Hype Cycle for Deep Technology, 2023

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Initiatives: I&O Platforms

Deep technology innovations combine science, R&D and engineering to solve the seemingly unsolvable with transformative impact across business and society over the next decade. I&O leaders anticipating emerging trends should prioritize resources aligned to their unique business contexts.

Additional Perspectives

- Invest Implications: Hype Cycle for Deep Technology, 2023 (03 August 2023)

More on This Topic

This is part of an in-depth collection of research. See the collection:

- 2023 Hype Cycles: Deglobalization, AI at the Cusp and Operational Sustainability

Analysis

What You Need to Know

I&O leaders seeking to innovate using new technologies and lay the foundation for continued success and growth must track innovations identified in the new Hype Cycle for Deep Technologies (Deep Tech). Rapid pace of innovation in AI, quantum technologies, non-CMOS-based computing and storage technologies, new satellite innovations, bidirectional brain-machine interfaces and their applications, have significant implications across business, government and society. To put the emergent deep tech hype in perspective, I&O leaders must help their organizations:

- Explore new deep tech innovations with potential for disruptive impact, while moderating hype by methodically tracking innovator capabilities.
- Set the right expectations across peer leaders and frugally invest in promising innovation pathways.
- Use a robust and professional innovation management approach to deal with all the risks and uncertainties of early-stage emerging tech.
- Architect a systematic approach that upskills the workforce and enables continuous generation of value from near-term exploration while also building in versatility for these future developments and disruptions.

The Hype Cycle

This Hype Cycle describes the 27 innovations with diverse phases of hype in the emerging deep technologies market. For each technology, we define and analyze the benefit to enterprises, the current level of market penetration and the likely time it will take to reach the Plateau of Productivity.

New: Pace of innovation in quantum continues to accelerate as captured by innovations in postquantum cryptography, quantum key distribution, quantum networking, crypto-agility, quantum algorithms, classical quantum simulators and quantum sensing. Innovations in satellite technologies, including optical satellite connectivity using lasers and low Earth orbit satellites, enable new use cases around short data bursts for IoT endpoints and beyond.

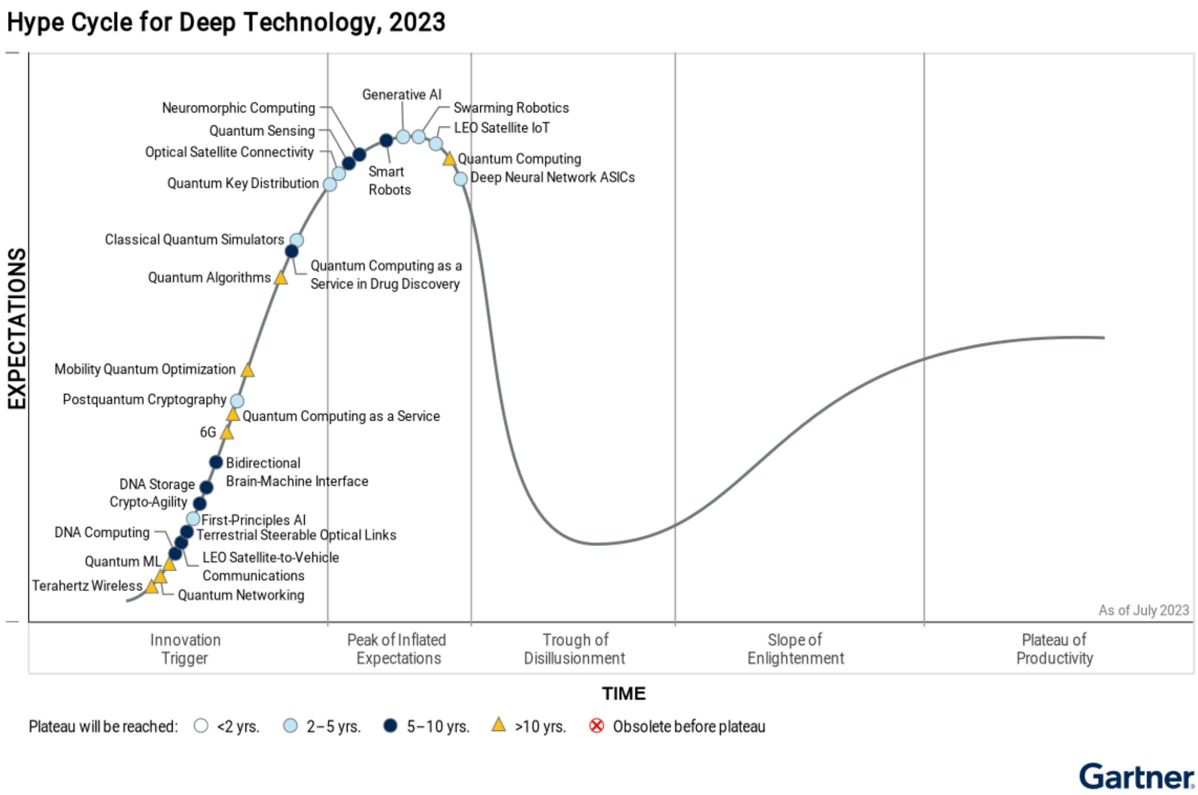
Peak Hype: A surge of interest in Generative AI is driving hype in innovative acceleration technologies, including neuromorphic computing and DNN ASICs. Adjacent segments, including potential edge, IoT and robotics applications and emerging systems, have precipitated the hype in robotic innovations, including smart robots and swarming robotics technologies.

Fast Movers: It is premature to comment on fast movers, but given the increased hype and level of investment, we anticipate AI and satellite technologies to be among the fast movers. Applications of quantum, including optimization, might accelerate as enterprises seek to explore potential applicability (or lack thereof) of quantum systems.

Slow Movers: Innovation domains, including DNA storage and computing, quantum and terahertz wireless, require fundamental problems to be resolved before significant progress can be achieved. In quantum, challenging aspects such as scaling, interconnects, error correction and effective control systems still need to be addressed before these technologies can be enterprise ready.

In the Trough: Given that the Hype Cycle covers technologies that are innovative and early stage, many have yet to make the transition into the Trough of Disillusionment. However, technologies, including Quantum Computing and Deep Neural Network ASICs, could enter into the Trough of Disillusionment if the hype exceeds capabilities and abilities of enterprises to create value from these promising innovations.

Figure 1: Hype Cycle for Deep Technology, 2023



The Priority Matrix

The Priority Matrix maps the benefit rating for each technology or innovation against the amount of time the technology or innovation is likely to take to achieve mainstream adoption. This perspective can help users decide how to prioritize their deep tech.

Transformational technologies, such as quantum and DNA computing, have immense transformative potential by enabling solutions to many classically intractable problems, including quantum-realistic materials simulations and extreme-scale optimization. AI continues to be among the top three priorities for enterprise leaders, partly due to the hype in Generative AI and the steady march toward more mature AI ecosystems. I&O leaders should start planning for phased exploration of these innovations to maximize value creation opportunities.

High-benefit entries such as optical satellite connectivity, LEO satellite-to-vehicle communications and terrestrial steerable optical links offer new ways to communicate and enable edge use cases. Additionally, the acceleration of innovative quantum applications (for example, QCaaS in drug discovery and mobility quantum optimization) could help the quantum industry stave off a potential "quantum winter" (where lack of ROI results in refactoring of the quantum marketplace). Combined with alternative acceleration techniques, including DNN ASICs and DNA technologies, this could provide new blueprints for I&O leaders to architect strategies in the last phase of Moore's law and beyond.

Table 1: Priority Matrix for Deep Technology, 2023

(Enlarged table in Appendix)

Benefit	*Years to Mainstream Adoption*			
↓	***Less Than 2 Years*** ↓	***2 - 5 Years*** ↓	***5 - 10 Years*** ↓	***More Than 10 Years*** ↓
Transformational		First-Principles AI Generative AI	DNA Computing Neuromorphic Computing Quantum Sensing	Quantum Algorithms Quantum Computing Quantum ML
High		Deep Neural Network ASICs Optical Satellite Connectivity Postquantum Cryptography	Bidirectional Brain-Machine Interface Crypto-Agility DNA Storage LEO Satellite-to-Vehicle Communications Quantum Computing as a Service in Drug Discovery Smart Robots Terrestrial Steerable Optical Links	6G Mobility Quantum Optimization
Moderate		LEO Satellite IoT Swarming Robotics		Quantum Computing as a Service Quantum Networking Terahertz Wireless
Low		Classical Quantum Simulators Quantum Key Distribution		

Source: Gartner (July 2023)

On the Rise

Quantum Networking

Analysis By: Andrew Lerner, Nauman Raja, Chirag Dekate

Benefit Rating: Moderate

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Quantum networking — also known as quantum communications — is a way to transmit information across a network. Quantum networking (QN) sends information in the form of entangled photons (qubits), while most existing networks are based on the binary encoding of 1s and 0s. Quantum networking enables the exchange of quantum information.

Why This Is Important

Quantum networking has the potential to address new use cases and enable a platform for future innovation and discovery. Quantum networks enable organizations to securely connect quantum systems, and cannot be decrypted using existing decryption mechanisms. One of the advantages of a quantum network is that it brings together many smaller, networked quantum computers. This way, it can operate at a larger scale and helps solving problems that are beyond the reach of a single machine.

Business Impact

Quantum networks have the potential to transform the way information is transmitted by security-sensitive industries — such as financial services, healthcare, energy, defense and government. New, disruptive applications of quantum networks — such as quantum sensing and interconnecting distributed quantum computers — have the potential to create the foundations of a next-generation “quantum internet.”

Drivers

- R&D innovations like testbed networks and pilots are driving interest in and awareness of quantum networks.

- Government and military organizations are funding quantum initiatives and exploring the feasibility of quantum networking to prepare for the next generation of network connectivity. They are focused on increased security and new use cases that involve interconnecting quantum sensors for applications (for example, helping people navigate in GPS-denied environments). China and Europe have been the most aggressive to date (see the AEI article, Quantum Computing: A National Security Primer). The EU has launched several centrally funded quantum testbeds and created an open system for ease of public private collaboration. Chinese initiatives are the most advanced with ground-ground, ground-satellite and satellite-satellite quantum communication infrastructures.

- Academic institutions are exploring the feasibility of using quantum networking to solve real-world connectivity challenges around scale, performance and security. Academic institutions are also creating interest and a corresponding talent pipeline.

- U.S. initiatives associated with QN are largely being driven by academic research activities.

- Quantum-based networks are not susceptible to known decryption mechanisms that can be used on existing networks. Thus, organizations concerned about the potential to break traditional VPN encryption are investigating quantum networking.

- Standards bodies are actively working on creating standardized protocols and mechanisms to use QN.

Obstacles

- Very few commercial entities are connected to existing quantum networks, limiting the value of connecting to them.

- QN are expensive to deploy, and there is no clear commercial ROI to build them.

- QN are not compatible with Ethernet and TCP/IP, thus they cannot be integrated easily into an organization's existing infrastructure or the internet.

- Deploying QN requires specialized infrastructures, such as photon detectors, that are hard to integrate with commercial telecom infrastructure.

- QN is in its infancy and technology stacks currently used to build QN are immature or have scalability challenges. QN require greater timing and synchronization granularity than what classical technologies can deliver, limiting growth.

- QN still have low qubit transmission rates and are sensitive to noise.

- While QN are more resistant to decryption than existing networks, applying postquantum encryption to existing networks can provide a similar functionality. This could deter or delay investments in QN.

User Recommendations

- Do not use quantum networking in production environments. Technology, protocol stacks and benchmarks are nonstandardized and ad hoc. Most quantum networks are associated with R&D exploration today.
- Work with your local university or government entities and join their emerging quantum networks to build a quantum network or gain experience with quantum networking. These partnerships can enable you to tap into the emerging quantum-enabled talent pipeline and form early relationships with quantum vendors.
- Look to traditional networking alternatives before investing in quantum networking. This is recommended due to the immaturity of the technology and market.

Sample Vendors

Aliro Quantum; IonQ; nodeQ; Qasky; QuDoor; Qunnect; QuTech; WeLink

Gartner Recommended Reading

Infographic: How Use Cases Are Developed and Executed on a Quantum Computer

Cool Vendors in Quantum Computing

Preparing for the Quantum World With Crypto-Agility

Terahertz Wireless

Analysis By: Nick Jones

Benefit Rating: Moderate

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Terahertz wireless refers to radio frequencies operating in the range between 300 GHz and 10 THz. In 2023, many aspects of terahertz wireless are technically extremely challenging and are still the subject of academic research.

Why This Is Important

Terahertz wireless is expected to be a key technology in future 6G cellular standards, which could be published around 2030. If technical challenges can be overcome, terahertz has the potential to deliver extremely high bandwidth and very low latency, while offering new sensing features and support for extremely small wireless devices.

Business Impact

Terahertz technology may become a significant innovation enabler. Terahertz could enable an order-of-magnitude performance improvement in wireless networking, and may enable major innovations in sensing. Terahertz equipment can measure distances with submillimetre accuracy, and the way in which Terahertz is absorbed and reflected can provide information about the material out of which an object is made. Terahertz wireless may also enable physically very small nanoscale devices with wireless interfaces.

Drivers

- There is potential for extremely high-bandwidth and low-latency communications.
- There is potential for submillimetre positioning accuracy, and new types of sensing and imaging combined with networking.
- The terahertz spectrum is virtually unused so it is uncongested.
- Terahertz wireless is less subject to certain forms of atmospheric disruption relative to laser point-to-point links.
- The very short wavelengths used by Terahertz systems may enable wireless devices that are physically very small (for example, the size of a biological cell).

Obstacles

- Viable commercial terahertz devices will require many fundamental breakthroughs in areas such as electronics, antennae and beam control. There is a possibility that terahertz may never become a viable technology for mass market deployment.
- Terahertz will be especially challenging in the case of moving endpoints.
- Very short range communications like terahertz frequencies are easily absorbed by physical objects. In 2023, the longest free-space terahertz link that has been demonstrated is only 2 kilometers.
- Most terahertz band technology that has been demonstrated is operating at sub 1 THz frequencies. Scaling up to higher frequencies may be challenging.
- Terahertz sensing can "see" through certain types of materials, including clothing, which could raise privacy concerns.

