Optical design and optimization strategies: state of the art and future developments

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Authors

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- Working on a PhD on freeform imaging systems.
- Took an interest in search algorithms for optical design.

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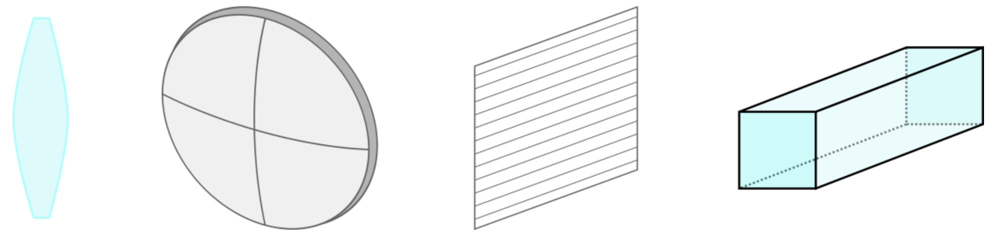
How do optical designers work?

OPTICAL DESIGN BASICS

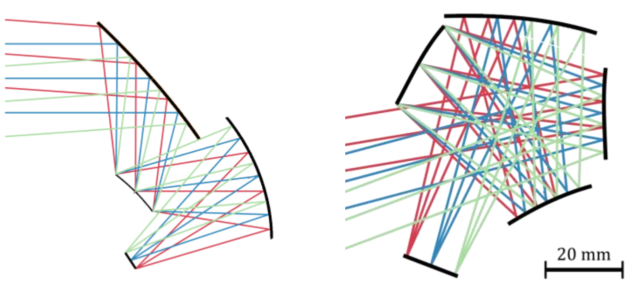
Optical design: Basic principle

Design systems to **direct light** using optical elements such as lenses, mirrors, gratings, light guides etc.



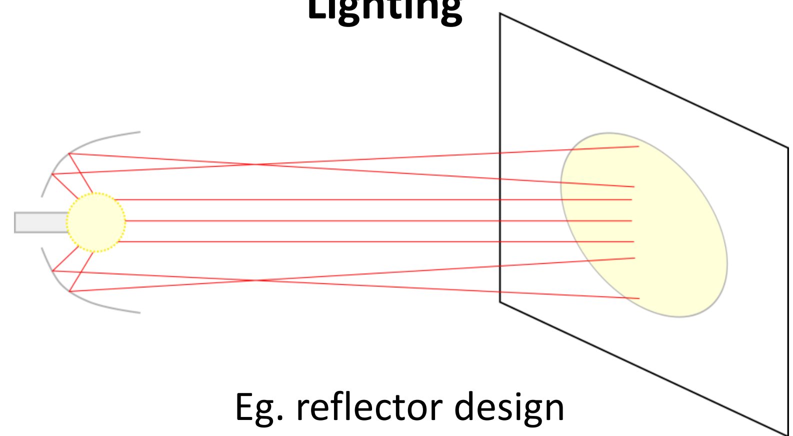
Two fields are often distinguished (although the frontier blurs more and more):

