



INSTITUTO DE FÍSICA
Universidade Federal Fluminense

Programa de Pós-graduação
em Ensino de Física

Instituto de Física
UFRJ

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Difração: Da corona lunar à dualidade onda-partícula

Reinaldo de Melo e Souza (IF-UFF)

Introdução



Augustin-Jean Fresnel

MÉMOIRE
SUR
LA DIFFRACTION DE LA LUMIÈRE;

PAR M. A. FRESNEL.*

INTRODUCTION.

AVANT de m'occuper spécialement des phénomènes nombreux et variés compris sous la dénomination commune de *diffraction*, je crois devoir présenter quelques considérations générales sur les deux systèmes qui ont partagé jusqu'à présent les savans relativement à la nature de la lumière. Newton a supposé que les molécules lumineuses lancées des corps qui nous éclairent arrivent directement jusqu'à nos yeux, où elles produisent par leur choc la sensation de la vision. Descartes, Hook, Huygens, Euler, ont pensé que

* En publiant ce Mémoire, qui a été couronné par l'Académie en 1819, on a fait quelques changemens à la rédaction du manuscrit déposé à l'Institut le 29 juillet 1818, mais sans apporter aucune modification à la théorie et aux expériences qu'il contient. Desirant y ajouter quelques expériences nouvelles et quelques développemens théoriques, on les a placés dans des notes à la suite du Mémoire.

Introdução

- Qual a natureza da luz?



<http://dark.pozadia.org/wallpaper/Let-there-be-light/>

Óptica Geométrica

- Qual a natureza da luz?
 - Formada por corpúsculos!



Óptica Geométrica

- Qual a natureza da luz?
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 - Capaz de explicar a refração e a reflexão!



<http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/refr2.html>

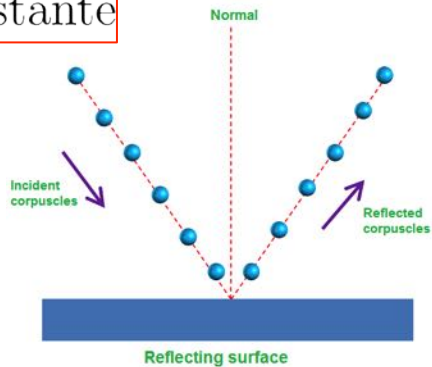


http://en.wikipedia.org/wiki/Reflection_%28physics%29

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$$v_{\parallel} = \text{constante}$$



<http://www.physics-and-radio-electronics.com/blog/corpuscular-theory-light/>



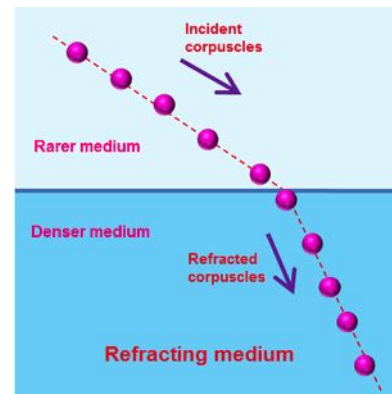
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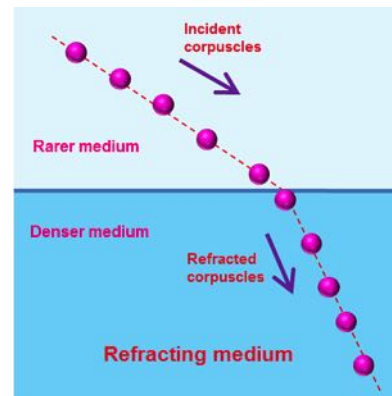
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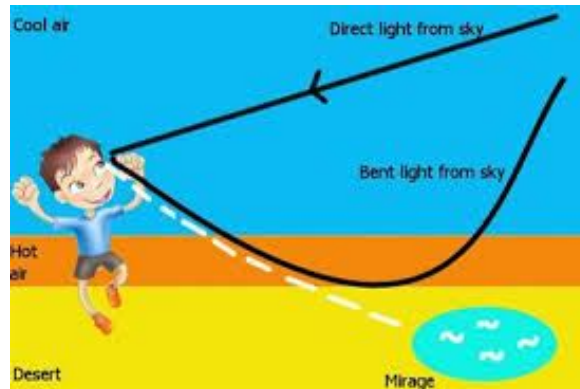
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$$v_{\parallel} = \text{constante}$$

A luz deve ser mais rápida
no meio mais denso!

Óptica Geométrica

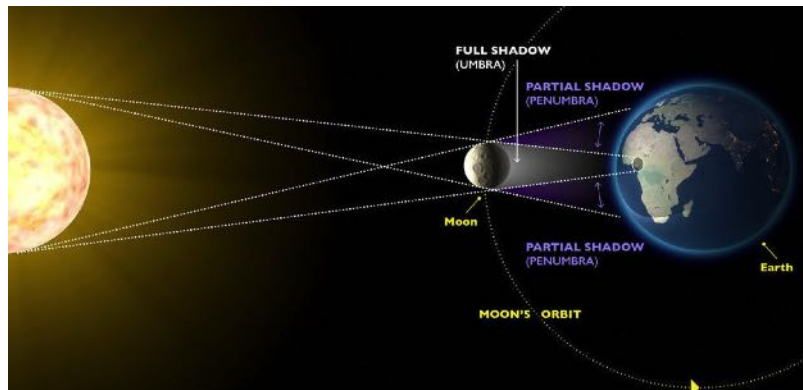
- Qual a natureza da luz?
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 - A óptica geométrica é totalmente compatível com esta concepção!



<http://www.planet-science.com/categories/under-11s/our-world/2012/01/what-is-a-mirage.aspx>

Óptica Geométrica

- Qual a natureza da luz?
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Sombras bem definidas!

Óptica Geométrica

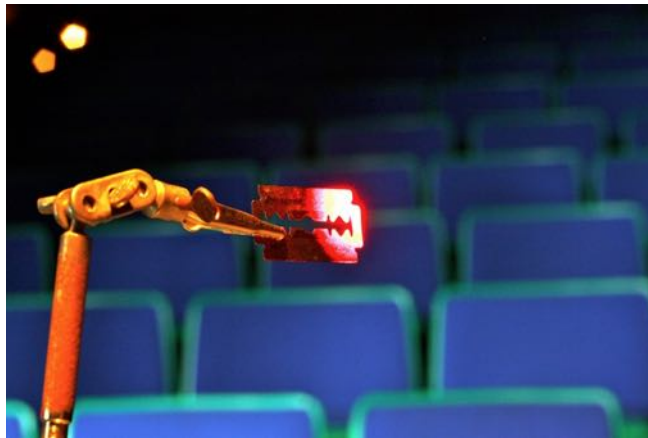
- Qual a natureza da luz?
 - Formada por corpúsculos!
 - Mas há problemas nesta concepção!

Por que o v é sempre o mesmo para um mesmo meio?



Luz nas Sombras

- Experimentos mais precisos mostraram que as sombras não eram tão bem definidas assim.



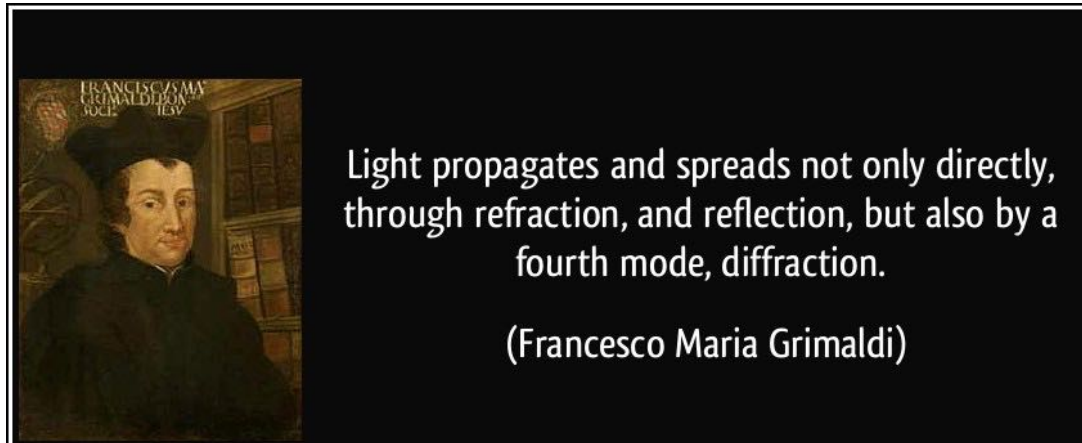
<http://isites.harvard.edu/fs/docs/icb.topic186199.files/images/EdgeDiffraction3-800x533.jpg>



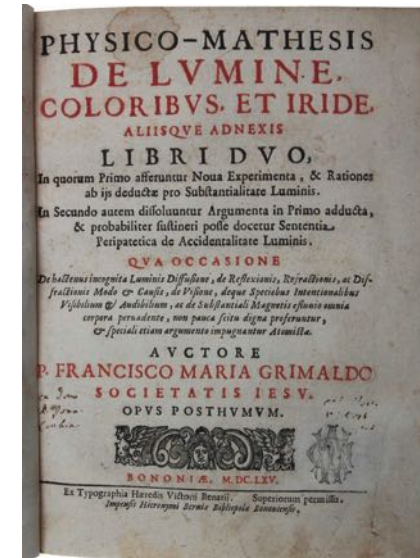
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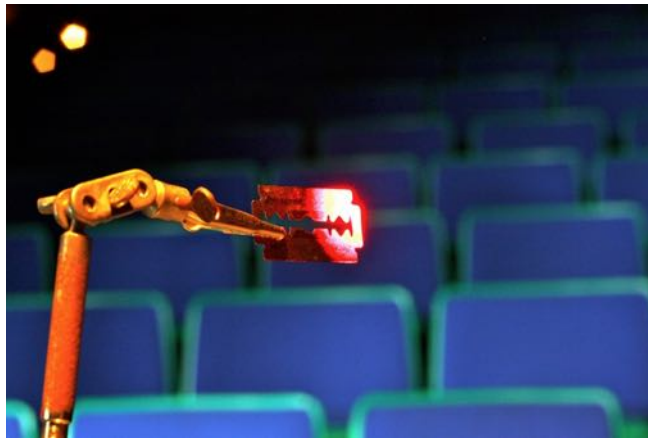
diffractionem = estilhaçamento



Physicomathesis de lumine (1665)

Luz nas Sombras

- A teoria corpuscular encontrou grandes dificuldades para explicar este tipo de comportamento.



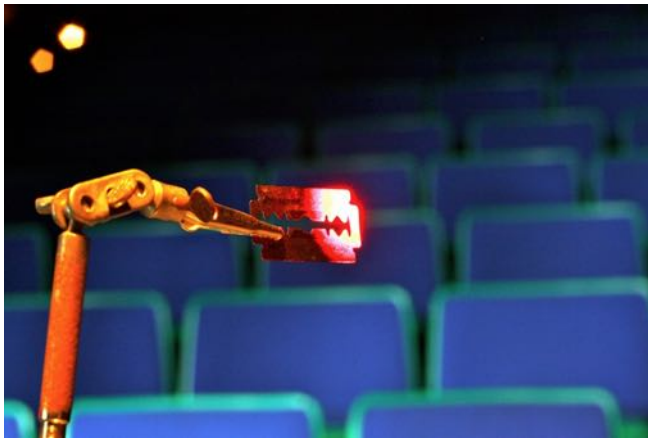
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Óptica Ondulatória

- Qual a natureza da luz?
 - É uma onda!



<http://sites.harvard.edu/fs/docs/icb.topic186199.files/images/EdgeDiffraction3-800x533.jpg>



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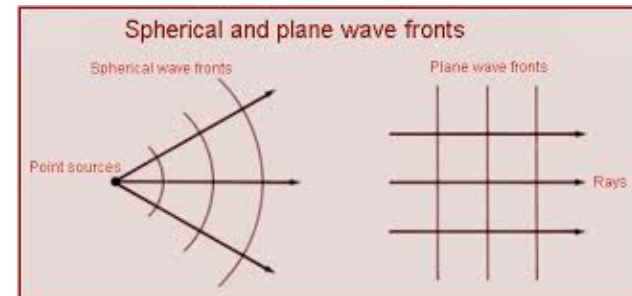
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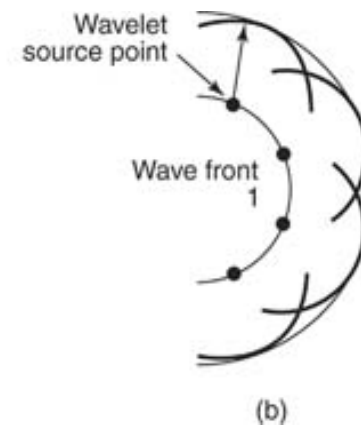
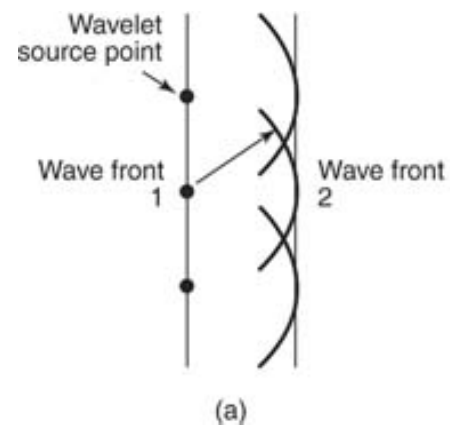


[http://nptel.ac.in/courses/117101054/Mod1/Slide\(mod1\)/7.html](http://nptel.ac.in/courses/117101054/Mod1/Slide(mod1)/7.html)



