

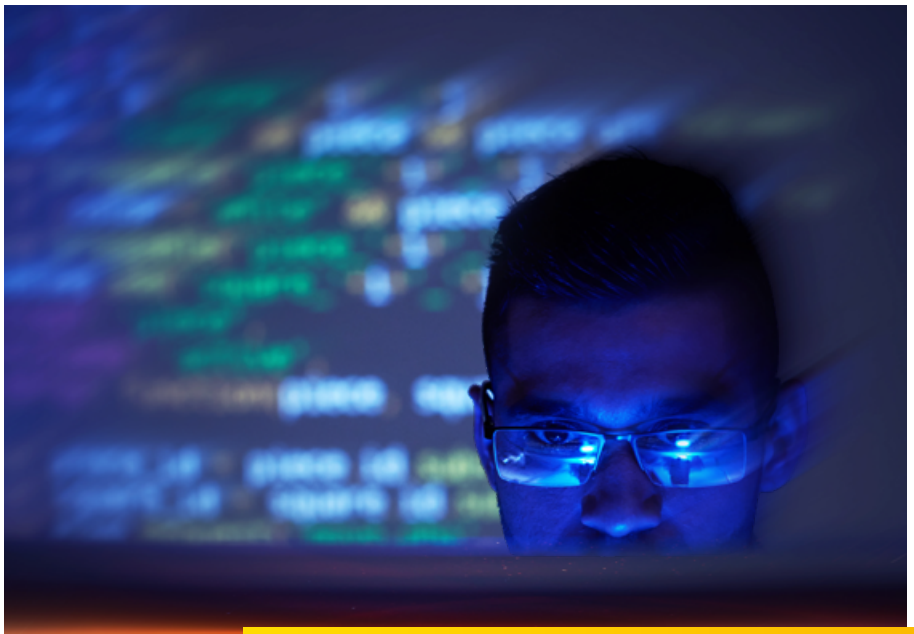
Understanding Technology Evolution

A framework for recognising disruptive change early enough to respond

Digital Intelligence & Land

BAE SYSTEMS

Abstract



Why do some technologies mature rapidly while others require decades to achieve widespread adoption?

Traditional horizon-scanning approaches often focus on individual technologies and specific forecasts. Yet, history suggests that transformative technologies rarely emerge as isolated breakthroughs. Instead, they evolve through recognisable phases of scientific discovery, research convergence, application exploration, industrialisation and mainstream adoption.

At the same time, the environment in which technologies develop is changing. Innovation cycles are compressing, geopolitical competition is accelerating adoption, and governance frameworks increasingly struggle to keep pace with technical capability.

This paper introduces a simple framework[1] for understanding technology evolution. Rather than attempting to predict precise outcomes, the framework seeks to identify where technologies sit within their maturity journey, how they are accelerating, and what signals indicate the transition from research to real-world impact.

Applying the framework to developments in autonomy, communications, human performance and quantum technologies suggests that the most significant disruptions of the coming decades may emerge not from individual breakthroughs, but from the convergence of multiple technologies whose capabilities are advancing faster than the institutions designed to govern them.

[1] Framework Provenance: The technology evolution framework presented in this paper is intended as an original analytical model developed to support horizon scanning and technology assessment. While it draws on established concepts relating to technology maturity, innovation diffusion, technology readiness and research commercialisation, the structure, terminology and application described here represent the author's synthesis of these themes. The framework is intended to provide a practical lens for analysing technology evolution rather than a replacement for existing maturity or adoption models.

"The environment in which technologies develop is changing. Innovation cycles are compressing and governance frameworks increasingly struggle to keep pace with technical capability."



Introduction

The Slow Birth of Fast Change

Technology rarely arrives suddenly.

What we call "emerging technologies" are usually the visible crest of ideas first explored decades earlier, often in obscure corners of research laboratories, universities and government programmes. The systems we rely on today, from advanced sensing and resilient communications to autonomy and cryptography, all began their lives long before they entered operational use.

Technologies typically progress through remarkably similar journeys. They begin as scientific observations. Years later, those observations converge into potential technologies. Prototypes emerge, followed by pilots and operational experimentation. Industrialisation and scaling then follow, before technologies eventually become so commonplace that people forget they were ever new.

