Quantum revolution(s)

Quantum technologies and industry

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2020 – 2021

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I.1. From invention to innovation: market or technology driven?

- An innovation strategy guides decisions on how resources are to be used to meet innovation objectives and thereby deliver value and competitive advantage.
- An innovation strategy identifies the technologies and markets that the company should better develop and exploit to create and capture value.
- Two visions that help guide a company's innovations are usually used: "**technology push**" and "**market pull**".

I.1. From invention to innovation: market or technology driven?

Lack of innovation strategy often results in frustrating pursuit in many companies, with frequent failure of innovation initiatives, despite massive investments of management time and money. Successful innovators such as Nokia, Yahoo or Hewlett-Packard have hard time sustaining their performances.

A striking example is the case of the company Kodak. Kodak was the world's largest photography company that pioneers the snapshot camera, invented the digital camera. It is best known for photographic film products.

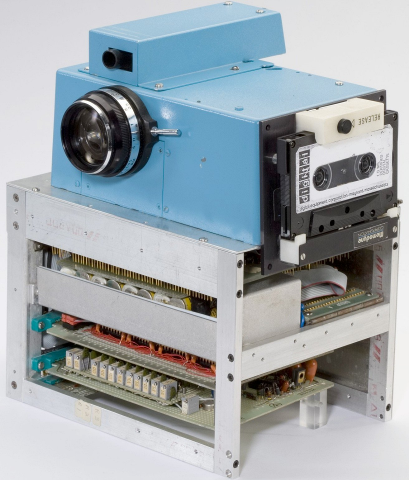
I.1. From invention to innovation: market or technology driven?

Kodak was the world's largest photography company that pioneers the snapshot camera. It is best known for photographic film products.

Kodak as developed the first digital camera in 1975.

Steven Sasson, a 24 years old engineer in charge to see whether there was any practical use for a charged coupled device (C.C.D.), invented a few years earlier.

I.1. From invention to innovation: market or technology driven?



lens.blogs.nytimes.com/2015/08/12/kodaks-first-digital-moment/

The very first digital camera created by Steven Sasson in 1973.

This prototype was the basis for the US patent issued on December 26th, 1978.

I.1. From invention to innovation: market or technology driven?

In 1989, he created the first modern digital single-lens reflex camera, with 1.2 megapixel sensor, and used image compression and memory cards.

But Kodak's marketing department was not interested in it. Steven Sasson was told they could sell the camera, but wouldn't — because it would eat away at the company's film sales.

I.1. From invention to innovation: market or technology driven?

So digital cameras have been developed by other players, and fortunately the invention had been protected with a US patent, which helped Kodak to earn billions of dollars of royalties.

But the patent expired in USA in 2007.

Kodak has begun to focus on digital photography and digital printing in the late 1990s.

It was too late: after an attempt to generate revenues through aggressive patent litigation, Kodak filed for bankruptcy in 2012. Kodak sold many of its patents for approximately $ 525 millions to a group of companies (including Apple, Google, Facebook, Amazon, Microsoft, Samsung, Adobe Systems, and HTC).

I.1. Technology push

Technology Push is when research and development in new technology, drives the development of new products.

Research labs are working on technological developments without any specific issues to solve on the market, but aim at creating new objects. This new objets will found their market (or not) afterwards.

It tends to start with a company developing an innovative technology and applying it to a product. The company then markets the product. **It's usually the situation when innovation occurs from fundamental research in an academic laboratory.**

Example of technology push good: touch screens

- In the mid 1960s: touch Screen technology appeared as published research by E.A. Johnson at the Royal Radar Establishment, a research center in United Kingdom.
- In the 1980s: Hewlett Packard introduced a touch screen computer.
- In 1993: hand writing recognition is introduced by Apple's Newton personal digital assistant (PDA).
- In 1996: Palm introduced its Pilot Series of personal assistant.
- Since 2007: a milestone has been reached with the development of smartphones, in which touch screen becomes a central element, followed by tablets.

I.1. Technology push

If today a touch screen is a natural objet in our all-day life, nobody was asking for a touch screen in the 1960s!

That is why it is a technology push innovation, because the technology has created a market without any demand from consumers.

The first research paper on the topic (1965) has been published more than forty years before its final most common application, with the presentation of the first smartphone in 2007.

I.1. Market pull

The term "Market Pull" refers to the need for a new product or a solution to an identified problem.

