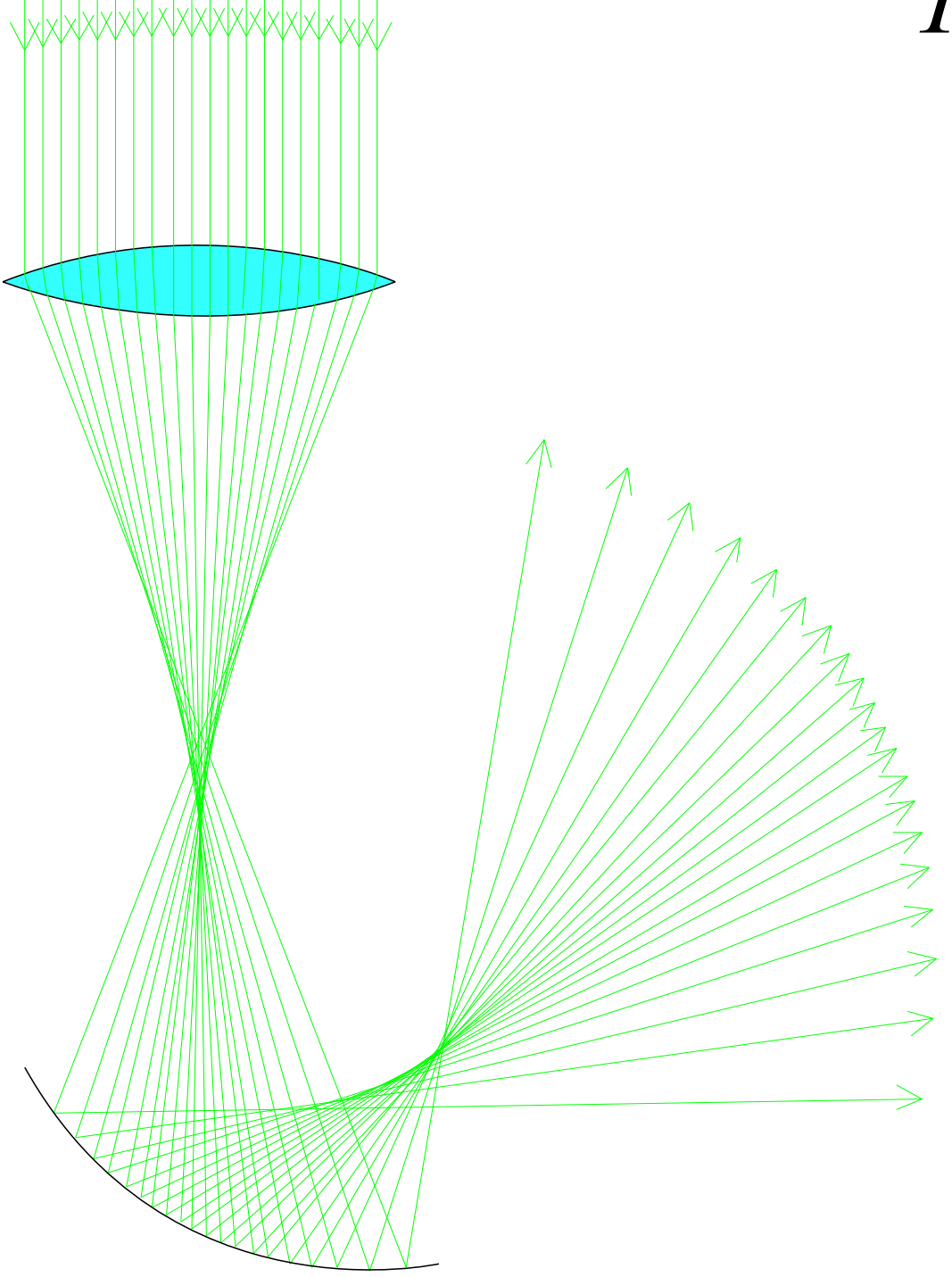
RAYTRACE

Tutorial



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Introduction

Welcome to Raytrace.

Raytrace is a powerful, interactive tool created specifically for the purposes of teaching geometrical optics and having fun while doing so. It is suitable for use at all levels by teachers and students alike and has many features which will allow students to extend the boundaries of their knowledge by exploring and experimenting. Optical designers will also find the program useful for rapidly testing out ideas and for producing a range of final designs.

The purpose of this manual is to get you started with Raytrace as quickly as possible. It includes summary information and step by step tutorial examples to help you master the key features of Raytrace. Not all features of Raytrace are covered in this manual and after you become more familiar with the operation of Raytrace you will find it useful to browse the Raytrace Reference Manual which discusses all the menu items in some detail. For installation instructions consult the Raytrace Reference Manual. For information on creating interactive scripts or demonstrations consult the RayScript Reference Manual.

Whatever your background, begin with the first section “Essential reading for a quick start”.

Essential reading

If you are not feeling very confident, read this section then skip to the first example "**Reflection and refraction by a rectangular prism**". After this, you might then like to come back and read the section, "**Summary information for a quick start**". You can then decide whether to work through more of the tutorial examples or branch out on your own.

If you are like the author and want to jump in and try Raytrace out as quickly as possible read this section and the following "**Summary information for a quick start**". It will tell you the basics and where to find additional information on some topics.

Conventions used in Raytrace manuals

Menu items are referred to using the notation:

Menu name -- item name

for example: **File -- Save As**.

In the case of further levels of popup menu the notation

Menu name -- popup name > item name

is used, for example: **Edit -- Select All > Rays**

Any actions which you should actually perform to complete an example are indicated by an asterisk, indentation and a different font, e.g.

* Perform this action

Comments and actions which may be of interest but which distract from the main commentary within examples are indicated in italics, e.g.

This comment may be of interest but will distract you from the main purpose here...

* *This action may also be of interest but will distract you as well...*

Using the mouse with Raytrace

Primary mouse button

This is what most people call the left mouse button. In Windows you can swap the action of the left and right buttons. Primary mouse button refers to the button which you would normally use to choose menu items in Windows applications.

Secondary mouse button

This is what most people call the right mouse button. See above.

Clicking mouse buttons

In many Windows applications you are required to hold the mouse button down while you drag the mouse in order to move an object. Except when choosing from a popup menu or using scroll bars (where holding the mouse button down is a Windows option) this is never the case in Raytrace. When a phrase like "click the mouse button" is used it means "click and release the mouse button. You begin operations in Raytrace with a single click and release of the mouse button and you complete the operation with another click and release.

There are basically three reasons why Raytrace does not use the "click and drag while holding" method commonly found in other applications:

- You will often need to use the primary mouse button to select from a popup menu which is activated by the secondary mouse button while you are dragging an object; if you have ever tried to click the secondary mouse button while holding down the primary mouse button you will find it quite awkward!

- It can sometimes take a while for Raytrace to calculate ray paths and update the diagram while you are dragging objects about - if you had to hold the mouse button down all the time this could be annoying.

- One of the intended uses for Raytrace is as a lecture demonstration tool; not having to hold the mouse button down frees you to move about or wave both hands at any stage during a drag without having to stop and re-start the operation.

Double clicking mouse buttons

Raytrace does not make use of double clicks except when choosing an item from a list box where you can choose an item and complete the operation with a double click rather than using a single click and then clicking on **Ok**.

Switching applications

In Windows you can switch between applications by positioning the cursor within the application window and clicking a mouse button. If you use this method to switch into the Raytrace application, the mouse click that switches to Raytrace does not perform any other action within Raytrace. So if you are switching between applications and nothing happens when you click on the mouse button in Raytrace, try clicking again.

Undo: The most important feature!

You will be a truly remarkable person if you manage to get everything "just right" the first time you try in Raytrace! However, don't despair and don't be afraid to try things out; if something goes wrong then the menu item **Edit -- Undo** can reverse up to the last five operations that you have performed. It can even reverse exiting without saving your diagram - simply restart Raytrace and immediately choose **Edit -- Undo** to bring back a diagram you forgot to save.

If your computer lacks a maths co-processor

Without a co-processor you may find that the time required to calculate all the ray paths becomes significant - particularly for more complex diagrams involving curved surfaces and many rays. If your computer lacks a maths co-processor then Raytrace should notify you of this when it starts. Unless you tell Raytrace otherwise, it will automatically uncheck the menu items **Options -- Update on Ray Drag** and **Options -- Update on Element Drag**. This will stop updating of the ray diagram while you drag parts of it about so you will not be able to make use of the animation capabilities of Raytrace. You can try re-checking these menu items and decide for yourself if the speed is adequate.

Summary information for a quick start

This section contains a brief summary of information which will allow you to make a good start in using Raytrace. If after reading this section you feel confident at “having a go” and experimenting a little, you will probably not need to refer to the tutorial examples. Some of the information presented here is duplicated elsewhere in either this manual or the Raytrace Reference Manual.

Elements

This section gives you a very brief introduction to creating elements. Specific examples are given in the tutorials in this manual and some additional information is contained in the Raytrace Reference Manual.

An element in Raytrace is any one of:

- A refracting region
- A reflecting surface
- A shape which does not interact with rays in any way
- A screen which stops all rays except for projected rays
- A par-axial mirror which approximates spherical mirrors
- A thin lens, either converging or diverging, which obeys standard thin lens approximations
- An iris which acts like a variable width aperture

You create these elements using the **Create -- Element > xxx** menu items (where **xxx** depends upon the type of element.

Region, surface, shape and screen elements

These are all created in the same manner - as a sequence of line, arc and conic segments. Once you have drawn all the segments in one of these element use the **Create -- Element > Finish element** menu item to complete the element; region elements will be closed automatically by a line segment joining the last vertex defined to the starting vertex.

Changing segment types

The default segment type whenever you start drawing an element is a straight line. You switch between line, arc and conic segments by clicking on the secondary mouse button and choosing one of the **Line segment**, **Arc segment** or **Conic segment** items from the popup menu.

Line segments are straightforward; just select the end of the segment.

Arcs require two points to be selected and there are three options for what the points are. The default method when Raytrace starts is called the **End/Tangent** method and you should probably use this for most cases. To use this you first select the end point of the arc chord then you select a point which indicates the direction of the tangent to the arc from the start point. This allows you to define any arc with the specified chord. If you want to use the other methods for creating arcs, they are invoked from a second level menu under the **Circular arc** item (once it is checked) in the popup menu.

Conics are somewhat more complicated and If you want to use conic segments then work through the tutorial example “Introduction to conics”.

Undoing a mistake

If you make a mistake on any segment when creating one of these elements either:

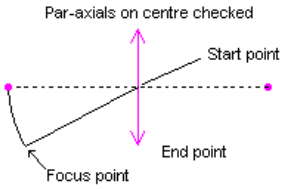
- Press the **U** key to undo the last segment. Repeatedly pressing **U** will undo all the way back to the first segment if you want.
- Choose **Create -- Element > Undo segment**.
- Click on the secondary mouse button and choose **Undo segment** from the popup menu.

Par-axial mirror and thin lens elements

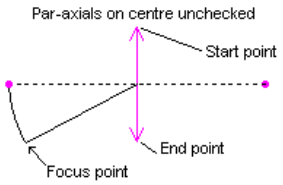
These are all created in a similar manner. After choosing the appropriate **Create -- Element >** menu item you must select three points:

- The starting point
- An end point which defines the orientation and size of the element's aperture (height of the lens or mirror)
- A focus point which defines the focal length of the element.

How the starting point is used depends on the on whether the menu item **Create -- Par-axials on centre** is checked or not. If it is checked, the starting point will be the centre of the lens or mirror and the end point will be one end of the lens or mirror aperture. If it is not checked then the starting point will be one end of the lens or mirror aperture and the end point will be the other end. In both cases the relative orientation of the start and end points sets the plane of the lens aperture.



The focal length is set to the distance between the mid point of the aperture and the point you choose as the focus point regardless of the orientation of where you select the focus point with respect to the lens aperture.

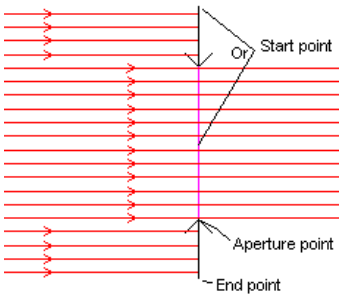


Iris elements

These are defined in a similar manner to par-axial elements. After choosing **Create -- Element > Iris** you must select three points:

- The starting point
- An end point
- An aperture point

The use of the starting and end points is affected by the **Create -- Par-axials on centre** menu item in the same manner as discussed above for par-axial elements. The aperture point defines the size of the opening in the iris. In a similar manner to the par-axial elements, the size of the opening is set to the distance between the mid-point of the iris and the point you select.



Aborting an element creation

If you start creating any type of element by mistake and want to abort the whole operation then either:

- Press the **ESC** key.
- Choose **Create -- Element > Cancel**.
- Click on the secondary mouse button and choose **Cancel** from the popup menu.

Removing an unwanted element

You can delete an element (or any other object for that matter) by selecting it (see one of the following sections) and then either press the **Del** key or choose **Edit -- Delete**.

Creating rays

You start creating one or more isolated rays by choosing **Create -- Ray** and then selecting the start and end points for each ray. When you have created all the rays you want, either press **ESC** or click on the secondary mouse button and choose **Finished** from the popup menu.

Sources (groups of rays)

You create sources using either **Create -- Source > Point** or **Create -- Source > Plane**. There is detailed information on how to define the orientation of sources and to modify sources in various ways in the

reference manual under the section on the menu items just mentioned and under the menu item **Modify -- Source >**. The information presented here is a brief guide to get you started quickly.

A point source

After choosing **Create -- Source > Point** enter the number of rays when prompted then select three points. The first is the centre from which the rays radiate. The next two define an "aperture" through which the rays will fan out. Try creating a point source without any elements in the diagram to get the feel of this.

A plane source

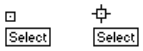
After choosing **Create -- Source > Plane** enter the number of rays when prompted then select three points. The first two points in combination define the direction in which the rays will point. The second and third points in combination define the "aperture" through which the rays will pass. Try creating a plane source without any elements in the diagram to get the feel of this.

Selecting objects

In Raytrace you "select" an object by clicking on it with the primary mouse button. Once an object is selected you can perform various operations on it either directly with the mouse or using menu items. For example, you can select a refracting element and change its refractive index or change its shape. You can have more than one object selected at a time if necessary.

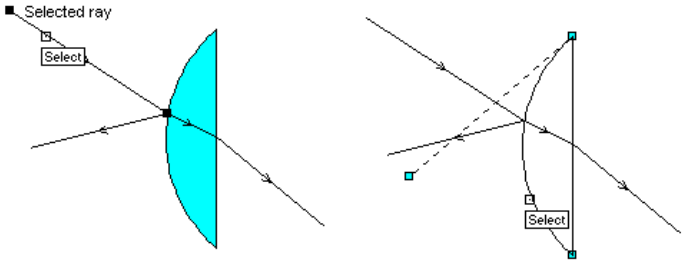
You can select objects whenever the cursor appears in either of the two forms shown here. The small box with the dot in the middle is called the **select box**. The second form of the cursor with the additional cross arms on the select box indicates that **Options -- Snap to grid** is checked. It is generally better not to try selecting objects when the snap to grid option is on.

