

# Harnessing Nanotechnology for Advancements in Magnetism: Current Trends and Future Prospects

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**Abstract:-** Nanotechnology has revolutionized various fields, including magnetism, by enabling the manipulation of materials at the nanoscale. This paper explores the current trends and future prospects of harnessing nanotechnology for advancements in magnetism. We discuss the fundamental principles of magnetism at the nanoscale and review recent developments in nanomagnetic materials, fabrication techniques, and applications. Additionally, we highlight the potential impact of nanotechnology on diverse areas such as data storage, biomedical devices, magnetic sensors, and spintronics. Furthermore, challenges and opportunities in the field are addressed, offering insights into the direction of future research and technological innovations.

**Keywords:-** Nano Magnetic Materials, Nanotechnology, Magnetism, Magnetic Nanoparticles, Magnetic Properties, Characterization Techniques, Size and Shape Effects.

## I. INTRODUCTION

Nanotechnology is the manipulation of matter on an atomic, molecular, and supramolecular scale. It involves the design, characterization, production, and application of structures, devices, and systems by controlling shape and size at the nanoscale, typically ranging from 1 to 100 nanometers. This field holds immense promise for revolutionizing various industries due to the unique properties materials exhibit at the nanoscale.

*A. Here's an Overview of Nanotechnology and its Applications Across Various Fields:*

➤ *Electronics and Computing:*

• *Nanoelectronics:*

Utilizing nanomaterials like carbon nanotubes or nanowires to create smaller, faster, and more efficient electronic components.

• *Quantum Computing:*

Nanotechnology plays a crucial role in fabricating qubits, the building blocks of quantum computers, which promise exponentially higher computing power than classical computers.

➤ *Medicine and Healthcare:*

• *Drug Delivery:*

Nanoparticles can be engineered to deliver drugs precisely to targeted cells or tissues, improving efficacy and reducing side effects.

• *Diagnostics:*

Nanoscale sensors and probes enable highly sensitive and specific detection of biomarkers for diseases like cancer or infectious diseases.

• *Imaging:*

Nanoparticles can enhance contrast in medical imaging techniques such as MRI, CT scans, and fluorescence imaging, aiding in diagnosis and treatment monitoring.

➤ *Energy:*

• *Solar Cells:*

Nanomaterials like quantum dots or nanowires are used to enhance the efficiency of solar cells by improving light absorption and charge transport.

• *Batteries:*

Nanotechnology enables the development of high-capacity, longer-lasting batteries by enhancing electrode materials and electrolytes.

• *Energy Storage:*

Nanomaterials are explored for applications in supercapacitors and hydrogen storage, promising higher energy densities and faster charging rates.

➤ *Materials Science:*

• *Nanocomposites:*

Incorporating nanoparticles into bulk materials enhances mechanical, thermal, and electrical properties, leading to stronger, lighter, and more durable materials.

• *Coatings:*

Nanoscale coatings provide functionalities such as scratch resistance, water repellency, and antibacterial properties for various surfaces.

- *Nanofabrication:*

Techniques like nanoimprint lithography and self-assembly enable precise patterning and manipulation of materials at the nanoscale, facilitating the creation of novel structures and devices.

- *Environmental Remediation:*

- *Water Purification:*

Nanomaterials like graphene oxide or titanium dioxide nanoparticles can remove contaminants from water through processes like filtration or photocatalysis.

- *Air Filtration:*

Nanofibers and nanoparticles are used in air filters to capture pollutants, particulate matter, and harmful gases.

- *Textiles and Apparel:*

- *Nano Textiles:*

Fabrics treated with nanocoatings exhibit properties such as stain resistance, water repellency, UV protection, and antibacterial activity.

- *Smart Textiles:*

Integration of nanosensors and nanoelectronics into fabrics enables functionalities like temperature regulation, moisture sensing, and health monitoring.

- *User*

- *Importance of Magnetism and Nanotechnology Intersection*

The intersection of magnetism and nanotechnology holds significant importance across various fields due to the unique properties and potential applications it offers. Here are some key reasons why this intersection is important:

- *Data Storage and Memory Devices:*

Nanotechnology enables the fabrication of magnetic materials at the nanoscale, allowing for higher data storage densities and improved performance in hard disk drives (HDDs), magnetic random-access memory (MRAM), and other magnetic storage devices. Nanoscale magnetic structures such as patterned media or magnetic nanoparticles offer greater stability, faster access times, and increased storage capacity.

