1

Introduction

To become a good optical designer for illumination applications, an engineer must acquire a very specific set of technical skills: he or she must understand the underlying theory, must know the toolbox of optical elements and know how to combine them, and must be a proficient user of (at least one) optical design software. In addition to reading books, experiencing projects, and learning from senior colleagues, as an engineer on your way to expanding your skills, you must also think through problems on your own, use your own mind, stumble over obstacles, and find your way to a solution – all by yourself. This may be hard, sometimes exhausting or even embarrassing. However, solving problems by yourself is an indispensable part of the journey.

For an introduction to approaches, processes and methods, we recommend our book *Designing Illumination Optics* [1]. In addition, we are also planning to publish a tutorial with the tentative title *Design Elements of Illumination Optics* intended to help readers to understand the function and design parameters of individual optical elements. Other books that we find useful and frequently consult ourselves are Julio Chaves’ *Introduction to Nonimaging Optics* [2] for the nonimaging part of illumination optics, Michael Kidger’s two books on *Fundamental* and *Intermediate Optical Design* [3, 4] for the imaging aspects, the SPIE *Field Guide on Illumination* [5] for short, concise definitions, and John Koshel’s great edition of selected chapters on *Illumination Engineering* [6].

The book you hold in your hands is the result of our own continuing journey and has its roots in a large number of live and online training courses we held over the years. Hence, the book contains a curated selection of exercises and problems, inspired by real problems we faced and the solutions of which we found instructive. Our goal was to touch upon numerous facets and fields of illumination design such as lighting design [7], imaging optics (e.g. to calculate image brightness [8, 9]), medical optics [10] or horticulture [11], to name just a few examples.

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1.1 Goals, or How to Use This Book

This text is a technical book aimed at professionals from many fields who want to dive deeper into optics or, specifically, practical illumination design. It is a collection of knowledge – much of it in terms of formulas – but it is *not* a textbook. Rather, it is intended as a *resource* and a *guide* for the many lateral entrants to the field of illumination optics as well as for those studying optics theory, optical design, and the function of optical elements or struggling to understand the details and inner workings of an optical design software. While the book does follow a story line (as laid out in Section 1.2), it is perfectly fine to scan the lists of exercises, knowledge items and simulations provided throughout the text and to jump back and forth between places of particular interest to you.

This book's primary goal is to let you learn by studying typical problems, solving them by yourself. We provide solutions to all exercises, but **we strongly encourage you to *not* peek ahead** to the solution before trying really hard to think through the problem yourself. What is printed in this book is mere *information*, but the ultimate goal is to build *knowledge*. Information is the score, but knowledge is the music [12]. It takes hard work, and time, to learn how to play.

On the way, we aim to expand your theoretical knowledge, to acquaint you with illumination laws and quantities, and to develop your intuitive feeling for units and numbers. You will expand your understanding of the laws by applying them repeatedly. After completing the exercises in this book, you will be able to deal with a wide variety of situations and to apply the appropriate fundamental laws with confidence.

Since this book is a practical guide and not a textbook, many basic laws are presented without proof (but with appropriate citations). We do not aim to replace a university course: we are simply showing the way toward solutions and designs, trying to adequately balance the level of detail to avoid overwhelming one half of the readers while boring the other half.

Designing good illumination optical systems requires creative thinking, juggling, combining and (rarely) inventing optical elements. But still quite early in the process, this creative thinking must be guided and fenced in by numbers that result from calculations. This book deals with the calculation part. In illumination optics, simple calculations can often be of great help to guide the optical designer. We aim to show you how. Always calculate before you embark on specific design work. If you fail to do this, you will likely end up with inefficient solutions (while not knowing they are inefficient) or failed attempts to violate fundamental laws (not knowing why you failed). Accordingly, this book also serves as a handbook of illumination *pre-design*.

Some books try to avoid formulas ("each formula will cut your number of readers in half", as the saying goes) and explain topics merely by pictures and descriptions. Such a presentation style, i.e. a style that invokes the readers' visualization capabilities, is very helpful to understand how things work *in principle*. However, solving specific engineering problems also requires skill and experience in using formulas and numbers. An engineer must be able to perform precise calculations, often with the help of computers. However, such calculations are always prone to errors.

