Systematizing serendipity for big science infrastructures: the ATTRACT project

AUTHORS:

- Jonathan Wareham, Laia Pujol Priego and Angelo Romasanta (Esade)
- Markus Nordberg and Pablo Garcia Tello (CERN)
- Thomas Wareham Mathiassen (Technical University of Denmark-DTU)

INDEX

ATTRACT

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AUTHORS

Ramon Llull University - Esade

- Jonathan Wareham
- Laia Pujol Priego
- Angelo Romasanta

CERN

- Markus Nordberg
- Pablo Garcia Tello

Technical University of Denmark-DTU

- Thomas Wareham Mathiassen

ABSTRACT

This paper explores how policy can promote the application of scientific research beyond its original purview. We analyze ATTRACT[1], a novel policy instrument in the European Commission's Horizon 2020 program, aiming to harness the detection and imaging technologies of the leading European research infrastructures towards entrepreneurship. In this initiative, 170 projects were funded with €100,000 for each to develop a proof-of-concept commercial application within one year. Leveraging the unique dataset from the projects funded under ATTRACT, our study finds different serendipity modes compared to the previously proposed typologies, as follows: (1) building on previous research, (2) combining different technologies, (3) applying a technology into a different field, and (4) using artificial intelligence or machine learning. This study contributes to the emerging literature on serendipity by showing the potential of policy interventions to enable individuals and organizations to find unexpected commercial applications of big science research.

[1]The members of ATTRACT are as follows: the European Organization for Nuclear Research (CERN), European Molecular Biology Laboratory (EMBL), European Southern Observatory (ESO), European Synchrotron Radiation Facility (ESRF), European X-Ray Free Electron Laser Facility (European XFEL), the Institut Laue-Langevin (ILL), Aalto University, Esade Business School, and the European Industrial Research Management Association (EIRMA).

1. Introduction

Some of the most pervasive technologies in society today, such as the internet, medical diagnostics and treatments, and information and communication technologies, result from leveraging the research generated by big science infrastructures to areas beyond their direct scientific purview. While the potential of big science to create social, cultural, and economic impacts is acknowledged, uncertainty remains on how these big science infrastructures can deliberately find novel applications outside of their immediate scopes of research. Moreover, there are also questions regarding the extent to which **policymakers can play an active role in enabling these research centers to find novel uses for their research that were previously unanticipated**. Exploring these questions, this paper examines a novel policy response by the European Union to promote the commercialization of technologies from some of Europe's most impactful research infrastructures.

The term serendipity has been evoked to describe various unintended discoveries, typically with some beneficial outcomes. For example, Fleming's discovery of penicillin is often cited as a serendipitous discovery with tremendous social value. The definition of serendipity, however, can be ambiguous. The Merriam Webster dictionary defines serendipity as "the faculty or phenomenon of finding valuable or agreeable things not sought for" (Merriam-Webster, 2020), while the Oxford dictionary defines it as "the occurrence and development of events by chance in a happy or beneficial way" (Oxford University Press, 2019). **In the management and innovation literature, creating conditions that foster serendipity is considered desirable for managers and policy-makers** (Yaqub, 2018).

On the surface, the argument that serendipity can play a positive role in scientific processes and policy has its immediate value as ex-post, anecdotal narratives with limited normative value. However, this misconception comes from interpreting serendipity as mere happenstance instead of resulting from deliberate effort (de Rond, 2014). A systematic analysis of serendipity is useful because it offers a more nuanced understanding of its antecedents and mechanisms (e.g., Yaqub, 2018; Garud 2018). By identifying the formative conditions of serendipity, the design of mechanisms to realize the peripheral benefits of scientific research infrastructures can be improved; in effect, one could attempt to systematize serendipity. However, to date, most of the research has been speculative or based on small-sample, anecdotal evidence from previous scientific discoveries.

> **Capturing the value of big science requires simulating exploration and the simultaneous fostering of commercial development through risk absorption and support**

This study examines the ATTRACT project, a €20M-funded initiative within the Horizon 2020 Framework Program that aims to systematize the discovery of breakthrough applications of imaging and detection technologies from the leading European science research infrastructures. Recognizing that the full potential of these detection and imaging technologies is unknown, ATTRACT was formulated with the understanding that capturing the value of big science will require both stimulating exploration and the simultaneous fostering of commercial development through risk absorption and support. Accordingly, **ATTRACT supported 170 projects with seed-funding grants of €100,000 each to leverage their various technologies** towards sustainable businesses and greater economic returns for the European economy.

Analyzing how the large research infrastructures can find new impactful uses for their science is highly relevant. Given their extreme sophistication and required investment levels, research infrastructures are normally funded by taxpayers via national ministries or funding agencies – often in pan-national consortia. As such, **it bears upon policymakers to seek mechanisms to optimize the potential socioeconomic value of these public investments**. ATTRACT brings six of the largest European scientific research infrastructures, which are also members of the EIROforum, together; they are as follows: European Organization for Nuclear Research (CERN), European Molecular Biology Laboratory (EMBL), European Southern Observatory (ESO), European Synchrotron Radiation Facility (ESRF), European X-ray Free Electron Laser Facility (European XFEL), and the Institut Laue-Langevin (ILL). These organizations work in diverse domains, such as nuclear, particle, and condensed matter physics; life sciences; molecular biology; astronomy; materials science; structural biology; and chemistry.

The 170 projects funded under ATTRACT provide a unique dataset to examine the processes towards serendipity. In this analysis, we find the following modes: (1) building on previous research, (2) combining different technologies, (3) applying technology into a different field and (4) using artificial intelligence or machine learning. We validate the previous typologies of serendipity and extend these notions by describing new categories. Unlike the previous studies that examined serendipity ex-ante, this study explores purposeful actions carried out in the pursuit of serendipity. Moreover, we explore how the intentional nature of the policy intervention by ATTRACT can help in finding new, previously unexplored applications of research technologies.

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The study proceeds by reviewing the history of big science, the polemics of its underlying social value, and the mechanisms and measures that policymakers use to stimulate the application of science towards social and economic impacts. We describe the literature on serendipity, summarizing the extant literature and the main research questions. We present the ATTRACT project and explore how it attempts to systematize serendipity. Contributing to the serendipity literature, we summarize the 170 projects funded under the call and examine the various modes used to discover previously unanticipated applications. We conclude with observations concerning serendipity and describe trajectories for future initiatives concerning big science and socioeconomic value.

2. Background: big science and social impact

In the following, we explore the history of big science and the issues related to its impact on society.

2.1 Definition and history

Big science infrastructures are defined by Florio and Sirtori (2016) as institutions with a) high capital intensity, b) long-lasting facilities or networks, c) operating in monopoly or oligopoly conditions affected by externalities, d) who produce social benefits via the generation of new knowledge (either pure or applied). As argued by Giudice (2012), the evolution of big science began early in the twentieth century with examples such as the factory-like conditions where Heike Kamerlingh Onnes made seminal discoveries on superfluidity and superconductivity in the early 1900s, or the Wilson Observatory, completed in 1917 and made famous by Edwin Hubble. What began to characterize research as big science was how it differed from the ideal of the lone genius in the laboratory with simple table-top experiments.

> **The cyclotron provides an early example of how big science research can have alternative applications for socioeconomic impact**

This **new model of scientific exploration was fully institutionalized by Ernest Orlando Lawrence at the University of California**, Berkeley with the development of the cyclotron, which is a device for accelerating nuclear particles to very high velocities to bombard, disintegrate and form completely new elements and radioactive isotopes. While the first cyclotron was merely a simple 4-inch device that could be held in the human hand, over time, larger versions that could achieve greater energy levels were created. With each subsequent generation of the cyclotron, a larger number of physicists, engineers, and chemists were needed for construction, operation, and maintenance. More importantly, he advanced a form of team-based, collaborative science that contrasted with the isolated model of 'smaller science'[2] (Hiltzik, 2016) and later matured into large research teams with hundreds of scientists and engineers. This new type of industrialized science eventually propagated to other American and European universities and was facetiously called the 'Cyclotron Republic' by Lawrence's numerous admirers and rivals (Hiltzik, 2016).

The cyclotron also provides an early example of **how big science research can have alternative applications for socioeconomic impact**. A serendipitous by-product of Lawrence's lab was the production of radioactive isotopes useful for cancer treatment (Hiltzik, 2016). With the help of his brother John Lawrence, a medical doctor who became the director of the university's Medical Physics Laboratory, Ernest was able to recraft the cyclotron's narrative to court funders intrigued by the potential of important isotopes. In a Faustian spirit, the laboratory metaphorically produced oncology-focused isotopes by day, while discretely conducting basic research by night, and while many on the team bemoaned the fact that commitments to medical research hindered advancement in fundamental physics, this shrewd strategy enabled Lawrence to fund his constantly moving targets of higher energy levels that required more sophisticated hardware, complex operating organizations, and generated unprecedented costs. This tactic further **institutionalized the future relationship between big science and big funders**, be they philanthropies, national ministries of defense or energy, or increasingly, supranational-coalitions (Crease et al., 2016).

