Aberrations

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- Degradation results when light rays from a given object-point fail to form a single sharp image-point
- *It's important to recognize that aberrations are the rule, not the exception*
  - Aberration-free vision essentially never occurs

Aberrations

- Some aberrations are attributable to corrective lenses

Aberrations

- Some aberrations are attributable to corrective lenses
- Others are intrinsic to the eye itself

Aberrations

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  - Three familiar forms:

Aberrations

- Some aberrations are attributable to corrective lenses
- Others are intrinsic to the eye itself
  - Three familiar forms:
    - Spherical error (myopia/hyperopia)
    - Cylinder (astigmatism)
    - Chromatic aberration

Aberrations

- Back in the day, only three aberrations were recognized by clinicians:

  1)

  2)

  3)

Aberrations

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  1) Spherical error (ie, myopia/hyperopia)
  2) Regular astigmatism
  3) Irregular astigmatism

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     - *Regular* meaning
  3) Irregular astigmatism

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Essentially, *irregular astigmatism* was a wastebasket term for aberrations that:
1) could not be measured in the clinic; and
2) could not be corrected (by glasses) even if they had been measureable

Aberrations

Old Lingo

Sphere
Myopia
Hyperopia

'Regular Astigmatism' — Cylinder

'Irregular Astigmatism' — Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses

This is how we thought of aberrations back in the day

Aberrations

- two words did away with the first problem

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Aberrations: Wavefront Analysis

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Aberrations: Wavefront Analysis

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  - Allows clinicians to identify/quantify many of the refractive problems previously consigned to the irregular-astigmatism wastebasket

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  - Several different technologies for measuring the wavefront have been developed, but one dominates current clinical practice:
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    The *Hartmann-Shack wavefront sensor*

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Aberrations: Wavefront Analysis

How does the Hartmann-Shack wavefront sensor (HSWS) work?

current clinical practice:

The ***Hartmann-Shack wavefront sensor***

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Aberrations: Wavefront Analysis

How does the Hartmann-Shack wavefront sensor (HSWS) work?
Essentially, by reversing the function of the eye. Instead of treating the eye as a light-gathering device, it treats the eye as a light-**emitting** device. It then analyzes the wavefront of light emitted by the eye with respect to how 'pure' (ie, how uniform and free of warpage) it is.

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How does the HSWS turn the eye into a light-emitting device?
By firing a low-power laser into the eye that reflects off the fovea. The reflected light then passes through the focusing structures of the eye (ie, the lens and cornea), and leaves the eye.

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OK, so the HSWS turns the eye into a flashlight of sorts. How does this allow for identification and quantification of aberrations?

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OK, so the HSWS turns the eye into a flashlight of sorts. How does this allow for identification and quantification of aberrations?
The HSWS contains an array of sensors that measure the 'emitted' light. If the refracting structures of the eye were perfect (ie, aberration-free), the wavefront of the emitted light would be perfectly flat--any deviation from flatness represents aberration, which in turn reflects imperfections in the eye's focusing structures.

current clinical practice:

The ***Hartmann-Shack wavefront sensor***

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Aberrations

Old Lingo		***New Lingo*** (from wavefront analysis)
Sphere (Myopia, Hyperopia)	=	Defocus
'Regular Astigmatism' – Cylinder		
'Irregular Astigmatism' – Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses		

Aberrations

Old Lingo		***New Lingo*** (from wavefront analysis)
Sphere	=	Defocus
Myopia	=	+ vs (-) defocus
Hyperopia	=	+ vs (-) defocus

'Regular Astigmatism' { Cylinder

'Irregular Astigmatism' { Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses

Aberrations

Old Lingo		***New Lingo*** (from wavefront analysis)
Sphere	=	Defocus
Myopia	=	*Positive* defocus
Hyperopia	=	*Negative* defocus

*To remember which is which, note that each is the same as the **error lens** responsible for each status*

'Regular Astigmatism' — Cylinder

'Irregular Astigmatism' — Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses

Aberrations

Old Lingo		*New Lingo* (from wavefront analysis)
Sphere	=	Defocus
Myopia	=	*Positive* defocus
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'Regular Astigmatism' — Cylinder	=	

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Aberrations

	Old Lingo		*New Lingo* (from wavefront analysis)
	Sphere	=	Defocus
	Myopia	=	*Positive* defocus
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'Regular Astigmatism'	Cylinder	=	Cylinder
'Irregular Astigmatism'	Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses		

Aberrations

	Old Lingo		***New Lingo*** (from wavefront analysis)	
	Sphere	=	Defocus	'Lower-order Aberrations'
	Myopia	=	*Positive* defocus	
	Hyperopia	=	*Negative* defocus	
'Regular Astigmatism'	Cylinder	=	Cylinder	

'Irregular Astigmatism': Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses

Aberrations

Old Lingo		*New Lingo* (from wavefront analysis)	
Sphere	=	Defocus	'Lower-order Aberrations'
Myopia	=	*Positive* defocus	
Hyperopia	=	*Negative* defocus	
'Regular Astigmatism' – Cylinder	=	Cylinder	
'Irregular Astigmatism' – Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses	=	two words; (Others, less clinically relevant)	

Aberrations

Old Lingo		*New Lingo* (from wavefront analysis)	
Sphere	=	Defocus	'Lower-order Aberrations'
Myopia	=	*Positive* defocus	
Hyperopia	=	*Negative* defocus	
'Regular Astigmatism': Cylinder	=	Cylinder	
'Irregular Astigmatism': Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses	=	Spherical aberration; Coma; Trefoil; (Others, less clinically relevant)	

Aberrations

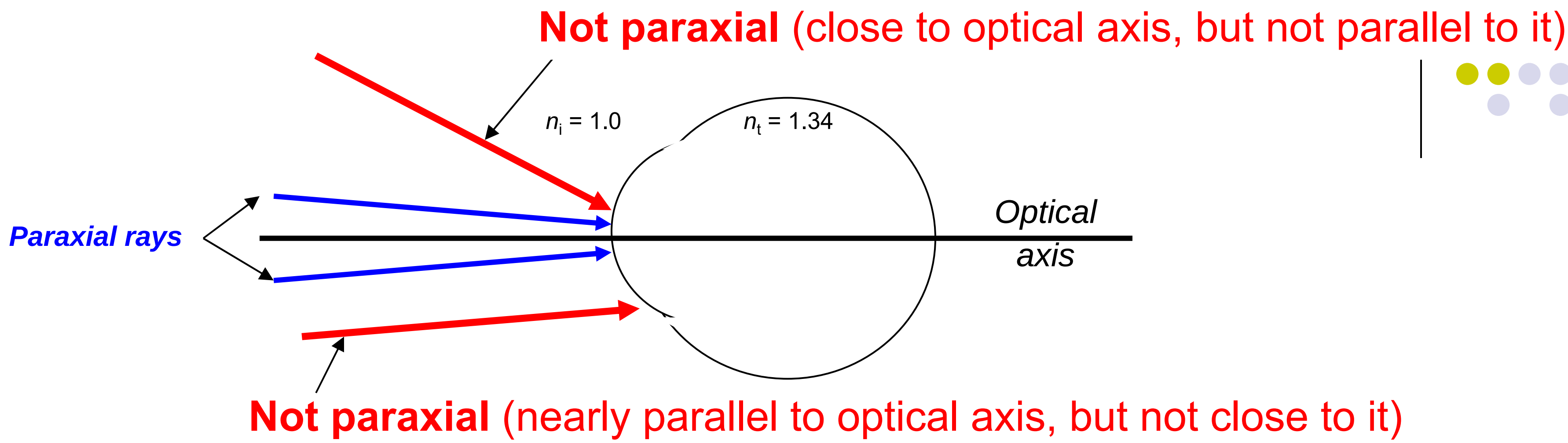
Old Lingo		***New Lingo*** (from wavefront analysis)	
	Sphere	=	Defocus	‘Lower-order Aberrations’
	Myopia	=	*Positive* defocus	
	Hyperopia	=	*Negative* defocus	
‘Regular Astigmatism’	Cylinder	=	Cylinder	
‘Irregular Astigmatism’	Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses	=	Spherical aberration Coma Trefoil (Others, less clinically relevant)	‘Higher-order Aberrations’

Aberrations

Old Lingo		*New Lingo* (from wavefront analysis)	
	Sphere	**Defocus**	'Lower-order Aberrations'
	Myopia	***Positive* defocus**	
	Hyperopia	***Negative* defocus**	
		Cylinder	
'Irregular Astigmatism'	Any component of refractive error that could not be remediated with spherical and/or cylindrical lenses	**Spherical aberration**	'Higher-order Aberrations'
		Coma	
		Trefoil	
		(Others, less clinically relevant)	

We will address these in greater detail later in this slide-set

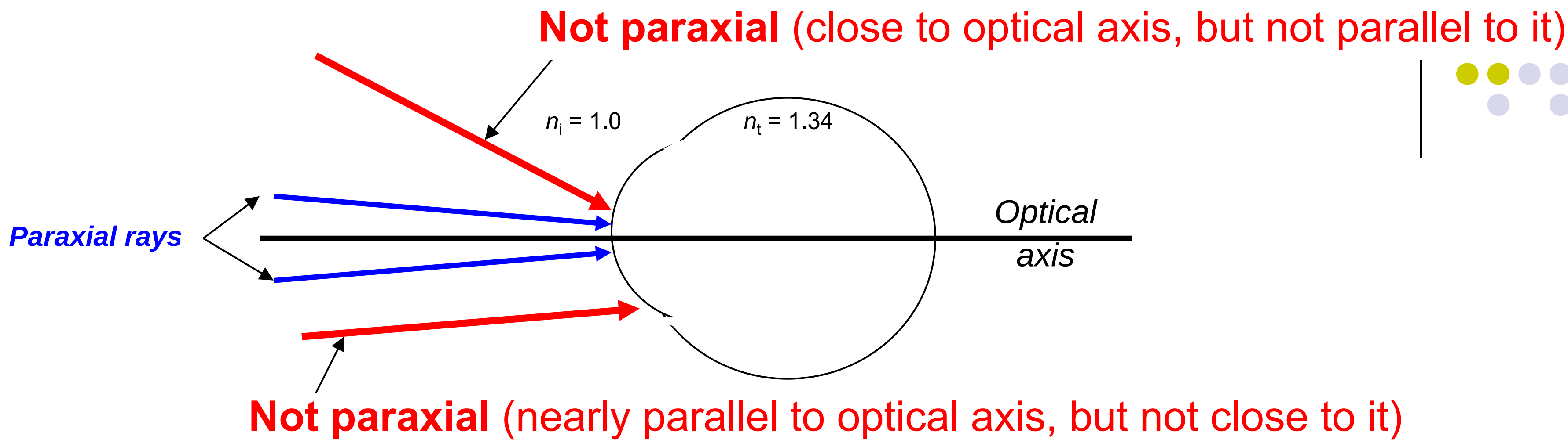
Aberrations



When dealing with refraction at a curved surface, we work only with the ***paraxial rays:*** *Those that are both **close to the optical axis** and **nearly parallel to it.***

(The above was presented first in the slide-set Basic Optics, *Chapter 17. If you have no idea what it's about, consider reviewing that chapter.)*

Aberrations



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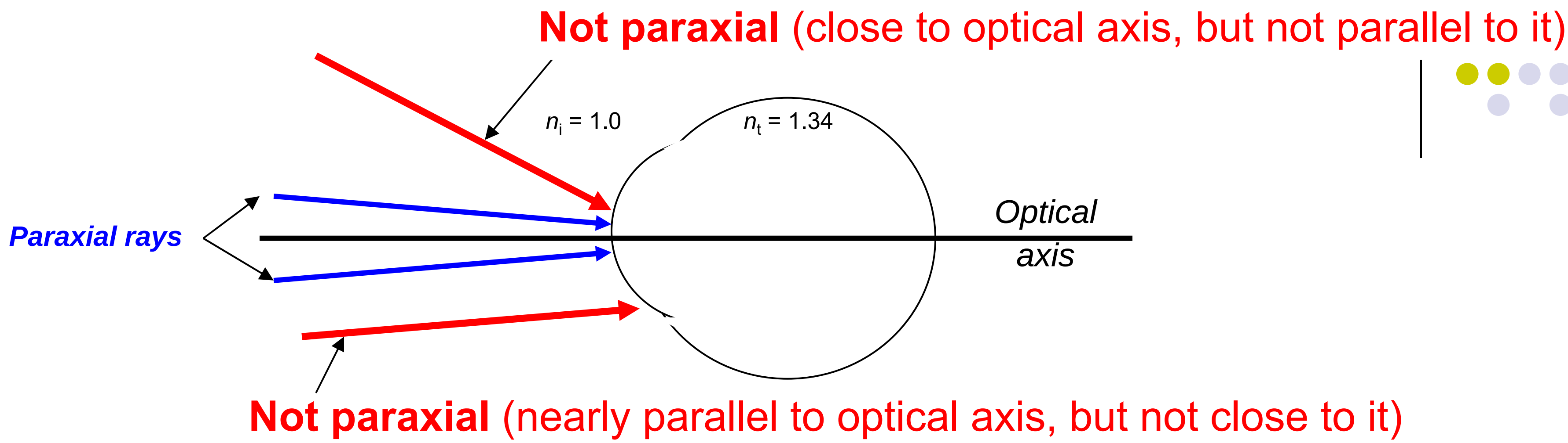
Until now, we have focused exclusively on the optics of paraxial rays. But to understand higher-order aberrations, we have to consider the optics of nonparaxial rays.

Aberrations



When dealing with refraction at a curved surface, we work only with the ***paraxial rays:*** *Those that are both* ***close to the*** ***optical axis*** *and* ***nearly parallel to it.***

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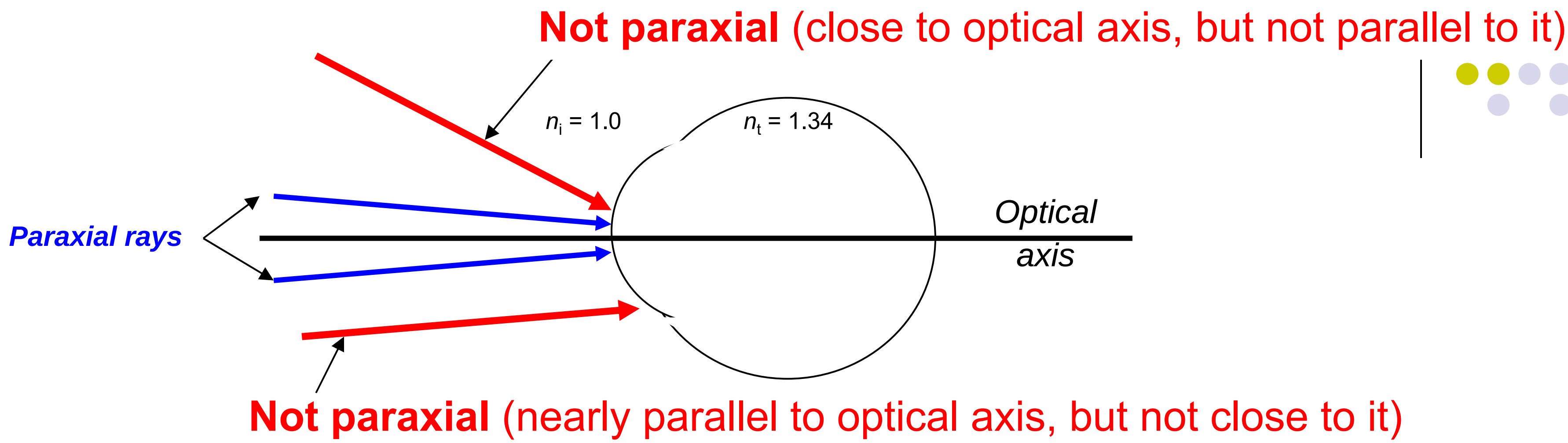
The clinically **most important** higher-order aberration stemming from nonparaxial rays is ______, so we'll discuss it first.

Aberrations



When dealing with refraction at a curved surface, we work only with the ***paraxial rays:*** *Those that are both **close to the optical axis** and **nearly parallel to it.***

Until now, we have focused exclusively on the optics of paraxial rays. But to understand higher-order aberrations, we have to consider the optics of nonparaxial rays.

The clinically **most important** higher-order aberration stemming from nonparaxial rays is *spherical aberration*, so we'll discuss it first.

Aberrations: *Spherical*

- A spherical lens is one for which the refracting surface(s) have a single

three words

Aberrations: *Spherical*

- A spherical lens is one for which the refracting surface(s) have a single radius of curvature

Aberrations: *Spherical*

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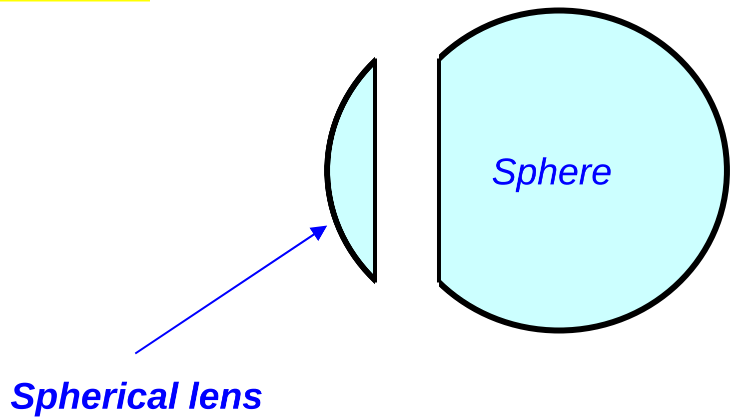
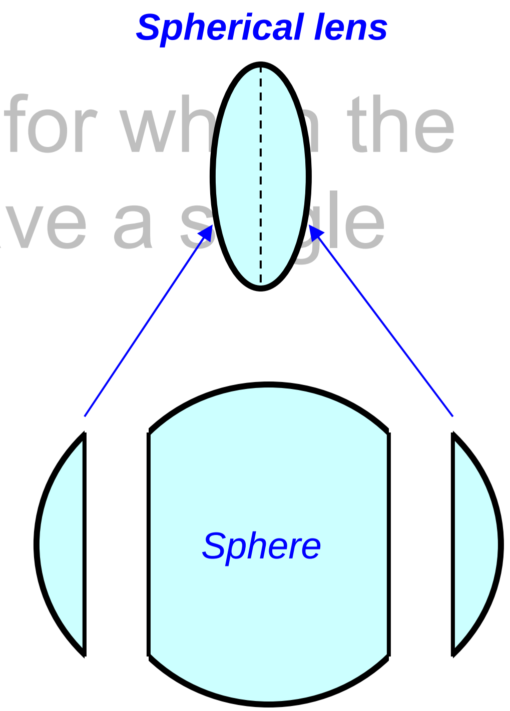


Note that a spherical lens need not be a sphere! For a lens to be ‘spherical,’ its refracting surface(s) must have a single radius-of-curvature—as if the lens was sliced off of a sphere.

Aberrations: *Spherical*

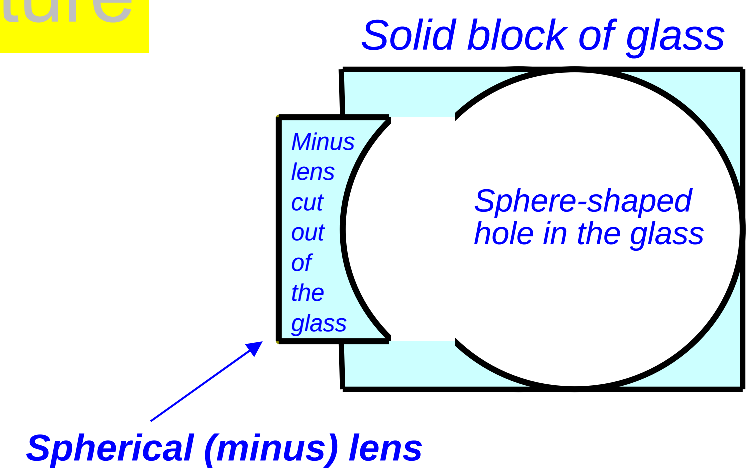
- A spherical lens is one for which the refracting surface(s) have a single radius of curvature



Note that a spherical lens need not have a single refracting surface.

