The economic returns on defense R&D

Far more 'bangs for the buck' vs civilian R&D

RaboResearch
Global Economics & Markets
mr.rabobank.com

Hugo Erken
Head of Netherlands Economics

Michael Every
Global Strategist

Wouter Remmen
Economist

Contents

Statecraft is back: so is higher defense spending	1
The defense > productivity historical heuristic	2
Productivity benefits from general R&D…	3
…but defense R&D? People are more defensive	3
Defense R&D: facts and figures	4
Economic returns on defense R&D investment	6
Conclusions	7
Annex 1: Modern innovations from defense R&D	9
Technical Annex	12
Literature	20

Summary

- The re-election of President Trump has accelerated Europe's impulse to rearm as the world returns to a 'Grand Macro Strategy' requiring states to possess military strength.
- We underline the importance of defense R&D expenditure in long-run productivity growth. We estimate the historical 'bang for the buck' at between $8.1 and $9.4 per $ in defense R&D. By comparison, for non-defense R&D it lies between $1.5 and $1.7.
- This hypothesis has further geopolitical and geoeconomic implications.

"The society that separates its scholars from its warriors will have its thinking done by cowards and its fighting by fools."

Thucydides

Statecraft is back: so is higher defense spending

War in Ukraine and the Middle East, the de facto closure of the Suez Canal, and alleged grey-zone attacks on EU infrastructure have all pushed defense up Europe's policy priority list. On 5 March 2024, the European Commission approved a Joint Communication aimed at bolstering the European arms industry; on 16 April, former ECB President and Italian Prime Minister Draghi gave a speech calling for "radical change", including the development of a hugely scaled-up, integrated European defense system; and on 25 April French President Macron's Sorbonne speech underlined that Europe can no longer rely solely on US military protection in the face of existential external threats, and that: *"…today, our Europe is mortal. It can die. It can die, and it all depends on our choices."*

The re-election of President Trump has accelerated this impulse. Trump's claim that Canada, the Panama Canal, and Greenland should all come under US control underline that, as we had predicted, the world has returned to 'Grand Macro Strategy' of economic statecraft over economic policy, requiring states to possess economic, political, *and* military strength. Trump is also insisting NATO members commit to spending 5% of GDP on defense at a time when many are failing to even reach the committed 2% level: the implied US threat is that without this burden sharing, it may walk away from its NATO commitments. Suggestions are therefore of trillions of euros being required for defense over the next decade to bring shriveled European militaries back in line with the force levels that prevailed during the last Cold War.

We will address the potential direct economic boost to the European economy from much higher defense spending in a future report. However, this study will focus specifically on the part of such spending which could hypothetically generate long-term positive spillovers to the broader civilian domain: defense R&D.

The defense > productivity historical heuristic

Despite some naysayers, there is academic recognition that defense spending can have a stimulatory effect on GDP. However, there is less --modern-- economic acceptance of the clear historical pattern: **that the military is a vital conduit for innovation that flows on to the civilian economy.**

Taking a historical view, however, the relationship is clear: war and innovation have always gone hand-in-hand. Thucydides was adamant scholars and warriors need to work together. Arrighi (2007), drawing from McNeill (1982), notes Marx argued ancient armies first developed the wage system, the division of labor, the first use of machinery on a large scale, and that "the commercialization of war and an incessant armament race have characterized the Western path of capitalist development from its earliest beginnings." He notes the Crimean War (1854-56) as a turning point in transitioning European capital-goods industry from craft methods to automatic or semiautomatic milling machines, which were only profitable if vast quantities of munitions could cover the initial capital outlay. War was also drove Europe's railway networks (Stevenson, 1999).

Moreover, WW1 introduced surgical dressings, gas masks, sonar, aircraft design, air traffic control, and affordable wrist watches. WW2 saw radar, the shipping container (vastly reducing the cost of trade), the jet engine, rocketry, computer technology), and nuclear power. In later decades, the US Defense Advanced Research Projects Agency (DARPA) launched the microchip; the graphic user interface; the mouse; the internet; cryptography; GPS; touch screens; voice recognition; modern robots; drones; and exoskeleton lifters – all technologies which our economies rely on today. For a non-exhaustive overview of modern innovations emerging from defense R&D over time, please see the table in the Annex. Today, there is still a pipeline of paradigm-shifting ideas taking place under defense auspices.

By contrast, Europe today lags in areas such as personal, cloud, and quantum computing, cybersecurity, and AI (see European Commission, 2024), to the detriment of its overall economic performance. Indeed, with the exception of the Netherlands' ASML, there are few leading global European tech champions. This could be linked with relatively low defense R&D spending. While it can still gain indirectly from others' research, as we shall show, currently there is little likelihood of the breakthrough technologies that emerge from defense R&D being seen in Europe.

Show me the money!

The military has also gone hand-in-hand with *financial* innovation. Funding military spending, including defense R&D, was traditionally pivotal to a polity's prospects, and its single largest expense, often draining public coffers. Today's EU spends vastly more on welfare than warfare.

Past military build-ups and conflict were responsible for: the origin of modern-day central banking (i.e., the Bank of England); Hamiltonian fiscal unity within previously disparate entities (i.e., the US); long-term bond issuance (i.e., perpetual bonds/Consols in the UK); and war bonds (in many places); financial repression (in many places); the age-old resort of seignorage (i.e., money printing), or Modern Monetary Theory today; the introduction of the global Bretton Woods system post-1945, and arguably its end in 1971. Going forwards, this trend could possibly also include a new hybrid fusion of simultaneously tighter and looser fiscal and monetary policy --"high rates and acronyms"-- as noted in our report on EU strategic autonomy; or another shift in the global financial architecture, such as China and Russia's push for an alternative to the US dollar system, and/or the potential US adoption of a strategic Bitcoin reserve.

Obviously, financial innovation can have a major positive *or negative* impact on the overall economy. Even though this falls outside our focus on the scientific and knowledge-based benefits of defense R&D, it is important to underline this long-run trend.

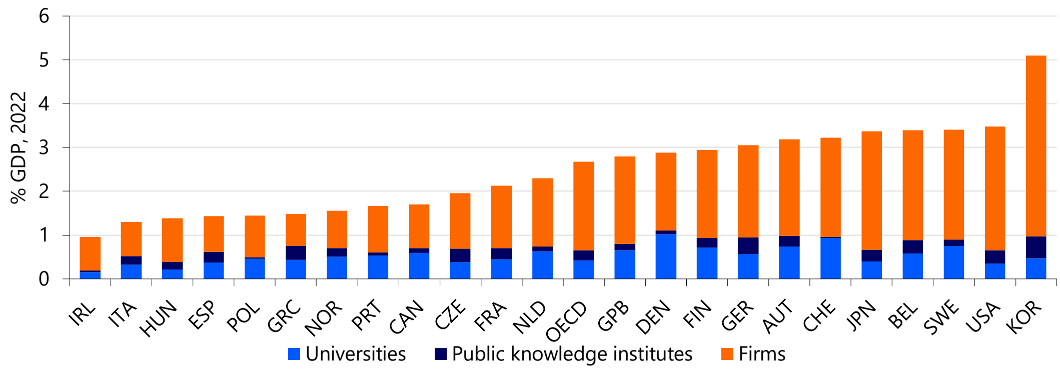
Productivity benefits from general R&D…

It is well established that R&D generates significant positive productivity effects for firms and society[1]. Indeed, Lucking, Bloom, and Van Reenen (2020) conclude that the *social return* compared to the private return to R&D is about four to one.

The reason for these large societal benefits is that R&D generates large spillover effects due to knowledge being: *non-rivalrous* and *non-excludable* (it spreads through all corners of an economy as patents expire or are ignored, and knowledge is vested in people, who are mobile)[2]. As the IMF (2016) says: "*…in advanced economies, private firms should invest 40% more in R&D to account for the positive knowledge spillovers they create to the wider economy*." However, due to knowledge spillovers, firms conducting R&D are unable to fully capture all economic benefits from their activities, which can reduce their propensity to do so.

From a societal perspective, this is suboptimal and implies a strong case for public support of R&D. In some fields, it is perhaps inevitable for the government to step in and organize publicly-financed R&D, especially when the distance to the market is larger, e.g., in fields such as space (where SpaceX has however taken the lead from the groundwork long done by NASA in the US), public health, energy, AI, *and defense*.

