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From Discovery to Impact: The Ideal Balance Between Exploratory and Applied Research in Engineering

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ABSTRACT

This paper discusses the current trends in the continuous discussion of exploratory and applied research in the engineering context: the necessity of a balance between both. Exploratory research extends the boundaries of knowledge in a scientific context, whereas applied research provides a leap toward effective solutions based on that knowledge. The paper suggested that engineering researchers' focus needed to be on applied research, which is the essence of all technology innovation, unless the exploratory research subject matter is still maturing. Each developing country can focus on an applied/supported effort to overcome an immediate community challenge, e.g., technologies for clean drinking water and renewable energy needs, whereas developed countries may continue an exploratory research line through applied research. Further, the paper proposed that scientists and engineers collaborate to mitigate research overlaps and efficiently apply discoveries to local challenges. Therefore, engineers can use existing knowledge and skills to create innovative technologies, improve the quality of life, and advance industrial development. All engineering applied research will provide a translationally appropriate balance as the core of both technological and societal sustainable growth. Applied research is the core of engineering growth.

Keywords: Exploratory research, Applied research, Engineering Innovation, Research priorities, Technological advancement.

1. INTRODUCTION

Research is a structured approach to exploring and collecting information to enhance knowledge, address challenges, or uncover new perspectives. The goal is to investigate, clarify, and utilize discoveries to improve understanding and foster innovation in different areas. Figure 1 shows five major research types [1], each playing a crucial role in advancing knowledge and technology. Fundamental (Basic) Research focuses on developing theoretical understanding, exploring new scientific principles without immediate practical application. In contrast, Applied Research aims to address real-world problems by applying existing knowledge to create practical solutions or innovations [2]. Descriptive Research is used to gather detailed information about a subject through methods like surveys, case studies, and observations, offering a comprehensive snapshot of the current state of a phenomenon. Exploratory Research is conducted in areas where little is known to generate hypotheses and identify potential avenues for future investigation. Finally, Explanatory Research seeks to uncover the causes and relationships behind a phenomenon, providing deeper insights into how and why certain variables are connected. Together, these research types represent the full spectrum of inquiry, from theoretical exploration to practical application.

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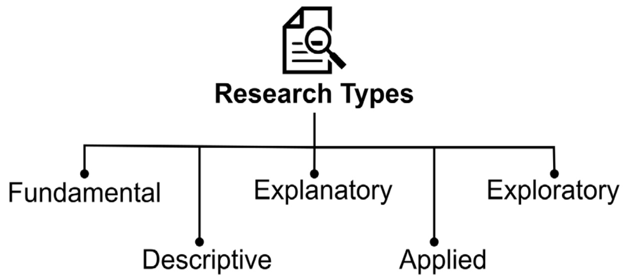

Figure 1: Major types of research.

As science advances and pushes the boundaries of engineering, the direction of research has always been an issue. In conducting engineering research, which approach is more preferable: to carry out exploratory research in order to discover new knowledge or to implement known scientific theories and methodologies to design practical solutions? This is a growing issue today, especially as engineering creativity increasingly aligns with scientific developments. Scientists, by contrast, are mainly preoccupied with advancing human knowledge and conducting research in the fundamental sciences, while engineers were traditionally seen as troubleshooting technicians, applying these new findings to the construction of socially beneficial devices.

In the engineering discipline, exploratory research is viewed as the process of seeking fundamentally new knowledge, while the preceding work falls under the domain of science [3]. In contrast, applied research uses these scientific findings to drive practical, tangible uses of the concepts, with emphasis on to actualization of the concepts in their purposeful application [4]. Engineering researchers are lately inclined toward exploratory work, while they more often than not try to come up with innovations in domains that may be as much scientifically grounded as not.

