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COMMENT

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# Towards a framework for a new research ecosystem

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There is a substantial disconnect between theoretical recommendations for how much a nation should invest in science, innovation, and technology, and the practical challenges of implementing those investments. In this note, we identify four key challenges that must be addressed to foster an environment conducive to collaboration across organizations and governments, while ensuring commercial rewards for both investors and innovators.

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> *"You may ask… How can I be a millionaire and pay no taxes…?"*
>
> *"FIRST: Make a million dollars…"*
>
> Steve Martin

## Introduction

Winston Churchill has been quoted[1] as admonishing that one should, "never let a good crisis go to waste." Churchill was commenting on the unique set of events that took place during and immediately following World War II that brought world leaders together to form the United Nations. Could a similarly coordinated approach be applied more broadly to help increase investments in science, innovation, and technology (SIT)? Perhaps. But several significant challenges need to be addressed.

First and foremost, structured SIT investment decisions are often impeded by the absence of a pressing crisis that would justify transformative objectives. Furthermore, identifying optimal R&D investment targets offers no guidance on how to implement them. Indeed, investing in transformative ("long shots") projects—costly initiatives with low probabilities of success but the potential for extraordinary returns—requires strong commitment and a long-term outlook, features that are often unattractive to the average investor (Fagnan et al., 2013). As a result, society may consistently miss opportunities to reap significant tangible and intangible benefits from long-term scientific research.

In this note, we outline and discuss four key issues that we have identified as critical challenges, which must be tackled to develop an environment conducive to collaboration across organizations and governments, while preserving commercial rewards for investors and innovators:

1. Encouraging researcher collaboration through physical and virtual cross-disciplinary laboratories that provide incentives and infrastructure for sharing research output at all stages of the scientific process.
2. Revising regulatory and legal frameworks for the governance and oversight of research, including mechanisms for protecting and sharing intellectual property (IP) rights.
3. Increasing funding incentives by adopting lower-risk financing models.
4. Demarcating specific roles and opportunities for governments and public institutions (GPI).

Rather than offering definitive solutions, our intention is to present a positive (i.e., non-normative) perspective on these challenges, and to outline a basic set of signposts to stimulate dialog among experts from various fields, including science, medicine, computer science, finance, law, policy, and academia. Our goal is to encourage global discussion, debate, and ultimately action that can contribute to the design of a new research ecosystem.

## Four challenges

**Challenge #1: Research collaborations**. Several studies provided empirical evidence of a sharp decline in research productivity over the first two decades of the 21$^{st}$ century, despite an increase in the number of researchers (see Bloom et al., 2020 and the literature discussed therein). There appear to be many reasons for this, including challenges in coordination and communication across various fields. From a practical perspective, one possible solution would be to encourage the formation of national and international research infrastructures (RIs) to benefit from economies of scale.

But are these coalitions desirable in the first place? And if so, how should they function? Our first challenge lies in establishing coordination mechanisms that enable them to be feasible and effective.

Within specific areas of basic research, feasible coalitions could take the form of what we call "virtual labs". Virtual labs consist of distributed teams of researchers and technicians who work remotely on various components of a given problem, integrating their work through virtual or in-person workshops.

Virtual labs offer the potential to overcome communication barriers by utilizing technological solutions that help form research communities.[2] In these communities, teams can discover others working in related, adjacent, or even seemingly unrelated areas, and who may possess the skills and expertise to fill key gaps in their research agenda. This flexibility is particularly valuable in emerging fields, where the need for cross-disciplinary expertise may only become apparent as research progresses. For instance, "science of science" studies that explore past relational structures between scientists or scientific disciplines could yield insights into the origins of scientific discovery (Fortunato et al., 2018) or help target specific scientific objectives.

As discussed in Appendix A, virtual labs, when combined with physical labs, can accelerate and enhance scientific collaborations in the form of enhanced RIs, fostering more efficient cross-disciplinary research networks.

**Challenge #2: Governance and regulation**. Proper governance, well-designed incentives, and the allocation of ownership rights are essential for the successful creation of new intellectual property through joint efforts among the participants of a venture (Lerner and Wulf, 2007; Tian and Twite, 2011). It is essential that individual contributors and organizations manage the sharing of information effectively through collaborative agreements that address both scientific and business goals.

Regulatory bodies will also have opportunities to reconsider the requirements and restrictions they have established for various forms of research and subsequent commercialization. Importantly, while these protocols shape the frameworks used for translational science in most domains, many of them are still relatively new.

To be clear, what we are suggesting is that researchers from industry, government and the private sector would benefit from controlled, sometimes coordinated, appeals for more eyes or minds on specific aspects of interesting problems, along with assurances that their contributions will be recognized and rewarded. It remains an open (and empirical) question whether this approach would be best achieved through consortia, jointly funded research projects, a marketplace for expertise and data, or some other form.