The rise of big science, however, is often associated with the Manhattan Project and the numerous technological innovations that were enhanced during WWII, such as radar and wireless communication. Motivated primarily by military and global political concerns, technological superiority was considered a central element of geopolitical competition (Galison and Hevly, 1992). This superiority was not limited to military research, although the defense industry was certainly a central protagonist. Espoused in the famous report of Vannevar Bush (1945), *Science: The Endless Frontier*,

[2] Quoting Luis Alvarez in Hiltzik (2015): There were no doors inside the Rad Lab. 'Its central focus was the cyclotron, on which everyone worked and which belonged to everyone equally (though perhaps more to Ernest). Everyone was free to borrow or use everyone else's equipment or, more commonly, to plan a joint experiment'. The team approach to physics, Alvarez judged, was 'Lawrence's greatest invention'. (Hiltzik 2015:129–30).

basic research was not only good for fundamental science but generated applied engineering and technologies that translated into products, spin-offs, jobs, and overall economic prosperity that benefited all social classes. The 'Bush legacy' (Wilson, 1991) was further catalyzed by the successful leap-start of the Soviet space program, an event that galvanized the American public to approve the astronomical funding levels of the American space program while having little concern for its scientific merit. With the perceived technological gap between the USA and the USSR, the Soviet space program was considered a severe existential threat that, similar to the Manhattan Project, could only be remedied by massive investments in basic, applied, and ever-bigger science (Giudice, 2012).

> **Currently, with the cold war decades in the past, the role of big science in society has transformed**

Currently, with the cold war decades in the past, **the role of big science in society has transformed**. The perception of grand existential geopolitical threats has turned into a more disperse narrative. As a result, investments in big science motivated by national security or geopolitical stability have decreased. This decrease has weakened the sacrosanct link between nuclear physics, weapons research, and geopolitical security and, as a consequence, has reduced the primacy of fundamental physics (Galison and Hevly, 1992; Hiltzik, 2016). Moreover, the tenacious success of the Standard Model has left aspiring physicists scrambling for new avenues to conduct physics, leading them to astrophysics and cosmology, as well as more distant fields, such as biology and life sciences (Galison, 2016).

In addition, **the nature of big science infrastructures has become more heterogeneous**. Today, traditional particle accelerators and nuclear reactors work alongside synchrotron radiation, neutron scattering, and free electron laser facilities, where the empirical scope has widened to materials science, chemistry, energy, condensed matter physics, nanoscience, biology, biotechnology and pharmacology (Doing, 2018; Heinze and Hallonsten, 2017). Finally, big science infrastructures are no longer constrained by national security mandates. These infrastructures must now compete in a global scientific market with increased mobility, transparency, and competition. As such, they are often in positions where they need to justify their utility and efficiency across diverse scientific communities and policymakers (Hallonsten, 2014; Heidler and Hallonsten, 2015).

2.2 Impact assessment of big science

The previously described changes have transformed the political context in which big science operates. An important early figure looking into the **new challenges faced by big science** was Alvin Weinberg, director for the Oak Ridge National Laboratory, where uranium was enriched for the atomic bomb in its early years. In his important articles in Science (1961) and Minerva (1964 and 1963), he voiced his concerns that big science had become a bloated self-serving institution of bureaucracy and complacency, disconnected from more basic human and social needs (Crease *et al.*, 2016). At the same time, the softening of geopolitical ethos did not free big science from excessive political influence (Hellström and Jacob, 2012; Weinberg, 1964, 1963, 1961). In contrast, since public budgets require substantial political support, there were concerns **that champions may be tempted to sell and defend their visions with a certain level of sensationalism** (Scudellari, 2017). Moreover, there were worries that the business of blockbuster science could undermine the more serious and less sensational work of normal science (Hellström and Jacob, 2012). Weinberg then wanted to establish some criteria for which investments in big science could be evaluated against alternative social priorities (Hellström and Jacob, 2012).

An obvious point of departure is to evaluate the scientific productivity levels of big science infrastructures, which are typically evidenced through citation and patent counts. While quantitative evaluation of these measures is easy, they are also considered very imperfect proxies of scientific value, as well as poor indicators of the many peripheral benefits of big science infrastructures (OECD, 2003; Schopper, 2016). As an example, Bianco *et al.* (2017) argue that the International Space Station, which has cost over $100 billion to build and $2 billion a year to operate, has, as of 2017, only produced 34 refereed articles and 4 patents. Given their long cycle times, publication and patent counts favor more mature infrastructures and are often used as post hoc justifications of sunk-cost investments.

> **The normal focus for researchers attempting to evaluate the value of big scientific research infrastructures is on the impacts of direct spending on high-tech procurement with subsequent multiplier effects**

Broadening the scope beyond scientific impact, the normal focus for researchers attempting to evaluate the value of big scientific research infrastructures is on the impacts of direct spending on high-tech procurement with subsequent multiplier effects (Autio *et al.*, 2003; Castelnovo *et al.*, 2018). For instance, aggregating numerous studies of CERN, Schopper (2016) estimates that **for every euro spent on high-tech products, an additional 4.2 euros are generated in supporting industries**. Beyond the impacts on immediate suppliers, another narrative used to justify investments in scientific research infrastructures are technology spinoffs, with their corresponding or assumed economic growth, job creation, and tax revenue (Aschhoff and Sofka, 2009). Here, NASA may be the most prolific example, boasting over 2,000 spinoffs since 19764 (NASA Spinoff)[3]. Like the early cyclotrons at Berkeley, **the value of spinoffs is that they often commercialize technologies in applications outside of a laboratory's principal scientific purview**, demonstrating how major research infrastructures can generate impacts beneficial to society without detriment to its main mission (OECD, 2014).

> **The value of spinoffs is that they often commercialize technologies in applications outside of a laboratory's principal scientific purview, demonstrating how major research infrastructures can generate impacts beneficial to society**

An important characteristic of technology spinoffs as a metric of social value is that the benefits are assumed to accrue to society well beyond the immediate scientific community, and this assumption is important in justifying the investments to taxpayers. However, estimating the indirect, or even direct, economic impacts becomes even more problematic when the technological derivatives are not protected by patents, trademarks, or citations (Schopper, 2016), as is often the case. Given that the political mandate of many research infrastructures is to generate scientific knowledge towards greater social value (Hammett, 1941), the decision not to protect technologies with property rights is frequent and explicit.

These practices are consistent with the ethos of open science and open innovation movements (Chesbrough, 2003; European Commission, 2016), **as well as specific mandates from funding agencies to make publicly funded research data accessible**, with research results published in open access platforms and FAIR data principles (European Commission, 2012). The most famous and recent case was the World Wide Web (specifically, HTTP, URL, HTML), i.e., when Tim Berners-Lee convinced CERN's managers in 1993 to place it in the public domain and make the IP freely available to everyone. By accepting this case, CERN effectively agreed not to draw revenues or economic value from it. In the words of a CERN senior scientific officer: 'In the case of a conflict between revenue generation and dissemination, dissemination takes precedence' (World Intellectual Property Organization, 2010). For a technology with this level of impact, any quantification of its socio-economic value almost approaches the surreal.

Researchers have attempted to derive more holistic models by conceptually defining the alternative social benefits of research infrastructures (Autio *et al.*, 1996). For example, Florio *et al.* (2016) derive a model that is based on the following six main dimensions:

1) impact on firms due to technological spillovers produced by access to new knowledge and learning by doing;
2) benefits to employees and students through increases in human capital;
3) the social value of scientific publications for scientists;
4) cultural benefits through outreach activities;
5) additional services provided to consumers; and
6) the value of the scientific discovery.

An earlier, complementary perspective was offered by Autio *et al.* (2004) who derived a number of propositions related to **the positive value that a big science infrastructure can have on its ecosystem of suppliers**. These include pushing the frontiers of technology and engineering standards, reducing uncertainty surrounding standards and technology investments, sharing their capacity to manage highly complex projects, aggregating highly diverse and specialized knowledge domains towards radical learning and novel combinations, access to international networks, prestige and reputation, network formation, an exceptional scale and a scope that supports extreme prototyping and testing.

Overall, the indicators are not perfect in terms of assessing the impacts of research infrastructures since they can be insufficient proxies of what they are measuring (e.g., citations), suffer from time-lag effects (Schopper, 2016), and can be myopic in capturing the value provided (spillover effects, human capital formation, or cultural value). As argued in Boisot *et al.* (2011), **the more that a research infrastructure deals**

[3] https://spinoff.nasa.gov/database/

with fundamental research, the greater the uncertainty surrounding the future value of the outputs. The lack of reliable data, or well-understood causality, means that more holistic conceptualizations are excessively difficult to quantify and can lead to politically oriented narratives.

In summary, the previous discussion leads to the following conclusions:

— For research at the forefront of science, a variety of big science organizations have been created with facilities, infrastructures, and instrumentation with unprecedented technical sophistication.

— With questions on how limited public resources are allocated, concerns have arisen on the social and economic value of big science and how to effectively measure these impacts.