Aberrations: *Spherical*

- A spherical lens is one for which the refracting surface(s) have a single radius of curvature

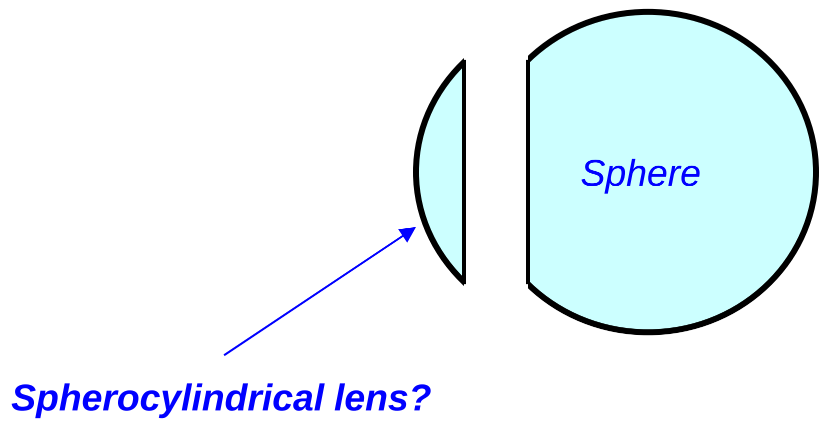


Note that a spherical lens need not be a **plus** lens, either.

Aberrations: *Spherical*

- A ~~spherical~~ ^spherocylindrical lens is one for which the refracting surface(s) have a single radius of curvature

*What about the refracting surface of a sphero**cylindrical** (S-C) lens?*



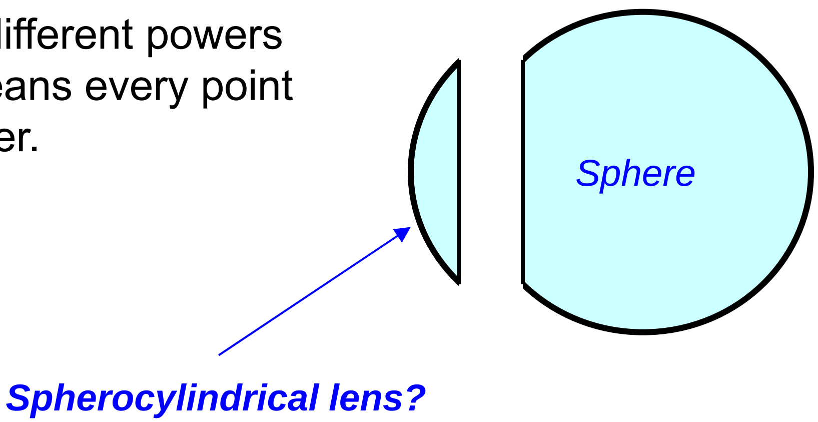
Rhetorical question—advance when ready

Aberrations: *Spherical*

- A ~~spherical~~ spherocylindrical lens is one for which the refracting surface(s) have ~~a single~~ two radi~~us~~i of curvature

*What about the refracting surface of a sphero**cylindrical** (S-C) lens?*

Recall that, by definition, an S-C lens has two different powers oriented at right angles to one another. This means every point on its surface has **two** radii—one for each power.



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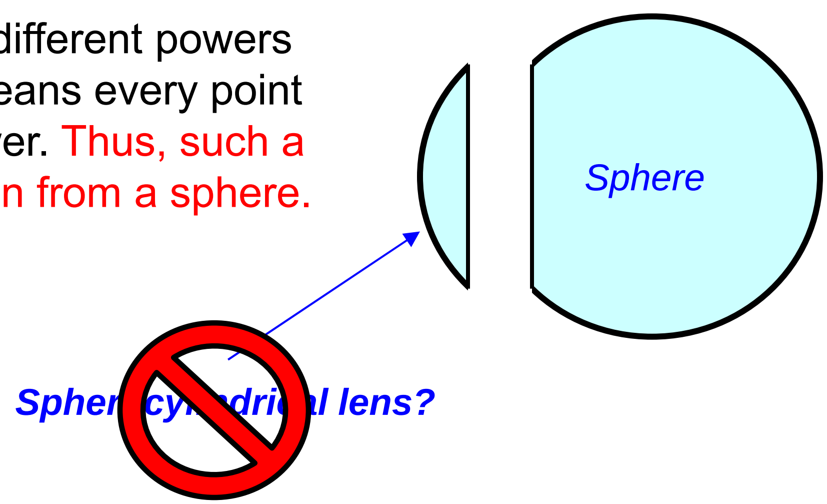
Recall that, by definition, an S-C lens has two different powers oriented at right angles to one another. This means every point on its surface has **two** radii—one for each power. Thus, such a lens could not be created by slicing off a section from a sphere.



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Can you think of an everyday (hint: and delicious) object from which a slice could be taken that would qualify as an S-C lens?

Aberrations: *Spherical*

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Can you think of an everyday (hint: and delicious) object from which a slice could be taken that would qualify as an S-C lens?
Yes—a donut.

Aberrations: *Spherical*

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Can you think of an everyday (hint: and delicious) object from which a slice could be taken that would qualify as an S-C lens? Yes—a donut. Every point on the surface of a donut has two radii—one determined by its distance from the center of the donut's hole, the other by its distance from the center of the part you bite into.

Aberrations: *Spherical*

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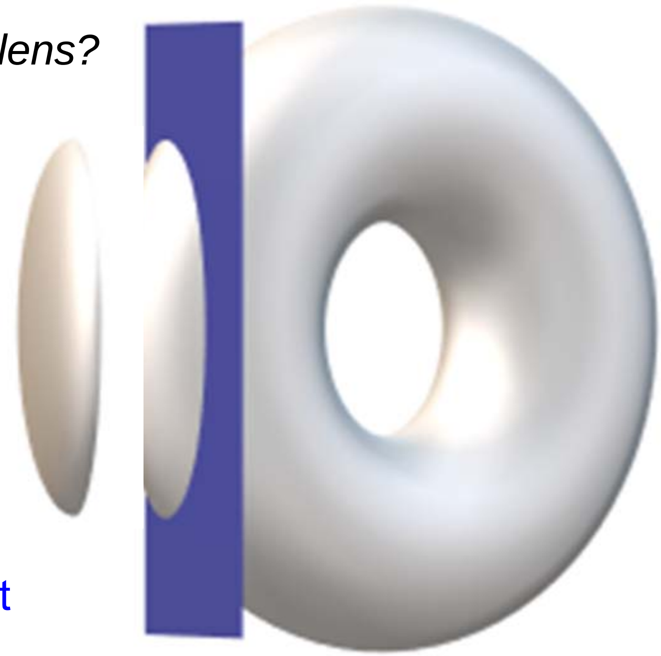
Can you think of an everyday (hint: and delicious) object from which a slice could be taken that would qualify as an S-C lens? Yes—a donut. Every point on the surface of a donut has two radii—one determined by its distance from the center of the donut's hole, the other by its distance from the center of the part you bite into. So, just as a spherical lens is created by taking a slice off a sphere, a sphero**cylindrical** lens is created by taking a slice off a donut.



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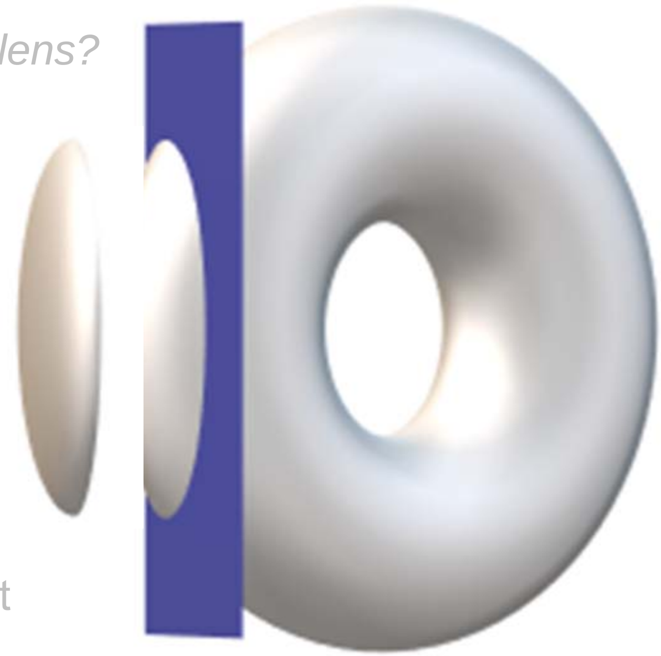
Recall that, by definition, an S-C lens has two different powers oriented at right angles to one another. This means every point on its surface has **two** radii—one for each power. Thus, such a lens could not be created by slicing off a section from a sphere.

There is a more formal/precise name for the shape from which a spherocylindrical lens is sliced—what is it?

Can you … *n*
which a … *s?*
Yes—a …
radii—o …
donut's … part
you bite into. So, just as a spherical lens is created by taking a slice off a sphere, a sphero**cylindrical** lens is created by taking a slice off a **donut**.



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There is a more formal/precise name for the shape from which a spherocylindrical lens is sliced—what is it?
A **torus**

Can you ... n
which a ... s?
Yes—a ...
radii—o...
donut's ... part
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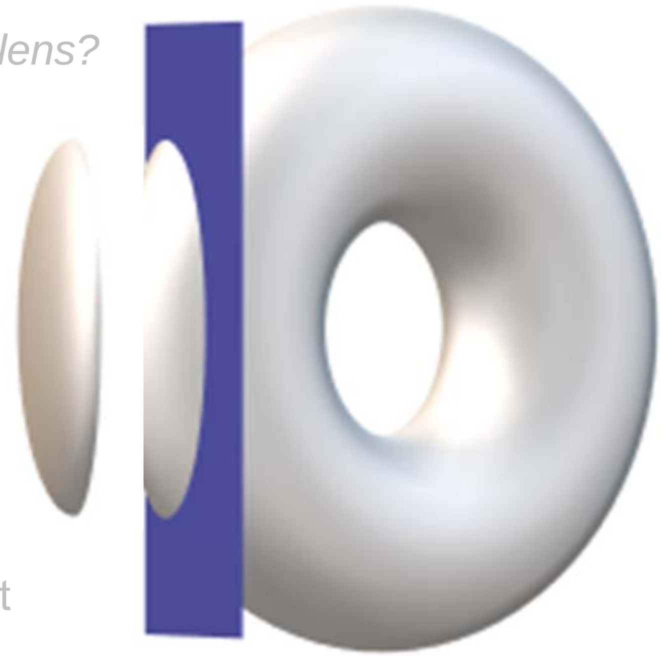

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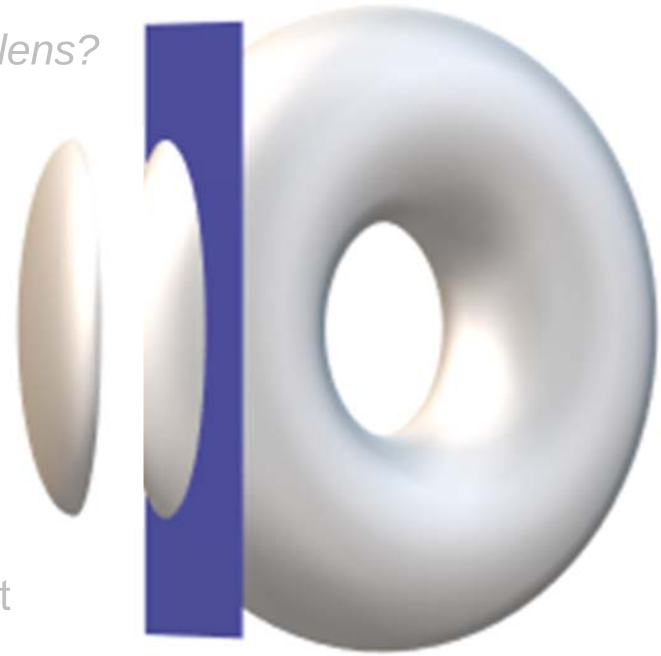
There is a more formal/precise name for the shape from which a spherocylindrical lens is sliced—what is it?
A **torus**

Similarly, this more-formal name gives rise to an alternate name for a spherocylindrical lens—what is it?

Can you ... n
which a ... s?
Yes—a ...
radii—o ...
donut's ... part
you bite into. So, just as a spherical lens is created by taking a slice off a sphere, a sphero**cylindrical** lens is created by taking a slice off a **donut**.



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- A ~~spherical~~ spherocylindrical lens is one for which the refracting surface(s) have ~~a single~~ two radii of curvature

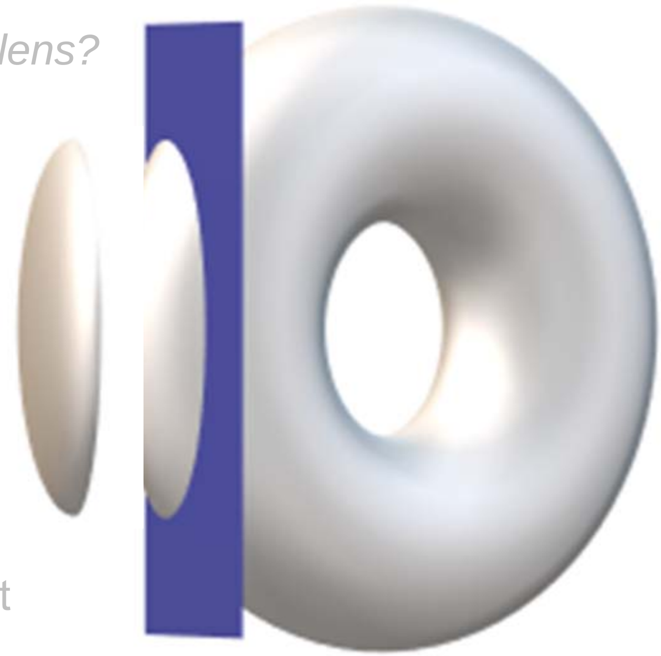
*What about the refracting surface of a sphero**cylindrical** (S-C) lens?*

Recall that, by definition, an S-C lens has two different powers oriented at right angles to one another. This means every point on its surface has **two** radii—one for each power. Thus, such a lens could not be created by slicing off a section from a sphere.

Can you
which a
Yes—a
radii—o
donut's
you bite into. So, just as a spherical lens is created by taking a slice off a sphere, a sphero**cylindrical** lens is created by taking a slice off a **donut**.

There is a more formal/precise name for the shape from which a spherocylindrical lens is sliced—what is it?
A **torus**

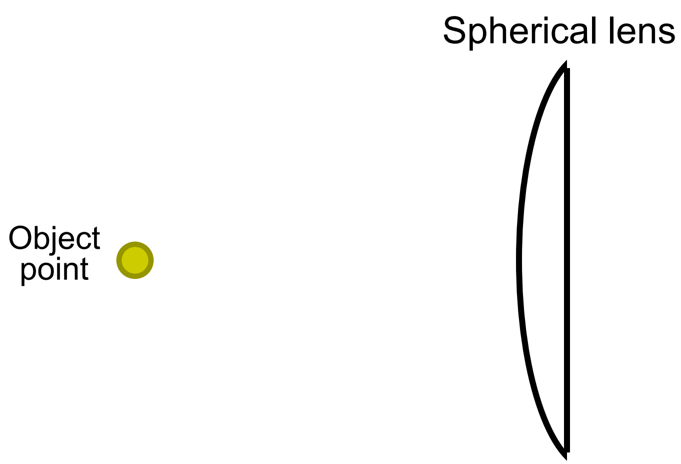
Similarly, this more-formal name gives rise to an alternate name for a spherocylindrical lens—what is it?
A **toric** lens



Aberrations: *Spherical*

Let’s drill down on how spherical aberration comes to pass:

Aberrations: *Spherical*



Consider an object-lens system as above.

Let's drill down on how spherical aberration comes to pass:

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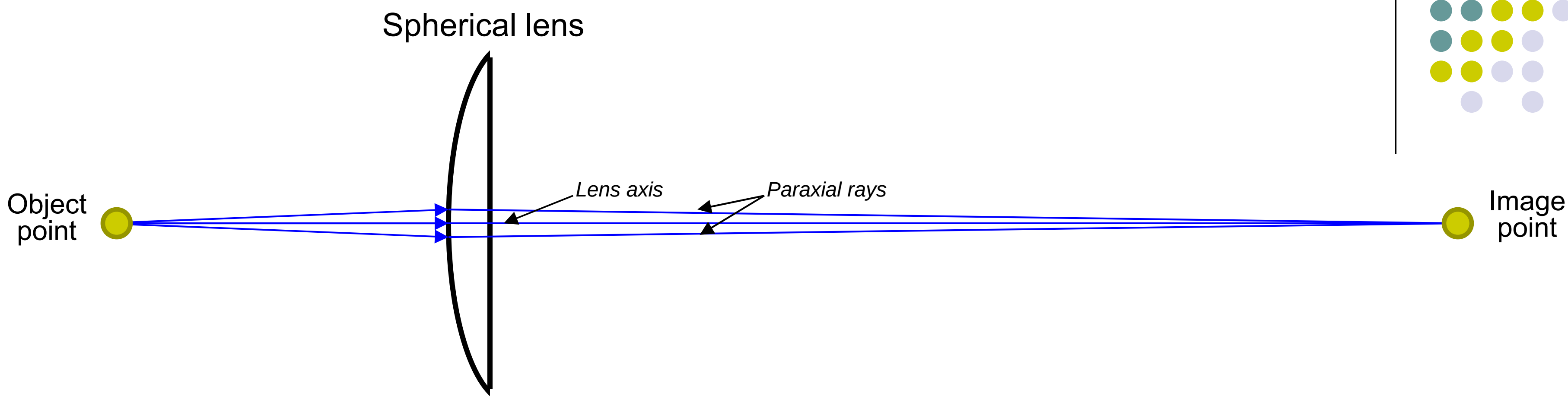
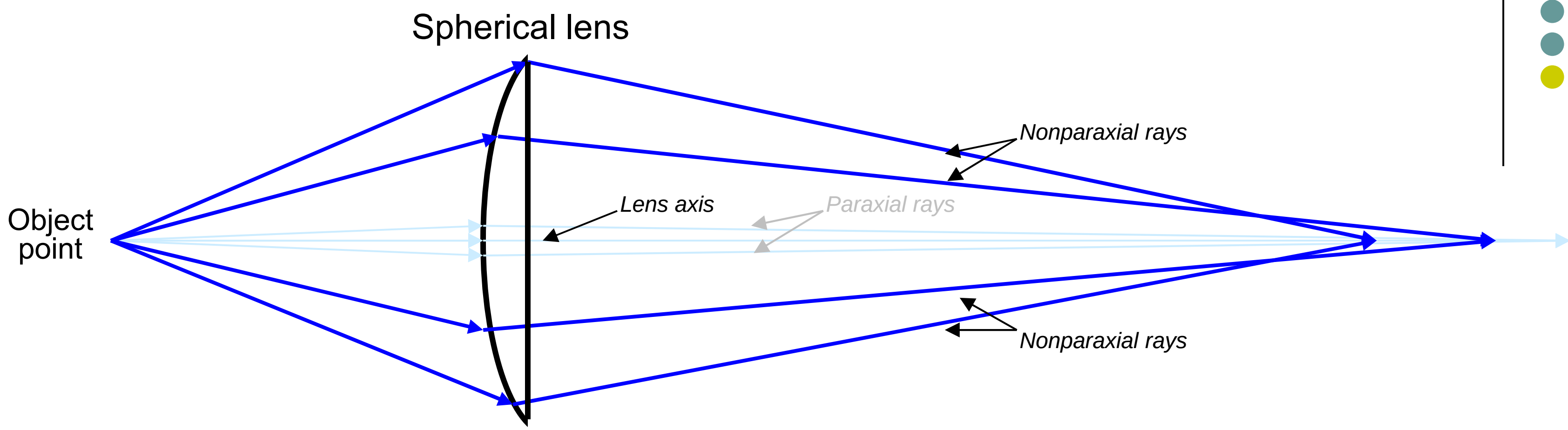


If we deal only with the paraxial rays, we find their focus closely approximates a perfect point, as predicted by first-order optics.

Let's drill down on how spherical aberration comes to pass:

Aberrations: *Spherical*



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However, when we look at the behavior of the **non**-paraxial rays, we find they do not focus at the same location as the paraxial rays; rather, because they are more sharply refracted, they focus anterior to the paraxial focal point.

