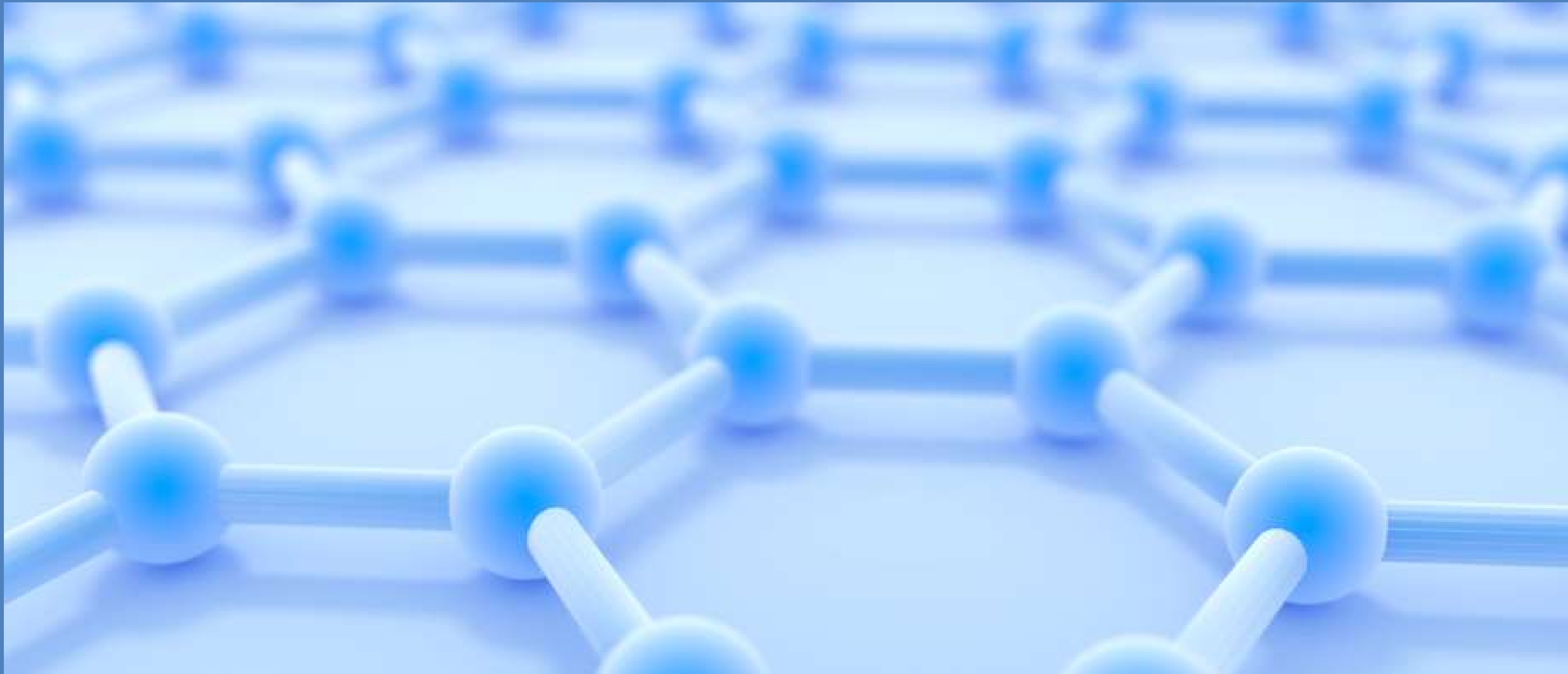

Photonics

aa 2021/2022

Prof. Maria Antonietta Vincenti
Università degli Studi di Brescia

General Information

Lessons start – end: 21/2/2021 – 10/6/2021

Class Meets:

Monday 9.00-12.00 ROOM B2.8
Thursday 11.00-13.00 ROOM B1.7

Office hours: DII - Studio 25
please e-mail for appointment

Contact Information:

- Email: maria.vincenti@unibs.it
- Phone: 0303715924

Course Material

Primary sources

- B. E. A. Saleh, M. C. Teich, *Fundamentals of Photonics*
- J. H. Haus, *Fundamentals and applications of nanophotonics*
- G. R. Fowles – *Introduction to Modern Optics*
- Lecture notes and handouts

Tentative Calendar (Photonics)

FEBRUARY 2022						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27

MARCH 2022						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
28	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17 HW1	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

APRIL 2022						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	

MAY/JUNE 2022						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
						1
2 HW2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26 HW3	27	28	29
30	31	1	2	3	4	5
6	7	8	9	10	11	12

Grading – Photonics

Final Score is the sum of the homework evaluation and final test score:

- Homework (3 during the semester) – 3 pts max

IMPORTANT: homework points will be given ONLY if all homework assignments are completed on time. If only 1 or 2 assignments are completed NO points will be given toward the final score.

- Final Test – 30 pts max
    - two dates during summer session
    - one date in the make up session

Detailed Program (Photonics)

1. Introduction to photonics (2h)
2. Ray Optics (3h +2h)
   - a) simple optical components (mirrors, planar boundaries, lenses, light guides);
   - b) graded index-optics (the ray equation, graded index optical components);
   - c) matrix optics (the ray transfer matrix, matrices of simple optical components, cascaded optical components, periodic systems);
3. Wave and Beam Optics (3h + 2h)
   - a) monochromatic waves;
   - b) relation between ray optics and wave optics;
   - c) simple optical components;
   - d) interference;
   - e) polychromatic and pulsed light;
   - f) gaussian beam and other solution of Helmholtz equation;

Detailed Program (Photonics)

4. Fourier Optics (3h + 2h)

   a) propagation in free space

   b) diffraction of light

   c) image formation

5. Recap of light-matter interactions (5h)

   a) Maxwell's equations in free space and in dielectric media

   b) boundary conditions and constitutive relations

   c) Wave equation

   d) Poynting Theorem

   e) Material properties: linear/nonlinear, homogeneous/inhomogeneous, isotropic/anisotropic, stationary/non-stationary, dispersive/non-dispersive

   f) propagation in dispersive media: group velocity and group velocity dispersion

Detailed Program (Photonics)

6. Polarization Optics (8h + 2h)
   - a) polarization of light
   - b) reflection and refraction
   - c) anisotropic media
   - d) optical activity and magneto-optics
   - e) liquid crystals
   - f) polarization devices
7. Photonic Crystals (5h)
   - a) matrix theory
   - b) Fabry-Perot etalon
   - c) one-dimensional photonic crystals
   - d) devices and applications
8. Plasmonics (2h)
9. Metamaterials (3h)

Detailed Program (Photonics)

10. Resonators (3h+2h)
    - a) planar resonators
    - b) two- and three-dimensional resonators
    - c) microresonators

13. Basics of numerical modeling of light-matter interaction (2h)

14. Numerical laboratory (8h)

UNIVERSITY OF BRESCIA

Tentative Calendar (NanoPhotonics)

FEBRUARY 2022						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27

MARCH 2022						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
28	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

APRIL 2022						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
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4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28 HW1	29	30	

MAY/JUNE 2022						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
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2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30 HW2	31	1	2	3	4	5
6	7	8	9	10	11	12

