DARPA: the Differentiator

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Abstract: today the U.S. is facing many internal and external challenges. Internally, productivity growth rate has slowed down significantly in the past 15 years; externally, rising powers, such as China and Russia, are challenging American hegemony. In this article we argue that the Defense Advanced Research Projects Agency (DARPA) is the differentiator that enables the U.S. prevail against these challenges. In the past 60 years DARPA has been the core engine for the development of breakthrough technologies. We examine how DARPA has continuously delivered breakthrough technologies to drive economic growth, and the impacts of DARPA technologies on the U.S. economy. Also, by comparing DARPA's performance against some of the world's leading technology venture capital firms, and other DARPA-like agencies around the world, we conclude that DARPA is the differentiator that guarantees American hegemony in this era.

1. the Times We Are Living Through

The United States emerged from World War II as the dominant economic, political, and technological power. America's only global rival in the twentieth century was the Soviet Union, but when the Soviet Union finally collapsed in 1991, American hegemony was complete. However, as we enter the second decade of the twenty-first century, American hegemony is facing challenges both internally and externally. Internally, the U.S. has been experiencing economic stagnation for the past 15 years, especially that the productivity growth rate has dropped to merely 1.3%. Robert J. Gordon's indicates that slow growth in the recent past is the result of the exhaustion of major innovations ¹. Gordon describes how economic life has been transformed by breakthrough innovations since the start of the industrial revolution, including steam power, electricity, the internal combustion engine, antibiotics and, most recently, digital technology. Gordon also argues that the period of very rapid decline in computer and semiconductor prices starting in the early 1990s resulted in a temporary surge of productivity. But now the last wave of innovation has passed and we should expect only incremental changes and hence slow productivity increase going forward.

Externally, rising powers, such as China and Russia, are challenging American hegemony. Specifically, the Belt and Road Initiative (BRI) spearheads a coherent Chinese grand strategy that

could weaken the foundations of America's post-World War II hegemony. To many, BRI closely resembled the Marshall Plan for Western Europe, which the United States launched while at the height of its power ².

In this article we argue that the Defense Advanced Research Projects Agency (DARPA) is the key differentiator that enables the U.S. prevail against these challenges. We demonstrate that, in the past 60 years, DARPA has established a sophisticated pipeline for the development of breakthrough technologies, which has continuously driven U.S. economic growth. Also, we compare DARPA against the world's leading technology venture capital firms, as well as other DARPA-like agencies around the world to show that DARPA is still leading by decades.

When the American hegemony was challenged by the Soviet Union during the Cold War, economic dominance helped the U.S. prevail. In this era, it could be the technological dominance that enables the U.S. to prevail again.

2. DARPA - the Engine of Developing Breakthrough Technologies

The genesis of DARPA dates to the launch of Sputnik in 1957, and a commitment by the United States that, from that time forward, it would be the initiator and not the victim of strategic technological surprises. The ultimate results of DARPA have included not only game-changing military capabilities such as precision weapons and stealth technology, but also modern civilian technologies such as the Internet, automated voice recognition and language translation, and the Global Positioning System (GPS) ³. In this section, we explore several reasons behind DARPA's continuous success on developing breakthrough technologies for the U.S. to remain as the technological hegemon.

Project Selection: while many research organizations focus on incremental advances, since its founding DARPA explicitly reaches for transformational change instead of incremental advances. Many of DARPA's projects took decades to incubate but led to technologies, such as the Internet and GPS, that completely changed our daily lives. We will delve into more details in the next section.

Collaboration: DARPA does not perform its engineering alchemy in isolation. Instead DARPA works within an innovation ecosystem that includes academic, corporate and governmental partners. DARPA's openness allows them to attract the best talents to work on the most transformational technologies.