— Despite these worries, big science infrastructures have a consistent track record in terms of finding alternative applications for their technologies that have tangible impacts on society.

— While it is common for big science to find serendipitous value in areas previously unanticipated, there is a limited amount of rigorous empirical research on the nature of serendipity and how it can be proactively cultivated.

We, therefore, review the literature on serendipity and its mechanisms in the following section.

3. Serendipity

Serendipity refers to a broad, multifaceted phenomenon related to the unanticipated discovery of something beneficial. As it has been used in various contexts, we trace its various conceptualizations over time. Moreover, we describe the current understanding of how serendipity can be fostered.

3.1 Definitions and typologies of serendipity

The term serendipity was coined by writer Horace Walpole in 1754, who was inspired by the Persian fairy tale, *Three Princes of Serendip* (Cunha *et al*., 2010; Rosenman, 2001). He refers to serendipity as an unexpected discovery found from the combination of accident and sagacity (Rosenman, 2001). Sagacity refers to having perception and sound judgment, or in other words, a prepared mind. As such, instead of being merely interchangeable with the words luck, happenstance or providence, **serendipity is better seen as a capability requiring the focus of attention** (de Rond, 2014). An equivalent formulation can be seen in the context of entrepreneurial opportunity, where serendipity has been seen as the combination of directed search, favorable accidents and prior knowledge (Dew, 2009). By stripping away the random and sometimes mystical aspects of serendipity, it becomes a concept that can be subject to rigorous evaluation, allowing an examination of its triggers, antecedents and mechanisms.

> **By stripping away the random and sometimes mystical aspects of serendipity, it becomes a concept that can be subject to rigorous evaluation, allowing an examination of its triggers, antecedents and mechanisms**

A methodical attempt to understand serendipity was initiated by Robert Merton in the 1950s, which eventually resulted in a book dedicated to serendipity in 2004 (Merton and Barber, 2004). Yaqub (2018) conducted a systematic review of Merton's archives to identify four specific archetypes of serendipity. Mainly focusing on scientific discoveries, he organizes these according to a) whether there is a targeted line of inquiry; and b) the type of solution discovered.

Yaqub (2018) defines ***Walpolian* serendipity** as a targeted line of inquiry that leads to discoveries that researchers were not in search of (solution to a different problem). ***Mertonian* serendipity** happens where the desired solution is achieved via an unexpected route (targeted problem – different path). ***Bushian* serendipity** is where untargeted exploratory research leads to a solution for a well-known problem. Finally, ***Stephanian* serendipity** is where untargeted research finds an unsought solution that may find a future application.

However, even earlier than Yaqub (2018), de Rond (2014) describes a different framework for the structure of serendipity. While he also organizes serendipity in a 2x2 matrix, he divides it differently according to a) whether the solution was the intended target and b) whether the original research design was causal to the solution. In his work, de Rond evokes the term *pseudo-serendipity* to describe when the solutions are intended in the first place, compared to (only) serendipity, where the solutions are completely unanticipated.

One key difference between the two is that de Rond (2014) already assumes that there is an intended target for serendipity to occur, while Yaqub (2018) also permits untargeted search in his framework. Nonetheless, we can see some equivalence between their categories. For instance, while not exactly the same, pseudo-serendipity corresponds to the Mertonian formulation of serendipity, while de Rond's serendipity is equivalent to the Walpolian formulation. Another difference is that whether the discovered solution is a consequence of random variation or deliberate design is not adequately captured by Yaqub's recent typology.

The role of design in serendipity is further emphasized in the work of Garud *et al* (2018). Taking insights from the evolutionary biology literature, they introduce the term 'exaptation' to the innovation literature to refer to the "emergence of functionalities for scientific discoveries that were unanticipated ex-ante." They identify two forms of exaptation, as follows: *franklins and miltons*.

— *Franklins* refer to the supplementary usage of existing structures in areas in which they were not originally intended for use (e.g., using coins as screwdrivers).

— *Miltons* refer to discoveries without a currently known function. A widely known image to illustrate miltons is that of spandrels, i.e., the triangular space unintentionally created by the shape of arches, which were later used as a blank canvas for painting (Bahar, 2018).

In contrast to the previous formulations of serendipity, Fink *et al*. (2017) propose another perspective altogether, wich is based on the crossovers of interdependent components. In an experimental study, they show that components early on do not have much benefit, as their utility depends on the existence of other components. However, as the innovation process continues and other components appear, **the potential of this original set of components can suddenly manifest**. This moment, which seems to come out of nowhere, is what is perceived as serendipity. Accordingly, they explain that serendipity is not only a matter of happenstance but is a result of the components' delayed fruition, which occurs from the existence of other important components.

> **Serendipity is not only a matter of happenstance but is a result of the components' delayed fruition, which occurs from the existence of other important components**

Finally, it is also important to note another field where the term serendipity has also gained ground, as it gives insights into what differentiates serendipity from other similar concepts. In the field of information systems, serendipity has become an important metric in recommender systems (Kotkov *et al*., 2016). Recommender systems seek to predict what rating a user would give to a certain product so that new products can be recommended. These systems have been the backbones powering widely used services such as Netflix, Spotify, and YouTube. In such systems, **serendipity means that users do not only receive results that are relevant but results that are significantly different from the user's previously rated items**. This component of surprise is what seems to define serendipity in this context.

3.2 Realizing serendipity

Aside from attempting to find better definitions of serendipity and understanding its nature, there has also been much progress made on the **various factors or mechanisms that can lead to serendipity**. McCay-Peet and Toms (2015) propose a process model for how individuals discover and perceive serendipitous events. Their model consists of the following components:

— Trigger
— Connection
— Follow-up
— Valuable outcome

The trigger refers to environmental cues sparking the interest of the individual. This trigger is then connected by the individual to their previous knowledge and experiences. Individuals then follow-up on these triggers to obtain a valuable outcome. The surprise occurs from noticing the unexpected thread present from the previous processes.

> **The strategies that individuals can pursue to increase the likelihood of serendipity include varying their routines, being observant, making mental space, relaxing their boundaries, drawing on previous experiences, looking for patterns and seizing opportunities**

The conditions that promote serendipity have also been explored. For instance, the strategies that individuals can pursue to increase the likelihood of serendipity include "varying their routines, being observant, making mental space, relaxing their boundaries, drawing on previous experiences, looking for patterns and seizing opportunities" (Makri *et al*., 2014). Yaqub (2018) also describes four mechanisms that we summarize as (1) examining deviations from theory, (2) activating previously acquired knowledge and experiences from individuals, (3) tolerating errors and following up on such occurrences, and (4) leveraging networks. In the organizational context, Cunha *et al*. (2010) identify some conditions related to serendipity, including boundary spanning, mindfulness, social networks, teamwork, free space for creativity and opportunities for playing with ideas.

Artificial intelligence has also been used to find novel solutions to various challenges. Computational methods can aid in the search for interesting information, enabling the discovery of new knowledge domains that have been previously unexplored (Arvo, 1999; Beale, 2007). In drug discovery, for instance, it has been used to repurpose drugs to new therapeutic areas (Mak and Pichika, 2019). As progress in the field increases, artificial systems that "catalyze, evaluate and leverage serendipitous occurrences themselves" are also increasingly explored (Corneli *et al*., 2014).

While serendipity at the personal and organizational level has been emerging, the literature on how serendipity can be actively pursued at a macro-level is still limited. Garud *et al*. (2018) describe arrangements to induce exaptation of science, as follows: exaptive pools, exaptive events, and exaptive forums. Exaptive pools refer to the maintenance of scientific discoveries such as through patent and publication databases. These ideas, however, remain decoupled until they are activated by exaptive events, such as technology fairs and workshops. These possibilities can be further developed and contextualized through exaptive forums, where actors become increasingly entangled.

In summary, the extant literature on serendipity has mostly been speculative or based upon small-sample, anecdotal examples of scientific discoveries. Moreover, the previous studies mainly focus on the individual scientists, lacking understanding of **how serendipity can be induced at a more macro-level**. As such, questions remain on how serendipity can be cultivated towards finding market applications for science and how it can be cultivated, for instance, with the help of policy. To move the serendipity literature forward, there is a need for studies based on empirical evidence, preferably using quasi-experimental conditions. By examining the novel policy response ATTRACT, this study puts forward a rigorous empirical examination of serendipity.

4. ATTRACT

The ATTRACT project is a €20M-funded initiative within the Horizon 2020 Framework Program that aims to systematize the discovery of breakthrough applications of research from the leading European big science infrastructures. In the following section, we describe its underlying philosophy, aims and results to date.

4.1 Philosophy

The assertion that the products of scientific research centers can have value outside of their intended scientific purview is not new[4]. It was demonstrated clearly by Lawrence's early cyclotrons in oncology, and the idea was perhaps best institutionalized as an important policy driver by Bush, who advocated large investments in untargeted scientific research as a source of serendipitous discoveries or solutions (Bush, 1945; Yaqub, 2018). In a more liberal interpretation, the Bush legacy favors large investments in research for its unknowable scientific value, as well as numerous unknown benefits that accrue as socio-economic derivatives (education, spin-offs, job creation, etc.).