The consumer require a technological solution to a problem he has, and companies are developing a technology with a well-defined goal: solving this problem.

The need is identified with a market analysis or by potential customers. Then, a product or an ensemble of products are developed, in order to solve the market's need identified.

Consumers groups or professional association may have a central role in market pull innovation, testing a concept design or an existing product. For example, in automotive industry, concept cars and automotive courses, such as Formula 1, are important in the innovation process.

Example of market pull good: the digital camera

- Twenty years ago, there was a "market" requirement for a camera that could take endless photographs, that could be viewed almost immediately.
- A premise of solution was the invention of Polaroid camera, but remains limited in number of pictures.
- A milestone has been reached when the first digital cameras have been developed.
- It has permit to revolutionize the camera market, and also photo editing software market.

I.1. Market pull

There was a real rush of people who are taking photos everywhere and processing them, and so the market really was telling companies that what we need is an easy way to handle all these digital photos with smaller and more efficient devices. And so the market did respond to that.

Market pull led to electronics companies developing digital cameras, miniature digital storage, processing power and improved battery performance was available. Market pull ensured that photo editing software also developed, in parallel with the development of digital camera technology.

Quantum revolution(s)

The Structure of Scientific Revolutions is a book written by the philosopher Thomas S. Kuhn in 1962.

Normal scientific progress was viewed as "development-by-accumulation" of accepted facts and theories. Kuhn argued for an episodic model in which periods of such conceptual continuity in normal science were interrupted by periods of **revolutionary science**.

The discovery of "anomalies" during revolutions in science leads to new paradigms.

Kuhn's scheme of scientific revolution

Phase 1: pre-paradigm

At the beginning, there is no consensus on any particular, well constructed, theory. This phase is characterized by several incompatible and incomplete theories.

Phase 2: normal science

In this phase, puzzles are solved within the context of the dominant paradigm. As long as there is consensus within the discipline, normal science continues. Over time, progress in normal science may reveal anomalies, facts that are difficult to explain within the context of the existing paradigm. While usually these anomalies are resolved, in some cases they may accumulate to the point where normal science becomes difficult and where weaknesses in the old paradigm are revealed.

I.2. *The Structure of Scientific Revolutions*

Phase 3: crisis

If the paradigm proves chronically unable to account for anomalies, the community enters a crisis period. Crises are often resolved within the context of normal science. However, after significant efforts of normal science within a paradigm fail, science may enter the next phase.

Phase 4: scientific revolution

A scientific revolution consists in a paradigm shift, a phase in which the underlying assumptions of the field are reexamined and a new paradigm is established.

Phase 5: post-revolution

The new paradigm's dominance is established and so scientists return to normal science, solving puzzles within the new paradigm.

Quantum revolution(s)

1. Innovation and industry
   - Innovation strategies
   - *The Structure of Scientific Revolutions* - thinking out of the box
   - Innovation in industry
   - Gartner's hype cycle
2. First quantum revolution
3. Second quantum revolution

I.3. Sustaining innovation

A sustaining innovation is an innovation that does not significantly affect existing markets.

An evolutionary innovation improves a product in an existing market in ways expected by the market itself (*i.e.* the customers). For example, it might be innovation for better fuel injection in gasoline motors, in order to decrease consumption and obtain better performances.

A revolutionary sustaining innovation is unexpected by the market, but nevertheless does not affect existing markets. For example, the first cars developed in the end of the 19th century were luxury goods, very expensive. So most people could offer themself such a luxury item and only few of them were sold.

In business theory, a disruptive innovation is an innovation that creates a new market and value network and eventually disrupts an existing market and value network. Not all innovations are disruptive, even if they are revolutionary.

For example, the first automobiles in the late 19th century were not a disruptive innovation, because early automobiles were expensive luxury items that did not disrupt the market for horse-drawn vehicles. The market for transportation essentially remained intact until the debut of the lower-priced Ford Model T in 1908. The *mass-produced automobile was a disruptive innovation*, because it changed the transportation market, whereas the first thirty years of automobiles did not.

I.3. Disruptive innovation

Disruptive innovations tend to be produced by outsiders and entrepreneurs in startups, rather than existing market-leading companies. The business environment of market leaders does not allow them to pursue disruptive innovations when they first arise, because they are not profitable enough at first and because their development can take scarce resources away from sustaining innovations (which are needed to compete against current competition).

