Section 6 – Best Practices for Optical Design Summary

Optical design is a complex process which can be made simpler and more efficient with some best practices by experienced engineers. By following some guidelines from optical designers, common mistakes can be avoided. While in section 5, you created your first design with a step-by-step guide, section 6 will discuss ways to improve your experience with optical design when you begin creating your own original systems.

6.1 Rules of Thumb and General Tips

In this subsection, we have gathered a few of the best practices from our own optical engineers to help you before and during the design process. It is worth thoroughly reading this section to ease the design process.

Before you start

Below are a few things you can do before you begin designing to facilitate and motivate the rest of the design process:

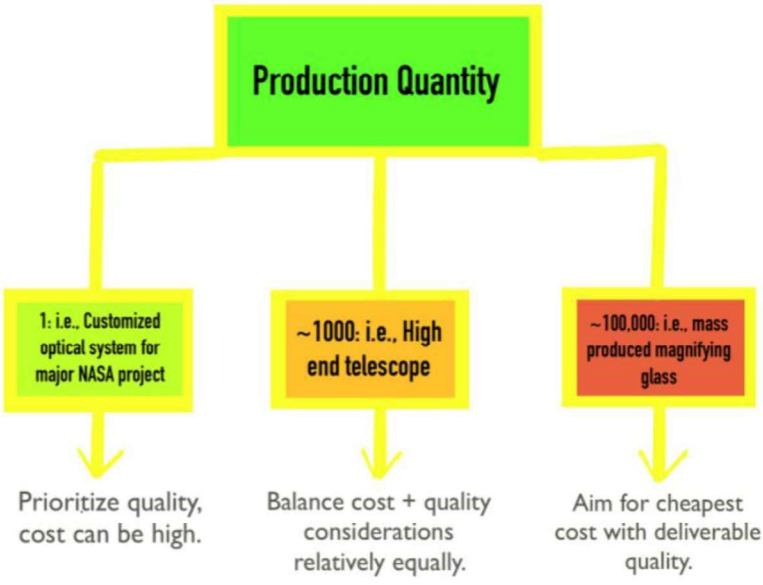


Figure 6.1: Flow chart from production quantity to design emphasis.

Let marketing specs dictate where effort will be emphasized.
→ Some factors to consider are: *cost, profit, quantity,* and *timeline*. It is always necessary to think ahead about the final stretch of the system design and how it will be present to, and reacted from, the market. Figure 6.1 is a tool to help you identify which of cost or quality among other implicit production/manufacturing factors should be prioritized based on the intended production volume.

1. **Think ahead on quantitative limitations.**
   → This means limitations which answer any of the following questions.

   - *What kind/size packaging does this product need to fit?*
   - *How much space is necessary?*
   - *What weight range must the final design stay within?*

2. **Keep environmental factors which may largely impact the physical state and/or functionality of the optical design in mind.**
   → Depending on where the technology is intended to be used, damage from *rain, wind, snow,* and *other forms of precipitation, solar radiation effects,* or *overall dramatic atmospheric differences* (i.e. use on Earth vs. use in outer space) will greatly affect the choices you make as the designer of your system. The choices made to combat environmental hazards are typically associated with materials and material properties used in the system.

3. **Predetermine the locations where attachments for stages, mounts, or other external working parts will be.**
   → Often, an optical system will require additional external components to function properly such as mounts for cameras or stages for telescopes. Predetermining the locations where these attachments will be made and integrating these connections into your design will avoid excess design editing at the end.

Figure 6.2: A few examples of stages and mounts.

4. **Understand your first order parameters.**
   → Be confident with your understanding of the first order parameters. It is worth calculating first order parameters based on the system specifications cautiously to avoid error after the design is already plenty developed. Mistakes in these first order calculations may require you to go back to square one on your design.

   a. **Calculate the field of view (FOV).**
      → The FOV and sensor size will dictate the focal length and image. Similarly, the parameters of the optical system will begin to build off each other until all specifications have been determined (an equation sheet is attached at the end of this section).

$$Horizontal\ FOV\ [mm] = 2WDtan\left(\frac{AFOV}{2}\right)$$

5. **Keep angles small in your design.**
   → Smaller angles will improve accuracy. Paraxial solutions use the approximation $sin\theta = \theta$ which deviates more as the angle increases.

