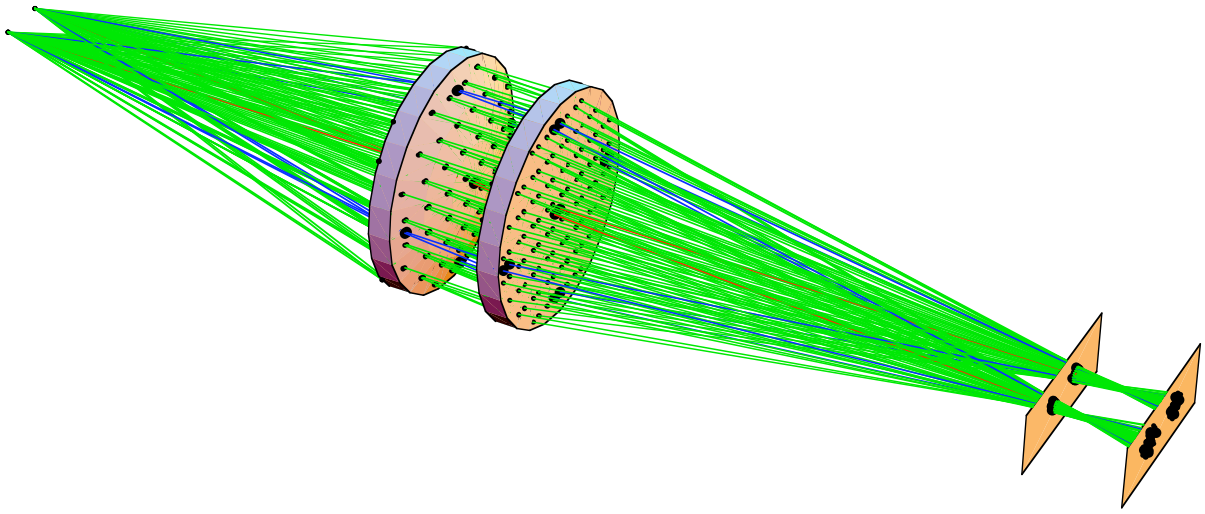
Rayica User Guide



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1. Introduction

Nearly every optical engineering endeavor can benefit from the use of *Rayica*, including but not limited to: optimization, lasers and resonators, non-sequential calculations, stray-light analysis, time-dependent optical systems, imaging systems, spectroscopic measurement, astronomical systems, solar concentrators, fiber-optic systems, opto-mechanical systems, polarization calculations, turbulent media, and photon-density calculations.

This guide will get you acquainted with *Rayica*'s most important features. By learning the functions introduced here, you will have a good foothold for using *Rayica*. In particular, you will learn how to model optical components and light sources together for ray tracing as well as receive an overview of *Rayica*'s most important capabilities. In addition to this User Guide, advanced information is provided in the companion Principles Of Rayica guide as well as through our website: www.opticasoftware.com. Before beginning, however, you must first load *Rayica* into memory.

Loading *Rayica*

The basic *Rayica* package is made up of two folders: *Rayica* and *RayicaTools*. The *Rayica* folder contains all of the essential files that make up *Rayica* while *RayicaTools* contains auxiliary functions for loading packages and working with *Mathematica*. Make sure that both the *Rayica* and *RayicaTools* folders are located together in a directory path recognized by *Mathematica* for packages. The *Rayica* package is loaded with the following command:

```
In[1]:= Needs["Rayica`Rayica`"]

        ++++++++++++++++++++++++++

        Rayica 2.0 was loaded in 18 s and needs 6019
          kilobytes of memory on top of 3499 kilobytes already used
```

This loading process can take a minute or two, depending on your computer's speed. In addition to being loaded as a package, all of *Rayica* files are formatted as *Mathematica* notebooks. The *Rayica* source code is made accessible in the *Rayica* folder so that you can develop new functions of your own by studying *Rayica*'s built-in functions. This is particularly helpful when you wish to model new component ideas in *Rayica*.

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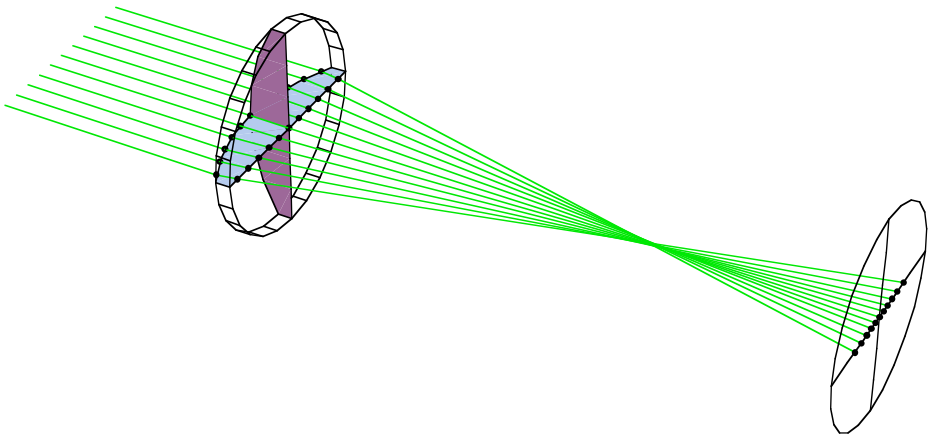
A basic *Rayica* example

The simplest way to learn *Rayica* is to experiment with its text-based interface. To this end, we have included a series of examples based on a simple optical system in this Introduction of the User Guide. The following series of examples will be used to demonstrate the elements necessary to create and analyze a basic optical system in *Rayica*. Each line of the initial example will be discussed in specific with references to later sections of this booklet for more extensive explanations of the functions used.

```
In[13]:= TurboPlot[{
              LineOfRays[45,NumberOfRays->11],
              Move[PlanoConvexLens[100, 50, 10], 50],
              Move[Screen[50], 200]
              }]
```



```
Out[13]= -traced system-
```

Inputting data

The first thing about this example to observe is the format. Because *Rayica* uses a text-based input system, it does not matter whether or not you include line breaks where they have been included. They have been put into this example for the sake of clarity. The generated image can be instantly resized by selecting a corner of the image and dragging the corner of the picture until in is the desired size.

Another important note about entering data in *Rayica* is that every function in *Rayica* has a specific input format. For example, the input format for **TurboPlot** is `TurboPlot[system, options]`. **TurboPlot** takes two different inputs: an optical system (system) and any option definitions (options). When any input variable contains multiple elements (in this case, an optical system) it is necessary to enclose those elements in curly brackets ("**{}**"). As with any mathematical system, it is important to close all brackets and parentheses appropriately or else the calculation will fail. Note that sometimes an input element is not required for final calculation. **TurboPlot** does not require that options be entered in order to perform a calculation (nor does any other function for that matter). It is always valuable to check a functions definition to see whether or not an input element is required for calculation or not.

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Modelling an optical system

When entering an optical system into *Rayica*, you should consider what elements to include. To produce any meaningful result, it is necessary to have two things: light sources and optical components. More often than not, you will have only one light source but several components though only one of each has been included in this example. The light source is **LineOfRays** and the optical component is **PlanoConvexLens**. Another essential element of this system is the **Screen**. While not an optical element per se, the **Screen** provides a necessary function in that it intercepts all rays which come in contact with it without changing the optical properties of the ray.

Just as important as the components and light sources that you include in an optical system is their position in the system. As such, you will make almost constant use of the **Move** function. **Move** allows any object to be moved to any location or position within an optical system. For more information on the **Move** function and its uses, see Section 4 of this guide.

The ultimate use of an optical system in *Rayica* is analysis and/or display. If you are unsure of the function that you wish to use to analyze the optical system you have created, you can access a list of available functions using the **RayicaFunctions** command.

Basic Steps to follow when creating an optical system:

1) Determine what light source to use

2) Create a component list (see the Resonate section if you have any composite lenses)

3) Position the components in your list using the **Move** function

4) Bound the system using a **Screen** or a **Boundary**

5) Assign the resulting system to a variable

6) Use different high level functions to analyze the system as necessary

Variable definition

It is an excellent idea to assign the system to a variable as shown below.

```
In[14]:= opticalsystem = {
         LineOfRays[45,NumberOfRays->11],
         Move[PlanoConvexLens[100, 50, 10], 50],
         Move[Screen[50], 200]
         }

Out[14]= {LineOfRays[45, NumberOfRays → 11],
          Move[PlanoConvexLens[100, 50, 10], 50.], Move[Screen[50], 200.]}
```

When an optical system is assigned to a variable, you can then use that variable to perform any number of calculations. It is always a good idea to assign an optical system to a variable if you intend to use the same system for repeated calculations as this can dramatically reduce input time. What is further, you can assign the output of a function to a variable as shown below

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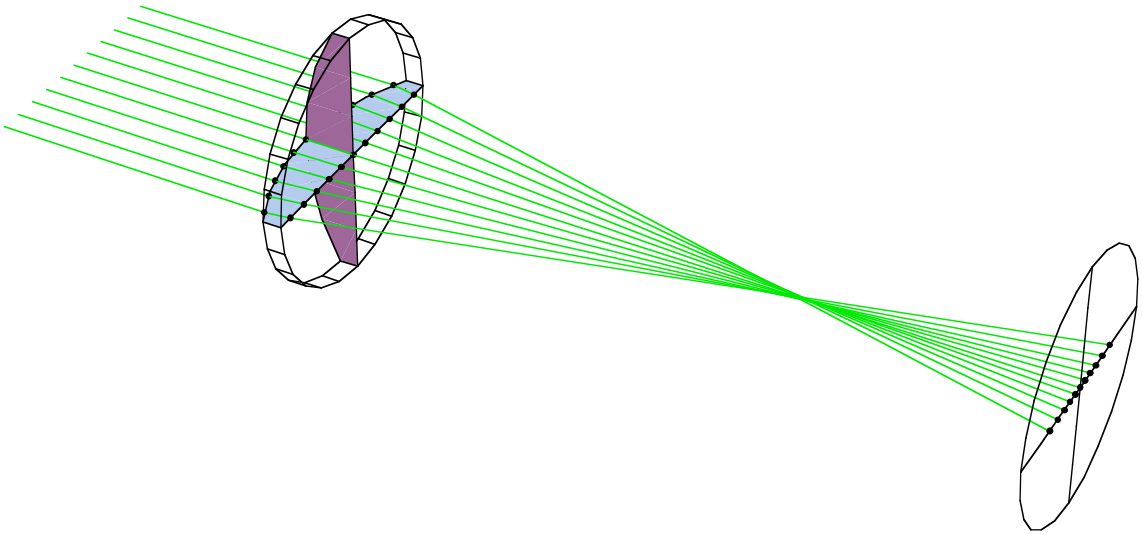
```
In[16]:= tracedresult = TurboPlot[opticalsystem]
```



```
Out[16]= -traced system-
```

Basic commands

If you already know the name of command that you want to include in your optical system but would like to review the definition before actually including it, you can use the **?** command to display the definition.

```
In[11]:= ?PlanoConvexLens

         PlanoConvexLens[focallength, aperture, thickness,
           label, options] denotes a lens with a planar surface on
           one side and a convex spherical surface on the other side.

         PlanoConvexLens is created with its first surface centered about the origin
           and its second surface positioned down the positive x axis. The aperture
           parameter may designate a circle, rectangle, or polygon depending on
           the number and type of elements listed by it. The user-named label
           parameter is optional and can be omitted. When it is present, its text
           content is used to identify the object in both the rendered graphics
           and the output cell expression. When it is omitted, Rayica uses the
           default setting of the Labels option with the rendered graphics.

         Note that the specified focallength is always determined for a particular
           setting of the DesignWaveLength and ComponentMedium options. By default,
           Rayica uses DesignWaveLength->0.5461 microns and ComponentMedium->BK7.
           Care should be taken to insure that these default settings are compatible
           with the intended experimental design or unintended results can occur.
```

The **?** command works with all defined elements of *Rayica*, from functions to light sources to options. Almost anything that can be evaluated by *Mathematica* can be defined using the **?** command.

Another very useful command is the **%** command. Use of **%** is discussed in the 10 minute introduction to *Mathematica* which you may wish to read. Essentially, **%** acts as a variable which stores the result of the previous calculation. So, if you wish to use the results of the last calculation performed, simply create a new input using **%** and evaluate it.

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The final fundamental command is **Options[ ]**. When you enter a *Rayica* function name into the square brackets and press Shift+Enter, a list of the options associated with that function name are displayed. Finding a rule and applying it will be discussed in the next section.

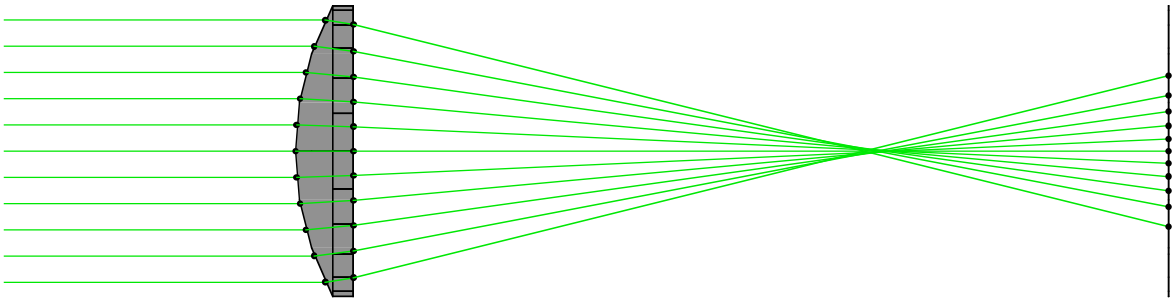
```
In[12]:= Options[Screen]

Out[12]= {Labels → S, LabelPositions → Automatic,
          ComponentDescription → Automatic, Transmittance → 100, GraphicDesign → Automatic,
          Automatic → {SurfaceRendering → Trace, CrossRendering → Trace},
          Sketch → {SurfaceRendering → Trace, CrossRendering → Trace},
          Wire → {SurfaceRendering → Mesh, CrossRendering → Empty},
          Solid → {SurfaceRendering → {Fill, Trace}, CrossRendering → Empty}}
```

Using Options

Options are available for almost every element of *Rayica*. To discover what options are associated with the elements that you are using, use the **Options[]** command as discussed in the Basic Commands section of this booklet. Options are assigned to *Rayica* elements using what is known as a rule ("**->**") in *Mathematica*. What this means is that you select an option (or options) to assign a value (like **PlotType** in the following example) and then assign it a new value using the rule arrow.

```
In[17]:= TurboPlot[tracedresult, PlotType->TopView]
```



```
Out[17]= -traced system-
```

If you are unsure of what new values can be assigned to an option, you can use the **?** command and the option's name to determine what values can be assigned to that option.

```
In[18]:= ?PlotType

          PlotType is an option of DrawSystem/AnalyzeSystem, TurboPlot, and
            ShowSystem that designates the display form of the graphics rendering.

          PlotType takes TopView, FrontView, SideView,
            Full3D, RealTime3D, Off, Surface, and ShadowProject as values.

          A list of one or two points specify a direction and center
            to project the graphics. The points can be specified as rules
            RaySelect -> sel, ComponentSelect -> sel and SurfaceSelect ->
            sel, with sel being a list of selection properties passed to the
            designated functions. See also: CreateStereoView and ProjectGraphics3D.
```

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Rayica's high-level functions

Rayica has a number of functions available for high-level calculations. Some (but not all) of these functions are shown in the following table.

`AnalyzeSystem[`*system*, *options*`]`** is used to trace rays through optical components and render the results for illustration purposes. This is also called **`DrawSystem`**.
`PropagateSystem[`*system*, *options*`]`** is used by **`AnalyzeSystem`** to trace rays through optical components. This method is much slower than **`TurboTrace`**.
`TurboTrace[`*optics*, *options*`]`** produces an accelerated ray trace of a system of light sources and optical elements.
`TurboPlot[`*system*, *options*`]`** works with **`TurboTrace`** to perform accelerated ray-tracing and rendering of a system of light sources and optical elements.
`ShowSystem[`*system*, *options*`]`** takes a *system* of rays and/or components and generates a graphical display of the *system*. **`ShowSystem`** works with **`AnalyzeSystem`** and **`TurboPlot`** results.
`ReadRays[`*results*, *rayparameters*, *selectionproperties*`]`** takes ray-traced *results* from **`AnalyzeSystem`**/**`TurboPlot`**/**`TurboTrace`** and returns a list of values for the *rayparameters* and *selectionproperties* given.
`OptimizeSystem[`*system*, *options*`]`** optimizes the performance of an optical system for a specified set of symbolic input parameters.
`FindFocus[`*objectset*, *options*`]`** determines the minimum spot size for a locus of rays at the last reported surface in the system and plots the results.
`FindSpotSize[`*objectset*, *options*`]`** determines the spot size for a locus of rays at the last reported surface in the system and plots the results.
`FindIntensity[`*system*, *options*`]`** calculates the intensity function for each optical surface that gets reported from the ray trace of the *system*.
`ModulationTransferFunction[`*intensitydata*, *options*`]`** calculates the modulation and phase transfer functions of an optical system for a given object source input.
`Resonate[`*listofcomponents*, *objectname*, *options*`]`** is a generic building block that causes a ray to be nonsequentially traced within all of the surfaces defined by *listofcomponents*.
`TransferTraits[`*donor-component*, *recipient-component*, *surfacenumbers*, *opts*`]`** is a function that transfers the surface traits of a donor component surface into the surfaces (specified by *surfacenumbers*) of a recipient component.

Rayica's most important high-level functions.

In various ways, these high-level functions assist the user in conducting the ray trace and interpreting the traced results. At the heart of every high level function in *Rayica* is the ray-trace calculation. For this, *Rayica* offers two parallel ways to trace rays through a system of optical elements in three-dimensional space, using either **`PropagateSystem`** or **`TurboTrace`**. In many cases, however, the ray-trace needs to be accompanied by a graphical rendering of the traced system. In such instances, either **`AnalyzeSystem`** or **`TurboPlot`** is called instead of **`PropagateSystem`** or **`TurboTrace`**. In other instances, **`ShowSystem`** is used to render isolated components or to rerender the results after the initial trace has taken place. **`ReadRays`** is used to extract numerical information from the traces previously conducted by **`AnalyzeSystem`**/**`PropagateSystem`** and **`TurboPlot`**/**`TurboTrace`**. The last five functions (**`OptimizeSystem`** , **`FindFocus`**, **`FindIntensity`**, **`ModulationTransferFunction`**, and **`TransferTraits`**) are the highest level functions of all and perform very specific tasks, as indicated by their given names.

Rayica offers four simple command tools that provide an overview of the functions used in the *Rayica* package: **`SourceFunctions`**, **`ComponentFunctions`**, **`MoveFunctions`**, and **`RayicaFunctions`**. These four commands create a list of the available light sources, optical components, move functions, and available optical functions respectively. For example, at any time that you wish while working with *Rayica*, you can access a listing of *Rayica*'s primary high-level functions with the **`RayicaFunctions`** command:

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```
In[7]:= RayicaFunctions
```

AddSurfaceRoughness	Fresnel	ReadRays
AnalyzeSystem	Hole	Resonate
ConstructMeritFunction	ModulationTransferFunction	SearchData
DataToRayica	Move	ShowSystem
FindFocus	MoveSurface	TransferTraits
FindIntensity	OptimizeSystem	TurboPlot
FindSpotSize	ReadData	TurboTrace

> *In Mathmatica,* **RayicaFunctions** *gives you hyperlinks to Rayica's most important high-level functions. Clicking on any name will give you a description of its use.*

Further, each of these lists is hyperlinked to the definitions of the different items contained in them. All you need to do is click on an item in the list to have its description displayed. In this Guide, we will explore many of these different functions in some detail. In some instances, this discussion serves as the primary reference for the subject matter. In other instances, however, the subject is discussed in more detail elsewhere. Next, we will learn how to create models of optical components and light sources.

2. Modeling Optical Components and Light Sources

Rayica has its own language for describing optical systems. In general, *Rayica* considers an optical system to be a collection of light sources and optical components. There are many different types of components and light sources in *Rayica* and each type is specified by a particular function. For example, a parallel light sheet is modeled by the **LineOfRays** function while a mirror is modeled by the **Mirror** function. After evaluation, these functions generate one of two special data structures that carry the optical properties. In particular, all component functions create a **Component** object, while all light source functions create a **Source** object. In this section, you will learn how to use component functions and light source functions to model optical components and light sources. Later on, you will learn how to define an optical system by listing together a combination of light sources and optical components. In particular, you will see that you can specify an optical system by placing your light sources and components in a list whose order describes the order of the light propagation through the optical components.

Coordinates

In *Rayica*, the X-axis runs in the horizontal direction, parallel to the computer screen, and is the default optical axis for optical systems, components within systems, and surfaces within components. The Z-axis encompasses the vertical direction and the Y-axis is right-handed with respect to the X and Z directions. Within an optical system, components and rays are located using the system's "world" coordinate system. Each surface within a component has its own local coordinate system and carries a three-dimensional rotation matrix plus a three-dimensional translation vector to transform a point or ray from the “world” coordinate system into the surface's local coordinate system, and back. This world-to-surface transform (matrix plus vector) is derived by combining the world-to-component and component-to-surface transforms during component initialization.

Modeling a light source

Next, we will take a closer look at light source functions. *Rayica* has a built-in series of functions that model different patterns of ray light sources. Here is a list of the most common built-in light source functions.

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SingleRay[*options***]** constructs a single ray of light with its starting position at the origin and is directed down the positive *x* axis.
CircleOfRays[*seed*, *size*, *options***]** initializes a set of rays distributed on the surface of a tube that points down the positive x-axis.
ConeOfRays[*seed*, *spread*, *options***]** initializes a set of rays distributed along a funnel-shaped surface that is oriented down the positive x-axis.
WedgeOfRays[*seed*, *spread*, *options***]** initializes a set of rays in the x-y plane that fan out with their chief direction oriented down the positive x-axis and are distributed across the y-coordinate with the specified fan spread.
LineOfRays[*seed*, *linewidth*, *options***]** initializes a set of rays in the x-y plane that point down the positive x-axis and are distributed along the y-coordinate with the specified linewidth.
GridOfRays[*seed*, *size*, *options***]** initializes a set of rays distributed throughout a tube-shaped volume that points down the positive x-axis.
PointOfRays[*seed*, *spread*, *options***]** initializes a set of rays distributed throughout a funnel-shaped volume that is oriented down the positive x-axis.
CustomRays[*seed*, {{*name*, *vector*}..}, *options***]** initializes a set of user-defined rays.
GaussianBeam[*beamspotsize*, *fulldivergence*, *options***]** and **GaussianBeam[***complexbeamparameter*, *options***]** is a light source that takes either the output beam spotsize radius (specified at 1/e of the axial value of the electric field amplitude peak in the starting plane) and far-field beam fulldivergence (specified as the full angle in radians at 1/e^2) or the complex beam parameter as input and creates an extended point source ray model of a Gaussian laser beam.
RainbowOfRays[*seed*, {*minwavelength*, *maxwavelength*}, *options***]** initializes a set of overlapping rays that point down the positive x-axis and are distributed over the specified range of wavelengths, given in microns.

Ten commonly used light source functions.

At any time that you wish while working with *Rayica*, you can access a listing of *Rayica*'s main high-level light source functions with the **SourceFunctions** command:

```
In[8]:= SourceFunctions
```

CircleOfRays	LineOfRays
ConeOfRays	PointOfRays
CustomRays	RainbowOfRays
GaussianBeam	SingleRay
GridOfRays	WedgeOfRays

In Mathmatica, **SourceFunctions** *gives you hyperlinks to Rayica's most important light-source functions. Clicking on any name will give you a description of its use.*

Most light sources in *Rayica* generate multiple rays of light. However, the simplest type of light source is the **SingleRay** function. This is designed for applications that require a single ray to be traced. When multiple rays are required, you could in principle specify a list of **SingleRay** functions for each ray, but it is always faster and more memory efficient to use one of the other built-in light source functions instead.

In *Rayica*, each light source function generates the information needed to describe a particular pattern of geometric rays. You can either store this generated information in an intermediate variable or immediately use it in a ray-trace calculation. Here is how you evaluate the **SingleRay** function and assign its information to a variable called **lightsource**.

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```
In[16]:=
 lightsource = SingleRay[]

Out[16]= SingleRay[]
```

Rayica normally hides the contents of its light sources by echoing the function input back to the screen. For a first-time user of *Rayica*, this can be a bit disconcerting since it appears that nothing has occurred at all. For this reason, *Rayica* changes the returned text color (typically to green) for valid entries instead of using the default black color of ordinary *Mathematica* output. This color change indicates that the input has been correctly evaluated by *Rayica*. If there is no color change, then the function has not been recognized by *Rayica* and, most likely, there has been a typographical mistake. In addition, if you use **InputForm**, as shown below, you can see that the **SingleRay** function has actually generated a hidden packet of information that is encapsulated by a **Source** object.

```
In[3]:= lightsource//InputForm

Out[3]//InputForm=
     Source[{}, SourceDescription :> SourceDescription[SingleRay[{Ray[]}, 1,
     SourceTransformation ->
          {{0., 0., 0.}, {{1., 0., 0.}, {0., 1., 0.}, {0., 0., 1.}}},
     SymbolicSourceTransformation ->
          {{0, 0, 0}, {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}}}]], SourceTransformation :>
       {{0, 0, 0}, {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}}}, SymbolicSourceTransformation :>
       {{0, 0, 0}, {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}}}, SourceLevel :> {1, 1}, NumberOfRays
     :> 1, BirthPoint :> {0, 0, 0},
      CoordinateSystem :> CartesianCoordinates, StartAtBirthPoint :> True, MonteCarlo :>
     False, SourceID :> 576,
      SourceFraction :> 1, SourceOffset :> 0, GridSpacing :> (#1 & )]
```

Because the **Source** object is automatically created by all of the built-in light source functions, the user of *Rayica* never has to worry about the contents of this object. In fact, unless you use **InputForm**, as demonstrated here, you will never even see the contents of another **Source** object again after this discussion! Nevertheless, it is helpful to understand what happens when you evaluate a light source function (ie: it creates a **Source** object.) This information is used later by *Rayica* for ray-tracing. In the previous result, the "SingleRay[ ]" returned to the screen merely identified the type of function that generated the **Source** object, namely by **SingleRay**! In advanced forms of *Rayica*, this "self-echoing" feature enables *Rayica* to support GUI-mouse gestures in addition to the textual entry of optics. For the basic *Rayica* operation discussed here, however, we will only consider the textual entry of optics.

