Electro-Optical System Analysis and Design

A Radiometry Perspective

SPIE PM236

Errata & Clarifications for First Printing

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Book website

The book states that you can find a supporting computational radiometry toolkit/library on Google Code. However, Google decided to close down Google Code. The pyradi library is now hosted at GitHub. The new urls since March 2015 are now:
pyradi source:
`https://github.com/NelisW/pyradi`.
pyradi documentation:
`http://nelisw.github.io/pyradi-docs/_build/html/index.html`.
pyradi docs repo:
`https://github.com/NelisW/pyradi-docs/tree/gh-pages`.

The pyradi library is also available on PyPI at
`https://pypi.python.org/pypi/pyradi`.
There are also a number of IPython notebooks demonstrating the use of the pyradi toolkit, at:
`https://github.com/NelisW/ComputationalRadiometry`.
Scroll down the website page to find links to HTML page renderings of the notebooks.

Chapter 1

1. Readers may find the new material given on pages 10 and 14 of this document of value.

Chapter 2

1. Page 21, Figure 2.1: change from ‘terrahertz’ to ‘terahertz’.

2. Page 22, fourth line: change 'force carrier' to 'energy carrier'.

3. Page 22, second paragraph: A reader of the first printing challenged the concept of the photon as a localized electromagnetic disturbance. Theoretical physicists still argue the exact nature of the photon as a particle. Replace the paragraph with the following if you are comfortable with these views:

   The photon (particle) nature of light is still shrouded in enigmatic mystery[1–6] more than a hundred years after its 'discovery'. The *photon*[7] is an elementary particle (massless at rest[4]) that models the energy in the electromagnetic wave. Photon particles have discrete energy quanta proportional to the frequency of the electromagnetic energy, $Q = h\nu = hc/\lambda$, where h is Planck's constant. Considering photon detection (Section 5.6), it is convenient to think of a photon as a spatially limited electromagnetic disturbance (a wave packet) propagating through space — but there are mixed views on this.[3,5] One limitation of the particle view is best illustrated by the question: "How does a single particle pass through both slits of a Young two-slit experiment?" Richard Feynman's answer[5] is "nobody knows and perhaps it is best if you try not to think of it." A similar problem[3] arises when a photon reaches a beam splitter: "Which half of the photon is reflected?" Perhaps the only 'safe' view is to consider the photon model as (1) an energy discretization concept, and (2) collections of *many* particles during creation in the source (Section 3.1) and in disappearance during absorption (Section 5.5.8), but not in between as a means of electromagnetic energy propagation.[2] In this book the photon is often graphically illustrated with the symbol shown in Figure 2.2(b). The figure also shows an artist's impression of the photon as a wave packet.

4. Page 24, Figure 2.3: In subfigure (d) the equation $L = \frac{d^2\Phi}{dAd\cos\theta\omega}$ must read $L = \frac{d^2\Phi}{dA\cos\theta d\omega}$.

5. Page 35, Section 2.6.1: the argument given does not fully prove conservation of radiance. Consider first the flux flowing between A_0 and A_1 as shown in the book, leading to the observation that the radiance L_{01} (from A_0 towards A_1) is the same as the radiance L_{10} (from A_1 towards A_0). Next construct a new surface A_2 and repeat the above argument to show that $L_{02} = L_{20}$. From the definition of a Lambertian surface, $L_{01} = L_{02}$, and hence $L_{10} = L_{20}$ proving by induction that radiance is conserved for a field created by a Lambertian source, for any arbitrary location of A_n.

6. Page 37, Equation (2.26) and following: we need to relax on the strict application of the n in d^n, from $d\Phi^2$ to $d\Phi$.