In this regard, the regulator's challenge of balancing the protection of intellectual property rights (IPR) with the generation of positive externalities from Open Science represents a complex landscape of trade-offs. On the one hand, IPR protection can stimulate innovation by granting creators exclusive control over their work, allowing them to recover their investments and generate financial returns. On the other hand, overly restrictive IPR regimes can hinder the dissemination of knowledge, limit collaboration, and delay follow-on innovation. Quite the opposite, Open Science approaches, which emphasize openness, transparency, and sharing of research results, can accelerate scientific progress, promote collaboration, and drive societal impact, at the cost of undermining private innovation incentives.

An efficient and effective research ecosystem needs to balance the rights of creators with the benefits of openness and sharing, particularly in areas such as data sharing, open access publishing, and collaborative research. Flexible licensing models, such as open licenses and Creative Commons licenses, can help achieve this balance by allowing for the free use and reuse of research outputs while still providing protection for intellectual property (see European Commission, 2022). Open Science can complement IPR protection by promoting the development of new ideas and innovations. A balanced approach to IPR protection and Open Science can foster a research environment that encourages collaboration, accelerates scientific breakthroughs, and ultimately benefits society as a whole (Crouzier, 2017).

**Challenge #3: Accelerating funding**. Although funding is often discussed as the primary challenge to enabling SIT (or "long-shot") investments, it is ironically the one for which we already seem to have some of the most well-developed solutions. We describe SIT investments as "long shots" in the sense of Hull et al. (2019), as they feature the following characteristics: (a) a very low probability of success; (b) a long time horizon; (c) substantial upfront capital requirements; but which also enjoy (d) extraordinary commercial returns upon success. Conversely, we refer to scientific investments that offer no direct economic returns and lack immediate practical applications—driven purely by a fundamental curiosity to uncover the universe's underlying truths—as "blue-sky" research.

Science-focused investment vehicles can potentially mitigate long-shot and blue-sky research problems by employing results from modern portfolio theory. This approach provides guidance on structuring investment portfolios to reduce volatility (risk) while maintaining attractive return profiles relative to individual investments in the short and the long run.

In this regard, recent work by financial economists has demonstrated that risk-pooling structures can serve as the basis for effective funding vehicles that provide longer-term capital for research, while delivering competitive market-rate returns for investors. Most notably, a new class of derivative securities known as Research-Backed Obligations (RBOs)—namely, debt and equity securities backed by the pool of underlying drug assets issued by 'mega-funds' to raise capital and finance the development of pipeline drugs in its portfolio—are designed to fund portfolios of pooled long-shot research investments in candidate medical therapies for cancer and rare genetic diseases by taking advantage of portfolio diversification to issue high-quality (and thus lower cost) portfolio-level debt (Fernandez et al., 2012; Fagnan et al., 2014).

Similarly structured financial vehicles could play a key role in increasing investment in other areas of scientific research. Importantly, these new structures do *not* require investors to forgo financial returns to achieve positive research impacts. Instead, they are designed to offer attractive risk-adjusted return profiles while *also* generating impact.

However, not all R&D challenges are suitable for vehicles such as RBOs. For example, the current state-of-the-art in Alzheimer's research, along with the dearth of viable AD (Alzheimer Disease) therapy projects appears to make funding research in that area via an RBO structure difficult due to an extremely high probability of failure and a lack of appropriate diversification options at the present time (Fagnan et al., 2014). Thus, while the RBO approach has broad applicability across many scientific domains—beyond just the pharmaceutical industry—and has shown early successes in biomedical research, there are still areas where this approach may not be suitable. In such settings, given the enormous scale of investment required and the exceedingly low ex-ante probability of success, it may be that only a well-funded, socially motivated entity, like a government agency, can ensure sufficient capital and investment discipline to fund research.

At this point, one might wonder how to organize a science-based investment vehicle (or Science-Based Fund, SBF) in practice. A possible structure is summarized in Fig. 1. In this