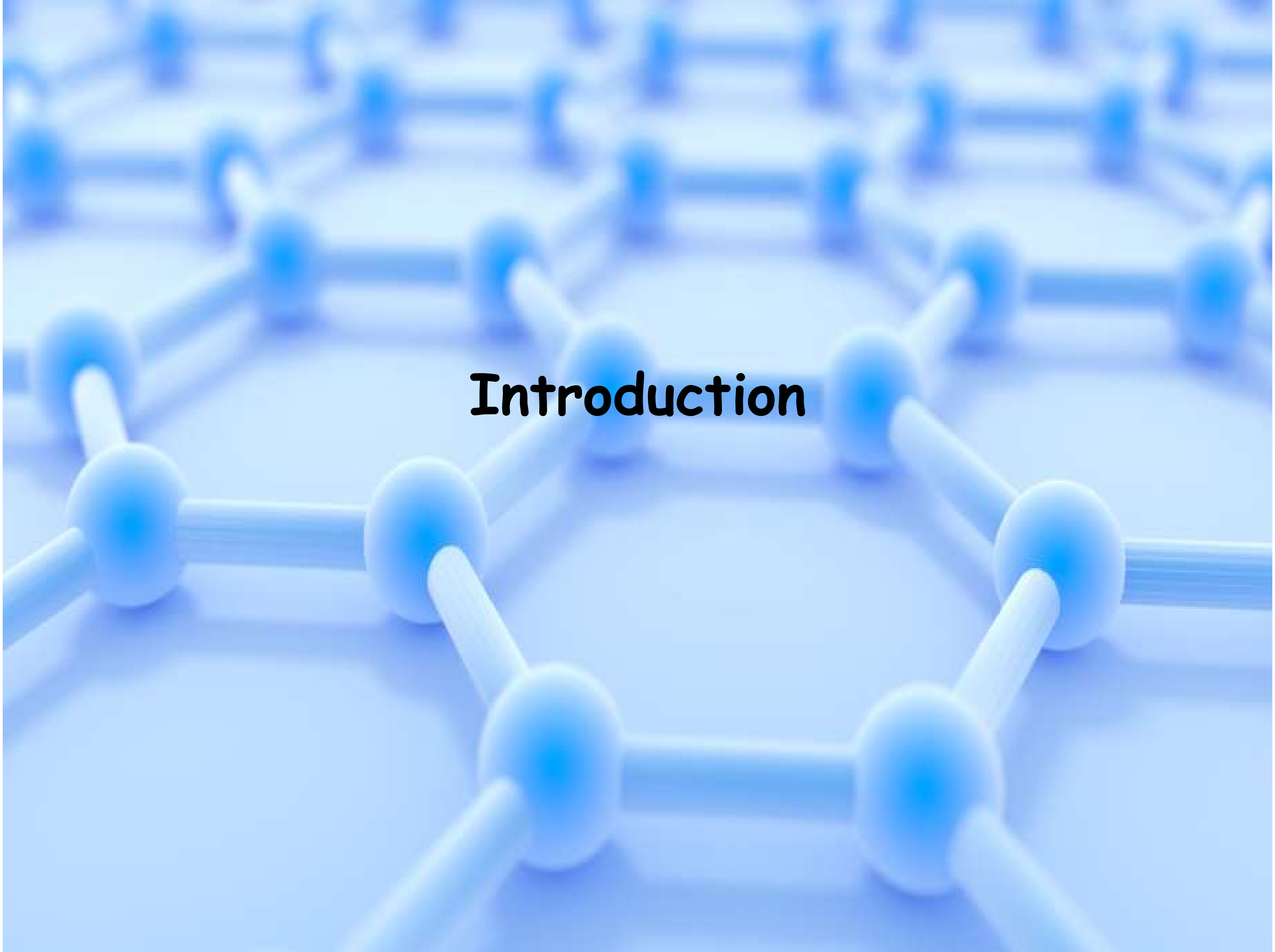
Detailed Program (Nanophotonics)

1. Introduction to photonics (2h)
2. Recap of light-matter interactions (4h)
   a) Maxwell's equations in free space and in dielectric media
   b) boundary conditions and constitutive relations
   c) Wave equation
   d) Poynting Theorem
   e) Material properties: linear/nonlinear, homogeneous/inhomogeneous, isotropic/anisotropic, stationary/non-stationary, dispersive/non-dispersive
   f) propagation in dispersive media: group velocity and group velocity dispersion
3. Polarization Optics (8h + 2h)
   a) polarization of light
   b) reflection and refraction
   c) anisotropic media
   d) optical activity and magneto-optics
   e) liquid crystals
   f) polarization devices

Detailed Program (Nanophotonics)

4. Photonic Crystals (5h)
   a) matrix theory
   b) Fabry-Perot etalon
   c) one-dimensional photonic crystals
   d) devices and applications
5. Plasmonics (2h)
6. Metamaterials (3h)
7. Basics of numerical modeling of light-matter interaction (2h)
8. Numerical laboratory (8h)

Introduction

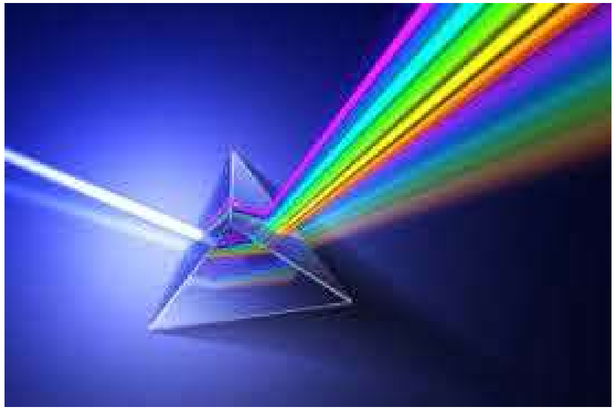


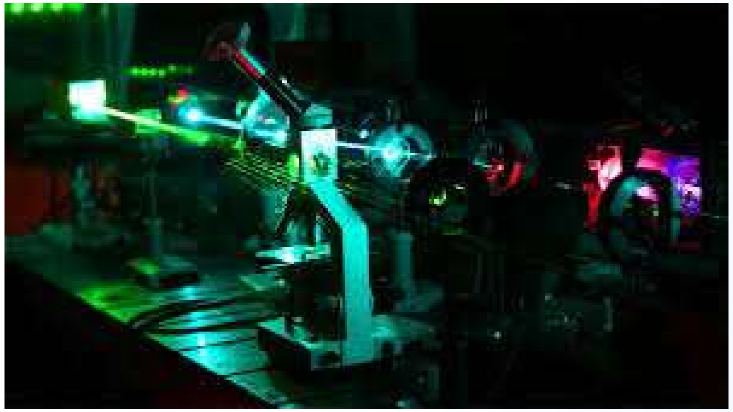
What is photonics?

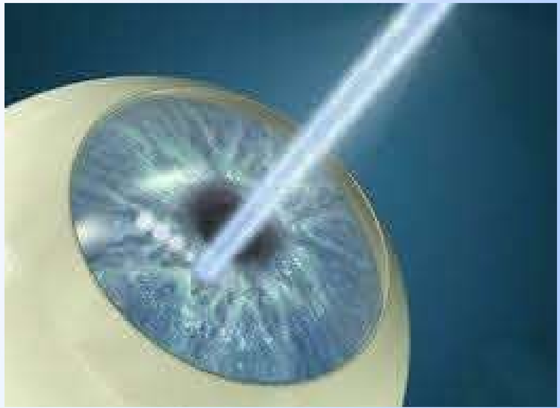
The term ***photonics*** was coined in analogy with electronics, reflects the growing tie between optics and electronics forged by the increased role that semiconductor materials and devices play in optical systems.

Electronics → ***Control of electric charge flow***

Photonics → ***Control of photons (in free space or matter)***







Introduction

The term ***photonics*** is used broadly to include the following areas/topics:

- The *generation* of coherent light by lasers and incoherent light by luminescence sources such as light-emitting diodes;
- The *transmission* of light in free-space and through optical components (lenses, apertures, waveguides and optical fibers);
- The *modulation* of light by means of switching, acousto-optics and all-optical devices;
- The *amplification* and *frequency conversion* of light by means of nonlinear materials;
- The *detection* of light.

The applications of photonics are numerous but the most important are:
- Optical communications;
- Signal processing;
- Optical computing;
- Sensing;
- Energy transport.

