Specific Lessons

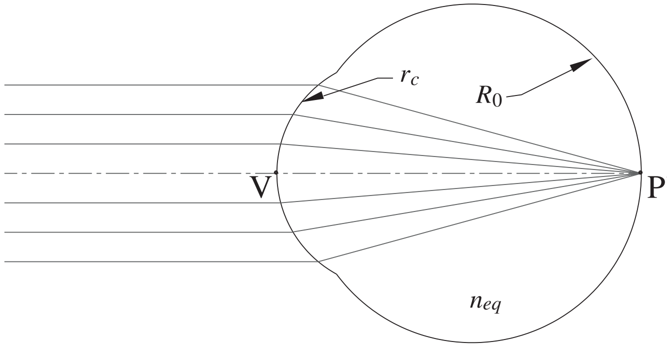
John Greivenkamp with an antique telescope (photo credit: Wyant College of Optical Sciences, University of Arizona).

Could Our Eye Be a Single Sphere?

Yobani Mejía
Universidad Nacional de Colombia, Colombia

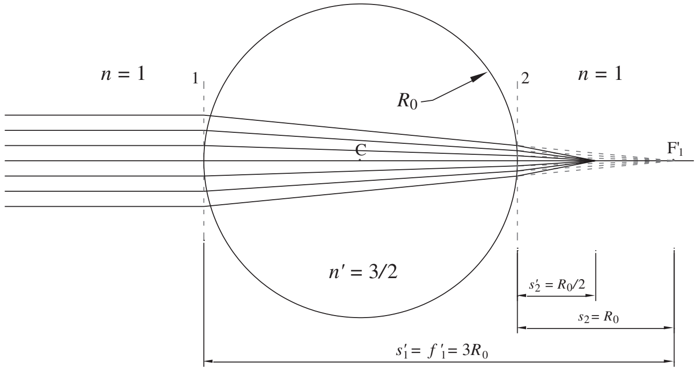
When I teach the Gaussian formula for a single spherical surface, $n'/s' - n/s = (n' - n)/R$, I like to mention two examples: the human eye and the refractive sphere.

In a first approximation, within the paraxial region, a reduced schematic eye estimates the image in the retina. It is composed of two parts: the rear part is a spherical surface of radius R_0, and the frontal part is also a spherical surface of radius $r_c < R_0$, as shown in the figure below. The medium bounded by these surfaces has an equivalent refractive index $n_{eq} \approx 4/3$.[1] With regard to the shape of this eye model, I ask students whether it is possible to have an eye as a single sphere.



Reduced schematic human eye.

Then, after some discussion, I pose the problem of the refraction of light at a glass sphere of radius R_0 and index 3/2 when it is immersed in air with index 1.0. First, I ask the students to sketch the refracting rays coming from the infinite. Some of them draw the point where the rays converge inside the sphere, and others draw it outside the sphere, but no one draws it in the second vertex. From the Gaussian formula, at each surface, it is found that the point at which all the rays converge is outside (at $R_0/2$) the second vertex, as shown in the figure below.



Refraction of a parallel beam at a sphere.

Finally, I ask them what we need to change in the schematic eye to have an eye like a single sphere, in order for a parallel incident beam to converge at the second vertex. The solution implies a change in the refractive index n'. From the Gaussian formula, with $s = -\infty$, and $s' = 2R_0$, the answer is $n' = 2$.

When I talk about this with eye specialists (optometrists, ophthalmologists), they are surprised, and tell me that they had never thought about it. In some way, the human eye must have the current shape because, in our bodies, the refractive index of fluids like the aqueous humor and vitreous humor are close to that of water.

This simple exercise allows students to understand that the general geometry of the human eye can be explained with the Gaussian formula.

Reference

1. D. Atchison and G. Smith, *Optics of the Human Eye*, Butterworth-Heinemann (2000).

Teaching Optics by Analogy and Association

Mitsuo Takeda
Utsunomiya University, Japan

Analogy and association help students to gain a systematic and unified understanding of seemingly different subjects and physical phenomena in optics.

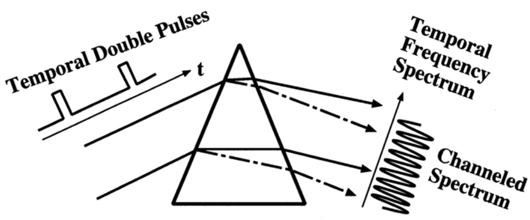
The wave equation,

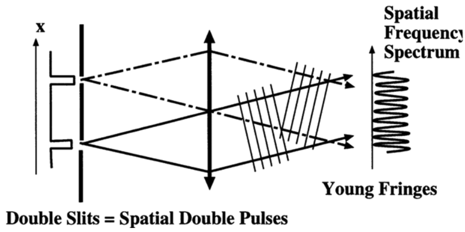
$$\nabla^2 u(\mathbf{r}, t) = (1/c^2)[\partial^2 u(\mathbf{r}, t)/\partial t^2]$$

has space–time symmetry. Its general solution can be expressed by superposition of elementary plane waves:

$$\exp[i(\mathbf{k} \cdot \mathbf{r} - \omega t)] = \exp(i\mathbf{k} \cdot \mathbf{r}) \exp(-i\omega t)$$

which have two-fold symmetries between the variables in space ($\mathbf{k}$, $\mathbf{r}$) and time (ω, t), as well as between those in the signal domain ($\mathbf{r}$, t) and the frequency domain ($\mathbf{k}$, ω). This permits an interchange of the roles played by the variables and thereby serves as the origin of analogy.