A **Source** object is not directly used for the ray-trace calculation. Rather, the **Source** information is only used at the start of the ray trace to initiate the rays for the trace. Essentially, the **Source** object informs *Rayica* how create the required rays at the start of the ray trace. In particular, the **Source** object indicates which type of function has created it (**SingleRay** in this case) and includes special instructions about how many rays are to be created as well as how to configure the created rays into a particular spatial pattern. All of *Rayica*'s light source functions generate a **Source** object in the same fashion as **SingleRay**. Each light source function always creates a single **Source** object regardless of the actual number of rays used in the trace. After a ray trace has been carried out, specific information is usually returned about the optical surface intersections encountered by the rays in the trace. However, **Source** objects are only used to initiate the trace and are not used to store the resulting information from the ray trace. Instead, the traced rays are stored either as **Ray** objects (with **AnalyzeSystem**/**PropagateSystem**) or as **TurboRays** objects (with **TurboPlot**/**TurboTrace**). In the next section, you will learn more about **Ray** and **TurboRays** objects and how they get created from **Source** objects by the ray-trace functions of *Rayica*.

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Ray versus TurboRays

In this section, we will examine how **PropagateSystem** and **TurboTrace** store ray information as either **Ray** or **TurboRays** objects. In general, however, the user of *Rayica* will never work directly with **Ray** and **TurboRays** objects. As such, the following discussion is simply provided to help the user gain further insight into how *Rayica*'s handles the ray-trace information. For the most part, these mechanisms are hidden away from the *Rayica* user. If you are learning about *Rayica* for the very first time, you can skip this section without penalty.

At the start of a ray-trace, both **PropagateSystem** and **TurboTrace** use the **CreateRays** function to convert **Source** objects into either **Ray** or **TurboRay** objects. This initializes the ray information for the trace.

> **CreateRays[***source*, *options***]** is used by **PropagateSystem** and **TurboTrace** to generate either **Ray** objects or a **TurboRays** object that represents a set of rays for the given light source.
>
> **Ray[***rules***]** contains *rules* that is used by **PropagateSystem** to characterize a single ray segment of light between two optical surfaces.
>
> **TurboRays[**{*raysegment1*, *raysegment2*, ...}**]** gives a collection of ray segment parameters for use with **TurboTrace**.

The **Ray** and **TurboRays** objects offer two parallel ways of storing the same information about rays. In particular, the **Ray** object is used by **PropagateSystem** to hold ray information, while the **TurboRays** object is used instead by **TurboTrace**. As an example, we will use the **WedgeOfRays** function to generate three rays. First, we will assign the **WedgeOfRays** result into a variable, called **wedgeofrays**.

```
In[20]:= wedgeofrays = WedgeOfRays[10]

Out[20]= WedgeOfRays[10]
```

With **InputForm**, we can see that, like **SingleRay**, **WedgeOfRays** also creates a single **Source** object. However, this **Source** object defines a wedge-shaped pattern of three rays.

```
In[23]:= wedgeofrays//InputForm

  Out[23]//InputForm=
       Source[{}, SourceDescription :> SourceDescription[WedgeOfRays[{Ray[]}, 10,
           SourceTransformation -> {{0., 0., 0.}, {{1., 0., 0.}, {0., 1., 0.}, {0., 0.,
       1.}}},
           SymbolicSourceTransformation -> {{0, 0, 0}, {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}}}]],
        SourceTransformation :> {{0, 0, 0}, {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}}},
        SymbolicSourceTransformation :> {{0, 0, 0}, {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}}},
       SourceLevel :> {1, 1},
        NumberOfRays :> 3, BirthPoint :> {0, 0, 0}, CoordinateSystem :> PolarCoordinates,
       StartAtBirthPoint :> True,
        MonteCarlo :> False, SourceID :> 2118, SourceFraction :> 1, SourceOffset :> 0,
       GridSpacing :> (#1 & ),
        PowerOutput :> 100, SymbolicValues :> {}]
```

Next, we will demonstrate how **CreateRays** is used by **PropagateSystem** to initialize the ray information as **Ray** objects. When we apply **CreateRays** to **wedgeofrays**, there are three **Ray** objects generated.

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In[22]:= **CreateRays[wedgeofrays]//InputForm**

Out[22]//InputForm=

```
{Ray[Intensity :> 100., IntensityScale :> 1., OpticalMedium :> Air, Polarization :>
{0., 1., 0.},
  RayEnd :> {0., 0., 0.}, RayLabelPositions :> {{0., 0., 0.}}, RayLength :> 0.,
RayLineRGB :> Automatic,
  RayPointRGB :> {0., 0., 0.}, RaySourceNumber -> {{1, 3}, {1, 0}}, RayStart :> {0.,
0., 0.},
  RayTilt :> {0.9961946980917455, 0.08715574274765817, 0.}, RefractiveIndex :>
1.0002694514570802,
  RotationMatrix :> {{0.9961946980917455, 0.08715574274765817, 0.},
{-0.08715574274765817, 0.9961946980917455, 0.},
    {0., 0., 1.}}, SourceID :> 2118, SourceTransformation :> {{0., 0., 0.}, {{1., 0.,
0.}, {0., 1., 0.}, {0., 0., 1.}}},
  WaveFrontID :> {{2118, 0}}], Ray[Intensity :> 100., IntensityScale :> 1.,
OpticalMedium :> Air,
  Polarization :> {0., 1., 0.}, RayEnd :> {0., 0., 0.}, RayLabelPositions :> {{0., 0.,
0.}}, RayLength :> 0.,
  RayLineRGB :> Automatic, RayPointRGB :> {0., 0., 0.}, RaySourceNumber -> {{2, 3},
{2, 0}}, RayStart :> {0., 0., 0.},
  RayTilt :> {1., 0., 0.}, RefractiveIndex :> 1.0002694514570802,
  RotationMatrix :> {{1., 0., 0.}, {0., 1., 0.}, {0., 0., 1.}}, SourceID :> 2118,
  SourceTransformation :> {{0., 0., 0.}, {{1., 0., 0.}, {0., 1., 0.}, {0., 0., 1.}}},
WaveFrontID :> {{2118, 0}}],
 Ray[Intensity :> 100., IntensityScale :> 1., OpticalMedium :> Air, Polarization :>
{0., 1., 0.},
  RayEnd :> {0., 0., 0.}, RayLabelPositions :> {{0., 0., 0.}}, RayLength :> 0.,
RayLineRGB :> Automatic,
  RayPointRGB :> {0., 0., 0.}, RaySourceNumber -> {{3, 3}, {3, 0}}, RayStart :> {0.,
0., 0.},
  RayTilt :> {0.9961946980917455, -0.08715574274765817, 0.}, RefractiveIndex :>
1.0002694514570802,
  RotationMatrix :> {{0.9961946980917455, -0.08715574274765817, 0.},
{0.08715574274765817, 0.9961946980917455, 0.},
    {0., 0., 1.}}, SourceID :> 2118, SourceTransformation :> {{0., 0., 0.}, {{1., 0.,
0.}, {0., 1., 0.}, {0., 0., 1.}}},
  WaveFrontID :> {{2118, 0}}]}
```

Here, each **Ray** object represents a different ray segment. When **TurboTrace** is used for ray-tracing, it works instead with a **TurboRays** object. The **OutputType** option is used with **CreateRays** to determine whether **CreateRays** generates a **Ray** object or a **TurboRays** object from the **Source** information. By default, **CreateRays** creates **Ray** objects. However, when **TurboTrace** calls **CreateRays**, it passes **OutputType -> TurboRays** to obtain a **TurboRays** object. Next we apply **CreateRays** to **wedgeofrays** for a second time with **OutputType -> TurboRays**.

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```
In[21]:= CreateRays[wedgeofrays, OutputType -> TurboRays]//InputForm

  Out[21]//InputForm=
       TurboRays[{{0., 0., 0., 0., 0., 0., 0.9961946980917455, 0.08715574274765817, 0.,
       -0.08715574274765817,
          0.9961946980917455, 0., 0., 0., 1., 0.532, 100., 0.33333333333333337, 0.,
       1.0002694514570802, 0., 0., 0., 0., 0., 0.,
          0., 2118., 2118., 1., 3., 1., 0., 1., 0., 0., 0., 1., 0.}, {0., 0., 0., 0., 0., 0.,
       1., 0., 0., 0., 1., 0., 0., 0.,
          1., 0.532, 100., 0.33333333333333337, 0., 1.0002694514570802, 0., 0., 0., 0., 0.,
       0., 0., 2118., 2118., 2., 3., 2.,
          0., 1., 0., 0., 0., 1., 0.}, {0., 0., 0., 0., 0., 0., 0.9961946980917455,
       -0.08715574274765817, 0.,
          0.08715574274765817, 0.9961946980917455, 0., 0., 0., 1., 0.532, 100.,
       0.33333333333333337, 0., 1.0002694514570802,
          0., 0., 0., 0., 0., 0., 0., 2118., 2118., 3., 3., 3., 0., 1., 0., 0., 0., 1., 0.}}]
```

This time, only a single **TurboRays** object is produced that contains three sets of numbers. In this case, each set of numbers represents a different ray segment. From this, we can see that **TurboRays** is much more efficient at holding information than **Ray** objects! This is gives **TurboTrace** the ability to work with very large ray-data sets and consume less memory. However, the **Ray** object is much more flexible at holding different sorts of optical parameters, such as user-defined parameters. This, in turn, gives **PropagateSystem** added flexibility over **TurboTrace** for tracing customized information. In general, however, the user of *Rayica* will never work directly with **Ray** and **TurboRays** objects and these conversions happen transparently. In the next section, we will learn about **Options[Ray]**. **Options[Ray]** is used by **CreateRays** to fill in any essential ray parameters missing from the specified **Source** object during its ray creation.

How *Rayica* manages default light source settings

In *Rayica* as well as *Mathematica*, most built-in functions have a way to pass default settings about certain parameters. This relieves the user from always having to specify all possible parameters required by the function to operate. Such default parameters are referred to as "options" because you can optionally decide to change the setting of such a parameter (but you don't have too!) As you will see shortly, each option follows the pattern: *optionlabel* -> *optionvalue*. (Such a pattern is also called a "rule" because it is internally evaluated by *Mathematica* as: **Rule[***optionlabel*, *optionvalue***]**.) As with all other types of *Rayica*'s light source functions, **SingleRay[]** has many options that help describe the generated ray.

Since all types of light sources must make the same basic assumptions about their created rays, *Rayica* uses a single location, called **Options[Ray]**, to store this information. The most important of these settings include physical attributes, such as: wavelength, polarization, intensity, and optical length. However, there are also a number of other non-physical attributes as well. You can check these default assumptions by examining the contents of **Options[Ray]**.

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```
In[4]:= Options[Ray]

Out[4]= {ComponentIncrement → Automatic, ComponentNumber → ComponentNumber,
         ConfinedNumber → ConfinedNumber, ConfinedPosition → ConfinedPosition,
         DiffractionMismatch → DiffractionMismatch,
         DiffractionOrderNumber → DiffractionOrderNumber, GenerationNumber → GenerationNumber,
         Intensity → 100., InternalDirectionChange → False,
         IntersectionNumber → IntersectionNumber, IntrinsicMedium → Air,
         NewAuthorizedOptions → NewAuthorizedOptions, OffAxis → OffAxis, OpticalLength → 0.,
         OpticalMedium → Automatic, Polarization → {0., 1., 0.}, RayEnd → {0., 0., 0.},
         RayLabelPositions → {{0., 0., 0.}}, RayLabels → {}, RayLength → 0., RayLineRGB → Automatic,
         RayLineStyle → {}, RayLineThickness → 0.5, RayPointRGB → {0., 0., 0.},
         RayPointSize → 2., RayPointStyle → {}, RaySourceNumber → RaySourceNumber,
         RayStart → {0., 0., 0.}, RayTilt → {1., 0., 0.}, RefractiveIndex → Automatic,
         RotationMatrix → {{1., 0., 0.}, {0., 1., 0.}, {0., 0., 1.}}, SourceID → Automatic,
         SourceTransformation → {{0., 0., 0.}, {{1., 0., 0.}, {0., 1., 0.}, {0., 0., 1.}}},
         SurfaceBoundary → SurfaceBoundary, SurfaceCoordinates → SurfaceCoordinates,
         SurfaceID → SurfaceID, SurfaceIncrement → 1, SurfaceNormalMatrix → SurfaceNormalMatrix,
         SurfaceNumber → SurfaceNumber, SymbolicWaveLength → SymbolicWaveLength,
         Temperature → 20., Tension → {{101300., 0., 0.}, {0., 101300., 0.}, {0., 0., 101300.}},
         UnconfinedIncrement → 1, UnconfinedPath → UnconfinedPath,
         UnconfinedPosition → UnconfinedPosition, WaveFrontID → Automatic, WaveLength → 0.532}
```

`Options[Ray]` applies to all of *Rayica*'s light sources since it determines what default values will be used by the rays at the start of the trace. In some cases, a parameter many not have a specific initial setting. In such cases, the *optionvalue* is given the same name as the *optionlabel*. In other cases, the *optionvalue* can simply be written as **`Automatic`**. In such a case, the option value is dynamically assigned. Regardless of its setting, every possible option parameter is listed in **`Options`** for the benefit of the user to know either that it exists or that it can be altered with a user-specified value.

In order to specify a new ray parameter setting, you simply pass the changed option setting as a parameter. For example, to change the wavelength setting to 0.633 microns, you would use:

```
In[15]:= SingleRay[WaveLength -> .633]

Out[15]= SingleRay[WaveLength → 0.633]
```

In this case, a subsequent ray-trace would use this new wavelength setting. In addition, **`SingleRay`** also has its own set of options that specifically applies to only the **`SingleRay`** function. These are found in **`Options[SingleRay]`**:

```
In[3]:= Options[SingleRay]

Out[3]= {NumberOfRays → 1, BirthPoint → Automatic, SymbolicBirthPoint → BirthPoint,
         CoordinateSystem → CartesianCoordinates, StartAtBirthPoint → True,
         BalancePhaseFront → True, MonteCarlo → False, SourceOffset → 0,
         SourceFraction → 1, GridSpacing → (#1 &), IntensityFunction → (#1 &),
         PolarizationFunction → (#1 &), SourceID → Automatic}
```

In the same manner as **`SingleRay`**, all other built-in light source functions also have their own specific option settings that are accessed with their function name, given by **`Options[`***function name***`]`**. In fact, a good way to learn more about any unfamiliar function in *Rayica* (or *Mathematica*) is to have a look at its built-in options because this often gives you a clue about the range of behaviors that the function can exhibit. You can learn more about *Rayica*'s built-in light source functions in Section 1.3.4 of the Principles of *Rayica* Guide.

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Modeling an optical component

Rayica has many more functions for modelling optical components than it has for light sources. In fact, there are presently 122 component functions in common use. At any time that you wish while working with *Rayica*, you can access a listing of the component functions with the **ComponentFunctions** command:

In[9]:= **ComponentFunctions**

ABCDOptic	CustomDiffuserMirror	LensDoublet	RodMirror
AnamorphicPrisms	CustomFiber	LensSurface	RoofPrism
ApertureStop	CustomFiberMirror	LensTriplet	SchmidtLens
AsphericLens	CustomGrating	LinearPolarizer	SchmidtLensSurface
AsphericLensSurface	CustomGratingMirror	Mirror	Screen
AsphericMirror	CustomLens	MirrorSpan	SlabPrism
Baffle	CustomLensSurface	ParabolicDiffuser	SnowConeLens
BaffleSpan	CustomMirror	ParabolicDiffuserMirror	SolidCornerCube
BaffleWithHole	CustomPrism	ParabolicLensSurface	Solitaire
BallBaffle	CustomScreen	ParabolicMirror	SphereGraphic
BallLens	CylinderGraphic	PechanPrism	SphericalBaffle
BallMirror	CylindricalBaffle	PellinBrocaPrism	SphericalBeamSplitter
BeamSplitter	CylindricalLens	PentaPrism	SphericalDiffuser
BeamSplitterCube	CylindricalLensSurface	PinHole	SphericalDiffuserMirror
BiConcaveCylindricalLens	CylindricalMirror	Pipe	SphericalGratingMirror
BiConcaveLens	CylindricalScreen	PlanoConcaveCylindricalLens	SphericalLens
BiConvexCylindricalLens	Diffuser	PlanoConcaveLens	SphericalLensSurface
BiConvexLens	DiffuserMirror	PlanoConvexCylindricalLens	SphericalMirror
BirefringentLensSurface	DirectVisionPrism	PlanoConvexLens	SphericalScreen
Boundary	DovePrism	PolarizingBeamSplitterCube	SquareConeMirror
Box	DTIRCLens	PolarizingPrism	SurfaceFacet
BoxGraphic	DTIRCLensSurface	PolygonalMirror	ThickLens
CircleGraphic	Fiber	PolygonGraphic	ThinLens
ClearBoundary	FresnelRhomb	PorroPrism	ToroidalLens
CompoundLens	FunnelLens	Prism	ToroidalLensSurface
ConjugateMirror	FunnelLensSurface	RectangleGraphic	ToroidalMirror
CustomBaffle	Grating	RetardationPlate	WedgePrism
CustomBeamSplitter	GratingMirror	ReversionPrism	Window
CustomBirefringentLensSurface	HalfBallLens	RhomboidPrism	WinstonConeMirror
CustomConjugateMirror	HollowCornerCube	RodBaffle	
CustomDiffuser	JonesMatrixOptic	RodLens	

> *In Mathmatica,* **ComponentFunctions** *gives you hyperlinks to Rayica's current component functions. Clicking on any name will give you a description of its use.*

In addition to ones listed here, you can build your own custom component functions as well as download new functions from the Optica Software web-site (www.opticasoftware.com). One of the most frequently used component functions is **PlanoConvexLens**.

PlanoConvexLens[*focallength*, *aperture*, *thickness*, *options*] refers to a lens with a planar surface on one side and a convex spherical surface on the other side.

Here is how you evaluate the **PlanoConvexLens** function.

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```
In[18]:= PlanoConvexLens[100, 50, 10]

Out[18]= PlanoConvexLens[100, 50, 10]
```

In the same fashion that ray source functions create **Source** objects, every component function creates a **Component** object. In this **PlanoConvexLens** example, hidden behind the "PlanoConvexLens[100,50,10]" output returned to the screen is a very large expression that is encapsulated with the **Component** head. It contains detailed information to describe a plano-convex lens having a focal length of 100 millimeters, a circular aperture 50 millimeters in diameter, and a lens center thickness of 10 millimeters. Instead of showing this entire expression, *Rayica* always hides the contents of **Component** by outputting back to the screen a description of how the component was generated. Here again, *Rayica* indicates a valid entry by returning the text in a different color from black.

As with light source functions and the **Source** object, since the **Component** object is automatically created by the built-in component functions, the user of *Rayica* will never need to worry about the details of this **Component** object. In fact, unless you use **InputForm**, as demonstrated previously with the **Source** object, the contents of the **Component** object are always hidden. Nevertheless, it is helpful to understand what happens when you evaluate a component function.

As with light sources, you can use these generated **Component** objects immediately after creating them for doing ray tracing and rendering, or you can assign them to a variable for future work. While *focallength*, *aperture*, and *thickness* are all parameters given explicitly to the **PlanoConvexLens** function, other implicit parameters, such as the type of refractive material are kept as options of **PlanoConvexLens**. You can use **Options[PlanoConvexLens]** to access the default options of **PlanoConvexLens**.

```
In[30]:= Options[PlanoConvexLens]

Out[30]= {Labels → L, LabelPositions → Automatic, ComponentDescription → Automatic,
          ComponentMedium → BK7, Temperature → Temperature, Tension → Tension,
          Transmittance → Transmittance, Reflectance → Reflectance,
          GraphicDesign → Automatic, CurvatureDirection → Front,
          DesignWaveLength → 0.5461, OffAxis → {0, 0}, SwitchDirectionOnReflection → False,
          Resonate → True, Automatic → {SurfaceRendering → Empty,
            EdgeRendering → Mesh, CrossRendering → {{Fill, Trace}}}, Sketch →
           {SurfaceRendering → Trace, EdgeRendering → Empty, CrossRendering → {{Fill, Trace}}},
          Wire → {SurfaceRendering → Mesh, EdgeRendering → Mesh, CrossRendering → {{Fill, Trace}}},
          Solid →
           {SurfaceRendering → {{Fill, Trace}}, EdgeRendering → Fill, CrossRendering → Empty}}
```

Notice the option **ComponentMedium -> BK7**. This option indicates that the refractive material of the planoconvex lens is assumed to be made of BK7 glass material. Here, the **BK7** symbol specifies a particular wavelength-dependent model for the refractive index. However, you can also specify a fixed numeric value for **ComponentMedium**, as shown below. In this case, the refractive index is held constant for all wavelength values.

```
In[19]:= PlanoConvexLens[100, 50, 10, ComponentMedium -> 1.5]

Out[19]= PlanoConvexLens[100, 50, 10, {ComponentMedium → 1.5}]
```

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3. Introduction to AnalyzeSystem and TurboPlot

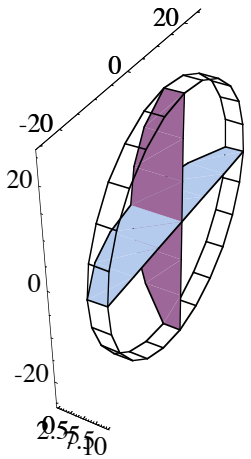
Rayica has two parallel methods for doing ray-tracing and rendering of optical systems. One method uses the **AnalyzeSystem** function (originally known as **DrawSystem**), while the second method uses the **TurboPlot** function. Each method offers similar functionally in a parallel way. **AnalyzeSystem** is good for generating illustrations for publication and tracing small numbers of rays while **TurboPlot** is best for working with large numbers of rays. After making some initial comparisons between these two methods, we will next consider the use of **AnalyzeSystem**. The application of **TurboPlot** will be explored further in Section 15.

> **AnalyzeSystem[***objectset*, *options***]** uses **PropagateSystem** and **ShowSystem** to trace rays through optical components and render the results.
>
> **TurboPlot[***system*, *options***]** works with **TurboTrace** to perform accelerated ray-tracing and rendering of a system of light sources and optical elements.

Both **AnalyzeSystem** and **TurboPlot** call other intermediate functions for their internal operations of ray-tracing and graphical rendering. They simply provide a single convenient interface for the *Rayica* user to conduct the ray-tracing and rendering. Both **AnalyzeSystem** and **TurboPlot** are used in the same fashion, as each accepts a list of light source and component functions for input. One key difference between **AnalyzeSystem** and **TurboPlot** is that **AnalyzeSystem** uses the interpreted language of Mathematica for ray-tracing while **TurboPlot** uses a highly-efficient, compiled function, which is more time-consuming to create initially but then performs the actual ray trace much faster. As a result of this, when only a small number of rays are needed, **AnalyzeSystem** can sometimes deliver a result more quickly than **TurboPlot**. In addition, **AnalyzeSystem** often works better than **TurboPlot** for the creation of optical schematics and illustrations for publication, since it is tailored for such purposes. However, it is always more advantageous to use **TurboPlot** and **TurboTrace** when large numbers of rays or iterative processes are required.

We will now consider **AnalyzeSystem** in more detail. When no light sources are included, **AnalyzeSystem** simply renders the optical components present. Here we use **AnalyzeSystem** to render a plano-convex lens.

```
In[20]:= AnalyzeSystem[PlanoConvexLens[100, 50, 10], Axes -> True]
```




```
AnalyzeSystem[{PlanoConvexLens[100, 50, 10]}]
```

```
Out[20]= -rendered element-
```

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Here, **PlanoConvexLens** is created with its first surface at the origin and its second surface positioned down the positive x axis. In general, the *aperture* parameter of **PlanoConvexLens** may designate a circle, rectangle, or polygon, depending on the number and type of elements listed by it. Here we created a circular lens that has a diameter of 50 millimeters by using `50` in the *aperture* parameter. After rendering the plano-convex lens, **AnalyzeSystem** first echoes back the input expression, and then returns the actual information (hidden within the -rendered element- expression). Shortly, in Section 7, we will use **AnalyzeSystem** for ray-tracing as well as rendering, but first we must learn how to position optical components and light sources in three-dimensional space.

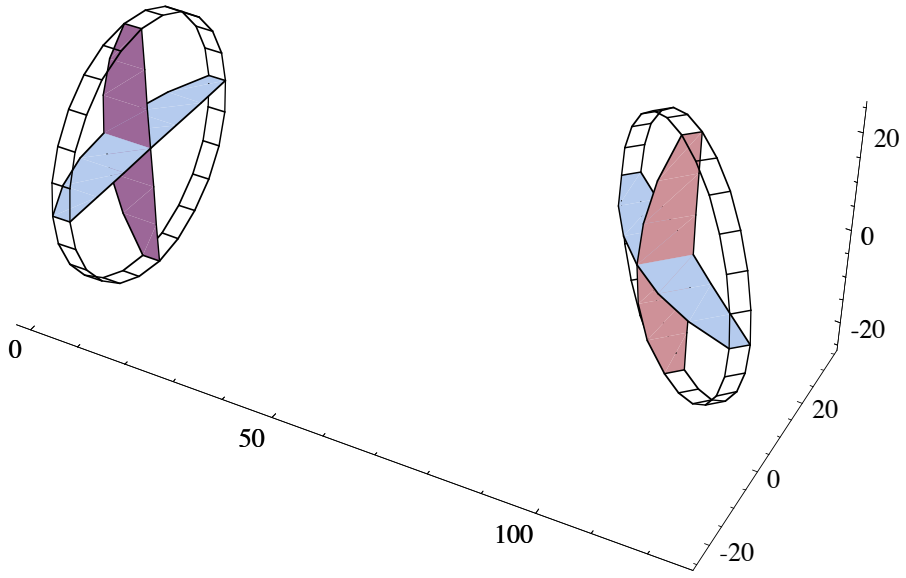
4. The Move Function

To put an optical element at a location other than $x = 0$, $y = 0$, and $z = 0$, you will need to use one of *Rayica*'s positioning directives. The most important positioning directive in *Rayica* is the **Move** function. You can use **Move** to position both light sources and rays in space. The basic definition for **Move** is shown below.

> **Move[***objectset*, {*x*, *y*}, *rotationangle*, *options***]** is used to move the relative position and orientation of a set of components and rays within a horizontal plane.

Here, the *rotationangle* determines the angular orientation of the object set within the horizontal plane. You can use the **TwistAngle ->** *angle* option to specify a rotation angle around the axis of orientation. Next we will use **Move** together with **AnalyzeSystem** to draw two lenses spaced apart from each other. Place the first one at $x = 0$, $y = 0$, with no rotation, and a second one at $x = 100$, $y = 10$, with a 45-degree rotation.