Imaging



Eg. telescope design

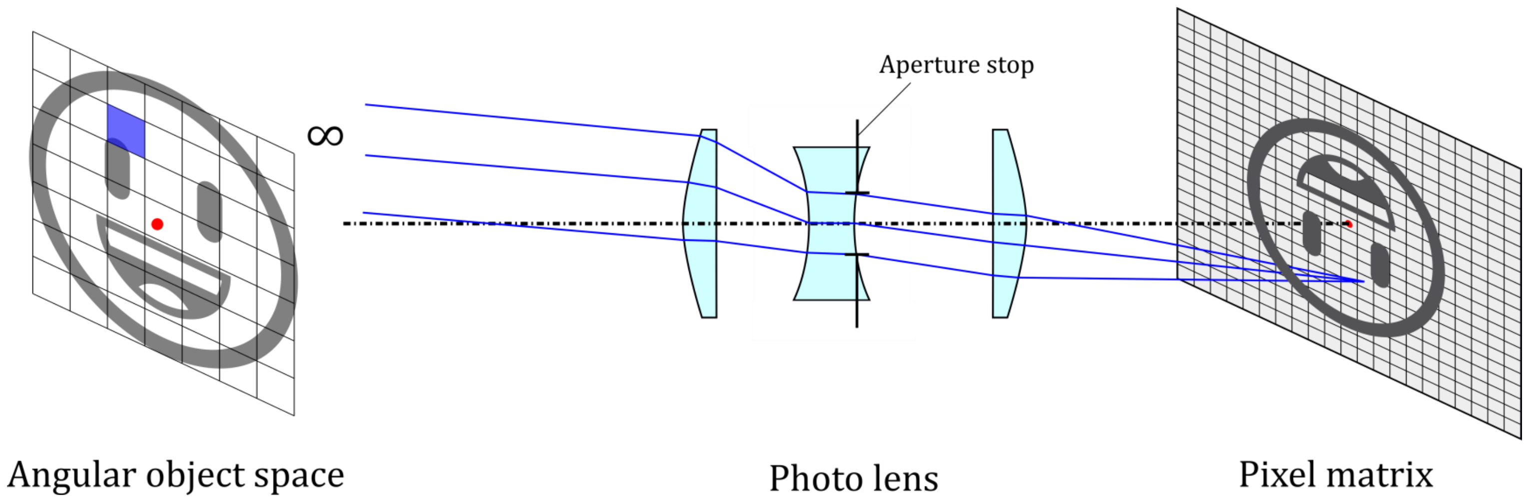
Lighting



Eg. reflector design

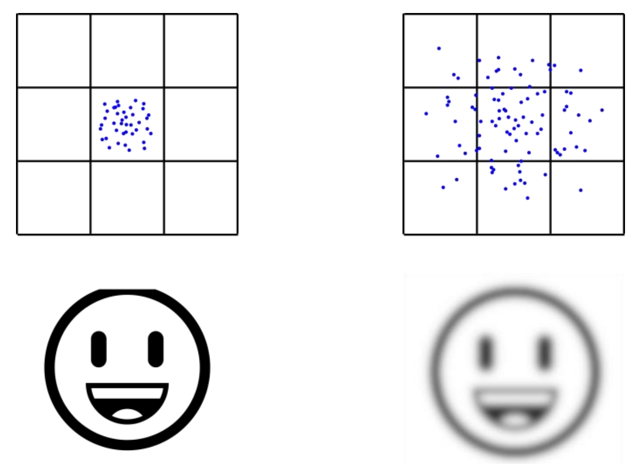
The core simulation tool is **raytracing**, complemented in rarer cases by wave propagation models, finite element method etc.

Modeling imagers: classic photographic lens

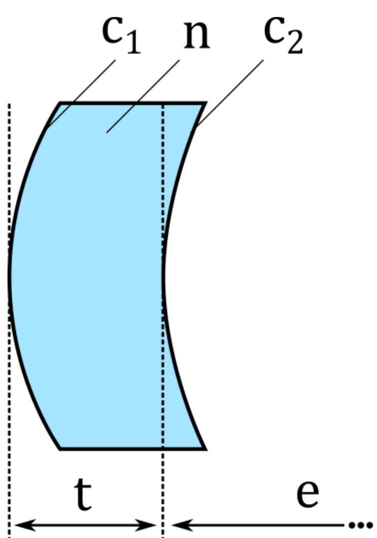


We **raytrace** (Snell law) bundles of rays through the system to assess the **image quality**.
One possible criterion is the spread of impacts on the image plane. The set of these impacts is referred to as a ***spot diagram***.

- Small spot => Good image quality
- Big spot => Bad image quality



Formulation as optimization problem

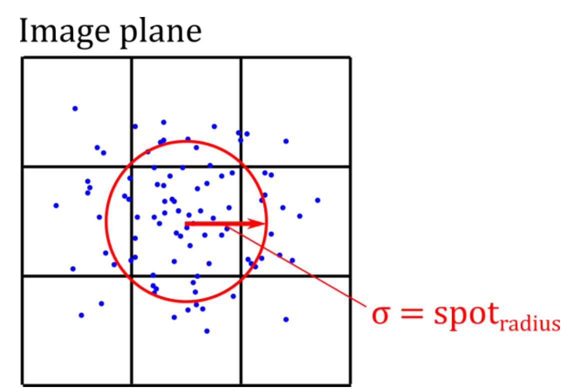


Every spherical lens can be seen as having 5 variable parameters:

- Curvatures c_1, c_2
- Index of refraction n
- Center thickness and distance to next element t, e

A simplistic ***merit function*** (scalar function of the system parameters) for spherical photographic lenses can be:

