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A journey through quantum technology

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Abstract. Technology aims to utilise physics to invent things that improve our lives. Our current information technology era is the result of quantum mechanics and the concept of wave-particle duality. Many revolutionary technologies, such as the laser, MRI and integrated circuits were developed from this first quantum revolution. This paper provides a brief summary of these key quantum technologies and investigates some of the ongoing research that may spark a second quantum revolution.

1. Introduction

The first quantum technology revolution ushered in many technologies that are now critical to our modern lives. These innovations are fundamentally based on the concept of wave-particle duality. However, quantum mechanics hosts a range of other phenomena such as entanglement and superposition that are not observed in current devices. Applications that can effectively use these concepts could ignite a second quantum technology revolution. This paper describes some of the key inventions thanks to our understanding of quantum mechanics and highlights the ongoing research towards a second technology revolution.

2. Wave-particle duality

The photoelectric effect sparked much of the first quantum technology revolution. Figure 1 shows the schematic experiment of the photoelectric effect that famous scientists like Heinrich Hertz and Philipp Lenard conducted in the late Victorian era. They observed that illumination of one of the metal plates could generate an electric current in the rest of the circuit. These scientists were puzzled that the generated current changed as the colour of the illuminating light changed. At low frequencies (red light), no current was measured even when they used extremely bright light sources. On the other hand, high frequency light (blue light) could generate a current in the circuit even at low intensities. These results opposed the classical understanding of electromagnetism, which suggested that the intensity of the light was important to the generated current.

Albert Einstein solved the mystery of the photoelectric effect in the early 20th century. He considered the energy of light to be quantised into small packets (photons) rather than continuously distributed throughout the wave. Each photon that struck the metal plate would transfer all of its energy to a single electron. If the energy was large enough, then the electron could escape from the metal plate and jump across the gap to complete the circuit. Einstein linked the energy of a photon to its frequency such that the high frequency photons provided sufficient energy to the electrons, whereas low frequency photons could not excite the electrons out of the metal plate. Further experiments by Robert Millikan confirmed Einstein's theory of the photoelectric effect and thus the mystery was

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solved. The photoelectric effect showed that light could behave as both a wave and as a particle – wave-particle duality.

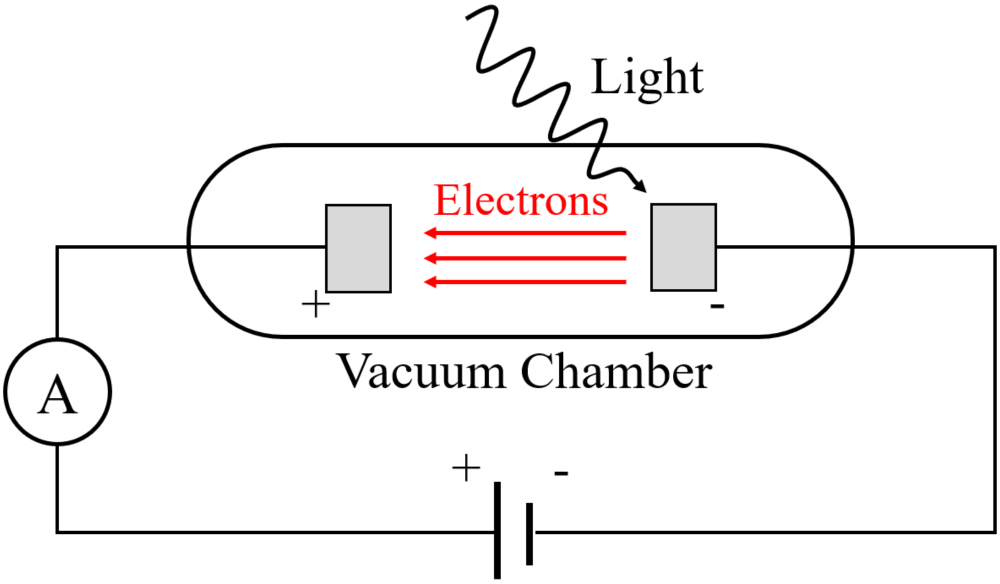

Figure 1. Schematic diagram of an experiment to detect the photoelectric effect.

3. The first quantum technology revolution

Louis de Broglie discovered that wave-particle duality applies to electrons as well as to light. This discovery was critical to the development of semiconductor technology as it allowed an understanding of how electrons can behave as waves. With this knowledge efficient integrated circuits could be developed that form the basis for all modern electronics. It is now known that all quantum-scale things behave according to wave-particle duality and this idea is central to innovations such as lasers, atomic clocks and magnetic resonance imaging (MRI).

3.1. Lasers

Lasers are sources of coherent light. In practice this means that their light is observed to propagate as a beam of a single colour (frequency). As only one colour is present all the energy can be concentrated into a small volume. This property is highly useful for both research, industry and everyday life. For example, manufacturers can use lasers to precisely cut metal and other materials. Another application for lasers is in Lasik eye surgery in which the high precision of lasers is used to directly imprint glasses onto human eyes. As a final example lasers can be used for hair removal by shining infrared light into the skin. The skin is transparent to this light so the laser penetrates the skin to reach and kill the root of the hair. It is important that the right type of light is used to avoid injury; for example, using UV light could easily burn the skin instead of killing the hairs. One of the most important qualities of lasers is the precise control of their colour.

