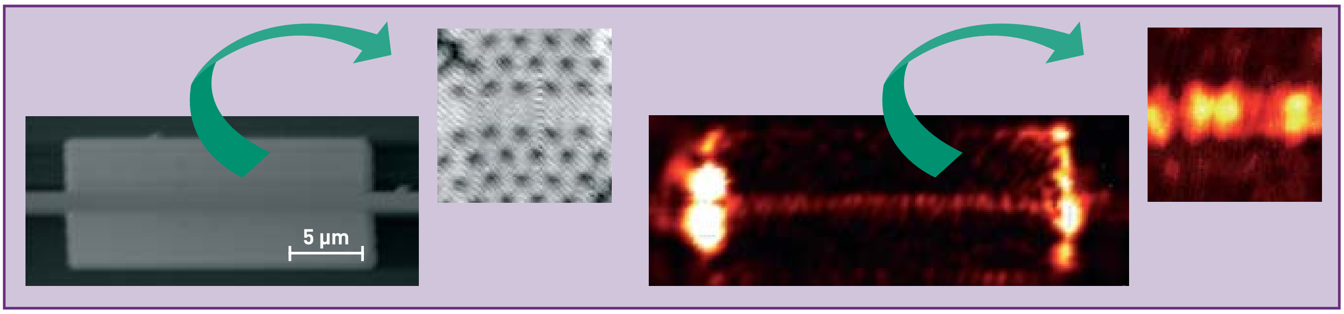
Nanophotonics: light generation and transport in the nanosystems of the future

One of the main challenges to the microsystems and nanosystems of the future is the integration of optical functions into microchips. The integration of optical functions such as light emission, guiding, modulation and detection on silicon chips would generate a breakthrough into optical data processing. Photonic crystals are key building blocks allowing the control at the wavelength scale of light emission and propagation in future-generation nanosystems.



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Local probe view (a technique called *near-field*) of the optical wave propagating in a photonic crystal waveguide. This experiment was a world first. The image on the left is a topographic view of the guide, and the image on the right is a near-field image.

Current technology appears capable of integrating *guiding functions* (**refractive** or **diffractive**) on a **silicon** chip, at least in the short term, for optical data processing. However, the fabrication of on-silicon *active functions* (emission, detection) will require new physical effects, such as light-emission enhancement by **nanostructures**, control of the **photon** emission diagram, boosting emission rate *via* the Purcell effect (Box) and reducing photon propagation velocity in the material or photon storage in an ultra-high-quality-factor resonator(1). The implementation of these effects may lead to the fabrication of the first silicon laser, a breakthrough that would herald the use of photons for calculation and logic operations in the nanoelectronics systems of the future.

Photon channelling and storage

To be able to carry information on a silicon chip, you first have to be able to channel or confine light between points on a microelectronic circuit. In practice, this means that photon walls have to be built on the scale of the wavelength to be propagated. Given the **optical refraction index** of silicon, a 1.5 **micron** wavelength typically requires structures engineered at only a few tens to a few hundred of **nanometres**. For instance, to channel the photons, it is possible to create a **waveguide** as a silicon strip 0.3 µm thick and between 0.3 µm and a few microns wide. The light is trapped inside, and is reflected off the walls of the guide due to the difference in optical index between the silicon and surrounding environment (in this case, air).

Following this principle, using a silicon-on-insulator (**SOI**) substrate, the photons could be confined or channelled through the thickness of the chip by the difference in indexes between the refraction index of the silicon and the underlying oxide (insulator). At this point, it is therefore possible to propagate the light, but ideally it would be possible to concentrate, slow down or even store it, in certain parts of the circuits. This storage capability would make it possible to hold information in the circuit in its optical form. However, putting this into practice remains an extraordinary challenge. In silicon, a photon propagates at around 10^{14} µm/s, which means that if it can't be stopped, it has to be made to travel 50 billion round trips in a 1 µm-long resonator to be able to stock just one thousandth of a second. That said, if we could slow the photon propagation velocity by one or two magnitudes or else make them travel 10, 100 or 1,000 round trips in an ultra-small volume of silicon, then it would already be possible to act on the interaction between light and silicon, and thereby modulate or absorb (detect) the photons, maybe even stimulate the emission of other photons. This is where photonic crystals, or more generally **photonic bandgap** structures, come into play.

