



Fundamental Theoretical Advances Driving Modern Applied Superconductivity: A Contemporary Review

Akanksha Agarwal*, Nutan Yadav

Department of Physics, Institute of Basic Sciences, Dr. Bhimrao Ambedkar University, Khandari
Campus, Agra-282002, Uttar Pradesh, India.

Abstract

Superconductivity, characterized by zero electrical resistance and the expulsion of magnetic fields, remains a cornerstone of condensed matter physics with transformative technological potential. This review provides a comprehensive overview of both theoretical and experimental developments in the field. We discuss foundational models, including the London, Ginzburg–Landau, Bardeen-Cooper-Schrieffer (BCS), and Eliashberg formalisms, as well as unconventional approaches such as the Resonating Valence Bond (RVB) theory, which address strong correlations and non-phonon pairing mechanisms. The review covers a broad spectrum of materials, from conventional low-temperature metals to high-temperature cuprates, iron-based superconductors, hydrogen-rich compounds under extreme pressure, and novel systems including twisted bilayer graphene, nickelates, two-dimensional materials, and topological superconductors. Key challenges for practical applications such as, cryogenic requirements, mechanical fragility, limited current-carrying capacity, fabrication difficulties, and vortex dynamics, are examined, alongside emerging strategies in scalable fabrication, vortex pinning engineering, and cryogen-free technologies. We also highlight the role of superconductors in quantum technologies, particularly superconducting qubits and topological platforms. Finally, we outline future directions, emphasizing material discovery, theoretical refinement, and engineering innovations aimed at achieving room-temperature, ambient-pressure superconductivity.

Keywords: Superconductivity; Meissner Effect; High temperature superconductors

Introduction

Modern technologies from energy infrastructure, electronic devices to the emerging quantum system, rely fundamentally on an understanding of the electrical properties of materials. The ability of a material to conduct or resist the flow of electric current governs its role in applications ranging from power transmission to signal processing². Traditionally, materials are classified as conductors or insulators based on their electronic behavior. Conductors, such as copper and silver, exhibit high electrical conductivity due to the presence of free electrons, making them indispensable in electrical wiring and interconnects. Insulators, on the other hand, such as glass and polymeric materials, have tightly bound electrons that inhibit charge flow, serving as essential components in dielectric barriers and safety insulation³. Bridging and ultimately surpassing these categories are superconductors, a class of materials that, under specific conditions, exhibit zero electrical resistance and perfect diamagnetism, enabling entirely lossless current flow and novel electromagnetic behaviour⁴. Magnetic resonance imaging (MRI) relies on superconducting magnets, as do maglev trains, high-field research magnets, and particle accelerators like the Large Hadron Collider (LHC) at European Organization for Nuclear Research (CERN). In power systems, superconducting cables and fault current limiters offer reduced energy losses and increased reliability. In computing, superconductors are enabling ultrafast digital circuits and quantum bits (qubits) in superconducting quantum computers, with companies like IBM, Google, and Rigetti pushing the frontiers of quantum technology⁵.

The phenomenon that governs behaviour of superconductors, known as superconductivity. It is a quantum mechanical phenomenon wherein a material exhibits exactly zero electrical resistance and perfect diamagnetism (the Meissner effect), allows for the unimpeded flow of electric current without any energy loss. This state, achievable under specific conditions such as extremely low temperatures or high pressures, offers revolutionary potential for energy transmission, magnetic levitation, medical imaging, and quantum computing. The discovery of superconductivity dates back to 1911, when Dutch physicist Heike Kamerlingh Onnes observed that the electrical resistance of mercury suddenly vanished when cooled below 4.2 K⁶. This striking departure from classical physics introduced a new state of matter and launched a century-long scientific journey into understanding and harnessing this exotic property. The phenomenon remained a mystery until 1957, when Bardeen, Cooper, and Schrieffer formulated the BCS theory, explaining superconductivity in conventional materials. According to BCS theory, electrons form weakly bound pairs 'Cooper pairs' mediated by phonon interactions. These pairs condense into a coherent quantum ground state that flows without scattering, resulting in zero resistance and the formation of an energy gap in the electronic density of states⁷.

While the BCS theory elegantly explains superconductivity in many elemental and alloy-based materials (such as lead, niobium, and aluminium), it falls short when applied to more complex, unconventional systems. The field witnessed a dramatic turning point in 1986, when Johannes Georg Bednorz and Karl Alexander Müller discovered high-temperature superconductivity (HTS) in a copper oxide ceramic, LaBaCuO, with a critical temperature (T_p) of 35 K⁸. This was soon surpassed by other cuprate superconductors, with some exhibiting superconductivity above the boiling point of liquid nitrogen (77 K), a milestone that reduced cooling costs and ignited an international research boom⁹. HTS materials, primarily layered perovskite oxides, posed new theoretical and experimental challenges. Unlike conventional superconductors, their behaviour cannot be explained by electron-phonon interactions alone. These materials often exhibit strong electronic correlations, anisotropic pairing, and coexistence with other complex phases such as antiferromagnetism, charge-density waves, and pseudogaps¹⁰. Despite decades of study, a complete and unified theoretical model for HTS remains elusive, pointing to the rich and intricate nature of electron interactions in these systems.

Following the HTS revolution, several other families of unconventional superconductors emerged. Iron-based superconductors, discovered in 2008, presented another class of materials exhibiting high critical temperatures and complex phase diagrams¹¹. More recently, systems such as twisted bilayer graphene¹², nickelates¹³, and topological superconductors¹⁴ have introduced new directions, merging concepts from topology, spin-orbit coupling, and quantum geometry into the superconductivity domain. These discoveries have not only expanded the scope of known superconducting materials but have also deepened the mystery surrounding the mechanisms that drive superconductivity in these systems. One of the most ground-breaking recent developments is the observation of near-room-temperature superconductivity in hydrogen-rich compounds such as LaH₁₀, YH₆, and carbonaceous sulfur hydrides, under extremely high pressures exceeding 150 GPa¹⁵. While these materials demonstrate superconductivity at temperatures approaching or exceeding 250 K, their requirement for megabar pressures limits their practical utility. Nevertheless, they offer valuable insights into designing materials with strong electron-phonon coupling and raise the possibility of achieving ambient-condition superconductors in the future.

Despite these transformative discoveries, several obstacles continue to hinder widespread application. Most superconductors still require cooling to cryogenic temperatures using liquid helium or liquid nitrogen, which adds complexity and cost¹⁶. Many HTS materials are brittle ceramics, posing fabrication and mechanical integration issues¹⁷. Moreover, the lack of a universal theoretical framework, particularly for high-temperature and pressure-induced superconductivity, limits our ability to predict and design new superconducting materials rationally¹⁸. Overcoming these barriers remains a central challenge

in both fundamental research and practical engineering. This review provides a detailed account of the current status of superconductivity research (**Table 1**). It traces the evolution of the field from its classical roots to the modern era of quantum materials, highlighting theoretical advances, experimental discoveries, and emerging technologies. Special emphasis is placed on the ongoing search for room-temperature superconductivity, understanding non-BCS mechanisms, and the future integration of superconductors into scalable, energy-efficient, and quantum-enabled devices.

Table 1. Literature Overview of Superconductors

Type	Material	T _c (K)	Year Discovered	Notable Feature	Ref.
Elemental Superconductor	Mercury (Hg)	4.2	1911	First known superconductor	19
	Lead (Pb)	7.2	~1908–1913	BCS-type conventional metal	20
	Niobium (Nb)	9.25	1930s	Highest among T _c elements	21
A15 Compound	Nb ₃ Sn	18	1954	Widely used in magnets	22
	Nb ₃ Ge	23.2	1954	Metallic, relatively high	22,23
	V ₃ Si	17	1950s	Early intermetallic superconductor	24
Cuprate HTS	LaBaCuO	~35	1986 [4]	First ceramic HTS	24
	YBa ₂ Cu ₃ O ₇ (YBCO)	93	1987 [5]	Operates above liquid nitrogen temperature	24
	HgBa ₂ Ca ₂ Cu ₃ O ₈ (Hg-1223)	135	1993	Highest T _c known at ambient pressure	24
MgB ₂	Magnesium diboride	39	2001	Metallic relatively simple structure	25
Iron-Based superconductor	LaOFeAs	26-56	2006	Layered, magnetic parent compound	26
Hydrogen-rich compounds	H ₃ S	>200	2015	Required high pressure (~200GPa)	27
Nickelate superconductors	La ₃ Ni ₂ O ₇	80	2023	Strong electronic correlations and potential spin, under high pressure	28

BCS-Bardeen Cooper Schrieffer; HTS- High Temperature Superconductors

Fundamental Properties of Superconductivity

Superconductivity is governed by two remarkable properties below a certain critical temperature: zero electrical resistance and perfect diamagnetism.

A. Zero Electrical Resistance

The complete absence of electrical resistance means that once an electric current is established in a superconducting loop, it can circulate indefinitely without any energy loss. This unique behavior is a

consequence of the formation of Cooper pairs, which move through the lattice without scattering ²⁹. Experimental measurements have shown that the resistivity of superconductors can be less than $10^{-25} \Omega\text{m}$, a value so low that it is practically immeasurable. In comparison, the resistivity of good conductors like copper is around $10^{-8} \Omega\text{m}$ ³⁰. Consequently, the decay time of current in a superconducting loop can exceed 100,000 years, whereas in ordinary metallic conductors, it is typically on the order of microseconds.