In this example of space–time analogy, Fizeau's channeled spectral fringes, generated by double time pulses in the temporal spectrum domain, are explained in association with Young's fringes, generated by double slits in the spatial spectrum domain, which is more familiar to students.

Viewing the lower figure, it should be easy for students to imagine that Young's fringes would become holographic fringes if one of the double slits were replaced by an aperture with its transmittance representing an object. By analogy, the students would be able to understand the principle of time holography—in which one of the double pulses is replaced by a waveform representing a temporal object—without much difficulty.

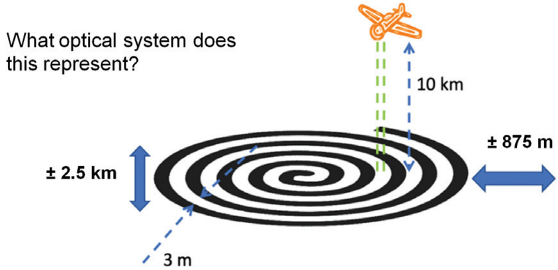
When learning interferometry, students can gain a unified understanding of the principles of temporal and spatial heterodyne techniques by noting their formal analogy.

Analogy is not only of interest per se, but suggests to students that, if there is a principle that works with a time variable, there is a similar principle that works with a space variable, and vice versa. Understanding this will help students increase their capacity for invention.

Six Myopic Engineers and the ?? System

Shanti Bhattacharya
Indian Institute of Technology Madras, India

Imagine you're in a plane, 10 km above the ground, and flying at an extremely high velocity. The plane will travel 12.5 million km, and throughout the flight, it must maintain its height with an error of only ±1.5 m. This plane has a very specific flight path or track that it must fly over. The width of the plane is only a couple of meters, and it must stay centered over the track, which is of a slightly smaller width. As if this wasn't challenging enough, the track below is moving both horizontally by ±875 m and vertically by ±2.5 km, as the plane flies. What optical system do you think this represents? If you haven't guessed by now, maybe this last clue will help. The flight path is not straight but a spiral.



This is how I start teaching the course Optical Engineering.[1] I always begin the very first lecture with the following statement, "I am going to present an analogy to an optical system. This is a system that you have all used, and many of you probably own."* I then ask students to guess the optical system represented by the analogy,[2] which, as you have seen, describes a plane flying in a flight path with very tight specifications.

Everyone loves a puzzle, so this is a great way to start any class, but the reason that it takes students time to get the answer to this particular question is that most of them

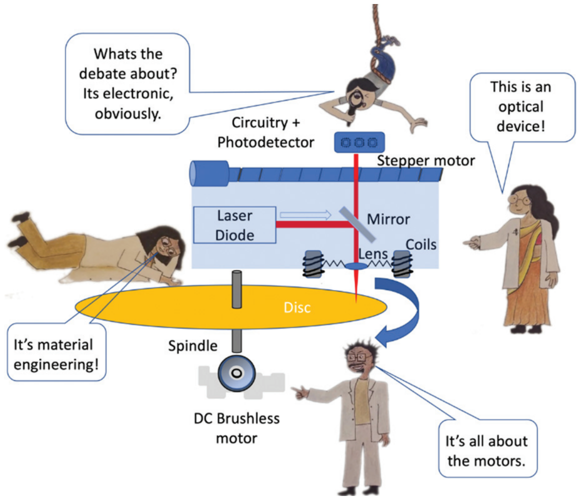
*This used to be true when I started teaching this course in 2005!

don't think of the CD pickup as an optical device. To be fair, I teach the course in the Department of Electrical Engineering. Most of the students are training to be electrical engineers, and the others are from departments such as Mechanical Engineering, Engineering Physics, Engineering Design, etc. For many students, their last encounter with optics would have been in high school. Whatever the reason, not surprisingly, most students classify the CD player as an electronic device. And that is another reason I love using this example—because that classification isn't wrong; the CD pickup is an electronic device. (Who am I to argue with Wikipedia?[3])

The ensuing discussion always reminds me of the story of the Six Blind Men and the Elephant.[**,***] Some students will insist that the CD player is an electronic device with some optics in it, and others will argue the reverse; the few mechanical engineers in the class, who probably never thought about the innards of this system before, start to wonder aloud about all the nifty little mechanical devices and motors in it. The class has just started, and a healthy discussion is already in progress, which sets the tone for the entire course. This is a good way to begin any class, but the great thing about teaching optics is that there is no dearth of examples of devices that students have used, or optical phenomena they have personally witnessed, that can kickstart such conversations. In addition, the CD pickup very quickly conveys to students the idea that "optical" systems are rarely purely optical. Most students electing to take this course probably already understand that optical systems are quite interdisciplinary. This particular example reinforces the importance of this diversity in a very elegant way. And isn't that the power of optics? Optics is used in so many systems today—and

[**]The full poem, called "The Blind Men and the Elephant" by John Godfrey Saxe (1816–1887) can be accessed at https://www.extension.iastate.edu/4h/files/page/files/The%20Blind%20Men%20and%20the%20Elephant.pdf.
[***]The scientists in the figure "Six Myopic Engineers and the CD Player" were drawn by my daughter, Sumitra Bhattacharya.

we're not talking about the obvious ones like cameras and microscopes. From easing our lives by giving us the ability to flick channels from the comfort of our armchair to the small but life-saving pulse oximeter, optics is quietly revolutionizing the world. I end that first class by telling students that this course will equip them to speak the language of optics and allow them to be part of this revolution.