Integrating optical functions

A photonic crystal is a material, such as a **semiconductor**, like silicon, inside which the optical index varies in periodic fashion. This index modulation is generally obtained by carving holes into the silicon. With a sufficient optical index variation and structuring built on the same scale as the light wavelength used, photons with certain energies can be prevented from propagating in certain directions. An ana-

(1) Resonator: an environment wherein a phenomenon of vibrational nature is amplified by a stimulatory vibration at the same frequency, or by passing through a cavity with one of the dimensions equal to the wavelength of the vibration. Thus, in the conventional production of a laser beam, the active medium is placed in a resonant cavity made up of two parallel-aligned mirrors, one of which – the *reflector* – is totally reflective, while the other, the *coupler*, is partially transmissive, allowing light to leave the cavity. Photons reflected by the mirrors can cross through the active medium several times and cause the stimulated emission of a large number of photons.

logy can be found in the structure of **electron energy bands** in semiconductors due to periodic variations in electronic potential.
Hence, the first producible function is *photon reflection*. To achieve this, physicists etch a triangular lattice of holes. If this lattice is etched in the middle of a waveguide, it becomes possible to prevent light propagation through this mirror. Newly-equipped with this first function, the physicist can then go on to produce a microresonator (or microcavity) integrated into the waveguide by fabricating two photonic crystal mirrors separated by a space forming a **Fabry-Perot cavity**. This generates a *filter function*, since the structure will only transmit Fabry-Perot resonant wavelengths (Figure 1). The mirror bandgap where photons are no longer transmitted can now be found in the spectrum, with a peak transmitted at the resonant wavelength. The resonance intensity inside the cavity is illustrated by the narrowness of the peak, giving the *Q*-factor, or quality factor, which in this case is around 200. In other words, this means that the strength of the electromagnetic field in the cavity has been boosted by a factor of 200 in relation to its initial value.

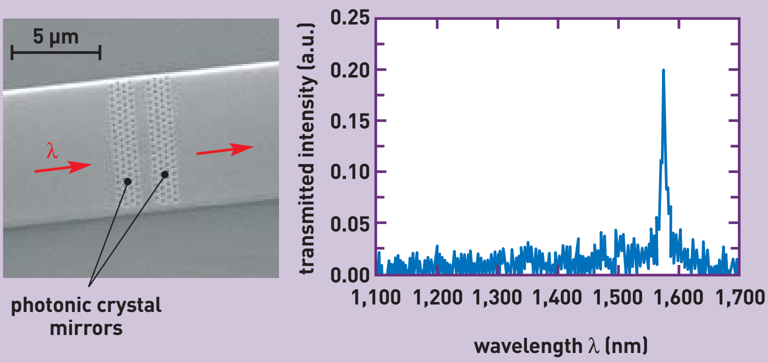

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Figure 1.
Left: top view of a silicon waveguide etched into a silicon-on-insulator (SOI) substrate 8 µm wide and 10 mm long. A photonic crystal microcavity was fabricated inside the guide by etching two photonic crystals (mirrors). Right: transmission spectrum measured for the photonic crystal microcavity showing the photonic bandgap present from 1,200 to 1,700 nm and the resonance mode of the microcavity that appears in this gap. The *Q*-factor obtained here is around 200.

The Purcell effect

The American physicist Edward M. Purcell predicted in 1947 that the spontaneous emission rate of an emitter placed in an optical cavity with energy coefficient *Q* and volume *V* could be inhibited or stimulated by a factor $F_p = 3Q\lambda^3/4\pi^2V$ in relation to its emission rate in free space, with λ the wavelength of the photons emitted. Later, in the 1980s, experiments led on **atoms** demonstrated for the first time that it was possible to modify their properties in the microwave regime. Then, in the early 90s, the phenomenon was observed in solid phase in **semiconductors** integrating **quantum boxes**. Today, with a *Q*-factor of 200 (the example in figure 1), the Purcell factor is estimated at 30 for this **silicon** microcavity. This means it would be possible to increase the material's emission rate, *i.e.* the number of **photons** emitted per second, by a factor of 30. Various experiments are currently being led to demonstrate this effect.