Laser is an acronym for Light Amplification by Stimulated Emission of Radiation which describes the principle of operation (figure 2). Lasers use carefully selected materials that have electron energy levels matching the desired application. The electrons are first excited into a high energy state and then photons of energy matching the gap between electron energy levels are passed into the material. These photons cause the electrons to drop to their lower energy states, emitting a photon with energy matching the energy gap in the process. These emitted photons have properties exactly matching the

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original photons such that they all have the same frequency and phase. This process is called stimulated emission and is critical to generating a coherent laser beam.

The colour of a laser can be changed by choosing materials with different gaps between electron energy levels. For example, ruby is a crystal that produces red light whereas Nd:YAG is a crystal that generates light in the near infrared. Significant research has gone into doping glass to tune the energy levels, which has led to the development of optical fibre lasers. Nowadays the energy levels can be controlled to be almost wherever they are needed.

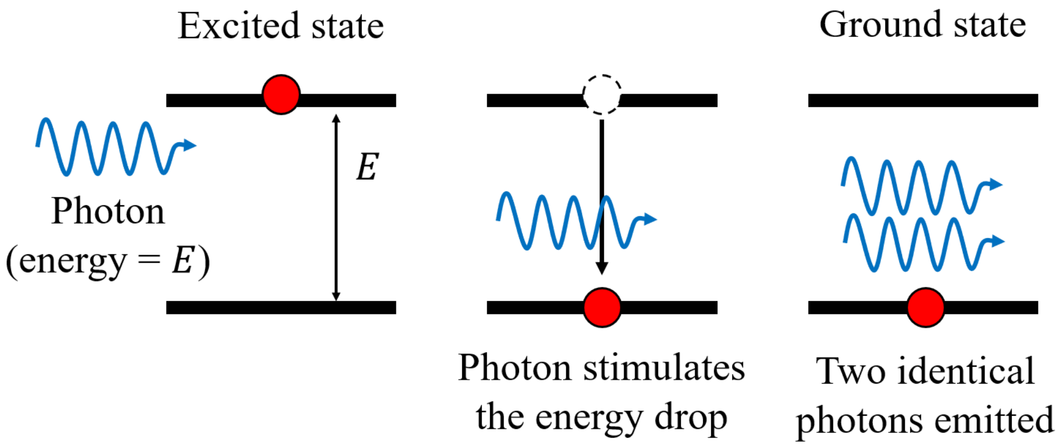

Figure 2. Physics of how a laser works. An incident photon with energy equal to the energy-level gap in the atom stimulates the emission of another identical photon – stimulated emission.

The advances in optical fibre technology are integral to the modern Internet because they enable huge amounts of data to be exchanged daily across the globe at rapid speed. Optical fibres absorb almost no energy, which makes the data communication ultra-efficient. The modern Internet would not be possible with old technology such as telephone cables because they dissipate too much energy as the signal travels.

3.2. Atomic clocks

Timing is essential to communication; messages must be reconstructed in the correct order for meaningful communication with people in different places. Nowadays the best tool for timing is the atomic clock. A typical clock is made of a reference (a pendulum in a grandfather clock) and a counter (a mechanism in the clock). An atomic clock works in a similar manner: there are two electron energy states and an electromagnetic wave is used to transition some of the electrons to the other state. The electromagnetic wave is tuned until the maximum number of electrons switch states. Such a wave resonates with the transition and the number of waves can now be counted. If two atomic clocks are made with caesium by different people, then the nature of the atom ensures the oscillations of both clocks are identical. This property is why the second is defined in terms of oscillations of a caesium atom (previously the Sun was used to define the second). Significant research has improved the counter and reference of the atomic clocks such that accuracies of 10^{-18} s are now possible.

4. Towards a second quantum technology revolution

Wave-particle duality is only one of the many strange phenomena of quantum mechanics. Concepts such as entanglement and superposition are yet to appear in everyday technologies, but there is immense potential for revolutionary innovations based on these phenomena. For example, quantum

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communication, quantum sensing and quantum computers are all being intensively researched across the world.

4.1. Next-generation atomic clocks
There is a great need for portable, small-scale atomic clocks that can provide accurate timing at exact locations on the ground. For example, local gravity sensors require time references so that an acceleration can be measured. These sensors would enable the mapping of what is beneath one's feet. Next-generation atomic clocks will also enable enhanced navigation, allowing for the Earth to be profiled to greater accuracy and for precision agriculture to be possible. Furthermore, these clocks would benefit stock exchanges by time tagging each trade, something that is currently quite challenging.

4.2. Enhanced MRI
MRI is a quantum technology that has already saved many lives. It works by aligning the spin of the atoms in the body with a magnetic field and sending radio waves through the body, which change the alignment of the atoms. When the radio waves are removed, the atoms will realign and emit their own radio signals in the process. The MRI detects these signals and uses their properties to identify the local environment of the atoms and what tissue they are part of. More accurate magnetic sensors are under development that aim to make MRI machines smaller with much greater accuracy.

4.3. Quantum computing
Conventional computers contain bits that are either in the on (1) state or the off (0) state. Through combinations of bits and logic, a computer can be created. A quantum computer works differently: it has qubits, which are in a superposition of the on and off states. If the number of superposition states is increased, then much information can be stored in a single particle, which would enable extremely efficient computation. Quantum computers offer advantages in solving certain problems, such as the factorisation of prime numbers and the generation of random numbers. These problems may appear abstract, but they are fundamental to cracking secure communications, which makes control of this technology critically important.

5. Conclusion
Quantum technologies have already revolutionised our lives, however there are many other quantum phenomena that promise new innovations. The second quantum technology revolution may soon arrive with technologies that will benefit society in the ways that the laser, the atomic clock and MRI already have.