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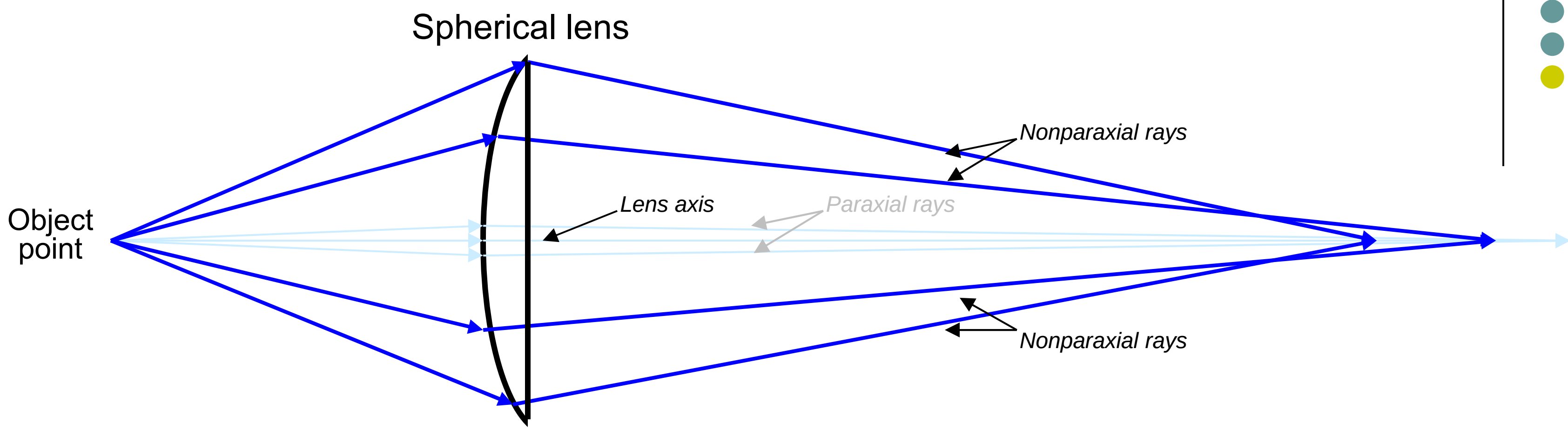

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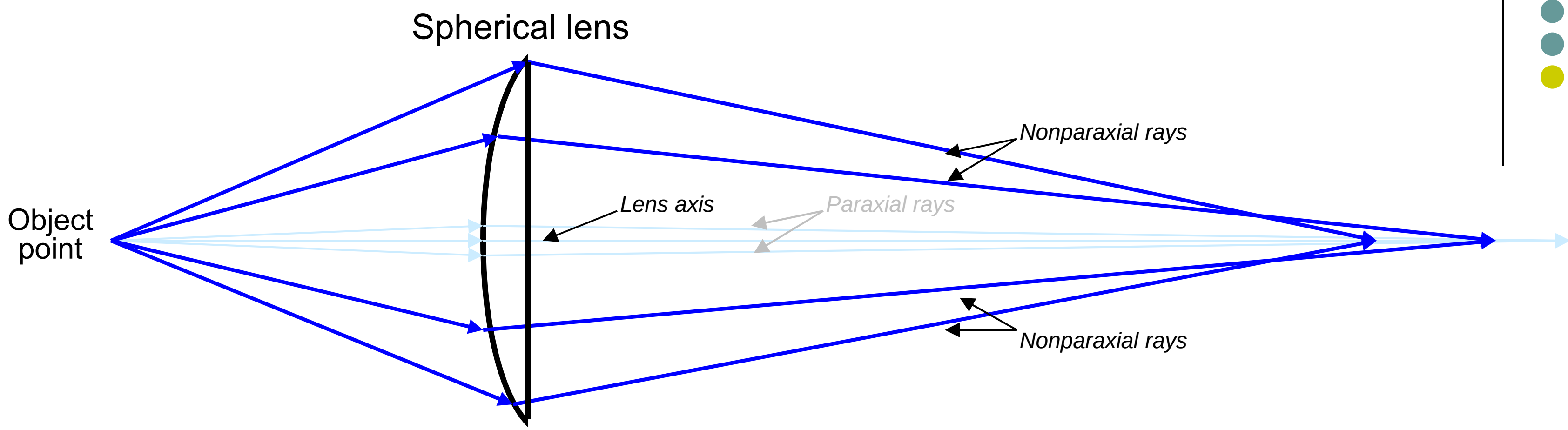
Why are nonparaxial rays refracted more than paraxial rays on a spherical lens?

Aberrations: *Spherical*



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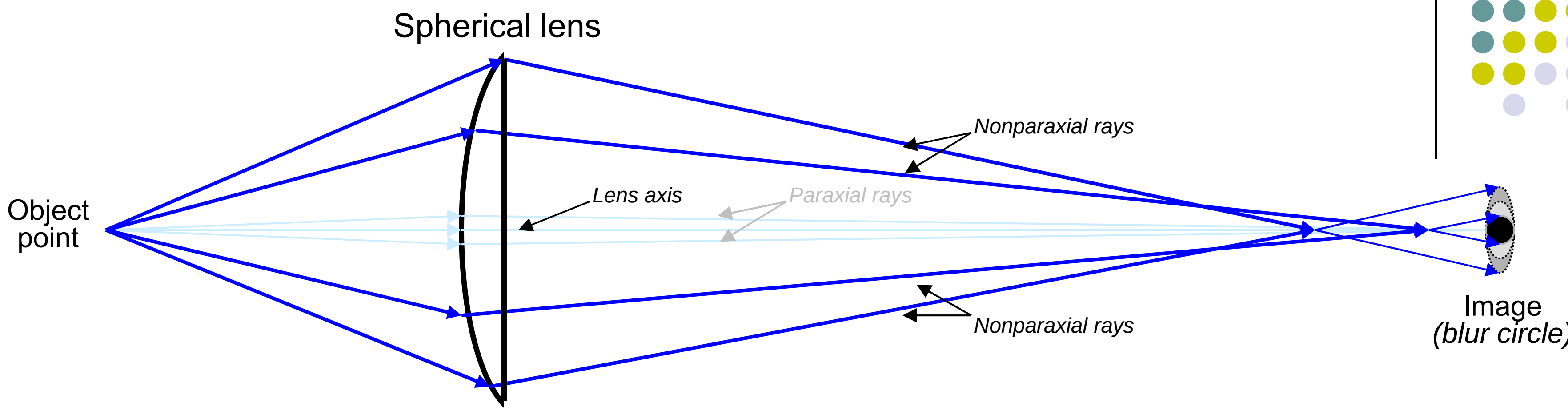
Why are nonparaxial rays refracted more than paraxial rays on a spherical lens?
Snell's Law states that the angle of refraction is a function of the angle of incidence. For paraxial rays, the angle of incidence is determined solely by the radius-of-curvature of the lens. However, the angle-of-incidence for **non-**paraxial rays is a function of both the radius of curvature ***and*** the fact that the surface of the lens becomes more and more oblique (relative to the path of the light) as you move away from the lens axis; ie, the lens periphery 'turns away' from the incoming light, thereby increasing the angle of incidence in a way unrelated to the radius of curvature.

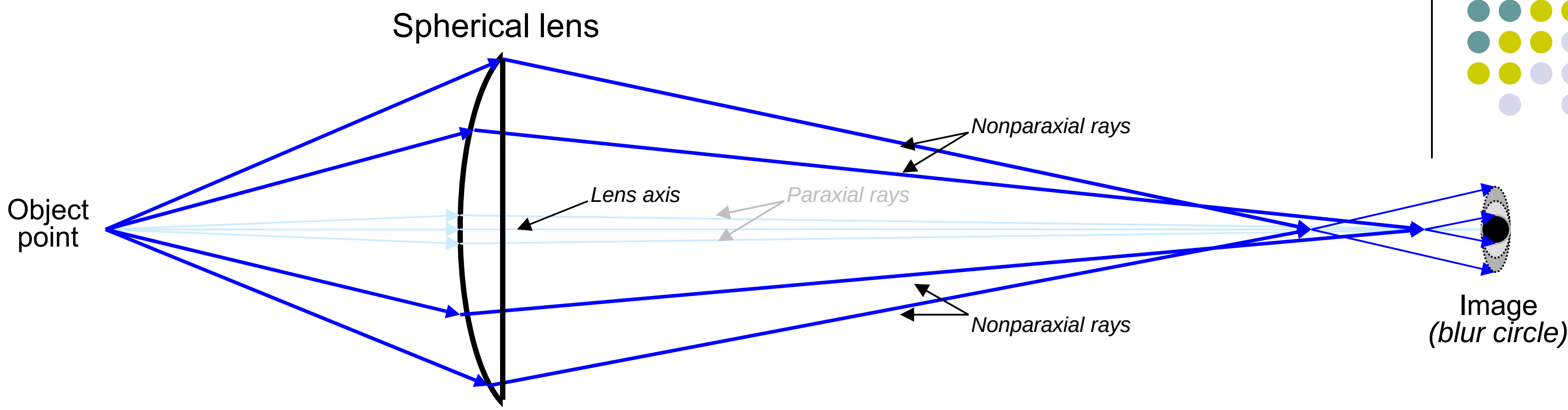
Aberrations: *Spherical*



If we deal only with the paraxial rays, we find their focus closely approximates a perfect point, as predicted by first-order optics.

However, when we look at the behavior of the **non**-paraxial rays, we find they do not focus at the same location as the paraxial rays; rather, because they are more sharply refracted, they focus anterior to the paraxial focal point. By the time these rays reach the focal plane for the paraxial rays, they are diverging. Thus, they contribute not to a focal **point**, but rather to a somewhat defocused area called a *blur circle*.

Aberrations: *Spherical*



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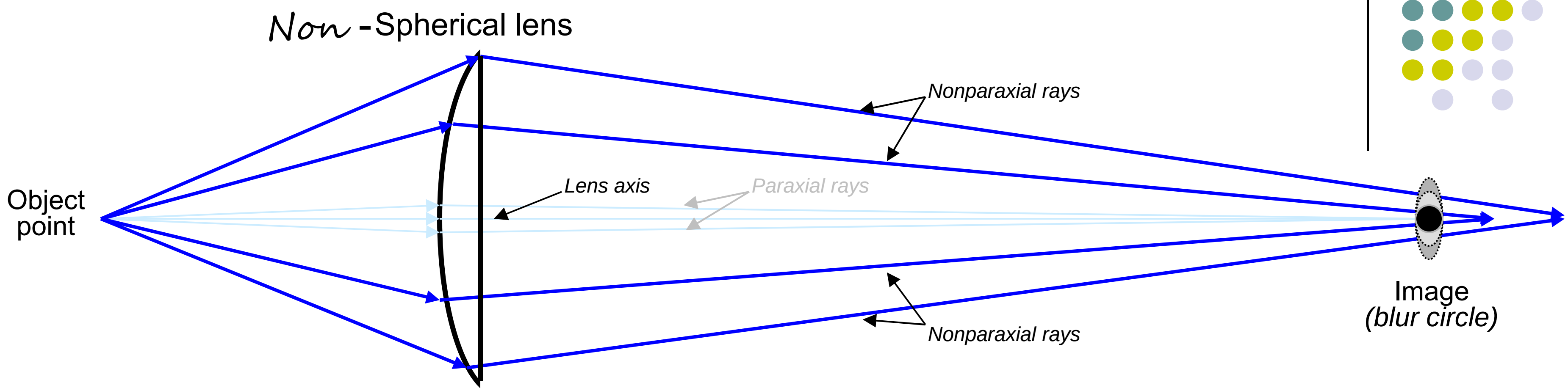
When progressively peripheral rays are refracted more and more sharply, the lens is said to possess ***positive*** *spherical aberration.*

Aberrations: *Spherical*



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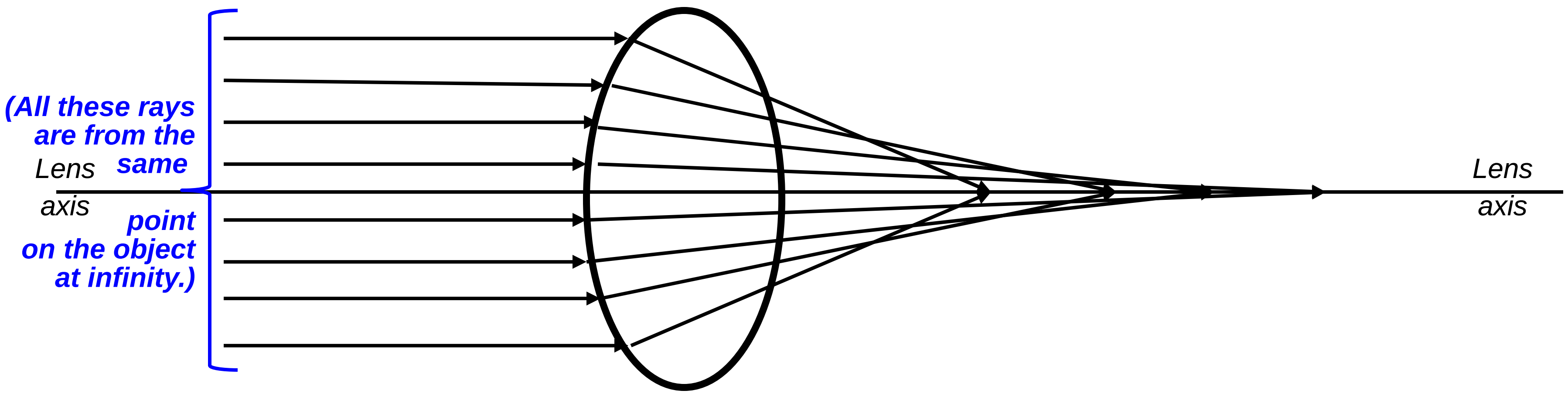
However, when we look at the behavior of the **non**-paraxial rays, we find they do not focus at the same location as the paraxial rays; rather, because they are ~~more~~ less sharply refracted, they focus ~~anterior~~ posterior to the paraxial focal point.

On the other hand, when progressively peripheral rays are refracted less and less sharply, the lens is said to possess **negative** *spherical aberration.*

Aberrations: *Spherical*



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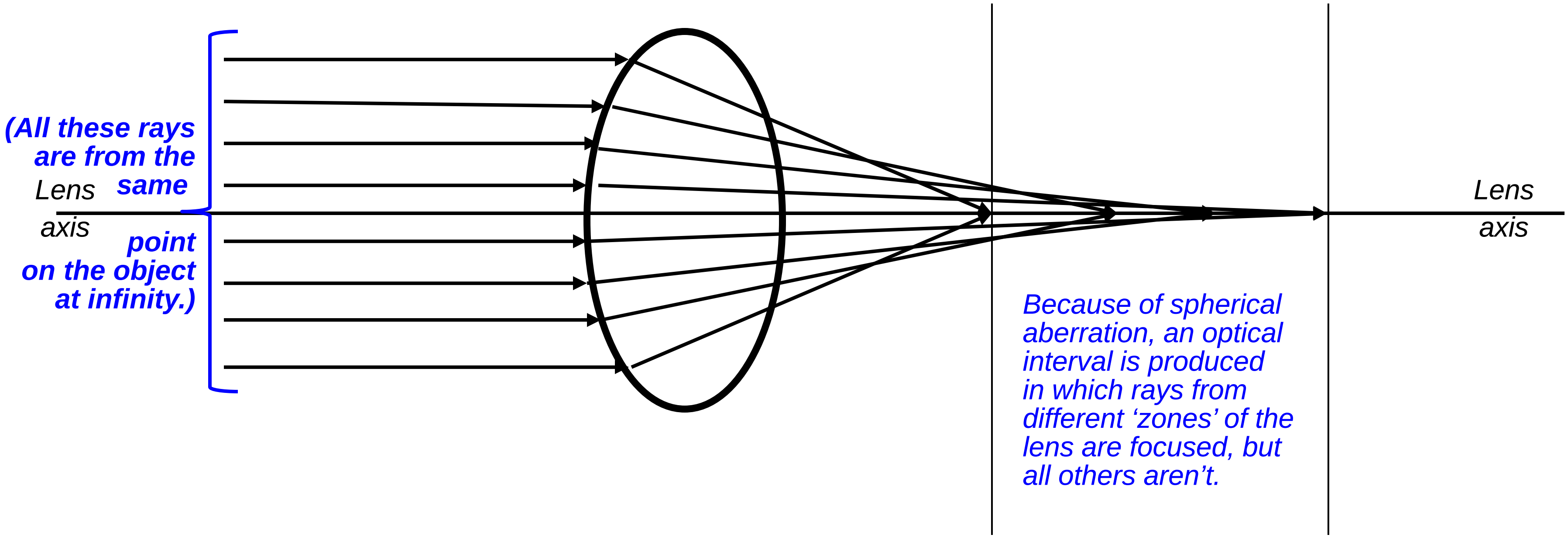
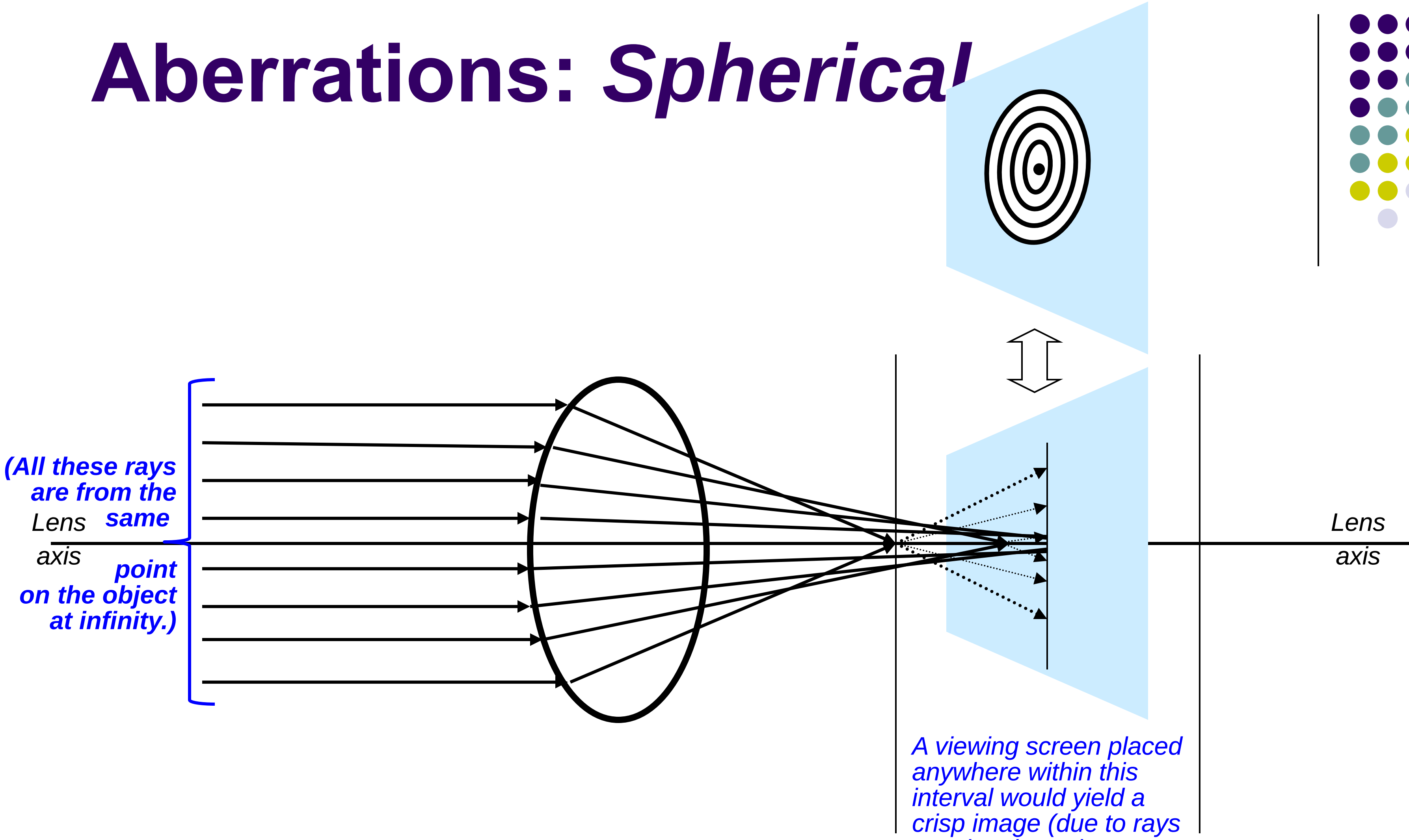
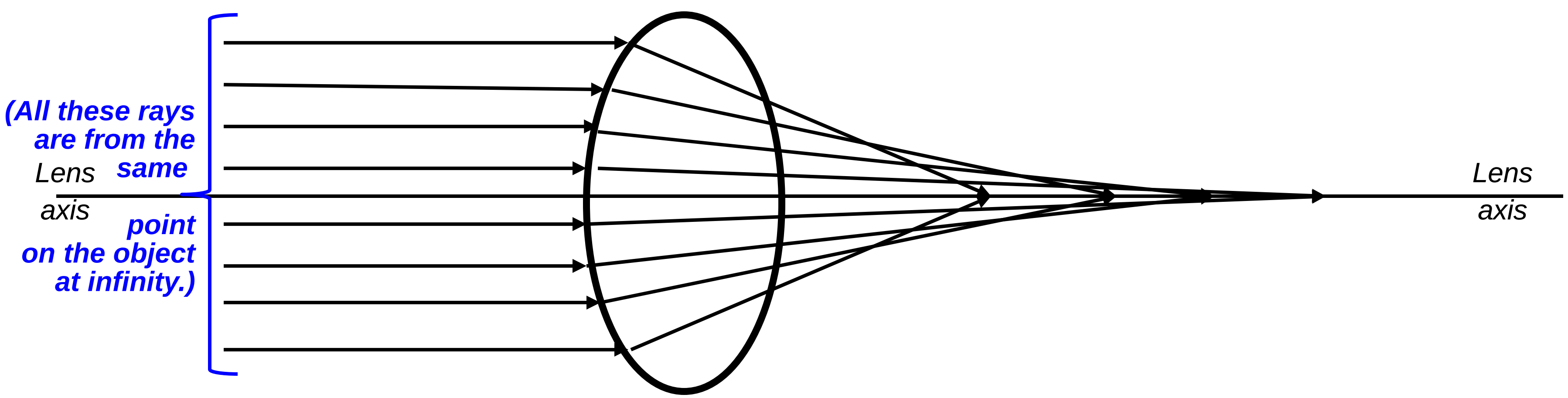