To select an object, position the select box so that part of the object that you want to select appears inside the box and click the primary mouse button.



On the left below, a ray has been selected by clicking the primary mouse button with the cursor in the position shown. On the right, the element has been selected by clicking with the select box on the element's outline. Clicking within the enclosed coloured region of the element does not select the element.

When an object is selected, "drag handles" (small squares) will be drawn at certain points on the object. As



shown above drag handles are drawn at both ends of selected rays. For elements, the drag handles are drawn at all vertices and any other points which are used in defining the shape of the element.

All objects that cross the select box are selected when the primary mouse button is clicked.

To select two or more separated objects, select the first object then hold the control key down while selecting the other object(s). Another method for selecting many objects in one operation is to choose **Edit -- Select extended**. This allows you to select all objects that cross a rectangular region. After choosing **Edit -- Select extended**, click with the primary mouse button where you want one corner of the rectangular region then drag out the rectangle and click at the other corner.

To clear the selection, click on the primary mouse button with the select cursor over a blank area of the display (with the control key released).

To select tape measure, protractor or annotation objects you must position the select box over one of the lines that make up the object not over the text.

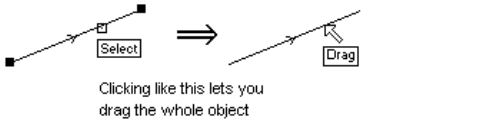
To select one object from several that are in close proximity you can use **Zoom -- In** to enlarge the region where you need to click to specify the object and then use **Zoom -- Previous** to reverse the zoom. Alternatively, you can press **Shift + F4** to enlarge an area around the cursor so that objects can be selected at the pixel resolution. Pressing **Shift + F4** a second time without clicking the mouse button removes the zoomed area.

Dragging

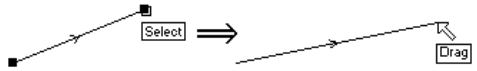
If you position the select box over an already selected object and click the primary mouse button then you will enter the drag mode and the cursor will change to the drag point form. The exception to this rule is if you click on a trail object; trail objects can be selected by they cannot be dragged.

If you click on the outline of a selected object away from a drag handle then you can move the whole object about.

If you click on the primary mouse button with the select cursor box positioned over a drag handle then you can drag that point to a new position.



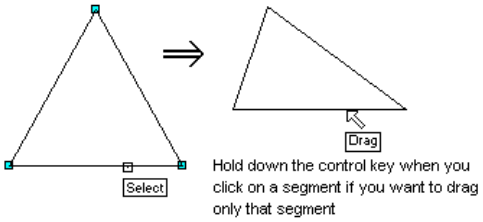
Clicking like this lets you drag the whole object



Clicking on a drag handle lets you drag that point

For elements, hold the control key down and click with the select box over a segment to drag only that segment rather than the whole element.

Raytrace will normally update the ray diagram as you drag a point or object about. However this may be unusably slow on computers without a co-processor so you can turn this off by unchecking **Options -- Update on Ray Drag** and **Options -- Update on Element Drag**.

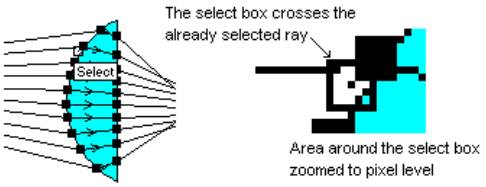


Hold down the control key when you click on a segment if you want to drag only that segment

For elements that have been grouped together using **Modify -- Element > Group**, dragging any one of the group will cause all the elements in the group to be dragged at the same time.

To move more than one object at a time, select all the objects and use **Modify -- Move**.

When selecting objects that cross, or are close together, be careful that you do not click on an already selected object as this will start dragging that object. For example, if you have selected all the rays in the diagram on the right and then want to select the element and clicked as shown, you would end up dragging the ray (or source if the rays came from a source).

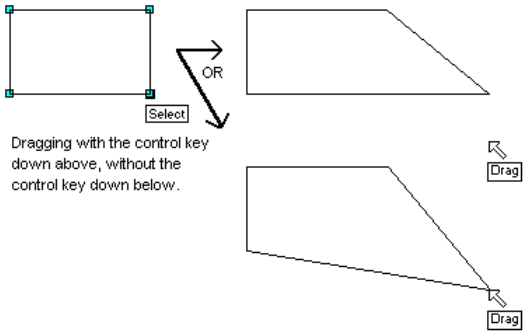


The problem could be avoided in this example by any one of:

- Choosing a better place to position the cursor when selecting the element.
- Selecting the element before selecting the rays (if you wanted both rays and elements selected).
- Using **Edit -- Select extended** to select the rays and element in one operation (again, if you want both selected).
- De-selecting the rays by clicking elsewhere in the diagram and then selecting the element (if you only wanted to select the element without the rays)
- Using **Shift + F4** to expand the area around the cursor position for finer resolution in selecting.

Ortho drag mode

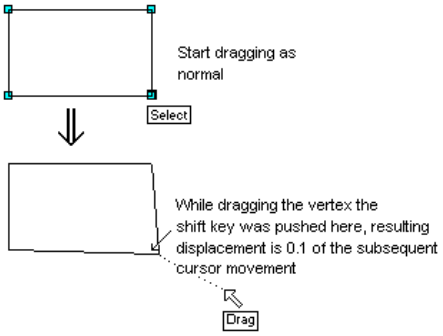
If you hold the control key down while dragging then the drag displacement will be forced to be either horizontal or vertical (whichever passes closest to the cursor position) relative to the point where the primary mouse button was last clicked. This mode can be used in conjunction with the fine drag mode mentioned below.



Use the Ortho drag mode as an alternative to the snap to grid to create line segments (or the chords/tangents of arcs etc.) that are vertical or horizontal.

Fine drag mode

If you hold the shift key down while dragging then the drag displacement (measured from the point where the shift key was pressed) is reduced by a factor of ten to allow fine dragging.



To stop dragging

To finish dragging, click the primary mouse button once.

When Raytrace is updating ray paths, an "hour-glass" appears in the cursor instead of the word “drag”. You can click the primary mouse button once while the hour-glass cursor is displayed and, when the calculations catch up with the mouse movement, the dragging will cease. Avoid clicking the mouse button more than once while the hour glass cursor is displayed because this re-starts the dragging operation and you will become increasingly frustrated!

Measuring tools

You can measure distances and angles using tape measures and protractors respectively. These are created using the menu items **Create -- Tape measure** and **Create -- Protractor** respectively. There is detailed information on how to use these tools in the reference manual under these menu items.

A question which sometimes arises is: "What are the units in Raytrace?". The answer is, that they are whatever you want them to be. You can think of a Raytrace "unit" as being a millimetre, centimetre, metre or even inches; whichever is most convenient for you.

Tape measures

To create a tape measure you simply need to select the two end points. Use **Modify -- Tape measures...** to change the options for tape measures that are selected.

Protractors

To create a protractor you must specify the centre point about which the angle is to be measured and then two points which define the “arms” of the protractor. Use **Modify -- Protractors...** to change the options for protractors that are selected.

Snapping

Snaps will be familiar to anyone who has used a computer aided design package. In Raytrace they serve two purposes:

- To enable you to precisely specify a point relative to some part of the ray diagram.
- To allow “linking” of some objects (sources, tape measures, protractors annotations, etc.) to points within the diagram so that when the diagram changes the linked objects are automatically moved or updated based on the new position of the specified points.

To make use of a snap, click the secondary mouse button once. For some operations this immediately presents you with a menu containing various types of snap. For other operations the snaps are listed in a second level popup which is accessible from the **Snaps >** item. Alternatively, snaps can be selected by a single key press, see the last page of this manual which lists the shortcut keys that can be used in Raytrace.

Snaps only act upon rays and elements and tape measures. You cannot snap to points on protractors, annotations or trails.

When a snap is active the cursor will change to a select box and a word indicating the type of snap. You position the select box over the point or object that you want to snap to. If more than one object crosses the select box then the snap will act on the object that was drawn or created first. Try and ensure that you position the cursor over only one object when using a snap to avoid any confusion.

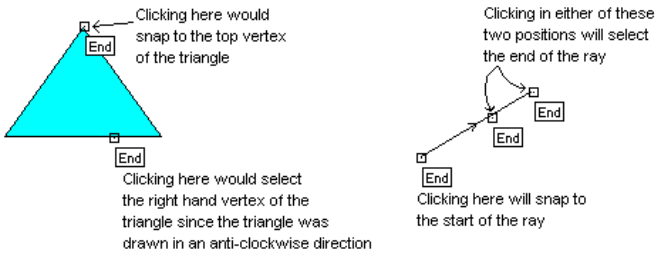
The object does not need to be selected for the snap to function; in some of the following illustrations the objects are shown as selected simply to indicate the position of some of the control points with the drag handles.

The remainder of this section introduces the different types of snaps and gives some examples of their use.

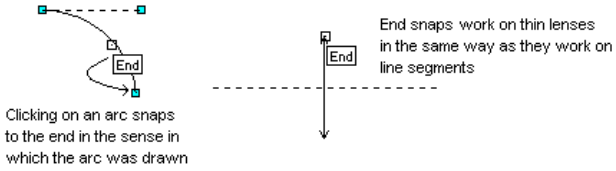
End snap

This snaps to either the end point that lies within the select box or to the end of the ray or segment that passes through the select box.

The end snap works on any type of segment: line, arc or conic and on the apertures of thin lens, par-axial mirrors and irises.

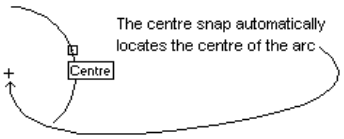


If you are not sure of the direction in which a segment was drawn then it is best to position the end select box over the end point that you want rather than over any part of the segment.



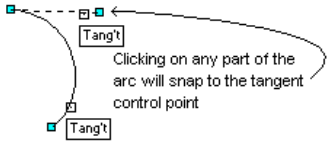
Centre snap

This snaps to the centre of an arc segment. You can position the centre select box over any part of the arc. If the tangent control point is co-linear with the start and end points of the arc then the centre snap will locate the mid-point of the line between the start and end points.



Tangent snap

This snaps to the tangent control point of the arc. The arc need not be selected, it is just shown that way here to indicate the position of the tangent control point.

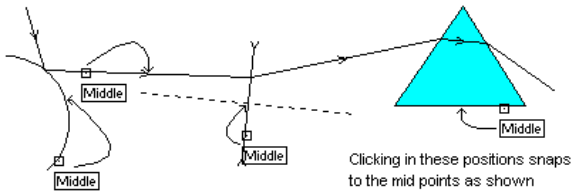


Mid point snap

This snaps to the middle of the ray, line or arc segment that is chosen.

The mid point snap works on thin lens and par-axial mirror elements and tape measures but does not work on conic segments.

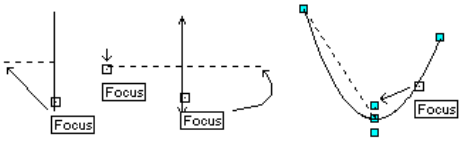
Focus snap



This snaps to the focal point of thin lens, par-axial mirrors and conic segments.

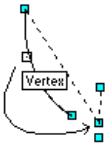
If you position the focus select box over a thin lens element then there is some ambiguity about which focus will be used. Raytrace resolves this by looking at the order in which the points defining the lens were specified. However you cannot tell how this will work by looking at the lens. To avoid confusion, position the focus select box over the actual focus point of the thin lens. There is no ambiguity with par-axial mirrors or conic segments so you can position the focus select box anywhere on these types of object.

Conic Vertex snap



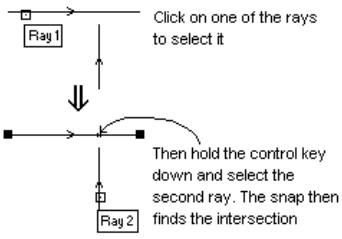
This snaps to the vertex of the conic segment (where the axis of the conic crosses the curve; indicated by a drag handle when the conic is selected). The vertex need not lie on the part of the segment that is drawn.

Ray Intersect snap

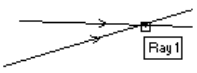


When you choose this type of snap you must specify the two rays whose intersection you want. When the cursor changes to the Ray 1 select form, select one of the rays. The cursor will then change to the Ray 2 select form. You must hold the control key down when you select the second ray. If you do not, then the ray you select with the Ray 2 cursor is taken as the first ray and the cursor will stay in the Ray 2 select form waiting for you to select another ray.

You can select both rays in the one operation if you position the Ray 1 select box so that it crosses both rays. However it must cross only two rays for this to work.



Ray intersections are the best way to locate image positions in a ray diagram.

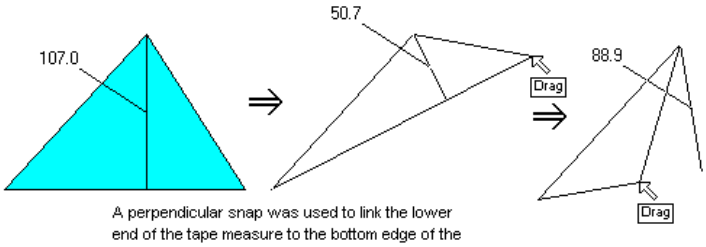


Clicking here would select the intersection of the rays in one operation

Clicking here would not succeed in finding the ray intersection because more than two rays would be selected

Perpendicular snap

Using this snap, you can make a tape measure or a protractor arm remain perpendicular to a line segment. For example, one end of the tape measure shown on the right has been linked to the upper vertex of the triangle and the other end to a perpendicular snap on the lower edge:



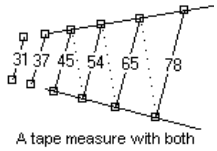
A perpendicular snap was used to link the lower end of the tape measure to the bottom edge of the triangle.

Perpendicular snaps work only on line segments of elements, rays or tape measures and not on arcs, protractors or conic segments.

A perpendicular snap obviously requires a point of reference in addition to the line segment to which it finds the perpendicular.

When a perpendicular snap is used, it bases the perpendicular on the last point at which the primary mouse button was clicked. However, when defining the end point of the second arm of a protractor or the second aperture point of a point source, Raytrace bases the perpendicular on the centre point of the protractor (or source) rather than the last mouse click.

It is possible to create a tape measure with one end linked to a perpendicular snap and then drag the other end of the tape measure and link it to another perpendicular snap. This will lead to a tape measure that shrinks with each update of the ray diagram as shown on the right. Eventually it will have zero length at the intersection of the two line segments involved in the perpendicular snaps. Avoid doing this!



A tape measure with both ends linked to perpendicular snaps

Terminal snap

A terminal snap acts on a ray and finds the end point of the final ray in its propagation path. In determining the final ray, Raytrace follows refractions and reflections from the selected ray (in that order of priority) at each boundary. This snap can be used to find where light finally strikes a screen regardless of the actual path taken to get there. For example, light might pass directly from a source through a lens to a screen or it might be reflected off a mirror then pass through the lens and strike the screen; a terminal snap used on one of the source rays will always find the end of the ray striking the screen.