This journey frequently spans decades. That simple fact has important consequences. No individual, however experienced, sees the entire lifecycle of a long-cycle technology. Technologies outlive careers.

Organisations therefore cannot rely solely on the expertise of a small number of specialists, however capable they may be. Long-cycle technologies demand institutional learning: structured ways of identifying early signals, tracking convergence and preserving knowledge as generations of technologists come and go.

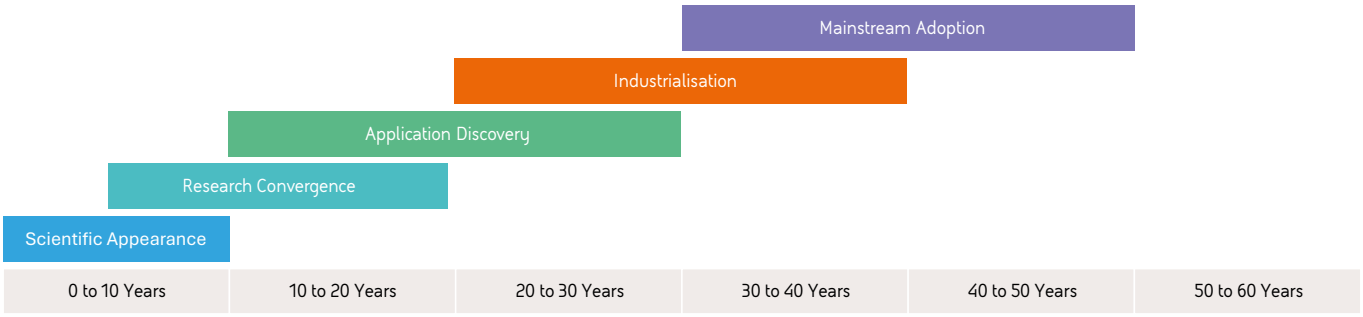
The organisations most likely to anticipate disruption are rarely those that make the most accurate individual predictions. More often, they are the organisations that develop a systematic understanding of how technologies evolve and how that evolution can be monitored over time.



1. A Framework for Technology Evolution

While technologies differ enormously, many appear to progress through a series of recognisable stages. The duration of each stage can vary significantly. Some technologies spend decades in research before finding practical applications, while others move rapidly due to market demand, geopolitical competition or advances in adjacent fields.

The value of the framework lies not in assigning precise timelines, but in helping organisations recognise where a technology sits today, what signals indicate progression, and where future opportunities or disruptions may emerge.



Scientific Appearance

Every technology begins with a scientific observation or principle. At this stage, researchers may have demonstrated that something is possible, but there is little understanding of how it might be applied.

The work is typically confined to universities, government laboratories and specialist research institutions. Publications focus on understanding the phenomenon rather than using it. Funding is generally research-driven and industrial interest is limited.

Many scientific discoveries never progress beyond this stage. Others may remain here for decades until complementary advances make practical applications possible.

Signals to watch include increasing research activity, growing academic interest and the emergence of multiple groups investigating related concepts.

Research Convergence

A technology begins to emerge when separate scientific disciplines start to converge around a common problem or opportunity.

Advances in materials science, computing, electronics, biology or physics may combine to create capabilities that were previously impossible. Researchers begin moving beyond scientific understanding towards practical experimentation. Early use cases become visible, patents increase and targeted research programmes begin to form.

This stage is often characterised by uncertainty. Competing technical approaches emerge and many ultimately fail. The challenge is no longer proving that a scientific principle exists, but determining whether it can be combined with other technologies to create something useful.

Key signals include increased research funding, growth in patents, the appearance of demonstrators and the formation of specialist communities focused on practical application.



Application Discovery

The transition from scientific possibility to operational relevance.

Prototypes, trials and pilot programmes begin to appear. Potential users start experimenting with the technology in real-world environments and organisations begin exploring practical use cases. At this stage, the question changes from "Does it work?" to "What is it useful for?".

The most successful technologies often lead to applications that were not originally anticipated. Requirements become better understood, standards begin to emerge and early adopters provide critical learning that shapes future development.

This is often the most important stage for horizon scanning because disruption starts to become visible while significant opportunities remain available to those willing to engage early.

Indicators include pilot deployments, operational trials, growing venture capital activity, increasing commercial investment and the emergence of early standards or regulatory discussions.