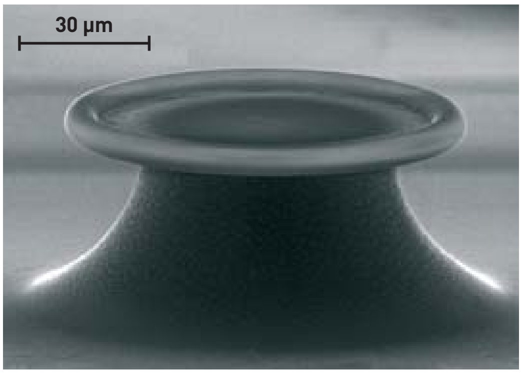

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Figure 2.
The "microtore" ultra-high-*Q*-factor microresonator. This microresonator can confine photons highly efficiently, enabling a very strong interaction with the material. This resonance technique may well provide the foundations for a prototype silicon nanolaser.

From this point on, in addition to the previously described filter function, it becomes possible to use this resonance effect to stimulate the emission of photons in particular directions, through the Purcell effect (Box).

Building the first silicon laser

In parallel, another approach to producing a light nanosource aims at achieving stimulated emission, *i.e.* the *laser effect*. The underlying idea is to develop microresonators with huge *Q*-factors (Figure 2). The wavelength gain available in silicon-based products is in fact generally very low due to silicon's **indirect gap**. This means that photons have to be confined extremely efficiently to be able to reach the laser effect threshold. This class of ultra-high-*Q*-factor microresonators may well provide the solution for producing the first silicon nanolaser, opening up possibilities for on-chip optical data processing and coding.

The first demonstrators

With the development of nanotechnologies, photonic bandgap materials are presented as the fundamental building blocks of future nanoelectronics components, which are expected to use photons and **electrons** to carry and process data. The initial results obtained with SOI are very promising, further increasing the field of applications for silicon, the kingpin of microelectronics. A major research effort, which is currently being led in various US (**Intel**, **Caltech**, the **MIT**, and others) and Japanese laboratories as well at the CEA, is opening up perspectives for building the first optical interconnect demonstrator for data transport and processing in microelectronic circuits.

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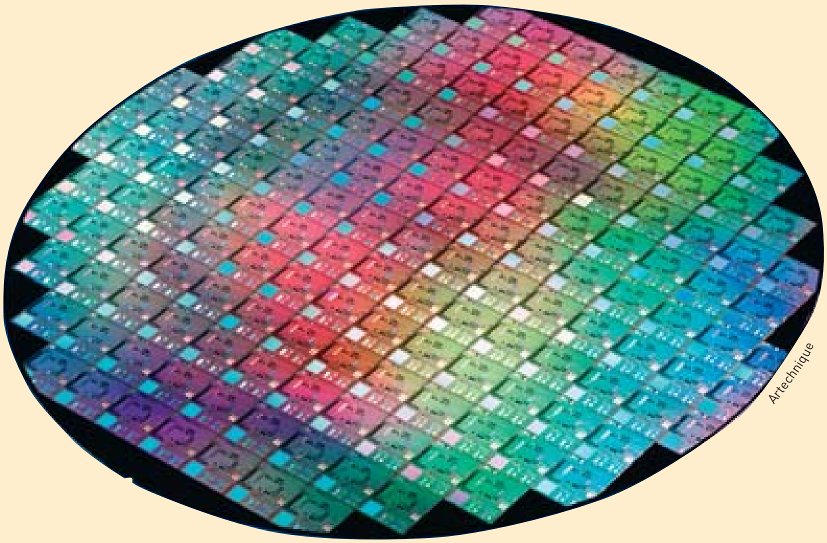
A From the macroscopic to the nanoworld, and vice versa…

In order to gain a better idea of the size of microscopic and nanoscopic* objects, it is useful to make comparisons, usually by aligning different scales, *i.e.* matching the natural world, from molecules to man, to engineered or fabricated objects (Figure). Hence, comparing the "artificial" with the "natural" shows that artificially-produced nanoparticles are in fact smaller than red blood cells.
Another advantage of juxtaposing the two is that it provides a good illustration of the two main ways of developing nanoscale systems or objects: *top-down* and *bottom-up*. In fact, there are two ways into the nanoworld: molecular manufacturing, involving the control of single atoms and the building from the ground up, and extreme miniaturization, generating progressively smaller systems.