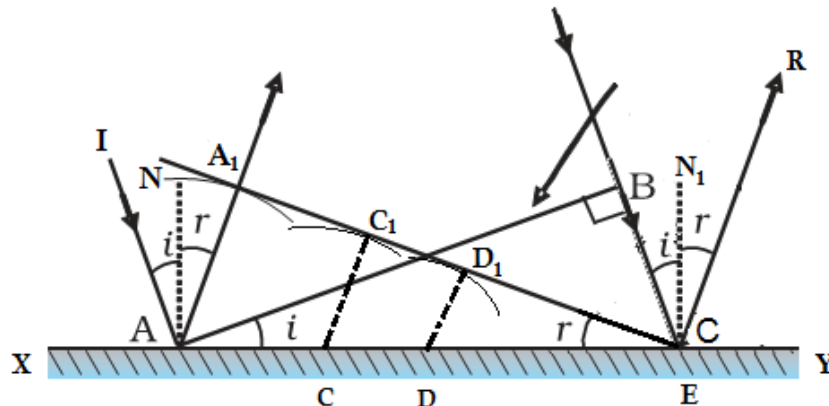
Óptica Ondulatória

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Óptica Ondulatória

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<http://letslearnnepal.com/class-12/physics/wave-and-optics/nature-and-propagation-of-light/laws-of-reflection-on-the-basis-of-huygens-wave-theory/>



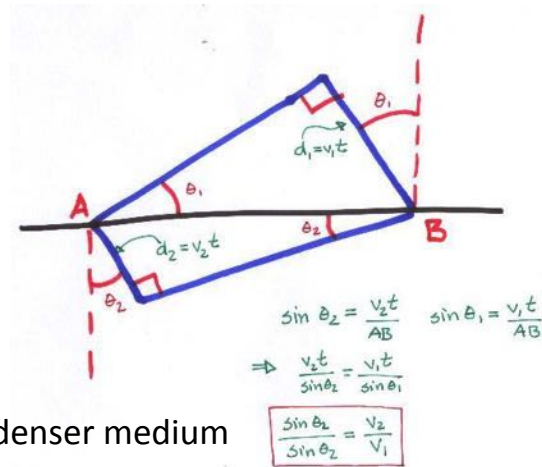
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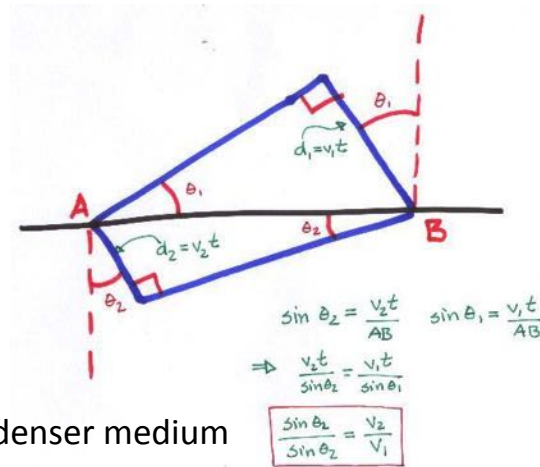
<http://ibphysicsstuff.wikidot.com/wave-properties>

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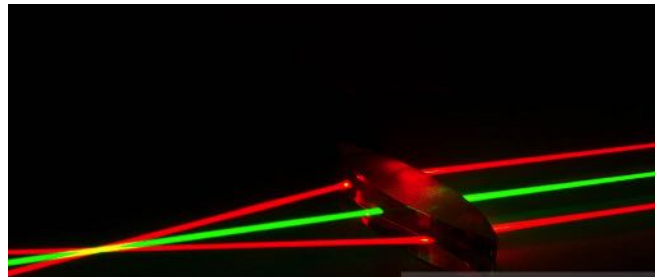


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A luz deve ser mais **lenta**
no meio mais denso!

Corpusculo vs Onda

- Como medir a velocidade da luz?



Corpusculo vs Onda

- Como medir a velocidade da luz?

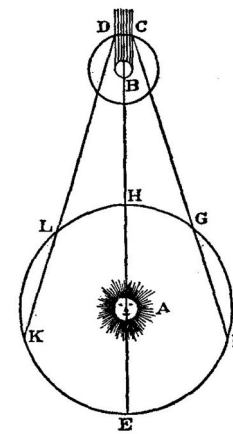
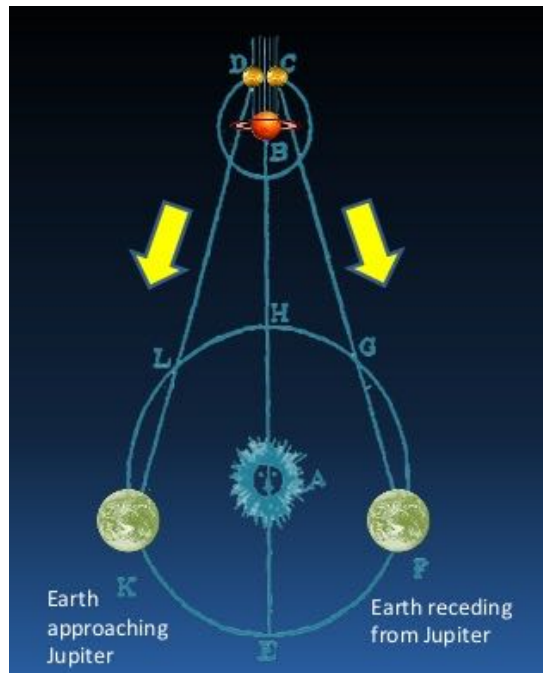


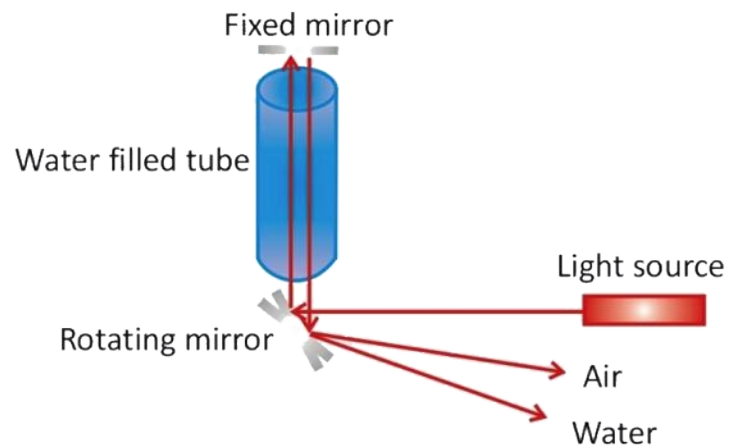
FIG. 70.

Rømer 1676
 $\approx 220,000$ km/s

https://en.wikipedia.org/wiki/R%C3%B8mer%27s_determination_of_the_speed_of_light

Corpusculo vs Onda

- Como medir a velocidade da luz?
 - E na matéria?



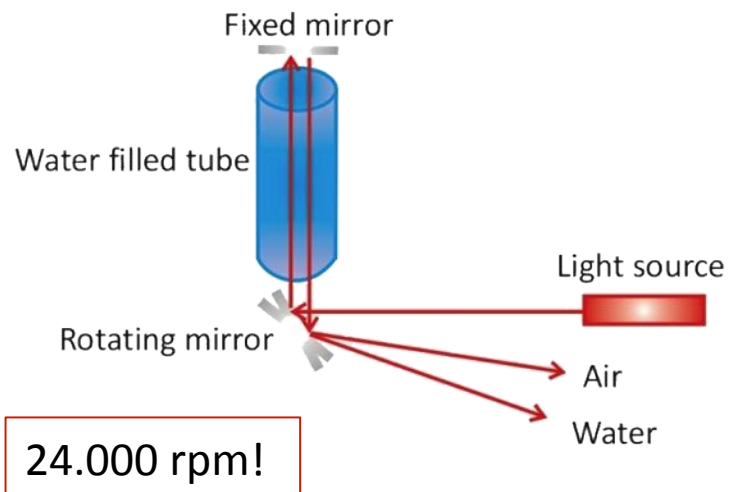
Rømer 1676 – Luz no vácuo

Foucault 1850 – Luz na água

Luz é uma onda!

Corpusculo vs Onda

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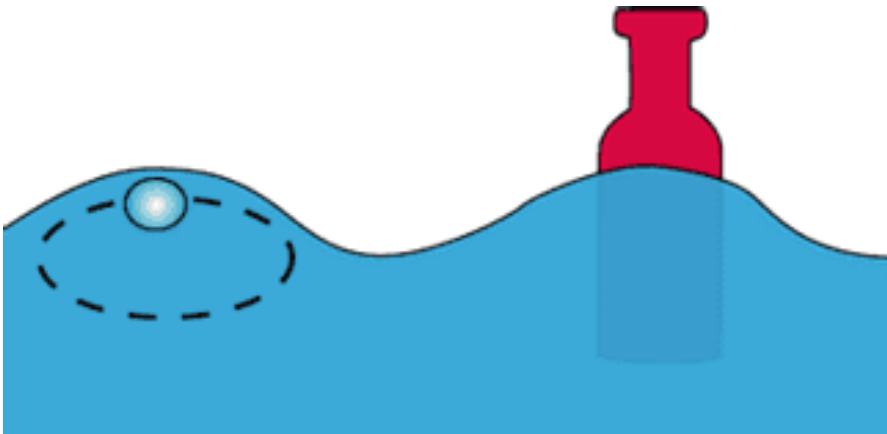
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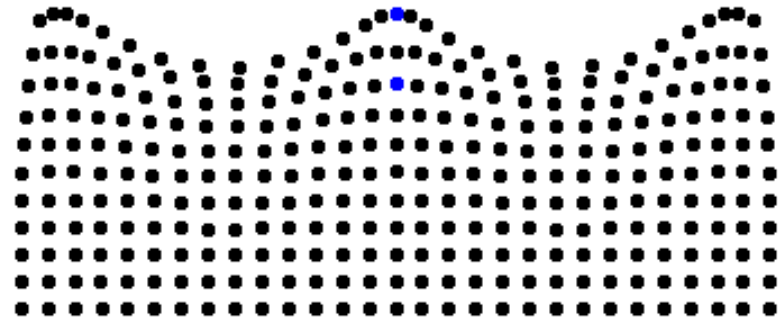
Luz é uma onda!

Óptica Ondulatória

- O que são ondas?
 - Transporta energia, mas não matéria.
 - Exemplos, ondas aquáticas, corda vibrante, mola, som, etc.



<http://www.onr.navy.mil/focus/ocean/motion/waves1.htm>

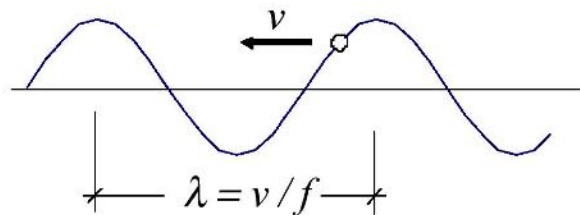


©1999, Daniel A. Russell

<http://www.acs.psu.edu/drussell/Demos/waves/wavemotion.html>

Óptica Ondulatória

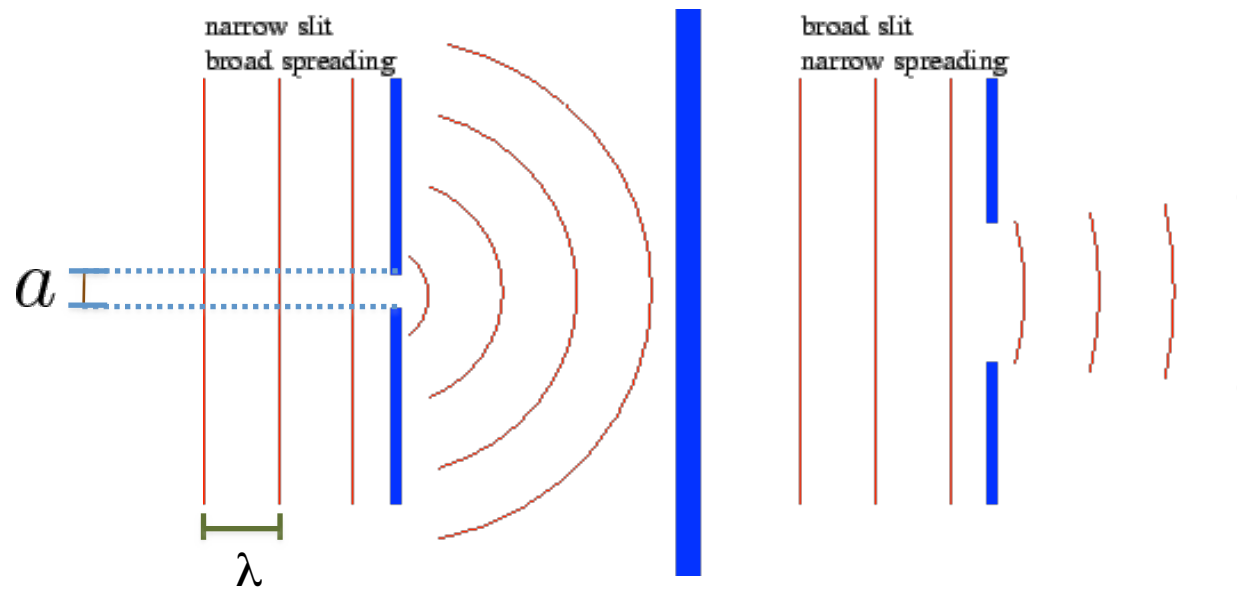
- O que define uma onda?



