# Chapter 1

# Introduction

## 1.1 Context and motivation

### 1.1.1 Optics and photonics: past and present

Originally thought of as two separate forces, it was not until the work of Maxwell in 1873 that electromagnetism became viewed as a single force. Although it is just one of four currently known fundamental forces in nature, the rest being weak nuclear force, strong nuclear force, and gravity, electromagnetic force is responsible for practically all physical phenomena one encounters in daily life above the nuclear scale, with the exception of gravity. For example, from binding atoms together to form molecules and compounds that make rocks, living things, and virtually everything on the planet, to delivering energy from the sun to the earth, to allowing plants to make food, to providing energy to living things, including humans. Throughout history, our knowledge has grown from observation of macroscopic electromagnetic phenomena to the understanding of the behaviors of elementary particles (photons) that mediate electromagnetic forces. This force carrier exhibits both wave-like phenomena (e.g., electromagnetic wave interference, diffraction) and particle-like phenomena such as the photoelectric effect as discussed by Einstein in 1905. It was not until the work of Dirac in 1920s that quantum electrodynamics theory was developed. Paul Dirac, who is regarded as the founder of quantum electrodynamics (QED), being the first to use that term, first developed the quantum theory that describes the interaction between matter and light (radiation). This work was key to the development of quantum electrodynamics theory by notable physicists Schwinger, Feynman, Tomonaga and Dyson, and with the work of Glauber and Sudarshan, formulating QED in a complete and coherent fashion, in full agreement with quantum mechanics and special relativity.

Over the centuries, man has learned how to utilize electromagnetism for countless improvements to our quality of life. Exploiting classical electromagnetic wave effects, optical apparatus have been