JASON: the JASON Defense Advisory Group, or simply JASON, is an independent and secretive committee formally established in 1960 to keep the DOD, especially DARPA, in direct contact with top-notch civilian scientists ⁴. JASON membership is by invitation only and is restricted to elite scientists: of the roughly one hundred JASONs over time, forty-three have been elected to the National Academy of Sciences; eight have won MacArthur awards; one won mathematics' Fields Medal; eleven have won Nobel Prizes. The JASONs are just one example of the caliber of the talents working with and for DARPA.

The JASONs had made numerous contributions to DARPA and DOD projects over the past fifty years. While many projects they worked on remain top secrets, as early as 1979, the JASONs already released a report titled “The Long Term Impact of Atmospheric Carbon Dioxide on Climate”, raising their concerns on global warming ⁵.

Organization: DARPA has a very efficient and effective organization, which comprises approximately 220 government employees in six technical offices, including nearly 100 program managers overseeing about 250 research and development programs. DARPA goes to great lengths to identify, recruit and support excellent program managers—extraordinary individuals who are at the top of their fields and are hungry for the opportunity to push the limits of their disciplines. These leaders, who are at the very heart of DARPA's history of success, come from academia, industry and government agencies for limited stints, generally three to five years. Each DARPA project is associated with a firm deadline, and the deadlines fuel the signature DARPA urgency to achieve success in less time than might be considered reasonable in a conventional setting.

Efficiency: DARPA has been very successful in the past 60 years on developing breakthrough technologies, but from a budgeting perspective, DARPA has an annual budget of only about \$3 billion, which pales in comparison to the top five private sector R&D spending in the U.S (Figure 1). For instance, as shown in Figure 1, DARPA's annual budget is only one-seventh of Amazon's R&D budget. Yet the technologies incubated by DARPA laid the technological foundations for companies like Amazon, Alphabet, Intel, Microsoft, and Apple *etc.*

Figure 1: DARPA funding compared to top five private sector R&D spending in the U.S.

3. How the DARPA Machine Works

In this section we zoom into the DARPA organization and understand how the DARPA machine works. Specifically, we try to understand how *project management* and *talent management* work in DARPA.

3.1 Project Management

To guarantee the development of breakthrough technologies, each DARPA project goes through a highly competitive and thorough selection and incubation process, as detailed in the following steps ²³:

Program Establishment: to initiate a new program, the program managers have to convince senior managers of a program's merits. Senior managers who do not consider a program to be ambitious enough or lacking in a technical basis have no hesitation rejecting the program.

Proposal Solicitation: when a program is approved, the program manager will begin soliciting proposals through a Broad Agency Announcement. Most commonly, these interactions take place in the form of workshops and program reviews. These exploratory workshops allow attending scientists get an early glimpse into future DARPA programs, give their input on the program idea.

Project Teaming: following these workshops, DARPA often creates a project website to allow prospective applicants describe their capabilities and identify potential collaborators. Note that DARPA's projects focus on the development of technological systems, combinations of multiple technologies that can produce the desired military capability. Hence, the breadth of required expertise is beyond that of a single research scientist. DARPA-sponsored research must be performed by teams of investigators, each investigator with a different capability.

Project Selection: unlike National Science Foundation (NSF) proposals, DARPA proposals are not evaluated by scientists in the general research community and are not evaluated on the basis of general technical merit. Instead, government employees with relevant technical knowledge, often from Department of Defense research laboratories, are assembled into a source selection panel which evaluates proposals based on which are most likely to achieve program goals. After the source selection panel evaluates the proposals, the program manager and senior managers decide on whether to make an award to the proposers. A DARPA research award is typically structured as a contract, rather than as a grant, that lays out a statement of work and holds awardees to meeting specific program goals.

Regular Program Reviews: program reviews occur once a research program is underway and are a vital means for program managers to monitor the ongoing progress of funded researchers. DARPA expects written progress reports typically quarterly or monthly and regularly calls for program reviews in person. Since a DARPA research award is structured as a contract, if the progress is not satisfactory, DARPA can terminate the contract immediately, this puts a lot of stress on the researchers to deliver good progress.