* From the Greek *nano meaning* "very small", which is also used as a prefix meaning a billionth (10^{-9}) of a unit.
In fact, the **nanometre** (1 nm = 10^{-9} metres , or a billionth of a metre), is the master unit for nanosciences and nanotechnologies.



300-mm silicon wafer produced by the Crolles2 Alliance, an illustration of current capabilities using top-down microelectronics.

Top-down technology is based on the artificial, using macroscopic materials that we chip away using our hands and our tools: for decades now, electronics has been applied using silicon as a substrate and what are called "wafers" as workpieces. In fact, microelectronics is also where the "top-down" synthesis approach gets its name from. However, we have reached a stage where, over and above simply adapting the miniaturization of silicon, we also have to take on or use certain physical phenomena, particularly from quantum physics, that operate when working at the nanoscale.
The bottom-up approach can get around these physical limits and also cut manufacturing costs, which it does by using component self-assembly. This is the approach that follows nature by assembling molecules to create proteins, which are a series of amino acids that the super-molecules, *i.e.* nucleic acids (DNA, RNA), are able to produce within cells to form functional structures that can reproduce in more complex patterns. Bottom-up synthesis aims at structuring the material using "building blocks", including atoms themselves, as is the case with living objects in nature. Nanoelectronics seeks to follow this assembly approach to make functional structures at lower manufacturing cost.
The nanosciences can be defined as the body of research into the physical, chemical or biological properties of nano-objects, how to manufacture them, and how they self-assemble by auto-organisazation.
Nanotechnologies cover all the methods that can be used to work at molecular scale to reorganize matter into objects and materials, even progressing to the macroscopic scale.