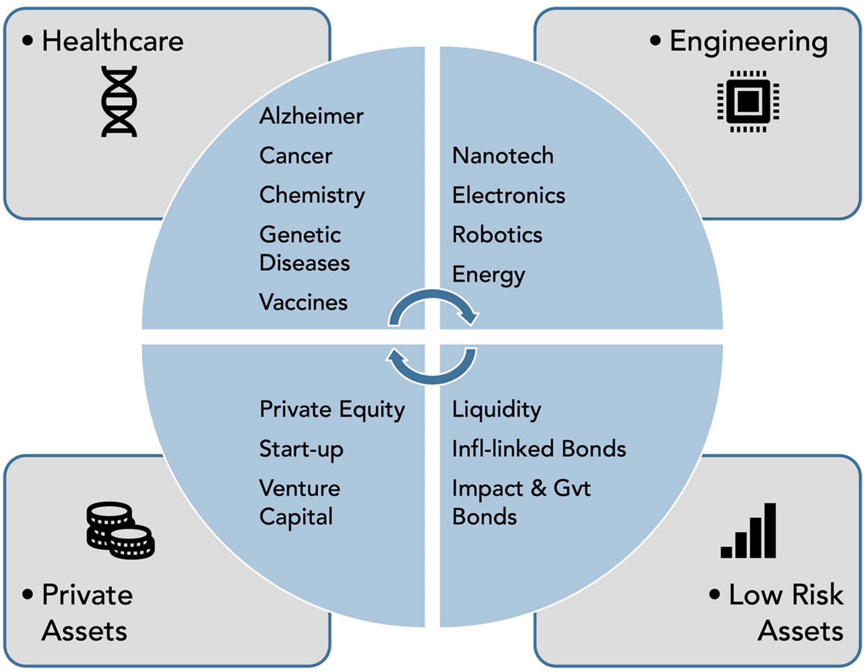


**Fig. 1 Science-based fund.** The Figure depicts the organizational structure of a Science-Based Fund. Investments are diversified between Private Assets (Pure and Secondary Market of successful Venture Capital, namely Private Equity and Start-up) and Low Risk Assets (investments in liquid assets to provide *interim* returns to the fund and reduce the overall portfolio risk). Private Assets are investments in healthcare and engineering sectors, spanning from Alzheimer, Cancer, Chemistry, Genetic Diseases, Vaccines, on the one hand, to Nanotechnology, Electronics, Robotics, Energy, on the other. High and low-risky research projects are combined with low-risky financial instruments under a cross-funding approach in which returns from financial vehicles and backup (low-risky) investments, together with rotational portfolio reallocations, are used to successfully fund lead (high-risky) projects.

example, the fund would focus on one or more broad scientific objectives, spanning multiple phases of R&D—from basic research to the translation of promising discoveries, and ultimately, commercialization.

Notably, such broad investment mandates require appropriate organizational architectures to minimize internal potential agency costs between principals (investors in and sponsors of the investment vehicles) and agents (the managers of the vehicles).[3] The investment vehicle might be sponsored in a number of ways. Examples include public sector coalitions of government agencies, private sector coalitions of venture capitalists and other institutional investment professionals, and public-private partnerships.

**Challenge #4: Roles and opportunities for governments and public institutions (GPI)**. Governments and public institutions can play a number of key roles to increase the feasibility of research ecosystems and to encourage their realization. Some of these roles include:

1. *Independent Project Evaluation*. One of the advantages of integrated research agendas and systems is that they offer the potential to scale up investment in R&D by channeling private capital, including capital from financial investors who do not have specific expertise in a particular research field. Unlike traditional venture capitalists, such investors are often not in a position to evaluate the merits or technical details of a specific project. Public Institutions, in the form of new agencies, can develop standards for independent projects' ratings or rankings relative to their expected marginal contribution to enhancing scientific knowledge and their environmental and societal impacts, while simultaneously providing regulatory clarity on the path to future commercialization.
   Practically, it will be useful to further segment evaluation functions into sets of very broad objectives. For example, it may be advantageous to use different rating methodologies and metrics to evaluate proposed initiatives depending on whether their objective is to (e.g.):

- Advance basic knowledge in some area—with no other specific goal or with goals that are likely unknown at the time of the research. (Such initiatives may be of little interest to private investors); or
- Translate research results into commercial applications in the form of long-term risky investments that have a goal, like reducing or curing cancer. (Such initiatives often involve intensive top private investors);
- Project pooling. In cases where public-private collaborations do make sense on both sides, members of the public sector can facilitate these collaborations by providing incentives for pooling projects that advance science in those fields where industry investment is insufficient or non-existent.
- In this context, GPIs can leverage their natural authority to:

   i. Convene participants and act as clearing houses for information;
   ii. Create incentive programs and tax relief;
   iii. Make direct investment (as discussed in the next point).

   Common practice used by governments and economists to evaluate the socio-economic-financial impacts of investment projects is the cost-benefit analysis (CBA). We suggest a more involved generalized evaluation approach, in which research investments are evaluated based on local (national/industry/firm) and global (world economy) costs and benefits using a general-equilibrium model to compute how much each country should invest in science and where to target basic and applied research, as in Gersbach et al. (2023).

