Science*, vol. 1, no. 2, pp. 1-21, https://www.emscience.org/en/article/doi/10.23919/emsci.2022.0011.
17. Syed, M.S.B., H.M. Attaullah, S. Ali, & M.I. Aslam. (2023). Wireless Communications beyond Antennas: The Role of Reconfigurable Intelligent Surfaces. *Engineering Proceedings*, vol. 32, no. 10. https://doi.org/10.3390/engproc2023032010.
18. Nie, S. & M. Can Vuran. (2023). AgRIS: wind-adaptive wideband reconfigurable intelligent surfaces for resilient wireless agricultural networks at millimeter-wave spectrum. *Frontiers in Communications and Networks*, vol. 4. https://www.frontiersin.org/articles/10.3389/frcmn.2023.1169266/full.
19. Wood, L. (2022). Global 6G Communications Reconfigurable Intelligent Surface Materials and Hardware Markets 2022-2023 and 2043. *Businesswire*. https://www.businesswire.com/news/home/20220726005634/en/Global-6G-Communications-Reconfigurable-Intelligent-Surface-Materials-and-Hardware-Markets-2022-2023-2043---ResearchAndMarkets.com.
20. *European Telecommunications Standards Institute (ETSI)*. (n.d.). *Reconfigurable Intelligent Surfaces*. https://www.etsi.org/technologies/reconfigurable-intelligent-surfaces#:~:text=RIS%20can%20be%20potentially%20deployed,RIS%20a%20sustainable%20technology%20solution.
21. Belmekki, B. E. Y. et al. (2024). Cellular Network From the Sky: Toward People-Centered Smart Communities. *IEEE Open Journal of the Communications Society*, vol. 5, pp. 1916-1936.
22. Lopez, E. (2024). Digital inequalities faced by older people have been exacerbated by COVID-19. *Universitat Oberta de Catalunya*. https://www.uoc.edu/en/news/2024/digital-inequalities-faced-by-older-people.
23. GSMA. (2021). *High Altitude Platform Systems Towers in the Skies*. https://www.gsma.com/solutions-and-impact/technologies/networks/wp-content/uploads/2021/06/GSMA-HAPS-Towers-in-the-skies-Whitepaper-2021.pdf.
24. GSMA. (2021). *High Altitude Platform Systems*. https://hapsalliance.org/wp-content/uploads/formidable/12/Driving_the_potential_of_the_stratosphere_HAPSAlliance_082021.pdf.

25. Grand View Research. (2022). *High Altitude Platforms Market Size & Trends*. https://www.grandviewresearch.com/industry-analysis/high-altitude-platforms-market-report.

26. International Civil Aviation Organization (ICAO). (2022). *Aviation Safety and Air Navigation Standardization*. https://www.icao.int/Meetings/a41/Documents/WP/wp_085_en.pdf.

27. Sweeney, M. (2021). *Global shortage in computer chips 'reaches crisis point'*. The Guardian. https://www.theguardian.com/business/2021/mar/21/global-shortage-in-computer-chips-reaches-crisis-point

28. Haider, M.A., & Y.D. Zhang. (2023). RIS-aided integrated sensing and communication: a mini-review. *Frontiers in Signal Processing*, vol. 3. https://www.frontiersin.org/articles/10.3389/frsip.2023.1197240/full.

29. Liberato Ullo, S. & G.R. (2020). Advances in Smart Environment Monitoring Systems Using IoT and Sensors. *Sensors*, vol. 20, issue 11. https://www.mdpi.com/1424-8220/20/11/3113.

30. *US Department of Energy*. (n.d.). *Smart Grid: What is a Smart Grid?* https://www.energy.gov/oe/services/technology-development/smart-grid.

31. Liu, Y., & K. Yang. (2022). Communication, sensing, computing and energy harvesting in smart cities. *IET Smart Cities*, vol. 4 issue 4, pp. 265-274. https://doi.org/10.1049/smc2.12041.

32. Metin, T., M. Emmelmann, M. Corici, V. Jungnickel, et al. (2020) Integration of Optical Wireless Communication with 5G Systems. *IEEE Xplore*. https://ieeexplore.ieee.org/document/9367502.

33. *ETSI*. (n.d.). *Industry Specification Group (ISG) Integrated Sensing and Communications (ISAC).* https://www.etsi.org/committee/2295-isac.