- Comprimento de onda: distância entre duas cristas.
- Freqüência: N^o de oscilações por unidade de tempo.
- Velocidade de propagação.

Óptica Ondulatória

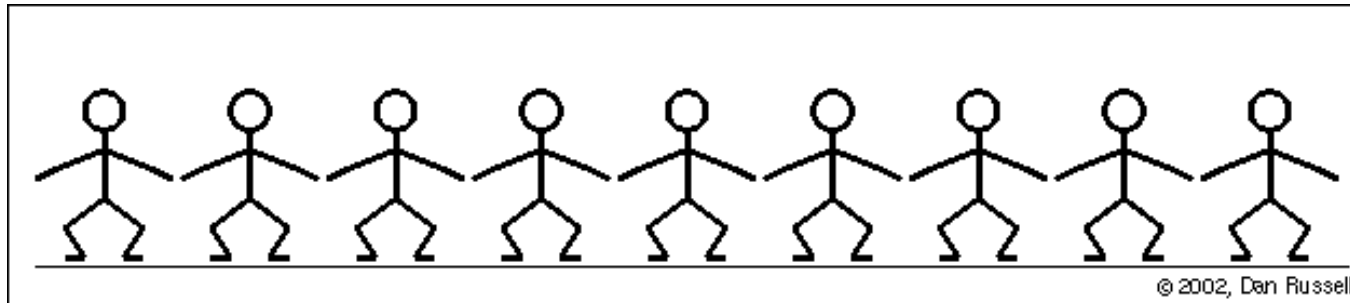
- Toda onda difrata! Difração é relevante para $\lambda \sim a$



http://en.wikibooks.org/wiki/Waves/Single_slit_Diffraction

Óptica Ondulatória

- Onda é um comportamento macroscópico emergente de uma coletividade microscópica.



<http://www.kettering.edu/physics/drussell/Demos/waves-intro/waves-intro.html>

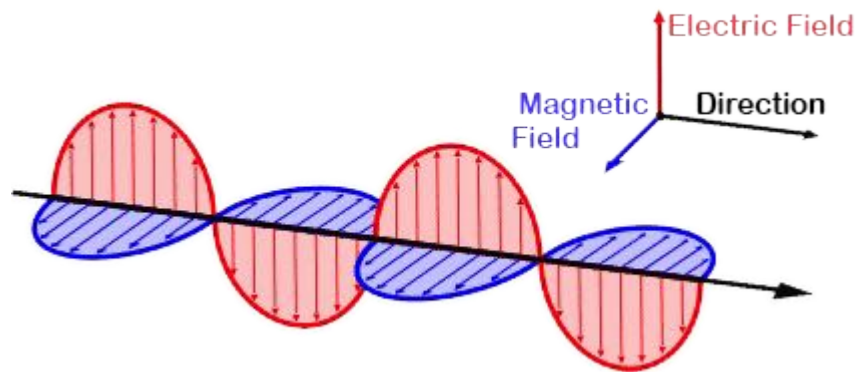
Óptica Ondulatória

- Se a luz é uma onda, **em que meio se propaga tal onda?**

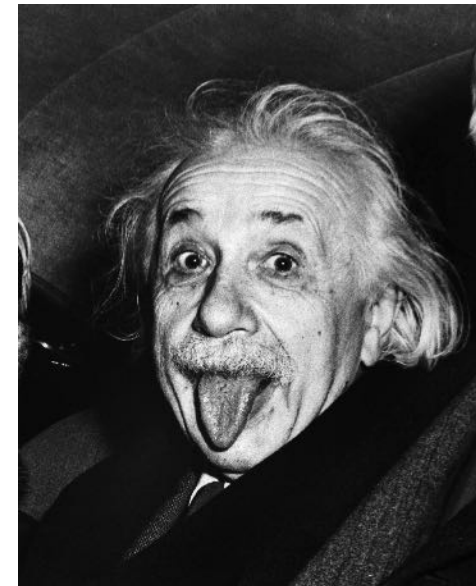


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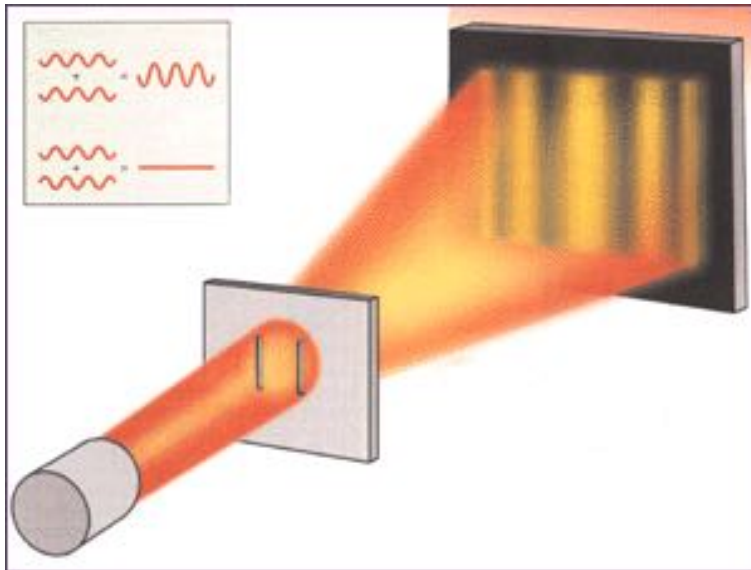


<https://physics.stackexchange.com/questions/376486/relationship-between-electromagnetic-wave-and-photon>



Experimento de Young

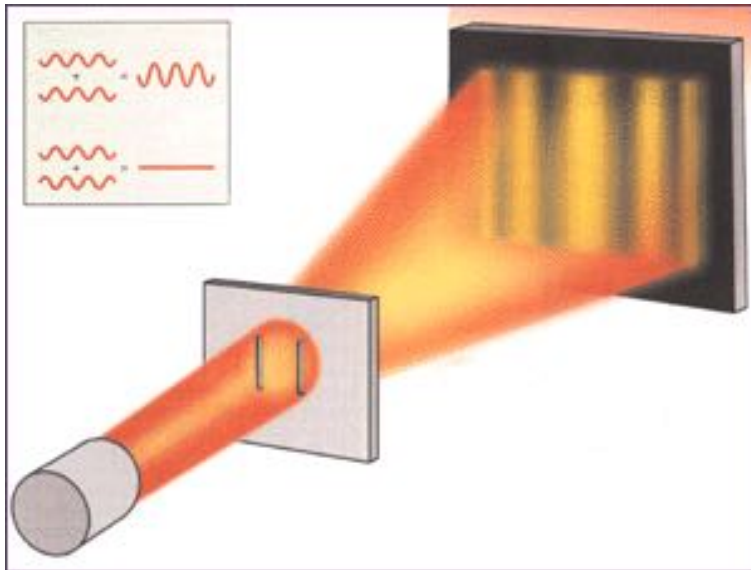
- Voltando ao início do século XIX...
 - Young (1808).



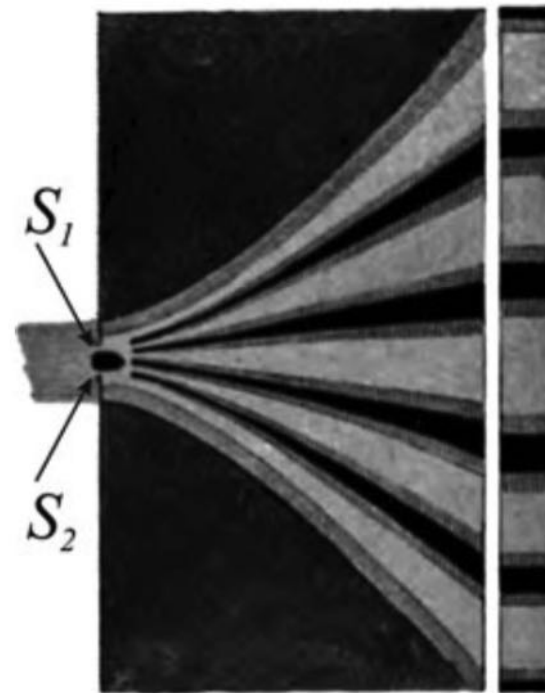
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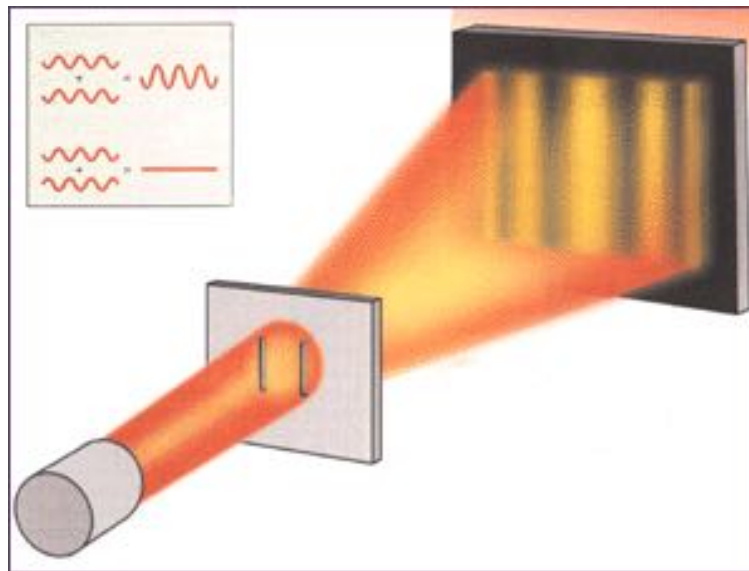
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Course of Lectures on Natural Philosophy and
the Mechanical Arts (Young 1807)

Experimento de Young

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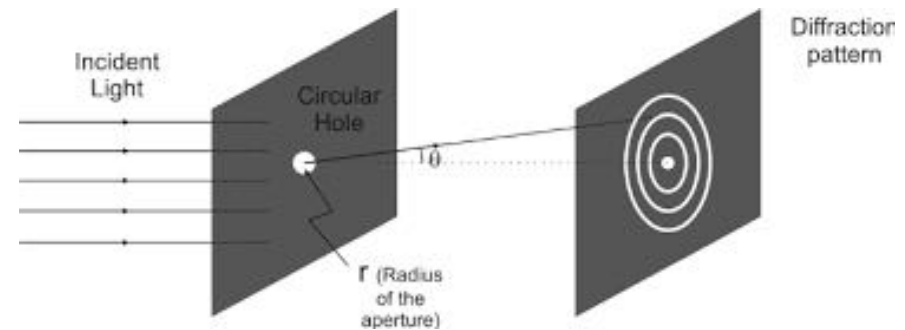
Luz+Luz = Sombra!

http://www.nobelprize.org/nobel_prizes/physics/articles/ekspong/

Mémoire de Fresnel

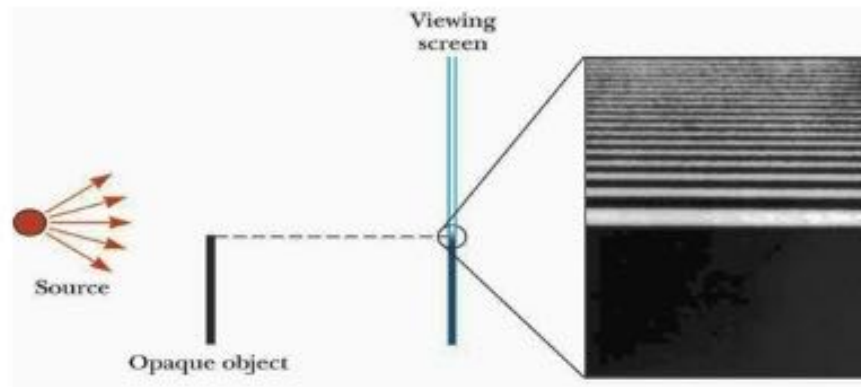
- Fresnel desenvolveu uma teoria matemática para a difração tratando a luz como uma **onda**!

$$U(P) = -\frac{i}{\lambda}U(r_0) \int_S \frac{e^{iks}}{s} K(\chi) dS$$

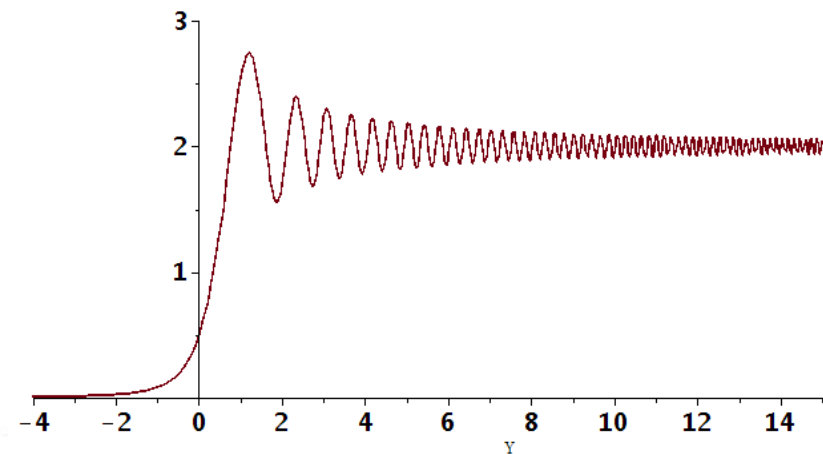


Mémoire de Fresnel

- Fresnel desenvolveu uma teoria matemática para a difração tratando a luz como uma **onda**!



