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# Emerging Technologies' Breadcrumbs: Leveraging Statistics to Detect Emerging Technologies and Charting a Path for a Safe and Secure Future

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**Abstract**

The identification and analysis of emerging technologies is key to ensuring an international strategic advantage and national security. Identifying and analyzing weak signals of emerging technologies is important to challenge and review the robustness and resilience of strategic plans and investments in the light of new developments. Emerging technologies need to be assessed for their potential impact – positive or negative – on current and future Defence and National Security operations through a balanced foresight approach. A case study of the foresight approach used at Defence Research and Development Canada (DRDC) is presented. Evidence and the scientific method are core to weak signal detection at DRDC. Following a review of the R&D Momentum statistical tool, the paper presents the Foresight to Action Framework (FAF), which enables the use of insights developed from weak signals to decision making and action. Continuous learning is key to growth and innovation, and serves as a key component to perpetuate future evolution of DRDC's foresight practice and more broadly of the defence, safety and security domains.

## 1. Introduction

Technology is reshaping the global order, redefining supply chains and geopolitical powers (Breznitz, 2021). According to Breznitz (2021), the move to a global fragmentation of production has been accompanied with a shift in the power distribution and innovation. As a result of a movement away from vertically integrated global supply chains to a globally fragmented production, companies and nations have been able to leverage "new entry points" to generate economic growth from innovation. Such strategies resulted in shifting positions of power gained by emerging technologies in key components and systems, not only in products. Furthermore, Breznitz describes the decoupling between owning the production of innovative products from a company's ability to accrue the highest profits share from the final sale and translate those to economic growth. By leveraging these windows of opportunities within the global supply chains, countries can capture critical advantages along supply chains, which can influence competitiveness, jobs, economic growth and security. This new dynamic changes the mainstream conventional thought on the link between innovation and economic growth. In this

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shifting global dynamic, the identification and analysis of emerging technologies is key to ensuring national strategic advantage.

This paper is organized as follows: section 2 provides an overview of the role of strategic foresight in a Defence organization. Section 3 introduces challenges to weak signal detection of emerging technologies. Section 4 presents a statistical approach that enables the identification of weak signals of emerging technologies. Section 5 describes how weak signals of emerging technologies are leveraged throughout the Foresight to Action Framework (FAF) that Defence Research and Development Canada (DRDC) has been using for over a decade to assess risks and opportunities of emerging technologies and inform strategic plans. In section 6, limitations of the approach and mitigation strategies are discussed.

## 2. Background

Anticipation of future threats and operational capabilities is a core function in defence, safety and security policymaking. In November of 2017, NATO released a report titled “Strategic Foresight Analysis” in which it discussed a strategic outlook to guide future force development within the alliance (NATO, 2017). In this strategic foresight analysis, NATO identified worldwide trends with potential long-term implications for the alliance. With respect to technology, the document highlights the increasing availability of autonomous technologies and artificial intelligence (AI), as well as the rapidly evolving private sector’s dominance in technological development and innovation. The report notes that the protection of the defence industrial base through targeted research and development (R&D) initiatives has been successful in some nations, however, R&D funding is likely to decrease over time and might poses some challenges (NATO, 2017). Furthermore, the document notes that intellectual property rights might become a barrier, preventing governments from adapting such technologies to fit their own unique defence requirements. NATO Allied Command Transformation and the Alliance’s Science and Technology Organization are pursuing initiatives to counter this negative trend, according to the report (NATO, 2017).

Further, the NATO Alliance Command Transformation released a “Framework for Future Alliance Operations” in 2018. This framework uses strategic foresight, among other tools, to guide NATO’s defence planning process through 2035 and beyond (NATO, 2018). This process sets defence capability targets, which are capabilities that NATO considers to be most relevant in the current defence and security environment. In this document, NATO considers anticipated characteristics of conflict in the future (i.e., 'Instability Situations’). Also, developments such as AI, autonomy, and human augmentation/enhancement, were identified as raising new legal and ethical considerations (NATO, 2018).