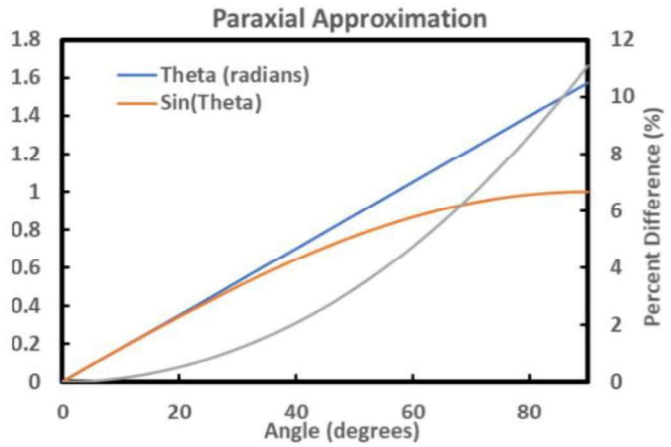


Figure 6.3: Plot demonstrating how θ and sinθ begin to deviate in value as t θ gets larger.

While you design

Just as there are suggestions to practice before the design and build process of an optical system begins, there are also a few tips which are helpful mid-designing. There are warning signs that an optical component may not be practically feasible. Catching these issues as early as possible will avoid delayed production and going over budget.

1. **A component is too thin.**
   → Lens precision is generally ~0.050mm, or ~0.010mm for high precision lenses. The thinner your optical component the greater this tolerance may affect your system. Thinner lenses sacrifice durability and robustness, so carefully consider how important the thickness of your lens is for the application before quickly decided on the thinnest lens.

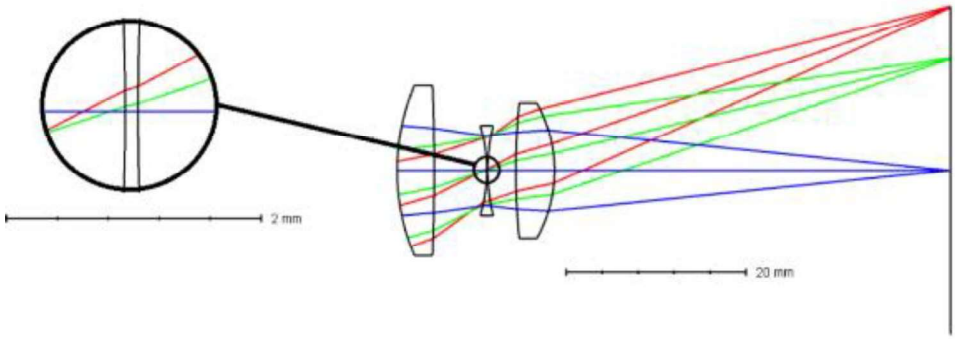


Figure 6.4: A very thin lens.

2. **The lens curvature is too weak.**
   → If the radius of curvature is too weak (very flat), aligning the lens will become difficult. The ROC should generally be greater than 1000mm. If ROC<1000mm, force it to be planar and compensate somewhere else in your system.

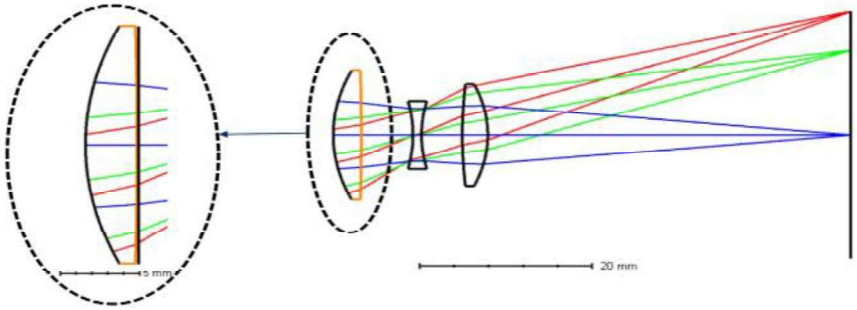


Figure 6.5: Radius of curvature.