Technology Transfer: research programs are expected to be technologically ambitious, reflect an understanding of the current state of the art science and technology, and target a very specific technological breakthrough. For example, the Maximum Mobility and Manipulation program developed a four-legged robot whose movement mimics animals known for their speed, for example, the “Cheetah” robot. The Revolutionizing Prosthetics program allows paralyzed patients to control a prosthetic arm by implanting micro-electrode arrays directly into the motor cortices of patient brains.

3.2 Talent Management

One of the most effective ways to attract talented program managers from a wide array of disciplines, organizations, and backgrounds—and to keep them intensely focused—is to set a finite term for a project and staff it with people working under contracts that last only as long as the jobs they perform contribute to the overall goal ²⁴.

Fixed Durations and Tenures: Projects with set time frames (up to five years at DARPA) leaders who leave when the projects end, and the scalability, diversity, and agility of contract performers have an edge over traditional captive research organizations. All of those things make it possible

to recruit high-caliber team members from a broader pool and get them on board faster. In addition, you can change the makeup of the group more quickly along the way as the team overcomes certain technical obstacles and others emerge. Another benefit of limited tenures is that—combined with a clearly articulated important need and a scientific challenge—they create a sense of urgency. This forces the team to act as a whole to benchmark progress and to continually challenge “how things have always been done.”

Dynamic Teams: DARPA doesn’t have any laboratories of its own. Its programs fund researchers who work at their respective organizations and get together at least twice a year to review progress and objectives. The same kind of interactions may happen across disciplinary lines. This dynamic produces a tremendously creative, fast, iterative cycle and generates breakthroughs in time frames that seem impossibly short.

Project Managers: The project leader orchestrates the entire effort. He or she determines what pieces of work are needed to produce a specific result, conducts a proposal competition, and contracts organizations to do the work. Project leaders who can successfully lead DARPA-like efforts possess the skills of the best CEOs of science- or engineering-based start-ups. Some project leaders may have held such positions. Others may come from academia, government labs, corporations, and nonprofits. They need to have deep technical or scientific knowledge, be natural risk takers, and be thought leaders who can create a vision that inspires an entire community. Project leaders oversee the collection of performers, manage the technical details, and make all major decisions. They handle budgets, contracts, execution issues, speaking engagements, and customer relations.

Independence: the DARPA project teams operate with some independence from the rest of the organization. Crucially, decisions about which projects to pursue must not be made by committee. Breakthrough innovations, by their very nature, do not lend themselves to consensus. Instead, the parent company should establish a multiyear budget with critical mass, ensure that the leaders of the advanced research group have visibility into—and the ability to influence—corporate objectives, and then give them the freedom to select projects. Within broad limits, they should also be able to reallocate and reprioritize spending within the group and among projects over time.

4. DARPA Impact on U.S. Economy

While it is extremely challenging to accurately account for DARPA's impact on U.S. economy, in this section we provide two examples on how DARPA incubated projects that eventually have made tremendous impact on the U.S. and world economies. But before delving into the examples, regarding government support of research, the general approach is to calculate what is referred to as *social return*. Note that the *private return* being the return to the original investor, whereas the *social return* represents the payoff to society as a whole. Particularly, in a study published in 1992, economist Edwin Mansfield estimated that the **annual social rate of return from investment in academic research during the time period was 40%** ⁶.

4.1 DARPA and the Global Positioning System (GPS)

In 1963, DARPA launched the first satellite in what would become the world's first global satellite navigation system. Known as Transit, the system provided accurate, all-weather navigation to both military and commercial vessels, including most importantly the U.S. Navy's ballistic missile submarine force. By 1968, a fully operational constellation of 36 satellites was in place, and it was the precursor of the modern GPS system ⁷.