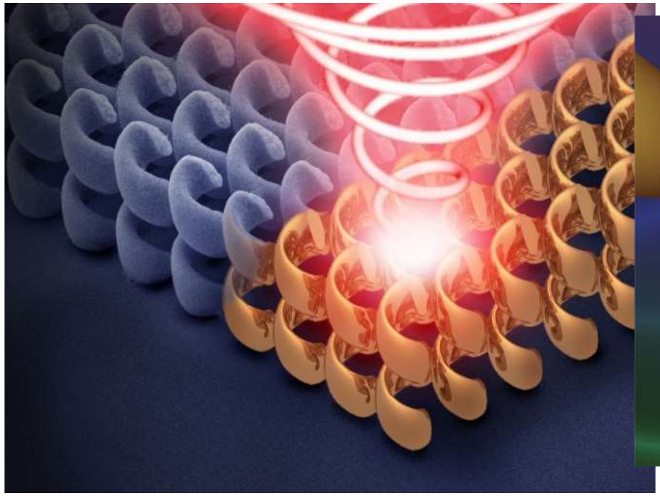
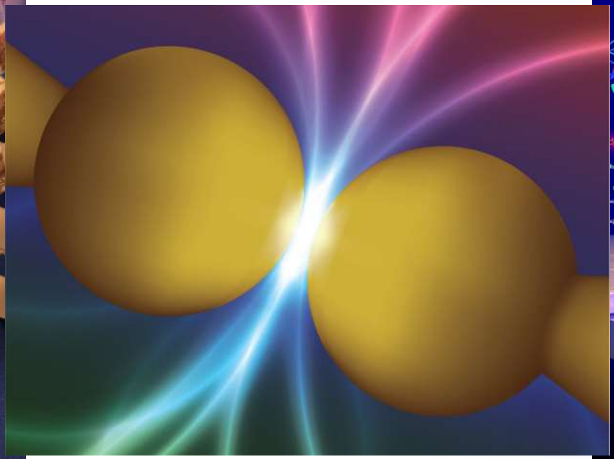
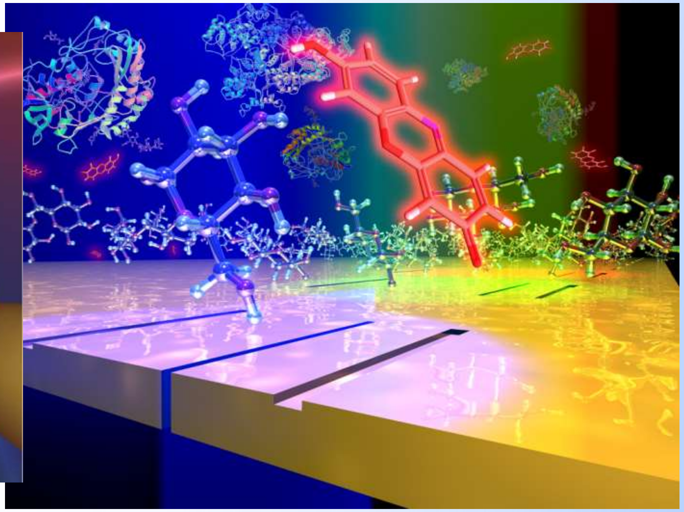
Introduction

Continuing advances in device-fabrication technology have stimulated the emergence of ***nanophotonics***, which deals with optical processes that take place over sub-wavelength scale.

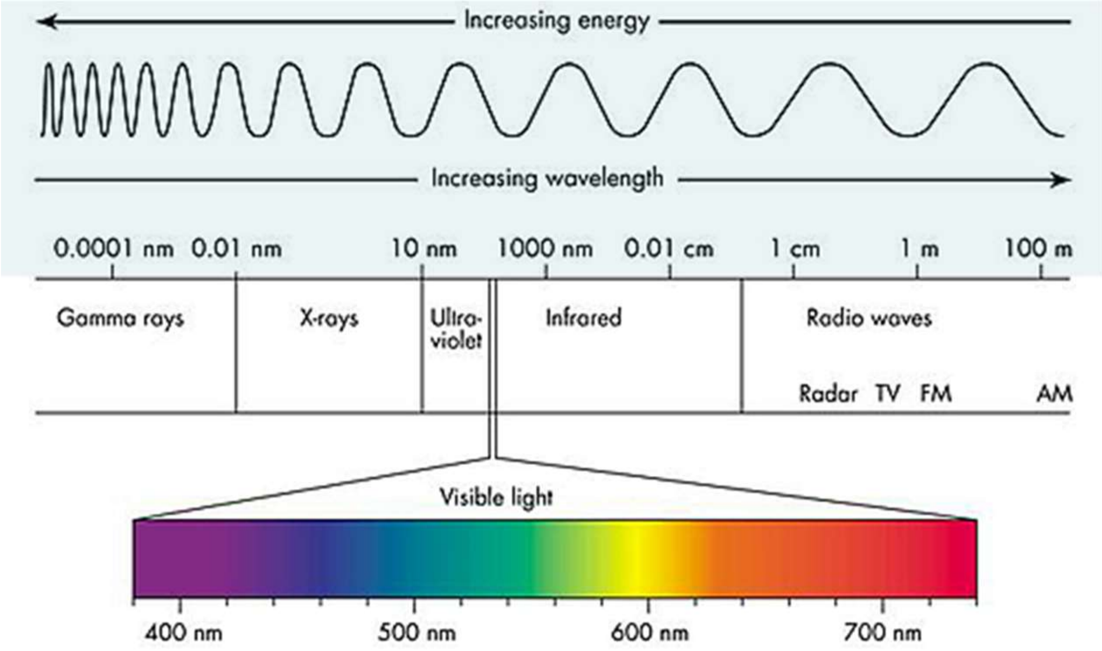
What is nanophotonics?

Nanophotonics is defined as *“the science and engineering of light–matter interactions that take place on wavelength and sub-wavelength scales of light where the physical, chemical or structural nature of natural or artificial nanostructured matter controls the interactions”*