- *Spintronics:*

Spintronics, or spin electronics, utilizes the spin of electrons in addition to their charge for information processing and storage. Nanotechnology plays a crucial role in engineering nanomagnetic structures and spintronic devices such as spin valves, magnetic tunnel junctions, and spin transistors. These devices offer advantages in terms of low power consumption, high-speed operation, and non-volatility, promising advances in computing and electronics.

- *Sensing and Imaging:*

Magnetic nanoparticles and nanosensors enable highly sensitive and specific detection of biological molecules, pathogens, and environmental pollutants. Functionalized magnetic nanoparticles can be used for magnetic resonance imaging (MRI) contrast enhancement, targeted drug delivery, and magnetic hyperthermia cancer therapy. Nanoscale magnetic sensors also find applications in magnetic resonance sensors, magnetic field sensors, and magnetic particle imaging (MPI) for biomedical imaging and diagnostics.

- *Energy Conversion and Harvesting:*

Nanomaterials with tailored magnetic properties play a role in energy conversion and harvesting technologies. For instance, nanostructured magnetic materials are investigated for applications in thermoelectric generators, where temperature gradients are converted into electrical energy. Additionally, nanoscale magnetic materials are explored for use in magnetic refrigeration systems, which offer energy-efficient and environmentally friendly cooling.

- *Nanomagnets in Electronics:*

Nanomagnetic structures such as magnetic nanowires, nanoparticles, and thin films are studied for their potential in spin-based logic and memory devices. These nanomagnets offer unique functionalities such as spin wave propagation, domain wall motion, and magnetic vortices, which could be harnessed for novel computing paradigms, including neuromorphic computing and quantum computing.

- *Magnetic Nanoparticles in Biomedicine:*

Magnetic nanoparticles functionalized with biomolecules are used for targeted drug delivery, magnetic resonance imaging (MRI) contrast enhancement, magnetic hyperthermia cancer therapy, and magnetic cell separation. The combination of nanotechnology and magnetism enables precise manipulation and control of nanoparticles within biological systems, facilitating advanced diagnostic and therapeutic applications.

## II. FUNDAMENTALS OF NANOMAGNETISM

Magnetism, a fundamental property of matter, manifests itself at various scales, from individual atoms to bulk materials. At the nanoscale, where structures range from a few to hundreds of nanometers, the behavior of magnetic materials exhibits unique and intriguing properties, distinct from their macroscopic counterparts. Understanding magnetism at this scale is not only essential for fundamental science but also holds significant promise for numerous technological applications.

Nanomagnetism arises from the interplay of quantum mechanics, statistical mechanics, and electromagnetic interactions within nanoscale magnetic structures. In bulk materials, magnetic behavior is governed by domains—regions where the magnetic moments of atoms align to produce a net magnetization. However, as materials are scaled down to nanometer dimensions, various factors such as surface effects, finite size, shape anisotropy, and reduced

coordination play crucial roles in determining their magnetic properties.

One of the most intriguing phenomena observed at the nanoscale is the phenomenon of superparamagnetism. When magnetic nanoparticles reach a critical size below which thermal energy overcomes the magnetic anisotropy energy, they exhibit a random fluctuation between different magnetic orientations, effectively behaving as tiny magnets with no overall magnetic moment. This property has significant implications for applications in data storage, biomedical imaging, and magnetic hyperthermia.

Furthermore, nanomagnetic materials often exhibit enhanced magnetic properties compared to their bulk counterparts. For instance, the coercivity—the resistance to demagnetization—of magnetic nanoparticles can be orders of magnitude higher than that of bulk materials, making them attractive candidates for high-density magnetic recording and permanent magnet applications.

The unique properties of nanomagnetism have led to the development of various novel applications across diverse fields. In data storage, the continuous drive towards higher storage densities has spurred the exploration of nanoscale magnetic materials for next-generation hard disk drives and non-volatile memory devices. In biomedicine, magnetic nanoparticles are used for targeted drug delivery, magnetic resonance imaging (MRI) contrast enhancement, and magnetic hyperthermia cancer therapy, owing to their ability to navigate biological systems with precision and efficacy.