<http://slideplayer.com/slide/8465591/>



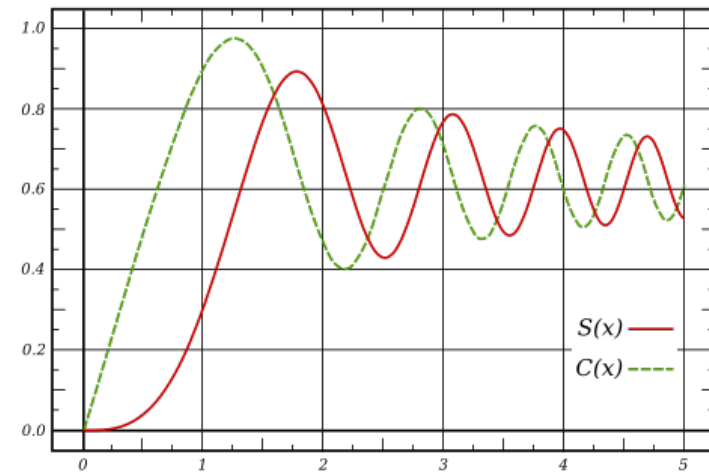
Fresnel diffraction at a straight edge

Mémoire de Fresnel

- Fresnel desenvolveu uma teoria matemática para a difração tratando a luz como uma **onda**!

$$C(x) = \int_0^x \cos(t^2) dt$$

$$S(x) = \int_0^x \sin(t^2) dt$$



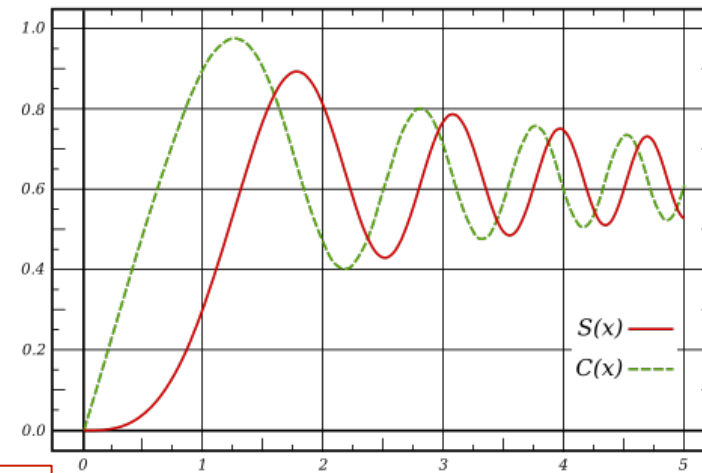
https://en.wikipedia.org/wiki/Fresnel_integral

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Acordo teoria-experimento dentro de uma margem de ~ 1.5 %

https://en.wikipedia.org/wiki/Fresnel_integral

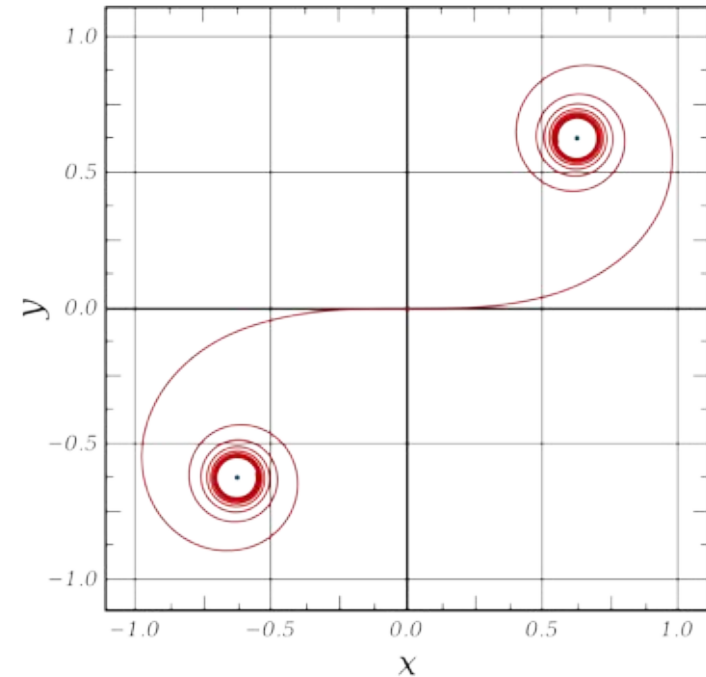
Mémoire de Fresnel

- As integrais de Fresnel parametrizam a **curva de Cornu**.

$$C(x) = \int_0^x \cos(t^2) dt$$

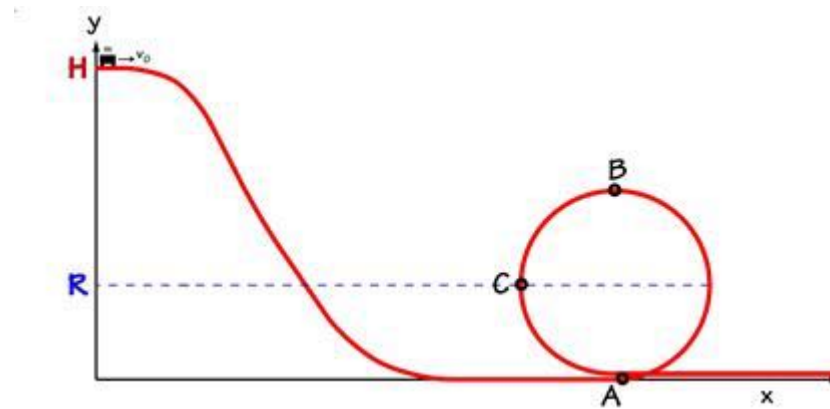
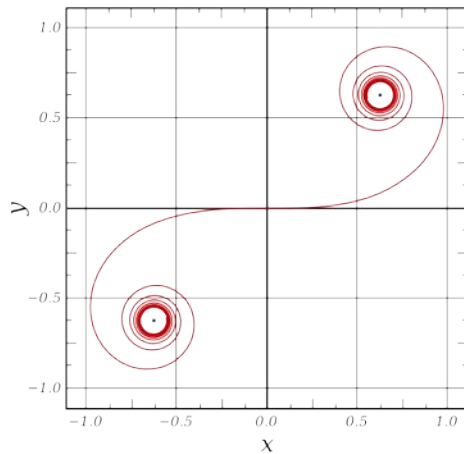
$$S(x) = \int_0^x \sin(t^2) dt$$

$$(x, y) = (C(t), S(t))$$

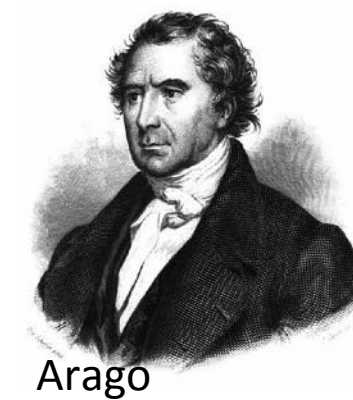
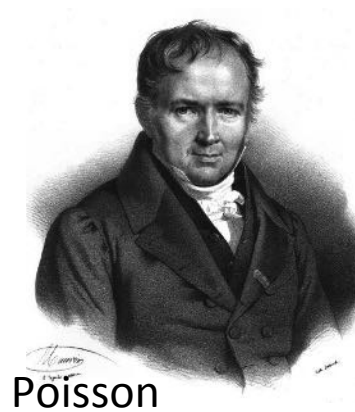
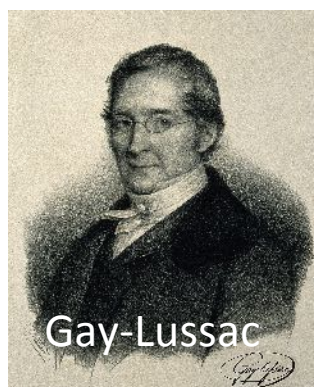
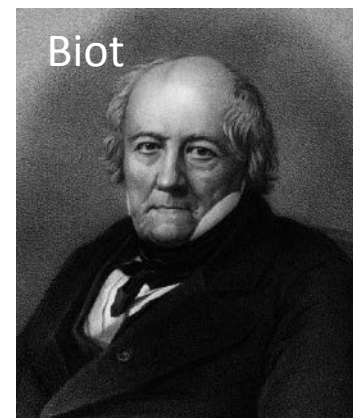
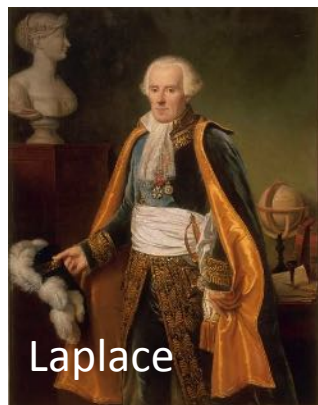


Mémoire de Fresnel

- As integrais de Fresnel parametrizam a **curva de Cornu**.
 - Curvatura proporcional ao comprimento da curva a partir da origem.

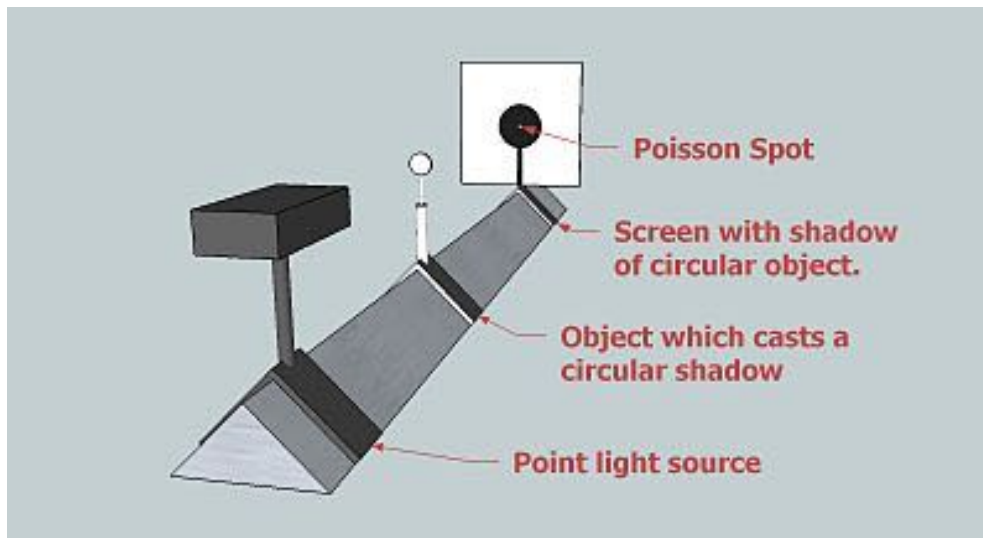


Comité

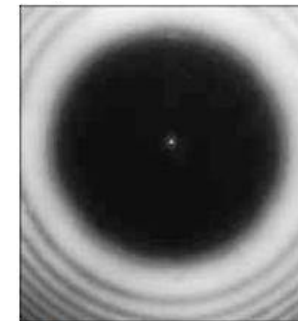


Mémoire de Fresnel

- Mancha de Poisson!



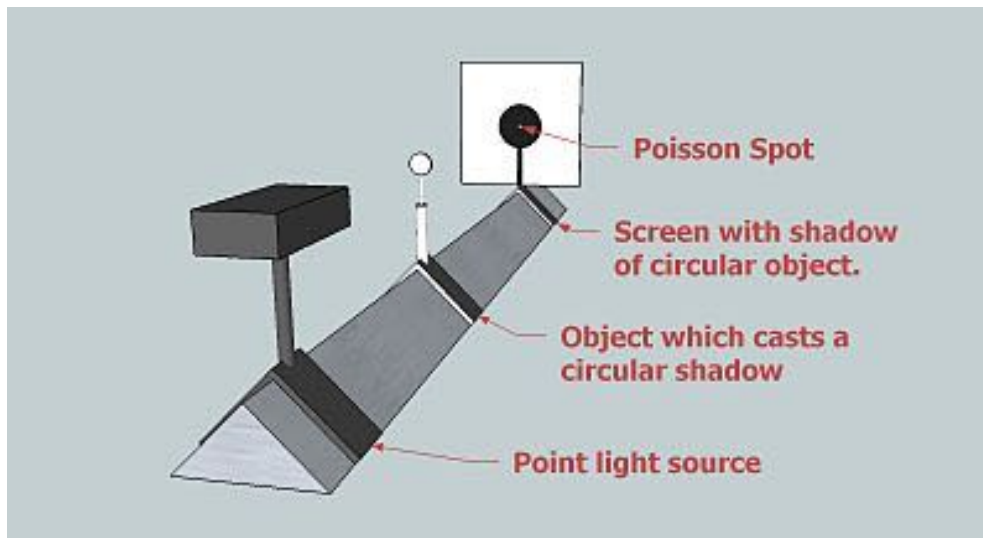
https://en.wikipedia.org/wiki/Arago_spot