Figure 1: Private and public R&D spending as a % of GDP



Source: OECD Main Science & Technology Indicators

…but defense R&D? People are more defensive

Defense R&D has the same properties as general R&D: indeed, its record at DARPA suggests one *more* positive for technological progress. However, it also comes with a parallel procurement and/or financial and/or political aspect which might explain why the few empirical studies assessing the impact of defense R&D on productivity find mixed results:

- Lichtenberg & Siegel (1991) and Lichtenberg (1992) find *no significant effect of defense R&D on productivity* at the firm- and country-level. The major caveat is the authors do not use data on defense R&D, but *all* government-funded R&D as a proxy for defense R&D.
- Guellec & Van Pottelsberghe (2003) find public defense R&D has a significant *negative* impact on productivity. The authors argue this might be the result of the party conducting R&D not being the owner of the output, hampering them in exploiting the technology on the market and limiting spillovers to others. However, this would not explain DARPA's success.
- Moretti, Steinwender, & Van Reenen (2025) find a *positive* effect of defense R&D on productivity with a "crowding in" effect of government funds creating additional private funds. The authors' estimates for an industry-level panel of 26 OECD countries covering 1987-2009

[1] See Coe and Helpman (1995), Coe, Helpman & Hoffmaister (2009), Lucking, Bloom & Van Reenen, (2020), Ciaffi, Deleidi & Mazzucato (2023), Audretsch & Belitski, (2023)

[2] See Romer (1990)

finds a permanent 1 percentage point (ppt) increase in defense R&D (as a ratio of value added) results in a higher growth of total factor productivity of 0.08 ppts. However, the study solely estimates a dynamic model in which an impulse in defense R&D leads to productivity growth *in the subsequent year*. We believe that a dynamic model is less suitable for capturing the complexities of defense R&D, as it often takes many years for such research to translate into commercial applications in the civilian sector.

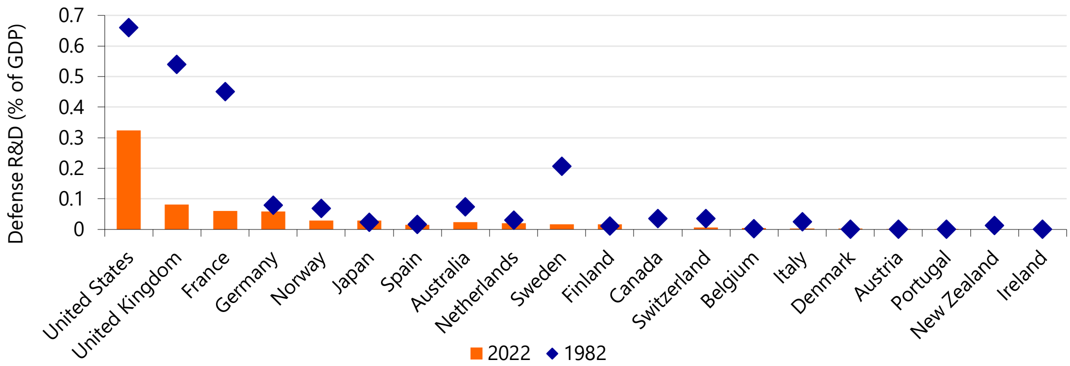
As a result, we have developed our own model which focuses on the **long-run relationship**[3] between defense R&D and productivity (see the Technical Annex for its detailed specification and estimation results). This allows us to examine whether defense R&D also generates the productivity gains caused by domestic/international knowledge-creation/spillovers and has similar properties as R&D conducted by firms, universities, or public research institutes.

Defense R&D: facts and figures

As a first step, we look at the data for defense-related R&D in 19 OECD countries[4] from 1981-2021. This is instructive in showing how far such R&D has declined since the Cold War. Not all economies used to spend on this area, but for those who did, the reversal has been marked. In the US, 1982 spending was 0.66% of GDP, but in 2022 just 0.32%; in the UK, it dropped from 0.55% to 0.08%; in France, from 0.45% to 0.06%; and in Sweden, from 0.2% to 0.01% (see Figure 2).

Of course, with US GDP being largest, it is responsible for the lion's share of total defense R&D, investing $65-70bn (in constant prices) annually over the last five years: to put this figure in perspective, the other 18 OECD countries *together* invested $7-10bn annually (see Figure 3).

Figure 2: Defense R&D spending trended lower and lower

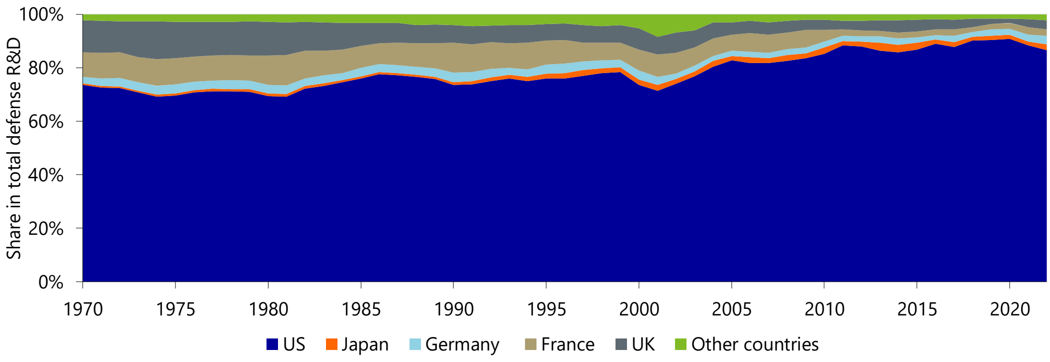


Source: OECD Main Science and Technology Indicators (MSTI)

[3] As we use panel cointegration techniques to estimate the long-run relationship between R&D and productivity, potential endogeneity is less of an issue compared to model estimates in first differences. Coe, Helpman and Hoffmaister (2009) argue that panel cointegration estimates are super consistent (see also Stock, 1987), and robust to problems such as omitted variables, simultaneity, and endogeneity.

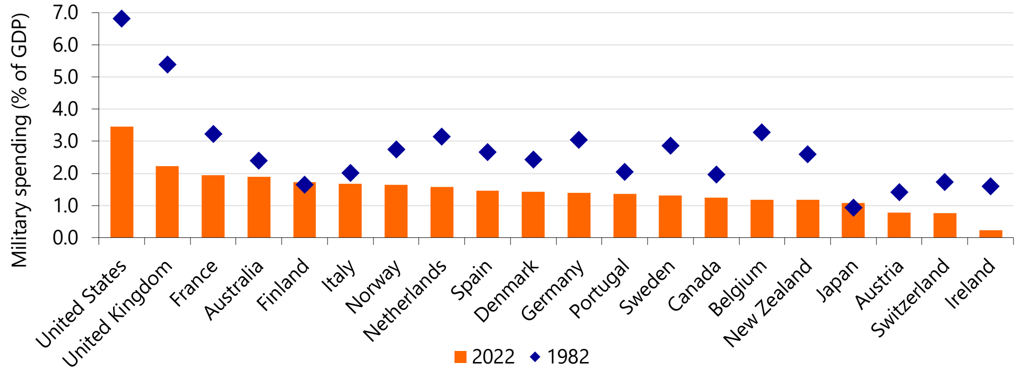
[4] For some OECD and many non-OECD countries, such as China, there is lack of information on the amount that is spent on defense R&D.

Figure 3: US responsible for the lion's share in defense R&D spending



Note: Other = AU, BE, AT, CA, DK, FI, IE, IT, NL, NO, NZ, PT, ES, SE, CH
Source: OECD MSTI

Figure 4: Substantial lower military spending as well

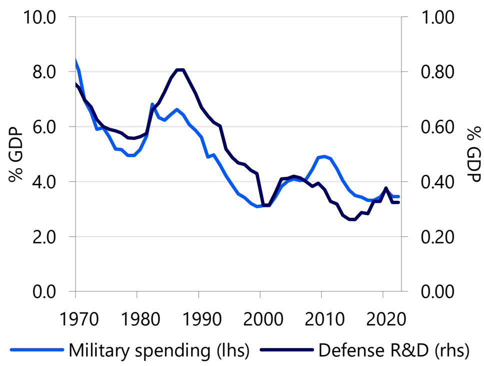


Source: World Bank

Logically, as military spending has plunged since the end of the Cold War (see Figure 4), so has defense R&D. The US, Canada, the UK, New Zealand, the Netherlands, and France all have a correlation coefficient of 85-90%; Switzerland, Sweden, Norway, Germany, Italy, and Australia 60-75%; and Belgium and Japan 30-40%. Austria, Finland, Denmark, Portugal, and Spain see military and defense R&D spending move in opposite directions. (See Figures 5-8 for some examples.)

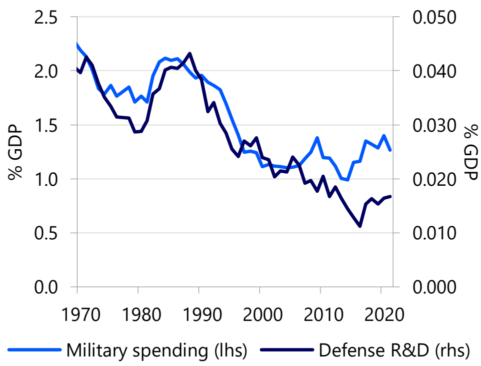
Nonetheless, the military-defense R&D correlation in the countries that used to spend the most on R&D, and the prospects of an increase in NATO defense spending from <2% to perhaps 5% of GDP, is still likely to generate a significant defense R&D impulse ahead, the effects of which would flow through to the broader economy with a lag.