User Recommendations

- Task innovation and technology tracking staff with monitoring terahertz technology and 6G standardization efforts to identify innovation opportunities in areas such as sensing.
- Evaluate terahertz point-to-point links as an alternative to optical communications when (and if) terahertz matures sufficiently.

Gartner Recommended Reading

Top Strategic Technology Trends for 2023: Wireless Value Realization

Emerging Tech Impact Radar: Semiconductor and Electronics Technologies

Quantum ML

Analysis By: Chirag Dekate, Matthew Brisse

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Quantum machine learning (QML) combines the principles of quantum mechanics and machine learning (ML) to develop new algorithms, hybrid methods and new processing techniques to analyze data faster, with more accuracy and efficiency than classical approaches alone. As of this writing, there are no competitive advantages using QML today due to hardware limitations. There is a large amount of research dedicated to the QML space for quantum computing and quantum simulation.

Why This Is Important

ML techniques, including quantum neural networks, or quantum kernel methods, rely on two key parts: quantum embedding of data that maps feature space using quantum approaches and an evaluation function applied to data embedding. Theoretically, quantum embedding of feature space may result in a quantum advantage for a subset of problems over classical alternatives.

Quantum ML is nascent, and increasing awareness of quantum ML plays a key role in determining its potential value.

Business Impact

Quantum ML continues to be in an embryonic stage, with most R&D activities clustered around devising quantum algorithms for key ML kernels. However, the scale of the systems and algorithms and the challenges associated with “data loading” will limit adoption in the near term. Potential applications of quantum computing in AI and ML include quantum search, recommendation algorithms, quantum algorithms for game theory,and quantum algorithms for decisions and learning.

Drivers

- Early research in developing quantum ML initially indicated the potential for applicability across a growing set of ML algorithms, including k-means, k-medians, hierarchical clustering, principal component analysis, neural networks, support vector machines, nearest neighbors, regression and boosting.
- However, new research in this ever-evolving field seems to call into question the potential applicability of quantum computing in ML. Additionally, considerable hardware and software challenges remain.
- R&D today is focused on developing different quantum algorithms for ML kernels. Vendors such as Google, IBM, Rigetti Computing and Xanadu have prototype ML algorithms implemented for very selected use cases.
- Developing scalable ML systems will require many qubits and fundamental advances in applicable quantum algorithms.
- There are five well-known QML algorithms in use today: Quantum Principal Component Analysis (PCA), Quantum Support Vector Machines (SVM), Quantum k-Nearest Neighbors (k-NN), Quantum Boltzmann Machines (QBM) and Variational Quantum Classifier (VQC).
- Vendors and academia are investigating leveraging quantum simulation on classical machines for specific use cases with promising results that are limited by noisy intermediate-scale quantum (NISQ) computers.

Obstacles

While quantum ML is theorized to work effectively in NISQ computers, it is not ready for mainstream adoption today, with key obstacles including:

- **A nascent quantum computing ecosystem —** Quantum computing is still at a very early stage of development, with many systems offering scaling limited to tens of qubits. As a result, algorithms executed on these systems are primarily exploratory in nature.
- **Data encoding —** Although quantum computing can hypothetically deliver dramatic boosts for certain classes of data, one challenge is encoding input data. For quantum ML to work at scale, large amounts of data must be encoded and loaded into the quantum system.

- **Lack of mature algorithms —** New algorithms that can take advantage of capabilities offered by near-term noisy quantum systems will need to be discovered.

User Recommendations

Data and analytics leaders seeking to leverage risk-minimized quantum ML should:

- **Reinvest budget in your classical ML ecosystems**, where the value return will be demonstrably higher than in simulated quantum environments. Explore quantum ML environments at your own risk created by a lack of near-term meaningful results and uncertain timeframes to value.
- **Increase your awareness of quantum computing capabilities** and the potential for applicability in ML use cases by exploring early quantum ML algorithm prototypes on current systems. Leverage free quantum computing access and tutorials to develop quantum computing competency.
- **Prepare for quantum ML** by partnering with quantum computing solution providers and consulting experts to devise new ML algorithm kernels.
- **Leverage quantum-as-a-service** capabilities for validating hypotheses involving quantum ML to minimize risk and maximize the accessibility of quantum computing resources.

Sample Vendors

Amazon Web Services (AWS); Google; IBM; Microsoft; Multiverse Computing; QC Ware; Quantinuum; Quantum Metric; Rigetti Computing; Xanadu

Gartner Recommended Reading

How Use Cases Are Developed and Executed on a Quantum Computer

Innovation Insight for Quantum Computing for the Automotive Industry

Cool Vendors in Quantum Computing

DNA Computing

Analysis By: Matthew Brisse, Chirag Dekate

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

DNA computing is a type of parallel computing that uses DNA molecules as the carrier of information as opposed to classical bits. It uses billions of different molecules of DNA to perform massive parallel computations simultaneously. For specific use cases, it could compute faster and with a lower energy consumption than classical methods. DNA computing will not replace classical systems, but will provide computational offloading for specific NP-complete use cases.

Why This Is Important

- DNA computing in eight to 10 years could be able to address huge parallel processing use cases requiring massive amounts of data.
- DNA compute technologies are important because of DNA's density, durability and sustainability characteristics.
- DNA computational devices have shown significant potential in a number of biosensing applications.
- DNA computational devices can perform functions such as Boolean logic and neural network algorithms.

Business Impact

As DNA computing matures, the impact could be transformational for data storage, parallel processing and computing efficiency. Adoption of a complete DNA ecosystem will likely occur in data-intensive industries that are typically first movers in new technology domains such as healthcare, finance, insurance, academia and government. Defense, research and the intelligence communities will most likely be early adopters.

Drivers

- The popularity of DNA computing is driven by computational use cases for devices with extremely low-power and high-capacity requirements that can be replicated at scale.
- DNA computing can address combinatorial problems and nondeterministic polynomial-time complete (NP-complete) problems such as 3-SAT, 3-CNF SAT and 3-satisfiability.
- Although still in the experimental phase, proof points range from simple rudimentary games to neural-network-based computing.

Obstacles

- DNA computing suffers from a lack of market awareness. It is expensive, slow, not scalable or practicable at this time and requires purpose-built hardware.
- The creation of synthetic DNA, the medium used to store digital data, must become much more efficient and cost-effective. This is different from DNA data storage, which could be used for very-long-term storage.
- It may be difficult to find the right skill sets. There is limited availability of expertise in the DNA computing industry. Organizations will find it difficult to find specific talent in this field of research.
- Access speeds and throughput rates for both DNA compute and data storage have to dramatically improve to compete with classical approaches. DNA self-assembly and other similar processes are essentially chemical reactions — much slower compared to today’s classical approaches.
- DNA computing needs to advance to address complex logic and math problems at polynomial speeds, and to support a robust developer ecosystem.

User Recommendations

- Perform an assessment of the long-term potential impact of DNA compute and data storage within your organization. Determine whether, in the future, there will be any opportunities for use cases that can only be exploited by DNA-based technologies.
- Exploit early opportunities to use DNA data storage for product-centric uses, such as embedding DNA tags into products to ensure authenticity and provenance.
- Monitor technology innovation in the DNA storage and computing space. Look out for cost and performance breakthroughs and sustained venture capital investment before beginning any proof of concept testing.
- Ensure you partner with a viable, scalable vendor with cross-domain expertise.
- Evaluate viability of DNA data storage, waiting for storage prices to fall to three to four orders of magnitude the cost of tape archival approaches, and for write speeds to reach the megabit per second range.

Gartner Recommended Reading

Emerging Tech Impact Radar: Compute and Storage

Top Trends in Building a Digital Future: Next-Gen Computing

First-Principles AI

Analysis By: Erick Brethenoux, Svetlana Sicular

Benefit Rating: Transformational

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

First-principles AI (FPAI) (aka physics-informed AI) incorporates physical and analog principles, governing laws and domain knowledge into AI models. In contrast, purely digital AI models do not necessarily obey the fundamental governing laws of physical systems and first principles — nor generalize well to scenarios on which they have not been trained. FPAI extends AI engineering to complex system engineering and model-based systems (like agent-based systems).

Why This Is Important

As AI expands in engineering and scientific use cases, it needs a stronger ability to model problems and better represent their context. Digital-only AI solutions cannot generalize well enough beyond training, limiting their adaptability. FPAI instills a more reliable representation of the context and the physical reality, yielding more adaptive systems. A better ability to abstract leads to reduced training time, improved data efficiency, better generalization and greater physical consistency.

Business Impact

Physically consistent and scientifically sound AI models can significantly improve applicability, especially in engineering use cases (using IoT data). FPAI helps train models with fewer data points and accelerates the training process, helping models converge faster to optimal solutions. It improves the generalizability of models to make reliable predictions for unseen scenarios, including applicability to nonstationary systems, as well as enhances transparency and interpretability to make models more trustworthy.

Drivers

- **FPAI approaches instill a more flexible representation of the context and conditions in which systems operate, allowing software developers to build more adaptive systems.** Traditional business modeling approaches have been brittle. This is because the digital building blocks making up solutions cannot generalize well enough beyond their initial training data, therefore limiting the adaptability of those solutions.

- **FPAI approaches provide additional physical knowledge representations, such as partial differential equations to guide or bound AI models.** Traditional AI techniques, particularly in the machine learning family, have been confronted with severe limitations — especially for causality and dependency analysis, admissible values, context flexibility and memory retention mechanisms. Asset-centric industries have already started leveraging FPAI in physical prototyping, predictive maintenance or composite materials analysis, in conjunction with augmented reality implementations.

- **Complex systems like climate models, large-scale digital twins and complex health science problems are particularly challenging to model.** Composite AI approaches provide more concrete answers and manageable solutions to these problems, but their engineering remains a significant challenge. FPAI provides more immediate answers to these problems.

- **First principles knowledge simplify and enrich AI approaches** by defining problem and solution boundaries, reducing the scope of traditionally brute force approach employed by ML; for example, known trajectories of physical objects simplify AI-enabled sky monitoring. First-principles-based semantics reveal deepfakes.

- **The need for more robust and adaptable business simulation systems will also promote the adoption of FPAI approaches.** With a better range of context modelization and more accurate knowledge representation techniques, simulations will be more reliable and account for a wider range of possible scenarios — all better anchored in reality.

Obstacles

- From a diagnostic perspective, the development of systematic tests and standardized evaluation for these models across benchmark datasets and problems could slow down the adoption of FPAI capabilities.
- Computationally, the scaling of the training, testing and deployment of complex FPAI models on large datasets in an efficient manner will also be an issue.
- Resourcewise, collaboration across many diverse communities (physicists, mathematicians, computer scientists, statisticians, AI experts and domain scientists) will also be a challenge.
- Brute force approach is prevalent in AI, and is easy to implement for data scientists, while first principles require additional fundamental knowledge of a subject, calling for a multidisciplinary team.

User Recommendations

- **Set realistic development objectives** by identifying errors that cannot be reduced and discrepancies that cannot be addressed, including data quality.
- **Encourage reproducible and verifiable models** starting with small-scoped problems; complex systems (in the scientific sense of the term) are generally good candidates for this approach.
- **Enforce standards for testing accuracy and physical consistency** for physics and first-principles-based models of the relevant domain, while characterizing sources of uncertainty.
- **Promote model-consistent training** for FPAI models and train models with data characteristics representative of the downstream application, such as noise, sparsity and incompleteness.
- **Quantify generalizability in terms of how performance degrades** with degree of extrapolation to unseen initial and boundary conditions and scenarios.
- **Ensure relevant roles and education** in a multidisciplinary AI team (with domain expertise), so the team can develop the most effective and verifiable solution.

Sample Vendors

Abzu; IntelliSense.io; MathWorks; NNAISENSE; NVIDIA

Gartner Recommended Reading

Innovation Insight: AI Simulation

Innovation Insight for Composite AI

Go Beyond Machine Learning and Leverage Other AI Approaches

Innovation Insight: Causal AI

Predicts 2023: Simulation Combined With Advanced AI Techniques Will Drive Future AI Investments

LEO Satellite-to-Vehicle Communications

Analysis By: Bill Ray

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

Satellites in low Earth orbit (LEO) may be used to provide high-bandwidth, low-latency communications to moving vehicles. Flat-panel antennas, built into the fabric of a car or truck, can deliver line-of-sight communications to orbit, sidestepping terrestrial networks to provide a direct link from vehicle vendor to end user.

Why This Is Important

Vehicles of all kinds increasingly need reliable connectivity. Such connectivity is used to update software, upsell additional features and services, track telematic data for preventative maintenance, and maintain the relationship between the vendor and the end user or driver. Cellular networks have limited coverage, and moving between countries can raise complications. By contrast, satellites can provide global connectivity whenever a view of the sky is available.

Business Impact

Satellites can provide global communications for connected cars, without the need for terrestrial cellular networks. This direct link cements the relationship between the vehicle vendor, which may also operate the satellites, and the end customer, avoiding any intermediary, such as a terrestrial network operator. International coverage and shipping are simplified, because vendors don't need to make multiple agreements or worry about vehicles moving within economic blocks, such as the European Union.

Drivers

Companies building LEO satellite constellations are keen to provide automotive connectivity, as their business requires scale to be economically viable. Automotive vendors are exploring the potential of LEO satellites for a combination or reasons:

- International roaming complicates the use of cellular networks, particularly where vehicles may be sold across country borders and permanently moved to a different country.
- Cellular connectivity can be expensive, and automotive vendors do not like being beholden to cellular operators that could change pricing or coverage with minimal warning.
- Cellular technologies are evolving at an accelerated pace. Automotive vendors are concerned that terrestrial networks might decide to refarm radio spectrum to new technologies, requiring in-field hardware upgrades to avoid connectivity loss.
- Terrestrial network coverage is far from ubiquitous, with rural areas often providing limited — or zero — network coverage.
- Satellite connectivity can provide a route for additional services, such as infotainment products and navigation services, which could provide additional revenue streams.
- Satellite networks can provide broadcast capabilities, allowing a mass update of vehicles in a single transmission. By contrast, terrestrial networks require individual downloads.