To avoid such errors, we found two approaches extremely beneficial in our work as optical designers. First, it is useful to develop some skill in "keeping a mental tab" on results by using approximations, quick estimates and mental arithmetic to

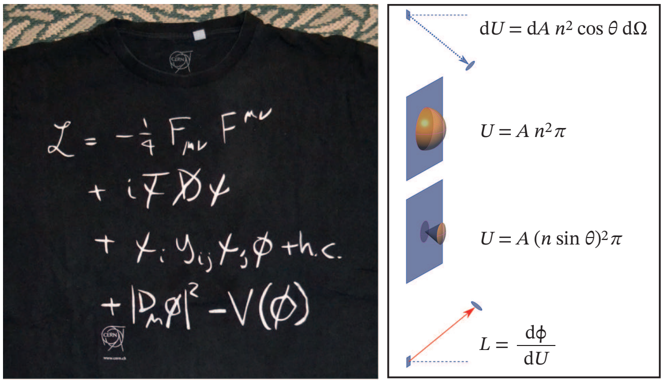

Figure 1.1 Left: Lagrange density with bosonic and fermionic parts and the Higgs field, on a T-shirt from CERN. Right: Important formulas for etendue and radiance.

judge whether a result can be correct. The most dangerous results are just a little too good to be true! Second, simulations may help. Ray tracing software just traces the propagation of rays, knowing nothing about our beautiful calculations, and this is exactly what we want: Confirmation or refutation by an independent referee.

This is the reason why this book introduces and discusses all topics with the help of many (really many!) calculations.[1]

To help you develop the "third eye" that comes with mental tab-keeping, we present many formulas that are simple enough to be used regularly (in contrast to, e.g. the world formula on the left side of Figure 1.1, which includes everything but is quite impossible to apply to daily work), but still profound enough to guide you in the world of illumination optics (e.g. the etendue and radiance formulas on the right side of Figure 1.1).

Talking about a "third eye": It is generally not easy to visualize the flow of light in an optical system just by looking at it from the outside. One approach for helping ourselves in this regard is to think of ourselves as being tiny – just a few μm –, but endowed with superpowers: We are able to fly, neither extreme temperatures nor immense radiation doses afflict us, we can swim through glass like it was water, and we have keen hyperspectral eyes with a sense for quantitatively correct radiometric values. Thus endowed, we take a mental virtual tour through the optical system and imagine what we see when the book, employing our "Lightman" character (see Section 1.4).

You will learn that many parameters of commercial light sources and luminaires can be calculated with some knowledge of the source at hand and a basic knowledge of the optics inside. *Vice versa*, you will learn how to interpret datasheet values, to fill the gaps in the datasheets, and to derive information about components and technologies.

Occasionally, we feel puzzled by little inconsistencies that are commonly glossed over. For example, we all (should) know that according to the celebrated inverse square law, irradiance E (flux per area) and intensity I (flux per solid angle) are related by $E = I/r^2$, where r is the distance of the irradiance sensor to a point-

1 As Henning's high school math teacher Dr. Schiemann put it: "Formeln sind klüger als Menschen" (Formulas are smarter than people).

like source, toward which it is oriented. But what about the units? I is measured in W/sr. Therefore, I/r^2 would be measured in W/m^2 sr (which would be the physical unit of radiance L – which is not applicable here), whereas the physical units of irradiance E must be W/m^2. We will reveal the mystery of the appearing and disappearing solid angle unit sr during the discussion of the *spherical excess* (Eq. 2.26), and we make it a somewhat unconventional habit to write, for example, 4π sr as opposed to $4r^2\pi$ when we mean solid angle (and not surface area!) of a sphere. Similar puzzles will be solved at appropriate places.

In summary: To become a proficient illumination optics designer, you will have to get your feet wet with formulas and calculations. Let's leave the beach and go swimming!

In illumination optics, many important properties of your systems can be calculated, and we show how to achieve this. Sometimes, you can analytically derive results such as a light distribution to an incredible degree of correspondence to the simulation (cf. Exercise 3.13 and Simulation 3.6). In other cases, you need the help of a spreadsheet or a Python/Matlab®/Mathematica® notebook.

