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Modeling leaf optical properties: what is the challenge?

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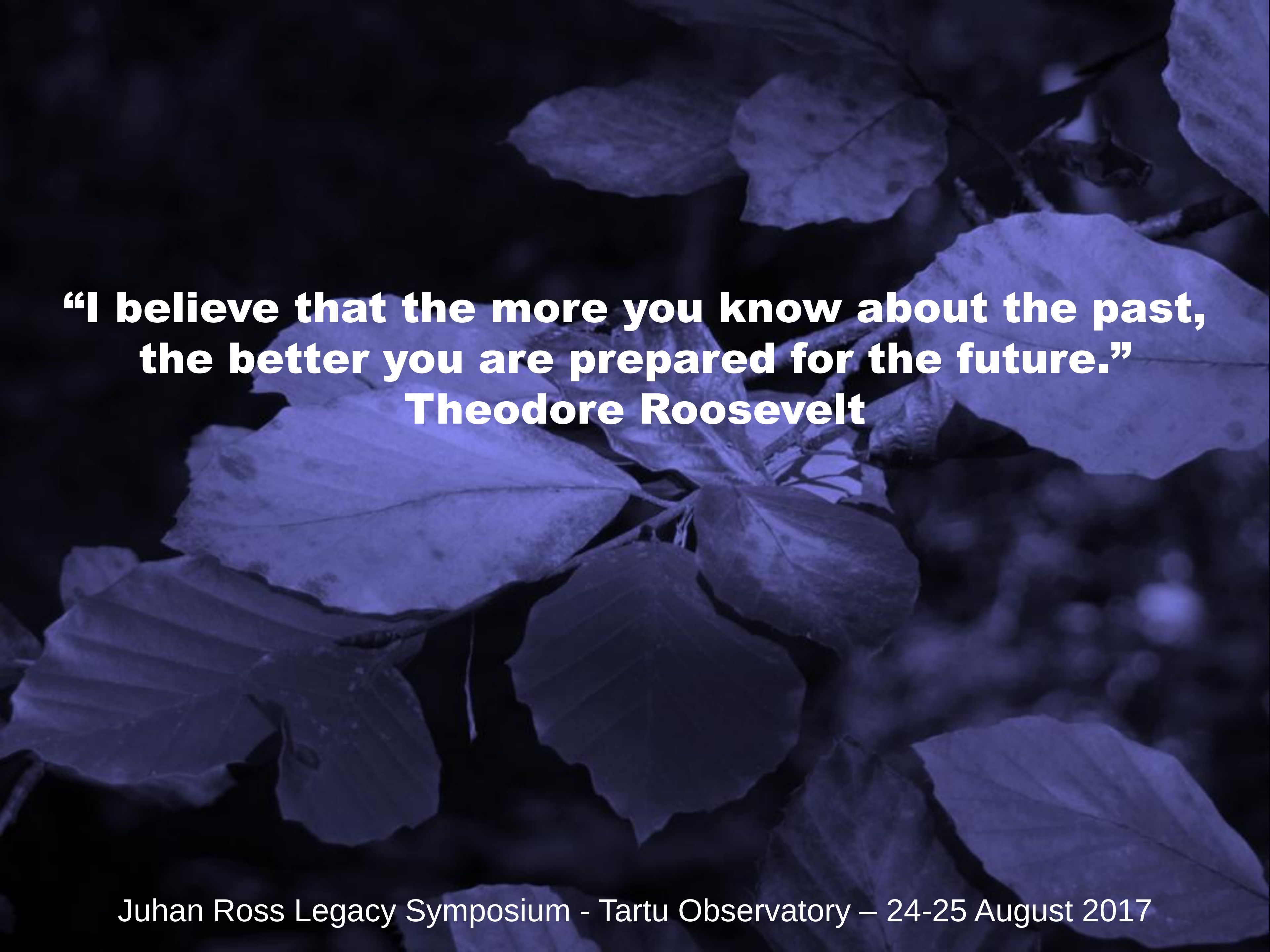
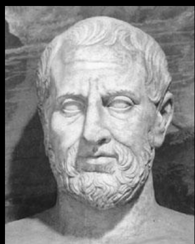


“I believe that the more you know about the past, the better you are prepared for the future.”

Theodore Roosevelt

A bit of history: in ancient times



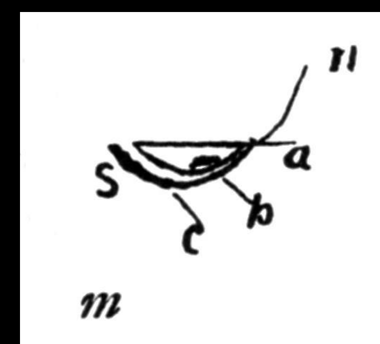
Theophrastus (371-287 BC), *De Historia Plantarum*

« Now all leaves differ as to their upper and under surfaces ; and in most trees the upper surfaces are greener and smoother, as they have the fibres and veins in the under surfaces, even as the human hand has its 'lines'but even the upper surface of the leaf of the olive is sometimes whiter and less smooth (book 1, chap. 10). »

Hort (translator), 1916, *Theophrastus: Enquiry into Plants*, Harvard University Press, Cambridge, MA, 475 pp. (http://www.archive.org/details/enquiryintoplant00theo)

Leonardo da Vinci (1452-1519), *Botany for Painters and Elements of Landscape Painting*

« The accidents of colour in the foliage of trees are 4. That is: shadow, light [reflected light], lustre [specularly reflected light] and transparency [transmitted light]. »



Richter (1970), *The Notebooks of Leonardo da Vinci compiled and edited from the original manuscripts*, Vol. I, Dover, 367 pp. (http://www.sacred-texts.com/aor/dv/index.htm)

A bit of history: in modern times

David Brewster (1781-1848)