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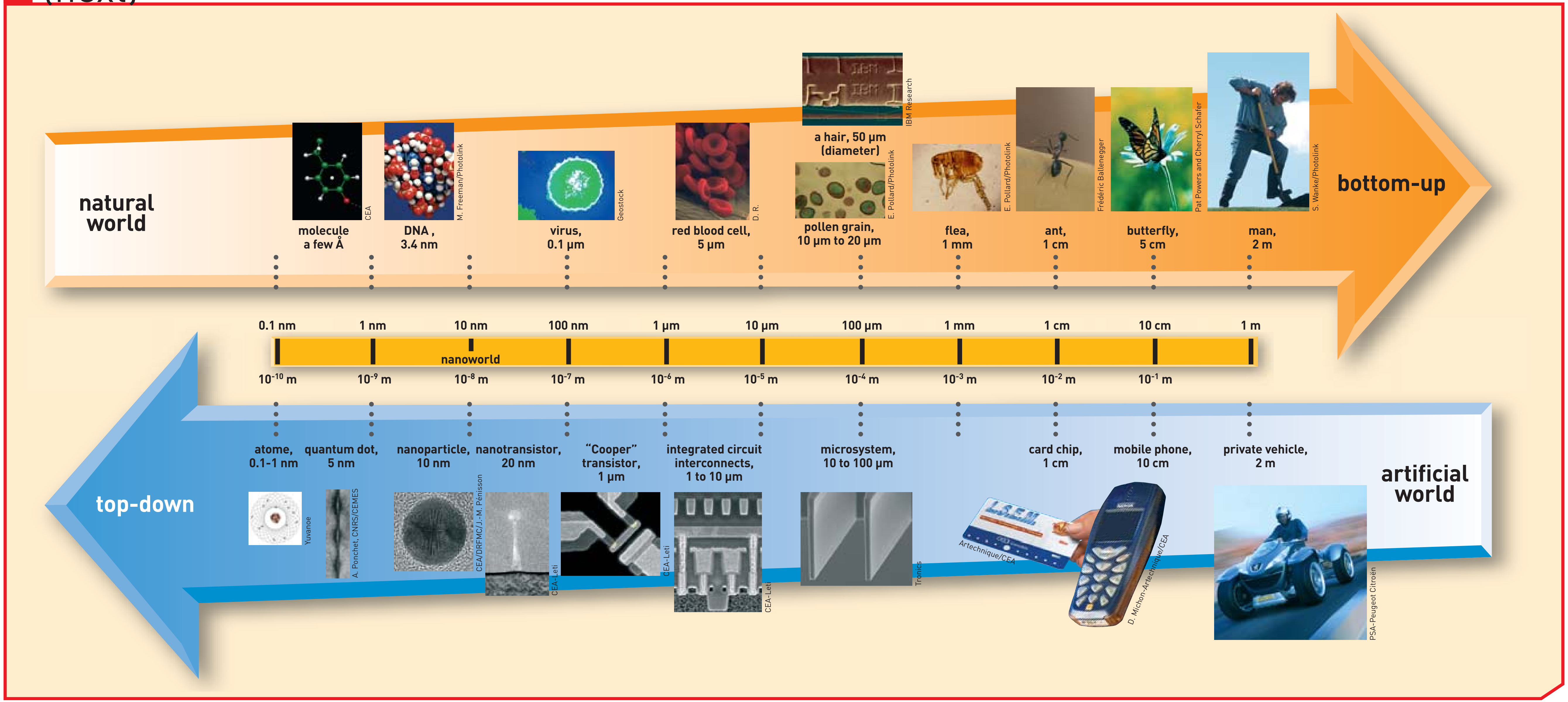
natural world
molecule a few Å
DNA , 3.4 nm
virus, 0.1 µm
red blood cell, 5 µm
a hair, 50 µm (diameter)
pollen grain, 10 µm to 20 µm
flea, 1 mm
ant, 1 cm
butterfly, 5 cm
man, 2 m
bottom-up
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
nanoworld
10^-10 m
10^-9 m
10^-8 m
10^-7 m
10^-6 m
10^-5 m
10^-4 m
10^-3 m
10^-2 m
10^-1 m
atome, 0.1-1 nm
quantum dot, 5 nm
nanoparticle, 10 nm
nanotransistor, 20 nm
"Cooper" transistor, 1 µm
integrated circuit interconnects, 1 to 10 µm
microsystem, 10 to 100 µm
card chip, 1 cm
mobile phone, 10 cm
private vehicle, 2 m
top-down
artificial world
CEA
M. Freeman/Photolink
Geostock
D. R.
IBM Research
E. Pollard/Photolink
Frédéric Ballenegger
Pat Powers and Cherryl Schafer
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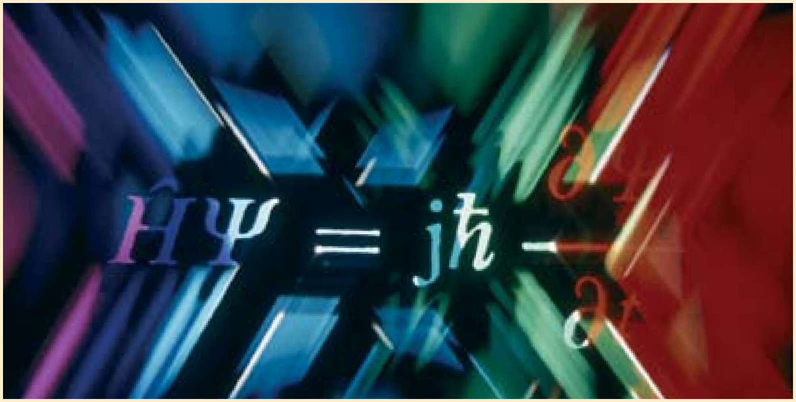
B A guide to quantum physics

Quantum physics (historically known as quantum mechanics) covers a set of physical laws that apply at microscopic scale. While fundamentally different from the majority of laws that appear to apply at our own scale, the laws of quantum physics nevertheless underpin the general basis of physics at all scales. That said, on the macroscopic scale, quantum physics in action appears to behave particularly strangely, except for a certain number of phenomena that were already curious, such as superconductivity or superfluidity, which in fact can only explained by the laws of quantum physics. Furthermore, the transition from the validating the paradoxes of quantum physics to the laws of classical physics, which we find easier to comprehend, can be explained in a very general way, as will be mentioned later.