Calculations are complemented by simulations – both are indispensable. We routinely use simple ray tracing simulations to test and (hopefully!) confirm our calculations (a habit we strongly recommend!), and we use ray tracing simulations of more complex systems in situations where calculations are too hard to apply (you will find many examples of this in the book, e.g. in Simulation 3.3). This book should help you to develop a feeling to distinguish those cases.

1.2 Structure

This book presents a colorful mixture of knowledge and formulas from various parts of optics that play a role in illumination. We begin by introducing some basics of optics and geometry that are crucial for proper handling of design tasks. We then introduce various aspects of phase space mathematics and etendue, fill phase space with light (radiometry), and extend the calculus to spectral concepts and colorimetry as far as needed for illumination problems.

At this point, you should be well prepared for the subsequent "practical" chapters. There, we consider ideal and real light sources, discuss lighting situations for various purposes, and evaluate how various quantities evolve as light propagates in optical systems. In the final chapter, we will demonstrate how to lay the groundwork for conceptual design, how to extract information from product sheets and how to select suitable light sources for various applications.

Sometimes, it is not obvious into which category (practice or design) a topic should fall. And since things are inevitably connected with each other, it is sometimes impossible to arrange topics in a linear sequence. In such cases we tried to ensure narrative continuity and we hope that our frequent cross-references may help.

1.2.1 Exercises and Solutions

Exercises play a central role in our approach. In our classroom and online courses, we found that exercises are crucial: Attendees are easily persuaded that something is so and so, but only when they apply the freshly presented information to actual problems, they convince themselves that it is indeed true. Their feedback told us time and again that exercises are particularly effective in converting information to knowledge, teaching us to transfer what we learned in an exercise to similar, but different, situations in real life. Accordingly, we greatly expand the selection of course exercises in this book.

Frequent insets about theory, formulas, simulation examples, and of course detailed solutions complement the exercise problems.

We teach technical content as a spin-off of the actual problem solving (see below for simulations and visits to the Knowledge Corner café). In many instances, we provide auxiliary materials, such as spreadsheet and optical simulation files for download, both with a clickable link for the electronic version of this book, and a corresponding QR code in the margin for using a mobile device with the paper version of this book.

Each exercise problem is described in an *Exercise* box:

Exercise 1.1: Snell's law applied to the mirage phenomenon

When looking along a hot summer road, we can sometimes see the sky above the horizon reflected by the road below, creating the illusion of water puddles; this phenomenon is known as a *mirage* (Figure 1.2).

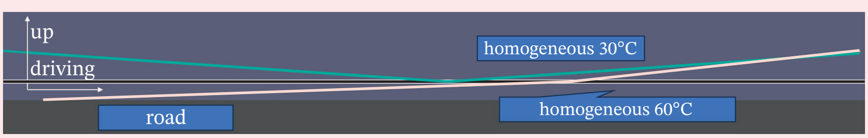

Figure 1.2 Top: A Highway Mirage – the road appears wet, caused by a layer of hot air above the road surface that leads to a redirection of rays by total internal reflection (TIR). The slightly irregular density profile of the hot air layer causes the wavy distortion of the mirror image. *Source:* Yuri Khristich/Wikimedia Commons/Public Domain. Bottom: A simplified model of the hot air layer in a cross section along the driving direction, here represented by two homogeneous layers of air with a sharp boundary between them. The orange ray from the right is refracted into the hotter layer and eventually absorbed by the road; the green ray with a direction slightly closer to the road suffers total internal reflection at the same interface. The image shows rays with higher angles and layers with larger index differences than for real air; otherwise, the angles could not be discerned in this image.

(Continued)

Exercise 1.1: (Continued)

Assume that a thin planar layer of air above a perfectly horizontal hot road has a temperature of 60 °C, with a sudden sharp transition to a temperature of 30 °C above, and that the air has a refractive index of $n_{\text{air},0\,°\text{C}} = 1.000293$ at 0 °C. Further assume that the refractive index n of air depends on its density ϱ as $n^2 - 1 = \text{const} \cdot \varrho$, and that the air is an ideal gas ($\varrho = \text{const}/T$ with absolute temperature T).

Since the hotter air has a slightly lower refractive index than the colder air above, total internal reflection can occur at the interface between the layers at large incidence angles, causing the mirage phenomenon.

Compute the critical angle for total internal reflection.

Most exercises are immediately followed by their *Solution*, often followed by a comment or advice providing additional information.