« The leaf of a plant, for example, appeared green in the white light of day, because it had the property of reflecting green light in greater abundance than any other. When the leaf was placed in homogeneous red light, it no longer appeared green, because there were no green rays in the red … The green leaf, for example, stops or absorbs the red, blue and violet rays of the white light which falls upon it, and reflects and transmits only those which compose its peculiar green. »

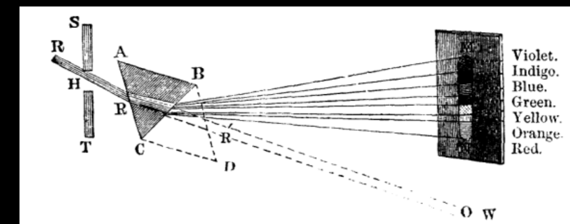
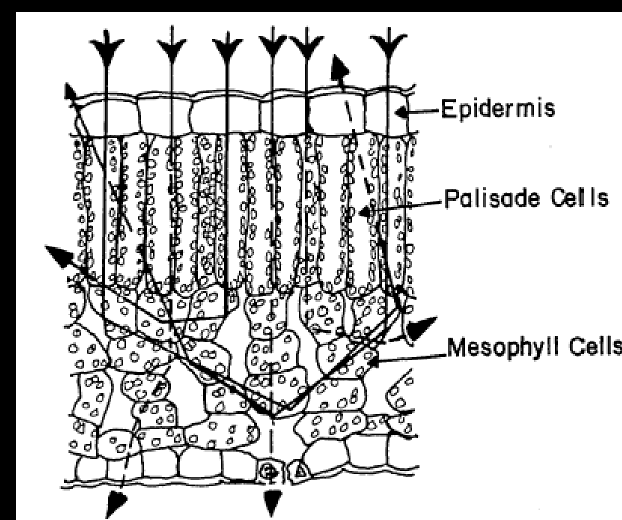


FIG. 2.

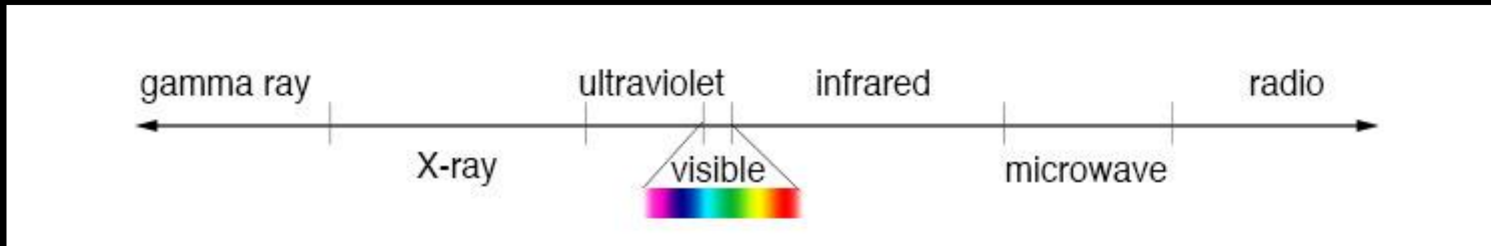
Brewster (1855), *Memoirs of the life, writings and discoveries of Sir Isaac Newton*, Thomas Constable and Co. (Edinburgh), 564 pp. (http://www.archive.org/details/memoirslifewrit00brewgoog)

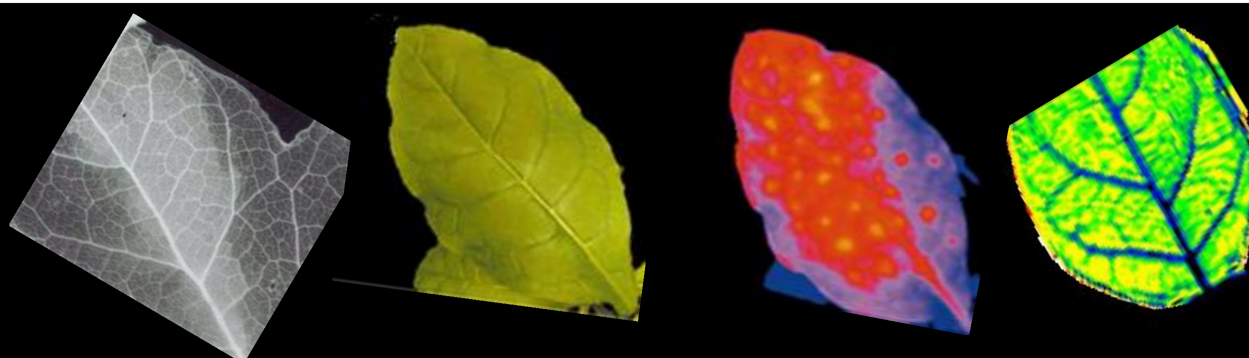
Richard Willstätter (1872-1942)
& Arthur Stoll (1887-1971)

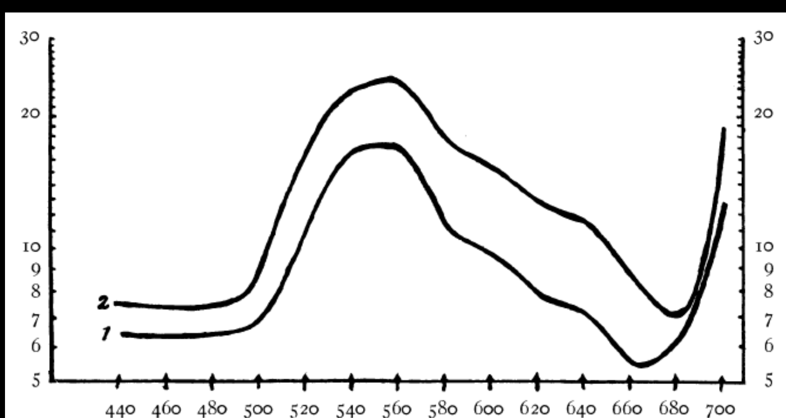


Willstätter & Stoll (1918), *Untersuchungen uber die Assimilation der Kohlensaure*, Verlag von Julius Springer, Berlin, 448 pp. (http://www.archive.org/details/untersuchungen00will)