Industrialisation

Once applications have been proven, the challenge becomes scale.

Technical performance is no longer the primary obstacle. Instead, attention shifts towards manufacturing, supply chains, workforce skills, certification, assurance, commercial viability and regulatory approval.

Many technologies encounter their greatest challenges at this point. An impressive prototype may prove difficult to manufacture economically, or may require supporting infrastructure that does not yet exist. For example, autonomous drones have demonstrated value across defence, logistics and emergency response applications, but widespread deployment remains constrained by the need for robust systems to safely manage shared airspace and integrate autonomous platforms into existing regulatory frameworks.

Successful industrialisation typically attracts significant commercial investment and often reshapes markets. New entrants emerge, incumbents are challenged and ecosystems begin forming around the technology.

Signals include rapid investment growth, production scaling, supply-chain development, increased regulatory activity and the entry of major industrial players.

Mainstream Adoption

A technology reaches maturity when it becomes part of everyday life.

Users no longer view it as innovative or experimental. Organisations assume its availability and design processes, policies and training around its existence. Markets stabilise and supporting infrastructure becomes commonplace.

At this point, the technology has effectively transitioned from competitive advantage to expected capability.

Ironically, technologies often attract the greatest commercial attention as they approach mainstream adoption. Large Language Models provide a contemporary example. While the broader field of artificial intelligence (AI) spans multiple stages of maturity, foundation models and conversational AI have achieved widespread public adoption in a relatively short period of time. As the strategic significance of these capabilities became apparent, incumbent organisations responded through major investment, partnership and acquisition activity designed to secure long-term positions within emerging ecosystems.

At this stage, market incumbents often respond through major investment, partnership and acquisition activity designed to protect or strengthen their market position. Microsoft provides a useful example. While many of the breakthroughs underpinning modern generative AI emerged from universities, research laboratories and specialist AI companies, Microsoft acted quickly. As the technology approached industrialisation, the company made a series of strategic investments and partnerships to secure access to talent, infrastructure and emerging AI ecosystems.

According to widely reported information, Microsoft has committed approximately $13 billion to OpenAI through a series of investments and commercial agreements, while also providing cloud infrastructure to support the development and deployment of advanced AI models.

Microsoft acquired Nuance Communications in 2021 in a transaction widely reported to be valued at approximately $19.7 billion, including debt, strengthening its position in speech recognition and healthcare applications.

In 2024, Microsoft entered into a widely reported agreement with Inflection AI involving technology licencing and the recruitment of key technical personnel, illustrating how competition for AI capability increasingly extends beyond products to talent, intellectual property and ecosystem access.

These were not research-stage investments. They were large-scale commercial transactions that strengthened Microsoft's access to AI capability, talent, intellectual property, infrastructure and markets.

Using the Framework

The framework is not intended to predict specific outcomes or assign fixed timescales. Technologies can move forwards, stall, converge with other technologies or disappear altogether. External factors such as conflict, regulation, economic conditions and breakthroughs in adjacent fields can dramatically accelerate or delay progress.

Its purpose is to provide a common language for discussing technology evolution and to help organisations focus on the transitions between stages, particularly the movement from Research Convergence to Application Discovery. It is often at these transition points that future disruption first becomes visible, while there is still time to respond.

The framework also supports a second, equally important objective: helping organisations decide where not to invest.

Every year, thousands of scientific discoveries, research programmes and emerging technologies compete for attention. Only a small proportion will ultimately progress to widespread industrial or commercial impact. Many will stall, fail to scale, prove economically unviable or simply be overtaken by alternative approaches.

For most organisations, the challenge is therefore not identifying technologies worth watching, but continuously narrowing the field to those most closely aligned with their strategic objectives and risk appetite.

By providing a structured view of how technologies mature, the framework can help organisations make more informed decisions. This includes when to increase investment, when to maintain observation, and when to consciously disengage from technologies that are no longer demonstrating sufficient potential. In doing so, it helps focus finite resources on the opportunities most likely to create future value.



2. Why Technology Evolution is Changing

Although the broad progression from scientific discovery to widespread adoption remains recognisable, the environment in which technologies mature is evolving rapidly.

The forces shaping innovation today are different from those that influenced previous generations of technology. Digital infrastructure, global connectivity, geopolitical competition and increasingly complex technology ecosystems are altering both the speed and character of technological change.