2. *Minimum return guarantee*. If a pool of projects can be made large and diversified enough, it is reasonable to expect that investments in them will be remunerated, with a potentially extraordinary upside potential. However, determining the value of a share in such an investment can be difficult due to the very large uncertainty surrounding future cashflows. It is often hard enough to estimate future cashflows that will accrue for translating research that has already been developed (but not yet commercialized), and far more difficult still to do so for earlier stage research and IP. In this context, GPIs could reduce investor uncertainty through some form of downside protection, either by:

- Providing direct guarantees, thereby reducing risk for private investments (by covering the first-loss piece, for example);
- Purchasing shares of a Science-Based Fund or designated classes of RBO securities that would stand in a first-loss positioning in the capital structure (perhaps doing so at below market rates if needed) (Fagnan et al., 2013);
- Providing purchase guarantees for the resulting products that are brought to market. It can be shown that investments in the form of backstop guarantees, for example, have the potential to amplify and multiply government investments by attracting traditionally reluctant private investors to participate (Fagnan et al., 2013).

Such forms of initiatives may be a game-changer in motivating innovation, since government-funded investment firms are able to develop expertise in better identifying target firms for subsidies and in evaluating their cost structure (Bayar et al., 2019).

## Operationalizing a research ecosystem

The purpose of this article is to outline what we have identified as key impediments to the formation of multidisciplinary pan-geographic collaboration projects to address critical and, in some cases, existential societal challenges. We have specifically not attempted to propose omnibus solutions to any of these. Such solutions require many more eyes and ideas that we can bring to bear in a single article, and will sometimes demand resources and legal frameworks which we have no standing to allocate.

However, there are things that can be done to start this process. For example, one way to begin such efforts is to create a research ecosystem architecture (see Fig. 2).

As an initial, much less demanding foray into such planning and discussions, it is reasonable for smaller groups of researchers and other participants to undertake a set of pilot studies to explore what is currently feasible for addressing the four challenges we have outlined in this article. Such pilots would include experts from various relevant parties—academic, industrial, government and finance—with the goal of rigorously exploring—and perhaps competing—theoretical, technical, and institutional frameworks for the addressing specific aspects of the challenges we outlined earlier.

It seems both productive and feasible to consider exploring several broad sets of questions in parallel. For example, different pilot groups might undertake topics relating to:

- Research Collaboration Platform: The mandate of this pilot would be to create a framework for building "knowledge maps" that would allow researchers across disciplines to more easily understand how innovations outside of their core field might be valuable to achieving a specific scientific goal. This would naturally precipitate scientific collaborations across researchers and ideas (Challenge #1).