This raises an important question: Where was the ‘exploratory’ engineering research needed, or did it only shift the efforts to areas that others could have covered and provided new tools for engineering research that could be used for applied research? This article will seek to analyze current trends in engineering research, with a focus on the following two segments. It will claim that although outstanding discoveries may be made every now and then in engineering, the fundamental goal of engineers should be to utilize advanced findings for development. Further, the article will discuss the appropriateness of research needs in developing and developed countries, and which research type is suitable for which country type.

2. DEFINITIONS AND CONCEPTS

The concepts of exploratory and applied research are central to decision-making when choosing an approach in the engineering field; therefore, it is important to analyze them.

It must be noted that exploratory research in engineering is conducted with a view to finding out new information or facts that may not have been defined. This is something that entails exploring the unknown frontiers, without necessarily having in mind the role that the exploration will play in solving practical problems. This type of research is motivated by curiosity and scientific and technical challenges, seeking to extend the limits of what is technically feasible within the bounds of scientific principles. Exploratory techniques may be quite risky and are not always likely to produce an immediate return on investment, but the conclusions obtained may become important at some point in the future. This results in creating solutions that, in the early stages of exploratory research, may appear useless or too daring, but in the long run become groundbreaking technologies or methodologies. For instance, while quantum mechanical research that started as more of a theoretical endeavor might have been groundbreaking at first, it has led to the creation of computers many years later.

On the other hand, applied research focuses to the practical application of existing scientific information to solve real-world problems. While executives transform exploratory studies or basic sciences into engineering formulations, engineers, on their part, try to translate what has been found or discovered into working systems or products. In general, applied research is more defined and intended to develop a technology or procedure that could be useful to industries or societies. Such a form of research is central, especially in connecting theory with practice or technology.

It is normal to start with exploratory research as the first step in advancing new information in the scientific environment, followed by applied research as engineers use these discoveries to develop new products [5][6]. However, there is a clear divide between the two, which may not be so hard and fast in application. In some circumstances, the findings of the applied research could reveal areas where further exploratory research might be possible or even necessary. However, exploratory research may at times be occasioned by practical issues that require further scientific investigation.

With respect to engineering practice, it must be understood that both fundamental and advanced investigations serve distinct purposes. However, it can be argued that the natural workflow, where exploratory research is conducted before applied work, should be maintained to avoid duplication. It may be seen that although theoretical knowledge can be applied to solving a particular problem, it would be most beneficial for engineers to devote their efforts to applying science and knowledge accumulated in practice, rather than reinventing the wheel or rediscovering concepts already discovered by scientists.

3. CURRENT TRENDS IN ENGINEERING RESEARCH

In the current engineering research landscape, most exploratory research seems to have more applied research undertones. Classically, engineering was primarily focused on the application of accumulated science to address practical issues in tangible settings, with scientists more directed towards fundamental exploratory research with the aim of extending theoretical knowledge. But over the last few years, many engineering researchers have opted for enterprise research and have gone further into exploring areas that belong to the science domain. This has resulted to disagreements over its efficiency, in addition to other complications regarding the best ways to deal with the two types of research.

Among the factors that can be behind such tendencies, there is a need to innovate and gain prestige. Discovery, in turn, is always valued more than application, and this outlook can lead engineering researchers to pursue more breakthrough research than actual, useful inventions. This approach can create new technologies, but it can also become unproductive, to engineering researchers may start exploring areas of technology that have already been intensively studied by scientists.

For instance, quantum computing was historically regarded as a discipline of fundamental physics, yet within recent decades, numerous engineers have joined the discourse on quantum algorithms and devices. This has contributed to the development of practical uses, and it has also had perceived effects, such as fragmentation of research: physicists and engineers working on quantum computation have, in some cases, duplicated efforts, and engineers have had to tackle problems that physicists have previously tackled.