3. **The edges are too sharp.**
   → Sharper edges are more fragile and prone to damage. Thick lenses whose diameter is not large enough to accommodte the radius of curvature near the edge are likely to have sharper edges. In handheld optics, there should be a 1:8 ratio roughly between the thickness and diameter of the lens.

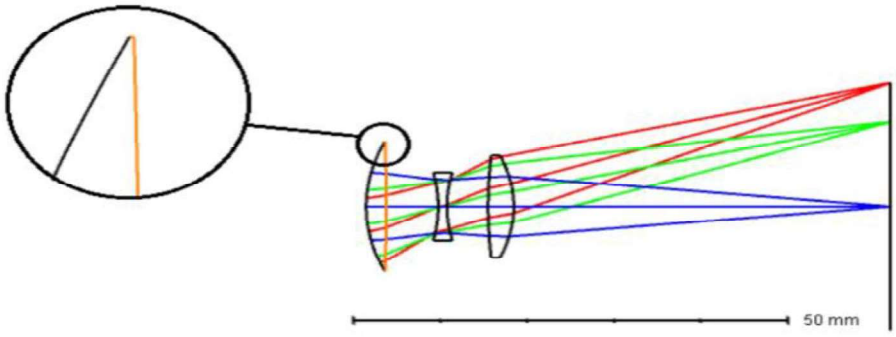


Figure 6.6: Sharp edges.

4. **The lens may not be quite symmetrical.**
   → If the two opposite surfaces of a lens are nearly symmetrical with slight variation, it is better to require symmetry. This is because if the difference between the two surfaces of the lens is not easily distinguishable by eye, the assembler will not know which direction to insert the lens into the system. This could cause components being inserted in the wrong orientation.

   a. **Design with symmetry.**
      → An optical system which is symmetrical around the aperture stop helps to reduce aberrations. For example, the double Gauss lens shown on the next page in Figure 6.7 is a common design that takes advantage of symmetry, allowing the aberrations of the lenses on the left side of the aperture to be counteracted by the aberrations on the right side of the aperture.

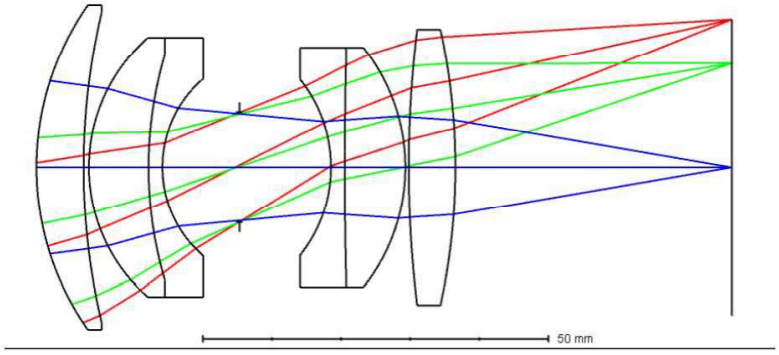


Figure 6.7: A double Gauss design whose symmetry undoes any aberrations on opposite sides of the aperture.

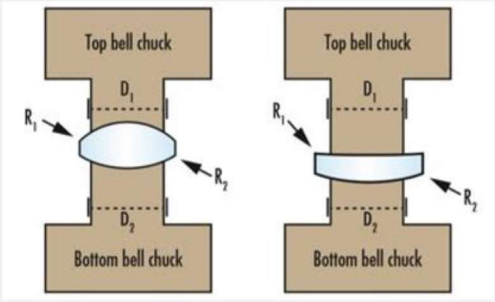
5. **The component is too sensitive.**
   → If small adjustments to the component produce large changes in the performance of the system, alignment will be challenging. Watch for components that produce sharp bends in ray tracing – these components will likely be sensitive to small changes.