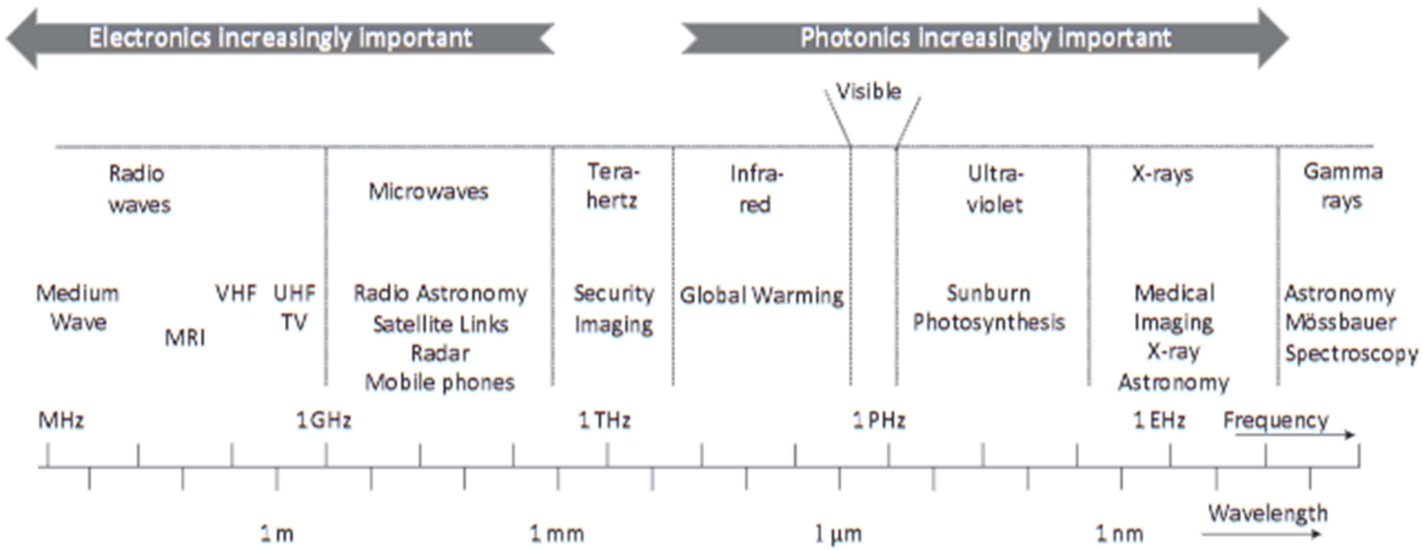
– National Academy of Science

Introduction



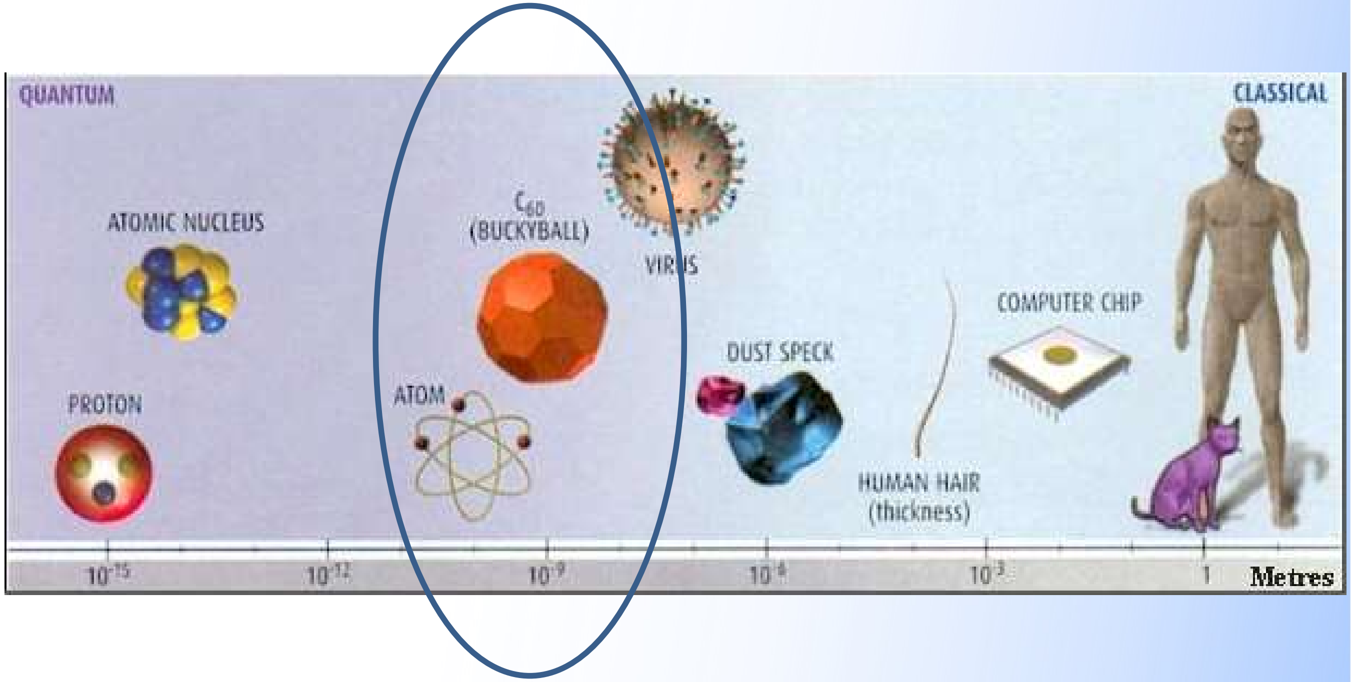
Electromagnetic length scale



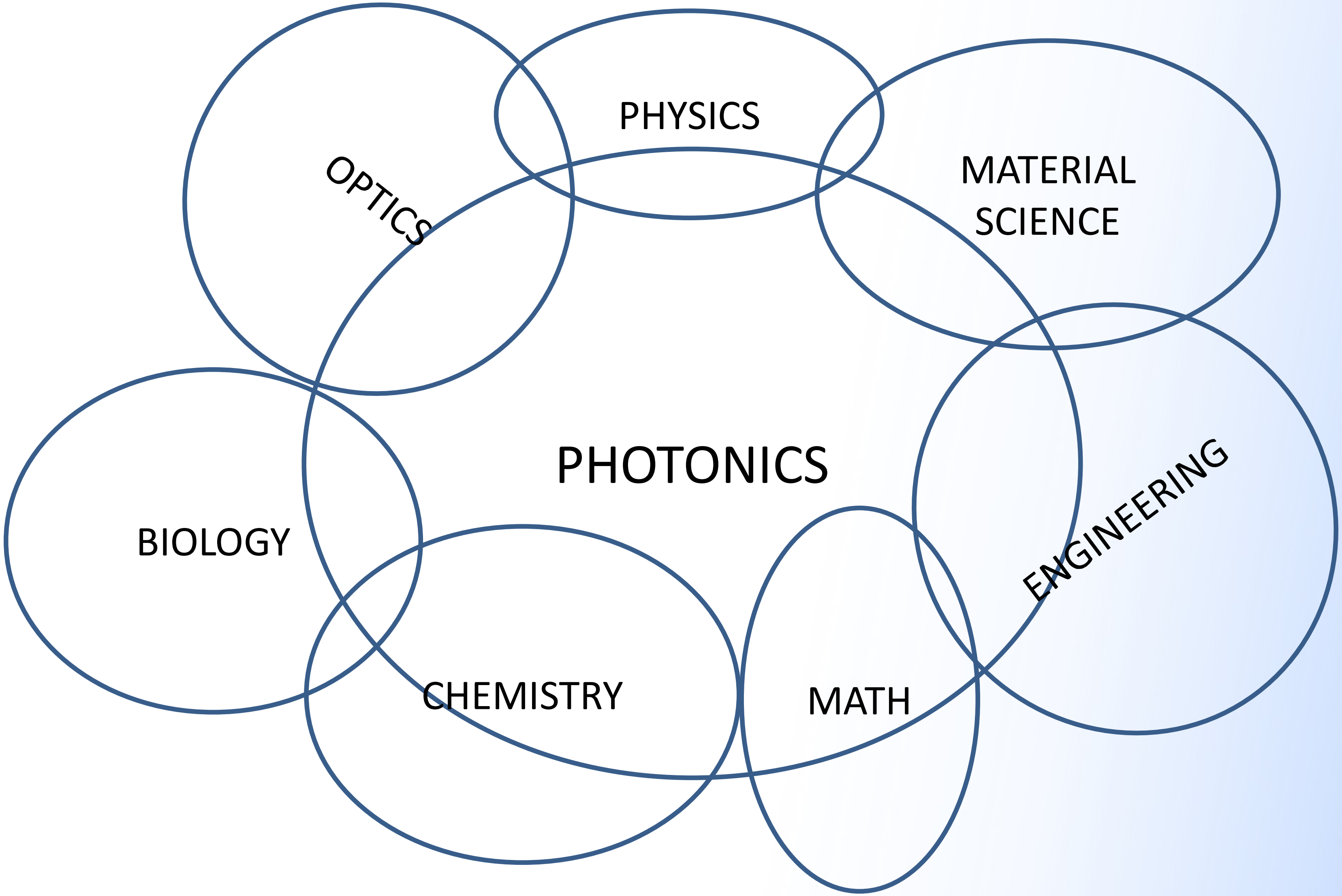
Applications at different wavelengths

Introduction

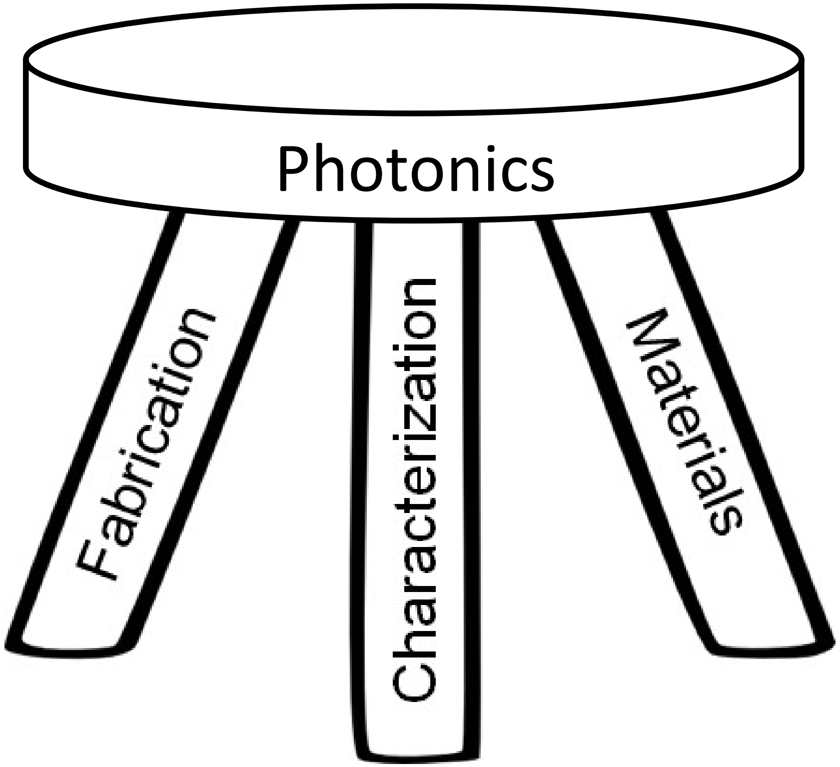
What do we look at the nanometer scale?