Figure 5: United States



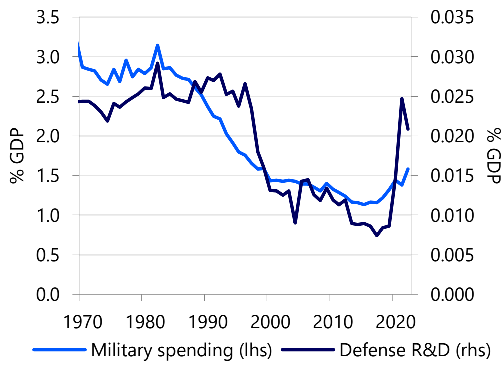
Source: World Bank, OECD

Figure 6: Canada



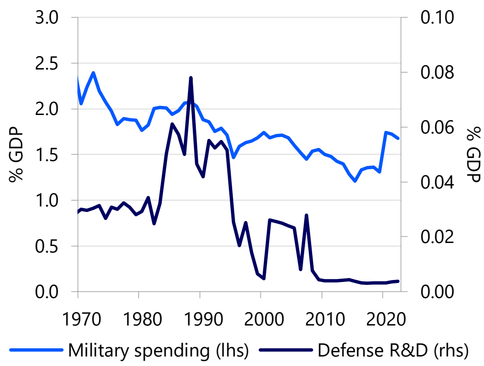
Source: World Bank, OECD

Figure 7: Netherlands



Source: World Bank, OECD

Figure 8: Italy



Source: World Bank, OECD

Economic returns on defense R&D investment

Table A.3 in the Technical Annex shows the results of our model estimates. Our preferred models are the ones in column (3) and (7). From the estimated coefficients we can derive the following long-term relationship:

A 1% increase in domestic defense R&D spending increases domestic productivity by 0.01% to 0.02% in the long run.

However, this is only the partial impact on the productivity level of a country. Countries benefit from each other's defense R&D spending too. Military innovations like computer chips, mobile phone, and the internet did not just benefit the US economy, but increased productivity globally. These spillovers increase the returns on defense R&D spending as follows:

If all related countries (measured by bilateral trade or technological similarity, NB, *and geopolitical alignment in this sample group*) increase their defense R&D spending by 1%, spillovers boost productivity by an additional 0.05% to 0.08% percentage point.

The combined 0.06% to 0.10% increased long-term productivity still might not seem like a lot, especially compared to the returns from civilian R&D, which we estimate at 0.04% to 0.07% (domestic) plus 0.10% to 0.16% (from spillovers), so 2 to 3 times higher.

However, given the low levels of defense R&D spending compared to civilian R&D activities in most countries, a 1% increase in defense R&D generally encompasses a much smaller investment than a 1% increase in non-defense R&D. If we calculate the additional GDP generated due to the increased productivity and set this off against the investment value, we arrive at the following, explosive, estimated relationship:

The effective 'bang for the buck' on defense R&D is between $8.1 and $9.4; by comparison, for non-defense R&D it is $1.5 to $1.7.

Why is the bang for the buck of defense R&D so much higher?

The vastly higher return on defense vs. non-defense R&D is most likely due to the radically different obstacles the former must overcome with trial-and-error approaches compared to more piecemeal and smaller targets in most civilian R&D spending. As DARPA notes of its own mission: *"Unlike other agencies, [we are] not satisfied with incremental advances. We push transformational breakthroughs – innovations that not only solve current challenges but also establish the US as the leading driver of strategic technological invention."* When key defense breakthrough innovations spillover to the civilian domain, everyone benefits hugely: think of the Manhattan Project > nuclear power, or a distributed communications system > the internet (see the table in the Annex for more examples).

Why is the bang for the buck of non-defense R&D lower than in other studies?

The bang for the buck that we find for non-defense R&D is lower than some other studies, albeit we are still talking about a societal return of 50 to 70%, which is still very substantial. However, Lucking, Bloom and Van Reenen (2019) find for a bang for the buck of one to four, based on micro-level data for US firms. Erken en Groenewegen (2019, in Dutch) report societal returns for the Dutch economy of 2.6 for private R&D and 4.2 for public R&D

The difference most likely is methodological in nature. While these studies examine the impact in individual countries, our sample consists of 19 countries, including some that do not have an innovation system in place which is as effective as that of the US or the Netherlands.[5] In addition, some of the countries in our sample might lack absorptive capacity to capture the full benefits of international R&D spillovers (see Cohen and Levinthal, 1990). The enormous heterogeneity in R&D returns between individual countries is also illustrated by Soete, Verspagen and Ziesemer (2022).

Conclusions

In short, while defense R&D is an area often overlooked by economic research, and immediately puts many on the defensive, our model estimates that its potential impact is downright explosive: **the defense 'bang for the buck' is potentially up to 6 times higher than equivalent spending on civilian R&D.** As we enter an increasingly volatile geopolitical age, this might also have positive implications for the American, European, and even the global productivity trajectory.

Of course, these high returns do not immediately manifest themselves even if countries decide to step up military and defense R&D investment. It took the US decades to build up a solid research infrastructure resulting in the groundbreaking innovations that have benefited global productivity. Ultimately, perseverance in R&D investment is crucial.

Considering these results more widely, one can even argue that part of the explanation for the notable trend towards lower productivity growth in developed economies since the end of the Cold War is not just: (i) a systemic shift towards cheap labor over capital investment via globalization, and; (ii) to Western financialization over physical production, where productivity gains are easier, but; (iii) *also due to a secular shift towards far lower defense and defense R&D expenditure* (and in the US case towards more monopolistic, less innovative defense R&D structures, which the Trump administration plans to address).

Spillovers or spill-enders?

Since the end of the Cold War, the US has been doing most of the heavy lifting on defense R&D, albeit at far lower levels than during it, while the rest of the world --including US allies like Europe, *and US rivals such as Russia and China, etc.*-- have been able to reap the flow-through benefits to the civilian economy.

From a Grand Strategy perspective, the US is likely going to step up such R&D ahead. It is also insisting that NATO allies greatly increase their own defense, and defense R&D, spending, which could see even higher long-term benefits within the Western alliance. Yet if Europe refuses, the US may opt to go it alone, both geopolitically and technologically, to others' detriment.

Moreover, from a Grand Macro Strategy perspective, even assuming a pan-NATO boost in defense R&D spending, the US is not likely to be willing to see civilian benefits rapidly transferred to its actual or potential rivals. If the US is unhappy with European 'freeriding' on its defense spending in recent decades, it is likely to be vehemently opposed to spillover productivity gains

[5] That said, we also do not have sufficient data to include Israel in our sample, where there has clearly been a productivity spillover from sustained high defence R&D into its civilian high-tech sector in areas like cybersecurity.

from NATO defense R&D into the Chinese or Russian military or civilian economies: we already see this in the recent US actions to limit exports of its highest level AI chips.

The implication is therefore that a return to Cold War-era defense and defense R&D spending will logically lead to Cold War-era bifurcation of research, technology, and goods markets.

In that respect the *global* benefits of such an approach may be lower even if the returns within NATO members could remain high. At the same time, however, recall that exactly the same defense-R&D-behind-a-firewall process will naturally be happening in China and Russia, etc. Indeed, *exactly this process of military competition*, seen as more existential than any national corporate rivalry, is what has always driven the push for rapid, boundary-pushing technological innovation in the first place.

Annex 1: Modern innovations from defense R&D

Time	Innovation	Type	Military project	Civil application
1800s	Canned Food	Food Industry	Preservation of food during Napoleonic wars, competition with a reward of 12,000 Francs for the discoverer	Food
1800s	Milling machine	Manufacturing	Eli Whitney (1798) created the milling machine for the production of muskets with interchangeable parts for the US government[6]	Manufacturing on large uniform scale, ranging from producing complex industrial parts to consumer goods
1880s	Wristwatches	Technology	Synchronized manoeuvres during war (e.g., Third Anglo-Burmese War)	wristwatches, smartwatches
1910s	Stainless Steel	Material Technology	To prevent erosion of gun barrels, in the lead-up to WWI	Various devices, from washing machines to artificial heart valves
1910s	Mobile telephones	Communication	Mobile radio telephones, used by the US army in WWI and on German Military Trains	Predecessor of modern mobile phone, Walkie-Talkie
1920s	Cryptography (Enigma)	Communication/ Encryption	German military for secure communication	Foundation for modern encryption in IT security and financial transactions
1920	Disposable sanitary pads/bandages	Medical	Stopping bleeding of soldiers with bandages containing cellulose	Sanitary pads
1930s	Radar (Radio Detection and Ranging)	Communication/ Detection	British Air Force - air defense	Use in meteorology, air traffic control, and automotive sensors such as adaptive cruise control
1930s	Jet Engine	Transport	Aircraft development in the lead-up to WWII	Commercial aviation, freight transport, and space applications
1940s	Super Glue	Material Technology	Accidentally during research on high precision targeting sights	Modern adhesives, medical glues
1940s	Duct Tape	Material Technology	US Army: Waterproofing ammunition boxes	Widely used in households, construction, repairs, and space missions
1940s	Mass Production of Penicillin	Medical	During WWII for treating infections	Revolution in antibiotics. Application in hospital care, veterinary medicine, and personal care
1940s	Nuclear Energy	Energy/Technology	US Defense Manhattan Project	Nuclear power plants, nuclear medicine, and scientific applications such as isotope research
1940s	SCUBA (Self-Contained Underwater Breathing Apparatus)	Medical/Technology	US Navy: Diving for sabotage and repairs	Recreational diving, technical diving operations, and rescue services

[6] Simeon North (1818), an US arms manufacturer, is credited for inventing a milling machine to produce uniform parts for firearms.