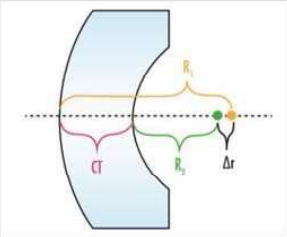
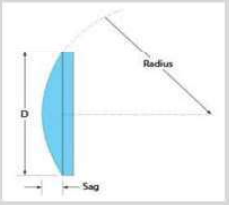
a. **Spread out your aberrations.**
→ Two optical systems can have the same performance and set of aberrations, but in one system, the aberrations may be distributed between the lenses while in the other, the aberrations are primarily coming from one lens. A system with concentrated aberrations coming from less components are harder to align and perform inconsistently.

6.2 Considerations, Tolerancing, and Assumptions

Geometric considerations

Geometric considerations are some of the most important considerations when designing an optical system. This is because often, optical software will not prevent nor warn their users from creating impossible designs. To ensure a manufacturable system, it is important to consider several details throughout the design process.

Geometric Considerations	
Consideration	**Reasoning**
Overestimate lens diameter by ~1mm early in the fabrication process.	Removing material from an oversized lens is easier than adding material to an undersized one.
Keep ET > ~0.7mm and do not make edges too sharp.	Too thin and sharp of edges can result in breakage and/or damage.
Maintain a Karow/Z-factor > 0.56 	Karow/Z-factor: measurement of a lens's ability to self-center between two bell chucks. Too small and the lens may need to be manually centered. $Z = \left\lvert \frac{D_1}{R_1} + \frac{D_2}{R_2} \right\rvert$

Geometric Considerations	
Consideration	**Reasoning**
Keep concentricity > 2mm $\|\Delta r\| = \|R_1\| - \|R_2\| - \mathrm{CT}$ 	Lenses with nearly concentric radii are difficult to center since a large amount of material must be removed to correct for surface-to-surface relative decentering.
Make center thickness (CT) intentionally thick when designing.	Processes such as adjusting surface quality after main lens production will naturally lessen the CT.
Avoid hemispherical ($\mathrm{R} \leq 0.7\mathrm{D}$) and near flat ($\mathrm{sag} \leq 100\mu\mathrm{m}$) surfaces 	Difficult to manufacture

Tolerancing process

Recall from section 1 that **tolerance** is the permissible limits of variation in physical dimensions, properties, or other significant measurements to the product/system. In simplest terms, tolerance is the allowable error. There is a proper tolerancing process which can be completed to tolerance effectively and efficiently. The next page includes a cycle diagram for this process.