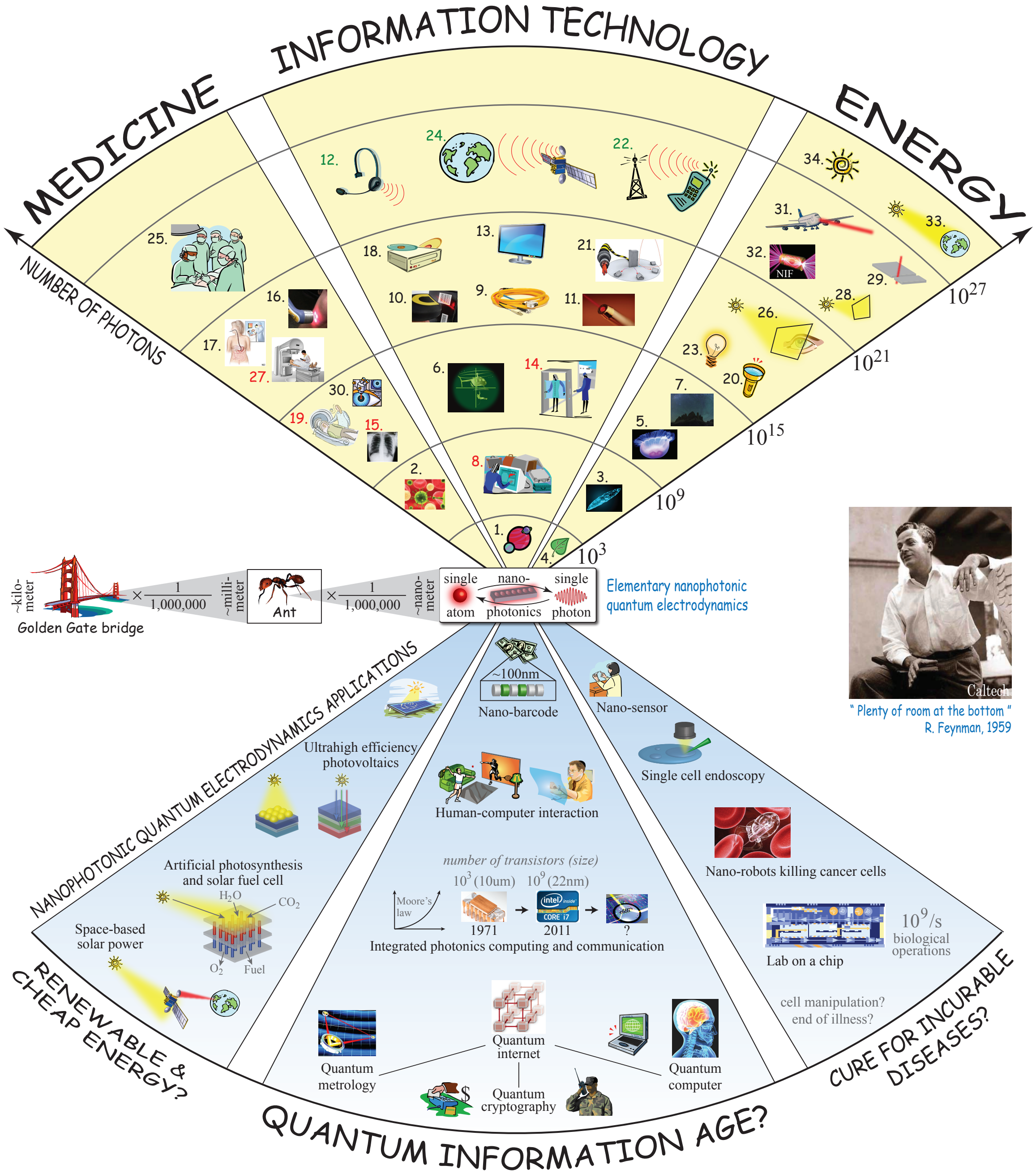


Figure 1.1: **Top:** Optics and photonics applications in medicine, information technology and energy, sorted by the number of photons along the radial axis, for radio/microwave (labelled in green), visible/infrared (black), and x-ray (red) photons. The number labels are ordered in increasing optical power, which correspond to Table 1.1. **Center:** Single atom and photon as the building block for elementary quantum matter-light interactions gives insights into future nanophotonics applications and powerful quantum technologies beyond the classical realm (bottom section), as predicted by celebrated physicist and Nobel laureate Richard Feynman in 1959.

Table 1.1: Descriptions and numerical values used for Figure 1.1. The relevant time scale for comparison, $\Delta t$, is 1 second in most cases except for certain processes as listed.

| No. | Item | Power (W) | $\lambda$ | Time, $\Delta t$ (s) | # photons/$\Delta t$ |
|---|---|---|---|---|---|
| 1 | Exoplanet signal | $4.10^{-20}$ | 1 $\mu$m | 3600 | 720 |
| 2 | Single cell microscope | $2.10^{-14}$ | 405 nm | 0.1 | $3.10^{3}$ |
| 3 | Plankton bioluminescence | $2.10^{-10}$ | 500 nm | 0.1 | $6.10^{7}$ |
| 4 | Photosynthesis (per $CO_2$) | $3.10^{-9}$ | 700 nm | $1.10^{-9}$ | 10 |
| 5 | Jellyfish bioluminescence | $8.10^{-8}$ | 500 nm | 1 | $2.10^{11}$ |
| 6 | Nightvision goggle | $2.10^{-6}$ | 555 nm | 1 | $4.10^{12}$ |
| 7 | Moonless night sky | $3.10^{-6}$ | 555 nm | 1 | $8.10^{12}$ |
| 8 | Security bag x-ray | $1.10^{-5}$ | 15 pm | 1 | $8.10^{8}$ |
| 9 | Optical fiber link | $1.10^{-3}$ | 1.55 $\mu$m | 1 | $8.10^{15}$ |
| 10 | Barcode scanner | $3.10^{-3}$ | 671 nm | 1 | $8.10^{15}$ |
| 11 | Laser pointer | $3.10^{-3}$ | 671 nm | 1 | $8.10^{15}$ |
| 12 | Bluetooth | $3.10^{-3}$ | 12.5 cm | 1 | $2.10^{21}$ |
| 13 | LCD screen | $5.10^{-3}$ | 464 nm | 1 | $1.10^{16}$ |
| 14 | Security person x-ray | $8.10^{-3}$ | 21 pm | 1 | $8.10^{11}$ |
| 15 | Chest x-ray | $1.10^{-2}$ | 25 pm | 1 | $1.10^{12}$ |
| 16 | Laser therapy | $1.10^{-2}$ | 800 nm | 10 | $5.10^{17}$ |
| 17 | Endoscopy | 0.1 | 500 nm | 1 | $3.10^{17}$ |
| 18 | DVD burner | 0.3 | 640 nm | 1 | $8.10^{17}$ |
| 19 | Chest CT scan | 0.4 | 25 pm | 1 | $5.10^{13}$ |
| 20 | Flashlight (5W) | 0.5 | 600 nm | 1 | $2.10^{18}$ |
| 21 | Telecom fiber network | 0.5 | 1.55 $\mu$m | 1 | $4.10^{18}$ |
| 22 | Cell phone | 1 | 17 cm | 1 | $8.10^{23}$ |
| 23 | Light bulb (60W) | 6 | 600 nm | 1 | $2.10^{19}$ |
| 24 | GPS satellite | 20 | 20 cm | 1 | $2.10^{25}$ |
| 25 | Laser surgery | 50 | 10 $\mu$m | 5 | $1.10^{22}$ |
| 26 | Sunlight (1m$^2$, visible) | $2.10^{2}$ | 555 nm | 1 | $4.10^{20}$ |
| 27 | Radiation therapy | $4.10^{2}$ | 12 pm | 1 | $2.10^{16}$ |
| 28 | Sunlight (1m$^2$, total) | $1.10^{3}$ | 500 nm | 1 | $3.10^{21}$ |
| 29 | Laser cut (1mm steel, 1m) | $5.10^{3}$ | 10 $\mu$m | 6 | $2.10^{24}$ |
| 30 | LASIK | $1.10^{5}$ | 193 nm | $1.10^{-8}$ | $1.10^{15}$ |
| 31 | Laser weapon | $1.10^{6}$ | 1.32 $\mu$m | 5 | $3.10^{25}$ |
| 32 | National Ignition Facility | $5.10^{14}$ | 351 nm | $2.10^{-8}$ | $2.10^{25}$ |
| 33 | Sun energy on earth | $1.10^{17}$ | 500 nm | 1 | $3.10^{35}$ |
| 34 | Sun energy (total) | $3.10^{26}$ | 500 nm | 1 | $7.10^{44}$ |