During the last three decades, policymakers have increasingly emphasized policies to accelerate innovation and economic growth (Edler and Fagerberg, 2017). Three main types of approaches have been developed.

1. The *mission-oriented approach* aims to support solutions to challenges that are part of an explicit political agenda. Here, policy-makers tend to anchor innovation policies in grand societal challenges, such as national defense, climate change, or other sustainable development goals (Galison, 2016; Galison and Hevly, 1992; Mazzucato, 2016; Mazzucato and Semieniuk, 2017; Mowery, 2012).

2. *Invention-oriented* approaches aim to stimulate the supply of inventions as derivatives of scientific discovery while leaving any commercial exploitation to the market (Bush, 1945; Wilson, 1991). This was the most widely adopted approach championed post-war by Bush, as policy-makers sought to advance science and technology as broad drivers of geopolitical policy (Galison, 2016; Galison and Hevly, 1992).

3. Finally, recent decades have seen *system-oriented* approaches that seek to foster interactions among the different actors taking part in the innovation ecosystem (Borrás and Laatsit, 2019; Lundvall, 2010; Lundvall and Borrás, 2009).

Within these main orientations, a wide range of policy instruments have been deployed in Europe to stimulate innovation (European Commission 2016), and different typologies have been suggested to understand them (e.g., Borrás and Edquist, 2013; Edler and Georghiou, 2007). The most widely accepted view considers instruments such as those focusing either on technology push or market pull. Technology push (supply-side) policies stimulate framework conditions and opportunities for innovation to thrive, including measures to support R&D collaboration, network formation, and incentives to attract highly skilled labor to focal regions and sectors. For example, in Europe, the Future and Emerging Technologies (FET) program has allocated €2.7 billion to pursue breakthrough ideas through unexplored collaborations of multidisciplinary scientific and cutting-edge engineering teams, which is indicative of the invention-oriented approach mentioned earlier.

> **Technology push policies stimulate framework conditions and opportunities for innovation to thrive, including measures to support R&D collaboration, network formation, and incentives to attract highly skilled labor to focal regions and sectors**

Market pull (demand-side) interventions have been emphasized with greater frequency in the most recent literature (Edler and Georghiou, 2007; European Commission, 2016b; Rolfstam, 2009). This perception recognizes that the derivatives of basic scientific research have limited value if specific market-pull mechanisms are not in place to facilitate their entry to the market (Scherer, 1982; Schmookler, 1962).

Demand-side policy instruments include measures to foster investments by private capital (brokering, tech-transfer, IP, subsidies, etc.) or, alternatively, pre-commercial procurement to nurture financial liquidity, investment, and operational scale in start-ups and SMEs (Edler and Fagerberg, 2017; Rolfstam,

[4] Detailed information can be found at https://attract-eu.com

2009). However, instruments that simultaneously stimulate both the supply-side and demand-side dynamics, especially for early-stage, high-risk technologies, are less common (Cunningham *et al*., 2013; European Commission, 2016b).

The challenge of bridging the supply and demand sides of the innovation cycle is not an exclusive concern of innovation policies. It is also a well-known challenge in entrepreneurship research, where it is frequently metaphorized as the valley of death

The challenge of bridging the supply and demand sides of the innovation cycle is not an exclusive concern of innovation policies. It is also a well-known challenge in entrepreneurship research, where it is frequently metaphorized as the valley of death (VoD) (Beard *et al*., 2009; Hudson and Khazragui, 2013). This metaphor describes the difficult phase in product development and commercialization where **many viable products or start-ups do not survive for a variety of reasons. Typically**, these include excessive and unforeseen costs for research, prototyping, testing and manufacturing, limited product development budgets, ineffective coordination and expertise, sub-critical market exposure, and the inability to obtain sufficient internal or external funding to bring the product or start-up to a revenue-generating state (Frank *et al*., 1996).

A substantial amount of research has focused on the various mechanisms that can be marshaled towards mitigating the VoD phenomenon, which include the following: innovation intermediaries (Islam, 2017); scientific parks; technology clusters and living labs (Almirall and Wareham, 2011); industry associations (Markham *et al*., 2010); business incubators and accelerators; technology brokers and tech-transfer functions (Beard *et al*., 2009); regional, national, and pan-national funding instruments, such as Horizon 2020, EIT and ERC of Europe, and NIH, NSF of the US (Hudson and Khazragui, 2013).

For technologies with high technology readiness levels, the VoD is potentially less fatal, particularly for incremental innovations with probable market uptake

Finally, particularly in the medical and life sciences fields, there has been a growth in initiatives in translational research (Butler, 2008). No single VoD scenario is applicable to all technologies. For technologies with high technology readiness levels (TRL) (Banke, 2010), the VoD is potentially less fatal, particularly for incremental innovations with probable market uptake. This condition is typically addressed by risk mitigation functions performed by private investment and venture capital. However, technologies with low TRLs require more extensive interventions, typically with both risk absorption (seed funding and early industry involvement) and risk mitigation (public/private investment mechanisms). It is important to note that TRLs are highly context dependent; i.e., the technology may be very mature and tested in its original application at the scientific research installation (high TRL), but immature in a larger system of commercialization when used in a different sector or market (low TRL) (Héder, 2017).

4.2 Purpose, design and results to date

Imaging and detection technologies will have core functions in almost all technically sophisticated commercial products and will constitute an annual market of over $100 billion in their own right

The main aim of ATTRACT is to harness and direct exploration towards breakthrough innovation opportunities in detection and imaging technologies, while also offering space for serendipity to stumble onto unforeseen applications. As such, there are no 'intended' technological applications or desired outcomes. Rather, the ATTRACT governance is designed to generate as many options and variety in the applications as possible. That acknowledged, **there are some obvious areas where detection and imaging technologies can be employed towards substantial, if not paradigmatic, advances in other domains.** Frost and Sullivan argue that imaging and detection technologies will have core functions in almost all technically sophisticated commercial products and will constitute an annual market of over $100 billion in their own right (Frost & Sullivan, 2015). These domains include medical device and imaging technology, biotechnology, energy, advanced manufacturing, automation, microelectronics, materials and coatings, environment and sustainability, and information and communication technology.

On many dimensions, ATTRACT has been designed to directly address the ineffectual transition – or disconnection

– between the technology-push instruments (applied in the early phases) and the market-pull instruments (the later entry of private capital) (Auerswald and Branscomb, 2003; Wolfe et al., 2014). In this respect, **ATTRACT is distinctive from recent instruments, such as FET, given that the focal actors include both research infrastructures and industrial players, and equal protagonism is given to both the supply and demand sides.** This is enabled by the pre-existing relationships between research infrastructures and their industrial suppliers; that is, the highly specialized SMEs that have contributed to the engineering, construction, and operation of some of the world's most sophisticated technologies. Thus, the industrial relevance and operational feasibility of the projects are verified from the start.

Specifically, for projects involving European research facilities and industrial organizations, the most immediate use of their technologies is guaranteed. In this sense, a first 'internal market' is assured. This 'internal market' paves the way for industry to target other applications and new commercial opportunities (i.e., the feasibility of the pilot technologies has been prototyped and tested in the real and demanding working conditions of big science facilities).

The completion of ATTRACT phase I is expected to lead to insights and findings that inform modifications and extensions to the design of ATTRACT phase II and related innovation policy initiatives. **ATTRACT phase II will aim to take a select group of 10-20 validated projects from ATTRACT phase I and scale them towards technology readiness levels 5-8.** ATTRACT phase II is specifically designed to address the intermediate or secondary phases of the valley of death phenomenon, which requires greater scalability, maturity, and support. In addition, emphasis will be placed on the transition to public sources of equity-based capital (e.g., the European Investment Fund and the European Investment Bank), as well as private capital sources, such as early and late-stage venture capital and private equity.

Table 1 highlights the main attributes of ATTRACT and how they are positioned relative to traditional EU funding instruments and private capital investments.

As of the writing of this paper, ATTRACT has implemented the following steps:

1. **An open call was launched to solicit project proposals** (1,211 submitted) for leveraging detection and imaging technologies towards potentially commercially sustainable products or services. While not exclusive, the emphasis was on concepts at technology readiness levels 2-4. The call solicited proposals leveraging the following four main technology groups: a) sensors; b) data acquisition systems and computing; c) software and integration; and d) front- and back-end electronics.

2. **All submissions were assessed on technical merit and innovation-potential.** Specifically, the evaluation dimensions included the project definition, scope, and technological feasibility, state-of-the-art, scientific/engineering merit, industrial potential, commercial feasibility, and social value.

3. **170 projects were awarded €100,000 for the development of a proof-of-concept or prototype** with an application outside of the original purview of the technology, over a period of one year.