```
In[21]:= AnalyzeSystem[{
           PlanoConvexLens[100, 50, 10],
           Move[PlanoConvexLens[100, 50, 10], {100, 10}, 45]}, Axes -> True]
```




```
          AnalyzeSystem[
           {PlanoConvexLens[100, 50, 10], Move[PlanoConvexLens[100, 50, 10], {100., 10.}, 45.]}]

Out[21]=  -rendered system without rays-
```

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Note that, again, the text output returned to the screen mimics the original input expressions, when, in fact, a great quantity of information is hidden behind the "-rendered system without rays-" statement. Although only a single format has been shown previously for **Move**, there are actually a variety of input formats used with **Move**. These are shown below.

Move[*objectset*, {*x*, *y*}, *rotationangle*]
Move[*objectset*, *x*, *rotationangle*]
Move[*objectset*, *x*]
Move[*objectset*, {*x*, *y*}]
Move[*objectset*, {*x*, *y*, *z*}]
Move[*objectset*, {*x*, *y*, *z*}, *axisvector*]
Move[*objectset*, {*x*, *y*, *z*}, *axisvector*, *twistangle*]
Move[*objectset*, {*x*, *y*, *z*}, *rotationmatrix*]

Common input formats for **Move**. *Although not shown, these formats all accept options.*

Including the **Move** function, *Rayica* has eight positioning directives. At any time that you wish while working with *Rayica*, you can access a listing of *Rayica*'s positioning functions with the **MoveFunctions** command:

```
In[10]:= MoveFunctions
```

Move	MoveDirected	MoveReflected	Rotate
MoveAligned	MoveLinear	MoveSurface	Translate

In Mathmatica, **MoveFunctions** *gives you hyperlinks to Rayica's most important positioning functions. Clicking on any name will give you a description of its use.*

You can learn more about how to use **Move** and the other directives in Chapter 2, the Placement Directives chapter, of the Principles of *Rayica* discussion.

5. Using AnalyzeSystem for Ray Tracing

Tracing a single ray

We are almost ready to use **AnalyzeSystem** for ray-tracing. First, however, we need to consider a boundary to contain the rays. Otherwise, the traced rays will terminate on the last surface of the last optical component in the system. The easiest way to define a boundary is with the **Boundary** function. Before continuing with the ray trace, lets first examine the **Boundary** function in more detail.

Boundary[*boundaryparameters*] denotes a rectangular box that absorbs rays intercepted by its walls.

There are three methods for specifying *boundaryparameters*: **Boundary**[{*x1*, *y1*, *z1*}, {*x2*, *y2*, *z2*}] uses the coordinates of top and bottom opposite corners of a rectangular box, **Boundary**[*side*] assumes a cube boundary, and **Boundary**[*aside*, *bside*] assumes a three-dimensional box having a length specified by *aside*, a width specified by *bside*, and a height specified by *bside*. Optical systems propagating rays usually have at least one boundary component listed at the end. In this example, we will use **Boundary**[200].

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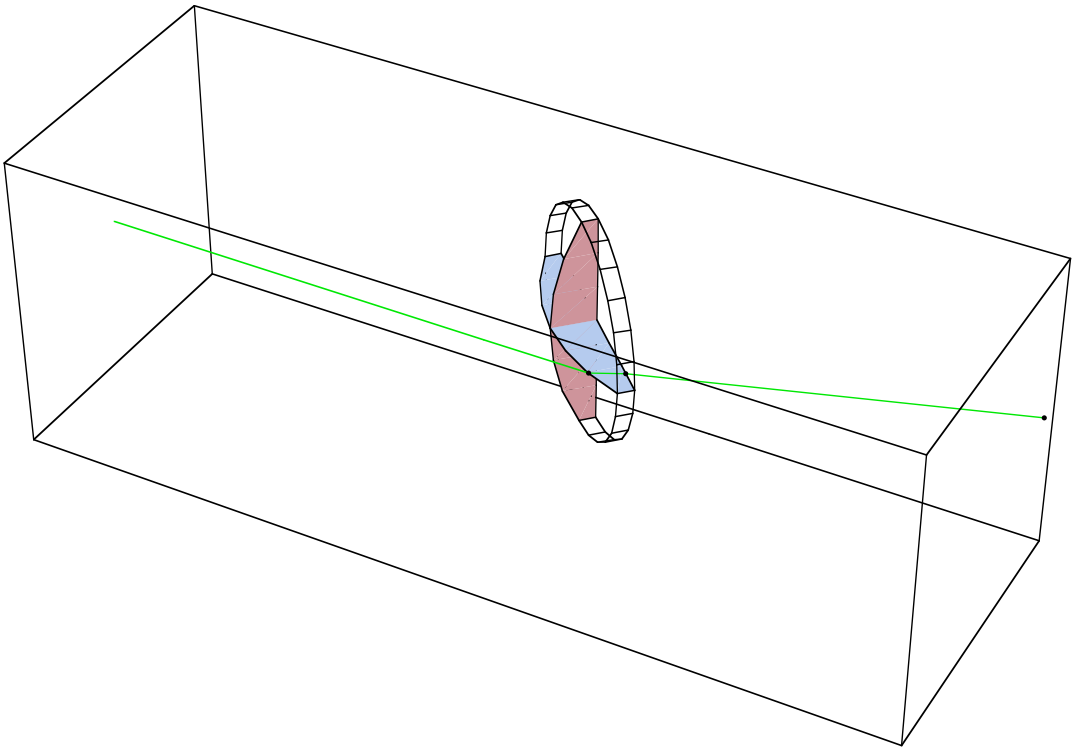
We can now use **AnalyzeSystem** for ray tracing. For this, we will trace a single ray through a lens using the **SingleRay**, **PlanoConvexLens**, and **Boundary** functions. This time we will store the ray-trace result in a variable called **trace**. This will allow us to examine the traced information later on with other functions.

```
In[22]:= trace = AnalyzeSystem[{
            SingleRay[],
            Move[PlanoConvexLens[100, 50, 10], {100, 10}, 45],
            Boundary[200, 70]}]
```



```
AnalyzeSystem[{SingleRay[], Move[PlanoConvexLens[100, 50, 10], {100., 10.}, 45.],
  Boundary[{0, -35, -35}, {200, 35, 35}]}]
```

```
Out[22]= -3 ray/surface intersections-
```

By default, *Rayica* always takes the x-axis to be the optical axis. This means that, by default, all of *Rayica*'s built-in light source functions automatically direct their rays along the positive x-axis. In this example, the **SingleRay** function has generated a ray that is exactly co-linear with the x-axis. In other, more complex light source functions, only the chief ray is precisely co-linear with the x-axis. Of course, you can always choose a different optical axis by re-aligning the light source and optics with a positioning directive such as **Move**.

Working with the ray-trace data

After calculating and rendering the ray trace, **AnalyzeSystem** passes back a data object that holds the ray-trace information. You can use this returned information to make further plots or exact numeric information about the generated ray trace. In general, depending on whether **AnalyzeSystem** or **TurboPlot** was used, the final ray-trace data is held in either an **OpticalSystem** object (as in this case) or a **TurboSystem** object (with **TurboPlot**). However, as discussed before with **Component** and **Source**, the information held in these returned objects are always hidden from the user. Rather than directly viewing these objects, you will normally examine the ray-trace results with one of *Rayica*'s ray-trace diagnostic functions. These are listed below.

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ShowSystem[*system*, *options***]** takes a *system* of rays and/or components and generates a graphical display of the *system*.
ReadRays[*results*, *rayparameters*, *selectionproperties***]** takes ray-traced *results* from **AnalyzeSystem**/**PropagateSystem** as well as **TurboPlot**/**TurboTrace** and returns a list of values for *rayparameters* given.
FindFocus[*system*, *options***]** determines the minimum spot size for a locus of rays at the last reported surface in the system and plots the results.
FindSpotSize[*objectset*, *options***]** determines the spot size for a locus of rays at the last reported surface in the system and plots the results.
FindIntensity[*system***,** *options***]** calculates the intensity function for each optical surface that gets reported from the ray trace of the *system*.
ModulationTransferFunction[*intensitydata***,** *options***]** calculates the modulation and phase transfer functions of an optical system for a given object source input.

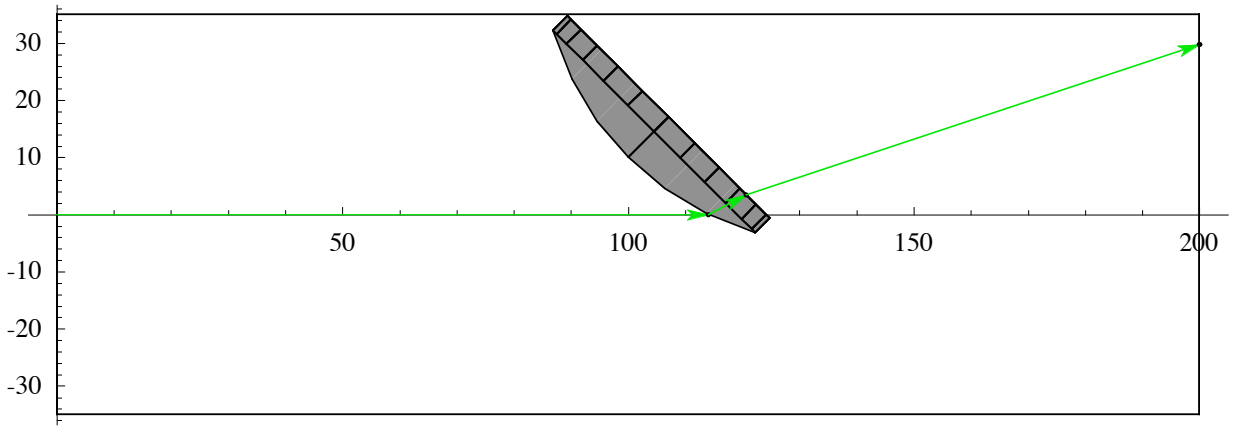
Rayica's ray-trace diagnostic functions.

In addition to the diagnostic functions listed in the above box, you can also reuse the ray-trace functions, **AnalyzeSystem** and **TurboPlot**, to make different visualizations of previously ray-traced information. There are also two other important high-level functions, **OptimizeSystem** and **FindIntensity**, that take an untraced optical system and perform their own internal ray-trace calculations. Many examples of these different functions are presented throughout the *Rayica* documentation. In the next section, we will examine the **ShowSystem** function and use it to rerender the previous **trace** result.

6. The ShowSystem Function

After making the ray-trace with **AnalyzeSystem** , you can redisplay the results more quickly with **ShowSystem**. Here we use the previous **AnalyzeSystem** output, stored in the **trace** variable, as the input to **ShowSystem**. (We will suppress the printed output text by including a semicolon at the end of the input expression.)

```
In[4]:= ShowSystem[trace, PlotType->TopView, Axes->True, MinimumArrowLength->0];
```



Here the rendered result shows three arrows that correspond with the three ray segments previously calculated by **AnalyzeSystem** during the trace. **ShowSystem** and **AnalyzeSystem** both use the same options for graphical rendering. Although there are a great many options available for graphical rendering, some of most important options are listed in the following table.

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```
AppendGraphics          PrependGraphics
Axes                    RayChoice
ColorView               ShowArrows
CreateStereoView        ShowClones
DefaultStyle            ShowComponents
GraphicDesign           ShowLabels
MinimumArrowLength      ShowRange
PlotType                ShowText
```

Important rendering options.

In most instances, only one or two rendering options will be needed to display any particular result. In the previous **ShowSystem** example, we used three different rendering options: **PlotType**, **Axes**, and **MinimumArrowLength**. Of these three options, however, only the **PlotType** option is frequently required. As such, we will now examine the **PlotType** option in more detail.

PlotType is an option of **AnalyzeSystem** , **ShowSystem**, and **TurboPlot** that designates the display form of the graphics rendering for the optical system.

PlotType can take eight different settings, as listed below.

TopView gives a two-dimensional orthoscopic rendering showing a projection onto the x-y plane of the optical system.
FrontView gives a two-dimensional orthoscopic rendering showing a projection onto the y-z plane of the optical system.
SideView gives a two-dimensional orthoscopic rendering showing a projection onto the x-z plane of the optical system.
Full3D gives the full three-dimensional rendering of the optical system.
RealTime3D allows the rendered three-dimensional graphics to be rotated interactively.
Off designates no graphical output.
Surface gives a two-dimensional plot that shows selected intersection points between rays and one or more optical surfaces.
ShadowProject gives a three-dimensional rendering of the optical system along with two-dimensional projections of the system onto the sides of a box.

*Settings of **PlotType**.*

Finally, we will demonstrate **ShowSystem** once again with the same **trace** result. This time, however, we will use **PlotType -> RealTime3D**. This option setting allows you to interactively rotate the ray-trace plot in three-dimensions with the mouse.

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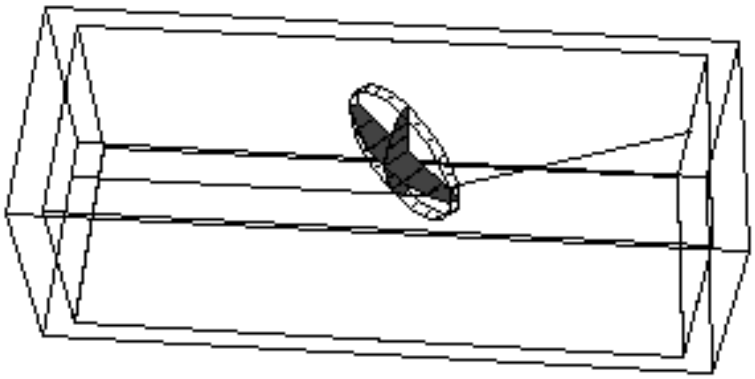
```
In[10]:= ShowSystem[trace, PlotType -> RealTime3D];
```



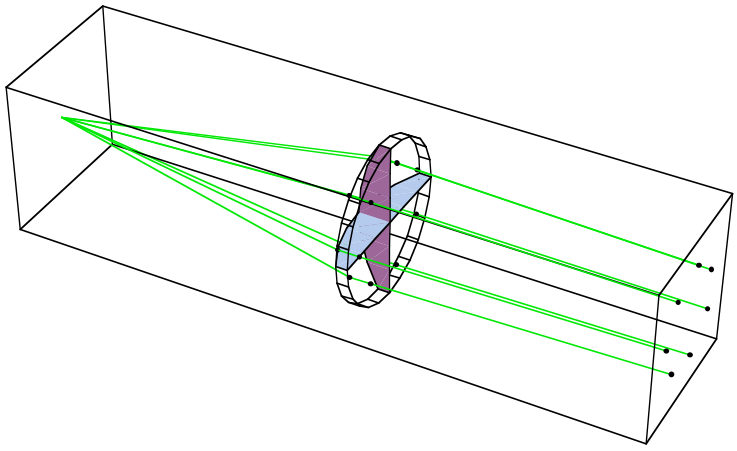
> *You can use the mouse to interactively grab and rotate this three-dimensional graphic in real time.*

Before concluding this brief introduction to **ShowSystem**, there is one final comment worth mentioning about the use of **ShowSystem** with **TurboPlot** results. Although you can always use **ShowSystem** to render results created by **TurboPlot**, **ShowSystem** will normally call **TurboPlot** to render **TraceTrace** data rather than doing the work itself. This is because **ShowSystem** is not efficient at directly displaying the large numbers of rays that are often associated with **TurboPlot** calculations. **TurboPlot**, on the other hand, is optimized for the rendering of **TurboTrace** results. This will be demonstrated in Section 14.

7. Tracing a Cone of Rays

To propagate several rays through a lens, you can use one of *Rayica*'s other built-in ray source functions. Here we use **ConeOfRays** with **AnalyzeSystem**.

```
In[5]:= AnalyzeSystem[{ConeOfRays[20, NumberOfRays->7],
          Move[PlanoConvexLens[100, 50, 10], 100],
          Boundary[{0,-25,-25}, {200,25,25}]}];
```



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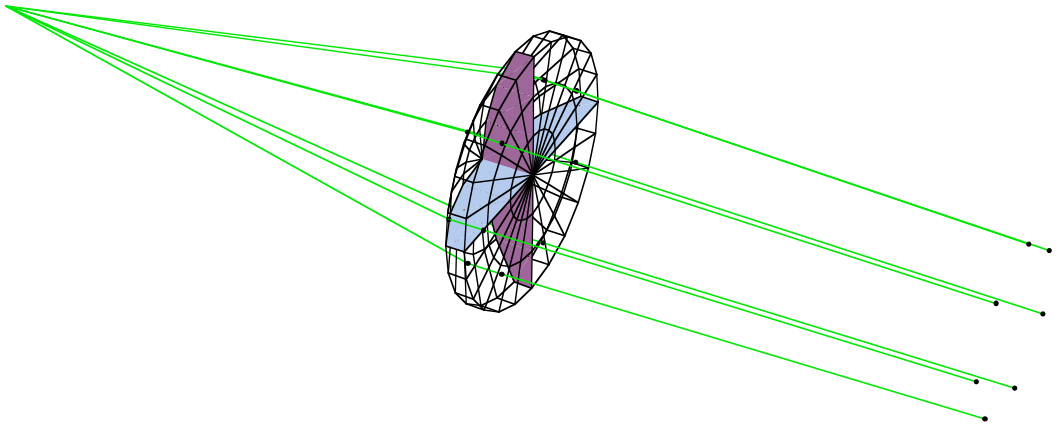
Note that this time, in order to position the **PlanoConvexLens**, we have passed the single numeric parameter of 100 to the **Move** function. When only single number is given to **Move**, the **PlanoConvexLens** is simply displaced along the x-axis by the given amount.

You can change the way a component function is rendered with the **GraphicDesign** option.

> **GraphicDesign ->** *style* is an option of all rendered components the designates the *style* of rendering.

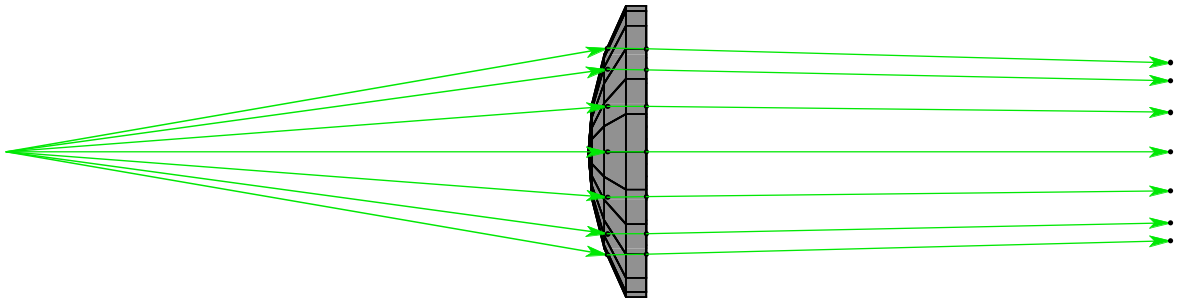
GraphicDesign can be set to a number of different style settings. These include: **Automatic**, **Sketch**, **Wire**, **Solid**, or **Off/False**. In most cases, **GraphicDesign** is used by component functions and is not passed directly to high-level rendering functions such as **ShowSystem** or **AnalyzeSystem**. Here we use **GraphicDesign -> Wire** with **PlanoConvexLens** and **GraphicDesign -> Off** with **Boundary**.

```
In[6]:= AnalyzeSystem[{ConeOfRays[20, NumberOfRays -> 7],
            Move[PlanoConvexLens[100, 50, 10, GraphicDesign -> Wire], 100],
            Boundary[{0,-25,-25}, {200,25,25}, GraphicDesign -> Off]}];
```



Now we use **PlotType -> SideView** with **ShowSystem** to look at the rendered result from the side.

```
In[21]:= ShowSystem[%, PlotType -> SideView];
```



The **%** symbol feeds the output from the previous result into the expression input. In this example, the output from **AnalyzeSystem** of the last example has been used as input to **ShowSystem**. You can also view the result from the front with **PlotType -> FrontView**.

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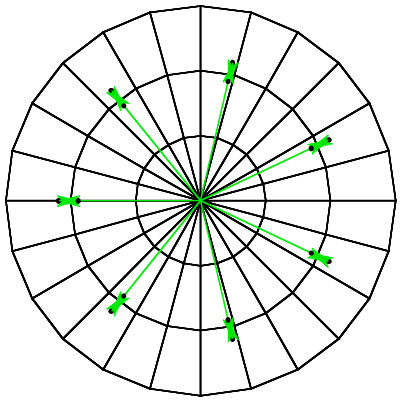
```
In[22]:= ShowSystem[%, PlotType -> FrontView];
```



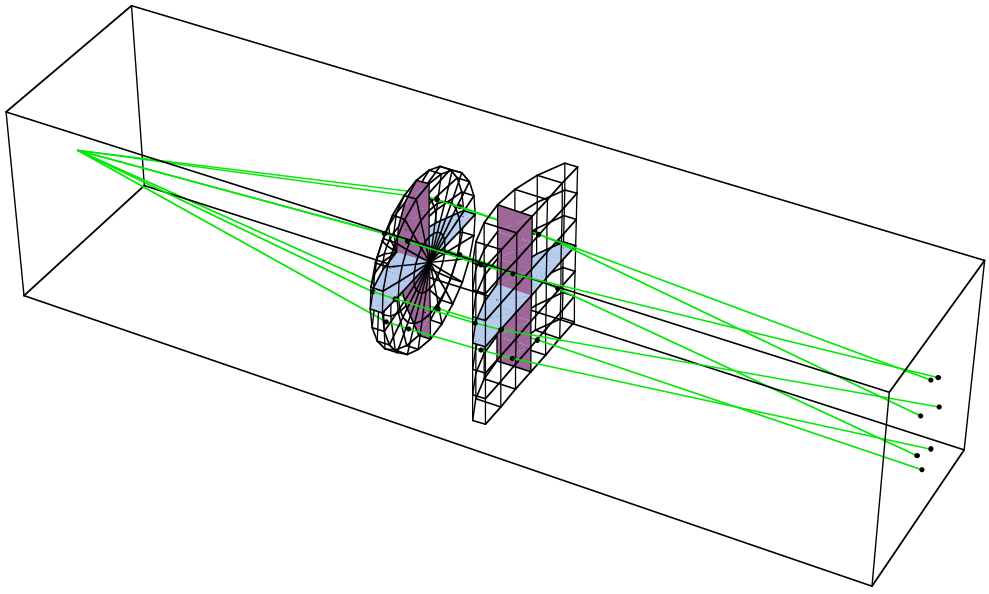
8. Adding a Cylindrical Lens to the System

For some additional interest, you can place a cylindrical lens directly behind the plano-convex lens. The cylindrical lens component is created with **PlanoConvexCylindricalLens**.

> **PlanoConvexCylindricalLens[***focallength*, *aperture*, *thickness*, *options***]** denotes a lens with a planar surface on one side and a convex cylindrical surface on the other side.