1940s	Helicopters	Transport	Use in WWII for evacuation and reconnaissance by the US and Nazi Germany	Medical evacuation, police, firefighting, and offshore industry
1940s	Electronic Computers	Technology	British military intelligence for cracking German codes, US for developing ballistic missiles	Basis for computers, smartphones, and virtually all modern electronics
1940s	Microwaves	Communication	RADAR, battlefield communication networks	TV, GPS, mobile phones, Wi-Fi, Bluetooth, microwave ovens
1940s	Night Vision Technology	Optics/Electronics	Combat operations in dark environments	Civil security cameras, wildlife observation, and medical applications such as laparoscopy
1950s	Transistor	Electronics	Developed for military radios	Basis for computers, smartphones, and virtually all modern electronics
1950s	Satellite Communication	Communication	Military spy satellites	Global telecommunications, GPS refinement, weather satellites, and television broadcasts
1960s	Touch screen	Technology	Invented at the UK's Royal Radar Establishment to accelerate response time and allow for better decision making for military air traffic control operators	Smartphones, smart screens
1960s	GPS (Global Positioning System)	Navigation/Technology	NAVSTAR by DARPA for precision navigation	Navigation systems in cars, fitness trackers, agricultural optimization, shipping, and aviation
1960s	Exoskeletons	Biotechnology	DARPA projects for soldier enhancement	Rehabilitation aids for the paralyzed, industrial applications for heavy work
1960s	Digital Photography	Technology	Spy satellites, eliminated the need to recover deorbited film canisters	Digital cameras
1970s	Internet (ARPANET)	Communication	DARPA network for military communication	Global internet infrastructure, e-commerce, social media, and cloud computing
1970s	Microchips (CPU)	Technology	Main flight control computer in the US Navy's F-14 Tomcat fighter-plane	Computers, mobile phones, many other devices
1970s	EpiPen	Medical	Antigen against nerve gas for military personnel	EpiPens (in case of allergy attacks)
1970s	Hypersonic Technology	Transport/Weapons	Development of fast military missiles	Research into ultra-fast commercial flights and space exploration
1990s	Modern Drones (Unmanned Aerial Vehicles)	Technology	Surveillance and combat purposes	Photography, agricultural inspection, logistics deliveries, and search and rescue missions
2000s	Modern VR	Technology/ Communication	When commercial VR development almost halted after the turn of the century, military development continued	VR headsets, VR gaming, VR simulation for pilots, doctors

1960s-2020s	AI and Autonomous Systems	Software/Technology	Autonomous weapon systems and analysis systems	Self-driving cars, medical AI diagnosis, industrial automation, and smart cities
2020s	Brain-Computer Interface (BCI)	Biotechnology/ Technology	DARPA research into BCI	Aids for the paralyzed, brain research, and virtual reality
2020s	Quantum Information Systems / Quantum Computing	Software/Technology	Enhance decision-making processes, improve simulations, optimize resource management, encryption	Accelerate drug discovery and development by simulating molecular interactions, AI and ML, finance, cryptography

Technical Annex

Framework

Starting point for our analysis is a standard Cobb-Douglas production function from Mankiw, Romer and Weil (1992), which is the augmented version of the standard Solow (1956) model, for country i = 1,…,N at time t:

$$Y_{i,t} = K_{i,t}^{\alpha} \cdot HC_{i,t}^{\beta} \cdot \left(A_{i,t} \cdot L_{i,t}\right)^{1-\alpha-\beta} \tag{1}$$

where Y is real output, L is effective labor (total hours worked), K denotes the capital stock, HC stands for human capital, i.e. skills that people acquire via education and training and A is an index for efficiency (i.e. total factor productivity).

The capital stock K of different asset classes j at time t for country i is given by:

$$K_{i,j,t} = K_{i,j,t-1} \cdot \left(1 - \delta_j\right) + I_{i,j,t} \tag{2}$$

where δ is the geometric depreciation rate of assets class I and I is investment at constant prices. Equation (1) can be rewritten to an equation of labor productivity:

$$\frac{Y_{i,t}}{L_{i,t}} = A_{i,t}^{1-\alpha-\beta} \cdot \left(\frac{K_{i,t}}{L_{i,t}}\right)^{\alpha} \left(\frac{HC_{i,t}}{L_{i,t}}\right)^{\beta} \tag{3}$$

Under the assumption of perfect competition in product markets and constant returns to scale in the production factors and taking natural logs, we get:[7]

$$\ln\left(\frac{Y_{i,t}}{L_{i,t}}\right) = (1-\alpha-\beta)\ln\left(A_{i,t}\right) + \alpha \ln\left(\frac{K_{i,t}}{L_{i,t}}\right) + \beta \ln\left(\frac{HC_{i,t}}{L_{i,t}}\right) \tag{4}$$

Following Jorgenson and Griliches (1967), the growth rate of the technology component $(1-\alpha-\beta)\ln\left(A_{i,t}\right)$ can be replaced by the growth rate of total factor productivity (*TFP*), which emerges as a residual in the growth accounting framework and basically measures how productive labor and capital are in generating value added. Expressed in growth rates (measured in natural log changes: Δln), we get:

$$\Delta\ln\left(\frac{Y_{i,t}}{L_{i,t}}\right) = \Delta\ln\left(TFP_{i,t}\right) + \omega_K \Delta\ln\left(\frac{K_{i,t}}{L_{i,t}}\right) + \omega_L \Delta\ln\left(\frac{HC_{i,t}}{L_{i,t}}\right) \tag{5}$$

or

$$\Delta\ln\left(TFP_{i,t}\right) = \Delta\ln\left(\frac{Y_{i,t}}{L_{i,t}}\right) - \omega_K \Delta\ln\left(\frac{K_{i,t}}{L_{i,t}}\right) - \omega_L \Delta\ln\left(\frac{HC_{i,t}}{L_{i,t}}\right) \tag{6}$$

with ω_K and ω_L representing the capital and labor income share within total value added. Although many databases using growth decompositions for various countries explicitly report on the contribution of human capital, we follow the approach by Erken, Donselaar and Thurik (2018) and do not adopt the contribution of human capital to productivity development of a country *a priori*. Hence, we estimate the impact of human capital on the broader definition of total factor productivity, including the effect of human capital per unit of labor.

Following Guellec and Van Pottelsberghe (2004) and Erken, Donselaar and Thurik (2018), we derive an index for total factor productivity:

[7] These assumptions imply that the marginal products of capital and labor are equal to the return on capital and the wage rate, respectively, and the output elasticities of capital and labor are equal to the shares of capital income and labor income in total factor income.

$$\ln\left(\frac{TFP_t}{TFP_0}\right) = \sum_{n=0}^{t} \ln{(TFP)} \tag{7}$$

To shape our empirical model, we take the most basic model by Coe and Helpman (1995) and Coe, Helpman and Hoffmaister (2009) as our starting point:

$$\ln\left(TFP_{i,t}\right) = \alpha_{i,t}^{0} + \alpha^{s}\ \ln\left(S_{i,t}\right) + \alpha^{f}\ \ln\left(FS_{i,t}\right) + \alpha^{HC}\ln\left(HC_{i,t}\right) + \varepsilon_{i,t} \tag{8}$$

Where *S* is the real domestic R&D capital stock, *FS* is an index for the foreign R&D capital development, which generate knowledge spillovers relevant for domestic productivity gains. The foreign R&D capital development index is calculated using the weighted sum of the development of the domestic R&D capital stock of 20 OECD countries excluding the domestic R&D capital stock of country *i*, weights are taken from the import-share matrix (following Coe and Helpman, 1995) or the technological distance matrix (following Jaffe, 1986). The import-share weighted foreign R&D capital development *FST* is calculated by:

$$FST_{i,t} = \sum_{i\neq j} \omega_{i,j,t} \cdot \frac{S_{j,t} - S_{j,(t-1)}}{S_{j,(t-1)}} \tag{9}$$

where *j* = 1, … ,18 OECD countries and $\omega_{i,j,t}$ is the share of imports of country *i* from country *j*, out of its total imports from the 18 countries considered.

The technological distance weighted foreign R&D capital development (*FSP*) is given by:

$$FSP_{i,t} = \sum_{i\neq j} \delta_{i,j,t} \cdot \frac{S_{j,t} - S_{j,(t-1)}}{S_{j,(t-1)}} \tag{10}$$

where *j* = 1, … ,18 OECD countries and the technological distance between country *i* and country *j* is defined as the uncentered correlation of its patent vectors :

$$\delta_{i,j,t} = \frac{F_i F_j'}{\sqrt{(F_i F_i')\cdot(F_j F_j')}}, \qquad F_i = \left[\frac{PAT_{1,i,t}}{\sum_k PAT_{k,i,t}}, \frac{PAT_{2,i,t}}{\sum_k PAT_{k,i,t}}, \dots, \frac{PAT_{n,i,t}}{\sum_k PAT_{k,i,t}}\right] \tag{11}$$

Where $PAT_{k,i,t}$ is the number of patents in a category *k* out of the 35 World Intellectual Property Organization categories. Following Guellec and Van Pottelsberghe de la Potterie (2004), weights are smoothed using a three year moving average, and scaled such that they add up to one for a country in a given year. Finally, *HC* is a human capital index and ε is an idiosyncratic error term.