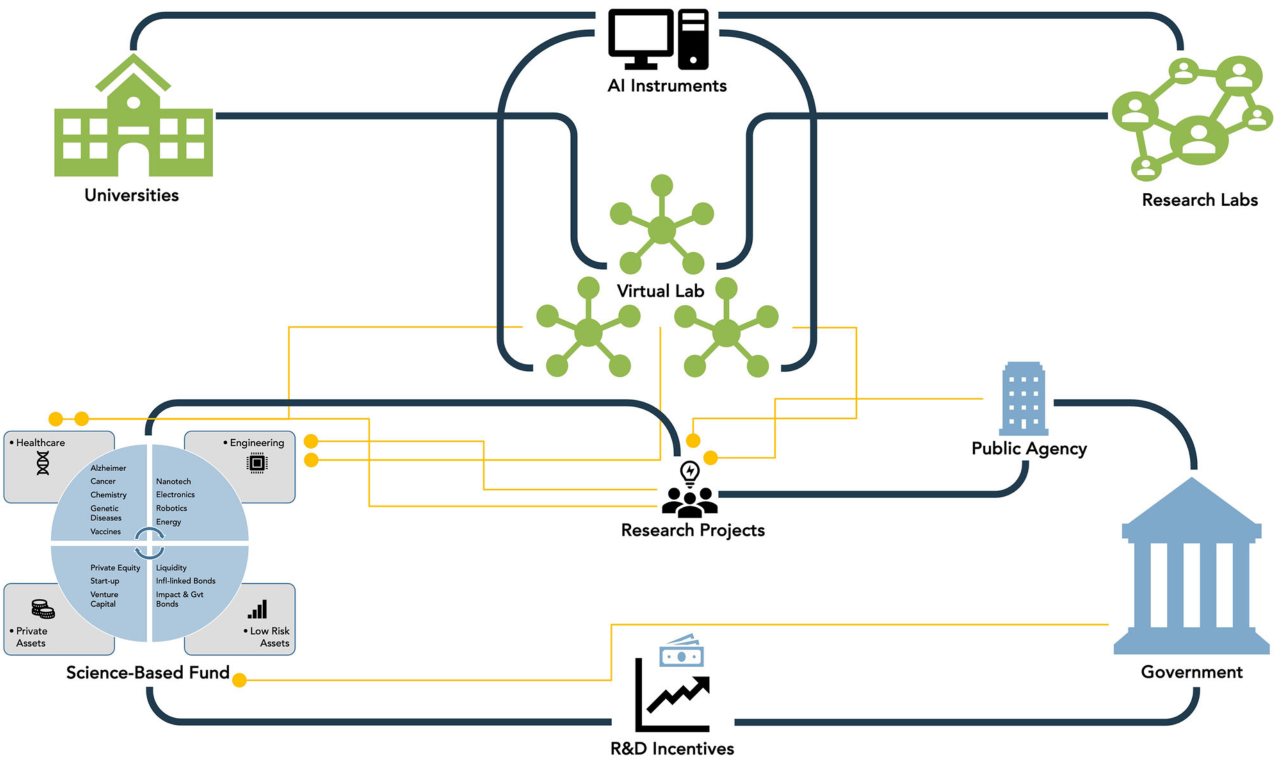


**Fig. 2 A hypothetical research ecosystem architecture.** The Figure shows a hypothetical Research Ecosystem Architecture with the three main actors: (1) Universities & Research Labs; (2) Science-Based Fund; (3) Government & Public Agency. Universities & Research Labs realize domain-specific academic research consortia and through advanced technology (AI Instruments) detect and cluster research ideas thereby forming Virtual Labs. Research Projects come from Virtual Labs, are evaluated by a Public Agency and incentivized (R&D Incentives) by the Government. Science-Based Funds invest in Research Projects, benefit from government incentives and collaborate with the Virtual Labs. A possible action plan to operationalize this Research Ecosystem Architecture is reported in Table 1.

- Marketplace of Ideas and translational IP: The mandate of this pilot would be to realize a decentralized market where innovators would be able to sell ideas to entrepreneurs and institutional investors using financial structures and instruments whose profitability was contingent on those ideas (Challenges #2, #3, and #4). Existing examples are EIC Marketplace (https://eic.ec.europa.eu/eic-communities/eic-marketplace_en), InvestEU Portal (https://ec.europa.eu/investeuportal/desktop/en/index.html), Innovation Radar (http://innovation-radar.ec.europa.eu), etc.
- Regulation and Supervision: The mandate of this pilot would be to draft a formal set of feasible options, both within current frameworks that could be achieved by introducing or modifying regulation and laws. This prolog would also enumerate and identify the roles and actors required to effectuate a research ecosystem supervision mechanism (Challenges #2 and #4).

Table 1 summarizes this example of the different pilots and how they fit together as part of the ecosystem. In addition, it gives examples of how each main actor might participate, and how they should interact with each other within the main challenges.

While biopharma (specifically, cancer, genetic & orphan diseases, mental disorder) is the first scientific area we could focus on, thanks to the abundant empirical evidence and proof-cases collected so far, the groups of pilots would offer insights on how to scale up to other scientific fields (engineering; energy; electronics; robotics; chemistry; nanotechnology).

## Closing the research funding gap

At the end of 2022, UNESCO estimated that global spending in R&D relative to GDP (R&D-to-GDP) was roughly 1.95%. As previously discussed, a fundamental issue is determining how much governments should globally invest in SIT.

Moving toward a global research ecosystem requires coordination among countries, which should quantify their individual research investments based on their distance from the technology frontier, while also accounting for the potential spillover effects.

To exemplify how this approach can be practically implemented, we consider a simplified version of the general-equilibrium framework proposed in Gersbach et al. (2023). We calibrate the model parameters using a sample of 23 high-income OECD countries, computing the theoretical R&D funding gap for each country based on data from 2018 to 2022 (technical details on the model, the data, and the calibration appear in Appendix B). Table 2 compares the average R&D-to-GDP ratios over the period 2018–2022 observed in the data and the corresponding optimal ratios according to the model.

Based on these numbers, we use end-of-2022 GDP data to estimate the R&D funding gap for each, as shown in Table 3. If the 23 countries considered in the experiment were to invest based on these estimates, they would need to close an aggregate R&D funding gap of about 605,908 million USD.

Even if there were the will to fill this gap, a second fundamental question arises: how could they invest in research while also compensating investors for the risks they take and/or providing minimum return guarantees?