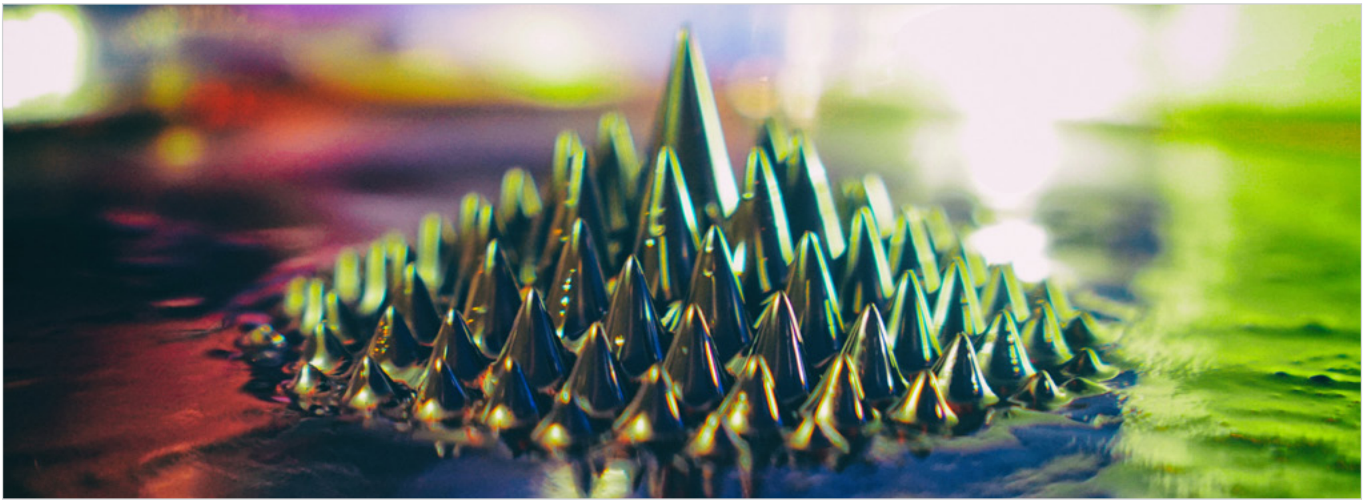


Table 1. Comparison between ATTRACT and other funding instruments

	ATTRACT	EU range public funding instruments[1]	Private instrument
Approach for crossing the valley of death	Considers that breakthrough technologies need two steps of risk absorption and risk mitigation.	Assumes that only one step is needed – normally risk mitigation (projects are funded on equal footing)[2]	Focuses on relatively low-risk technologies with no need for risk absorption.
Risk absorption (reduce large TRL gap)	Public seed funding to foster ideas with breakthrough potential (100k EUR). ATTRACT2 aims to continue with public scale funding for selected projects (2-4M EUR).		
Risk mitigation (close TRL gap)	Public/private investment mechanisms.[3]	Public/private investment mechanisms.	Angel, Venture capital funding.
Pre-competitive market	Ensured in projects with participation of research infrastructures.	Not ensured and depending on a project-by-project case.	Not ensured.
Scaling up	Late-stage VC funding instruments, private equity, IPOs, etc.		

[1] We are referring to EU funding programs such as Horizon 2020. We do not consider national public funding programs.

[2] Exceptions exist, such as the SME instrument **https://ec.europa.eu/programmes/horizon2020/en/h2020-section/smeinstrument**. Nevertheless, they differ from ATTRACT because a project needs to apply for seed funding, and subsequently, for scale funding. In ATTRACT, the transition between seed and scale is streamlined.

[3] **http://www.eif.org/; http://www.eib.org/en/index.htm**

4.3 The 170 Funded ATTRACT Projects

The call was open from 1 August to 31 October 2018. In that period, 1,211 proposals were received. The top 10 countries submitting applications were as follows: Italy (261); Spain (230); Switzerland (108); France (96); the United Kingdom (81); Germany (67); Finland (65); the Netherlands (59); Portugal (33); and Austria (26). From these submissions, 170 projects were selected for funding.

To analyze these different projects, we carried out the following: We collected the text proposal of the 170 funded projects for analysis. Each proposal submitted contained a maximum of 3,000 words, including the following parts: a) summary; b) project description; c) technology description and external benchmarks; d) envisioned innovation potential (scientific and/or industrial), as well as envisioned social value; e) project implementation, budget, deliverables, and dissemination plan. The proposals of these 170 funded projects were read by the authors and three master's students for evaluation.

Three master's students with backgrounds in biomedical engineering, mechanical engineering/physics and entrepreneurship evaluated each project independently. They coded for the following project characteristics: technology readiness level (scale of 1 to 9), scope of market application (specific, specific but easily expandable, or general), location in the value chain (upstream or downstream), technology novelty (scale of 1 to 5), technology relevance to the market (scale of 1 to 5) and credibility of budget and milestones (scale of 1 to 5).

After analyzing each project separately, their findings were integrated. In cases where the codes were not consistent, discussions were held to reach agreement. The coding was then validated in an additional round of coding by the authors and then tabulated. As such, each project was evaluated and coded by a minimum of three independent evaluators. The results are presented in the following paragraphs.

The ATTRACT project call required the participation of a minimum of two collaborating organizations. While the majority of projects were the result of two organizations collaborating, as many as five organizations can be seen collaborating in a single project (Figure 1A).

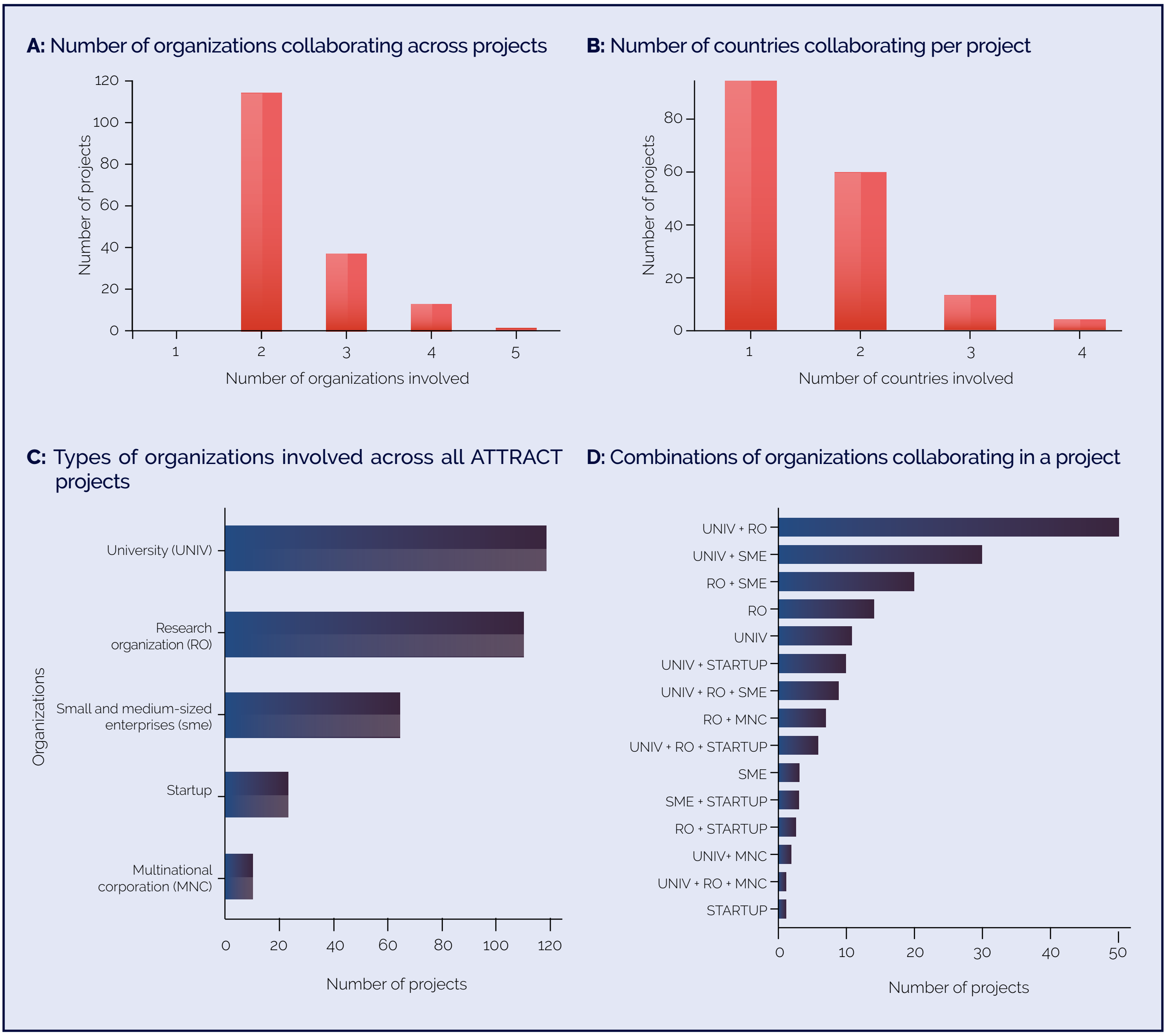


Figure 1. Summary of organizations Involved in ATTRACT projects.