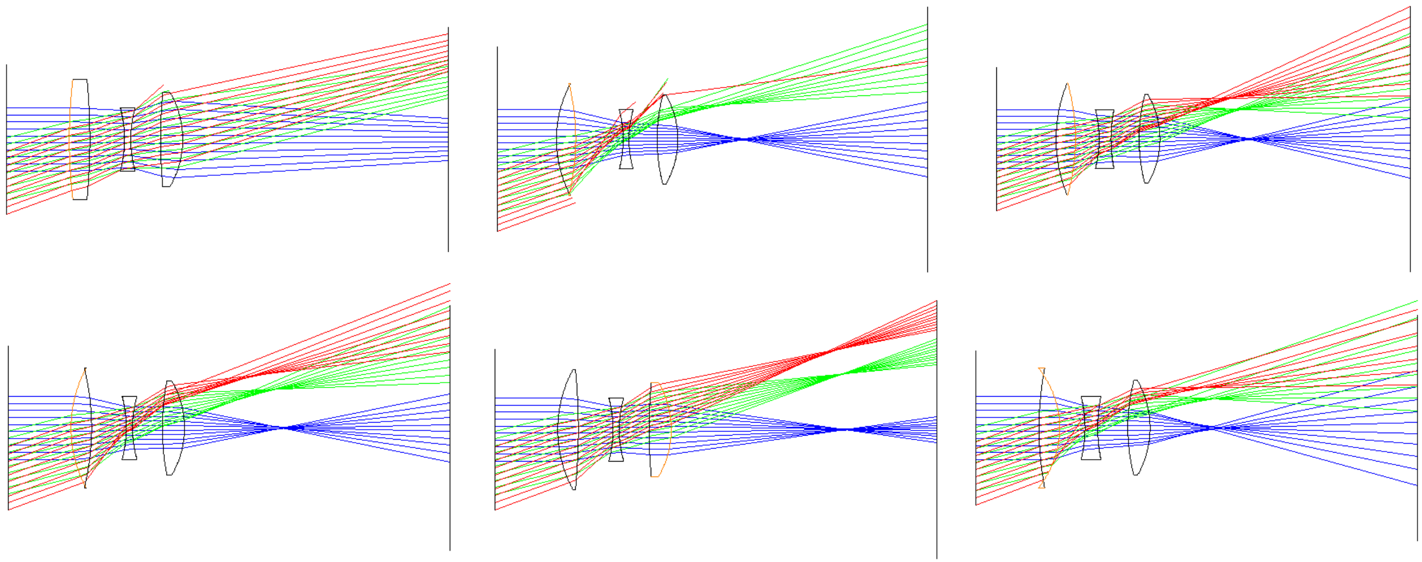
$$Spot_{radius}(c_i, n_i, t_i, e_i)$$



We want to find the set of system parameters giving the lowest score, which is here the best image quality.
Many other optical performance criteria exist: Distortion, Modulation Transfer Function, sum of aberrations etc. etc.

Solving the optimization problem

A search strategy simulates the raytracing through systems with varying parameters of radii of curvature and thicknesses until good performance is achieved.



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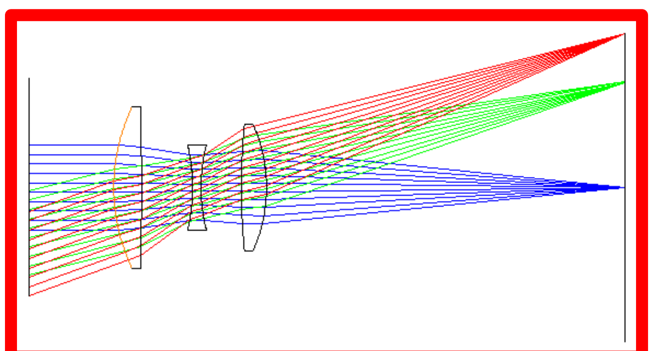
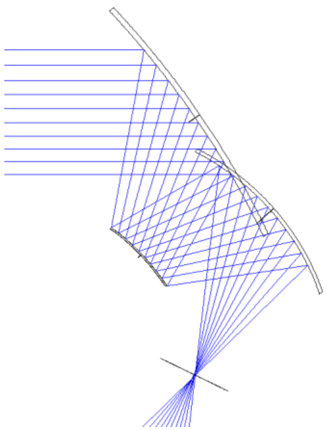


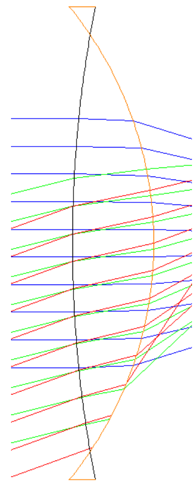
Some constraints and infeasible cases

Constraints

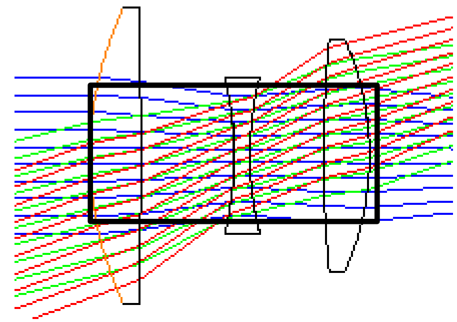
- Computation still possible
- We want to penalize these cases



Colliding elements



Impossible lenses



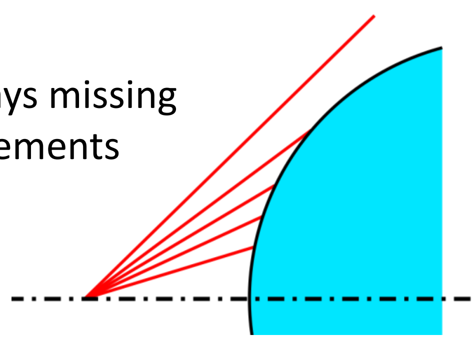
Packaging constraints

And many, many more

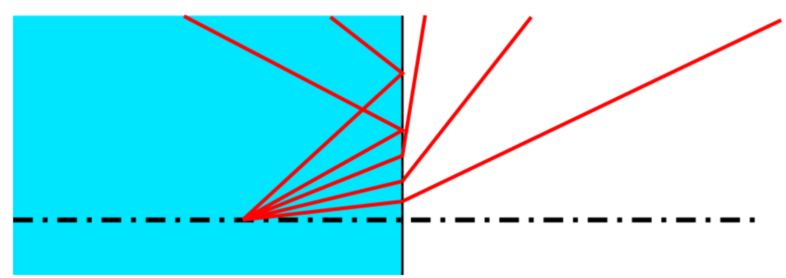
Unevaluable cases

- Computation is usually just thrown out

Rays missing elements



Total internal reflection



Tools available

- **Commercial programs** are available from multiple vendors.
- They provide the possibility to **model** every common optical component. In imaging or lighting applications.
- Some programs in lighting start leveraging GPUs, but still not the norm.
- They are mostly GUI programs. Modularity can be difficult to achieve between raytracer and optimization engine.