The R&D capital stock is calculated using the perpetual inventory method:

$$S_t = S_{t-1} \cdot (1-\delta) + s_t \tag{12}$$

where δ is the depreciation rate of R&D capital, which is generally set at 15% (Griliches, 2000) and *s* is new investment in R&D. The initial stock of R&D capital is calculated using:

$$S_0 = \frac{s_0}{1-\varphi(1-\delta)} \tag{13}$$

in which the subscript *0* denotes the first year in the time series and φ stands for the growth rate of *s*.

To model the impact of defense R&D, we follow Lichtenberg (1995) and disaggregate R&D into a defense R&D (S^d) and non-defense R&D component (S^{non-d}), which yields:

$$\ln\left(TFP_{i,t}\right) = \alpha_{i,t}^{0} + \alpha^{d}\ \ln\left(S_{i,t}^{d}\right) + \alpha^{non-d}\ln\left(S_{i,t}^{non-d}\right) + \alpha^{f}\ \ln\left(FS_{i,t}\right) + \alpha^{HC}\ln\left(HC_{i,t}\right) + \varepsilon_{i,t} \tag{14}$$

We can also disaggregate foreign R&D capital into a defense and non-defense component:

$$\ln(TFP_{i,t}) = \alpha_{i,t}^{0} + \alpha^{s,d}\ln(S_{i,t}^{d}) + \alpha^{s,non-d}\ln(S_{i,t}^{non-d}) + \alpha^{f,d}\ln(FS_{i,t}^{d}) + \alpha^{f,non-d}\ln(FS_{i,t}^{non-d}) + \alpha^{HC}\ln(HC_{i,t}) + \varepsilon_{i,t} \quad (15)$$

As both total factor productivity and human capital are expressed per unit of labor equation (6), we also divide the domestic R&D capital variables as well as the foreign R&D capital variables by the amount of hours worked, which yields:

$$\ln(TFP_{i,t}) = \alpha_{i,t}^{0} + \alpha^{s,d}\ln\left(\frac{S_{i,t}^{d}}{L_{i,t}}\right) + \alpha^{s,non-d}\ln\left(\frac{S_{i,t}^{non-d}}{L_{i,t}}\right) + \alpha^{f,d}\ln\left(\frac{FS_{i,t}^{d}}{L_{i,t}}\right) + \alpha^{f,non-d}\ln\left(\frac{FS_{i,t}^{non-d}}{L_{i,t}}\right) + \alpha^{HC}\ln(HC_{i,t}) + \varepsilon_{i,t} \quad (16)$$

Finally, we take a number of controls into our final specification:

$$\ln(TFP_{i,t}) = \alpha_{i,t}^{0} + \alpha^{s,d}\ln\left(\frac{S_{i,t}^{d}}{L_{i,t}}\right) + \alpha^{s,non-d}\ln\left(\frac{S_{i,t}^{non-d}}{L_{i,t}}\right) + \alpha^{f,d}\ln\left(\frac{FS_{i,t}^{d}}{L_{i,t}}\right) + \alpha^{f,non-d}\ln\left(\frac{FS_{i,t}^{non-d}}{L_{i,t}}\right) + \alpha^{HC}\ln(HC_{i,t}) + \alpha^{X}\ln(X_{i,t}) + \alpha_{i,t}^{D}\cdot D + \varepsilon_{i,t} \quad (17)$$

where *X* represents a vector of control variables, i.e. hours worked per worker (*H*), the number of workers as a share of total population (*P*) and a variable (*BC*) capturing business cycle fluctuations. The business cycle variable is defined as: $BC_{i,t} = \frac{(100-U_{i,t})}{(100-U_{i,t}^{*})}$, where *U* is the unemployment rate and U^{*}denotes structural unemployment. Finally is a dummy variables to take into account the impact of the global financial crisis of 2008/2009 and the corona crisis in 2020.

Econometrics

As we are interested in gauging the long-run relationship between defense R&D and total factor productivity, we do not want to estimate our model in first differences. However, in case of non-stationarity of individual time series, we need to take resort to cointegration techniques to estimate our models. Kao, Chang and Chen (1999), however, show that using standard OLS lead for cointegrated panel can result in biased estimates. Therefore, we adopt cointegration regressions using fully-modified OLS (FMOLS) and dynamic OLS (DOLS) estimators, which overcomes the problem of serial correlation and endogeneity of variables. One advantage of using FMOLS and DOLS for a large panel of countries across time is that with these models one can capture the long-run information in the panel, while at the same time permitting short-run dynamics and fixed effect to be heterogenous across countries (see Pedroni, 2001).

We start of by defining our equation in the form of the following fixed effect panel regression for $y_{i,t} = \ln(TFP_{i,t})$:

$$y_{i,t} = \alpha_{i}^{0} + x_{i,t}^{'}\beta + \varepsilon_{i,t} \quad (18)$$

Where β is a $k \times 1$ vector of the slope vector of the *k* control variables $x_{i,t}$. The control variables follow an integrated process of order one for all countries i. That is:

$$x_{i,t} = x_{i,t-1} + u_{i,t} \quad (19)$$

Next, we define the innovation vector $w_{i,t} = (\varepsilon_{i,t}, u_{i,t}')'$, which has the long-run covariance matrix:

$$\Omega = \sum_{j=-\infty}^{\infty} E[w_{i,j}w_{i,j}'] = \begin{pmatrix} \Omega_{\varepsilon} & \Omega_{\varepsilon u} \\ \Omega_{u\varepsilon} & \Omega_{u} \end{pmatrix} \quad (20)$$

And one-sided (forward) long-run covariance:

$$\Gamma = \sum_{j=0}^{\infty} E[w_{i,j} w_{i,j}'] = \begin{pmatrix} \Gamma_{\varepsilon} & \Gamma_{\varepsilon u} \\ \Gamma_{u\varepsilon} & \Gamma_{u} \end{pmatrix} \tag{21}$$

The FMOLS estimator is then constructed by making corrections for endogeneity and serial correlation to the OLS estimator. Define:

$$\begin{aligned} \varepsilon_{i,t}^{+} &= \varepsilon_{i,t} - \Omega_{\varepsilon u} \Omega_{u}^{-1} u_{i,t} \\ y_{i,t}^{+} &= y_{i,t} - \Omega_{\varepsilon u} \Omega_{u}^{-1} u_{i,t} \Delta x_{i,t} \end{aligned} \tag{22}$$

Then, given we have consistent estimates of the long run covariances $\hat{\Omega}$ and $\hat{\Gamma}$

$$\hat{y}^{+}{}_{i,t} = \alpha_i^0 + x_{i,t}^{'} \beta + \varepsilon_{i,t} - \hat{\Omega}_{\varepsilon u} \hat{\Omega}_{u}^{-1} u_{i,t} \Delta x_{i,t} \tag{23}$$

The serial correlation correction term has the form:

$$\hat{\Gamma}_{ue}^{+} = \hat{\Gamma}_{ue} - \hat{\Gamma}_{u} \hat{\Omega}_{u}^{-1} \hat{\Omega}_{ue} \tag{24}$$

The FMOLS estimator then takes the following form:

$$\hat{\beta}_{FM} = \left[\sum_{i=1}^{N} \sum_{t=1}^{T} (x_{i,t} - \bar{x}_{i,t})(x_{i,t} - \bar{x}_{i,t})' \right]^{-1} \left[\sum_{i=1}^{N} \left(\sum_{t=1}^{T} (x_{i,t} - \bar{x}_{i,t}) \, \hat{y}^{+}{}_{i,t} - T \hat{\Gamma}_{ue}^{+} \right) \right] \tag{25}$$

The DOLS estimator, $\hat{\beta}_D$, then uses the past and future values of $\Delta x_{i,t}$ as additional regressors. It can be shown that it has the same limiting distribution as the FMOLS estimator, but finite sample properties are different. Following Kao and Chiang (2001) we can write the process $\{\varepsilon_{i,t}\}$ as:

Our DOLS estimator takes the following form:

$$\ln{(TFP_{i,t})} = \alpha_{i,t}^0 + x_{i,t}^{'} \vartheta + \sum_{j=-m}^{j=m} x_{i,t+j} + \varepsilon_{i,t} \tag{26}$$

where $x_{i,t}^{'}$ is our matrix of independent variables, ϑ is our cointegration vector. To capture short-term dynamics of the cointegrated system, DOLS included lags and leads (m indicating the number of lags and leads) of the differenced independent variables.

