Cordus optics: Part 2.3 Refraction

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Abstract
Explaining basic optical effects is not possible with classical particle mechanics, and even with quantum mechanics it is not straight forward and not particularly intuitive. The problem is much simpler when solved in the cordus domain. This paper provides cordus explanations for Snell's Law and Brewster's Angle, and quantitative derivations too. This is significant because the cordus mechanics were derived for single photons, and immediately generalise also to beams of light. Therefore cordus can explain particle behaviour, fringes, and optical effects, using a single coherent mechanics. The cordus explanation does not need the conventional concept of 'interference'.

Keywords: electromagnetic wave theory; refraction; Snell's Law; Brewster's angle;
Revision 1

1 Introduction

Refraction in general

The bending of light as it enters an inclined boundary is usually explained in optical wave theory as a change in the speed (phase velocity), such that the wavelength changes but not the frequency. The angle of refraction θ_2 in the second medium 2 is given by Snell's law: $\sin\theta_2 = v_2/v_1 .\sin\theta_1 = n_1/n_2.\sin\theta_1 = \lambda_2/\lambda_1.\sin\theta_1$ where the angles are measured from the normal to the surface, and v are the velocities in the two media. Thus the net angular deflection [$\theta_\delta = 90^o -(\theta_1+\theta_2)$] is not constant but depends on the angle of incidence. The refracted ray may be partly polarised. At the same time, some of the light may be reflected.

The refractive index n measures the speed relative to that of light in a vacuum. Refractive index is usually linear, but may be non-linear for high-intensity light. Refractive index increases approximately linearly with density for glasses of similar chemical composition. Explanations vary for *how* the change in speed occurs. The wave interpretation is that the delay occurs because the electric field interacts with the electrons to radiate a delayed wave, thereby forming the new but slower wave. Hence the Huygens–Fresnel principle that each point on the wave propagates

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new waves and these interfere. Surface waves of water also refract, and provide a visual confirmation of the effect.

This paper explains refraction from the cordus perspective. The concept of a cordus is that a photon consists not of a point but of two reactive ends (RE) connected together with a fibril. The REs emit hyff (hyperfine fibrils), which are lines of electrostatic force. The method is described in the previous papers, and the lemmas included here are a continuation of the previous numbering.

2 Cordus refraction

The cordus model for refraction uses the frequency lemma from the earlier paper in the series, and elements of the reflection lemma. It also requires additional assumptions as follow:

Lemma O.4 Refraction

O.4.1 From the cordus perspective, reflection results from the interaction of the incoming photon with the electrons in the surface plane, i.e. surface plasmons. In contrast, refraction is an interaction with the bulk of the material. Furthermore, that interaction starts to occur *before* the photon reaches the bulk material , and it is that preliminary interaction that bends the locus.

O.4.2 On approaching the interface (e.g. air to glass) the hyff probe through both the cis- and trans-dermis. The RE therefore responds to the upcoming medium *before* it physically reaches it (Principle of Wider Locality, see 'Cordus Matter'). That response varies depending on the frequency state, and may be attractive or repulsive.

O.4.2.1 In fact it will be both attractive and repulsive in turn, due to the frequency effect.

O.4.2.2 See the dermis concept in O.3.5.5, part 2.2

O.4.3 The strength of the response is not constant but becomes stronger with proximity to the interface.

O.4.4 The material with higher refractive index exerts the stronger force.

O.4.5 The cumulative effect over several frequency cycles determines the outcome.

O.4.5.1 Thus the precise frequency state of the RE as it approaches the surface will the starting point of the summation and therefore determine the overall outcome attractive or repulsive result.

O.4.5.2 The immediately previous locus also affects the outcome, i.e. momentum is involved, see O.3.9, part 2.2

O.4.5.3 The next photon has a different frequency state and instantaneous direction of momentum may therefore experience a different reflection or refraction result.

O.4.6 The geometric positioning of the dynamic hyff with respect to the two materials, i.e. the angle of incidence, determines the outcome.