Abs Coords snap

When you choose this type of snap a dialog box appears in which you can enter the Cartesian co-ordinates of the point you want. When Raytrace starts the co-ordinate origin is in the centre of the Raytrace window and one drawing unit is equivalent to one pixel spacing.

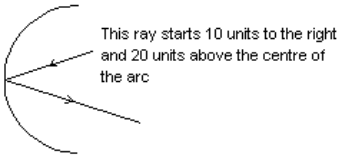
Rel Coords

This option allows you to specify a point as a displacement relative to some base point. When you choose this item the cursor changes to the base point form and you must select the base point - you can use a snap to do this if you want.

Once you have selected the base point, a dialog box appears and you enter either the Cartesian or polar displacement from the base point to the point you want to specify.
For example to specify the start point of the ray 10 units to the right and 20 units above the centre of the arc in the diagram at the right follow these steps:

* Choose **Create -- Ray** to start drawing the ray.

* Press **R** or click on the secondary mouse button and select **Rel Coords** to specify a relative coords snap.


This ray starts 10 units to the right and 20 units above the centre of the arc

The cursor will change to the base point form and you need to use a centre snap to specify the centre of the arc as the base point.

* Press **C** or use the secondary mouse button to specify a centre snap.

* Position the centre select box over the arc and click the primary mouse button.

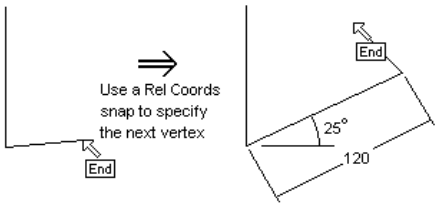
A dialog box will then appear with spaces to allow you to enter the displacement from the base point.

* Enter the relative displacement as either x,y coordinates or a radius and angle then click on **Ok**.

For polar displacements the angle is specified in degrees. Whenever you move between the edit boxes in this dialog box the x,y and radius,angle numbers are updated to be consistent.

The **Base = Previous point** button allows you to use the previous point at which the primary mouse button was clicked as the base point - over-riding the base point specified just before the dialog box started. You can use this, among other things, to draw elements where the co-ordinates of the vertices are specified relative to the previous vertex.

For example if you have drawn the first side of an element as shown on the right and want the second side to be 120 units long extending at an angle of 25 degrees to the horizontal you can use a relative coords snap.



After specifying the relative coords snap you must still select a base point to bring up the **Relative Displacement Entry** dialog but the point you pick is irrelevant - in response to the base point cursor simply click somewhere in the Raytrace window. When the dialog box appears press the **Base = Previous point** button and the base point co-ordinates in the dialog box will change to those of the last primary mouse button click (ignoring the click in response to the base point cursor), i.e. the last vertex specified. Enter the relative displacement and click on **Ok** to complete the operation.

Grid Snap

This snap option is slightly different to the others in that it does not specify a point relative to an object. A small cross is displayed in the cursor rather than a box. The point chosen is the grid intersection closest to the point at the centre of the small cross in the cursor. Using grid snap from the popup menu is the same as checking **Options -- Snap to grid** but it applies for only one point. A grid snap will always succeed; the grid does not have to be displayed. See: **Options -- Grid**, **Options -- Grid size...** and **Options -- Snap to grid** in the Raytrace Reference Manual for more information.

None

This is included to allow you to cancel an unwanted snap. If you select a snap and then decide that you want to choose the point freehand either press the **N** key or click on the secondary mouse button and select **None** to cancel the snap.

When snaps don't succeed...

When you specify a snap, Raytrace does not accept the selected point unless the snap is successful. For example, if you specify a centre snap and do not position the cursor over an arc segment when you click the primary mouse button then the snap is unsuccessful and the cursor remains in the centre select form. You can change to another type of snap or you can select **None** from the snap menu to return to freehand pointing.

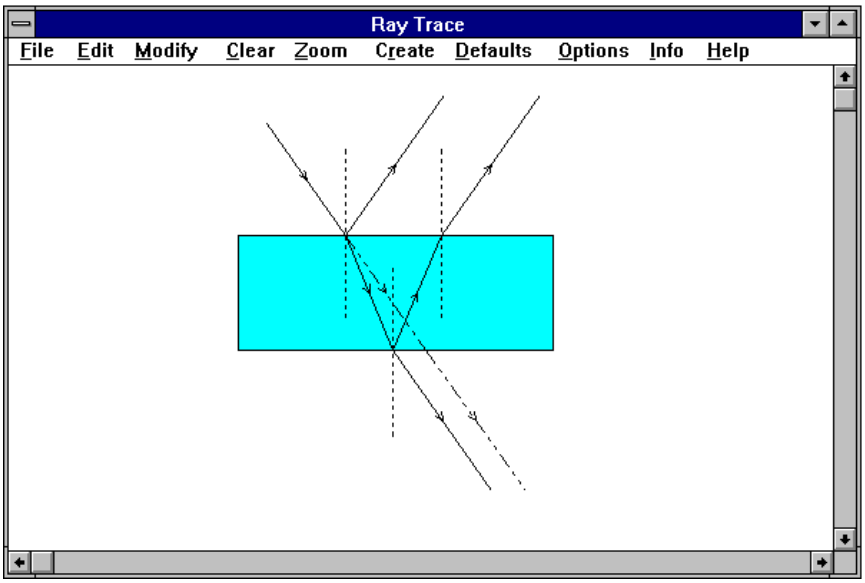
Reflection and refraction by a rectangular prism

In this example you will:

- Gain practice in using the mouse with Raytrace
- Create a simple optical element (rectangular prism)
- Create a ray
- Control the propagation of rays through the element
- Practice the basics of dragging parts of a ray diagram
- Save the ray diagram in a file

At the end of the example you will have created a ray diagram like this:

which demonstrates the reflection and refraction of a ray at two surfaces of a rectangular prism and the lateral displacement of the ray transmitted through the prism.



This example assumes that you are starting from the default values of Raytrace. If you have been using Raytrace then it would be best to exit (Choose **File -- Quit**) and restart Raytrace to ensure all the settings are as assumed.

Creating the rectangular prism

* Choose the menu item **Create** -- **Element > Region**.

* Move the mouse so that the cursor lies within the Raytrace window somewhere.

The cursor will change to the "start point" form as a prompt that you must select the point at which you will start drawing the element, i.e. one vertex of the rectangle.

There are several ways in which to specify the vertices of the rectangle. This example will use Raytrace's grid facility

* Choose the menu item **Options** -- **Grid** to turn on the grid display or use the short cut method which is to press the **G** key.

A grid will appear in the Raytrace window. Next time you use the **Options** menu the **Grid** item will have a check mark next to it. For reference, the default grid spacing is 20 units in both the vertical and horizontal directions.

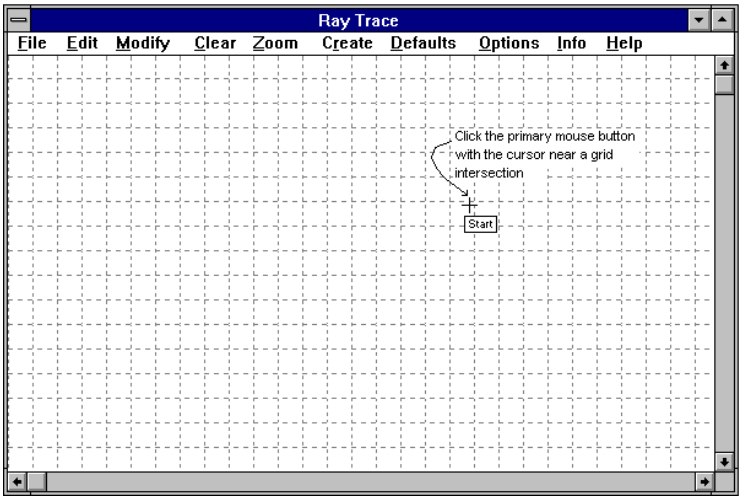
You can now use the grid intersections to specify the vertices of the rectangle. Rather than position the cursor precisely on the grid intersections, make use of the "snap to grid" option:

* Either choose the menu item **Options -- Snap to grid** or make use of the shortcut method which is to press the **S** key.

When the snap to grid option is on, a check mark appears beside the option in the menu. Also, a small cross appears in the cursor as a reminder that the snap to grid option is active.

* Position the cross so that it is near one of the grid intersections as shown below then click and release the primary mouse button.

The cursor will now change to the "end point" form as a prompt that you must specify the end of the first side of the element.



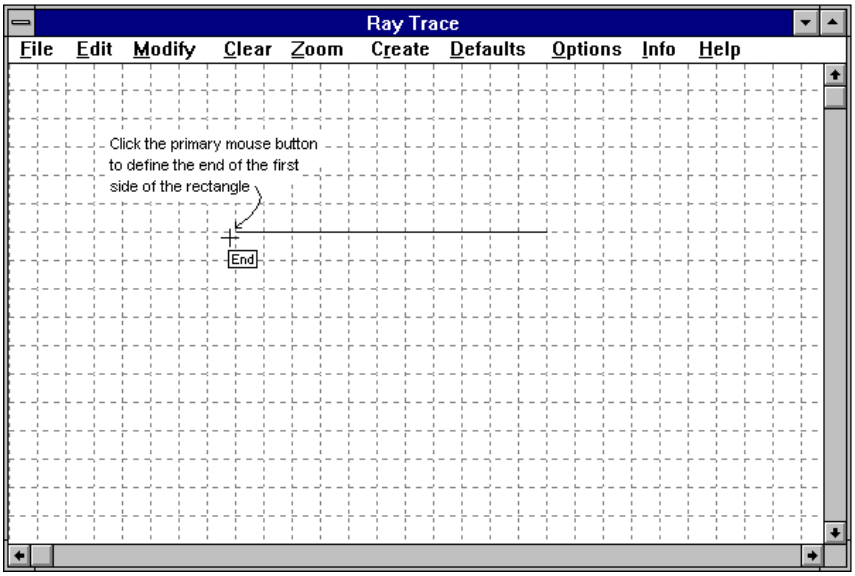
* Drag the mouse away from the point chosen as the start point.

As the cursor moves a "rubber band" line will stretch between the cursor and the point chosen for the starting vertex.

Since the snap to grid option is set, the rubberband always "snaps" to the nearest grid intersection and the starting point that was chosen will be exactly on a grid intersection.

* Position the "end point" cursor as shown below and click and release the primary mouse button to define the first side of the rectangle..

* Draw the next two sides of the rectangle in the same manner.



If you make a mistake when drawing an element simply hit the **U** key to "undo" the last segment and then continue drawing. You can undo all the segments you have created using this method if you want.

To complete the rectangle it is not necessary (and it is not a good idea) to draw the final side. Instead, tell Raytrace that you have finished drawing the element; because it is a region, Raytrace will close the element automatically.

* Click the secondary mouse button - a popup menu will appear. Choose the item **Finished**. An alternative is to choose the menu item **Create -- Element > Finished**.

Raytrace will complete the rectangle and fill it with the current fill colour.

The reason it is not a good idea to draw the final side of the rectangle manually is because Raytrace remembers all the vertices that you enter and allows vertices to lie on top of each other. If you completed the rectangle yourself then you would have entered two vertices at the same location and when you tried to drag that corner of the rectangle then only one of the vertices would be dragged. You would then end up with a five sided figure since Raytrace always adds a closing side between the last vertex and the starting point for regions.

Creating the incident ray

* Choose the menu item **Create -- Ray**:

The cursor will again appear in the "start point" form with the small cross to indicate a "snap to grid" is active. Both the grid and the "snap to grid" are no longer of much use so turn them off.

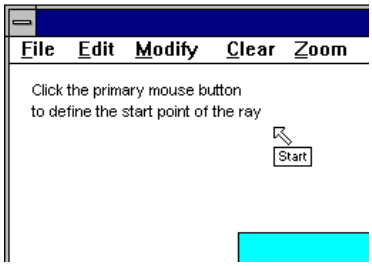
* Turn off the grid either by pressing the short cut key **G** or choosing the menu item **Options -- Grid**.

You will notice that the cursor still appears in the "snap to grid" form. The "snap to grid" option is independent of the grid display.

* Turn off the "snap to grid" by pressing the **S** key or choosing the menu item **Options -- Snap to grid**.

The cursor will now return to the normal "start point" form with the small arrow.

* Position the cursor where you want the ray to start and click and release the primary mouse button.

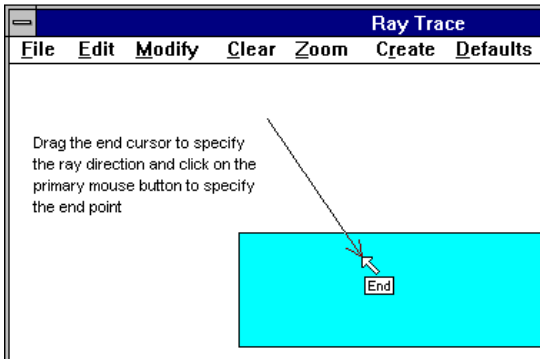


The cursor will change to the "end point" form when you click the mouse button.

Drag the cursor down toward the rectangular prism at an angle.

A "rubberband" line with an arrow head will follow the cursor. It does not matter if you position the end cursor so that the rubberband crosses the edge of the prism or not. Only the direction is important in this case since Raytrace will extend or truncate the ray so that it meets the prism boundary exactly.

* Click the primary mouse button to specify the end point of the ray.

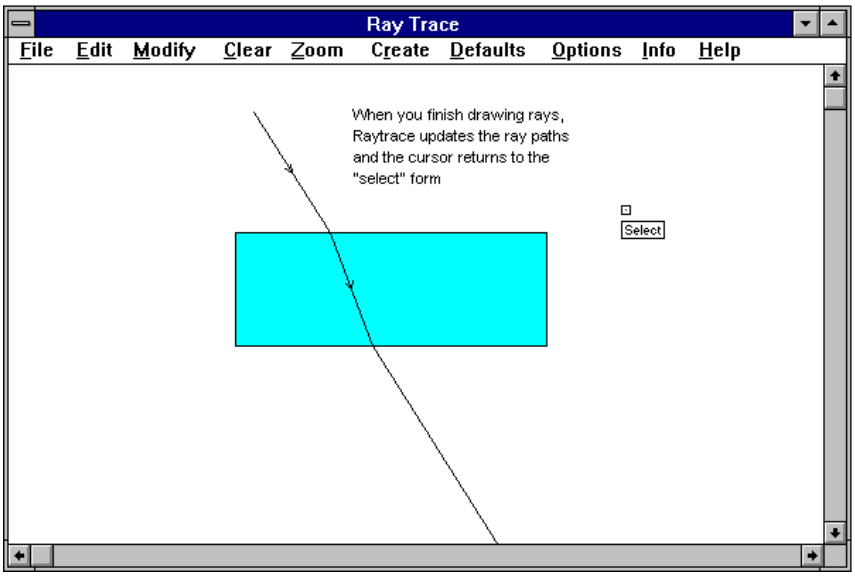


When you click on the primary mouse button to specify the end point, the ray is drawn but Raytrace does not yet calculate any resulting ray paths and does not modify the ray you have drawn. You could add more rays to the diagram at this stage by repeating the last two steps. However one ray is all that is wanted so you need to tell Raytrace you have finished drawing rays.