Solution 1.1:

First, we calculate the densities of air at 30 °C and 60 °C relative to that at 0 °C = 273.15 K:

$$\varrho_{\text{rel, 30 °C}} = \frac{0 + 273.15}{30 + 273.15} = 0.9010$$

$$\varrho_{\text{rel, 60 °C,rel}} = \frac{0 + 273.15}{60 + 273.15} = 0.8199$$

Next, we calculate $n^2 - 1$ for all three temperatures:

$$n_{0\,°\text{C}} = 1.000293$$

$$n^2_{0\,°\text{C}} - 1 = 5.8609 \cdot 10^{-4}$$

$$n^2_{30\,°\text{C}} - 1 = (n^2_{0\,°\text{C}} - 1) \cdot \varrho_{\text{rel, 30 °C}} = 5.2809 \cdot 10^{-4}$$

$$n^2_{60\,°\text{C}} - 1 = (n^2_{0\,°\text{C}} - 1) \cdot \varrho_{\text{rel, 60 °C}} = 4.8053 \cdot 10^{-4}$$

These equations can be solved for the refractive indices:

$$n_{30\,°\text{C}} = \sqrt{1 + 5.2809 \cdot 10^{-4}} = 1.0002640$$

$$n_{60\,°\text{C}} = \sqrt{1 + 4.8053 \cdot 10^{-4}} = 1.0002402$$

The critical "mirage angle" is then:

$$\alpha_{\text{mirage}} = \arcsin\left(\frac{n_{60\,°\text{C}}}{n_{30\,°\text{C}}}\right) = 89.605°$$

You might as well get advice from experienced teachers (which will be introduced shortly, see Section 1.4) in special advice sections such as this one:

Dr. Wisenheimer:
I am aware that the authors did not introduce me and my cousins yet, but I still want to say: Try a web search for the term “mirage ship”! You will be presented a huge number of reports and photos of “hovering” ships.
And check out Les différents types de mirage.

1.2.2 Insights from the Knowledge Corner Café

In our daily professional lives, we keep encountering interesting questions to which we would like to find answers, such as “Where is this index of refraction coming from?” We just love to think such questions through, very often with help from the literature. Or, we might go to our favorite corner café to read a science book (yes, we are indeed nerdy enough to do that!) and discuss it with a friend. In this book, we call this place the “Knowledge Corner” science café (Figure 1.3).

From time to time, when such a question arises, we will invite you to follow us to the Knowledge Corner café for a discussion. There, we will introduce useful facts, theories – and occasionally trivia as well. Since this book is not a university course textbook, we do not even attempt to give full explanations or proofs; the Knowledge Corner conversations are intended to present information in a succinct, (hopefully) easy-to-understand way. We do, however, add many citations for further study.

Exercise 1.1, for example, uses a certain relation between density and refractive index that turns out to be quite useful for environmental tolerancing.

Figure 1.3 Our Knowledge Corner science café.

Knowledge Corner Topic 1.1: Lorenz–Lorentz equation

One way to understand the refractive index is by coherent scattering: The incoming electromagnetic disturbance makes polarizable atoms and molecules oscillate and therefore radiate with a phase delay. For refractive media such as glass or air, the superposition of all these dipole radiations with the incoming wave will result in a "drag", slowing the incoming wave down and thus shortening its wavelength [13]. Coherence ensures that in a homogeneous, isotropic, and linear medium (a so-called HIL medium), these dipole radiations have a combined effect only in the direction of propagation, while scattering to the side is suppressed by destructive interference. (Rayleigh scattering in air, which is responsible for the blue sky, is different because of the random density fluctuations in air that are absent in glass). If a material expands thermally, reducing its density but leaving the molecular structure unchanged, there will be fewer dipoles per volume and the refractive index n will decrease with density ϱ.

A detailed analysis [13] shows that

$$\frac{n^2 - 1}{n^2 + 2} = \text{const} \cdot \varrho \tag{1.1}$$

This relation is known as the Lorenz–Lorentz equation, named after Ludvig Lorenz and Hendrik Lorentz, who discovered it around 1870. For gases, the change of the numerator is negligible compared to the change of the denominator so that the relation $n^2 - 1 = \text{const} \cdot \varrho$ holds. For glasses and plastics, however, the full Lorenz–Lorentz relation from Eq. 1.1 should be used. The relation is valid for each wavelength individually. When the full dispersion curve $n(\lambda)$ is known for one temperature, the Lorenz–Lorentz equation gives us dispersion curves for a whole temperature range.