O.4.7 Note that the effect is not symmetrical for layout. Thus for passage to a material with higher refractive index, e.g. air to glass, the denser material at n_2 causes refraction to dominate. In contrast, at glass to air, the denser material is at n_1 and reflection dominates.

O.4.8 Photons displace electrons (plasmons) in the medium through which the light travels.

O.4.8.1 Note that the electrons have the higher mobility as per O.3.15.

O.4.8.2 An ineffective plasmon transport mechanism means that the material exerts forces on the reactive end.

2.1 Derivation of Snell's Law

The Cordus explanation for refraction is that the inclined incoming cordus strikes the surface and one reactive-end and then the next penetrates into the second medium n_2. Assuming the case where n_2 is more dense, e.g. from air to glass, then the cordus slows down. The case is shown in Figure 1.

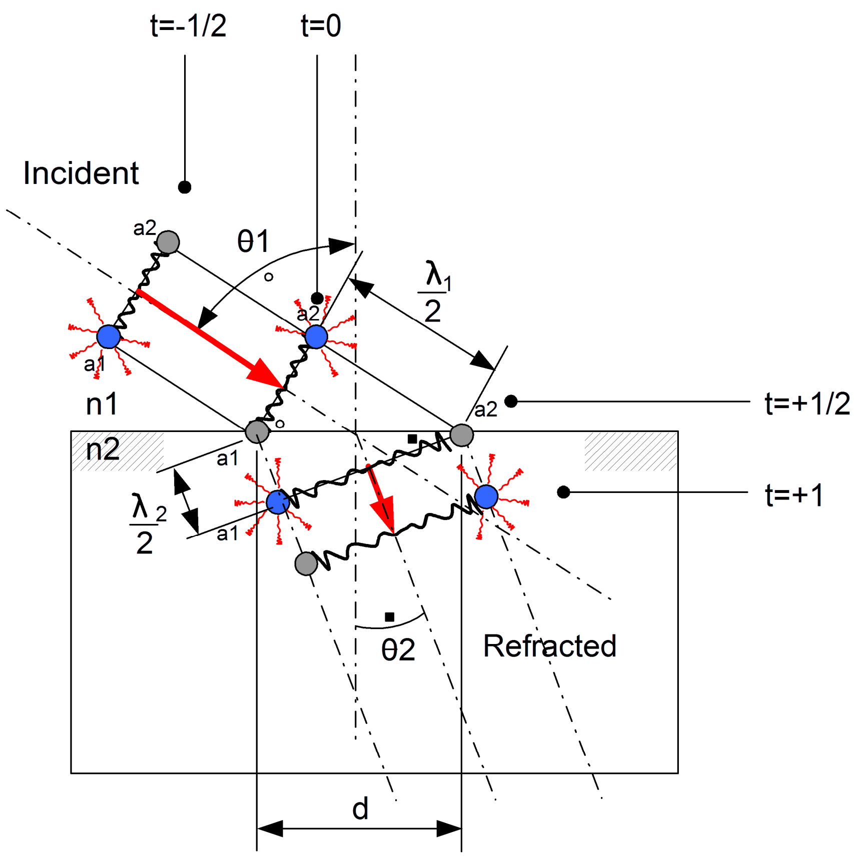

Figure 1: Refraction involves a dormant reactive-end penetrating into the second medium, and being angularly deflected with reduction in speed.

Cordus derivation of Snell's Law

The refraction geometry is shown in Figure 2, this being the two triangles comprising the incident cordus and the surface, and the refracted cordus and the same surface. Since dimension d is common to both triangles, and the cordus is perpendicular to the loci, it follows by trigonometry that $d = \lambda_2/(2.\sin\theta_2) = \lambda_1/(2.\sin\theta_1)$. This becomes $\lambda_2/\sin\theta_2 = \lambda_1/\sin\theta_1$ which is Snell's law. The frequency and other forms arise by noting that v_1=f. λ_1 and v_2=f. λ_2 and n = c/v where c is velocity of light in vacuum.