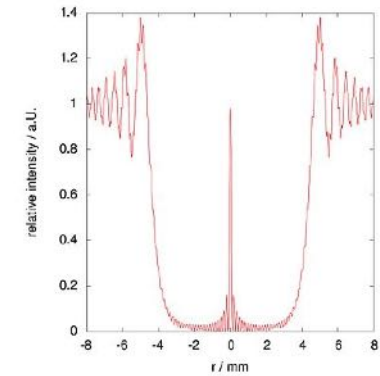
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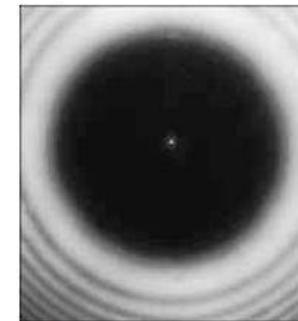
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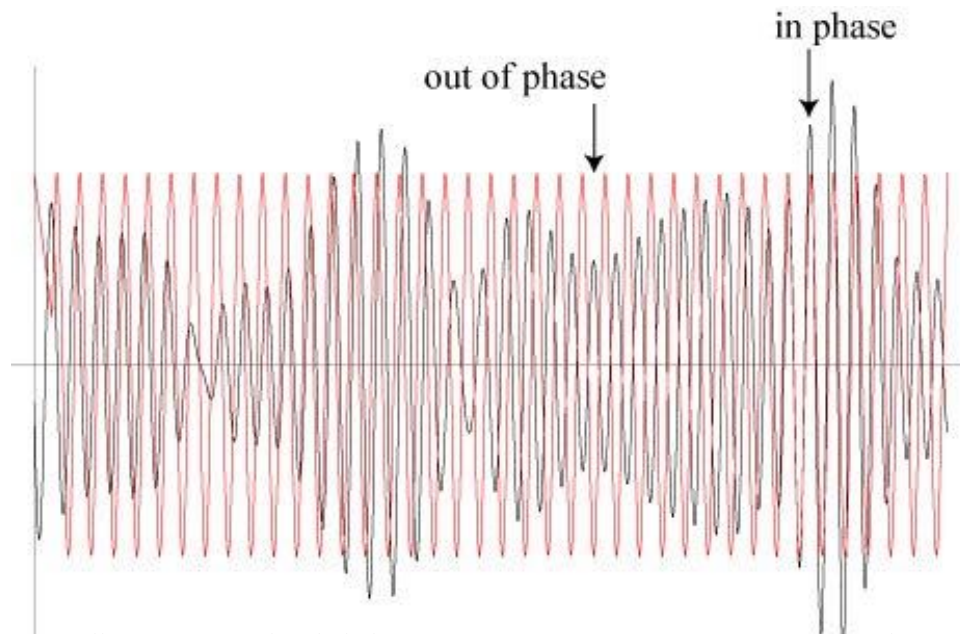
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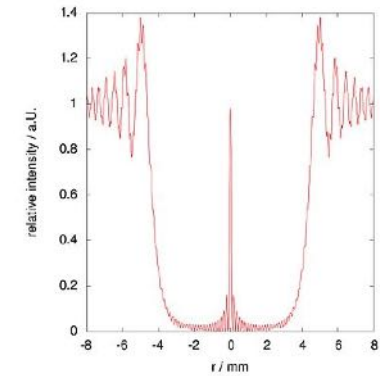
<http://slideplayer.com/slide/8465591/>

Mémoire de Fresnel

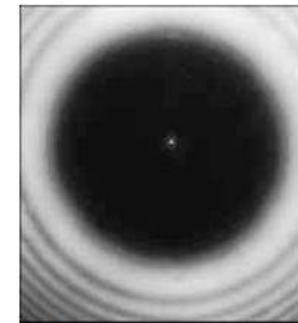
- Mancha de Poisson!



<http://skullsinthestars.com/2008/09/12/interference-between-different-photons-never-occurs-not+1963/>



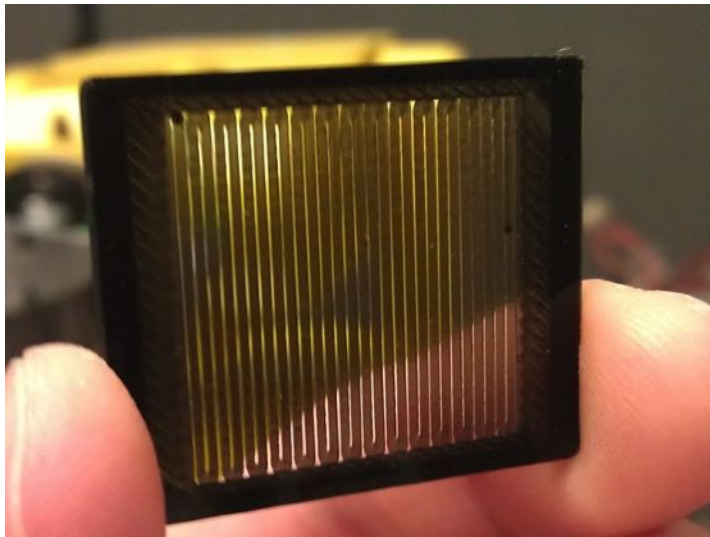
https://en.wikipedia.org/wiki/Arago_spot



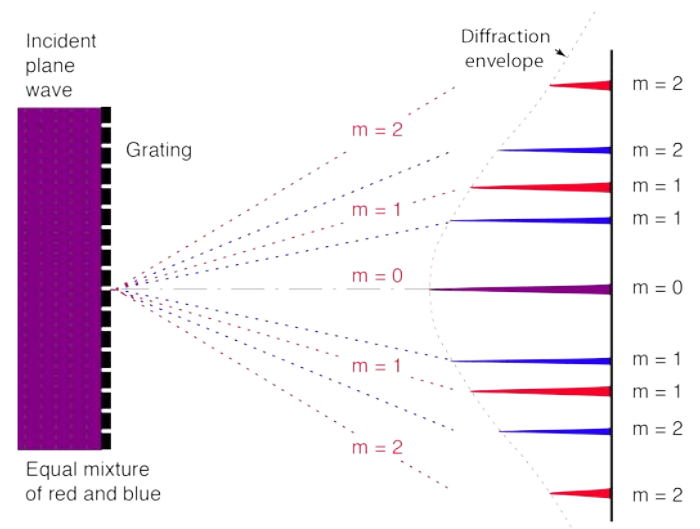
<http://slideplayer.com/slide/8465591/>

Redes de difração

- A luz visível difrata ao passar por pequenas fendas.

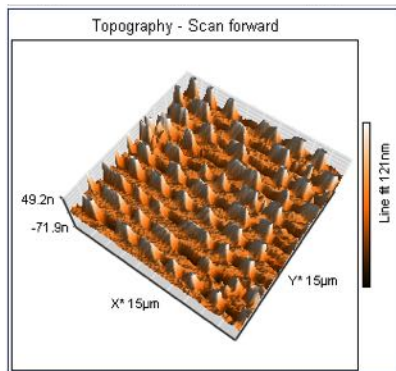


<https://www.thingiverse.com/thing:209015>

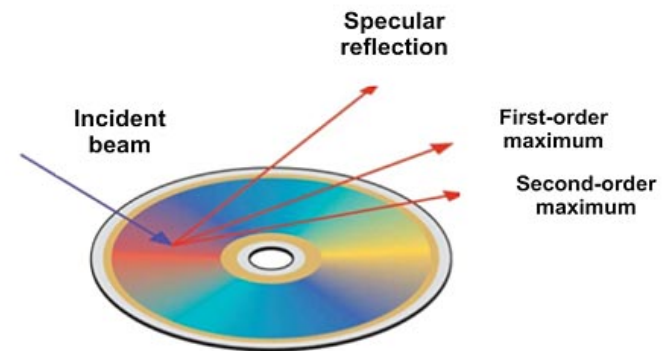
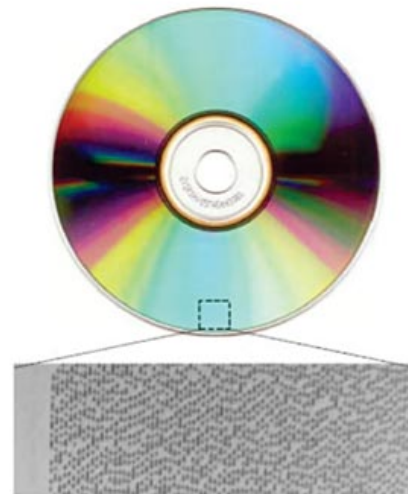


<http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html>

Difração no cotidiano



https://en.wikipedia.org/wiki/Compact_disc#Physical_details

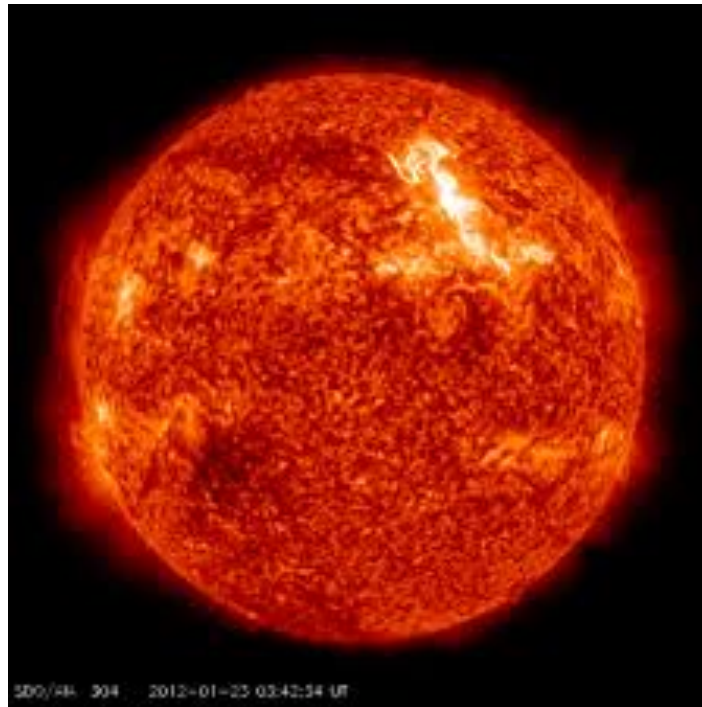


http://www.holmarc.com/differ_reflection_grating.php

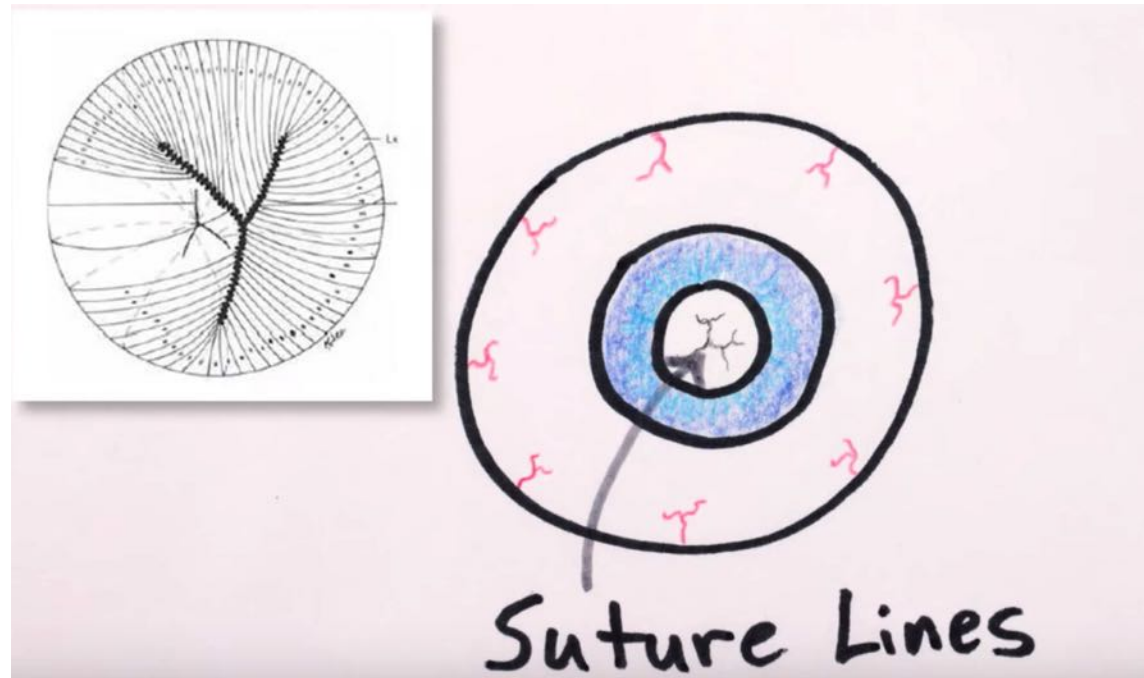
Difração no cotidiano



Difração no cotidiano



Difração no cotidiano



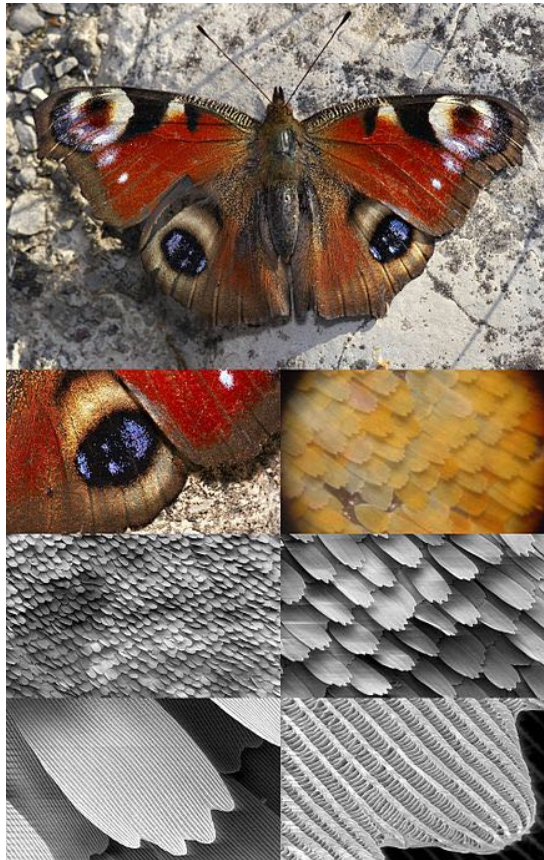
<https://www.youtube.com/watch?v=VVAKFJ8VVp4>

