

**NIS**  
Università di Torino

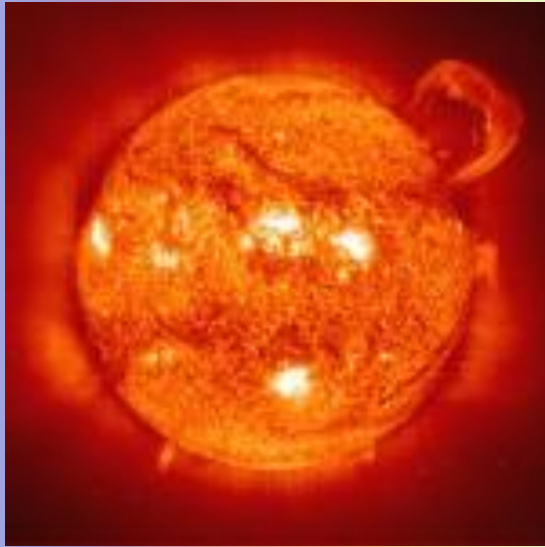
**Nanostructured Interfaces and Surfaces**  
Centre of Excellence

# COLORE COME SPIA DELLA STRUTTURA DEI MATERIALI

*Progetto Scienza dal Vivo*

**Francesca Bonino**

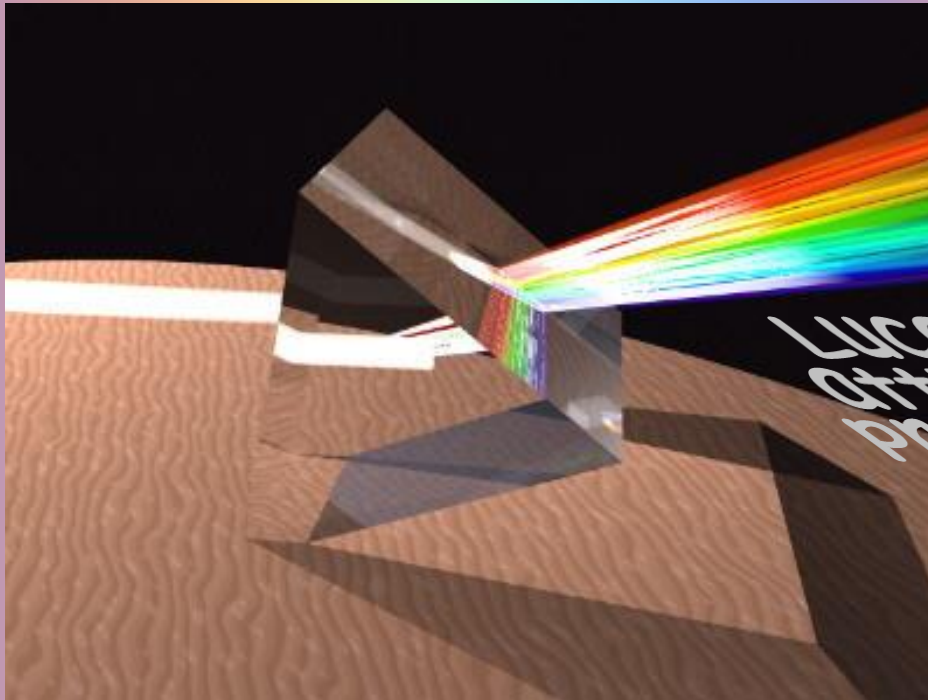
**Dipartimento di Chimica I.F.M. e NIS Centro di eccellenza  
Università degli Studi di Torino**



## luce bianca

La radiazione solare è ritenuta costante e corrisponde, al limite dell'atmosfera, a  $1.400 \text{ W/m}^2$ .

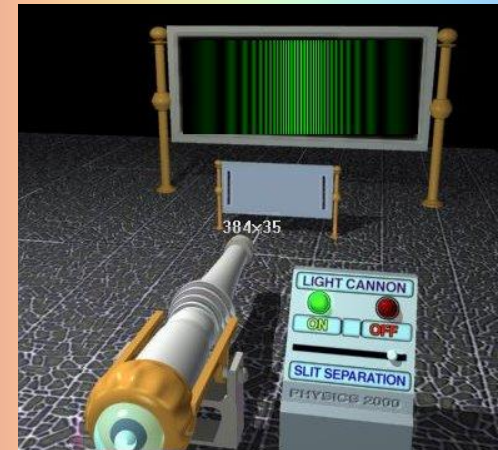
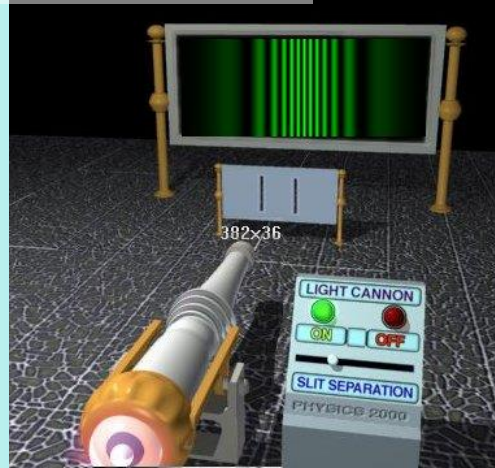
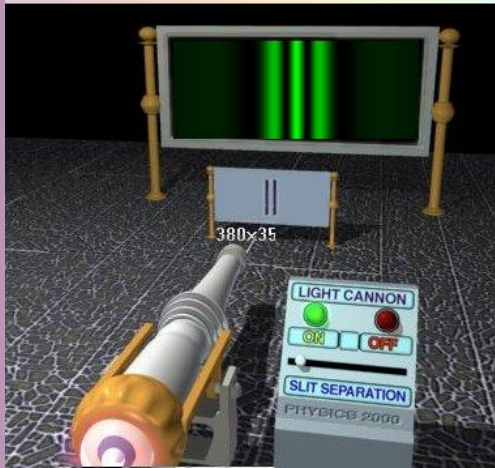
Il Sole emette radiazioni che vanno dai raggi gamma alle onde radio. Quantitativamente il picco delle radiazioni corrisponde alla radiazione cosiddetta "visibile".



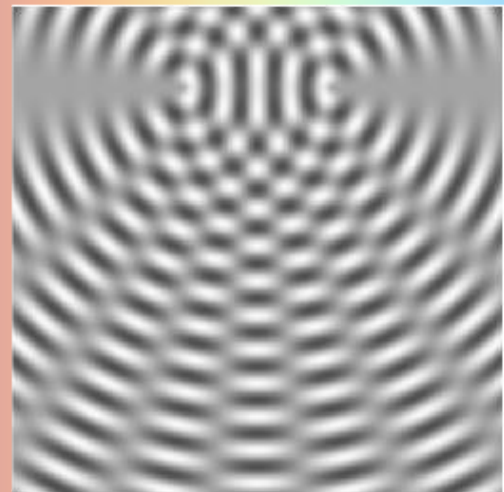
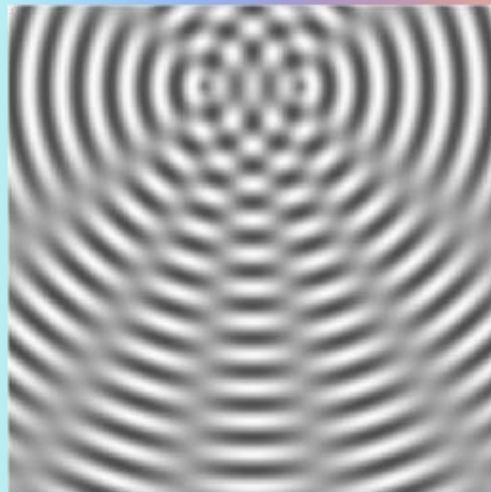
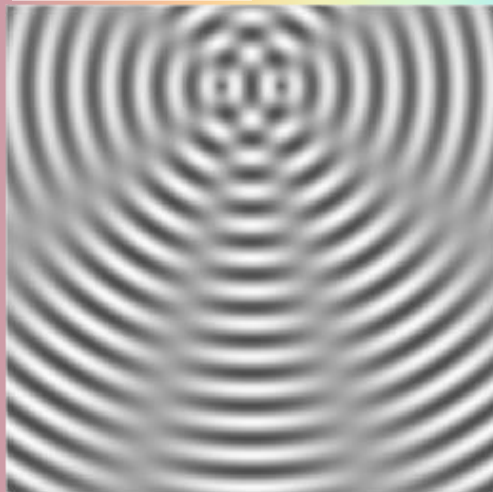
LUCE bianca  
attraverso un  
prisma rivela la  
sua natura  
COMPOSITA:  
perchè?

# Esperimento di Young (1803)

luce monocromatica: laser

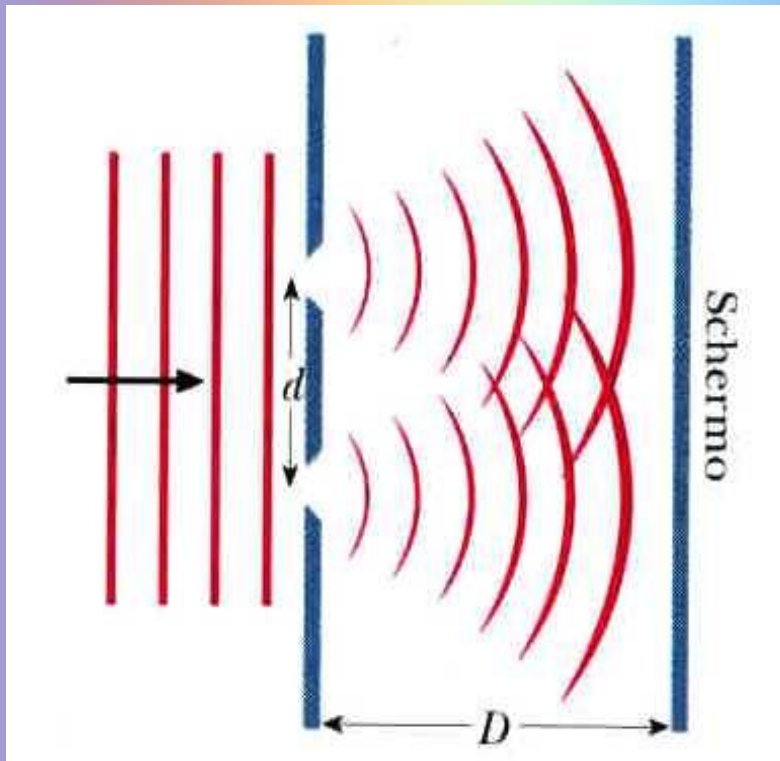


liquido





interferenza da doppia fenditura:



interferenza di onde sulla  
superficie di acqua causate  
da due ostacoli

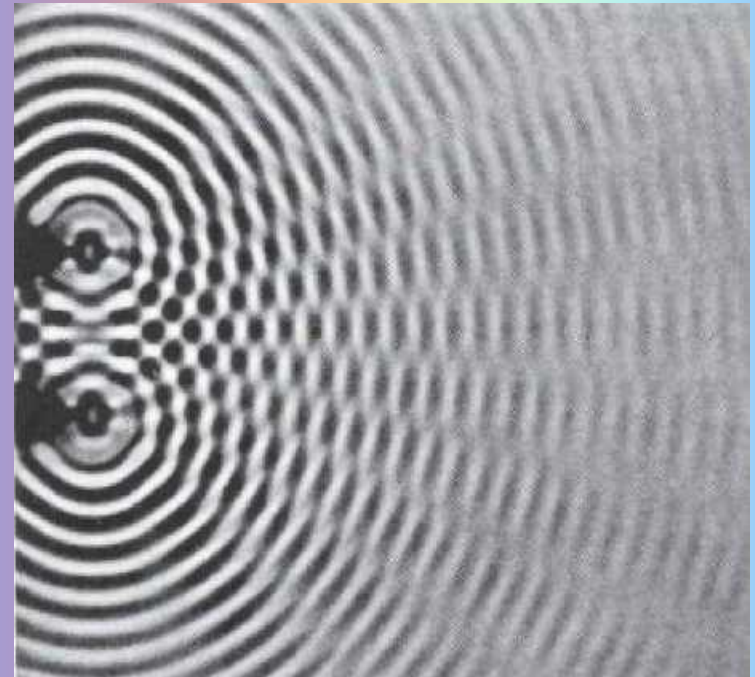
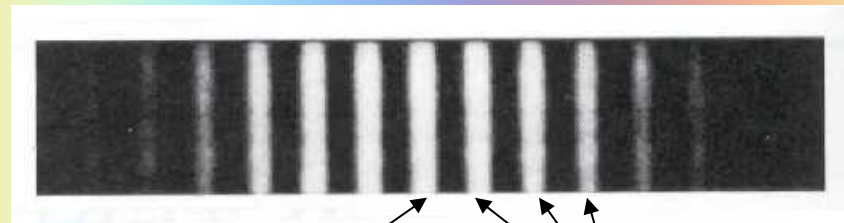