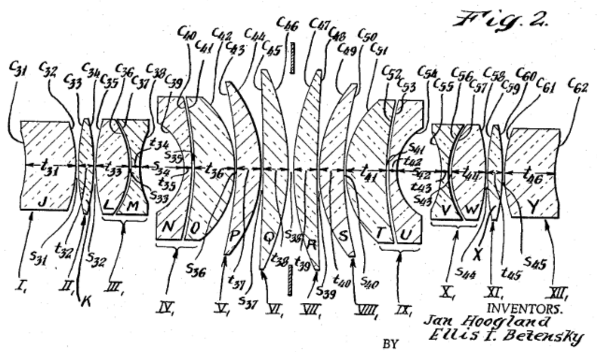
Design resources

Optical system optimization problems are generally too hard for the tools we have. Designers rely on catalogs of **starting points** and search for systems that are close to their own target specifications.

We can cite **books**:

- Smith, Warren J. "Modern optical engineering: the design of optical systems."(1966)
- Welford, W. T., and R. Winston. "High collection nonimaging optics." New York: Academic Press, 1989 (1989).
- Laikin, Milton. Lens Design. CRC Press, 2001.

And **patents** (radii of curvatures, thicknesses etc. are patented):



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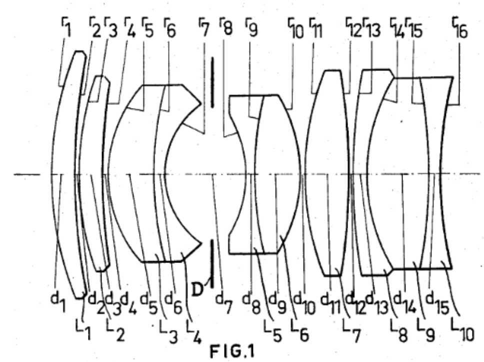

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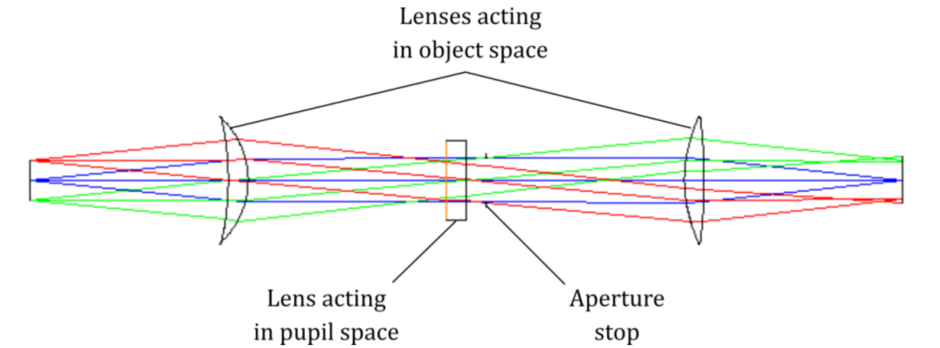
Designer's experience

Optical designers rely on their **experience** and bag of tricks. Examples:

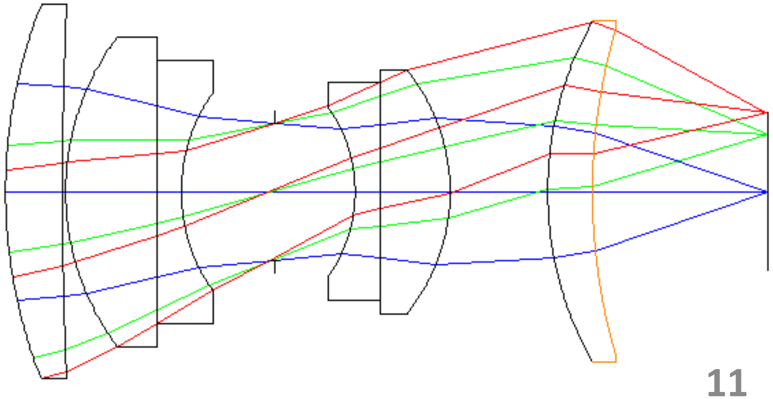
- Being able to divide an optical systems into more or less definite functional **blocks** (see also zoom lenses):



The designer then knows which part of the system to modify and input into the automated search methods.

- Looking at incident angles on optical surfaces.

Looking at ray bundles through a design, the designer can identify weak points.
Here the last lens will be very **sensitive** to mechanical positioning errors!
It can also be an indication that the design isn't the best one.



DEMO: A doublet objective lens in Zemax.

What optical designers would like

- It is safe to say that the **integrated search algorithms** in any of the commercial programs are not state of the art.
- The default in commercial tools is to start from a **single starting point** (although alternatives exist).
- Most of the time we use a **single objective function** (that covers all our specs and constraints).

We need tools adapted to:

- High dimensionality.
- Non-linear behavior, ill conditioning.
- Hybrid variable types (continuous or discrete) in the case of glass selection.
- Independent of starting point.
- Many local optima in the merit function.
- Human interaction. It is often too hard or costly to express all the specifications in the merit function and we discard many mathematically optimal systems before finding the right one.
  … But not too much. There are areas where we think the designer's experience can be replaced by datasets and models.