B. Meissner effect

Another distinctive property of superconductors is their perfect diamagnetism, known as the Meissner effect. When a material is cooled below its critical temperature in the presence of a magnetic field, it not only exhibits zero electrical resistance but also actively expels magnetic flux from its interior, resulting in a net internal magnetic field of zero. This flux expulsion is a fundamental thermodynamic property of the superconducting state and not merely a consequence of perfect conductivity ³¹. In contrast, ordinary materials respond to magnetic fields in various ways. Paramagnetic materials develop weak internal fields aligned with the external field; ferromagnetic materials retain this alignment even after the external field is removed; and diamagnetic materials produce a weak opposing field. Superconductors go a step further—they completely cancel the applied magnetic field within the bulk, due to persistent surface currents, thus behaving as perfect diamagnets. This expulsion is not absolute at the surface. A small region near the boundary allows limited field penetration, characterized by the London penetration depth (λ), typically around 100 nm. Within this depth, the magnetic field decays exponentially before vanishing entirely inside the material.

It is important to distinguish the Meissner effect from the diamagnetic behavior expected in a perfect conductor ³². In a zero-resistance conductor, Lenz's law predicts that a changing magnetic field will induce currents that oppose the change. However, this is a response to external variation. The Meissner effect, by contrast, represents a spontaneous expulsion of magnetic flux as the material transitions into the superconducting state even if the applied magnetic field is static. For example, a material cooled below its critical temperature in a constant field will suddenly expel that field, demonstrating a true phase transition unique to superconductors.

Critical Parameters defining Superconductivity

Superconductivity is governed by a set of key physical parameters that dictate the onset, stability, and limitations of the superconducting state ³³. These parameters not only distinguish between different classes of superconductors but also determine their suitability for practical applications ranging from quantum devices to high-field magnets.

A. Critical Temperature (T_c)

The critical temperature T_c represents the threshold below which a material undergoes a phase transition from the normal resistive state to the superconducting state. This transition is characterized by the complete disappearance of electrical resistance and the onset of the Meissner effect. Above T_c , thermal energy is sufficient to disrupt the Cooper pairs responsible for superconductivity.

Each superconducting material has a distinct critical temperature, determined by its microscopic pairing mechanism and crystal structure³⁴. Conventional superconductors such as niobium-titanium (NbTi) exhibit relatively low $T_c \sim 9.2$ K, while high-temperature superconductors (HTS), such as yttrium barium copper oxide (YBCO), display $T_c \sim 92$ K. Recent breakthroughs in hydride-based superconductors under extreme pressures have yielded materials with T_c values exceeding 200 K, renewing interest in room-temperature superconductivity³⁵.

B. Critical Magnetic Field (H_c)

The critical magnetic field is the maximum magnetic field strength, a superconductor can sustain before the superconducting state is destroyed³⁶. Its behavior differs markedly between Type I and Type II superconductors. In Type I superconductors, superconductivity is abruptly suppressed when the applied field exceeds a single critical value H_c , typically in the range of tens to hundreds of millitesla. This transition is of first-order and marks a sharp boundary between the superconducting and normal phases. Type I behavior is typically observed in pure elemental metals, such as aluminum, lead, and mercury. Although less common, a few binary compounds, including tantalum disilicide (TaSi₂) and boron-doped silicon carbide (SiC:B), also exhibit Type I superconductivity³⁷. These materials are characterized by low critical fields and are generally limited in practical applications due to their sensitivity to magnetic fields and lack of flux pinning.

In contrast, Type II superconductors are characterized by two critical field values: the lower critical field H_{c1} and the upper critical field H_{c2} . For $H < H_{c1}$, the magnetic field is fully expelled from the material, and the superconductor remains in the pure Meissner state. As the field increases beyond H_{c1} , the system enters a mixed or vortex state, where quantized magnetic flux lines penetrate the material while superconductivity persists in the regions surrounding these vortices. The superconducting state is completely destroyed only when the applied field exceeds H_{c2} . Because of their ability to remain superconducting even under strong magnetic fields, Type II superconductors such as various metallic alloys (e.g., niobium-titanium, niobium-tin) and high-temperature ceramic superconductors (e.g., YBCO), are extremely valuable in real-world applications³⁸. They are widely used in technologies requiring strong

magnetic fields, including MRI machines, particle accelerators, and superconducting magnets for power systems.

C. London Penetration Depth (λ)

The London penetration depth (λ) describes how deeply a magnetic field can enter a superconductor. In the superconducting state, magnetic fields do not penetrate the material completely; instead, the field strength decreases rapidly from the surface inward³⁹. The distance over which the field strength drops to about 37% of its original value is defined as the penetration depth. This phenomenon is a direct result of the Meissner effect, where superconductors actively expel magnetic fields. The penetration depth reflects how effectively the material can shield its interior from magnetic fields. It arises due to the response of superconducting electrons (Cooper pairs) to the applied electromagnetic field. The magnetic field inside a superconductor decays exponentially with distance x from the surface according to the expression⁴⁰:

$$B(x) = B_0 e^{-x/\lambda} \quad (1)$$

Where, B_0 is the magnetic field at the surface, x is the depth into the material, λ is the penetration depth.

Typical values of λ range from 50 to 500 nm, depending on the type of material and its temperature. In high-temperature superconductors, the penetration depth tends to be larger and may vary with direction (anisotropic behavior).

D. Coherence Length (ξ)

The coherence length ξ is a fundamental length scale that describes the spatial variation of the superconducting order parameter (or wavefunction)⁴¹. It can also be interpreted as the average size of a Cooper pair, the bound electron pair responsible for superconductivity. In conventional BCS superconductors, ξ can be on the order of hundreds of nm. In contrast, in strongly coupled or high-temperature superconductors, ξ is significantly shorter (1-3 nm), reflecting tighter binding and shorter-range coherence. The coherence length plays a crucial role in determining the response of a superconductor to inhomogeneities and external fields. It is also central to the classification of superconductors via the Ginzburg Landau parameter.

E. Ginzburg Landau Parameter (κ)

The Ginzburg Landau parameter κ is defined as the ratio of the London penetration depth to the coherence length⁴²:

$$\kappa = \frac{\lambda}{\xi} \quad (2)$$

Physically, this parameter compares two key length scales in a superconductor: how deeply magnetic fields can penetrate (λ) and how far the superconducting order parameter can vary (ξ). The value of κ determines how a superconductor responds to an external magnetic field. If $\kappa < 1/\sqrt{2}$, the material is a Type I superconductor, which expels magnetic fields completely until a critical field is reached, beyond which superconductivity is abruptly destroyed. On the other hand, if $\kappa > 1/\sqrt{2}$, the material is classified as a Type II superconductor, which allows partial penetration of magnetic flux in the form of quantized vortices between two critical field values, H_{c1} and H_{c2} . Most practical superconductors, including all high-temperature superconductors, fall under this category due to their large κ values.

F. Critical Current Density (J_c)

The critical current density J_c is the maximum current per unit cross-sectional area a superconductor can carry without losing its superconducting state. Exceeding J_c leads to the motion of vortices (in Type II superconductors) or depairing of Cooper pairs, thereby restoring finite resistance⁴³. The value of J_c is influenced by material purity, temperature, and microstructural defects that act as flux pinning centers. These pinning centers help immobilize vortices, enhancing J_c and enabling the use of superconductors in high-current applications such as power cables, magnets, and fault current limiters.

Theoretical Evolution of Superconductivity

The phenomenon of superconductivity was first discovered in 1911 by Dutch physicist Heike Kamerlingh Onnes, who observed that the electrical resistance of mercury vanished abruptly at 4.2 K, marking the beginning of a new field in condensed matter physics⁴⁴. This remarkable finding raised fundamental questions about the nature of electrical conduction at low temperatures, which could not be explained by classical or early quantum theories. The first major theoretical attempt to describe superconductivity came in 1935, when Fritz and Heinz London introduced the London equations, which provided a phenomenological framework for understanding the expulsion of magnetic fields ‘the Meissner effect’ superconductors⁴⁵. Although the London theory did not address the microscopic origin of superconductivity, it laid the groundwork for understanding the electromagnetic response of superconductors. In 1950, Vitaly Ginzburg and Lev Landau extended the theoretical landscape with the Ginzburg–Landau (GL) theory, a macroscopic theory based on the concept of a complex order parameter that varies smoothly in space⁴⁶. This theory introduced two fundamental length scales - the coherence

length (ξ) and the London penetration depth (λ), led to the definition of the Ginzburg Landau parameter (κ), which allowed the classification of superconductors into Type I and Type II.

The most significant breakthrough came in 1957, when John Bardeen, Leon Cooper, and Robert Schrieffer proposed the BCS theory, providing the first microscopic explanation of superconductivity⁴⁷. The theory described how electrons in a superconductor form Cooper pairs due to an effective attractive interaction mediated by lattice vibrations (phonons). These pairs condense into a collective quantum ground state that can carry current without resistance. The BCS theory successfully explained many experimental results, including the energy gap, isotope effect, and critical temperature dependence. Later advancements included Eliashberg theory, developed in the 1960s, which extended the BCS framework to strong-coupling superconductors by incorporating more rigorous treatment of electron-phonon interactions⁴⁸. This theory became especially important for explaining superconductors where the BCS assumptions of weak coupling were not valid.