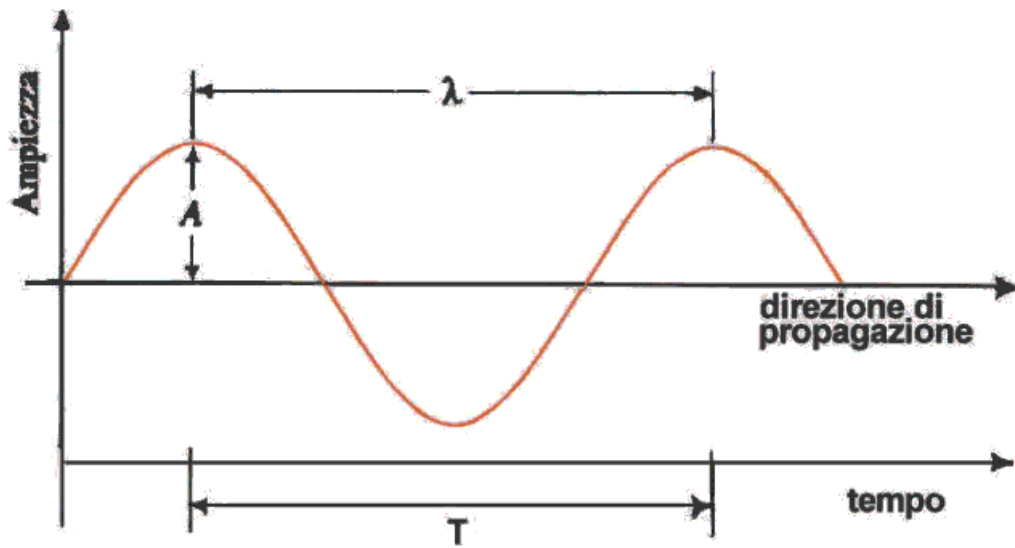
immagine che  
si osserva sullo  
schermo



*massimo  
centrale*

*massimi laterali: si formano a una distanza  
regolare rispetto al massimo centrale*

## onda armonica



$$\xi(x, t) = \xi_0 \sin k(x - vt)$$

$$\xi(x, t) = \xi_0 \sin(kx - \omega t)$$

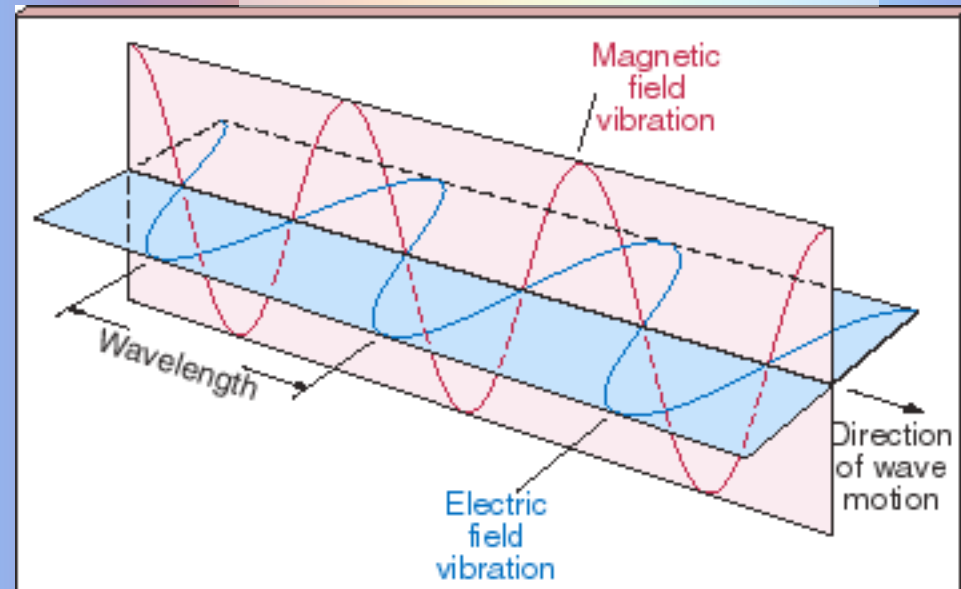
$$k = \frac{2\pi}{\lambda} \quad \omega = kv = \frac{2\pi v}{\lambda}$$

$$P = \frac{2\pi}{\omega} \quad \lambda v = v$$

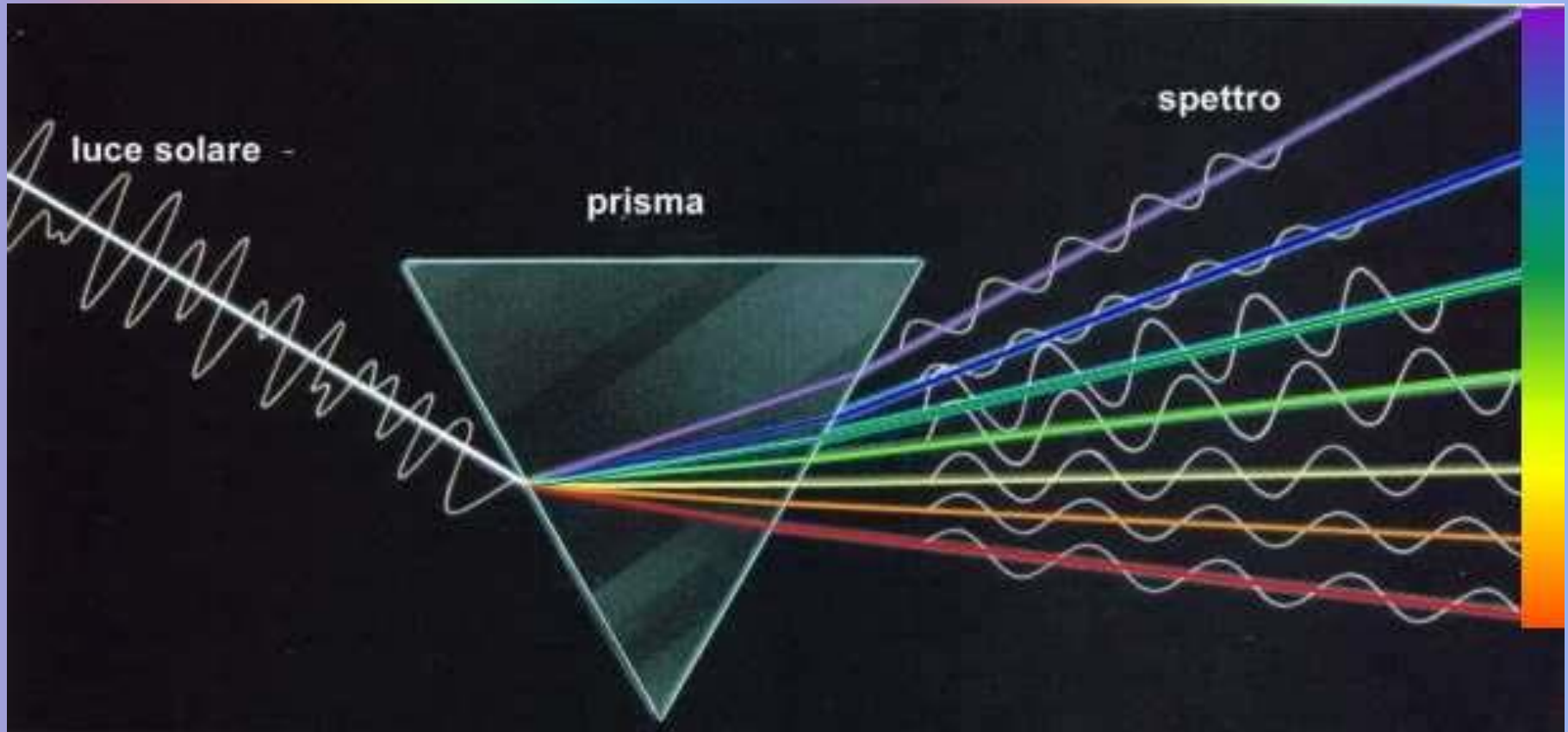
$$E(x, t) = E_0 \sin k(x - ct)$$

$$B(x, t) = B_0 \sin k(x - ct)$$

## onda elettromagnetica



# Esperimento di Newton (1666)



# Rifrazione

$$\frac{\sin i}{\sin r} = \frac{n_r}{n_i}$$

Legge di Snell

Angolo  $r$  è funzione di  $\lambda$

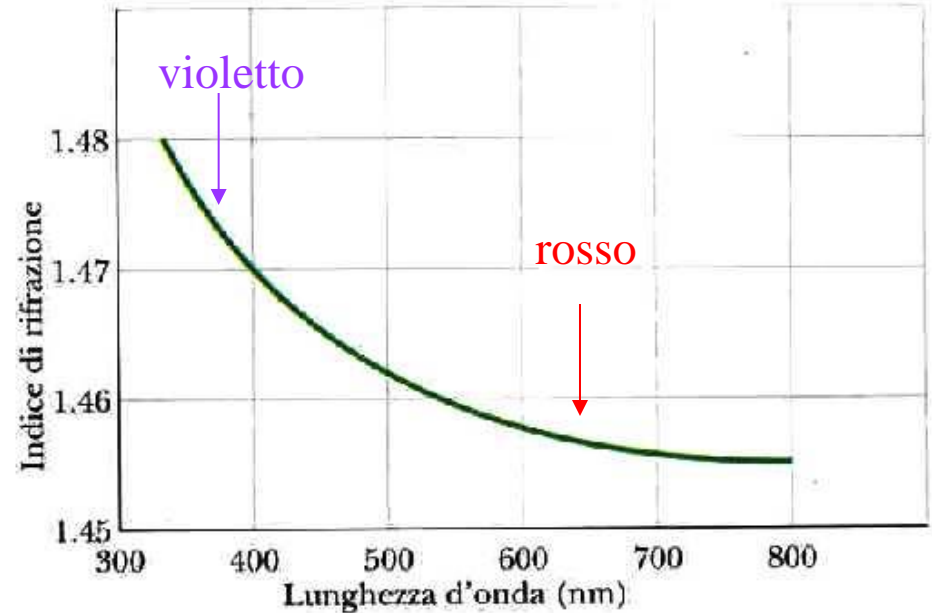
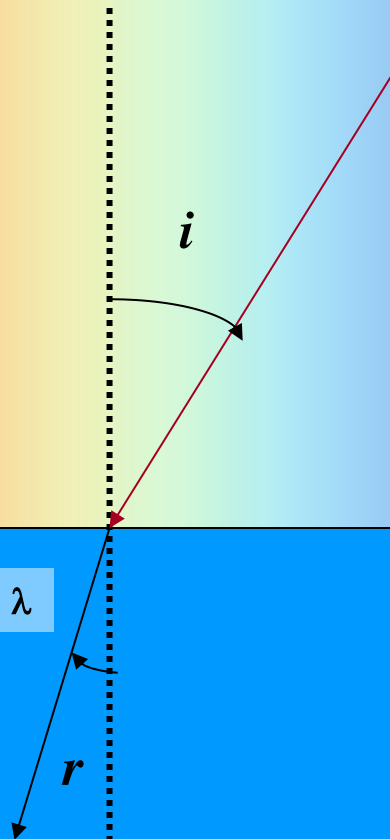


Figura 4 Indice di rifrazione del quarzo fuso in funzione della lunghezza d'onda.