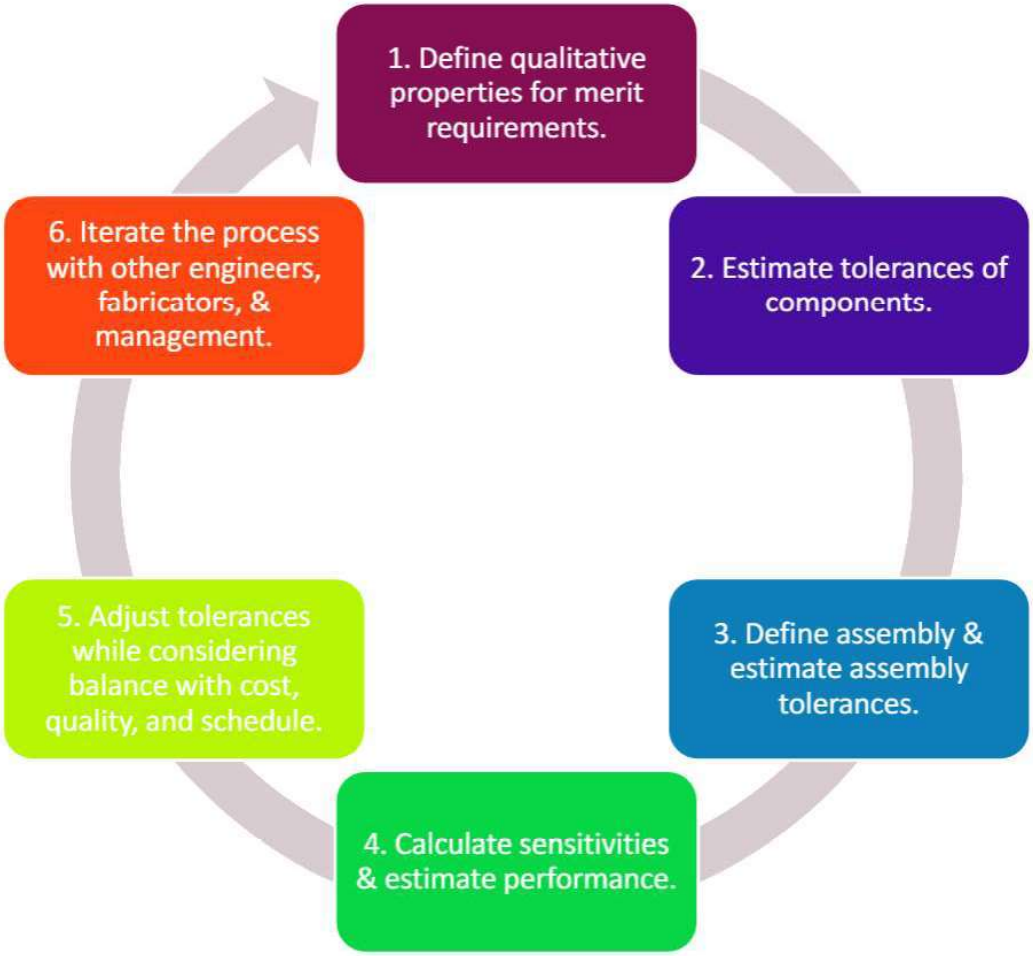


Figure 6.8: Tolerancing process.

Monte Carlo tolerancing method

The **Monte Carlo method** generates random combinations of optical elements by selecting indiscriminate parameter values within each tolerance range, simulation a single production of one product. The outcomes of this method are:

- Simulations of unique optical systems which may be produced in real life.
- Ability to analyze how individual fabrication and assembly of a single unit will perform given components which have measurements lying in different places of the tolerance range.
- Allows engineer to dictate whether tolerances must be tightened or may be loosened to still ensure proper functionality.

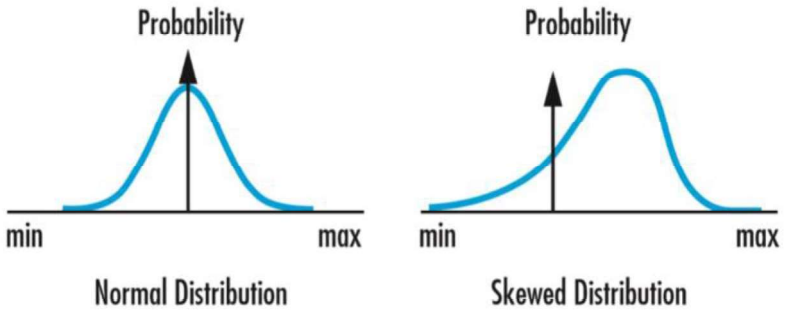


Figure 6.9: Normal vs Skewed Distribution from Monte Carlo.

Diameter tolerance

The **diameter tolerance** of a circular optical component provides the acceptable range of values for the diameter. This manufacturing specifications can vary based on the skill and capabilities of the optical shop that is fabricating the optical component. The diameter tolerance does not have any effect on the optical performance of the optic itself, but it is very important to be considered if the optic is going to me mounted to any type of holder. If the diameter of an optical lens deviates from its nominal value it is possible that the mechanic axis can be displaced from the optical axis in a mounted assembly.

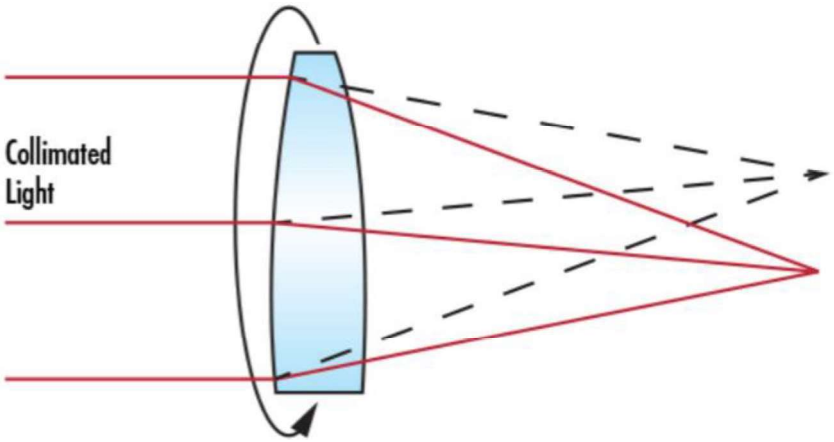


Figure 6.10: Decentering of collimated light.