Understanding these factors is becoming as important as understanding the technologies themselves.



Innovation Cycles are Compressing

Historically, transformative technologies often required decades to progress from scientific discovery to practical and widespread use.

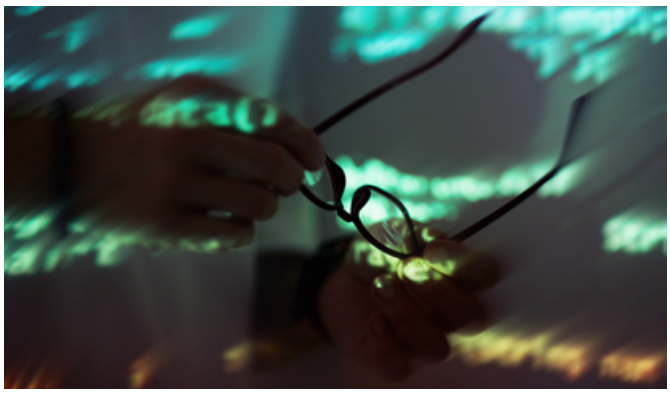
The transistor was invented in 1947, yet many of the digital products that now define modern life emerged decades later. The internet originated from research programmes in the 1960s and 1970s, but only became a truly mass-market platform in the 1990s. Global Positioning System (GPS) technology was initially developed for military purposes before eventually becoming embedded within everyday consumer devices.

Today, the environment is very different.

Cloud computing provides immediate access to scalable infrastructure. Open-source communities accelerate experimentation and knowledge sharing. Digital distribution enables new products and services to reach global markets almost instantly. Increasingly, artificial intelligence is helping researchers, engineers and developers create and test new capabilities more rapidly than ever before.

As a result, technologies still progress through similar stages of maturity, but many are moving through those stages at significantly greater speed.

The challenge for organisations is no longer simply to identify important technologies early enough. It is recognising when a technology has crossed an adoption threshold before competitors do.



Conflict and Competition Accelerate Adoption

Major disruptive events rarely create technologies from nothing. More often, they accelerate technologies that already exist.

RADAR provides a useful example. The underlying scientific principles were understood decades before practical systems emerged. The Second World War dramatically accelerated their development, industrialisation and deployment, compressing years of progress into a much shorter period.

More recent examples can be seen in satellite navigation, autonomous systems, artificial intelligence and advanced communications. Geopolitical competition continues to act as a powerful accelerator of innovation.

Technology evolution is therefore shaped not only by scientific discovery, but also by the urgency created by external events.



Technologies are Ecosystems

One of the most common mistakes in technology forecasting is treating technologies as single entities.

Most transformative technologies are not individual innovations, but collections of interdependent technologies that evolve at different speeds and often influence one another.

Quantum technology provides a useful example. The term encompasses quantum sensing, quantum communications, quantum navigation, quantum computing and post-quantum cryptography.

While some of these technologies are already finding practical applications, others remain at a much earlier stage of maturity.

Artificial intelligence exhibits a similar pattern. What appears externally as a single technology is, in reality, a diverse ecosystem comprising machine learning, computer vision, natural language processing, foundation models, copilots, intelligent agents, multi-agent systems and longer-term concepts associated with artificial general intelligence.

Each element follows its own maturity trajectory.

This distinction matters because strategic decisions made at the level of a broad technology category can be misleading. A technology may appear immature overall while specific components are already generating significant operational value. Equally, excitement surrounding a rapidly advancing component can create unrealistic expectations for the broader ecosystem.

Effective horizon scanning therefore requires understanding of not only where a technology sits today, but which parts of the ecosystem are driving progress and which remain constrained.