Six myopic engineers and the CD player.

The first CD players were sold in 1982. And while some labs or fabrication facilities still insist on using only CDs as storage devices (no pen drives allowed!), and music CDs sold more than expected in 2021, it's probably time to change this example. I think the smart phone will be a wonderful system to use. I just need to find an analogy as impressive as the CD–airplane one. Any suggestions?

References

1. https://nptel.ac.in/courses/108106161
2. https://www.repairfaq.org/sam/cdfaq.htm
   Note: While the main idea of the analogy is taken from this reference, I've modified the numbers using a linear conversion scale. In the end, the exact numbers used are not that important, except to highlight what a difficult task this is.
3. https://en.wikipedia.org/wiki/CD_player

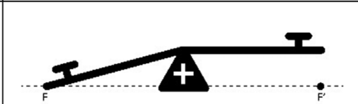
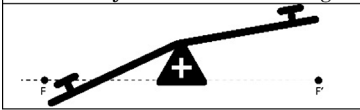
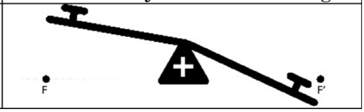
Bent Seesaw

Jim Schwiegerling
The University of Arizona, USA

John taught geometrical optics to multiple generations of graduate students. For several of those years, I taught the undergraduate version of his course. We had many discussions regarding teaching the material. While we could never agree on the correct way of writing the imaging equation, we did agree that the students who struggled with the material seem to struggle with the most fundamental concepts. Lacking the proper foundation meant that these students were lost with more advanced concepts. Many of our discussions were coming up with easy visualizations for this fundamental material. One of John's favorites was the bent seesaw.

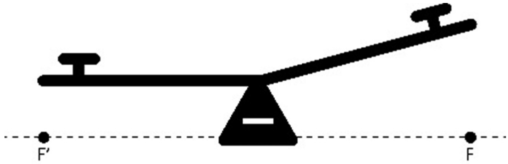
The bent seesaw is a visualization to illustrate the object and image locations. While these relationships are easily determined from the imaging equation, students may have difficulty visually analyzing a system, especially when the object or image is virtual. For positive-powered lenses, the seesaw is bent such that, when the left side is horizontal, the right side is bent toward, the ground as shown below.

The planks of the seesaw schematically represent the upper marginal ray before and after the lens. The lens serves as the fulcrum of the seesaw. The optical axis lies along the ground plane, with the front and rear focal points placed as shown. In this particular case, the left plank is horizontal, so the object is located at infinity. The right plank is bent downward, passing through the rear focal point.

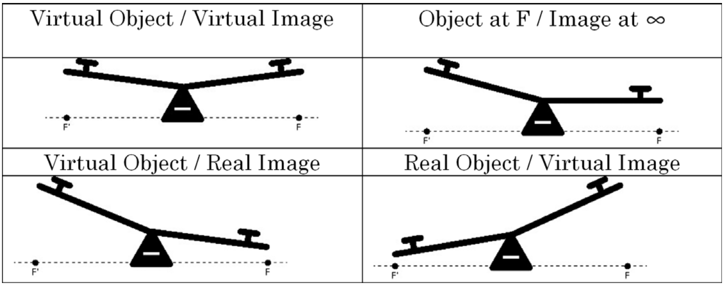
Real Object / Real Image	Object at F / Image at ∞
	
Real Object / Virtual Image	Virtual Object / Real Image
	

As the seesaw tips through different angles, the object and image locations follow from the orientations of the left and right planks. When the left plank is tilted downward, the object is real. If the right plank is tilted downward, the image is real. If the object is to the left of the front focal point, the real image is to the right of the rear focal point. If the object is to the right of the front focal point, the virtual image is to the left of the front focal point. From these illustrations, the various object/image relationships are easily visualized for a positive-powered lens.

For a lens with negative power, the seesaw simply needs to be bent in the opposite direction. When the left plank is horizontal, the right plank is now bent upward to appear as if it is angled toward the rear focal point (which is now on the left side).



Tilting the seesaw now gives the various combinations of object and image relationships. As the left plank moves up, denoting a virtual object, the right plank moves down, giving a virtual image. When the left plank appears to pass through F, the right plank is horizontal. Further raising the left plank now tilts the right plank downward to give a real image. Tilting the left plank downward means that a real object is formed with a virtual image to its right.

