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A Study of Changes in the Efficiency of Scientific Research

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Abstract: The hypothesis of declining scientific research efficiency has been actively discussed in the scientific community recently, and a number of studies have been presented on this topic. However, it is noteworthy that the actual scientific and technological progress observed in the real sectors of the economy has not slowed. Based on this, this paper analyzes the efficiency of scientific research, examining not only publication activity but also citation rates and the number of patents. Data on scientific activity at large companies is presented. Based on this work, conclusions are drawn regarding structural changes in the organization of scientific research. The results can be used for the effective management of scientific research.

1 INTRODUCTION

The hypothesis of declining scientific research efficiency is actively debated in the scientific community. There is compelling evidence that scientific productivity (number of articles, researchers, funding) is increasing, while efficiency (breakthrough discoveries per unit of resources expended) is declining across many metrics. However, the picture is ambiguous and depends on the field of science and the measurement methods. This line of research is often referred to as the "Age of Slowing Progress" (Figs. 1, 2).

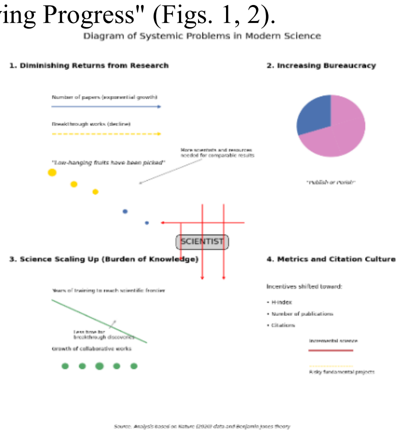

Figure 1: Scheme of systemic problems of modern science.

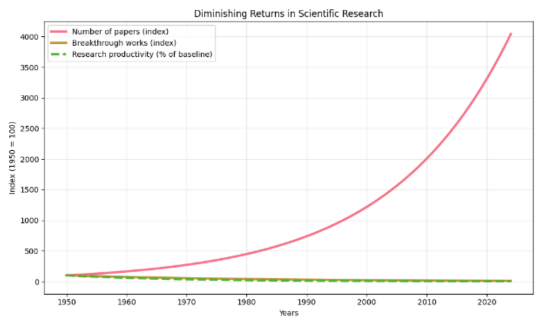

Figure 2: Declining returns on scientific research.

However, upon closer examination, the picture appears to be not so clear (Fig. 3, 4)

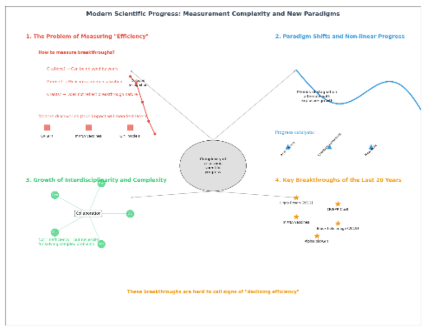

Figure 3: Modern progress: complexity of measurements and new paradigms.

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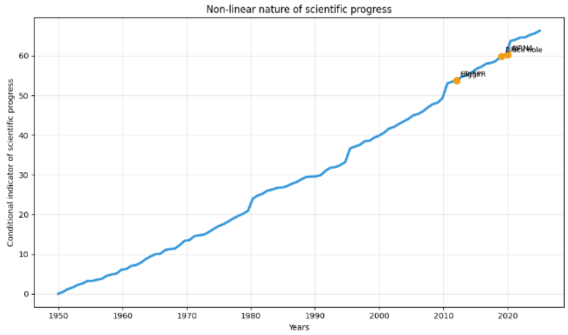

Figure 4: The nonlinear nature of scientific progress.

In this regard, the present study aims not only to analyze the obvious metrics of scientific activity, but also to analyze possible structural changes in the organization of research that may influence the final conclusions about the effectiveness of R&D.

2 S-SHAPED CURVE HYPOTHESIS

The sigmoidal (S-shaped) hypothesis is perhaps the most systematic and compelling way to explain the observed efficiency recession. Let's explore this idea in detail. The S-curve describes the life cycle of a technological paradigm or scientific field:

1. Inception (lower curve): Slow growth, formation of basic principles.
2. Rapid growth (central, almost linear portion): A period of exponential progress, low-hanging fruit is actively plucked.
3. Saturation (upper curve): Progress slows as the fundamental limits of the paradigm are reached. Enormous effort is required for minor improvements.
4. Plateau: Further progress within this paradigm is virtually impossible. A paradigm shift is required.

If we are observing a "efficiency recession" on a scientific scale, this may mean that many major technological paradigms that defined 20th-century progress are simultaneously plateauing (fig.5).