Aberrations: *Spherical*



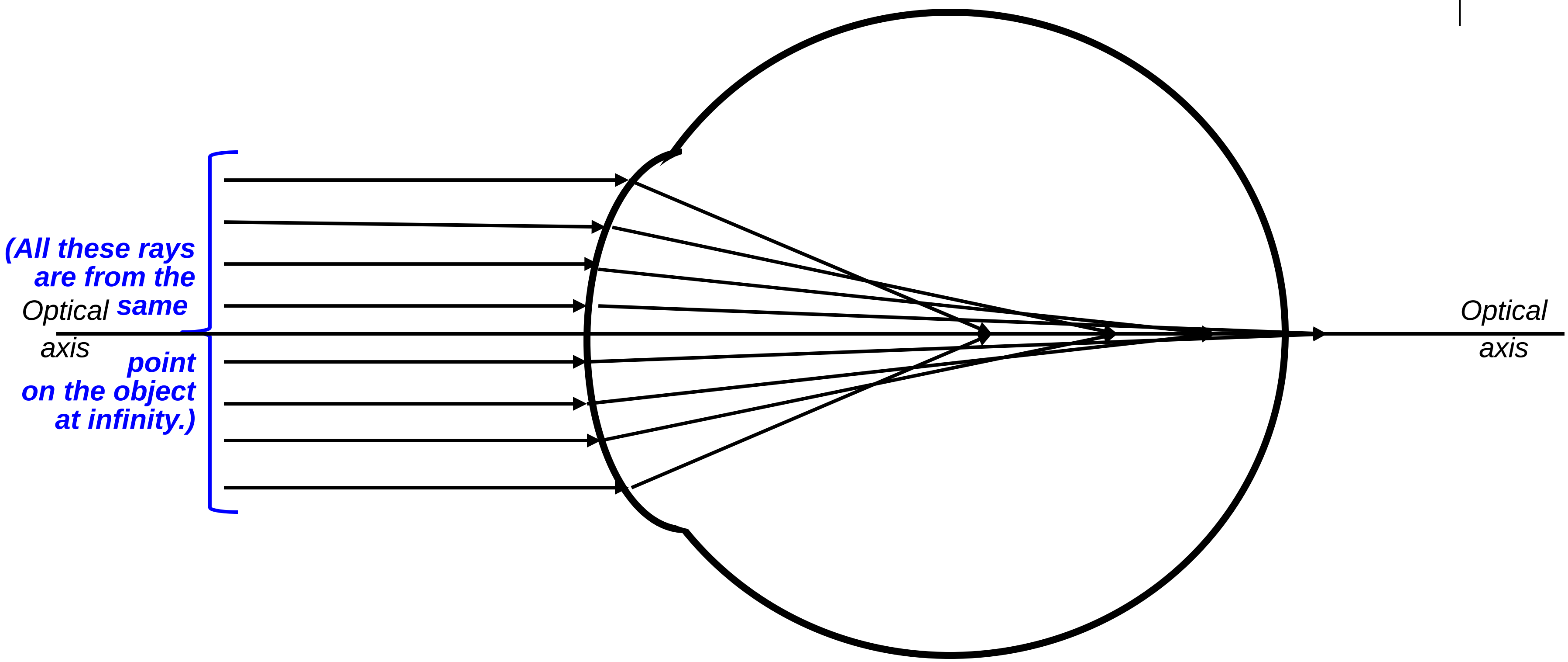
A viewing screen placed anywhere within this interval would yield a crisp image (due to rays passing through one zone of the lens), with surrounding 'halos' representing rays from the other zones (and therefore out-of-focus at this point in the interval)

Aberrations: *Spherical*



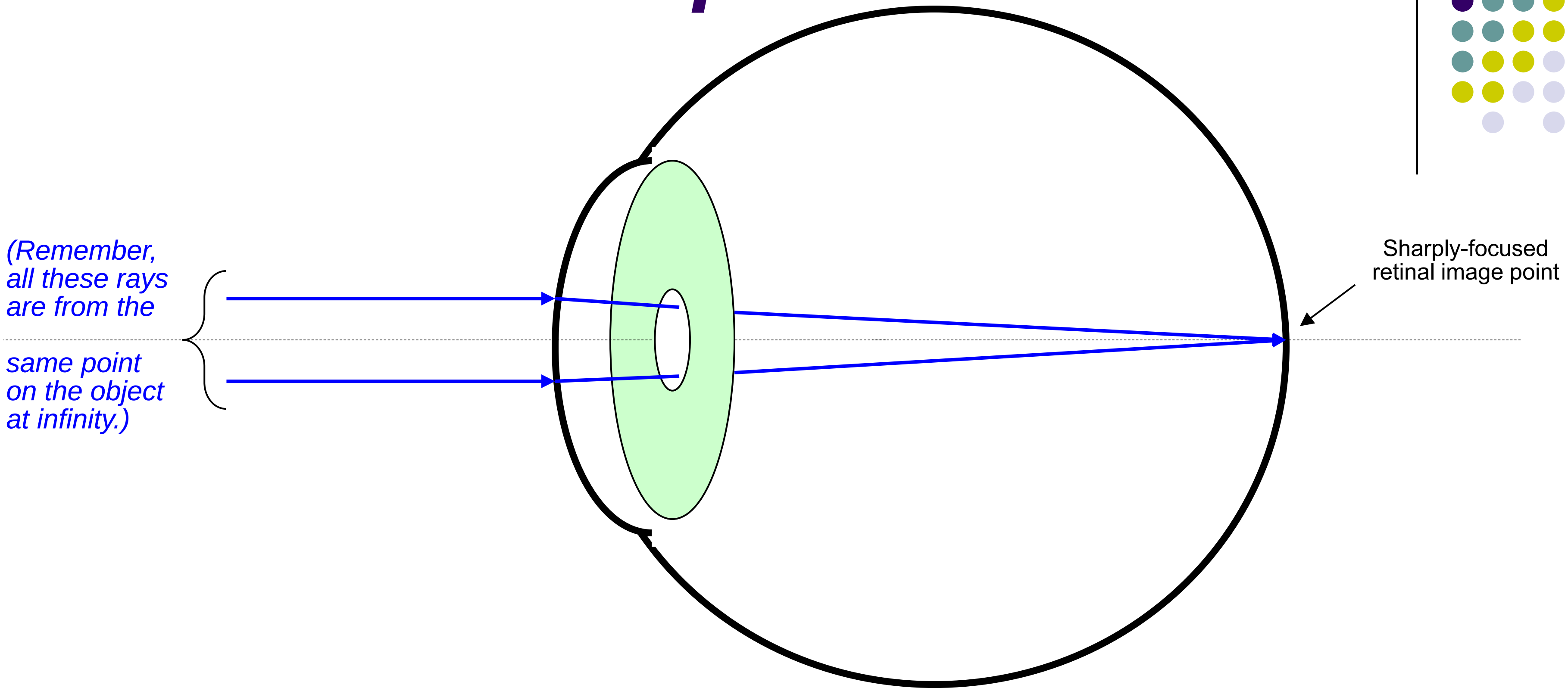
And because it is an optical instrument…

Aberrations: *Spherical*

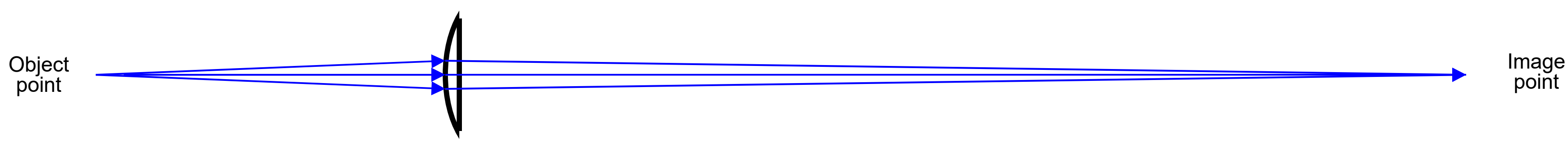


And because it is an optical instrument…the eye is subject to the same phenomenon.

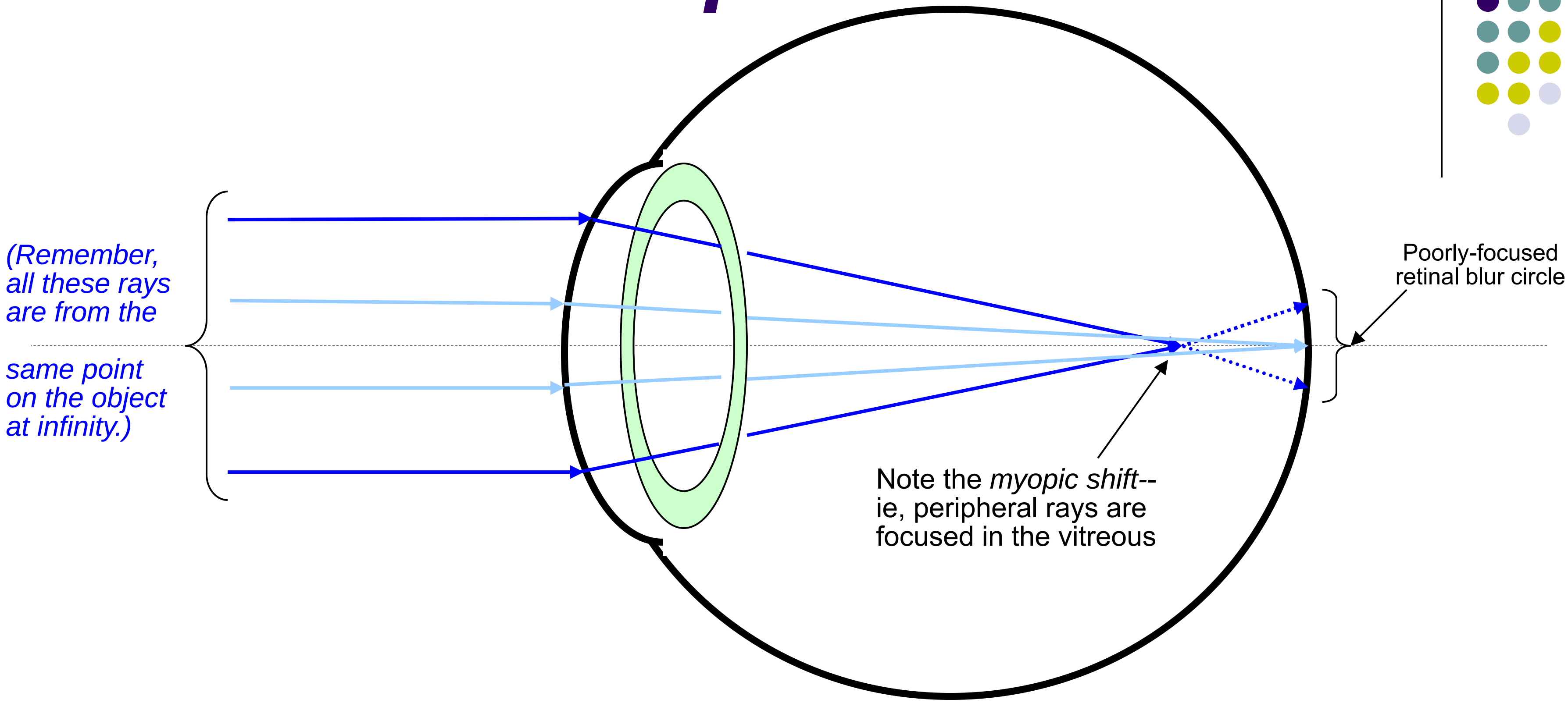
Aberrations: *Spherical*



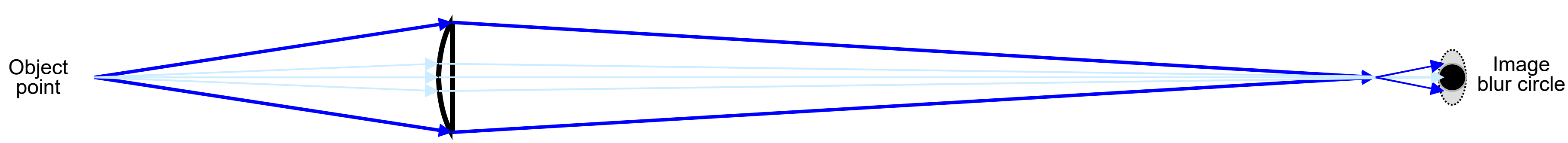
When the pupil is small, light reaching the retina consists largely of paraxial rays; ie, rays passing through the central portion of the cornea.



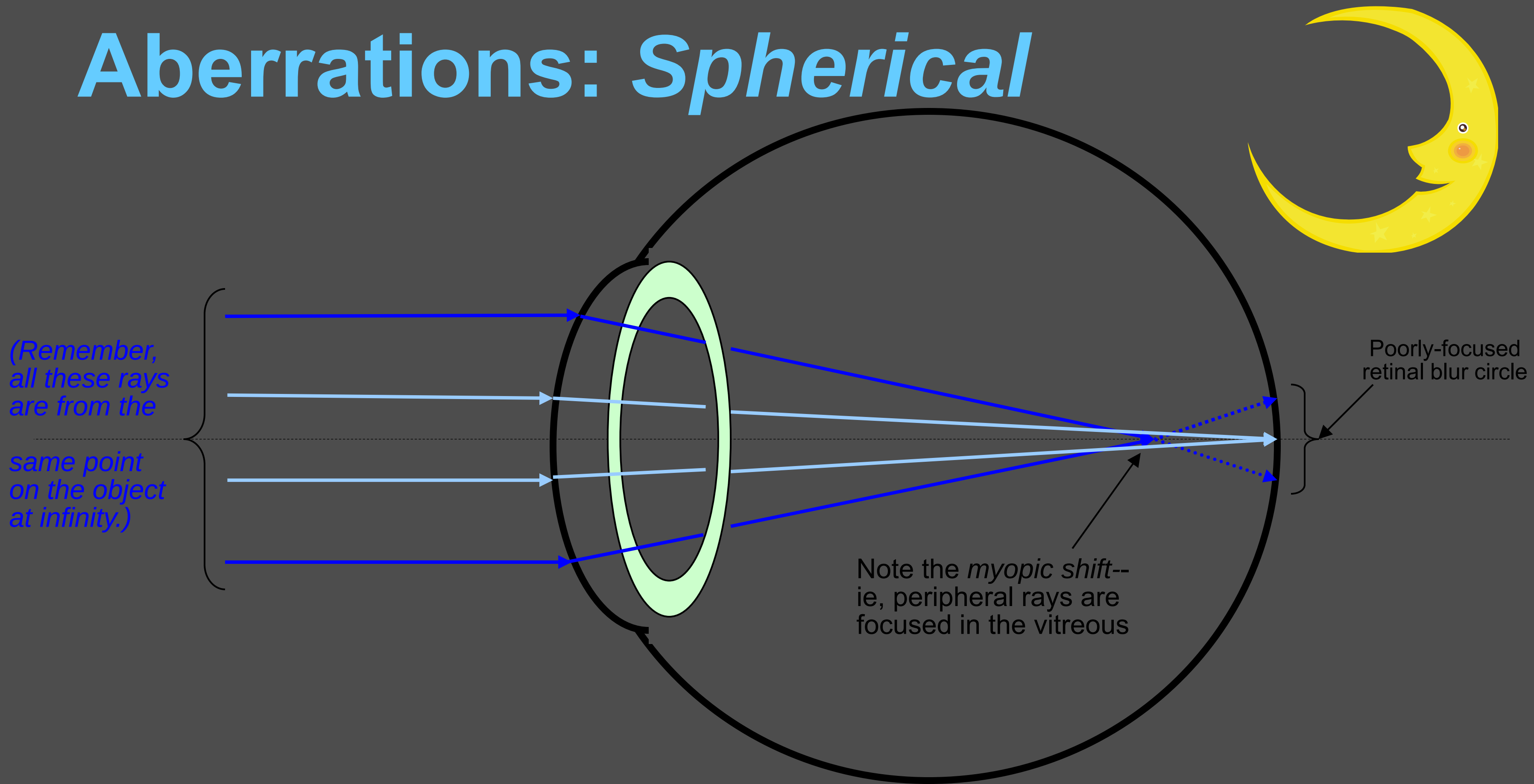
Aberrations: *Spherical*



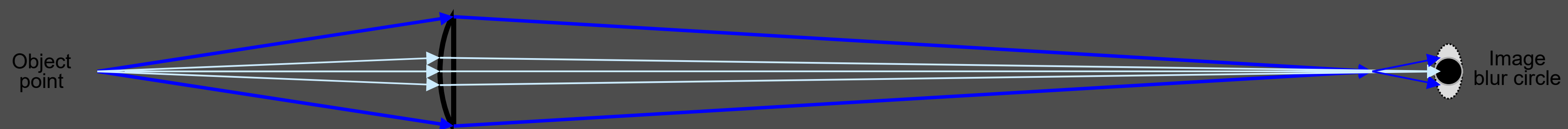
When the pupil is small, light reaching the retina consists largely of paraxial rays; ie, rays passing through the central portion of the cornea. However, when the pupil is large, rays passing through the peripheral cornea come into play, and spherical aberration causes these rays to be focused more anteriorly, resulting in a myopic component to the final image.