A disruptive process can take longer to develop than by the conventional approach and the risk associated to it is higher than the other more incremental or evolutionary forms of innovations, but once it is deployed in the market, it achieves a much faster penetration and higher degree of impact on the established markets.

A disruptive innovation disrupted a market, not necessarily with a novel technology, but with a alternative approach of the market. But disruptive innovation might appears thanks to a novel technology.

For example, CDs ans USB flash drivers have disrupted the market of data storage which was dominated by floppy disk. Writable CDs have been developed photosensitive polymers while USB sticks have been developed based on the discovery of giant magnetoresistance (GMR), discovered in 1988 by Albert Fert and Peter Grünberg, awarded Nobel Prize in 2007 for their contribution to that topic.

I.3. Disruptive innovation

Disruptive innovations can hurt successful, well-managed companies that are responsive to their customers and have excellent research and development.

These companies tend to ignore the markets most susceptible to disruptive innovations, because the markets have very tight profit margins and are too small to provide a good growth rate to an established (sizable) firm.

Disruptive technology provides an example of an instance when the common business-world advice to "focus on the customer" can be strategically counterproductive. For example, text message (SMS) were not a demand of customers: nobody wanted to write short messages with a 9 touches keyboard. But it was a success.

I.3. Disruptive technologies

Technology always evolves: it starts, develops, persists, mutates, stagnates, and declines. When a new high-technology core emerges, it challenges existing technologies which are forced to coexists with it.

A Technology Support Net (TSN) is the required physical, energy, information, legal and cultural structures that support the development of technology core.

When a new technology emerges, it fits into the existing TSNs, then high-technologies becomes regular technologies, fitting the same TSN. This established technology then resists being interrupted by a technological mutation; then new high technology appears and the cycle is repeated.

I.3. Disruptive technologies

In 1995 in Harvard Business Review, Clayton M. Christensen as introduced the notion of *disruptive technologies*.

Few technologies are intrinsically disruptive or sustaining in character; rather, **it is the business model that the technology enables that creates the disruptive impact.**

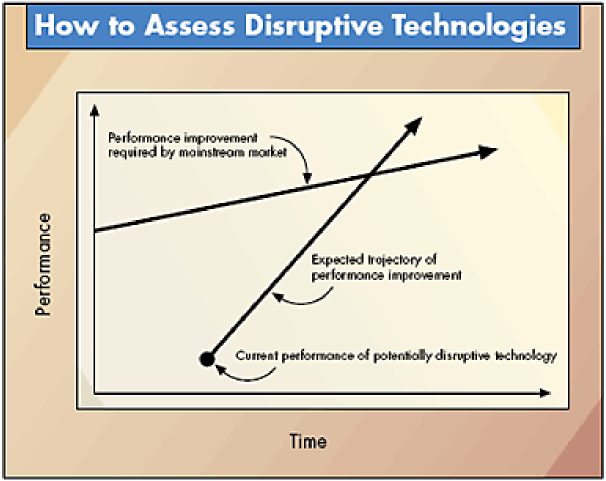
In 2009, Milan Zeleny (an american economist) described high technology as disruptive technology and raised the question of what is being disrupted.

I.3. Disruptive technologies

According to Zeleny, **the support network of high technology is disrupted**.

For example, introducing electric cars disrupts the support network for gasoline cars (network of gas and service stations).

On a long term timescale, disruptive technologies upgrades or replaces the outdated support network of the established regular technology. Consequently, **a disruptive technology may dramatically transforms some industries through its requisite its own TSN.**



Role of disruptive technologies in innovation, especially the increase in performances. https://hbr.org/1995/01/disruptive-technologies-catching-the-wave

I.4. Gartner's hype cycle

Gartner Inc. is a private company is a global research and advisory firm which provides information and advice in IT, finance, human ressources, customer service, marketing ,sales and supply chain.

Gartner provide every year a *hype cycle* of emerging technologies, *i.e.* a graphical and conceptual representation of the maturity of emerging technologies through five phases.

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I.4. Gartner's hype cycle

1. Technology Trigger

A potential technology breakthrough kicks things off. Early proof-of-concept stories and media interest trigger significant publicity. Often no usable products exist and commercial viability is unproven.

2. Peak of Inflated Expectations

Early publicity produces a number of success stories — often accompanied by scores of failures. Some companies take action; many do not.