* Click on the secondary mouse button and choose the item **Finished** from the popup menu or simply press the **ESC** key.

Raytrace will calculate and display the resulting ray path through the slab and modify the ray you drew appropriately. The cursor will return to the "select" form and you will have a diagram similar to that shown below

Some terminology: Child and Parent rays

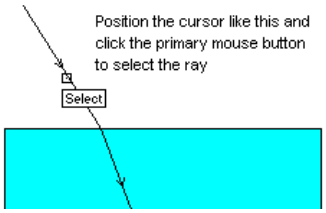


The terms "child ray" and "parent ray" are used to refer to the relationship between rays where a change in the ray path occurs at a boundary. The original ray which you drew has given rise to two generations of child rays. The ray exiting the prism at the bottom has a parent ray, that is the ray traversing the prism, which in turn has its own parent: the original ray.

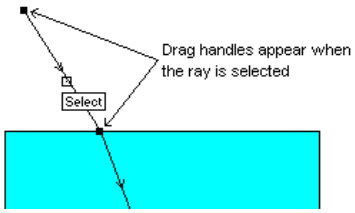
Controlling the ray propagation

Now you can change the ray properties so that the reflected and forward projected rays and normals are shown as in the diagram at the start of this example.

* Select the original incident ray. To do this position the small box in the cursor so that some part of the ray passes through the box then click and release the primary mouse button.



When you click the mouse button, the ray will be selected and "drag handles" will appear at either end of the ray as shown on the left.

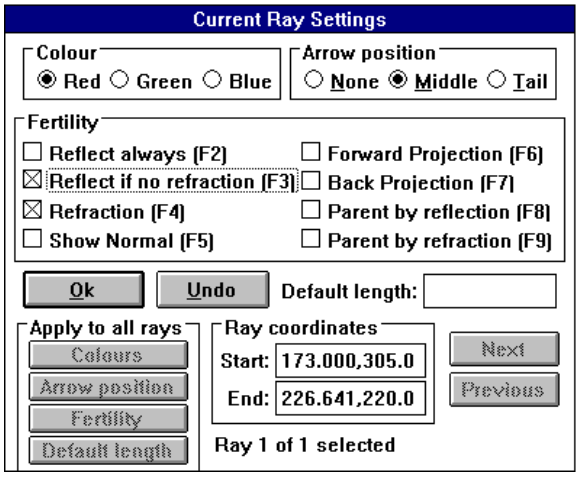


Once the ray is selected you can change its properties.

* Choose the menu item **Modify -- Ray....**

The **Current Ray Settings** dialog box will appear.

The **Fertility** box is the area of interest at this stage.



Notice the function key numbers after each option, (F2), (F3) etc. These are short cut keys which you can use directly without starting the dialog box. They will be used later in the example. They perform no function within the dialog box and are only shown as a reminder.

The **Fertility** of a ray specifies which "child rays" Raytrace will generate. The settings are those which apply to the selected ray - the one you created. The items **Reflect if no refraction** and **Refraction** are checked. These tell Raytrace to attempt to generate a refracted ray at any boundary the ray intersects. If no refracted ray exists - for example if the boundary is a reflecting surface or the angle of incidence exceeds a critical angle - then Raytrace will generate a reflected ray instead. In this example, reflected, forward-projected and refracted rays and a normal are all required.

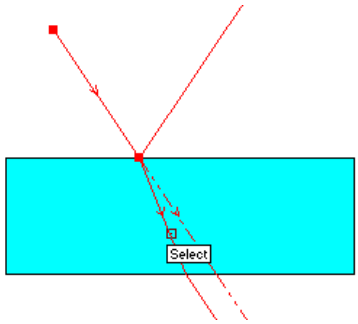
The **Reflect if no refraction** option and the **Reflect always** are mutually exclusive options and checking one will cause the other to be unchecked automatically.

* Check the **Reflect always**, **Show Normal** and **Forward Projection** options then click on **Ok**.

The dialog box will close and Raytrace will add the requested rays.

Notice that the forward projected ray automatically projects beyond the edge of the prism. The refracted ray has the default fertility of **Reflect if no refraction** and **Refraction**, the same as the ray you originally created. This needs to be changed to generate the reflected ray and the normal at the lower prism edge.

* Select the refracted ray by positioning the select cursor as shown and clicking and releasing the primary mouse button.



For the rest of this and most examples, the short cut function keys will be used to change the fertility of rays but you can use the dialog box if you prefer.

* Press the **F2** key followed by the **F5** key.

The reflected ray and the normal will then be added with each key stroke.

* Select the reflected ray inside the prism and press **F5** to generate the last normal at the top of the prism.

The diagram is now essentially complete. However you will notice that the rays that Raytrace has generated all extend beyond the region shown by the Raytrace window.

* To see the full extents of the ray diagram choose the menu item **Zoom --Extents**.

Raytrace will change the viewing scale of the diagram to fit everything within the window.

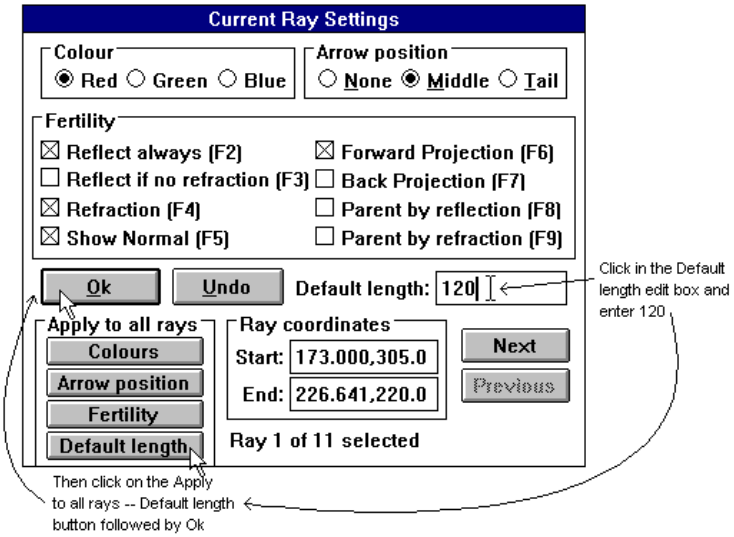
It is important to realize that zooming in Raytrace does not change the actual dimensions of any of the objects that have been drawn - it is simply the scale at which they are viewed which changes.

* Choose the menu item **Edit -- Select All > Rays**

All the rays will now be selected and will be shown with drag handles.

* Choose the menu item **Modify -- Ray...** and enter the number 120 in the default length edit box of the **Current Ray Settings** dialog box. Then click on the **Default length** button to tell Raytrace that you want the default length to apply to all the selected rays. Click on **Ok** to exit the dialog box. These steps are illustrated below.

After the dialog box closes you will see the rays change length. Now return the diagram to the previous scale.



* Choose **Zoom -- Previous**.

* Position the "select cursor" so that the small box is over a blank area of the Raytrace window and click and release the primary mouse button.

That last step simply removes all the drag handles from the rays, it has no other effect.

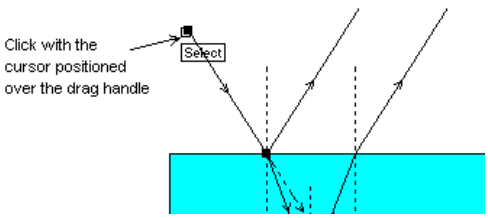
The ray diagram should now look similar to the one shown at the start of this example and you should save it before starting to drag things around.

* Choose **File -- Save As**, type example1.ray (or another name of your choice) in the filename box of the **Save As** dialog box the click on **Ok**.

Dragging the rays

* Select the original incident ray that you drew.

* Position the "select cursor" so that the centre of the drag handle at the start of the incident ray lies somewhere within the small box, then click and release the primary mouse button:

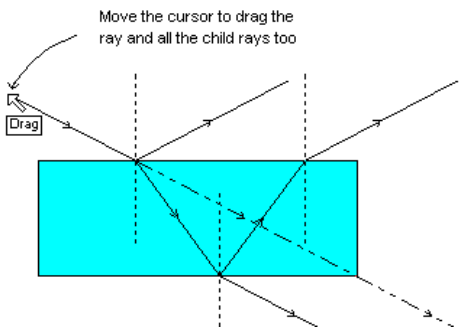


The cursor will change to the "drag point" form when you click the primary mouse button.

* Move the cursor around to drag the starting point of the ray.

* When you want to stop dragging, simply click and release the primary mouse button.

* Try selecting and dragging the ends of each of the rays in your ray diagram (including the normals). If you make a change that you want to reverse, choose **Edit -- Undo** or press the **U** key to go back to the state before the last modification.



* Press the **G** and **S** keys to turn on the grid and snap to grid option and notice the effect this has on dragging. (Remember that the small arrow in the cursor changes to a small cross when the snap to grid option is on)

* Turn the grid and snap to grid options off by pressing the **G** and **S** keys again.

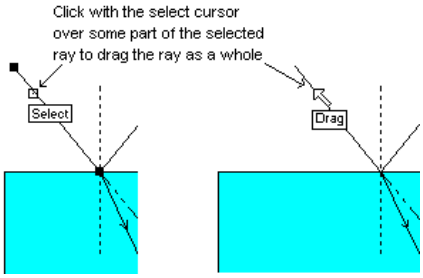
If you drag a child ray, only its child rays are updated not its parent rays. Also when you finish dragging a child ray it will not stay where you put it at the end of dragging; instead it will be recalculated and put back in the position dictated by its parent ray.

A tip: You can change the length of a child ray that does not end on an element boundary without using the **Modify -- Ray...** menu item; simply drag its end point in any direction and when you finish the ray will have the new length and will be placed in the correct position automatically.

You can also drag a ray as a whole without changing its direction.

* Select the incident ray.

* Position the select cursor so that the select box lies over some part of the ray rather than over a drag handle and click the primary mouse button.



Now when you move the mouse, both ends of the ray will move.

Dragging the prism

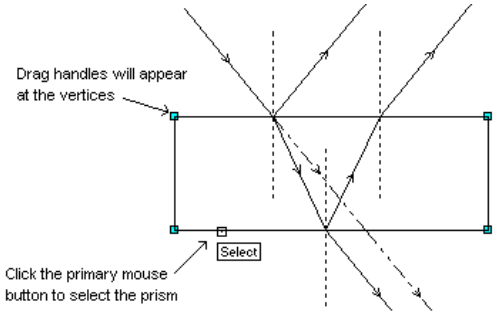
* Select the element by positioning the select cursor box over some part of the outline of the element. and clicking the primary mouse button.

Once the element is selected drag handles appear at all the vertices and it is no longer filled with colour.

To drag any vertex:

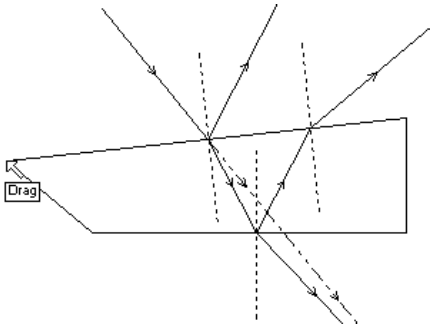
* Position the select cursor box over one of the drag handles (as you did for dragging a ray end) and click the primary mouse button.

* Drag the mouse about to change the position of the vertex.



The ray paths will update automatically unless you have unchecked the **Options -- Update on Element Drag**.

* While you are still dragging the vertex, turn on the grid and snap to grid options by pressing the **G** and **S** keys.



Notice that the grid does not appear. This is normal - the grid display is suppressed when you drag an element for the sake of speed of display. The snap to grid option however still functions as is indicated by the cursor arrow changing to a small cross.

* Turn off the grid and snap to grid options by pressing the **G** and **S** keys again.

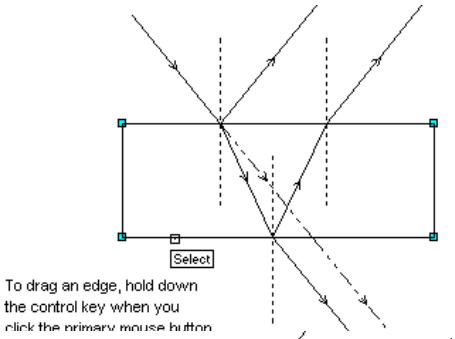
* When you want to finish dragging, click the primary mouse button once.

* Choose **Edit -- Undo** or press the **U** key to return the diagram to it previous state.

Note: In this example you could have returned the vertex (and the diagram) to its original state using the snap to grid option but this does not always apply.

You can drag an edge of the element too. Make sure the element is still selected then:

* Position the select cursor box over the edge you want to move, hold down the control key on the keyboard, click the primary mouse button then release the control key.



If the snap to grid option is still set then the box in the cursor will have small cross arms added to it. In general, you should turn off the snap to grid option when selecting objects otherwise you may have difficulties.

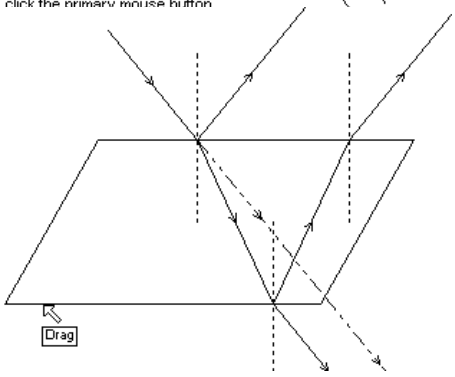
Now when you move the mouse the edge will maintain its shape and the adjoining edges will stretch accordingly:

* Click the primary mouse button to finish dragging again.

* Return the diagram to its original state using **Edit -- Undo**.

You can also drag the whole element around without changing its shape.

* Make sure the element is still selected then position the select cursor box on the element outline and without holding down the control key, click the primary mouse button.



* Drag the element around then click the primary mouse button to finish.

If you want to recover the diagram as it was saved:

* Choose **File -- Open** and either type example1.ray (or the filename you used previously) in the filename box and click on **Ok** or double click on the filename appropriate filename in the list box in the **Open** dialog box.

Suggestions for further activities

- Practice creating elements of different shapes with and without the snap to grid option - you can delete an element simply by selecting it and choosing **Edit -- Delete** or pressing the **Del** key.
- Change the fertility of the rays and see what ray paths you can generate.
- Load some of the example ray diagrams that are supplied with Raytrace (using **File -- Open**) and practice dragging parts of them around.