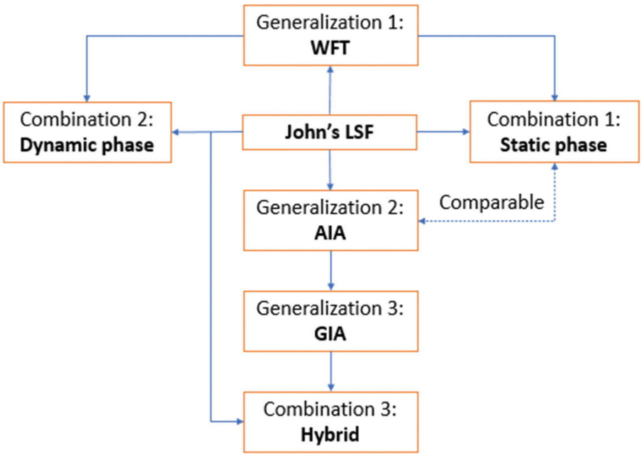


As I take over John's class in the Fall of 2022, I only hope that I can match his dedication and enthusiasm. His efforts will be continued.

Phase Measurement: Simplicity, Beauty, and Uncertainty

Qian Kemao and Yuchi Chen
Nanyang Technological University, Singapore

In 1997, Kemao started his PhD study on phase measurement for precision engineering. He initially knew of Dr. John Greivenkamp's work through his 1984 paper.[1] (Kemao finally met John at the SPIE Optics + Photonics Conference in San Diego in 2014.) This paper used least-squares fitting (LSF) for phase estimation from phase-shifted fringe patterns with random and known phase shifts. The simplicity and beauty of this three-page article make it a classic work. The idea to use LSF influenced Kemao's work implicitly and explicitly. Some of his related works are depicted in the flowchart and described in the text as three generalizations and three combinations.



Some related works on phase measurement.

Generalization 1: Kemao proposed using the windowed Fourier transform (WFT) for fringe pattern analysis such as phase extraction and denoising. It was later found that the WFT is a maximum-likelihood estimator, and it turned out to be a LSF in a very general sense.[2]

Generalization 2 vs Combination 1: In John's work, the phase shifts need to be known. Wang and Han proposed the advanced iterative algorithm (AIA), which essentially used LSF alternatively for phase estimation and phase shift estimation until converged, and thus was applicable for unknown phase shifts.[3] Later, Kemao et al. combined WFT with John's LSF to achieve the same goal, where the WFT and the LSF were responsible for phase-shift estimation and phase extraction, respectively.[4] In general, the phase is static since phase shifting is involved.

Combination 2: The WFT and the LSF were combined again, in a slightly different way, to extract a dynamic phase from a sequence of fringe patterns in a frame-wise manner, where the WFT and the LSF were responsible for phase denoising and phase extraction, respectively. A unique feature of this method is that neither phase shifting nor a carrier was needed during this process.[5]

Generalization 3 and Combination 3: The AIA's convergence and accuracy are uncertain when various error sources are present. Yuchi Chen (the second author), in his 4 years of PhD study starting from 2018, worked on this problem. The convergence was confirmed through thousands of simulations; the error sources were handled by the proposed general iterative algorithm (GIA),[6] and more interestingly, the phase-shifting algorithms for known and unknown phase shifts were integrated as a hybrid solution.[7] We had the goal of making the GIA a simple and beautiful framework, and indeed we accomplished this. However, we still need to see how it works in other applications, which is a new uncertainty for us to address.

The pursuit of simplicity and beauty and the emergence of uncertainty has been consistently encouraging researchers to move forward. John was one of these researchers.

References

1. J. Greivenkamp, "Generalized data reduction for heterodyne interferometry," *Optical Engineering* **23**(4), 234350 (1984) [doi: 10.1117/12.7973298].

2. Q. Kemao, *Windowed Fringe Pattern Analysis*, SPIE Press (2013) [doi: 10.1117/3.1002080].
3. Z. Wang and B. Han, "Advanced iterative algorithm for phase extraction of randomly phase-shifted interferograms," *Optics Letters* **29**(14), 1671–1673 (2004).
4. Q. Kemao, H. Wang, W. Gao, L. Feng, and S. H. Soon, "Phase extraction from arbitrary phase-shifted fringe patterns with noise suppression," *Optics and Lasers in Engineering* **48**(6), 684–689 (2010).
5. L. Kai and Q. Kemao, "Dynamic phase retrieval in temporal speckle pattern interferometry using least squares method and windowed Fourier filtering," *Optics Express* **19**(19), 18058–18066 (2011).
6. Y. Chen and Q. Kemao, "General iterative algorithm for phase-extraction from fringe patterns with random phase-shifts, intensity harmonics and non-uniform phase-shift distribution," *Optics Express* **29**(19), 30905–30962 (2021).
7. Y. Chen and Q. Kemao, "Phase-shifting algorithms with known and unknown phase shifts: comparison and hybrid," *Optics Express* **30**(5), 8275–8302 (2022).

Writing a Good Scientific Paper

Chris A. Mack
Fractilia, LLC, USA

Learning to write a high-quality paper benefits both the writer and the reader, and is thus a useful part of graduate-level education in science and engineering. Fortunately, you do not have to be a good writer to write a good science paper, but you do have to be a careful writer. Typically, writing for a peer-reviewed journal requires learning and executing a specific formula for presenting scientific work, with the goal that readers will judge it by the quality of the science rather than the quality of the writing. That formula begins with the structure of the paper, and most papers follow the "IMRaD" format: Introduction, Method (materials, experiment, theory, design, model), Results and Discussion, Conclusions.