34. United Nations Environmental Programme. (2023). *Building Materials And The Climate: Constructing A New Future*. https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future,

35. *Digital Twin Consortium*. (n.d.). *Why Sustainability for Buildings?* https://www.digitaltwinconsortium.org/the-why-and-the-what-of-digital-twin-building-performance-and-sustainability-an-owners-perspective-form.

36. Associated Builders and Contractors. (2024). *ABC: 2024 Construction Workforce Shortage Tops Half a Million* [Press release]. https://www.abc.org/News-Media/News-Releases/abc-2024-construction-workforce-shortage-tops-half-a-million.

37. *McKinsey & Company*. (2022). *What is the metaverse?* https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-the-metaverse.

38. *Shimizu*. (2024). *Remote Inspections of Under-Construction Buildings in the Metaverse*. https://www.shimz.co.jp/en/company/about/news-release/2024/2023063.html.

39. Babalola, A., S. Musa, M.T. Akinlolu, & T.C. Haupt. (2023). A bibliometric review of advances in building information modelling (BIM) research*. Journal of Engineering, Design and Technology*, vol. 21, no. 3, pp. 690-710.

40. International Energy Agency. (2018). *The Future of Cooling*. https://www.iea.org/reports/the-future-of-cooling.

41. US Department of Energy. (2014). *Energy Savings Potential and RD&D Opportunities for Non-Vapor Compression HVAC Technologies*. p.7. https://www.energy.gov/sites/prod/files/2014/03/f12/Non-Vapor%20Compression%20HVAC%20Report.pdf.

42. Ibid.

43. Wang, Y., Y. Liu, S. Xu, G. Zhou, et al. (2023). Towards practical elastocaloric cooling. *Communications Engineering*, vol. 2, no. 79. https://doi.org/10.1038/s44172-023-00129-5.

44. Ibid; Qian, S., D. Catalini, J. Muehlbauer, B. Liu, et al. (2023). High-performance multimode elastocaloric cooling system. *Science*, vol. 380, no. 6646, pp. 722-727. https://doi.org/10.1126/science.adg7043; Tusek, J., K. Engelbrecht, D. Eriksen, S. Dall'Olio, et al. (2016). A regenerative elastocaloric heat pump. *Nature Energy*, vol. 1, no. 16134. https://doi.org/10.1038/nenergy.2016.134; Kirsch, S-M., F. Welsch, N. Michaelis, M. Schmidt, et al. (2018). NiTi-Based Elastocaloric Cooling on the Macroscale: From Basic Concepts to Realization. *Energy Tech*, vol. 6, no. 8, pp. 1567-1587. https://doi.org/10.1002/ente.201800152; Zhou, G., Y. Zhu, S. Yao, & Q. Sun. (2023). Giant temperature span and cooling power in elastocaloric regenerator. *Joule*, vol. 7, no. 9, pp. 2003-2015. https://doi.org/10.1016/j.joule.2023.07.004; Exergyn. (n.d.). *SMA Technology*. https://www.exergyn.com/technology/.

45. Wang, Y., Y. Liu, S. Xu, G. Zhou, et al. (2023). Towards practical elastocaloric cooling. *Communications Engineering*, vol. 2, no. 79. https://doi.org/10.1038/s44172-023-00129-5.

46. Yaashikaa, P.R, A. Saravanan, P. Senthil Kumar, P. Thamarai, & G. Rangasamy. (2024). Role of microbial carbon captue cells in carbon sequestration and energy generation during wastewater treatment: A sustainable solution for cleaner environment. *Internation Journal of Hydrogen Energy*, vol. 52, part D, pp. 799-820. https://www.sciencedirect.com/science/article/abs/pii/S0360319923027234.

47. Lim, J., S.Y. Choi, J.W. Lee, S.Y. Lee, & H. Lee, H. (2023). Biohybrid CO_2 electrolysis for the direct synthesis of polyesters from CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, vol 120, issue 14, e2221438120. https://doi.org/10.1073/pnas.2221438120.

48. Examples of companies active in the field: Using photosynthetic organisms: Algae Systems (https://www.algaesystems.com), CyanoCapture (https://www.cyanocapture.com), Photanol (https://photanol.com), Phytonix (https://phytonix.com); Using other microbes: Cemvita (https://www.cemvita.com), Deep Branch Biotechnology (https://deepbranch.com), Novonutrients (https://www.novonutrients.com).