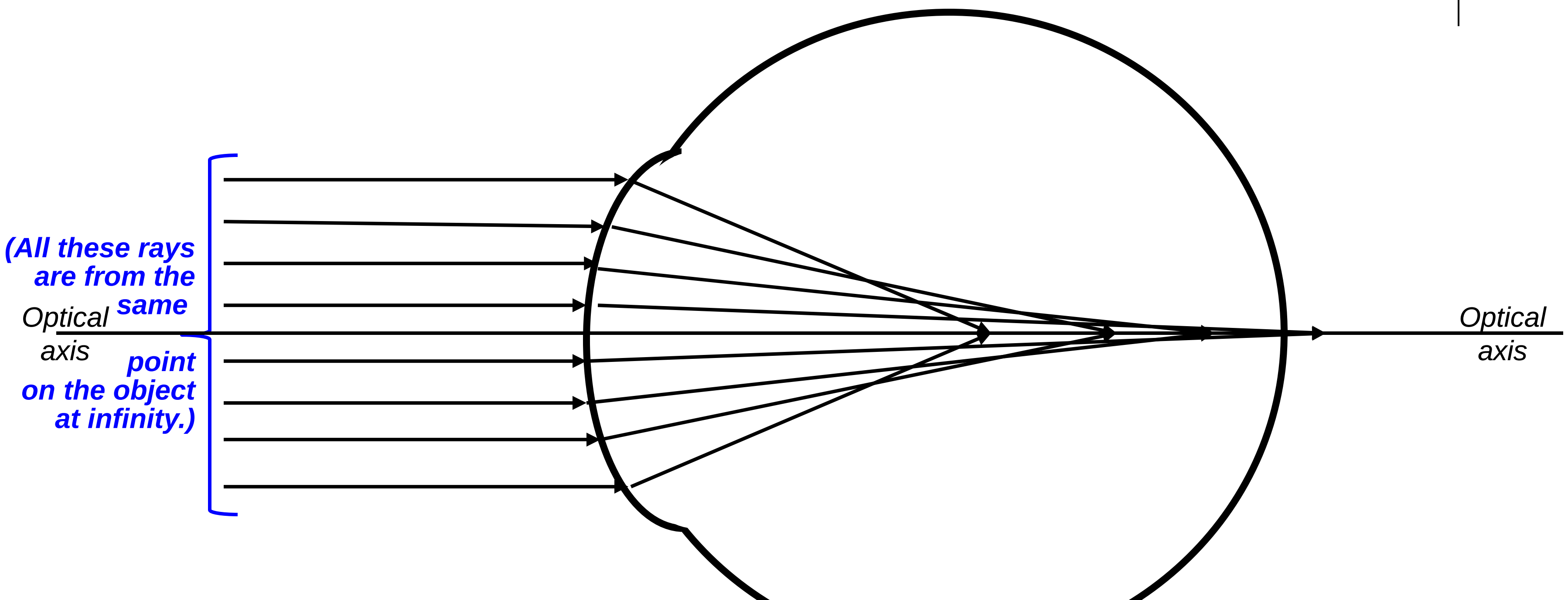
Aberrations: *Spherical*



When the pupil is small, light reaching the retina consists largely of paraxial rays; ie, rays passing through the central portion of the cornea. However, when the pupil is large, rays passing through the peripheral cornea come into play, and spherical aberration causes these rays to be focused more anteriorly, resulting in a myopic component to the final image. **Spherical aberration is a factor in the phenomenon called *night myopia*, in which pts complain of blurred vision brought on by dusk- and night-time illumination levels.**

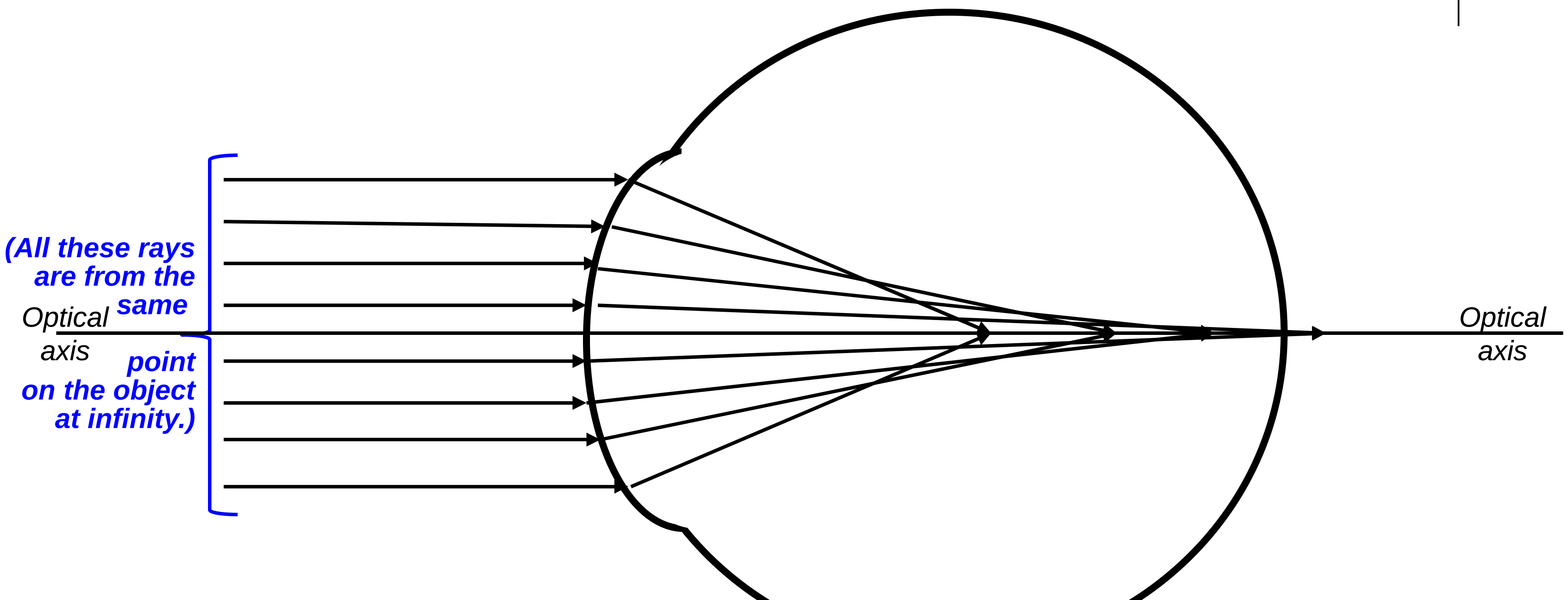


Aberrations: *Spherical*



How much spherical aberration does the average human cornea possess?

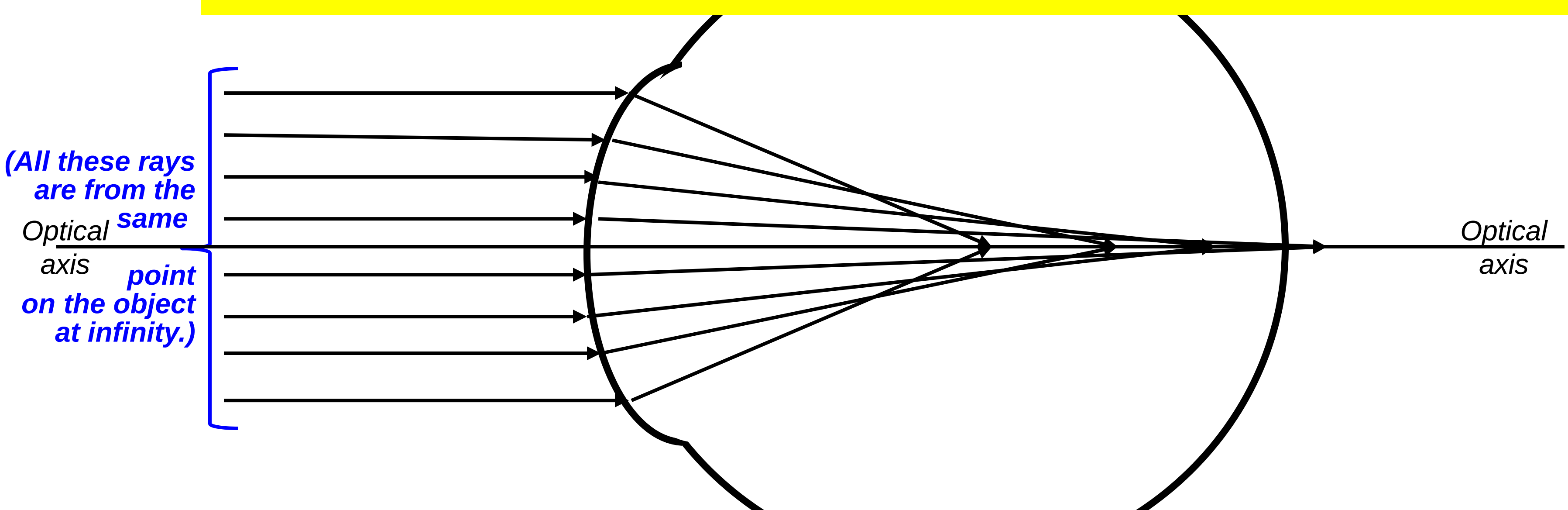
Aberrations: *Spherical*



How much spherical aberration does the average human cornea possess?
About +0.27 μm

Ab

Why is the unit of spherical aberration microns--*a unit of distance? What distance is being referred to?*



How much spherical aberration does the average human cornea possess?
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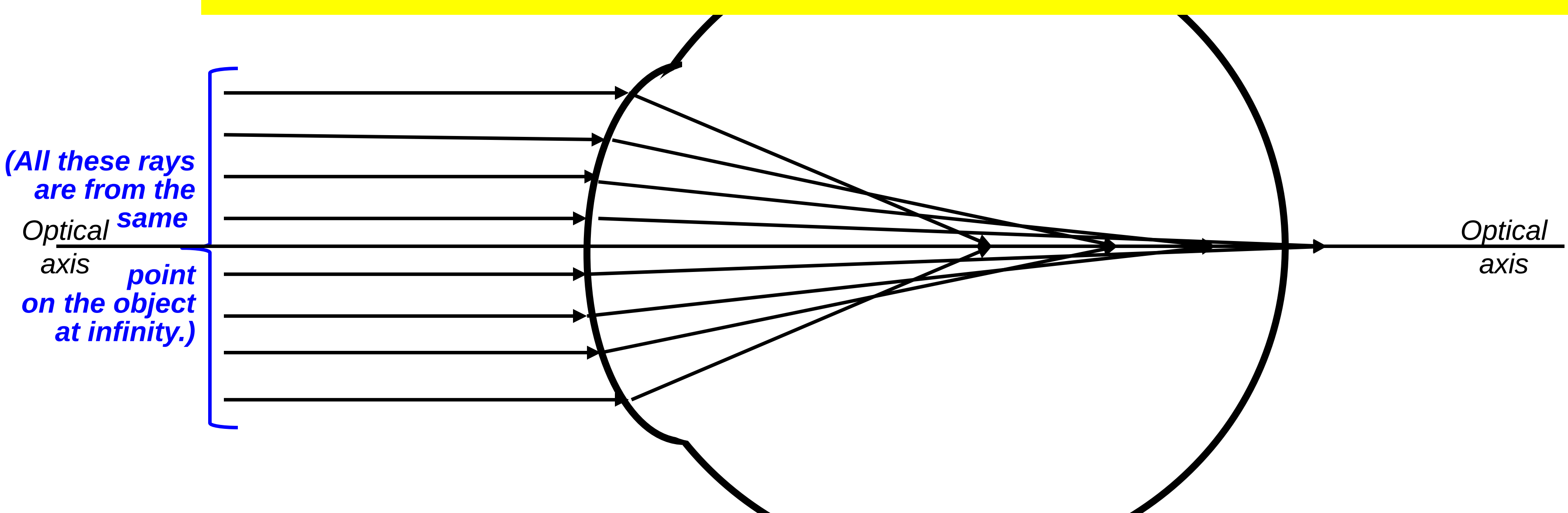
Why is the unit of spherical aberration microns--*a unit of distance? What distance is being referred to?*
It refers to the distance between the location where central rays form a focal point and where the peripheral rays form a focal point



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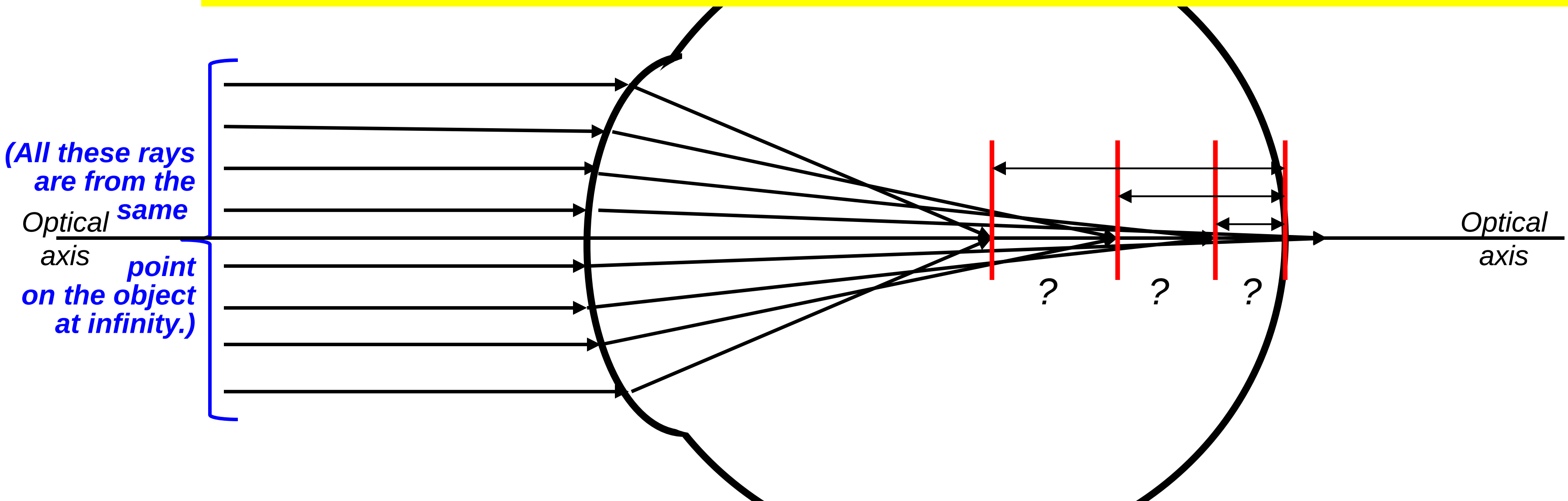
But as can be seen in the figure, the location of the focal point for rays passing through the corneal periphery is a function of 'how peripheral' those rays are. Given this, how can one measure spherical aberration?



How much spherical aberration does the average human cornea possess?
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Ab... (title partially covered)

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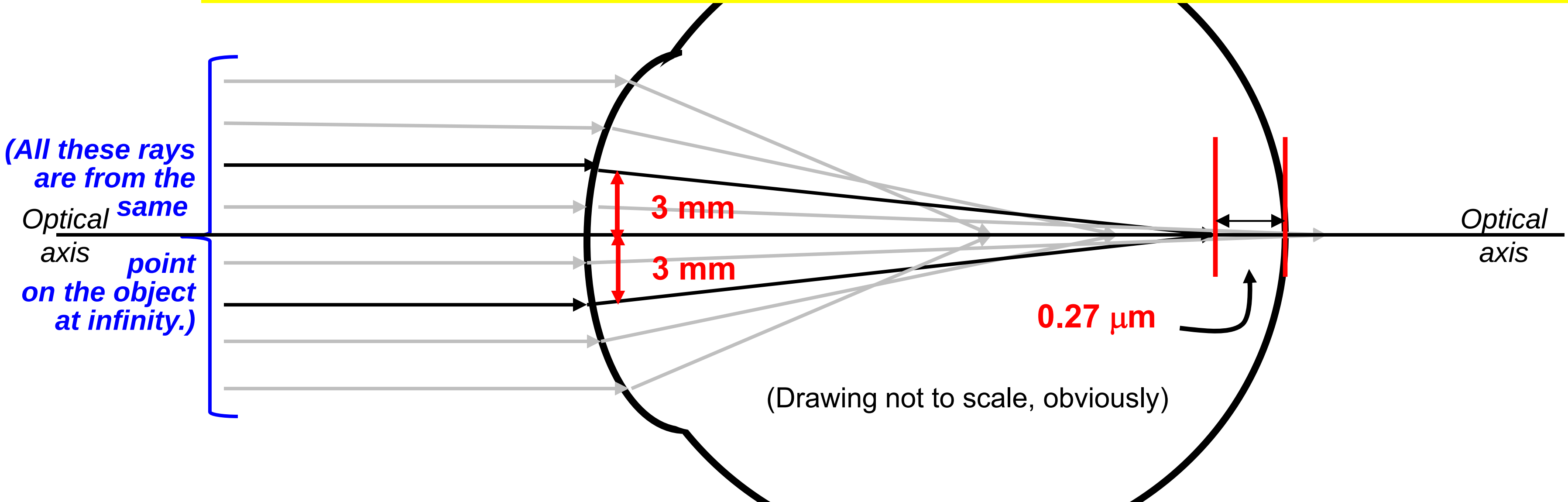
But as can be seen in the figure, the location of the focal point for rays passing through the corneal periphery is a function of 'how peripheral' those rays are. Given this, how can one measure spherical aberration?
By convention, rays passing through the cornea 6 mm from the optical axis are used



How much spherical aberration does the average human cornea possess?
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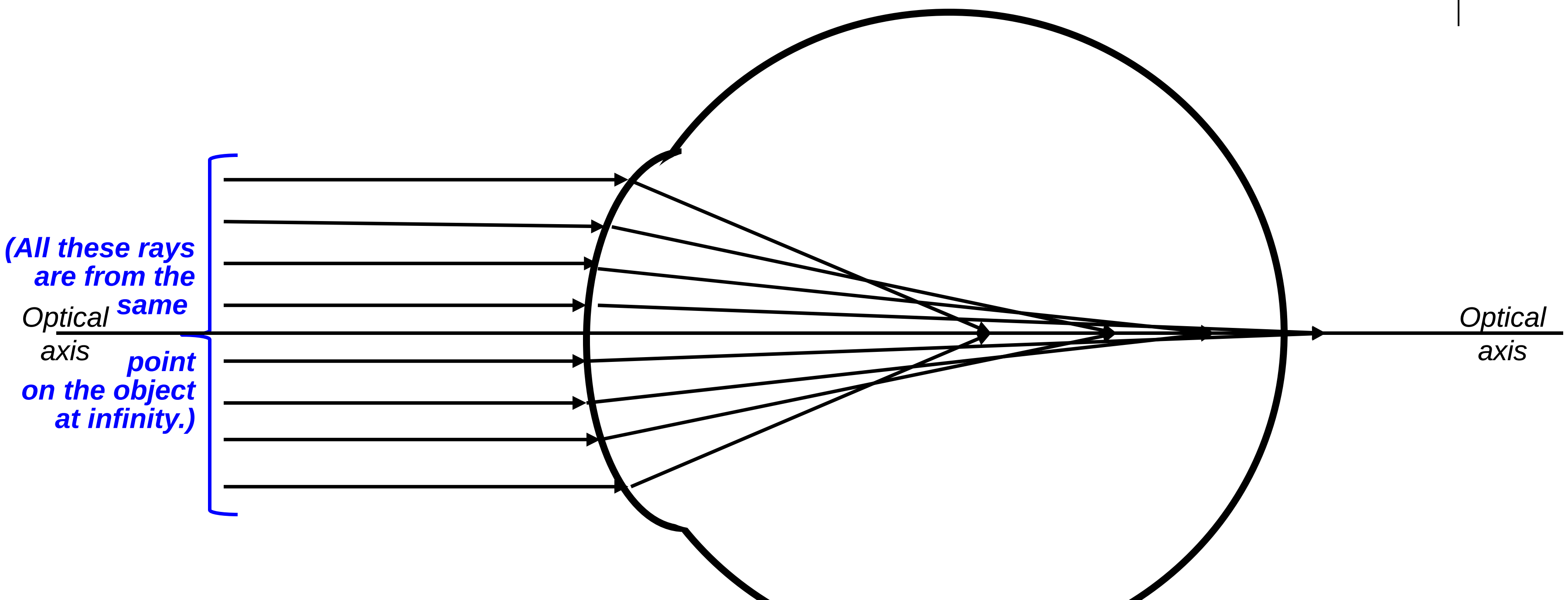
Aberrations: *Spherical*