Indeed, tracing to the history of strategic foresight in the United States (Scoblic, 2020), it was conceived in 1962 in the context of defence as a systematic approach to deliberate about the future. It began as an attempt to enable “thinking about the unthinkable” in the context of the cold war (Kahn, 1962). In his book, Kahn who was an analyst in the RAND Corporation, proposed leveraging a set of scenarios, games, and current and historical assessments to enable the imagination about possible futures, associated risk and opportunities if a thermonuclear war was to begin, along with the implications of such scenarios to national policies, given various desired outcomes. From its early days, the practice of strategic foresight in defence has been grounded on a multidisciplinary approach integrating evidence, various methodologies and disciplines to help generate creative possibilities about possible futures. Strategic foresight was also conceptualized with the end goal of supporting and informing the strategic planning process and investment decisions in the context of the cold-war era.

While the practice of strategic foresight could be traced back to 1962 in the United States, thinking about the future has been part of public policy for a long time. For example, in Canada, the practice of strategic foresight in policy making has evolved over the last few decades. Depending on the scope, it could be traced back to 1945 and the establishment of the Ministry of State and Technology[3]. Over the years, the practice of strategic foresight has evolved and changed. Over time, the Canadian government has sought to link strategic foresight and policymaking across departments through evidence-based foresight research relying on a multidisciplinary mix of methodologies (School of International Futures, 2021; Jones, 2017). In 2010, once Policy Horizons Canada (PHC) was established, it provided an opportunity to collate and centralize the various foresight practices that evolved over the years into a central centre (School of International Futures, 2021) that followed a systematic foresight method, coined the Horizons Foresight Method (Padbury, 2020).

In addition PHC, serving as Canada’s foresight centre of excellence, different departments across the Canadian government have developed their own foresight capacity, including the Department of National Defence, Global Affairs Canada, Canadian Forest Services, Immigration, Refugees, and Citizenship Canada, Standards Council of Canada and employing a variety of methods that match their requirements (Wilner and Roy, 2020; School of International Futures, 2021). Over the years, the groups and the team at Policy Horizons Canada have developed a variety of outlook and foresight products to advise and inform policy making, including putting together future scenarios in dynamically changing contexts (Jones, 2017; Policy Horizons Canada, 2020; Wilner and Roy, 2020).

Jones (2017) argues that while there has been progress in the application of foresight methods in the Canadian public service, the Canadian government is not fully integrated across departments or functions. According to Jones, this lack of coordination across departments and agencies hinders the level of formal sharing of foresight products and thus the government does not fully utilize the work produced by its different foresight units to its full potential. However, according to a report by the School of International Futures assessing various foresight practices across countries (2021), Canada’s foresight capacity was profiled as one with high activity across the ecosystem and a high impact at the system levels. Typically, the foresight capacity and activities fall under the responsibility of line ministries and help them to deliver on their objectives (School of International Futures, 2021). In order to overcome fragmentation and increase collaboration, in Fall 2019 a Federal Foresight Network was established by Policy Horizons Canada. The objective of this network is to build capacity, share knowledge, resources and best practices across the federal government to advance and strengthen foresight work in the Canadian federal government. It is not uncommon for foresight analysts, policy analysts and

[3] A detailed historical chronology is provided by the School of International Futures, 2021

scientists from across the government to participate in foresight workshops and provide meaningful input into horizontal projects via the network. Furthermore, since governance is key; PHC is governed by an inter-departmental committee, the Deputy Minister Steering Committee, and is co-chaired by the Deputy Minister of Employment and Social Development Canada, the Deputy Secretary to Cabinet (Plans and Consultations) and Deputy Minister of Intergovernmental Affairs, Privy Council Office, there are opportunities to share, analyze and distill information from across the federal government. The Privy Council Office serves as the key bridge connecting strategic foresight into mainstream policy (School of International Futures, 2021). As in every horizontal process, there are opportunities for continuous learning and improvements to increase effectiveness and impact. However, the key building blocks to enable interdepartmental collaboration were put in place.

In the context of national security and defence, strategic foresight has been particularly helpful to strategic advisors. The methods and systematic approach help to understand and analyze critical future challenges where longer time horizons and higher levels of uncertainty prevail. In defence, the amount of time required for the acquisition of new capabilities ranges from a few years to several decades. The ability to anticipate future technologies is key (Kott and Perconti, 2018). The repercussions of not anticipating technological development or anticipating the wrong technologies can be detrimental to defence teams and nations. As illustrated by the Canadian Defence Policy: *Strong, Secure, Engaged* (Minister of National Defence, 2017), anticipation of future threats and operational capabilities is a core function in defence, safety and security. Strategic plans are developed based on the anticipated future operating environment (FOE). A number of key drivers such as climate security, social trends and demographics, geo-political dynamics, economic factors, and technological developments contribute to shaping the likely future operating environment in which defence, safety and security organizations will need to remain successful. Strategic foresight has been used in defence organizations for decades to develop plausible scenarios and plan accordingly.