Why is this relation important for illumination optics? The reason is that particularly for plastics and silicones, the thermal expansion is so substantial that it cannot be neglected in many cases; one needs to take into account both the thermal shape change and the thermal refractive index change. However, while the refractive index at some standard wavelength and temperature is often known from datasheets, as well as the coefficient of thermal expansion (CTE), the refractive index as a function of temperature is rarely published. In such cases, the Lorenz–Lorentz equation is a good (and probably the only practical) way to calculate the refractive index at varying temperatures. However, beware of two pitfalls: (i) The CTE is sometimes listed as linear CTE and sometimes as volume CTE. We need the volume CTE here, which is three times the linear CTE (why three times? – Think about it!). (ii) The molecular polarizability changes at phase transitions – even phase transitions of higher order – such as, e.g., the glass transition of thermoplastics. This fact has been used to determine precise transition temperatures from refractive index measurements [14, 15]. Accordingly, you should make sure that no phase transition occurs in your temperature range: Apply the Lorenz–Lorentz equation only with great care when approaching, for example, the softening temperature of a thermoplastic.

Simulations often give additional insights beyond the mathematical results. For this mirage example, the sudden temperature change above the road is a crude, yet surprisingly valid model of the true, gradual temperature distribution. We show a gradient-index (GRIN) ray tracing simulation in a *Simulation* box, accompanied by further discussion and insights.

Simulation 1.1: GRIN ray trace

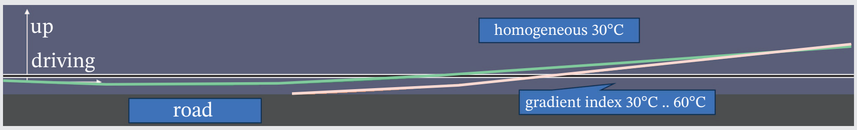

Figure 1.4 A similar simulation as in Figure 1.2, but now with a gradient-index layer. The same orange ray eventually hits the road; the same green ray enters into the GRIN layer, but returns eventually back up. The simulation file is provided here.

In reality, the air above the road should be described as a gradient-index (GRIN) material, since there is a temperature gradient, not a sudden temperature step. In Figure 1.4, the green ray enters the gradient-index section at a grazing incidence angle that would fulfil the condition for total internal reflection; it is bending its way back into the homogeneous air. The orange ray with a steeper incidence angle is also bending back, but not enough to avoid being absorbed (or scattered) by the road surface. To visualize the effect in this real ray trace with a linear GRIN profile, the rays are much steeper and the index gradient is much stronger than in the exercise; in the exercise situation, the rays travel quite long in the gradient layer before returning back, too long to show here.

Bonus question: As long as the temperature gradient and thus the index gradient is strictly vertical, so that you can think of the GRIN air as being composed of many thin planar parallel layers, but still with a minimum of 30 °C on top and a maximum of 60 °C at the bottom, do the details of the index profile influence whether the ray hits the road or is bending back into air, creating a mirage? The answer is no – the distribution details only influence the lateral shift and the precise path of bending, but not whether a ray hits the road or not, and also not its final angle back into homogeneous air. But why? To answer, apply Snell's law in the form of $n_i \sin\theta_i = n_{i+1} \sin\theta_{i+1}$ (Eq. 2.44) repeatedly for each interface. This result also tells you how the idea of using a multilayer coating to avoid TIR fails in terms of geometrical optics.

(The LightTools system file is available here.)

Besides a host of accompanying online materials, and eventually a list of errata, we provide supporting files (helpful or necessary for the solution) for download from our Illumination Optics website. We expect to add (hopefully much) additional material there in the coming months and years, beyond what we directly link to in this book. This is because sometimes it is adequate to use a spreadsheet or a Python notebook for numerical evaluation of a derived formula. We will also maintain a (hopefully short) list of errata there.

Finally, this book contains many useful links, which is adequate for an e-book, but also carries the risk of expiring content. We will try to add each link to the Wayback machine, to mitigate the expiring content issue at least to some degree. We apologize if some links may not be working anymore at a later date, and may provide updates on illuminationoptics.net.