Concerning the field of renewable energies, it is found that there is a strong coalition between basic research in materials science and mechanical engineering. For example, while scientific researchers have conducted extensive research on using certain materials in solar cells, some engineering researchers continue to hunt for new materials rather than finding ways and means to get the best out of Solar Heating (SH) and Photovoltaics (PV) technologies [7]. This convergence may aid the continued sluggishness in the shift to renewable-based solutions for electricity demand.

Artificial intelligence (AI) is a branch of computer science that involves exploratory and applied research. Engineers specializing in autonomous systems based on AI can also conduct theoretical research as opposed to only exploring enhanced AI functionality for practical applications, such as self-driving cars or factory automation. This ambiguity creates a gray zone between computer science, which is heavily oriented toward theoretical developments in AI and engineering applications.

4. IS EXPLORATORY RESEARCH NECESSARY IN ENGINEERING?

The usefulness of exploratory research in engineering is questionable and has therefore been a subject of discussion for a long time. Science has always brought about discoveries that have served as breakthrough solutions to many problems, while engineering has always been the one to translate such findings to reality. The key issue applying to engineering researchers at the current state of the scientific development could be described as the following: meanwhile, the traditional avenue of explorative research is still apparently open, the question arises, whether the further promotion of fundamental innovations should be viewed as the primary task of present-day researchers, or whether their priority should be directed toward finding practical uses for the scientific achievements already made?

Perhaps one of the major drawbacks of undertaking exploratory research in engineering is that the research ends up being repetitive. Engineering sciences have benefited from many other sciences and the works of physicists, chemists, and biologists who have already developed several basic theories. The research also fills a knowledge gap by showing that engineers could be more productive in developing applied research, which is widely called for.

For example, in electric vehicles, the informative knowledge about lithium-ion batteries has been studied by scientists for decades now. Well understood are the fundamental properties of electrochemistry and the realized performance indexes of batteries, and research on this subject, along the line of discovering new effects and phenomena, provides less and less information. At this point, engineers are required to take the next step in optimizing the design and enhancing the effectiveness and practicality of these batteries. These are external indications that more focus should be given on engineering improvements in battery management techniques [8], thermal issues, and manufacturing trends than on the discovery of new principles. Future automobile research and development efforts should provide technologies that will increase the demand for electric automobiles worldwide, especially by enabling faster, more efficient charging, longer battery life, and more efficient manufacturing [9].

Another clear example is the field of renewable energy, where solar and wind energy convert to electrical energy. Innovative investigations into new materials and technologies to enhance the efficiency of energy harvesters are ongoing, but most of the initial technologies and inventive ideas associated with renewable electrical power conversion have already been developed [10]. Instead, there is a need for practical engineering now to scale up these technologies, determine how they can be integrated into the energy grid, and assess how they can operate effectively across different climates. Innovation solutions are now needed to deploy these technologies on a commercial scale, rather than making new scientific discoveries about how to generate electricity.

The nature of the education and training engineers receive to from college through internships is a major preparation for problem-solving, design, and the application of scientific principles [11]. They are completely different from the scientific method, in which creative discovery and theoretical development are emphasized. Engineers are taught to work with the ideas that scientists develop and adapt them for real-world applications; engineering students often work in groups to develop innovations or enhance current ones.

Engineers can become true innovators by shifting the focus from basic research to applied research. In this way, they can directly address current technological problems by applying methodologies inspired by creativity. The fact that exploratory research is displaced for commercial purposes stimulates engineers to actively pursue innovation to chart success in the field. Furthermore, the most fundamental component of their expertise and experience was derived from adding new technologies to existing ones, such as applying practical solutions and adopting a new approach to enhancing the supply of such solutions. Instead of engineers taking the role of scientific workers, they should be seen as people who can contribute to scientific work by making changes and designing useful objects for real-world use.

Exploratory research has the potential to yield discoveries that might become of great importance in the future, but the actual need to do this kind of work is not always urgent for engineers. In many cases, engineers should focus on applied research while scientists concentrate on the pursuit of new fundamental principles and knowledge generation.