devised dating back to 8000 years ago (e.g., one of the earliest man-made mirrors found in Anatolia) [75] and 3000 years ago where ancient Egyptians made one of the very first lenses [252]. Since then more advanced and delicate instruments have been discovered and engineered, with increasing levels of precision and care to the microscopic details of both matter and light; for example telescopes, microscopes and cameras. It was not until the invention of the laser in 1960 that sources of high spectral and angular brightness were realized and utilized. This important capability marks the birth of a new field known as *photonics*, the study of light and other forms of electromagnetic energy whose quantum unit is the photon. The invention of the laser has really changed our society, for example through the discoveries of fiber optic communication that support today's global communication network including the internet, barcode readers, and all the way to laser surgery in medicine. Some applications of optics and photonics in medicine, information technology and energy (including in low energy radio and microwave domains, and in the high energy x-ray domain) are shown in Figure 1.1. They are sorted by the number of photons associated with each system along the radial axis, from $10^{45}$ total photons emitted by the sun in one second, all the way down to 10 photons absorbed in a plant photosynthesis process per one $CO_2$ molecule absorbed. The number labels are in order of increasing electromagnetic power, as shown in Table 1.1 along with the wavelength, time-scales and estimated number of photons. Note that although GPS satellite and cell phone transmissions emit many more photons per Watt than x-ray screeners, the photons are less energetic and importantly less penetrating to the human tissues, such that they are much less harmful to health.

In this context, this thesis focuses on investigating the interaction between matter and light, at one of the most elementary building block levels[1]. More precisely, I report investigations of the interaction between a single atom and a single photon. Although there has been a tremendous global effort in this subject of research, this thesis brings a new dimension to the field, through the study and realization of single atom and photon interactions on a micro- and nano-photonics platform. The significance of micro-/nano-photonics platforms (and nanotechnology in general) will be discussed in Sec 1.1.2. As first predicted in 1959 by the celebrated physicist and Nobel laureate Richard Feynman in his famous quote 'there is plenty of room at the bottom', nanotechnology promises countless revolutionary advancements for the future, even beyond our current imagination.

### 1.1.2 Nanophotonic single atom-photon interaction and the future

In the previous section, we discussed how matter-light interactions in the context of optics and photonics have developed and impacted our world and saw some specific examples shown at the top of Fig 1.1. Although historically there has been a trend of developing understanding towards the increasingly microscopic nature of light leading to powerful and revolutionary technologies (e.g., the laser), one might wonder: Why continue to pursue the trend down to the study of the elementary single atom and single photon interaction at the small nano-scale level (i.e., the focus of this thesis)?

While there are many good fundamental science motivations for pursuing this study, already at the time of writing, there are also numerous practical motivations. Some specific examples are

[1]Although at the time of writing, photons are understood as an elementary particle according to the Standard Model, an atom is not an elementary particle. An atom consists of sub-atomic elementary particles including quarks, gluons and electrons. Detailed study of these sub-atomic particles is a subject of particle physics.

illustrated at the bottom of Fig. 1.1 and discussed below.

#### 1.1.2.1 Medicine

In the world of medicine, nanotechnology offers promising diagnostic (such as nano-sensors and sub-cellular endoscopy) and therapeutic applications. For example, glucose-sensitive nanosensors that fluoresce as glucose levels increase could offer a minimally invasive tool for regular blood glucose monitoring by diabetes patients [37]. In sub-cellular endoscopy, a nanowire waveguide attached to a tapered optical fiber tip could function as a light source inside a single cell and detect optical signals from sub-cellular regions with high spatial and temporal resolution. Furthermore, through light-activated mechanisms the endoscope can provide high-throughput gene and drug delivery with spatio-temporal specificity [256]. The small dimensions and mechanical strength and flexibility as well as high refractive index gives mechanical stability and allows nanowire probes to strongly guide light inside a high refractive index medium of physiological liquids and living cells.

In terms of therapeutic applications, an example is the capability to selectively deliver drugs to diseased tissues or cells [118]. Most of the current schemes typically involve 'decorating' the surface of a nanoparticle that is injected into the body to attach to a specific diseased cells to deliver drugs. Some other schemes involve gold-based nanoparticles that efficiently absorb light in the near-infrared range, which is used for photothermal therapy of cancer [118]. By illuminating the gold nanoparticles that accumulate in a tumor with a laser, an extreme heat can be generated that then destroys the cancer tissues. As time passed, these nano-objects have eventually become advanced nano-robots, capable of fighting diseases from inside the human body. A basic example of this is a logic-gated nanorobot that is made up of DNA strands that can perform molecular logical gates to activate and release its drug payload [68].