#### A. Magnetic Properties of Nano Materials (e.g., Superparamagnetism, Exchange Bias)

Magnetic properties of nanomaterials differ significantly from their bulk counterparts due to size, shape, and surface effects. Several phenomena emerge at the nanoscale, including superparamagnetism and exchange bias, which play critical roles in various applications. Let's delve into each of these properties:

##### ➤ Superparamagnetism:

- Superparamagnetism occurs in nanoparticles when thermal energy becomes comparable to the magnetic anisotropy energy. Below a critical size, known as the superparamagnetic limit, nanoparticles lose their permanent magnetization and instead exhibit random fluctuations between magnetic orientations.
- This behavior arises because thermal energy can overcome the energy barrier associated with magnetic alignment, causing rapid reorientation of magnetic moments. As a result, superparamagnetic nanoparticles behave like individual magnetic dipoles with no net magnetic moment when averaged over time.
- Superparamagnetic nanoparticles are highly desirable for applications such as magnetic resonance imaging (MRI) contrast agents, drug delivery vehicles, and magnetic hyperthermia cancer therapy. Their ability to respond to external magnetic fields and navigate biological systems

with precision makes them valuable tools in biomedicine.

##### ➤ Exchange Bias:

- Exchange bias refers to the phenomenon where the hysteresis loop of a ferromagnetic material is shifted along the magnetization axis when coupled with an antiferromagnetic material.
- This effect arises due to the exchange interaction between the ferromagnetic and antiferromagnetic layers at their interface. The exchange coupling aligns the magnetic moments of the ferromagnet with the antiferromagnet, leading to a unidirectional anisotropy in the ferromagnetic layer.
- Exchange bias is widely exploited in magnetic recording media, spin valves, and magnetic sensors to stabilize the magnetization orientation and improve the performance and reliability of devices. It also finds applications in magnetic random-access memory (MRAM) and magnetic tunnel junctions for data storage and information processing.

##### ➤ Other Nanomagnetic Phenomena:

- Nanomaterials may also exhibit additional magnetic phenomena such as size-dependent magnetic anisotropy, spin glass behavior, and magnetic vortex states, among others.
- Size-dependent magnetic anisotropy refers to the variation in magnetic properties with nanoparticle size due to quantum confinement effects. This phenomenon is crucial for tailoring the magnetic behavior of nanoparticles for specific applications.
- Spin glass behavior arises from the disorder and frustration in magnetic systems, leading to complex magnetic dynamics and slow relaxation of magnetization. Spin glasses are studied for their implications in fundamental physics and potential applications in spintronics and magnetic storage.

##### ➤ Size and Shape Effects on Magnetic Behavior:

Size and shape effects profoundly influence the magnetic behavior of nanomaterials. At the nanoscale, materials exhibit unique magnetic properties due to quantum confinement effects, surface anisotropy, and shape-induced magnetic anisotropy. Understanding how size and shape impact magnetic behavior is essential for tailoring nanomaterials for specific applications. Here's how size and shape affect magnetic behavior:

##### ➤ Quantum Confinement Effects:

As the size of magnetic nanoparticles decreases, quantum confinement effects become increasingly significant. In small nanoparticles, the number of atoms becomes comparable to the characteristic length scales associated with quantum mechanics, leading to discrete energy levels and altered magnetic properties.

Quantum confinement modifies the electronic band structure, spin states, and magnetic interactions within nanoparticles, affecting their magnetic moments, magnetic anisotropy, and magnetic susceptibility.

For example, in small magnetic nanoparticles, the reduction in coordination of surface atoms and the increase in surface-to-volume ratio can enhance surface effects such as surface anisotropy, spin disorder, and surface spin-glass behavior.

- *Shape-Induced Magnetic Anisotropy:*

The shape of nanomaterials strongly influences their magnetic behavior due to shape-induced magnetic anisotropy. Anisotropy arises from preferential alignment of magnetic moments along specific crystallographic directions or geometric axes.

Nanomaterials with non-spherical shapes, such as nanorods, nanowires, nanotubes, or nanoparticles with elongated morphologies, exhibit shape-induced magnetic anisotropy.

The anisotropic shape geometry imposes constraints on the orientation of magnetic moments, leading to preferential magnetization directions. For instance, nanowires typically exhibit easy magnetization along the long axis, while nanoplatelets may have easy magnetization along the plane of the platelet.