Cointegration tests

A very clear risk in estimating panel models in levels with non-stationary time series is that we end up estimating spurious correlations. Spuriousness occurs when two variables over time appear to be statistically related, but are in fact not causally related. There is even a website keeping track of these very strong correlations, such as popularity of the name Marquis and robberies in Kansas, or the number of movies Johnny Depp appeared in and seasonal wins of the Los Angeles Chargers.

To avoid estimation of spurious correlations, Nobel Prize winners Robert Engle and Clive Granger in 1987 introduced the concept of cointegration (Engle and Granger, 1987), which checks whether a pre-specified cointegrating vector is valid. Their line of thought has later been applied to panel data models by Kao (1999) and Pedroni (2004).

The results in Table A.1 show that, regardless the number of variables used, the panel cointegration test rejects the null hypothesis of no cointegration. These implies that we can use cointegration regression techniques to estimate long-run relationships.

Table A.1: Panel cointegration tests

	Pedroni a)		Kao
	Within ADF b)	Between ADF	ADF
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})$	-1.93**	-2.16**	-3.44**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC)$	-2.65**	-2.95**	-3.61**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC^{alt})$	-2.65**	-2.62**	-3.12**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC)\ \ln(FS^{d})\ \ln(FS^{non-d})$	-3.27**	-3.22**	-4.61**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC^{alt})\ \ln(FS^{d})\ \ln(FS^{non-d})$	-2.85**	-2.86**	-4.57**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC)\ \ln(FSP^{d})\ \ln(FSP^{non-d})$	-2.83**	-2.92**	-4.45**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC^{alt})\ \ln(FSP^{d})\ \ln(FSP^{non-d})$	-2.28**	-1.91**	-4.53**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC)\ \ln(FS^{d})\ \ln(FS^{non-d})\ \ln(P)\ \ln(H)\ \ln(BC)$	-	-	-4.57**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC^{alt})\ \ln(FS^{d})\ \ln(FS^{non-d})\ \ln(P)\ \ln(H)\ \ln(BC)$	-	-	-4.34**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC)\ \ln(FSP^{d})\ \ln(FSP^{non-d})\ \ln(P)\ \ln(H)\ \ln(BC)$	-	-	-4.45**
$\ln(TFP)\ \ln(S^{d})\ \ln(S^{non-d})\ \ln(HC^{alt})\ \ln(FSP^{d})\ \ln(FSP^{non-d})\ \ln(P)\ \ln(H)\ \ln(BC)$	-	-	-4.24**

Note: Significant at * 10%; ** 5%; (a) estimated with deterministic intercept and trend; (b) weighted; c) the Pedroni test does not allow for more than seven variables. Estimation period: 1969-2022

Data

We use data for 19 OECD countries (Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the UK and the US), covering 52 years (1971-2022). Table 1 provides a detailed overview of the data sources and the construction of the variables. Data on total factor productivity are taken from the Penn World Tables 10.1 and extended for later year by using the Total Economy Database of the Conference Board. These databases contain series on GDP, hours worked, capital services, employment and productivity for a large set of countries over decades. Data on R&D is taken from the OECD Main Science & technology Indicators (MSTI).

Data on defense R&D is constructed using information on government budget R&D outlays by socio-economic objective, which include fields like environment, exploration and exploitation of the Earth and space, transport, infrastructure, energy, health, agriculture, education, industrial production and technology and defense. The share of defense R&D outlays within total government R&D outlays is subsequently combined with total government allocations for R&D (in constant prices, $PPP). Data for the 19 OECD countries only cover the period 1981-2022. We have backcasted the series on defense R&D by using data on total government funding of R&D in the MSTI dating back to 1963, assuming the share of allocated towards defense has remained fairly stable from 1981 backwards. All R&D series are denoted in constant prices of 2015, USD PPP and are conventionally expressed in indices (2015 =100).

We use two different specifications of the foreign R&D capital stock, as explained in the previous section. In the first specification we weigh the foreign R&D capital stock based on the relative imports of a foreign country in the total imports from all countries in the sample. We use data on imports from the IMF's Direction of Trade Statistics (DOTS). In the second specification base the weighting on relative patent similarity. We use patent data from the OECD, where we take the patent grants from the USPTO and use the WIPO technology classification. The data is available for the period 1977 tot 2019. We keep the weight for 1971 to 1976 constant at the 1977 levels and the years 2020 to 2022 at the 2019 levels.

Human capital is captured by the percentage of the population aged 25 to 65 years who have either completed or partially completed tertiary education. The data is processed by the website Our World in Data based on data by Barro and Lee (http://barrolee.com) and Lee and Lee (https://barrolee.github.io/BarroLeeDataSet/DataLeeLee.html). In a few alternative specifications, we use data from Cohen and Soto (2007) on average years of schooling.[8] For later years, we have extended the series using data on the mean years of schooling by using Barro and Lee data. Furthermore, for Belgium and US we also adopt the Barro and Lee series on human capital instead of Cohen and Soto (see for argumentation: Penn World Tables).

Table A.2: Variables and description

Variable	*Description*	*Data source*
TFP	Index of total factor productivity (2005 = 100)	Penn World Tables 10.1 and Total Economy Database of The Conference Board
S^{d}	Defense R&D capital (2005 = 100), constant prices, USD PPP	OECD Main Science and Technology Indicators, Government Allocations for R&D, Defense Budget R&D (% of total GBARD) combined with GBARD data
$S^{non\text{-}d}$	Non-defense R&D capital (2005 = 100), constant prices, USD PPP. Total R&D capital minus defense R&D capital	OECD Main Science and Technology Indicators, Gross Domestic Expenditure on R&D (GERD)
FST^{d}	Index of the import-weighted foreign domestic defense R&D capital (2005 = 100)	OECD Main Science and Technology Indicators. IMF Direction of Trade Statistics (DOTS) for bilateral trade flows
$FST^{non\text{-}dd}$	Index of the import-weighted foreign non-defense R&D capital (2005 = 100)	OECD Main Science and Technology Indicators. IMF Direction of Trade Statistics (DOTS) for bilateral trade flows
FSP^{d}	Index of the technological distance-weighted foreign defense R&D capital (2005 = 100)	OECD Main Science and Technology Indicators
$FSP^{non\text{-}dd}$	Index of the technological distance-weighted foreign non-defense R&D capital (2005 = 100)	OECD Main Science and Technology Indicators
HC	Percentage of the population aged 25 to 65 years who have either completed or partially completed tertiary education	Our World in Data based on Barro and Lee and Lee and Lee (2016)
HC^{alt}	Average/mean years of schooling, index (2005 = 100)	Cohen and Soto (2007) and Barro and Lee
P	Labor participation measured by persons employed as share of total population, index (2005 = 1)	Penn World Tables 10.1 and Total Economy Database of The Conference Board
H	Average hours worked per person employed, index (1969 = 1)	Penn World Tables 10.1 and Total Economy Database of The Conference Board
U	Unemployment rate (unemployment as % of labor force)	European Commission (DG ECFIN), AMECO database. IMF International Financial Statistics (IFS)
U^{*}	Structural unemployment measured by non-accelerating wage rate of unemployment or HP-filtered trend of unemployment	European Commission (DG ECFIN), AMECO database. IMF International Financial Statistics (IFS)

Note: Note: The full data set including a complete table of correlation coefficients is available from the authors.
Source: RaboResearch

Finally, structural unemployment is measured by using data from the AMECO database of the European Commission on the non-accelerating wage rate of unemployment (NAWRU), or, if these

[8] The complete database can be found on https://www.parisschoolofeconomics.eu/en/cohen-daniel/international-educational-attainment-database/.

data series are not available for individual countries, we adopt a HP-filtered trend of unemployment.

Estimation results

We estimate equation (17) using both DOLS and FMOLS. The results using different sets of independent variables are given in Table A.3.