5. APPLIED RESEARCH: THE CORE OF ENGINEERING INNOVATION

While fundamental research stretches the borders of scientific knowledge, applied research gathers these insights and makes it workable technologies that determine the everyday running of our world. Engineers, who are equipped with problem-solving and design knowledge, are the only ones capable of bridging the gap between the fundamentals of research and real-world applications. The application of scientific principles to develop new technologies and optimize systems drives technological progress and social improvement.

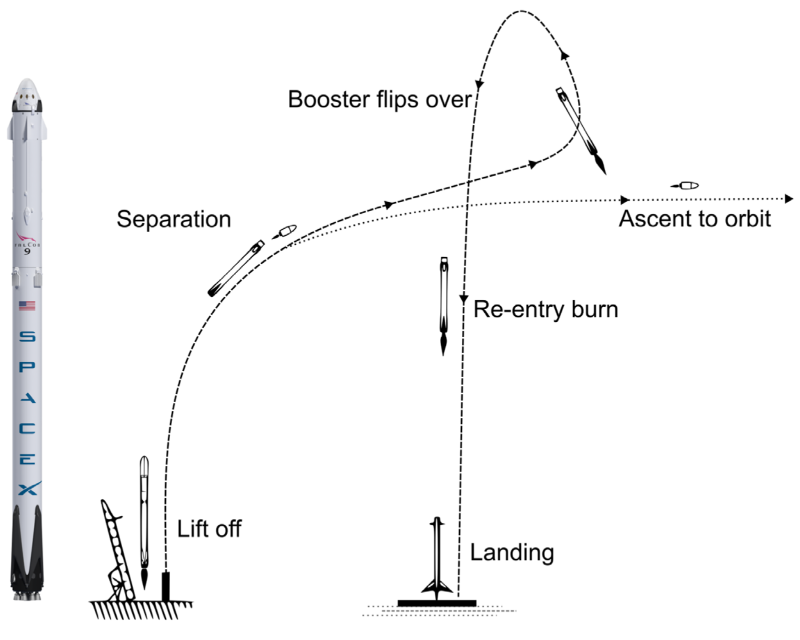

Figure 2: SpaceX reusable rocket.

One of the most notable instances of applied research resulting in groundbreaking engineering innovations is SpaceX's work. SpaceX, under the direction of Elon Musk, has developed advanced aerospace technologies based on basic research in physics, materials science, and aerodynamics. Instead of venturing into new scientific frontiers, SpaceX engineers have been able to solve the rocket's complexity by applying the existing principles in fields such as rocket design, reusability, and reducing the cost [12]. The original creation of the Falcon 9 rocket, the first reusable orbital rocket, remains the best example of the power of applied research, as shown in Figure 2. SpaceX used the knowledge of propulsion and materials science gained through years of scientific research and applied it to produce rockets that could land and be reused, thus substantially reducing the cost of space travel. This accomplishment is not only a feat of engineering but also a clear demonstration of the effectiveness be applied research.

In electronic establishments, as an example, the smartphone has become a standout example of progress. The role of basic knowledge in physics and computer science in the invention of semiconductors, radio waves, and microprocessors was driven by exploratory research on these topics, while the engineer's efforts focused on applying these discoveries to mass production for the consumer market. It was learned which components were miniaturized, which technologies were integrated into a single device, and how user interfaces for applied engineering were constructed. The shift from theoretical knowledge of tangible technologies that can have real-world effectsn people is the clearest example of how applied research innovates [13][14].

Renewable energy is an area where applied research has been vital [15]. The discovery of the photovoltaic effect was made through basic research, and it was followed by decades of successful development of solar panels that could be produced at scale by applied engineers. Solar energy has become a much better alternative to fossil fuels due to advances in materials engineering, manufacturing, and system integration to harness the sun's power [16].