3. Trough of Disillusionment

Interest wanes as experiments and implementations fail to deliver. Producers of the technology shake out or fail. Investments continue only if the surviving providers improve their products to the satisfaction of early adopters.

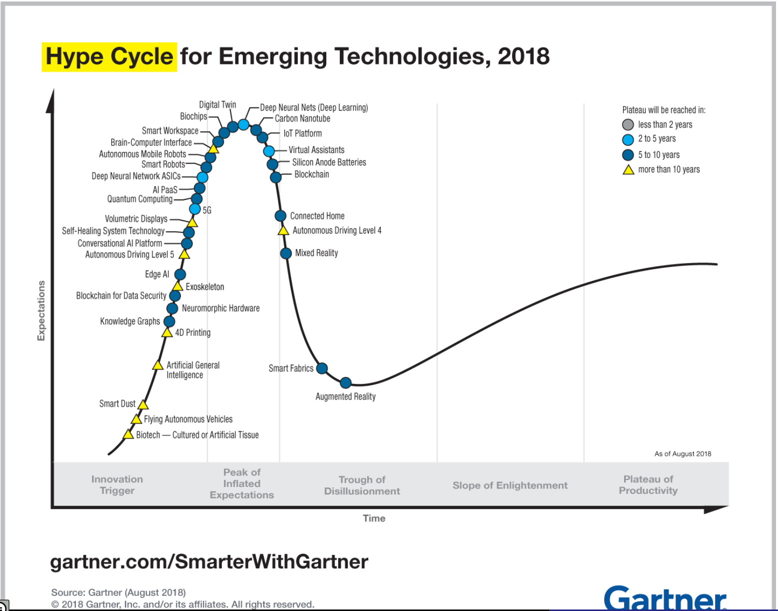
4. Slope of Enlightenment

More instances of how the technology can benefit the enterprise start to crystallize and become more widely understood. Second- and third-generation products appear from technology providers. More enterprises fund pilots; conservative companies remain cautious.

4. Plateau of Productivity

Mainstream adoption starts to take off. Criteria for assessing provider viability are more clearly defined. The technology's broad market applicability and relevance are clearly paying off.

I.4. Gartner's hype cycle



Quantum revolution(s)

II.1. Quantum mechanics: half a century of elaboration

Until the 20th century, so-called classical physics has permitted to provide an ensemble of theory and models that explained almost all physical phenomena observed.

But two remaining problems were still unsolved: the black-body radiation spectrum and the discrete radiation spectrum of light source made of electrical discharge in atomic vapor.

Several models were proposed in order to try to explain these phenomena but with severe difficulties to provide a general theory.

A paradigm shift has been introduced by the construction of quantum mechanics that has permit to understand those phenomena in a complete different formalism. This new theory has offered a novel vision of matter and consequently has resulted in many scientific and technological developments.

The construction of a science takes decades.

- 1877: Ludwig Boltzmann suggested that the energy states of a system might be discrete.
- 1887: Heinrich Hertz discovered the photoelectric effect.
- 1900: the quantum hypothesis by Max Planck, which assumes that any atomic system emits radiation with an energy that is an integer discrete number of 'quanta'.

These quantas ε are proportionnal to the frequency ν of the radiation, such that

$$\varepsilon = h\nu,$$

where h is a universal constant called Planck's constant.

This model has permitted to derive a formula for the observed frequency dependence of the energy emitted by a black body, called Planck's law, that included a Boltzmann distribution

$$I(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_B T}}},$$

where $I(\nu, T)$ is the surfacic power emitted in the normal direction per unit solid angle per unit frequency for a black body at temperature T, h Planck's constant, c speed of light, k_B Boltzmann constant and ν the radiation frequency.

II.1. Quantum mechanics: half a century of elaboration

- 1905: Albert Einstein explained the photoelectric effect using Planck's quantum hypothesis.
- 1913: Niels Bohr used Planck's quantum theory to calculate the magnetic moment of the electron, and explained the spectral lines of the hydrogen atom in his paper intituled *On the Constitution of Atoms and Molecules*.
- 1921: Albert Einstein has been awarded the Nobel Prize of physics 1921 "*for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect*".
- 1923: Louis de Broglie argues that particles can exhibit wave characteristics and waves may have particles behavior (*wave-particle duality*).