In more recent decades, the discovery of high-temperature superconductors in 1986 by Bednorz and Müller posed new theoretical challenges, as these materials could not be fully explained by traditional BCS or Eliashberg theories. This led to the development of alternative frameworks such as the resonating valence bond (RVB) theory by Anderson, and models based on spin fluctuations, non-Fermi liquid behavior, and quantum criticality⁴⁹. Despite intense research, a complete and universally accepted microscopic theory for high- T_c superconductivity remains an open question (**Figure 1**).

A. LONDON THEORY

The London Theory, developed by Fritz and Heinz London in 1935, marks a foundational advancement in the theoretical understanding of superconductivity. As a phenomenological approach, it provides a macroscopic description of superconductors by introducing the concept of a superconducting electron fluid and formulating the now-famous London equations⁵⁰. These equations establish a direct relationship between the current density (\mathbf{J}_s) and the electromagnetic fields (E and B) within a superconducting material, as follows;

$$\mathbf{J}_s = -\frac{1}{\mu_0 \lambda^2} \mathbf{A} \quad (3)$$

$$\nabla \times \mathbf{J}_s = -\frac{1}{\mu_0 \lambda^2} (\nabla \times \mathbf{A}) = -\frac{1}{\mu_0 \lambda^2} \mathbf{B} \quad (4)$$

where, \mathbf{A} denotes magnetic vector potential, and μ_0 stands for the permeability of free space.

One of the key successes of the London Theory is its explanation of the Meissner effect, the complete expulsion of magnetic flux from the interior of a superconductor below its critical temperature. To quantitatively describe this phenomenon, the theory introduced the London penetration depth (λ), which characterizes how far magnetic fields can penetrate into a superconducting material before decaying exponentially⁵¹. While the London Theory does not address the microscopic mechanisms responsible for superconductivity, its macroscopic predictions are consistent with experimental observations and have proven invaluable in shaping further developments in the field. By providing a bridge between empirical results and theoretical interpretations, the London Theory laid the essential groundwork for subsequent quantum-mechanical models, including the Ginzburg-Landau theory and the microscopic BCS framework.

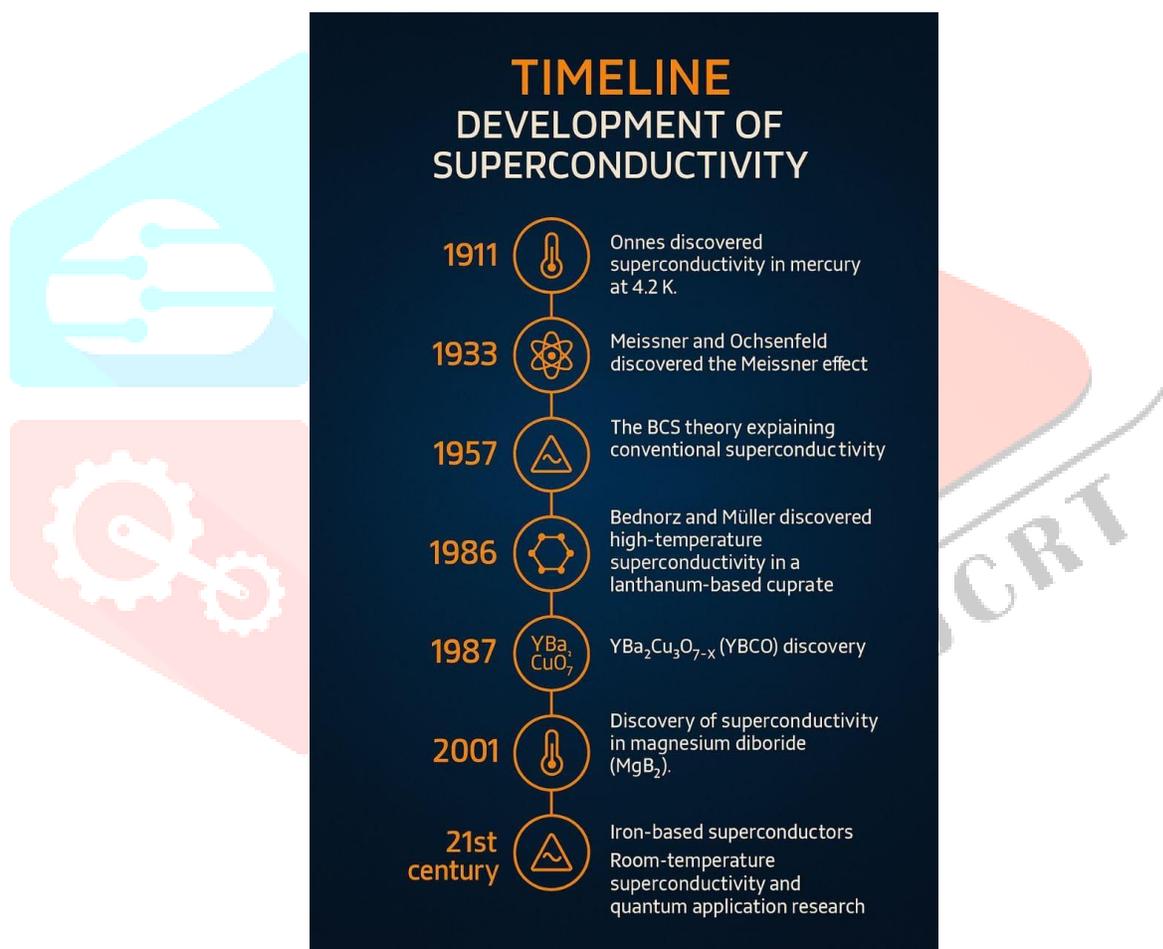
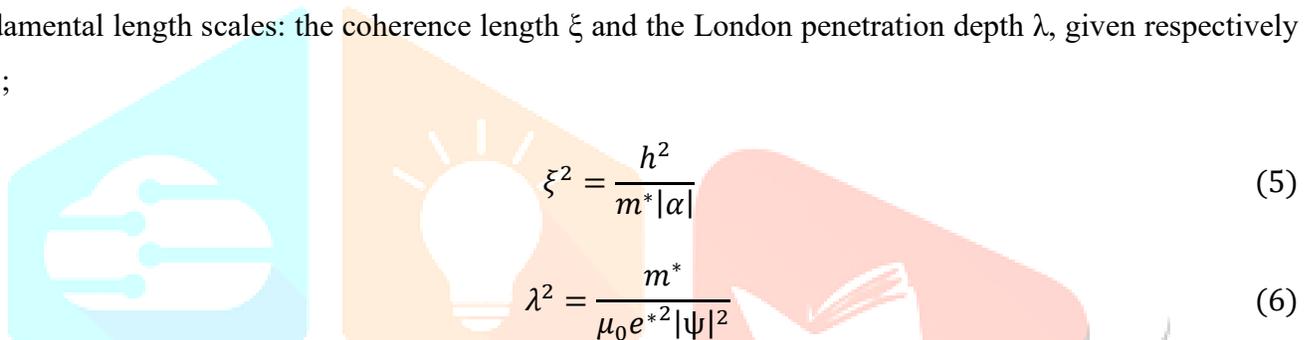


Figure 1. Evolution of superconductivity

B. GINZBURG LANDAU THEORY

In 1950, Soviet physicists Lev Landau and Vitaly Ginzburg developed a phenomenological theory to describe the transition between the normal and superconducting states. The Ginzburg Landau (GL) theory bridges thermodynamics and quantum mechanics, incorporating magnetic field effects and providing

insight into the spatial variation of superconducting properties near the critical temperature T_c . The central idea of the GL theory is the introduction of a complex order parameter or wave function ψ , whose magnitude squared $|\psi|^2$ is proportional to the density of superconducting electrons (Cooper pairs) ⁵². This parameter characterizes the superconducting state: $\psi = 0$ for $T > T_c$ and $\psi \neq 0$ for $T < T_c$, indicating the presence of superconductivity only below the critical temperature. As the temperature approaches T_c from below, the magnitude $|\psi|^2$ gradually decreases, reflecting the reduction in the number of superelectrons. Ginzburg Landau theory also distinguishes between the supercurrent (J_s) and normal current (J_n) contributions to the total current ($J_t = J_s + J_n$). The theory derives the spatial variation of ψ and electromagnetic fields by minimizing a free energy functional, leading to coupled differential equations. The Ginzburg Landau theory not only provided a macroscopic quantum description of superconductivity, but also introduced two fundamental length scales: the coherence length ξ and the London penetration depth λ , given respectively as ⁵³;



$$\xi^2 = \frac{h^2}{m^*|\alpha|} \quad (5)$$

$$\lambda^2 = \frac{m^*}{\mu_0 e^{*2} |\psi|^2} \quad (6)$$

Where, where h is Planck's constant, m^* is the effective mass of a Cooper pair, and α is a temperature-dependent phenomenological parameter, where e^* is the charge of a Cooper pair and μ_0 is the permeability of free space. Together, these parameters form the basis for the Ginzburg–Landau parameter $\kappa = \lambda/\xi$, which fundamentally distinguishes between Type I and Type II superconductors. These length scales, therefore, not only emerge from the theory but also serve as essential tools in classifying and understanding the physical behavior of superconducting materials under magnetic fields.