Since the 1960s the strategic foresight toolkit has expanded to include a variety of qualitative, quantitative and quasi-quantitative methods (Popper, 2008; UK Government Office for Science, 2017). While the foresight toolkit contains many methods (Popper, 2008), one of the foundational challenges in strategic foresight is the lack of facts about the future. How might one employ evidence-based foresight? One of the key building blocks of evidence-based foresight is the need to identify signals of change that are grounded in reputable and reliable data. According to Webb (2016) “the future doesn’t simply arrive fully formed overnight but emerges step by step” (p.2). The task of science and technology foresight analysts and researchers is to find the trail of “technological breadcrumbs” that may point to plausible future changes and how those signals interact with broader social, economic, environmental, political and values context. While these “technological breadcrumbs” are only one part of the bigger societal, economic, political, environmental context, they are key in shaping tomorrow’s world. Kott and Perconti (2018) refer to those signals as whispers from the future. In the literature, those “breadcrumbs” or “whispers from the future” are called *weak signals*. Weak signals are important because they are one of the first building blocks of analyzing the future. With a lack of facts about the future, weak signals serve as the evidence at the core of many foresight methods. While weak signals are useful in grounding foresight practices in present reality, they can be seen as an independent component of many foresight methods.

## 3. Weak signals of emerging technologies

From early stages of research to commercial applications, emerging technologies are a catalyst for economic growth, productivity and innovation (Schumpeter, 1942; Solow, 1957; Romer, 1994; Breznitz, 2021). However, as opposed to the early theorists of economic growth theory and innovation, Breznitz demonstrates that with a shift to a fragmented global production, the gains from innovation may not necessarily accrue any longer where the investment was made. As global production of goods and services changes so is the distribution to the associated benefits and costs (Breznitz, 2021). With a fragmented global production, nations can capture strategic elements of supply chains by focusing on innovating components of a final product. For example, due to concerted public policy, Taiwan became the hub of innovation in the semi-conductors production and design over the years, while the United States leadership in this industry declined. This shift has implications to national security (*id.*). Therefore, it is critical for policy makers to be able to identify early signs of technical change and innovation along the supply chain and be able to detect technologies as they emerge and potentially alter power dynamics along critical supply chains.

However, what is an emerging technology? Several definitions have been proposed in the recent years. The most cited paper for defining emerging technologies is the foundational framework proposed by Rotolo *et al.* (2015). After a comprehensive review of existing definitions for emerging technologies, the authors proposed five key attributes that define the emergence of a technology: (i) radical novelty, (ii) relatively fast growth, (iii) coherence, (iv) prominent impact, and (v) uncertainty and ambiguity.

*Radical novelty* is not only a characteristic of new technological or technical breakthrough but also applies to new use of existing technologies. Radical novelty is a qualitative measure that could lead to transformational changes. *Fast growth* is a quantitative attribute of emerging technologies that indicate rapid increase of activity or output in a given period of time relative to other technologies. *Coherence* is a characteristic of emerging technologies gaining persistence and specific identity over time. Coherence of an emerging field develops as communities of interest are increasingly involved and adopt the proposed concepts or developments. *Prominent impact* refers to the potential of an emerging technology to have implications in various spheres of the socio-economic system. This is typically the case for most of so-called “dual use” technologies that can have applications in many different socio-economic domains. Finally, since emerging technologies are nascent developments that may or may not succeed or persist over time, *uncertainty* is inherent to emerging technologies. Variables such as potential applications, financial support and infrastructures, access to skilled personnel, standards, patents, production costs, legal and ethical implications, and social acceptance can all influence the extent to which an emerging technology will be viable.

Before any of those attributes can be assessed, emerging technologies need to be detected. Emerging technologies are difficult to detect, and even more difficult to detect early. In the scientific literature, emerging technologies have a very low signal-to-noise ratio. They are typically drowned out by numerous hot research topics and have very little visibility and diffusion. So how to detect emerging technologies?