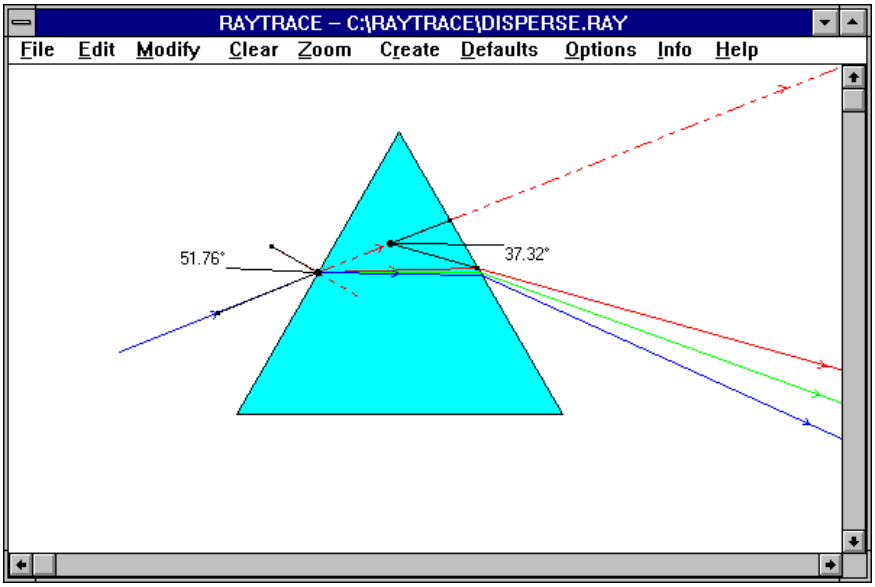
Dispersion by a triangular prism

In this example you will:

- Paste an element from a library file
- Create overlaid red, green and blue rays to mimic a "white light" ray
- Measure angles using "protractor" tools
- Make use of object snaps to specify points.
- See examples of "linking" objects with snaps
- Change the refractive properties of an element

At the end of the example you will have created a ray diagram that looks like this:

Start by clearing the workspace and re-establishing some default settings:



* Choose **File -- New** then uncheck **Options -- Snap to grid** if it has been set.

Pasting the element

You could construct your own triangular prism but this example makes use of Raytrace's element-library facility.

* Choose **Edit -- Library > Paste from...**

This will bring up a **Paste Library Element** dialog box. The first thing you need to do is choose the library file that will be used:

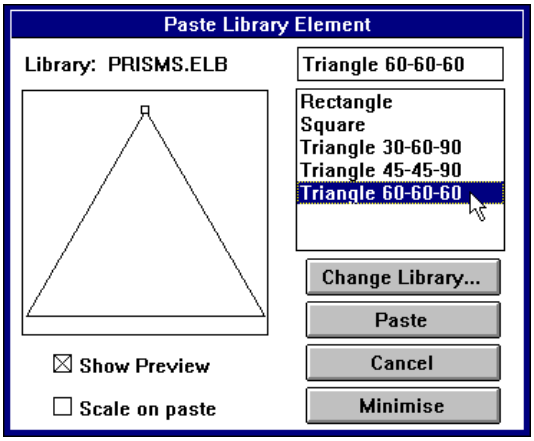
* Click on the **Change Library...** button.

A standard "open file" type dialog box with the caption **Open Raytrace Element Library** will appear with the file type set to *.elb - this is the default extension for Raytrace element libraries.

* Select the file either by typing prisms.elb in the filename box and clicking on **Ok** or double click on prisms.elb in the list box.

Now the **Library:** field at the top right corner of the Paste Library Element dialog box will contain the library file name and a list of prisms will appear in the list box.

* If necessary, scroll down the list of library elements and click on **Triangle 60-60-60** in the list box and a preview of the element will appear in the box on the left hand side of the dialog box.



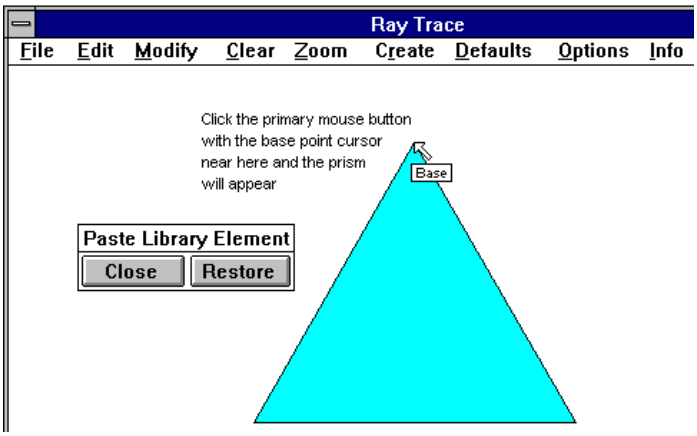
Note that a box like a drag handle appears at the apex of the triangle. This was the point at which drawing started when the element was originally created and it will be the point you specify when you paste the element into your ray diagram; the small box is not part of the prism.

* Click on the **Paste** button.

A "minimized" version of the **Paste Library Element** dialog box which only contains two buttons, **Close** and **Restore** will remain. Ignore this for the moment (you can move it out of the way if you like) and notice that if you move the cursor into the Raytrace window it will be in the "base point" form.

* Move the cursor to a point roughly as shown below and click the primary mouse button.

The triangular prism will appear in your ray diagram; the point that was indicated by the small box in the preview will be located at the point where you clicked the mouse button.



If you were going to paste more elements into your diagram you might want to make use of the **Paste Library Element** dialog box again.

* Click on the **Restore** button in the minimized **Paste Library Element** dialog box.

The full sized **Paste Library Element** dialog box will re-appear and you could select and paste another element. In this example there is no further need for the paste function so:

* Click on the **Cancel** button in the **Paste Library Element** dialog box.

It was not necessary to restore the dialog box to cancel it, that was only done to show the function of the **Restore** button in this example. You could have clicked on the **Close** button in the minimized version of the dialog box to achieve the same result.

*Note that you can move both the normal and minimized versions of the **Paste Library Element** dialog box to some convenient location on the screen and they will always return to the same position during the one Raytrace session.*

Creating a "white Ray"

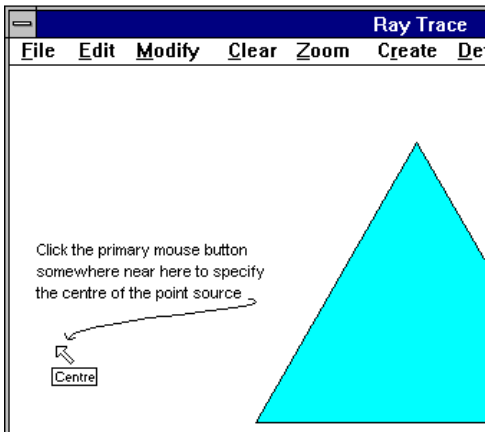
Raytrace does not have white rays as such. Instead, you need to overlay a red, green and blue ray to mimic the effect of white light. You could do this by creating three individual rays, but then you would not be able to drag them in one operation. Instead make use of a "source":

* Choose **Create -- Source > Point...** and enter 3 as the **Number of Rays** in the **Point Source** dialog box and click on **Ok**.

You now need to specify three points to finish creating the source. The first of these is the "centre" of the point source (the cursor should now be in the “centre point” form) followed by two "aperture" points. Rays will emanate from the centre point and spread out between the two aperture points. Since all three rays coming from this source need to overlap exactly the same point should be specified for both aperture points. The simplest way to do this is as follows:

* Specify the centre point approximately as shown by clicking the primary mouse button.

The cursor will then change to the "aperture point # 1" form.



Next the aperture points will be linked to the middle of the side of the prism using snaps.

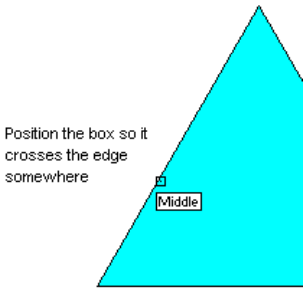
* Click on the secondary mouse button and choose **Mid point snap** from the popup menu. (A short cut method is to press the **M** key.)

The cursor will change to the "mid point select" form, a small box and the word Middle.

* Position the mid point select box somewhere over the left hand edge of the prism and click the primary mouse button.

The cursor will then change to the "aperture point # 2" form. To ensure you select the same point again use another mid point snap.

* Press the **M** key. (Or use the secondary mouse button and the pop-up menu.)



The cursor again changes to the "mid point select" form.

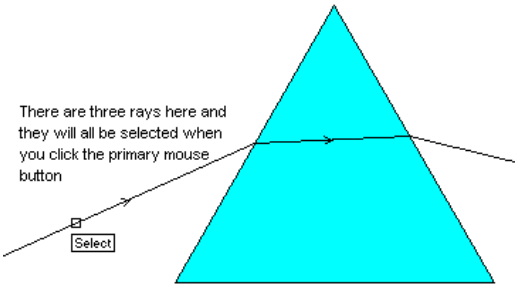
* Position the mid point select cursor box over the same edge of the prism and click the primary mouse button.

You should now see a red ray extending from the specified centre point to the middle of the edge of the prism and refracted rays passing through the prism.

There are actually three rays all identical and overlaid. You now need to change the colour of two of these rays to green and blue.

* Select all three rays by placing the select box over them and clicking the primary mouse button.

* Choose **Modify -- Ray...**



When the **Current Ray Settings** dialog box appears, note that near the bottom edge it says **Ray 1 of 3 selected**.

* In the **Fertility** section of the dialog box check the **Forward Projection** option and the **Show Normal** option.

* Click on the **Next** button in the **Current Ray Settings** dialog box.

At the bottom it should now read **Ray 2 of 3 selected**.

* Click on the **Green** radio button.

* Click on the **Next** button again.

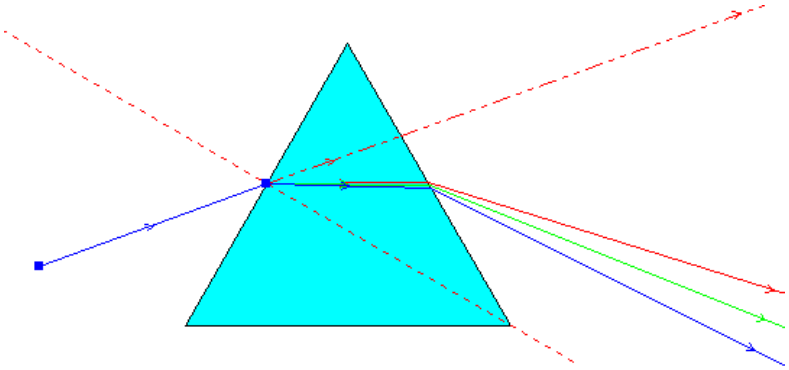
At the bottom it should now read **Ray 3 of 3 selected**.

* Click on the **Blue** radio button.

* Click on the **Ok** button in the **Current Ray Settings** dialog box.

You will still only see one (blue) ray entering the prism but you will see the three different coloured rays refracted through the prism. The red ray will also be projected forward across the prism and a red normal will be shown at the point of contact with the prism.

* Select the normal and drag one end closer to the point of intersection with the prism. Finish dragging and note how the normal is repositioned with the new length. Repeat the process if you are not satisfied with the



new length.

Measuring the angles

Start by measuring the angle of deviation using a protractor tool.

* Choose **Create -- Protractor**

You need to specify three points: The centre about which the angle is measured and two points which define the angle. The cursor will now be in the "centre point" form. In this case the centre of the angle is the intersection point of the forward projected red ray (or the original ray) and the deviated red ray.

* Click on the secondary mouse button and choose **Ray Intersect Snap** from the popup menu. (A short cut is to press the **I** key.)

The cursor will change to the “ray 1 select” form.

* Position the cursor box over the deviated red ray (the one outside the prism) and click the primary mouse button.

The cursor will then change to the “ray 2 select” form.

* Position the cursor box over the forward projected ray (either within or outside the prism), hold down the control key and click the primary mouse button. Release the control key after you have clicked the mouse button.

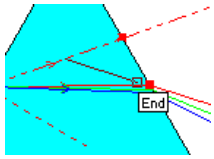
If you don't hold down the control key when selecting the second ray then the cursor will stay in the Ray 2 form and the second ray just selected becomes Ray 1 while the first ray is unselected.

Now the centre point of the protractor is specified the cursor will change to the "end 1 point" form and a rubberband will stretch from the intersection point that you just selected to the cursor. Now link the first end of the protractor to the start of the deviated red ray (equivalently the end of the red ray within the prism) by using an end snap.

* Press the **E** key or click on the secondary mouse button and choose **End snap** from the popup menu.

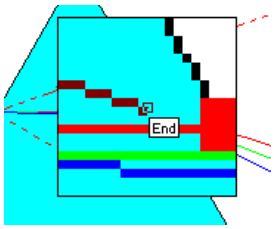
The scale of the drawing makes it almost difficult, if not impossible, to select the end point of the deviated red ray without also selecting one of the other deviated rays. Raytrace includes a facility to help you select objects that are close together like this.

* Position the cursor close near the end of the deviated red ray as shown on the right but do not click the mouse button.

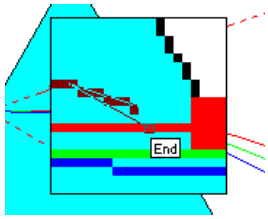


* Press **Shift+F4**.

The area around the cursor will be expanded so that the individual pixels are easily resolved as shown on the left. If you have not positioned the cursor close enough to the ray then you might not see it in the expanded window; to rectify this, simply press **Shift+F4** again to remove the expanded window, re-position the cursor and try again.



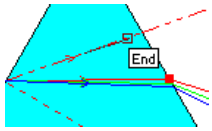
* Position the end point select cursor box over the one of the pixels of the deviated red ray as shown on the right and click the primary mouse button as if you were selecting the ray normally.



The cursor will now be in the "end 2 point" form. Attach the second end of the protractor to the end of the forward projected ray inside the prism.

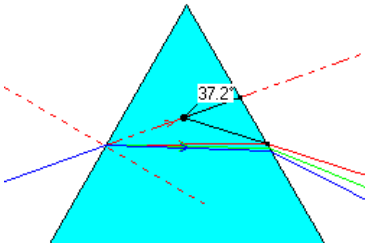
* Press the **E** key

* Position the end select cursor box over the red ray inside the prism as shown on the right and click the primary mouse button.



*An alternative to using **Shift+F4** in the previous steps is to zoom in on the area of interest using **Zoom -- In** so that the rays within the prism are easily distinguished before starting to create the protractor.*

At this point the protractor has been drawn and should appear as shown on the right here. The angle (measured in degrees) will be displayed in the readout at the end of a short “leader” attached to the centre of the protractor (positive angles are measured anti-clockwise with the sense of the angle being defined by rotating the first end point towards the second end point through the minimum possible angle).



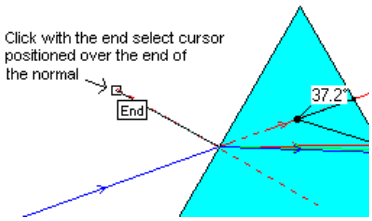
Now create a protractor to measure the angle of incidence of the original rays.

* Choose **Create -- Protractor**.

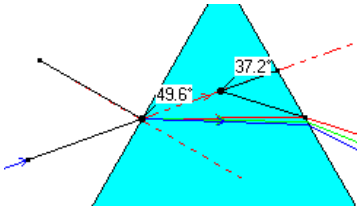
* Link the centre of the protractor to the end of the incident ray by pressing the **E** key then positioning the cursor somewhere over the incident ray and clicking the primary mouse button.