Obstacles

While LEO satellites offer many advantages, the business model is far from certain, given the following factors:

- It costs billions of dollars to build and maintain an LEO satellite constellation. Thus, some market instability is likely as the industry matures.
- Data services provided by satellites are more expensive than the same services delivered by terrestrial networks, as satellite operators must recover the high capital cost of building a constellation.
- The cost of ground equipment (the antenna that must be fitted to every car) remains above $500. The antenna is also more easily installed during vehicle design and production.
- Connectivity will still be limited to line of sight, so vehicles in tunnels will be cut off. Coverage in urban canyons (between skyscrapers) will depend on the number of satellites deployed, with only the largest megaconstellations able to provide ubiquitous urban coverage.
- Aftermarket accessories, such as roof racks or metallic paint, could interfere with the satellite connection.

User Recommendations

- Explore cooperative or partnership arrangements to provide competitive services against companies that can leverage sibling relationships (such as Tesla/Starlink and Geely).
- Look for partnerships with constellations that aren't owned by companies with an interest in automotive, such as Amazon Project Kuiper or Hanwha Systems.
- Evaluate hybrid services, using terrestrial networks where possible and switching to satellite where necessary.
- Conduct a cost-benefit analysis to work out at what price it would make sense to integrate a phased-array antenna into the roof of every vehicle.

Sample Vendors

Geely Space; Hanwha Systems; SpaceX

Gartner Recommended Reading

Forecast Analysis: Enterprise and Automotive IoT, Worldwide

Tool: Connected Vehicle Use-Case Opportunity Assessment

Terrestrial Steerable Optical Links

Analysis By: Bill Ray

Benefit Rating: High

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Optical communication with an aircraft, drone or robot offers high bandwidth and high security, but requires steerable transceivers that are capable of tracking the target in real time and aiming the laser used. Tracking is often done visually, while aiming can be done with microelectromechanical mirrors or spatial light modulation. However, both techniques require significant onboard processing and can be vulnerable to vibration or shock damage.

Why This Is Important

Communications with aerial assets is limited by the radio frequencies and network coverage available, with drones often unable to stream high-quality video or provide remote operations due to limited bandwidth. Aircrafts are often reliant on satellite communications, which can only offer limited bandwidth at a significant cost. Military applications are particularly important, as laser communications are difficult to detect and disrupt.

Business Impact

High-speed communications with and between aircraft will enable new use cases, such as real-time asset inspection and high-definition aerial observation. A high-resolution camera flying (or floating) at 2 km can easily track individuals or vehicles on the ground, and laser communications can provide an effective way to get that data back. Remote operation of an aircraft, including cargo-carrying drones, also requires the kind of bandwidth and long range which lasers can deliver.

Drivers

- Being able to stream live, high-quality video from a drone in flight permits real-time analysis of data collected during asset inspection or security patrolling.
- AI analysis can be moved from the drone into the cloud, reducing onboard power consumption and increasing flight time.
- Remote operation of multiple drones becomes viable, thanks to the high bandwidth available and the limited interference generated.
- The demand for intraconstellation satellite communications, particularly within LEO (low earth orbit) networks, is driving technical development of steerable lasers and tracking techniques.
- The difficulties in detecting or disrupting laser communications are particularly attractive to military users, who see steerable laser links as a key enabling technology for air-to-air and air-to-ground communications.

Obstacles

- The technical challenges in tracking the target and aiming the laser are both at the experimental stage, and investment is limited by the forecast market size.
- Laser range is quite limited — existing systems operate over a kilometer or so, though the range is rapidly increasing.
- Aiming systems are currently quite fragile and unsuited to fitting in high-vibration environments.
- Bright sunlight can still generate interference with some laser systems.

User Recommendations

- Create a benefit analysis on the value of high-bandwidth communications with mobile endpoints for existing and planned products, which can be matched against the falling cost of the technology.
- Identify new use cases that could be enabled by high-capacity wireless communications, and create a cost analysis for the price of laser communications needed to make such a use case viable.
- Track development of spatial light modulation, which could substantially reduce the cost and complexity of steerable optical communications.

Sample Vendors

AAC Hyperion; Aalyria Technologies; Mynaric; QinetiQ

Crypto-Agility

Analysis By: Mark Horvath

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

Crypto-agility is the capability to transparently swap out encryption algorithms and related artifacts in an application, and replace them with newer, different and, presumably, safer algorithms. Because quantum computing poses an increasing threat to existing cryptography, Gartner expects crypto-agility to be a significant differentiator for technology vendors.

Why This Is Important

As quantum computing matures, asymmetric encryption faces the threat of being damaged or broken during the next five to seven years. Algorithms threatened are hard-wired into many applications, and most organizations lack a clear idea of the cryptography they're using.

Standard network/PKI protocols (e.g., Diffie-Hellman key exchange and TLS) will need quantum-safe deployments.

The National Institute of Standards and Technology (NIST) is standardizing quantum-safe alternatives for widespread use.

Business Impact

- Applications/communications using encryption or PKI need to be inventoried. Data about algorithms, key sizes, expiration dates and uses must be gathered into a metadata database.
- Suitable replacements must be identified for applications and use cases.
- The new algorithms are not drop-in replacements for cryptography, so alternatives must be tested and replacement policies must be generated.
- Vendor cryptography products must be identified, and vendors will need to provide a replacement schedule.

Drivers

- The development of quantum computers capable of breaking cryptography through Shor's or Grover's algorithms is estimated to be five to seven years away. This is much shorter than the typical life span of sensitive information found in most organizations.
- Keybreaking with Shor's algorithm goes linearly with key size but is limited by the number of available qubits; once it's been achieved, larger keys sizes will fall quickly, leading to a short runway to implement changes.
- Most organizations that have inventoried their cryptographic metadata have found they already have considerable technical debt with respect to PKI (e.g., expired certs, deprecated algorithms, short keys). Cleaning that up will substantially lower the organization's risk profile.
- New algorithms have additional uses that can foster novel business cases (e.g., stateful signatures, homomorphic encryption).
- Government organizations are beginning to require a quantum-safe encryption strategy for vendors selling to them (e.g., U.S. NSM-10, EO-14028). This includes all products or code that is included in the final product, including open-source software (OSS) and other vendor's products. Like with a software bill of materials (SBOM), this significantly expands the scope of these orders to include many vendors not otherwise selling directly to the government.
- Cryptography in vendor products will need to be identified, and vendors will need to provide a schedule for potential replacement.

Obstacles

- The time scale for change (five to seven years) is significantly beyond the expected tenure of many senior executives, leading to a “someone else's problem” mentality, leaving some decision makers to prioritize shorter-term projects.
- Many organizations don't know how to inventory their cryptographic usage, leaving them to choose between a vendor to do the work, or spinning up an internal program.
- The NIST standardization of current, approved algorithms has not been completed, leaving clients with nonstandard OSS versions of the algorithms.
- Many organizations lack the expertise needed to lead a cryptographic project of this magnitude.
- There is still some market confusion about what “quantum-safe” means, sometimes leading organizations to evaluate relatively useless technologies that talk about “quantum” but don't solve the problem.

User Recommendations

- Start looking at your cryptographic inventory sooner, rather than later. This will help scope the project and identify key systems and data, allowing a controlled rollover to quantum-safe encryption.
- Experiment with the OSS version of the NIST standardization candidates to determine what effect this will have on your infrastructure (e.g., lattice encryption is generally slower, and ciphertext sizes are larger than existing algorithms).
- Ask vendors what their plans are for replacing algorithms, and when quantum-safe versions of their products will be available.
- Explore off-brand uses for some of the new algorithms (e.g., homomorphic encryption).

Sample Vendors

Cryptomathic; DigiCert; Entrust; IBM; IronCore Labs; ISARA; Sandbox AQ; Thales; Utimaco; Venafi

Gartner Recommended Reading

Preparing for the Quantum World With Crypto-Agility

Infographic: How Use Cases Are Developed and Executed on a Quantum Computer

Cool Vendors in Quantum Computing

DNA Storage

Analysis By: Matthew Brisse

Benefit Rating: High

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Deoxyribonucleic acid (DNA) data storage is the process of encoding and decoding binary data to and from synthesized strands of DNA. Any binary sequences can be encoded in DNA sequence, which can then be synthesized and stored. To retrieve the data, the DNA molecule must be sequenced and decoded. DNA is emerging as an increasingly attractive medium for the archiving of data, due to its superior density, durability and sustainability.

Why This Is Important

- DNA data storage is important, due to its density, durability and sustainability; it addresses long-term data retention and sustainability needs.
- DNA performs error checking and self-repair, making it an ideal data storage medium and computing platform for applications.
- DNA data storage has a long-term, cost-reduction impact on physical data center space, carbon-dioxide emissions and the avoidance of operating expenditures (opex), by not having to refresh the technology every five to 10 years.

Business Impact

As DNA storage matures, its impact could be transformational for data storage, parallel processing and computing. Adoption of a complete DNA ecosystem as a consumable enterprise product is likely to occur at approximately eight years for data-intensive industries that are often first movers among new technology. The domains include healthcare banking, finance, insurance, utilities and government. The defense, research and intelligence communities are the most likely to be early adopters.

Drivers

- Future DNA data storage use cases will focus on power and space-sensitive, long-term storage requirements.
- Once DNA storage is written to, synthetic strands of DNA digital data require minimal storage space and almost no power. In theory, they can be accessed for thousands (if not millions) of years by a variety of devices in a future-proof manner, with no necessity of data migration.
- Long-term operational costs are reduced, because data migrations due to technology obsolescence or data degradation will not be issues with DNA-based storage.
- The business drivers for DNA-based data storage are density, stability, durability, sustainability and long-term operational cost.
- The world creates several hundred petabytes of new data every day, and a single gram of DNA could store all of it. One gram of DNA can store approximately 215 petabytes of data with a minimum life span of hundreds to, theoretically, thousands of years.
- DNA data storage will have a power efficiency profile that could significantly reduce the physical infrastructure space and the carbon-dioxide footprint over the life of the data.
- Data in DNA storage can endure for thousands of years and remain unchanged, free from degradation or drive failure, compared with current technologies.
- In the future, DNA data storage will be used in combination with DNA computing for extremely large, massively parallel, processing use cases.

Obstacles

- DNA technologies face many of the same challenges as any other startups early in their life cycles: speed, time to market, standards and cost.
- DNA data storage patents are likely to cross industry segments, making patents and licensing agreements challenging. IP submissions accelerate when a market matures, so expect increased numbers of investors.
- The creation of synthetic DNA, the medium that will store data as DNA, needs to become efficient and cost-effective.
- Access speeds and throughput rates for DNA data storage must dramatically improve to compete with classical approaches. DNA self-assembly and other similar processes are essentially chemical reactions, which are much slower, compared with today's classical approaches.
- Data security and regulatory challenges will be an issue, because DNA will someday store personal, sensitive and classified materials.
- The industry needs to develop and accelerate standards on the automation of DNA data storage and the associated retrieval processes.

User Recommendations

- Prepare for increased hype as technologies mature, realizing that DNA data storage is nascent. Savvy organizations will see through the hype to the practical use-case initiatives DNA storage offers.
- Focus on due diligence of startup companies, and align risks with the justification of use-case returns.
- Avoid long-term lock-in with early providers. Startups will emerge and fail until technologies mature, and winners and losers are identified.
- Anticipate difficulties in the development of DNA data storage. Explore the promise of near-infinite, enterprise-grade, reliable, durable capacity at a fraction of the cost of conventional enterprise-grade media.
- Prioritize DNA storage for early use cases, when available, focusing on write-once, read-never or write-once, read-seldom, if ever large-scale datasets.
- Evaluate DNA data storage viability by gauging when storage prices fall to three to four orders of magnitude the cost of tape archival, and when write speeds reach the megabit/second range.

Sample Vendors

Ansa Biotechnologies; CATALOG; DNA Script; Helixworks Technologies; Iridia; Kilobaser; Molecular Assemblies; Spectra Logic; Twist Bioscience

Gartner Recommended Reading

Emerging Tech Impact Radar: Compute and Storage

Top Trends in Building a Digital Future: Next-Gen Computing

Bidirectional Brain-Machine Interface

Analysis By: Sylvain Fabre, Annette Jump

Benefit Rating: High

Market Penetration: Less than 1% of target audience

Maturity: Adolescent

Definition:

Bidirectional brain-machine interfaces (BMIs) are brain-altering neural interfaces that enable two-way communication between a human brain and a computer or machine. Bidirectional BMIs not only monitor the user's EEG and mental states, but also allow some action to be taken to modify the state of the brain based on analytics and insights. Brain state modification occurs via noninvasive electrostimulation through a head-mounted wearable or an invasive implant.

Why This Is Important

BMI wearables can be as simple as a noninvasive, affordable headband, yet they can provide a massive net societal impact and benefit in terms of illness and accident prevention, comparable to a simple vaccination program. Therefore, this is not only a futuristic, expensive, invasive solution for the few, like Neuralink, but also a simple gadget for the benefit of the many, provided adequate security and privacy measures are in place. When connected, these enable the Internet of Brains (IoB).

Business Impact

Over the next 3 to 10 years, BMIs will enable business use cases, including authentication, access and payment, and support immersive analytics and workplaces; interactions in the metaverse; and control of power suits or exoskeletons. What is unique about "bidirectional" BMIs versus other classes of wearables/ingestibles is their brain-altering capability. Examples may include boosting alertness in response to a pilot's EEG markers of fatigue or applying relaxing cortical currents to the brain of a harried nurse.