Other tolerancing tips

Finally, here are a few more quick tolerancing tips which may be helpful in the design process.

- Round to 3 decimal places unless more are necessary → more decimals yield a higher cost.
- 1:8 thickness to diameter ratio for hand-held optics.
- Maximize self-centering components → active alignment is time consuming and costly.

Stack-ups of Assembled Systems

When manufacturers assemble lenses into assemblies, they must be able to ensure that groups of lenses still perform within specification. Physical assemblies have some degree of deviation from ideal design specifications such as tilt and decenter effects. Optical assemblies require additional attention to individual element wedge and tilt as well as system-level stack-ups as elements and spacers push against each other but are subject to limitations of the inner diameter of the barrel. Stack-up models should attempt to accumulate tilt and decenter effects, while keeping elements anchored to the optical axis for additional accuracy.

Centering

Centering, also known as concentration or decenter, of a lens is specified in terms of beam deviation δ.

$$\delta = \frac{\Delta}{f}$$

Once mean deviation is known, wedge angle W can be calculated using the refractive index of the lens material.

$$W = \frac{\delta}{n-1}$$

The amount of decenter in a lens is the physical displacement, Δ, of the mechanical axis from the optical axis. The **mechanical axis** of a lens is the geometric axis of the lens and is defined by its outer cylinder. The **optical axis** of a lens is defined by the optical surfaces and is the line that connects the centers of curvature to the surfaces.

To test for centration, a lens is placed into a cup upon which pressure is applied automatically situating the center of curvature of the first surface in the center of the cup, which is also aligned with the axis of rotation.

Collimated light directed along this axis of rotation is sent through the lens and comes to a focus at the rear focal plane. As the lens is rotated by the rotating cup, any decenter in the lens will cause the focusing beam to diverge and trace out a circle of radius Δ at the rear focal plane.

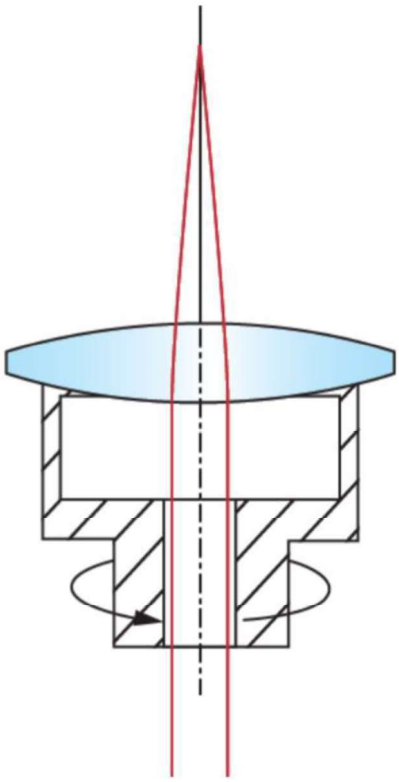


Figure 6.11: Test for centration.

Drop in vs. active alignment assemblies

For **drop in alignment**, lenses are dropped into a lens barrel. The center of the barrel defines the common optical axis and the lens rest on a ring mount. It is then centered by press fitting. The pressure causes the curvature of the lens to align with the center of the barrel. Drop in assemblies are cheaper and easier to do, therefore they are practical for mass productions.

Active alignment is a much more tedious process, as well as a time consuming and costly one. After each lens is added to the barrel, a laser is shined trough the optical axis and the assembly is rotated. If it is not aligned properly, the laser will make a circle. Three set screws are used to adjust the lens to center the laser. The next optical element is then added, and process is repeated

The Monte Carlo method, as introduced in section 6.2, can be used to test how different tolerances of optical components in an assembly will combine.