Difração no cotidiano



<https://en.wikipedia.org/wiki/Peafowl>

Difração no cotidiano

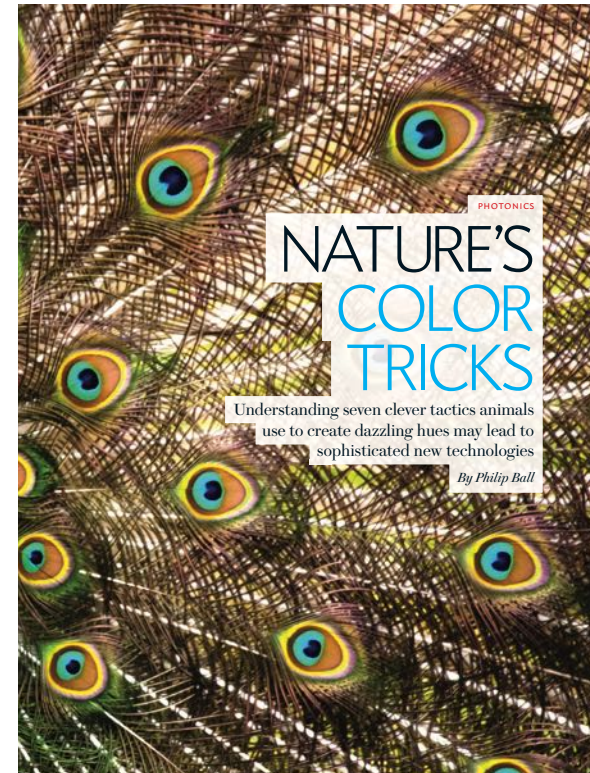


https://en.wikipedia.org/wiki/Structural_coloration

Difração no cotidiano

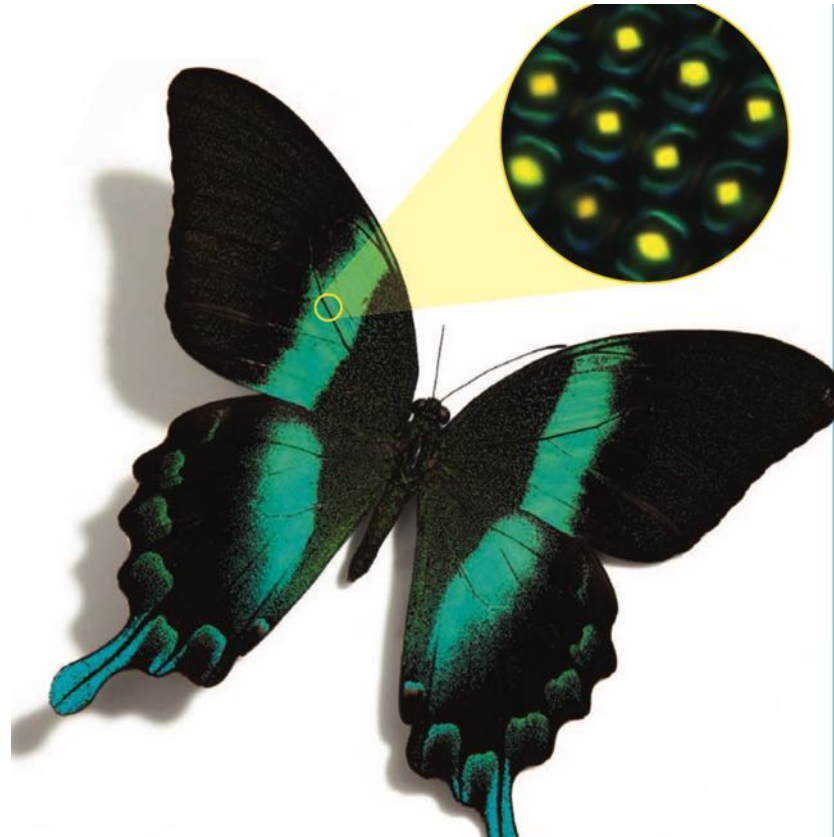


https://en.wikipedia.org/wiki/Structural_coloration



Philip Ball, Scientific American May 2012

Difração no cotidiano



Philip Ball, Scientific American May 2012

Difração no cotidiano



<https://www.atoptics.co.uk/droplets/corona.htm>



© Sergio Montúfar

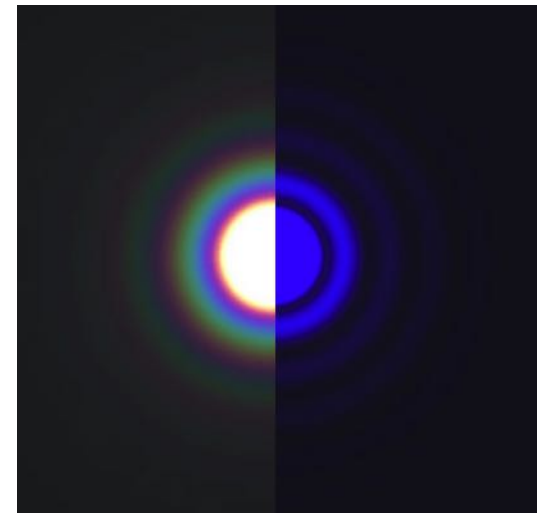
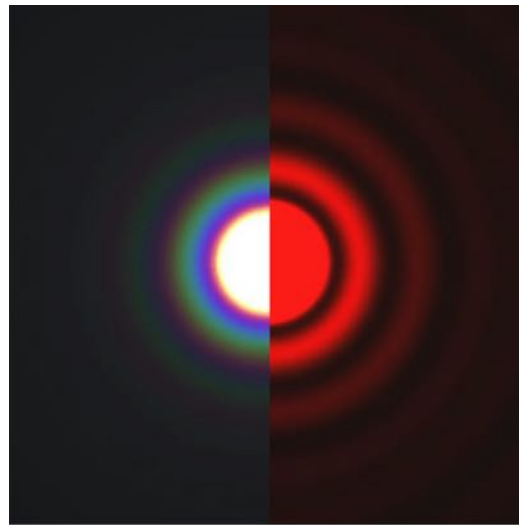
<https://apod.nasa.gov/apod/ap150615.html>

Difração no cotidiano



<https://www.atoptics.co.uk/droplets/cormoon.htm>

Difração no cotidiano



<https://www.atoptics.co.uk/droplets/corcols.htm>

Difração no cotidiano



<https://www.atoptics.co.uk/droplets/cormoon.htm>

VS



Difração no cotidiano



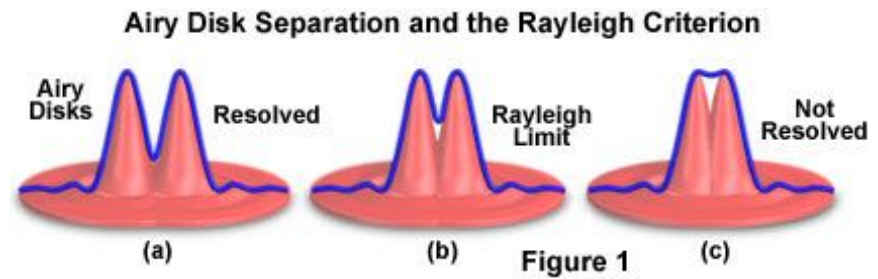
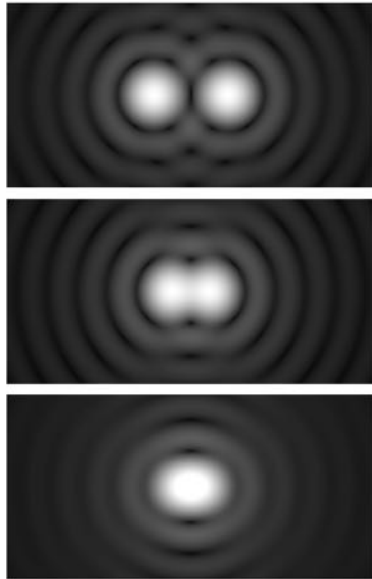
<https://www.atoptics.co.uk/droplets/cormoon.htm>

VS



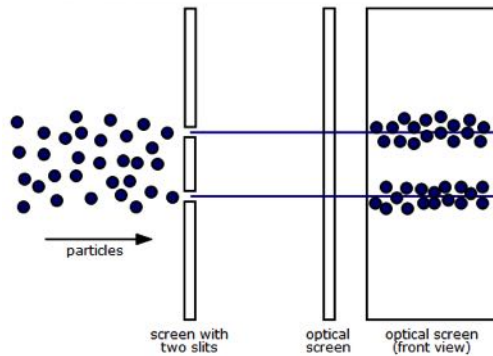
<https://www.tes.com/lessons/1lc4hk5nwWM8dg/dispersion-of-light-through-a-glass-prism>

Limite de Rayleigh

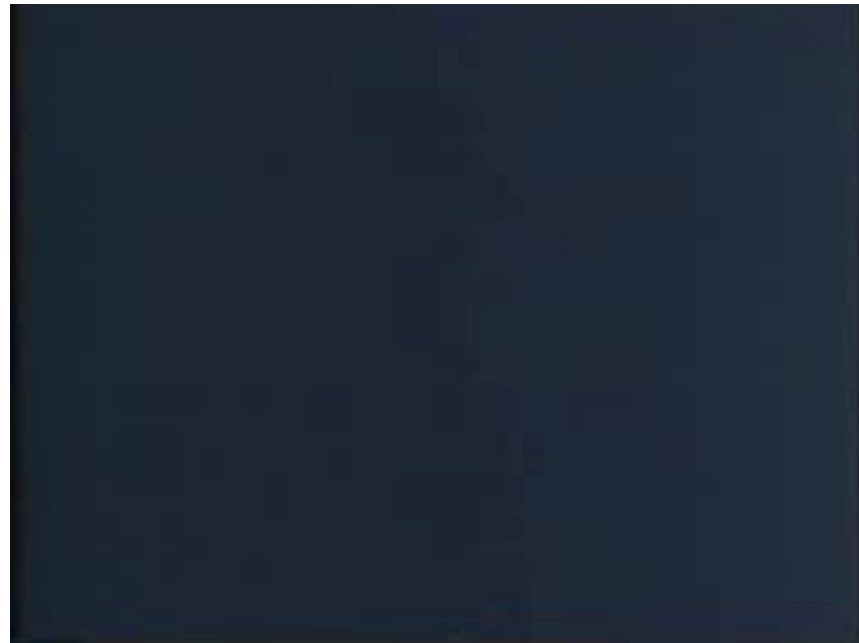


https://en.wikipedia.org/wiki/Angular_resolution

Difração de Matéria?



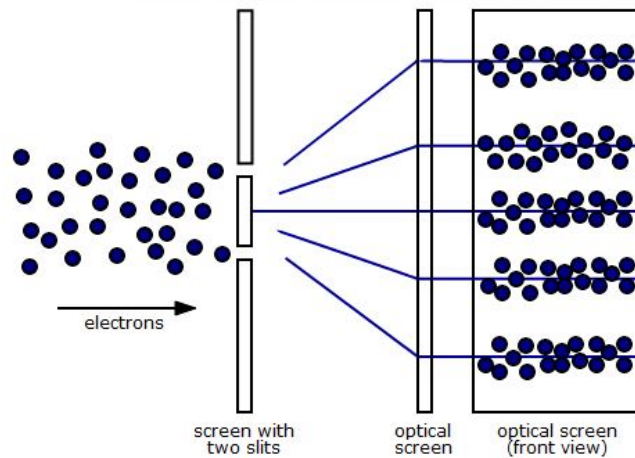
http://en.labs.wikimedia.org/wiki/Materials_in_Electronics/Wave-Particle_Duality/The_Two-Slit_Experiment



A. Tonomura *et al.*, Am.J.Phys **57** 117 (1989)

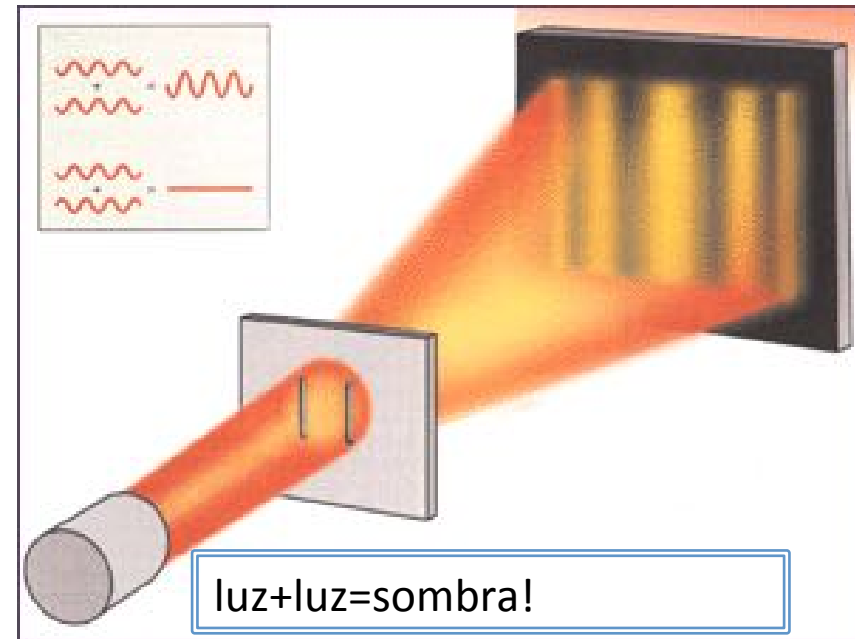
Difração de Matéria?

Padrão de interferência!



elétron+elétron=vácuo!