Drivers

- Industrial safety, sports performance, marketing and audience testing, as well as consumer wellness, appear to be the most promising early drivers for bidirectional BMIs.
- Demand is growing from large consumer-focused corporations and media companies, as some of these solutions can measure the response and attitude of consumers toward products, content and companies.
- There are already applications of one-way BMI wearables, where the focus is about monitoring the state of the user or using the user's intent to operate some external device. Examples include measuring fatigue and alertness in a driver without trying to externally modify the user's mood.
- Further adoption of consumer and corporate wellness; for example, using neurotechnology to both monitor and stimulate brain function, as well as improve sleep.
- Use of BMIs as a human-machine interface to interact with emerging metaverse environments among consumers and business users.
- Direct read-and-write access to brain activity creates many opportunities for workforce enablement.
- Productivity and neurodiversity initiatives will increase the need for connections between humans, the Internet of Things (IoT) and the IoB.
- Neuralink obtained FDA approval for human trials from implantable chips in May 2023.

Obstacles

- Bidirectional BMI faces some of the same problems linked with smart wearable devices, such as high cost for early products, slow user adoption, high drop-off rates for some smart wearables and the complexity of integration between various data systems.
- Since bidirectional BMIs are a more advanced and extreme form of wearable (in effect, an implant equivalent, with bidirectional connectivity), providers must offer more affordable products with increased functionality, without added invasiveness to improve acceptability
- Bidirectional BMIs create very specific security challenges, because they directly interface with the human brain. This creates new vulnerabilities to individuals and their companies by adding a vector of attack into users' psycho-physical space.
- Social acceptance, especially for the more conspicuous form factors, may be a long way off.
- Bidirectional BMI raises serious ethical concerns, including human factor issues such as altering users' perception of reality, memories or even their personality.

User Recommendations

- Prepare for bidirectional BMI devices creeping into enterprises; "bring your own device" (BYOD) may occur long before specific legislation is in place.
- Ensure customer safety and business security by implementing data anonymity and privacy (beyond current legislation such as General Data Protection Regulation [GDPR]) for brain-wearable data collection and management.
- Highlight trade-offs in wellness solutions: more data may not equate to improved outcomes when looking at complex systems such as the human brain.
- Set up an independent steering board to monitor products sold to consumers and provided for employees. Preempt potential legal liability by regularly reviewing implanted wearables' features, data governance policies and their use cases, and deciding on what is acceptable in terms of read/write from and to users' brains.
- Establish policies for unauthorized implantables: While they cannot easily be removed, users may be prohibited from some roles such as operating vehicles or machinery, or advanced security clearance due to increased hacking risk.

Sample Vendors

Blackrock Neurotech; BrainCo; Kernel; Meta; Neuralink; Neuroelectrics; NYX Technologies; Paradromics

Gartner Recommended Reading

Maverick Research: “Metasuits” Will Be Key to Compelling Metaverse Experiences

6G

Analysis By: Kosei Takiishi

Benefit Rating: High

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

6G is the generic name for the next-generation cellular wireless, also called Beyond 5G. In 2023, the features and timetable for 6G are not clearly defined, although it’s expected to be commercialized in 2028 by some communications service provider (CSP) pioneers. 6G will enhance 5G capabilities and is intended to provide higher peak data rate (e.g., 100 Gbps to 1 Tbps), lower latency (e.g., 0.1 ms) and much more connection density and energy efficiency (e.g., 10 times more efficient).

Why This Is Important

The U.N.’s 2030 Agenda for Sustainable Development, including 17 goals, is heavily impacted by the mobile industry. Many of these social issues and ambitious goals will result in technologies that will become a part of 5G or future 6G cellular deployments. Design and research for 6G is already underway by many industrial associations and academic and commercial organizations. 5G can solve some of these challenges; however, 6G is indispensable for continuous growth and problem solving in the 2030s.

Business Impact

6G will enable end users, including consumers and enterprises, to transfer and process large volumes of data in real time, which enables true immersive experiences as well as more mission-critical human machine communications. Much richer and advanced connectivity of the physical world with the digital world — digital-physical fusion — is expected. There is no clear 6G definition, but 6G is aiming to improve 5G capabilities by adding one generation every 10 years (same as before).

Drivers

- Different from 4G and current 5G, 6G will become a sort of national network supported or impacted by countries and national policies. Some leading countries have started their initiatives, which will drive further research and discussions. In February 2023, the South Korean Minister for Science and ICT unveiled the K-Network 2030 plan, calling for South Korean tech firms to lead the way in developing world-class 6G technologies and software-based networks. The Chinese government has nominated 6G as one of its priority projects for 2023. In March 2023, the Beyond 5G Promotion Consortium in Japan published its B5G White Paper 2.0.
- Academics and commercial organizations want to be part of the 6G process, and active research has already begun. Working group one6G in Europe hosted a summit and held related open webinars in 2022. In February 2023, NTT DOCOMO hosted Open House'23, where 6G was one of the main topics. In November 2022, NTT DOCOMO published the 6G White Paper 5.0.
- Many commercial organizations and academic institutions have started their 6G research to be a part of the future 6G patent pool.

Obstacles

- The 5G journey is still in its early years, and its best practices and monetization are not clear. Success or failure of 5G to drive revenue and new business opportunities will have a major impact on 6G commercialization and business.
- The telecommunications industry has formulated its own specifications and standardization (such as 2G, 3G, 4G and 5G). It is unclear whether 6G will be able to incorporate external opinions, extending the start provided by some other industries' participation in developing 5G standards.
- Some 6G technologies, such as THz wireless, may not prove to be technically viable or cost-effective for most cellular users' needs.

User Recommendations

- Monitor discussion of the currently emerging 6G carefully.
- Prepare early trials and proofs of concept (POCs) in the late 2020s with vendors to learn more about the capabilities of 6G and early use cases, and begin building skill sets.
- Support your regulators and government to create their new national policy for 5G-Advanced and 6G. Technology innovation and strategy leaders should look at evolving 6G standards to get an early idea of future networking technologies.

Sample Vendors

Ericsson; Huawei; Nokia; NTT DOCOMO; Qualcomm; Samsung Electronics; SK Telecom

Gartner Recommended Reading

Emerging Tech Impact Radar: Communications

Postquantum Cryptography

Analysis By: Mark Horvath, Matthew Brisse

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Embryonic

Definition:

Postquantum cryptography (PQC), also called quantum-safe cryptography, are algorithms designed to secure against both classical and quantum-computing attacks. PQC will replace existing asymmetric encryption, which will weaken over the next decade, deprecating existing classical encryption methodologies and processes.

Why This Is Important

PQC offers organizations a higher level of cryptographic protection, which will remain strong as quantum computers enter the mainstream.

Existing asymmetric algorithms like Diffie-Hellman, RSA and ECC are vulnerable and will be unsafe to use by the end of the current decade, requiring replacement for common cryptographic functions, such as digital signatures, public key encryption and key exchanges.

Business Impact

PQC has the following impacts:

- With the advent of stronger quantum computers, existing asymmetric algorithms must be replaced with quantum-safe ones. This includes all network, file and data encryption, IAM, as well as any other uses of asymmetric cryptography.
- There are no drop-in alternatives for existing cryptographic algorithms, leading to discovery, categorization and reimplementation efforts.
- As new algorithms have different performance characteristics, current applications must be retested and, in some cases, rewritten.

Drivers

- Existing asymmetric encryption algorithms will become vulnerable to quantum decryption attacks by the end of the decade, potentially requiring reencryption of all data where the risk of exposure of the symmetric keys or tokens is considered important.
- Governments around the world are preparing and issuing mandates and legal frameworks requiring government agencies and enterprises to start devising PQC strategies. For example, in the U.S., Quantum Computing Cybersecurity bill requires owners and operators of national security systems and organizations supplying to the U.S. government to start using postquantum algorithms.
- “Harvest now and decrypt later” attacks are an ongoing concern, leading to the urgency to implement PQC security measures sooner rather than later.
- Secondary uses of new encryption (e.g., homomorphic encryption, stateful signatures, etc.) will offer new business opportunities beyond data protection.
- Once PQC is adopted by an organization, data should be secure for the foreseeable future.

Obstacles

- Most organizations don't know how cryptography functions within their organization, where keys and algorithms are used, or how secrets are stored and managed. Swapping them out for new algorithms will be challenging.
- Encrypted file sizes and digital signatures for new algorithms are typically much bigger than existing equivalents, necessitating hardware and network infrastructure improvements.
- New PQC algorithms will require new standards. The current set of PQC candidates' standards are expected to be released in late 2023 or early 2024, while fresh algorithm development will continue for the rest of the decade, affecting hardware, firmware, software and credentials used along with supported algorithms.
- Most vendors are typically unprepared when it's time to upgrade the cryptography and often require some pushing from their clients to recognize the demand.
- Some very important protocols lack built-in crypto-agility. For instance, no one is developing plans on how to incorporate new algorithms into WS-Security, which is used to safeguard SOAP APIs (a crucial type of API for all financial transactions).

User Recommendations

- Build a cryptographic metadata database of all in-use cryptographic algorithms.
- Develop crypto policies for easing the transition to new algorithms.
- Perform an exercise for data identifying the expected end-of-life targets in the short, medium and long-term time scales, and create a key life cycle policy to reflect risks to asymmetric and symmetric crypto keys.
- Create a transition phase plan identifying which algorithms are suitable for particular use cases.
- Implement transitional crypto policies for when algorithms should be replaced and which new algorithms should be used in each use case.
- Implement crypto-agile application development and stage to production after extensive testing.
- Vet and test new PQC algorithms to understand their characteristics and uses.
- Implement crypto-agility initiatives with an object-based approach to address future changes in PQC algorithm updates and replacement.
- Prioritize business impact potential when selecting potential PQC use cases.

Sample Vendors

Amazon; Google; IBM; ISARA; Microsoft; Qrypt; Quantum Xchange; SandboxAQ

Gartner Recommended Reading

Preparing for the Quantum World With Crypto-Agility

Emerging Tech: How to Make Money From Quantum Computing

Emerging Tech: Critical Insights on Quantum Computing

Infographic: How Use Cases Are Developed and Executed on a Quantum Computer

Quantum Computing as a Service

Analysis By: Chirag Dekate, Mark Horvath, Matthew Brisse

Benefit Rating: Moderate

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Quantum computing as a service (QCaaS) provides enterprises with access to quantum computing systems and associated services that enable them to explore enterprise-relevant use cases and devise quantum algorithms for highly specialized sets of problems. QCaaS provides vendors with access to their own technologies, and some cloud service providers offer QCaaS that supports access to various quantum computing implementations, vendors and solution approaches.

Why This Is Important

The torrid pace of innovation in quantum computing systems means that on-premises quantum systems are impractical for most users today, given their limited utility and rapid aging. QCaaS enables enterprises to derisk quantum strategies and leverage cloud services to access, test, validate and utilize diverse quantum technologies. QCaaS environments enable enterprises to focus on exploring a variety of use cases and devising quantum algorithms, as opposed to negative ROI, on-premises acquisitions.

Business Impact

Enterprises pioneering quantum initiatives are focusing on five key applications: optimization, simulation, search, linear systems and security-related use cases. QCaaS enables enterprises to explore different types of quantum systems and accelerate quantum skills development in a relatively low-risk environment. QCaaS continues to evolve in maturity. However, these environments are not ready for production use cases, primarily due to the limited scale of underlying quantum systems.

Drivers

- Many scientific problems are unsolvable using traditional computing technology. QCaaS offers access to quantum computing technologies for organizations pursuing solutions to computationally hard problems, without the risks and costs associated with dedicated systems that are likely to age faster, given the pace of innovation in the industry.
- Rather than acquiring expensive quantum systems on-premises, enterprises can minimize cost, complexity and time to value by using QCaaS-based quantum computing services.
- Some leading cloud service providers offer access to diverse quantum systems, simulators, resource estimators and high-performance computing (HPC) for hybrid workflows, simplify identity and data management and offer streamlined pricing across diverse quantum providers. In some cases, this approach can simplify exploration of quantum technologies and significantly lower risk.
- Continued scaling of underlying quantum computing systems and implicit advancement of the field (including scalable error correction schemes) is seminal to the evolution and eventual success of QCaaS.
- The ability to address the growing set of use cases beyond the traditional five — optimization, simulation, search, BQP and security — will be essential to create virtuous business cycles.

Obstacles

- A lack of ROI, limited applicability and the inability to demonstrate value creation are key business obstacles limiting enterprise investments in quantum.
- A lack of sufficient scale in underlying quantum computing systems powering QCaaS limits the scale of applications that can be explored or run. Current classical approaches deliver better, more impactful results than any quantum alternative.
- Quantum computing systems continue to be nascent in maturity, with more than half a dozen different ways of representing qubits and organizing systems to deliver error correction and scaling. Quantum technologies that now look promising may not be the ones that deliver value in the future.
- There remains a lack of skills to leverage QCaaS effectively, including the development of applications to fully exploit quantum computing capabilities.

User Recommendations

- Leverage QCaaS to devise quantum initiatives: Avoid acquiring on-premises quantum systems. The rapid pace of innovation in quantum technologies means that most on-premises systems will be obsolete faster, as newer systems and scalable technologies come online. QCaaS minimizes the risk associated with these dynamics.
- Select single-provider QCaaS for specialization and value creation: Direct QCaaS capabilities enabled by quantum vendors can provide highly specialized access to quantum systems, while derisking your strategies. Engage in this approach if your main goal is value creation and scaling.
- Select multiquantum system QCaaS for exploration and broader enterprise cloud strategy integration: Some CSPs offer access to multiple quantum providers, enabling enterprises to evaluate diverse technologies and simplified integration to existing cloud practices.

Sample Vendors

Google; IBM; Origin Quantum; Oxford Quantum Computing; PASQAL; Quandela; Quantinuum; Rigetti Computing; Xanadu

Gartner Recommended Reading

Cool Vendors in Quantum Computing

Infographic: How Use Cases Are Developed and Executed on a Quantum Computer

Preparing for the Quantum World With Crypto-Agility

Mobility Quantum Optimization

Analysis By: Pedro Pacheco

Benefit Rating: High

Market Penetration: Less than 1% of target audience

Maturity: Emerging

Definition:

Quantum computing (QC) is a type of nonclassical computing that operates on the quantum state of subatomic particles to address problems with vast combinatorial complexity. One of the many areas where quantum computing offers potential for polynomial improvement is optimization. In mobility, this capability can be used to optimize traffic, as well as highly complex operational ecosystems.

