The Role of Physics in Modern Multidisciplinary Research: Applications in Healthcare, Energy, Environment, and Artificial Intelligence

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Abstract
Physics as the basic science of matter, energy and their interactions has transformed from a science of pure research to specifically a science that is the backbone of applied research in almost all areas of scientific and technological advancements. The review provides insight into physics' impact on four key disciplines which have a significant cross-over interest, but where physics is playing a growing role: healthcare, renewable energy, environmental monitoring and artificial intelligence, which is essentially an umbrella technology enabling the other key technologies, here under the label 'nanotechnology'. Physical concepts had been introduced into modern medicine by the use of diagnostic imaging techniques (X-rays, MRI, biopsy) and radiotherapy; the study of physical systems that transform energy efficiently into other form, including PV systems and thermodynamic systems, is an indicator of moving towards sustainable energy system. The atmosphere belongs to the realm of statistics (condensed matter theory) and quantum information science: Environment could be measured remotely with high precision, and physics of the atmosphere may be used for developing environment dependent software for machine learning and computational modelling. Following the end of the Review, a summary of the frontier areas of physics where multidisciplinary (multi-physics) physics is central and will be expected to play a key part in the future applications is added, including quantum sensing, physics-informed AI, quantum computing, etc.
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1. Introduction

Throughout the history of the world physics has been able to study the fundamental laws of matter and energy. However, in the last decades the number of applications has dramatically increased and beside the activities of physical modelling and measurements, a lot of research topics were opened up including modelling and prediction of climate change, medicine and energy engineering, and recently, the AI models. The change in the Science paradigm is part of a recent trend, the problem in the real world is rarely purely physical, besides some involve a mixture of processes belonging to different sciences and increasingly important: science driven processes, of the computer science and engineering side, or processes of biological and environmental sciences, or driven by physics [2].

As well, it is emerging as a new power in the field that is attempting to unite physics with other disciplines such as medical labs using magnetic resonance imaging, photovoltaic cells on roofs, atmospheric temperature probes at altitudes above the earth and statistical physics for deep learning algorithms [3]. In this review paper, occurrences will be summarized for those themes and a few idea sessions will be added to the potential future themes. This was not intended to be an in-depth discussion of any of the sub-fields, nor were any one of the papers discussed on any level technologic; rather it was hoped that the use of illustrative examples and representative papers of the day would demonstrate that physics is still a connecting agent in the continuing research, multidisciplinary in nature, and will remain so in the future.

Where physics adds anything to these other fields, it gives them a whole bunch of new ideas that others don't have: wave mechanics, thermodynamics, the notions of statistical inference, quantum theory, and even the notion of 'equation. In medicine, mathematics of wave propagation is used to create images from information transmitted by the signal, in energy engineering waves are used to limit the efficiency of all generation technologies (theorem of the heat engines and thermodynamics of the heat engines are used), in environmental studies, the use of wave propagation is needed to interpret data from the satellites, and in artificial intelligence, knowledge of the interaction of particles and its description are used to explain how a network learns. They are general and so physics is not just an applied special subject but it is a language that others use which they need to learn to use when they formalize their problems in the formal language of the other's subject of problems.

2. Physics in Medicine

One of the most of the oldest and important branches of physics / applied physics is medical physics. The different diagnostic imaging techniques, which are based on the principles of electromagnetism, nuclear physics and wave mechanics, include: X-ray computed tomography (CT); magnetic resonance imaging (MRI); positron emission tomography (PET) and ultrasound [5]. For instance, CT differentiates between tissue types based on physics of x-ray attenuation and reconstructing algorithms to render cross section images of the body would have been recognised with the Nobel Prize in Physiology or Medicine for its development [6]. Unlike MRI however, which exploits the quantum mechanical effect of MRI generated by a powerful magnetic field and radiofrequency pulse that are used to probe the properties of tissues in terms of their nuclear magnetic relaxation properties [7] .

Yet another example of physics helping to shed light on a medical need. Precise dosimetry calculations, based on the physics of particle interaction with material, and utilized for instance in intensity-modulated radiation therapy (IMRT) and proton beam therapy, can be used to modulate therapeutic doses of radiation and not affect surrounding healthy tissues [8]. The medical physicists have to assist the physicians in their daily clinical work—acts as a liaison between medicine and physics—when treating patients in treatment planning, in quality assurance and also radiation harm reduction [9].