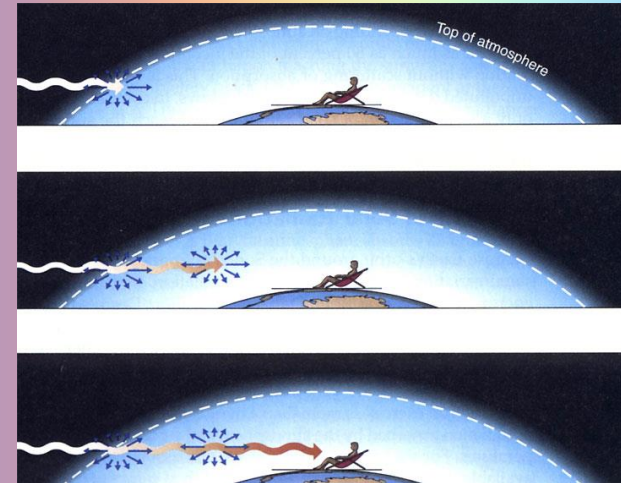
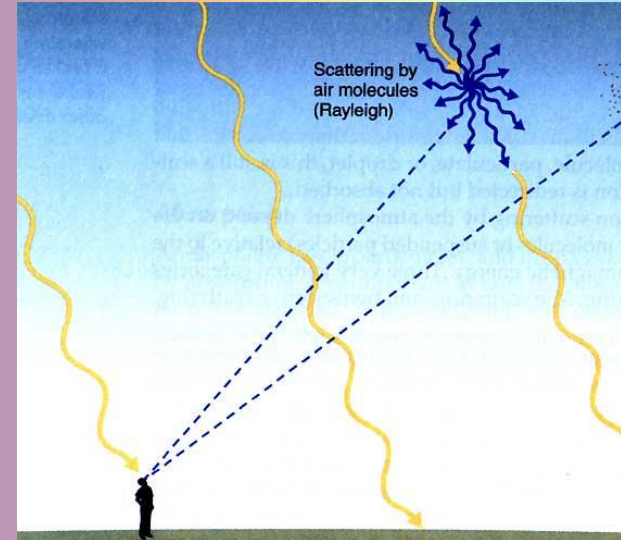
Dipendenza dell'indice di rifrazione dalla lunghezza d'onda: il "rosso" ha indice di rifrazione minore del violetto, quindi è meno deviato



# I colori del cielo

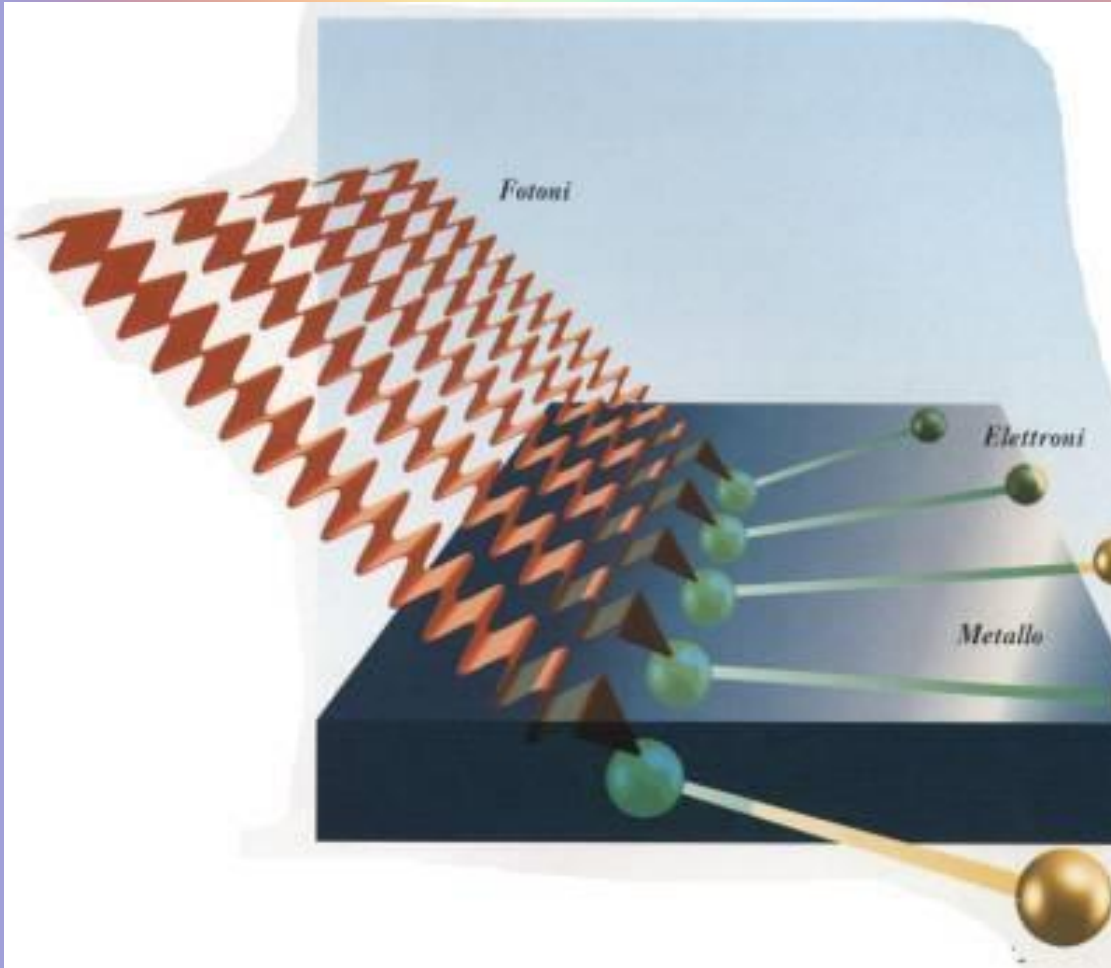


*Scattering* della luce blu da parte delle molecole dell'atmosfera (effetto Rayleigh).  $I_{scatt} \propto 1/\lambda^4$





# Effetto fotoelettrico



Emissione di elettroni in seguito ad assorbimento di energia da un'onda elettromagnetica

Albert Einstein 1905

$$E_k = h\nu - \phi$$

$E_k$  è l'energia cinetica dell'elettrone

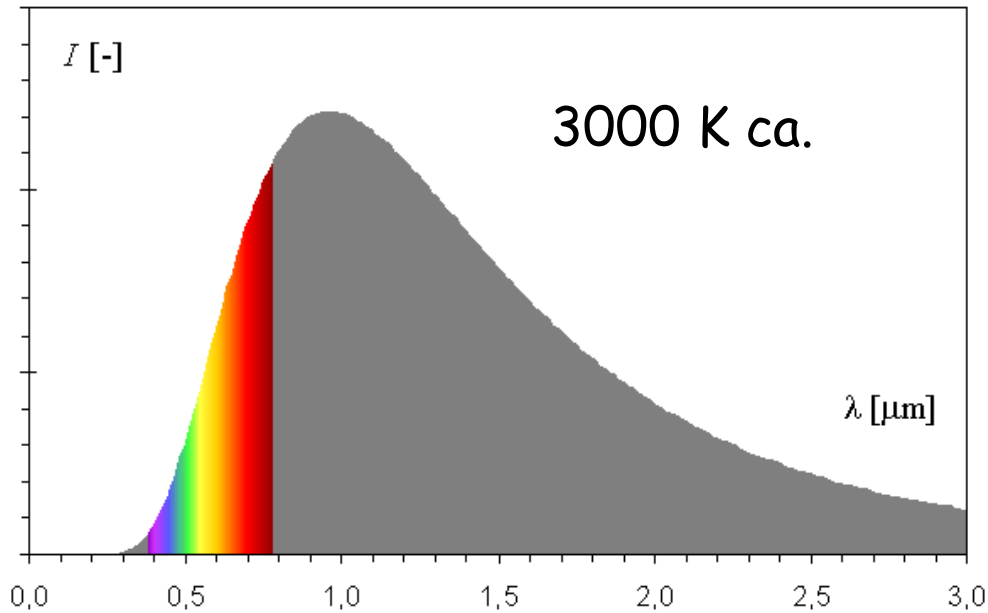
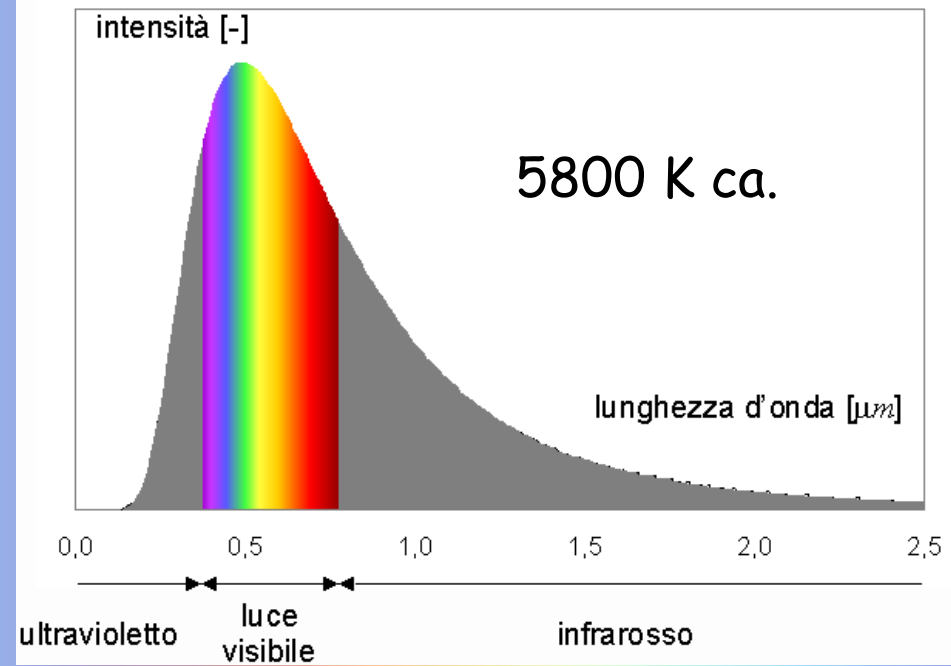
• L'esperimento di Young evidenzia il carattere ondulatorio della luce (radiazione elettromagnetica).