These examples indicate precisely the indispensability of applied research in the engineering sector. Basic research is the humble beginnings of these technologies, and it is through applied research that engineers are able to make these technologies become a reality. The ability of engineers to gather scientific knowledge and to develop technological solutions that correspond to the needs of society is what drives technological innovation; thus, applied research is the direct cause of engineering innovation.

6. THE IDEAL BALANCE: BRIDGING EXPLORATORY AND APPLIED RESEARCH

Finding an appropriate balance between exploratory and applied research is critical to achieving innovation without redundancy. While exploratory research advances knowledge and generates new scientific principles, applied research seeks to translate these principles to technology solutions. In the engineering profession, both exploratory and applied research are critical and need to be done compatibly with efficiency and societal benefit in mind.

A well-coordinated framework that aligns exploratory and applied research can reduce the frequency of duplicate innovation and accelerate technological advances. Engineers should be directing their innovative research as applied researchers based on existing new fundamental discoveries, instead of exploring exploratory research, or what scientists call "basic" research, unless they believe the fundamental aspects of the subject are not mature enough. An engineer's focus on maximizing societal benefit would keep them from unnecessary overlap with scientists and stimulate innovation in the engineering profession, while also seeking a solution to their problem with technology.

When designing and being engaged in applied research, the applied researcher must call attention to the fact that, when it comes down to it, their job is to innovate themselves and expand science.

The applied researcher's job is not to rediscover or explore the fundamental principles in the research topic they are involved in; they are supposed to take the findings of new basic scientific discoveries and apply them to develop new technologies [17]. This mode of thinking is necessary to facilitate efficiency and avoid unnecessary exploration of science that has already been well researched and solved [18]. Only in cases where the fundamental research they are currently involved in has yet to reach maturity should the applied researchers consider performing exploratory research.

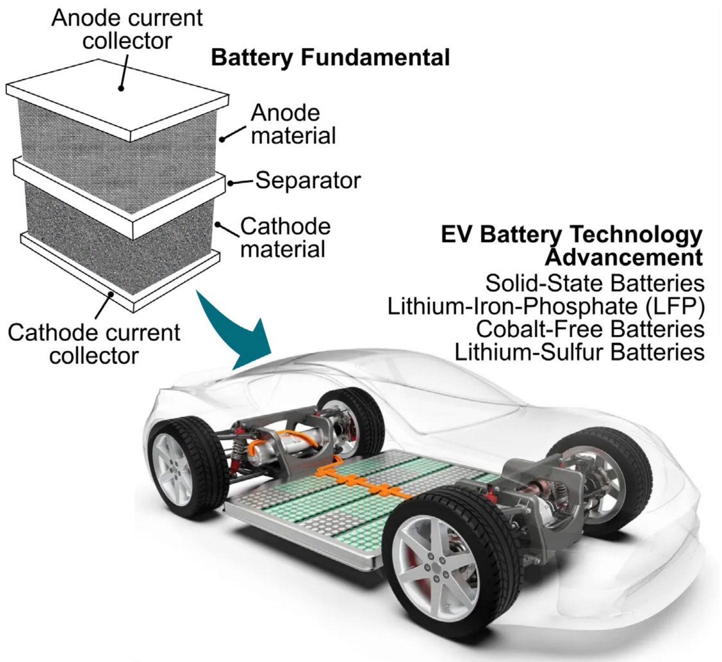

Figure 3: EV battery from fundamental research to battery advancement.

In the case of innovation associated with electric vehicle (EV) technologies (Figure 3), applied researchers are focusing on developing methodologies to enhance battery performance [8], optimize vehicle architecture, and improve production methods. Once scientific advancements in basic battery electrochemistry have reached a sufficient level of maturity, the researcher should continue to perform innovative research within the applied research domain. However, if it involves the development of advanced technologies, such as solid-state batteries, which require new battery-chemistry research [19], additional exploration may be required. Therefore, in determining whether foundational exploratory research will be needed, applied researchers must make decisions and evaluations about when more exploratory basic research is warranted and when it is not.