Table A.3: Estimation results

Independent variables		Dependent variable: ln(*TFP*)							
		(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
$\ln\left(\frac{S_{i,t}^{d}}{L_{i,t}}\right)$	Domestic defense R&D capital	0.015** (2.72)	0.019** (3.50)	0.016** (2.57)	0.008 (1.49)	0.011** (2.00)	0.014** (2.27)	0.015** (2.47)	0.014** (2.12)
$\ln\left(\frac{S_{i,t}^{non-d}}{L_{i,t}}\right)$	Non-defense R&D capital	0.14** (15.06)	0.11** (9.05)	0.07** (3.45)	0.05** (2.82)	0.06** (3.02)	0.04** (2.14)	0.04** (2.14)	0.04** (2.22)
$\ln(HC)$	Human capital: share of tertiary education	-	0.22** (5.92)	0.10* (1.66)	-	-	-	-	-
$\ln(HC^{alt})$	Human capital: average years of schooling	-	-	-	0.29** (2.74)	0.16 (1.50)	0.22** (2.44)	0.18** (2.00)	0.07 (0.68)
$\ln\left(\frac{FS_{i,t}^{d}}{L_{i,t}}\right)$	Foreign defense R&D capital, trade-weighted	-	-	0.07** (3.88)	0.06** (4.23)	0.05** (3.71)	0.05** (3.24)	0.05** (3.61)	-
$\ln\left(\frac{FS_{i,t}^{non-d}}{L_{i,t}}\right)$	Foreign non-defense R&D capital, trade-weighted	-	-	0.15** (4.38)	0.10** (4.25)	0.11** (4.76)	0.15** (6.02)	0.16** (6.50)	-
$\ln\left(\frac{FSP_{i,t}^{d}}{L_{i,t}}\right)$	Foreign defense R&D capital, technology-weighted	-	-	-	-		-	-	0.06** (3.54)
$\ln\left(\frac{FSP_{i,t}^{non-d}}{L_{i,t}}\right)$	Foreign non-defense R&D capital, technology-weighted	-	-	-	-		-	-	0.15** (5.51)
$\ln(H)$	Hours worked per worker	-0.72** (-9.57)	-0.52** (-5.16)	-0.28** (-2.27)	-0.39** (-4.54)	-0.37** (-4.10)	-0.52** (-7.19)	-0.42** (-6.03)	-0.54** (-7.22)
$\ln(P)$	Participation rate	-0.14** (-2.07)	-0.21** (-3.25)	-0.24** (-3.51)	-0.16** (-2.40)	-0.15** (-2.27)	-0.42** (-6.07)	-0.48** (-6.62)	-0.45** (-5.84)
$\ln(BC)$	Business cycle variable	0.79** (3.29)	0.53** (2.48)	0.40* (1.69)	0.63** (3.31)	0.42** (2.15)	0.98** (4.74)	0.88** (4.21)	1.01** (4.63)
	Estimation method	DOLS	DOLS	DOLS	DOLS	DOLS	FMOLS	FMOLS	FMOLS
	Dummy for GFC	YES	YES	YES	YES	NO	YES	NO	YES
	Dummy for COVID	YES	YES	YES	YES	NO	YES	NO	NO
	Adj. R^2	0.96	0.97	0.98	0.98	0.98	0.92	0.92	0.91
	Observations	982	982	982	982	982	986	986	986
	Period	1971-2022	1971-2022	1971-2022	1971-2022	1971-2022	1971-2022	1971-2022	1971-2022

Note: cs
Source: RaboResearch

The results show that a 1% increase in the domestic defense R&D capital stock increases the total factor productivity index in the long run by about 0.015 percentage point, which is lower than the elasticity of 0.083% estimated by Moretti, Steinwender, & Van Reenen (2025). The difference in outcomes might be explained by the reduced form regression that is used in their research, where defense R&D is the only R&D variable in their model. By not explicitly including non-defense R&D in this equation, their coefficient might capture both the direct effect of defense spending and any indirect effects that may occur through changes in private and public non-defense R&D. Furthermore, their regression estimates the relation between the defense R&D capital stock and TFP growth in the subsequent year. This differs from the long-run relationship between defense R&D and productivity that we try to capture with our model.

Our estimates also show that a 1% increase in the domestic non-defense R&D capital is estimated to increase TFP by 0.04% to 0.07% (model 3-8), but is higher when not including the foreign stock (model 1-2). Hence, the coefficients in models 1-2 might be capturing some of the effects of foreign R&D, leading to omitted variable bias. Including foreign R&D allows the model to better attribute the effects to the correct variables, thus lowering the coefficient of domestic R&D. Furthermore, domestic and foreign R&D might complement each other, enhancing the effectiveness of domestic R&D when foreign R&D is present, which can also contribute to the observed lower coefficient.

When adding up the coefficients for domestic defense and non-defense R&D, we arrive at a coefficient which is almost identical to those found in the seminal study by Coe and Helpman (1995). The coefficients for foreign R&D (spillovers) in our study is, however, higher, at 0.16 to 0.22 versus 0.05 to 0.08 found by Coe and Helpman. Since their sample only covers the years 1971-1990, this could indicate that, while the domestic return to R&D has stayed constant in the years after 1990, spillovers have increased by further globalization. The results of our estimates for R&D are also much in line with the DOLS estimates of the 'all in the family' model by Erken, Donselaar and Thurik (2018), as well as the range of estimates by Coe, Helpman and Hoffmaister (2009).

Literature

Arrighi, G. (2009). *Adam Smith in Beijing: lineages of the 21st century*. Verso books.

Audretsch, D. B., & Belitski, M. (2020). The role of R&D and knowledge spillovers in innovation and productivity. *European Economic Review, 123, 103391*.

Barro, R. J., & Lee, J. W. (2013). A new data set of educational attainment in the world, 1950–2010. *Journal of Development Economics, 104, 184-198*.

Coe, D. T., & Helpman, E. (1995). International R&D spillovers. *European Economic Review*, 39(5), 859-887.

Coe, D. T., Helpman, E., & Hoffmaister, A. W. (2009). International R&D spillovers and institutions. *European Economic Review*, 53(7), 723-741.

Cohen, W.M., & Levinthal, D.A. (1989). Innovation and learning: the two faces of R&D. *The Economic Journal, 99(397), 569-596*.

Cohen, D., & Soto, M. (2007). Growth and human capital: good data, good results. *Journal of Economic Growth, 12, 51-76*.

Ciaffi, G., Deleidi, M., & Mazzucato, M. (2024). Measuring the macroeconomic responses to public investment in innovation: evidence from OECD countries. *Industrial and Corporate Change*, 33(2), 363-382.

Engle, R. F., & Granger, C. W. (1987). Co-integration and error correction: representation, estimation, and testing. *Econometrica, 251-276*.

Erken, H., Donselaar, P., & Thurik, R. (2018). Total factor productivity and the role of entrepreneurship. *Journal of Technology Transfer*, 43(6), 1493-1521.

Erken, H. and J. Groenewegen (2019). 50 miljard euro investeren in onderwijs en innovatie verdubbelt economische groei, *MeJudice*.

European Commission (2024). *The future of European competitiveness*.

Lichtenberg, F. R. (1995). Economics of defense R&D. *Handbook of defense economics*, 1, 431-457.

Mankiw, N. G., Romer, D., & Weil, D. N. (1992). A contribution to the empirics of economic growth. *Quarterly Journal of Economics*, 107(2), 407-437.

Griliches, Z. (2000). *R&D, education, and productivity. A retrospective*. Cambridge (MA): Harvard University Press

Guellec, D., & Van Pottelsberghe de la Potterie, B. (2004). From R&D to productivity growth: Do the institutional settings and the source of funds of R&D matter? *Oxford Bulletin of Economics and Statistics, 66(3), 353-378*.

IMF (2016). Acting Now, Acting Together, Washington.

Jaffe, A.B. (1986). Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value. *American Economic Review 76(5), 984-1001*.

Jorgenson, D. W., & Griliches, Z. (1967). The explanation of productivity change. *Review of Economic Studies*, 34(3), 249-283.

Kao, C., Chiang, M. H., & Chen, B. (1999). International R&D spillovers: an application of estimation and inference in panel cointegration. *Oxford Bulletin of Economics and Statistics*, 61(S1), 691-709.

Kao, C. (1999). Spurious regression and residual-based tests for cointegration in panel data. *Journal of Econometrics, 90(1), 1-44*.

Lucking, B., Bloom, N., & Van Reenen, J. (2020). Have R&D spillovers declined in the 21st century?. *Fiscal Studies, 40(4), 561-590*.

McNeill, W. H. (2013). *The pursuit of power: technology, armed force, and society since AD 1000*. University of Chicago Press.

Moretti, E., Steinwender, C., & Van Reenen, J. (2025). The intellectual spoils of war? Defense R&D, productivity, and international spillovers. *Review of Economics and Statistics*, 107(1), 14–27.

Pedroni, P. (2001). Fully modified OLS for heterogeneous cointegrated panels. In: *Nonstationary panels, panel cointegration, and dynamic panels*. Emerald Group Publishing Limited, 93-130.

Pedroni, P. (2004). Panel cointegration: Asymptotic and finite sample properties of pooled time series testswith an application to the PPP hypothesis. *Econometric Theory, 20, 597–625*.

Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, 98(5, Part 2), S71-S102.

Soete, L., Verspagen, B., & Ziesemer, T. H. (2022). Economic impact of public R&D: an international perspective. *Industrial and Corporate Change*, 31(1), 1-18.

Solow, R. M. (1956). A contribution to the theory of economic growth. *Quarterly Journal of Economics, 70(1), 65-94*.

Stevenson, D. (1999). War by timetable? The railway race before 1914. *Past & present*, (162), 163-194.

Stock, J. H. (1987). Asymptotic properties of least squares estimators of cointegrating vectors. *Econometrica*, 1035-1056.