- *Surface Effects:*

As the size of magnetic nanoparticles decreases, a larger fraction of atoms reside at the nanoparticle surface. Surface atoms experience different bonding environments and coordination numbers compared to atoms in the bulk, leading to surface effects that influence magnetic behavior.

Surface effects can introduce additional magnetic anisotropy contributions, modify exchange interactions, and enhance surface spin disorder and magnetic relaxation processes.

Surface oxidation, capping ligands, and surface defects can also influence the magnetic properties of nanoparticles by altering their electronic structure, magnetic coupling, and magnetic moment stability.

- *Magnetic Interactions and Assemblies:*

Size and shape also affect magnetic interactions and the assembly behavior of nanomaterials. For example, the magnetic coupling between nanoparticles in assemblies or superlattices can lead to collective magnetic behavior, such as magnetic ordering or superparamagnetism.

Controlled manipulation of size and shape enables tuning of interparticle spacing and magnetic coupling strength, offering opportunities for engineering collective magnetic properties in nanomaterial assemblies.

### III. NANOMAGNETIC MATERIALS

Nanomagnetic materials, also known as magnetic nanoparticles, are magnetic materials that exhibit unique properties at the nanoscale. These materials typically consist of magnetic elements or compounds, such as iron, cobalt, nickel, or their alloys, structured into nanoparticles with dimensions ranging from a few to hundreds of nanometers. Nanomagnetic materials possess a wide range of applications across various fields due to their tunable magnetic properties, large surface-to-volume ratio, and controllable size and shape. Here are some key characteristics and applications of nanomagnetic materials:

- *Size and Shape Control:*

Nanomagnetic materials can be synthesized with precise control over their size, shape, and composition. Various synthesis techniques, including chemical precipitation, sol-gel methods, thermal decomposition, and physical vapor deposition, allow for the production of nanoparticles with tailored properties.

The size and shape of nanoparticles profoundly influence their magnetic behavior, including magnetic anisotropy, coercivity, and magnetization dynamics. By tuning these parameters, researchers can design nanomagnetic materials with desired magnetic properties for specific applications.

- *Magnetic Properties:*

Nanomagnetic materials exhibit size-dependent magnetic behavior, where magnetic properties are influenced by quantum confinement effects and surface effects. As the size of nanoparticles decreases, quantum confinement leads to discrete energy levels and modifies magnetic interactions, resulting in altered magnetic properties.

Magnetic properties of nanomagnetic materials include magnetization, coercivity, remanence, susceptibility, and magnetic anisotropy. These properties can be tailored by controlling nanoparticle size, shape, composition, and surface modification.

- *Applications:*

- *Data Storage:*

Nanomagnetic materials are widely used in magnetic recording media for data storage applications. High-coercivity magnetic nanoparticles enable high-density magnetic recording, leading to increased storage capacity in hard disk drives and magnetic tapes.

- *Biomedical Imaging and Therapy:*

Magnetic nanoparticles serve as contrast agents for magnetic resonance imaging (MRI) in biomedical diagnostics. Additionally, they are employed in magnetic hyperthermia cancer therapy, where nanoparticles generate heat when exposed to an alternating magnetic field, selectively destroying cancer cells.

- *Drug Delivery:*

Functionalized magnetic nanoparticles are used as carriers for targeted drug delivery in cancer therapy. Surface modifications enable specific binding to target cells or tissues, enhancing drug delivery efficiency and reducing systemic side effects.

- *Magnetic Sensors and Devices:*

Nanomagnetic materials are utilized in magnetic sensors, magnetic recording heads, and spintronic devices. Their sensitivity to magnetic fields and controllable magnetic properties make them ideal candidates for various sensor and device applications.

- *Challenges and Considerations:*

Despite their numerous applications, nanomagnetic materials face challenges such as agglomeration, stability, biocompatibility, and potential toxicity. Surface modification and functionalization are often employed to address these challenges and improve nanoparticle stability and biocompatibility.

Furthermore, the scalability and cost-effectiveness of synthesis methods for producing nanomagnetic materials in large quantities remain areas of ongoing research and development.