• L'esperimento di Newton dimostra la natura composita della luce bianca.

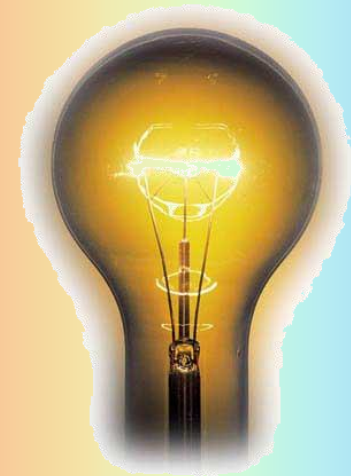
• Il fenomeno della rifrazione permette di associare a ciascun colore diverse lunghezze d'onda (o frequenze).

• L'effetto fotoelettrico evidenzia la natura corpuscolare della radiazione elettromagnetica: radiazioni a frequenza diversa trasportano fotoni a energia diversa.

## Luce solare



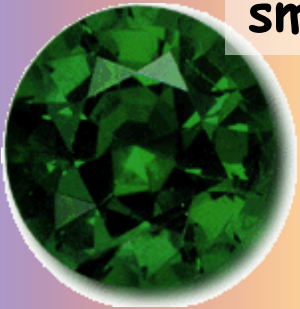
## Luce a incandescenza



# Il colore nelle gemme



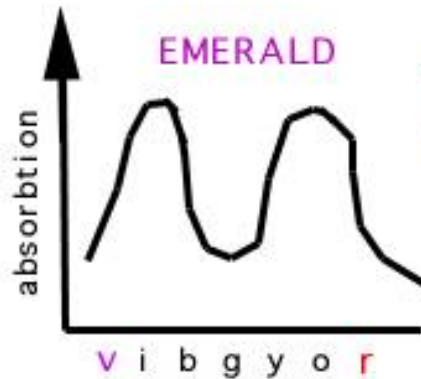
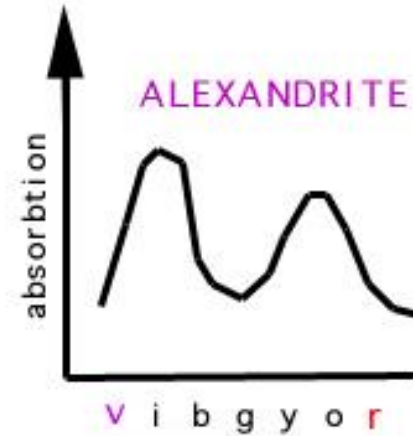
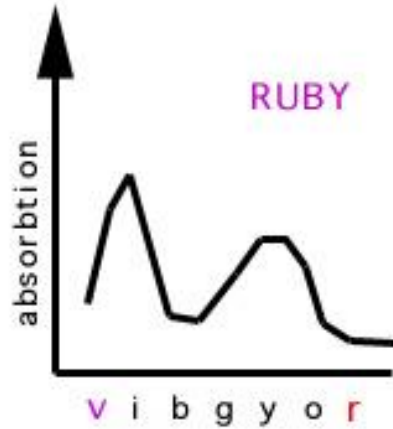
rubino



smeraldo

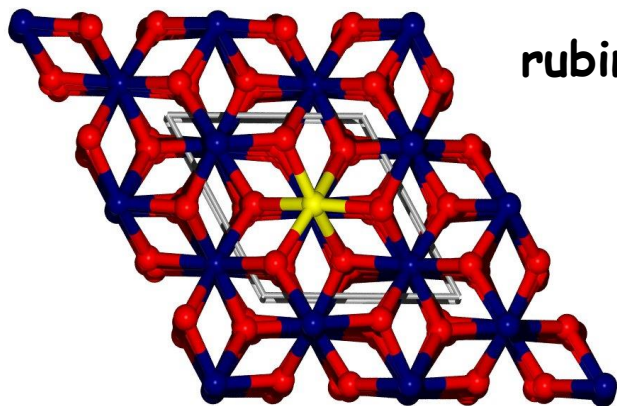


alexandrite

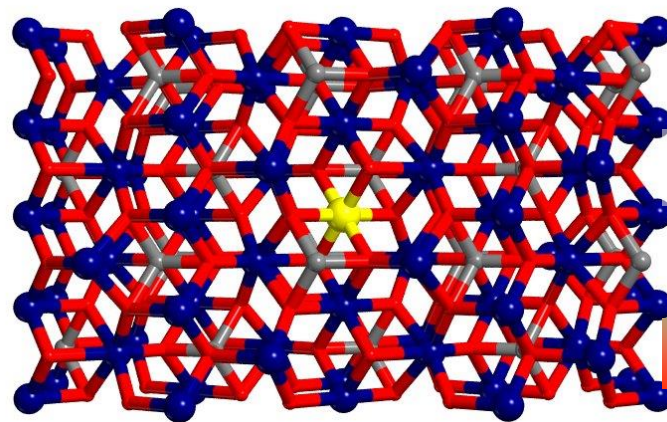


The Cr<sup>+++</sup> in ruby, alexandrite and emerald is in octahedral coordination

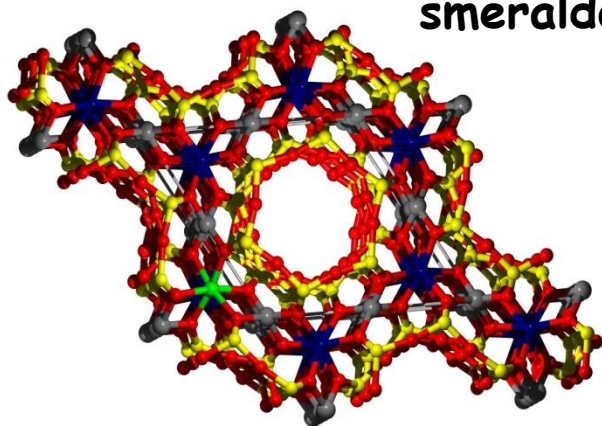




rubino



alessandrite

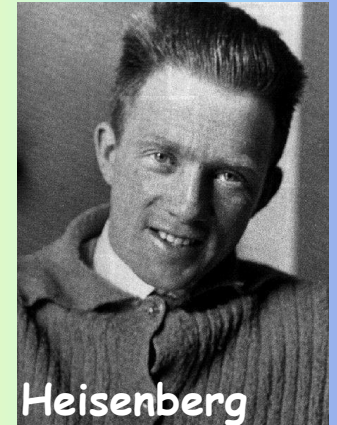
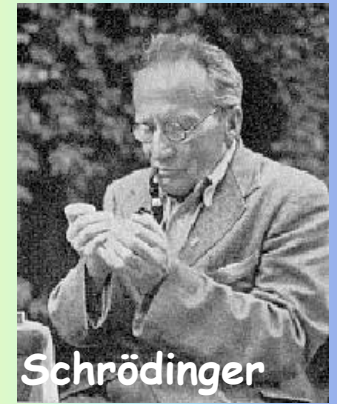
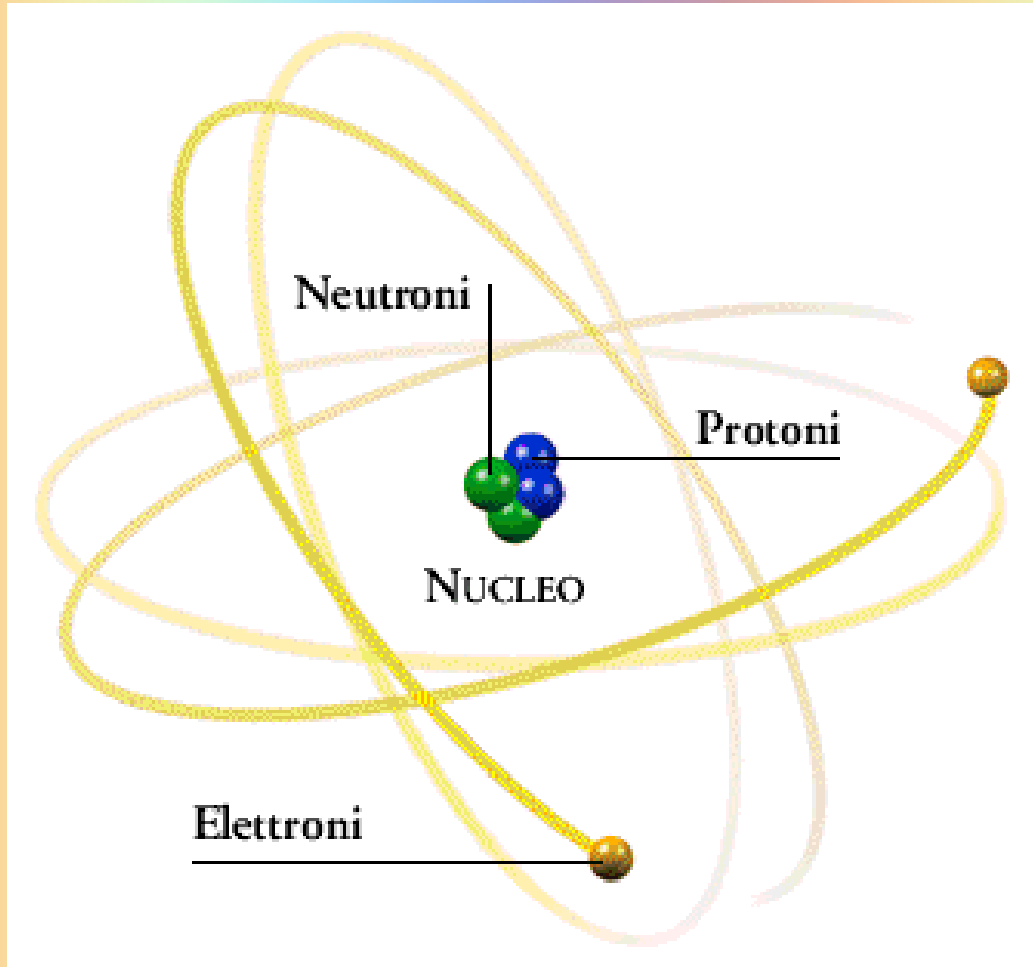
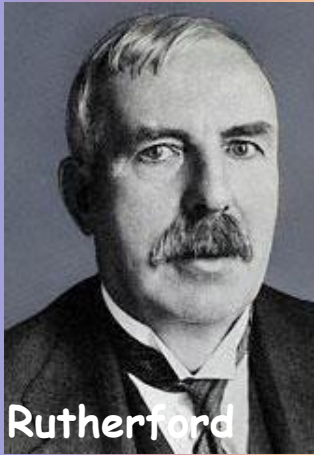
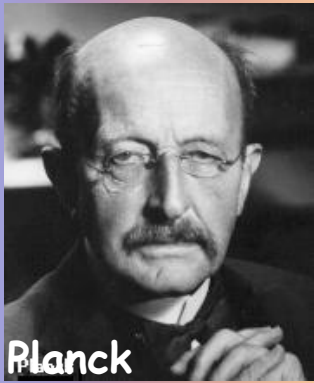