Why This Is Important

QC uses quantum mechanical principles, including superposition and entanglement, to effect extreme scale parallelism in computationally explosive problems. One of the early impact areas with potential for polynomial speedup is optimization where annealing algorithms have shown early promising results. Quantum systems designed to address optimization at scale have the potential to solve major transport optimization problems not addressed by classical computers.

Business Impact

The United Nations expects that 68% of the world's population will live in urban cities by 2050. Transit authorities have been looking to optimize urban mobility by improving routing and reducing commute times and traffic congestion while seeking a better quality of life for residents. Quantum systems designed to solve optimization problems at scale and specialized quantum-emulation classical technologies can potentially optimize the combined efficiency of transportation in a large ecosystem.

Drivers

Quantum computing has a strong potential in transportation as it allows companies to explore annealing-based solutions to problems that were previously seen as unsolvable or too time-consuming:

- QC's ability to model and forecast complex ecosystems, like traffic environment and urban planning, is a point of attraction for several organizations, as it could bring substantial improvements in increasing the efficiency with which people and goods are transported. Volkswagen has already started to test the technology in traffic optimization, using a QC from D-Wave. Ford is working with Microsoft on a use case that utilizes QC to optimize vehicle navigation route guidance. Besides making use of swarming effect information, the model uses QC to run frequent optimizations that take into consideration thousands of other vehicles on the road.

- Several transportation providers feature highly complex operations, like in the case of airlines or railway companies. Some of these companies see quantum annealing systems and classical quantum emulation alternatives as a tool that can unlock opportunities in terms of planning and running these operational processes, including running complex “what if” scenarios for better disruption preparedness. For instance, these are among the reasons why Delta Air Lines is partnering with IBM to explore quantum applications.

- Vehicle design also entails several processes of optimization, and some of them are already evaluating QC as a way to unlock significant additional improvements, be it in several parameters of vehicle performance or cost. As an example, Airbus launched the Quantum Computing Challenge back in 2019 as a way to accelerate cooperation with academia and startups in this area, with the aim of introducing QC for commercial applications.

Obstacles

The obstacles pertain to usage practicality and the complexity of using a computer in a totally different way for problem solving:

- **Decoherence.** QC is extremely sensitive to decoherence, a process where the surrounding environment (like magnetic and electric fields and heat sources) destabilizes qubits, leading to information loss and diverse results.

- **Shortage of QC programming skills.** QC programming languages are different from other existing languages, which entails the need to hire or train specific expertise.

- **Complexity of mapping business problems** and refactoring them into quantum applications. None of the existing classical applications and algorithms used in classical systems work in a quantum context.

- **Immaturity of the quantum ecosystems,** scale of systems and limited vendor maturity creates challenges in enterprise ability to develop sustainable optimization solution roadmaps.

User Recommendations

QC becomes more commercially accessible but is still in an early phase. Transportation CIOs must plan QC initiatives with a future mindset:

- Modernize optimization algorithms and leverage classical technologies, including accelerators and quantum emulation accelerators. Apply logical constraints to problems to optimize complexity.
- Identify inflection points where quantum alternatives become better than classical advantage. Most optimization problems may not need a quantum approach.
- Develop a long-term technology adoption plan focused on quantum ecosystem selection and choice. Roll out use cases in line with the evolution of QC technology. Focus on a five-year horizon to deploy real-time applications where calculation speed is essential.
- Set up a QC internal innovation and exploration team, with a strong executive sponsor, clear innovation processes and cross-functional support. Nurture QC expertise to achieve a major QC unit in the long run.
- Leverage QC-as-a-service providers as a start.

Sample Vendors

Alibaba Cloud; D-Wave; Fujitsu Group; Gurobi Optimization; IBM; Microsoft; NVIDIA; Rigetti Computing

Gartner Recommended Reading

Innovation Insight for Quantum Computing for the Automotive Industry

Quantum Computing Planning for Technology General Managers

Quantum Algorithms

Analysis By: Matthew Brisse, Chirag Dekate

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Quantum algorithms are a set of instructions that enable the utilization of quantum phenomena, including entanglement and superposition, to solve some mathematical problems faster than classical counterparts. Traditional classical algorithms cannot be used directly in quantum systems and have to be refactored into quantum algorithms. New quantum algorithms continue to be devised, enabling the expanded applicability of quantum systems.

Why This Is Important

- Top innovation areas for quantum algorithms include optimization; materials simulation; linear systems; partial differential equations; factorization and search; and quantum machine learning (QML).
- Researchers continue to devise new quantum algorithms with the potential to impact various industries, such as manufacturing, healthcare, pharmaceuticals, financial services, transportation, government and defense.
- Quantum algorithms are applicable in a narrow set of bounded-error quantum polynomial time (BQP) problems.

Business Impact

Quantum algorithms can solve certain problems that are beyond the capabilities of conventional classical technologies, such as:

- Supply chain and logistics optimization: Quantum algorithms can improve operational efficiencies and reduce costs.
- Realistic drug discovery with more efficient drugs and faster time to market.
- Improved Monte Carlo simulations for financial modeling and risk analysis.
- Improved machine learning (ML) innovations with augmented QML algorithms.

Drivers

Unlike classical systems, quantum algorithms have the potential to solve hard problems that take too long or are overly complex. They could revolutionize and transform entire industries, companies and initiatives by providing unprecedented advantages, such as bringing new products with faster time to market and improved efficiency. Also, quantum algorithms can break cryptography that introduces new quantum threats and vulnerabilities to an organization. Therefore, organizations must understand their current cryptography risk profile. Examples of quantum use cases include:

- Simon's Algorithm: One of the first computational problems to prove that quantum algorithms can solve a problem exponentially faster than a classical algorithm.
- Quadratic unconstrained binary optimization (QUBO): An optimization problem related to the Ising model used for binary object functions.
- Variational quantum eigensolver (VQE): A foundation algorithm that simulates molecules and chemical reactions. It can compute energies of Hamiltonians — that is, all the operations run by kinetic and potential energies of a system.
- Quantum approximate optimization algorithm (QAOA): Provides approximate solutions for combinatorial optimization problems, such as maximum-cut problems.
- Grover's search algorithm: A search algorithm used for unsorted databases of "n" entries in O(sqrt(n)) time.
- Shor's algorithm: It can discover prime factors of integers in polynomial time. It has the potential to break modern public-key cryptography.
- QML: It has multiple approaches, such as QML algorithms on quantum systems, classical algorithms inspired by quantum approaches and classical ML on quantum data.
- Stochastic series expansion (SSE): A widely used quantum Monte Carlo (QMC) method for simulating models of quantum many-body systems.

Obstacles

- The maturity of quantum hardware is hampering the development of quantum algorithms — although there are promising classes of quantum algorithms. Still, without being able to simulate their behavior on large problems, it is impossible to know how they will perform in practice and at scale.
- There are roughly 50 known quantum algorithms today. Academic and commercial algorithmic development is critical to developing future quantum use cases.
- Skilled and experienced quantum developers are in high demand, but they are hard to find.
- Quantum hardware limitation associated with decoherence limiting the execution time of the circuit can impact algorithmic width and depth to address a specific problem.
- Most quantum algorithms today are designed to address classical problems. In the future, innovative quantum algorithms could address new and currently unknown classes of quantum problems that are executed in fault-tolerant, large-scale quantum systems.

User Recommendations

- Capitalize on the capabilities of quantum computing as a service (QCaaS) — available across multiple vendors — to help with the creation, testing and tuning of quantum algorithms.
- Address the quantum skills gap by developing quantum algorithmic counterparts to classical algorithms — for example, optimization algorithms. Professionals with industry-specific quantum skill sets will continue to be in high demand.
- Work with academia, vendors and service providers to learn how quantum algorithms could address your computational pain points within your industry.

Sample Vendors

Google; IBM; Multiverse; Phasecraft; QC Ware; SandboxAQ; Strangeworks; Zapata Computing

Gartner Recommended Reading

Infographic: How Use Cases Are Developed and Executed on a Quantum Computer

Classical Quantum Simulators

Analysis By: Chirag Dekate, Matthew Brisse

Benefit Rating: Low

Market Penetration: Less than 1% of target audience

Maturity: Adolescent

Definition:

A classical quantum simulator (CQS) — also known as a quantum emulator or quantum simulator — is classical technology that simulates/emulates a quantum system, using graphics processing units (GPUs), field-programmable gate arrays (FPGAs), custom chips and emulation software. Quantum simulators support the design of quantum algorithms under idealized conditions (with artificial noise and error sources), offering a development environment for rapidly evolving quantum technologies.

Why This Is Important

The CQS is important because it enables researchers to analyze, simulate and predict the behavior of multiple complex quantum systems and problem sets with which it is difficult or impossible to generate results in today's noisy, intermediate-scale quantum (NISQ) systems. CQS is one of many tools that theoretically could be used to develop quantum algorithms, enabling researchers to test and tune quantum-simulated algorithms on quantum systems.

Business Impact

Organizations can experiment with CQS by leveraging open-source models and training, reducing upfront infrastructure commitment costs. CQS could be used in materials science and chemistry, where complex chemical interactions would benefit from quantum-realistic accuracy. Algorithmic development work on CQS systems will need to be refactored when migrating to quantum systems. In some cases, this will require a redesign of algorithms to take advantage of quantum-system-specific attributes.

Drivers

- The scale of noisy NISQ systems continues to be small and limited. CQS offers potential pathways for vendors and enterprises to explore systems design and algorithm design pathways.
- Leading technology vendors (e.g., NVIDIA and Intel) are creating software development kits (SDKs) that aid classical simulation of limited-scale quantum technologies.
- Cloud providers (e.g., Alibaba, Amazon, Baidu, Google, IBM, Microsoft, Oracle and Tencent) offer cloud-based NVIDIA GPU-accelerated CQS, simplifying ease-of-access challenges for enterprises and vendors.
- Key drivers of quantum simulators are the emerging standards bodies, such as the Quantum OpenSource Foundation (QOSF). The following eight items are examples.
- Microsoft QuArC LIQUi|> is a tool suite for quantum simulation, and QuSpin is an exact diagonalization and dynamics of arbitrary boson, fermion and spin many-body systems.
- IBM Qiskit Aer is a high-performance simulator for quantum circuits that include nose models.
- Intel Quantum Simulator is a distributed qubit register quantum simulator, using OpenMP and MPI.
- Quirk is a browser-based, drag-and-drop quantum circuit simulator that reacts, simulates and animates in real time.
- Rigetti’s QVM is a high-performance quantum virtual machine (VM).
- QuTiP is an efficient numerical simulation of a wide variety of pen quantum systems.
- Quantum++ is a high-performance, general-purpose quantum simulator that can simulate d-dimensional qubits.
- SQUANCH is a distributed simulation framework for quantum networks and channels.

Obstacles

- CQS is NOT a quantum technology. Given its many shortcomings and its nonquantum nature, CQS is likely an intermediate/transitory technology, and is not necessarily an area for high investment.
- The results generated using CQS are classical and not quantum, affecting the precision and speed that could be achieved in the emerging, larger-scale NISQ systems.
- CQS are limited in scalability, because, as you add qubits to scale, memory is doubled with each added qubit.
- There are no guarantees that today's CQS and associated algorithms will be portable across new quantum systems, when they become available.
- CQS often rely on accelerated instances, which can be expensive and require specialized equipment and skills.
- CQS are not 100% error-free; they can be subject to biases and algorithmic errors.

User Recommendations

- Evaluate CQS to simulate quantum algorithms on classical systems, especially if you do not have access to quantum systems. When you have access to quantum systems, use them over CQS environments.
- When investing in CQS initiatives, make sure to de risk for lack of interoperability across classical and quantum environments.
- Leverage CQS for skills development, especially when augmented with open-source quantum techniques. However, for practical use cases, focus on quantum computing alternatives instead.

Sample Vendors

Fujitsu; Google; IBM; Intel; Microsoft; NVIDIA; QCircuits; Rigetti Computing

Gartner Recommended Reading

Predicts 2021: Disruptive Potential During the Next Decade of Quantum Computing

Innovation Insight for Quantum Computing for the Automotive Industry

Quantum Computing as a Service in Drug Discovery

Analysis By: Michael Shanler, Reuben Harwood

Benefit Rating: High

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Quantum computing as a service (QCaaS) in drug discovery provides enterprises with access to quantum computing systems and associated services that enable them to explore use cases (such as molecular generation) and devise quantum algorithms for highly specialized sets of problems. QCaaS provides vendors with access to their own technologies, and some cloud service providers offer QCaaS that supports access to various quantum computing implementations, vendors and solution approaches.

Why This Is Important

QCaaS is a type of nonclassical computing that operates on the quantum state of subatomic particles. The particles represent information as elements denoted as quantum bits (qubits). A qubit can represent all possible values of its two dimensions (superposition) until read. Quantum algorithms manipulate linked qubits in their entangled state, and quickly address vast combinatorial complexity — especially in the drug discovery space because creating and managing QC hardware itself is still a significant cost and technical barrier.

Business Impact

Today, QCaaS has an impact on biomolecular optimization, genomics analysis, machine learning for pathway analysis, drug discovery, and organic chemistry and synthesis. QCaaS is accelerating in-silico activities and reducing timelines in drug discovery. R&D leaders will be able to augment and potentially replace screening efforts and work at the lab bench, especially as more QCaaS hits the market. This impacts key drug research partnerships and helps augment drug pipelines.