Introduction: What is the paper about, and why should the reader care? To answers these questions, the introduction should cover the scope, novelty, and significance of the work. Writing from the general to the specific, establish a territory (what is the field of the work, why is this field important, what has already been done?), then establish a niche (indicate a gap, raise a question, or challenge prior work in this territory—pose the research questions), and finally occupy that niche (outline the purpose and announce the present research). Avoid unnecessary background (things you can assume the intended audience already knows) and avoid exaggerating the importance of your work.

Method: Describe how the results were generated, with sufficient detail (including citations) so that another in the field can validate your conclusions. Internal validity means that the conclusions drawn are supported by the results presented. External validity refers to the degree that the conclusions can be generalized (rather than being applicable only to the narrow confines of this one work). Avoid including results in the method section, extraneous detail, or treating the method as a chronological history of events.

Results and Discussion: Present the results, organized to make them as accessible as possible to the reader, clearly indicating what is new to this work. Evidence does not explain itself. The purpose of the discussion section is to explain the results and show how they help to answer the research questions posed in the introduction. This discussion generally passes through the stages of summarizing the results, discussing whether results are expected or unexpected, comparing these results to previous work, interpreting and explaining the results (often by comparison to a theory or model), and hypothesizing about their generality. Avoid presenting results that are never discussed, discussing results that are not presented, ignoring results that do not support the conclusions, or drawing conclusions from results without providing sound logical arguments to back them up.

Conclusions: Provide a very brief summary of the results and discussion, showing how each research question posed in the introduction has been addressed, then explain how the work is significant. The goal here is to provide the most general claims that can be supported by the evidence. The conclusion should concisely provide the key message(s) the author wishes to convey. Avoid repeating the abstract, repeating background information from the introduction, introducing new evidence or new arguments not found in the results and discussion, repeating the arguments made in the results and discussion, or failing to address all of the research questions set out in the introduction.

There are, of course many other considerations in writing a good scientific paper, but the most important one is to be reader-focused. Think always about serving the needs of the reader. Only then will your paper go beyond that and serve your needs as well.

Reference

1. C. Mack, *How to Write a Good Scientific Paper,* SPIE Press (2018) [doi: 10.1117/3.2317707].

Exciplexes and Excimers and the Importance of Calling Them by Their Proper Names

Uzodinma Okoroanyanwu
University of Massachusetts Amherst, USA

Research on electronically excited supermolecules *exciplexes* and *excimers* and their applications continue to fill the pages of scientific and technical journals and books, especially those dealing with laser systems, including those published by SPIE. One cannot help but notice some confusion and inconsistency in the nomenclature of these excited supermolecules. Unfortunately, *excimer* has become the generic term used to broadly describe these excited supermolecules, especially in technical publications in optics and related fields. The error and confusion arise primarily from sloppiness and a lack of understanding of the roots of these terms and thus their true meaning.

The precision required in science in the accurate naming of objects in the natural world underscores the need for rational scientific nomenclature. As a system of names or terms, or the rules for forming these terms, rational scientific nomenclature has always been instrumental in the development of scientific fields. It facilitates the reproducibility of experimental results, which is a central pillar of the scientific method. Standard scientific nomenclature also ensures that everyone is reading from the same page. This explains why today we have internationally adopted codes of nomenclature governing specific scientific disciplines ranging from biology to chemistry to physics to astronomy. For biology, we have the Linnaeus system of binomial nomenclature for biological species. For chemistry, we have the International Union of Pure and Applied Chemistry nomenclature for chemical elements and compounds, as well as for uniform definitions and description of chemical principles. For physics, we have the Système Internationale (International System) (SI), otherwise known as the metric system for measurements of physical quantities and their definitions. For astronomy, we have the International Union of Astronomy nomenclature for official names and designations of astronomical objects, as well as for uniform definitions for astronomical principles.

I believe the time has come to open a discussion on the adoption of the proper nomenclature for electronically excited supermolecules in publications in optics and related fields. What better place to initiate this discussion than SPIE's *Field Guide to Education of Optics*: *A Tribute to John Greivenkamp*, a book with a focus on optics education? Were he alive today, I believe that Prof. Greivenkamp would be in support of this proposal. Accounts by people who knew him personally attest to his vehement argument over specific language and wording in scientific writing in general and the Field Guide series in particular. Given the extensive applications of ultraviolet lasers (see the table) made possible by these excited supermolecules, this publication offers a potential opportunity to begin this discussion. Some of these ultraviolet laser-based applications include deep-UV lithography, optical microscopy, and micromachining, to mention but a few.

Examples of exciplex and excimer lasers in use in optical technologies.