* Link the first end of the protractor to the end of the normal outside the prism by using an end point snap (press the E key) and clicking as shown on the right.

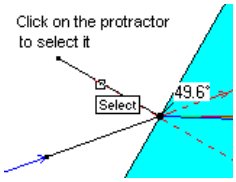
* Link the second end point of the protractor the middle of the incident ray by using a mid point snap (press the **M** key) and clicking on the incident ray.



This should produce another protractor as shown on the left here.

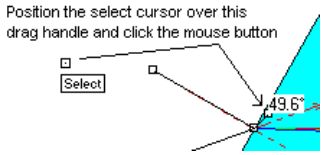


* Select the protractor you have just drawn by clicking on it somewhere. For example as shown on the right.



* Once the protractor is selected, position the select cursor over the drag handle at the end of the leader and click the primary mouse button. You can then drag the leader to a new position. Click on the primary mouse button again when you have the leader where you want it.

If you want to change the number of decimal places in the protractor readouts or use radians instead of degrees then you can do so by selecting the protractors you want to change and choosing the menu item **Modify -- Protractor...**



Once you have the protractor readouts where you want them it would be a good time to save you diagram.

Dragging the incident rays

* Select the incident rays then position the select cursor box over the starting point of these rays and click the primary mouse button just as you would to drag any ray.

Because the rays you have selected emanate from a source, a dialog box giving you some options will appear.

* Choose the **Drag all Rays from this source** option.

Because you selected the start of the rays you will be dragging the centre of the source.

* Drag the centre of the source around and see what happens. To stop dragging, click and release the primary mouse button.

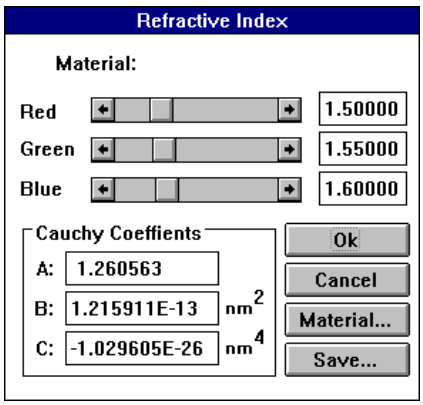
Note that the incident rays will always point towards the middle of the left edge of the prism and the protractors will change in response to the movement of the rays. This is because the protractors and the source were "linked" to the rays and prism by the snaps you used in creating them. If you drag the prism around you will see that the incident rays move to follow it.

Changing the refractive properties of the prism

* Select the prism then choose **Modify -- Element > Refractive Index...**

A **Refractive Index** dialog box will appear. Move the dialog box (by clicking in its caption bar area and dragging) so that you can see the element and rays in your ray diagram and use the dialog box controls at the same time:

The default values for the three refractive indices which appear at this stage are not meant to represent realistic values for any material.



* Change the refractive index for each of the three colours either by:

- clicking on the scroll buttons at the ends of the three scroll bars,
- clicking on and dragging the scroll bar thumbs, or
- entering values in the boxes adjacent to the scroll bars.

As you change the refractive indices the ray diagram changes accordingly (unless you have unchecked **Options -- Update on Element Drag**).

*The Cauchy coefficients are also calculated and displayed - these depend upon knowing the wavelengths of the three colours. You can change the wavelengths or see their current values using the **Modify -- Wavelengths** menu item. If you know the Cauchy coefficients for a particular material then you can enter these in the boxes and the refractive indices will be calculated for you - if you enter unrealistic values the refractive indices will be limited to the range 1 to 5.*

* Click on the **Material...** button in the **Refractive Index** dialog box.

Another dialog box containing a list box will appear.

* Move this dialog box so that you can see the refractive index values in the **Refractive Index** dialog box and also some of the ray diagram.

* Click on one of the materials in the list box.

The values in the **Refractive Index** dialog will change to those for this material and the ray diagram will update.

* Either double click on a material from the list box or click on **Ok** to finalize the choice of material. Click on **Cancel** to return to the previous state.

If a material that you are interested in does not appear in the list box then you can add your own provided you know either the Cauchy coefficients or the refractive index at three different wavelengths. To save a new material:

* *In the **Refractive Index** dialog box, enter the values you want for the refractive indices (after setting the wavelengths) or enter the Cauchy coefficients and click on the **Save...** button - you will be prompted for a name for the material.*

Suggestions for further activities

- Browse through some of the element libraries and paste a few examples - check the **Scale on paste** option in the Paste Library Element and see how you can change the size of the pasted element by specifying the two corners of a rectangle within which it will just fit.
- Practice creating protractors and varying their options. You can create a protractor without attaching its end points to snaps if you want.
- Create some protractors to measure the prism angles.
- Open the example1.ray file that you saved from the first example and try measuring the angle of incidence of the initial ray.

Using a par-axial mirror element

In this example you will:

- Create a par-axial mirror element and examine its function
- Create a plane source
- Compare the focusing of a par-axial mirror with a circular arc
- Look briefly at spherical aberration and coma

When developing simple equations for image formation with spherical mirrors the par-axial approximation is made and text-book diagrams show the image formation using this assumption. Raytrace also allows you to generate ray diagrams making the same approximation by using a "par-axial mirror".

* Clear the ray diagram by choosing **File -- New.**

* Turn on the grid and snap to grid options.

* Choose **Defaults -- Child Rays...**

A Current Ray Settings dialog box will appear.

* Enter the 150 in the **Default length** edit box and click on **Ok**.

Creating a par-axial mirror element.

There are two ways to specify the size of the aperture of par-axial elements. The menu item **Create -- Par-axials on centre** controls which method is used. This example assumes that **Create -- Par-axials on centre** is checked so make sure it is. In this case you specify the size and position of the mirror aperture by first selecting the centre point and then one end of the aperture.

* Choose **Create -- Element > Par-axial mirror** and choose a starting point near the centre of the Raytrace window.

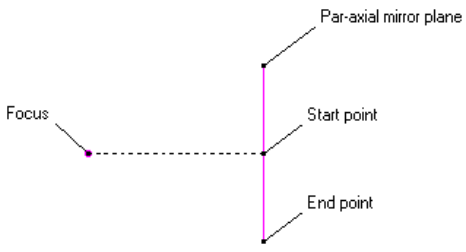
* Select an end point three grid spacings vertically below the starting point.

Once you have selected the end point the cursor changes to the "focus point" form (with snap to grid option on). You now have to specify the focal length of the mirror. A rubberband will stretch from the first point you selected. The focal length will be set to the length of this rubberband; the direction in which you drag the rubberband is irrelevant.

* Drag the cursor to the left so that the rubberband is six grid spacings long and click the primary mouse button.

The focal point of a par-axial mirror element is always drawn on the same side of the mirror plane. To determine which side it will be drawn on, imagine you are standing at the start point and looking towards the end point; the focal point will always be to your right.

You should now have a mirror as shown on the right. (The grid has been turned off for clarity.) The mirror plane and aperture are indicated by the line drawn in the current par-axial colour. The axis is indicated by the dashed line and the focus by a dot at the end of the axis line. The annotations have been added to indicate the points used in creating the mirror.



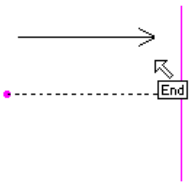
You can imagine the element as a spherical mirror (without the aberrations) which is concave on the side with the dashed line.

Rays parallel to the par-axial mirror axis

* Turn off the grid and snap to grid options

* Choose **Create -- Ray** and select a start point somewhere to the left of the mirror.

* Hold down the control key and drag the end point cursor towards the mirror and click the primary mouse button to select the end point.



Holding down the control key turns on the "ortho" drag mode and the ray will be forced to be either horizontal or vertical depending upon the predominant direction in which you drag the cursor.

* Either press the **Esc** key or click on the secondary mouse button and choose **Finished** from the popup menu to tell Raytrace that you have finished creating rays.

The ray will be extended to intersect the mirror and reflected.

* Select and drag the incident ray as a whole.

As the incident ray is moved up and down the mirror aperture the reflected ray always passes through the focal point because the incident ray is parallel to the axis.

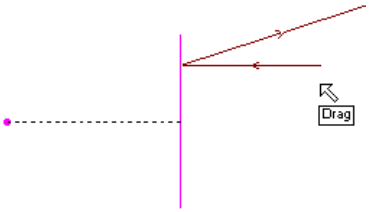
* Finish dragging the ray as a whole.

* Position the select cursor box over the drag handle at the ray's starting point and click the primary mouse button to drag its starting point.

* Drag the starting point around to the other side of the mirror. Hold the control key down to force the ray to remain horizontal. Finish dragging when you have the ray positioned near the position shown on the right.

* Select the reflected ray and press **F7** to turn on its back projection.

* Select and drag the incident ray around as a whole and then try dragging just the start point.



Notice that the back projection of the reflected ray always passes through the focal point when the incident ray is parallel to the mirror axis.

By reversing the rays in your mind you should be able to see that any ray heading towards the focus will be reflected parallel to the mirror axis. The next steps show how to demonstrate this; you can skip them if you like.

* Drag the end point of the incident ray, that is the point of the ray on the mirror aperture.

* Press the **F** key or click on the secondary mouse button and choose **Focus snap** from the popup menu.

* Position the focus point select cursor box on any part of the par-axial mirror element and click the primary mouse button.

* While the incident ray is still selected, press F6 to turn on its forward projection.

The end point of the ray snapped to the focal point of the mirror even though the ray is stopped at the mirror plane. Notice that the forward projected ray passes through the focus and the reflected ray is parallel to the axis.

Rays not parallel to the axis

What happens to rays that are not parallel to the mirror axis and not directed at its focus?

* Choose **Clear -- Rays**.

* Choose **Create -- Source > Plane** and enter 5 as the number of rays for the source.

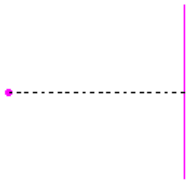
When creating a plane source you must specify three points. The first of these is called the base point.

* Select a base point above and to the left of the mirror (somewhere near the position shown on the right) and click the primary mouse button.

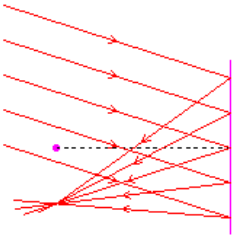
The next two points you specify define the aperture through which rays from the source will pass. The cursor should now be in the “aperture point 1” form.

* Press **E** and position the end select cursor box over the upper end of the par-axial mirror and click the primary moue button.

* Press **E** again and position the end select cursor box over the lower end of the par-axial mirror and click the primary mouse button.



The source will now be drawn and should look similar to the result shown on the right. Rays from the source travel in the direction of a line joining the base point to the first aperture point. The rays are spaced equally along a line joining the two aperture points with an offset at either end.



Now attach a "trail" to the intersection of the reflected rays so that the focal plane (line) of the mirror can be investigated.

* Choose **Create -- Trail.** Specify a ray intersection snap by pressing the **I** key and select two of the reflected rays (holding the control key down to select the second ray or clicking on two rays at once with the Ray 1 cursor).

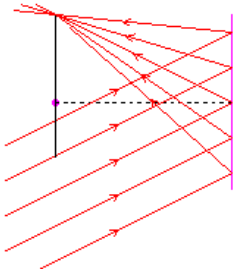
Now drag the source so that the angle of incidence on the mirror changes.

* Select the top ray of the source and click on its start point as if you were going to drag it normally.

Because the ray comes from a source the drag options dialog box of options will appear.

* Choose **Drag all rays from this source**

* Drag the source and note the trail left behind at the intersection of the reflected rays.



The reflected rays always intersect on a straight line as shown in the diagram at the right. The line lies parallel to the mirror and passes through the focal point hence the name focal plane (the line represents the intersection of the focal plane with the plane of the diagram)

Comparison with a spherical mirror

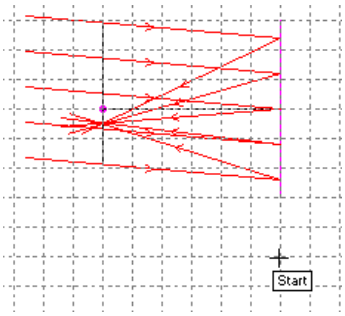
You probably remember that using the par-axial approximations, a spherical mirror has a focal length equal to half the radius of the sphere. Here you can compare the behaviour of the idealised par-axial mirror with a spherical mirror. A circular arc will be used to represent the cross section of the spherical mirror.

* Turn the grid and snap to grid options on again.

* If necessary, use the vertical scroll bar on the right of the Raytrace window to pan the display so that there is enough room in the Raytrace window below the par-axial element to create the curved mirror.

* Choose **Create -- Element > Surface** and choose a starting point directly below the par-axial mirror as shown on the right.

Probably the easiest way to create this arc is to specify the end and tangent points as in the previous example and then set the arc radius afterwards by dragging the tangent point and using the **Set arc radius** facility. However this example will demonstrate another method which allows you to specify the arc radius by dragging at the time of creation.



* Click the secondary mouse button and choose **Circular Arc** from the popup menu.

* Click on the secondary mouse button to bring up the popup menu again and click on the **Circular Arc** item to bring up the second level of popup menu with the arc options. Choose **Radius/End** from the second popup menu.

* Click on the secondary mouse button to bring up the popup menu and choose **Circular Arc** again.

This time the second level popup menu will contain a fourth item: **Clockwise arc**.

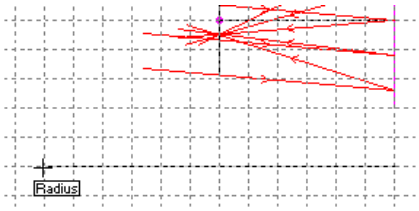
* Choose the **Clockwise arc** option.

The cursor will now be in the radius point form with the snap to grid indicated by the small cross.

The radius of the arc will be set to the length of the rubberband stretching from the starting point to the cursor. The par-axial mirror had a focal length of six grid spacings so you need a radius equal to twelve grid spacings.

* Move the cursor near to the grid intersection twelve spacings to the left of the start point as shown and click the primary mouse button.

The cursor now changes to the end point form to prompt you to specify the end of the circular arc.

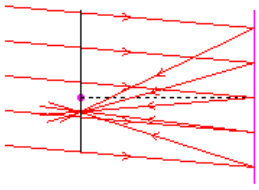


* Move the end point cursor near to the grid intersection six grid spacings below the start point and click the primary mouse button.

* Click on the secondary mouse button and choose **Finished** to complete the surface.

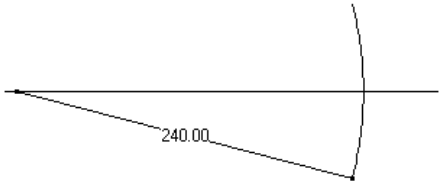
* Turn off the grid and snap to grid options.

The resulting arc should look as shown opposite.



Here a shape element has been drawn to show the axis and a tape measure has been added to indicate the centre of the arc and its radius. These are options you might like to add yourself.