7. Page 38, Equation (2.27): change to $I = \frac{d\Phi}{dA_1 \cos\theta_1 / R_{01}^2} = L\, dA_0 \cos\theta_0$.

8. Page 47, x-axis in the graph in Figure 2.15 should be 'nm' not 'µm'.

Chapter 3

1. Page 59, last paragraph: The variable x in the Planck equation is unitless. It does *not* have units [W/(m^3·K)].

2. Page 59, last line on the page: reference to Table A.2 should be to Tables A.2 and A.3.

3. Page 60, paragraph after Equation (3.1): reference to Table A.2 should be to Table A.3.

4. Page 64, Equation (3.20): Note that $\zeta(3)$ is the Apéry constant.

5. Page 65, second paragraph: reference to Table A.2 should be to Table A.3.

6. Page 66, Table 3.1: reference to Table A.2 should be to Table A.3.

7. Page 70, Table 3.2: Spectral hemispherical emissivity ϵ_λ must add $\sin\theta$:

$$\frac{\int_0^{\pi/2}\int_0^{2\pi} L_{\lambda s}(\theta,\varphi)\cos\theta\sin\theta\, d\varphi\, d\theta}{\int_0^{\pi/2}\int_0^{2\pi} L_{\mathrm{bb}\lambda}(\theta,\varphi)\cos\theta\sin\theta\, d\varphi\, d\theta}$$

   Hemispherical total emissivity ϵ must add $\sin\theta$:

$$\frac{\int_0^{\infty}\int_0^{\pi/2}\int_0^{2\pi} L_{\lambda s}(\theta,\varphi)\cos\theta\sin\theta\, d\varphi\, d\theta\, d\lambda}{\int_0^{\infty}\int_0^{\pi/2}\int_0^{2\pi} L_{\mathrm{bb}\lambda}(\theta,\varphi)\cos\theta\sin\theta\, d\varphi\, d\theta\, d\lambda}$$

8. Page 78, Section 3.4.4: The first sentence should read: "... polarization of the incident light relative to the plane of incidence."

   The second sentence should read: "For light polarized perpendicular to the plane of incidence, ..."

   Note that the plane of incidence is defined by the unit vectors $\widehat{I}$ and $\widehat{N}$.

9. Page 79, line just above Equation (3.29): "The reflectance of light polarized parallel to the plane of incidence is ... "

10. Page 87, Equation (3.47): Note that $L_{\mathrm{bb}\lambda}(T_\mathrm{s})$ is a blackbody radiator at temperature T_s.

11. Page 93, Problem 3.6: The two surfaces are opaque (there is no background specified). Assume that the two surfaces face each other. Unless otherwise stated, all radiators can be assumed to be Lambertian.

12. Page 95, Problem 3.15: Complete Problems 3.15.2 and 3.15.3 for aluminium with complex refractive index of $25.00601 + i85.965$ at a wavelength of 10 µm.

Chapter 4

1. Page 97, first paragraph, fourth line: "(in the case of lasers)".
2. Page 110, Figure 4.6: where Mie scattering and Rayleigh scattering are defined, change the symbol for radius and the relationships should read:

   Particle radius (r)
   Mie forward scattering $2\pi r > \lambda$
   Rayleigh omni scattering $2\pi r < \lambda$
3. Page 127, just after Equation (4.36): end of the paragraph currently reads "must be in the same units" must be reworded as follows: "must have the same unit prefixes (m or km)".

Chapter 5

1. Page 143, third paragraph, third line: "Beacuse" should be "Because".
2. Page 147, Equation (5.24): $2AB$ should be $2A\Delta f$. The symbol B is used in elsewhere for noise equivalent bandwidth Δf.
3. Page 151, second paragraph, first line: "Seeback" should be "Seebeck".
4. Page 154, Equation (5.40): should read (note the negation ($-$) in the transient component):

$$\Delta T = \Delta T_0 \exp(-t/\tau_\theta) + \frac{\epsilon(\Delta\Phi)e^{i\omega t}}{G + i\omega C}, \tag{F.1}$$

5. Page 181, Section 5.6.4: αl_x should be αd.
6. Page 192, Equation (5.115): should read

$$NEP_\lambda = \frac{2hc}{\lambda}\sqrt{\left(\frac{A_d \Delta f}{\int_0^{\lambda_c} E_q d\lambda \eta}\right)} .$$

7. Page 202, Section 5.9.3.4: the equation in the first line should read $I = -I_{\text{sat}} - I_{ph}$.

8. Page 207, item 1: The Varshni parameters used in the example do not correspond with the values in Table A.6.

   The Varshni model [Equation (5.3)] is an *approximated* empirical fit to predict a semiconductor bandgap at a given temperature. The approximation employs three parameters: the reference bandgap at a given temperature (usually 0 K), plus two parameters to predict the bandgap at other temperatures (relative to the reference bandgap). Several sets of different parameters were proposed using different reference bandgap values, and also based on different experimental data. For example Dhanaraj[8] provides values ($E_g(0)$, A, B) of (0.235 ± 0.003 eV, $3.1 \pm 1.1 \times 10^4$ eV/K, 452 ± 190 K). Piprek[9] provides the values in Table A.6. Madelung[10] provides values of ($E_g(0)$, A, B) of (0.2352 eV, 6×10^4 eV/K, 500 K).