Laser type	Excited-state complex	Characteristic spectrum	Emission wavelength (nm)
F_2	Excimer	UV	157
ArF	Exciplex	UV	193
KrF	Exciplex	UV	248
XeCl	Exciplex	UV	308

In chemistry, the word *complex* is used to describe an association of molecules. Just as a molecule is an association of atoms, a complex is an association of molecules, and the word *supermolecule* may be appropriately used when the association energies are relatively large. A dimer is a diatomic molecule in which the two constituent atoms are identical. The association of an electronically excited molecule M^* with a ground-state molecule N leads to an exciplex (*exci*ted comp*lex*) if $N \neq M$, or leads to an excimer (*exci*ted di*mer*) if $N = M$:

$$M^* + N \rightleftharpoons (MN)^* \quad \text{(exciplex)}$$
$$M^* + M \rightleftharpoons (MM)^* (\text{or } M_2^*) \quad \text{(excimer)}$$

The term *exciplex* is therefore the recommended general term for all electronically excited complexes, while *excimer* is a special case of exciplex when the excited and ground state species are identical. A laser in which the lasing species of the excited-state complex is a dimer, such as F_2, is correctly called an excimer laser, while that in which the lasing species of the excited-state complex comprises two heteroatoms, such as ArF, KrF, or XeCl, is appropriately called an *exciplex laser*. The lasing mechanisms of these systems have been described in the literature.[1–5]

Finally, accuracy in scientific and technical publications in optics and related fields should not only be about the actual experimental results; it should also include the use of the proper nomenclature of the involved electronically excited supermolecules—be they exciplexes or excimers. This will prevent unnecessary confusion and inconsistency.

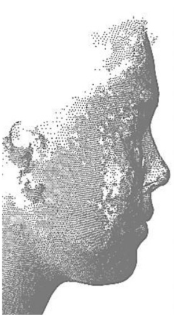
References

1. U. Okoroanyanwu, *Chemistry and Lithography*, SPIE Press, pp. 610–616 (2010) [doi: 10.1117/3.821384].
2. K. Jain, *Excimer Laser Lithography*, SPIE Press, pp. 91–131 (1990).
3. A. Reiser, *Photoreactive Polymers: The Science and Technology of Resists*, John Wiley & Sons, p. 254 (1989).
4. D. L. Andrews, *Lasers in Chemistry*, Springer-Verlag, pp. 39–40 (1986).
5. J. Ewing, “Rare-gas halide lasers,” *Phys. Today* **31**(5), 93 (1978).

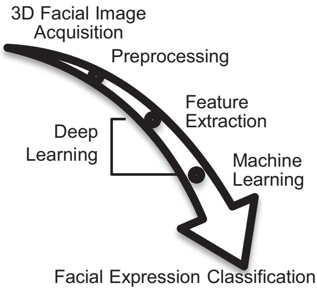
Advances in 3D Human Face Imaging and Automated Facial Expression Analysis

Megan A. Witherow and Khan M. Iftekharuddin
Old Dominion University, USA

Ubiquitous to interpersonal communication and more universal than language, human facial expressions have been a source of intrigue since the time of Darwin. Widespread applications in psychology, medicine, education, marketing, security, human–computer interactions, and more have motivated decades of research in automated facial imaging and facial expression analysis (FEA). Among many promising methods, FEA using constituent action units (AUs) has gained attention. Advances in modern sensing offer rich 2D and 3D facial imaging data that are amenable to automated FEA. Recent advances in sensing and machine learning (ML), and specifically deep learning (DL) methods, offer advantages in processing 3D imaging data. Thus, sensing and analysis of 3D expressions has emerged as an active multidisciplinary area for optical and digital information processing education and research.



Stereophotogrammetry is the use of multiple photographic imaging measurements to estimate the 3D coordinate points of an object, such as a face. Modern 3D stereophotogrammetric imaging systems represent the facial surface with near–ground-truth dense point clouds. These point clouds often undergo preprocessing steps such as 3D image registration and normalization followed by feature extraction from the 3D point cloud data. In a traditional ML pipeline, feature engineering is performed to compute geometric features (such as 3D curvature features) and spatial features (such as geodesic distances between facial landmarks). The features are subsequently input into ML models, such as *k*-nearest neighbor or support vector machines, for learning and classification. By contrast, DL models learn feature extraction and classification steps directly from the data. Different types of DL



models require different input representations for the 3D facial data. Common representations include 3D occupancy grids for models such as 3D convolutional neural networks (CNNs), 3D meshes for graphical CNNs, and raw point clouds for PointNets.

Teaching 3D FEA occurs best through hands-on experiments that apply theory to solve real problems. Advances in imaging technology, processing power, and storage capability have opened the doors for experiential learning opportunities in sensing and processing of 3D data. There remain many exciting open research areas for students and researchers. Powerful ML/DL methods have proved promising for robust AU-based analysis of neutral, happy, sad, and surprised expressions. However, expressions of fear and anger, with confounding subtle and co-occurring AUs, remain challenging. Current state-of-the-art 3D imaging and FEA methods still have a long way to go before they are ready to address the challenges of real-world applications such as automated expression analysis in autism intervention. Furthermore, due to large-scale variations in 3D data, existing methods fail to generalize to subjects outside of the training set. Overcoming these exciting challenges will be the next frontier to expanding 3D FEA beyond the laboratory and into real-world applications.

Notes on Photonic Concepts and Ideas vs. Algebra

Brian Culshaw
University of Strathclyde, United Kingdom

Photonics is a fascinating subject, principally because it is the only branch of physics that we can see! There are also countless useful equations, which tend to dominate the teaching process. However, the fact that we can see light is a powerful tool in teaching, understanding, and using photonics. Among the phenomena we can see and use, we have scattering of light and diffraction, focusing of light, and reflection and refraction. Let's spend a little time exploring a few examples. We also need a few kit pieces to illustrate concepts. A laser pointer can be used for much more than putting a dot on a projector screen, and a magnifying glass is also a very good contributor.