**Table 1 Example high-level plan for topics and actors in research ecosystem implementation working pilots.**

| | Research collaboration | Market of ideas | Regulation & supervision |
|---|---|---|---|
| University Presidents Research Labs | Forming and participating in domain-specific academic research consortia Forming Consortia of Research Labs | IP agreements: joint ownership and foreground. Forming special independent vehicles for selling ideas in the market | Forming stakeholder groups within the Market of Ideas Board and contribute to define market regulation protocol. Interact within regulatory sandbox platforms (Governments) |
| Researchers | Propose requirements for and structure of Virtual Labs, potentially forming small scale proof-cases | Create and test framework for Virtual Labs for pilot working research projects (perhaps selected and evaluated by Governments) | |
| Investment Funds | Networking with solicited and unsolicited researchers (meetings, on-line platforms, open contests) to detect new forms of research combinations and start with new curiosity- or mission-driven projects | Structure and launch investment vehicles such as megafunds or Science-Based Funds, perhaps through private-public initiative | |
| Funding Agencies | Provide funding for realizing Virtual Labs. Defining mission-oriented projects. Provide funding and scientific coordination of meetings and activities | Provide funding for Market of Ideas infrastructure | |
| Governments | Providing independent project evaluation. Realizing project pooling. Designing appropriate IP agreements | Draft feasible mechanisms for providing various forms of downside protection for investors (direct guarantees, direct investments, etc.) | Design potential structures for regulatory sandbox platforms, including appropriate safeguards to contain inefficiencies and maintain the overall safety and soundness of the research ecosystem |

The Table reports an example of Research Ecosystem Implementation Working Plan: (1) *University Presidents, Research Labs, Researchers.* Domain-specific academic researchers constitute Consortia of Research Labs focusing on small-scale proof-cases along the lines discussed in section "Challenge #1: Research collaborations". They realize Virtual Labs and propose pilot working research proposals. Research projects are evaluated and selected by government-based agencies (section "Challenge #4: Roles and opportunities for governments and public institutions (GPI)"). IP agreements oversee the process of forming special independent vehicles for selling ideas in the market. Stakeholder groups contribute to defining market regulation protocols, interacting within government-based regulatory sandbox platforms. (2) *Investment Funds, Funding Agencies.* The target is to form portfolios of curiosity- or mission-driven projects through networking with solicited and unsolicited researchers. Meetings and online platforms (connected with virtual labs) are used to detect new forms of research combinations. Pilots should explore forms of project selection such as: open contests, lottery, equal allocation, automated scores, prediction markets, peer-to-peer evaluation (Barnett et al., 2017), as well as random allocation. All forms of project selection, alone and combined, would lead to portfolios of research projects and experimentation with research-based asset allocation strategies (section "Challenge #3: Accelerating funding"). (3) *Governments.* The role of governments is crucially important as they should maximize cross-country knowledge spillovers along the lines discussed in section "Challenge #4: Roles and opportunities for governments and public institutions (GPI)" (investments coordination across countries and industries), estimating how much countries should invest globally in STI also identifying feasible forms of downside protection for investors (direct guarantees, direct investments, etc.). The main target is to elaborate a regulatory framework including appropriate tools to contain inefficiencies and maintain the overall efficiency of the research ecosystem. This can be done, for example, through an integrated evaluation plan for designing optimal transformative innovation policies (as the framework suggested in Haddad and Bergek (2023). The approach should help identify the links between the policy intervention and its expected effects (economic, financial, societal) and then identify concrete STI goals and feasible targeted development paths.

A possible answer involving science-focused institutional investors—such as those discussed in Section "Challenge #3: Accelerating funding"—requires setting up and solving a suitable dynamic portfolio problem. In the problem, a fund manager wants to finance an intertemporal R&D spending plan by using the cashflows generated by its (risky and risk-free) asset holdings, managing its financial risks to ensure a minimum return at maturity (e.g., the long-run inflation rate). The spending plan entitles the fund to earn exceptionally high returns following low-probability, successful innovations. We design and solve a theoretical framework describing this problem in Appendix C. We parametrize the model with real data and use Monte Carlo simulations to evaluate the performance of its investment strategy over a 10-year horizon. Figure 3 summarizes the outcome of this exercise.

By construction, the investment strategy ensures that one-third of the fund's initial endowment is invested in R&D over 10 years, while preserving its real value after inflation. On top of this, and *even* in the absence of successful innovations, the fund yields an average return of about 29% (i.e., 2.5% a year). When at least one successful innovation occurs—which happens with a 4% probability in our simulations, based on the assumption of one successful innovation every 25 years (in line with Adams, 1990)—the fund grows by approximately 50% (i.e., 4% a year) net of R&D spending.

Implementing this investment strategy in practice to close the previously estimated R&D funding gap of 605,908 million USD would require an initial total endowment of approximately $605{,}908/0.3 = 2{,}019{,}693$ million USD, so that its total R&D investment would be 605,908 million USD at the end of the tenth year. At the same time, investors would be compensated for their risk—including a minimum return guarantee, which governments could adjust to incentivize private investment.