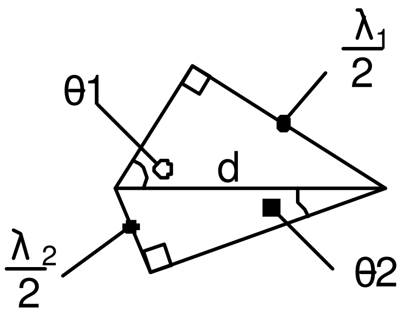

Figure R: Refraction geometry

The explanation above has been given for the neat case where the second reactive end neatly strikes the surface in turn, i.e. t=1/2 gives a precise $\lambda_1/2$ displacement for RE a2. It may be shown that the explanation also works for the messy case where a2 strikes not a half wavelength later but a fraction k.

The above derivation is for a p-polarised photon. The situation for s-polarisation is believed to be similar in that the denser material pulls the reactive end in, thereby deflecting it. However this is yet to be validated.

Birefringence

Some materials show birefringence. These materials have different refractive indices in two (or three) directions and therefore light experiences different refraction depending on its polarisation. Thus the refractive index varies depending on the orientation (polarisation) of the incident light. The effect is generally believed to depend on anisotropic material structure. This may arise from the arrangement of the molecules, mechanical strain, strain from cooling of plastics from the melt, or application of an electric or magnetic field.

The Cordus explanation is that the atomic spacing affects the electron compliance. The different geometric spacing in the different directions creates, through the bonds, corresponding different tension on the electrons, and this affects their preferred orientation and thus availability to engage with incoming hyff. For an anisotropic material those bonds differ with direction. Any strains deform the bonds and thereby affects the ability of electrons to interact with the hyff, hence changing refraction. The orientation, i.e. polarisation, of the incoming cordus determines which bonds it will interact with. The speed of the cordus in the material depends on the amount of handshaking it has to do with electrons, and therefore electrons that are less compliant in one direction than another will affect the passage of the cordus differently. Incidentally, this is further evidence in support of the idea that the hyff are not spherical.

2.2 Brewster's angle

Brewster's angle θ_B is an optical refraction and reflection effect that is dependent on polarisation. For p-polarised light (electric field oscillates in the plane of the incident ray and the normal to the surface), and for given refractive indices n_1 and n_2, there exists an angle of incidence Brewster's angle $\theta_1 = \theta_B$, such that there is no reflection, and all the light is refracted, this angle being $\tan(\theta_B) = \lambda_1/\lambda_2 = n_2/n_1$ where λ is the wavelength in the incident (1) and substrate (2) materials. It is approximately 56^o for light from air to glass. The effect may be derived theoretically using the Fresnel equations of Wave theory. The challenge is to show how the effect occurs with a single photon.

The Cordus interpretation is that the reactive-end is doomed to refract, *whatever* its frequency state C+ or C-. There is an equifinality about the outcome, and the RE cannot reflect. This arises because in these special circumstances of incident angle and refractive indices all loci for reactive-ends are positioned right through the transdermis. Therefore they are too deep to reflect: no subsequent frequency state can recall them back to the first medium. However, that is not to say all loci are co-linear, as will be shown.

Any one reactive-end has numerous loci across an interface, depending on its frequency state at the time. For purposes of illustration we consider the extreme cases of a single RE in either the C+ or C- state, see Figure 3. We define the two extreme loci as <u>defgh</u> and <u>qrstuv</u>. Note that these are for a single reactive-end, nominally termed a1. The a2 reactive-end is not shown here, but the same explanation applies even if it is a different phase at contact.