Here we use `{50,50}` in the *aperture* parameter of **PlanoConvexCylindricalLens** to make a rectangular-edged cylindrical lens.

```
In[56]:= opticalsystem = AnalyzeSystem[{
           ConeOfRays[20, NumberOfRays -> 7],
           Move[PlanoConvexLens[100, 50, 10, GraphicDesign -> Wire], 100],
           Move[PlanoConvexCylindricalLens[100, {50,50}, 10, GraphicDesign -> Wire], 130],
           Boundary[{0,-30,-30}, {250,30,30}]}];
```



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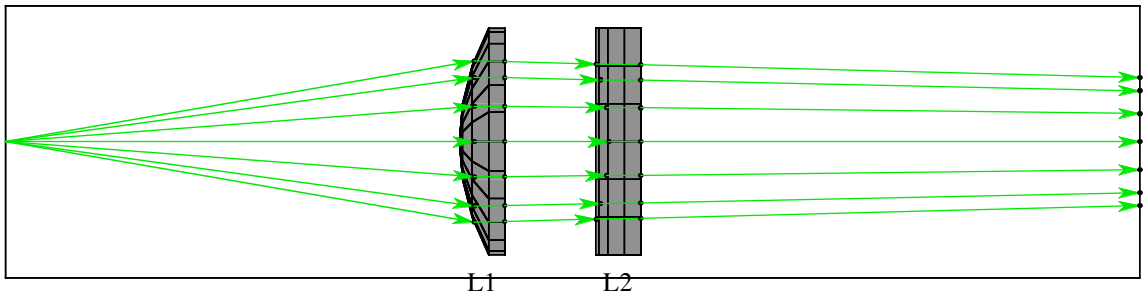
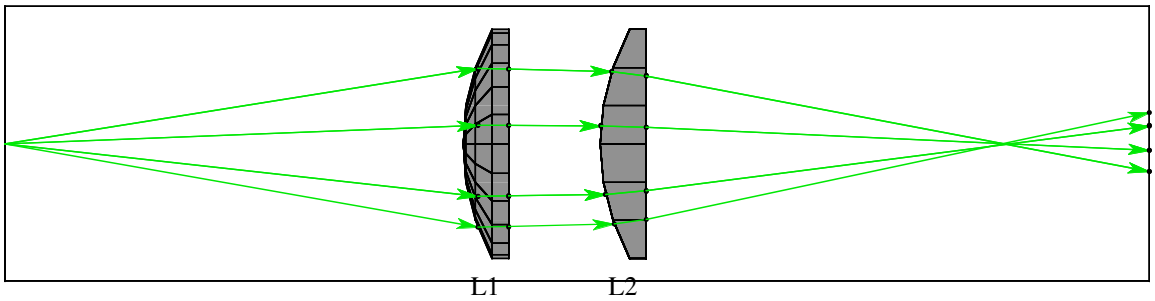
Again, you can see different views of the system.

```
In[57]:= ShowSystem[opticalsystem, PlotType -> SideView];
```




```
In[58]:= ShowSystem[opticalsystem, PlotType -> TopView];
```



Notice that in the two previous graphics, *Rayica* has automatically attached labels to the two lenses, L1 and L2. This feature can be helpful to make illustrations in publications. You can learn more about *Rayica*'s treatment of graphics in Chapter 6 of the Principles of *Rayica* Guide. You can make exact positional measurements in the two-dimensional fields by clicking the graphics display cell and then holding down the Command key while moving the cursor over the image. The cursor coordinates are displayed in the bottom corner of the window. More accurate measurements can be taken by expanding the graphic display size. By examining the `TopView` image, you can measure the focus position to be $x = 218$ millimeters.

9. The RayChoice Option

You can use the **`RayChoice`** option to display portions of the ray-tracing result. Here we define **`RayChoice`**.

> **`RayChoice ->`** *selectionproperties* uses *selectionproperties* to selectively display ray segments in **`AnalyzeSystem`** and **`ShowSystem`**.

Next we will use **`RayChoice`** to examine the ray segments after the cylindrical lens in the system. Use **`RayChoice->{ComponentNumber->3}`** to view the ray segments immediately following the cylindrical lens. In general, you can use **`ComponentNumber`** with **`RayChoice`** to choose ray segments associated with any particular component.

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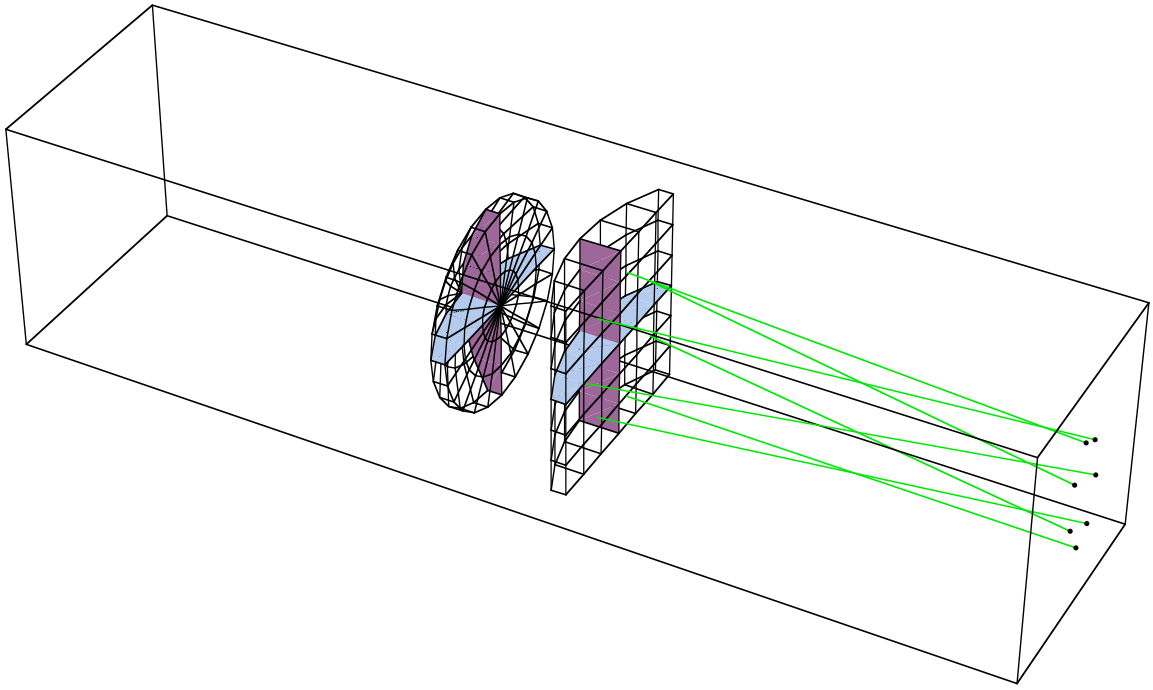
In[61]:= **ShowSystem[opticalsystem, RayChoice->{ComponentNumber->3}];**

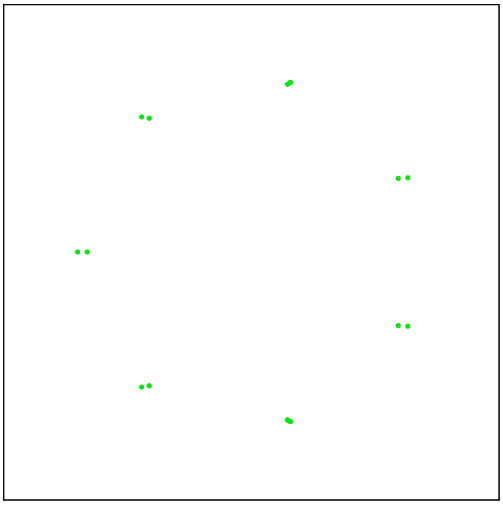


You can also use **PlotType->Surface** with **RayChoice** to look at the ray intersection points on any surface in the ray-tracing result. We now define **Surface**.

> **Surface** is a value of **PlotType** giving a two-dimensional plot showing selected intersection points between rays and one or more optical surfaces.

Next use **RayChoice->{ComponentNumber->2}** with **PlotType->Surface** to view the intersection points on the two surfaces of the cylindrical lens.

In[28]:= **ShowSystem[opticalsystem, PlotType->Surface, RayChoice->{ComponentNumber->2}];**



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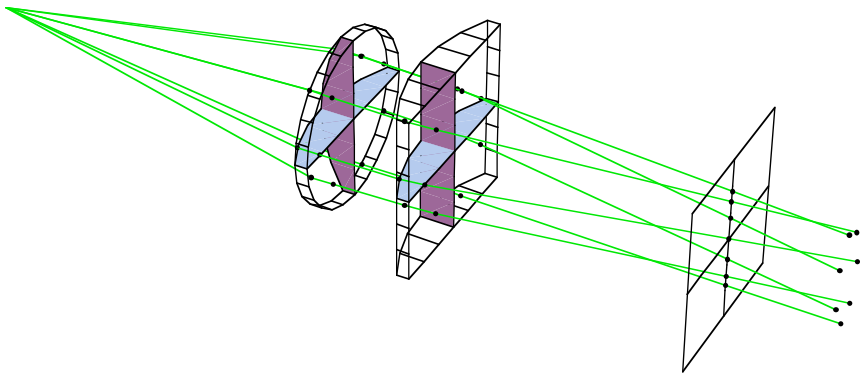
10. Using Screen to Look at the Focal Plane

The **Screen** component function models a single surface that samples rays at a given plane in space. You can use **Screen** to look at the focal plane of a system or to get the planar cross-section of ray information anywhere in the system. More advanced screens can have curved surfaces and circular or polygonal boundaries. Here is the definition of **Screen**.

> **Screen[***aperture*, *options***]** denotes a planar component that intersects rays without disturbing them.

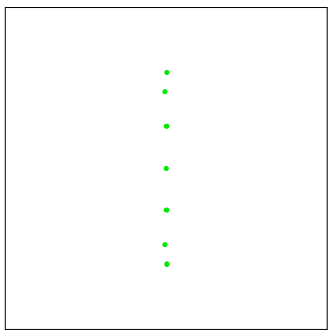
Next we use **Screen** with **AnalyzeSystem** to inspect the focal plane of the optical system from Section 9. Here we use **Move** to place the screen at the focal position $x = 218$ as measured previously.

```
In[29]:= screensystem = AnalyzeSystem[{
             ConeOfRays[20, NumberOfRays -> 7],
             Move[PlanoConvexLens[100, 50, 10], 100],
             Move[PlanoConvexCylindricalLens[100, {50,50}, 10], 130],
             Move[Screen[{50,50}], 218],
             Boundary[{-100,-100,-100}, {250,200,200}, GraphicDesign -> False]}];
```



By using **PlotType->Surface** with **RayChoice->{ComponentNumber->3}**, you can clearly see ray intersection points at the screen surface.

```
In[31]:= ShowSystem[screensystem, PlotType->Surface, RayChoice->{ComponentNumber->3}];
```



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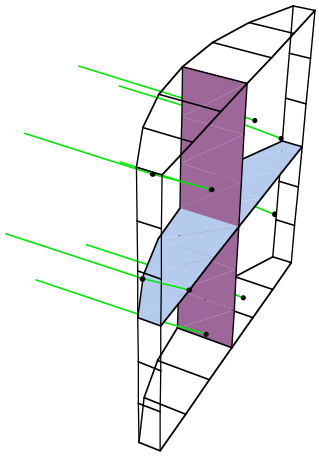
11. The ShowRange Option

Another useful option is **ShowRange**. You can use **ShowRange** to zoom in on a particular portion of the system.

> **ShowRange ->** *values* uses **ComponentNumber** values to select the components and ray segments displayed.

ShowRange can take either the value **All** or a list of the **ComponentNumber** values. Here we examine the ray segments connected with the cylindrical lens.

```
In[63]:= ShowSystem[screensystem, ShowRange -> {2}];
```



ShowRange works differently from **RayChoice** because **ShowRange** displays selected components associated with the selected ray segments. In addition, **ShowRange** only works with **ComponentNumber** values whereas **RayChoice** works with many different selection parameters. See Section 6.4 in the Principles of *Rayica* Guide for more discussion about **ShowRange**.

12. The ReadRays Function

It is often desirable to get specific numeric values for a selected set of parameters from the ray trace. This can be accomplished with **ReadRays**.

> **ReadRays[***results*, *rayparameters*, *selectionproperties***]** takes ray-traced *results* from **AnalyzeSystem**/**PropagateSystem** and returns a list of values for *rayparameters* and *selectionproperties* given.

Here we use **ReadRays** to examine the optical path-length of rays at the focal plane. Using the optical path-length parameter **OpticalLength**, you can use the **ComponentNumber -> 3** as a selection property to examine the optical path-length from the ray starting point to the surface of the screen component.

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```
In[33]:= ReadRays[screensystem, OpticalLength, {ComponentNumber -> 3}]

Out[33]= {228.591, 228.435, 228.369, 228.538, 228.538, 228.369, 228.435}
```

To see more decimal places, you can use **InputForm**.

```
In[34]:= InputForm[%]

  Out[34]//InputForm=
       {228.591359124603, 228.43455070396408, 228.3688128926051, 228.53755280486945,
       228.53755280486945,
        228.36881289260504, 228.43455070396408}
```

Note that, addition to working with **AnalyzeSystem**/**PropagateSystem** , **ReadRays** can also employed with results from **TurboPlot**./**TurboTrace**. In such instances, however, **ReadRays** makes an internal call to **ReadTurboRays** for its results. **ReadTurboRays** is discussed further in Section 16.

13. The PropagateSystem Function

PropagateSystem is called internally by **AnalyzeSystem** to perform its ray-trace calculations. Here we define **PropagateSystem**.

> **PropagateSystem[***objectset*, *options***]** takes *objectset* made up of a mixed list of **Source**, **Component**, and **OpticalSystem** objects, traces the rays through the components, and returns the ray-tracing result as an **OpticalSystem** object carrying the final ray-trace information.

Since **PropagateSystem** performs ray tracing without rendering the results, you can use **PropagateSystem** when you are interested only in quantitative results without the pictures. Here we use **PropagateSystem** together with **ReadRays** on the optical system shown previously.

```
In[29]:= screensystem = PropagateSystem[{
             ConeOfRays[20, NumberOfRays -> 7],
             Move[PlanoConvexLens[100, 50, 10], 100],
             Move[PlanoConvexCylindricalLens[100, {50,50}, 10], 130],
             Move[Screen[{50,50}], 218],
             Boundary[{-100,-100,-100}, {250,200,200}]}];
         ReadRays[screensystem, OpticalLength, {ComponentNumber -> 3}]

Out[33]= {228.591, 228.435, 228.369, 228.538, 228.538, 228.369, 228.435}
```

Because **AnalyzeSystem** performs both the ray tracing and rendering, **PropagateSystem** is seldom used by the examples in this guide. Nevertheless, you can use **PropagateSystem** in precisely the same fashion as **AnalyzeSystem** for strictly numerical studies. Next, we will learn about **TurboTrace** and **TurboPlot** as high-speed alternatives to **PropagateSystem** and **AnalyzeSystem** when large numbers of rays or trace iterations are required.

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14. Using TurboPlot for High-Speed Ray Tracing and Rendering

In Version 1, **AnalyzeSystem**/**PropagateSystem** were the only functions available for ray-tracing. Now, however, *Rayica* offers an entirely new suite of functions for high-speed ray tracing of large ray data-sets. At the heart of this new capability is **TurboTrace**. On most occasions, as with **PropagateSystem**, **TurboTrace** is not called directly by the user. Instead, either **TurboPlot**, **OptimizeSystem**, or **FindIntensity** is employed. In this section, we will examine **TurboPlot**. Then, in Sections16 and 17, **OptimizeSystem** and **FindIntensity** will be discussed.

> **TurboTrace[***optics*, *options***]** produces an accelerated ray trace of a system of light sources and optical elements.
>
> **TurboPlot[***optics*, *options***]** works with **TurboTrace** to perform accelerated ray-tracing and rendering of a system of light sources and optical elements.

On the outside, **TurboPlot** behaves in much the same fashion as **AnalyzeSystem**. In particular, **TurboPlot** also accepts a list of light source and optical component functions for its input, traces the rays through the components, and renders the results. **TurboPlot** also uses many of the same options as **AnalyzeSystem** and **ShowSystem** for rendering its information. Internally, however, **TurboTrace** and **TurboPlot** are designed with one objective in mind: namely, speed. For its ray-trace calculations, **TurboPlot** depends on **TurboTrace** just as **AnalyzeSystem** uses **PropagateSystem**. When it is called with a new optical system, **TurboTrace** first constructs a compiled function, called a **RayTraceFunction**, that performs the ray-trace calculation and is returned as a part of the ray-trace result. Initially, this construction process can consume a significant amount of time and, for this reason, **TurboPlot**/**TurboTrace** can sometimes be slower than **AnalyzeSystem**/**PropagateSystem** when only a small number of rays are traced. However, if a larger number of rays are needed or if many trace iterations are required, then **TurboTrace**-based calculations are always the best way to go. As an example, consider the following optical system.

```
In[3]:= system = {GaussianBeam[10, .1, NumberOfRays->11, FullForm->True],
           Move[PlanoConvexLens[100,50,10],50],
           Move[Screen[50],150]};
```

This example uses the **GaussianBeam** light source function. **GaussianBeam** simulates the intensity and optical phase characteristics of a Gaussian laser beam (see Section 2). In our system, the spot size and beam divergence were given by 10 and .1, respectively. Here, we used the **FullForm -> True** option to specify a three-dimensional pattern of rays. (Otherwise, with the default setting of **FullForm -> False**, **GaussianBeam** only creates a fan of rays within a light-sheet.) Since we specified **NumberOfRays -> 11** with **FullForm -> True** in the **GaussianBeam**, there will be in fact $11^2 = 121$ rays created. This is because, for three-dimensional sources, **NumberOfRays** refers to the number of rays along each dimension of the ray cross-section. If **FullForm -> False** were used instead to construct a two-dimensional fan of rays, then only 11 rays would have been initiated in total.

AnalyzeSystem versus TurboPlot

Let us first trace this system with **AnalyzeSystem**, to get a timing baseline, and then follow this up with the use of **TurboPlot** on the same system. We can use the **Timing** function to measure the length of time for an activity to occur in *Mathematica*.

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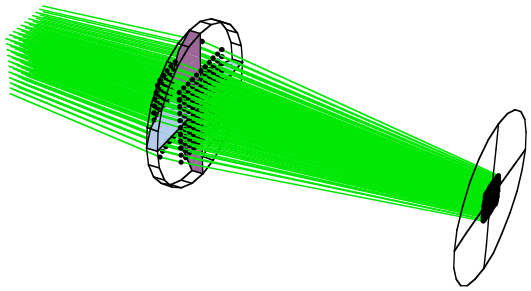
In[23]:= **Timing[AnalyzeSystem[system]]**

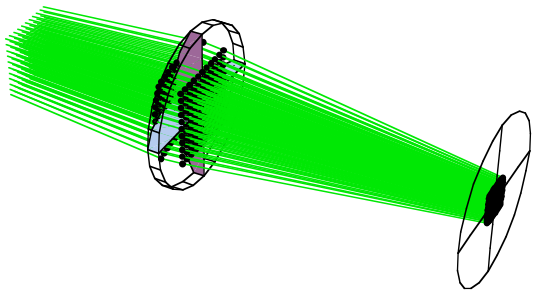


```
AnalyzeSystem[{GaussianBeam[10, 0.1, FullForm → True, NumberOfRays → 11],
  Move[PlanoConvexLens[100, 50, 10], 50.], Move[Screen[50], 150.]}]
```

Out[23]= {40.5167 Second, -363 ray/surface intersections-}

In this ray-trace, it is evident that the **GaussianBeam** with **FullForm -> True** has produced a rectangular-shaped array of rays. Nevertheless, although it is not apparent from the rendering, the transverse intensity and optical phase profile of the traced rays have the radial symmetry of an actual Gaussian laser beam. Now we will use **TurboPlot** on the same system.

In[15]:= **Timing[TurboPlot[system]]**



Out[15]= {10.7833 Second, -traced system-}

Although the overall trace time depends on the particular computer in use (the author's computer is particularly slow by today's standards), the timing ratio from two different traces will remain fairly constant for different computer systems (but perhaps not for different *Mathematica* versions). In the previous example, we can see that **TurboPlot**, in its default setting, is about four times faster than **AnalyzeSystem**. Although this speed increase is useful, it is still not particularly dramatic. However, with **TurboPlot**, most of this time was actually spent in the construction of the **RayTraceFunction** source code and only a tiny fraction of the time was actually spent on the ray-trace. In particular, as the number of rays used in a trace is increased, the calculation time of **TurboPlot**, relative to **AnalyzeSystem**, improves. In addition, the trace speed of **TurboPlot** depends on the option settings used in the trace. For some settings of **TurboPlot**, the actual ray-tracing speed can be as much as 30 times faster than **AnalyzeSystem**. This speed improvement with **TurboPlot** becomes particularly clear when you run multiple traces of the same system, because **TurboPlot** can reuse the **RayTraceFunction** source code from a previous calculation (since this code is passed in the trace output). For example, what if we wished to observe how the trace appears for different lens focal lengths? With **TurboPlot**, we can introduce a symbolic parameter, **f**, that represents the lens focal length and then rerun the trace with different settings for **f**. This is accomplished by including both a symbolic and a numeric setting **{f,100}** for the focal length parameter in **PlanoConvexLens** as follows:

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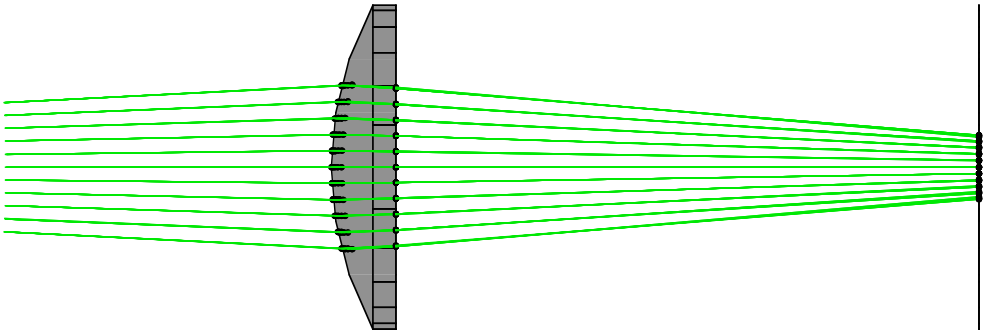
```
In[6]:= fsystem = {GaussianBeam[10,.1,NumberOfRays->11,FullForm->True],
            Move[PlanoConvexLens[{f,100},50,10],50],
            Move[Screen[50],150]};
```

When we call **TurboPlot** the first time, the result is the same as before:

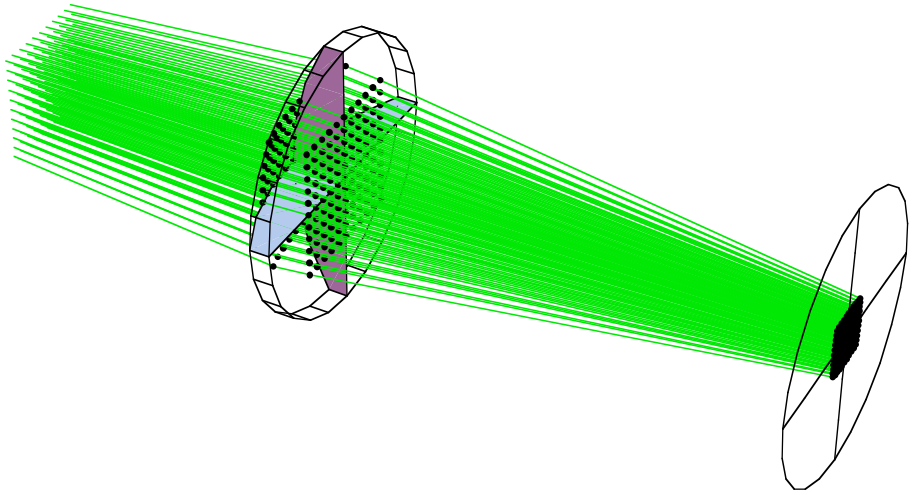
```
In[7]:= Timing[trace = TurboPlot[fsystem, PlotType->TopView]]
```



```
Out[7]= {10.4833 Second, -traced system-}
```

After this trace has occurred once, we can then rerender the ray-trace information much more quickly by passing **trace** back to **TurboPlot**.

```
In[8]:= Timing[TurboPlot[trace]]
```



```
Out[8]= {1.38333 Second, -traced system-}
```

Because we have not changed any parameters, **TurboPlot** has simply rerendered the previous calculation without rerunning the trace. In this instance, **TurboPlot** takes the role of **ShowSystem**, discussed previously in Section 7. However, we can also run a new ray trace with different symbolic parameter values at much greater speed. In order to accomplish this, we use the **SymbolicValues** option.

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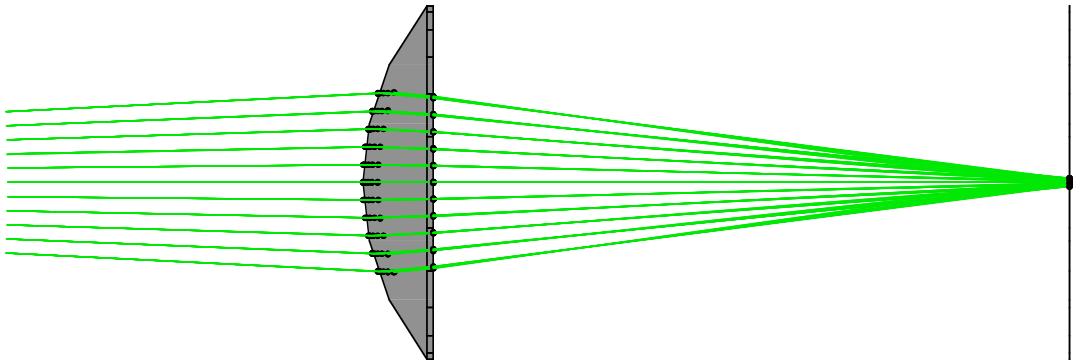
> **SymbolicValues -> {***symbol->value,...***}** is an option that attaches numerical values to the specified symbolic variable names.

Next we will change the value for the lens focal length, **f**, from 100 to 75.

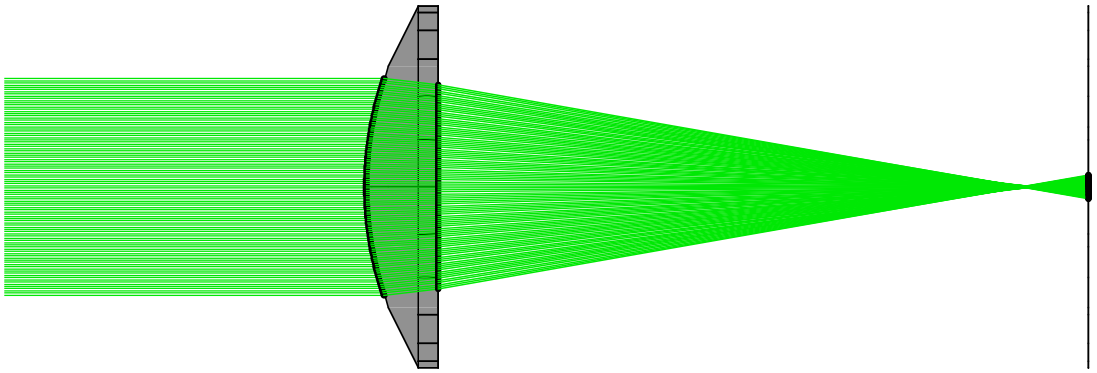
```
In[54]:= Timing[TurboPlot[trace, SymbolicValues->{f->75}, PlotType->TopView]]
```



```
Out[54]= {4.58333 Second, -traced system-}
```

This time, the overall trace and rendering time is 10 times shorter than **AnalyzeSystem** could have managed (if it indeed accepted symbolic settings). In addition to using different symbolic settings, **TurboPlot** also accepts new light sources on the fly without having to recompile the ray-trace information. This is accomplished by passing, to **TurboPlot**, a new light source function as the first parameter and the previous trace result as the second parameter. Here, we swap the **GaussianBeam** source with a **LineOfRays** source as well as change the focal length value to **f-> 90**.