   The results shown on page 202 were determined with the Varshni parameters from Madelung[10]. Comparing the Madelung and Piprek predictions yields the following:

$\boldsymbol{E_g(0)}$	$\boldsymbol{A}$	$\boldsymbol{B}$	E_g(77 K)	$\boldsymbol{\lambda_c}$
0.235	3.2×10^{-4}	170	0.227	5.47
0.24	6.0×10^{-4}	500	0.233	5.31
eV	eV/K	K	eV	µm

   These results are within the uncertainty of measurement and approximation, and certainly within the accuracy of the simple model presented on page 202.

9. Page 218, Problem 5.5: Clarification: for bonus points you may consider using the information in `DP04.zip`. The intent with the problem is not, however, to do a detailed design.

10. Page 219, Problem 5.14:

    The *specific* heat capacity of water is 4.15 kJ/(K·kg) (correction to the units).

11. Page 220, Problem 5.23: Use the information in `DP04.zip`, Appendix A and a bandgap of 0.108 eV for the HgCdTe detector.

    Clarification: Calculate the spectral D^* for the above detectors, for *background limited operation* (BLIP, Equation (5.154)).

Chapter 6

1. Page 242, Equation (6.13) should start with $d\Phi_\lambda = \ldots$.

2. Page 249, equation in the middle of the page should read:

$$\begin{aligned}\Phi &= \left(\frac{L}{n^2}\right) n^2 A\Omega, \\ &= \frac{LA_0A_1}{R_{01}^2}.\end{aligned}$$

3. Page 253, Problem 6.8: The statement for combinations of sensors and sources are somewhat confusing.

   The requirement is to calculate the detector current for three sources: the sun, a 1300-K hemispherical ambient, and a 2800-K hemispherical ambient. Calculate the current for the four combinations of with/without optics and with/without filter. In total there should be 12 results.

Chapter 7

1. Page 260, sixth line from the bottom: "OFT" must be "OTF".

2. Page 268, second text line: the equation $R^2/\tau_a(R)$ should be interpreted as $R^2/\exp(-\gamma R)$

Chapter 8

1. Page 281, Equation (8.1), the last term: the surface bidirectional reflection distribution function is a function of four parameters $f_r(\theta_i, \theta_s, \varphi_i, \varphi_s)$, not two (See Page 80).

2. Page 294, last line: "is a challenge".

3. Page 302, Figure 8.11: the two labels in the graph should be switched around.

Chapter 9

1. At least one book is known to be missing pages 353 to 360. The text of the missing pages are attached to this document.

2. Page 326, Equation (9.34): should read

$$SNR = \frac{E_R(R)}{E_n}. \tag{F.2}$$

3. Page 332, Equation (9.47): should read

$$NEE = \frac{NEL\ A_0 \cos\theta_0}{R^2} = NEL\ \omega = \frac{NEM\ \omega}{\pi}. \tag{F.3}$$

4. Page 335, third paragraph, third line: 'effected' should read 'affected'.

Chapter 10

1. Page 368, two-thirds down the page, the dimensional unit for charge is C not Q. The dimensional analysis should read:

$$i_n = \sqrt{2qIB} \quad \sqrt{\left[\frac{C}{1}\right]\left[\frac{A}{1}\right]\left[\frac{1}{s}\right]} \rightarrow [A]\,.$$

2. Page 377, Table A.3, correct the radiation constants units for spectral domain $\tilde{\nu}$ from

	Name	Magnitude	Units
Radiation constants, $\tilde{\nu}$ expressed in spectral units of [cm^{-1}]			
$c_{1e\tilde{\nu}}$	First radiation constant ($2\pi hc^2$)	$3.74177152466413 \times 10^{-8}$	W·µm^4/m^2
$c_{1q\tilde{\nu}}$	First radiation constant ($2\pi c$)	$1.88365156730885 \times 10^{15}$	q·µm^3/(s·m^2)
$c_{2\tilde{\nu}}$	Second radiation constant (hc/k)	1.43877695998382	µm·K

to

	Name	Magnitude	Units
Radiation constants, $\tilde{\nu}$ expressed in spectral units of [cm^{-1}]			
$c_{1e\tilde{\nu}}$	First radiation constant ($2\pi hc^2$)	$3.7417715246641 \times 10^{-8}$	W/(m^2·cm^{-4})
$c_{1q\tilde{\nu}}$	First radiation constant ($2\pi c$)	$1.8836515673088 \times 10^{15}$	q/(s·m^2·cm^{-3})
$c_{2\tilde{\nu}}$	Second radiation constant (hc/k)	1.43877695998382	K/cm^{-1}