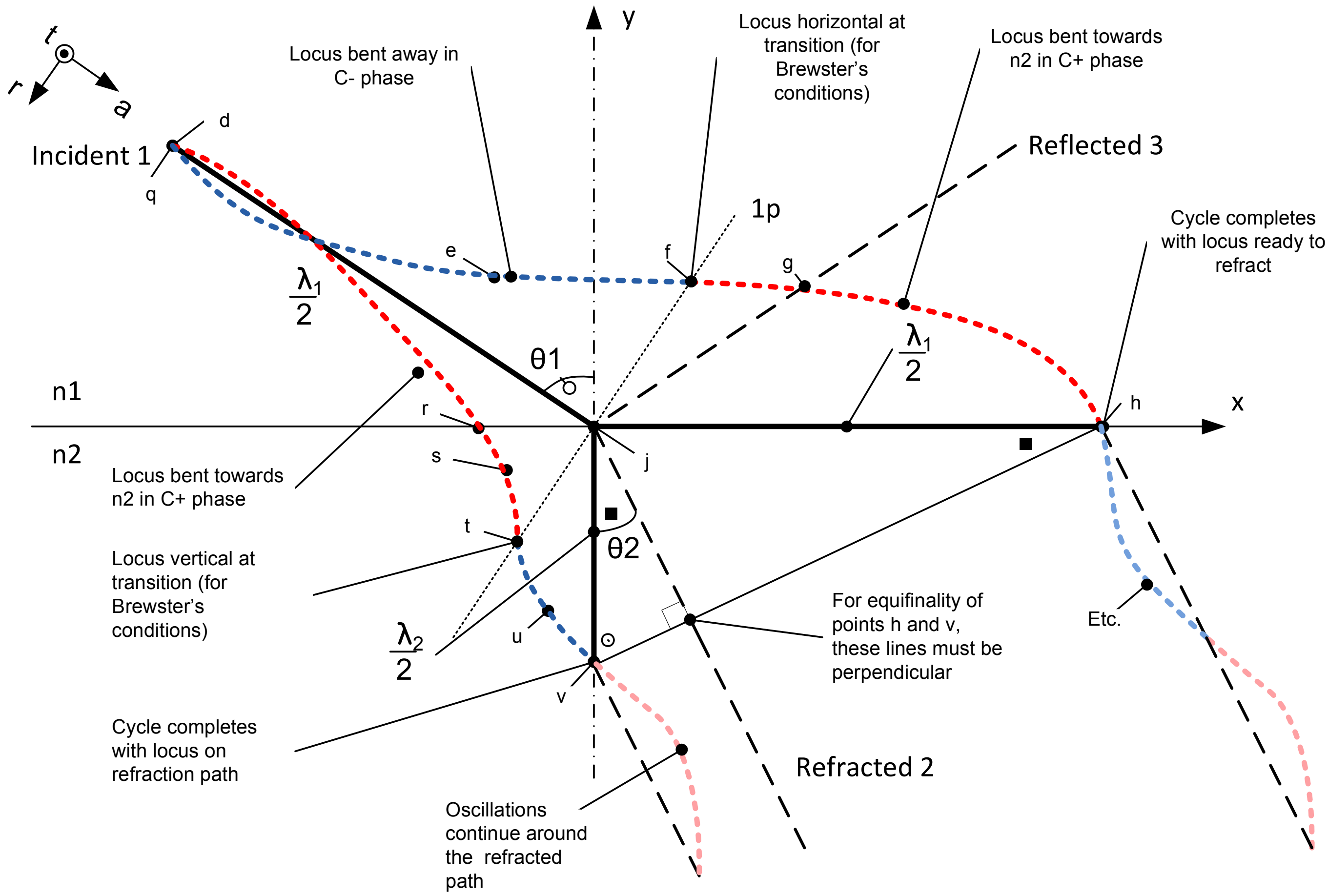

Figure 3: Locus diagram for refraction of a p-polarised photon under Brewster's conditions. The two extreme loci defgh and qrstuv are shown for a single reactive-end, for one frequency cycle. The frequency states C- (blue) and C+ (red) are shown. Also included in this diagram is the simplified path diagram (dark lines), from which Brewster's formula may be derived. Points f and t are on the perpendicular to incident ray 1.

Extreme path defgh: For a reactive-end initially in the C- state the hyff detects the heavier transdermis n_2 before the RE actually encounters it, and moves the RE away, at least initially. By the end of that state the RE is positioned parallel to the interface (f). Thereafter it changes to the C+ state which pulls it in towards the denser material. This puts it onto the refracted path θ_2 at h.