```
In[64]:= Timing[TurboPlot[LineOfRays[30,NumberOfRays->100], trace, SymbolicValues->{f->90},
         PlotType->TopView]]
```



```
Out[64]= {3.71667 Second, -traced system-}
```

In addition to shorter computation times, **TurboPlot** consumes far less memory than **AnalyzeSystem**. In particular, the traced ray information is stored much more efficiently, by an order of magnitude in some cases, with **TurboPlot**.

Until now, the performance gains of **TurboPlot** have been an order of magnitude better than **AnalyzeSystem**. Next, we will introduce the **CreateClones** option for modeling repetitive optical elements. In particular, with this option, we can obtain performance gains, in terms of both speed and memory, that are three orders in magnitude better than **AnalyzeSystem**!

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CreateClones

With **TurboPlot**/**TurboTrace**, *Rayica* now has an enhanced capability for modeling repetitive optical elements. This feature is not present in **AnalyzeSystem**, (although you can still display the results with **ShowSystem** if you wish). This capability is managed with the **CreateClones** option.

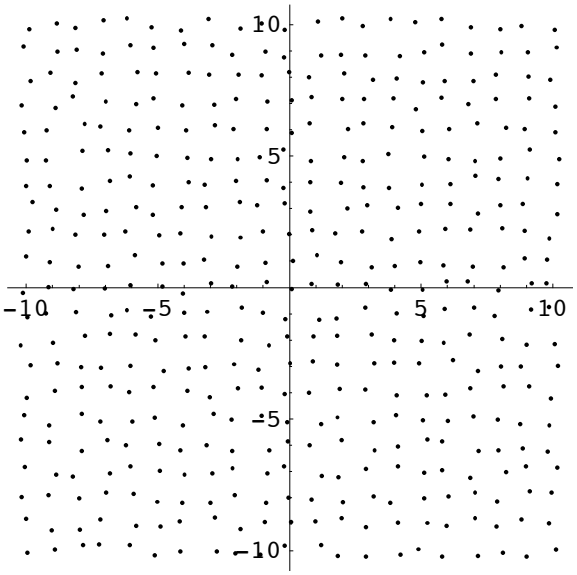
> **CreateClones -> {{***coordinates*, *rotationmatrix*, *componentnumber*, *scale***}, ...}** specifies the placement of one or more phantom optical components to be used during the ray trace. These component aliases exhibit the ray-trace behavior of the original component members but do not consume additional computer memory. This permits the efficient nonsequential ray tracing of large arrays of optical elements.

CreateClones accepts a wide range of data structures for managing different forms of repetitive elements. With the most general format of **CreateClones**, it is possible to specify different three-dimensional *coordinates*, orientations (via *rotation-matrix*), and sizes (via *scale*) for every repeated element. In addition, you can specify a mixture of different components in **CreateClones** (by passing the corresponding *componentnumber* of each template element). For the purposes of this discussion, however, we will only demonstrate the simplest possible formulation for **CreateClones**. In particular, we will specify the {x ,y} coordinates, for different clone positions, along the x and y dimensions of space and we will not alter the relative size or orientation of the cloned elements. As such, we need only to construct a list of two-dimensional positions for **CreateClones**. Because no z coordinate is given, the resulting system will automatically use z=0 and bi-sect the x-y plane. However, you can also position your cloned elements in three-dimensions if you pass three-dimensional coordinates to **CreateClones**. To generate a list of coordinates, we will use the **Table** function of *Mathematica*. In addition, we will add a random perturbation to the coordinates with *Mathematica*'s built-in **Random** function.

```
In[6]:= positions = Apply[Join,
            Table[
                {Random[Real,{-.25,.25}]+x, Random[Real,{-.25,.25}]+y},
                {x,-10,10,1},{y,-10,10,1}
            ]
        ];
```

Next, we use the **ListPlot** function of *Mathematica* to examine the spatial distribution of coordinate points.

```
In[7]:= ListPlot[positions,AspectRatio->1];
```



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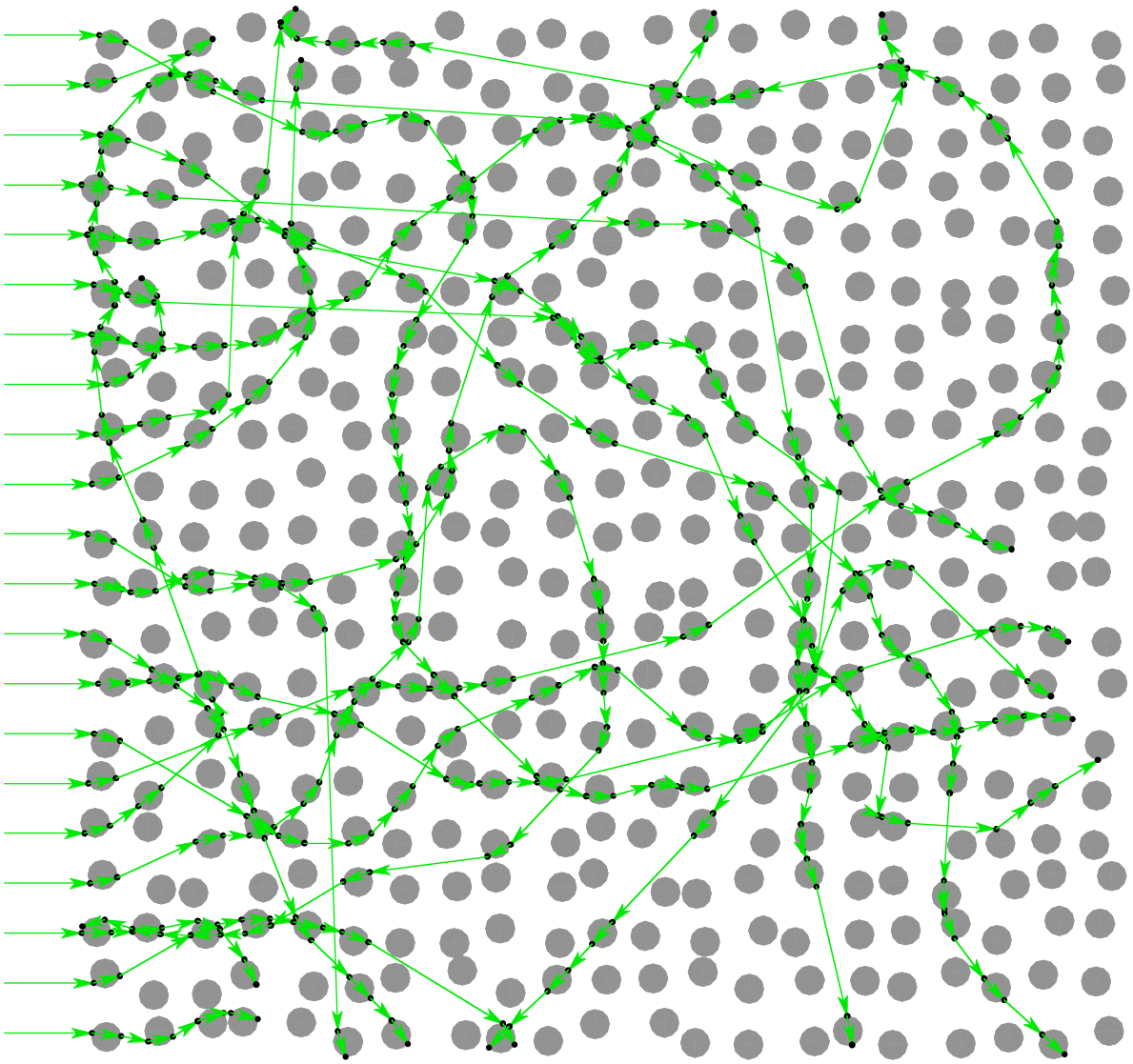
We will now use **CreateClones** together with **TurboPlot** to trace rays through a randomized array of spherical glass ball lenses. In order to model a ball lens in *Rayica*, we will use the **BallLens** component function.

> **BallLens[***diameter*, *options***]** denotes an entire spherical refractive component.

Finally, we trace the system with **TurboPlot**. Here we use **CreateClones->positions** to specify the spatial positions of the cloned lenses and the **LineOfRays** function to generate the rays in the system.

```
In[8]:= TurboPlot[{Move[LineOfRays[20,NumberOfRays->21],-12], BallLens[.6]},
              CreateClones->positions, ShowClones->True, PlotType->TopView,
              RunningCommentary -> TurboTrace, ShowArrows->All];

        System traced in 11.5 seconds with 504 ray segments getting reported.
```



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In this example, *Rayica* has modelled a system of 882 optical surfaces. By using **CreateClones**, this result is 1200 times faster than the same calculation would have been with **AnalyzeSystem** and 66 times faster than **TurboPlot** alone. In addition, in this example, **CreateClones** has consumed only 1/400 of the memory that would otherwise have been required to describe the same optical system. The performance of **CreateClones** improves even further as its number of repetitive elements is increased. In some cases, **CreateClones** can reach efficiencies that are tens of thousands times better than otherwise possible. You can learn more about **CreateClones** in Chapter 7 of the Principles of *Rayica* Guide.

In addition to the **CreateClones** option, this example has used three other new options. These are defined below.

> **ShowClones -> True/False** is an option that denotes whether the phantom clones of optical components are rendered.
> **ShowArrows -> True/False/All/***maxnumber* is an option that switches between arrow and simple line rendering of rays.
> **RunningCommentary -> True/False/All/TurboTrace/ComponentFoundation** is an option of **PropagateSystem**, **TurboTrace**, and other *Rayica* functions that controls reporting of the calculation process.

This section has provided a glimpse of new capabilities now made possible with **TurboPlot** and **CreateClones**. In the next section, we will see how **OptimizeSystem** makes optimization problems easy to manage in *Rayica.*

15. Optimization with OptimizeSystem

Previously, we learned how to incorporate used-defined symbolic parameters into optical systems. In particular, we saw how to assign a symbolic focal length to a lens and then assign different numeric values for different ray-trace calculations. **OptimizeSystem** also uses such symbolic parameters in order to iteratively optimize some aspect of an optical system.

> **OptimizeSystem[***system*, *options***]** optimizes the performance of an optical system for a specified set of symbolic input parameters.

While in its default operation, **OptimizeSystem** tries to minimize the ray-locus spot-size on a last surface of the optical system, you can also customize **OptimizeSystem** for nearly any other characteristic that you wish. In this section, however, we will stick with the default settings of **OptimizeSystem** to find the best focus for a lens system. Next, we will create a double-surface lens with the **SphericalLens** function.

> **SphericalLens[***r1*, *r2*, *aperture*, *thickness*, *options***]** denotes a lens having two spherical surfaces with radius of curvatures given by *r1* and *r2*.

In this case, we will use two symbolic parameters, **r1** and **r2**, to represent the radius of curvature of each lens surface.

```
In[2]:= sphericalsystem =
            {GaussianBeam[10,.1,NumberOfRays->11],
            Move[SphericalLens[{r1,100}, {r2,-100}, 50, 10],50],
            Move[Screen[50],150]};
```

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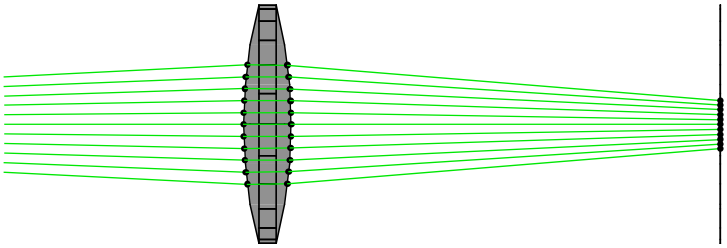
OptimizeSystem uses the numeric value that accompanies every symbolic parameter as an initial starting value for the numeric minimization process. As a user, you can influence the minimization process through your choice of these settings. In this case, the initial numeric setting for **r1** is 100 mm and for **r2** is -100 mm. When we call **TurboPlot** directly, we can trace of the lens system with its initial numeric settings.

```
In[3]:= Timing[trace = TurboPlot[sphericalsystem, PlotType->TopView]]
```



```
Out[3]= {7.83333 Second, -traced system-}
```

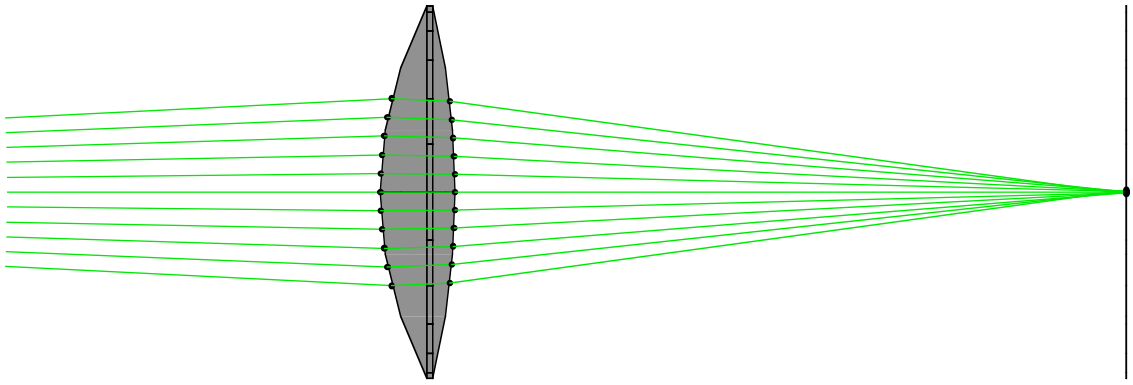
Finally we call **OptimizeSystem** with the untraced **sphericalsystem** information.

```
In[4]:= Timing[soln = OptimizeSystem[sphericalsystem]]

Out[4]= {36.15 Second, {SymbolicValues → {r1 → 53.2884, r2 → -106.975},
          NumberOfCycles → 216, FinalMerit → 0.0880703}}
```

Here we have stored the resulting answer from **OptimizeSystem** in the **soln** variable. In this case, the system was iteratively traced 216 times before the optimal value was determined. (Note that the standard **OptimizeSystem** cannot always find the global minimum and may only find a local minimum. In many cases, however, this is already a big help! However, other extensions do exist for *Rayica* that enable **OptimizeSystem** to perform global optimization. See the Optica Software web site: www.opticasoftware.com for further details.) We can now rerun **TurboPlot** with the information from **soln** to see a trace of the optimal result.

```
In[5]:= plot = TurboPlot[trace, soln, PlotType->TopView];
```



As one final speed-up, we can add the option **SequentialTrace -> True** to **OptimizeSystem**. Both **OptimizeSystem** and **TurboTrace** use **SequentialTrace -> False** by default. In this case, however, we can use **SequentialTrace -> True** because the rays in this optical system are all passing through the same sequence of optical surfaces without back-tracking or having multiple bounces.

```
In[4]:= Timing[soln = OptimizeSystem[sphericalsystem, SequentialTrace->True]]

Out[4]= {30.4 Second, {SymbolicValues → {r1 → 53.2884, r2 → -106.975},
          NumberOfCycles → 216, FinalMerit → 0.0880703}}
```

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In this final example, **SequentialTrace->True** has given us a further increase in speed. With larger systems that have many optical surfaces, there can be even greater gains in performance from this setting. Although the example given here has optimized the surface curvatures of the lens, many other optical parameters can be also optimized by simply assigning a symbolic value to each desired parameter. This could include the thickness of a component or the position of a component or light source in space. You can include equations with your symbols or even assign a symbolic wavelength to a light source and subsequently optimize the system at different colors.

16. ReadRays with TurboTrace and TurboPlot

As shown previously with **ReadRays** and **AnalyzeSystem** in Section 12, it is often desirable to get specific parameter values for a selected group of intersection points at an optical surface. **ReadRays** also offers such functionality for **TurboTrace** and **TurboPlot** calculations by calling **ReadTurboRays** internally.

> **ReadTurboRays[***results*, *rayparameters*, *selectionproperties***]** takes ray-traced *results* from **TurboPlot**/**TurboTrace** and returns a list of values for *rayparameters* and *selectionproperties* given. However, the *selectionproperties* parameter is optional and can be omitted.

Consequently, you either call **ReadRays** or **ReadTurboRays** without any change in behavior. As a demonstration, we will use the **plot** result from the previous section to examine the optical path-length of rays at the screen surface. For this we will use the **OpticalLength**, as the *rayparameter*, together with **ComponentNumber->2**, as the *selectionproperty*, in **ReadRays**.

```
In[6]:= ReadRays[plot, OpticalLength, ComponentNumber->2]

Out[6]= {155.274, 155.243, 155.232, 155.231, 155.232,
          155.232, 155.232, 155.231, 155.232, 155.243, 155.274}

In[6]:= ReadTurboRays[plot, OpticalLength, ComponentNumber->2]

Out[6]= {155.274, 155.243, 155.232, 155.231, 155.232,
          155.232, 155.232, 155.231, 155.232, 155.243, 155.274}
```

Since **ReadRays** and **ReadTurboRays** both work with **TurboTrace** and **TurboPlot**, it can be easiest to simply use **ReadRays** all of the time. You can learn more about **TurboTrace**, **TurboPlot**, **OptimizeSystem**, and **ReadTurboRays** in Section 3.6 of the Principles of *Rayica* Guide.

17. Energy Calculations with FindIntensity

In addition to optimization, *Rayica* can also help you determine the light intensity profile at specified optical surfaces and to measure the transmitted energy through the optical system. This is accomplished with the **FindIntensity** function.

> **FindIntensity[***system*, *options***]** calculates the intensity function for each optical surface that gets reported from the ray trace of the *system*.

For its input, **FindIntensity** works best with either an untraced "raw" optical system or a previously calculated result by **FindIntensity**. However, when required, **FindIntensity** can also work with externally generated trace results. **FindIntensity** works equally well for surfaces that either are close to a focal plane or far from any focus. If a light sheet source is used (ie. **WedgeOfRays** or **LineOfRays**), then a one-dimensional intensity function is automatically calculated by **FindIntensity**. If a volume-filling source is used (ie. **PointOfRays** or **GridOfRays**), then the intensity calculations are automati-

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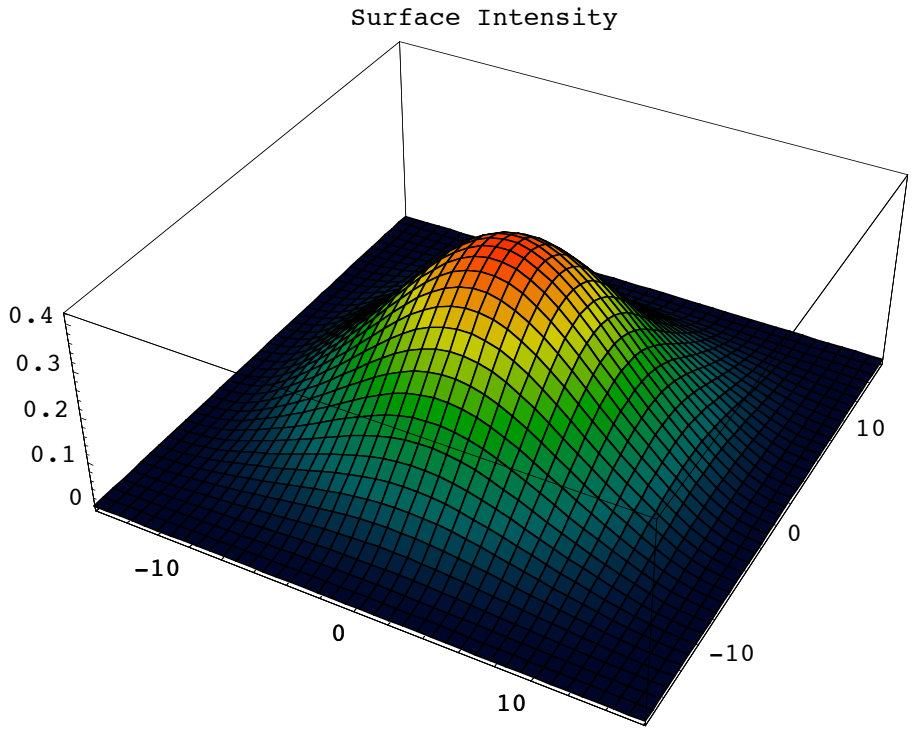
cally carried out for each reported surface in two-dimensions. Because **FindIntensity** does not calculate interference or keep track of the coherent phase information, it can only measure incoherent light flux properties.

2-D Calculations with FindIntensity

As an example, we will plot the intensity present for a planar cross-section of a Gaussian beam. We will use **FullForm -> True** with the **GaussianBeam** function to generate a three-dimensional pattern of rays. **FindIntensity** uses the **Plot2D** option to specify how the intensity information is rendered. With **Plot2D -> False**, the intensity is rendered as a three-dimensional plot. (**Plot2D -> True** constructs a two-dimensional plot.) In addition, the plot is colored according to the intensity levels present.

```
In[2]:= intensityresult =
          FindIntensity[{
          GaussianBeam[10, .1, NumberOfRays->64, FullForm->True],
          Move[Screen[50],50]}, Plot2D -> False]

        Surface Information : {ComponentNumber → 1.,
          SurfaceNumber → 1., NumberOfRays → 4096, SmoothKernelSize → 2.38095}
```




```
Out[2]= {ComponentNumber → 1., Energy → 100., Full3D → True,
          IntensityFunction → CompiledFunction[-intensity data-], NumberOfRays → 4096,
          OutputGraphics → {- SurfaceGraphics -}, RayBoundary → {{-12.5, 12.5}, {-12.5, 12.5}},
          SmoothKernelSize → 2.38095, SurfaceNumber → 1., WaveFrontID → 1.}
```

Note that since we specified **NumberOfRays -> 64** with **FullForm -> True** in the **GaussianBeam**, there have been, in fact, $64^2 = 4096$ rays created. This was the result of **FullForm -> True**. If **FullForm -> False** has been used instead, then only 64 rays would have been generated in total. In general, you are free to choose the number of rays to be traced with **FindIntensity**. Bear in mind, however, that there needs to be a sufficient number of ray samples to make the **FindIntensity** result meaningful. As a rule of thumb, **NumberOfRays -> 64** is the minimum value required for reasonable full-surface calculations (to produce 4096 rays) and **NumberOfRays -> 256** is the minimum required for light-sheet ray-traces (to produce 256 rays).

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You can use **Options[FindIntensity]** to observe its default option settings.

```
In[3]:= Options[FindIntensity]

Out[3]= {KernelScale → Relative, SmoothKernelSize → 6, SmoothKernelRange → 3,
         IntensitySetting → Automatic, Energy → Automatic, IntensityScale → 1,
         Print → True, Show → True, ReportedSurfaces → Last, SequentialTrace → False,
         GenerationLimit → 200, PlotRange → All, PlotDomain → Automatic, PlotPoints → 40,
         Plot2D → ContourPlot, ContourLines → False, Contours → 50, Full3D → Automatic,
         ColorFunction → (Hue[0.65 - #1 0.65, 1, #1 0.9 + 0.1] &), FilterTrace → True,
         ScoutTrace → Automatic, ScoutRays → Automatic, ThresholdIntensity → 0.001,
         CosineCompensation → True, SequentialRead → Automatic, InterpolatingFunction → False,
         InterpolationOrder → 1, SampleFactor → 2, RecenterData → False, RunningCommentary → False}
```

Here we can see that **FindIntensity** uses a number of options that we have not encountered before. The most significant of these are listed below.