Governance is Falling Behind Capability

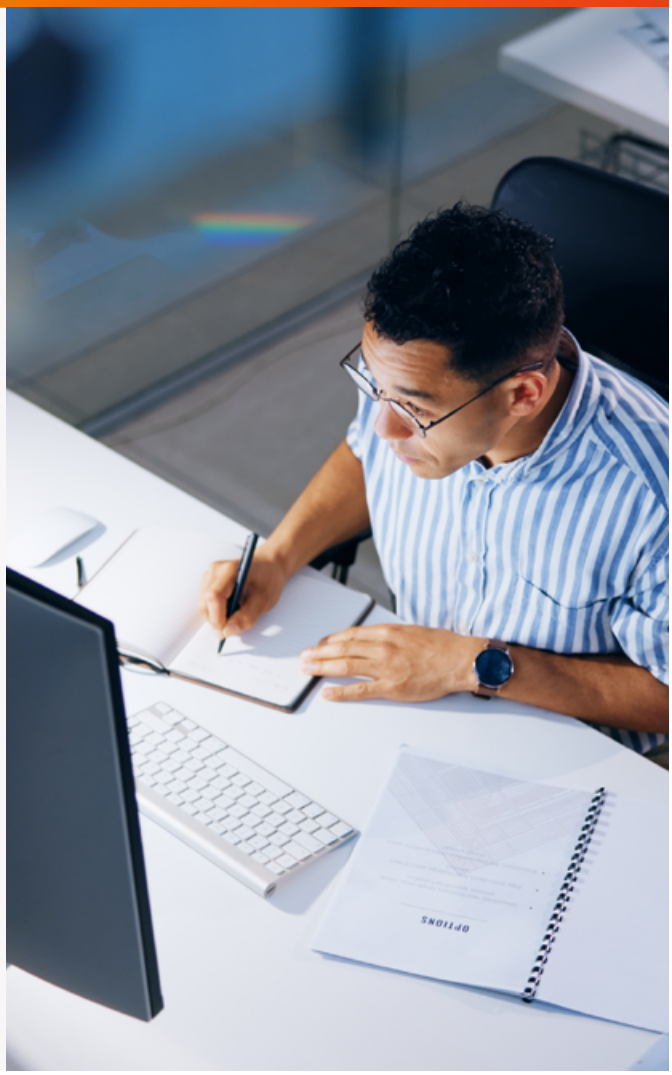
Perhaps the most significant shift in modern technology evolution is the growing gap between technical capability and institutional readiness.

Historically, technological development was often limited by scientific understanding, engineering challenges or manufacturing capability. Today, entirely new constraints are emerging.

Agentic artificial intelligence provides a contemporary example. Organisations are beginning to deploy intelligent agents capable of reasoning, planning and interacting with enterprise systems, data sources and business processes. Yet, the governance frameworks required to assure, control and regulate these capabilities remain comparatively immature.

A similar pattern can be seen across many emerging technologies. Advances in capability frequently outpace the development of standards, policy, regulation, ethics and assurance mechanisms. The consequence is that technological feasibility is no longer the sole determinant of adoption.

Increasingly, the critical question is whether organisations, governments and societies possess the structures necessary to deploy new capabilities safely, responsibly and at scale. In many cases, the greatest barrier to innovation may not be our ability to create technology, but our ability to govern it effectively.



3. Applying the Framework

When technologies reach the Application Discovery stage, meaningful prediction becomes possible. Prototypes exist, pilots are underway and industrialisation challenges begin to emerge.

Several areas stand out as particularly significant today.

Autonomy and Human-Machine Teaming

Autonomy is evolving from individual systems performing isolated tasks towards collaborative ecosystems of autonomous agents.

A useful analogy can be found in the drone swarm displays now replacing fireworks at major events around the world. A single drone is relatively simple. Hundreds or thousands operating together can create behaviours and outcomes that no individual platform could achieve alone.

Future autonomous systems are likely to evolve in much the same way. Rather than operating independently, they will share information, coordinate actions and adapt collectively to changing circumstances. Driverless vehicles provide a useful illustration. Early autonomous vehicles can operate independently, but the greatest gains in safety and efficiency may emerge when large numbers of autonomous vehicles share information in real time about road conditions, hazards and traffic flow. The value comes less from individual autonomy and more from collective coordination.

Humans will increasingly become conductors rather than operators, setting objectives and constraints, while teams of autonomous systems collaborate to achieve them.

Autonomous inspection, maintenance and repair are also moving steadily towards deployment. Critical infrastructure, spacecraft and hazardous environments can increasingly be monitored without exposing people to unnecessary risk.

Communications and RF Sensing

Communications technologies are beginning to serve a dual purpose.

The emergence of dual-use spectrum, particularly within higher-frequency bands, allows systems both to communicate and to sense their environment at the same time.