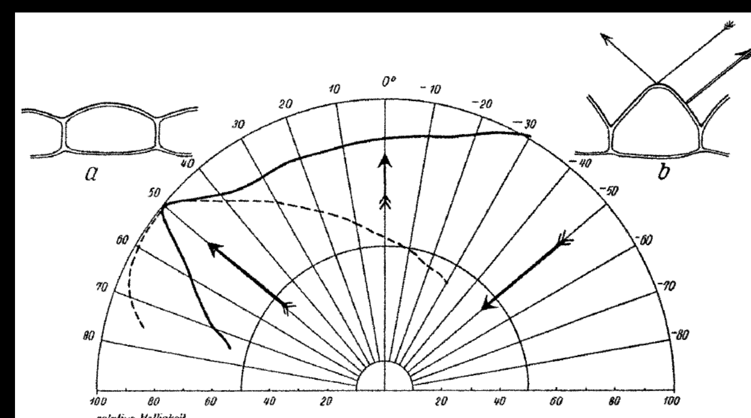
Measuring leaf optical properties: the 20th century







Shull (1929), *Botanical Gazette*, 87(5):583-607.



Metzner (1957), *Die Kulturpflanze*, 5(1):221-239.

Modeling leaf optical properties: the pioneers

ОПТИЧЕСКАЯ МОДЕЛЬ ЛИСТА РАСТЕНИЯ

Х. Молдау

Предложена математическая модель, позволяющая обосновать некоторые закономерности в спектральных рассеивающих свойствах листьев растений. Индикатриса отражения рассматривается состоящей из внешней и внутренней компонент. Внешняя компонента вычисляется по законам зеркального отражения с учетом профиля поверхности. Внутренность листа моделируется как плоскопараллельный мутный слой, к которому с двух сторон примыкают частично отражающие поверхности листа. Экспериментально определены коэффициент преломления и профиль поверхности листа. Полученные расчетным путем индикатрисы сравнены с экспериментально измеренными.

Moldau H. (1967), Optical model of plant leaf, in *Photoactinometric investigations of plant canopy*, Valgus Publishers, Tallinn, pp. 89-109 (in Russian).

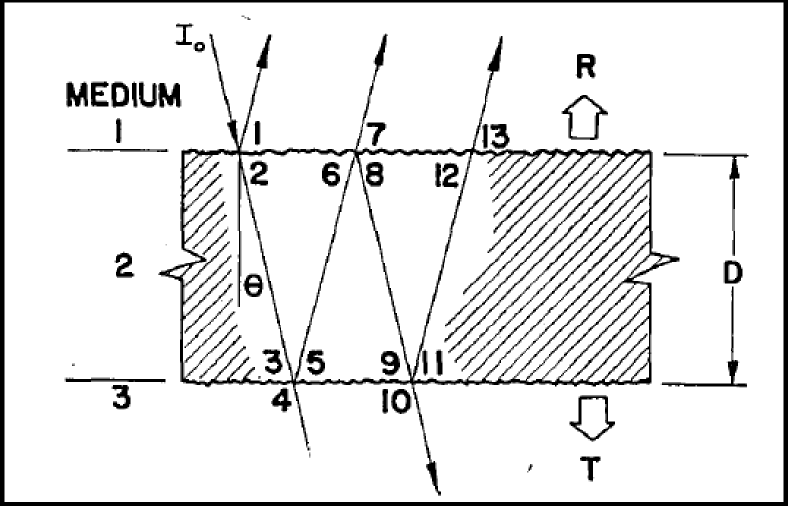
Modeling leaf optical properties: the pioneers