A significant concern in current research is the grey area between exploratory and applied research, which leads to unnecessary duplication of effort and wasted time. To address this issue, a clear and consistent understanding between scientists engaged in exploratory research and engineers conducting applied research and development is essential. Institutions, organizations, or funding agencies will play the role by establishing agreed-upon research pathways that clarify when exploratory approaches are necessary. Clarity of definition and objectives helps to ensure engineers appropriately incorporate foundational investigations when required and effectively leverage existing scientific advances to support the development of practical applications.

Collaboration across these two areas of research is critical. Applied researchers should work closely with scientists to learn about the latest advances in frontier research and ensure that their research is focused on resolving practical issues. This collaboration provides a means to avoid redundancy and a mechanism to convert scientific discoveries into technological opportunities. Specifically, scientists studying fundamental biological processes in biomedical engineering should collaborate with engineers to translate their discoveries into medical devices or treatments [20]. This is an example of taking a discovery to the application.

In summary, exploratory research expands the boundaries of knowledge through curiosity and investigates new scientific principles. Applied research focuses on optimizing these principles into functional, scalable technologies that address society's needs. A systematic comparison reveals that the main difference between the two studies is their operational maturity. Exploratory research is often high-risk and theoretical, whereas applied research is solution-oriented and relies on a transition from the "discovery" phase to the "utility" phase. As a result, the "grey zone" of overlapping efforts in certain fields such as AI and quantum computing stems from a lack of coordinated frameworks. This shows that the ideal balance is achieved not just by choosing a research type, it also lies in integrating institutional pathways. Once the basic discoveries of certain scientific principles have reached a stable threshold, applied research must be carried out. Table 1 presents comparisons between exploratory and applied research.

Table 1: Comparison of Exploratory and Applied Research.

Aspect	**Exploratory Research**	**Applied Research**
Primary Objective	Discover new scientific principles.	Solve a practical engineering problem.
Motivation	Driven by curiosity and technical challenges.	Driven by the need to solve real-life problems and address community challenges.
Research output	New scientific theories, material, or concepts.	Product, prototypes, or engineering system.
Time to Impact	Long-term impact.	Short to medium-term impact.
Role of an Engineer	Act as a scientific worker seeking fundamentally new knowledge.	Act as a problem solver, bridging the gap between theory and practice.
Example Activities	Investigate new battery chemical or quantum materials.	Improving the battery management system.

7. CONCLUSION

The equilibrium between exploratory and applied research in engineering is fundamental for advancing new technologies across any engineering domain while minimizing discontinuity. Exploratory research is critical for discovering scientific principles, while applied research is the process of taking those discoveries and turning them into innovations and technologies we can utilize. In engineering, our ultimate goal must be to ameliorate social issues by applying existing scientific principles rather than pursuing exploratory research toward basic discovery, unless the area of research is particularly in its infancy and still considered unscientific.

Developing countries are especially reliant on scientific innovation to address basic social needs, especially for communities that lack access to potable water, renewable energy, or sustainable farming. Developed nations can certainly pursue both exploratory and applied research, funded primarily through expanded revenues, infrastructure, and raw materials, thanks to better fortune.

Applied research ought to infuse innovation into the advancement of existing scientific discoveries, thereby preventing subgroups from replicating findings and instead enhancing their translation into technological applications. Consequently, the equilibrium between exploratory and applied research signifies a juxtaposition that is not only effectively maintained but also competitive, given that scientific discovery necessitates subsequent dissemination through novel technologies that more directly benefit society.

In summary, when both exploratory and applied research take place, and when the roles are defined clearly and establish maximum function for a project, engineering researchers who focus on an applied view emerge fulfilling their role in potentiality to transfer scientific discoveries to consideration in engaging a new technological paradigm for living life, while furthering industry or product sectorization.

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