In the more distant future, matter-light interaction and nanoscience may play an even more powerful role in the realization of the very large scale integration of a laboratory on a chip [203], where millions and billions of biological operations may be performed at a rapid rate, and where diagnosis and therapy may be conducted at the cellular or sub-cellular levels using a chip-integrated platform similar to today's computer microprocessor chip that contains billions of little transistors. The difference, however, would be that the billions of operations could be performed on biological entities. This could then potentially open the door towards cell-manipulation and even maybe the end of physiological illness. Global efforts that advance this research front are underway, with one of the leading efforts carried out by an international research collaboration led by Caltech's

Prof. Michael Roukes between Caltech and CEA/LETI-Minatec in Grenoble, France, known as the Alliance for Nanosystems VLSI.

#### 1.1.2.2 Energy

Another main area in which nanophotonic matter-light interaction could play a major role is future energy generation or harvesting. Despite the continuous decline in global energy intensity usage due to advancement of technology, the global energy consumption is projected to increase by at least two-fold from 13.5 TW in 2001 to 27 TW in 2050 due to population and economic growth [148]. Although it is estimated that there exist fossil energy reserves to support a 30-TW energy consumption rate globally for at least several centuries, the accumulation of $CO_2$ emission into the atmosphere is already happening at an alarming rate. If it continues to rise, it may surpass a level that has not been present on the planet in at least the past 650,000 years and probably in the past 20 million years, potentially causing severe impacts in weather and the entire planet's ecosystem balance [148]. Among the green renewable energy resources, solar energy is by far the largest exploitable resource, providing more energy in 1 hour to the earth than all of the global energy consumption in an entire year [148].

Some specific examples where nanophotonic matter-light interaction plays a role in futuristic applications are in increasing solar photovoltaic cell efficiencies, for example from $\sim 30\%$ today to $\sim 90\%$, using nanophotonic structures where light density of states can be engineered favorably, and in the utilization of multi-junction solar cells to absorb over a wide range of spectrum of sunlight [188]. Although solar energy is very promising, the intermittency of solar insolation requires a robust and efficient energy storage capability allowing uninterrupted on-demand energy usage by the end user. An exciting idea to solve this problem, which has the added benefit of absorbing $CO_2$ gas, is to create an artificial photosynthesis process where-by using the energy provided by sunlight, water and $CO_2$ molecules can be turned into solar fuel and $O_2$ molecules. That is, to store solar energy in the form of chemical bonds present in the fuel molecules [148]. One research center that currently pursues this area is the Joint Center for Artificial Photosynthesis (JCAP) at Caltech. In the longer term, beyond terrestrial solar energy harvest, one day the world may see space-based solar power, where even more sunlight energy can be harvested as it has not been absorbed by the earth's atmosphere.

#### 1.1.2.3 Information technology

Finally, one of the most directly related applications that utilizes nanophotonic matter-light interaction is information technology. From nano-structured barcodes, potentially saving the world economy hundreds of billions of dollars in annual cost associated with fake banknotes and counterfeiting [163, 27], to the future potential of quantum information technology. As computers become increasingly integrated in our daily lives, human-computer interaction plays an increasingly important role. Emerging display technologies such as transparent, 3D, flexible displays, as well as future computer senses (touch, sight, hearing, taste, smell) applications may utilize nanoscale matter-light interactions. For example, nanophotonic devices could play a role in significantly increasing the out-coupling efficiency of flat screen displays made of organic light emitting diodes (OLEDs) [260], in three-dimensional display technology [76], in information storage devices [230] and in moulding the flow of light more generally [116].

Since the invention of the first transistor in 1947 by Shockley, Bardeen and Brattain at Bell Labs, computer technology has been dramatically transformed and continuously advanced. Starting from Intel's very first microprocessor in 1971 consisting of 2250 transistors, the number of transistors in a microprocessor has roughly doubled every 18 months, a trend known as Moore's law, named after Intel's founder Gordon Moore. The increase in number of transistors has been enabled by continuous miniaturization that reduces the transistor physical size from $10\mu$m in 1971 down to 22 nm for one of Intel's latest iCore 7 microprocessors (in 2011) that consists of about a billion transistors. As this scaling trend continues, the transistor size will ultimately reach atomic length scales, where intrinsic physical limits will arise including quantum effects (e.g., electron tunnelling) and limitations of lithography technology. Even before this limit is reached however, the variability in device performance caused by the statistical nature of individual dopant atom number and locations will impose a scaling limit [82]. In this microscopic regime, precise dopant atom positioning in the semiconductor transistor is critical. Despite this, a single-atom transistor has successfully been demonstrated in a laboratory setting [82], but it is not clear whether this will be what future microprocessors are made of, or whether a transformation towards optical transistor system will occur prior to that point, where photons of light become the carriers of information instead of electrons.

As a carrier of information, light (photons) has several significant advantages over the electron. Firstly, it can travel in a dielectric material at much greater speeds than an electron in a metallic wire. Secondly, it can carry a larger amount of information per second (e.g., the bandwidth of fiber-optic communication[2] is $\sim$ 10 THz whereas the bandwidth of an electronic system such as the telephone is only $\sim$ 100 kHz). Lastly, photons are not as strongly interacting as electrons, which helps in reducing energy losses. Photonics will not only advance computation power but also would dramatically increase the speed of communication. For example, at the time of writing, IBM [199] and Intel have developed a commercial fiber-optic link device with a speed of 25 Gbps and 50 Gbps, envisaging $>$ 1 Tbps speed in the future [181]. Compared with one of the fastest commercially available standard USB 3.0 (5 Gbps) and Thunderbolt electrical connection (10 Gbps) in 2012, it is a significant advancement with more than 100-fold potential speed increase. Although photonic communication technology has already reached commercial ground, the development of optical transistors for future photonic computing has still mainly been developed in a laboratory setting. For example, experimental demonstrations have been achieved to realize various all-optical switches [186, 175, 2], a single-molecule optical transistor [111], and even a single-atom optical transistor [42, 168].