How much spherical aberration does the average human cornea possess?
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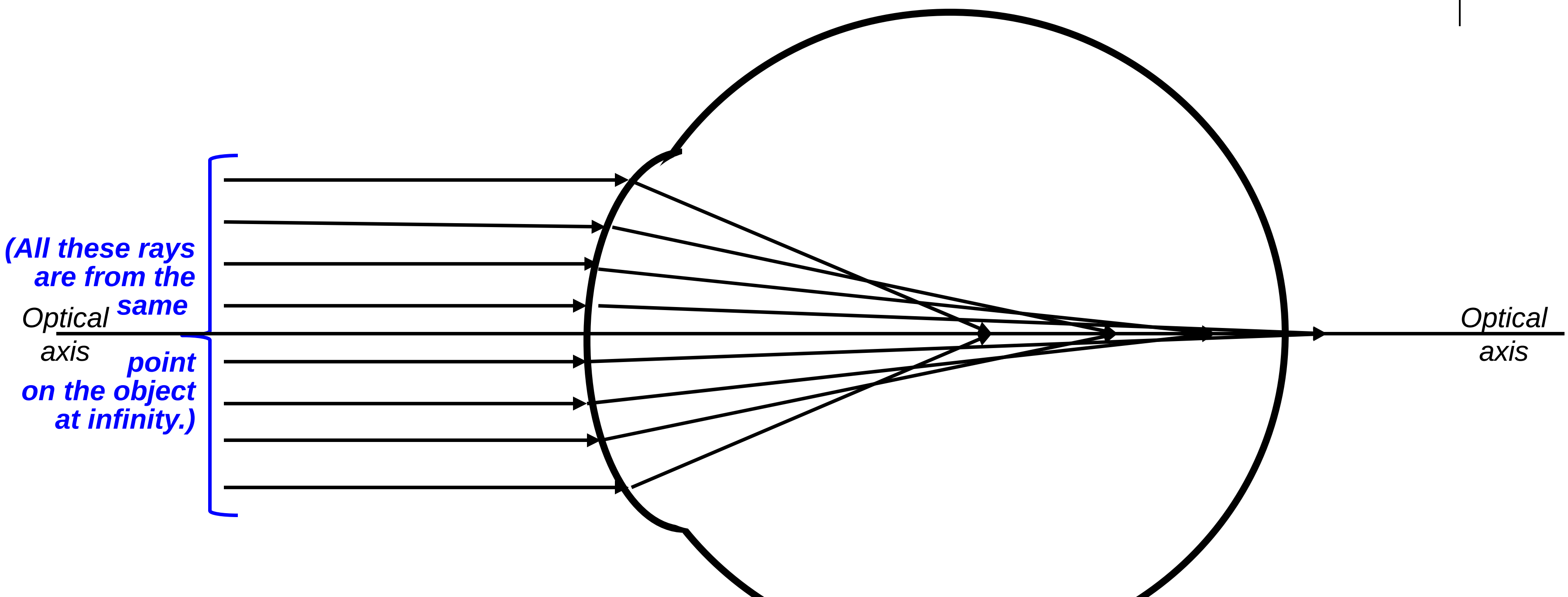
*So this means the cornea possesses **positive** spherical aberration. But the cornea's Q factor is negative. What gives?*

Aberrations: *Spherical*



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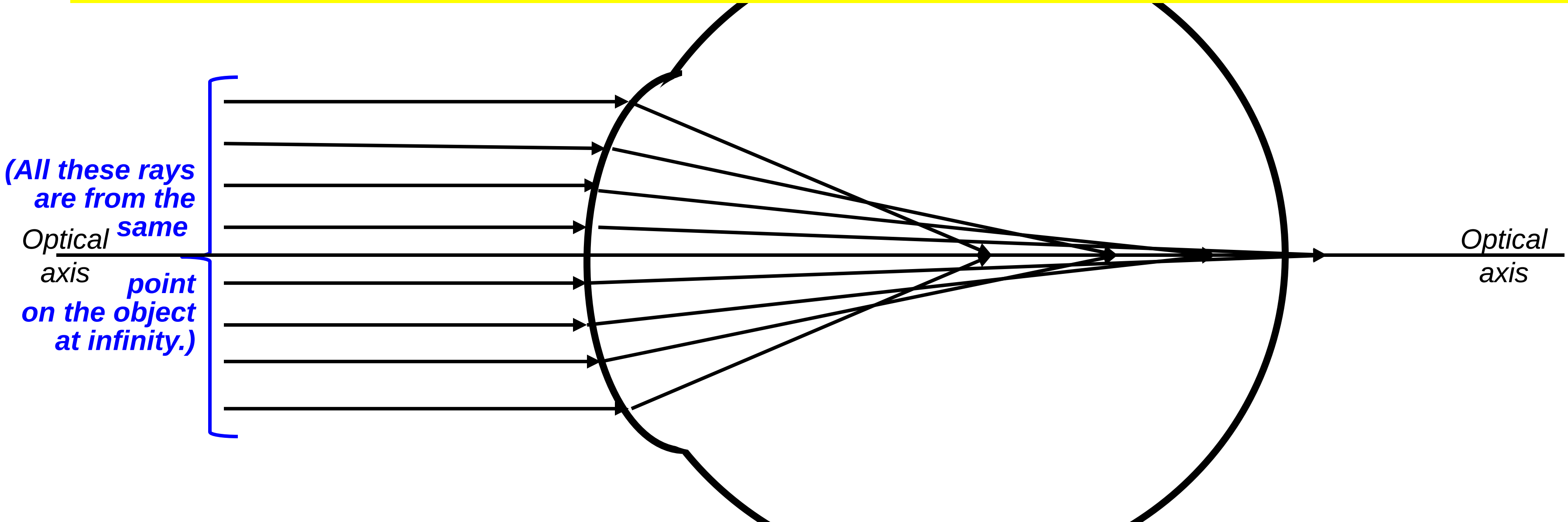
Recall that the cornea's Q factor is -0.26. What would it be if the cornea had no spherical aberration?



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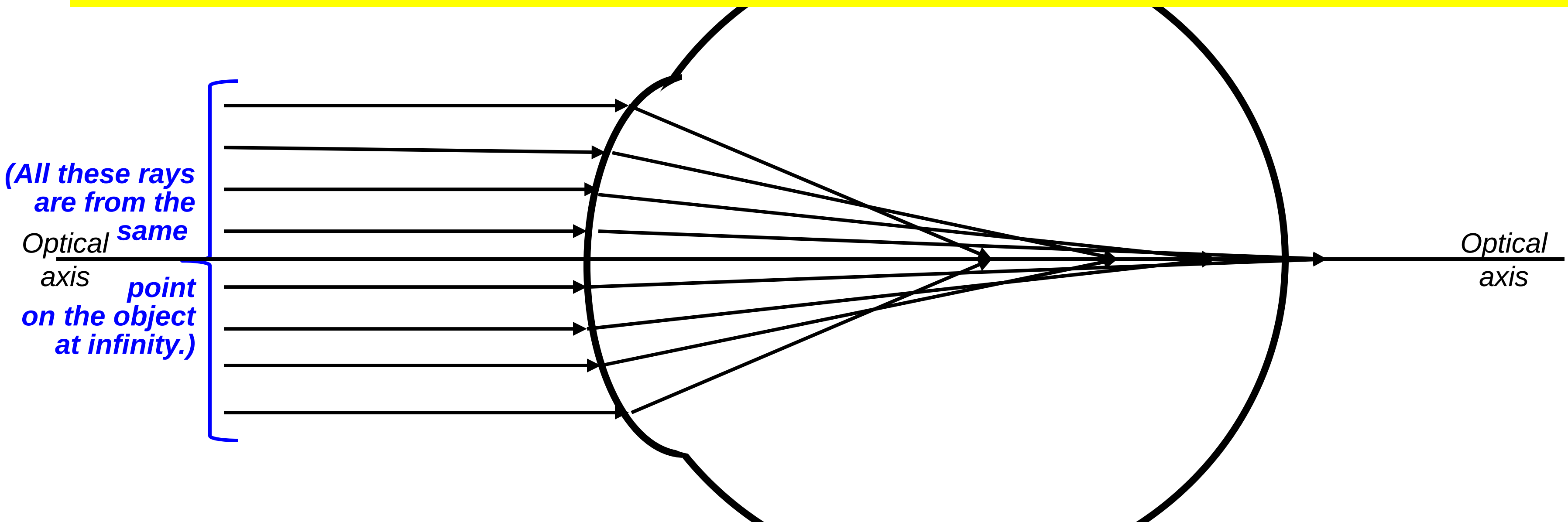
About -0.52



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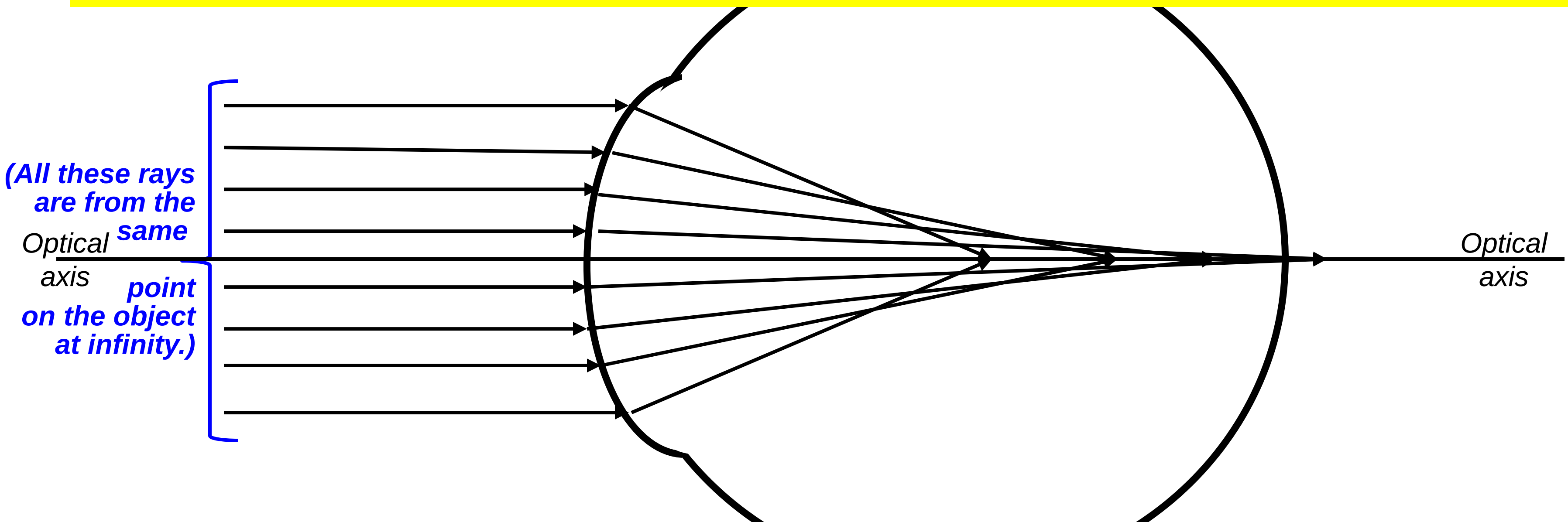
Why didn't we evolve corneas with a Q factor of -0.52?



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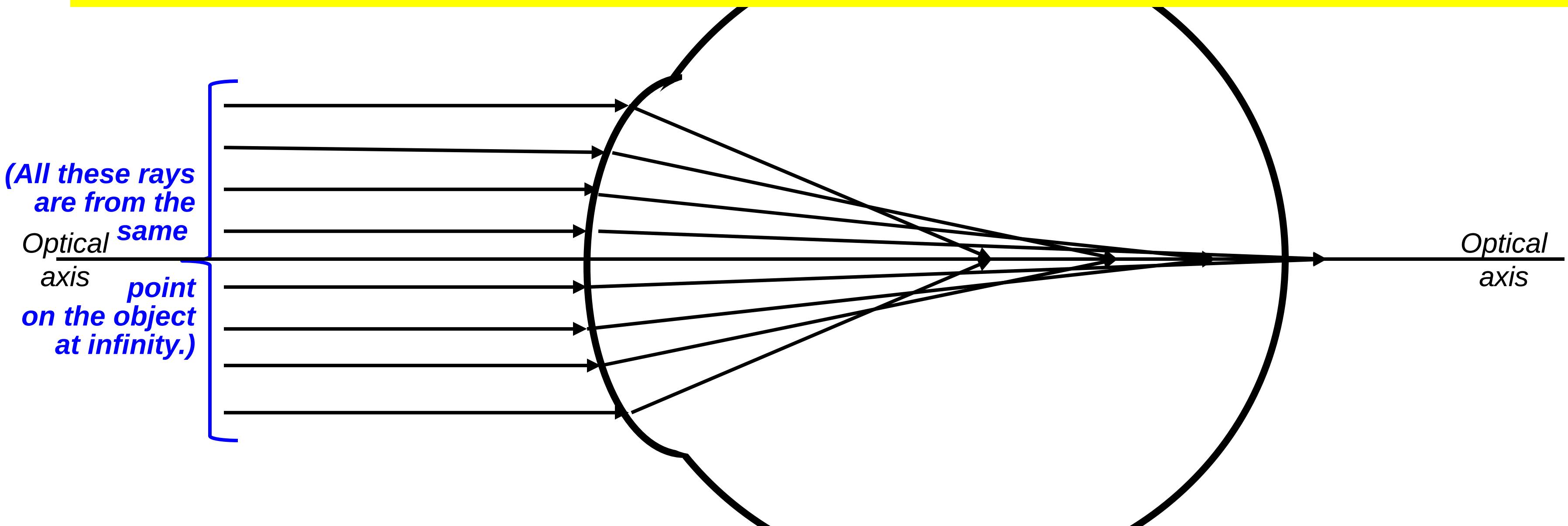
Recall that the cornea's Q factor is -0.26. What would it be if the cornea had no spherical aberration?
About -0.52

Why didn't we evolve corneas with a Q factor of -0.52?
Well, no one can say for sure of course. But what **can** be said with certainty is that a Q factor of -0.52 would require a radically different angle between the cornea and the sclera--an angle that could not be achieved given the biomechanics and size of the normal human globe. Thus, a Q factor of -0.52 would require a very radical 're-design' of the globe--and thus of the orbits, and the cranium, and etc.



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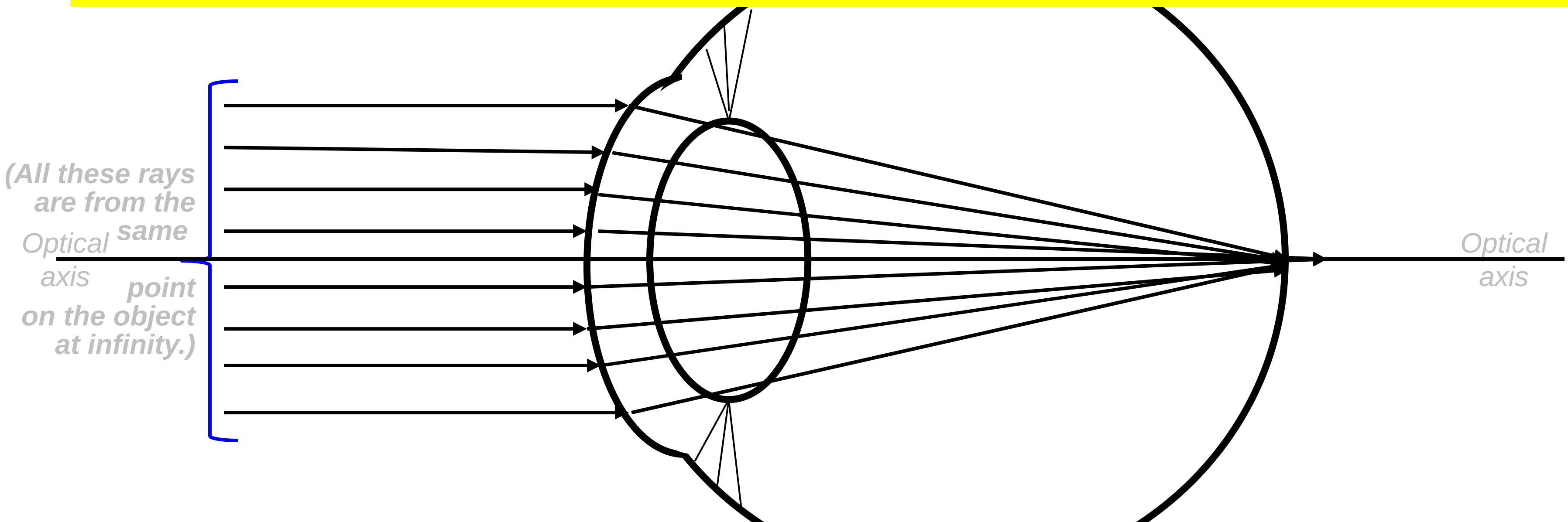
About -0.52

Why didn't we evolve ~~corneas~~ eyes with a Q factor of -0.52? We did!
Well, no one can say for sure of course. But what **can** be said with certainty is that a Q factor of -0.52

Interestingly, while we didn't evolve **corneas** with a Q factor of -0.52, we did evolve **eyes** with it. The human lens of a young adult has an average Q value of about -0.25. Thus, the entire refracting system of the average young adult human eye has a total Q factor very close to -0.52, and thus has little to no spherical aberration!



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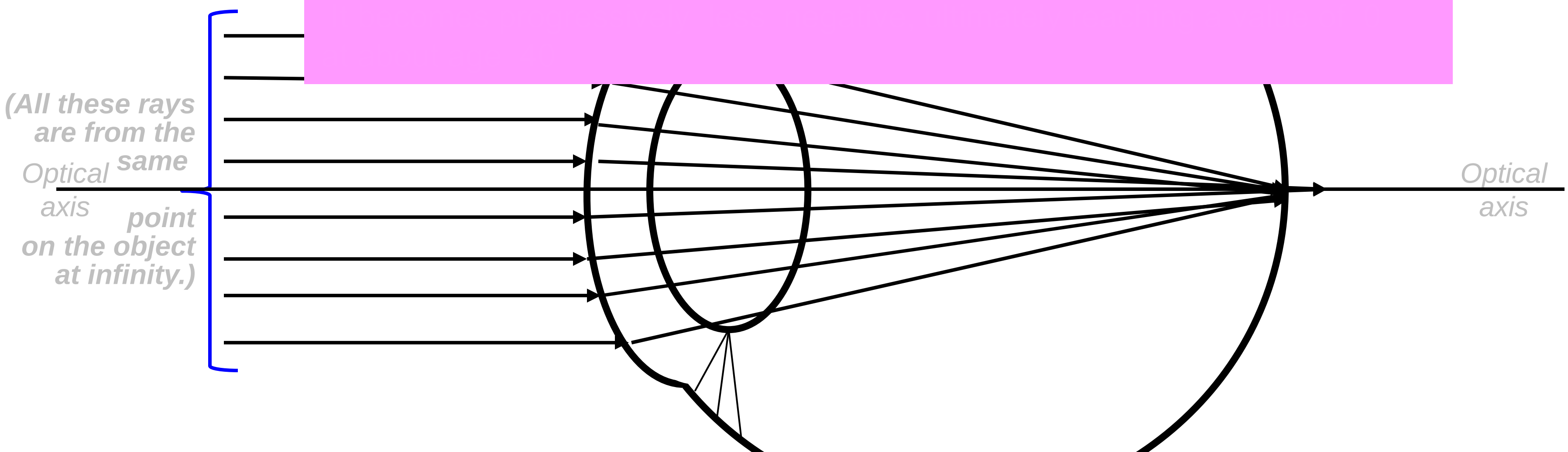
'Young adult' *seems to be emphasized, implying that the Q factor is* **not** *-0.25 in older adults. What happens to the Q factor of the lens as we age?*