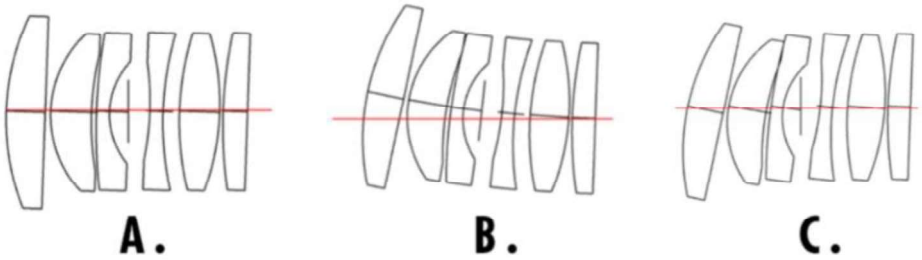


Figure 6.12: Three difference combinations of lenses in an assembly with different tolerances produced via the Monte Carlo method.

Element coupling

When rolling or decentering occurs to one element in an assembly, it can affect the other elements around it. Connected elements will be coupled into a single rolling/decentering element and roll/decenter together.

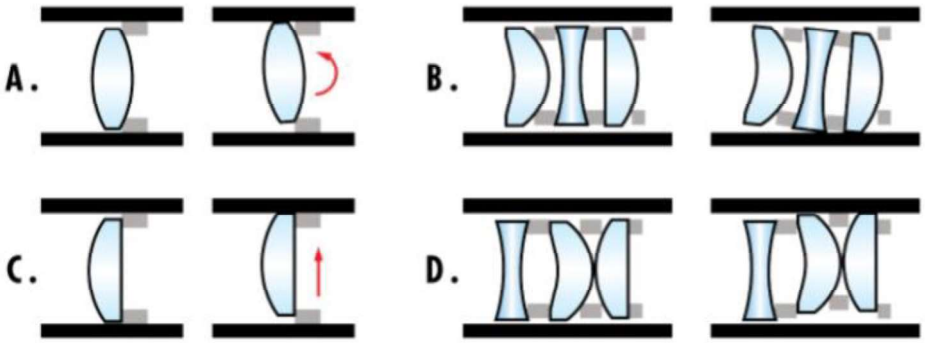


Figure 6.13: A) Singlet rolling. B) Element couple rolling. C) Singlet decentering. D) Element couple decentering.

6.3 Describing Surface Irregularities

The **wavefront** is an imaginary surface connecting all the rays passing through a system at the point where each ray has travelled the same optical path length. For an imaging system, the ideal wavefront between the optics and the imaging plane is spherical in shape.

Irregularity is a type of surface accuracy specification which describes how the shape of a surface deviates from the shape of the intended design. Surface irregularity corresponds to the wavefront produced by the optical system, and any surface irregularity will produce a change in the wavefront and degrade the optical performance of a system.

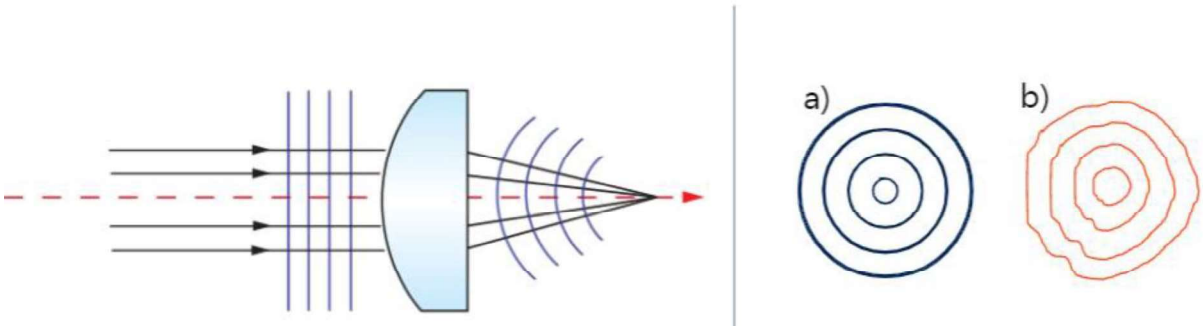


Figure 6.14) *Left*: Plano-Convex lens changing plane wavefront to spherical wavefront. *Right*: (a) the ideal wavefront measurement (b) a distorted wavefront from surface irregularities.