smeraldo



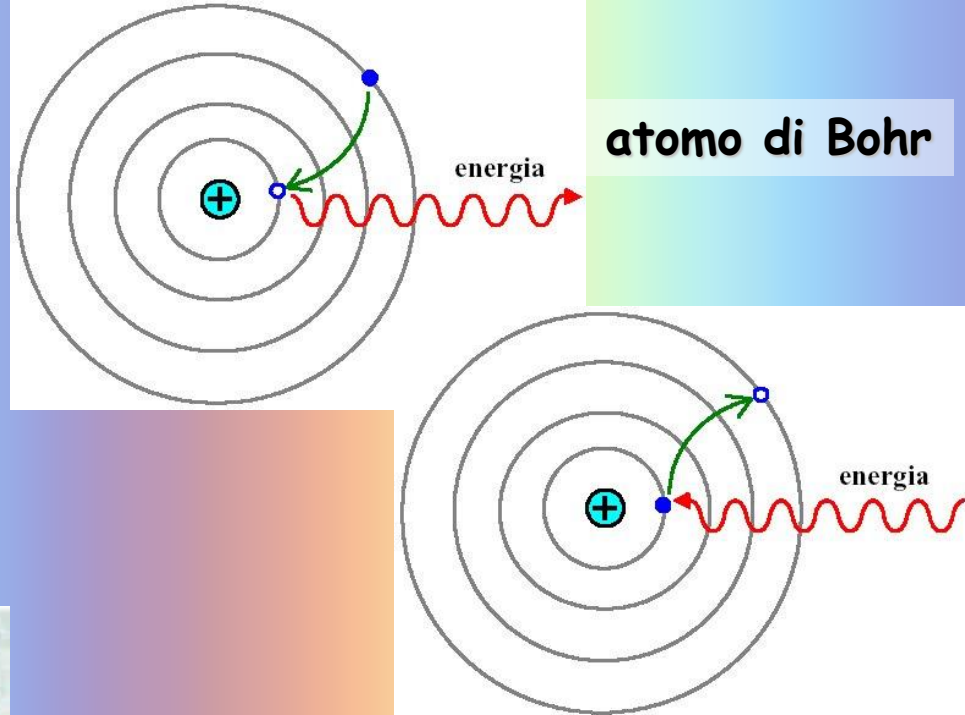
Gem	Formula	Color	Origin of color
Ruby	$\text{Al}_2\text{O}_3$	Red	$\text{Cr}^{3+}$ replacing $\text{Al}^{3+}$ in octahedral sites
Emerald	$\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$	Green	$\text{Cr}^{3+}$ replacing $\text{Al}^{3+}$ in octahedral site
Alexandrite	$\text{Al}_2\text{BeO}_4$	Red/Green	$\text{Cr}^{3+}$ replacing $\text{Al}^{3+}$ in octahedral site
Garnet	$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$	Red	$\text{Fe}^{2+}$ replacing $\text{Mg}^{2+}$ in 8-coordinate site
Peridot	$\text{Mg}_2\text{SiO}_4$	Yellow-green	$\text{Fe}^{2+}$ replacing $\text{Mg}^{2+}$ in 6-coordinate site
Tourmaline	$\text{Na}_3\text{Li}_3\text{Al}_6(\text{BO}_3)_3(\text{SiO}_3)_6\text{F}_4$	Pink	$\text{Mn}^{2+}$ replacing $\text{Li}^+$ and $\text{Al}^{3+}$ in octahedral site
Turquoise	$\text{Al}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$	Blue-green	$\text{Cu}^{2+}$ coordinated to 4 $\text{OH}^-$ and 2 $\text{H}_2\text{O}$
Sapphire	$\text{Al}_2\text{O}_3$	Blue	Intervalence transition between $\text{Fe}^{2+}$ and $\text{Ti}^{4+}$ replacing $\text{Al}^{3+}$ in adjacent octahedral sites
Aquamarine	$\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$	Blue	Intervalence transition between $\text{Fe}^{2+}$ and $\text{Fe}^{3+}$ replacing $\text{Al}^{3+}$ in adjacent octahedral sites
Diamond	C	Colorless, pale blue or yellow	Color centers from nitrogen atoms trapped in crystal

# L'atomo

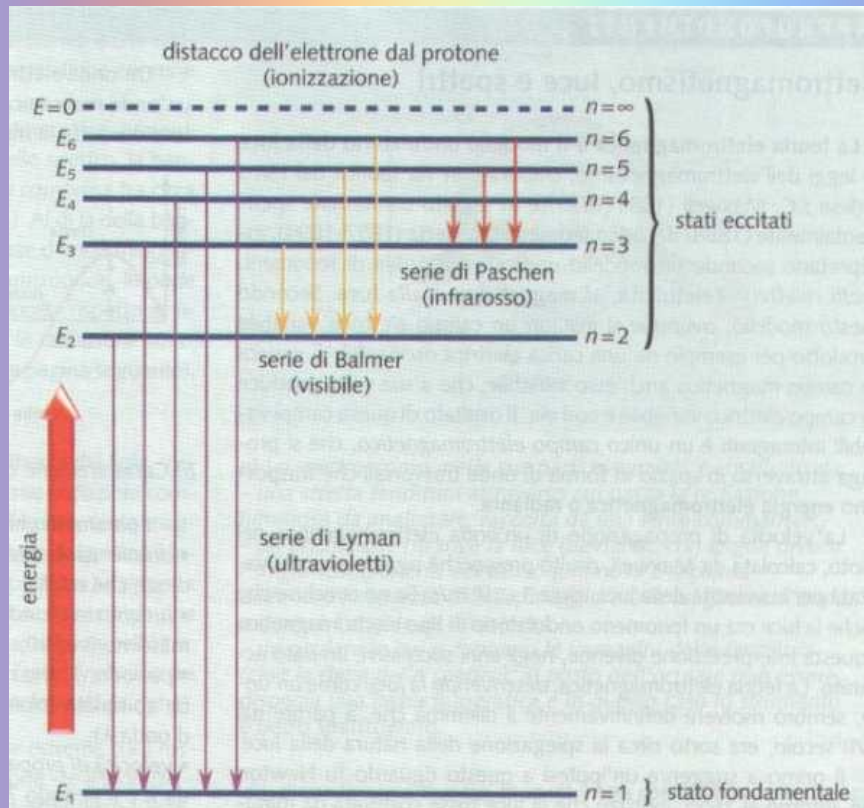
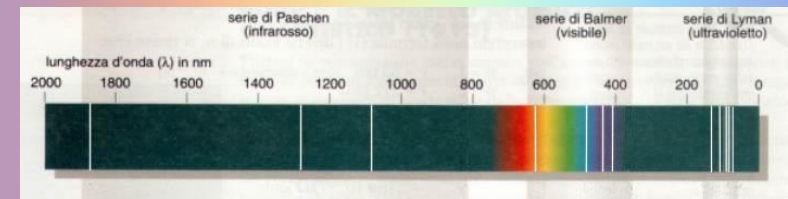


# Quantum numbers

- Each atomic orbital identified by four quantum numbers
  - Principal quantum number,  $n$  - Specifies shell and energy of an electron in an atom
  - Azimuthal quantum number,  $l$  - Specifies sub-shell and governs the shape of the orbital
  - Magnetic quantum number,  $m_l$  - Specifies orbitals and labels the different orbitals of a given sub-shell
  - Spin quantum number,  $m_s$  - Specifies the direction of spin of the two electrons within an orbital

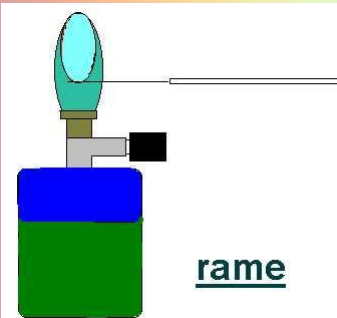
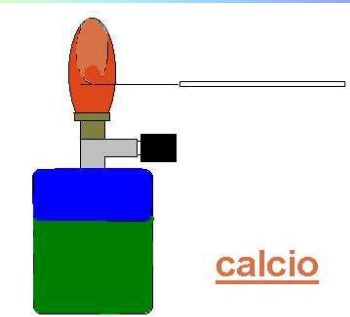
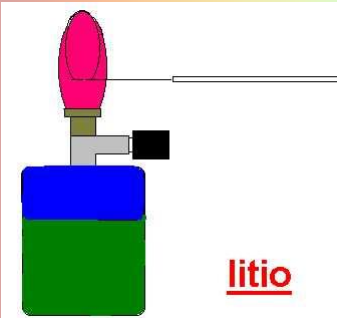
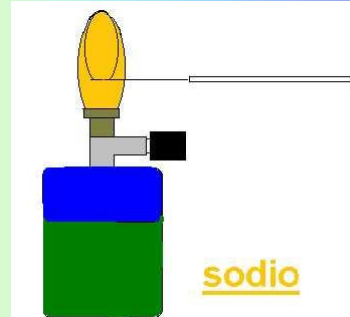
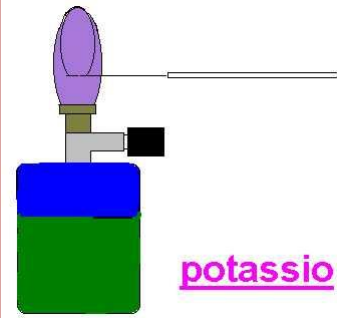
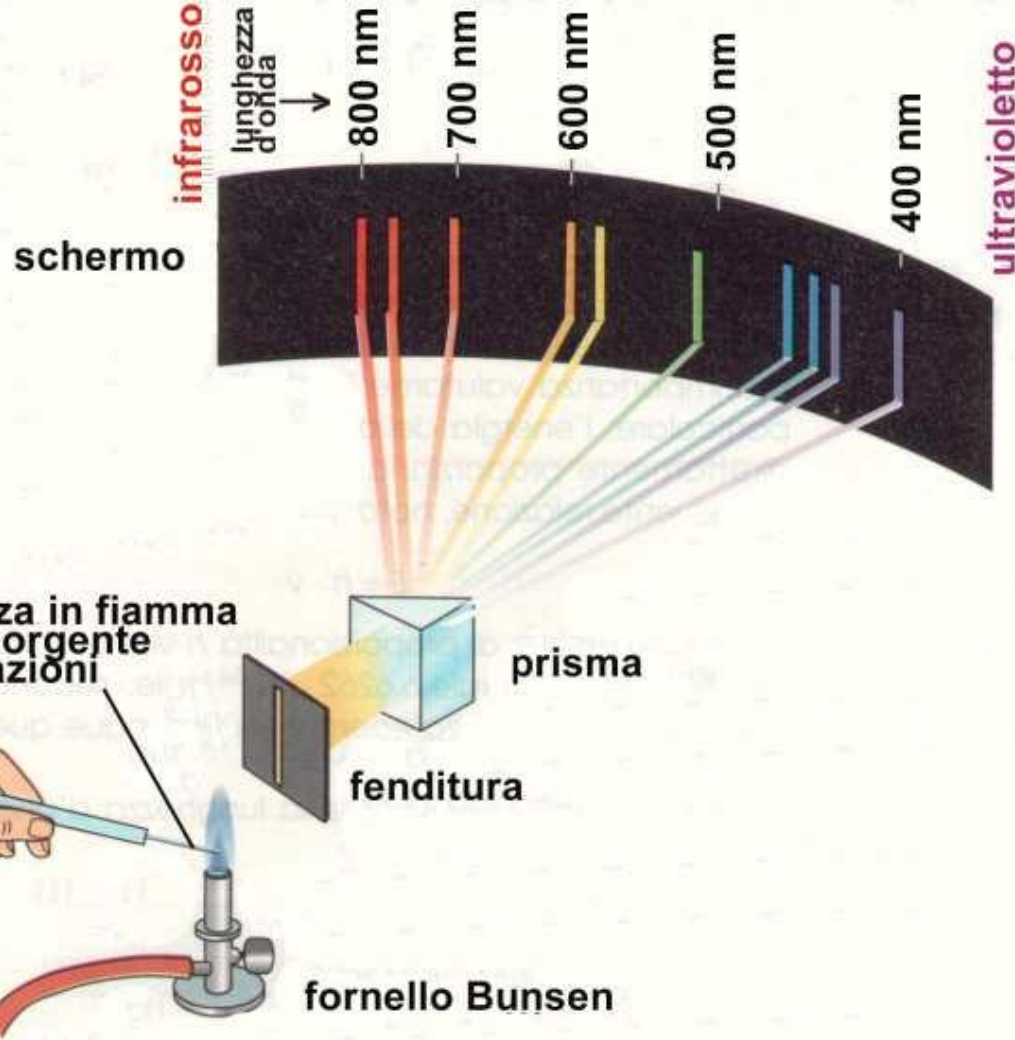