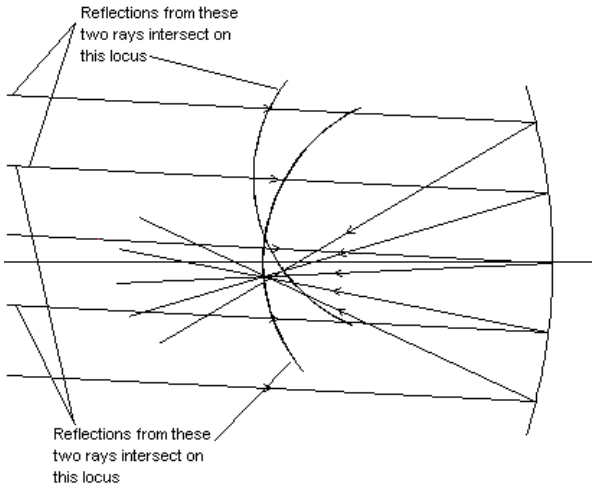
To show the differences between the focusing of rays by the arc and the par-axial mirror you need another plane source striking the circular arc.



* Create another plane source striking the arc in the same manner as you did for the par-axial mirror - specify a base point then link the aperture points to the ends of the arc with end snaps.

* Create a trail attached to the intersection of two of the reflected rays (the ones closest to the axis would be best) and drag the source around to show the focal plane as before.

The focal "plane" that you obtain depends upon which two rays you used for the intersection snap when creating the trail. Two different results are shown on the right. Choosing two of the rays reflected from near the limb of the mirror gives a locus that is asymmetrically displaced about the axis line.

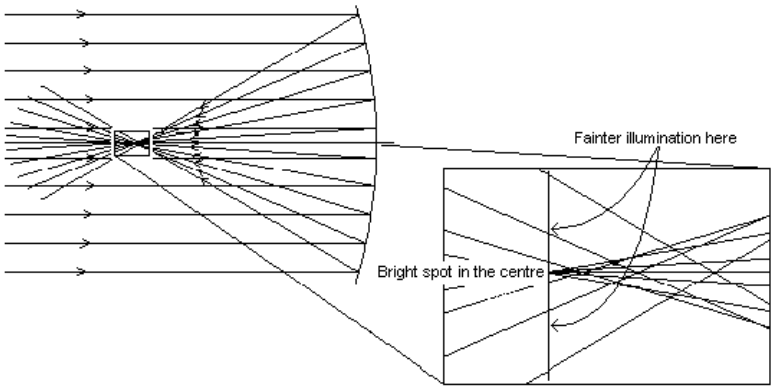


Spherical aberration

* Drag the source so that the rays strike the mirror horizontally.

* While the source is still selected choose **Modify -- Source > Ray count...** and change the number of rays to 10 and click on **Ok**.

* Zoom in on the area around where the rays are focused.



You can see clearly that the rays that strike the mirror away from the axis are focused closer to the mirror than rays near the axis. If you imagine a screen placed vertically through the focal spot of the mirror (shown by the vertical line in the figure above) then those rays that intersect closer to the mirror will strike the screen away from the axis and form a halo around the focal spot. You can imagine that the intensity on the screen is inversely proportional to the spacing between the rays crossing it. The intensity near the middle where the rays are clustered together is high and further from the axis where the spacing between rays increases the intensity drops off.

Coma

* Choose either **Zoom -- previous** or **Zoom -- Extents** to get back to the previous display where you can see all the ray diagram.

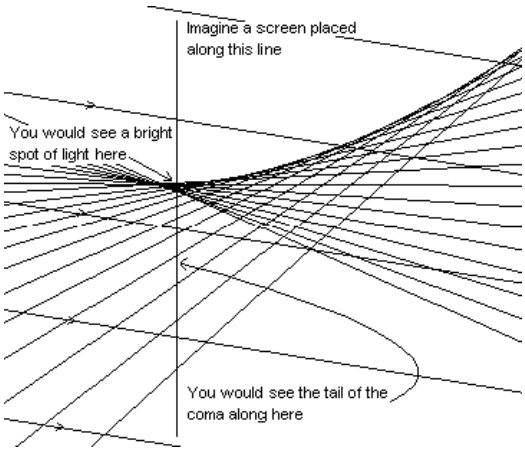
* Select a ray coming from the source then choose **Modify -- Source > Ray count...** and increase the number of rays to 20.

* Drag the source so that the rays strike the mirror at about 20° to the axis and zoom in on where the rays are focused.

You should see something like what is shown here.

Again, imagine a screen placed vertically as shown on the right and think of the intensity as being inversely proportional to the spacing between the rays crossing the screen.

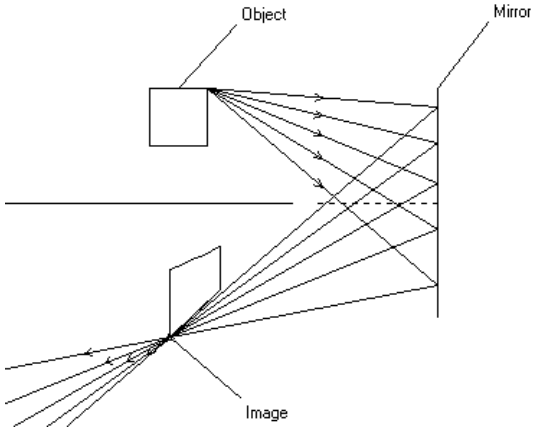
There is an obvious spot where a lot of rays crowd together and cross - this is the focal spot of the mirror. You can also see that there are a number of rays that cross the screen below the spot - these form the fainter coma tail.



Suggestions for further activities

- Investigate the image produced when the object is on the other side of the mirror.

- After you finish the next example "**Reflection from a circular arc**" try repeating it with a par-axial mirror instead of a circular arc. If you save your work at the end of that example you can simply open the file, delete the arc and replace it with a par-axial mirror. You can link the aperture points of the source to the new reflector by dragging the ends of the extreme rays (choose the **Drag all rays from this source** option) coming from the source and "snapping" them to the reflector end points. You should be able to produce a new ray diagram like the one shown here with very little effort even starting from scratch.



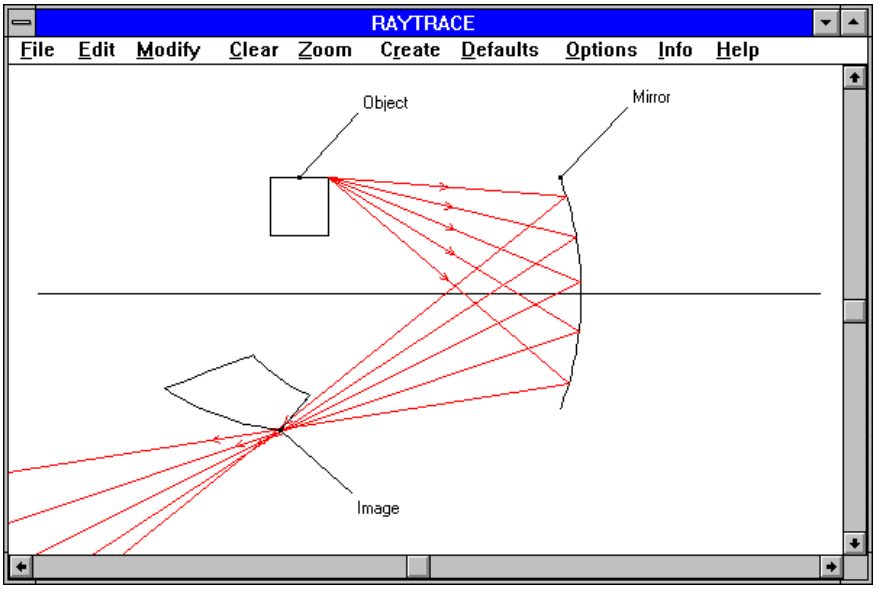
Reflection from a circular arc

In this example you will:

- Construct a simple element consisting of a circular arc segment
- Use "Shape" elements
- Annotate a diagram
- Use a "trail" object
- Use Raytrace's "Auto trace" feature
- Measure distances using "tape measures"

At the end of the example you will have created a ray diagram that will look similar to this:

The diagram can be used to demonstrate both real and virtual image formation in curved and flat reflectors.



* As usual, start by clearing the workspace with **File -- New**

Creating the axis line (a shape element)

* Turn on the grid and snap to grid options.

* Choose **Create -- Element > Shape**.

* Position the cursor somewhere near the left hand edge of the Raytrace window about half way down the window and click the primary mouse button.

* Drag the cursor to the right to a grid intersection horizontally opposite the starting point and near the right hand edge of the Raytrace window then click the primary mouse button.

* Click the secondary mouse button and choose **Finished** from the popup menu.

You should now have a horizontal line extending almost all the way across the Raytrace window:

This is a shape element. Shape elements do not interact with rays. They are useful for construction lines and other things as will become apparent later in this and other examples.

Creating the circular arc reflector

* Choose **Create -- Element > Surface**.

* Position the cursor 4 grid spacings above the axis line and a bit to the right of centre in the Raytrace window and click the primary mouse button.

* Click on the secondary mouse button and choose **Circular Arc** from the popup menu.

* Click on the secondary mouse button and position the cursor over the **Circular Arc** item; another level of popup menu will appear; choose the **End/Tangent** item from this menu if it is not already checked.

The cursor should be in the “end point” form as a prompt to select the point for the end of the arc.

* Position the cursor 4 grid spacings below the axis line and vertically below the start point then click the primary mouse button.

The cursor should appear in the "tangent point" form with the grid snap option indicated by the small cross.

* Position the cursor three grid spacings to the right of the end point chosen in the previous step and click the primary mouse button.

The arc will be drawn. The "tangent point" specifies the direction of the tangent to the arc at the start point and, because the arc always moves initially towards the tangent control point, whether the arc is drawn clockwise or counter-clockwise.

The axis of the arc will be aligned with the axis line because the start and end points are symmetrically placed about the axis line.

At this point you are still creating the element and you could draw more arcs joined to this one in the same fashion, however one is all that is needed, so complete the element.

* Click on the secondary mouse button and choose **Finished** from the popup menu.

Your diagram should now include the axis line and the circular arc reflector.

Creating the "object" shape

The "object" is the small square as shown in the diagram at the start of this example. You do not have to use a square shape, you can draw anything you like for this element but the square is described below.

* Choose **Create -- Element > Shape**.

* Position the cursor near a grid spacing where you want the top right hand corner of the small square object to be and click the primary mouse button.

* Draw all four sides of the square (you must close it manually unlike a region element) and "finish" the element as you did before, i.e. click on the secondary mouse button and choose **Finish**.

* Turn off both the snap to grid and grid options.

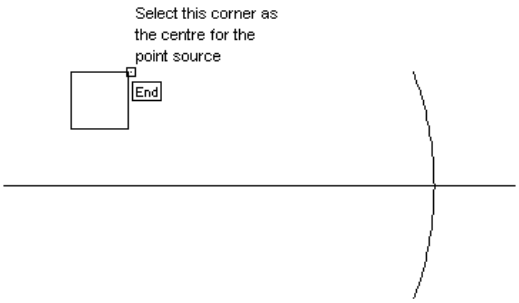
Creating the source

Now you need a point source attached to the "object" shape.

* Choose **Create -- Source > Point** and enter 5 as the number of rays. You can use another number if you like but too many and the diagram will be cluttered.

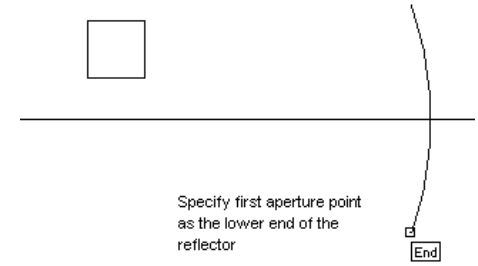
* Select an "end snap" either by pressing the **E** key or clicking on the secondary mouse button and choosing **End Snap** from the popup menu.

* Position the end select cursor box over the first point you defined on the square shape element and click the primary mouse button.



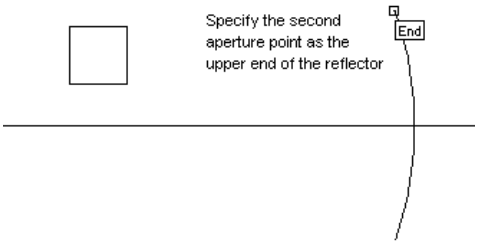
The cursor should currently be in the “aperture 1 point” form. The next steps will link the two aperture points of the point source to the ends of the circular arc. Because the rays emanating from the point source will spread from the first point towards the second point in an anti-clockwise sense, choose the first aperture point as the bottom end of the arc.

* Press **E** to specify an end then position the end select cursor box over the lower end of the arc and click the primary mouse button.



The cursor will then change to the “aperture 2 point” form - like before but with the number 2 in the box.

* Press **E** again to specify another end snap, position the end select cursor box over the upper end of the arc and click the primary mouse button.



The source will now be drawn.

If you make a mistake at some point in the procedure for creating the point source then hit the **Esc** key to abort the procedure and start again.

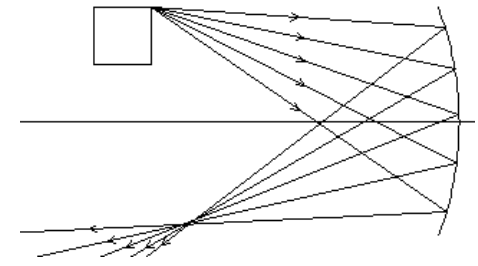
*If you finish creating a point source and find that you have specified the aperture points in the wrong order and find the rays are fanning out in the wrong direction then select one of the rays of the source and choose the menu item **Modify -- Source > Flip Point Sources**.*

*If you complete the procedure and decide that you have done it wrong then delete the source and try again. To delete the source, select one or more of the rays emanating from it and press the **Del** key or choose **Edit -- Delete**.*

The rays will be reflected from the circular arc and will converge towards an "image point" - the convergence is not exact - that only happens in "text book" diagrams.

Exactly where the rays converge will depend on where you drew the square in the first place.

* Selecting the square and drag it around.



If you drag the square element about, the point source will follow it because it was linked with the end snap used in creating it. The same is true if you move the reflector but don't try it until you have finished the diagram and saved it otherwise you might spoil the alignment of the axis line.

Annotating the diagram

* Choose **Create -- Annotation** and enter “Object” in the resulting dialog box.

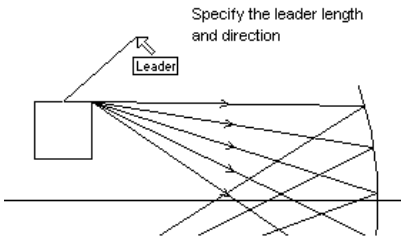
The cursor will now be in the base point form. You must select the point to which the annotation will be anchored. Since it will be nice to have the annotation move when you move the object, link the annotation with a snap as follows.

* Press the **M** key or click on the secondary mouse button and choose **Mid point snap** from the popup menu.

* Position the mid point select cursor over one edge (preferably the top edge) of the square "object" and click the primary mouse button.

The cursor will change to the “leader point” form as a prompt to specify the length and direction of the leader to the text.

* Drag the mouse to a convenient point for the text and click the primary mouse button.



That completes the first annotation.

* Choose **Create -- Annotation** again and type “Image” in the dialog box.