Exploring the countries represented in each project funded in ATTRACT, Figure 1B shows that **the majority of projects involve collaborations between organizations located in the same country**. Such arrangements allow the partners to closely interact and meet frequently as they work on their projects. Interestingly, almost half of the projects (45%) involve international collaboration. Especially when projects require highly specialized, scarcely available expertise among partners, it is necessary for collaborations to occur across borders.

As seen in Figure 1C, the majority of projects involve research organizations (ROs) or universities. Aligning with the goals of ATTRACT, **many projects also involve input from industrial partners**, including startups, small and medium-sized enterprises (SMEs) or multinational corporations (MNCs). The most represented configuration involves collaborations between universities and research organizations (Figure 1D). These research organizations typically have expertise in spinning out technologies. Aside from this configuration, industry-academia collaborations are extremely common, most notably between universities and SMEs and ROs and SMEs.

We visualize the 170 projects in Figure 2 through automated processing of the textual data from the proposals. As the showcased projects reveal, **ATTRACT covers wide ground in the domains of technologies sourced and targeted application areas.** There is a huge cluster of projects applying big science research to impact the field of healthcare, such as through better diagnostics and treatments (blue cluster). Aside from this cluster, there are many more projects applying the imaging and detection technologies of big science to various commercial applications, such as consumer electronics, environmental monitoring, and security (green cluster). Finally, we see efforts to further improve the technologies themselves, with the immediate market of serving the big science infrastructures (orange cluster).

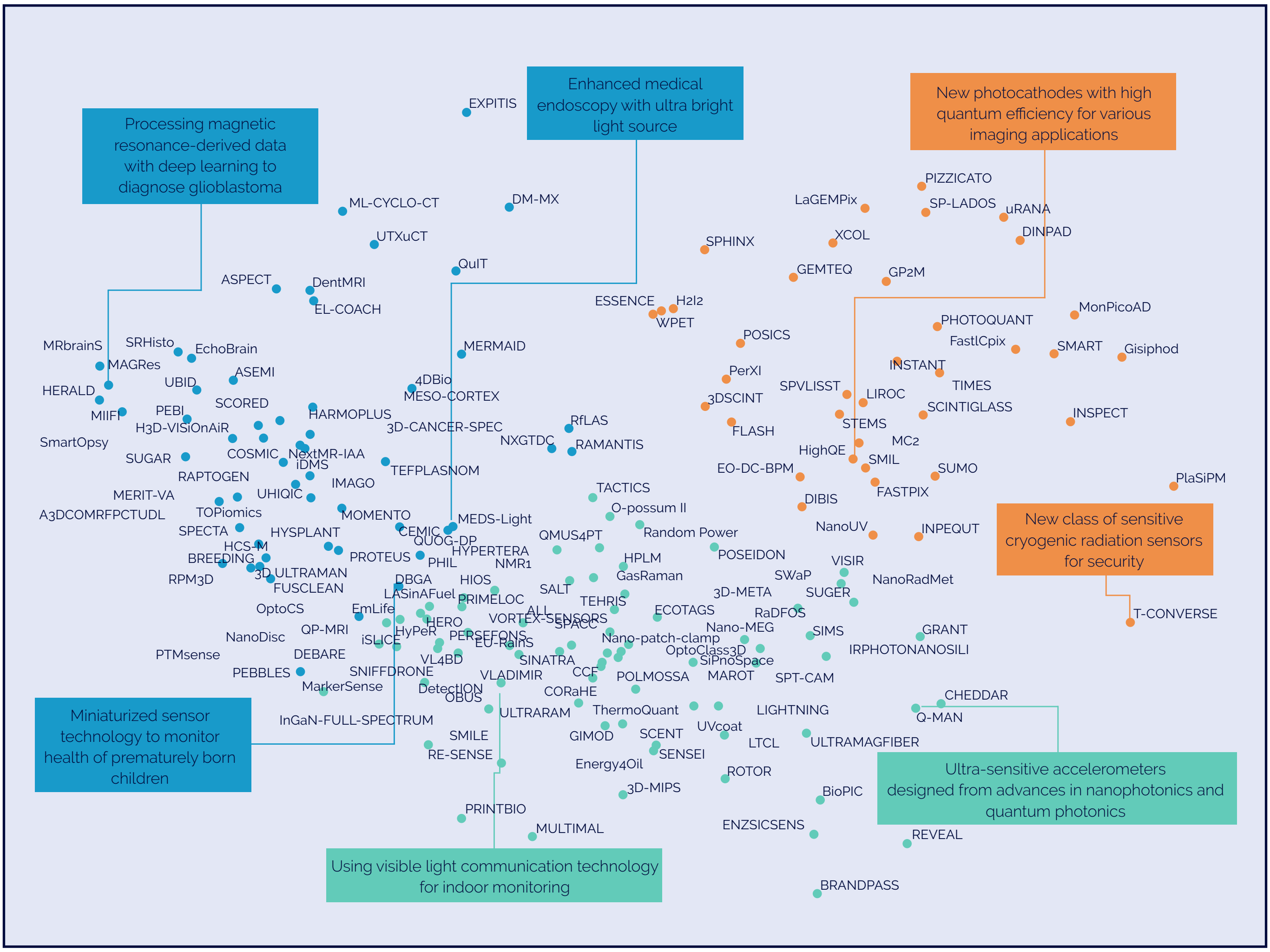


Figure 2. Visualization of the 170 Funded Projects under ATTRACT. Each project is labeled by its acronym. The projects are plotted by processing their textual data (removal of stop words, lemmatization, inclusion of n-grams), performing TF-IDF vectorization and decomposing by PCA into two components. The colors were generated by K-Means clustering. The blue cluster refers to projects in healthcare. The green cluster refers to applications of detectors to various areas. The orange cluster refers to upstream advances in sensor technologies. The code will be available online.

The automated classification was, however, not adequate to fully understand the projects included within ATTRACT. We, thus, conduct further analyses by manually evaluating the textual data of the projects. Figure 3A shows the different technological domains as submitted the participants, which are as follows: sensors (70%), data-acquisition systems and computing (32%), software and integration (30%) and front and back-end electronics (16%). Note that the projects can belong to more than one domain so they do not add up to exactly 100%. As observed, a large percentage of projects are in the domain of sensors. This percentage is not unexpected, as big science infrastructures are generally known for the sophistication of their imaging and detection technologies. The high expertise of these groups in sensor technology, together with the versatility of sensors towards various uses, make them good candidates for exploring alternative commercial applications.

Figure 3. Summary of the Various Coded Dimensions of the ATTRACT Projects.

Further analysis was carried out to describe the different features of the funded projects under ATTRACT (Figure 3). Figure 3B shows that **ATTRACT caters to a diverse range of application areas, including healthcare (36%), electronics (20%), environment (12%), energy (6%),** security (6%) and manufacturing (6%). These projects commit to these areas in varying degrees. Figure 3C shows that the projects are almost equally split in terms of the degree of specificity in the application area. While 35% of the projects are specific to their mentioned application area, there are also a large number of projects offering a general solution to different application areas (28%).

An interesting category is the 38% that are specific but expandable projects that have already identified their pilot market but then can easily extend their reach to other areas.

Furthermore, Figure 3D shows that there are slightly more projects located upstream in the value chain. These upstream projects (55%) aim to supply companies with knowledge and technologies that can be further processed and integrated towards their offerings. In contrast, downstream projects (45%) cater directly towards solving the problems of its intended market.

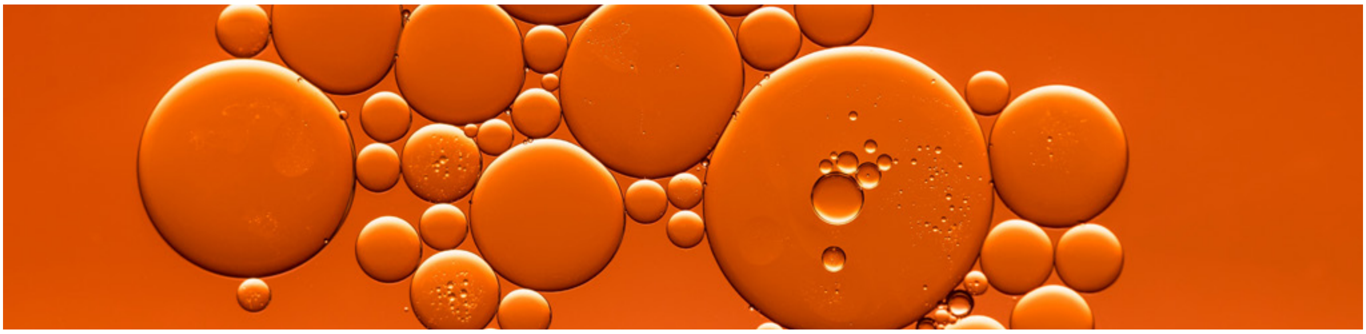
Figure 3E shows that the most common technology readiness level was 2, meaning that the projects are only in the stage where the technology and/or application area has been conceptualized. The average TRL across all projects was 1.8. These low TRL values are in line with what was expected from the projects during the proposal call. The low TRLs show that **these technologies are still in their early stages, requiring further development towards becoming viable solutions.** Their low TRLs have the benefit, however, of giving them the flexibility to find the serendipitous area where their application will have the most impact.