Extreme path qrstuv: For a reactive-end initially in the C+ state the hyff detect the approaching transdermis n_2 and draw the RE into taking a short-cut into material 2. By the end of that state it is positioned in the material

n_2 and heading normal to the surface. Thereafter it changes to a C- state which attempts to undo the changes. However the C- phase cannot bend the path sufficiently to pull it out of the material and back into a reflection path, and instead the RE refracts.

The RE refracts regardless of the frequency state or the locus taken. This is a consequence of the combination of the momentum (direction determined by the incident angle) and strength of the subsequent forces (from the refractive indices). These prevent the RE from completing a reflection manoeuvre. The situation only exists for p-polarisation because any deviation from this orientation would result in forces that were out-of-plane.

Derivation of Brewster's relationship

The above is a qualitative description of the refraction and lack-of-reflection effect at Brewster's angle $\theta_{B.}$ The cordus explanation also provides a way to quantify the relationship, as shown in the Figure. The curved loci are simplified by assuming a small n_2 close to n_1, which makes straight lines of the loci and moves points f and t in to the nominal optical contact point. The result are the lines djh and qjv, shown in dark in Figure 3.

On path qjv the a1 reactive-end travels $\lambda_2/2$ into material 2, along the *normal* to the surface. In the *same time interval* the djh path moves the RE a distance of $\lambda_1/2$ *parallel* to the surface and still in material 1. Subsequently each path is bent to conform to θ_2. The derivation of Brewster's relationship is given in terms of the wavelength λ and the geometry:

- Since the djh and qjv paths have equifinality regarding time, line hv must be perpendicular to the exit trajectory θ_2.
- This allows the angle JHV to be identified as θ_2.
- Thus from triangle JHV it emerges that $\tan(\theta_2) = \lambda_2/\lambda_1 = \sin(\theta_2)/\cos(\theta_2)$ *(Eqn 1)*
- Snell's Law identifies angle JVH as θ_1. The derivation is:
    - Snell's Law: $\mathrm{Sin}(\theta_1) = \lambda_1/\lambda_2.\sin\theta_2$ *(Eqn 2)*
    - Substitute Eqn 1: $\mathrm{Sin}(\theta_1) = \cos(\theta_2)/\sin(\theta_2).\sin\theta_2 = \cos(\theta_2)$
    - Thus $\theta_2 = 90^\circ - \theta_1$
- Thus $\tan(\theta_1) = \lambda_1/\lambda_2 = n_2/n_1$ which is the relationship for Brewster's angle

Note that different REs may take different loci across the surface (O.3.2). Consequently this model predicts a braiding of the loci through material 2. The loci will all be parallel to θ_2 but laterally displaced to various extents within the boundary made by the extreme paths. In addition they have a superimposed sinusoidal lateral wriggle.[8]

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[8] Brewster's angle is interesting for its corollary: At Brewster's angle $\theta_1 = \theta_B$ all light except p-polarised is reflected, AND emerges s-polarised regardless of

Thus Cordus is able to provide qualitative and quantitative explanations of Brewster's angle, for an individual photon. This demonstrates that optical phenomena may be explained by particuloid mechanisms too. However it is not yet a full proof, because it has only been shown for the extreme loci (as per O.3.4) and by simplifying the paths to segments of straight lines. We leave a more complete validation as a future task.

2.3 Mixed reflection and refraction

For transparent surfaces some light is reflected and some refracted (transmitted). The Fresnel equations describe the proportion of light transmitted (2) or reflected (3). The equations are for either p- or s-polarisation. Those for p-polarisation follow. These are more commonly given in terms of refractive index n, whereas here the wavelength λ form is also given.

$$r_{p.3reflect} = \frac{n_1.Cos\theta_2 - n_2.Cos\theta_1}{n_1.Cos\theta_2 + n_2.Cos\theta_1} = \frac{\lambda_2.Cos\theta_2 - \lambda_1.Cos\theta_1}{\lambda_2.Cos\theta_2 + \lambda_1.Cos\theta_1}$$

$$r_{p.2transmitted} = \frac{2n_1.Cos\theta_1}{n_1.Cos\theta_2 + n_2.Cos\theta_1} = \frac{\lambda_2.Cos\theta_1}{\lambda_2.Cos\theta_2 + \lambda_1.Cos\theta_1}$$

The Fresnel equations give the proportions: these depend on the angles of incidence and refraction, and the refractive indices, also the polarisation of the incident light.