Technology Paradigm Lifecycles: Growth, Saturation, and Successors

Domain/Paradigm	Rapid Growth Phase (Golden Age)	Saturation Phase (Why efficiency declines)	Possible New Paradigm
Moore's Law (Silicon Microelect	1970s - 2000s: Exponential growth in transistor cou	~2010s - present: Hitting physical limits (quantum effects, heat dissipation). Fabrication co	Quantum computing, neuromorphic computing, op
Pharmacology ('One pill - one t	Mid-20th century: Discovery of antibiotics, vaccines,	Present: Most 'easy' drug targets found. New drug development requires >$10 and 10 years	Gene therapy (CRISPR), personalized medicine, m
Aviation (Fossil fuel aircraft)	1930s - 1960s: Transition from propellers to jet engi	Since 1970s: Speed and efficiency of passenger transport not growing radically. 1-2% impro	Electric aviation, new engine concepts (e.g., hydro
Classical Physics (Mechanics, E	17th - 19th centuries. Newton, Maxwell, Faraday. Fu	Early 20th century. Paradigm exhausted. Couldn't explain micro-world or black holes	Quantum mechanics, theory of relativity (paradigm
Artificial Intelligence (Deep Lea	2010s - present. Explosive growth due to data and c	Beginning now: Require increasingly larger models and data volumes for linear quality grow	AI neuroarchitectures, hybrid models, artificial gen

Figure 5: The nonlinear nature of scientific progress.

How does this explain the "efficiency recession"?

1. Coincidence of saturation phases: We live in an era when many macro-paradigms that have driven progress over the past 50-70 years (silicon, hydrocarbons, classical pharmacology) are simultaneously reaching their S-shaped plateaus. Enormous resources (money, scientists) are pouring into systems whose marginal returns are approaching zero.
2. Delay between paradigms: Between the death of an old paradigm and the emergence of a new one, there is a "valley of death." During this period, investments seem fruitless, and efficiency declines. We may be in precisely this phase.
3. Data aggregation: When we look at overall statistics (all patents, all publications), we average breakthroughs in new areas (e.g., CRISPR) with incremental improvements in old ones (e.g., a new alloy composition for a turbine). The share of the latter is much higher, which pulls the overall efficiency curve downward.

Imagine not a single S-curve, but a superposition of many such curves (fig.6).

Conclusion: the decline in scientific efficiency is not an anomaly, but an expected stage within the sigmoid model of technological progress.

We are witnessing the Great Plateau of several technological paradigms fundamental to our civilization. The decline in efficiency is a symptom of the old growth engines reaching the end of their useful life (fig.6).

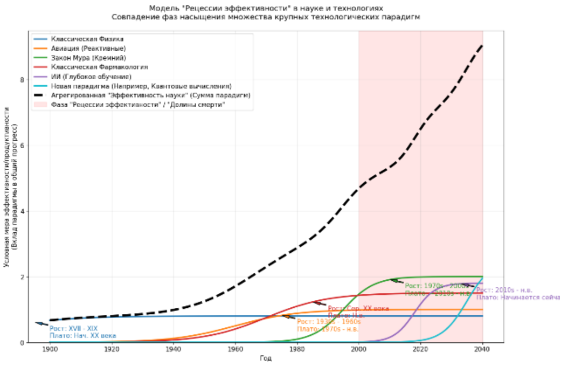

Figure 6: The nonlinear nature of scientific progress.

Therefore, the way out of this recession lies not in pouring more money into obsolete paradigms, but in:

1. Identifying new, emerging paradigms (quantum technologies, synthetic biology, AGI).
2. Redirecting resources to their development, recognizing that returns in the nascent phase will be low and risky.
3. Stop measuring the effectiveness of new research with old-world metrics (for example, the number of papers in quantum physics should not be assessed in the same way as in organic chemistry).

Therefore, the observed decline is not the end of progress, but perhaps a painful transition period before the next leap, which will occur when the new S-curves begin their exponential growth.

3 R&D BECOMES CORPORATE

The shift in focus from fundamental research conducted at universities to applied, problem-oriented research in the corporate sector is one of the key trends changing the scientific landscape. Ignoring this fact is missing a huge piece of the puzzle.

Let's integrate this analysis into our overall picture and look at how corporate R&D is changing the structure and metrics of science.

Large companies (Apple, Google, Pfizer, Tesla) operate according to a different logic than academic institutions. Their research:

• Problem-oriented: The goal is not publication, but rather solving a specific business problem (increasing battery life, creating a new drug, improving a recommendation algorithm).

• Closed: Results are often protected by trade secrets or patents, rather than published in open journals. This creates "shadow" science, invisible to classic bibliometric analyses.

• Development-oriented, not research-oriented: The R&D ratio is shifting toward "D." This means faster, but also more incremental (gradual) activity.