> **Originating from the leading big science infrastructures, the projects feature some of the most advanced, cutting-edge technologies**

Originating from the leading big science infrastructures, the projects feature some of the most advanced, cutting-edge technologies. Figure 3F shows that **the projects are highly novel, with an average rating of 3.4 out of 5**. The problem typically with technologies that are too novel is finding areas that would be relevant for their application. However, as seen in Figure 3G, the projects have generally high relevance to the markets they are hoping to serve. Across all projects, the average rating was 3.5 out of 5. This rating implies that a project such as ATTRACT can help activate researchers to find relevant applications for the technologies they are working on. Otherwise, for projects lower in rating, the support provided by ATTRACT enables these projects to refine their technologies to find a better fit with their market of choice or to find a more applicable market to which their solutions can be of value.

> **A project such as ATTRACT can help activate researchers to find relevant applications for the technologies they are working on**

To systematically explore the space in the development of their technologies, it is important for the project's team to have a credible plan and list of milestones. Figure 3H shows that the projects were rated highly on this aspect, with an average rating of 3.5 out of 5.



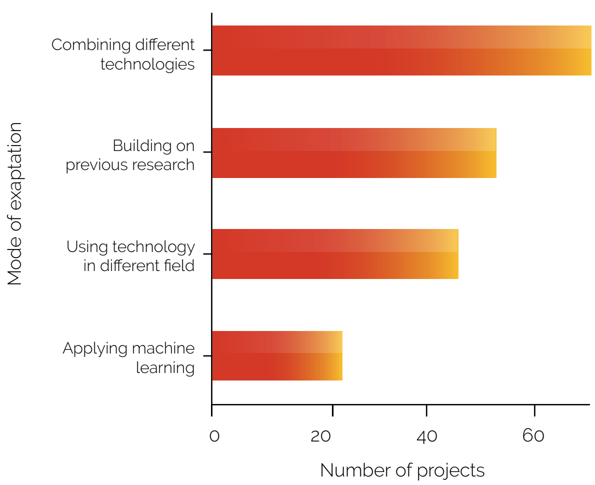
4.4 Modes towards serendipity

In the project text, the researchers typically narrate the mode by which they were able to develop new applications for their scientific research. We identified the recurrent themes by which serendipitous discoveries were actively pursued by project members in our first read through the 170 projects. In the second and third readings, we categorized the projects according to the following criteria:

- **Combination of different technologies** – technologies or knowledge from different research domains is combined, integrated or assembled together to produce a new application.
- **Building on previous research** – technologies from previous research work are extended or improved to be more effective or efficient but are still within the same domain or application area.
- **Applying technology to another field** – technology or knowledge from one domain is used in a new research domain or application area.
- **Using machine learning or artificial intelligence** – when the computational advances in machine learning or artificial intelligence are used to augment or find new uses for existing technologies.

Note that the projects typically combine these modes to different degrees and so, we coded them according to what is explicitly mentioned in the text. The number of projects in each category is summarized in Figure 4.

I: Modes towards serendipity in the ATTRACT projects



4.4.1 Combination of different technologies

The most represented mode was the combination of different technologies (41%). Under this category, technologies could come from adjacent or distant domains. Moreover, these technologies could be combined with varying degrees of integration. On one extreme, we identify a subset of projects (16%) where existing, readily available technologies are assembled to develop a new application. For instance, a project called PHIL, which aims to use a photonic system for liquid biopsy, mentions the following:

> *"We will design and build the system using mainly commercial solutions for the different system aspects."*

Otherwise, many projects combine the latest advances from distant research areas to create novel solutions. A notable example is the SCENT project, which aims to create new gas sensors. The project mentions that it is:

> *"based on merging two up-to-now disjointed macro-disciplines: high-pressure technology and gas-sensing; whose scientific communities are still far one another: the former focusing mainly on synthesis of materials, the latter unaware of HP-potentialities."*

4.4.2 Building on previous research

The second mode we identified is extending and building on previous research (31%). Typically, this mode proceeds from re-examining previous research so that new features that have not been previously identified or explored can surface. Pursuing this re-examination typically requires a meticulous re-examination of previously acquired knowledge and finding new perspectives in the existing data. A notable example is the project Random Power, which is a random bit generator for cryptography. According to their proposal:

> *"The genesis of the project is an example of ingenuity and serendipity and can be tracked to the effort of understanding random events affecting the response of state-of-the-art detectors of light with single-photon sensitivity."*

Another way that previous research is reinterpreted is by exaggerating features or taking things to the extreme. For instance, there are many projects that examine what possibilities would be opened if current detectors could be applied at extremely cold temperatures or in environments with very high radiation. Similarly, there are projects that develop new application areas through imagining what opportunities can be created if a technology becomes a magnitude more efficient or powerful.

The previous research can also be extended by projecting from the current state of their research a laudable target. By setting a difficult goal, the researchers then leave it to their abilities and to successful development of the project so that they can bridge the gap between this goal and their current state.

4.4.3 Applying technology to another field

Another set of projects (27%) applied a technology from one field to another field. This category coincides best with the previous notions of serendipity – finding new uses from existing things. By exposing a technology to a field that it has not been previously used for, new use cases for the technology potentially emerge. Especially for the big science institutes in ATTRACT, their technologies might be narrowly used within their scientific domain. These new technologies are also able to provide a fresh perspective to the field, proposing new ways to deal with the problems that the existing technologies currently employed within the field may not adequately address.

> **By exposing a technology to a field that it has not been previously used for, new use cases for the technology potentially emerge**

A notable example of a project is SIMS, which involves designing a seismic imaging and monitoring system. They mention that they will develop a:

> *"next-generation MEMS sensor that utilizes patented technology inspired by the search for gravitational waves."*

4.4.4 Using artificial intelligence or machine learning

The final mode we identified involved the application of machine learning for a specific application, accounting for 14% of the projects. This category can be considered a subset of the previous category since machine learning is a breakthrough originating from the computational sciences that is finding new uses in different domains. By being able to find patterns that humans cannot easily identify, it can be said that **applying AI or machine learning increases the efficacy of various sensors** in what can be obtained from the data it is able to collect.

Many of the projects in this category are in the field of healthcare. The usage of machine learning **allows data collected from the various imaging technologies to be brought together and processed to reveal new insights on certain diseases.** For instance, the project MAGres plans to integrate various magnetic resonance techniques to obtain a better understanding of the brain tumor glioblastoma. They mention the following:

> *"ML [machine learning] methods are the key to unlock the predictive power from the complex and high-dimensional data to be acquired."*

5.Discussion

We identify four categories of how big science research can be used in previously unexplored ways towards commercial applications. These four modes towards serendipity are (1) a combination of different technologies, (2) building on previous research, (3) applying technology to another field and (4) using AI or machine learning. Compared to the previous studies of serendipity, the categories we describe do not completely coincide with any one proposed typology of serendipity, as summarized in Table 2.

<table>
<tr><th>CULTIVATING SERENDIPITY</th><th colspan="3">SERENDIPITY VIEWED FROM ITS OUTCOME</th><th>OTHER LITERATURE ON SERENDIPITY</th></tr>
<tr><td>Categories from ATTRACT (This Article)</td><td>Structure of Serendipity (de Rond, 2014)</td><td>Typology of Serendipity (Yaqub 2018)</td><td>Exaptation of Science-based Innovation (Garud 2018)</td><td></td></tr>
<tr><td rowspan="2">Applying a technology to another field</td><td>Serendipity by way of random variation</td><td rowspan="2">Walpolian targeted search solves an unexpected problem</td><td rowspan="2">Franklin's character was previously shaped for some use but is now coopted for a different role (ex. coin as screwdriver)</td><td rowspan="2"></td></tr>
<tr><td>Serendipity as the unintended consequence of design</td></tr>
<tr><td rowspan="2">Building on previous research</td><td>Pseudo-serendipity by way of random variation</td><td rowspan="2">Mertonian targeted search solves problem via an unexpected route</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Pseudo-serendipity as the unintended consequence of design</td></tr>
<tr><td>Combining together different technologies</td><td></td><td></td><td></td><td>Crossovers between components (Fink et al., 2017)</td></tr>
<tr><td>Applying AI/Machine learning</td><td></td><td></td><td></td><td>Computer-aided serendipity (Arvo, 1999)</td></tr>
<tr><td rowspan="2">Untargeted search (during research before ATTRACT)</td><td rowspan="2"></td><td>Bushian untargeted search solves an immediate problem</td><td></td><td rowspan="2"></td></tr>
<tr><td>Stephanian untargeted search solves a problem later</td><td>Milton's character was not shaped for some use but has the potential to be coopted for another use (ex. spandrels)</td></tr>
</table>

The category of applying technology from one field to another coincides highly with the previous notions of Walpolian serendipity (Yaqub, 2018) and the idea of exaptation (Garud *et al.*, 2018). These two formulations, on a fundamental level, refer to the unanticipated usage of a certain item. A nuanced difference, however, between these previous notions on serendipity is that our categorization stems from a different view of serendipity, i.e., exploring the modes towards its realization. Instead of characterizing it ex-ante, our category describes the actions that researchers are actually taking in the hopes of finding serendipitous applications for their scientific research.