## atomo di idrogeno: righe di emissione





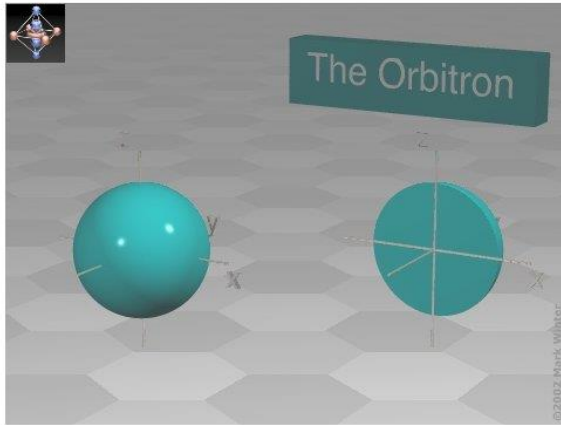
# Saggi alla fiamma





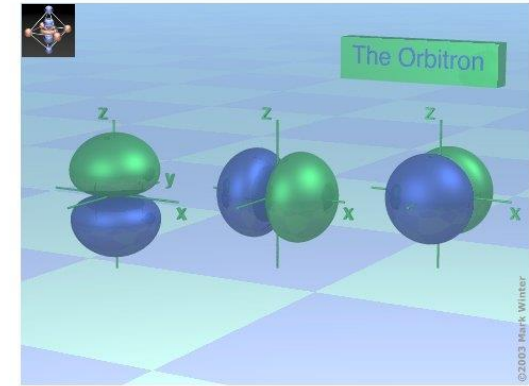
# Orbitali atomici

## orbitali s



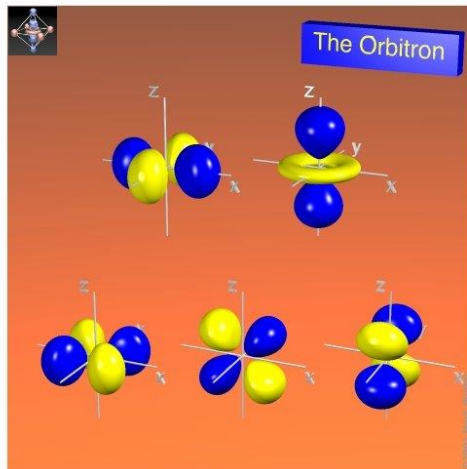
The shape of the 1s orbital.

## orbitali p



The shape of the three 2p orbitals. From left to right:  $2p_z$ ,  $2p_x$ , and  $2p_y$ . For each, the blue zones are where the wave functions have negative values and the green zones denote positive values.

## orbitali d



The shape of the five 3d orbitals. From left to right: (top row)  $3d_{x^2-y^2}$  and  $3d_{z^2}$  (bottom row)  $3d_{xy}$ ,  $3d_{xz}$  and  $3d_{yz}$ . For each, the yellow zones are where the wave functions have negative values and the blue zones denote positive values.

$$n=1,2,3\dots$$

$$l=0,1,2,n-1$$

$$m_l=l,l-1,l-2,\dots,-l$$

$$m_s=\pm 1/2$$

$$\text{orbitali s: } n=1,2,3\dots \quad l=0 \quad m_l=0$$

$$\text{orbitali p: } n=2,3\dots \quad l=1 \quad m_l=1,0,-1$$

$$\text{orbitali d: } n=3\dots \quad l=2 \quad m_l=2,1,0,-1,-2$$

**Principio di esclusione di Pauli:**  
max. 2 elettroni per orbitale

# Tavola periodica

period	group 1*												13	14	15	16	17	18
	1a	2											IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	H	He																
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			IIIa**	IVa	Va	VIa	VIIa	VIIIa					IIIa	IVa	Va	VIa	VIIa	0
			IIIb***	IVb	Vb	VIb	VIIb	VIIIb					IIIb	IVb	Vb	VIb	VIIb	0
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****

6	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
7	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

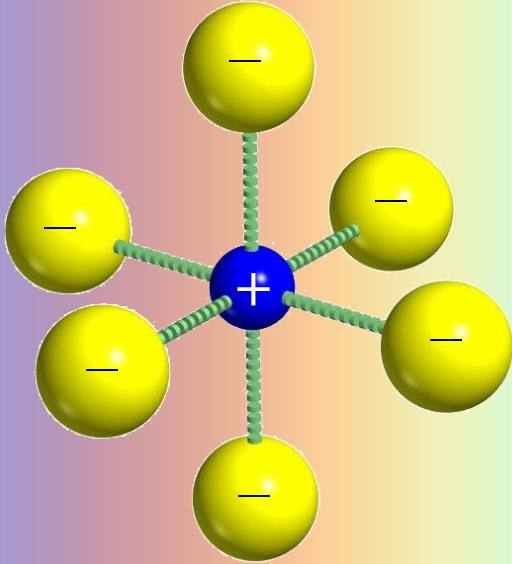
\* Numbering system recommended by the International Union of Pure and Applied Chemistry (IUPAC)

\*\* Previous IUPAC numbering system

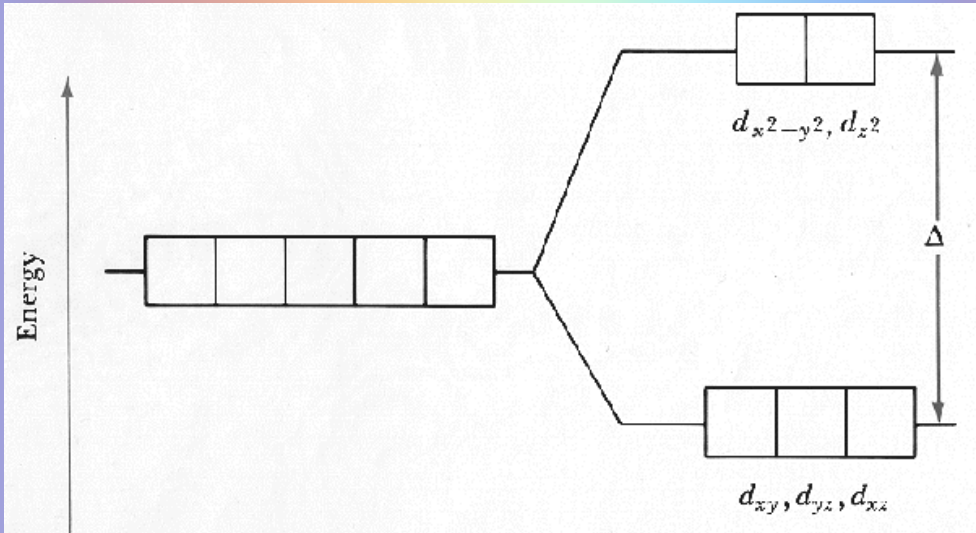
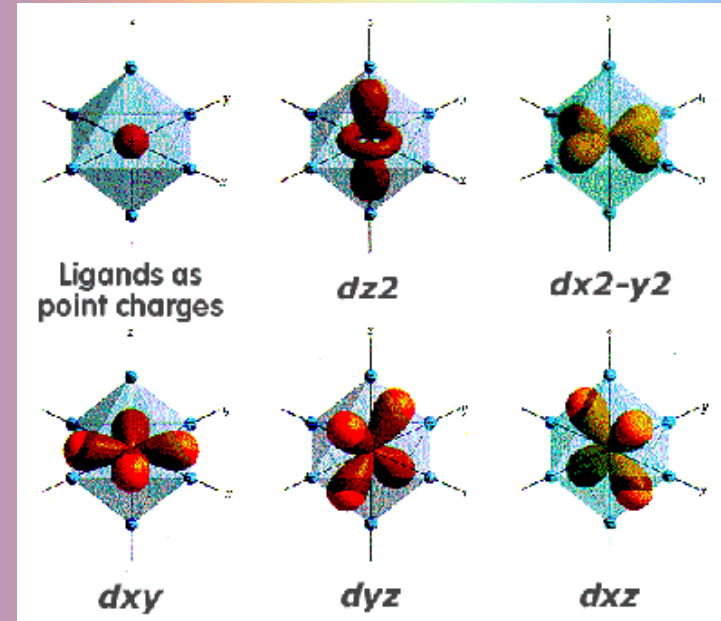
\*\*\* Numbering system recommended by the Chemical Abstracts Service

\*\*\*\* For the names of elements 104–112, see table.