## Conclusion

In the past half century, a number of rigorous theoretical results have emerged in the economics literature and provided explanations for *why* investments in novel, ground-breaking scientific projects drive increases in overall welfare (Romer, 1986; Romer, 1990). However, a major gap exists between the *conceptual* suggestion of how much a nation "should" invest in core R&D and the *practical* implementation of what is done. One key reason for this gap is the difficulty that investors (and the public sector) have in trading off short-term costs against long-term planning and investing benefits.

In this short note, we have offered a coarse roadmap to some of the issues that we see as critical, and which must be driven to consensus in full or in part to motivate a more aggressive and fulsome scientific and financial transformation and redeployment of resources.

Our roadmap only provides a guide to the *hazards* in this rough terrain, rather than a *course* through them.

Nonetheless, if these issues can be resolved, and initiatives of the sort we have sketched here were adopted on a larger multinational and multidisciplinary scale, a massive science-oriented portfolio allocation could potentially open the door to new ways of research collaboration.

Achieving such scale will require that private investors are (financially) motivated to channel their capital towards science-based funding by investing in financial vehicles that can achieve

**Table 2 Optimal R&D-to-GDP spending.**

| | R&D-to-GDP (data) | R&D-to-GDP (optimal) | | |
|---|---|---|---|---|
| **Country** | **2018–2022** | **Min** | **Max** | **Average** |
| Luxembourg | 1.13% | 2.55% | 3.37% | 2.96% |
| France | 2.22% | 2.81% | 3.59% | 3.20% |
| Belgium | 3.20% | 2.85% | 3.62% | 3.23% |
| Austria | 3.18% | 2.86% | 3.63% | 3.24% |
| Norway | 2.08% | 2.87% | 3.63% | 3.25% |
| Greece | 1.42% | 2.88% | 3.64% | 3.26% |
| UK | 2.80% | 3.05% | 3.78% | 3.42% |
| Spain | 1.33% | 3.08% | 3.80% | 3.44% |
| Sweden | 3.41% | 3.13% | 3.84% | 3.48% |
| Japan | 3.28% | 3.14% | 3.86% | 3.50% |
| New Zealand | 1.44% | 3.17% | 3.87% | 3.52% |
| Netherlands | 2.18% | 3.21% | 3.91% | 3.56% |
| Italy | 1.43% | 3.23% | 3.92% | 3.58% |
| Australia | 1.73% | 3.40% | 4.06% | 3.73% |
| United States | 3.30% | 3.62% | 4.22% | 3.92% |
| Portugal | 1.54% | 3.63% | 4.23% | 3.93% |
| Germany | 3.08% | 3.70% | 4.29% | 3.99% |
| Canada | 1.82% | 3.76% | 4.33% | 4.05% |
| Finland | 2.90% | 3.94% | 4.46% | 4.20% |
| Switzerland | 3.25% | 4.01% | 4.52% | 4.27% |
| Denmark | 2.95% | 4.06% | 4.55% | 4.31% |
| Israel | 5.61% | 5.38% | 5.46% | 5.42% |
| Korea | 4.52% | 5.61% | 5.61% | 5.61% |
| **Min** | **1.13%** | **2.55%** | **3.37%** | **2.96%** |
| **Average** | **2.60%** | **3.48%** | **4.10%** | **3.79%** |
| **Max** | **5.61%** | **5.61%** | **5.61%** | **5.61%** |

The Table reports average basic R&D-to-GDP ratios (minimum, maximum, and average) over the period 2018–2022 and corresponding optimal ratios computed using the model proposed in Gersbach et al. (2023) for 23 OECD high-income countries. See Appendix B for technical details.

**Table 3 R&D investment gaps.**

| | GDP (Mln $) | Desirable R&D Investing (Mln $) | | |
|---|---|---|---|---|
| **Country** | **2022** | **Min** | **Max** | **Average** |
| Luxembourg | 93,643 | 1329 | 2095 | 1712 |
| France | 3,823,962 | 22,623 | 52,282 | 37,452 |
| Belgium | 796,098 | −2770 | 3354 | 292 |
| Austria | 639,574 | −2047 | 2862 | 407 |
| Norway | 672,046 | 5322 | 10,469 | 7896 |
| Greece | 406,715 | 5945 | 9053 | 7499 |
| UK | 3,957,839 | 9897 | 38,818 | 24,357 |
| Spain | 2,411,672 | 41,981 | 59,498 | 50,739 |
| Sweden | 696,077 | −1954 | 3030 | 538 |
| Japan | 5,930,404 | −7859 | 34,404 | 13,273 |
| New Zealand | 274,519 | 4749 | 6692 | 5720 |
| Netherlands | 1,365,670 | 14,133 | 23,661 | 18,897 |
| Italy | 3,319,367 | 59,728 | 82,781 | 71,254 |
| Australia | 1,888,029 | 31,596 | 43,982 | 37,789 |
| United States | 26,006,893 | 82,794 | 240,094 | 161,444 |
| Portugal | 464,925 | 9685 | 12,490 | 11,088 |
| Germany | 5,663,889 | 35,059 | 68,163 | 51,611 |
| Canada | 2,475,480 | 48,066 | 62,146 | 55,106 |
| Finland | 340,851 | 3525 | 5309 | 4417 |
| Switzerland | 801,577 | 6147 | 10,176 | 8162 |
| Denmark | 456,897 | 5071 | 7311 | 6191 |
| Israel | 511,942 | −1166 | −761 | −963 |
| Korea | 2,845,652 | 31,011 | 31,042 | 31,026 |
| **Total** | **65,843,723** | **402,864** | **808,951** | **605,908** |