OPTICAL MODEL OF PLANT LEAF

H. Moldau

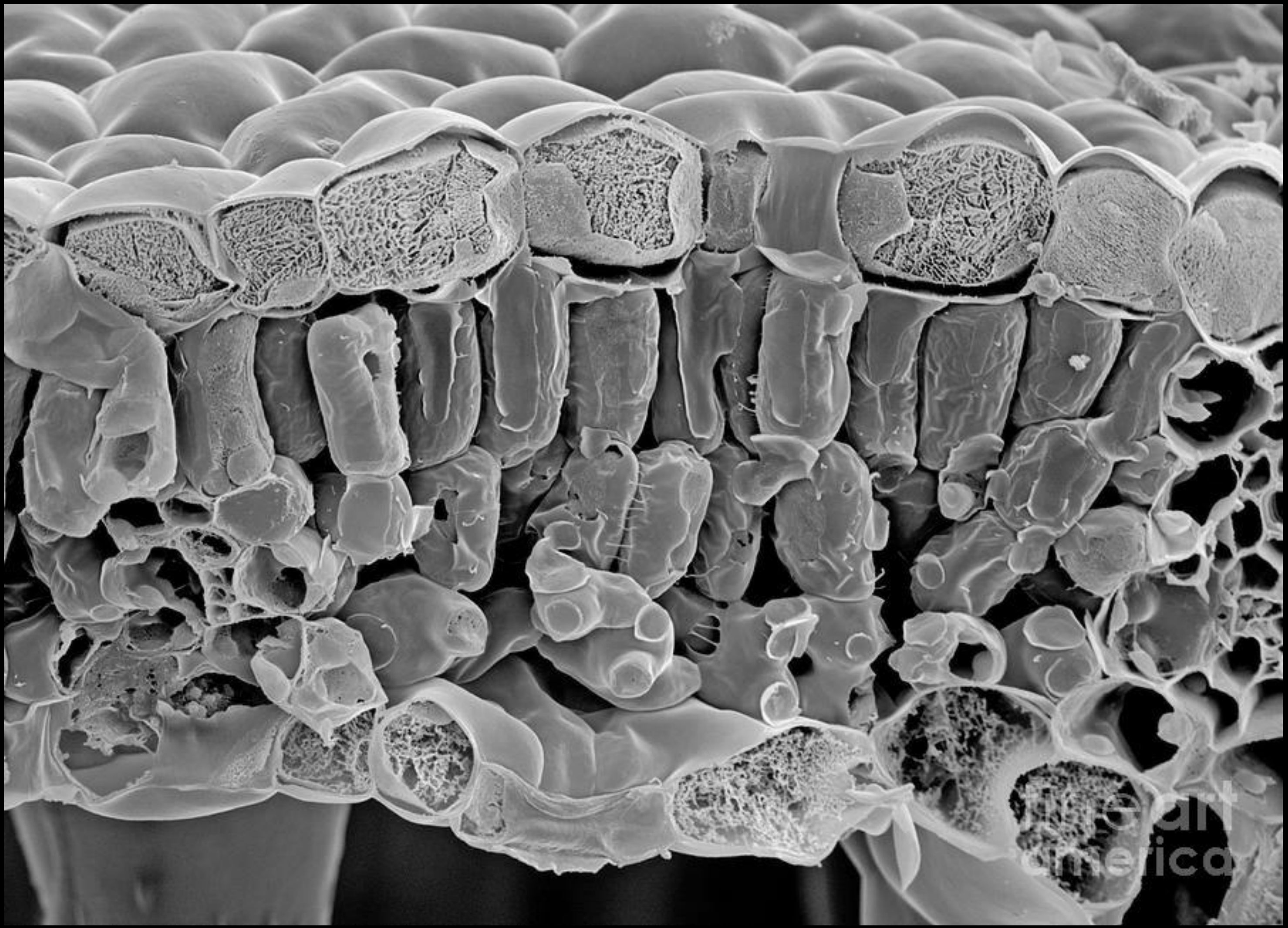
This report proposes a matematical model of plant leaf which permits to explain several regularities in the spectral diffusing properties of them. The reflection indicatrixe is divided into external and internal components. The first calculated on the base of Fresnel reflection from a rough surface. The interior of the leaf is assumed to a plane-parallel layer of absorbing-diffusing medium, restricted from both sides with two reflecting surfaces. Some parameters, needed for calculation (refraction index and roughness of the surface) are determined by means of optical methods. The mean parameters of leaf's interior (absorption and scattering coefficients, optical thickness) are evaluated.

Moldau H. (1967), Optical model of plant leaf, in *Photoactinometric investigations of plant canopy*, Valgus Publishers, Tallinn, pp. 89-109 (in Russian).



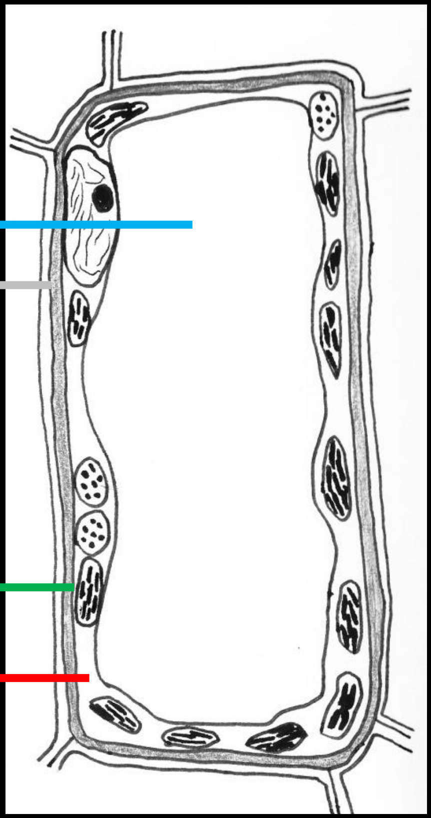
Allen et al. (1969), *Journal of the Optical Society of America*, 59(10):1376-1379.

Modeling leaf optical properties: an issue of botany



Modeling leaf optical properties: an issue of chemistry

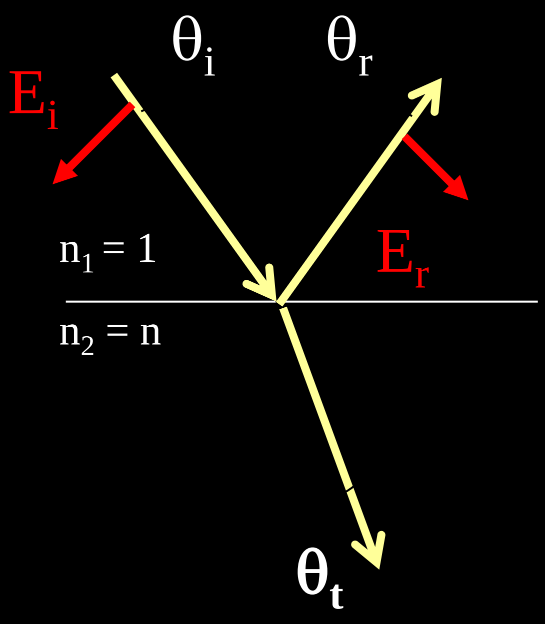
- water (vacuole): 90-95%
- dry matter (cell walls): 5-10%
  - cellulose: 15-30%
  - hemicellulose: 10-30%
  - proteins: 10-20%
  - lignin: 5-15%
  - starch: 0.2-2.7%
  - sugar
  - etc.
- chlorophyll *a* and *b* + carotenoids (chloroplasts)
- other pigments (cytoplasm)
  - anthocyanins
  - flavons
  - brown pigments
  - etc.
- wax (cuticle)