Drivers

- R&D teams are under immense pressure to deliver new molecular leads and refine offerings in their portfolios. Only recently has QCaaS for drug discovery become available through new software vendors, consultants and biotechnology companies. Once the technology has evolved and stabilized, Gartner expects QC to provide a high-value tool, handling the more complex computational challenges in drug discovery.
- Scientists' expectations of QC capabilities will rapidly increase as new vendors get involved in drug discovery. Conventional silicon computation speed has been handicapped over the past 10 years as silicon chip engineers have reached the upper limit. QCaaS provides a tantalizing alternative, boosting certain types of computational operations that are much faster than conventional designs.
- We see an increase in QC staff training. Initial QC-knowledgeable personnel are already becoming managers attempting to drive competitive differentiation through the application of this technology.
- Sponsor clients running discovery programs are increasingly engaging science-as-a-service companies and in-silico contract research organizations (CROs).
- The promise of QCaaS for drug discovery continues to drive proofs of concept (POCs) and collaborations with pharma and technology companies, such as Bayer's investment with Google and Moderna's collaboration with IBM.
- While we do not expect QC hardware in life science to reach the mainstream for well over 10 years, QCaaS and specifically its usage in drug discovery are accelerating. Life science companies will adopt this technology faster than most other industries. Although the technology is still in the Innovation Trigger phase, it is ascending to peak hype in the next few years.

Obstacles

- While QC itself is near peak hype, it is poorly understood and supported in the market. While we see advancements in quantum algorithmic development on the horizon, adoption will take time.
- QCaaS adoption within the life science industry is outpacing most other industries, but clients are moving quickly with POCs and have unrealistic expectations about exactly how much can be delivered via QCaaS partners.
- While many clients report successful pilots for QCaaS projects, the ones with less technical teams and staff are less confident in the ability to sustain financial justifications and move POCs into production with the proper POC gates (scientific, technologic, economic).
- While a handful of large pharmaceutical companies have sponsored quantum projects (e.g., Biogen worked with 1QBit and Accenture for quantum-enabled molecular comparisons in 2017), results remain unproven for more than a handful of molecular leads.
- Organizations do not yet have dedicated scientific informatics disciplines nor prepackaged workflows, upping the sticker price for investments due to extensive consultancy and partnering fees.

User Recommendations

- Start limited pilots today for QCaaS in drug discovery to develop the skills and refine the strategy required for a longer-term program.
- Evaluate if QCaaS is a good fit for these application areas: binding site prediction, high-content imaging, antibody design and research, catalyst research, molecular generation, affinity calculations, quantitative structure-activity relationship (QSAR), screening, docking programs, predictive spectra, quantum mechanics, molecular dynamics, protein structure design and predictions, molecular-molecule interactions, large molecule dynamics, and material and formulation design.
- Evaluate the benefits of using a general QCaaS provider that will require extra consulting and services to implement (such as those provided by D-Wave, Honeywell, IBM, IonQ, Microsoft, QCI and Rigetti Computing) versus the more focused QCaaS companies that have life science domain expertise and applications.

- Follow existing consortiums and projects for inspiration, such as the Novo Nordisk Foundation's $200M investment.

Sample Vendors

ApexQubit; ChemAlive; Cloud Pharmaceuticals; PharmCADD; POLARISqb; ProteinQure; Riverlane; Silicon Therapeutics; Xanadu; XtalPi

Gartner Recommended Reading

Emerging Tech: Top Use Cases for Quantum Computing

Infographic: How Use Cases Are Developed and Executed on a Quantum Computer

Quick Answer: How Is AI Being Used in Preclinical Drug Development?

At the Peak

Quantum Key Distribution

Analysis By: Mark Horvath, Brian Lowans

Benefit Rating: Low

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Quantum key distribution (QKD) is a tamper-evident communication method that implements a cryptographic protocol for transporting keys based on quantum mechanics. It enables two parties to produce a shared secret known only to them, which then can be used to encrypt and decrypt messages. These keys are created and exchanged in such a way that the system can detect the interference of any third party trying to gain knowledge of the key, and terminate the link.

Why This Is Important

QKD is an important, early-stage technology for creating, moving and preserving the entanglement of two or more quantum particles. QKD claims to provide a tamper-evident channel for data exchange by maintaining the quantum entanglement of particles (usually photons) as they transfer data (e.g., keys) between systems. The nature of entanglement is such that any disturbance will result in automatic channel collapse, destroying the key and preventing the transmission of further data.

Business Impact

- QKD's main property, tamper evidence, is needed by companies that need to exchange high-value encryption keys in as secure a way as possible.
- QKD provides a demonstrably secure channel that allows high-value data to be transmitted without compromising the integrity of the data.
- A quantum random number generator (QRND) can generate cryptographically better keys than classical sources of entropy.
- Governments and military departments have a need for extremely secure methods of key exchange, which are becoming increasingly commercialized.

Drivers

- As quantum computers become more realistic, organizations are looking to move to "quantum-safe" technologies, sparking renewed interest in QKD.
- QKD is a crucial, foundational technology for quantum networks and quantum information science.
- QKD is the foundational technology for the next generation of secure satellite-based networking.

Obstacles

- While QKD is sometimes advertised as "quantum safe," keys or other data transmitted through a QKD channel will then rely upon traditional key management life cycle technologies.
- QKD is a channel with relatively low bandwidth, when compared to classical cryptographic channels like Transport Layer Security (TLS).
- Currently, QKD channels cannot be boosted and cannot use repeaters without breaking the entanglement, making large scale routing difficult. The technology is currently limited to a few hundred kilometers when routed through existing fiber optics.
- Existing classical systems for key exchange typically provide a high enough level of trust for most purposes, especially when using quantum-safe cryptographic keys.

User Recommendations

Security and risk management leaders evaluating QKD should:

- Evaluate if QKD is needed as part of their plan for moving to postquantum networking.
- Identify high-value or sensitive data that could benefit from tamper-evident key exchange.

Sample Vendors

AUREA Technology; ID Quantique; iXblue; MagiQ Technologies; Qasky; QNu Labs; QuantumCTek; Thorlabs; Toshiba

Gartner Recommended Reading

Neuromorphic Computing

Analysis By: Alan Priestley

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Neuromorphic computing is a technology that provides a mechanism to more accurately model the operation of a biological brain using digital or analog processing techniques. These designs typically use spiking neural networks (SNNs), rather than the deep neural networks (DNNs) of the current generations of AI technologies, feature non-von Neumann architectures and are characterized by simple processing elements, but very high interconnectivity.

Why This Is Important

Currently, most AI development leverages parallel processing designs based on GPUs. These are high-performance, but high-power-consuming, devices that are not applicable in many deployments. Neuromorphic computing utilizes asynchronous, event-based designs that have the potential to offer extremely low power operation. This makes them uniquely suitable for edge and endpoint devices, where their ability to support object and pattern recognition can enable image, audio and sensor analytics.

Business Impact

AI techniques are rapidly evolving, enabled by radically new computing designs.

- Today’s deep neural network (DNN) algorithms require the use of high-performance processing devices and vast amounts of data to train these systems, limiting scope of deployment.
- Neuromorphic computing designs can be implemented using low-power devices, bringing the potential to drive the reach of AI techniques out to the edge of the network, accelerating key tasks such as image and sound recognition.

Drivers

- Different design approaches are being taken to implement neuromorphic computing designs — large-scale devices for use in data centers, and smaller-scale devices for edge computing and endpoint designs. Both these paths leverage spiking neural networks (SNNs) to implement asynchronous designs that have the benefit of being extremely low power when compared with current DNN-based designs.
- Semiconductor vendors are developing chips that utilize SNNs to implement AI-based solutions.
- Neuromorphic computing architectures have the potential to deliver extreme performance for use cases such as DNNs and signal analysis at very low power.
- Neuromorphic systems can be trained using smaller datasets than DNNs, with the potential of in situ training.

Obstacles

- Accessibility: GPUs are more accessible and easier to program than neuromorphic computing. However, this could change when neuromorphic computing and the supporting ecosystems mature.
- Knowledge gaps: Programming neuromorphic computing will require new programming models, tools and training methodologies.
- Scalability: The complexity of interconnection challenges the ability of semiconductor manufacturers to create viable neuromorphic devices.
- Integration: Significant advances in architecture and implementation are required to compete with other DNN-based architectures. Rapid developments in DNN architectures may slow advances in neuromorphic computing, but there are likely to be major leaps forward in the next decade.

User Recommendations

- Prepare for future utilization as neuromorphic architectures have the potential to become viable over the next five years.
- Create a roadmap plan by identifying key applications that could benefit from neuromorphic computing.
- Partner with key industry leaders in neuromorphic computing to develop proof-of-concept projects.
- Identify new skill sets required to be nurtured for successful development of neuromorphic initiatives, and establish a set of business outcomes/expected value to set management's long-term expectations.

Sample Vendors

AnotherBrain; Applied Brain Research; BrainChip; GrAi Matter Labs; Intel; Natural Intelligence; SynSense

Gartner Recommended Reading

Emerging Technologies: Tech Innovators in Neuromorphic Computing

Emerging Technologies: Top Use Cases for Neuromorphic Computing

Forecast: AI Semiconductors, Worldwide, 2021-2027

Emerging Tech Impact Radar: Artificial Intelligence

Optical Satellite Connectivity

Analysis By: Nick Jones

Benefit Rating: High

Market Penetration: Less than 1% of target audience

Maturity: Emerging

Definition:

Optical satellite connectivity uses lasers to provide high-speed data links between satellites and from satellites to the Earth — and vice versa. It provides higher bandwidth and better immunity to interception than radio frequency (RF) systems.

Why This Is Important

Low Earth orbit (LEO) satellite applications, such as broadband communications or Earth observation, involve transmitting very large amounts of data. Optical links are attractive because they are unregulated and provide higher bandwidth than RF communications. Optical links will be used between satellites and from satellites to Earth, providing improved performance and greater operational flexibility.

Business Impact

Most organizations will use optical satellite connectivity as a side effect of buying other services, such as satellite broadband and Earth observation. Optical satellite connectivity can improve the performance of such services and, in some cases, reduce response times — for example, in situations where large amounts of data must be downlinked from a satellite. In the future, organizations launching private satellites may need to specify optical links to complement wireless communications.

Drivers

- Better performance than RF communications: In 2023, speeds exceeding 200 Gbps have been demonstrated and terabit links are now expected.
- More difficult to observe or intercept than radio communications.
- Optical links to and from the Earth are typically unregulated and not constrained by radio spectrum allocations or frequency congestion.
- Optical links between satellites of the same constellation improve resilience and operational flexibility by providing more communication paths that allow satellites to access a wider range of ground stations.
- Optical links are faster than terrestrial fiber links. Therefore, routing via an orbital mesh to a ground station close to the end user could significantly reduce latency in some situations.

Obstacles

- Optical links may be impacted by weather conditions.
- Optical satellite connectivity is immature and still the subject of academic and industry research.
- Lack of standards and interoperability.
- Ground station equipment is complex, physically large and expensive. It's unsuitable for individual users or small organizations.

User Recommendations

- Favor satellite service providers with optical capabilities when buying services, such as Earth observation or satellite broadband. They are likely to be able to provide services with better performance or resiliency.
- Organizations that own high-capacity conventional ground stations in 2023 should monitor optical technologies to determine when to augment them with optical capabilities.

Gartner Recommended Reading

LEO Satellites Will Be an Essential Part of Your Future Networking Strategy

Quantum Sensing

Analysis By: Matthew Brisse

Benefit Rating: Transformational

Market Penetration: 1% to 5% of target audience

Maturity: Adolescent

Definition:

Quantum sensors are a class of measurement devices that exhibit extreme sensitivity and linearity by harnessing quantum effects. This means they can detect changes in the environment at a quantum level. Quantum sensors are capable of providing highly accurate information, which helps this technology gain traction. Examples include accelerometers, gyroscopes, gravimeters, magnetometers and random number generators.

Why This Is Important

- Quantum sensing operates at the atomic level, enabling improved sensitivity and precision in fields such as medical and healthcare, industrial applications, aerospace and defense applications, and enhancing positioning capabilities in autonomous cars.
- Quantum sensors improve GPS-denied navigation with low-drift hybrid atomic accelerometers to enhance earth observation with low-drift atomic gravimeters/gradiometers.

Business Impact

- Quantum sensors are capable of providing highly accurate information, and some can sustain in extreme climatic conditions, enabling applicability in diverse defense and industrial use cases.
- Although not a new technology, quantum sensing is still nascent, and is maturing slowly.
- Quantum sensing could affect use cases from climate change to robotics to cybersecurity.
- Single-function quantum-sensors provide a use-case-specific advantage.

Drivers

- The need for quantum sensing to provide increased accuracy and precise measurements is driving demand from a number of industries.
- Quantum sensing often offers alternative approaches to classical sensing approaches, enabling increased accuracy and quantum-based measurements with exacting precision.
- For some applications, we have reached the limit where classical implementations can no longer support the environmental conditions or accuracy demands.
- Increased sensitivity and performance of measurements enable faster, more accurate decisions to radical changes in information accumulation, leading to faster response times.
- Food safety analysis — Quantum-based sensing technologies are used in the detection of food contaminants, including pathogens, pesticides, toxic elements, antibiotic and metal contaminants.
- Environmental monitoring — Quantum-enhanced sensors are ideal candidates for environmental pollution monitoring in a precise, authentic, real-time and sensitive manner.
- Communications receiver — Rydberg-atoms-based quantum sensing offers higher sensitivity and can detect the entire radio frequency spectrum, from 0 to 100 GHz, enabling the detection of RF signals for geolocation.

Obstacles

- Quantum sensing is still six to eight years out from becoming mainstream because few vendors are getting quantum sensors to commercial production for each application.
- Quantum-sensing obstacles include development cost, customer adoption and scaling.
- Technical obstacles include environmental noise reduction, ever-increasing sensitivity requirements and postdeployment calibration.
- Most sensors are single-function, one-off designed to address a specific use case. This limits scale, which increases costs.
- There is a limited range of quantum sensors available on the market today.
- There are increased security and regulatory concerns due to espionage or other privacy issues.
- Limited skills and expertise in the field are also key obstacles.

User Recommendations

- Focus on business value, but expect results to be at least five years out, by identifying break-even profitability points for quantum-sensing implementations.
- Perform a gap analysis to see if you can possibly take advantage of quantum sensing by seeking out accuracy and or precision improvements.
- Address the quantum skills gap. Individuals with industry-specific quantum skill sets are in high demand.
- Research and experiment with new quantum-sensing approaches to augment or replace classical approaches.
- Leverage the academic and commercial sectors to learn how quantum sensing could possibly address specific sensing needs.