II.1. Quantum mechanics: half a century of elaboration

- 1925: Werner Heisenberg and Max Born developed matrix mechanics/
- 1925: Erwin Schrödinger invented simultaneously wave mechanics and the non-relativistic Schrödinger equation as an approximation of de Broglie's theory general case.
- 1927: Heisenberg formulated his uncertainty principle.
- 1927: Copenhagen interpretation of quantum mechanics started to shape.
- 1928: Paul Dirac derived its equation, so-called Dirac equation, describing the wavefunction of an electron in the relativistic limit, and unified quantum mechanics with special relativity. He also introduced the bra-ket notation.

II.1. Quantum mechanics: half a century of elaboration

Building of modern quantum mechanics as started only in 1925, 48 years after Ludwig Boltzmann's quantization of energy levels.

It took almost half a century from initial model to initiate really the construction of a new theory called *quantum mechanics*, which will result in a scientific revolution in the sense of Thomas Kuhn. This scientific revolution has resulted in many technological development during the second half of the 20th century, referred as the **first quantum revolution**.

The first quantum revolution refers to all technological innovations which have resulted from quantum mechanics theories. Most of those innovations hade resulted from a major paradigm shift introduced by quantum mechanics: the wave-particle duality.

II.2. The wave nature of matter

Quantum mechanics has then offer the appropriate formalism to describe atoms and molecules structure, and consequently material structures and electronic properties.

In particular, it has results in band theory of matter and more specifically the physics of semiconductors. Semiconductors have permit the development of integrated circuits, and therefore all the modern electronic has been developed thanks to quantum mechanics.

Applications of electronics have expanded dramatically since the first transistor was invented in 1948. It has resulted in **the industry of semiconductors**, which has impact almost all sector of goods thanks to microelectronics and miniaturization.

II.2. The wave nature of matter

Electronics and its miniaturization has permitted the development of computers, and the development of automation. Productivity in industry has been increased thanks to the use of computer, automation and robots: this evolution is called **industry 3.0** (or third industrial revolution).

The development of IoT (*Internet of Things*) results from the interconnexion between Internet and objects. The development of internet results from the progress of telecommunications technologies. WiFi and wireless communications used in IoT are based on high frequencies (GHz typically) semiconductors.

These technologies has initiate the emergence of **industry 4.0**, which is a trend towards automation and data exchange in manufactoring technologies and processes which include cyber-physical systems (CPS), IoT, industrial IoT (IIoT), cloud computing, cognitive computing and artificial intelligence.

II.2. The particle nature of light

On the other side, wave-particle duality has permit to think the concept of photon for the description of light, with a better description of light-matter interaction. Two majors inventions have resulted from this concept:

- LASER sources of light;
- photonic devices.

A major technological breakthrough is the development of laser sources of light, continuous-wave (CW) or pulsed ones. It has permit the development of light source of high power, high directivity and high coherence. Lasers have wide applications in industry.

- alignement;
- laser velocimetry;
- distance measurements;
- profilometer (surface inspection);
- scientific lasers for spectroscopy;
- multiphotonic microscopy;
- laser soldering, melting or sublimation (fast marking);
- heat treatment;

- LIDAR;
- laser printer;
- laser scanner;
- military applications (guidance, disorientation, target designator, firearms, defensive countermeasures);
- medical applications (eye's surgery, dermatology);
- CD, DVD;
- ...

Photonic devices are components for creating, manipulating or detecting light. This can include laser diodes, light-emitting diodes, solar and photovoltaic cells, displays and optical amplifiers. Other examples are devices for modulating a beam of light and for combining and separating beams of light of different wavelength.

Applications of photonics included all areas from everyday life to the most advanced science

- light detection;
- lighting;
- telecommunications;
- information processing;
- photonic computing;
- metrology;
- spectroscopy;
- holography;

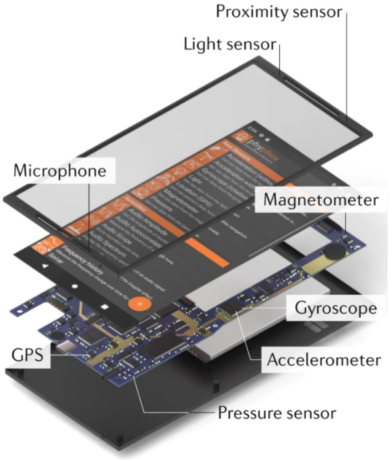
II.2. The particle nature of light

- medicine (endoscopy, health monitoring);
- art diagnostics (involving InfraRed Reflectography, Xrays, UltraViolet fluorescence, XRF);
- agriculture;
- robotics;
- aviation (photonic gyroscopes);
- military applications (IR sensors, command and control, navigation, search and rescue, mine laying and detection);
- solar cells and photovoltaic generation of electricity;
- ...