Modeling leaf optical properties: an issue of physics

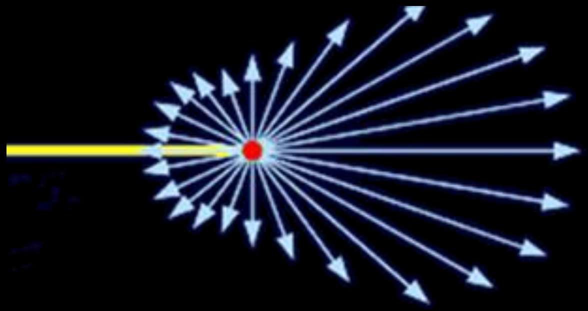
Surface scattering: reflection and refraction

⇒ Snell's law + Fresnel's equation



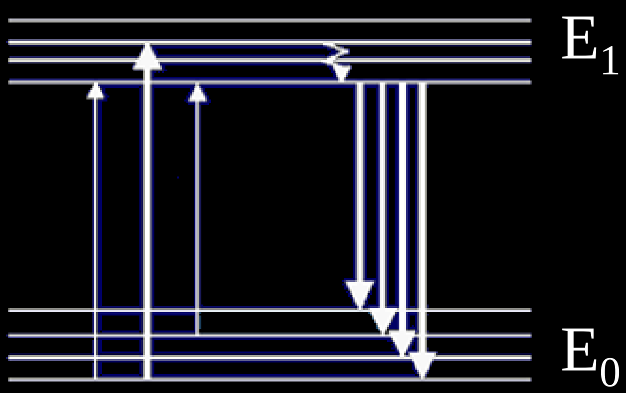
Volume scattering

⇒ Mie scattering + non-selective scattering



Absorption + emission

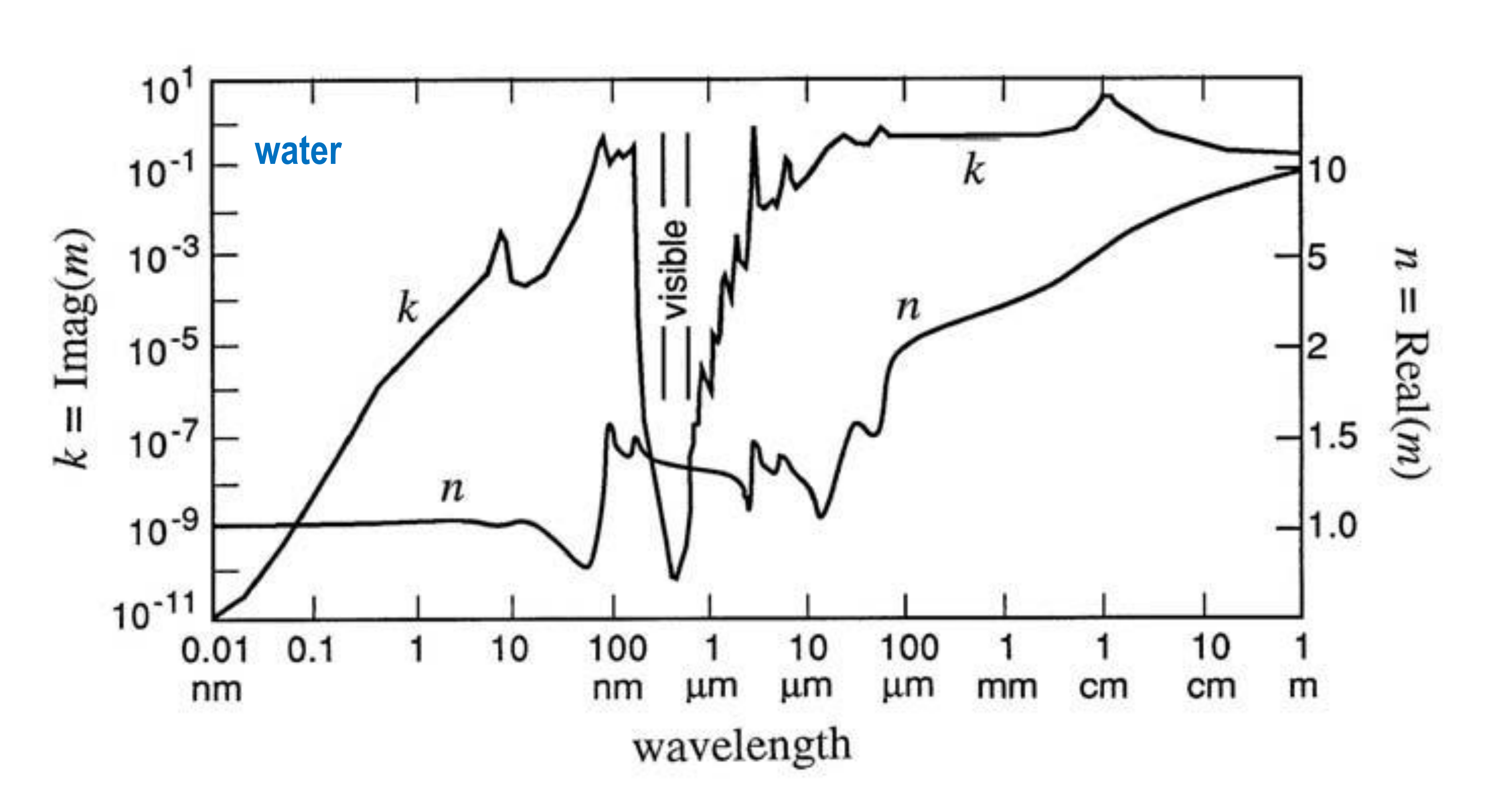
⇒ molecular spectroscopy + Beer's law



Intrinsic optical properties: the complex refractive index

$$\tilde{n} = n_r + i\, n_i$$

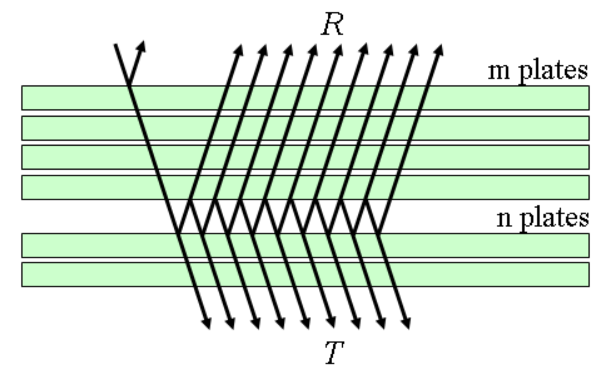
Real part = refractive index
Imaginary part = extinction coefficient ↔ absorption coefficient



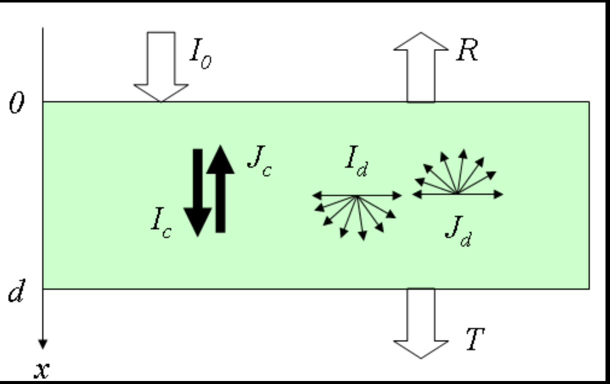
Zoloratev & Demin (1977), *Optics and Spectroscopy*, 43:157-161.