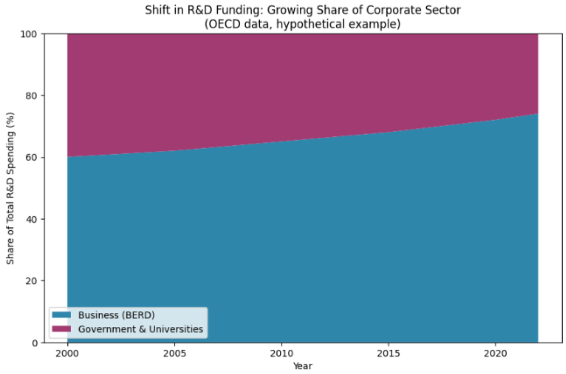

Figure 7: The nonlinear nature of scientific progress.

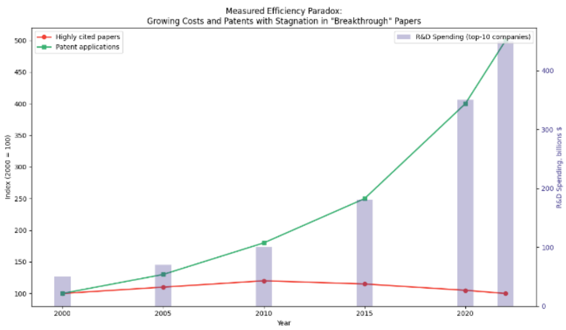

Figure 8: The nonlinear nature of scientific progress.

How does this affect overall "efficiency"?

This trend has a dual impact and can explain the decline in some metrics while simultaneously masking true productivity.

1. Negative impact on measured efficiency (Creates a statistical artifact)

• Bias toward incremental improvements: The goal of corporate R&D is to reduce risk and ensure reliable returns. This encourages countless small improvements rather than risky fundamental breakthroughs. Therefore, the number of breakthrough ideas per dollar spent may fall.

• Distortion of patent statistics: As mentioned, patents are often filed for defense—to create a "patent umbrella," block competitors, or used as bargaining chips in litigation. This "noises" the data: the number of patents increases, but their true innovative value does not.

• Concealment of real breakthroughs: The company will never publish its most valuable discoveries. All progress in fields like semiconductors or batteries is a trade secret at Apple and Tesla. From the outside, it appears that progress has slowed, although within corporations it can be colossal.

2. Positive Impact (which is difficult to measure)

• Invisible Efficiency: The effectiveness of corporate research is measured not by citations, but by market share, profits, and the consumer properties of the product. From a business perspective, their R&D can be super-efficient. The growing market capitalization of tech giants is indirect evidence of this.

• Powerful Focus of Resources: A company can throw billions of dollars and thousands of engineers at solving a single, narrow problem (for example, creating its own chip). This produces results unattainable for fragmented academic groups.

• Science-Market Connection: Corporations excel at turning abstract knowledge into a concrete product. This accelerates innovation. To measure this, it's necessary to use new metrics for analysis and seek out unconventional data:

1. Cost analysis:

o Share of BERD (Business Expenditure on R&D) in total R&D spending: If the share of business is growing, while that of government and universities is declining, this confirms a shift in focus. Data: OECD.

o R&D intensity (R&D / Revenue) at major companies: Shows how much they invest in research. Data: annual company reports, Bloomberg, Reuters.

2. Results analysis (problem-oriented):

o Time from idea to product: Is it decreasing? This is a key performance metric for companies. Difficult to measure, but industry reports exist.

o Product meta-analysis: Evaluate breakthroughs not by product category, but by the appearance of products with fundamentally new features on the market (the first iPhones, mRNA vaccines, mass-market electric vehicles). o Specific indicators: For example, the decline in the cost of solar energy per watt ($/W), the growth of battery capacity (Wh/kg). These curves often have a pronounced sigmoidal shape and accurately reflect the effectiveness of applied research in a given field.

3. Analysis of "hidden" science:

o Number of PhD vacancies in industry: The growth of this indicator indicates a "brain drain" from academia to the corporate sector.

o Patent analysis: Not just quantity, but an analysis of citation networks between patents from different companies. This can reveal hidden pockets of technological development.

This shift is another explanation for the observed decline in traditional metrics (citation impact, number of publications). It does not invalidate the sigmoidal curve hypothesis, but rather complements it:

• Academic science is reaching the limits of fundamental paradigms (sigmoidal curve). • Corporate science focuses on "pushing" these paradigms, optimizing and fine-tuning them, which is an activity with inherently lower marginal returns (incremental improvements on the plateau of the S-curve).

4 CONCLUSIONS

It can be concluded that we are witnessing a duality:

1. A statistical decline in formal indicators of scientific efficiency, caused by the exhaustion of paradigms and the shift of resources to incremental, closed, corporate R&D.

2. A possible increase in unobserved, applied efficiency, which manifests itself in the quality and complexity of consumer and industrial technologies.

Thus, the overall picture becomes even more complex. It is quite possible that "efficiency" is not declining globally, but is being transformed, moving from the realm of public measurement to the realm of commercial competition. This does not eliminate the problems for fundamental science, but it explains why technological progress in the popular perception continues, while "breakthroughs" are declining.

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