The Transit program operated for 28 years until 1996, and it has been found that GPS has generated an estimated \$1.4 trillion in economic benefits during the last two decades. Thus a thirty year seed investment from DARPA into the GPS technology has led to a \$1.4 trillion growth on U.S. economy. Particularly in the past decade, GPS's impact on U.S. economy grew from \$20 billion in 2007 to \$300 billion in 2017, and this trend is expected to continue ⁸.

4.2 DARPA and the Internet

DARPA research played a central role in launching the Information Revolution. DARPA developed and furthered much of the conceptual basis for the ARPANET, a prototypical communications network, and invented the digital protocols that gave birth to the Internet. A seminal step in the birth of the Internet took place in 1968 when ARPA contracted BBN Technologies to build the first routers, which one year later enabled ARPANET to become operational ⁹.

Today the Internet is changing the way we work, socialize, create and share information, and organize the flow of people, ideas, and things around the globe. Yet the magnitude of this transformation is still underappreciated. As one McKinsey Global Institute report suggests, the Internet has accounted for 21% of the GDP growth in mature economies from 2005 to 2010 ¹⁰.

The Internet Association estimated that in 2018, **the Internet sector contributed \$2.1 trillion to U.S. economy, about 10% of the U.S. GDP**, suggesting that the Internet sector represents the fourth largest sector of the U.S. economy, only behind real estate, government and manufacturing ¹¹. The study also found that the Internet sector has nearly 6 million direct jobs, which accounts for 4% of U.S. jobs. the Internet Association also estimated the sector was responsible for 6% GDP in 2014.

4.3 Summary

There are some interesting patterns from these two examples. Both projects were initiated by DARPA, and then took nearly 30 years to incubate within U.S. military, then followed by a commercialization stage (20 years thus far) during which we observed an explosive growth on the technology's impact on economy. Now, after about 50 years of the initiation of Transit and ARPANET, the GPS technology contributes \$300 billion, and the Internet sector contributes \$2100 billion, to the U.S. GDP, accounting for 1.5% and 10% of U.S. GDP respectively, and both sectors are expected to enjoy high growth rate in the near future.

DARPA has successfully established an extremely powerful *breakthrough innovation engine*, such that we expect the technology investments made by DARPA in the 70s, 80s, 90s, will contribute to over 12% of the U.S. GDP in the 2020s, 2030s, 2040s, *etc.* Assuming DARPA can remain as efficient and effective for the years to come, through the DARPA engine, the U.S. government is investing less than 0.015% of U.S. GDP to get a return that is over 10% of the U.S. GDP. Even by a conservative estimate, **it generates a social rate of return of a whopping 66000%**. Not to mention that other rising economies have been enjoying the social benefits brought by DARPA innovations. For instance, in 2018, the Internet Services industry in China maintained rapid growth of about 38.7% to reach \$527.01 billion, or 4% of China's GDP ¹².

5. DARPA vs. Leading Technology Venture Capital Firms

In this section, we compare the performance of DARPA versus the world's leading technology venture capital (VC) and private equity (PE) firms, and attempt to understand why DARPA outperformed the best technology venture capital firms. Figure 2 shows the 10-year internal rate of return (IRR) data of Sequoia Fund ¹³, one of the best U.S. VC funds, the average of U.S. VC firms ¹⁴, the average of U.S. PE firms ¹⁵, and the S&P 500. Note that we choose the 10-year IRR because most VC and PE funds have a duration less than 10 years.

Figure 2: U.S. venture capital and private equity internal rate of return

In the past 10 years, U.S. VC and PE funds, as well as the S&P 500 generate about 9 % to 11% of IRR, whereas in the previous sections we have shown that DARPA has generated a social rate of return of 66000%. While it may not be fair to directly compare IRR and social rate of return, the comparison does indicate the efficiency and effectiveness of DARPA and the impact of DARPA on U.S. economy, and we think it is fair to conclude that DARPA outperformed top U.S. VC and PE firms tremendously. We also summarize three reasons why top U.S. VC and PE firms pale in comparison with DARPA:

Technology trends: DARPA is the designer and the driving force behind technology trends, whereas the VC and PE firms are trying to make profit by riding on technology trends. In addition to the Internet and GPS, DARPA has started many technology trends that have been tightly integrated into our daily lives. To just name a few, in the 1960s, DARPA sponsored the development of on-Line System (NLS), which included the first use of onscreen windowing with

a mouse - without which there couldn't have been Microsoft Windows and Apple Macintosh. Also, in 1979, DARPA funded the Aspen Movie Map project, Google Street View would not have been possible without the technical foundation provided by the Aspen Movie Map project. As discussed in depth in Section 3, DARPA initiates a breakthrough technology, and transfers the technology to military for it to incubate for decades, and then commercialization will take another decade or two to develop before the technology becomes a major GDP contributor. VC and PE firms only come in early or mid-stage of the commercialization process, decades after DARPA, therefore their IRRs are naturally much lower than DARPA's social rate of return.

Talents: DARPA is always able to attract the best talents in technology, such as the JASON scientists, and the program managers. Most scientists work for DARPA for their passions on technology and their patriotism. In contrast, although VC and PE firms are able to attract top talents as well, their motives are mostly financial incentives, and these VC and PE talents are not technologists who are capable to advance the state of the art. In other words, the VC and PE talents are employed to make investment decisions, whereas the DARPA scientists are employed to guide the nation's technological directions.

Duration: VC and PE funds are *shortsighted* compared to DARPA, as the longest duration for a VC or PE fund is usually 10 years, whereas DARPA is patient enough to initiate a project and let it incubate within military for decades, until the technology is mature enough to benefit the whole society. For technology incubation, time is often one of the essential elements, and patience always gets rewarded.

In summary, we have yet to see a private sector organization that can incubate breakthrough technologies like DARPA does. Even with advanced industry research labs such as Google X and Microsoft Research who are willing to invest a decade to incubate a project, they often build on top of what DARPA has incubated, such as how Waymo built on top of the results of DARPA Urban Challenge.

6. DARPA Equivalents of Other Nations

The Commission for Science, Technology and Industry for National Defense (COSTIND) was a civilian ministry within the State Council of China, and it was considered as the Chinese counterpart of DARPA. COSTIND was formed in 1982, responsible for military research and development, weapons procurement, and coordination of military production of defense industries.

In 2018, China's central government spent \$175 billion on defense, but the amount allotted to defense research and development remains a state secret. Since the 1950s military research facilities and factories are reported to have China's best-trained personnel, highest level of technology, and first priority for funding. China's military research and development work evidently has successfully resulted in the largely independent development of nuclear and thermonuclear weapons, intercontinental ballistic missiles, nuclear submarines and submarine-launched ballistic missiles, and the successful launch and recovery of communications and reconnaissance satellites ¹⁶. Nonetheless, in China the military sector has developed in isolation from the civilian economy, and COSTIND has made little contribution to the national economy. Although there have been efforts to break down some of the administrative barriers separating the military and civilian research and development systems, there has not been any major GDP contributor in China incubated by COSTIND.

The New Energy and Industrial Technology Development Organization (NEDO), is Japan's largest public management organization promoting research and development as well as deployment of industrial, energy and environmental technologies, and NEDO is considered as Japan's version of DARPA. For fiscal year 2009, NEDO's budget was \$2.6 billion, and in 2019, the budget has dropped to \$1.43 billion. About \$890 million of the 2019 budget went to energy related research, \$417 million went to industrial technology research, and \$56.3 million went to fostering technology related startups ¹⁷. Although NEDO is more open to collaboration compared to COSTIND, there has not been any major GDP contributor in Japan incubated by NEDO yet, and the NEDO budget cut in the past few years is not a good sign for Japan's breakthrough technology R&D efforts.