In a homogeneous medium, light obligingly travels in a straight line. Usually, the air we breathe is homogeneous enough to make the point—although even shining your laser pointer through a darkened room illustrates that we can, after all, see scattered light, which tells us where the laser beam is traveling. This is a very useful accidental tool by which to visualize light rays and trace the path they take.

The same tool—the laser pointer—also obligingly illustrates refraction at media interfaces, diffraction gratings, and the impact of a variety of diffracting media, for example, some thinly woven cloth; there's some in every household. You'll very easily see the impact of spacing on direction. Stretch some partially transparent cloth—your shirt or blouse, for example—and see how the diffraction angle changes as the tension increases and/or changes direction.

Refraction is a little more evasive—simply because you're really looking for a change in the direction of a light beam as it reaches an interface. However, a little imagination soon gives some straightforward examples. Even a pane of glass can give some insight when light is incident at an angle to the glass surface then that angle changes by the amount by which the beam moves—including incident perpendicular to the surface when the beam doesn't change direction at all!

These are but a few examples of how the essential concepts of optics—reflection, diffraction, and refraction—can be readily demonstrated using everyday equipment. It also helps all concerned to see and expect the results of an illumination source on the object you see and the light reflected or scattered from it. The general idea is to raise awareness among all concerned of the simple observation that the sometimes apparently complex concepts of optics are in the everyday environment. See the light!!!

The see-to-teach-and-use factors:
See:

- Light travels in straight lines except for scatter and refraction.
- Scatter can be seen in even slightly dusty, but otherwise transparent, media.
- Refraction can be seen, too.
- Color and color changes—combinations of material and illumination—can be perceived.

What's needed as tools?

- a visible laser
- dust to create scatter
- vapor from which to scatter to see light beams
- a focused torch or similar light source

A Classical Approach to Teaching Light–Matter Interaction

Eric Van Stryland and David Hagan
University of Central Florida, USA

One of the authors (EVS) had a teacher in his third year of college who said that the most important problem in physics was the simple-harmonic oscillator (SHO). As the years have gone by, the truth of his statement has continued to be reinforced. Teaching a course on the interaction of light with matter can be greatly facilitated by spending considerable time teaching aspects of the damped, driven SHO. Modeling matter as "electrons on springs" provides remarkable insight into absorption and refraction in atomic/molecular/semiconductor/dielectric materials:

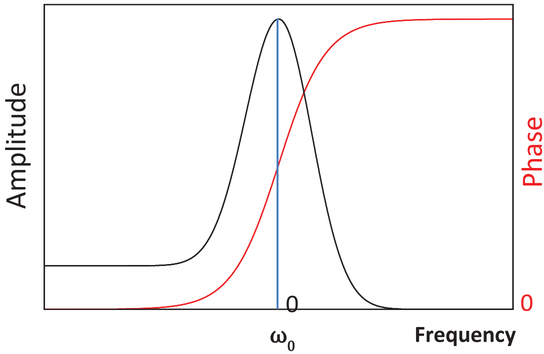
$$m\frac{\partial^2 \vec{r}(t)}{\partial t^2} + \Gamma m\frac{\partial \vec{r}(t)}{\partial t} + m\omega_0^2\vec{r}(t) = -e\vec{E}(t), \text{ with solution}$$

$$\vec{r}(\omega) = -\frac{e}{m}\frac{\vec{E}(\omega)}{\omega_0^2 - \omega^2 - i\omega\Gamma}$$

When teaching a course in this area, it is useful to include in the first lecture a computer simulation of the solution of the SHO equation of motion. Rather than focusing on the temporal growth of the oscillator versus time after a harmonic force is turned on (e.g., turning on a laser), we show several aspects of the steady-state solution while varying the frequency of the driving force. This shows the amplitude and phase with respect to that of the driving force of oscillation going through resonance. Using this model for electron displacement (or nuclear displacement for vibrations) allows for calculation of the polarization $\vec{P}(\omega) = -Ne\vec{r}(\omega)$ with the electron density N, giving the optical susceptibility:

$$\chi(\omega) = \frac{Ne^2}{\epsilon_0 m}\frac{1}{\omega_0^2 - \omega^2 - i\omega\Gamma} = \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\omega\Gamma}$$

Along with the relationship $\epsilon(\omega) = 1 + \chi(\omega)$ this allows for discussion in some detail of the complex Lorentz optical susceptibility, absorption and refraction, 2-level atoms and optical transitions, Lorentzian line shapes, polarization, metals and Drude theory, vibrations, plasma frequency, and the dielectric function from which we can calculate the transmission, reflection, and absorption of some sample material. Some key points about $\chi(\omega)$ are (see figure):



1. The maximum amplitude is in resonance at $\omega \approx \omega_0$ and is purely imaginary.
2. At resonance, the phase difference between **E** and **r** is 90 deg.
3. At high frequencies ($\omega \gg \omega_0$), the amplitude of $\chi(\omega)$ goes to 0.
4. At low frequencies ($\omega \ll \omega_0$), a finite real amplitude of ω_p^2/ω_0^2 is obtained.