Radio waves no longer simply carry information. They are simultaneously being used to perceive the world. Emerging Wi-Fi sensing technologies can detect movement, occupancy and even falls by analysing how radio signals change as people move through an environment. Millimetre-wave (mmWave) 5G sensors and devices operate in high-frequency spectrum bands (typically 24 GHz to 100 GHz) to deliver multi-gigabit data speeds, ultra-low latency and high-resolution spatial sensing.

Unlike optical sensors, radio frequency (RF) sensing remains effective in environments affected by the likes of smoke, fog, darkness, dust and clutter. As autonomous systems become more common, these capabilities are likely to become increasingly important.

At the same time, static approaches to spectrum management will become increasingly difficult to sustain. Dynamic spectrum allocation is likely to evolve from a specialist capability into essential infrastructure.

Human Performance Technologies

Human performance technologies are beginning to move from research into application.

Cognitive load sensing is becoming capable of detecting when users are overloaded, distracted or under-utilised. This creates opportunities for systems that can adapt information flow according to an individual's workload and context.

Emerging systems are drawing inspiration from biology, replicating capabilities developed through evolution. Examples include bat-inspired sensing, neuromorphic vision systems and adaptive interfaces that respond to indicators of human cognitive workload.

Future interfaces may not remain fixed. Instead, they may continuously reshape themselves around the user, simplifying when workload is high and expanding functionality when capacity is available.

Alongside this, bio-inspired sensing technologies are beginning to demonstrate capabilities that complement traditional approaches to measurement and monitoring.

One example of this trend can be seen in efforts to make autonomous and uncrewed systems more accessible to operators through intuitive human-machine interfaces.

For example, BAE Systems has publicly demonstrated its AI Drone Controller concept, which uses natural-language interaction to support the tasking and control of autonomous and uncrewed platforms. The concept is intended to reduce the complexity traditionally associated with drone operation and explore new approaches to human-machine teaming through conversational interfaces.

While still representative of a broader area of technological development rather than a mature operational capability, such approaches illustrate how advances in artificial intelligence, autonomy and interface design may converge to reduce training burdens, increase accessibility and enable more effective interaction between people and autonomous systems.

Quantum Technologies

Quantum technologies are often discussed as though they represent a single field. In reality, they occupy multiple stages of maturity simultaneously.

Quantum-safe cryptography, often referred to as post-quantum cryptography, involves replacing today's widely used encryption algorithms with alternatives designed to remain secure against future quantum computers. The urgency stems not from the immediate arrival of large-scale quantum computers, but from the significant time required to upgrade existing digital infrastructure and protect sensitive data with long-term value. The UK's National Cyber Security Centre (NCSC) has set a 2035 deadline for complete migration to post-quantum cryptography (PQC), aligning with foundational standards formalised by the US National Institute of Standards and Technology (NIST).

Quantum sensing appears likely to become the first widely deployed quantum capability, offering advances in navigation, gravimetry and magnetometry, including the potential for navigation independent of satellite positioning systems.

Quantum communications will likely find its first applications in environments where trust and assurance are paramount, such as government, defence and critical infrastructure networks. While traditional encryption focuses on making intercepted data difficult to read, quantum communications offer the additional advantage of detecting whether interception has occurred at all.

Quantum computing remains comparatively immature when viewed through the technology evolution framework. Nevertheless, it is strategically important because its long-term potential is profound. Organisations and nations that develop practical quantum computing capabilities could gain significant advantages in fields ranging from materials science and optimisation to cryptography and defence analysis.