## 4. Identifying weak signals in scientific literature: R&D Momentum

Over the past decade, scientometric research, or scientometrics, has developed quantitative methods and tools to detect emerging topics in scientific and technical literature. Because scientometrics uses peer-reviewed scientific papers as primary data sources, it has proven to be a reliable approach to identifying emerging technologies. Other sources exist such as social media, crowdfunding web sites, news articles, to name a few, but they may be unreliable and subject to disinformation although new methods and tools are being developed to detect online disinformation[4].

One of the methods that DRDC has been using extensively since 2012 in its Science and Technology Foresight and Risk Assessment program is the R&D Momentum originally developed in partnership with the National Research Council (NRC) in Canada (Tang *et al.*, 2012). R&D Momentum[5] is a statistical model derived from two measures: standardized growth rate and standardized volume of publications over a specific period of time. Using those two variables, the R&D Momentum can plot scientific topics on four quadrants, as illustrated in Figure 1.

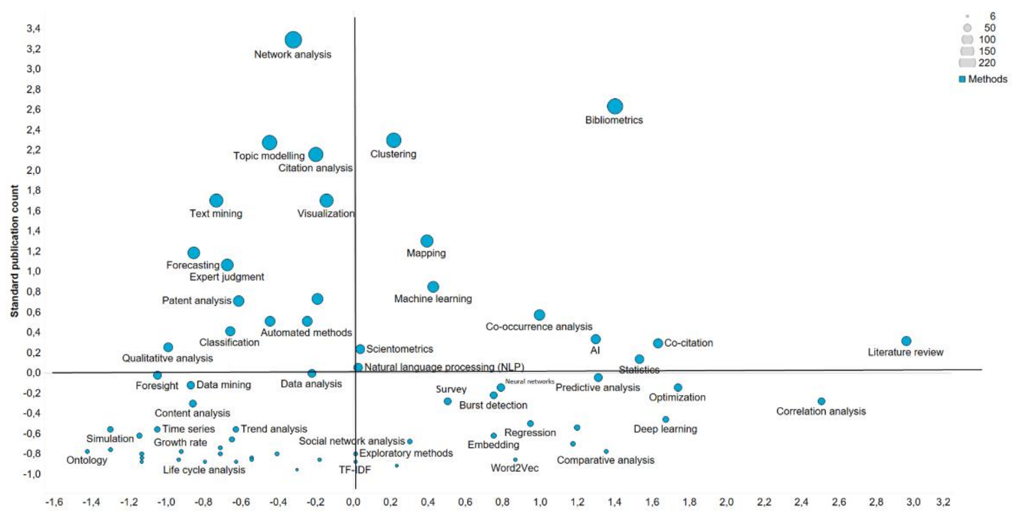


*Figure 1: Methods used to detect emerging technologies in the scientific literature*

[4] See for instance https://www.rand.org/research/projects/truth-decay/fighting-disinformation/search.html
[5] For a detailed description of the R&D Momentum, see Tang, D., Wiseman, E. and Archambeault, J. "Using Four-Quadrant Charts for Two Technology Forecasting Indicators: Technology Readiness Levels and R&D Momentum" GTM conference 2012.

A four-quadrant bubble chart is used to visually represent the set of z-scores for growth rate and volume of publications. The X axis represents negative or positive standardized growth rate of topics in the dataset. The Y axis represents the negative or positive standardized volume of publications of each topic. The size of each bubble is relative to the volume of publications. (*id*.).

Using this approach, we can categorize topics along the measures as illustrated in Table 1:

*Table 1: R&D Momentum measures*

| Volume rate (Y-axis) | Growth rate (X-axix) | R&D Momentum quadrant | Topics from Fig. 1 |
|---|---|---|---|
| Negative | Negative | Brand new / disappearing topics | Ontology; simulation |
| **Negative** | **Positive** | **Emerging topics** | **Social network analysis; survey; burst detection; correlation analysis** |
| Positive | Positive | Hot topics | Bibliometrics; literature review; machine learning; co-occurrence analysis |
| Positive | Negative | Established topics | Citation analysis; topic modeling; network analysis |

**Emerging topics** closer to the X axis have *smaller* positive growth values and are *slowly* emerging, whereas emerging topics with *higher* positive values are *rapidly* emerging.