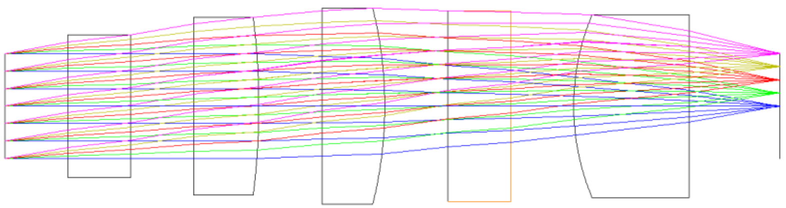
Freeform optics and the problems we have in the design of these systems.

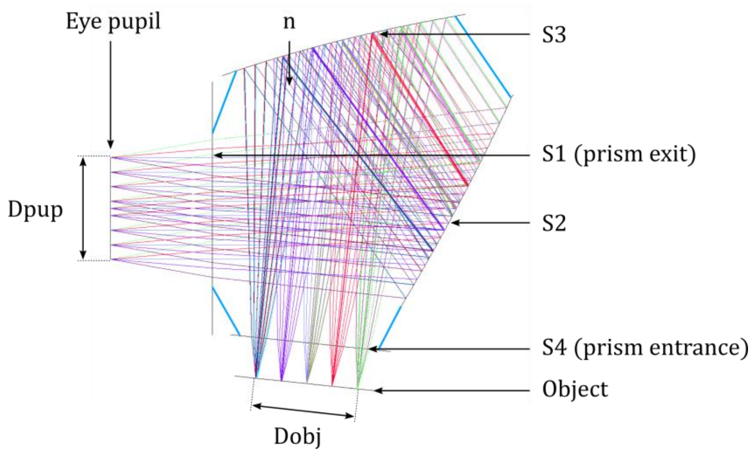
THE ADVENT OF FREEFORM OPTICS

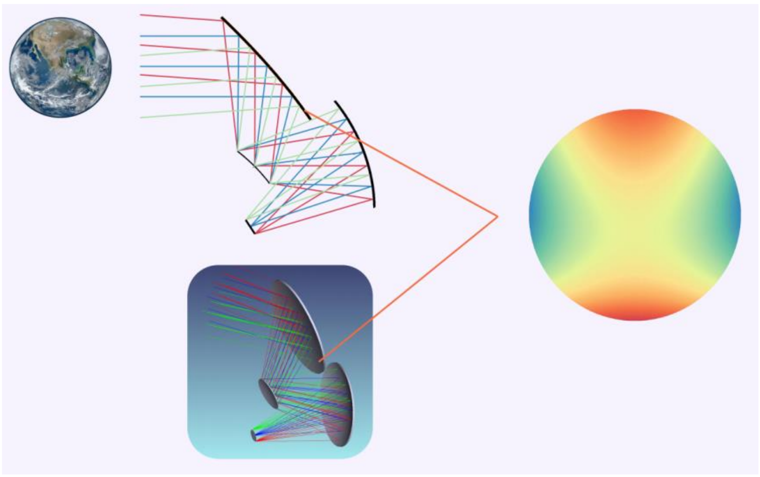
What is freeform optics? Why do we use it?

We use **complex surface shapes** to obtain better optical systems in cases where **compactness** and **performance** is critical. It covers all fields of application. Two examples:

Compact Head Mounted Display
Spherical versus Freeform
(to scale, eye pupil is 5 mm)







Compact unobscured telescope (TMA) for nanosatellite Earth observation.
We need freeform optics to obtain a telescope that has:

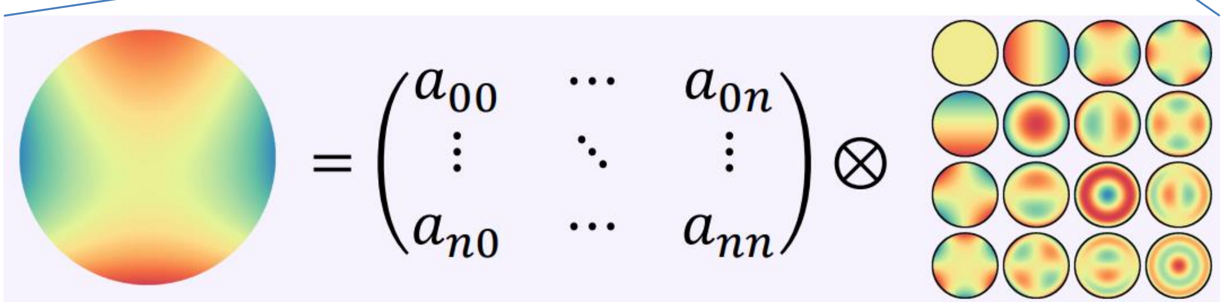
- Compactness
- No obscuration
- Performance

Freeform surfaces mathematical descriptions

By *convention*, we call “freeform” optical surfaces that do not possess an axis of **rotational symmetry**.

The most popular type of freeform model is **2D polynomials**. Other representations include grids of altitude and normals, piecewise patches etc.

$$z(x,y)=\underbrace{\frac{c_x x^2 + c_y y^2}{1+\sqrt{1-(1+\varepsilon_x)c_x{}^2 x^2-(1+\varepsilon_y)c_y{}^2 y^2}}}_{\text{Biconic base shape}}+\underbrace{\sum_j a_j Z_j(x,y)}_{\text{Freeform component}}$$



See also:
Broemel, A., Lippmann, U. & Gross, H. (2017). Freeform surface descriptions. Part I: Mathematical representations. *Advanced Optical Technologies*, 6(5), pp. 327-336

Problems we encounter

- The **dimensionality** of optimization problems goes from ~10 to dozens or hundreds.
- The **evaluation cost** of these systems is higher.
- Optical designers have **no experience** or bag of tricks to rely on in freeform optics.
- There are no large collections of **starting points** to draw from. **Patenting** is becoming rarer.