```
Out[12]//TableForm=
```

IntensitySetting	Print
SequentialRead	ReportedSurfaces
IntensityScale	Show
KernelScale	SmoothKernelRange
Plot2D	SmoothKernelSize

Options that help characterize **FindIntensity**.

While some of these options will be considered further in this section, others will be left to discussion elsewhere.

In addition to showing information as a three-dimensional plot, the **Plot2D** option in **FindIntensity** has several other settings. Its settings are shown below.

False or **Full3D** gives the full three-dimensional rendering of the intensity profile.
True or **SideView** gives a two-dimensional cross-section rendering at the x-z plane of the intensity profile.
FrontView gives a two-dimensional cross-section rendering at the y-z plane of the intensity profile.
ContourPlot gives a contour plot of the intensity profile.

Settings of **Plot2D**.

Next we shall plot the same **FindIntensity** calculation with its default plot setting (**Plot2D -> ContourPlot**). This time we call **FindIntensity** with the previous results stored in **intensityresult**. This saves us from having to rerun the ray trace and intensity calibration. We will use **Print -> False** to switch off the printed messages. (**Show -> False** can be used to switch off the graphical rendering.)

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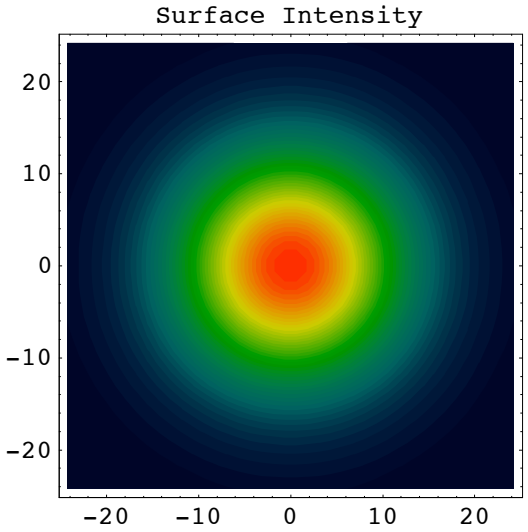
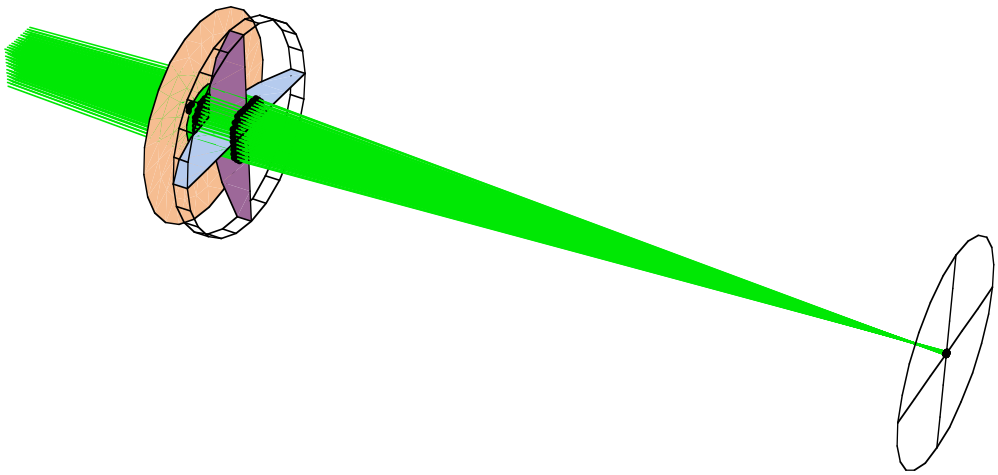
```
In[5]:= FindIntensity[intensityresult, Print -> False];
```



FindFocus

In the previous example, we examined the intensity at a single surface. However, if multiple surfaces are reported, **FindIntensity** can measure the energy losses in the system that occurs between the first reported surface and every subsequent reported surface. We will see this in the next example. Here, we use an **ApertureStop** as a pupil that restricts the transmitted light through a lens. In addition, we will use **FindIntensity** to calculate the point spread function of the optical system by placing one of the reported surfaces at the lens focal point. Before running **FindIntensity**, we will first use **TurboPlot** to show a ray-trace of our intended system.

```
In[43]:= trace = TurboPlot[{GaussianBeam[5,.05,NumberOfRays->12, FullForm->True],
            Move[ApertureStop[50,15],49],
            Move[PlanoConvexLens[100,50,10],50],
            Move[Screen[50],225]}, PlotType->Full3D];
```



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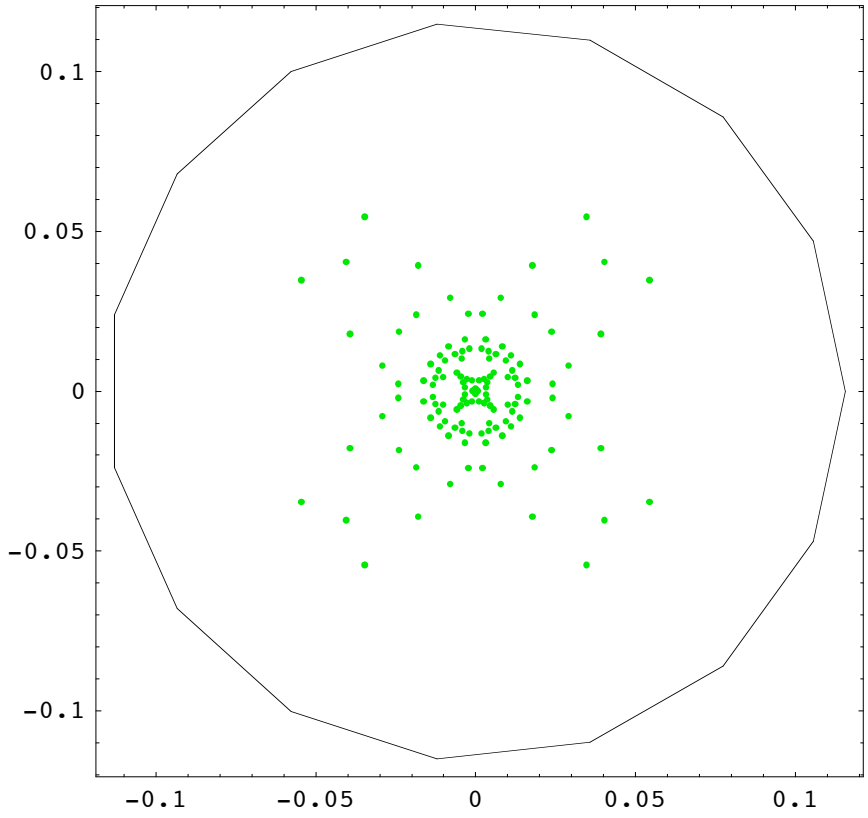
In order to measure the point spread function of the lens system, you first need to determine the focal point of the system. You can use the **FindFocus** function for this. Here is a description of **FindFocus**.

> **FindFocus[***objectset***,** *options***]** determines the minimum spot size for a locus of rays at the last reported surface in the system and plots the results.

Next, we can use the **FindFocus** function to find focal point of our lens system. In this case, since we have already calculated a ray trace using **TurboPlot**, we can simply pass to **FindFocus** the result of our previous calculation.

```
In[44]:= focus = FindFocus[trace]
```




```
Out[44]= {Screen → Move[Screen[0.231204], 218.522], TurboSystem → -traced system-,
          FocalPoint → {218.522, 0, 0}, FocusType → RMSFocus,
          WeightedSpotSize → 0.0170665, SpotSize → 0.0264831, BackFocalLength → 158.522,
          FocalPlaneTilt → {1., 0, 0}, TurboRays → -ray intercepts of 1 surfaces-}
```

FindFocus has automatically generated a plot of the locus of rays at the focal plane. In addition, **FindFocus** returns a series of rules that describe various aspects of its focus calculation. You can learn more about **FindFocus** in Section 1.3.5 of the Principles of *Rayica* discussion. Of the different rules returned by **FindFocus**, we are only presently interested in the **FocalPoint** rule since it holds the three-dimensional focal-point coordinates. As such, we can assign the focal point result to a **focalpoint** variable in the following way:

```
In[45]:= focalpoint = FocalPoint/.focus

Out[45]= {218.522, 0, 0}
```

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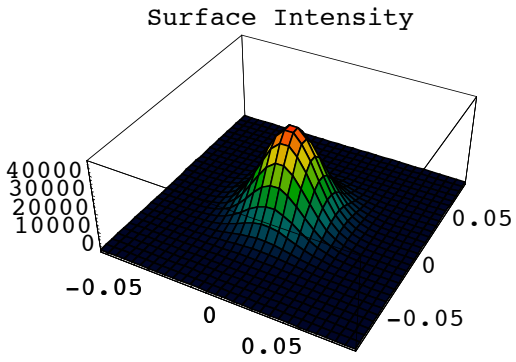
Measuring the Point Spread Function

We are now ready to apply **FindIntensity** to our lens system to measure the point spread function of the system. This time, we will place a **Screen** object at the focalpoint determined by **FindFocus**.

```
In[47]:= focusintensity =
         FindIntensity[{GaussianBeam[5, .05, NumberOfRays->32, FullForm->True],
             Move[ApertureStop[50,15],49],
             Move[PlanoConvexLens[100,50,10],50],
             Move[Screen[{.6,.6}],focalpoint]}, Plot2D -> False]

           Surface Information : {ComponentNumber → 3.,
             SurfaceNumber → 1., NumberOfRays → 956, SmoothKernelSize → 0.020986}
```

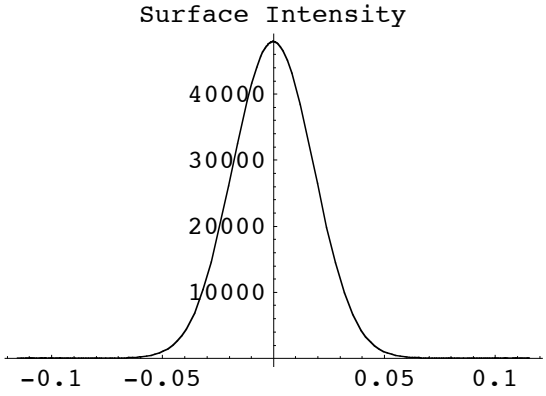



```
Out[47]= {ComponentNumber → 3., Energy → 99.257, Full3D → True,
           IntensityFunction → CompiledFunction[-intensity data-],
           NumberOfRays → 956, OutputGraphics → {- SurfaceGraphics -},
           RayBoundary → {{-0.0524651, 0.0524651}, {-0.0524651, 0.0524651}},
           SmoothKernelSize → 0.020986, SurfaceNumber → 1., WaveFrontID → 1.}
```

Previously, we had used **Plot2D -> False** to display a three-dimensional plot of the surface intensity profile. Next we will call **FindIntensity** for a second time with **Plot2D -> True** to examine the intensity function along the horizontal-axis of each surface.

```
In[48]:= FindIntensity[focusintensity, Plot2D -> True];

           Surface Information : {ComponentNumber → 3.,
             SurfaceNumber → 1., NumberOfRays → 956, SmoothKernelSize → 0.020986}
```



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The last intensity plot is taken at the focal plane of the system and shows the point spread function. **FindIntensity** works by convolving a Gaussian smoothing kernel with the ray-trace data. However, the result may not accurately depict the diffractive performance of the system. In particular, **FindIntensity** automatically adjusts the smooth kernel size to maximize the measurement resolution to the available ray-density. In this way, if the number of input rays are sufficiently great, **FindIntensity** models the geometric behavior of the system. However, you can approximate some effects of the diffraction performance if you have independent knowledge of the diffraction-limited spot-size for the system. In this case, you can manually set the **SmoothKernelSize** option to correspond with the diffraction-limited spot-size of the optical system (together with **KernelScale -> Absolute**). In that case, the intensity plot generated by **FindIntensity** can depict both the geometric and incoherent diffractive properties of a system. However, if the **SmoothKernelSize** is manually set, it is always necessary that make sure that there are a sufficient number of rays are present in order to meet the Nyquist sampling criterion. Otherwise, the resulting calculation will not be correct. Here is the definition of **SmoothKernelSize**.

> **SmoothKernelSize ->** *radius* is an option that specifies the *radius* of a Gaussian smoothing kernel: **Exp[-***s***^2/***radius***^2]**, where *s* is distance along the surface. In particular, this smoothing kernel is convolved with another function in order to low-pass filter its shape along a spatial surface.

SmoothKernelSize works together with the **KernelScale** option to smooth the calculated intensity function. Here is the definition of **KernelScale**.

> **KernelScale -> Relative / Absolute** is used with **FindIntensity** to specify the form of the **SmoothKernelSize** option.

KernelScale -> Relative indicates that the specified **SmoothKernelSize** dimensions is a relative multiplicative factor of the minimum estimated spatial sampling dimension, as determined from Nyquist sampling criteria. **KernelScale -> Absolute** denotes that the specified **SmoothKernelSize** dimensions are given in absolute spatial dimensions.

Measuring the Modulation Transfer Function

Now that we have used **FindIntensity** to determine the point spread function of this lens system, we can also calculate the **ModulationTransferFunction** of this system. First we define **ModulationTransferFunction**.

> **ModulationTransferFunction[***intensitydata***,** *options***]** calculates the modulation and phase transfer functions of an optical system for a given object source input.

ModulationTransferFunction works together with **FindIntensity**. As input, **ModulationTransferFunction** takes the returned output from **FindIntensity**. The optical system must contain a light source followed by the imaging optics with the focal surface as its last element.

```
In[49]:= Options[ModulationTransferFunction]

Out[49]= {SpatialScale → 1, FrequencyCutoff → Automatic, PaddingFactor → 7, NormalizePlot → True,
          InterpolationOrder → 1, PlotPoints → 40, Plot2D → True, ContourLines → False,
          Contours → 50, ColorFunction → (Hue[0.65 - #1 0.65, 1, #1 0.9 + 0.1] &),
          RenderedParameters → {ModulationTransferFunction}}
```

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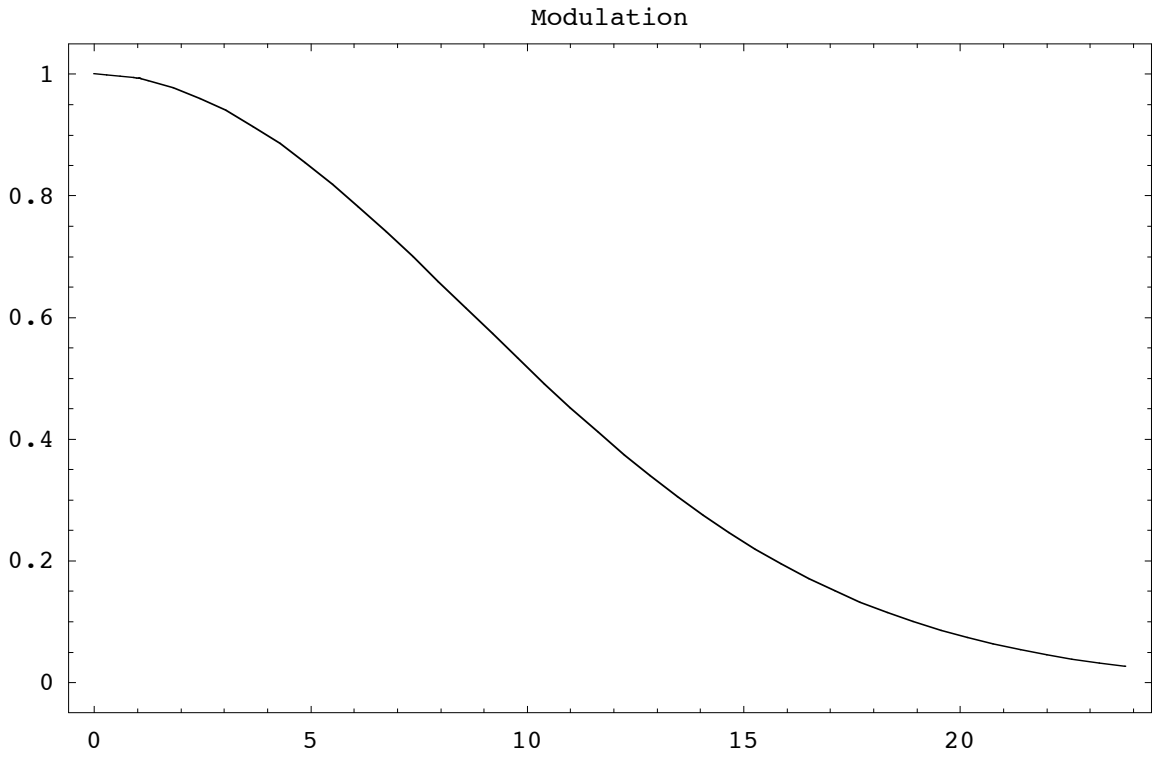
In[50]:= **ModulationTransferFunction[focusintensity]**




```
Out[50]= {ComponentNumber → 3., Energy → 99.257, FrequencyCutoff → {23.8254, 23.8254},
 Full3D → True, ImageSampleSize → {0.01499, 0.020986},
 IntensityFunction → CompiledFunction[-intensity data-], ModulationTransferFunction →
  InterpolatingFunction[{{-33.3555, 32.3132}, {-23.8254, 22.8724}}, <>],
 NumberOfPoints → {8, 6}, NumberOfRays → 956,
 OutputGraphics → {- SurfaceGraphics -, ModulationTransferFunction → (- Graphics -)},
 PhaseTransferFunction →
  InterpolatingFunction[{{-33.3555, 32.3132}, {-23.8254, 22.8724}}, <>],
 RayBoundary → {{-0.0524651, 0.0524651}, {-0.0524651, 0.0524651}},
 SmoothKernelSize → 0.020986, SurfaceNumber → 1., WaveFrontID → 1.}
```

ModulationTransferFunction works equally well for both point sources and planar sources, as long as the described imaging system contains a focus. If a one-dimensional light source is used (ie. **WedgeOfRays** or **LineOfRays**), then a one-dimensional modulation transfer function is calculated. If a two-dimensional light source is used (ie. **PointOfRays** or **GridOfRays**), then the optical transfer function calculations are carried out in two-dimensions.

1-D Calculations with FindIntensity

Next we will examine a light-sheet intensity calculation of the same optical system. This is accomplished by setting **Full3D -> False** in **GaussianBeam**. An initial trace of the optical system with **TurboPlot** reveals that the rays occupy a two-dimensional plane.

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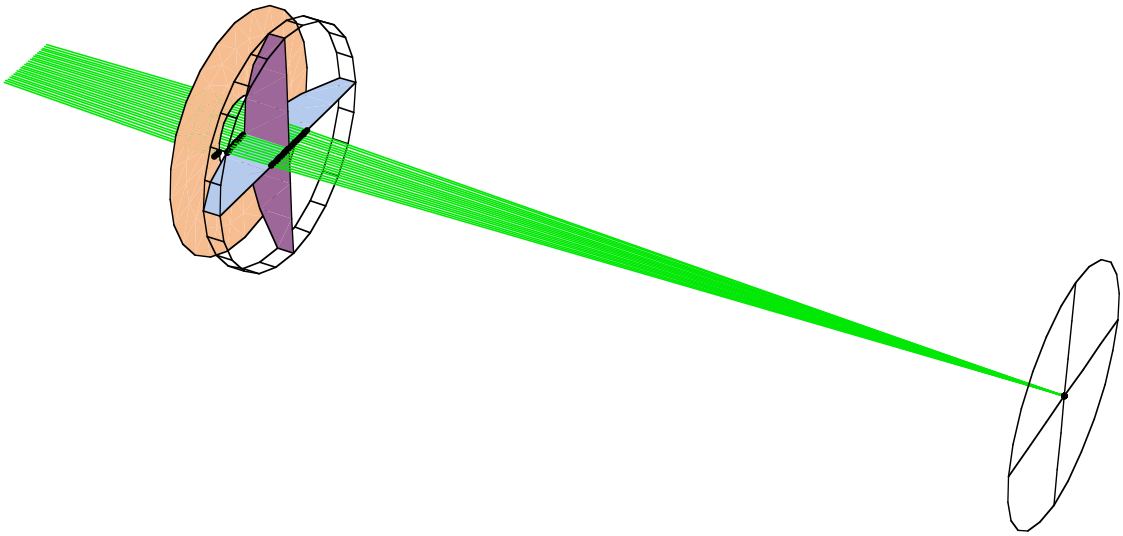
```
In[51]:= TurboPlot[{GaussianBeam[5,.05,NumberOfRays->32, FullForm->False, SpotSizeFactor->2],
           Move[ApertureStop[50,15],49],
           Move[PlanoConvexLens[100,50,10],50],
           Move[Screen[50],focalpoint]}, PlotType->Full3D];
```



We will now apply **FindIntensity** to this system. This time, however, we use **NumberOfRays->1024** with **GaussianBeam**. With such a large number of rays, **FindIntensity** can accurately model the geometric intensity properties of the light flux. In addition, we will use the **ReportedSurfaces** option to specify the optical surfaces that we are interested in measuring intensity. In this case, we specify **ReportedSurfaces -> {{1,1},{3,1}}** to examine the first and third components. In this case, each surface is specified with a list of two ordered numbers where the first number gives the component list order and the second number indicates a particular surface within the component-grouping of surfaces.

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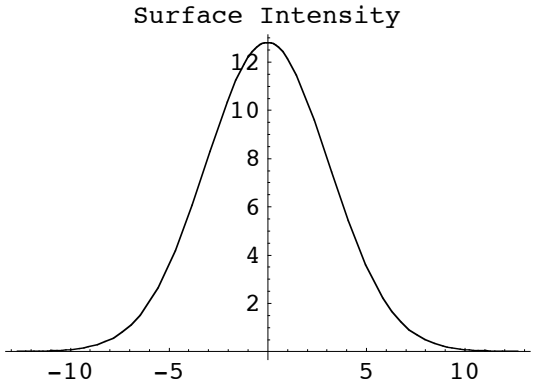
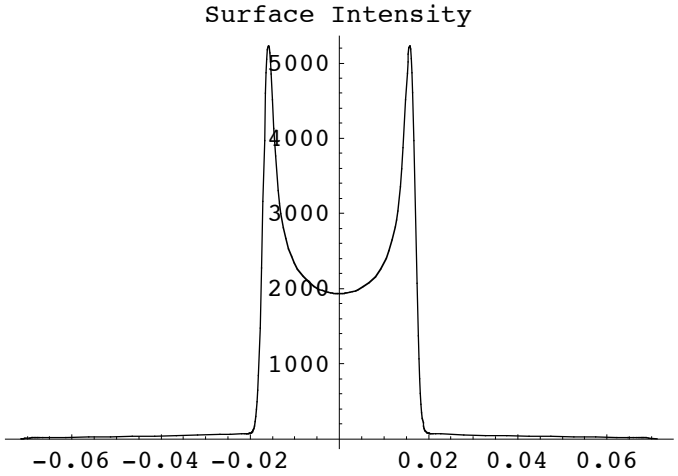
```
In[52]:= intensity = FindIntensity[{GaussianBeam[5, .05, NumberOfRays->1024, FullForm->False,
         SpotSizeFactor->2],
             Move[ApertureStop[50,15],49],
             Move[PlanoConvexLens[100,50,10],50],
             Move[Screen[{.6,.6}],focalpoint]},
             ReportedSurfaces->{{1,1},{3,1}}]

           Surface Information : {ComponentNumber → 1.,
             SurfaceNumber → 1., NumberOfRays → 1024, SmoothKernelSize → 0.146041}
```




```
           Surface Information : {ComponentNumber → 3.,
             SurfaceNumber → 1., NumberOfRays → 616, SmoothKernelSize → 0.00135192}
```




```
Out[52]= {{ComponentNumber → 1., Energy → 100., Full3D → False,
            IntensityFunction → CompiledFunction[-intensity data-], NumberOfRays → 1024,
            OutputGraphics → (- Graphics -), RayBoundary → {-12.45, 12.45},
            SmoothKernelSize → 0.146041, SurfaceNumber → 1., WaveFrontID → 1.},
           {ComponentNumber → 3., Energy → 98.3994, Full3D → False,
            IntensityFunction → CompiledFunction[-intensity data-], NumberOfRays → 616,
            OutputGraphics → (- Graphics -), RayBoundary → {-0.0692861, 0.0692861},
            SmoothKernelSize → 0.00135192, SurfaceNumber → 1., WaveFrontID → 1.}}
```

Here we see that reported **`Energy`** information shows a decrease in the transmitted energy between the first and last reported surface. In particular, there is a slight loss as a result of the aperture stop. With this particular system, the Fresnel losses associated with refractive lens surfaces are not taken into account. However, you could use the **`FresnelReflections -> True`** option with **`PlanoConvexLens`** to include this effect as well. (The **`FresnelReflections`** option is examined in Section 3.4.2 of the Principles of *Rayica* discussion.)

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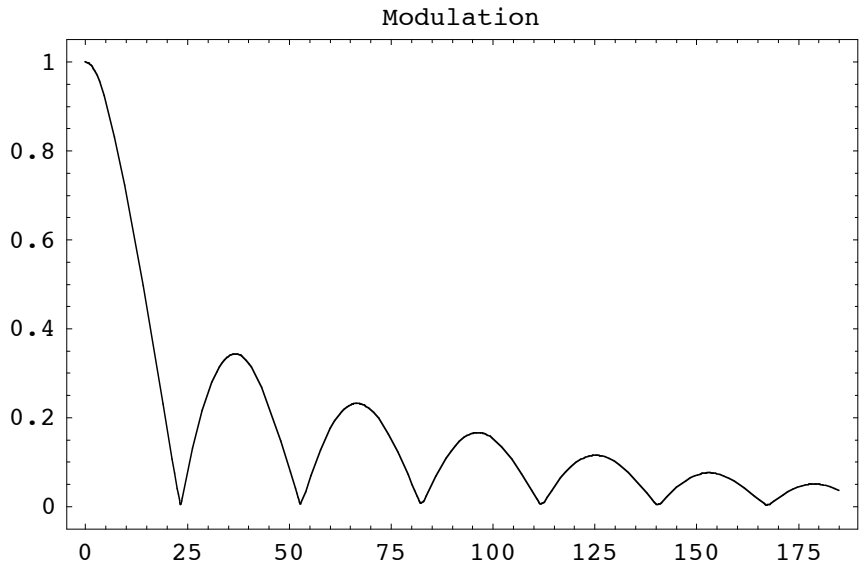
We can again use **ModulationTransferFunction** with our **FindIntensity** result. This time, however, we need to pass only the information from the focal surface. In addition, we can abbreviate the **ModulationTransferFunction** command with **MTF**.