We provide mainly LightTools® files for the simulations, apologizing to the users of ASAP®, CODE V®, FRED®, KostaCLOUD®, LucidShape®, OSLO®, Photopia®, Quadoa®, RayJack ONE®and other software packages. However, perhaps you accept the challenge and set the systems up your way.

For some simulations, you may need some ray files and download them yourself.

1.3 Quick Estimates

As we already mentioned in Section 1.1, we find it extremely useful to be able to keep a "mental tab" on results, to develop and nurture your ability to tell quickly if some quantitative statement may be correct or not. Again, the most dangerous results are just a little too good to be true, but still wrong. Quick estimates are the key. If possible, do them in your head, without a computer. This requires experience and mental arithmetic practice, but it allows you to follow the discussion, and it trains the "muscle".

Some quick estimates are useful, but dangerous – "dirty tricks" of the do-not-try-this-at-home variety: Rotational symmetry, for example, simplifies things greatly, but alas – square LED chips are not rotationally symmetric. As long as you know what you are doing, simply assuming rotational symmetry for the moment, and then taking "a quarter more" of the result will get you very close (actually, you need to multiply the result with the square-to-circle area ratio $4/\pi$, but $4/\pi \approx 1.273239 \approx 1.25 = 1 + 1/4$). We will tag such foolhardy approximations with a 

sticker. While you develop such skills, it is a good idea to later simulate [16] the actual case and compare with your quick and dirty estimate.

Other quick estimates are beautifully simple, yet precise, for example the etendue of a telecentric, round beam, $U = A\,(n\ \sin\alpha)^2\pi$ sr (see Section 3.2). Many *specific* quick estimate formulas will appear in the exercises, solutions and knowledge boxes. Here in the introduction, we would like to introduce a few general quick estimate *techniques*.

Knowledge Corner Topic 1.2: Big *O* calculus

When dealing with the effects of small relative changes, big O calculus, also known as "big O notation", is very useful [17]. The idea is to approximate a complicated function $f(x)$ in a small region $x \approx x_0$ by a simple function $g(x)$ such that (i) $g(x_0) = f(x_0)$ and (ii) the approximation error $g(x) - f(x)$ vanishes faster than $x - x_0$. The small-angle approximation ($\alpha \approx \sin\alpha \approx \tan\alpha$, see Knowledge Corner Topic 2.3) is one example of this technique.

Another example: Recall the discussion of volume vs. linear coefficient of thermal expansion (CTE) in Knowledge Corner Topic 1.1, where we stated that the volume CTE_V equals three times the linear CTE_l. How did we know? Let us consider a cube at temperature T_0 with side lengths l_0 and thus volume $V_0 = l_0^3$, made of a material with known CTE_l. Then, by definition,

$$\begin{aligned} l(T_0 + \Delta T) &= l_0(1 + \Delta T \cdot \text{CTE}_l) \\ V(T_0 + \Delta T) &= V_0(1 + \Delta T \cdot \text{CTE}_V) \end{aligned} \tag{1.2}$$

By expanding $V = l^3$ and setting $\varepsilon = \Delta T \cdot \text{CTE}_l$, we obtain

$$\begin{aligned} V(T_0 + \Delta T) &= (l(T_0 + \Delta T))^3 = l_0^3(1 + \varepsilon)^3 \\ &= V_0(1 + 3\varepsilon + 3\varepsilon^2 + \varepsilon^3) \\ &= V_0(1 + 3\varepsilon + O(\varepsilon^2)) \\ &\approx V_0(1 + 3\varepsilon) \end{aligned} \tag{1.3}$$

from which we see that $3\varepsilon = 3\,\text{CTE}_l \Delta T = \text{CTE}_V \Delta T$. Done!

More formally, "vanishing faster than ..." means to take a smooth function of a small quantity ε, to consider its Taylor expansion $\sum_{i=0}^{\infty} a_i \varepsilon^i$, and to ignore higher order terms, $O(n) = \sum_{i=n}^{\infty} a_i \varepsilon^i$, retaining only terms with $i < n$. In our case, we used $n = 2$, the most common choice, often called "linearizing around x_0."