Quantum revolution(s)

II.3. Materials

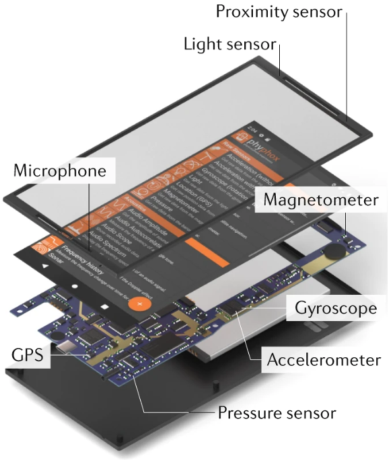
Fig. 1: Smartphone sensors.



- Electronics inside requires elements such as silicon, phosphorous, gallium, arsenic, antimony and indium.
- Mechanical elements (for acoustic functions) are made out of dysprosium, praseodymium, neodymium, boron and iron.
- The packaging itself is made out of aluminium and AlSi glass.

II.3. Materials

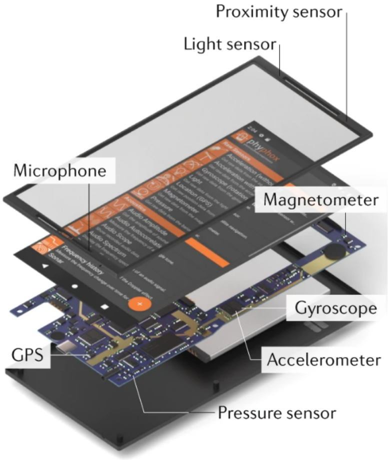
Fig. 1: Smartphone sensors.



- The screen is made of Indium Oxide and liquid crystal.
- Battery are made out of lithium, cobalt, oxygen, carbon and aluminium.

All those elements have been development in materials which properties have been understand thanks to quantum mechanics.

Fig. 1: Smartphone sensors.

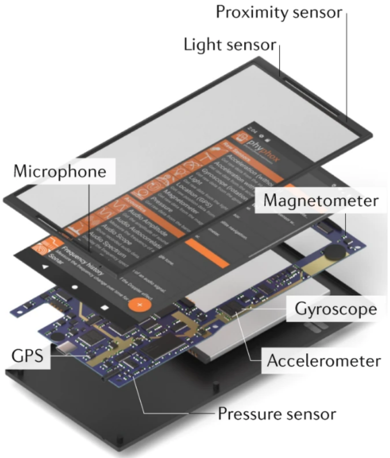


An other contribution of quantum mechanics consists in a better understanding of phases transitions in material (ferromagnetic, ferroelectric, liquid crystal,...). Better

understand of phases transistions have opened the way of technological development exploiting them for application, such as liquid crystal display for screens, or magnetic memories in computers.

II.3. Phases

Fig. 1: Smartphone sensors.



If one considers a smartphone, such phases transitions are present in almost every part of it.

The packaging is made out of conductor and glass.

The battery is made of electrolyte, insulator and conductor.

The screen is made of transparent conductor and liquid crystal.

Acoustic elements are made out of ferromagnetic and ferroelectric.

II.3. Miniaturization of devices

The disruptive innovation proposed by Apple in 2007 with the first smartphone relies on combining several devices in a single object: a phone, a camera, a music player, an agenda,...

If the innovation relies in this paradigm shift, it has been possible only because **all those devices have been miniaturized**.

This miniaturization results essentially from progress in semiconductors technologies and photonics.

The smartphone might be seen as **a small computer with a processor, memory and wireless emitters/recievers**.

II.3. Miniaturization of devices

Technological progress in semiconductor industry has permitted to decrease severely transistor size (Moore's law) and permit to obtain miniaturized chips with enough calculation ability for a smartphone.

Optical elements such as camera ou LED flash light are only few millimeter size now. The display is governed by miniaturized LCD display (liquid crystal), with tactile ability thanks to microfabrication.