```
In[53]:= MTF[intensity[[2]]]
```




```
Out[53]= {ComponentNumber → 3., Energy → 98.3994, FrequencyCutoff → 184.922, Full3D → False,
 ImageSampleSize → 0.00261457, IntensityFunction → CompiledFunction[-intensity data-],
 ModulationTransferFunction → InterpolatingFunction[{{0., 190.371}}, <>],
 NumberOfPoints → 54, NumberOfRays → 616, OutputGraphics → {- Graphics -},
 PhaseTransferFunction → InterpolatingFunction[{{0., 190.371}}, <>],
 RayBoundary → {-0.0692861, 0.0692861},
 SmoothKernelSize → 0.00135192, SurfaceNumber → 1., WaveFrontID → 1.}
```

This example demonstrates one of the great pitfalls in using a two-dimensional result to model a three-dimensional system. In particular, it is a strong temptation to assume that one can use the results from a two-dimensional ray trace to gauge the performance of a three-dimensional system. Unfortunately, this can be an erroneous assumption. As illustrated by this example, such intensity calculations can be very different from a three-dimensional ray-trace. This is particularly evident at the focal plane in this example, where both the point spread function and modulation transfer function looks very different from the previous three-dimensional example. This is because the energy density from the three-dimensional trace through a radially symmetric lens system is much more concentrated along optical axis. This last result actually depicts the behavior of a cylindrical lens system better than a plano-convex lens in three dimensions. However, because the ray density is far greater in this recent example, it has a much better spatial resolution than the previous example and quite accurately depicts the geometric light flux behavior of the two-dimensional system.

18. The Resonate Function

Resonate is used to create non-sequential behavior between formerly distinct optical elements. **Resonate** is routinely used by many built-in component functions of *Rayica* to describe complex optical elements, such as multi-faceted prisms. Since many optical systems do require non-sequential ray interactions between multiple component surfaces, **Resonate** is one of the most important functions in *Rayica*. Here we define **Resonate**.

Resonate[*listofcomponents*, *options***]** causes a ray to be nonsequentially traced within all of the surfaces defined by *listofcomponents*.

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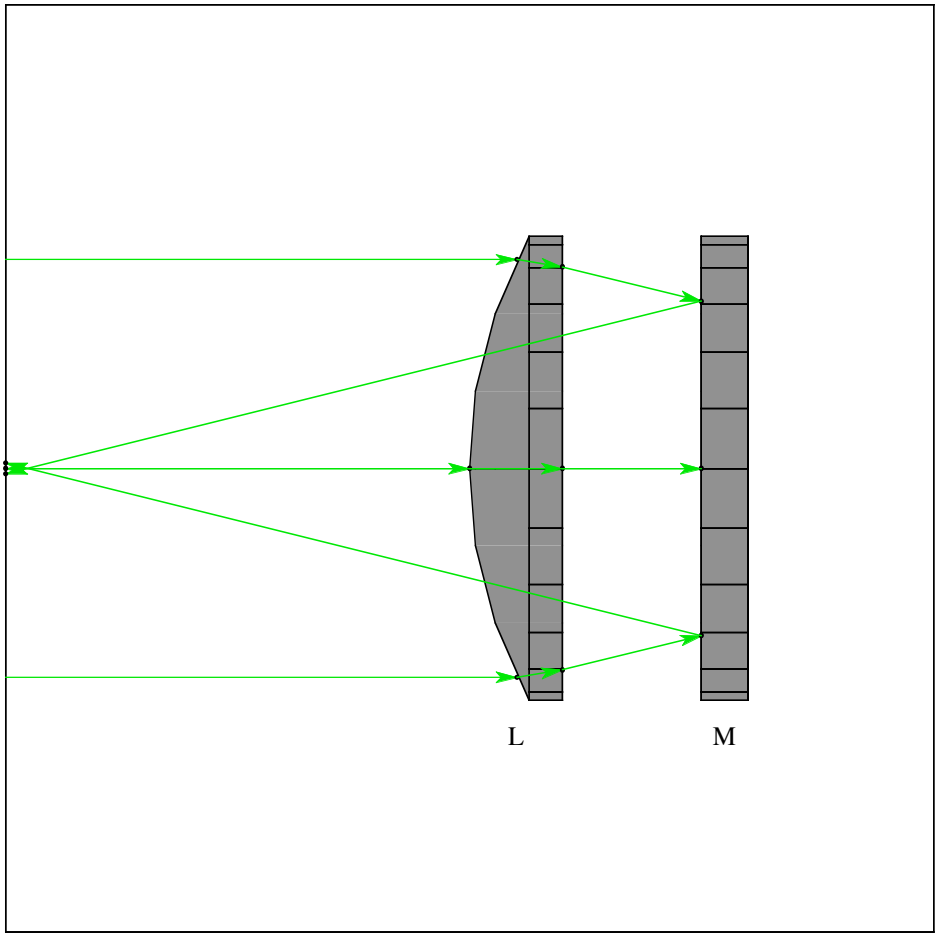
Rayica always traces rays between distinct optical components in a sequential fashion. This means that the ray-trace is always occurring in the same sequence as the component list order. However, anytime the ray trace occurs within the surfaces of an optical component (such as a **Prism**) then non-sequential ray-tracing becomes possible. In some cases, however, it becomes necessary for rays to travel non-sequentially between one or more components. For this purpose, you can use **Resonate**. Lets take, for an example, the case of a lens-mirror combination. Here, the rays might travel through a lens, reflect off a mirror, and then travel back through the same lens for a second pass. In its normal mode of operation, *Rayica* does not see the lens on the second pass when the components are listed separately.

```
In[81]:= AnalyzeSystem[{
             LineOfRays[45],
             Move[PlanoConvexLens[100,50,10],50],
             Move[Mirror[50,5],75],
             Boundary[100]},PlotType->TopView];
```



We can instead combine the lens and mirror with **Resonate** to create a self-contained non-sequential aggregate of the surfaces present.

```
In[24]:= lensMirror =
             Resonate[{
                 Move[PlanoConvexLens[100,50,10],50],
                 Move[Mirror[50,5],75]
             }]

Out[24]= Resonate[{Move[PlanoConvexLens[100, 50, 10], 50.], Move[Mirror[50, 5], 75.]}]
```

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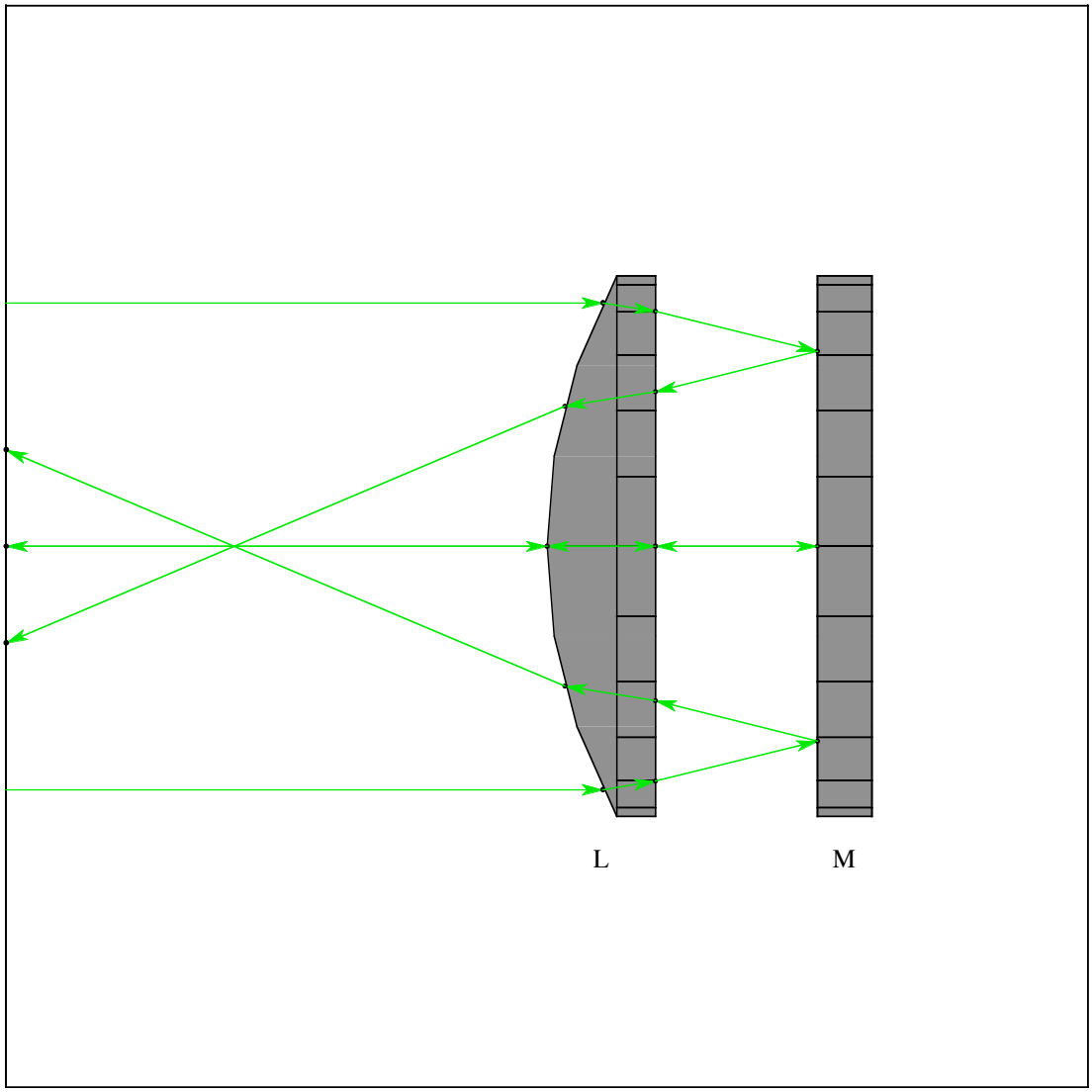
Although the lens and mirror are still identified in the output as independent elements, in fact, **Resonate** has melded their information into a single **Component** object. This can be observed if we examine the **Head** of the **lensMirror** variable assignment:

```
In[9]:= Head[lensMirror]

Out[9]= Component
```

This indicates that the lens and mirror surfaces have been joined together under a single **Component** roof! The rays now correctly trace through this new arrangement.

```
In[99]:= AnalyzeSystem[{
             LineOfRays[45],
             lensMirror,
             Boundary[100]},PlotType->TopView];
```



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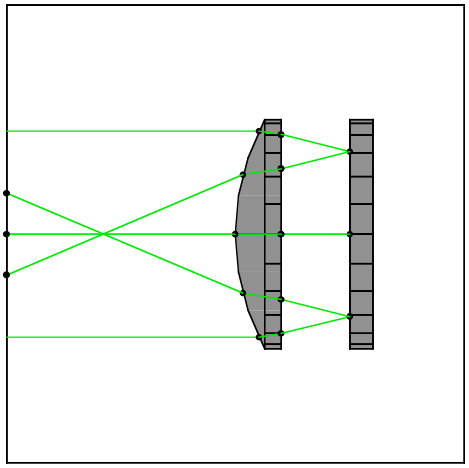
Resonate works independently from whether **AnalyzeSystem** or **TurboPlot** is used for tracing. Here, the same system is traced with **TurboPlot**:

```
In[100]:=
     TurboPlot[{
         LineOfRays[45],
         lensMirror,
         Boundary[100]},PlotType->TopView];
```



You can learn more about **Resonate** and non-sequential tracing in Section 3.3 of the Principles of *Rayica* Guide.

19. *Rayica*'s Database

Rayica now supports a database system that contains information on a wide variety of optical materials and components. These items represent the manufactured products of many different companies. This information is initially stored on the computer's hard disk, but once loaded, the entire database contents is held in the computer's memory. *Rayica*'s database is not initially loaded into the computer's memory until it is accessed for the first time. After this point, all of the database contents stay in the computer's memory for the remaining duration of the *Mathematica* session. *Rayica* has a suite of functions for managing the database information. The most important are: **DataToRayica**, **SearchData**, and **ReadData**. (For the full listing of database-related functions, see Section 5.2 of the Principles of *Rayica* Guide.)

DataToRayica[*selectionproperties*, *options***]** is used to build models in *Rayica* of optical components, light sources, coatings, and materials from the information given in databaselist. **DataToRayica** first calls **SearchData** to select for specific data items.

SearchData[*selectionproperties*, *options***]** uses the internally loaded catalog database to give a selected listing of catalog entries.

ReadData[*parameters*, *selectionproperties*, *options***]** uses the internally loaded database to give a selected listing of the specified data-related parameters.

Of these three functions, **DataToRayica** operates at the highest level and converts the database information into a functioning optical component or material model for use with *Rayica*. **DataToRayica**, however, usually retrieves only a single item from the database listing. Very often, therefore, you will want to use **SearchData** and **ReadData** first, to survey which of the neighboring database items also have a close match to your specifications, in order to make the best choice for **DataToRayica**.

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In essence, *Rayica*'s database contains an array of information that is stored in the form of lists of rules. Each rule describes a particular data attribute, given by *parametername->value*. As an example, the following database entry describes the BK7 optical glass.

```
In[10]:= SearchData[OpticalMedium -> BK7]

Out[10]= {{AcidResistance → 1., AlkaliResistance → 2., BubbleClass → 0, ClimaticResistance → 2,
    ColorCode → {330, 300}, CompanyName → Schott, ComponentLabel → glass,
    Date → {1999, 4, 18}, Dispersion → {{1.5168, 64.17}, {63.96, 0.}, 0.008054, 0.00811},
    ElasticModulus → 82000., FileName → Schott.m, GlassCodeNumber → 517642,
    IndexCoefficients → {1.03961, 0.231792, 1.01047, 0.0060007, 0.0200179, 103.561},
    InternalTransmittance →
     {{2325., 0.0976501}, {1960., 0.0282324}, {1530., 0.0026255}, {1060., 0.0003478},
      {700., 0.0003478}, {660., 0.0005219}, {620., 0.0005219}, {580., 0.0006963},
      {546., 0.0006963}, {500., 0.0006963}, {460., 0.0010454}, {436., 0.0010454},
      {420., 0.0012203}, {405., 0.0012203}, {400., 0.0015705}, {390., 0.0019215},
      {380., 0.0035096}, {370., 0.0045764}, {365., 0.0054705}, {350., 0.0126068},
      {334., 0.0454037}, {320., 0.182373}, {310., 0.461961}, {300., 0.609152}},
    KnoopHardness → 610., MassDensity → 2.51, OpticaFunction → SellmeierFunction,
    OpticalMedium → BK7, PhosphateResistance → 2.3,
    PoissonRatio → 0.206, SpecificHeat → 8.58 × 10^6, SpectralIndex →
     {{none, 2325.4, 1.48921}, {none, 1970.1, 1.49495}, {none, 1529.6, 1.50091},
      {none, 1060., 1.50669}, {t, 1014., 1.50731}, {s, 852.1, 1.5098}, {r, 706.5, 1.51289},
      {C, 656.3, 1.51432}, {Cprime, 643.8, 1.51472}, {HeNe, 632.8, 1.51509},
      {D, 589.3, 1.51673}, {d, 587.6, 1.5168}, {e, 546.1, 1.51872}, {F, 486.1, 1.52238},
      {Fprime, 480., 1.52283}, {g, 435.8, 1.52668}, {h, 404.7, 1.53024},
      {i, 365., 1.53627}, {none, 334.1, 1.54272}, {none, 312.6, 1.54862}},
    StainResistance → 0, TemperatureCoefficientIndex → {1.86 × 10^-6, 1.31 × 10^-8,
      -1.37 × 10^-11, 4.34 × 10^-7, 6.27 × 10^-10, 0.17}, ThermalConductivity → 1114.,
    ThermalExpansion → {{-30, 70, {7.1 × 10^-6}}, {20, 300, {8.3 × 10^-6}}}},
    TransformationTemperature → 557., ViscousTemperature1 → 557.,
    ViscousTemperature2 → 719., WaveLengthRange → {0.3, 2.325}}}
```

In this entry, all of these listed rules describe some aspect of the BK7 glass material. *Rayica*'s database is made up of thousands of entries that are formatted in the same fashion. In order to get an item from the database, you must specify one or more of the properties that you require. In this example, we had specified **`OpticalMedium -> BK7`** to recover the database entry for BK7 glass. When you first begin to use *Rayica*'s database, you will need to have some idea of the information that you are searching for. In particular, you must decide whether you are searching for a particular type of optical component or optical glass, for example. The problem is that *Rayica*'s database can contain many different types of information for each database entry. In order to gain a listing of all database *parametername*s that are available, you can call **`SearchData[]`** without specification:

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```
In[69]:= SearchData[]

Out[69]= {A, AcidResistance, AlkaliResistance, AngleTolerance, BackFocalLength, Baffled,
          BubbleClass, CatalogFocalLength, CatalogNumber, Centered, CenterThickness,
          ClearAperture, ClimaticResistance, ColorCode, CompanyAddress, CompanyName,
          ComponentBoundary, ComponentLabel, ComponentMedium, Country, CurvatureTolerance,
          D, DataComments, DataSource, Date, DefaultAngleSetting, DesignRefractiveIndex,
          DesignWaveLength, DiffractionLimitedRange, DimensionalTolerance, Dispersion,
          EdgeThickness, ElasticModulus, EntrancePupilDiameter, EquivalentMagnification,
          EvenFunction, FaxNumber, FieldOfView, FieldStopLocation, FileName, FlatSubstrate,
          FNumber, FocalLength, FrontFocalLength, FullForm, GlassCatalogs, GlassCodeNumber,
          Hole, HousingBoundary, IndexCoefficients, InputEdgeThickness, InternalTransmittance,
          KnoopHardness, Magnification, MassDensity, MeltingPoint, Mirrored, ModelIntensity,
          NA, NumberElements, NumberOfElementGroups, NumberOfSurfaces, OffAxis, OpticaFunction,
          OpticalMedium, PhosphateResistance, PoissonRatio, PrincipalPointSeparation,
          RadiusOfCurvature, ReferenceWaveLengthNumber, Reflectance, RefractiveIndex, SAY,
          ScratchDig, Solubility, SpecificHeat, SpectralIndex, SplitRays, StainResistance,
          StopPosition, SurfaceAccuracy, SurfaceBoundary, SurfaceCoating, SurfaceCurvature,
          SurfaceFunction, SurfaceLabel, SurfaceSeparation, SurfaceShape, SurfaceValue,
          TelephoneNumber, TemperatureCoefficientIndex, ThermalConductivity, ThermalExpansion,
          ThicknessTolerance, TransformationTemperature, TransmissionRange, Transmittance,
          Units, V1H1, V2H2, ViscousTemperature1, ViscousTemperature2, WaveFrontFlatness,
          WaveLengthRange, WebSiteAddress, WindowParameters, WorkingDistance}
```

Of these many *parameternames*, only a few are really useful for conducting searches. The most useful *parameternames* include **CatalogNumber**, **ComponentBoundary**, **CompanyName**, **FocalLength**, **RayicaFunction**, and **OpticalMedium**. These are defined below.

CatalogNumber -> *string* specifies the catalog identification number for a component.
ComponentBoundary -> *boundary* specifies the entrance dimensions for a lens and the overall dimensions for a prism.
CompanyName -> *name* gives the name of a component manufacturer.
FocalLength -> *focallength* specifies the effective focal length of a lens.
RayicaFunction -> *functionhead* specifies the *Rayica* function used to create a model representation of the database item in *Rayica*.
OpticalMedium -> *symbol* identifies the optical material medium traversed by each ray segment.

Some important database parameters.

Of these different database parameters, the **RayicaFunction** is of particular importance because it declares the purpose of the database entry to *Rayica*. As such, every database entry usually contains **RayicaFunction** as a *parametername*. We can use **ReadData** with **RayicaFunction** to list the declared types of database entries that are present in *Rayica*'s database.

```
In[35]:= ReadData[RayicaFunction, ReportedInterval->All, Union -> True]

Out[35]= {AnamorphicPrisms, AsphericLens, BallLens, BeamSplitter, BeamSplitterCube,
          BiConcaveLens, BiConvexLens, CompoundLens, CustomMirror, CylindricalLens,
          DirectVisionPrism, DovePrism, FresnelRhomb, HerzbergerFunction, HollowCornerCube,
          IndexFunction, IndexInterpolationFunction, JonesMatrixOptic, LensDoublet, LensTriplet,
          LinearPolarizer, Mirror, ModelRefractiveIndex, ParabolicMirror, PechanPrism,
          PentaPrism, PlanoConcaveCylindricalLens, PlanoConcaveLens, PlanoConvexCylindricalLens,
          PlanoConvexLens, PolarizingBeamSplitterCube, PorroPrism, Prism, RetardationPlate,
          ReversionPrism, RhomboidPrism, RoofPrism, SellmeierFunction, SolidCornerCube,
          SphericalLens, SphericalMirror, WedgeBeamSplitter, WedgePrism, Window, {}}
```

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Here, we used **ReportedInterval -> All** to retain all of the valid elements from the database search. (Otherwise, *Rayica* truncates the search result to the first 1000 elements.) The **Union -> True** option is then used to generate a logical union of the results. From this, we see that most of the database items are used with component function entries, such as **PlanoConvexLens**, **Prism**, and **Mirror**. The remaining items, such as **IndexFunction**, are used with optical material entries. When you wish to search for a particular optical component, often a good starting point is to use the official name of the component function in *Rayica*, such as **PlanoConvexLens**. You can then use **SearchData** to do a search for this name to discover which other attributes are listed with it. You can then narrow your search further with some of these attributes. It is good idea to first limit the total number of reported elements with **ReportedInterval**. Otherwise, the reported number of entries can be overwhelming. Here is a description of **ReportedInterval**.

> **ReportedInterval** is an option that restricts the total number of items getting reported by a function.

In general, **ReportedInterval** can take several different formats. **ReportedInterval ->** *reportednumber* indicates an upper limit to the number of items getting reported. **ReportedInterval -> {**startnumber, endnumber**}** gives both lower and upper bounds to the number of items getting reported. **ReportedInterval -> Interval[**{min, max}**]** can also be used. In the next example, we use **ReportedInterval->3** to limit the length of the result to 3 elements. In this particular search, we will use **PlanoConvexLens** to seek out database entries that relate to plano-convex lenses.

```
In[68]:= SearchData[PlanoConvexLens, ReportedInterval->3]

Out[68]= {{CatalogNumber → 34-2949, CenterThickness → 3.4, CompanyName → Coherent-Ealing,
    ComponentBoundary → 12.7, ComponentLabel → plano-convex lens,
    ComponentMedium → Quartz, Date → {1999, 4, 18}, DesignRefractiveIndex → 1.45843,
    DesignWaveLength → 0.5876, FileName → CoherentEaling.m, FocalLength → 25.37,
    OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {11.63, ∞},
    SurfaceBoundary → {12.7, 12.7}, SurfaceSeparation → {3.4, 0}},
   {CatalogNumber → 34-2964, CenterThickness → 2.7, CompanyName → Coherent-Ealing,
    ComponentBoundary → 12.7, ComponentLabel → plano-convex lens,
    ComponentMedium → Quartz, Date → {1999, 4, 18}, DesignRefractiveIndex → 1.45843,
    DesignWaveLength → 0.5876, FileName → CoherentEaling.m, FocalLength → 38.06,
    OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {17.45, ∞},
    SurfaceBoundary → {12.7, 12.7}, SurfaceSeparation → {2.7, 0}},
   {CatalogNumber → 34-2972, CenterThickness → 7., CompanyName → Coherent-Ealing,
    ComponentBoundary → 25.4, ComponentLabel → plano-convex lens,
    ComponentMedium → Quartz, Date → {1999, 4, 18}, DesignRefractiveIndex → 1.45843,
    DesignWaveLength → 0.5876, FileName → CoherentEaling.m, FocalLength → 38.06,
    OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {17.45, ∞},
    SurfaceBoundary → {25.4, 25.4}, SurfaceSeparation → {7., 0}}}
```

In general, you can use many different formats for conducting a search in the *Rayica*'s database. Such formats include: strings, rules, lists of numbers, and symbols. In this past example, we have searched for the **PlanoConvexLens** symbol. We could have instead searched for **RayicaFunction -> PlanoConvexLens**. However, this turns out to be unnecessary since **PlanoConvexLens** is only used with the **RayicaFunction** in the database. From this result, we can see that there are about 15 separate *parametername*s available for the **PlanoConvexLens** entry. We can now decide on the top 2 or 3 most important *parameternames* for a more specialized search. For example, we can search for specific values of **ComponentBoundary** and **FocalLength**:

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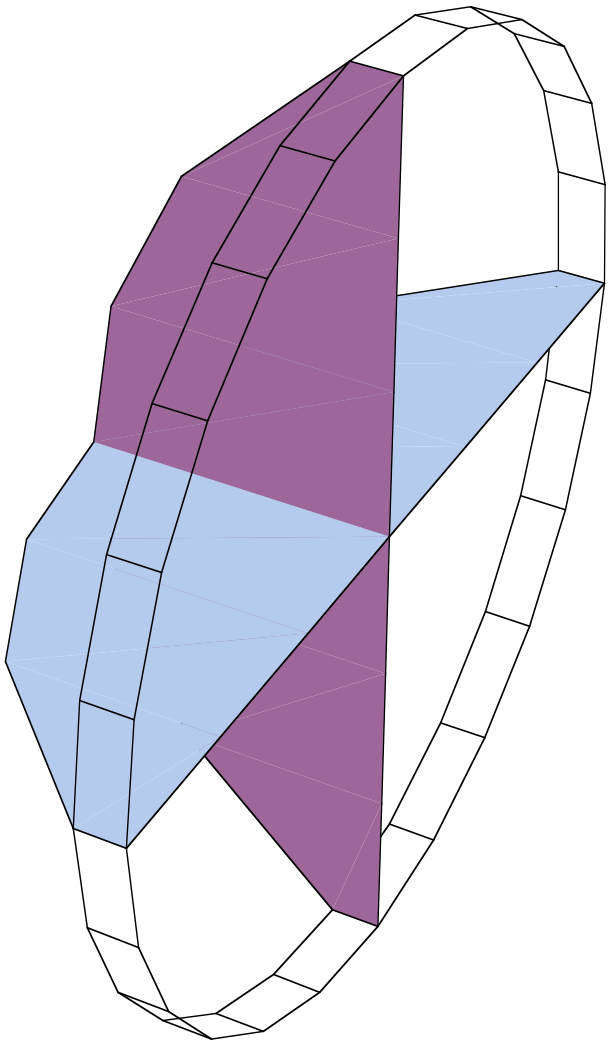
```
In[73]:= SearchData[PlanoConvexLens, ComponentBoundary->50, FocalLength->65]

Out[73]= {{BackFocalLength → 53.9, CatalogFocalLength → 65., CatalogNumber → FPX11700/000,
    CenterThickness → 16.2, CompanyName → JML, ComponentBoundary → 50.,
    ComponentLabel → PlanoConvexLens, ComponentMedium → Quartz, Date → {1999, 4, 18},
    DesignWaveLength → 587.6, EdgeThickness → 2.6, FileName → JML.m, FNumber → 1.3,
    FocalLength → 65., OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {29.8, ∞},
    SurfaceBoundary → {50., 50.}, SurfaceSeparation → {16.2}, V1H1 → 0, V2H2 → -11.1}}
```

In this particular case, *Rayica* has isolated a single database entry that perfectly matches the desired parameters. At this point, we can call **DataToRayica** to create the chosen component in *Rayica*.

```
In[25]:= lens  = DataToRayica[PlanoConvexLens, ComponentBoundary->50, FocalLength->65]
         ShowSystem[lens];

Out[25]= PlanoConvexLens[65., 50., 16.2, {ComponentMedium → Quartz, DesignWaveLength → 0.5876}]
```



In other cases, when more than one match exists, *Rayica* will recover the closest matches that fit within a certain tolerance. In this next example, *Rayica* finds six close candidates.