The Table reports an estimate of R&D investments to close the gap between optimal (model-implied) and actual R&D-to-GDP ratios for 23 OECD high-income countries based on 2022 GDP data.

adequate (i.e., market-level) risk-return profiles while also providing positive societal impacts. While these financial issues and structures appear to be relatively easier to address, compared to those of governance, and so forth, this financial structuring itself is by no means trivial.

For policymakers in government and at academic institutions, the message is similarly clear: collaborative thinking and planning involving industry, academic and government decision makers is a precursor to developing regulatory, policy and academic incentives that enable such broad investment vehicles to form and operate at scale.

However, with these vehicles in place, capital from private sector investors will naturally flow towards funding scientific research in order to achieve attractive risk/return profiles, while also providing asset-class diversification. Such investment, in concert with public allocations, may well enable public-private partnerships that would encourage investment at levels that today appear practically viable for only the most advanced economies.

Coming full circle, then, we conclude by revising the joke at the beginning of this article to reflect our conclusions about the current state of play for the four challenges we discussed:

> *"How can we create an infrastructure that solves the problems of organizing large-scale scientific research communities and then fund it?*
>
> *FIRST: Create an infrastructure that solves the problems of organizing large-scale scientific research communities …"*

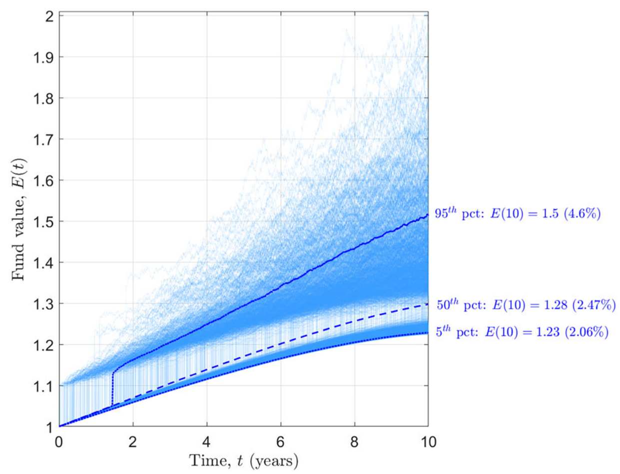


**Fig. 3 Monte Carlo simulations of R&D investments.** The Figure displays 5000 Monte Carlo simulations of the R&D investment fund performance in our model over a period of 10 years. We normalize its initial endowment (value) to 1. We report the fund's terminal value and performance expressed on an annual basis for the 5th, 50th, and 95th percentiles.

## Disclaimer

Where authors are identified as personnel of the International Agency for Research on Cancer/World Health Organization, the authors alone are responsible for the views expressed in this article, and they do not necessarily represent the decisions, policy or views of the International Agency for Research on Cancer/World Health Organization.

## Data availability

All data and replicating code supporting the findings of this study are available at: https://doi.org/10.7910/DVN/GZ9GFU.

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## Notes

1 Though Churchill does appear to have said this, it is not clear that he was the first; the provenance of the original quote is ambiguous.
2 Historically, the barriers to forming and operating such organizational structures have been significant, but these barriers are reducing at a fast and increasing pace. Advances in distributed ledgers, video conferencing technologies, cloud storage and computing infrastructure, and virtual reality communication tools have made it significantly more feasible to form distributed working groups and teams that operate both synchronously and asynchronously.
3 A possible architecture might contemplate: (1) Holding Company: investors forming the "visionary" group contributing to the general scientific mission of the fund. (2) Investment Company: managers investing in financial activities and research projects. (3) Research co: researchers providing services to the Investment Company, including technical valuation of investment cases as well as support in the scouting activity, and connected with Physical and Virtual Labs, with which such business unit could collaborate (e.g., research proposals, technical project evaluation, etc.).

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## Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

## Ethical approval

This study does not involve human participants or their data.

## Informed consent

This article does not contain any studies with human participants performed by any of the authors.

## Additional information

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