3. Page 377, Table A.3, units are correct but for clarification and consistency rewrite the radiation constants units for spectral domain ν from

	Name	Magnitude	Units
Radiation constants, ν expressed in spectral units of [Hz]			
$c_{1e\nu}$	First radiation constant ($2\pi h/c^2$)	$4.63227628074287 \times 10^{-50}$	J·s^3/m^2
$c_{1q\nu}$	First radiation constant ($2\pi/c^2$)	$6.99098648422864 \times 10^{-17}$	s^2/m^2
$c_{2\nu}$	Second radiation constant (h/k)	$4.79924334848949 \times 10^{-11}$	s·K

to

	Name	Magnitude	Units
Radiation constants, ν expressed in spectral units of [Hz]			
$c_{1e\nu}$	First radiation constant ($2\pi h/c^2$)	$4.63227628074287 \times 10^{-50}$	W·s^4/m^2
$c_{1q\nu}$	First radiation constant ($2\pi/c^2$)	$6.99098648422864 \times 10^{-17}$	q·s^3/(s·m^2)
$c_{2\nu}$	Second radiation constant (h/k)	$4.79924334848949 \times 10^{-11}$	s·K

Appendix F

1. Add a new section with the following contents:

F.3 Structure the Problem and Penetrate to its Essence

"It's become clear to me, the great mysteries have unraveled. I have penetrated to the very core of things, and I have stumbled on the answer. It is a rare thing

to come upon this answer, the answer to the mysteries". . . Leonard Cohen.[11] Classical conductor Leonard Bernstein once remarked that playing a musical composition is not about playing the notes, but about discovering the essence of the music: composer's deeper intent with the notes. *"The essence of architecture lies not in its usefulness — the purely practical solutions it offers to the human need of shelter — but in the way it meets the much profounder spiritual need to shape our habitat"*. . . Mario Botta.

Solving a radiometry problem is not about using equations to calculate results, as much as music is not about playing notes, or architecture is not about drawing lines on paper. The solution to any real-world problem requires structuring the problem. Problem structuring requires you to step back from the immediacy of the stated facts; look beyond the facts into the underlying principles. What are these principles? Music and architecture require you to penetrate to the spiritual and emotional "core of things." Radiometry problems require you to build a conceptual model at the "core of things," (while actively ignoring the details). What are the essential elements in the problem? How are these elements related to each other and to external elements? What is the nature of the interdependencies between these elements? How do magnitude/scale, space/distance, and spectrum affect the elements and their interdependencies? How does time affect these elements?

Drawing pictures and compiling mathematical descriptions should be attempts to express your visualizing the elements in the problem: draw and notate them for this specific purpose. Don't simply copy someone else's work, it is of no value to your own understanding. The drawings and mathematics should express the train of your thoughts, as you struggle to clarify the concepts.

Problem solving is a creative endeavor; it entails bringing to light something not previously existing (at least in your own mind). *"Creativity results from the interaction of a system composed of three elements: a culture that contains symbolic rules, a person who brings novelty into the symbolic domain, and a field of experts who recognize and validate the innovation. All three are necessary for a creative idea, product, or discovery to take place."* Mihaly Csikszentmihalyi.[12] In the context of this section, creative problem solving therefore requires the concise expression of the essential elements (symbolic rules) of the system, the manipulation of these elements and the external testing of the manipulation. In view this definition, *drilling down to the essence* is central to creative problem solving. You can only (creatively) solve a problem for which you created a set of symbolic rules. The elemental symbolic rules, of course, depend on the specific problem and its domain; be that engineering, music, or architecture. In any domain, however, penetrating to the core is an essential requirement for creative problem solving.