The basic principle underpinning the Fresnel equations is that the electric field components in the plane of the interface are continuous, which means the planar-components (hence the Cosθ terms) of the incident (1) plus reflected (3) electric field amplitude equals that of the transmitted (2). Likewise for the magnetic field, which is at right-angles to the electric field. For p- and s-polarisation the electric and magnetic fields hit the interface differently, hence the polarisation effect. However, this explanation does not explain how the path of an individual photon is determined.

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its initial polarisation. The tentative Cordus interpretation for the s-polarised reflected light is that the same Brewster's conditions (θ_1, n2/n1) that provide the p-polarised RE with only sufficient momentum to stall against n2, also means that other polarisations have insufficient momentum to penetrate n2, and only sufficient momentum to get to the minimal reflected state of flat s-polarisation.

Being based on Wave theory, the premise underlying the Fresnel equations is that the incident and exit beams of light exist *at the same time.* Thus that particular explanation cannot be applied to a single photon, which is supposed to exist as a 1D point. The QM solution to *that* problem is to instead model the photon as a wave function in superposition. That has problems of its own, because it is uncertain whether that mathematical solution is really representative of reality. An alternative qualitative description is that the incident light causes surface plasmons (moving electrons) that *later* recombine to form the exit photon.

The cordus explanation is that this depends on the state of the reactive end at the time of impact: those RE in or close to an energised state are reflected, while those that are dormant are refracted (O.4.5).

Phase change revisited

It is useful to consider the mechanism for phase change (see part 2.2) and elaborate. Consider the interaction of the horizontal and vertical components of the hyff force, as it approaches the optical interface. Consider also the mobility of the electrons in that medium, and their response to the photon. There are two cases to consider

Case A: On entry to a denser material, e.g. air to glass, the surface plasmons (electrons) can easily move aside and back again (see O.3.15) in response to the dynamic *horizontal* component of the hyff electric field. Therefore there is no *net* horizontal force applied to the RE (though there are dynamic forces) and hence the horizontal component of momentum of the photon is unhindered.

However the vertical mobility of electrons in the transdermis bulk is limited because doing so would build up electrostatic force resisting further electron transport. Therefore the *normal* component of the hyff electric field is either resisted by the n_2 transdermis and the RE reflects back into n_1, or is attracted into n_2 the case of refraction.

The outcome depends on the frequency state at the time (O.4.5) i.e. a net dominance of the C- state gives reflection and C+ results in refraction. In addition, the angle of incidence provides the direction of initial momentum, so low angle θ_1 (steep incidence) tends to predispose towards the photon continuing straight ahead, which is refraction. With steep incidence, a large amount of vertical force impulse is required to turn the reactive end around and reflect it. This does not happen often, not because the n_2 substrate is unable to provide the reaction, but because it is sensitive to the timing of the frequency: if the reactive end changes back to C+ before completing the reflection manoeuvre then refraction will take over.

Case B: For a photon approaching a less dense medium, e.g. glass to air, internal reflection is the favoured outcome and occurs becomes the exclusive outcome when the angle of incidence exceeds the critical angle,

$\theta_1 > \theta_c$. Consider a photon in denser n_1 and approaching an interface. While the photon has been deep in n_1 the plasmon (electron) transport mechanisms are fully mobile in both the horizontal and normal directions (actually the radial and axial). However, as the photon approaches the air interface, the *horizontal* transport mechanisms are still fine, but the *normal* transport becomes increasingly ineffective. An ineffective plasmon transport mechanism means that the material exerts forces on the reactive end (O.4.8.2). Therefore the horizontal momentum of the photon is not impeded, but the normal is. The denser material is at n_1 which thus provides the greater force on balance, so the RE tends to be pulled back into n_1 and reflection. At shallower incidences than the critical angle, the momentum is sufficient to ensure reflection regardless of the frequency state.