Introduction



Introduction



We can divide the field of photonics (and nanophotonics) into three broad categories, that can be distinguished by their functionality:

1. Materials;
2. Fabrication;
3. Characterization;

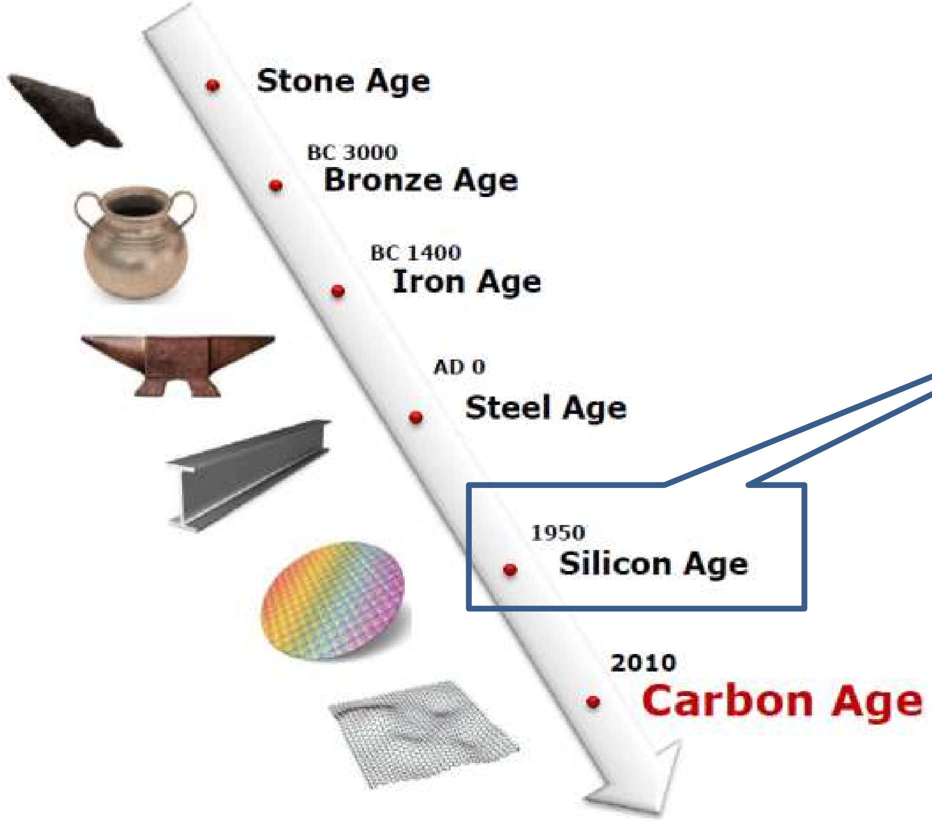
These three aspects are analogous to the legs of a three-legged stool.

The image of the stool wants to convey the idea that all three aspects are essential to embrace the field of photonics!

Materials

Technological progress ⟺ development of new materials

Some historical examples are…



Microelectronics

MEMS

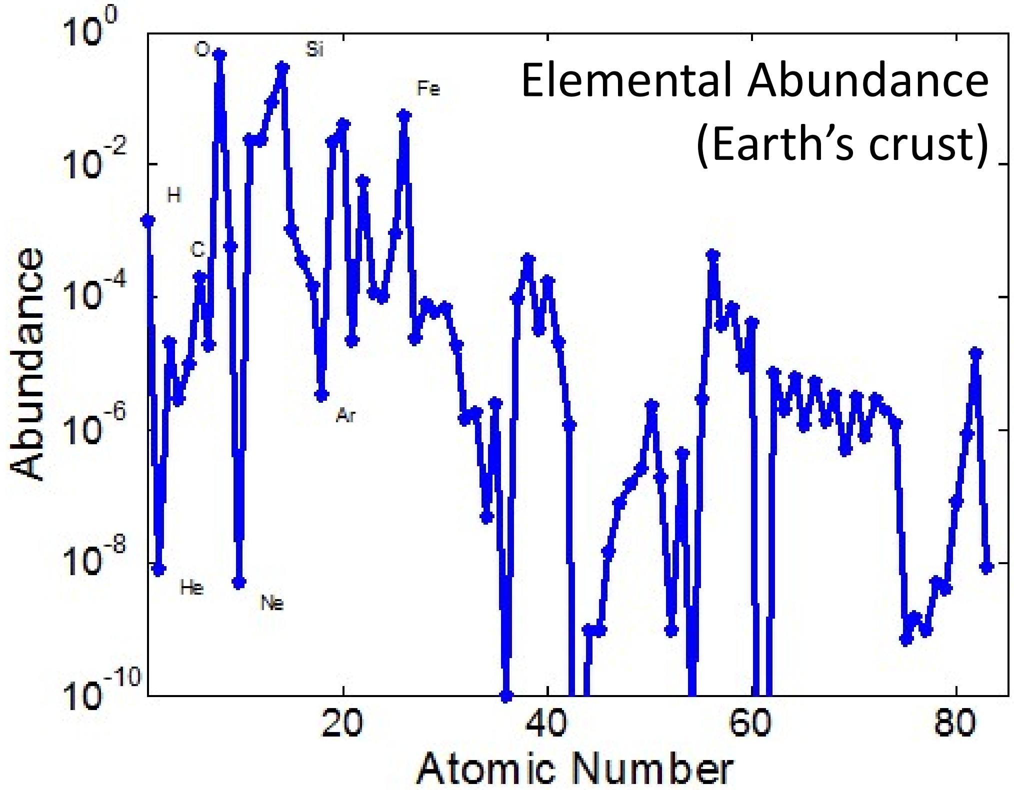
Sensors

Photonics

Today research is devoted to creating new materials with functionalities that are not ordinarily available in natural elements or compounds.

Materials

Element's abundance is important when pursuing new technologies



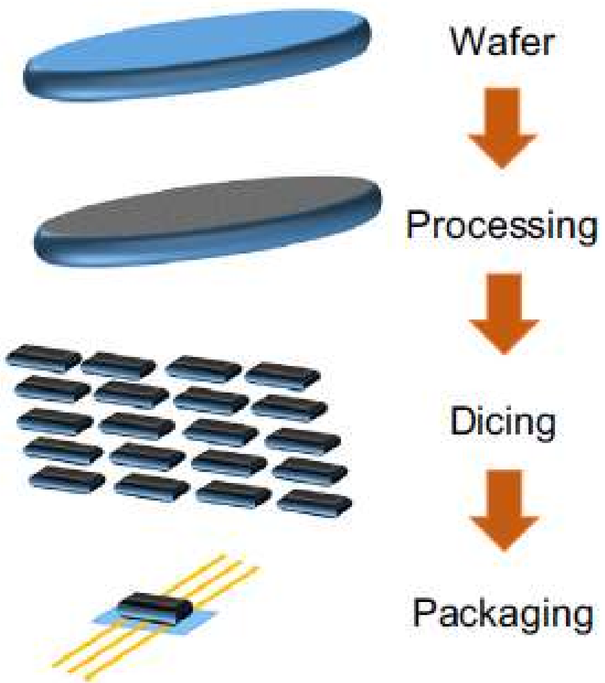
Abundant elements are inexpensive and easy to procure. They are also not subject to political crises or pressures. However, some less abundant elements might be useful too:

Example: Rare-earth metals are extremely important for electronics, lighting, displays, and communications
Technologies. These elements are not particularly abundant but their use for those applications is limited to tiny amounts.