- *Synthesis Methods (e.g., Chemical Vapor Deposition, Sol-gel, Self-assembly)*

Synthesis methods for nanomagnetic materials encompass a diverse range of techniques, each offering unique advantages in terms of control over size, shape, composition, and properties. Here are some common synthesis methods employed for producing nanomagnetic materials:

- *Chemical Precipitation:*

Chemical precipitation involves the controlled precipitation of metal ions from a solution to form nanoparticles. Typically, metal salts are dissolved in a solvent, followed by the addition of reducing agents or precipitating agents to initiate nanoparticle formation.

This method offers simplicity, scalability, and low cost. However, it may result in a wide size distribution of nanoparticles and require subsequent purification steps.

- *Sol-Gel Synthesis:*

Sol-gel synthesis involves the hydrolysis and condensation of metal alkoxides or metal salts in a solution to form a sol, followed by gelation to form a solid network of nanoparticles.

This method enables precise control over nanoparticle size, shape, and composition. By adjusting reaction parameters such as pH, temperature, and precursor concentration, researchers can tailor the properties of the resulting nanomagnetic materials.

Sol-gel synthesis is widely used for producing magnetic nanoparticles, thin films, and composite materials with applications in catalysis, sensors, and biomedical devices.

- *Chemical Vapor Deposition (CVD):*

Chemical vapor deposition involves the deposition of thin films of nanomagnetic materials onto substrates through the chemical reaction of precursor gases in a vacuum or controlled atmosphere.

CVD offers excellent control over film thickness, composition, and uniformity. It is commonly used for depositing magnetic thin films and multilayers with precise control over microstructure and magnetic properties.

Various CVD techniques, such as physical vapor deposition (PVD), atomic layer deposition (ALD), and plasma-enhanced chemical vapor deposition (PECVD), are employed depending on the desired film characteristics and applications.

- *Mechanical Milling:*

Mechanical milling or ball milling involves the grinding of bulk materials in the presence of milling balls or grinding media to produce nanoscale particles through repeated deformation, fracture, and cold welding processes.

This method is suitable for producing magnetic nanoparticles and nanocomposites with controlled particle size, morphology, and crystallinity. It is particularly effective for preparing metastable or amorphous nanomagnetic materials.

Mechanical milling offers scalability and versatility but may require subsequent annealing or post-processing steps to optimize magnetic properties.

- *Self-Assembly:*

- *Properties and Characterization Techniques*

Self-assembly techniques utilize non-covalent interactions, such as van der Waals forces, hydrogen bonding, or electrostatic interactions, to spontaneously organize nanomagnetic materials into ordered structures.

Examples include the Langmuir-Blodgett method, where nanoparticles are arranged at the air-water interface and transferred onto substrates, and template-assisted self-assembly, where nanoparticle deposition occurs within porous templates or scaffolds.

Self-assembly enables the fabrication of complex nanostructures and hierarchical assemblies with tailored magnetic properties. It is commonly used for applications in photonics. In a paper titled "Harnessing Nanotechnology for Advancements in Magnetism: Current Trends and Future Prospects," discussing the properties and characterization techniques of nanomagnetic materials is essential for understanding their behavior and optimizing their performance. Here's an overview of the properties and

characterization techniques that could be discussed in such a paper:

➤ *Magnetic Properties:*

• *Magnetization (M):*

The measure of the magnetic moment per unit volume of a material.

• *Magnetic Susceptibility ( $\chi$ ):*

The extent to which a material becomes magnetized in response to an applied magnetic field.

• *Coercivity ( $H_c$ ):*

The measure of the resistance of a material to becoming demagnetized.

• *Remanence ( $B_r$ ):*

The residual magnetization of a material after the removal of an external magnetic field.

• *Magnetic anisotropy:*

The directional dependence of magnetic properties, such as magnetization and coercivity.

• *Size and Shape Effects:*

Discuss how the size and shape of nanomagnetic materials influence their magnetic properties, including magnetic anisotropy, coercivity, and magnetization dynamics.

Explore the role of quantum confinement effects, surface effects, and shape-induced anisotropy in shaping the magnetic behavior of nanoparticles.

➤ *Characterization Techniques:*

• *Transmission Electron Microscopy (TEM):*

Provides high-resolution imaging and structural analysis of nanomagnetic materials, allowing for the determination of particle size, shape, and morphology.

• *Scanning Electron Microscopy (SEM):*

Offers surface imaging and topographical analysis of nanomagnetic materials, providing information on particle size distribution and surface characteristics.