Modeling leaf optical properties: state of the art

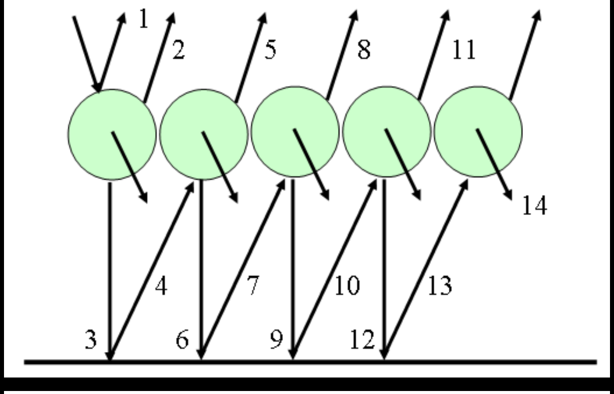
Multilayer models
PROSPECT, DLM



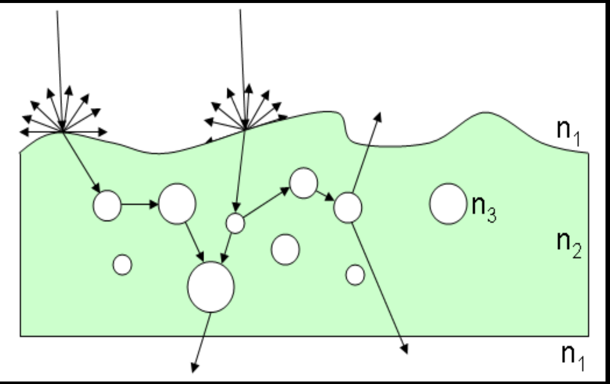
Kubelka-Munk theory
FRT



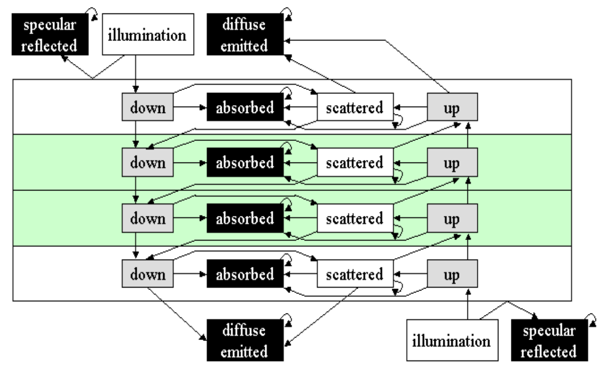
Melamed model
LIBERTY



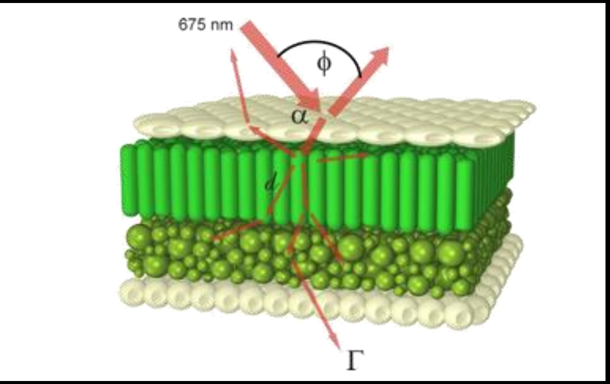
Radiative transfer equation
LEAFMOD



Stochastic approach
LFMOD1, SLOP



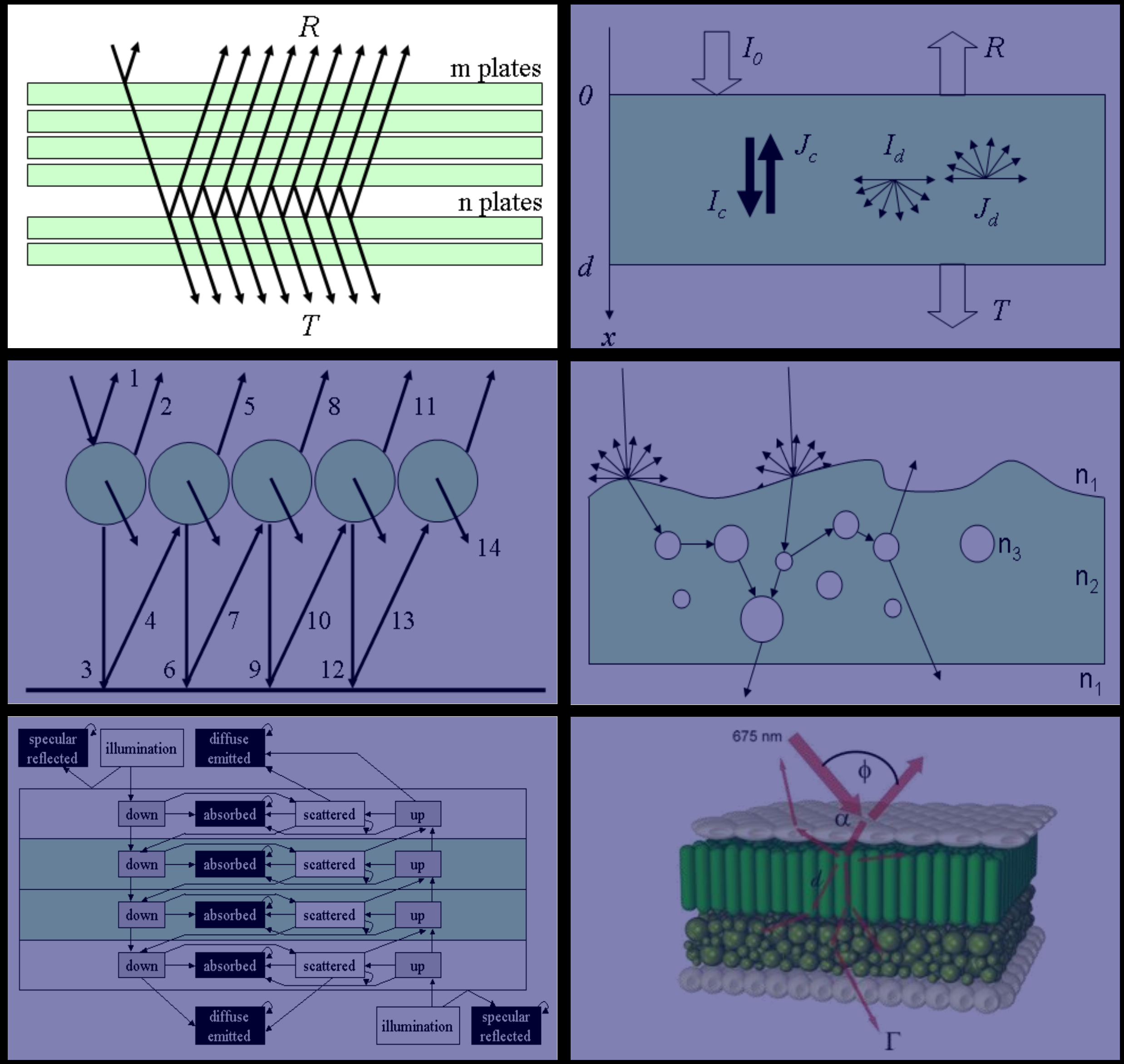
Monte Carlo methods
FSM, ABM-U, ABM-B, RAYTRAN