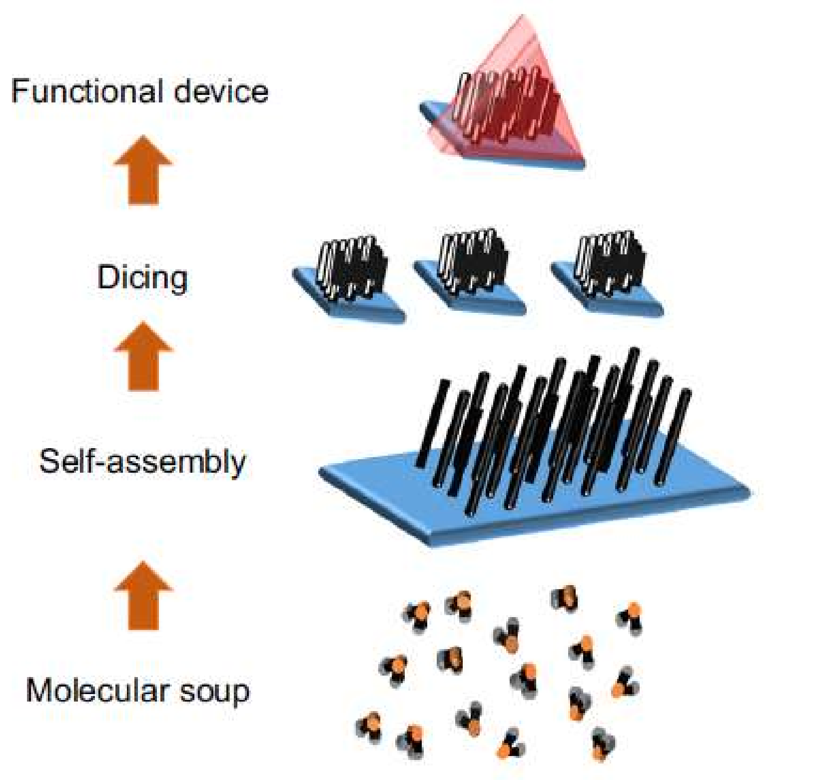
Fabrication

The techniques to create new photonic devices and optical materials have been divided into two areas:

Top down



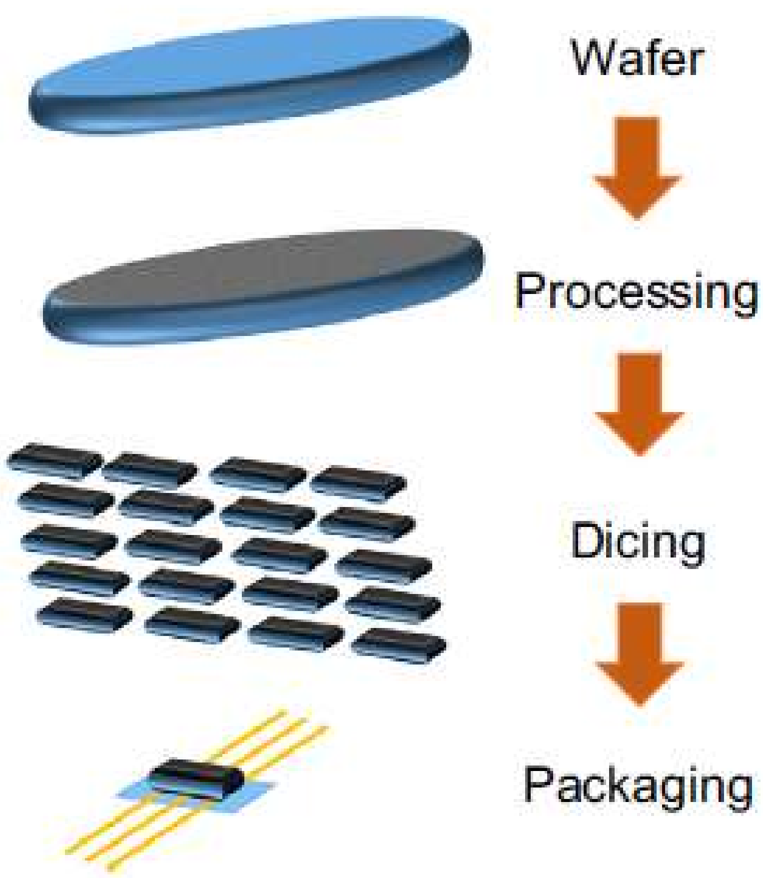
Bottom up



Fabrication

Top-down techniques are commonly used to make **electronic circuitry** and **MEMS devices**

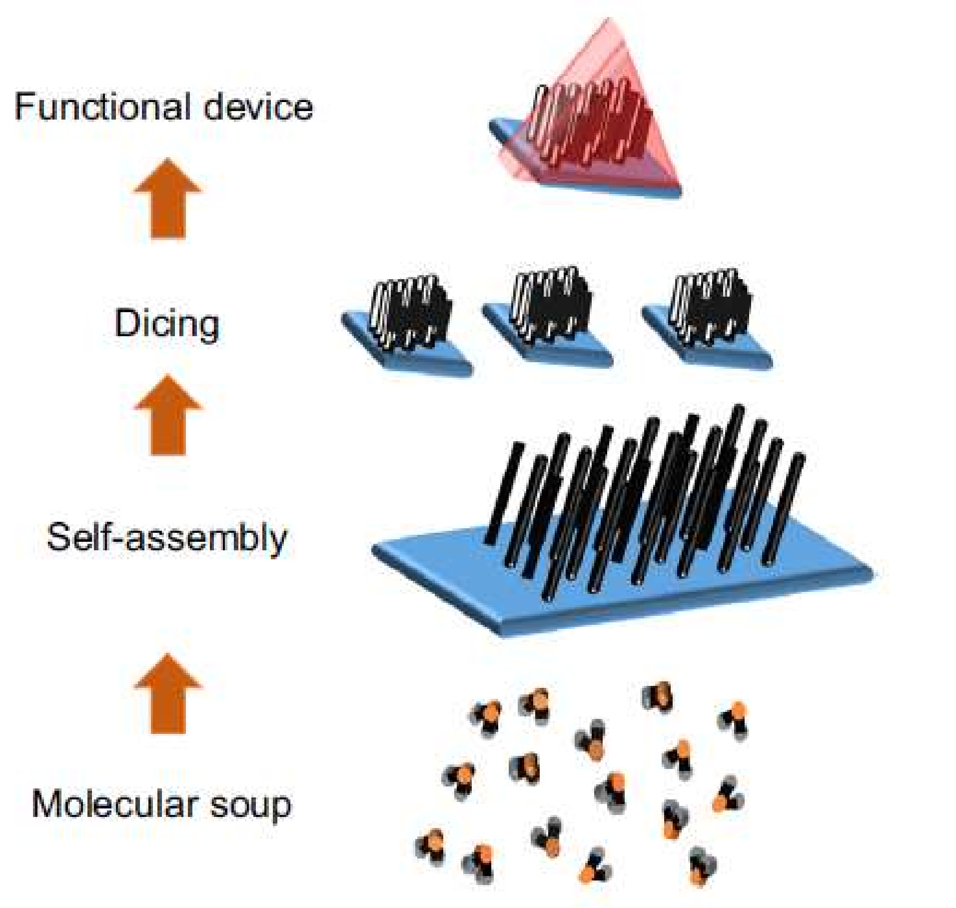
The starting point is a wafer substrate that is a building block with required characteristics. The wafer has material removed, added, or doped using the available suite of fabrication tools. A high yield of devices demands that the environment be controlled using a cleanroom. After completing the fabrication process, the wafer may contain thousands of functional chips. By dicing the wafer, the chips are available for packaging to produce the final product. The available processing tools have seen several generations of improvements because of the electronics industry's relentless drive to make smaller and smaller devices.



Fabrication

Bottom-up approaches are often used to fabricate novel materials with properties not available in nature.

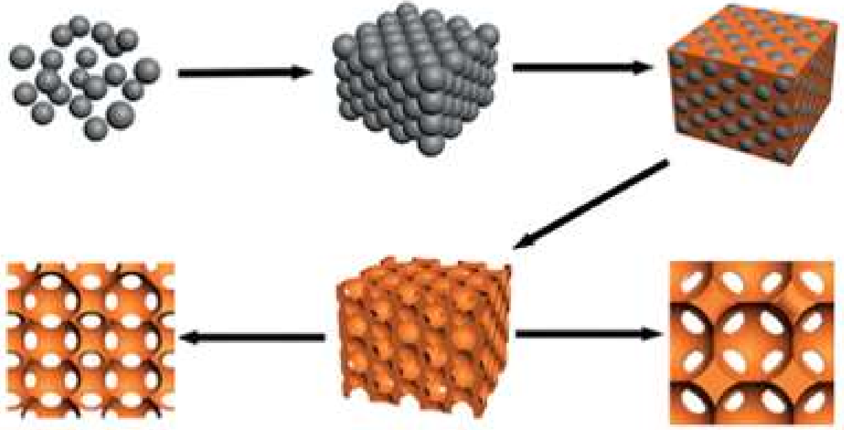
They are characterized by controlled chemical synthesis or by physically directing growth of an initial “molecular soup” with all the ingredients to build the final structure. The processes that organize the constituents into a final product are broadly called self-assembly techniques. Many of the approaches are bio-inspired following nature’s ability to build complex systems from molecular building blocks. In self-assembly, the molecules are collected into nano-sized structures that can be termed super-atoms.