**Hot topics** are characterized by high volumes and fast growth rate. When the growth rate stabilizes and the volume remains high, topics are now considered as **Established**. If the volume of established topics decreases over time, they are considered as **Disappearing**. Disappearing topics typically show small negative values on both axes. **Brand New** topics are characterized by higher negative values in terms of volume and growth rate.

Applying the R&D Momentum statistical model at various time intervals enables the tracking of brand-new topics. As the research and enabling conditions evolve and accelerate, brand new topics become emerging topics. Similarly, emerging topics will either disappear or become Hot topics depending on a number of enabling conditions. The typical lifecycle of emerging topics across the R&D Momentum is illustrated in Figure 2.

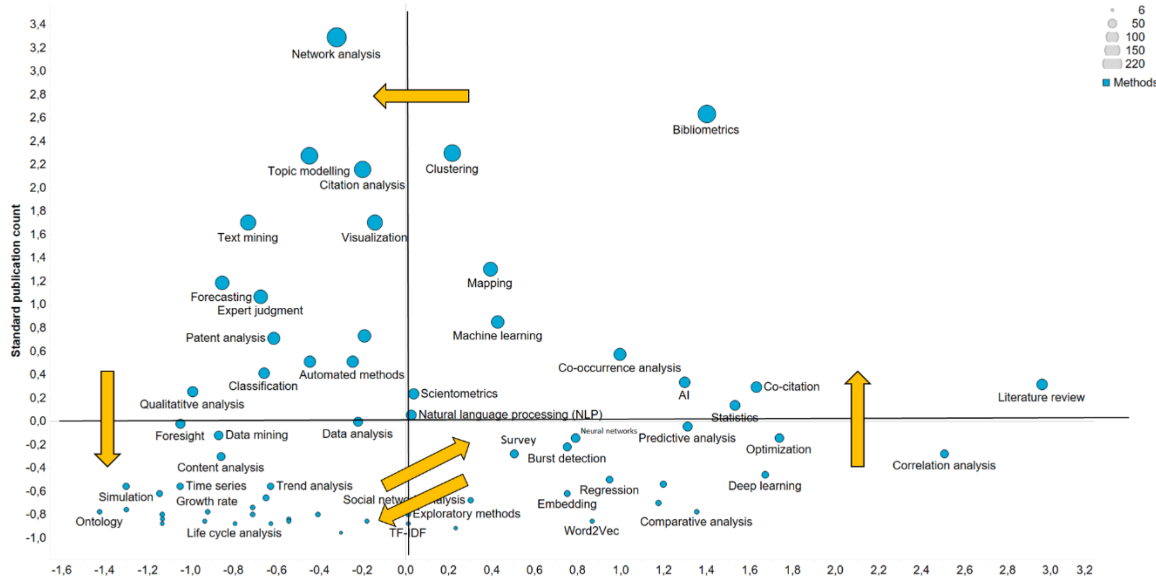


*Figure 2: Typical dynamics of topics over time*

The use of the R&D Momentum evidence-based method has proven very reliable over the past 10 years at DRDC to identify and track emerging technologies that could impact future Defence and National Security operations. Not all emerging technologies and scientific discoveries will materialize (Khun, 1962) and not all will bring the same levels of risks and opportunities. Emerging technologies need to be assessed for their potential impact – positive or negative – on current and future Defence and National Security operations through a balanced foresight approach.

## 5. From weak signals to future Defence capabilities: the Foresight to Action Framework (FAF)

While the detection of weak signals is foundational to anticipation of the future environment, their detection is not enough to make decisions. To ensure organizations are equipped with the information needed to advance planning and investment decisions, weak signals need to be interpreted and analyzed in the context of an organization's vision, mission and strategic goals. This is where a balanced foresight approach will be required to further explore risks and opportunities.

As scientific developments and technologies evolve, continuous monitoring and assessment of emerging threats and opportunities needs to be part of the planning cycle. As speed is one of the factors impacting national strategic advantage, the identification of weak signals becomes critical. Weak signals of emerging technologies are also important to challenge and review robustness and resilience of strategic plans and investments in the light of new developments. Such a process allows for proactive and faster learning, assessment, adjustment and integration of new knowledge, which is characteristic of agile organizations.