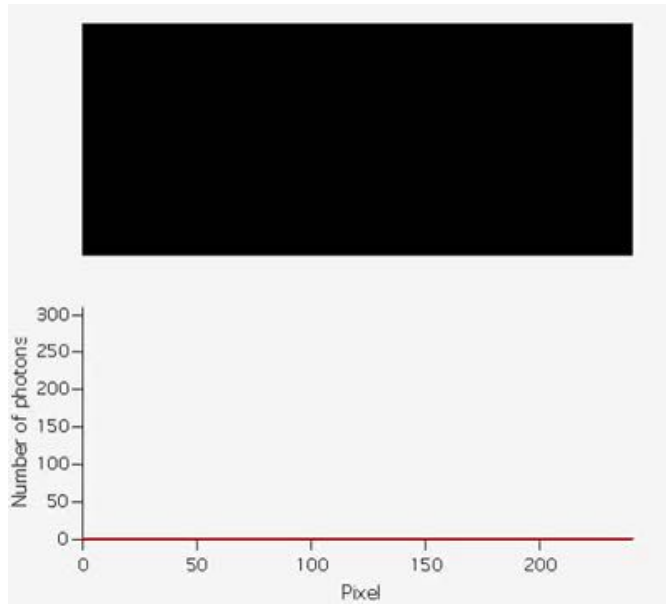
http://en.labs.wikimedia.org/wiki/Materials_in_Electronics/Wave-Particle_Duality/The_Two-Slit_Experiment



luz+luz=sombra!

http://nobelprize.org/nobel_prizes/physics/articles/ekspong/

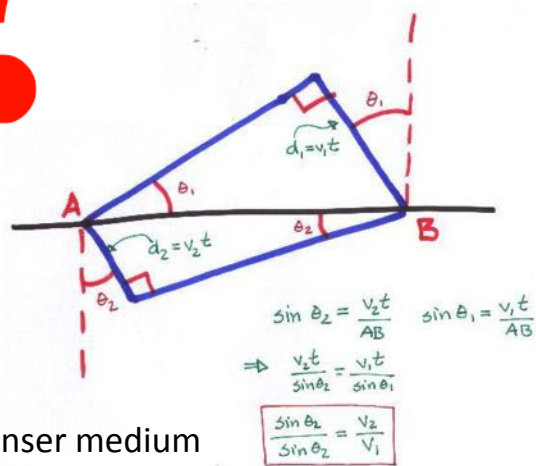
Dualidade Onda-Partícula



Dualidade Onda-Partícula



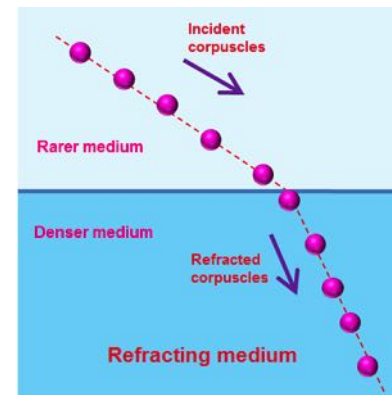
Onda



A luz deve ser mais **lenta** no meio mais denso!



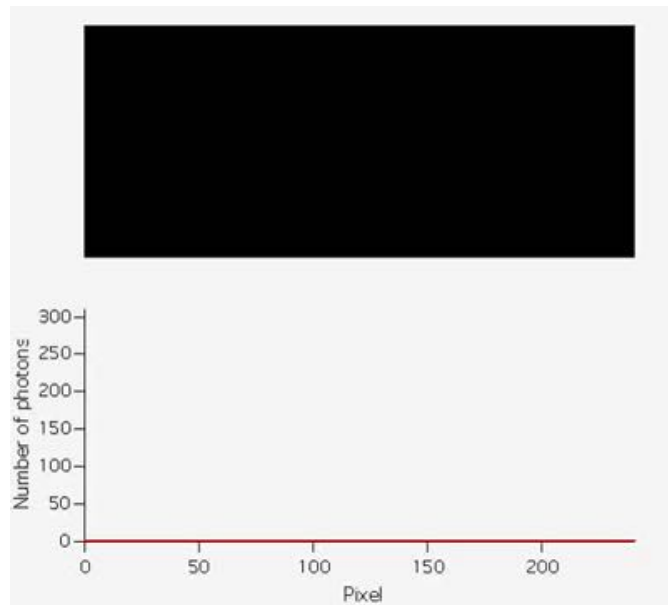
Partícula



$v_{\parallel} = \text{constante}$

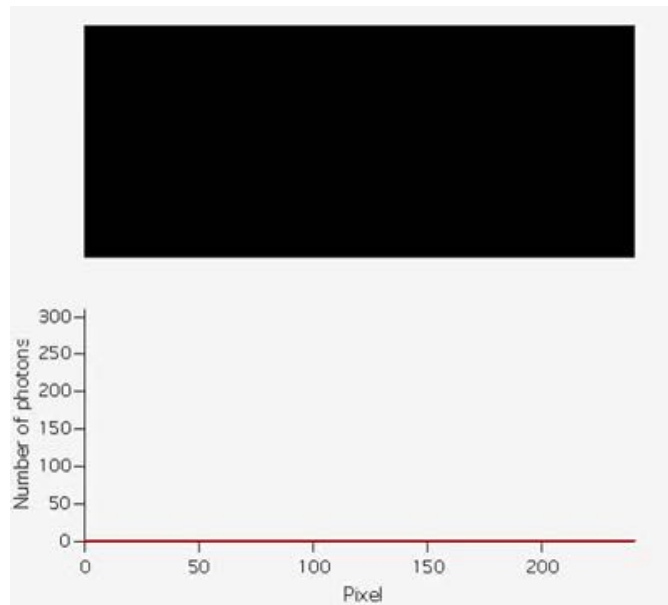
A luz deve ser mais **rápida** no meio mais denso!

Dualidade Onda-Partícula



$$p = \frac{h}{\lambda} = \frac{E}{\lambda f} = \frac{E}{v}$$

Dualidade Onda-Partícula

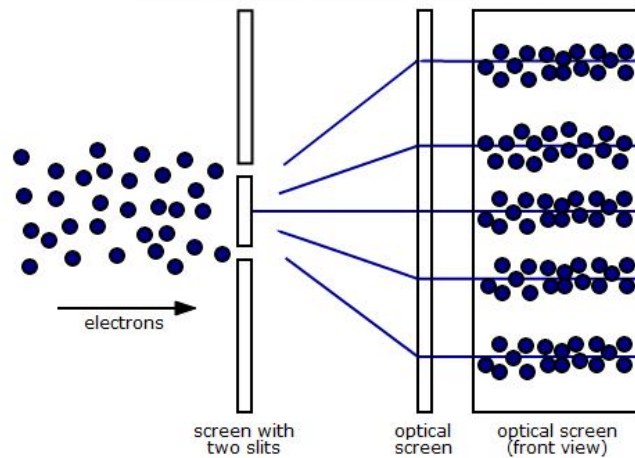


$$p = \frac{h}{\lambda} = \frac{E}{\lambda f} = \frac{E}{v}$$

**Unificação dos princípios de
Maupertuis e de Fermat!**

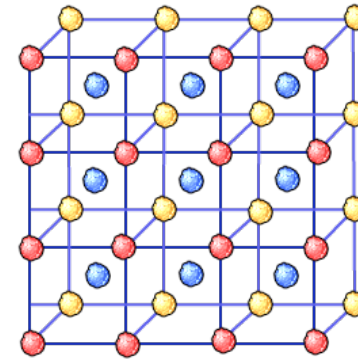
Difração de Matéria?

Padrão de interferência!

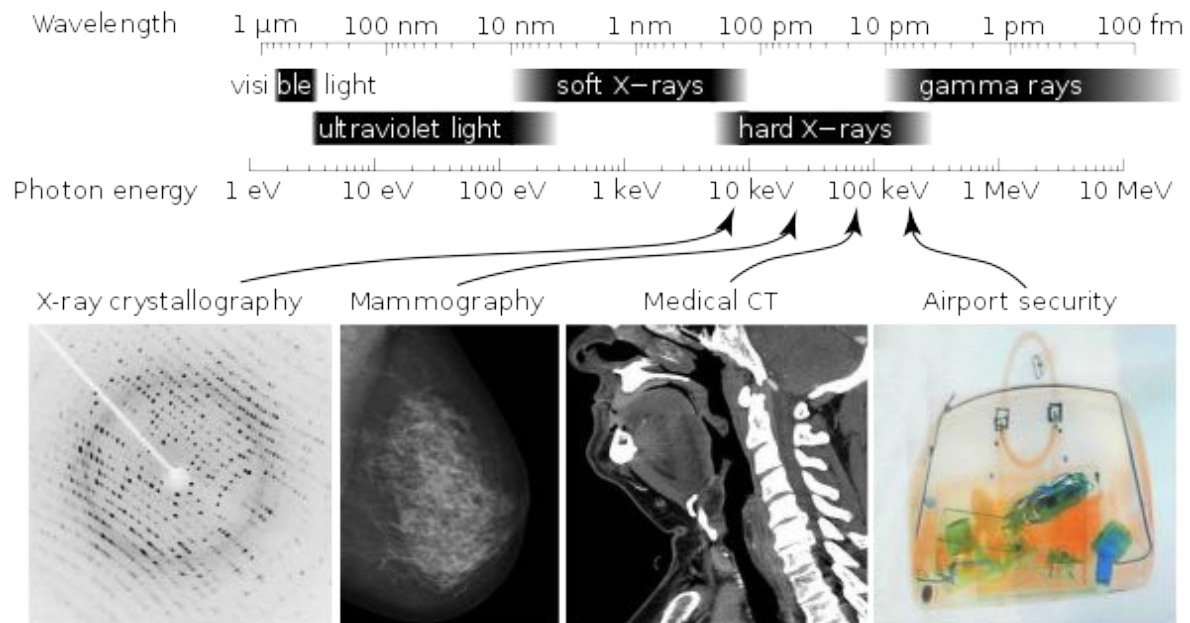


elétron+elétron=vácuo!

$$\lambda_{\text{elétrons}} \sim 10^{-12} \text{ m}$$

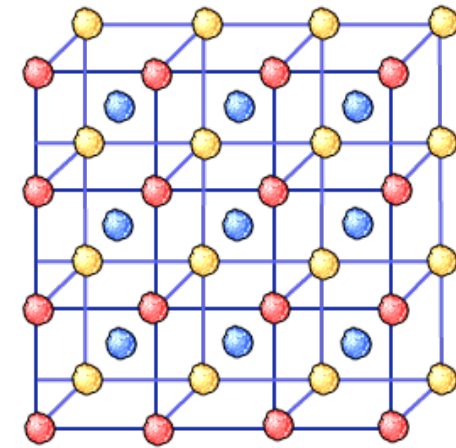
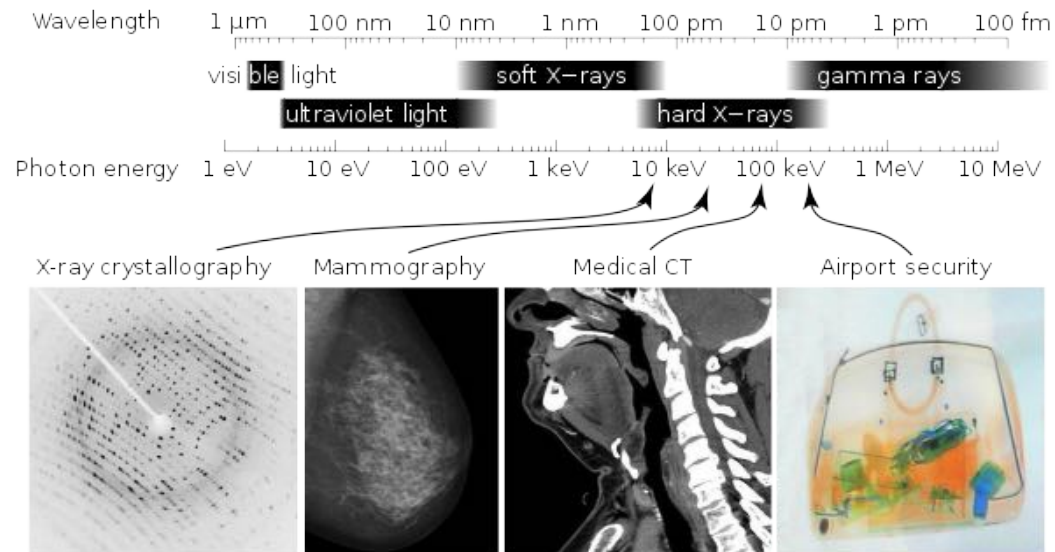


Raios-X



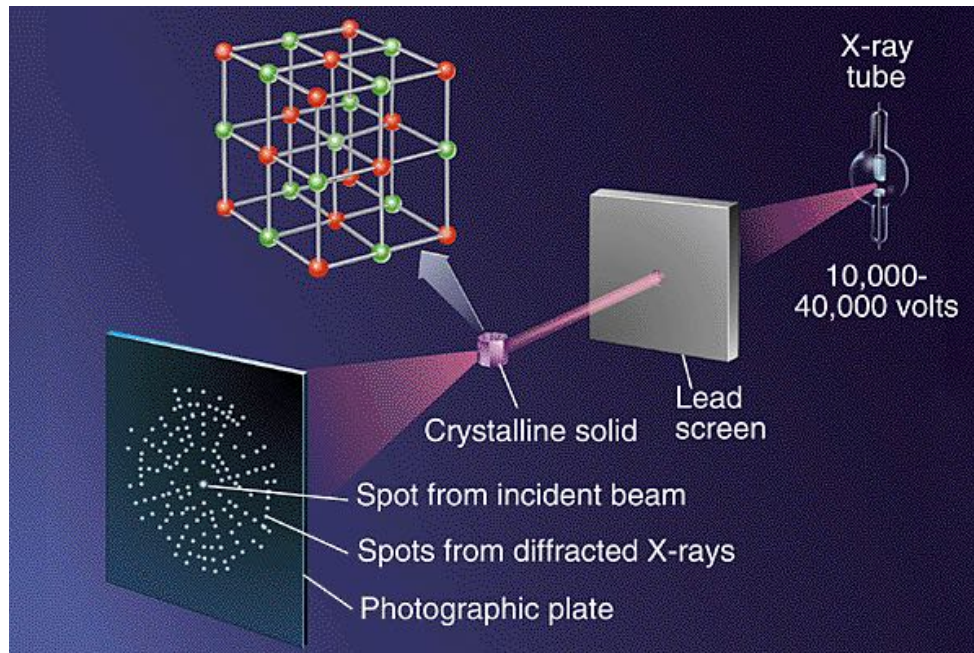
Raios-X

Os cristais funcionam como uma rede de difração para os raios-X!