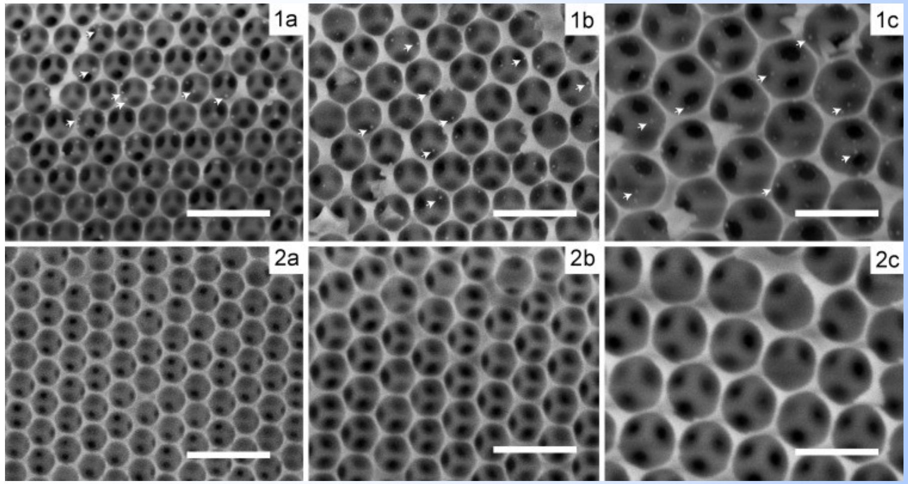


Fabrication

An example of nature's self-assembled bottom-up approach is found in *opaline materials*. The beautiful colors of opals are the result of light interference and diffraction from a periodic arrangement of silica spheres.

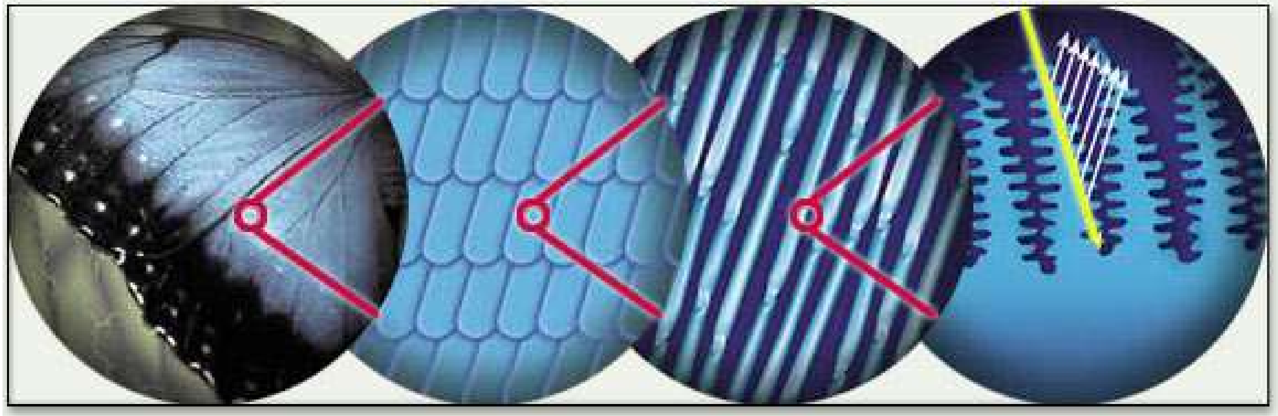
Nowadays these structures would be called *photonic crystals*. The bottom-up creation of inverse opals as an example of stepping beyond nature to create a material not naturally found.





Fabrication

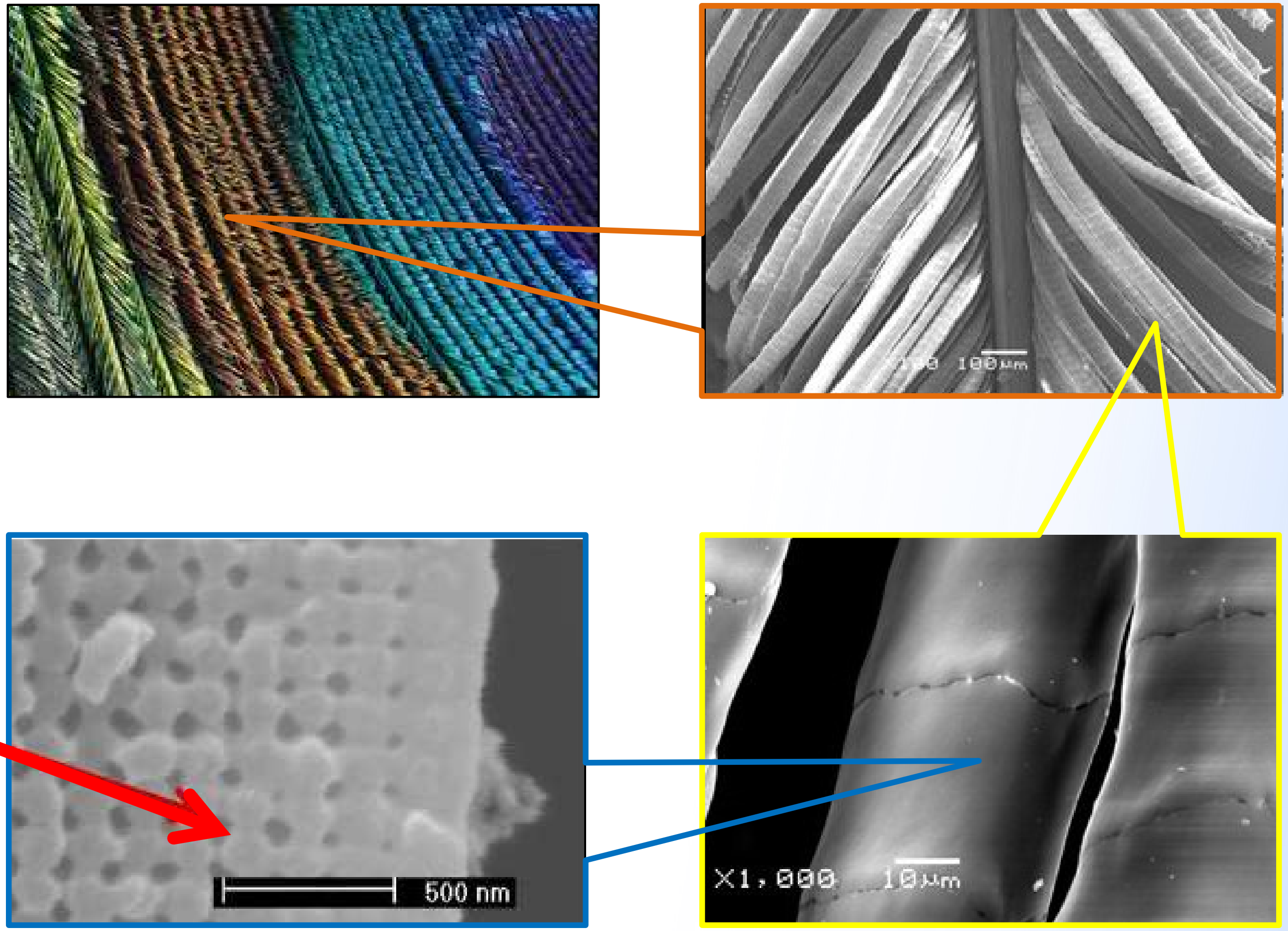
Nanostructures in nature:
the Morpho butterfly