This means that biophysics at the fundamental level (of biological process) and at the molecular and cell level contributes significantly to imaging and therapy. These physical phenomena based technologies are all valuable for understanding the structure of protein and guiding drug development – X-ray crystallography, cryo-EM and single molecule spectroscopy. But the benefits pretty much speak for themselves: and there's also the potential to use computational biophysics to model molecular interactions, predict potential binding sites of a drug molecule to a biological target and enhance pharmaceutical research and personalized medicine.

Furthermore, the technique of low-coherence interferography, which is a fundamental principle of the optical coherence tomography (OCT), employed in physics for developing new diagnosis devices such as the creation of cross sectional images of tissue with high resolution. There are other methods such as photoacoustic imaging, which uses optical excitation/detection of ultrasonic signals for imaging vascular structures. In medicine, fluid dynamics can be applied to help describe the flow of blood in blood vessels and through heart valves etc. It can also be applied to assess cardiovascular risk, design heart valves etc. In the current context, wearable health monitors are in use for the continuous measurement of physiological parameters such as heart rate, blood oxygen saturation or physical activity sectorial fields focused on transforming the physiological signals and outputs into clinically relevant information through the signal processing, piezoelectricity and optic means. All of them are medical uses of Physics in the three stages of a medical diagnosis, therapy/treatment and monitoring of the patient.

Modality	Underlying Physics Principle	Primary Clinical Role
X-ray CT	X-ray attenuation & tomographic reconstruction	Cross-sectional anatomical imaging
MRI	Nuclear magnetic resonance	Soft-tissue imaging without ionizing radiation
PET	Positron-electron annihilation, gamma detection	Metabolic and functional imaging
Ultrasound	Acoustic wave reflection	Real-time soft-tissue and fetal imaging
IMRT / Proton Therapy	Particle-matter interaction, dosimetry	Targeted tumor irradiation
Optical Coherence Tomography	Low-coherence interferometry	High-resolution retinal/tissue imaging

Table 1. Representative medical physics modalities, their governing physical principles, and clinical applications.

3. Physics in Renewable Energy

The effort to making sustainable energy systems—a next fundamental level—in most respects is a physics based exercise. The PV technology is based on the photoelectric effect and the semiconductor band theory [11] which was proposed in the beginning of the twentieth century and was fully developed in the following decades in the course of the physics of solids. Solar devices such as perovskites and multi-junction devices have brought PV near to the thermodynamic limits-Ze Busc? Delarowe! and significant progress has been made in materials science & physics to the thermodynamic limitation.

Wind energy also uses the principles of fluid mechanics to optimize the design of wind turbines and extract as much energy as possible from the fluctuating wind speeds since they are also variable [13]. Beyond the battery designs of lithium-ion battery systems and new solid state batteries, electrochemistry and condensed matter physics are important to control various alternative energy storage systems that are crucial to meet the intermittency of non-conventional energy sources. Last but not least, thermodynamics find its applications in the study of a new generation of nuclear fusion reactors that aims at reproducing thermonuclear processes in a laboratory setting on the Earth, where the first generation of reactors that maintained stable fusion for long periods is recent and brought fusion closer than ever to ''net energy gain''' for the first time in the history of research [15].

Network theory, Statistical physics of networks are also well used tools to solve the problems related to load balancing and energy management (energy resiliency in the case of variable energy supply of renewable energies). Based on real-time data from sensors and through the use of the prediction models of the algorithmic functions (which are based in control-theory and statistical mechatronics) smart grid technologies predict which needs vary and reconroute power in certain ways to minimize the losses of the distribution that result in an overall more stable performance of the system. Another field of physics that is currently just starting to grow is hydrogen energy systems: electrolysis and catalysis, as well as thermodynamic efficiencies, are used to shed light on the potential of hydrogen as a clean energy source and a method of transferring energy in more complex energy systems that have been in operation for a longer time, such as heavy industry and long-distance transport. All of these highlight the physics of these energy supplies and energy storage, transport and of integrating renewable energy into current energy infrastructure.

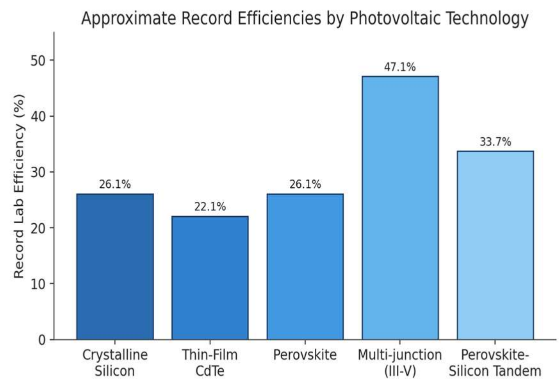

Figure 1. Approximate record laboratory efficiencies by photovoltaic technology (illustrative).