**Cr:**  $Z=24$ ,  $1s^2 2s^2 2p^6 3s^2 3p^6 3d^5 4s^1$



**Cr<sup>3+</sup> (d<sup>3</sup>) in coordinazione ottaedrica**

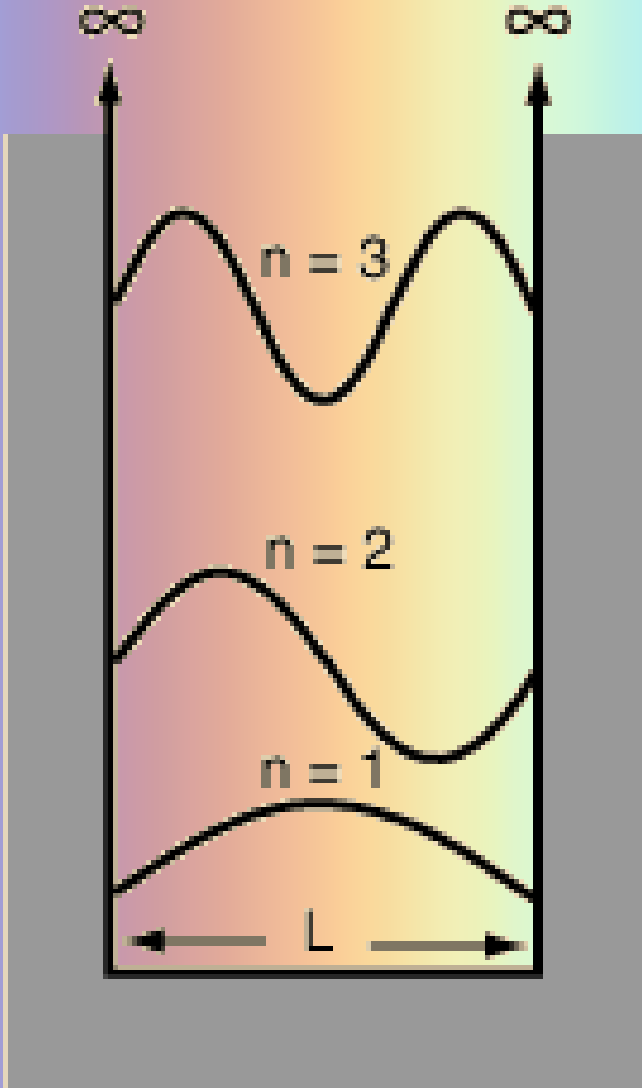


**presenza di cariche negative causa la perdita di degenerazione degli orbitali d: transizioni elettroniche d-d.**



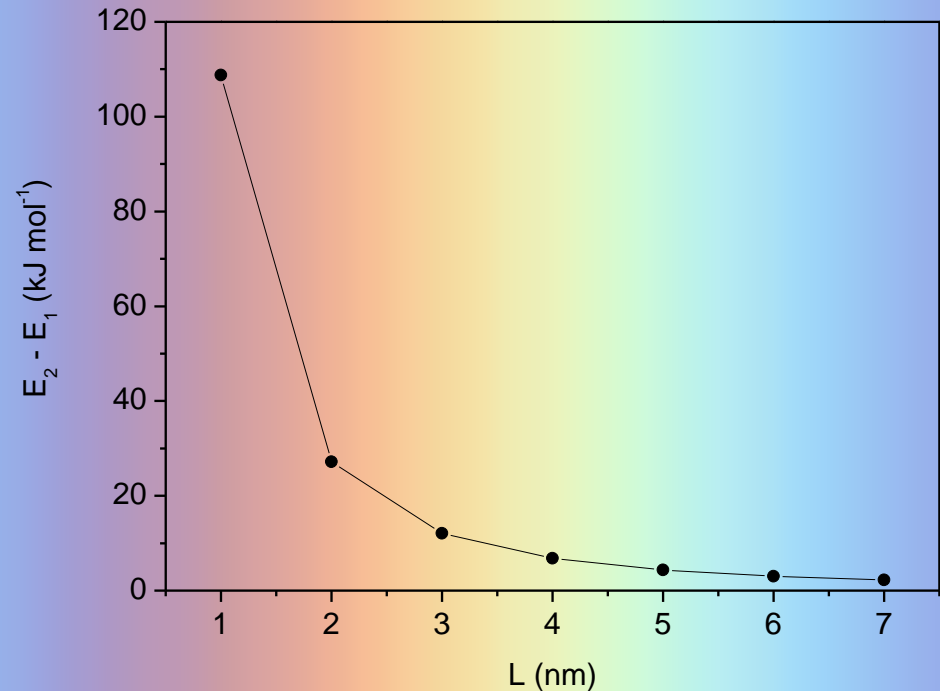
**Assorbimento di porzioni di luce bianca: colore nelle gemme!!**

# La particella nella scatola



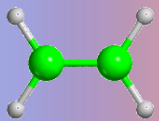
$$E_n = \frac{n^2 h^2}{8mL^2}$$

$$\Delta E = E_{n+1} - E_n = \frac{(2n + 1)h^2}{8mL^2}$$

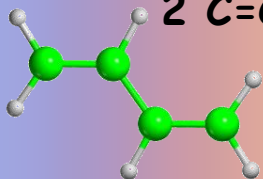




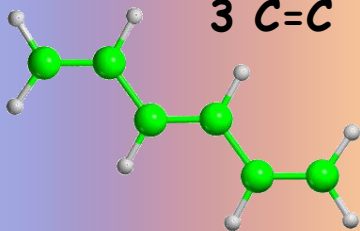
1 C=C



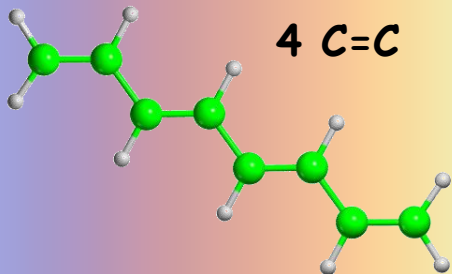
2 C=C



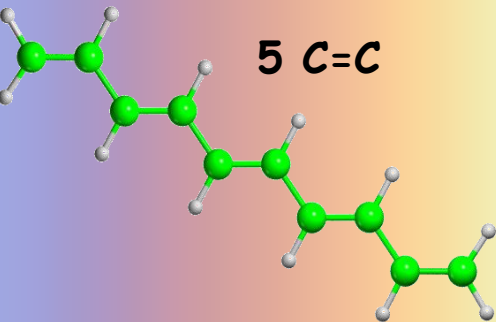
3 C=C



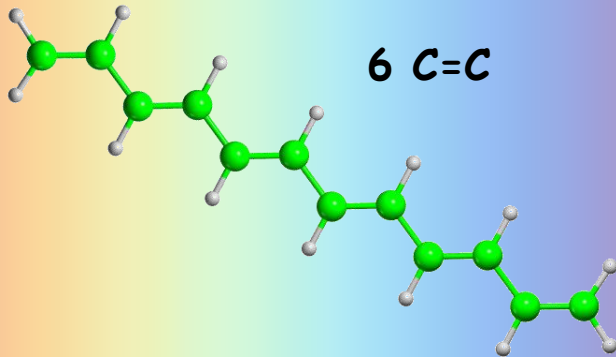
4 C=C



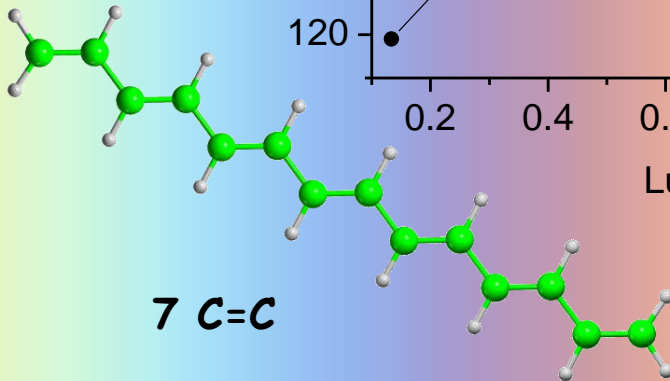
5 C=C



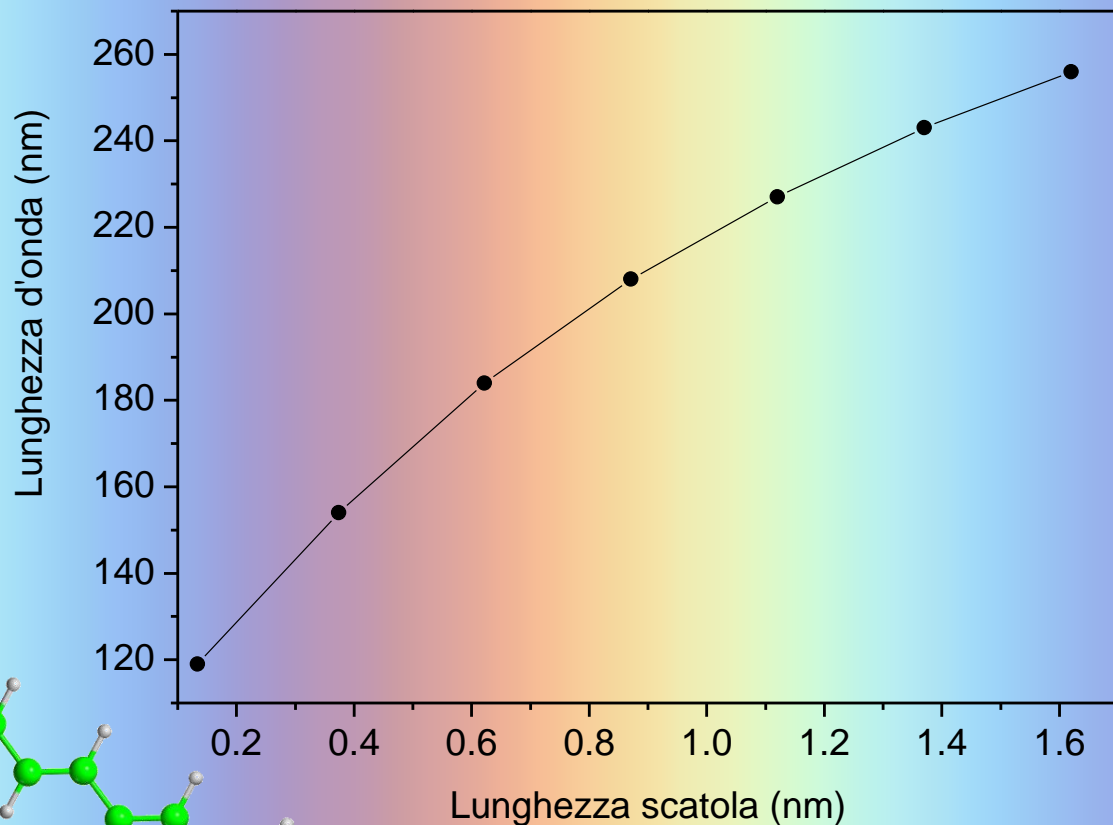
6 C=C



7 C=C

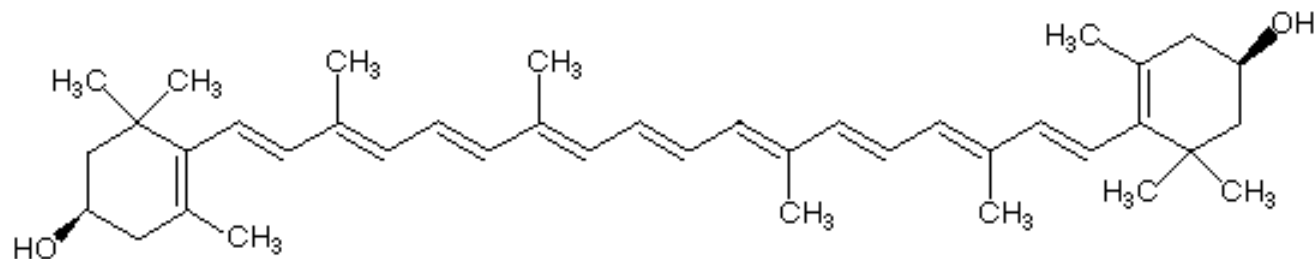
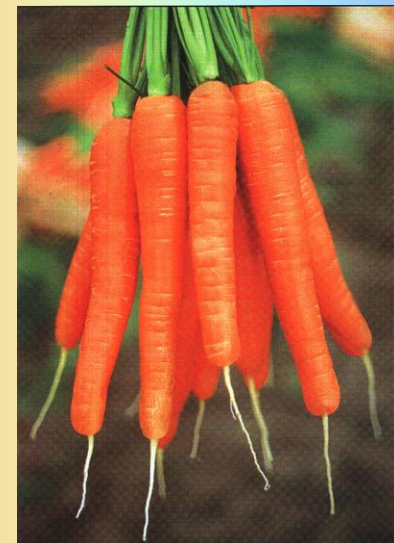
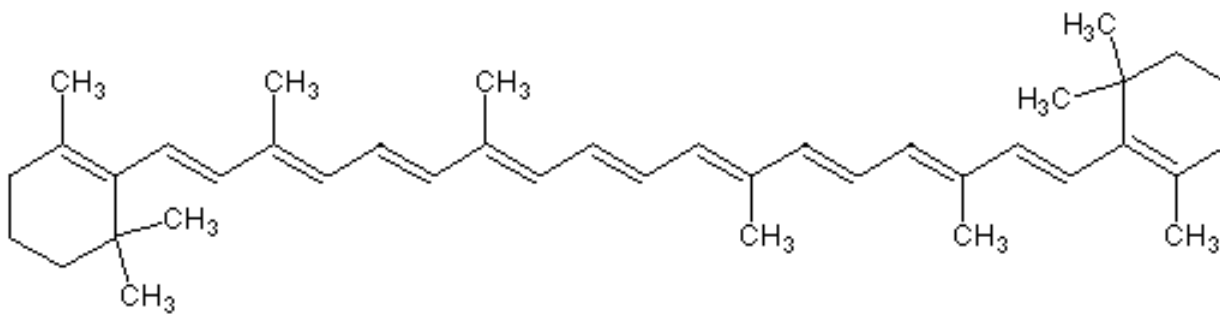