http://opticleaf.ipgp.fr/
http://www.photobiology.info/Jacq_Ustin.html

Modeling leaf optical properties: PROSPECT

Multilayer
models
PROSPECT

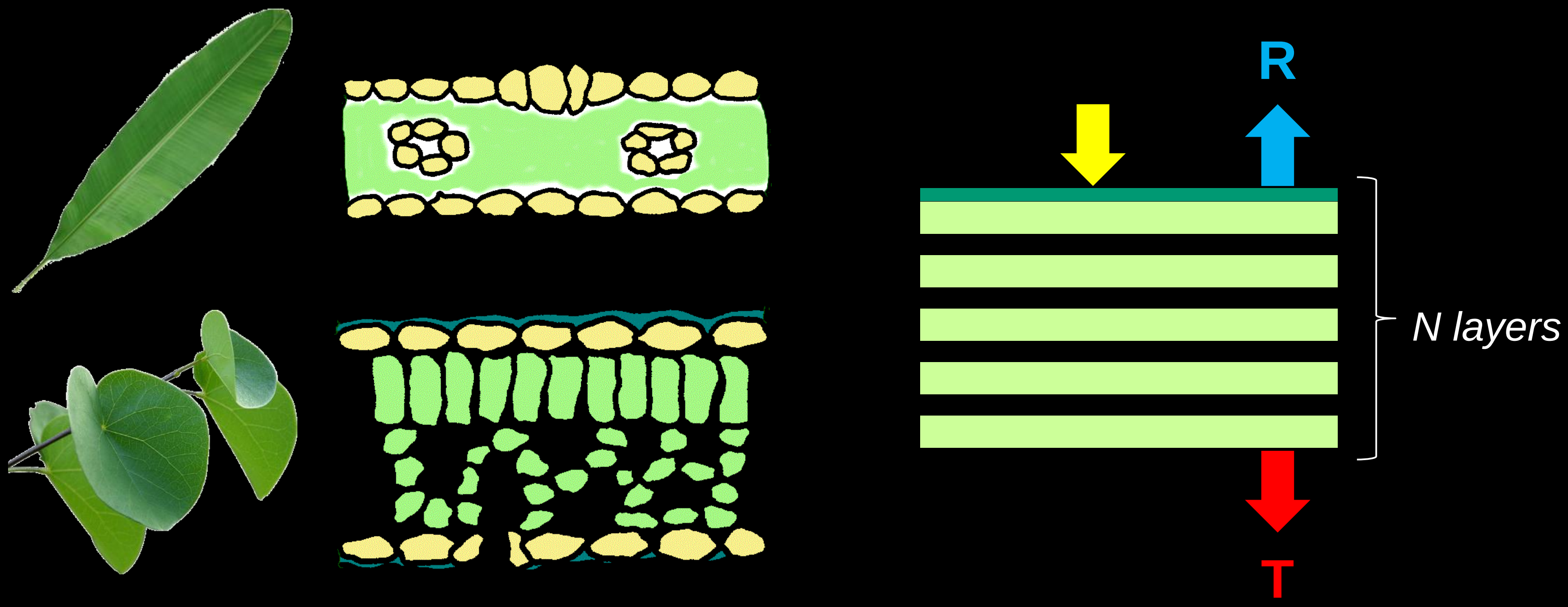


http://opticleaf.ipgp.fr/
http://www.photobiology.info/Jacq_Ustin.html

PROSPECT: physical bases

Modeling leaf diffuse/directional reflectance/transmittance as a function of biochemical content and anatomical structure

- Surface optical properties: interface between two dielectrics (Fresnel equations)
- Volume optical properties: transmission through an elementary layer (Beer-Lambert law) and multiple reflections between N layers (Stokes system)



PROSPECT: direct vs inverse mode

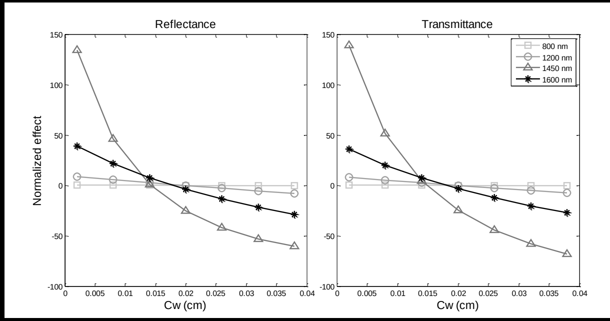
OPTICAL CONSTANTS
Refractive index
Specific absorption coefficients

INPUT VARIABLES
Biochemical content
Leaf structure parameter

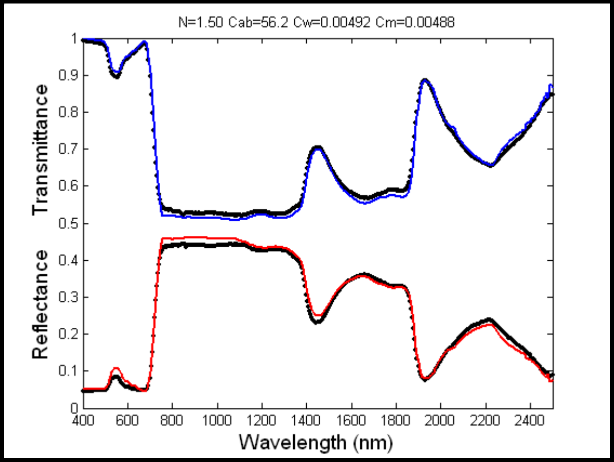
Direct mode

PROSPECT

Inverse mode



Leaf reflectance and transmittance



Féret et al. (2008), *Remote Sensing of Environment*, 112:3030-3043.

PROSPECT: a 27-year-old model

Plate model	1 layer (Allen et al., 1969)
Generalized plate model	N layers (Allen et al., 1970)
PROSPECT	N, C_{ab}, C_w (Jacquemoud & Baret, 1990, 981 citations on 22-Aug-17)
	cellulose, hemicellulose, lignin, protein, starch (Fourty et al., 1996; Wang et al, 2015)
PROSPECT-4	N, C_{ab}, C_w, C_{dm} (Baret & Fourty, 1997) + brown pigments (Baret)