Quantum physics gets its name from the fundamental characteristics of quantum objects: characteristics such as the angular momentum (spin) of discrete or discontinuous particles called quanta, which can only take values multiplied by an elementary *quantum*. There is also a quantum of action (product of a unit of energy multiplied by time) called Planck's constant (symbolized as h) which has a value of 6.626 x 10^{-34} joule·second.



An "artist's impression" of the Schrödinger equation.

While classical physics separates *waves* from *particles*, quantum physics somehow covers both these concepts in a third group, which goes beyond the simple wave-particle duality that Louis de Broglie imagined. When we attempt to comprehend it, it sometimes seems closer to waves, and sometimes to particles. A quantum object cannot be separated from how it is observed, and has no fixed attributes. This applies equally to a particle - which in no way can be likened to a tiny little bead following some kind of trajectory - of light (photon) or matter (electron, proton, neutron, atom, etc.).

This is the underlying feature behind the Heisenberg uncertainty principle, which is another cornerstone of quantum physics. According to this principle (which is more *indeterminacy* than *uncertainty*), the position and the velocity of a particle cannot be measured *simultaneously* at a given point in time. Measurement remains possible, but can never be more accurate than *h*, Planck's constant. Given that these approximations have no intrinsically real value outside the observation process, this simultaneous determination of both position and velocity becomes simply impossible.

B (next)

At any moment in time, the quantum object presents the characteristic of *superposing* several states, in the same way that one wave can be the *sum* of several others. In quantum theory, the amplitude of a wave (like the peak, for example) is equal to a **probability amplitude** (or probability wave), a complex number-valued function associated with each of the possible sates of a system thus described as quantum. Mathematically speaking, a physical state in this kind of system is represented by a **state vector**, a function that can be added to others *via* superposition. In other words, the sum of two possible state vectors of a system is *also* a possible state vector of that system. Also, the product of two vector spaces is also the sum of the vector products, which indicates **entanglement**: as a state vector is generally spread through space, the notion of local objects no longer holds true. For a pair of entangled particles, *i.e.* particles created together or having already interacted, that is, described by the *product* and not the *sum* of the two individual state vectors, the fate of each particle is linked - entangled - with the other, regardless of the distance between the two. This characteristic, also called *quantum state entanglement*, has staggering consequences, even before considering the potential applications, such as quantum cryptography or - why not? - teleportation. From this point on, the ability to predict the behaviour of a quantum system is reduced to probabilistic or statistical predictability. It is as if the quantum object is some kind of "juxtaposition of possibilities". Until it has been measured, the measurable size that supposedly quantifies the physical property under study is not strictly defined. Yet as soon as this measurement process is launched, it destroys the **quantum superposition** through the "collapse of the wave-packet" described by Werner Heisenberg in 1927. All the properties of a quantum system can be deduced from the equation that Erwin Schrödinger put forward the previous year. Solving the **Schrödinger equation** made it possible to determine the energy of a system as well as the **wave function**, a notion that tends to be replaced by the probability amplitude.

According to another cornerstone principle of quantum physics, the **Pauli exclusion principle**, two identical half-spin ions (**fermions**, particularly electrons) cannot simultaneously share the same position, spin and velocity (within the limits imposed by the uncertainty principle), *i.e.* share the same *quantum state*. **Bosons** (especially photons) do not follow this principle, and can exist in the same quantum state.

The coexistence of **superposition states** is what lends **coherence** to a quantum system. This means that the theory of **quantum decoherence** is able to explain why macroscopic objects, atoms and other particles, present "classical" behaviour whereas microscopic objects show quantum behaviour. Far more influence is exerted by the "environment" (air, background radiation, etc.) than an advanced measurement device, as the environment radically removes all *superposition of states* at this scale. The larger the system considered, the more it is coupled to a large number of degrees of freedom in the environment, which means the less "chance" (to stick with a probabilistic logic) it has of maintaining any degree of quantum coherence.

TO FIND OUT MORE:

Étienne Klein, *Petit voyage dans le monde des quanta*, Champs, Flammarion, 2004.