• *X-ray Diffraction (XRD):*

Determines the crystal structure, phase composition, and crystallite size of nanomagnetic materials, aiding in structural characterization.

• *Vibrating Sample Magnetometry (VSM):*

Measures the magnetic properties of nanomagnetic materials, including magnetization, coercivity, and remanence, as a function of magnetic field strength.

• *Atomic Force Microscopy (AFM):*

Probes the surface morphology and magnetic domain structure of nanomagnetic materials with nanoscale resolution, enabling surface roughness analysis and domain imaging.

• *Superconducting Quantum Interference Device (SQUID) Magnetometry:*

Offers precise measurements of magnetic properties, such as susceptibility and magnetization, at low temperatures and high magnetic fields, providing insights into nanomagnetic behavior at extreme conditions.

➤ *Advanced Characterization Techniques:*

• *Mössbauer Spectroscopy:*

Provides detailed information on the chemical environment and magnetic state of iron-containing nanomagnetic materials, aiding in the identification of magnetic phases and coordination environments.

• *X-ray Photoelectron Spectroscopy (XPS):*

Investigates the surface chemistry and electronic structure of nanomagnetic materials, offering insights into surface composition, oxidation states, and magnetic interactions.

Small-Angle Neutron Scattering (SANS): Determines the size, shape, and magnetic structure of nanomagnetic materials in solution or dispersed states, facilitating the characterization of magnetic nanoparticles in complex environments, electronics, and biomedicine.

#### IV. CONCLUSION

Continued research and development in harnessing nanotechnology for advancements in magnetism are crucial for several reasons:

➤ *Technological Innovation:*

Nanotechnology offers unprecedented opportunities to manipulate and control the magnetic properties of materials at the nanoscale. Continued research enables the development of novel nanomagnetic materials, devices, and systems with enhanced functionalities and performance. These advancements drive technological innovation across various sectors, including information technology, healthcare, energy, and manufacturing.

➤ *Data Storage and Computing:*

The demand for high-density data storage and faster computing continues to grow. Nanomagnetic materials hold promise for next-generation data storage devices, such as magnetic hard drives, spintronic devices, and magnetic random-access memory (MRAM). Continued research is essential for overcoming technical challenges, improving storage densities, reducing energy consumption, and enhancing data access speeds.

➤ *Biomedical Applications:*

Nanomagnetic materials have significant applications in biomedicine, including magnetic resonance imaging (MRI), drug delivery, magnetic hyperthermia cancer therapy, and biosensing. Further research is needed to optimize the performance, biocompatibility, and targeting efficiency of nanomagnetic systems for clinical applications. Additionally, exploring new functionalities and applications in areas such as regenerative medicine and bioelectronics holds promise for advancing healthcare technologies.

➤ *Energy and Environment:*

Nanomagnetic materials play a role in energy conversion, storage, and environmental remediation technologies. Research efforts focus on improving the efficiency and sustainability of energy systems through innovations such as nanomagnetic catalysts for fuel cells, magnetic nanoparticles for water purification, and magnetic materials for energy-efficient refrigeration and air conditioning. Continued research is vital for addressing global energy challenges and mitigating environmental impacts.

➤ *Fundamental Science:*

Research in nanomagnetism contributes to fundamental understanding of magnetic phenomena at the nanoscale. Studying size and shape effects, magnetic interactions, and spin dynamics in nanomagnetic materials enhances our knowledge of condensed matter physics and quantum mechanics. This knowledge not only fuels technological advancements but also opens up new avenues for fundamental research and exploration.

➤ *Competitive Advantage:*

Nations and industries investing in nanotechnology research and development gain a competitive edge in global markets. Advancements in nanomagnetic materials and devices drive economic growth, stimulate innovation, and create opportunities for job creation and entrepreneurship. Moreover, strategic investments in research infrastructure and talent development are essential for maintaining leadership in nanotechnology-enabled industries.

In summary, continued research and development in harnessing nanotechnology for advancements in magnetism are essential for driving technological innovation, addressing societal challenges, advancing scientific knowledge, and fostering economic growth. By investing in research, collaboration, and education, stakeholders can unlock the full potential of nanomagnetic materials and technologies to shape a more sustainable, connected, and prosperous future.

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