To demonstrate this, Table 2 lists some of the principal engineering challenges faced for several examples of renewable/energy storage technologies and highlights that engineering challenges of each of these technologies are associated with well-defined physical mechanisms and not purely the economics or engineering.

Technology	Governing Physics	Principal Challenge
Photovoltaics	Photoelectric effect, band theory	Approaching thermodynamic (Shockley–Queisser) efficiency limits
Wind turbines	Fluid dynamics, aerodynamics	Optimizing blade geometry across variable wind regimes
Lithium-ion batteries	Electrochemistry, condensed matter physics	Energy density, cycle life, thermal stability
Nuclear fusion	Plasma physics, thermodynamics	Sustained confinement at net energy gain
Hydrogen electrolysis	Electrochemistry, catalysis, thermodynamics	Conversion efficiency and catalyst cost

Table 2. Physical mechanisms and key engineering challenges across renewable energy and storage technologies.

4. Physics in Environmental Monitoring

Within the CCD class of instruments, depending on the physics of the atmosphere, remote sensing, etc. specialized instruments are used, based on concepts of electromagnetic radiation and of spectroscopy to measure the average composition of the upper layers of atmosphere and sea surface temperature, the thickness of ice sheets and the vegetation condition throughout the globe [16]. Predictions of international climate change rely on the physics of models of radiative energy transfers in the atmosphere, a system that can transfer radiative energy and interact with the GHGs found in the atmosphere [17].

To map terrain and forest canopy structure and dispersion of pollutants, high-spatial-resolution mapping is conducted using laser-based light detection and ranging (LiDAR), with the assistance of physical sensor networks, similar to how airborne – and terrestrial – LiDAR are used to measure forest canopy structure and pollutant dispersion. A subfield of geophysics, seismic wave propagation is studied in earthquake engineering and seismology to learn about what goes on in the earth, such as determining the risk of natural hazards; and in Oceanography, acoustic and pressure measurement tools are used to investigate ocean currents, temperature differential, the health of the ocean, and the propagation of sound and pressure throughout ocean habitats.

Monitoring based on environmental physics is also important in monitoring anthropogenic changes, such as monitoring of air quality degradation and growth in greenhouse gases. At parts per billion (ppb) trace levels of atmospheric gas detection is able to assist regulatory agencies and researchers in precisely measuring certain emissions of particular interest and therefore gaining more knowledge about these emissions and what products they come from, thereby helping to develop more scientific solutions that address environmental degradation [20]

To explain how the ocean and atmosphere interact it is important to utilize physical modelling techniques, and to study phenomena like El Niño-Southern Oscillation (ENSO) events and their global climatic response. Likewise, instruments measurements, ice cores, sediment layers, and tree rings can allow scientists to dissect natural climates from human-induced climates due to the methods they use that are based on the physics of radioactive decay. In concert, these physics based tools are the observational and analytical backbone of modern day environmental science, both as a means to scientific discovery, and as evidence-based environmental policy.

Technique	Physical Principle	Representative Application
Satellite spectroscopy	Electromagnetic absorption/emission spectra	Atmospheric composition monitoring
LiDAR	Laser time-of-flight ranging	Forest canopy and terrain mapping
Seismometry	Elastic wave propagation	Earthquake detection and hazard assessment
Radiative transfer modeling	Energy transport through absorbing media	Climate prediction
Radiometric dating	Radioactive decay kinetics	Paleoclimate reconstruction

Table 3. Environmental monitoring techniques, their physical basis, and representative applications.

5. Artificial Intelligence and Computational Physics

Physicists and AI are going hand-in-hand and it's picking up speed. In contrast, statistical mechanics and dynamical systems theory have traditionally had a connection to mathematical foundations of neural networks, specifically the energy-based models, and dynamical Boltzmann machines [21]. On the contrary, machine learning techniques are also having new applications inside physics, these include leveraging the technique to uncover patterns in the data associated to high-energy particle collider experiments (e.g., the Large Hadron Collider) and its application to predict properties of substances in condensed matter physics [22].