	improved specific absorption cofficients (Jacquemoud et al., 2005)
	leaf BRDF/BTDF (Bousquet et al., 2005)
QSPECT	dorsiventral leaf (Ma et al., 2007)
DLM	dorsiventral leaf + epidermis (Stuckens et al., 2009)
PROSPECT-5	N, C_{ab}, C_{car}, C_w, C_{dm} (Féret et al., 2008)
FluorMODleaf	Chl fluorescence (Pedrós et al., 2010; Zhao et al., 2015)
PROSPECT-VISIR	extension to the SWIR (Gerber et al., 2011)
FLUSPECT	Chl fluorescence (Verhoef, 2011; Verrelst et al., 2015)
	extention to Cu absorption (Zhu et al., 2014)
PROCOSINE	PROSPECT-5 + leaf BRDF (Jay et al., 2016)
PROSPECT-D	N, C_{ab}, C_{car}, C_{anth}, C_w, C_{dm} (Féret et al., 2017)
PROSPECT-MP	N, C_a, C_b, C_{car}, C_w, C_{dm} (Zhang et al., 2017)

Conclusion

<u>Consolidate and validate present model(s)</u>

- Mesophyll heterogeneity
- Chl fluorescence
- Leaf BRDF

<u>Investigate new wavelength domains</u>

- Ultraviolet
- LWIR (thermal infrared radiation)
- FWIR (terahertz radiation)

<u>Add new capabilities</u>

- Leaf chemical composition (brown pigments, xanthophyll cycle, flavonoids…)
- Leaf surface effect (roughness, wax, hair…), polarization
- Leaf temperature
- Dynamic properties: seasonal variation of leaf optical properties

Challenges

- Complex refractive index of leaf material
- Leaf traits and covariance
- Seasonal variation of leaf traits for different ecosystems
- An integrated model including all versions + a detailed manual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