49. Ibid.

50. *Bloomberg Finance* (2024). *Carbon Capture Investment Hits Record High of $6.4 Billion*. https://about.bnef.com/blog/carbon-capture-investment-hits-record-high-of-6-4-billion/.

51. Bhatia S.K. et al. (2019). Carbon dioxide capture and bioenergy production using biological system - A review. *Renewable and Sustainable Energy Reviews*, vol. 110, pp. 143-158.

52. Hong, W.Y. (2022). A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO_2 emissions future. *CCST*, vol. 3, 100044. https://doi.org/10.1016/j.ccst.2022.100044.

53. Nappa, M., M. Lienemann, C. Tossi, P. Blomberg, et al. (2020). Solar-Powered Carbon Fixation for Food and Feed Production Using Microorganisms – A Comparative Techno-Economic Analysis. *ACS Omega*, vol. 5 no. 51, pp. 33242-33252. https://dx.doi.org/10.1021/acsomega.0c04926.

54. *Food and Agriculture Organization of the United Nations (FAO)*. (n.d.). *FAOSTAT - Food and Agriculture Data*. https://www.fao.org/faostat/en/#data.

55. *World Wide Fund for Nature (WWF)*. (n.d.). *Deforestation and Food: Your Questions Answered*. https://www.wwf.org.uk/food/deforestation-and-food-your-questions-answered.

56. Guo, R., et al. (2021). Microalgal-based feed: promising alternative feedstocks for livestock and poultry production. *Journal of Animal Science and Biotechnology*, vol. 12, no. 5. https://jasbsci.biomedcentral.com/articles/10.1186/s40104-021-00593-z.

57. Altman, A.W., et al. (2024). Review: Utilizing industrial hemp (Cannabis sativa L.) by-products in livestock rations. *Animal Feed Science and Technology*, vol. 307, no. 115850.

58. Li, H., & A. Chaudhuri. (2022). Animal Design Through Functional Dietary Diversity for Future Productive Landscapes. *Frontiers in Sustainable Food Systems*, vol. 6, no. 933571. https://www.frontiersin.org/articles/10.3389/finsc.2022.933571/full.

59. *Verified Market Reports*. (n.d.). *Top Companies in the Edible Insects Market*. https://www.verifiedmarketreports.com/blog/top-companies-in-the-edible-insects/.

60. *Future Market Insights*. (n.d.). *Animal Feed Alternative Protein Market Report*. https://www.futuremarketinsights.com/reports/animal-feed-alternative-protein-market.

61. Chase, B. (2024). *World's First Genetically-Edited Pig Kidney Transplant into Living Recipient Performed at Massachusetts General Hospital*. Massachusetts General Hospital. https://www.massgeneral.org/news/press-release/worlds-first-genetically-edited-pig-kidney-transplant-into-living-recipient.

62. *US Department of Health & Human Services*. (n.d.). *Organ Donation Statistics*. https://www.organdonor.gov/learn/organ-donation-statistics.

63. Anand, R.P., J.V. Layer, D. Heja, et al. (2023) Design and testing of a humanized porcine donor for xenotransplantation. *Nature*, vol. 622, no. 7982, pp. 393-401. https://pubmed.ncbi.nlm.nih.gov/37821590/.

64. *American Diabetes Association*. (n.d.). *Diabetes Statistics*. https://diabetes.org/about-diabetes/statistics/about-diabetes.

65. *Parkinson's Foundation*. (n.d.). *Parkinson's Disease Statistics*. https://www.parkinson.org/understanding-parkinsons/statistics.

66. Griffith, B.P., C.E. Goerlich, A.K. Singh, et al. (2022). Genetically-modified porcine-to-human cardiac xenotransplantation. *New England Journal of Medicine*, vol. 387, pp. 35-44.

67. Cooper, D.K.C., & E. Cozzi. (2024). Clinical pig heart xenotransplantation - where do we go from here? *Transplant International*, vol. 37, no. 12592.

68. Mallapaty, S., & M. Kozlov. (2024). First pig kidney transplant in a person: what it means for the future. *Nature*, vol. 628, no. 8006, pp. 13-14.

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