Besides building a DARPA-like agency, venture investing can be a strategy other nations use to transfer U.S. developed technologies. In a 2018 DIUX report ²², Brown and Singh argue that Chinese participation in venture-backed startups has grown quite rapidly in the past seven years and in 2017 it could have reached 16% of all venture deals in the U.S. Specifically, the technologies where China has been investing include artificial intelligence, autonomous vehicles, augmented/virtual reality, robotics and blockchain technology, the same technologies of interest to the U.S. Defense Department. Brown and Singh also worry that, as the U.S. economy is open, foreign investors are able to invest in the newest and most relevant technologies gaining experience with those technologies at the same rate as the U.S. does. Nonetheless, the U.S. federal government

indeed already possesses policy tools to block or mitigate foreign investment in critical technologies, such tools include the Committee on Foreign Investment in the United States (CFIUS) and the U.S. export control regime.

We argue that DARPA remains far superior compared to other DARPA-like organizations around the world, for several reasons: first, *the U.S. immigration system is able to attract the best technology talents around the world*, whereas in comparison, CONSTIND of China, and NEDO of Japan, do not have the same access to the global talent pool like DARPA does. Second, *the openness of DARPA allows DARPA to work closely with academia and the industry*, which allows much easier technology transfer after the technology completes its incubation process within DARPA, the Internet is a perfect example of technology transfer. Third, and most importantly, after 60 years, *DARPA has already established a mature technology incubation pipeline*, and we expect more breakthrough technologies being produced continuously through this pipeline, sustaining an extremely high social rate of return for DARPA. In contrast, the DARPA-like organizations around the world are still in their infancy, and their first incubation projects are unlikely to generate significant outputs in the next decade or two. Then if the central government gets impatient, it is very likely that these DARPA-like agencies will suffer from funding cuts, like in the case of NEDO, and many projects going through the infancy stage of the incubation pipeline will suffer from the risk of being cancelled. Even if these DARPA-like agencies are able to access the same talent pool, have sufficient budget support, and execute as efficiently and effectively as DARPA, it will still take them decades to get to where DARPA is today.

8. Conclusions

Economists have long argued that technology contributes to the growth of a nation's economic output. In 1957, Nobel laureate Robert Solow, examined economic data from 1909 through 1949 for changes in GDP, and Solow calculated that approximately 87% of U.S. economic growth between 1909 and 1949 was due to technological advances ¹⁸.

A general form of Solow's growth accounting equation can be written as $Y = F(A, K, L)$, or simply put, a nation's economic output depends on the labor force L , the capital input K , and the technological advances A . However, as automation technologies advanced in recent years ¹⁹, the

population size may gradually play a less important role in the growth accounting equation, and a nation's economic output will depend more on A and K .

Back to the time of the Cold War, especially after the launch of Sputnik in 1957, the Soviet Union's technologies were on a par with, if not better than, the U.S. technologies. Thus, at that time, A could not have been a differentiator between the U.S. and the Soviet Union. Indeed, during the Cold War, the U.S. and the Soviet Union got into a technological and space race, but it was the U.S. capital, or K , that eventually led to the Soviet Union collapse. Although it was the NSC 68²⁰ that laid out the "containment" strategy against the Soviet Union, the weapon and the true differentiator at that time was K , the U.S. capital. After all, the US owned half of the World's gold reserves by the end of WWII, there was no way for the Soviet Union to win against the U.S. on a capital race.

Looking at the world today, there have been concerns that our era may mark the end of the American hegemony²¹. In this paper, we argue that DARPA is the U.S.'s key differentiator against other rising powers. We have studied the impact of DARPA on the U.S. economy, compared DARPA's performance versus the best technology venture capital firms, and reviewed the DARPA-like organizations around the world. We conclude that DARPA is the core engine for incubating breakthrough technologies to continuously fuel U.S. productivity growth. Also, when it comes to incubating breakthrough technologies, DARPA is still ahead by decades compared to any other organization. Going back to the growth accounting equation, DARPA guarantees that A , is the weapon and the true differentiator the U.S. have against its challengers in this era.

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