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```
In[74]:= SearchData[PlanoConvexLens, ComponentBoundary->50, FocalLength->75]

Out[74]= {{CatalogNumber → LQF066, CenterThickness → 13.8, CompanyName → MellesGriot,
    ComponentBoundary → 50., ComponentLabel → OpticalQualityPlanoConvex,
    ComponentMedium → FusedSilica, Date → {1999, 4, 18}, DesignRefractiveIndex → 1.46008,
    DesignWaveLength → 0.5461, FileName → Melles.m, FocalLength → 75.0089,
    OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {34.51, ∞},
    SurfaceBoundary → {50., 50.}, SurfaceSeparation → 13.8},
   {CatalogNumber → LQP005, CenterThickness → 13.8, CompanyName → MellesGriot,
    ComponentBoundary → 50., ComponentLabel → UVGradePlanoConvex,
    ComponentMedium → FusedSilica, Date → {1999, 4, 18}, DesignRefractiveIndex → 1.46008,
    DesignWaveLength → 0.5461, FileName → Melles.m, FocalLength → 75.0089,
    OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {34.51, ∞},
    SurfaceBoundary → {50., 50.}, SurfaceSeparation → 13.8},
   {CatalogNumber → PCX45246, CenterThickness → 11., CompanyName → EdmundScientific,
    ComponentBoundary → 50., ComponentLabel → PlanoConvex, ComponentMedium → BK7,
    Date → {1999, 4, 18}, DesignRefractiveIndex → 1.51678, DesignWaveLength → 0.588,
    FileName → Edmund.m, FocalLength → 75.0027, OpticaFunction → PlanoConvexLens,
    RadiusOfCurvature → {38.76, ∞}, SurfaceBoundary → {50., 50.}, SurfaceSeparation → 11.},
   {BackFocalLength → 66.3, CatalogFocalLength → 75., CatalogNumber → FPX11730/000,
    CenterThickness → 12.7, CompanyName → JML, ComponentBoundary → 50.,
    ComponentLabel → PlanoConvexLens, ComponentMedium → Quartz, Date → {1999, 4, 18},
    DesignWaveLength → 587.6, EdgeThickness → 1.9, FileName → JML.m, FNumber → 1.5,
    FocalLength → 75., OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {34.38, ∞},
    SurfaceBoundary → {50., 50.}, SurfaceSeparation → {12.7}, V1H1 → 0, V2H2 → -8.7},
   {BackFocalLength → 67.5, CatalogFocalLength → 75, CatalogNumber → CPX10195/100,
    CenterThickness → 11.4, CompanyName → JML, ComponentBoundary → 50,
    ComponentLabel → PlanoConvexLens, ComponentMedium → BK7, Date → {1999, 4, 18},
    DesignWaveLength → 632.8, EdgeThickness → 2.2, FileName → JML.m, FNumber → 1.5,
    FocalLength → 75, OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {38.63, ∞},
    SurfaceBoundary → {50, 50}, SurfaceSeparation → {11.4}, V1H1 → 0, V2H2 → -7.5},
   {CatalogNumber → 43-0462, CenterThickness → 11.6, CompanyName → Coherent-Ealing,
    ComponentBoundary → 50., ComponentLabel → 43-0462 PLANO-CONVEX PlanoConvexLens,
    ComponentMedium → BK7, Date → {1999, 4, 18}, DesignRefractiveIndex → 1.5168,
    DesignWaveLength → 0.5876, EntrancePupilDiameter → {45.}, FileName → CoherentEaling.m,
    FocalLength → 75.0003, GlassCatalogs → {SCHOTT, MISC, INFRARED},
    OpticaFunction → PlanoConvexLens, RadiusOfCurvature → {38.76, ∞},
    StopPosition → 1, SurfaceBoundary → {50., 50.}, SurfaceCurvature → {0.0257998, 0.},
    SurfaceLabel → {SphericalShape, SphericalShape}, SurfaceSeparation → 11.6}}
```

With so many reported entries, the **SearchData** results can get to be confusing. In order to clarify the important information, you can use **ReadData**, instead of **SearchData**, in order to view isolated parameters from the data base search. We will now use **ReadData** with the same parameter search as before:

```
In[75]:= ReadData[{ComponentBoundary, FocalLength, CatalogNumber}, PlanoConvexLens,
          ComponentBoundary->50, FocalLength->75]
```

Out[75]//DisplayForm=

ComponentBoundary	FocalLength	CatalogNumber
50.	75.0089	LQF066
50.	75.0089	LQP005
50.	75.0027	PCX45246
50.	75.	FPX11730 / 000
50	75	CPX10195 / 100
50.	75.0003	43 - 0462

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From this information, we can see that two items actually match up perfectly with the desired parameters. We can now place the **CatalogNumber** from our favorite result in **DataToRayica** to define an actual lens in *Rayica*.

```
In[27]:= lens = DataToRayica["FPX11730/000"]

Out[27]= PlanoConvexLens[75., 50., 12.7, {ComponentMedium → Quartz, DesignWaveLength → 0.5876}]
```

In some instances, there may not be any suitable match with a database entry. In such cases, an empty list is returned.

```
In[39]:= SearchData["nothing"]

Out[39]= {}

In[38]:= DataToRayica["nothing"]

Out[38]= {}
```

You can learn more about *Rayica*'s database system in Chapter 5.

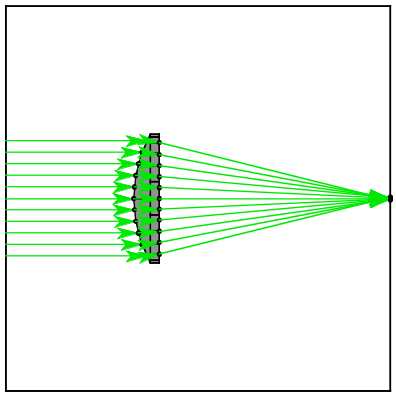
20. The TransferTraits Function

One of the most recent additions to *Rayica*'s constellation of high-level functions is **TransferTraits**. **TransferTraits** offers the user a powerful way to quickly customize a built-in optical component by transferring some of the characteristics from a second component.

> **TransferTraits[***donor-component*, *recipient-component*, *surfacenumbers*, *opts***]** is a function that transfers the surface traits of a donor component surface into the surfaces (specified by *surfacenumbers*) of a recipient component.

As an example, lets change the behavior of a plano-convex lens.

```
In[10]:= lens = Move[PlanoConvexLens[100,50,10],50];
         AnalyzeSystem[{
             LineOfRays[45,NumberOfRays->11],
             lens,
             Boundary[150]},PlotType->TopView];
```



We can now use **TransferTraits** add a reflective surface onto the first surface of the lens by transferring these traits from a simple mirror.

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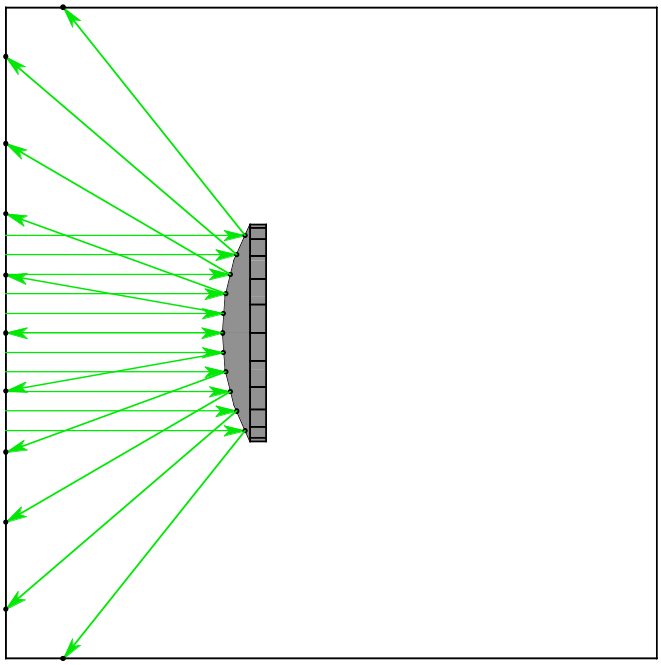
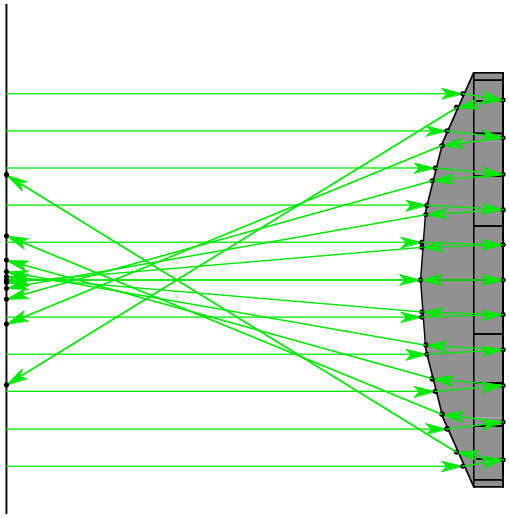
```
In[12]:= mirror = Mirror[50];
         AnalyzeSystem[{
             LineOfRays[45,NumberOfRays->11],
             TransferTraits[mirror,lens,{1}],
             Boundary[150]},PlotType->TopView];
```



We can instead add the reflective behavior of a mirror onto the second surface of the lens by using **{2}** instead of **{1}** for the surface number specification.

```
In[11]:= AnalyzeSystem[{
             LineOfRays[45,NumberOfRays->11],
             TransferTraits[mirror,lens,{2}],
             Boundary[150]},PlotType->TopView];
```



Furthermore, by rotating the mirror slightly first, **TransferTraits** will transfer not only the reflective characteristic of the mirror, but also the amount of rotation imposed on the mirror surface.

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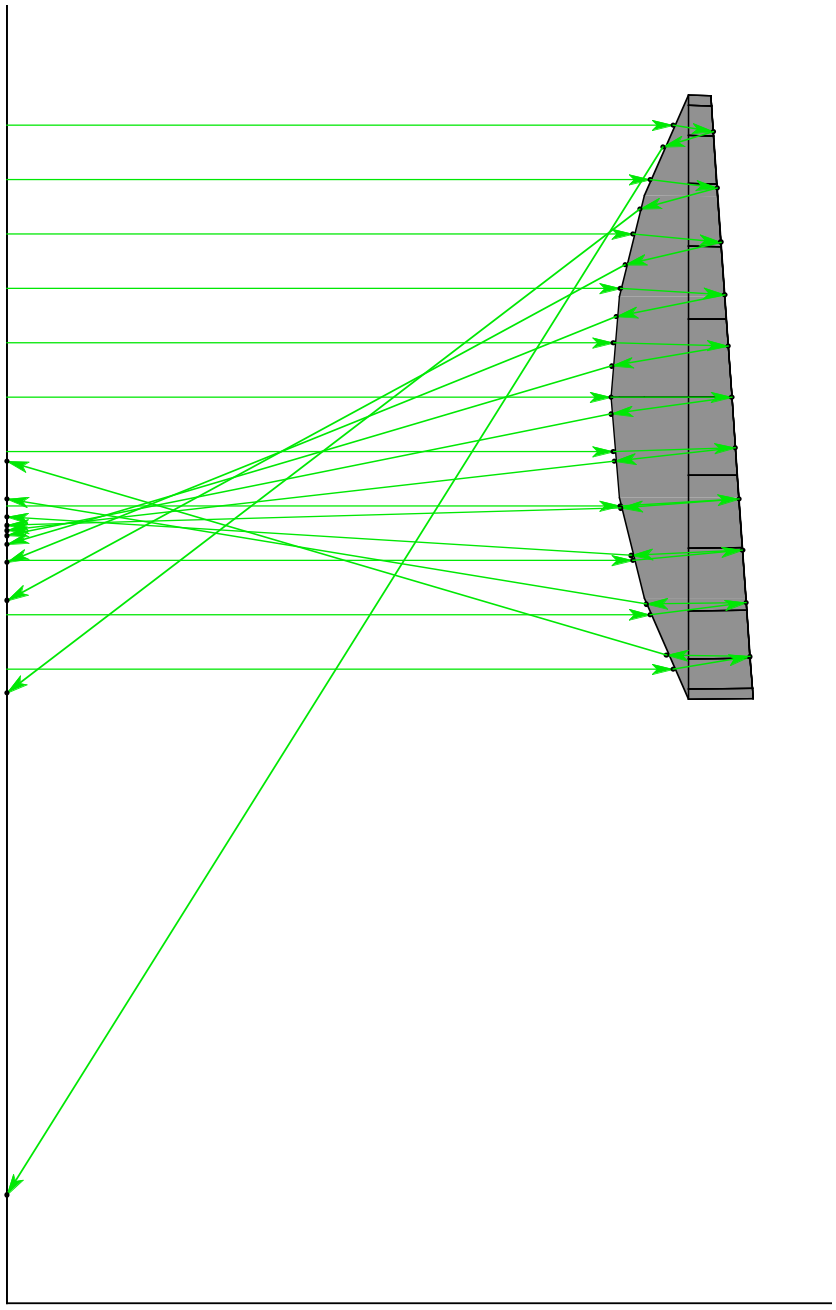
```
In[9]:= AnalyzeSystem[{
            LineOfRays[45,NumberOfRays->11],
            TransferTraits[Move[mirror,0,4],lens,{2}],
            Boundary[150]},PlotType->TopView];
```



If the donor component contains more than one surface, then only the traits from a single surface (specified by the **DonorSurfaceNumber** option) will be used. In general, the *surfacenumbers* parameter of **TransferTraits** can pass either: a list of integers, **First**, **Last**, or **All** as a setting. **TransferTraits** uses the options: **TransferSurfaceFunction**, **TransferDeflectionFunction**, **TransferRendering**, and **DonorSurfaceNumber**.

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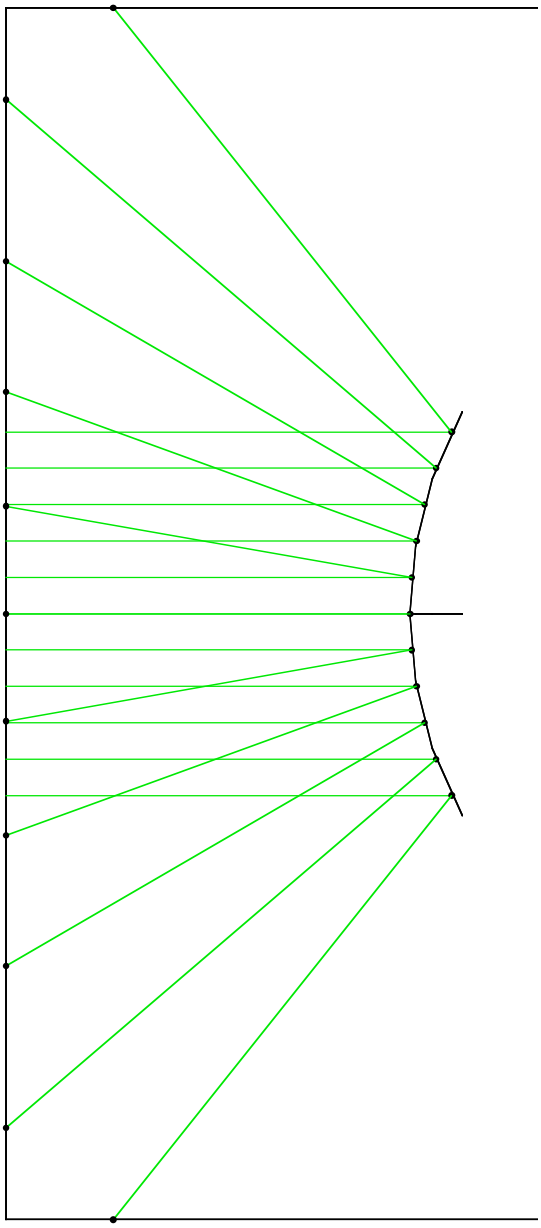
TransferTraits works equally well with both **AnalyzeSystem** and **TurboPlot** ray-trace functions. Here is an example using **TurboPlot**. This time, however, we will make the lens a donor and transfer its shape characteristics to the mirror by using the **TransferSurfaceFunction->True** option setting. This time, however, we will use **TransferDeflectionFunction->False** in order to not transfer the optical properties of the lens (keeping the mirror reflective).

```
In[15]:= TurboPlot[{
            LineOfRays[45,NumberOfRays->11],
            TransferTraits[lens, mirror, {1}, TransferSurfaceFunction->True,
            TransferDeflectionFunction->False],
            Boundary[150]},PlotType->TopView];
```



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21. What's Missing?

This section provides a road map of the features missing from either the User Guide discussion or the basic *Rayica* package as a whole. The User Guide discussion has been designed to help the novice user become familiar with the basic features in *Rayica*. In some instances, in order to avoid overwhelming the user with the more specialized capabilities of *Rayica*, some topics have been omitted from this discussion. In other instances, certain aspects of optical modelling have not been included in the basic *Rayica* package, but have instead been incorporated into extensions of *Rayica*. Finally, there can be occasions when a feature is not yet built into the *Rayica* system. This section will help you to determine the status of any particular feature not discussed previously in the User Guide discussion. If you should discover that a desired feature is missing from *Rayica*, then please contact optica support and let us know about it. We will try our best to help you to find an appropriate solution to your modelling problem. In addition, Optica Software offers a consulting service for custom solutions in *Rayica*.

Features not discussed here

The User Guide discussion does not discuss every feature present in *Rayica*. In particular, there has been no mention about the modelling of: optical coatings, polarized elements/polarization ray-tracing, bi-refringence, diffraction gratings, customized optical elements, or user-defined surface shapes. Nevertheless, all of these capabilities are a part of the basic *Rayica* package and is documented further in the companion Principles Of Rayica guide as well as through our website: www.opticasoftware.com.

The basic package also includes special functions for importing data from other ray-trace packages such as Zemax and Code V. Using *Mathematica*'s **`Import`** function, you can also import and export some data formats between mechanical CAD packages and *Rayica*. You can also build new refractive material models and create your own new deflection models with the same mechanisms that enable *Rayica* to model refraction, reflection, and diffraction on optical surfaces. You can model new optical components from scratch with the generic building block language used by *Rayica* to model its built-in component functions. There is also a built-in facility to model bulk material effects such as gain and absorption, as well as user-created bulk material behaviors such as photon diffusion and graded-index refraction. The *Rayica* database is also fully extensible and *Rayica* provides special functions to help you add your own database items. Unfortunately, the complete coverage of the every aspect of *Rayica*'s capabilities is simply too vast to mention within a single introductory discussion or even within the scope of a basic user manual. It is the expectation of the author that *Rayica*'s documentation will, by necessity, be an on-going endeavor that is continually updated as a result of feedback from the *Rayica*-user community. For this purpose, a new Optica Software web-site (www.opticasoftware.com) has been erected to provide on-line documentation, additional examples, up-to-date software, and advanced technical support.

Features not covered in the basic package

It is important to consider which features are not built into the basic *Rayica* package. In particular, Rayica does not model the following: wave-front propagation, coherent point spread functions, analytical solutions to optical systems, and Gaussian optics/paraxial analysis. Although *Rayica* can model diffraction gratings, its does not model diffractive behavior in general. These items are instead a part of a separate package, called *Wavica*. In the future, *Rayica* and *Wavica* may be combined into a single package, but at the moment, they are distributed separately (although they work together seamlessly). The basic *Rayica* system is therefore limited to three-dimensional, geometric ray-trace calculations, intensity measurements, publication illustrations, and optimizations. However, *Rayica*'s geometric results do contain information about the optical path length and, from this, it is possible to calculate the optical phase information on a surface. (This is demonstrated in Section 3.6.3 of the Principles of *Rayica* Guide.) However, since this is not the main focus of the basic *Rayica* package, in general, such efforts will be left to Wavica. Instead, most of the topics and examples given in this User's Guide will concentrate on the use of *Rayica* for endeavors that involve geometric ray-trace calculations.

In addition to *Wavica*, there are several other extensions for *Rayica* either being planned or presently developed. At the time of this writing, there are three additional extensions to *Rayica* under consideration. These are: global optimization, distributed ray-tracing on networked computer systems, and a laser design package.

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Features left to the future

Until now, all parts of *Rayica* and its extensions have utilized ray-trace calculations for some aspect of its package function. Unfortunately, this has left out some important optical design tools, which, for example, depend heavily on coupled-wave theory or finite element analysis. Such applications include thin film design and integrated optics/ optical waveguides. Until now, we simply haven't had the time and resources to development these important tools. In general, we always welcome possible collaborations with scientists and engineers that could lead to such applications in *Mathematica*.

Finally, some of *Rayica*'s present limitations are due to the current state of *Mathematica*. In particular, *Mathematica* does not yet have a simple, built-in facility to generate stand-alone Java or C-code. Once available, this will enable high-speed ray-trace capabilities that are on par with every other optical design package on the market. In addition, *Mathematica* is still missing an interactive, graphical user interface capability. However, once such features do become available in *Mathematica*, we have already prepared *Rayica* to take advantage of them. In the near future, it is likely that *Rayica* and *Wavica* will be packaged together with a custom *Mathematica* engine to permit a single integrated optical design product that has wider appeal to non-*Mathematica* users.

22. Backward Compatibility Issues

The new *Rayica* system has been rebuilt from the ground up. As a consequence, users of the original *Optica* will notice some important changes in the basic functional behavior of *Rayica*, such as the use of **Source** objects to model light sources. Such changes have resulted in many important new capabilities for *Rayica*. While many of the changes in functional behavior have already been discussed in the User Guide presentation, there have also been some important changes made to the input formats of certain functions in *Rayica* that have not been covered. In this section, we will examine some of these input format changes that may affect legacy code from *Optica* version 1. In general, such format changes have been made to simplify the usability of the affected functions. Perhaps the most important format changes have been with the **Move** functions. These changes to **Move** are discussed next.

Move3D is now obsolete

It is no longer necessary to use separate functions for three-dimensional positioning. In particular, **Move3D**, **MoveLinear3D**, **MoveDirect3D**, and **MoveReflected3D** functionalities have now been absorbed by the **Move**, **MoveLinear**, **MoveDirect**, and **MoveReflected** functions. However, the original **3D** functions will continue to be supported in the new *Rayica* edition.

Move[object, {x,y,z}] now works

There is a new pattern of **Move** called **Move[***object***, {***x***,***y***,***z***}]** that gives a simple three-dimensional translation. Unfortunately, this new pattern conflicts with an older pattern of **Move** and can create a legacy problem for some pre-existing system designs made in original *Optica* edition. This is explained further next.

Move[object, {x,y,angle}] has become Move[object, {x,y}, angle]

Move[*object***,{***x***,***y***,***rotationangle***}]** has now been superseded by **Move[***object***,{***x***,***y***},***rotationangle***]**. This change has been made in order to support the **Move[***object***,{***x***,***y***,***z***}]** format shown previously. Unfortunately, this has adverse implications for any legacy code that used **Move[***object***,{***x***,***y***,***rotationangle***}]**.

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How to recover version 1 behaviors

Some of *Rayica*'s new behaviors are irreversible. However, if you are interested to recover the original **Move** behaviors of Version 1, you can call **SetOptions** with **Move** as shown.

```
SetOptions[Move, RayicaVersion->1]
```

Here, the default setting is **RayicaVersion->2**. In order to recover many of the default option behaviors from the original *Optica* edition, including the original **Move** behaviors, you can call **SetOptions** with *Rayica* as shown.

```
SetOptions[Rayica,RayicaVersion->1]
```

New Function Name Alias: AnalyzeSystem for DrawSystem

Previous users of *Optica* will notice that the new version has adopted a new naming alias for **DrawSystem**.that is called **AnalyzeSystem**. Nevertheless, the original **DrawSystem** still exists and works the same as before. The only change in **AnalyzeSystem** is that the **Options[AnalyzeSystem]** contains a reduced subset of the **Options[DrawSystem]** in order to reduce option clutter.

New Parametric Surface Function Format

A new format can now be used to specify parametric surfaces in *Rayica*. While the original parametric format for *Rayica* required a distinct **Function** to specify each spatial coordinate direction, the new format embeds all three coordinates within a single **Function** head. In particular,

Function[{*s***,***t***},{***xcoordinate***[***s***,***t***],** *ycoordinate***[***s***,***t***],** *zcoordinate***[***s***,***t***]}]**

can now be used instead of

{Function[{*s***,***t***},***xcoordinate***[***s***,***t***]], Function[{***s***,***t***},** *ycoordinate***[***s***,***t***]], Function[{***s***,***t***},***zcoordinate***[***s***,***t***]]}**

New Grating Vector Format

There is a new coordinate order used to specify grating vectors in *Rayica*. The grating vector now has a different coordinate order that is more intuitive. In particular, **Function[{***s***,***t***},{***Gx***[***s***,***t***],** *Gy***[***s***,***t***],** *Gz***[***s***,***t***]}]** for grating functions and **{***Gx***,** *Gy***,** *Gy***}** for constant grating vectors are now used instead of **Function[{***s***,***t***},{***Gy***[***s***,***t***],** *Gz***[***s***,***t***],** *Gx***[***s***,***t***]}]** and **{***Gy***,** *Gz***,** *Gx***}**.

If you are interested to recover the original **Grating** behaviors of *Optica*, you can call **SetOptions** with **Grating** as shown.

```
SetOptions[Grating, RayicaVersion->1]
```

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