Only once the problem is well structured and (almost perfectly) understood, should you return to the detailed facts as given. Avoid, at all cost, the urge to immediately manipulate the numbers, equations and drawings, before deeply understanding the problem at a conceptual level. The shallow euphoria obtained by finding equations that seem to match with problem details is simply not strong enough for a good solution. Strive instead for experiencing the deeper magic of unraveling new mysteries; experience the joy of penetrating through the fog into clarity. A poorly-structured problem understanding will always result in a poor (and mostly wrong) solution. A well-structured problem understanding does not guarantee success, but at least it is within reach! The musician and architect have to penetrate to the very core of human experience at a deep emotional and spiritual level to create their masterpieces. As a radiometry expert, you have to reach similar depths of understanding of your problem domain.

It is all about unraveling the mysteries. . ..

Analysis and Synthesis

Optimizing a design requires analysis and synthesis: analysis of the factors that determine the optimal performance and synthesis of these factors into a working design. The word analysis come from (classical) Greek and mean "to loosen up" or to "dissolve" — it is the procedure whereby a complex concept is broken down, by detailed and methodical examination, into a structure of essential features or parts, with cognisance of the relationships between the parts. The thesis is that by understanding the parts, we are better equipped to understand the meaning of the parts and the whole. The word synthesis come from Greek and mean "to put together" — it is the procedure where simpler parts are put together in a coherent manner into a complex whole. The thesis is that if we put together the known parts, we can be sure of the whole. Of course, this is not always the case and there is often a repeated cycle of analysis and synthesis. Careful study of the interplay between these complementary processes raises understanding and insight. "Analysis and synthesis always go hand in hand; they complement one another. Every synthesis is built upon the results of a preceding analysis, and every analysis requires a subsequent synthesis in order to verify and correct its results."[13]

Ritchey[13] provides a fascinating discourse on an unfinished paper by Bernard Riemann, "The Mechanism of the Ear" (c. 1866). Riemann played an important role in the history of Mathematics, but, as Ritchey shows, Riemann often also reported his thought processes that underlie his analysis and discoveries. Riemann's paper under discussion served as much as a case study of his methods, as it serves to describe the working of the human ear. He shows how analysis and synthesis serve as investigative techniques in the scientific process — the very methodology followed in this book. Most of this section is extracted from Ritchey's paper, which is in turn extracted from Riemann's paper. Ritchey's paper is readily available and well worth the read.

The analysis process must start with a clear formulation of the problem to be solved by the system under study. The analysis must not follow the system's structure or anatomy, but rather: what task does the system have in order to accomplish its function? The analysis starts with the task at hand. Riemann also considers the structure and role of each component on the basis of its relationship to the whole, rather than by the relationship between the components. Using the laser rangefinder example, the laser power is considered in terms of the operating range, rather than in terms of the receiver noise.

The systems under study in this book have at least two levels: the system as a whole, and any number of lower levels of components (Figure F.1). "It is this distinction between system levels — between the behavior of the

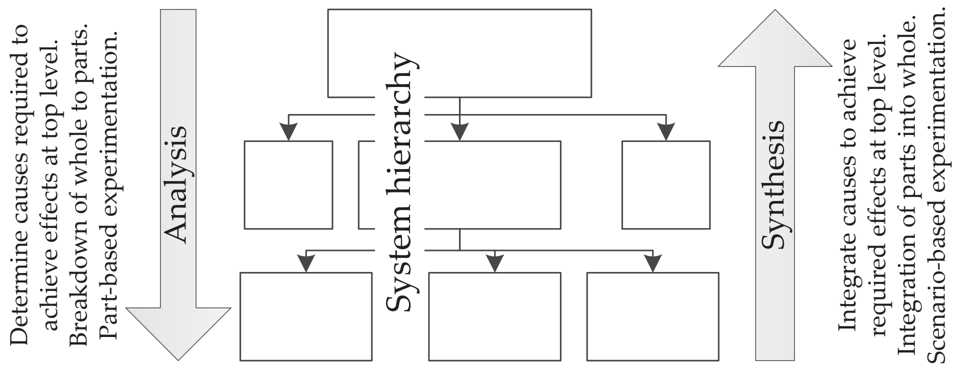

Figure F.1 Analysis and synthesis in system context.

system as a whole and the specific relationships between its parts — which is fundamental to the concept. The idea of a system would be meaningless without this distinction."[13] At the system level we consider it as a black box, asking what it does. As a set of components, we consider the system's construction and its internal processes. We gain knowledge about the system by considering both these levels, each providing a different type of knowledge.