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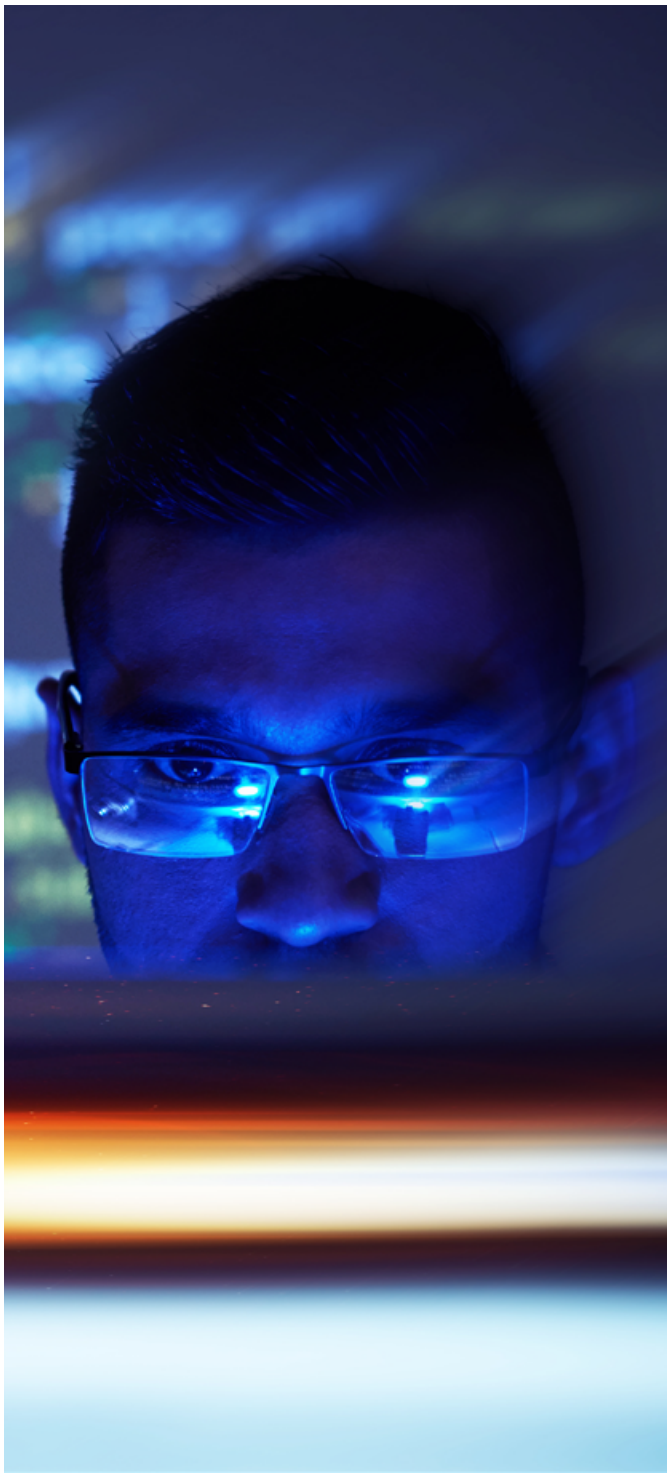
4. Key Considerations for Organisations



The purpose of understanding technology evolution is not to predict the future with perfect accuracy. That is impossible.

The objective is to recognise when technologies are transitioning between stages and to understand the implications while there is still time to respond.

Most organisations invest seriously only once technologies have entered industrialisation or mainstream adoption where return on investment is already being demonstrated in the field. By that point, competitive advantage has often already been established elsewhere.

The greatest opportunities frequently arise as technologies transition from 'Research Convergence' to the 'Application Discovery' stage.

This is the point at which future disruption begins to become visible while remaining early enough to influence strategy, investment and capability development.

Success therefore depends less on predicting specific technologies and more on building the institutional capability to identify technological transition points.

This requires structured horizon scanning, cross-disciplinary analysis, long-term knowledge management and an organisational culture capable of learning across timescales that exceed individual careers.

"Success therefore depends less on predicting specific technologies and more on building the institutional capability to identify technological transition points."

Conclusion

Seeing Further by Looking Earlier

Rather than predicting which technologies might shape the future, the more important challenge is arguably understanding how technologies evolve.

If organisations want to anticipate disruption, they must look beyond products, prototypes and headlines. They must look earlier, at the scientific principles emerging in laboratories, the convergences forming between disciplines and the signals that indicate when technologies are beginning to accelerate.

The future is already here. It is simply hidden within the early stages of technology evolution. The organisations best positioned to thrive will be those that build the institutional learning needed to see it.

Technology Trends Disclaimer: This paper reflects analysis and opinion regarding the evolution of emerging technologies based on publicly available information at the time of writing. References to future developments, technology trajectories and potential applications are intended to support discussion of long-term trends and should not be interpreted as predictions, commitments or assurances regarding future outcomes. The pace and direction of technological development remain subject to scientific, commercial, regulatory, geopolitical and societal factors that may influence adoption and implementation.

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