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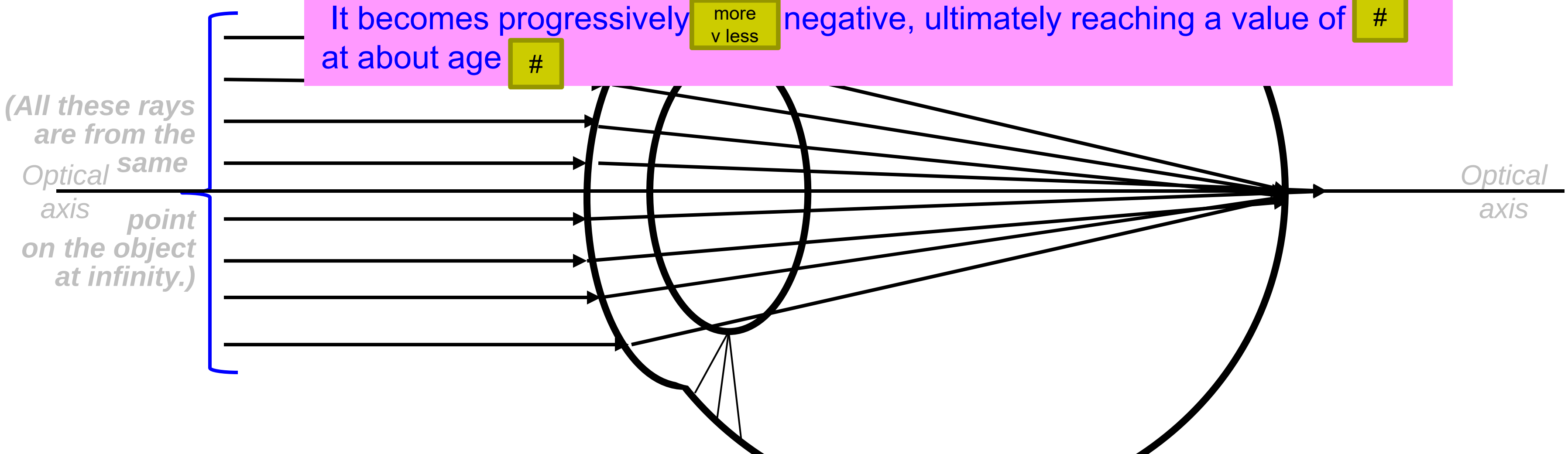
It becomes progressively [more v less] negative, ultimately reaching a value of [#] at about age [#]



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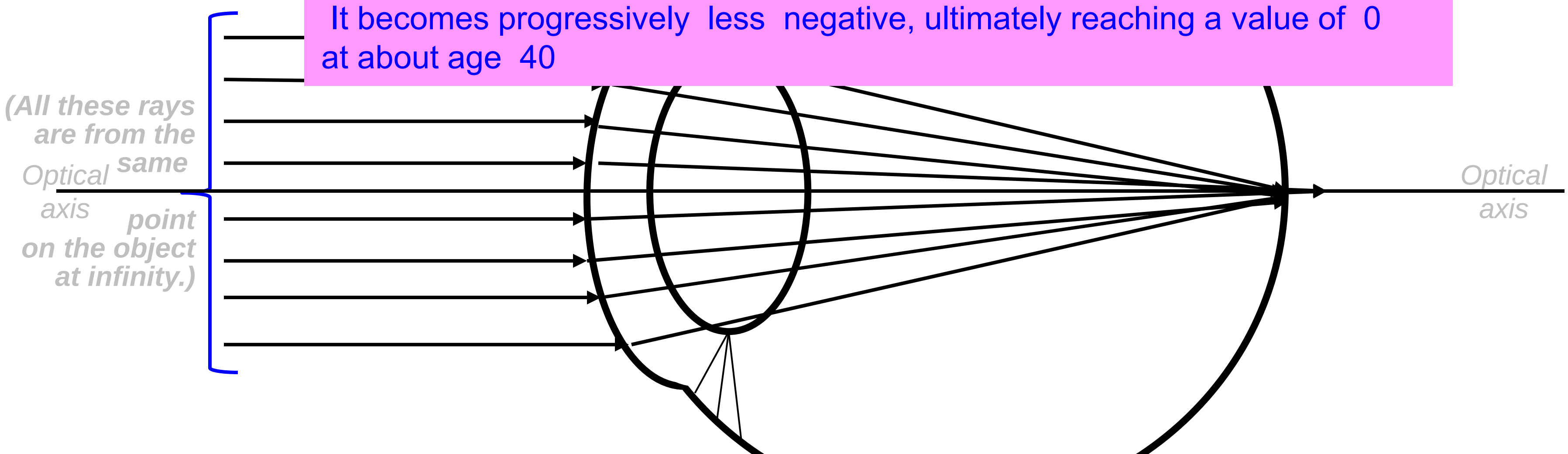
It becomes progressively less negative, ultimately reaching a value of 0 at about age 40



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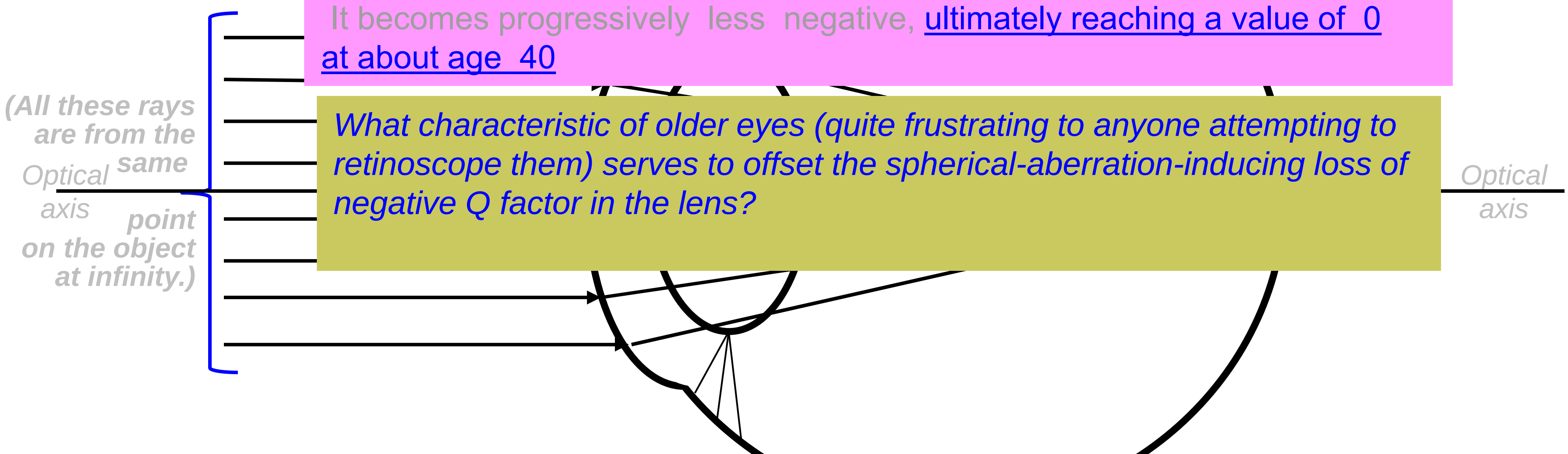
The Q factor measures the *relative* asphericity of the cornea. A negative Q factor simply means the corneal periphery has less power than the central cornea; it does not mean the cornea as a whole doesn't have spherical aberration!

Recall that the cornea's Q factor is -0.26. What would it be if the cornea had no spherical aberration?
About -0.52

Why didn't we evolve ~~corneas~~ eyes with a Q factor of -0.52? We did!
Well, no one can say for sure of course. But what **can** be said with certainty is that a Q factor of -0.52

Interestingly, while we didn't evolve **corneas** with a Q factor of -0.52, we did evolve **eyes** with it. The human lens of a young adult has an average Q value of about -0.25. Thus, the entire refracting system of the average young adult human eye has a total Q factor very close to -0.52, and thus has little to no spherical aberration!

'Young adult' *seems to be emphasized, implying that the Q factor is* **not** *-0.25 in older adults. What happens to the Q factor of the lens as we age?*
It becomes progressively less negative, ultimately reaching a value of 0 at about age 40



What characteristic of older eyes (quite frustrating to anyone attempting to retinoscope them) serves to offset the spherical-aberration-inducing loss of negative Q factor in the lens?

How much spherical aberration does the average human cornea possess?
About +0.27 µm

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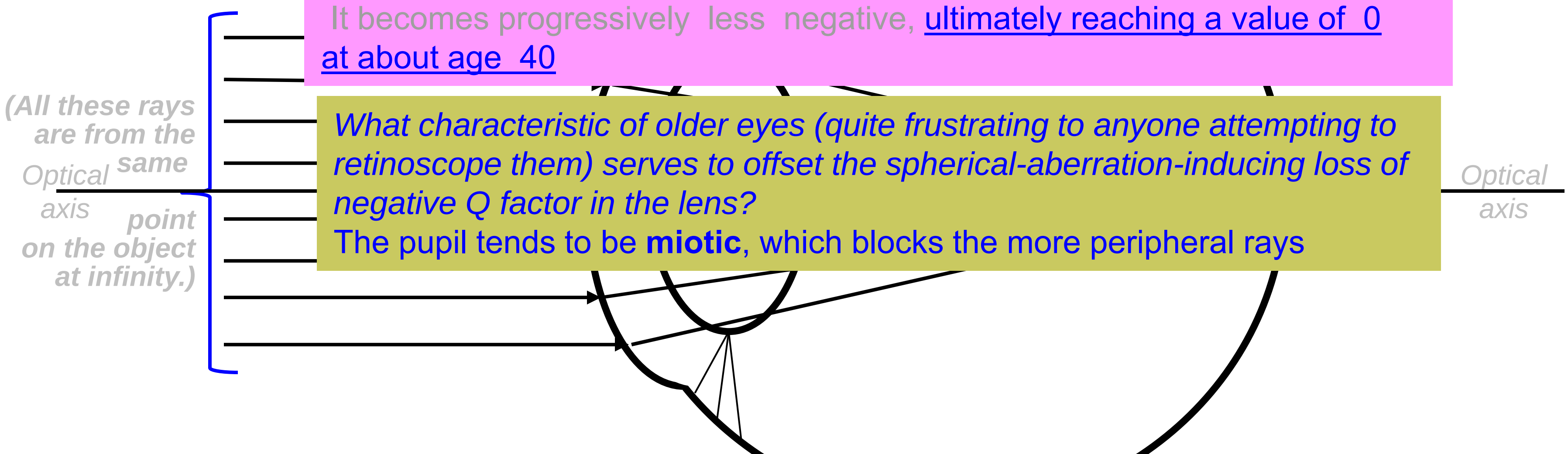

What characteristic of older eyes (quite frustrating to anyone attempting to retinoscope them) serves to offset the spherical-aberration-inducing loss of negative Q factor in the lens?
The pupil tends to be **miotic**, which blocks the more peripheral rays

How much spherical aberration does the average human cornea possess?
About +0.27 μm

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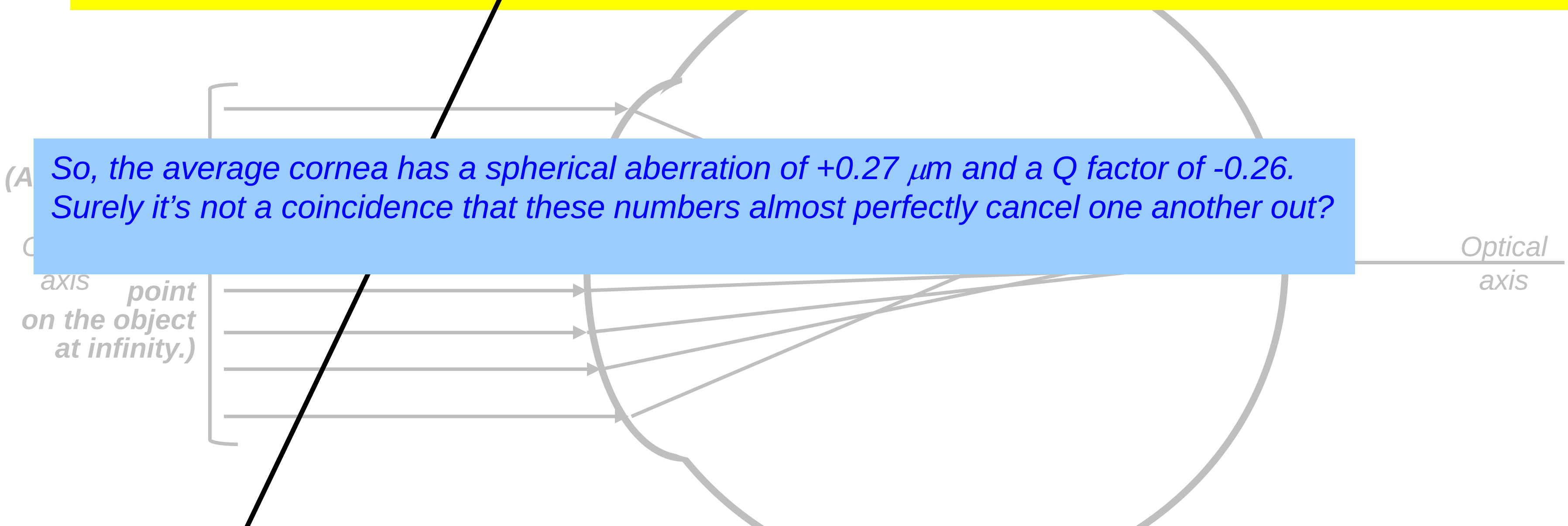
About -0.52

Why didn't we evolve corneas with a Q factor of -0.52?
Well, no one can say for sure of course. But what **can** be said with certainty is that a Q factor of -0.52 would require a radically different angle between the cornea and the sclera--an angle that could not be achieved given the biomechanics and size of the normal human globe. Thus, a Q factor of -0.52 would require a very radical 're-design' of the globe--and thus of the orbits, and the cranium, and etc.



So, the average cornea has a spherical aberration of +0.27 μm and a Q factor of -0.26. Surely it's not a coincidence that these numbers almost perfectly cancel one another out?

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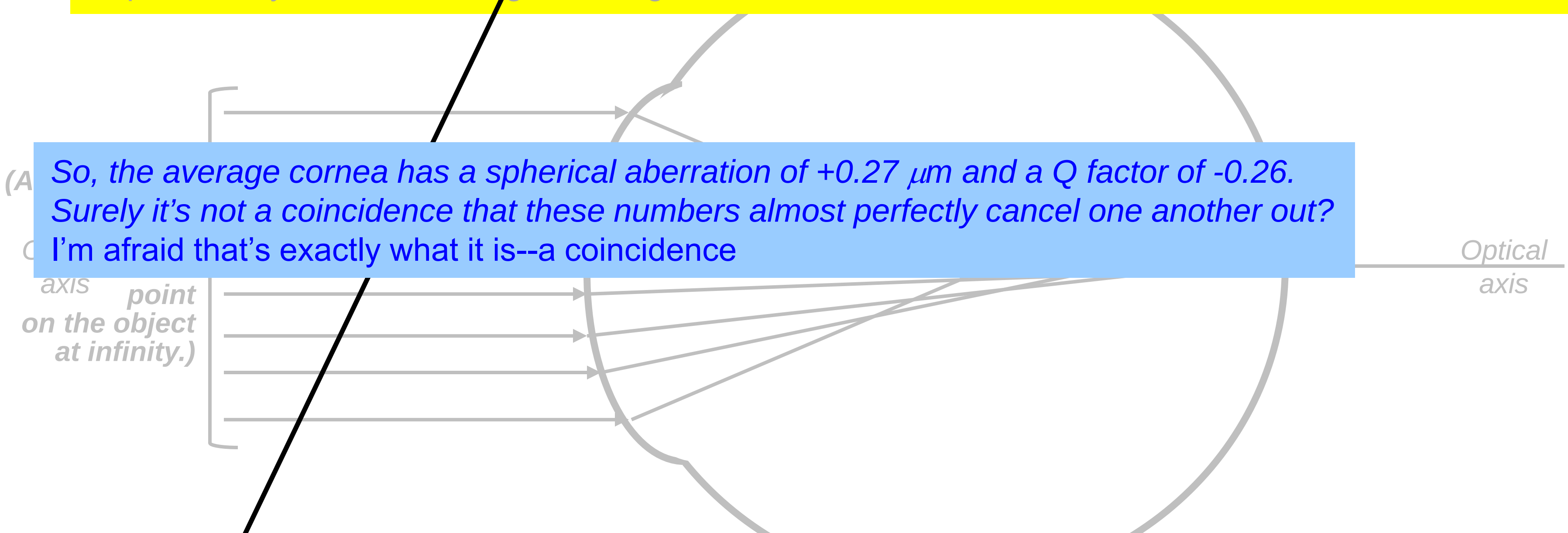

So, the average cornea has a spherical aberration of +0.27 μm and a Q factor of -0.26. Surely it's not a coincidence that these numbers almost perfectly cancel one another out?
I'm afraid that's exactly what it is--a coincidence

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Aberrations: *Zernike Polynomials*

- A mathematical system for describing and systematizing optical aberrations

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Aberrations: *Zernike Polynomials*

- A mathematical system for describing and systematizing optical aberrations
  - A series of shapes; when combined, they can account for the overall contour of a wavefront

In other words: Any wavefront, no matter how complex its shape, can be 'broken down' into a set of Zernike shapes

Aberrations: *Zernike Polynomials*

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  - A series of shapes; when combined, they can account for the overall contour of a wavefront
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    - The progression is described by the *order* of a given shape
      - Order start at zero, and goes up from there

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order	***New Lingo***	***Shape***
2nd	Defocus *Positive* defocus *Negative* defocus	
2nd	Cylinder	
4th	Spherical aberration	
3rd	Coma	
3rd	Trefoil	

Intentionally out of order! While coma and trefoil are of lower-order than spherical aberration, SA is clinically more significant.

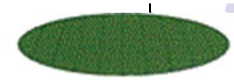
(Others, less clinically relevant)

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order		***New Lingo***	***Shape***
0th	↔	***?***	
1st	↔	***?***	
	→	Defocus *Positive* defocus *Negative* defocus	
2nd	↔	Cylinder	
4th	↔	Spherical aberration	
3rd	↔	Coma	
3rd	↔	Trefoil	
		(Others, less clinically relevant)	

Wait--you said ZPs start at zero and go up from there. What are the 0th and 1st-order aberrations?

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order		***New Lingo***	***Shape***
0^{th}	←→	'Piston'	 PISTON
1^{st}	←→	'Prism'	 VERTICAL PRISM  HORIZONTAL PRISM (aka *tip* and *tilt*)
	→	Defocus: *Positive* defocus, *Negative* defocus	
2^{nd}	←→	Cylinder	
4^{th}	←→	Spherical aberration	
3^{rd}	←→	Coma	
3^{rd}	←→	Trefoil	

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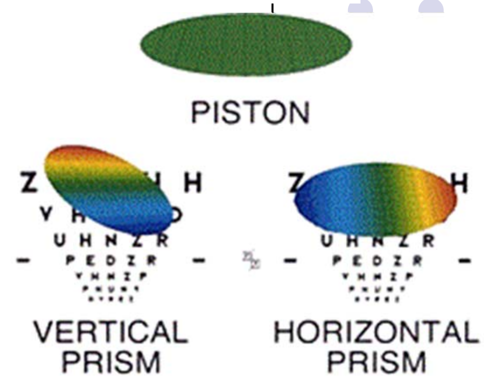
Aberrations: *Zernike Polynomials*

Zernike Polynomial Order	***New Lingo***
0th ↔	'Piston'
1st ↔	'Prism'
2nd ↔	Defocus *Positive* defocus *Negative* defocus
2nd ↔	Cylinder
4th ↔	Spherical aberration
3rd ↔	Coma
3rd ↔	Trefoil

(Others, less clinically relevant)

Shape



(aka *tip* and *tilt*)

Why haven't we talked about piston and prism?