Sample Vendors

ADVA; AOSense; Apogee Instruments; LI-COR Biosciences; Q-CTRL; Rydberg Technologies; Skye Instruments; Solar Light

Gartner Recommended Reading

Emerging Tech Impact Radar: Sensing Technologies and Applications

Infographic: How Use Cases Are Developed and Executed on a Quantum Computer

Predicts 2021: Disruptive Potential During the Next Decade of Quantum Computing

Innovation Insight for Quantum Computing for the Automotive Industry

4 Advanced Computing Algorithms That Lead to Next-Generation Profits

Smart Robots

Analysis By: Annette Jump

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

A smart robot is an AI-powered, often-mobile machine designed to autonomously execute one or more physical tasks. These tasks may rely on, or generate, machine learning, which can be incorporated into future activities or support unprecedented conditions. Smart robots can be split into different types based on the tasks/use cases, such as personal, logistics and industrial.

Why This Is Important

Smart robotics is an AI use case, while robotics in general does not imply AI. Smart (physical) robots had less adoption compared with industrial counterparts but received great hype in the marketplace; therefore, smart robots are still climbing the Peak of Inflated Expectations. There has been an increased interest in smart robots in the last 12 months, as companies are looking to further improve logistic operations, support automation and augment humans in various jobs.

Business Impact

Smart robots will make their initial business impact across a wide spectrum of asset-, product- and service-centric industries. Their ability to reduce physical risk to humans, as well as do work with greater reliability, lower costs and higher productivity, is common across these industries. Smart robots are already being deployed among humans to work in logistics, warehousing, police as well as safety applications.

Drivers

- The market is becoming more dynamic with technical developments of the last two years, enabling a host of new use cases that have changed how smart robots are perceived and how they can deliver value.

- The physical building blocks of smart robots (motors, actuators, chassis and wheels) have incrementally improved over time. However, areas such as Internet of Things (IoT) integration, edge AI and conversational capabilities have seen fundamental breakthroughs. This changes the paradigm for robot deployments.

- Vendor specialization has increased, leading to solutions that have higher business value, since an all-purpose/multipurpose device is either not possible or is less valuable.

- Growing interest in smart robots across a broad number of industries and use cases like: medical/healthcare (patient care, medical materials handling, interdepartment deliveries and sanitization); manufacturing (product assembly, stock replenishment, support of remote operations and quality control [QC] check); last-mile delivery; inspection of industrial objects or equipment; agriculture (harvesting and processing crops); and workplace and concierge robots in workplaces, hospitality, hospitals and so forth.

Obstacles

- **Companies are still struggling to identify valuable business use cases and assess ROI** for robots, especially outside of manufacturing and transportation. Therefore, the position of "smart robots" is still climbing to the Peak of Inflated Expectations.
- **Hype and expectations will continue to build around smart robots during the next few years**, as providers expand their offerings and explore new technologies, like reinforcement learning to drive a continuous loop of learning for robots and swarm management.
- **Lack of ubiquitous wireless connectivity solutions outside of smart spaces and immaturity of edge AI technologies** can inhibit the pace at which smart robots become semiautomated and mobile.
- **The need to offload computation to the cloud** will decrease from 2024, as robots will make more autonomous decisions.
- **The continuous evolution of pricing models**, like buy, monthly lease or hourly charge versus robot as a service for robotic solutions can create some uncertainty for organizations.

User Recommendations

- Evaluate smart robots as both substitutes and complements to their human workforce in manufacturing, distribution, logistics, retail, healthcare or defense.
- Begin pilots designed to assess product capability and quantify benefits, especially as ROI is possible even with small-scale deployments.
- Examine current business processes for current deployment of smart robots and also for large-scale deployment over the next three to five years.
- Consider different purchase models for smart robots.
- Dissolve the reluctance from staff by developing training resources to introduce robots alongside humans as an assistant.
- Ensure there are sufficient cloud computing resources to support high-speed and low-latency connectivity in the next two years.
- Evaluate multiple global and regional providers due to fragmentation within the robot landscape.

Sample Vendors

Ava Robotics; Geek+; GreyOrange; iRobot; Locus Robotics; Rethink Robotics; SoftBank Robotics; Symbotic; Temi; UBTECH

Gartner Recommended Reading

Emerging Technologies: Top Use Cases for Smart Robots to Lead the Way in Human Augmentation

Emerging Technologies: Top Use Cases Where Robots Interact Directly With Humans

Emerging Technologies: Venture Capital Growth Insights for Robots, 2021

Emerging Technologies: Smart Robot Adoption Generates Diverse Business Value

Generative AI

Analysis By: Svetlana Sicular, Brian Burke

Benefit Rating: Transformational

Market Penetration: 1% to 5% of target audience

Maturity: Adolescent

Definition:

Generative AI technologies can generate new derived versions of content, strategies, designs and methods by learning from large repositories of original source content. Generative AI has profound business impacts, including on content discovery, creation, authenticity and regulations; automation of human work; and customer and employee experiences.

Why This Is Important

Generative AI exploration is accelerating, thanks to the popularity of Stable Diffusion, Midjourney, ChatGPT and large language models. End-user organizations in most industries aggressively experiment with generative AI. Technology vendors form generative AI groups to prioritize delivery of generative-AI-enabled applications and tools. Numerous startups have emerged in 2023 to innovate with generative AI, and we expect this to grow. Some governments are evaluating the impacts of generative AI and preparing to introduce regulations.

Business Impact

Most technology products and services will incorporate generative AI capabilities in the next 12 months, introducing conversational ways of creating and communicating with technologies, leading to their democratization. Generative AI will progress rapidly in industry verticals, scientific discovery and technology commercialization. Sadly, it will also become a security and societal threat when used for nefarious purposes. Responsible AI, trust and security will be necessary for safe exploitation of generative AI.

Drivers

- The hype around generative AI is accelerating. Currently, ChatGPT is the most hyped technology. It relies on generative foundation models, also called “transformers.”
- New foundation models and their new versions, sizes and capabilities are rapidly coming to market. Transformers keep making an impact on language, images, molecular design and computer code generation. They can combine concepts, attributes and styles, creating original images, video and art from a text description or translating audio to different voices and languages.
- Generative adversarial networks, variational autoencoders, autoregressive models and zero-/one-/few-shot learning have been rapidly improving generative modeling while reducing the need for training data.
- Machine learning (ML) and natural language processing platforms are adding generative AI capabilities for reusability of generative models, making them accessible to AI teams.
- Industry applications of generative AI are growing. In healthcare, generative AI creates medical images that depict disease development. In consumer goods, it generates catalogs. In e-commerce, it helps customers “try on” makeup and outfits. In manufacturing, quality inspection uses synthetic data. In semiconductors, generative AI accelerates chip design. Life sciences companies apply generative AI to speed up drug development. Generative AI helps innovate product development through digital twins. It helps create new materials targeting specific properties to optimize catalysts, agrochemicals, fragrances and flavors.
- Generative AI reaches creative work in marketing, design, music, architecture and content. Content creation and improvement in text, images, video and sound enable personalized copywriting, noise cancellation and visual effects in videoconferencing.
- Synthetic data draws enterprises’ attention by helping to augment scarce data, mitigate bias or preserve data privacy. It boosts the accuracy of brain tumor surgery.
- Generative AI will disrupt software coding. Combined with development automation techniques, it can automate up to 30% of the programmers’ work.

Obstacles

- Democratization of generative AI uncovers new ethical and societal concerns. Government regulations may hinder generative AI research. Governments are currently soliciting input on AI safety measures.
- Hallucinations, factual errors, bias, a black-box nature and inexperience with a full AI life cycle preclude the use of generative AI for critical use cases.
- Reproducing generative AI results and finding references for information produced by general-purpose LLMs will be challenging in the near term.
- Low awareness of generative AI among security professionals causes incidents that could undermine generative AI adoption.
- Some vendors will use generative AI terminology to sell subpar “generative AI” solutions.
- Generative AI can be used for many nefarious purposes. Full and accurate detection of generated content, such as deepfakes, will remain challenging or impossible.
- The compute resources for training large, general-purpose foundation models are heavy and not affordable to most enterprises.
- Sustainability concerns about high energy consumption for training generative models are rising.

User Recommendations

- Identify initial use cases where you can improve your solutions with generative AI by relying on purchased capabilities or partnering with specialists. Consult vendor roadmaps to avoid developing similar solutions in-house.
- Pilot ML-powered coding assistants, with an eye toward fast rollouts, to maximize developer productivity.
- Use synthetic data to accelerate the development cycle and lessen regulatory concerns.
- Quantify the advantages and limitations of generative AI. Supply generative AI guidelines, as it requires skills, funds and caution. Weigh technical capabilities with ethical factors. Beware of subpar offerings that exploit the current hype.
- Mitigate generative AI risks by working with legal, security and fraud experts. Technical, institutional and political interventions will be necessary to fight AI's adversarial impacts. Start with data security guidelines.
- Optimize the cost and efficiency of AI solutions by employing composite AI approaches to combine generative AI with other AI techniques.

Sample Vendors

Adobe; Amazon; Anthropic; Google; Grammarly; Hugging Face; Huma.AI; Microsoft; OpenAI; Schrödinger

Gartner Recommended Reading

Innovation Insight for Generative AI

Emerging Tech Roundup: ChatGPT Hype Fuels Urgency for Advancing Conversational AI and Generative AI

Emerging Tech: Venture Capital Growth Insights for Generative AI

Emerging Tech: Generative AI Needs Focus on Accuracy and Veracity to Ensure Widespread B2B Adoption

ChatGPT Research Highlights

Swarming Robotics

Analysis By: Ivar Berntz

Benefit Rating: Moderate

Market Penetration: 1% to 5% of target audience

Maturity: Emerging

Definition:

Swarming robotics is an approach to physically and behaviorally control a set of communicating robots — for example, drones — to jointly accomplish a mission while responding to a changing environment. This enables self-propelled individual robots to move as a group and modify their movements to attain the goal of coverage or exploration of an area or situation.

Why This Is Important

A robot swarm operates as a single entity, despite the parts being physically separated. Charged with a mission, a swarm may consist of several homogeneous, low-cost robots working together. The loss of any individual robot should have minimal impact on overall performance. Simple examples include multiple wheels working together to move a large object, or drones creating a coordinated light show, while more complex tasks include mapping a building or searching a disaster zone.

Business Impact

System-directed multirobots and automated guided vehicles (AGVs), like those utilized in warehouses, are increasingly in use. Swarming goes one step further, by mimicking the behavior of social insects, using individual robots with communication and sensing capabilities, but without centrally curated algorithms and systems. This has potential applications in many industries, such as construction, healthcare, agriculture and space exploration.

Drivers

Robots are becoming more ubiquitous, smaller, cheaper and more capable, making the number of use cases for swarming grow even more. This brings this innovation closer to the Peak of Inflated Expectations.

- Standardization, size, simplification, improvements in software, algorithms and scale economies will continue to drive robot prices down for the foreseeable future.
- To also help drive prices down, some companies are starting to use key sensors (accelerometer, gyroscope, GNSS) from popular, less expensive, mobile phone components.
- A swarm of cooperating robots gains a number of characteristics that are not found in individual robots. They can divide a workload, respond to risks, and even create complex structures in response to changes in the environment or perform difficult tasks unreachable for individual robots.
- One very specific experiment in transportation found swarms to be five times more efficient than individual robots (see Molecular Robots Work Cooperatively in Swarms, ScienceDaily).
- Having robots that become more efficient over time helps companies meet demands for faster delivery, as well as reducing labor costs and human error.

Obstacles

- Technological advances, like simultaneous localization and mapping (SLAM), already enable robots to move in unstructured environments, like factory floors.
- Robot prices can be high, as the sensors, cameras, motors and other parts are expensive and not created for robots, but adapted from other applications, requiring extensive integration.
- There is a lack of interoperability between vendors and readily available coordination algorithms and applications to allow robots to solve a problem on their own.
- For swarming, robots must communicate wirelessly with each other directly, using robust and resilient protocols, but trade-offs between communication methods, battery life and reach limit applicability.
- While swarming behaviors have been established in macroscale system-directed robots, it has remained a challenge in smaller, cheaper robots, largely due to the size of sensors and actuators.
- Most experiments require a homogeneous robot landscape, with little to no room for specialization.

User Recommendations

- **Do the math:** Focus on areas with the highest potential for improvement as emerging technologies lack standardization and vendors are still learning and mergers or bankruptcies can impact your plans.
- **Go for gradual testing, piloting and rollout:** Start with simpler implementations as big-bang approaches can be overwhelming due to complexity, cost and operational risks.
- **Design for human intervention and override:** Think of situations where the self-controlled environments do not function as planned. Having human interventions and overrides will also enhance the system's trustworthiness.
- **Play it safe:** Run pilots in controlled environments. Challenges pertaining to the collaborative aspects of different systems need to be identified early on to reduce the risks and uncertainties during actual deployments.
- **Design for security:** As machines and processes become more connected, they will inevitably be exposed to vulnerabilities and can pose a significant threat to critical industrial infrastructure.

Sample Vendors

Apium; DJI; Geek+; Raytheon Technologies; Siemens

Gartner Recommended Reading

Maverick Research: Biomimicry: How Honeybees Can Inspire Future Supply Chain Design

Emerging Technologies: AI Roadmap for Smart Robots — Journey to a Super Intelligent Humanoid Robot

Emerging Tech Impact Radar: Smart Robots and Drones

LEO Satellite IoT

Analysis By: Bill Ray

Benefit Rating: Moderate

Market Penetration: 5% to 20% of target audience

Maturity: Adolescent

Definition:

Low Earth orbit (LEO) satellites offer low-power communications with a global footprint, being able to collect short data bursts from Internet of Things (IoT) endpoints for tracking locations or environmental monitoring. Data is generally in the form of short messages made available through a cloud service, but battery life may be five years or more and data costs are comparable with terrestrial low-power wide-area (LPWA) networks.