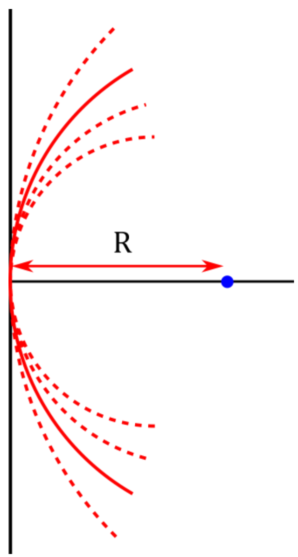
Optical designers are facing harder than ever design problems with a lack of appropriate tools and resources.

Hooks into how machine-learning experts could contribute to optical design (in the view of optical designers) and related subjects.

SUBJECTS FOR MACHINE-LEARNING IN OPTICAL DESIGN (NON-EXHAUSTIVE)

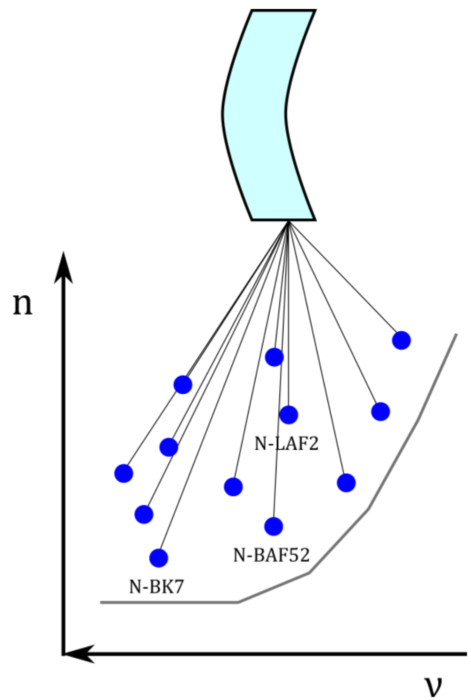
Optimization variable types

Optimization strategies must take into account the **different types** of variables. Decisions are what human optical designers would do with the software. Applying complex automated decision processes to optical design is not yet investigated.



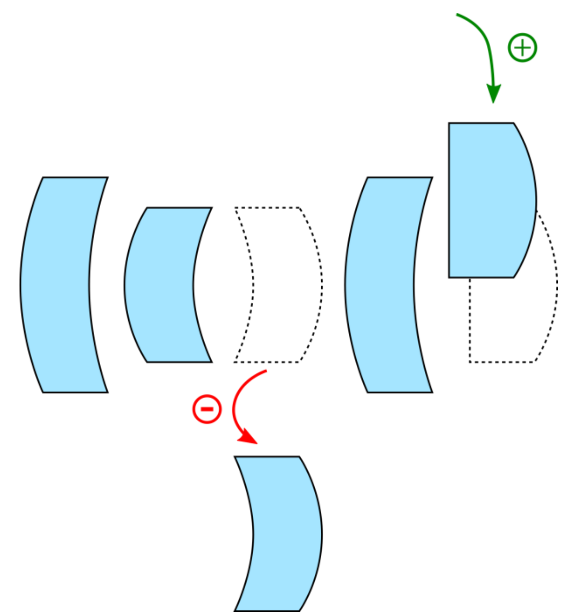
- Radii of curvature
- Freeform coefficients
- Geometrical positions (length and angles)

Continuous



- Optical glasses
- Coatings

Discrete



- Adding or removing elements

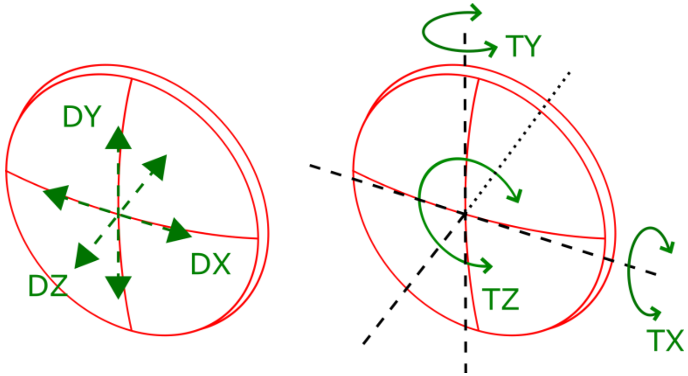
Decision

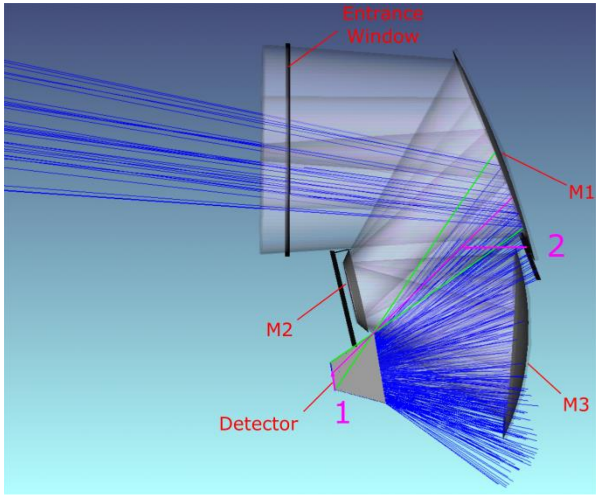
Using costly simulation results

We can include more in-depth but **costly** analysis in our **objectives**.