Yet another example is

$$\sqrt{x_0 + \varepsilon} = \sqrt{x_0} + \frac{1}{2\sqrt{x_0}}\varepsilon - \frac{1}{8\sqrt{x_0^3}}\varepsilon^2 + O(\varepsilon^3) \tag{1.4}$$

The approximation

$$\sqrt{x_0 + \varepsilon} \approx \sqrt{x_0} + \frac{1}{2\sqrt{x_0}}\varepsilon \tag{1.5}$$

is extensively used in Knowledge Corner Topic 3.8.

Knowledge Corner Topic 1.3: Rounding, or how much precision is just right?

Most quick estimates are not entirely accurate. On the other hand, it is just as wrong to report a luminous flux of 12.46295 lm. To quote Jimmy Efird [18]:

> Rounding is a compromise strategy that involves replacing a true or more accurate value with one having less accuracy. The intent is to preserve the meaning and interpretation of the original result. It represents a balance between reporting too few significant digits and losing information versus failing to achieve parsimony (i.e. retaining too many inessential digits). In some cases, the numbers are rounded beyond the capacity of the

(Continued)

Knowledge Corner Topic 1.3: (Continued)

measurement device (spurious accuracy) or practical aspects of the problem at hand. The degree of rounding imposed in a situation depends on the desired accuracy and precision of the result. Additionally important is the need to minimize the error that may accumulate when performing complex computations on rounded values. Such sequential operations can lead to ill-conditioned and inaccurate findings.

In illumination optics, we mostly consider radiometric values such as flux, radiance, illuminance etc. It is extremely difficult, and often just not practical, to achieve a precision of 1 % in measurements! During production, LEDs are individually measured and then sorted into bins, such that LEDs with similar electro-optical properties are packed together. In a typical brightness bin, flux may vary by about 15 % from min to max. On top of this variation comes the measurement uncertainty during binning: In many of their LED data sheets, ams-OSRAM states: "Brightness values are measured ... with a tolerance of ±7 %". This uncertainty may appear large, but it is actually an achievement. Billions of LEDs must be binned each year, using many spectrometers, which are calibrated in a cascaded process against (ultimately!) a calibration standard lamp, which itself comes from national standardization institutes with uncertainties of about 1 %. And then, LED flux varies with current and temperature, neither of which are perfectly controlled in most applications.

Similar considerations apply to other light sources. We have seen a reflectorized Xenon discharge lamp, specified with "aperture lumens min. 1400 lm, max. 2300 lm".

In our experience, reporting radiometric values and etendue values with 1 % accuracy, wavelength values with 1 nm accuracy, and CIE x/y color coordinates with 0.001 accuracy is a good compromise: more precise than what can be measured, but allowing just enough additional precision for complex computations performed on rounded values.

1.4 Introducing the Wisenheimers

We have enlisted the assistance of four members of the international Wisenheimer family clan of scientists (Figure 1.5): Dr. Mary Wisenheimer, Dr. Linda Wisenheimer, Dr. John Wisenheimer, and Dr. Thomas Wisenheimer (left to right). (You have already experienced Dr. Mary Wisenheimer commenting on mirage images.) Their comments are always correct and helpful, but sometimes a little bit over the top, we're afraid.

From time to time, three other special characters will chime in as well (Figure 1.6):

First, we introduce Rube, a very kind but slightly confused inventor, kind of a Gyro Gearloose character. He will introduce what he thinks are bright ideas, but he lacks some respect for the fundamentals and gets carried away quite easily.

Figure 1.5 The Wisenheimers giving unsolicited advice.

Figure 1.6 Rube, the mad inventor, Ike, the stern boss, and the Lightman (from left to right).

Then there is Ike, a stern boss ruling the engineering department and single-handedly negotiating specifications with customers, while being oblivious to both the needs of his staff and the laws of nature. Similarities to a certain pointy-haired comic character are of course purely coincidental.

And finally, we sometimes call the Lightman for help when we don't understand how the light flows through a particular optic system. Lightman is really small, but he has superpowers: He can fly, even the highest temperatures and radiation doses do not affect him, he can swim through glass like a fish through through water, and he has keen hyperspectral eyes with a sense for quantitatively correct radiometric values.

Characters were produced by the authors using Stable Diffusion text to image AI.

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