Modeling surface irregularity

The modeling of surface irregularities can range from simple to complex depending on the requirements of the application. Some commonly used simplified surface irregularity models include:

- Fitting a surface to either a 50/50 combination of spherical aberration and astigmatism
- Using 100% astigmatism

It is not recommended to disregard coma, trefoil, and other higher-order effects for lens assemblies with many elements or for optically sensitive systems. While convenient, the above simplifications of surface irregularity models do not sufficiently reproduce the wavefront error or irregularity of a system.

Zernike function

A **Zernike polynomial** is a sequence of polynomials that describe the surface modes on a disk and are commonly used to describe wavefront aberrations. The number of polynomials is infinite, and more polynomials yield a better description of the wavefront.

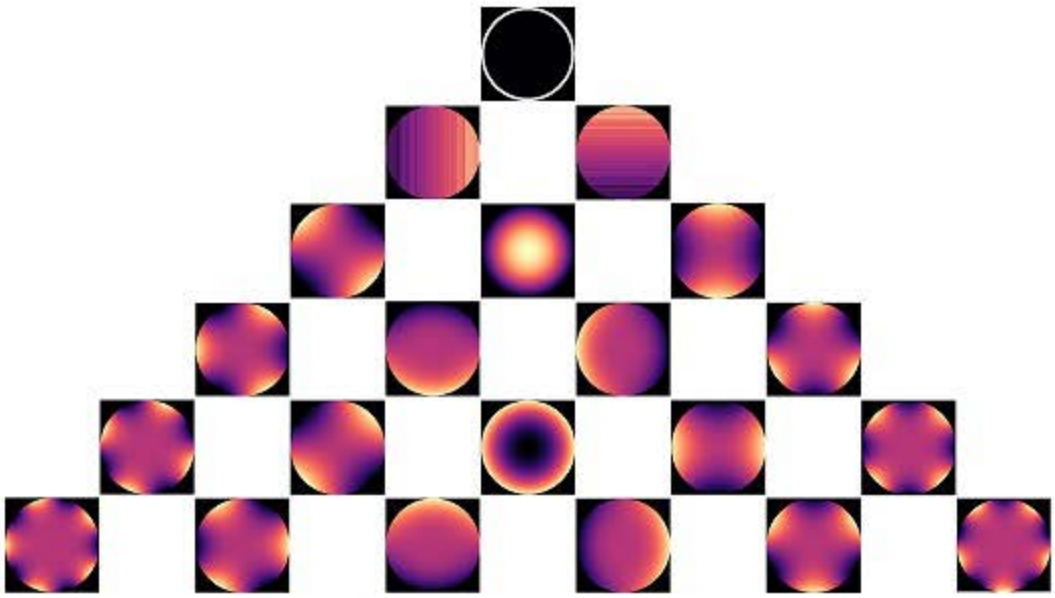


Figure 6.15) 21 Zernike polynomials

The **Zernike terms** represent different components of the wavefront error, and they are each independent of one another. These terms correspond to different aberrations. Figure 6.16 show the contributors up to the third order aberrations such as: tilt, astigmatism, defocus, coma, spherical.

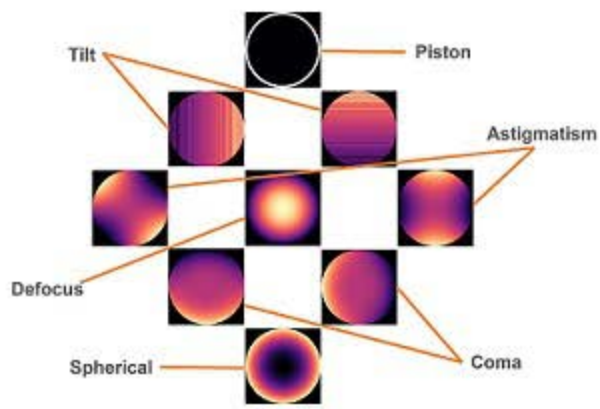


Figure 6.16) Corresponding aberrations for Zernike functions up to the third order polynomials