The potential of nanophotonic matter-light interaction at the elementary microscopic level does not stop here. Beyond the classical realm lies the powerful prospect of the direct exploitation of quantum effects that arise at these microscopic level. The prospect and power of quantum information technology are tremendous and may one day exceed even today's most ambitious imagination. One of the biggest challenges lies in the ability to realize and control a network of many quantum objects that can coherently interact internally and externally, which at the same time are highly isolated from the environment. This core enabling architecture known as a quantum network or quantum internet, is central to the development of quantum information technology, and is indeed one of the main focuses of this thesis, as is discussed in the next section (Sec. 1.1.3). Though it may take a long time for transformation from science fiction into reality, more modest technological applications have already become a reality and rapid global research efforts are underway.

### 1.1.3 The quantum internet

A quantum network or quantum internet is a system that consists of many quantum nodes coherently connected by quantum channels [132]. As one of the most rapidly progressing research fields in the last few decades, quantum networks provide opportunities and challenges across a vast range of intellectual and technical frontiers both in fundamental and applied sciences. A review of this subject can be found in this article [132] by Prof. Jeff Kimble of Caltech, my PhD advisor. From an

[2]For example, $\sim 10^3$ wavelength division multiplexing at 10 GHz/channel.

information science perspective, one can view a quantum network as a system that generates, stores, or processes quantum information locally in nodes, which are coherently connected (entangled) with high quantum fidelity by quantum channels. In this view, quantum networks provide a platform for the fundamental study of quantum mechanics, for example in teleportation [83] and entanglement [48] of quantum states, and for applications in quantum information technology including quantum metrology, cryptography, and for the realization of a quantum computer, as illustrated in Fig 1.1. A quantum network can also be viewed alternatively as a collection of components of a physical system making up the nodes, which interact by way of quantum channels. In this context, a quantum network functions in such a way as to simulate the evolution of a quantum many-body system [132].

#### 1.1.3.1 Quantum metrology

Although most current quantum metrology (measurement) systems are modular in the sense that they function as an individual device performing measurements of space and time in the quantum regime, magnificent theoretical and experimental advances have been realized including the measurement of the size of a proton [100], a record-precision optical clock for frequency reference [120], the measurement of Casimir effects [198], and increased sensitivity of gravitational wave detectors using squeezed light [214, 151], where quantum states of light enable ultra-high precision measurements beyond the classical limits [89]. In addition to advancing our fundamental scientific understanding, these have direct practical impacts; for example, a record-precision frequency reference using a single $Al^+$ ion with better than 1 part in $10^{17}$ precision could measure the effect of general relativity through time dilation effects associated with a height difference of 33 cm near the earth's surface [47, 46]. These capabilities have important implications for cosmology and tests of the laws of physics, such as Einstein's theories of special and general relativity, and might lead to new types of gravitational sensors for exploring underground natural resources and fundamental studies of the earth, as well as in ultra-precise global positinioning systems allowing, for example, autonomous landing of aircraft guided by GPS one day. In the further future, one could envisage a network of quantum metrology systems where collective and coherently linked quantum measurements of space and time can be made.

#### 1.1.3.2 Quantum cryptography

In today's information age, information security has become increasingly important and central to many aspects of our society, from enabling secure credit card transactions and global financial trading, to classified government and military communication. Today's state of the art public key cryptography is based on the computational difficulty of factoring large biprime numbers, an algorithm known as the RSA, named after its inventors Rivest, Shamir and Adleman of MIT in 1977. Although it is currently 'secure' because it will take a relatively long time (e.g., tens of years[3]) for today's fastest super computers to break, eventually computing power will increase to a level where this classical algorithm is no longer secure and can be readily broken. Fortunately, there is a solution to this potentially catastrophic end of secure communication, known as quantum cryptography. Here, information security is guaranteed by the laws of physics and hence is in principle unbreakable as long as nature behaves in accordance with the laws of quantum mechanics.

The idea of quantum cryptography was first proposed by Wiesner in 1983 and by Bennett of IBM and Brassard of the University of Montreal in 1984 [90]. In this first generation scheme known as BB84 [22], weak laser pulses at the single photon level are utilized to distribute one-time-pad keys across a quantum channel between two nodes. Here, the laws of quantum mechanics guarantee that it is impossible for any potential eavesdropper to have information about the keys shared between the two nodes, without its presence being detected. Despite tremendous technological advances based on this original scheme leading to the commercialization of companies such as MagiQ Technologies (1999, USA) and idQuantique (2001, Switzerland), major limitations exist with these systems due to their use of weak laser pulses at the single photon level, which lead to slow transfer rate and high cost due to the specialized single photon generator and detector components required. At the time of writing, even the record-performance transfer rate has only achieved $\sim 10^2$ kbit/s [182], and this represents a two order of magnitude improvement over the previous record [182]. Being at the single photon level, another challenge is integration with existing optical fiber communication networks, which operate at a bright ($\sim 10^8$ photons per bit slot of $\sim 10^{-10}$ second) light level. Ensuring the survival of single photons in the midst of these hundreds of millions of photons, and their information security, for two nodes separated by kilometers, is really a tremendous challenge.