On the surface, extending the previous research does not seem to be related to serendipity. The implied incremental nature of the progress that comes from building on previous research makes it seem that it is not a viable way to cultivate serendipity. However, as we find in the different projects, **extending the previous research can be productive, especially if it allows the accumulated wealth of knowledge and experience of various actors to be activated and re-examined.** This productivity coincides with how Cunha *et al*., (2010) sees serendipity, i.e., as the process of metaphorical association – seeing things in a new way. Such activation facilitates researchers to pursue a laudable target that they have not considered doing before.

Compared to the previous typologies of serendipity, we find two new categories. The first one is the combination of different technologies. This conceptualization of the phenomenon is consistent with that of Fink *et al.* (2017), which relates serendipity to the surprise from the crossover of interdependent components. On a fundamental level, the innovation research has greatly emphasized the role of combining knowledge from diverse domains to generate breakthrough innovation (e.g., Guan and Yan, 2016; Schoenmakers and Duysters, 2010). Nonetheless, it has not been explicitly linked to serendipity due to the lack of empirical studies on its realization.

Finally, in the ATTRACT projects on AI and machine learning were used to process and make sense of the huge quantities of data generated by the various sensors. **These technologies are valuable, as they are able to see subtle patterns that are invisible to the human eye.** AI and machine learning improve the performance of certain technologies by being able to process large amounts of data and integrate different sources of information to obtain new insights. However, it is important to make a distinction that AI and machine learning were mainly used to integrate the data resulting from the detectors instead of for discovering new applications. Machine learning was not used on a meta-level to discover new serendipitous applications of the technologies, for instance, from mining text from publications and patents. However, with the ongoing progress in these technologies (as in recommender systems), it would be interesting to see how AI and machine learning can directly be used to generate leads for serendipitous connections between various topics (e.g., Arvo, 1999; Giles and Walkowicz, 2019).

5.1 Implications for theory

The research on serendipity has evolved beyond the simple conceptualization as an accident or happenstance. Recent developments have allowed serendipity to be scientifically examined by having reformulated it as a capacity, requiring the focus of attention (de Rond, 2014). This paper validates the previously proposed typologies on serendipity through the unique dataset of ATTRACT. While the previous research on serendipity mainly relied on anecdotal stories in the history of science, ours is grounded on the data from the 170 funded projects under ATTRACT. With these projects spanning different domains and varying in their technological features, this gives us access to a large dataset that we can probe to study how serendipity is actively pursued.

> **While the previous research on serendipity mainly relied on anecdotal stories in the history of science, ours is grounded on the data from the 170 funded projects under ATTRACT**

Unlike the previous studies of serendipity, which view the phenomenon after it has already occurred, we provide another perspective by looking at the modes towards its realization. **This process-oriented data-driven approach allowed us to find two previously unidentified modes wherein serendipity can be cultivated,** as follows: combining technologies and using machine learning. More systematic analyses with other novel datasets are needed to corroborate our findings and identify other means that serendipity can be realized.

5.2 Implications for policy and practice

Our paper shows how policy can enable researchers to find alternate serendipitous uses for their technologies. The ATTRACT project is consistent with calls by Mazzucato (2013, 2016, 2017), who argues that **the government can go beyond its role as a regulator or fixer of markets towards an entrepreneurial role, absorbing the risks in strategic sectors until technologies have reached a sufficiently mature state** to be attractive to private and venture capital.

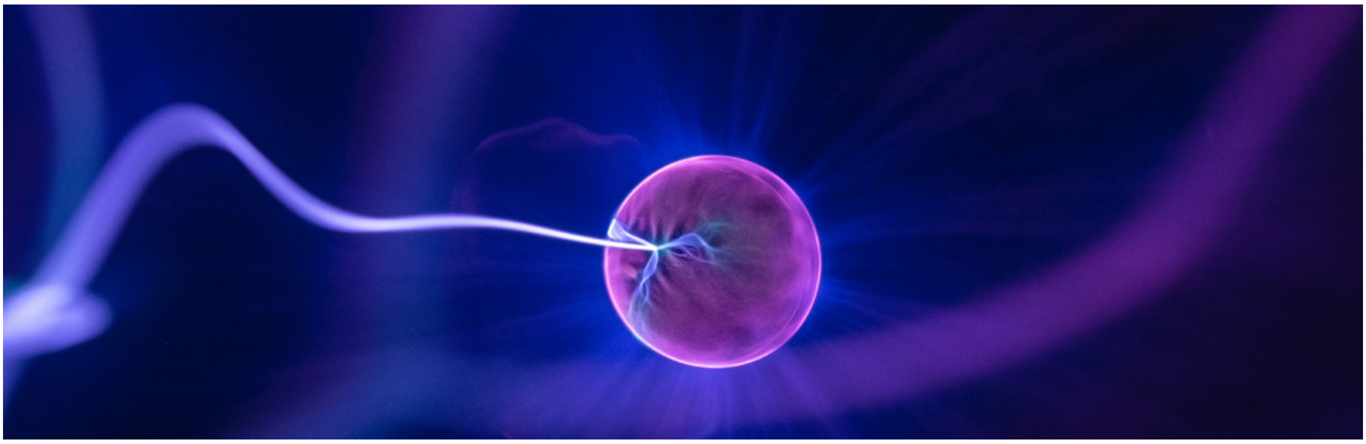
> **Market mechanisms and private capital alone may not be the most efficient routes to realizing innovation via basic to applied research**

This assumes that market mechanisms and private capital alone may not be the most efficient routes to realizing innovation via basic to applied research (Martin, 2016). Specific industrial policies and stimulus instruments are needed to absorb the risks in basic research settings when working with low TRL technologies. This is particularly relevant to ATTRACT in light of the empirical research suggesting that the more the research infrastructure is involved in basic research as part of its mission, the less likely that the organization will be involved in technology transfer activities (Boisot *et al.*, 2011; Rahm *et al.*, 1988); this is certainly the case for several ATTRACT partners.

ATTRACT also resonates with the 'cooperative technology' model of technology transfer described by Bozeman (2000), which assumes that **government laboratories and research infrastructures can play an important role in technology innovation and economic growth**. With some variation, authors such as Mazzucato and Bozeman echo the original doctrine of Vannevar Bush, i.e., that basic research has a substantial and positive impact on socio-economic innovation via direct and indirect mechanisms.

Interestingly, however, the recent literature has argued that while it is commonly believed that Bush maintained an unquestioning faith in an integrated and linear model of innovation, his notion was more sophisticated and involved symbiotic cross-fertilization (Leyden and Menter, 2018). In this view, the authors argue that while Bush saw that basic research and applied research benefit each other, they also succeed by working as separate systems, or stacks. Consequently, **scientific and economic policy mechanisms should seek to coordinate the two systems**, allowing each to operate through its own logic and success criteria, yet simultaneously cultivating specific points where they can nurture each other (Cunningham *et al.*, 2013; European Commission, 2016b; Leyden and Menter, 2018). ATTRACT does not presume to be the definitive word on how to accomplish this coordination task. Indeed, faithful to its genesis in scientific institutions, ATTRACT should be seen as an experiment in innovation policy (Bakhshi *et al.*, 2011). With its focus on the revelation of information and cross-fertilization of technology and entrepreneurial options, it is experimental at an operational level. With its novel constellation of actors, resources, design, and governance, ATTRACT is very much an experiment in innovation policy.

> **ATTRACT should be seen as an experiment in innovation policy**



6. Conclusions

The 170 projects allow us to probe serendipity in a quasiexperimental setting with some controls

We have described the ATTRACT project, which is a novel innovation policy instrument to find new applications for the breakthrough imaging, detection, and computational technologies of Europe´s leading scientific research infrastructures.

We have described the philosophy behind the project, discussing the history of big science and the issues with regard to assessing its socioeconomic impact. Where ATTRACT is still in-process, the large data set from the proposals allows us to view serendipity in a unique, unprecedented manner. Specifically, the 170 projects allow us to probe serendipity in a quasi-experimental setting with some controls. We identify several novel modalities of serendipity that emerge from the data.

There are many interesting avenues for future research. First, it is a widely accepted wisdom that **increasing the collisions between different actors promotes the chances of serendipity**. As such, it is valuable to understand how the various partners working in the projects were able to find each other and create new applications for their previous technologies. Incorporating insights from the alliance and network literature would create new insights in the serendipity literature.

Faithful to its genesis in scientific institutions, ATTRACT is best viewed as a policy experiment. Where a complete evaluation of it will require more time, the initial evidence suggests that **policymakers can play a purposeful and effective role in fostering derivative benefits from public investments in big scientific research infrastructures.**

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8. References

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