Pressures caused by the demand for machine learning algorithms to be learned from a known physical process that they are required to model are one example of an important area in which physics and machine learning are converging today, known as physics-informed machine learning (PIML). For example, physics-informed machine learning in fluid mechanics is learning machine learning from the physics of the modeled fluid process that must abide by: flow conservation in fluids. Its ability to do joint interpretation of the model and reduce training data, potentially to improve model interpretability, has also been suggested [23] and is important in some specific fields such as the modeling of fluid dynamics, of climate, or of structures.

Furthermore, there is a close relationship between physics and computation as found in other entities as well, such as quantum computers. The superposition and entanglement are ubiquitous in the Internet today, and will also be used in quantum processors to perform types of calculations that are impossible to perform in a conventional computer. It is now possible, but there is still much research underway looking for a meaningful, early application that will take advantage of a quantum advantage for some specific class of computational problems, with applications to cryptography, optimization and drug discovery in particular being transformative [24].

The physics community simulation with high performance provides on the whole, all the tools necessary to simulate great phenomena, that would be too difficult to view in real time. Modeling air over airplane wings and blood in arteries; protein folding and material fracture on atomic scales; and the production of galaxies on cosmological scales—these are just a few examples of the variety of phenomena that can be modeled using computational fluid dynamics, molecular dynamics and astrophysical simulations, respectively. Relationship of computational physics and other sciences with the research of artificial intelligence (AI) will complement each other even more: computational physics will benefit from the advances of AI research and vice versa AI will benefit from the advances of computational physics.

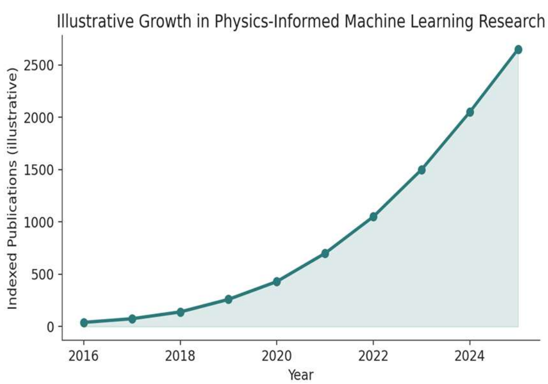

Figure 2. Illustrative growth trend in physics-informed machine learning research activity, 2016–2025.

Table 4 lists some illustrative crossovers of physics and computation, including instances in which AI provides support to physics, and instances in which physics is a collaborator to AI in advancing research in physics.

Convergence Area	Direction of Influence	Representative Example
Energy-based models	Physics → AI	Boltzmann machines inspired by statistical mechanics
Physics-informed neural networks	Physics → AI (constraint)	Networks constrained by PDEs (e.g., Navier–Stokes)
Particle physics data analysis	AI → Physics	Pattern recognition in LHC collision data
Materials discovery	AI → Physics	ML-predicted properties in condensed matter systems
Quantum computing	Physics → Computation	Superposition/entanglement enabling new algorithms

Table 4. Representative convergence points between physics and artificial intelligence/computation.

6. Physics in Nanotechnology

Manipulation scale of 1-100 nm based on quantum physics and condensed matter physics since Manipulation of matter – or what may be termed nanotechnology – is about its manipulation at a scale so small that quantum physics and condensed matter physics is the basis. This uncertainty exists with materials of this size because the electronic band structure and surface to volume ratio might be different from that of bulk materials and such quantum confinement effects could have a significant impact on the behavior of the materials. The interesting is there is a correlation between quantum dots and their optical and electronic properties: Medicines which target specific disease cells, semiconductor quantum dots for efficient LED-displays, tunable properties in designed semiconductor nanostructures in general, are all correlated to the size of the quantum dots.

The field of nanotechnology is interrelated with the others mentioned in this review. In medicine, nanoparticles are used to make images more visible by using contrast agents, in the other alpha-nanoparticles they use engineered nanoparticles that can specifically target cancer cells and not normal cells. The enhanced charge transport properties, surface reactivity in nanostructured materials increase efficiency of solar energy cells and batteries in the field of renewable energy. The ability of nanomaterials to provide an enabling physics platform for a variety of research areas in the environmental sciences, some potentially being realized by a relay, has been identified as a field with great potential for nanotechnology developments.A nanomaterial sensor has been identified as one such nanomaterial with high sensitivity towards pollutants and pathogens and hence will be the enabler Physics Platform for a number of nanoprjective research areas of Environment Sciences.