One scheme that overcomes the abovementioned problems associated with first generation cryptography schemes uses bright light signal, known as post-selection based continuous variable quantum cryptography [220, 251]. This second generation quantum cryptography scheme significantly increases the bandwidth and speed, which could go beyond gigabits/s —orders of magnitude beyond the record bit rate demonstrated in first generation schemes [182]. In 2006, a successful experimental demonstration [232] of this quantum cryptography scheme was realized under realistic environmen-

[3]For example, an estimate of 20 years secure lifetime for an RSA-2048 key (2048 bits), as discussed in page 233 of [78].

tal conditions for the first time. The focus of my undergraduate research thesis at the Australian National University [4], this proof-of-principle achievement in the laboratory paves the path towards the first commercialization of second generation quantum cryptography technology giving birth to the company QuintessenceLabs, incorporated in 2007 in Australia by our group, cofounded by my undergraduate advisor Prof. Ping Koy Lam and my colleague Dr. Vikram Sharma. An important aspect of the experiment [232, 4], particularly relevant in commercial context, is the ability to utilize standard off-the-shelf components for this bright light system, which significantly lowers the production cost of this type of system. Furthermore, the system allows high integrability to today's optical fiber network infrastructure that continuously carries bright light signals.

#### 1.1.3.3 Quantum computer

Although in performing specific tasks such as searching for an entry in a database and factoring a large number, one can view a quantum computer as a transformatively more powerful version of current classical computers, potentially billions of times faster than all of the current classical computers combined[4], this represents only a glimpse of a small part of the entire prospect and nature of a quantum computer. Fundamentally, a quantum computer is a different kind of computer compared to the classical computers we know today, where unlike classical computers that process information stored in classical states, quantum computers process information stored in coherent quantum mechanical states [143]. Analogous to this is the light that comes from a lightbulb and a laser. While the light from a lightbulb is 'incoherent' in the sense that the many electromagnetic waves generated by the source are emitted at random times with respect to each other[5], a laser light represents a different kind of light where the electromagnetic waves are coherently generated in phase (in time). Unlike a classical computer, central to a quantum computer is its capability to control coherent quantum mechanical waves.

Just as the laser has led to countless useful applications ranging from barcode readers to eye surgery, quantum computers open up prospects for potential new technologies impossible for classical computers. Analogously, just as lasers do not replace lightbulbs for all intents and purposes, a quantum computer is also not necessarily a substitute for a classical computer, but they may rather be complimentary or simply independently useful for different applications. For example, a potential future application of a quantum computer that may be impossible or very difficult for a classical computer to perform is the simulation of complex quantum systems, from artificial nanotechnology

[4]Note that this is the case only for very restricted set of problems of which factoring is most famous.

[5]Strictly speaking, the coherence depends on the length scale in consideration. The light emitted by a light bulb is coherent within its coherence volumes, which are much smaller than the coherence volumes of a typical laser light.

and nanomachinery of biological molecules, to the neural network of the human brain. As nanotechnology engineering advances and changes our world in the coming decades, quantum computers may play an increasingly important role in helping us understand and engineer such technology at the atomic level.

With the abovementioned potency and promise of quantum computers, known and yet to be known, a natural question to ask is what is it that makes the realization of these computers challenging today, and what are the limitations and problems that must be overcome. A formal set of criteria, known as the DiVincenzo criteria, first proposed in 2000 by David DiVincenzo of IBM, outlines seven specific criteria or requirements to be met in the physical implementation of a quantum computer [65, 172]. It is a difficult question, and the simple answer below is likely not complete. One can say however, that there are at least three main physical challenges or requirements at the time of writing that are core to the realization of a practical quantum computer. Firstly, the requirement to isolate the quantum system from the environment, down to the quantum level where, fundamentally, the leak of information from the system out to the environment must be suppressed. Secondly, the efficiency and robustness of the system to perform quantum information initialization, processing and readout, which includes fault tolerance of the system to realistic imperfections. Last but certainly not least, is the requirement of scalability of the system. That is, the ability to scale up the system with an increasing number of qubits (quantum bits) and hence the information processing capacity. Although rapid progress has been made in various platforms using atomic systems, ionic systems, quantum optics, nuclear magnetic resonance, quantum dots and other dopants in solids, superconductors, carbon-based nanomaterials, and even 'anyons' (a type of quantum excitation with fractional quantum statistics), the journey towards a full realization of a quantum computer is still quite long [143, 191]. With each of the systems having its own strengths and limitations, it is not clear which will be the best system to realize a quantum computer in the long term, and it may also be that a heterogeneous system consisting of multiple types of subsystems working in collaboration is required.