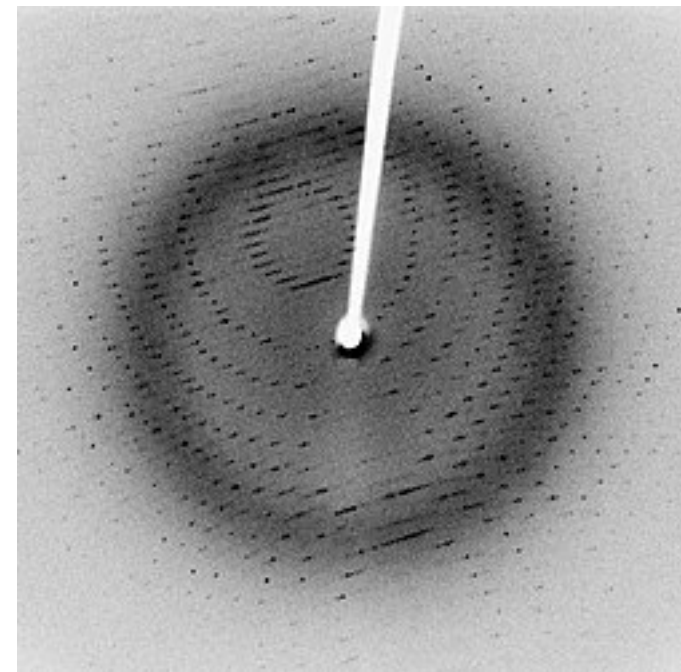


Cristalografia de Raio-X

- Aparato experimental



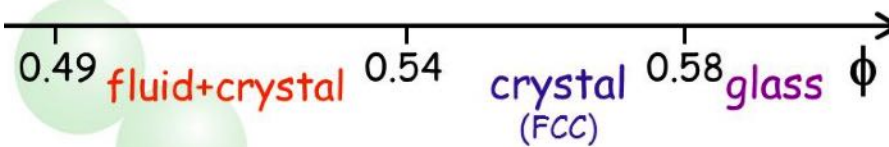
<http://phys4030.blogspot.com.br/2011/03/crystals-structure-by-x-ray-diffraction.html>



https://en.wikipedia.org/wiki/X-ray_scattering_techniques

Cristalografia de Raio-X

- **Cristais Coloidais!** Pusey & Van Megen (Nature, **320**, 340, 1986)

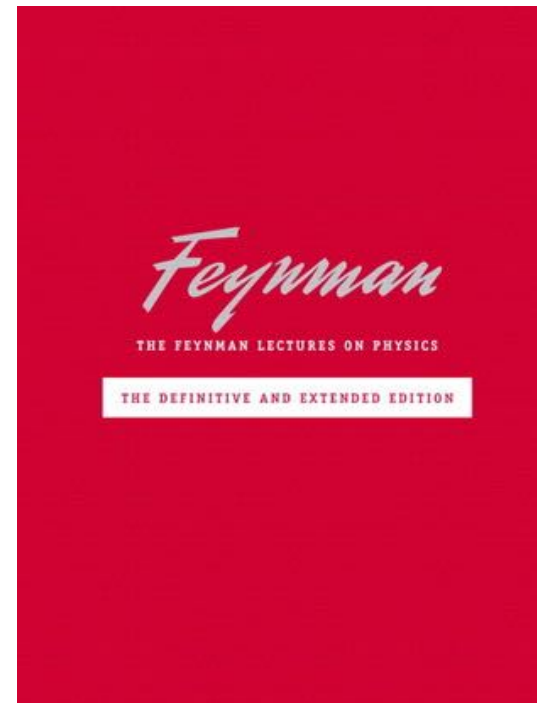
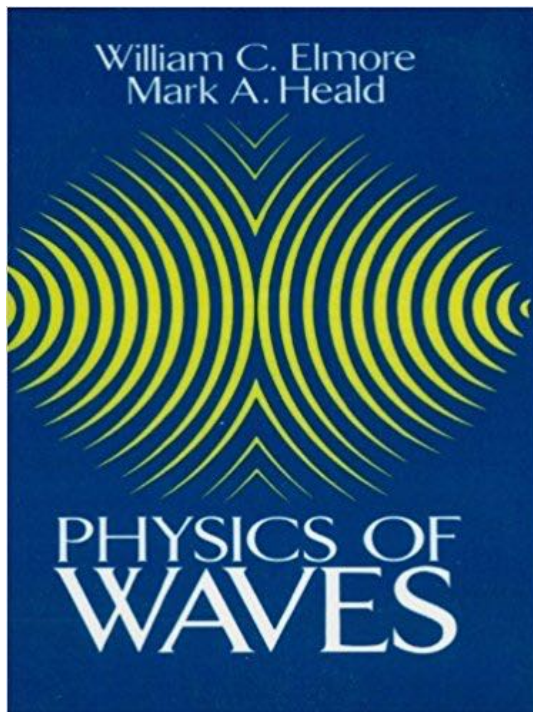


Comentários Finais

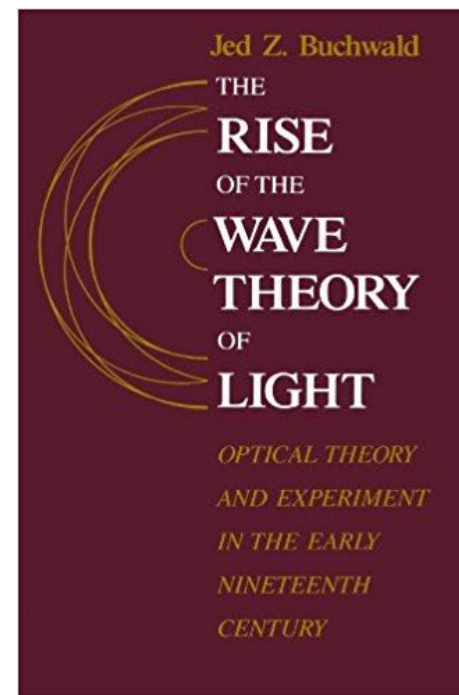
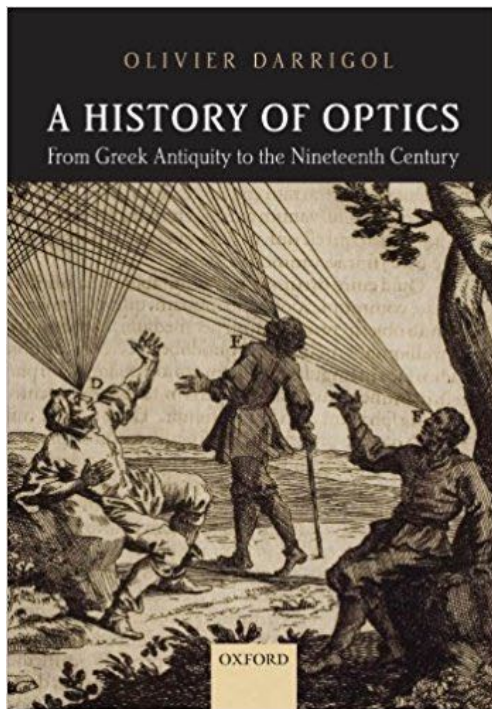
- A técnica de difração cristalográfica por raios-X revolucionou a ciência.

Year [hide] ♦	Laureate ♦	Prize ♦	Rationale ♦
1914	Max von Laue	Physics	"For his discovery of the diffraction of X-rays by crystals" ^[126] an important step in the development of X-ray spectroscopy.
1915	William Henry Bragg	Physics	"For their services in the analysis of crystal structure by means of X-rays" ^[127]
1915	William Lawrence Bragg	Physics	"For their services in the analysis of crystal structure by means of X-rays" ^[127]
1962	Max F. Perutz	Chemistry	"for their studies of the structures of globular proteins" ^[128]
1962	John C. Kendrew	Chemistry	"for their studies of the structures of globular proteins" ^[128]
1962	James Dewey Watson	Medicine	"For their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material" ^[129]
1962	Francis Harry Compton Crick	Medicine	"For their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material" ^[129]
1962	Maurice Hugh Frederick Wilkins	Medicine	"For their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material" ^[129]
1964	Dorothy Hodgkin	Chemistry	"For her determinations by X-ray techniques of the structures of important biochemical substances" ^[130]
1972	Stanford Moore	Chemistry	"For their contribution to the understanding of the connection between chemical structure and catalytic activity of the active centre of the ribonuclease molecule" ^[131]
1972	William H. Stein	Chemistry	"For their contribution to the understanding of the connection between chemical structure and catalytic activity of the active centre of the ribonuclease molecule" ^[131]
1976	William N. Lipscomb	Chemistry	"For his studies on the structure of boranes illuminating problems of chemical bonding" ^[132]
1985	Jerome Karle	Chemistry	"For their outstanding achievements in developing direct methods for the determination of crystal structures" ^[133]
1985	Herbert A. Hauptman	Chemistry	"For their outstanding achievements in developing direct methods for the determination of crystal structures" ^[133]
1988	Johann Deisenhofer	Chemistry	"For their determination of the three-dimensional structure of a photosynthetic reaction centre" ^[134]
1988	Hartmut Michel	Chemistry	"For their determination of the three-dimensional structure of a photosynthetic reaction centre" ^[134]
1988	Robert Huber	Chemistry	"For their determination of the three-dimensional structure of a photosynthetic reaction centre" ^[134]
1997	John E. Walker	Chemistry	"For their elucidation of the enzymatic mechanism underlying the synthesis of adenosine triphosphate (ATP)" ^[135]
2003	Roderick MacKinnon	Chemistry	"For discoveries concerning channels in cell membranes [...] for structural and mechanistic studies of ion channels" ^[136]
2003	Peter Agre	Chemistry	"For discoveries concerning channels in cell membranes [...] for the discovery of water channels" ^[136]
2006	Roger D. Kornberg	Chemistry	"For his studies of the molecular basis of eukaryotic transcription" ^[137]
2009	Ada E. Yonath	Chemistry	"For studies of the structure and function of the ribosome" ^[138]
2009	Thomas A. Steitz	Chemistry	"For studies of the structure and function of the ribosome" ^[138]
2009	Venkatraman Ramakrishnan	Chemistry	"For studies of the structure and function of the ribosome" ^[138]
2012	Brian Kobilka	Chemistry	"For studies of G-protein-coupled receptors" ^[139]

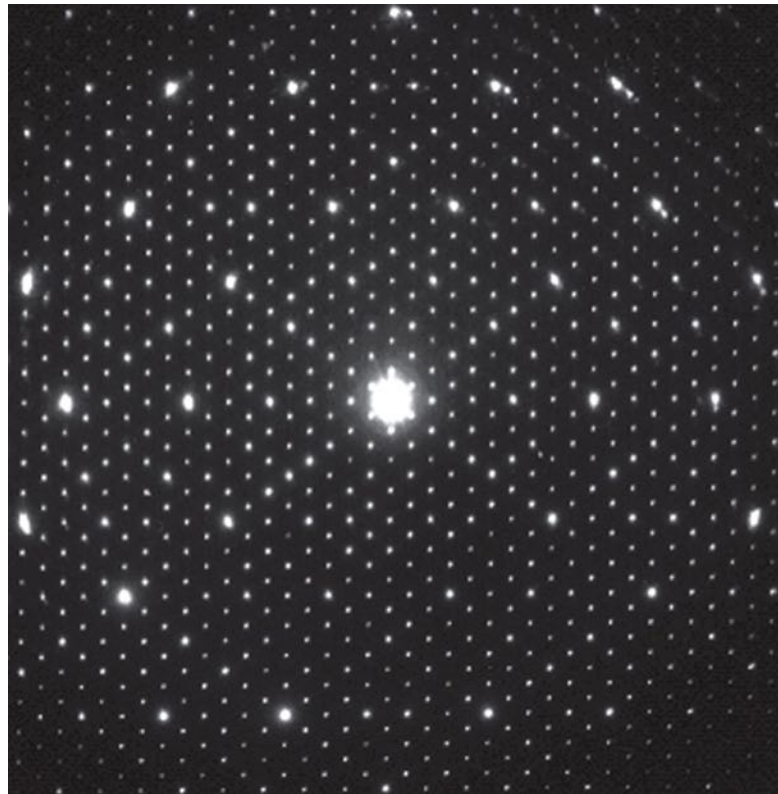
Referências Modernas



Referências Históricas



Obrigado pela presença!



Contato:
reinaldo@if.uff.br