There are four main lines of activities that enable foresight to action:

1. Detection of weak signals of emerging technologies
2. Collation of information about the signals of interest
3. Contextualization and assessment of emerging technologies
4. Action plans via methods such as technology roadmaps, strategic plans, investments.
5. Learning, continuous evaluation, and assessment to validate impact and relevance over time.

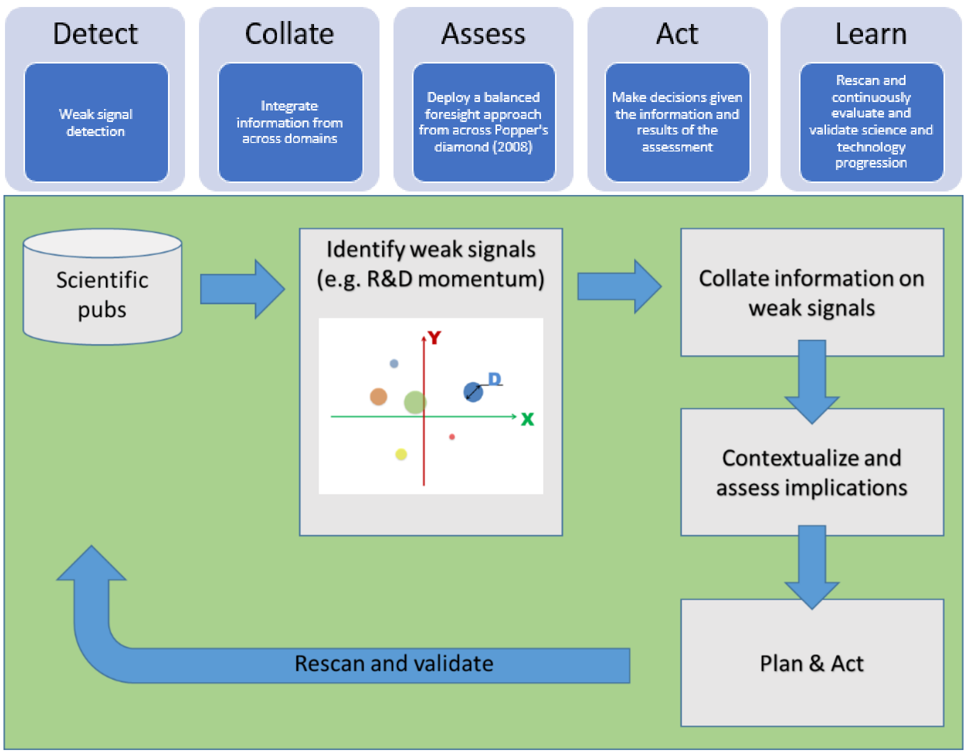


*Figure 3. DRDC's Foresight to Action Framework (FAF)*

**Detection** can be compared to a radar function. Identification of signals of interest can be made through quantitative methods such as the R&D Momentum, and through qualitative methods such as Delphi surveys with subject matter experts (SMEs). Engaging with a multidisciplinary group of practitioners, analysts, operators, and SMEs facilitates the identification of new trends, new weak signals. Detection of weak signals is a very active research field with approaches that leverage statistics (Tang *et al*, 2012), natural language processing and machine learning (Ebadi *et al.* 2022) as well as variational quantum circuits in quantum computers (Griol-Barres *et al.* 2021).

**Collation** is an activity aimed at gathering as much information as possible on signals of interest. The collation activity tends to address a number of key questions: What is the technology?; How mature is it?; Who are the key leaders?; What are known applications?, etc. All the information collated about signals will be useful to assess potential risks and opportunities. Collation of information about weak signals is essential to better understand their origin, maturity, level of uncertainty, and intended applications. The collation of information also provides insights into potential legal, societal, or ethical issues that such weak signal could trigger, should they gain strength. Information gathered during collation is then used to explore and assess the likely implications for the organization.

**Contextualization** is key to **assessment**. Signals will have different significance, will be perceived differently depending on the vantage point. Multiple stakeholders' participation is important to consider maximum vantage points in the assessment. Several key questions will need to be addressed in the context of the organization's mission and goals. For example, is this emerging technology posing a risk to our capacity to operate in the future?  Does the technology represent opportunities for innovation? Do we anticipate barriers to adopting this new technology?