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order — ***New Lingo*** — ***Shape***

0th ↔ 'Piston'

1st ↔ 'Prism'

2nd ↔ Defocus
Positive defocus
Negative defocus

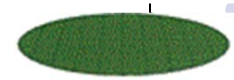
2nd ↔ Cylinder

4th ↔ Spherical aberration

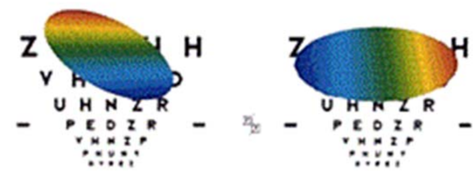
3rd ↔ Coma

3rd ↔ Trefoil

(Others, less clinically relevant)



PISTON



VERTICAL PRISM

HORIZONTAL PRISM

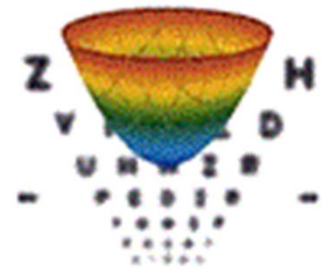
(aka *tip* and *tilt*)

Why haven't we talked about piston and prism?
Because while they are technically aberrations in the ZP system, they do not degrade the quality of the visual image, and are thus **clinically irrelevant**

Aberrations: *Zernike Polynomials*

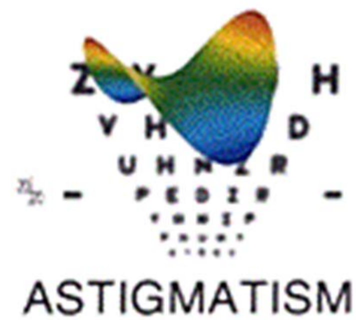
Zernike Polynomial Order		***New Lingo***
0th	↔	'Piston'
1st	↔	'Prism'
2nd	↔	Defocus
Myopia	=	*Positive* defocus
Hyperopia	=	*Negative* defocus
2nd	↔	Cylinder
4th	↔	Spherical aberration
3rd	↔	Coma
3rd	↔	Trefoil
		(Others, less clinically relevant)

Shape



DEFOCUS
(positive)
'Bowl'

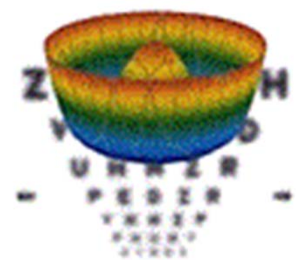
Aberrations: *Zernike Polynomials*

Zernike Polynomial Order		***New Lingo***	*Shape*
0^{th}	↔	'Piston'	
1^{st}	↔	'Prism'	
2^{nd}	↔	Defocus	
Myopia	↔ = ↔	*Positive* defocus	
Hyperopia	↔ = ↔	*Negative* defocus	
2^{nd}	↔	Cylinder	
4^{th}	↔	Spherical aberration	
3^{rd}	↔	Coma	
3^{rd}	↔	Trefoil	

'Saddle'

(Others, less clinically relevant)

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order		***New Lingo***	***Shape***
0^{th}	↔	'Piston'	
1^{st}	↔	'Prism'	
2^{nd}	↔	Defocus	
Myopia	↔ = ↔	*Positive* defocus	
Hyperopia	↔ = ↔	*Negative* defocus	
2^{nd}	↔	Cylinder	
4^{th}	↔	Spherical aberration	 SPHERICAL ABERRATION 'Bundt cake pan' 
3^{rd}	↔	Coma	
3^{rd}	↔	Trefoil	
		(Others, less clinically relevant)	

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order	***New Lingo***	*Shape*
0^{th} ↔	'Piston'	
1^{st} ↔	'Prism'	
2^{nd} ↔	Defocus	
Myopia ↔ = ↔	*Positive* defocus	
Hyperopia ↔ = ↔	*Negative* defocus	
2^{nd} ↔	Cylinder	
4^{th} ↔	Spherical aberration	
3^{rd} ↔	Coma	 'Recliner'
3^{rd} ↔	Trefoil	
	(Others, less clinically relevant)	

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order | ***New Lingo*** | ***Shape***

0th ←→ 'Piston'

1st ←→ 'Prism'

2nd ←→ Defocus

Myopia ← = → *Positive* defocus

Hyperopia ← = → *Negative* defocus

In layman's terms, what is the problem with the incoming light that leads to the higher-order aberration of coma?

4th ←→ Spherical aberration

3rd ←→ Coma

3rd ←→ Trefoil

(Others, less clinically relevant)

'Recliner'

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order	**New Lingo**	*Shape*
0th ⟷	'Piston'	
1st ⟷	'Prism'	
2nd ⟷	Defocus	
Myopia ⟷ = ⟷	*Positive* defocus	
Hyperopia ⟷ = ⟷	*Negative* defocus	
4th ⟷	Spherical aberration	
3rd ⟷	Coma	 'Recliner'
3rd ⟷	Trefoil	
	(Others, less clinically relevant)	

In layman's terms, what is the problem with the incoming light that leads to the higher-order aberration of coma?
Coma occurs when **the source of the rays is located off the optical axis**. Because of its location, light from this source reaches one side of the pupil before the other. The result is that rays entering the 'near' side and the 'far' side of the pupil are focused not at as a single point, but rather as a point with a 'smear' attached (not unlike a comet's tail, which is why the words share a root).

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order	***New Lingo***	***Shape***
0th ⟷	'Piston'	
1st ⟷	'Prism'	
2nd ⟷	Defocus	
Myopia ⟷ = ⟷	*Positive* defocus	
Hyperopia ⟷ = ⟷	*Negative* defocus	
2nd ⟷	Cylinder	
4th ⟷	Spherical aberration	
3rd ⟷	Coma	
3rd ⟷	Trefoil	 TREFOIL 'Three peaks'

(Others, less clinically relevant)

Aberrations: *Zernike Polynomials*

Zernike Polynomial Order		***New Lingo***	***Shape***
0^{th}	⟷	'Piston'	
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2^{nd}	⟷	Defocus	
Myopia	⟷ = ⟷	*Positive* defocus	
Hyperopia	⟷ = ⟷	*Negative* defocus	
2^{nd}	⟷	Cylinder	
3^{rd}	⟷	Coma	
3^{rd}	⟷	Trefoil	

In layman's terms, what is the problem with the incoming light that leads to trefoil?

(Others, less clinically relevant)

'Three peaks'

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Zernike Polynomial Order	**New Lingo**	*Shape*
0th	'Piston'	
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2nd	Defocus	
Myopia =	*Positive* defocus	
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2nd	Cylinder	
3rd	Coma	
3rd	Trefoil	
	(Others, less clinically relevant)	

In layman's terms, what is the problem with the incoming light that leads to trefoil?
Happily, the BCSC books do not spend much time on trefoil, so you don't need to know much more about it that 1) the fact that it is a clinically significant (albeit modestly so) higher-order aberration, and 2) to be able to recognize its wavefront analysis profile (more on this later).

TREFOIL

'Three peaks'

Aberrations: *Zernike Polynomials*

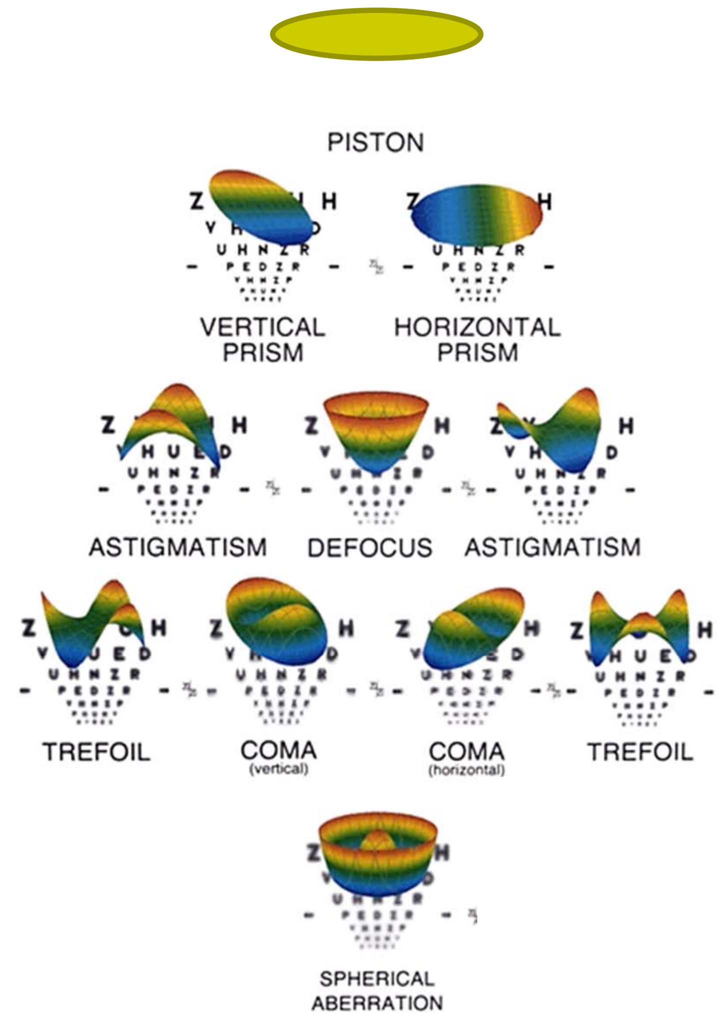
0th

1st

2nd

3rd

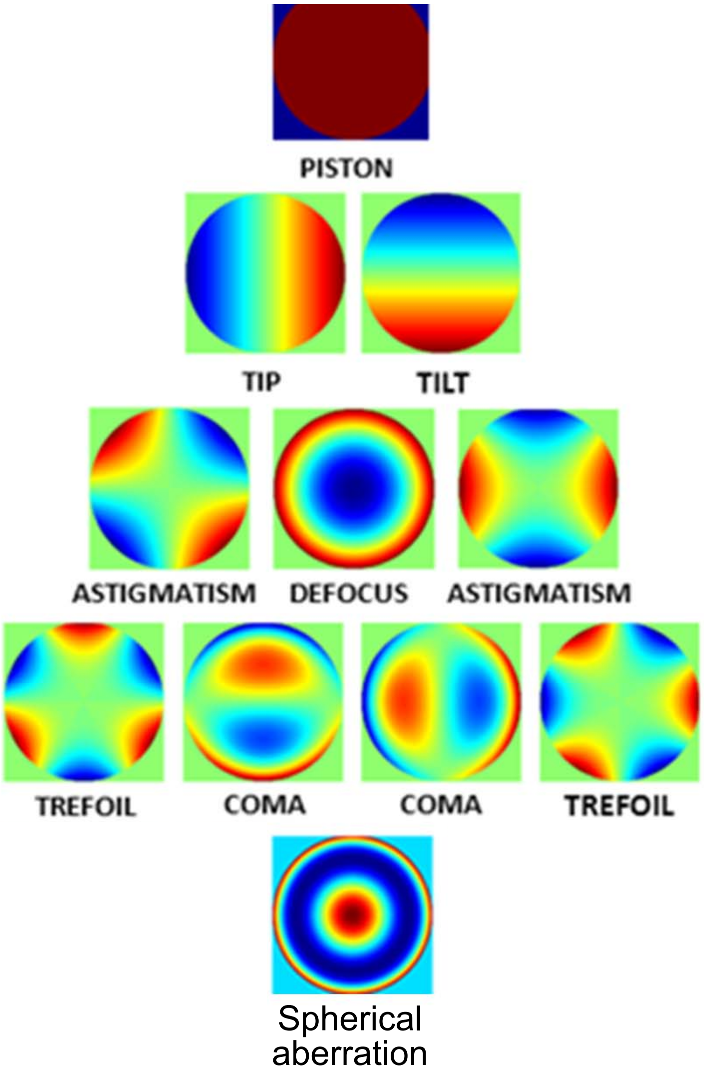
4th



In addition to the 3-D representation of each shape…

3-D representation

Aberrations: *Zernike Polynomials*



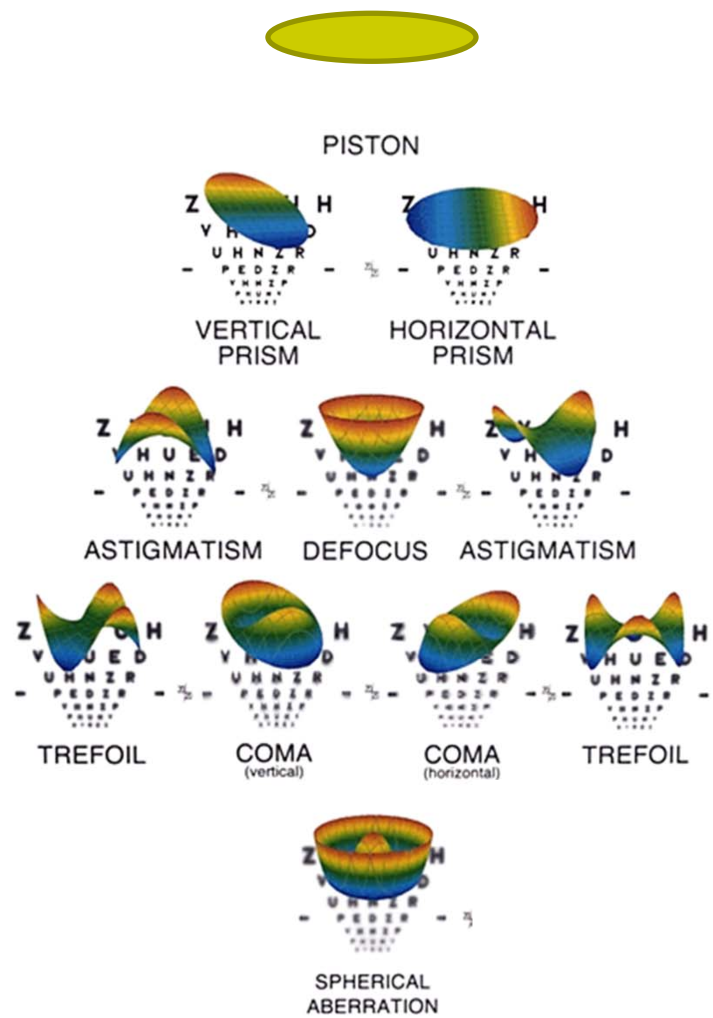
0^{th}

1^{st}

2^{nd}

3^{rd}

4^{th}

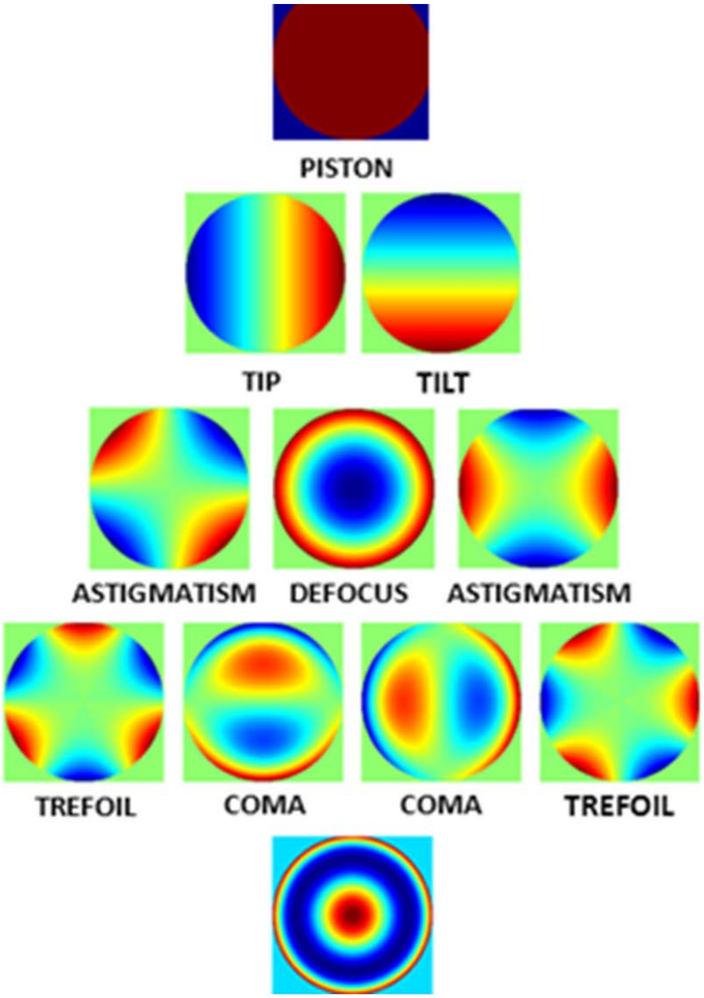


2-D representation

In addition to the 3-D representation of each shape… __You need to be able to recognize its 2-D image as well!__

3-D representation

Aberrations: *Zernike Polynomials*



Spherical aberration

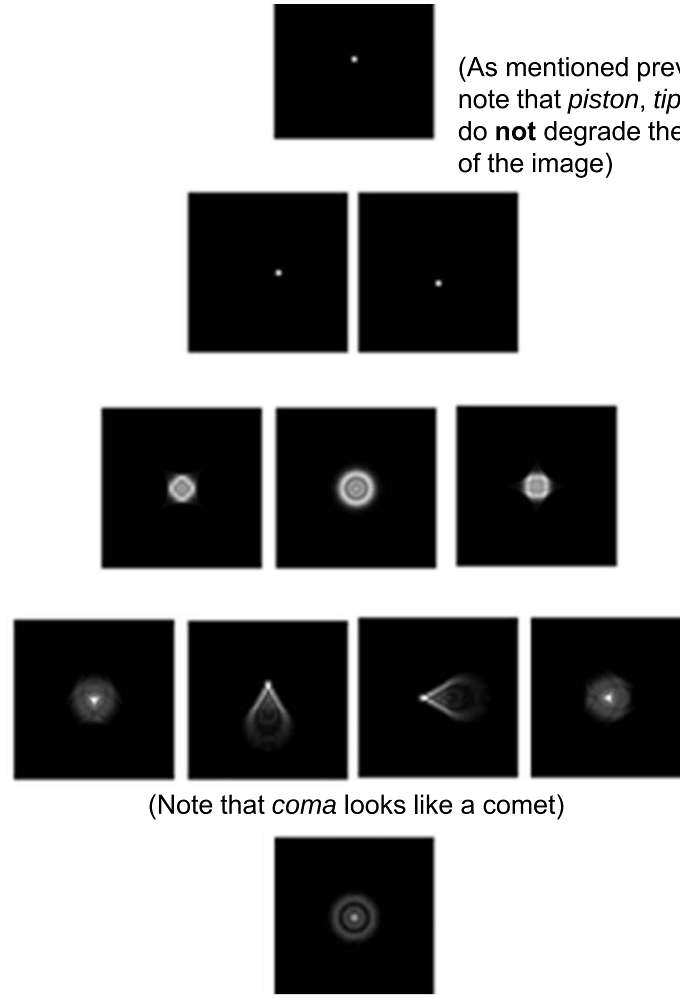
0th

1st

2nd

3rd

4th



(As mentioned previously, note that *piston*, *tip* and *tilt* do **not** degrade the quality of the image)

(Note that *coma* looks like a comet)

2-D representation

Optical effect of each on a point-image

Aberrations

- two-words *keratorefractive surgery* did away with the second problem

Essentially, *irregular astigmatism* was a wastebasket term for aberrations that:

1) ~~could not be measured in the clinic; and~~
2) ~~could not be corrected even if they had been measureable~~

Aberrations

- *Wavefront-guided keratorefractive surgery* did away with the second problem

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Aberrations

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  - Allows surgeons to correct/minimize the higher-order aberrations identified via wavefront analysis

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Aberrations

- *Wavefront-guided keratorefractive surgery* did away with the second problem
  - Allows surgeons to correct/minimize the higher-order aberrations identified via wavefront analysis
  - That said, precisely *which* higher-order aberrations should be corrected (and to what degree) is an unsettled issue at this time

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r

unsettled issue at this time

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How does a wavefront-optimized ablative procedure differ from a so-called conventional ablative *procedure?*

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How does a wavefront-optimized ablative procedure differ from a so-called conventional ablative *procedure?*
In a conventional procedure, the ablation is determined solely by a standard phoropter-based refraction obtained by the surgeon during pre-op. That is, the phoropter-based refraction is used to program the correction of sphere and cyl. In a wavefront-optimized ablation, the wavefront analysis is used to program the correxction of sphere and cyl.

Essentially, *irregular astigmatism* was a wastebasket term for aberrations that:
1) ~~could not be measured in the clinic; and~~
2) ~~could not be corrected even if they had been measureable~~

Aberrations

- *Wavefront-guided keratorefractive surgery* did away with the second problem

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In a wavefront-*guided* procedure, the information obtained from wavefront analysis is used to correct certain higher-order aberrations along with the more-important lower-order (ie, sphere and cyl) aberrations.
In contrast, a wavefront-*optimized* procedure corrects only sphere and cylinder; no attempt is made to address higher-order aberrations. Instead, the wavefront information is used to 'fine tune' the ablation in such a way as to minimize the *creation* or *exacerbation* of higher-order aberrations.

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In addition to wavefront-guided, wavefront-optimized and conventional approaches to ablation, there is one more. What is it?

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So, there are *four basic techniques* for performing keratoablative refractive surgery

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