Why This Is Important

International IoT projects have been hampered by terrestrial IoT networks operating on different frequencies, and require negotiated roaming agreements between different carriers. Coverage is also limited, while asset tracking and environmental monitoring are often required across very rural areas. Satellite services can provide global tracking, and the 3rd Generation Partnership Project (3GPP) is working toward integrating satellite connectivity into its IoT connectivity standards.

Business Impact

Being able to track anything, anywhere, has immediate implications on supply chain management and visibility. Fleet operators can improve efficiency, while remotely monitoring temperature and other shipping conditions. Remote monitoring of wide-scale projects, such as construction and mining projects, water seepage in dams or pipeline conditions, is made possible (and economically viable) through low-power satellite communications.

Drivers

- Enterprises are seeking greater visibility of supply chains and operations, which isn't available from terrestrial networks.
- The growth of digital twins, and the value of preventative maintenance, is increasing demand for real-time (or near-real-time) monitoring of remote assets.
- Technical innovations (largely from the smartphone industry) have reduced the cost of satellite development and deployment.
- The development of successful services has proved the technical viability, encouraging new entrants and business models.
- Wide-area monitoring of environmental change, particularly in remote regions, is increasingly important as governments are prioritizing environmental spending.

Obstacles

- Satellite services often require line of sight, or near line of sight, which can limit applications to outdoor use cases.
- The quantity of new entrants anticipates a period of disruption, and consolidation, which could leave some customers disconnected as vendors restructure or collapse.
- Competitive pressure is driving down the cost of terrestrial IoT connectivity, making satellite service comparatively more expensive (if still comparable).
- Few services are truly global, with regulator licensing and radio spectrum access still proving barriers to ubiquitous service.

User Recommendations

- Complement IoT connectivity services by including satellite communication as a global network option in IoT deployments, particularly in supply chain management and industries such as agriculture, energy and maritime, where terrestrial coverage is limited.
- Consider how hybrid solutions may be applicable in mobile applications, where standards such as LoRa and/or NB-IoT may enable roaming between satellite and terrestrial services.
- Identify projects where gateway solutions may provide an additional option, using a satellite to backhaul local endpoints equipped with LPWA network technologies via a hub.

Sample Vendors

Iridium Communications; Myriota; Swarm

Quantum Computing

Analysis By: Chirag Dekate, Matthew Brisse

Benefit Rating: Transformational

Market Penetration: Less than 1% of target audience

Maturity: Embryonic

Definition:

Quantum computing is a type of nonclassical computing that operates on the quantum state of subatomic particles. These particles represent information as elements denoted as quantum bits (qubits). Qubits can be linked with other qubits, a property known as entanglement. Quantum algorithms manipulate linked qubits in their entangled state, a process that addresses problems with vast combinatorial complexity.

Why This Is Important

Quantum computing will not displace conventional computers. However, it will disrupt areas such as some classes of BQP (bounded-error, quantum, polynomial time) problem, quantum realistic simulations (used in material science, chemical simulations and drug discovery) and cryptography (security), where it will deliver results beyond what is feasible using classical techniques. Quantum computing could also advance the speed and/or quality of machine learning and optimization solutions.

Business Impact

With minimal investment required to investigate a broad range of quantum use cases, the potential rewards hugely outweigh the risks. Multiple use cases, such as optimization, run optimally on quantum computing system architectures. Also, the growing maturity of quantum ecosystems enables organizations to choose from a variety of quantum computing as a service (QCaaS) offerings. Enterprises need to plan for four key areas of impact: optimization, simulation, BQP and security.

Drivers

- Significant investments by governments, major corporations and startups amount, in aggregate, to more than $2 billion yearly.
- Enterprise and academic research teams have produced promising results for diverse use cases, including optimization and materials simulation, using current-generation noisy intermediate-scale quantum (NISQ) systems.
- Demonstrations of foundational quantum technology using electrons, ions, cold/neutral/helium atoms and photons are resulting in potential pathways to scalable quantum computing.
- The scale of superconducting gate-based quantum systems continues to increase, with some quantum computing vendors developing systems that scale to hundreds of qubits.
- Error correction algorithms and new methods such as error mitigation and error suppression are in development. These promise to make NISQ systems more usable.
- Managed service providers, including boutique quantum services companies, are partnering with enterprises to identify use cases and develop quantum algorithms.

Obstacles

- With few use cases guaranteeing an ROI, enterprises might deprioritize investments in quantum computing.
- Current, limited-scale qubit technology is too noisy and delivers returns of limited value.
- Standardization is lacking across programming, middleware and ecosystems.
- The market is highly fragmented, with over 600 startups operating in high-risk macroconditions. This exposes enterprises to innovation risk.
- Although small numbers of qubits can represent large amounts of data, quantum computers cannot convert large amounts of data to a quantum state, due to quantum RAM's immaturity.
- Unlike computing-on-silicon technology, there is no single physical computing stratum for quantum computing, and it is not possible to mix platforms at the quantum level. This results in a highly diverse range of potential platforms and in enterprises choosing platforms that might prove incompatible with future quantum computers.
- Enterprise leaders recognize that quantum computing will take more than 10 years to mature. This results in limited short-term investment.

User Recommendations

- Be frugal when it comes to investment in quantum computing. Focus on the problem you want to solve and ways to mature the quantum computing ecosystem. Quantum innovation is a long-term endeavor, so it is imperative to temper expectations.
- Create a pipeline for quantum computing talent by funding academic research projects that closely align with your use cases. When quantum computing becomes relevant to your organization, even a few quantum-capable employees will make a material difference.
- Plan for quantum-inspired classical optimization projects for skills development in areas such as warehouse routing, traffic routing, portfolio balancing and workforce planning.
- Plan for innovations in chemistry and materials science. Quantum computing has the potential to enable quantum-realistic simulations that could prove important in diverse fields, such as manufacturing, aerospace and defense.

Sample Vendors

Classiq; Google; IBM; Infleqtion; IonQ; IQM; PASQAL; Quandela; SandboxAQ; Zapata Computing

Gartner Recommended Reading

Cool Vendors in Quantum Computing

Infographic: How Use Cases Are Developed and Executed on a Quantum Computer

Preparing for the Quantum World With Crypto-Agility

Deep Neural Network ASICs

Analysis By: Alan Priestley

Benefit Rating: High

Market Penetration: 1% to 5% of target audience

Maturity: Adolescent

Definition:

A deep neural network (DNN) application-specific integrated circuit (ASIC) is a purpose-specific chip designed to execute the computations utilized in a wide range of artificial intelligence (AI) applications. These chips can be deployed in either data center servers, edge computing systems or endpoint devices.

Why This Is Important

Many applications leverage DNN-based techniques to analyze captured data. These include object detection and classification in images and video streams, social media recommendation engines, autonomous vehicles, pharmaceutical analytics, and more recently, the large language models (LLMs) used in generative AI applications. To effectively execute many of these applications require the use of DNN ASICs optimized for specific workloads.

Business Impact

Leveraging DNN ASIC-based systems enables:

- Efficient analysis of high-volume complex datasets, such as videos, images and audio streams, enabling video analytics, object detection and classification, image recognition, LLM, and recommendation systems.
- Edge computers and endpoint devices capable of sophisticated local automated decision making and delivering enhanced user experience.
- Better performance and power efficiency, than solutions based on graphics processing units (GPUs) or general-purpose CPUs.

Drivers

- Increasing volume of complex unstructured data requires the use of processing techniques that leverage DNN models to analyze and enable business decisions to be made based on the data content.
- Executing DNN-based applications typically requires the use of computer systems that are capable of executing high volumes of highly parallel math operations.
- Many DNN models require training using large sets of known good data. GPUs can be used for this task but high-performance DNN ASICs designed for data center deployments can deliver a better solution to this problem.
- DNN ASICs can offer significantly better performance, at lower power, than many existing CPU- or GPU-based solutions available to execute DNN-based workloads.
- Often, trained DNN applications are deployed in locations, such as edge computing or endpoint devices, where power or form factor constraints prevent the use of many high-power AI devices. Many DNN ASICs are designed specifically for these deployments.

Obstacles

- Today, discrete GPUs are still the device of choice for many companies developing DNN-based AI applications.
- Most of the open-source software frameworks used by AI developers have native support for GPUs but require dedicated software tools and workflows to support DNN ASICs.
- Many companies developing DNN ASICs are startups, and while they often have the funding to develop a DNN ASIC, and supporting software, they lack the size to scale and grow their business, due to limited resources to support a broad range of AI developers.
- There is no standardization in DNN ASIC hardware design, with every vendor offering their own unique design and requiring specific software implementation to support each DNN ASIC.
- The large hyperscale cloud service providers are developing ASICs optimized for their specific DNN-based workloads, such as Google's Tensor Processing Units (TPUs) optimized for its TensorFlow-based applications and Amazon Web Services' (AWS') Trainium and Inferentia chips.

User Recommendations

- Use CPUs or cloud when DNN workloads are light enough to fit in conventional CPU-based infrastructure.
- Use GPUs or dedicated AI servers with DNN ASICs when DNN workloads would otherwise consume excessive server resources.
- Select DNN ASICs and vendors that offer or support the broadest set of DNN frameworks and toolsets.
- Specify edge computing and endpoint devices that integrate low-cost DNN ASICs to support edge inferencing and local decision making, in locations where power, form factor and communications cost are critical.

Sample Vendors

Amazon Web Services; Cerebras Systems; Google; Graphcore; Intel; NVIDIA; SambaNova Systems

Gartner Recommended Reading

Emerging Technologies: Tech Innovators in Neuromorphic Computing

Forecast: AI Semiconductors, Worldwide, 2021-2027

Forecast Analysis: AI Semiconductors, Worldwide

Emerging Technologies and Trends Impact Radar: Artificial Intelligence

Appendixes

Hype Cycle Phases, Benefit Ratings and Maturity Levels

Table 2: Hype Cycle Phases

(Enlarged table in Appendix)

Phase ↓	*Definition* ↓
Innovation Trigger	A breakthrough, public demonstration, product launch or other event generates significant media and industry interest.
Peak of Inflated Expectations	During this phase of overenthusiasm and unrealistic projections, a flurry of well-publicized activity by technology leaders results in some successes, but more failures, as the innovation is pushed to its limits. The only enterprises making money are conference organizers and content publishers.
Trough of Disillusionment	Because the innovation does not live up to its overinflated expectations, it rapidly becomes unfashionable. Media interest wanes, except for a few cautionary tales.
Slope of Enlightenment	Focused experimentation and solid hard work by an increasingly diverse range of organizations lead to a true understanding of the innovation's applicability, risks and benefits. Commercial off-the-shelf methodologies and tools ease the development process.
Plateau of Productivity	The real-world benefits of the innovation are demonstrated and accepted. Tools and methodologies are increasingly stable as they enter their second and third generations. Growing numbers of organizations feel comfortable with the reduced level of risk; the rapid growth phase of adoption begins. Approximately 20% of the technology's target audience has adopted or is adopting the technology as it enters this phase.
Years to Mainstream Adoption	The time required for the innovation to reach the Plateau of Productivity.

Source: Gartner (July 2023)

Table 3: Benefit Ratings

Benefit Rating ↓	*Definition* ↓
Transformational	Enables new ways of doing business across industries that will result in major shifts in industry dynamics
High	Enables new ways of performing horizontal or vertical processes that will result in significantly increased revenue or cost savings for an enterprise
Moderate	Provides incremental improvements to established processes that will result in increased revenue or cost savings for an enterprise
Low	Slightly improves processes (for example, improved user experience) that will be difficult to translate into increased revenue or cost savings

Source: Gartner (July 2023)

Table 4: Maturity Levels

(Enlarged table in Appendix)

Maturity Levels ↓	Status ↓	Products/Vendors ↓
Embryonic	In labs	None
Emerging	Commercialization by vendors Pilots and deployments by industry leaders	First generation High price Much customization
Adolescent	Maturing technology capabilities and process understanding Uptake beyond early adopters	Second generation Less customization
Early mainstream	Proven technology Vendors, technology and adoption rapidly evolving	Third generation More out-of-box methodologies
Mature mainstream	Robust technology Not much evolution in vendors or technology	Several dominant vendors
Legacy	Not appropriate for new developments Cost of migration constraints replacement	Maintenance revenue focus
Obsolete	Rarely used	Used/resale market only

Source: Gartner (July 2023)

Recommended by the Authors

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Understanding Gartner's Hype Cycles

Tool: Create Your Own Hype Cycle With Gartner's Hype Cycle Builder

2022 Strategic Roadmap for Compute Infrastructure

Cool Vendors in Quantum Computing

Rethink Supercomputing for a Digital Era

Market Guide for Consumption-Based Models for Data Center Infrastructure

Table 1: Priority Matrix for Deep Technology, 2023

Benefit	*Years to Mainstream Adoption*			
↓	***Less Than 2 Years*** ↓	***2 - 5 Years*** ↓	***5 - 10 Years*** ↓	***More Than 10 Years*** ↓
Transformational		First-Principles AI Generative AI	DNA Computing Neuromorphic Computing Quantum Sensing	Quantum Algorithms Quantum Computing Quantum ML
High		Deep Neural Network ASICs Optical Satellite Connectivity Postquantum Cryptography	Bidirectional Brain-Machine Interface Crypto-Agility DNA Storage LEO Satellite-to-Vehicle Communications Quantum Computing as a Service in Drug Discovery Smart Robots Terrestrial Steerable Optical Links	6G Mobility Quantum Optimization
Moderate		LEO Satellite IoT Swarming Robotics		Quantum Computing as a Service Quantum Networking Terahertz Wireless

Benefit	*Years to Mainstream Adoption*			
↓	***Less Than 2 Years*** ↓	***2 - 5 Years*** ↓	***5 - 10 Years*** ↓	***More Than 10 Years*** ↓
Low		Classical Quantum Simulators Quantum Key Distribution		

Source: Gartner (July 2023)

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Phase ↓	*Definition* ↓

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