A promising system in quantum information science, a quantum network that consists of neutral atoms in its nodes (stationary qubits) coherently linked by photons of light (flying qubits) in its quantum channels has been an active and rapidly evolving global research subject in the last few decades [132]. Here, one challenge is in the realization of a quantum node (atom-photon interface), which demands strong coupling between a single atom and photon despite the intrinsically small atom-photon interaction cross-section. While some limited quantum electrodynamics coupling between a single atom and photon in free-space had been attained [233], the coupling can be greatly enhanced by the use of an optical resonator, a technique that gives birth to a field known as *cavity quantum electrodynamics* (cQED). Here, an atom positioned within the cavity mode volume can interact with the circulating cavity photons millions of times in high finesse cavities, and furthermore, the interaction can be enhanced by increasing the intensity of the electromagnetic field of a single photon, by reducing the cavity optical mode volume, which concentrates the energy of a single photon into a small confined space.

The birth of cavity QED gave great hope for the future of quantum networks utilizing single atoms and photons. Since the first experimental realization of a strongly coupled optical photon and a single atom in 1992 [236], much global progress has been made, leading to demonstrations of various functionalities essential for a quantum network system [131], all the way to a full elementary quantum network unit consisting of two nodes linked by a quantum channel [197].

Although the advances and capabilities demonstrated as mentioned above have been exceptional and critical, it is only a small part of the entire journey towards a fully functional and practical quantum network system. One big challenge is the requirement to make the system scalable, essential for realizing a quantum network with potentially more than hundreds and thousands of quantum nodes. One of the abovementioned conventional systems, for example, could require a large optical table of the size of half of a room full with optical elements weighing more than a tonne, providing the necessary infrastructure support to control and stabilize a single Fabry-Perot cavity, which requires years to make and to function [131, 194]. Here, much detailed attention to the quality and stability of the linear cavity (e.g., of length $\sim 10-50\mu$m), made up of two highly polished mirrors, is required. Moreover, mirror reflectivity exceeding 0.999998 giving a cavity finesse of $> 10^6$, along with $\sim 10^{-15}$ m relative position stability of the mirrors would be required [131, 194]. To move beyond proof-of-principle experiments involving just one or two conventional optical cavities requires a new approach to quantum networks, involving a completely different platform. One of such approach, which is the central topic of this thesis, is to utilize the rapidly developing lithographic micro- and nanotechnology as a platform to perform cavity QED on a nanophotonic chip, opening new possibilities for exploiting parallel fabrication processes to one day realize a quantum network with $N \gg 1$ quantum nodes on a chip. This marriage of cavity QED and nanophotonics is the central theme of this thesis, and is briefly introduced below.

#### 1.1.3.4 The marriage of cavity QED and nanophotonics

As discussed earlier, a few of the main challenges in the realization of a quantum network include isolation from environment, robustness and efficiency, and scalability. With the rapidly progressing field of micro- and nano-fabrication technology driven by the semiconductor industry and fastly growing nanotechnology research community, micro- and nano-scale devices are becoming increasingly advanced and realiable, with increasing quality. Examples of these devices include high quality nanophotonic devices, which can be fabricated in parallel using lithographic techniques, allowing multiple devices to be made simultaneously on a chip. Devices such as a silica optical microtoroidal optical resonator that supports whispering-gallery-modes with quality factors approaching $10^9$, pioneered by Prof. Kerry Vahala of Caltech [240], and high quality silicon nitride nanobeams and photonic crystal cavities developed by Prof. Oskar Painter at Caltech [73], open countless new possibilities in fundamental and applied research and applications, including for atom-photon interaction research, such as cavity QED and quantum networks in general, the theme of this thesis. The projects described in this thesis have been made possible by our close collaboration with Prof. Vahala and Prof. Painter at Caltech, who contributed their expertise in these photonic devices utilized in the experiments in this thesis. These nanophotonic devices interact with an atom located at the $\sim 100$ nanometer scale, which leads to various advantages and challenges. For example, in contrast to conventional Fabry-Perot cavity QED systems, atom-surface interactions play a much bigger role in these nanophotonic device platforms, and certainly is non-negligible. Here, manifestations of Casimir-Polder interactions and presence of surface modes affect an atom's internal electronic structure and its decay rates into the environment, all of which need to be taken into account in consideration of the system's quantum electrodynamics and the spatial confinement of the atoms at these short $\sim 100$ nanometer scale distances. On the upside however, these small nanophotonic structures promise strong atom-photon coupling, intrinsic scalability in their lithographic fabrication, and other capabilities and features such as the formation of 1- or 2-dimensional lattices of atoms with good lattice spacing control, and potentially other more exotic properties that are unique to these types of systems. We note that the intrinsic scalability of these lithographically fabricated nanophotonic devices represents an important step towards the future realization of a quantum network with $N \gg 1$ quantum nodes, fully integrated on a chip. The marriage of these nanophotonic devices and cavity QED advances the frontiers of the study of atom and quantum optics in general. In this thesis, we explore a small subset of these new and exciting possibilities, by looking at some of the issues involved in the setting of waveguide quantum electrodynamics (using optical nanofibers and nanophotonic beams), and cavity quantum electrodynamics (using microtoroidal resonators and nanophotonic cavities), where as we will discuss, in these settings surface-atom interactions play a significant role.