The synthesis of fast, superficial analysis and costly, in-depth analysis in the optimization process is usually done by the designer. Automated frameworks are lacking.

Tolerancing analysis.
Monte Carlo simulations of perturbed optical systems.





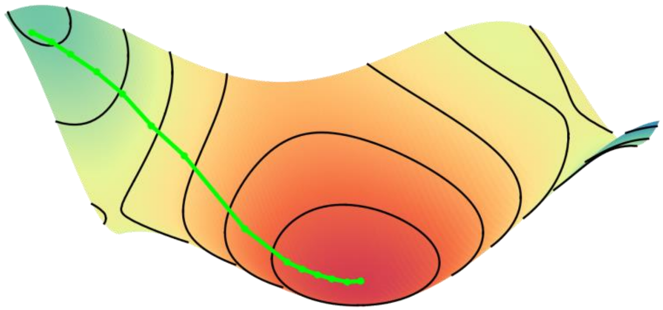
Straylight analysis.
Raytracing millions/billions of rays to check for unintended light paths under conditions of diffraction, diffusion etc. leading to degraded performances.

Search algorithms

- As a general rule, we do not use state of the art search algorithms.
- We have done some work in applying various simple search algorithms to conventional and freeform optical design [1].
- We are collaborating with experts to apply state of the art algorithms to optical design [2].

Our current conclusion is that advanced algorithms allow:

- Reaching good optical systems **faster** in computational time
- Reaching **lower global minima** (even in simple cases!).
- **No single starting point** needed.



Search algorithms involve finding global minima in functions search spaces.

1. Thomas Houllier and Thierry Lépine, "Comparing optimization algorithms for conventional and freeform optical design," Opt. Express 27, 18940-18957 (2019)
2. Maxim Sakharov, Thomas Houllier and Thierry Lépine. "Optimization of Optical Systems with the Mind Evolutionary Computation Co-Algorithm". 4th International Scientific Conference Intelligent Information Technologies for Industry. (submitted)

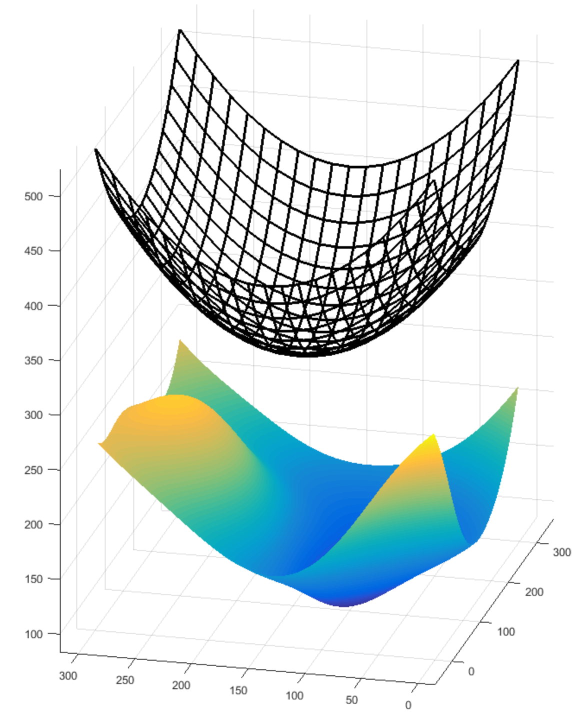
Leveraging analytical surrogate models

Analytical optical aberration theories can be used to assess the optical quality of a solution.

- **Faster** (in most cases) than raytracing simulations.
- Easier access to **derivatives**.
- Usually does not describe the detailed performance of optical systems.

These theories are:

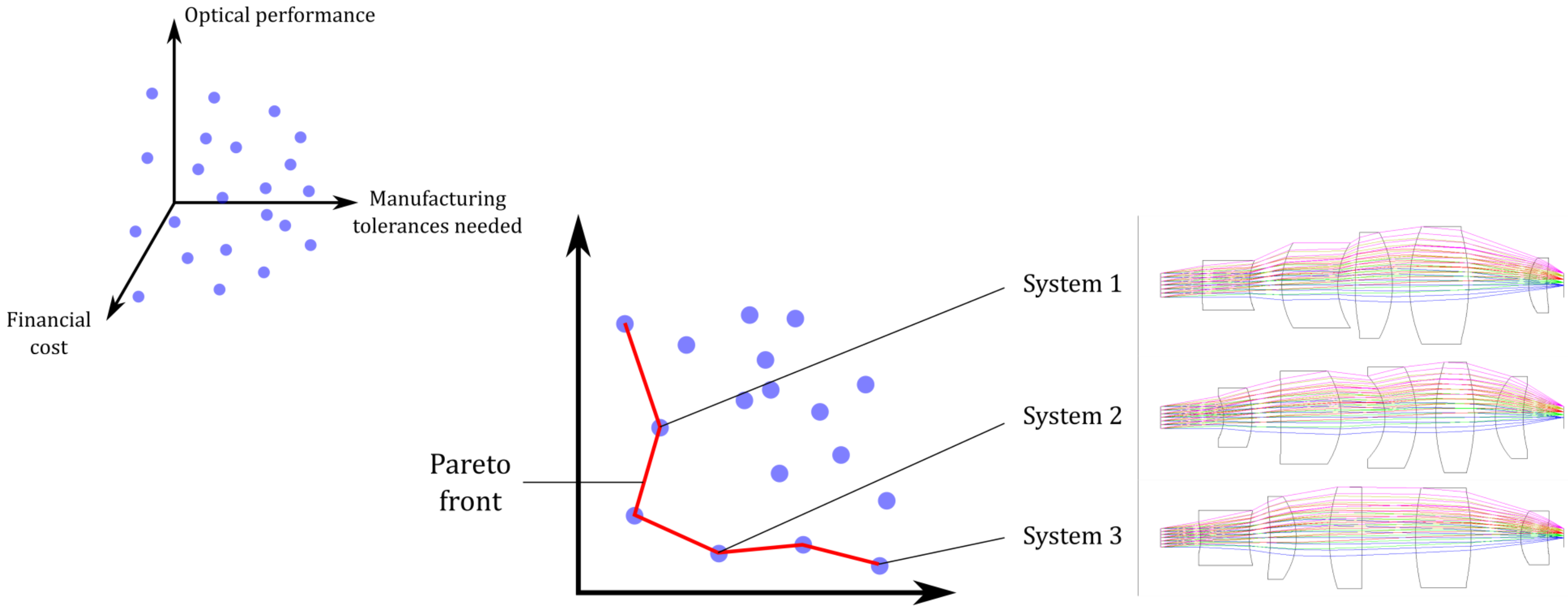
- Well known for **axio-symmetric spherical** systems (Seidel)
- Under research for the general case of **freeform optics** (Nodal aberration theory) [1-3].



Analytical models can be used to guide the optimization process

1. Guohao Ju, Hongcai Ma, Zhiyuan Gu, and Changxiang Yan "Experimental study on the extension of nodal aberration theory to pupil-offset off-axis three-mirror anastigmatic telescopes," Journal of Astronomical Telescopes, Instruments, and Systems 5(2), 029001 (9 April 2019).https://doi.org/10.1117/1.JATIS.5.2.029001
2. K. P. Thompson, T. Schmid, P. Kao, and J. P. Rolland, "Recent Discoveries from Nodal Aberration Theory," in International Optical Design Conference and Optical Fabrication and Testing , OSA Technical Digest (CD) (Optical Society of America, 2010), paper IThB2.
3. Kyle Fuerschbach, Jannick P. Rolland, and Kevin P. Thompson, "Extending Nodal Aberration Theory to include mount-induced aberrations with application to freeform surfaces," Opt. Express 20, 20139-20155 (2012)

Multi-objective optimization



Not typically included in optical design software.
We generally merge all the objectives together in the same MF.

Separating objectives is desirable since we can often accept **compromises** once we know they exist.

Neural networks

[1] demonstrated that neural networks (NN) could be used to **model freeform TMA**.

Inputs:

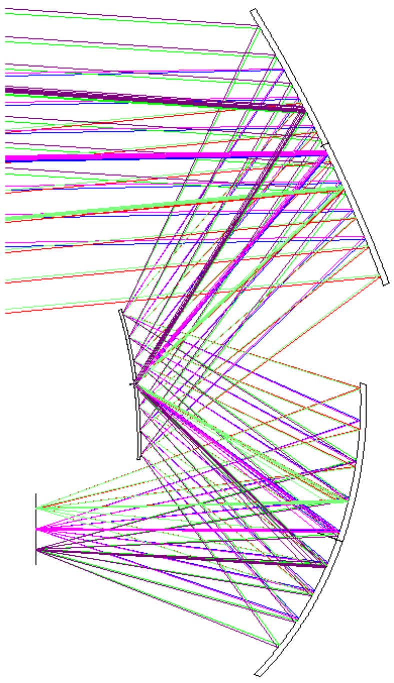
1. FOV
2. Focal length
3. F#

Output:

Freeform telescope description with good optical quality.

This means that the complex interactions between **system geometry**, **surface shapes** and **optical quality** can be modeled by NN.

We could imagine modelling: tolerances, design decisions etc.



A TMA layout

1. Tong Yang, Dewen Cheng, and Yongtian Wang, "Direct generation of starting points for freeform off-axis three-mirror imaging system design using neural network based deep-learning," Opt. Express 27, 17228-17238 (2019)

Concluding remarks

- Optical design relies heavily on **computerized** design of optical systems.
- Optical designers are facing challenges requiring **better tools**.
- Several leads for improvements using machine-learning are **left unexplored** (optical design is a small community, lack of experts).

We can use the help of optimization/machine-learning/IA specialists!

Call for collaborations

- What we feel is hampering research at the moment between optical design and machine learning is the fact that no **simple** and **practical forward model** software exists. The researchers must have commercial licenses and make calls through an API.
- We should soon have **black-box executables modeling optical systems** based on a software we developed. We think this will allow very easy collaborations and applying, at last, state of the art machine learning methods to optical design.

Thank you for your attention