For the study of any system, there are three foundations by which we can gain knowledge about the system: one general foundation and two special foundations. These are (1) our knowledge of the laws of nature, (2) the knowledge of the task the system accomplishes and its performance in this regard, and (3) the knowledge of the system's internal construction.

"The first, general foundation consists of our knowledge of the laws of nature; knowledge which has been developed through centuries of scientific activity. This takes the form of scientific 'laws' and principles, and systematic, empirically validated relationships. The laws of (theoretical) mechanics are an outstanding example of such acquired knowledge. This knowledge is not absolute; it does not represent the final truth. We can, however, trust such knowledge as an approximate truth within its area of application and use it as a stepping-stone to new scientific discoveries."[13]

The knowledge of the system-level behavior is obtained by observation and experiment: how does the system (as a black box) behave to external stimuli. Knowledge of the system's internal construction is gained by a detailed study of the internal structure, the part's processes, and the essential relationships between its parts.

There are two ways to gain knowledge about the system: (1) proceed from its construction (as parts) and integrate the parts to determine the system level behavior, or (2) proceed from the system's required task and then attempt to account for its behavior by breaking down the system into parts and analyzing the parts. "By the first route we infer effects from given causes, whereas by the second route we seek causes of given effects. We can call the first route synthetic, and the second analytic. The cause and effect relationship is translated between the two special foundations."[13]

"A system's internal processes — i.e., the interactions between its parts — are regarded as the cause of what the system, as a unit, performs. What the system performs is thus the effect. From these very relationships we can immediately recognize the requirements for the application of the analytic and synthetic methods. The synthetic approach — i.e., to infer effects on the basis of given causes — is therefore appropriate when the laws and principles governing a system's internal processes are known, but when we lack a detailed picture of how the system behaves as a whole. The analytical approach — drawing conclusions about causes on the basis of effects — is appropriate when a system's overall behavior is known, but when we do not have clear or certain knowledge about the system's internal processes or the principles governing these."[13]

"In order to formulate an hypothesis about how a system works — a system whose internal properties cannot be determined with any certainty — we must identify something about the system which is 'analyzable', but which is not directly dependent upon knowledge about its construction. In order to do this, we must recreate the system in principle, i.e., build up a conceptual model of the system which, in some abstract way or another, contains the 'sense of its functioning', so to speak. It is this conceptual model which is the object of analysis. But how — on what foundation — do we 'reinvent' or 'recreate' the system? It is here that we turn the synthetic method on it head: instead of using cause to explain effect, we use effect to explain (something about) cause. If we cannot, to any sufficient degree, understand the system's construction in order to explain what it accomplishes, then we ought to begin with what the system accomplishes in order to secure a (sound) theoretical framework within which to explain its construction."[13]

"The functional/task analysis proceeds in the following way: the main task or problem that the system must solve is broken down into a number of secondary tasks or problems, the solutions of which, in turn, are necessary for the solution of the main task. We continue this process, constructing a network or hierarchy of subordinate tasks, all of which must be solved in order that the originally formulated main task be solved. We stop the analysis when we notice that we are no longer formulating tasks to be solved, but have begun to formulate possible means by which they may be solved. A task-analysis of this sort is no simple matter. It demands both sound empirical knowledge about a system's actual performance, and basic insight into the principles and 'natural laws' that may be relevant to that performance. When one has succeeded in mapping out this network or hierarchy of tasks, which contains all the conditions for the system to achieve the effect that it does, then one has formulated an hypothesis which is sufficient to account for the system."[13]

The core methodology in this book is to employ complementary analysis and synthesis to grow a deeper understanding of the electro-optical system under study. Earlier chapters focus more on analysis, whereas later chapters increasingly introduce elements of synthesis. The theory is supplemented by a strong computational focus, providing the software tools to analyze and model the system under study. Software-based system modeling is akin to design synthesis and construction. It may be argued that accurate software-based system modeling requires equivalent or better insight than that required to construct hardware of the same system. The developer requires the relevant design knowhow in both cases, but the simulation developer requires the additional knowledge of the internal operation and performance of each part, as well as the nature of the interaction between the parts.