While the Ginzburg Landau theory provided a successful phenomenological framework to describe many macroscopic aspects of superconductivity such as the spatial variation of the superconducting order parameter and the distinction between Type I and Type II superconductors. However, it lacked a microscopic foundation. The GL theory treated superconductivity as a phase transition and introduced the order parameter ψ , but did not explain the origin of this parameter or the mechanism that leads to zero resistance ⁵⁴. As experimental techniques advanced, it became clear that a deeper, microscopic theory was needed to explain phenomena such as the formation of the energy gap, the role of lattice vibrations, and the temperature dependence of superconducting properties. This gap in understanding set the stage for a major breakthrough in 1957, when Bardeen, Cooper, and Schrieffer developed a microscopic theory of

superconductivity that successfully explained its origin in terms of electron pairing through lattice-mediated interactions.

C. BCS THEORY

Another breakthrough came in 1957 with the development of the Bardeen Cooper Schrieffer (BCS) theory, formulated by American physicists John Bardeen, Leon N. Cooper, and John Robert Schrieffer. Their pioneering work provided the first theoretical explanation of the underlying mechanism behind superconductivity and earned them the Nobel Prize in Physics in 1972. At the heart of the BCS theory is the concept of Cooper pairing - a phenomenon where electrons near the Fermi surface form bound pairs via a weak attractive interaction mediated by lattice vibrations, known as phonons⁵⁵. Although electrons naturally repel each other due to their negative charge, the BCS model showed that an indirect attraction can arise: as one electron moves through the crystal lattice, it causes a slight local distortion in the positive ion cores, and a second electron is drawn to this deformation. This interaction results in the formation of a Cooper pair, which behaves collectively and occupies a lower energy state, enabling resistance-free current flow. The formation of Cooper pairs opens an energy gap in the electronic density of states at the Fermi level, which must be overcome to break a pair and scatter electrons. This gap is a defining feature of the superconducting state and accounts for the abrupt disappearance of electrical resistance. Moreover, the energy gap is directly linked to the coherence length, one of the characteristic length scales in superconductivity.

Experimental validation of the BCS theory came from observations such as the measurement of this energy gap through microwave absorption experiments and the dependence of the critical temperature on the isotopic mass of the lattice atoms, clear evidence supporting the role of phonons in the pairing mechanism⁵⁶. The BCS theory marked a significant milestone in the understanding of superconductivity, offering the first microscopic explanation for the phenomenon in conventional, low-temperature superconductors (LTS). These materials exhibit superconductivity below a critical temperature $T_c < 30$ K and typically require cooling with liquid helium. LTS materials are generally metallic in nature and include widely used compounds such as niobium-titanium (Nb-Ti) and niobium-tin (Nb₃Sn)⁵⁷. Their stable and predictable superconducting behavior has led to important applications in magnetic resonance imaging (MRI), scientific instrumentation, and particle accelerators. Despite its success, the BCS theory is fundamentally a weak-coupling approximation, assuming that the electron-phonon interaction is small and occurs instantaneously⁵⁸. While this assumption holds for many conventional superconductors, deviations from BCS predictions have been observed in some materials, such as larger energy gaps, enhanced specific heat jumps, and non-standard temperature dependencies⁵⁹. These anomalies pointed to the presence of

strong electron-phonon interactions not captured by the original BCS framework. To address these limitations, the Eliashberg theory was developed in the early 1960s. It extends the BCS theory by incorporating strong-coupling effects and retardation phenomena, acknowledging that the interaction between electrons and phonons is not instantaneous.

D. ELIASHBERG THEORY

Eliashberg theory is an advanced extension of the BCS theory that accounts for strong-coupling and retardation effects in electron-phonon interactions ⁶⁰. Developed by G.M. Eliashberg in 1960, it incorporates a frequency-dependent superconducting gap and electron self-energy through a set of coupled integral equations. Unlike BCS theory, which assumes instantaneous electron pairing, Eliashberg theory includes the finite time delay (retardation) between electron interactions mediated by phonons, making it more accurate for materials with strong electron-phonon coupling. It also introduces the spectral function $\alpha^2F(\omega)$, which quantifies the strength of electron-phonon interactions across different phonon frequencies, and includes the Coulomb pseudopotential (μ^*) to account for electron-electron repulsion ⁶¹. Eliashberg theory successfully explains superconducting behavior in conventional superconductors with greater precision and is essential for understanding high-pressure hydrides and other materials where BCS approximations fail.

The Eliashberg formalism extends the BCS theory to the strong-coupling regime by explicitly incorporating the energy and frequency dependence of the electron-phonon interaction. Unlike the weak-coupling BCS model, which assumes an instantaneous pairing potential, the Eliashberg equations account for retardation effects arising from the finite phonon frequency and describe superconductivity in terms of two self-consistent functions: the frequency-dependent superconducting gap function, $\Delta(\omega)$, and the mass renormalization function, $Z(\omega)$. In the Matsubara frequency representation, the Eliashberg eqns. are expressed as ⁶²;

Mass renormalization function:

$$Z(i\omega_n) = 1 + \frac{\pi T}{\omega_n} \sum_m \lambda(i\omega_n - i\omega_m) \frac{\omega_m}{\sqrt{\omega_m^2 + \Delta^2(i\omega_m)}} \quad (7)$$

Gap function:

$$\Delta(i\omega_n) = \pi T \sum_m [\lambda(i\omega_n - i\omega_m) - \mu^*(\omega_c)] \frac{\Delta(i\omega_m)}{\sqrt{\omega_m^2 + \Delta^2(i\omega_m)}} \quad (8)$$

Where, $\Delta(i\omega_n)$ is the superconducting order parameter, μ^* is the Coulomb pseudopotential describing screened electron–electron repulsion, and ω_c is the characteristic cutoff frequency.

E. RESONATING VALENCE BOND (RVB) THEORY

Resonating Valence Bond (RVB) theory, originally proposed by P.W. Anderson in 1973 and later extended in the context of high-temperature superconductivity in 1987, offers an alternative to conventional electron-phonon pairing mechanisms⁶³. In RVB theory, superconductivity arises from the quantum superposition of singlet valence bond states in a strongly correlated electron system. It is particularly relevant to materials like cuprates, where Mott insulating behavior and antiferromagnetic correlations dominate in the undoped state. Upon doping, these localized singlet pairs become mobile and can condense into a superconducting state without the need for phonon mediation. The underlying physics is captured by the repulsive Hubbard model⁶⁴;

$$H = -t \sum_{\langle i,j \rangle, \sigma} (c_{i\sigma}^\dagger c_{j\sigma} + h.c.) + U \sum_i n_{i\uparrow} n_{i\downarrow} \quad (9)$$

Where, t is the nearest-neighbor hopping amplitude and U is the on-site Coulomb repulsion.

The RVB ground state can be expressed as a superposition of singlet dimer coverings of the lattice with C representing a specific dimer configuration⁶⁵;

$$|RVB\rangle = \sum_C |C\rangle \quad (10)$$

The RVB framework captures the importance of strong electron-electron interactions and spin fluctuations, which are central to the physics of high- T_c superconductors. Unlike BCS or Eliashberg theory, RVB does not rely on a Fermi liquid ground state but instead on a quantum spin liquid picture, making it a cornerstone in theories of unconventional superconductivity.

Superconductivity: Real-World Applications

A. Transportation: Maglev Trains

One of the most striking technological uses of superconductivity is in magnetic levitation (Maglev) trains. These systems harness the unique properties of superconductivity, particularly the Meissner effect, which enables the train to levitate above the track, eliminating physical contact and thereby reducing friction to nearly zero (**Figure 2**).

In a typical setup, the train is equipped with superconducting magnets, while the track contains conventional wire coils⁶⁶. As the train moves, the phenomenon of superconductivity allows these magnets to induce strong and stable currents in the coils, creating dynamic magnetic fields. These fields interact with the superconducting state to provide levitation, stability, and propulsion through a traveling magnetic wave. In this way, Maglev trains achieve high-speed, low-noise, and energy-efficient transportation, demonstrating how this quantum phenomenon can be applied at the macroscopic scale.

B. Medical Applications

The medical applications of superconductivity are a relatively recent development, originating from research conducted during the 1970s⁶⁷. Among the most notable applications is Magnetic Resonance Imaging (MRI), which has become an indispensable diagnostic tool in modern medicine. MRI technology relies on superconducting magnet coils to produce strong, stable, and spatially uniform magnetic fields. These fields are critical for aligning nuclear spins in the body, which then interact with radiofrequency pulses to generate detailed cross-sectional images of internal soft tissues. The use of superconducting materials allows for the creation of magnetic fields in the range of several tesla, while maintaining high field homogeneity over the imaging volume. This capability enables high-resolution and high-contrast imaging, particularly useful for the brain, spinal cord, muscles, and other soft tissue structures⁶⁸.

C. Power Transmission

Superconductors offer a transformative potential for electrical power transmission due to their zero electrical resistance below a critical temperature. In contrast to conventional conductors such as aluminum or copper, which experience resistive losses during transmission, superconductors can carry large currents without energy dissipation. When integrated into the power grid, superconducting cables could eliminate the need for voltage transformation, a process currently used to reduce resistive losses over long distances⁶⁹. This would allow for simplified grid architecture, enhanced transmission efficiency, and substantial cost savings in infrastructure and energy delivery. Additionally, superconducting transmission lines can handle higher current densities, making them particularly advantageous for high-demand urban centers or for transmitting renewable energy over long distances

D. Defence Applications

Superconductors have emerged as critical components in various defence and strategic technologies due to their exceptional electromagnetic properties. In particular, superconducting sensors and magnetometers exhibit extreme sensitivity to weak magnetic fields, making them ideal for detecting subtle magnetic or electromagnetic signals. In space-based defence systems, superconducting devices can be

utilized to identify missile launches by sensing faint thermal or electromagnetic signatures against background noise. Similarly, superconducting magnetometers deployed in marine environments can detect the minute magnetic anomalies produced by submarines, enabling high-precision underwater tracking⁷⁰. These capabilities not only enhance surveillance and early warning systems but also support advanced targeting and situational awareness in complex defence scenarios.