Lunghezza d'onda  $\lambda$  (nm)  
(inversamente proporzionale  
all'energia necessaria per la  
transizione HOMO $\rightarrow$ LUMO)  
aumenta con la lunghezza della  
scatola.



# Carotenoidi

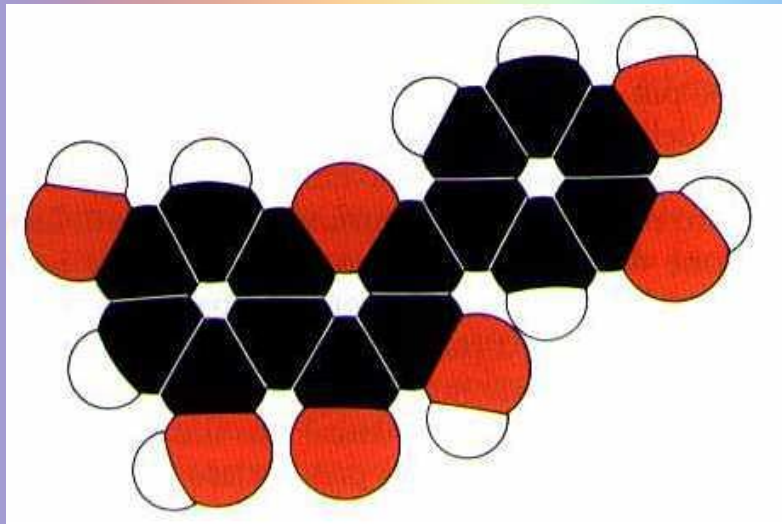
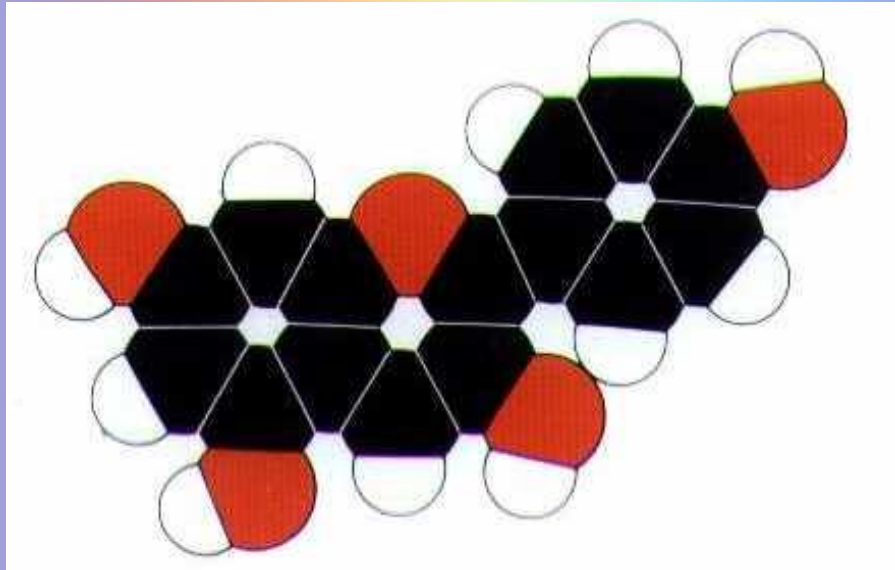
## Beta-carotene



## Zeaxantina



# Flavonoidi



# Pelargonidina

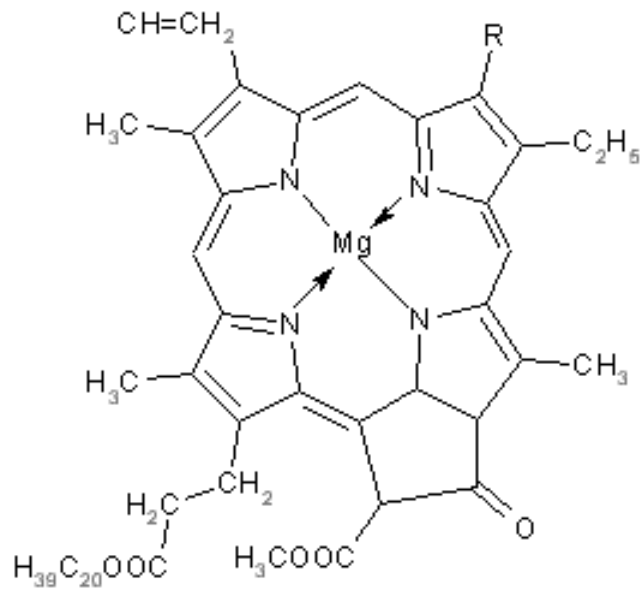


# Quercetina





# Clorofilla



**13.31** R = CH<sub>3</sub>      clorofilla a  
**13.32** R = CHO      clorofilla b



*Every once in a while,  
Take the road less traveled.*

Il verde delle foglie è dovuto alla clorofilla, che assorbe le radiazioni rosse e violette. In autunno tale molecola si degrada e la quercetina e altre antocianidine derivanti da flavonoidi diventano predominanti.

# Dalla scala atomica alla scala nanometrica...



*Nel 1480-1486 Nicolò da Varallo per colorare di rosso alcune tessere delle vetrate del Duomo di Milano, inseriva particelle di oro nel vetro. Egli senza saperlo utilizzava dei sistemi confinati. Infatti le particelle d'oro, se opportunamente dimensionate, emettono luce di colore rosso.*

**Nanoparticelle di oro sono un esempio di "punti quantici" (quantum dot); essi presentano una forte analogia con gli "atomi naturali", in quanto in essi gli elettroni si dispongono su livelli discreti di energia, ma hanno una dimensione maggiore rispetto agli atomi e per questo vengono spesso chiamati "atomi artificiali" o "macroatomi".**



**Lo stesso materiale confinato su scala nanometrica, può assorbire o emettere luce di colore diverso a seconda delle sue dimensioni.**

*Progettando opportunamente le dimensioni di un quantum dot si può, dunque, decidere il colore col quale ci appare.*



*La Coppa di Licurgo si distingue da tutti gli altri diatreta per il risalto delle sue figure tridimensionali e la loro eccezionale vitalità. Inoltre essa ha anche la particolare proprietà del dicroismo, vale a dire la capacità di mutare colore: con la luce riflessa è verde, quando è controluce diventa rossa. L'artigiano che eseguì l'intaglio intese utilizzare il cambiamento di colore per simboleggiare la maturazione dei grappoli e la loro trasformazione in vino.*

**Il dicroismo era un effetto voluto, ottenuto aggiungendo piccole quantità d'oro e argento nella fòndita. L'argento fa sì che il vetro diventi verde opaco con la luce riflessa e l'oro, quando si fissa alla giusta temperatura, lo fa diventare rosso in controluce.**



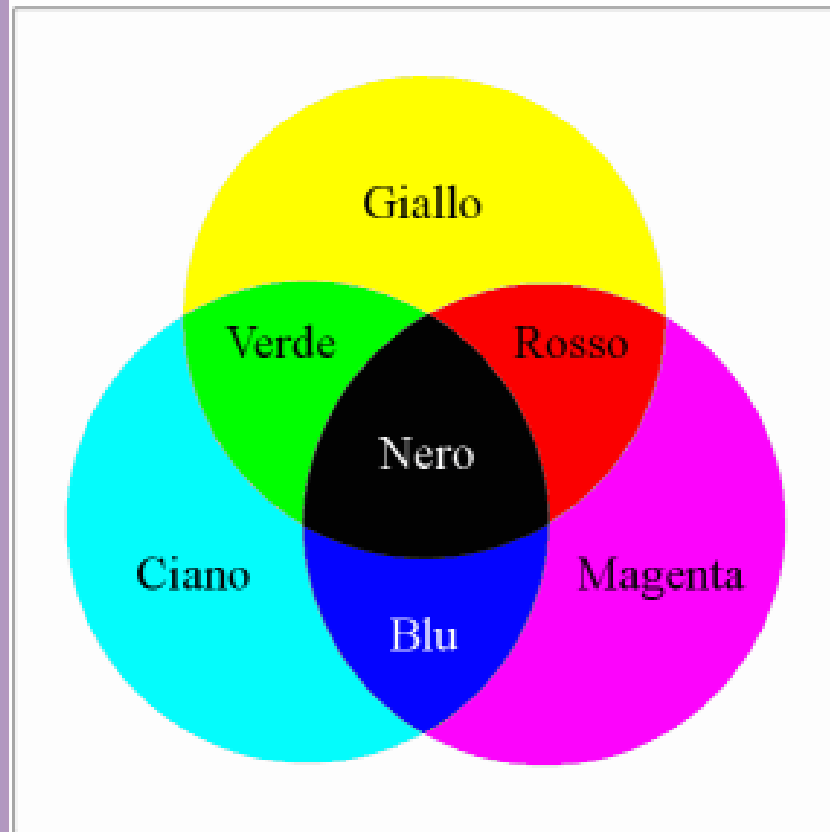
Assenza di luce = nero



La presenza dei tre diversi tipi di coni nella retina avvalorava la teoria dei colori elaborata quasi duecento anni fa da Young. Secondo tale teoria la visione umana dei colori può essere interpretata come un fenomeno tricromatico: la vasta gamma dei colori può essere ottenuta dalle diverse combinazioni dei tre colori primari: **rosso**, **blu** e **verde**.

*Colore complementare* quello che si ottiene sottraendo dal bianco il colore dato. I rispettivi colori complementari di rosso, verde e blu, e cioè ciano, magenta e giallo, costituiscono una base per la sintesi sottrattiva dei colori.

Assenza di pigmento = bianco





# Pittori puntinisti



Paul Signac. *Two Milliners, Rue du Caire*. c. 1885/86. Oil on canvas. 111.8 x 89 cm. Foundation E.G. Bührle collection, Zurich, Switzerland

## Televisione a colori