We acknowledge that this is only a descriptive explanation, not a quantitative one, of mixed reflection and refraction. The full derivation of the Fresnel equations from a cordus basis is an open question. In addition polarisation in reflection and refraction looks to be an area of further investigation and potentially deeper insights.

3 Discussion

Explaining basic optical effects is not possible with classical particle mechanics, and even with quantum mechanics it is not straight forward and not particularly intuitive. The problem is much simpler when solved in the cordus domain, as this paper shows for several cases of refraction. Both Snell's Law and Brewster's Angle are explained and quantitative derivations provided. This is significant because the cordus mechanics were derived for *single photons*, and immediately generalise also to beams of light. Therefore a single mechanism can explain both particle and wave behaviour, which is otherwise difficult to achieve. This becomes even more significant when considering that the same cordus concept can also explain the path dilemmas and fringes of *individual* photons in the double slit device. Cordus is therefore one of only a few concepts that can explain the double slit device as well as conventional optics. We do not dispute that quantum mechanics can do much of this, but that cordus does it without resorting to metaphysical effects is unique. Note also that the cordus explanation does not need the conventional concept of 'interference'.

All the same, we do emphasise that cordus is a *conceptual* solution, and while it has been thought-tested against several physical phenomena, it has not been checked against all. Furthermore, it is based on intuition and conjecture, and makes many assumptions (lemmas) that have yet to be tested. There are many open questions still, the Fresnel equations being one.

Contrast: Cordus and EM Wave theory

EM wave theory is the dominant way of thinking for explaining optical effects, including interference patterns. It has tacit lemmas of its own: e.g. that light is a disturbance in the electromagnetic field. It relies heavily on the concept of frequency, particularly that a half wave-length ($\lambda/2$) shift will cause destructive interference. As a theory it is enormously successful. Even single photons show interference patterns and by implication 'must be' a wave, hence the wave-function concept in quantum mechanics.

However wave theory has some limitations: the origins of frequency are mysterious; it does not explain the quantum effects of single photons; and destructive interference implies destruction of energy.

If the Cordus Conjecture is correct, wave theory is a convenient mathematical representation of the external behaviour of light en masse, but not of the internal variables. Light itself is not simply an EM wave: that is only the physical manifestation of the passage of hyff. The internal dynamics of the cordus give rise to the externally visible EM fields: the fields are not the entire existence. Another areas where the perspectives differ is the interpretation of amplitude (brightness): Wave theory perceives amplitude to be the strength of the EM field. The Cordus Conjecture perceives amplitude to be only the cumulative effect of multiple cordi that are in a similar location at about the same time: an *en masse* effect.

The Cordus Conjecture suggests that wave theory is an appropriate method for modelling photons, with two caveats: it applies to light in transit; and to light en masse (not single photons).

Conclusion

This paper shows that optical effects can also be explained as the interaction of cordus photon with the optical surface and the substrate. Thus Wave theory is not the only way of conceptualising effects like reflection and refraction.

The conceptual contribution of this bracket of papers is first the creation of a novel theoretical model for the internal structure of the photon and the origins of frequency. This model is useful in later work, where it is generalised to matter particuloids and provides foundational material for a description of the strong force and the internal structure of the proton.

The second is the evidence, at least at a conceptual level, that the cordus conceptual framework is able to explain conventional optical effects. This is significant, because the same framework has separately provided a resolution of wave-particle duality in the double-slit device (ref. 'Cordus conjecture'), and can explain various matter effects that are normally the preserve of Quantum mechanics (ref. 'Cordus matter'). Thus cordus offers a novel mechanics with a high degree of logical consistency across these various effects.