E. SQUID (Superconducting Quantum Interference Device)

A Superconducting Quantum Interference Device (SQUID) is an ultra-sensitive magnetometer capable of detecting extremely weak magnetic fields, often in the femtotesla (10^{-15} T) range. The operation of a SQUID is based on two key quantum phenomena: the Josephson effect and magnetic flux quantization⁷¹. Structurally, a SQUID consists of a superconducting loop interrupted by two Josephson junctions, which allow the device to respond to minute changes in magnetic flux with high precision. Due to their exceptional sensitivity, SQUIDs have found widespread application in both civilian and strategic domains. They are employed in landmine and unexploded ordnance detection, biomagnetic field measurement (such as magnetoencephalography for brain activity mapping), and geophysical surveys for resource exploration and tectonic studies. Their capability to operate in low-field environments with high signal-to-noise ratios makes them indispensable in areas requiring precise magnetic field measurements.

F. Quantum Computing

Superconducting qubits represent one of the most advanced and promising platforms for quantum computing⁷². These qubits are implemented using superconducting circuits, which behave as artificial atoms capable of storing and manipulating quantum information. When operated at ultra-low temperatures—typically in the millikelvin range—these circuits exhibit macroscopic quantum coherence, allowing the qubits to exist in superposition and entangled states, essential features for quantum computation. The intrinsic properties of superconductors, such as zero resistance and low energy dissipation, make them ideal for building scalable, fast, and controllable quantum processors. Significant progress in this field has been driven by major technology companies including Google, IBM, and Rigetti, all of which are actively developing multi-qubit superconducting architectures with the goal of achieving quantum advantage and fault-tolerant computation.

G. Particle Accelerators

Superconductors play a critical role in the operation of modern particle accelerators, enabling the achievement of higher energy levels and improved performance with greater efficiency⁷³. Superconducting magnets are employed to generate strong, stable magnetic fields required to precisely steer and focus high-

energy particle beams along their designated paths. Unlike conventional electromagnets, superconducting magnets operate with negligible resistive losses, significantly reducing the power consumption and cooling requirements of accelerator systems ⁷⁴. In addition, superconducting radio-frequency (SRF) cavities are used to accelerate charged particles to relativistic speeds. These cavities provide high accelerating gradients with minimal energy dissipation, enabling compact accelerator designs and longer operational cycles. The use of superconducting technology has become foundational in large-scale facilities such as the Large Hadron Collider (LHC) at CERN, and is essential for future high-energy physics experiments and advanced accelerator designs.

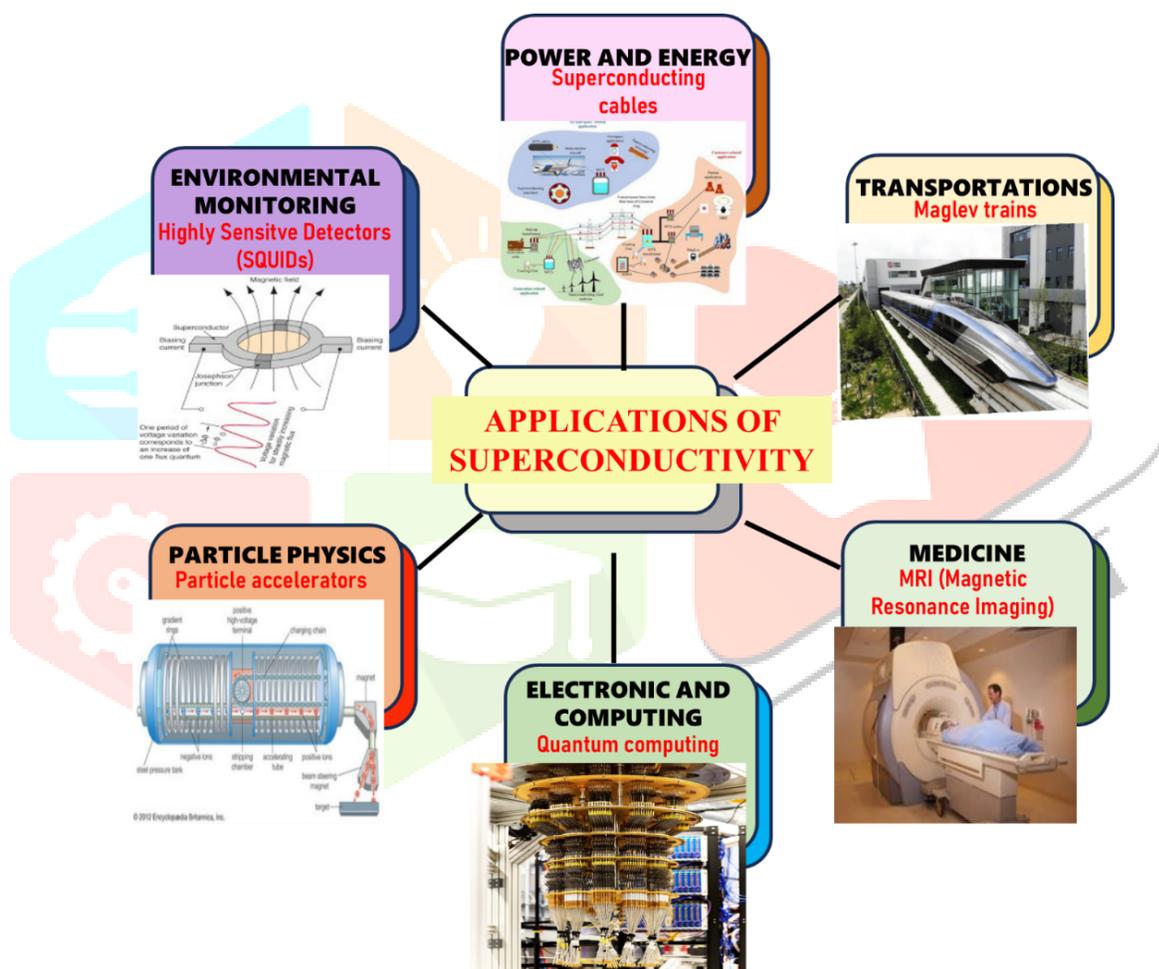


Figure 2. Applications of superconductivity in diverse fields.

Current Challenges and Future Outlook

Although superconductivity presents revolutionary possibilities in energy, computation, and materials science, several persistent challenges continue to hinder its widespread implementation. These challenges span material properties, operational constraints, scalability, and fundamental scientific understanding.

A. Cryogenic Cooling Requirements

Most superconductors require extremely low temperatures, far below ambient conditions, to remain in the superconducting state ⁷⁵. Conventional superconductors typically operate below 10 K and demand liquid helium cooling, while high-temperature superconductors (HTS) such as YBCO function at liquid nitrogen temperatures (77 K). The associated cryogenic systems present significant challenges: they are expensive and energy-intensive, demand complex maintenance with sophisticated thermal insulation and continuous cooling, and are generally impractical for mass-market or decentralized applications. Consequently, the requirement for sustained cryogenic environments remains one of the major barriers to the widespread adoption of superconducting technologies, particularly in mobile, compact, or consumer-oriented devices ⁷⁶.

B. Mechanical and Fabrication Limitations

High-temperature superconductors (HTS) are typically brittle ceramic oxides, which makes them mechanically fragile and difficult to process ⁷⁷. Their brittleness poses several fabrication challenges, including the difficulty of forming flexible wires or tapes, susceptibility to cracking under mechanical strain or thermal cycling, and weak-link behavior at grain boundaries that severely limits current-carrying capability. Although advanced approaches such as coated conductor fabrication and powder-in-tube (PIT) techniques have been developed to overcome these limitations, they remain costly and technologically demanding, thereby hindering large-scale commercial deployment ⁷⁸.

C. Theoretical Limitations

The Bardeen–Cooper–Schrieffer (BCS) theory provides a robust explanation for conventional, phonon-mediated superconductivity; however, it fails to account for the properties of unconventional superconductors such as cuprates, iron-based compounds, and topological materials ⁷⁹. These systems exhibit strong electronic correlations, anisotropic or non-phonon-mediated pairing mechanisms, and often host coexisting or competing orders such as magnetism or charge-density waves. The absence of a unified theoretical framework that can fully capture these complexities remains a major barrier, limiting both predictive material design and a comprehensive understanding of the superconducting state in advanced materials.

D. High-Pressure Constraints

Hydrogen-rich superconductors, such as LaH₁₀ and YH₆, have demonstrated superconductivity at temperatures exceeding 250 K, representing a significant breakthrough toward room-temperature

superconductivity⁸⁰. However, these phenomena occur only under extreme pressures exceeding 150 GPa, necessitating the use of specialized laboratory-scale equipment such as diamond anvil cells, highly controlled environments, and samples of very limited size. The lack of scalable synthesis methods and the impracticality of maintaining such extreme pressures severely restrict their technological potential. Thus, while these materials are of immense scientific interest and provide valuable insights into high-temperature superconducting mechanisms, their applicability remains limited until superconductivity at ambient pressure can be realized.