Once this model has been discussed for bound (Lorentz) and free (Drude) electrons, we extend it to vibrations in molecules and phonons in crystals, which are again closely related to the SHO. The model even extends to the modes of cavities (e.g., to describe the density of states in semiconductors/dielectrics) and thus black-body radiation. And this model can be easily extended to nonlinear optics by adding a small term in the restoring force that is proportional to a higher-order of **r**, e.g., $\mathbf{r}^2$.

These models allow for discussion of other concepts, such as local field correction factors, Kramers–Kronig relations, Sellmeier equations, etc. It is remarkable that so much of light–matter interaction can be described without the need for quantum mechanics. Although many of these approaches can occasionally be found in condensed matter or spectroscopy texts, there are a few textbooks on light–matter interaction that follow this approach, notably Hopf and Stegeman,[1] Wooten,[2] and Fox.[3]

References

1. F. A. Hopf and G. I. Stegeman, *Applied Classical Electrodynamics, Vol 1: Linear Optics*, Wiley (1985).
2. F. Wooten, *Optical Properties of Solids*, Academic Press (1972).
3. M. Fox, *Optical Properties of Solids*, Oxford University Press (2003).

Laboratory Courses as the Foundation / Pillars of Optomechnical Engineering

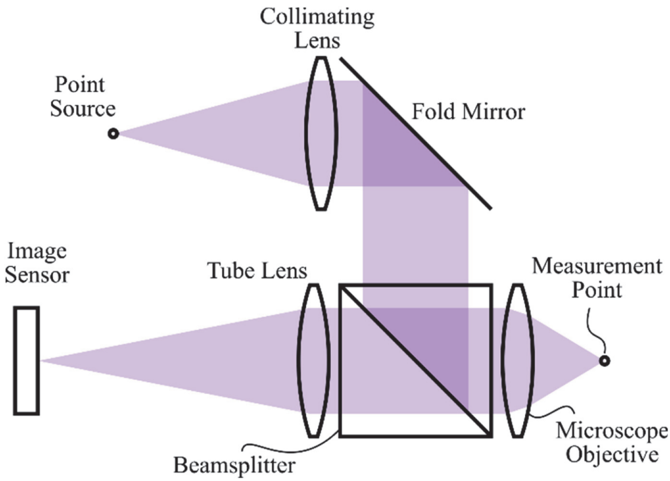
Jonathan Ellis
Micro-LAM, Inc., USA

Learning practical concepts requires getting outside one's comfort zones. Often, learning by doing, such as in laboratory classes, can cement concepts that are first introduced in lecture courses. However, a concept need not necessarily be taught in a lecture first or from first principles. Rather, the application of concept often necessitates understanding broad concepts that are related and can only be fully understood by *doing*. Two examples of this are learning in laboratory classes and learning cross-disciplines such as optomechanical engineering.

In laboratory classes, building and aligning a simple Michelson interferometer or point source microscope using benchtop components can take hours. Those hours are not lost, rather they are used to understand mounting the optics, or the painstaking process of alignment, or the sensitivity of one degree of freedom over another. It may seem frustrating at first, but these are skills that are only fully realized by physically performing them. Similarly, immersing oneself in a new disciple can be painstaking at first. But learning and understanding a few key concepts can build a foundation for future success.

Laboratory Courses as the Foundation

Laboratory courses require more resources to educate students effectively, from equipment, software, and space to instructors, and time. Building a relatively simple optical device, a point source microscope (PSM), can be used to impart many optical concepts and can be accomplished with generic, off-the-shelf components and several key laboratory devices.



The first step in building a PSM is beam collimation from a simple fiber source. This can be accomplished with a shear plate, which also demonstrates interference. The focus through the beam is found by placing a mirror at the measurement point, demonstrating retroreflection.

The reflected beam through the beamsplitter can then be collimated again with the shear plate by correctly aligning the mirror to the measurement point. Lastly, a tube lens is aligned to achieve the smallest focal point.

This can be easily expanded or modified for other concepts. Adding a mirror on the beamsplitter and removing the tube lens changes this to an interferometer. And each of these systems can be reinforced via first-principles calculations and then modeling and analysis can be performed with optical design software!

Pillars of Optomechanical Engineering
Summarizing another discipline, mechanical engineering, such that optical engineers and scientists can utilize key information, is a difficult endeavor. Nomenclature, variable notation, and common abbreviations are some of the issues faced when crossing disciplines. For example, the acronym TIR to many in the optics industry is total

internal reflection. But TIR can also readily refer to total indicator runout for lens centering, metrology, and manufacturing. Understanding the language across disciplines is the first step to branching out to new fields.

For optomechanical engineering, many concepts are required to truly master the discipline. However, many of those concepts can be distilled into three different concepts that form the pillars of optomechanical engineering and affect optical and mechanical components alike.

Everything is a spring. No component has infinite material stiffness, and geometry can affect the compliance, even for supposedly large, rigid bodies.

$$\Delta L = \frac{F}{k}$$

ΔL: displacement
F: applied force
k: stiffness

Everything is a thermometer. Every component has property changes (dimensional, optical, etc.) as a function of temperature.

$$\Delta L = \alpha L \Delta T$$

α: thermal expansion coefficient
L: length
ΔT: temperature change

$\frac{dn}{dT}$ Refractive index changes as temperature changes.

Whatever happens mechanically will be imprinted on an optical wavefront. Optomechanical Engineering is the discipline of understanding and mitigating the impact of mechanical effects on optical systems.