Such miniaturization has been predicted by Richard Feynman, in his 1959 talk entitled "There's Plenty of Room at the Bottom" (delivered more than 50 years ago)

II.3. Miniaturization of devices

Feynman proposed shrinking computing devices toward their physical limits, where "wires should be 10 or 100 atoms in diameter". Several devices have been reported with sizes lower than 15 nm, which is to say, with wires at Feynman's 100-atom scale. When Feynman spoke, a single computer could fill a room.

Feynman suggested that focused electron beams could write nanoscale features on a surface; this is now called "e-beam lithography". He pointed to complex, active, nanoscale biological mechanisms as an inspiration for nanoscale technology; these have become the basis of what is called "biotechnology", which has delivered what are in some ways the most advanced nanotechnologies developed to date.

Feynman was the first to outline a world of technologies that would work and build at the ultimate, atomic scale.

II.3. Miniaturization of devices

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He viewed this world from a top-down perspective, as the ultimate frontier for miniaturization.

This ultimate atomic scale has permit to initiate the second quantum revolution.

III.1. Quantum engineering

In the 20th century quantum mechanics revealed the secrets of the nature at atomic scales. In the 21st century, we are going to make quantum machines, complex systems governed by the laws of quantum physics.

- Miniaturization is the dominant trend in modern technology. The electronic, optical and mechanical devices are reaching to the length scales that need design based on quantum principles.
- The principles of quantum mechanics offer the promise of exceptional performance over what classical physics has offered to us.

III.1. Quantum engineering

As a consequence, technologies are oriented toward systems so small that it requires to deal and to control quantum effects. Furthermore, it opens the possibility to fully exploit the quantum strangeness, with the development of individual quantum systems.

This is the second quantum revolution.

The fundamental difference with the first quantum revolution relies in the manipulation of individual quantum systems. It permits to fully exploits two majors aspects of quantum effects that were not in the first quantum revolution:

- **entanglement** (*i.e.* fundamental quantum correlations between states);
- **quantum state superposition**.

This second quantum revolution is expected be responsible for most of the key physical technological advances for the 21st century.

Such technologies are then called quantum technologies.

Quantum technology allows us to organise and control the components of a complex system governed by the laws of quantum physics. This is in contrast to conventional technology which can be understood within the framework of classical mechanics (including transistor developed in the context of the first quantum revolution).

There are two imperatives driving quantum technology.

- The first is practical : the dominant trend in a century of technological innovation is miniaturisation. To build devices on a smaller and smaller scale. Ultimately this will deliver devices at length scales of nanometres and action scales approaching Planck's constant. At that point design must be based on quantum principles.
- The second imperative is more fundamental. The principles of quantum mechanics appear to offer the promise of a vastly improved performance over what can be achieved within a classical framework.

III.1. Quantum engineering

In the **first quantum revolution**, we used quantum mechanics to understand what already existed. We could explain the periodic table, but not design and build our own atoms. We could explain how metals and semiconductors behaved, but not do much to manipulate that behavior. The difference between science and technology is the ability to engineer your surroundings to your own ends, and not just explain them.

In the **second quantum revolution**, we are designing quantum object with expected properties that results from quantum mechanics law, for our own purpose.

For example, in addition to explaining the periodic table, we can make new artificial atoms—quantum dots and excitons — which we can engineer to have electronic and optical properties of our own choosing.

These new man-made quantum states have novel properties of sensitivity and nonlocal correlation that have wide applications to the development of computers, communications systems, sensors and compact metrological devices.

Those applications are so-called **quantum technologies**.

While quantum mechanics is a mature science, all its direct application have resulted in the first quantum revolution. Nowadays, quantum engineering as a technology is now emerging on its own right.

Quantum engineering is the key feature of the development of quantum technologies in this second quantum revolution.

Quantum revolution(s)

III.2. Quantum technologies

Quantum technologies is an emerging field of physics and engineering, which relies on the exploitation of quantum physics law on individual quantum systems. Quantum Technologies result from **our ability to detect and manipulate single quantum objects, such as atoms, photons or electrons**.

They represent an intermediate step in the second quantum revolution, between academic fundamental research activities and industrial products.

Their development inherently involve cooperation between academic labs and industrial players.

III.2. Quantum technologies

It is about creating practical applications such as

- quantum computing;
- quantum sensors;
- quantum cryptography;
- quantum simulation;
- quantum metrology;
- quantum imaging—based on properties of quantum mechanics (quantum entanglement, quantum superposition and quantum tunnelling);

Quantum computing: a technology of the futur already present (PWC).