Fabrication

Nanostructures in nature:
the Peacock feather

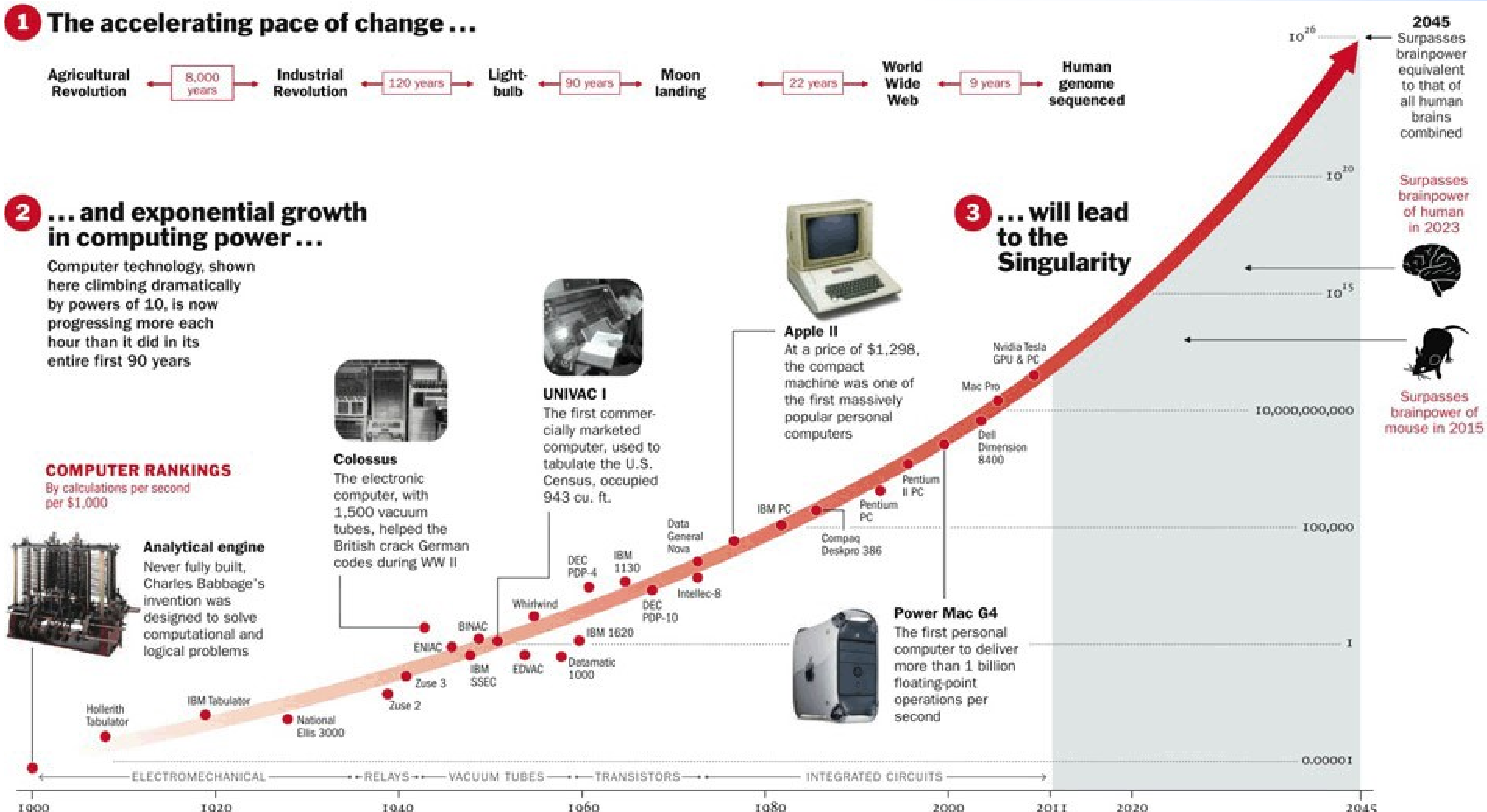
Periodic arrangement of holes



A periodic nanostructure reflects light at a specific wavelength and gives the iridescent colors of the feathers we can see!

Fabrication

The top-down fabrication techniques used to make photonic devices and materials leverage on decades of progress and investments made in the electronics industry to develop higher precision tools and control of nanometer-sized critical dimensions sustained over wafer-sized areas. The drive toward nanofabrication is most evident in the electronics industry.



Fabrication

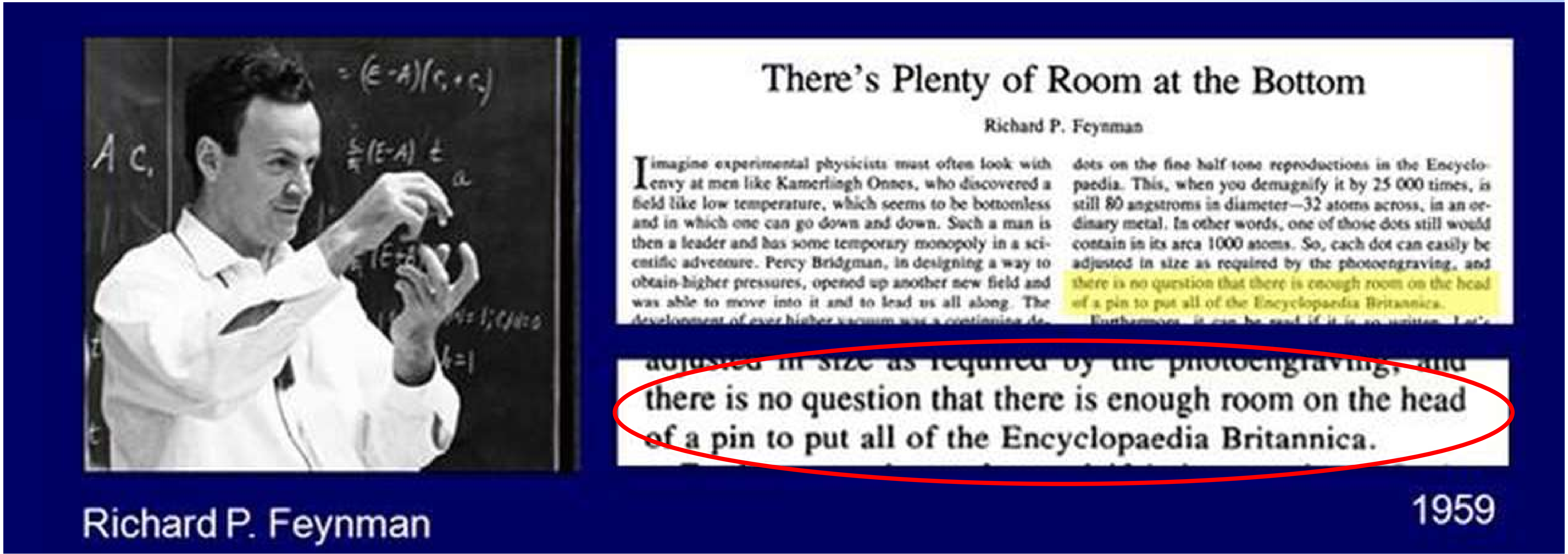
To keep pace with Moore's law, the industry developed new techniques and tools that improved the production and yield of the products. Modern nanotechnology requires a suite of instruments performing specific tasks that are needed to make the final product.

In general, making high-performance devices requires lithography and patterning, materials etching techniques, and materials deposition to fabricate. The table lists the major nanofabrication technology steps.

Process	Examples
Lithography and patterning	Ultraviolet or extreme ultraviolet light, X rays, electron beams, dip-pen, and nanoimprint lithographies
Deposition techniques	Physical vapor deposition, chemical vapor deposition, molecular beam epitaxy
Etching	Wet and dry (plasma) techniques

Fabrication

We mention as a historical reference a 1959 lecture by the iconic Nobel Laureate Richard Feynman. In December 1959, Feynman presented a talk entitled “There’s Plenty of Room at the Bottom.” He saw no physical limitations to writing information on a much smaller scale. In Feynman’s words: “there is plenty of room to make them (computers) smaller. There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now”.



Characterization

In the same lecture Feynman also challenged the community to improve metrology by developing higher resolution instruments to image the written features.

Writing the Encyclopedia Britannica on the head of a pin is a simple fabrication challenge demonstration that Feynman proposed; however, writing information is only one part of the process.

FABRICATION AND CHARACTERIZATION ARE COMPLEMENTARY

To be complete and useful, an instrument is needed that can faithfully read the written content, for example, on the head of a pin. Without the reader, the fabrication process would be incomplete without a process to verify the faithful writing of the data!

Characterization

Fabrication is not complete until the process has been monitored and verified at all stages. Characterization is a necessary and important step in the development of our understanding of nanostructured materials and the processing steps so that the fabrication can be cyclically improved. Here is a list of common characterization techniques:

Imaging technique	Examples
Optical techniques	Optical microscopy, ellipsometry, optical spectroscopies, laser pulse-probe techniques
Electron microscopes	Scanning electron and transmission electron microscopy
Scanning probe techniques	Atomic force, scanning tunneling and near-field optical microscopies, etc.

Nonlinear optical techniques have also added to our repertoire of instruments that enable submicron-feature resolution.