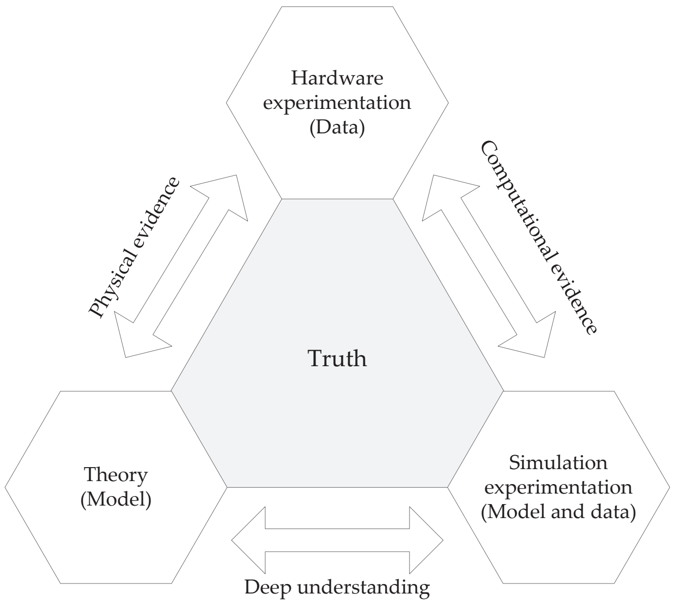

Figure F.2 Computational analysis and experimentation in context (adapted from Landau[14]).

Computational Analysis in Electro-Optical Systems

F.3.1 The Role of Computing in Analysis

The principles of classical physics were largely determined by laboratory experiments. The availability of considerable computing power and appropriate scientific software libraries opens up new possibilities in physics experimentation. The terms 'computational science' or 'computational physics' represent a new way of thinking about experimentation, discovery and learning. Provided that the models are representative, computational science provides a viable alternative in experimental investigation.

"Traditionally, physics employs both experimental and theoretical approaches to discover scientific truth (Figure F.2). Being able to transform a theory into an algorithm requires significant theoretical insight, detailed physical and mathematical understanding, and a mastery of the art of programming. The actual debugging, testing, and organization of scientific programs is analogous to experimentation, with the numerical simulations of nature being essentially virtual experiments. The synthesis of numbers into generalizations, predictions, and conclusions requires the insight and intuition common to both experimental and theoretical science. In fact, the use of computation and simulation has now become so prevalent and essential a part of the scientific process that many people believe that the scientific paradigm has been extended to include simulation as an additional dimension."[14]

In a SciPy 2014 keynote address[15], Barba made a compelling case for computational experimentation as a learning tool. Knowledge is not about remembering, it is a distributed entity, created by conversations and interactions — science is a conversation between scientists and the body of knowledge, and also between scientists (Stephen Downes). Computing interactively is a conversation with the system under study, and creates knowledge — it is a form of learning. During interactive exploration one discovers much more effectively than by just scribbling notes and equations. Reproducibility of the work is a key element in computational exploration, it is required to sustain the conversation, thereby supporting the learning.

In a milestone contribution, Wing[16] points out that computational thinking is about conceptualizing a problem in a fundamental manner, exploiting human thinking and reasoning. It complements and combines mathematical and engineering thinking, using abstraction and decomposition when attacking a large complex task or designing a large complex system. The value of computational thinking is evident in the breakthroughs in fields such as biology and chemistry resulting from computer-based research.

Computer simulation techniques have been used extensively for 'static' design optimization in areas of optical design and electromagnetic antenna design. Computer simulation has also been used in the simulation of time-evolving applications in fields such as computational fluid dynamics and the control of dynamic systems. The implementation of theoretical constructs in validated computer models opens up new areas of experimentation hitherto not achievable in the laboratory. The appearance of several introductory books[14,17,18] on, and tools for, computational science significantly lowers the entry barrier: computational analysis is now within the easy reach of most scientists and engineers. In particular, in the context of this book, complex electro-optical systems can be modeled and optimized effectively using computer modeling techniques, at various levels of detail — for an example see Appendix B.

The approach followed in this book it to provide a thorough coverage of theoretical fundamentals, but also to provide computational tools to experiment with the theory. The term 'computational radiometry' seems an apt description of the experimental part of the material covered here. To get the most benefit, the reader is urged to work through the example code, and perhaps even attempt a few of the problems. Solving the problems in an interactive computational manner will bring learning and insight much beyond reading the theory. To assist the reader, a complete computational radiometry tool suite is available[19,20].

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