E. Scalability and Industrial Integration

The transition from laboratory-scale superconducting materials to industrial-scale technologies faces significant challenges, particularly in the fabrication of long, uniform, and defect-free superconducting wires and tapes⁸¹. High-temperature superconductors, being ceramic in nature, complicate scalable processing and demand advanced fabrication techniques that are often costly and time-consuming. Furthermore, compatibility with existing device platforms and integration into practical systems remains a bottleneck, as does ensuring long-term environmental stability against factors such as humidity, vibration, and thermal stress. While considerable progress has been made in developing coated conductors, thin films, and powder-in-tube architectures, efficient mass production with reliable performance and reduced costs is still under development, hindering large-scale commercialization⁸².

F. Magnetic Field and Current Limitations

Superconductors are characterized by critical parameters such as the critical magnetic field and the critical current density, beyond which the superconducting state collapses. For practical applications—including power transmission lines, high-field magnets, and MRI systems, materials must be capable of withstanding strong magnetic environments while carrying large currents without quenching. Additionally, effective engineering strategies are required to suppress energy losses arising from vortex motion and flux creep, which otherwise degrade performance under high-field conditions. Achieving higher critical fields and enhancing vortex pinning stability therefore remains a central challenge, particularly for the development of high-performance superconductors suitable for large-scale and technologically demanding applications.

Future Development of Superconductivity

Despite existing challenges, the field of superconductivity continues to advance rapidly, driven by the pursuit of room-temperature materials, scalable technologies, and deeper theoretical understanding. Future

progress depends on overcoming material limitations, improving theoretical models, and integrating superconductors into practical devices across industries.

A. Toward Room-Temperature Superconductors

One of the most ambitious goals in condensed matter physics is achieving superconductivity at or near room temperature under ambient pressure. Although hydrogen-rich materials such as LaH_{10} and YH_6 have already demonstrated superconductivity above 250 K, they still require extreme pressures exceeding 150 GPa, which makes them unsuitable for practical use. To address this challenge, ongoing research focuses on designing hydride materials stable at lower pressures, exploring alternative crystal structures and light-element compounds, and applying modern approaches such as machine learning and high-throughput simulations to accelerate the identification of promising superconducting candidates ⁸³.

B. Discovery of Novel Superconducting Materials

Beyond hydrides, researchers are actively investigating new families of superconductors such as nickelates, layered two-dimensional materials, and topological superconductors ⁸⁴. Nickelate compounds, often regarded as analogs of cuprates, have exhibited intriguing superconducting behavior and may provide fresh insights into high-temperature mechanisms ²⁸. Two-dimensional materials, including graphene and transition-metal dichalcogenides, display unconventional superconductivity that can be tuned through strain, doping, and interfacial engineering ⁸⁵. Meanwhile, topological superconductors are particularly significant for quantum computing as they can host Majorana quasiparticles capable of supporting fault-tolerant quantum states. Recent advances highlight unconventional superconductivity in twisted bilayer graphene, where moiré superlattices give rise to flat electronic bands and correlated phases, in nickelates with orbital characteristics distinct from cuprates, and in topological superconductors with potential applications in robust quantum information processing. The continued exploration and synthesis of these novel material systems-including layered compounds, organic superconductors, and engineered heterostructures-are critical not only for achieving higher transition temperatures but also for deepening theoretical understanding and uncovering new quantum phenomena ⁸⁶.

C. Theoretical Advancements

The absence of a universal theory for high-temperature and unconventional superconductors remains a major limitation, motivating future theoretical efforts to develop models that incorporate strong electron correlations, quantum fluctuations, and non-traditional pairing mechanisms ⁸⁷. A key goal is to establish connections between superconductivity and broader quantum phases such as spin liquids, charge density waves, and topological order, while also refining non-BCS frameworks, including spin-fluctuation and

resonating valence bond (RVB) models. Such theoretical insights are expected to play a pivotal role in guiding the discovery of new materials and in interpreting the increasingly complex experimental observations⁸⁸.

D. Scalable Fabrication and Integration

Translating laboratory-scale superconducting materials into real-world devices requires scalable and reliable fabrication methods, with future efforts focused on advancing coated conductor technology for flexible, long-length HTS tapes, engineering vortex pinning centers to enhance current-carrying capacity, and developing cryogen-free cooling systems for compact and energy-efficient applications⁸⁹. Integration into practical systems including power cables, fault current limiters, maglev trains, MRI scanners, and quantum processors, is already underway, and continued innovations in fabrication and system-level engineering will be critical for enabling broader and more sustainable deployment.

E. Superconductors in Quantum Technologies

Superconducting circuits are at the forefront of quantum computing, serving as qubits in platforms developed by IBM, Google, and others, with future research focused on improving coherence times and gate fidelity, enhancing scalability for large qubit arrays, and exploring topological protection strategies to reduce quantum error rates⁹⁰. Given their unique advantages, superconducting qubits, sensors, and interconnects are expected to play a central role in advancing quantum technologies over the coming decades.

Conclusion

Superconductivity continues to be one of the most intriguing and transformative phenomena in condensed matter physics. By enabling zero electrical resistance and the complete expulsion of magnetic fields (the Meissner effect), superconductors offer unique opportunities for energy-efficient technologies and advanced applications. Significant theoretical and experimental progress has been made over the past century. Conventional superconductors are well described by the BCS theory, while high-temperature and unconventional superconductors, including cuprates, iron-based compounds, nickelates, and hydrogen-rich materials, challenge our understanding and highlight the importance of strong electronic correlations, spin fluctuations, and non-phonon pairing mechanisms. Recent discoveries in twisted bilayer graphene, two-dimensional materials, and topological superconductors further expand the landscape, offering insights into novel quantum phases and potential routes toward room-temperature superconductivity.

Despite these advances, major practical challenges remain. The reliance on cryogenic cooling, the mechanical fragility of many high-temperature superconductors, limits on current-carrying capacity, and difficulties in scalable fabrication continue to constrain their widespread adoption. Addressing these issues will require improvements in material design, fabrication methods, and system-level integration, along with the development of cryogen-free and energy-efficient cooling solutions. Looking ahead, superconductors hold promise for transformative applications in power grids, transportation, medical imaging, and quantum computing. By combining advances in materials discovery, theoretical understanding, and engineering, the field is poised to bridge the gap between laboratory breakthroughs and real-world technologies, unlocking the full potential of this remarkable quantum phenomenon.

References:

- [1] Sanjinés, R.; Abad, M. D.; Vāju, C.; Smajda, R.; Mionić, M.; Magrez, A. (2011). Electrical Properties and Applications of Carbon Based Nanocomposite Materials: An Overview. *Surf Coat Technol*, 206 (4), 727–733.
- [2] Santana, L. M.; Hickman, C.; Bilak, J.; Singh, C. (2023). Investigating and Improving Student Understanding of Conductors and Insulators. *Educ Sci (Basel)* 13 (3), 242.
- [3] García-Tabarés, L.; Toral, F.; Munilla, J.; González, L.; Puig, T.; Obradors, X. (2025). Perspectives in Power Applications of Low and Mainly High Temperature Superconductors: Energy, *Transport and Industry*. *Riv. Nuovo Cim.* 48 (7), 435–536.
- [4] Bottura, L.; Prestemon, S.; Rossi, L.; Zlobin, A. V. (2022). Superconducting Magnets and Technologies for Future Colliders. *Front Phys*, 10, 1–26.
- [5] Maas, A.; Kox, A. J. (2025). Albert Einstein, Heike Kamerlingh Onnes and the Discovery of Superconductivity. *Eur J Phys*, 46 (5), 055805.
- [6] Bardeen, J.; Cooper, L. N.; Schrieffer, J. R. (1957). Theory of Superconductivity. *Phys Rev*, 108 (5), 1175.
- [7] Cava, R. J.; Batlogg, B.; Krajewski, J. J.; Farrow, R.; Rupp, L. W.; White, A. E.; Short, K.; Peck, W. F.; Kometani, T. (1988). Superconductivity near 30 K without Copper: The Ba_{0.6}K_{0.4}BiO₃ Perovskite. *Nature*, 332 (6167), 814–816.
- [8] Rao, C. N. R.; Raveau, B. (2002). Structural Aspects of High-Temperature Cuprate Superconductors. *Acc Chem Res*, 22 (3), 106–113.
- [9] Bednorz, J. G.; Müller, K. A. (1988). Perovskite-Type Oxides—The New Approach to High-Tc Superconductivity. *Rev Mod Phys*, 60 (3), 585.