RaboResearch
Global Economics & Markets
mr.rabobank.com

Global Head

Jan Lambregts
+44 20 7664 9669
Jan.Lambregts@Rabobank.com

Macro Strategy

Global

Michael Every
Senior Macro Strategist
Michael.Every@Rabobank.com

Europe

Elwin de Groot
Head Macro Strategy
Eurozone, ECB
+31 30 712 1322
Elwin.de.Groot@Rabobank.com

Bas van Geffen
Senior Macro Strategist
ECB, Eurozone
+31 30 712 1046
Bas.van.Geffen@Rabobank.com

Stefan Koopman
Senior Macro Strategist
UK, Eurozone
+31 30 712 1328
Stefan.Koopman@Rabobank.com

Maartje Wijffelaars
Senior Economist
Italy, Spain, Eurozone
+31 88 721 8329
Maartje.Wijffelaars@Rabobank.nl

Americas

Philip Marey
Senior Macro Strategist
United States, Fed
+31 30 712 1437
Philip.Marey@Rabobank.com

Christian Lawrence
Senior Cross-Asset Strategist
Canada, Mexico
+1 212 808 6923
Christian.Lawrence@Rabobank.com

Mauricio Une
Senior Macro Strategist
Brazil, Chile, Peru
+55 11 5503 7347
Mauricio.Une@Rabobank.com

Renan Alves
Macro Strategist
Brazil
+55 11 5503 7288
Renan.Alves@Rabobank.com

Molly Schwartz
Cross-Asset Strategist
+1 516 640 7372
Molly.Schwartz@Rabobank.com

Asia, Australia & New Zealand

Teeuwe Mevissen
Senior Macro Strategist
China
+31 30 712 1509
Teeuwe.Mevissen@Rabobank.com

Benjamin Picton
Senior Macro Strategist
Australia, New Zealand
+61 2 8115 3123
Benjamin.Picton@Rabobank.com

FX Strategy

Jane Foley
Head FX Strategy
G10 FX
+44 20 7809 4776
Jane.Foley@Rabobank.com

Rates Strategy

Richard McGuire
Head Rates Strategy
+44 20 7664 9730
Richard.McGuire@Rabobank.com

Lyn Graham-Taylor
Senior Rates Strategist
+44 20 7664 9732
Lyn.Graham-Taylor@Rabobank.com

Credit Strategy & Regulation

Matt Cairns
Head Credit Strategy & Regulation
Covered Bonds, SSAs
+44 20 7664 9502
Matt.Cairns@Rabobank.com

Bas van Zanden
Senior Analyst
Pension funds, Regulation
+31 30 712 1869
Bas.van.Zanden@Rabobank.com

Cas Bonsema
Senior Analyst
Financials
+31 6 127 66 642
Cas.Bonsema@Rabobank.com

Maartje Schriever
Analyst
ABS
+31 6 251 43 873
Maartje.Schriever@Rabobank.com

Agri Commodity Markets

Carlos Mera
Head of ACMR
+44 20 7664 9512
Carlos.Mera@Rabobank.com

Oran van Dort
Commodity Analyst
+31 88 723 8647
Oran.van.Dort@Rabobank.com

Energy Markets

Joe DeLaura
Senior Energy Strategist
+1 212 916 7874
Joe.DeLaura@Rabobank.com

Florence Schmit
Energy Strategist
+44 20 7809 3832
Florence.Schmit@Rabobank.com

Client coverage

Wholesale Corporate Clients

Martijn Sorber	Global Head	+31 30 712 3578	Martijn.Sorber@Rabobank.com
Hans Deusing	Europe	+31 30 216 9045	Hans.Deusing@Rabobank.com
Neil Williamson	North America	+1 212 808 6966	Neil.Williamson@Rabobank.com
Adam Vanderstelt	Australia, New Zealand	+61 2 8115 3102	Adam.Vanderstelt@rabobank.com
Ethan Sheng	Asia	+852 2103 2688	Ethan.Sheng@Rabobank.com
Ricardo Rosa	Brazil	+55 11 5503 7150	Ricardo.Rosa@Rabobank.com

Financial Institutions

Short-term Interest Rates

Marcel de Bever	Global Head	+31 30 216 9740	Marcel.de.Bever@Rabobank.com

Bonds & Interest Rate Derivatives

Henk Rozendaal	Global Head Fixed Income	+31 30 216 9423	Henk.Rozendaal@Rabobank.com

Solutions

Sjoerd van Peer	Global Head	+31 30 216 9072	Sjoerd.van.Peer@Rabobank.com

Relationship Management

Rogier Everwijn	Global Head	+31 30 712 2440	Rogier.Everwijn@Rabobank.com
Rob Eilering	Banks	+31 30 712 2162	Rob.Eilering@Rabobank.com
Petra Schuchard	Insurers		Petra.Schuchard@Rabobank.com
Frank Dekkers	Asset Managers		Frank.Dekkers@Rabobank.com
Javier Alvarez de Eerens	MDB	+31 30 712 1015	Javier.Alvarez@Rabobank.com
Christel Kleinhaarhuis	Fintech		Christel.Klein.Haarhuis@Rabobank.com

Capital Markets

Laura Bijl	Global Head	+31 88 726 3254	Laura.Bijl@Rabobank.com
Christopher Hartofilis	Capital Markets USA	+1 212 808 6890	Christopher.Hartofilis@Rabobank.com
Ian Baggott	Capital Markets Asia	+852 2103 2629	Ian.Baggott@Rabobank.com
Adriana Gouveia	Capital Markets Brazil	+55 11 5503 7305	Adriana.Gouveia@rabobank.com
Willem Kröner	Global Head ECM	+31 30 712 4783	Willem.Kroner@Rabobank.com
Harman Dhami	DCM Syndicate	+44 20 7664 9738	Harman.Dhami@Rabobank.com
Crispijn Kooijmans	DCM FIs & SSAs	+31 30 216 9028	Crispijn.Kooijmans@Rabobank.com
Bjorn Alink	DCM Securitisation & Covered Bonds	+31 30 216 9393	Bjorn.Alink@Rabobank.com
Othmar ter Waarbeek	DCM Corporate Bonds	+31 30 216 9022	Othmar.ter.Waarbeek@Rabobank.com
Joris Reijnders	DCM Corporate Loans	+31 30 216 9510	Joris.Reijnders@Rabobank.com

Brian Percival	DCM Leveraged Finance	+44 20 7809 3156	Brian.Percival@Rabobank.com

Disclaimer

Non Independent Research

This document is issued by Coöperatieve Rabobank U.A. incorporated in the Netherlands, trading as "Rabobank" ("Rabobank") a cooperative with excluded liability. The liability of its members is limited. Authorised by De Nederlandsche Bank in the Netherlands and regulated by the Authoriteit Financiële Markten. Rabobank London Branch (RL) is authorised by De Nederlandsche Bank, the Netherlands and the Prudential Regulation Authority, and subject to regulation by the Financial Conduct Authority and limited regulation by the Prudential Regulation Authority. Further details are available on request. RL is registered in England and Wales under Company no. FC 11780 and under Branch No. BR002630. This document is directed exclusively to Eligible Counterparties and Professional Clients. It is not directed at Retail Clients.

This document does not purport to be impartial research and has not been prepared in accordance with legal requirements designed to promote the independence of Investment Research and is not subject to any prohibition on dealing ahead of the dissemination of Investment Research. This document does NOT purport to be an impartial assessment of the value or prospects of its subject matter and it must not be relied upon by any recipient as an impartial assessment of the value or prospects of its subject matter. No reliance may be placed by a recipient on any representations or statements made outside this document (oral or written) by any person which state or imply (or may be reasonably viewed as stating or implying) any such impartiality.

This document is for information purposes only and is not, and should not be construed as, an offer or a commitment by RL or any of its affiliates to enter into a transaction. This document does not constitute investment advice and nor is any information provided intended to offer sufficient information such that is should be relied upon for the purposes of making a decision in relation to whether to acquire any financial products. The information and opinions contained in this document have been compiled or arrived at from sources believed to be reliable, but no representation or warranty, express or implied, is made as to their accuracy, completeness or correctness.

The information contained in this document is not to be relied upon by the recipient as authoritative or taken in substitution for the exercise of judgement by any recipient. Any opinions, forecasts or estimates herein constitute a judgement of RL as at the date of this document, and there can be no assurance that future results or events will be consistent with any such opinions, forecasts or estimates. All opinions expressed in this document are subject to change without notice.

To the extent permitted by law, neither RL, nor other legal entities in the group to which it belongs accept any liability whatsoever for any direct or consequential loss howsoever arising from any use of this document or its contents or otherwise arising in connection therewith.

Insofar as permitted by applicable laws and regulations, RL or other legal entities in the group to which it belongs, their directors, officers and/or employees may have had or have a long or short position or act as a market maker and may have traded or acted as principal in the securities described within this document (or related investments) or may otherwise have conflicting interests. This may include hedging transactions carried out by RL or other legal entities in the group, and such hedging transactions may affect the value and/or liquidity of the securities described in this document. Further it may have or have had a relationship with or may provide or have provided corporate finance or other services to companies whose securities (or related investments) are described in this document. Further, internal and external publications may have been issued prior to this publication where strategies may conflict according to market conditions at the time of each publication.

This document may not be reproduced, distributed or published, in whole or in part, for any purpose, except with the prior written consent of RL. By accepting this document you agree to be bound by the foregoing restrictions. The distribution of this document in other jurisdictions may be restricted by law and recipients of this document should inform themselves about, and observe any such restrictions.

A summary of the methodology can be found on our website