Finally, results from the contextualized assessment are then used to inform **action** and decision making. This step usually involved deliverables such as strategic plans, technology roadmaps, and new policy development. Following a common practice in agile and lean process, as well as best practice in quality management, the final stage is continuous **learning**. The learning stage is an opportunity to validate and assess the effectiveness of the foresight process itself, and integrate lessons learned into the next cycle. It is also an opportunity to reflect on the weak signals themselves and their implications as technology progresses and as the operating environment evolved. Continuous learning ensures monitoring the relevancy and applicability of the findings and associated decisions and actions.

Foresight offers a collection of methods based on quantitative, qualitative and quasi-quantitative methodologies to help analysts anticipate plausible futures in a systematic way (Popper, 2008). These methods play a role across the FAF stages. According to Popper, foresight methods exhibit four attributes: creativity, expertise, interaction, and evidence. These attributes appear in varying degrees across foresight methods. Popper found that a foresight study uses on average four to five different foresight methods, likely suggesting that using one foresight method is not sufficient for most foresight projects.


*Figure 4: Foresight methods (Popper 2008)*

The United Kingdom Government Office for Science compiled a comprehensive list of various foresight methods and their respective utility, outcomes and risks associated with leveraging them (2017), it is clear that various foresight methods are useful to gain different insights about the future and plausible paths. Organizations may choose which methods suit their desired outcomes. For example, Policy Horizons Canada, the Government of Canada's centre of expertise on foresight unit, often leverages a variety of methods from across Popper's (2008) foresight diamond such as brainstorming, futures workshops, stakeholder analysis, expert interviews, cross-impact analysis, scanning, literature reviews, and scenario building to inform futures analysis. Best results have been obtained at DRDC with a balanced mix of foresight methods relying on expertise of SMEs, evidence of trends analysis and R&D Momentum, interaction with multiple stakeholders through creative futures workshops.

At DRDC, we developed and implemented the Foresight to Action Framework (FAF) in the early 2000's. The FAF is a 5-stage process to leverage evidence-based weak signal identification to inform program formulation and investment decisions. Each stage of the process leverages various tools from the foresight toolkit, which results in a comprehensive impact assessment of implications for future defence and security operations. The process begins with evidence-based weak signal detection and identification (detect). It continues with developing outlook products through the collection, analysis of data, and collation of the relevant reliable data sources (collate). The collation stage involves engagement with subject matter experts (SMEs), field operators of various ranks, policy and legal professionals, defence scientists and other members of the defence team. This stage typically leverages a combination of foresight methods from across Popper's diamond. During the engagements, the goal is to generate creative insights about risks, opportunities, limitations, new concepts, and identify various users and uses of the emerging technology under assessment in the context of plausible future scenarios or environments which were constructed by evidence-based STEEP-V[6] trend analysis. The third stage (assess) involves an assessment of the emerging technology's risks and opportunities identified during collation on the defence and safety domains and their policy implications. With a comprehensive, multidisciplinary and 360° view of the emerging technology, results inform actions (act) and strategic plans. And finally, a learning, validation and continuous assessment is integrated to ensure relevancy as science and technology evolve over time.

## 6. Discussion

Evidence and the scientific method are core to the approach of detecting weak signals at DRDC. Statistics plays a key role in providing the disciplinary rigor to ensure a systematic approach is taken. However, using exclusively scientific publications to detect emerging technologies has the limitation of looking into the near past. Any weak signal of emerging technology detected in the scientific literature is already at twelve to eighteen months old. Hence, this reliable data-driven approach needs to be complemented with multidisciplinary, multi-stakeholder and interdepartmental elements. This means, that science and technology foresight and risk assessment need to establish a network of connections across scientific disciplines, defence functions, national and international subject matter experts from government departments, academia and civil society. Being able to complement, compare and contrast the evidence from the data driven science and technology detection system with other sources of information, methodologies and disciplines, can provide a more robust and holistic coverage of a specific domain, which ultimately advance the path to a safe and secure future.

## 7. Conclusions

In this paper, we have presented the Foresight to Action Framework that DRDC has developed and implemented to detect weak signals of emerging technologies, collate information from multiple stakeholders on signals of interest, contextualize and assess the likely implications for Defence and Security, use results to inform action plans, and continuously learn.

The early detection of weak signals remains a challenging task as new methods are being developed by an increasing number of academics worldwide. Based on the trend in publications, it is highly likely that more methods and data sources will become available to support the detection of weak signals of emerging technologies in the global competition for innovation.

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