Another not so recent subfield, nanophotonics, which entails the intersection of optical and engineering issues in the nanoscale, additionally plays a job in manufacturing materials with a detrimental refractive index, and even those that soak up light up to 100% percent. They have a wide variety of applications such as ultra thin solar absorber, advanced research paper about application of camouflages and cloaking etc. In a field that uses the quantum spin information of electrons and magnetic molecules, instead of charge characteristics, it is employed to design a faster, less-energy consuming computer memory and logic device, hence it is called "spintronics. Moreover, as the development of the fabrication techniques go forward, it will be possible to continue to accurately engineer matter at the atomic and molecular level, where this may for now be one of the most fruitful areas of physics driven interdisciplinary innovation.

Domain	Nanoscale Physical Effect	Application
Medicine	Quantum confinement, surface functionalization	Targeted drug delivery, imaging contrast agents
Energy	Increased surface-area-to-volume ratio	Higher-efficiency solar cells and batteries
Environment	Enhanced surface reactivity	Ultra-sensitive pollutant/pathogen sensors
Electronics	Quantum spin (spintronics)	Energy-efficient memory and logic devices
Optics	Engineered sub-wavelength structures	Metamaterials, near-perfect light absorbers

Table 5. Nanoscale physical effects and their cross-disciplinary applications.

7. Future Scope

There are several new research lines emerging in the coming decades that will become more prominent – physics and other subject areas will be increasingly knitted into one. On the medical front, the merging of quantum sensing with biomedical imaging could offer a qualitatively improved sensitivity and/or disease detection – the earliest time possible diagnosis – as well as an enhanced biophysical modeling and offer a new opportunity for personalized disease treatment.Advances in sensing and imaging systems based on quantum devices may lead to squeezing more information at the 'highest sensitivity of disease detection' at the earliest stages of the disease; and progresses in the field of biophysical modelling could facilitate a much more personalised treatment plan from realising. The energy industry will bring this change by transition to sustainable energy systems, together with the constant progressions of next generation batteries, applications as grid storage and Fusion.

More approximately dense response figures, with higher spectroscopic sensitivity, and physics-based climate models combined with machine learning to better improve the accuracy of climate forecasts, would improve the monitoring of the environment. Last, however, scientists go to great lengths to find another innovation in every of these fields so important to break-throughs that it will have quantum effects – but new and large-scale phenomena: the science of the phenomena observed at scale smaller than the human body – will continue to influence the field in new ways. Combined, all of these trends indicate that, in a few years' time, the science will no longer only be used to realize emerging multidisciplinary research, but will, more and more, also be the method and the very concept of research itself.

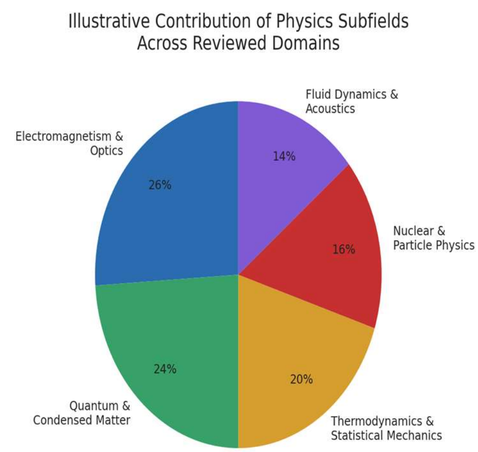

Figure 3. Illustrative contribution of major physics subfields across the domains reviewed in this paper.

8. Conclusion

From the rest of healthcare, to the energy sector, to environmental monitoring, to artificial intelligence and nanotechnology, this review discusses the increasingly crucial applications of physics, and the integral role that physics plays in innovation, outside its strict limits. Many innovations fundamental in today's technological applications such as diagnostic imaging and radiotherapy, photovoltaic energy conversion, remote sensing of the environment from satellites, physics-informed machine learning and nanoscale materials engineering are based on physics. In the description of each of the individual technologies considered, it is clear that the theoretical foundation for a whole technology or research programme, is a specific physical effect such as NMR, the photoelectric effect, radiative transfer, statistical mechanics or quantum confinement. It is even more important to know this structure as a way of positioning physics within the larger framework of scientific activity, but it is also important to understand the way it allows one to foresee the potential sources of future developments: typically where a physicist knows a certain principle in one field, but applies it to a new one, where the scientific problem is new.

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