- [10] Ren, Z. A.; Zhao, Z. X. (2009). Research and Prospects of Iron-Based Superconductors. *Adv Mater*, 21 (45), 4584–4592.
- [11] Löthman, T.; Schmidt, J.; Parhizgar, F.; Black-Schaffer, A. M. (2022). Nematic Superconductivity in Magic-Angle Twisted Bilayer Graphene from Atomistic Modeling. *Commun Phys*, 5 (1), 92
- [12] Yue, C.; Miao, J. J.; Huang, H.; Hua, Y.; Li, P.; Li, Y.; Zhou, G.; Lv, W.; Yang, Q.; Yang, F.; Sun, H.; Sun, Y. J.; Lin, J.; Xue, Q. K.; Chen, Z.; Chen, W. Q. (2025). Correlated Electronic Structures and Unconventional Superconductivity in Bilayer Nickelate Heterostructures. *Natl Sci Rev*, 12 (10).
- [13] Sato, M.; Ando, Y. (2017). Topological Superconductors: A Review. *Rep Prog Phys*, 80 (7), 076501.
- [14] Boeri, L.; Hennig, R.; Hirschfeld, P.; Profeta, G.; Sanna, A.; Zurek, E.; Pickett, W. E.; Amsler, M.; Dias, R.; Eremets, M. I.; Heil, C.; Hemley, R. J.; Liu, H.; Ma, Y.; Pierleoni, C.; Kolmogorov, A. N.; Rybin, N.; Novoselov, D.; Anisimov, V.; Oganov, A. R.; Pickard, C. J.; Bi, T.; Arita, R.; Errea, I.; Pellegrini, C.; Requist, R.; Gross, E. K. U.; Margine, E. R.; Xie, S. R.; Quan, Y.; Hire, A.; Fanfarillo, L.; Stewart, G. R.; Hamlin, J. J.; Stanev, V.; Gonnelli, R. S.; Piatti, E.; Romanin, D.; Daghero, D.; Valenti, R. (2022). The 2021 Room-Temperature Superconductivity Roadmap. *J Phys Condens Matter*, 34 (18), 183002.
- [15] da Silva, F. F.; Fernandes, J. F. P.; da Costa Branco, P. J. (2021). Barriers and Challenges Going from Conventional to Cryogenic Superconducting Propulsion for Hybrid and All-Electric Aircrafts. *Energies*, 14 (21), 6861.
- [16] Zhou, Y. H.; Park, D.; Iwasa, Y. (2023). Review of Progress and Challenges of Key Mechanical Issues in High-Field Superconducting Magnets. *Natl Sci Rev*, 10 (3).
- [17] Papageorgiou, P. G.; Oureilidis, K. O.; Christoforidis, G. C. (2023). A Systematic Review of Hybrid Superconducting Magnetic/Battery Energy Storage Systems: Applications, Control Strategies, Benefits, Limitations and Future Prospects. *Renew Sustain Energy Rev*, 183, 113436.
- [18] Onnes, H. K. (1911). The Resistance of Pure Mercury at Helium Temperatures. *Commun Phys Lab Univ Leiden*, 120.
- [19] Roque, A.; Sousa, D. M.; Fernão Pires, V.; Margato, E. (2017). Superconductivity and Their Applications. p 4.
- [20] Bauch, T., Babaev, E., Blamire, M.G., Brun, C., Buzdin, A., Carlström, J., Cren, T., Dobrovolskiy, O., Ge, J., Gladilin, V.N. and Goltsman, G.N., 2017. *Superconductors at the Nanoscale: From Basic Research to Applications*. Walter de Gruyter GmbH & Co KG.
- [21] Balachandran, S.; Tarantini, C.; Lee, P. J.; Kametani, F.; Su, Y. F.; Walker, B.; Starch, W. L.; Larbalestier, D. C. (2019). Beneficial Influence of Hf and Zr Additions to Nb_{4at%}Ta on the Vortex Pinning of Nb₃Sn with and without an O Source. *Supercond Sci Technol*, 32 (4), 044006.

- [22] Yao, C.; Ma, Y. (2021). Superconducting Materials: Challenges and Opportunities for Large-Scale Applications. *iScience*, 24 (6).
- [23] Bednorz, J. G.; Müller, K. A. (1986). Possible High T_c Superconductivity in the Ba-La-Cu-O System. *Z Phys B Condens Matter*, 64 (2), 189–193.
- [24] Kamihara, Y.; Watanabe, T.; Hirano, M.; Hosono, H. (2008). Iron-Based Layered Superconductor La[O₁-XF_x]FeAs (X=0.05–0.12) with T_c = 26 K. *J Am Chem Soc*, 130 (11), 3296–3297.
- [25] Chow, S. L. E.; Ariando, A. (2025). Nickel Age of High-Temperature Superconductivity. *Adv Mater Interfaces*, 12 (4), 2400717.
- [26] Zhang, Y.; Su, D.; Huang, Y.; Shan, Z.; Sun, H.; Huo, M.; Ye, K.; Zhang, J.; Yang, Z.; Xu, Y.; Su, Y.; Li, R.; Smidman, M.; Wang, M.; Jiao, L.; Yuan, H. (2024). High-Temperature Superconductivity with Zero Resistance and Strange-Metal Behaviour in La₃Ni₂O₇- δ . *Nat Phys*, 20 (8), 1269–1273.
- [27] Tinkham, M. (2012). *Introduction to Superconductivity*, 2nd ed.
- [28] Kozhevnikov, V. (2021). Meissner Effect: History of Development and Novel Aspects. *J Supercond Nov Magn*, 34 (8), 1979–2009.
- [29] Parhizgar, F.; Black-Schaffer, A. M. (2021). Diamagnetic and Paramagnetic Meissner Effect from Odd-Frequency Pairing in Multiorbital Superconductors. *Phys Rev B*, 104 (5), 054507.
- [30] Matasov, A.; Krasavina, V. (2020). Prediction of Critical Temperature and New Superconducting Materials. *SN Appl Sci*, 2 (9), 1482.
- [31] Guidry, M.; Sun, Y.; Wu, L.-A.; Pluchino, A.; Rodríguez, A.; Tirnakli, U. (2021). The Superconducting Critical Temperature. *Symmetry*, 13 (5), 911.
- [32] Huang, H.; Wang, M.; Yan, X.; Song, H.; Duan, D.; Cui, T.; Du, M. (2025). High-Temperature Superconductivity of Ternary Cs-In-H Compounds at Low Pressure. *Phys Rev B*, 111 (22), 224502.
- [33] Black, W. C.; Johnson, R. T.; Wheatley, J. C. (1969). Critical Magnetic Field Curve of Superconducting Tungsten. *J Low Temp Phys*, 1 (6), 641–667.
- [34] Gottlieb, U.; Lasjaunias, J. C.; Tholence, J. L.; Laborde, O.; Thomas, O.; Madar, R. (1992). Superconductivity in TaSi₂ Single Crystals. *Phys Rev B*, 45 (9), 4803.
- [35] Bennár, M.; Španková, M.; Talacko, M.; Gregor, M.; Kronek, J.; Chromik, Š. (2024). Enhancement of YBCO Superconductivity by Chemical Surface Treatment. *J Mater Sci Mater Electron*, 35 (21), 1472.
- [36] Hanaguri, T.; Iino, Y.; Maeda, A.; Fukase, T. (1995). Magnetic-Field Dependence of the London Penetration Depth in Type-II Superconductor V₃Si. *Physica C*, 246 (3–4), 223–227.
- [37] Bluhm, H. (2007). Magnetic Fields above the Surface of a Superconductor with Internal Magnetism. *Phys Rev B*, 76 (14), 144507.

- [38] Benfatto, L.; Toschi, A.; Caprara, S.; Castellani, C. (2002). Coherence Length in Superconductors from Weak to Strong Coupling. *Phys Rev B*, 66 (5), 054515.
- [39] McConville, T.; Serin, B. (1965). Ginzburg-Landau Parameters of Type-II Superconductors. *Phys Rev*, 140 (4A), A1169.
- [40] Ramzi, A.; Taoufik, A.; Senoussi, S.; Tirbiyine, A.; Abaragh, A. (2005). The Critical Current Density J_c in High Quality $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Thin Films. *Physica A*, 358 (1), 119–122.
- [41] Maas, A.; Kox, A. J. (2025). Albert Einstein, Heike Kamerlingh Onnes and the Discovery of Superconductivity. *Eur J Phys*, 46 (5), 055805.
- [42] Kozhevnikov, V. (2021). Meissner Effect: History of Development and Novel Aspects. *J Supercond Nov Magn*, 34 (8), 1979–2009.
- [43] Talantsev, E. F.; Hänisch, J.; Minkov, V. S. (2025). Intrinsic and Extrinsic Characteristic Lengths, Ginzburg-Landau and Ginzburg-Levanyuk Parameters in Superconducting Elements, Compounds, Hydrides and Ruddlesden-Popper Nickelate Thin Films. SSRN Preprint.
- [44] Bardeen, J.; Cooper, L. N.; Schrieffer, J. R. (1957). Theory of Superconductivity. *Phys Rev*, 108 (5), 1175.
- [45] Marsiglio, F. (2020). Eliashberg Theory: A Short Review. *Ann Phys*, 417, 168102.
- [46] Baskaran, G.; Zou, Z.; Anderson, P. W. (1987). The Resonating Valence Bond State and High-T_c Superconductivity—A Mean Field Theory. *Solid State Commun*, 63 (11), 973–976.
- [47] Edwards, W. F. (1981). Classical Derivation of the London Equations. *Phys Rev Lett*, 47 (26), 1863.
- [48] Mikitik, G. P. (2025). Determination of the London Penetration Depth with the Tunnel Diode Oscillator Technique. *Phys Rev B*, 111 (2), 024514.
- [49] Miloević, M. V.; Geurts, R. (2010). The Ginzburg–Landau Theory in Application. *Physica C*, 470 (19), 791–795.
- [50] Stoof, H. T. C. (1993). Time-Dependent Ginzburg-Landau Theory for a Weak-Coupling Superconductor. *Phys Rev B*, 47 (13), 7979.
- [51] Berger, J. (2024). Case of Thermodynamic Failure in the Ginzburg-Landau Approach to Fluctuation Superconductivity. *Phys Rev B*, 109 (2), 024501.
- [52] Anghel, D. V. (2019). New Phenomenology from an Old Theory—The BCS Theory of Superconductivity Revisited. *Physica A*, 531, 121804.
- [53] Henheik, J.; Lauritsen, A. B. (2022). The BCS Energy Gap at High Density. *J Stat Phys*, 189 (1), 5.
- [54] Yang, H. D.; Lin, J. Y.; Lin, J. G.; Ho, J. C. (2019). Low-Temperature Specific Heat of Superconductors II: Progress in the New Era. *Chinese J Phys*, 61, 212–226.