## 1.2 Thesis outline

In this first chapter, we describe the context of this thesis and discuss its relevance to fundamental scientific research and applications in the areas of energy, medicine, and information technology, with focus on quantum network [132] as a promising tool for future quantum metrology, information security, and computation. This thesis investigates matter-light interactions at the building block level of a single atom and photon. More specifically, in this thesis we investigate single atom-photon interactions at $\sim$ 100 nm scale, using nanophotonic devices in a cavity quantum electrodynamics (QED) setting. This marriage between cavity QED and nanophotonics promises great prospects for future quantum and nanophotonic technology and moves forward the research frontier in this field of elementary matter-light interaction.

In Chapter 2, we describe the generic underlying physics of atom-photon interactions in the weak, intermediate, and strong coupling regimes. We explore some of the main atom-photon interfaces developed to date, we discuss and compare the history, current state-of-the-art systems, and the ultimate physical limitations of the various platforms. These platforms include systems without any optical cavity (e.g., free-space and nanophotonic waveguides), and systems with optical cavities (e.g., Fabry-Perot, microtoroidal, and nanophotonic crystal based cavities). We provide a quantitative comparison between the various platforms using atom-photon interaction strength as a figure of merit.

In Chapter 3, we present an experimental overview of three specific platforms considered in this thesis, namely microtoroidal cavity, optical nanofiber, and nanophotonic crystal based structures. In each of the platforms, we present theoretical models relevant to each system, and the setups utilized in the experiments conducted in this thesis. For the optical nanofiber, we also include an overview of the fabrication setup used to make our device. The microtoroidal cavity and nanophotonic crystal based structures are fabricated by our collaborating groups at Caltech, namely the groups of Prof. Kerry Vahala and Prof. Oskar Painter respectively, who shared their pioneering expertise and provided us with the photonic devices central to the experiments described in this thesis.

In Chapter 4, we discuss our experiment where we realized a robust and efficient single photon router using a microtoroidal cavity and single cesium atoms. In this non-classical system, single photons are extracted from an incident coherent state of light and redirected to a separate output with an internal coupling efficiency (probability of a photon being emitted by an atom into the cavity) of $\sim 70\%$ and external coupling efficiency (probability of an intracavity photon being emitted into an optical fiber) of $\sim 90\%$. The ability to generate single photons using a robust and efficient single photon source is one of the basic and important requirements for the realization of quantum networks. Publication related to this chapter: [10].

In Chapter 5, we discuss our experiment where we observed for the first time, strong coupling between a single atom and photon using a monolithic microtoroidal resonator in real time, revealing non-perturbative cavity quantum electrodynamic effects and perturbative atom-surface interaction phenomena due to single atoms located at $\sim 100$ nm from the surface of a silica microtoroidal resonator. While these factors associated with the behavior of electromagnetic field and atom-surface interactions at these sub-wavelength $\sim 100$ nm scales are not significant in conventional cavity QED systems such as in Fabry-Perot cavities, this investigation reveals their importance and provides an initial framework that applies more generally to cavity QED systems based on dielectric nanophotonic devices. While this leads to new challenges, the prospects of cavity QED systems based on lithographically fabricated nanophotonic devices are great, including the realization of quantum networks with $N \gg 1$ nodes. Publication related to this chapter: [5].

In Chapter 6, we discuss our investigations on the dynamics of an atom as a massive particle and quantum electrodynamics of an atom as it interacts with electromagnetic fields near dielectric surfaces of nanophotonic devices. We describe an explicit system consisting of a microtoroidal optical resonator and a tapered optical nanofiber. We present the results of our Monte-Carlo simulations and investigations on possible atom trapping schemes near a microtoroidal resonator. Publication related to this chapter: [228].

In Chapter 7, we discuss our investigations on the utilization of a tapered optical nanofiber device as an interface for trapping and interacting single atoms and photons, building on the pioneering work of Prof. Rauschenbeutel's group of the University of Vienna [248]. We present a state-insensitive (non-intrusive) atom trapping scheme that our group proposed, we discuss the fabrication system that we developed to make high quality tapered nanofibers with the required specifications, and we discuss our experiment that successfully realized our atom trapping scheme using our optical nanofiber, demonstrating state-insensitivity (negligible atomic transition frequency shift and small inhomogeneous broadening) of up to $\sim 800$ trapped atoms and significant atom-photon coupling (single atom resonant absorption of $\approx 8\%$) as measured by absorption spectroscopy. Publications related to this chapter: [91, 142].

In the last chapter (chapter 8), we discuss our initial investigations on nanophotonic crystal based structures for cavity QED with trapped atoms. More specifically, we discuss the feasibility of using silicon nitride nanophotonic waveguides and cavities in the context of single atom-photon interactions. We describe the experimental setup that we developed for this investigation, and discuss the requirements and realization of the cold atom cloud surrounding the nanophotonic device. We present the optical trapping schemes that we investigated, using single- and double-nanobeam structures, and discuss their properties and limitations for experimental implementation. This work is part of an on-going project at the time of writing.