- [55] Baran, V. V.; Dukelsky, J. (2021). Variational Theory Combining Number-Projected BCS and Coupled-Cluster Doubles. *Phys Rev C*, 103 (5), 054317.
- [56] Drozdov, A. P.; Eremets, M. I.; Troyan, I. A.; Ksenofontov, V.; Shylin, S. I. (2015). Conventional Superconductivity at 203 Kelvin at High Pressures in the Sulfur Hydride System. *Nature*, 525, 73–76.
- [57] Marsiglio, F. (2020). Eliashberg Theory: A Short Review. *Ann Phys*, 417, 168102.
- [58] Xiong, S. (1990). Eliashberg Equations and Coulomb Pseudopotential for Superconductivity via Sign-Opposite Interactions. *Commun Theor Phys*, 14 (2), 203.
- [59] Norman, M. R. (1987). Mass Renormalizations and Superconductivity in Heavy-Fermion UPt₃. *Phys Rev Lett*, 59 (2), 232.
- [60] Pauling, L. (1968). The Resonating-Valence-Bond Theory of Superconductivity: Crest Superconductors and Through Superconductors. *Proc Natl Acad Sci USA*, 60 (1), 59–65.
- [61] Zhang, F. C. (1988). High T_c Superconductivity—Hubbard Model? *Recent Progress in Many-Body Theories*, 31–37.
- [62] Zhang, F. C.; Gros, C.; Rice, T. M.; Shiba, H. (1988). A Renormalised Hamiltonian Approach to a Resonant Valence Bond Wavefunction. *Supercond Sci Technol*, 1 (1), 36.
- [63] Bray, J. W. (2009). Superconductors in Applications: Some Practical Aspects. *IEEE Trans Appl Supercond*, 19 (3), 2533–2539.
- [64] Boiko, O.; Stryczewska, H. D. (2025). Superconductivity and Cryogenics in Medical Diagnostics and Treatment: An Overview of Selected Applications. *Appl Sci*, 15 (23), 12579.
- [65] Lvovsky, Y.; Jarvis, P. (2005). Superconducting Systems for MRI—Present Solutions and New Trends. *IEEE Trans Appl Supercond*, 15 (2), 1317–1325.
- [66] Thomas, H.; Marian, A.; Chervyakov, A.; Stückrad, S.; Salmieri, D.; Rubbia, C. (2016). Superconducting Transmission Lines—Sustainable Electric Energy Transfer with Higher Public Acceptance. *Renew Sustain Energy Rev*, 55, 59–72.
- [67] Fan, Z. (2025). Superconducting Magnets for High Power Microwave Systems: Performance Enhancement and Future Prospects. *Superconductivity*, 15, 100194.
- [68] Vasyukov, D.; Anahory, Y.; Embon, L.; Halbertal, D.; Cuppens, J.; Neeman, L.; Finkler, A.; Segev, Y.; Myasoedov, Y.; Rappaport, M. L.; Huber, M. E.; Zeldov, E. (2013). A Scanning Superconducting Quantum Interference Device with Single Electron Spin Sensitivity. *Nat Nanotechnol*, 8 (9), 639–644.
- [69] Huang, H. L.; Wu, D.; Fan, D.; Zhu, X. (2020). Superconducting Quantum Computing: A Review. *Sci China Inf Sci*, 63 (8), 180501.
- [70] Rossi, L.; Bottura, L. (2012). Superconducting Magnets for Particle Accelerators. *Rev Accel Sci Technol*, 5, 51–89.

- [71] Qiu, D.; Gong, C.; Wang, S. S.; Zhang, M.; Yang, C.; Wang, X.; Xiong, J. (2021). Recent Advances in 2D Superconductors. *Adv Mater*, 33 (18), 2006124.
- [72] da Silva, F. F.; Fernandes, J. F. P.; da Costa Branco, P. J. (2021). Barriers and Challenges Going from Conventional to Cryogenic Superconducting Propulsion for Hybrid and All-Electric Aircrafts. *Energies*, 14 (21), 6861.
- [73] Liang, G.; Caldwell, R. R. (2025). Cold Dark Matter Based on an Analogy with Superconductivity. *Phys Rev Lett*, 134 (19), 191004.
- [74] Zhou, Y. H.; Park, D.; Iwasa, Y. (2023). Review of Progress and Challenges of Key Mechanical Issues in High-Field Superconducting Magnets. *Natl Sci Rev*, 10 (3).
- [75] Huang, H.; Yao, C.; Dong, C.; Zhang, X.; Wang, D.; Cheng, Z.; Li, J.; Awaji, S.; Wen, H.; Ma, Y. (2017). High Transport Current Superconductivity in Powder-in-Tube Ba_{0.6}K_{0.4}Fe₂As₂ Tapes at 27 T. *Supercond Sci Technol*, 31 (1), 015017.
- [76] Sharma, R. G. (2015). A Review of Theories of Superconductivity. *Springer Series in Materials Science*, 214, 109–133.
- [77] Eremets, M. I.; Minkov, V. S.; Drozdov, A. P.; Kong, P. P. (2024). The Characterization of Superconductivity under High Pressure. *Nat Mater*, 23 (1), 26–27.
- [78] Yamada, Y. (2024). Large-Scale Commercialization of High-Temperature Superconducting Wires and Challenges in Compact Fusion. *JSAP Review*, 2024, 240102.
- [79] Liu, S. M.; Shi, J. J.; He, Y.; Tian, C.; Zhu, Y. H.; Wang, X.; Zhong, H. X. (2024). High-Throughput Study of Ambient-Pressure High-Temperature Superconductivity in Ductile Few-Hydrogen Metal-Bonded Perovskites. *Adv Funct Mater*, 34 (41), 2315386.
- [80] Kopelevich, Y.; Torres, J.; da Silva, R.; Oliveira, F.; Diamantini, M. C.; Trugenberger, C.; Vinokur, V. (2024). Global Room-Temperature Superconductivity in Graphite. *Adv Quantum Technol*, 7 (2), 2300230.
- [81] Seegmiller, C. C.; Baird, S. G.; Sayeed, H. M.; Sparks, T. D. (2023). Discovering Chemically Novel High-Temperature Superconductors. *Comput Mater Sci*, 228, 112358.
- [82] Yan, X.; Zheng, H.; Li, Y.; Cao, H.; Phelan, D. P.; Zhang, Z.; Hong, H.; Wang, G.; Liu, Y.; Bhattacharya, A.; Zhou, H.; Fong, D. D. (2025). Superconductivity in an Ultrathin Multilayer Nickelate. *Sci Adv*, 11 (1), 4572.
- [83] Wines, D.; Choudhary, K.; Biacchi, A. J.; Garrity, K. F.; Tavazza, F. (2023). High-Throughput DFT-Based Discovery of Next Generation Two-Dimensional Superconductors. *Nano Lett*, 23 (3), 969–978.
- [84] Alade, I. O.; Rahaman, M. S.; Qahtan, T. F. (2022). A Comprehensive Review of Superconductivity Research Productivity. *J Supercond Nov Magn*, 35 (10), 2621–2637.

- [85] Li, Y.; Xu, Y. (2021). First-Principles Discovery of Novel Quantum Physics and Materials: From Theory to Experiment. *Comput Mater Sci*, 190, 110262.
- [86] Tolpygo, S. K.; Bolkhovsky, V.; Rastogi, R.; Zarr, S.; Day, A. L.; Golden, E.; Weir, T. J.; Wynn, A.; Johnson, L. M. (2019). Advanced Fabrication Processes for Superconductor Electronics: Current Status and New Developments. *IEEE Trans Appl Supercond*, 29 (5).
- [87] Ersoz, T. T.; Mohamed, A. E. M. A.; Attallah, M. M. (2025). Additive Manufacturing of Superconductors: Opportunities and Challenges. *Mater Res Bull*, 189, 113448.
- [88] AbuGhanem, M. (2025). Superconducting Quantum Computers: Who Is Leading the Future? *EPJ Quantum Technol*, 12 (1).
- [89] Wang, T. X.; Huang, D. X.; Ding, F. Z.; Dong, H.; Yu, H.; Dun, C. C.; Gu, H. W. (2024). A Review of Vortex Pinning in REBa₂Cu₃O_{7-x} Coated Conductors. *cMat*, 1 (1), e12.
- [90] Columbus Chinnappan, C.; Thanaraj Krishnan, P.; Elamaran, E.; Arul, R.; Kumar, T. S. (2025). Quantum Computing: Foundations, Architecture and Applications. *Engineering Reports*, 7 (8), e70337.