Anchor the image annotation to the intersection of two of the reflected rays as described below.

* Press the **I** key or click on the secondary mouse button and choose **Ray Intersect Snap** from the popup menu.

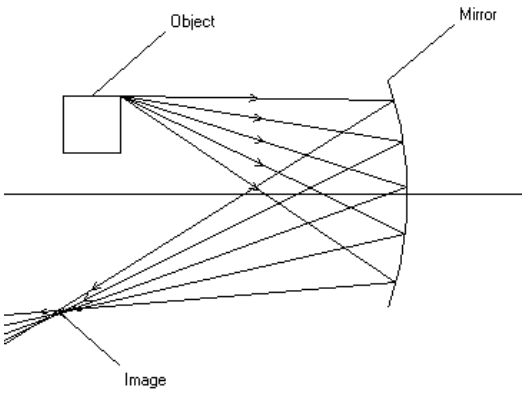
* Select two of the reflected rays. You can either select these one at a time so long as your remember to hold down the control key when the cursor is in the Ray 2 form or you can position the Ray 1 cursor over two (and only two) rays and select both rays in the one operation.

* Again specify the leader length for the annotation.

* Add the “Mirror” annotation in the same manner, using an end snap to attach the annotation to the upper end of the arc.

Your diagram should now look similar to that shown here.

* Try dragging the square object around now and see how the object and image annotations move.



Creating the "image" (using a trail)

When you drag the object at present you can see the image point move but it is hard to visualize the path along which it moves. A trail object makes this easier.

* Choose **Create -- Trail**.

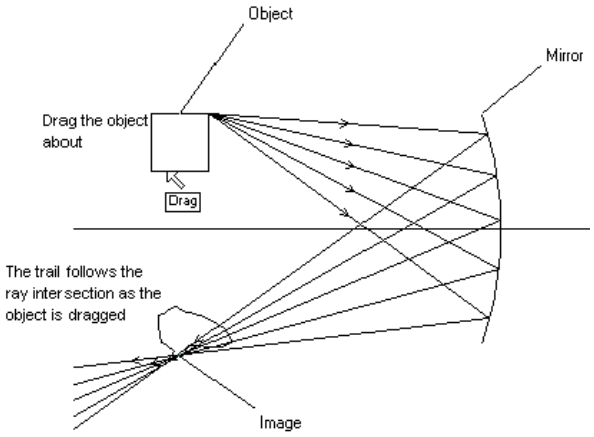
The cursor will change into the "point point" form - you are being prompted to select a point in the diagram which the trail will follow. You must use “snap” otherwise the trail will not be created.

* Specify the point as the same ray intersection as you used for the image annotation - use the **Ray Intersect Snap** as before.

* Now try dragging the object about.

Notice the trail left behind as the image point moves.

The shape of the trail depends on how you drag the object freehand about the screen. This does not give you the shape of the image formed from the object.



Using Auto trace to create the image

* Choose **Modify -- Reset trails**.

The trail image that you created will disappear when you choose this item. However the trail object that you created still exists and if you dragged the object again a new trail would be drawn.

* Select the square object and the point source.

If neither the square or the source was selected then you could select both in one operation by placing the select cursor box over the corner of the square with the point source attached to it and clicking the primary mouse button. If either the square or the source is already selected then take care that you do not click on it a second time when selecting the other object as this will start a drag operation.

* Once you have both square and source selected, choose **Defaults -- Auto drag settings...**. Make sure the **Press space to step** option is unchecked in the resulting dialog box.

* Choose **Modify -- Auto trace** and click on the **Centre/Base** button in the resulting dialog box.

Raytrace will now move the centre of the point source around the square shape. The trail object will trace out the outline of the resulting image.

There are many cases where you can use a trail to trace out an image formed by an optical system. It is important to realise that the image traced out here is a cross section taken at right angles to the direction the image would be viewed. You must imaging that your eye is in the same plane as the screen when viewing the image.

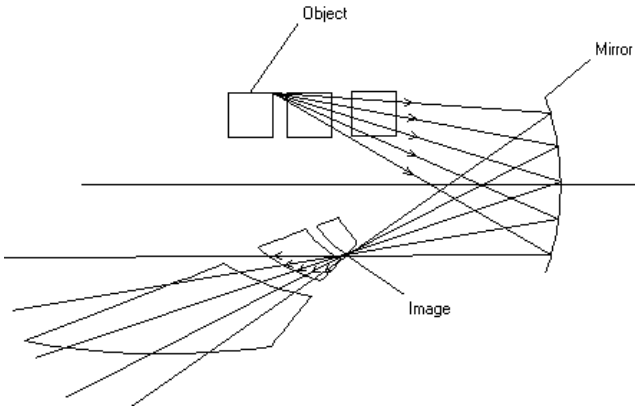
If you check the **Press space to step** in the **Defaults -- Auto drag settings...** dialog box then Raytrace will wait for you to press the space bar between each step of the point source around the square.

* Save the diagram so that you can return to it at this stage.

Some things to try

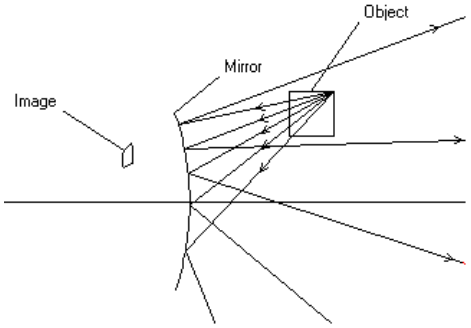
- Try moving the square object and repeating this procedure to see how the image changes with object mirror distance.
- Change the number of steps along each segment of the square using the **Defaults -- Auto drag settings...** menu item.
- Change the shape of the square element (by dragging), repeat the procedure just described and see how the image shape changes.

Trails are "static" - they can not change their shape once formed. However you can pause their function and create a series of trail segments using the **Modify -- Pause trail update** menu item (shortcut is to press the **P** key). For example the series of object and image positions on the right was created by adding a trail to the start of one of the rays coming from the point source - and repeatedly using **Modify -- Auto trace** and **Modify -- Pause trail update** and moving the square object.



The trail on the point source was added to trace out the shape of the square in each position so that when the square was moved the trail shape remained. Pausing the trail update separated the three images otherwise they would be connected by lines caused when the square was moved.

* Try moving the square object to the other side of the mirror, reset the trail and using the auto trace function again.

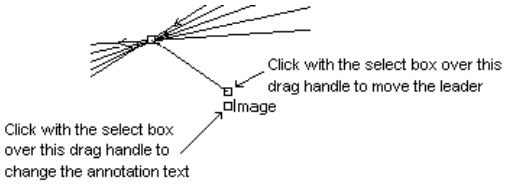


You can pan the window view sideways if necessary by clicking on the Raytrace window scroll buttons.

The image will still form in the correct position because the ray intersect snap does not depend on the rays actually extending to the intersection point.

If you do this you will probably want to turn on the back project option for the reflected rays - you do this by selecting the rays and using the **Modify -- Rays...** menu item or pressing **F7**.

You might note that the image annotation leader has been moved to a more convenient orientation in the previous picture. If you want to do this simply select the annotation by clicking with the select cursor box over the leader - drag handles will appear. There will be two drag handles near the text - the one on the end of the leader allows you to move the leader. If you click on the other one you can change the annotation text. You can also drag the annotation as a whole or drag the base point just as with a ray but the "link" to the ray intersection will be lost and you would have to re-link it by dragging its base point and snapping it onto the ray intersection again.



Measuring distances

If you want to do quantitative work then you will have to measure some distances on the ray diagram. The first thing you might be interested in is the radius of the mirror.

* Choose **Create -- Tape Measure**.

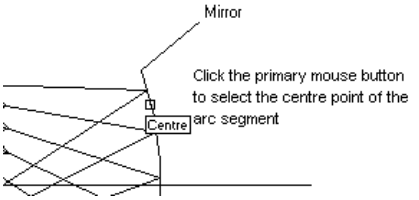
Link one end of the tape measure to the centre of the arc segment:

* Press the **C** key or click on the secondary mouse button and choose **Centre Snap** from the popup menu.

The "End 1" cursor will change to a "centre select" cursor.

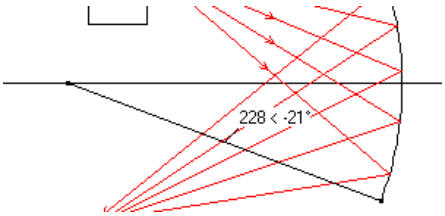
* Position the centre select box somewhere over the arc segment and click the primary mouse button.

* Link the second end of the tape measure to the lower end of the arc segment using an end snap.



This should result in a tape measure as shown on the right.

The "readout" of the tape measure is attached to the middle of the tape measure line by a short leader. The default readout setting is for a format of **distance < angle** with a leader but you can change these settings for each tape measure that you create.



* Select the tape measure by clicking the primary mouse button with the select cursor box somewhere over the tape measure line or the leader.

* Move the readout by clicking on and dragging the drag handle at the end of the leader.

* Choose **Modify -- Tape Measures....**

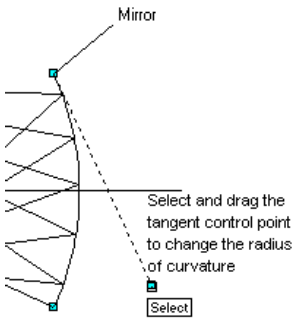
* In the resulting dialog box choose the **Distance** option then click on **Ok**.

Take a note of the other options available for the tape measure readout. You might like to change the number of decimal places used or turn the leader option off.

Now try changing the radius of curvature of the mirror by dragging its tangent control point.

* Select the arc and then click the primary mouse button with the select cursor box over the tangent control point.

As you move the mouse the shape of the mirror will change. The tape measure will display the changing radius of curvature of the mirror. You can make the mirror flat if you like, simply by dragging the tangent point into line with the start and end points of the arc.



You can stop dragging the arc simply by clicking with the primary mouse button again OR you can set a specific radius of curvature by clicking on the secondary mouse button and selecting **Set arc radius** from the popup menu.

*If you want the readout of the tape measure to remain in the one place while you drag the shape of the arc you can select the tape measure and set the **Leader fixed** option in the **Modify -- Tape measures...** dialog box.*

Suggestions for further activities

- Create two more tape measures that measure the distances from the middle of the arc segment to the object and image.
- Change the square object to an asymmetrical shape so you can see the relative image orientation.
- Try making the mirror flat - either drag the tangent control point so that it is co-linear with the start and end points of the arc or use the **Set arc radius** facility mentioned above and enter a value of “inf”.
- Now that you can use tape measures, open the example1.ray file that you saved from the first example and measure the displacement of the transmitted ray relative to the forward projected ray. Anchor one end of the tape measure to the mid point of the transmitted ray and use a perpendicular snap to anchor the other end to either the forward projected ray or the incident ray.

Using a thin lens element

In this example you will:

- Create thin lens elements
- Link a source to the lens
- Learn how to generate the principal rays

An ideal thin lens element is one which obeys the rules: rays striking the lens parallel to the axis are refracted through the focus, rays passing through the centre of the lens are un-deviated and rays coming from (or passing through) the focus are refracted parallel to the axis. You can create either converging or diverging thin lenses in Raytrace.

Creating the lens

* Clear the ray diagram by choosing **File -- New**.

* Press **S** and **G** to turn on the grid and snap to grid options.

* Click on the **Create** menu item and check the **Par-axials on centre** item if it is not already checked.

* Choose **Create -- Element > Converging thin lens**.

* Click somewhere near the centre of the Raytrace window. This will be the centre of the thin lens.

The cursor will change to the end point form.

* Click near a grid intersection a few grid spacings below the point you just selected - a rubber band will extend from the centre point to the cursor. This will be the lower point on the aperture of the thin lens.

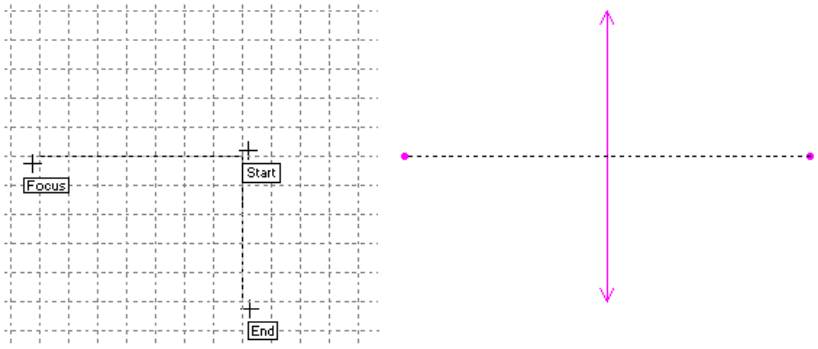
The cursor will change to the focus point form.

* Click on a grid intersection out to the right or left of the original start point - a rubber band will extend to the cursor as before.

The length of the rubber band will be the focal length of the lens.

* Turn off the grid and snap to grid options.

You should now have a thin lens element. The aperture of the lens is indicated by the line with arrow heads and the axis by the dotted line ending in large dots on the focal points.

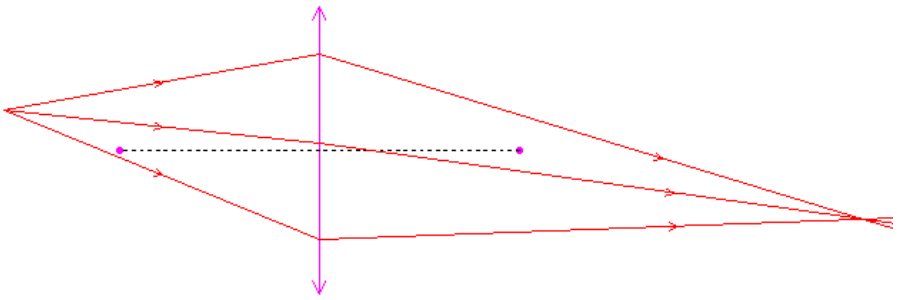


Link a source to the lens

* Choose **Create -- Source > Point** and enter 3 as the number of rays.

* Select a centre point for the source out to the left of the lens somewhere. Link the first aperture point of the source to the lower end of the lens aperture using an end snap then link the second aperture point to the upper end in the same manner. You should have a diagram similar to that shown below at this stage. If you select the lens you can change the aperture size or focal length by clicking on the appropriate drag handles and dragging.

Snapping to a par-axial element for principal rays

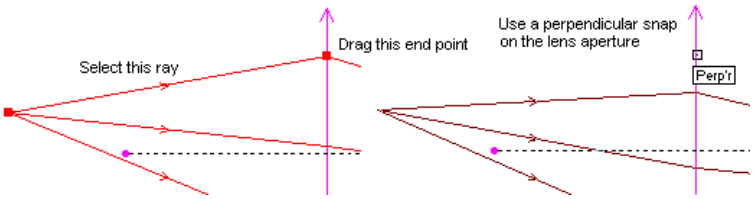


One of Raytrace's important features is the fact that it will trace any ray through an ideal thin lens. However it's nice to be able to demonstrate the principle rays diagrams too. Raytrace includes a feature to force a point source like the one just created to generate the principal rays.

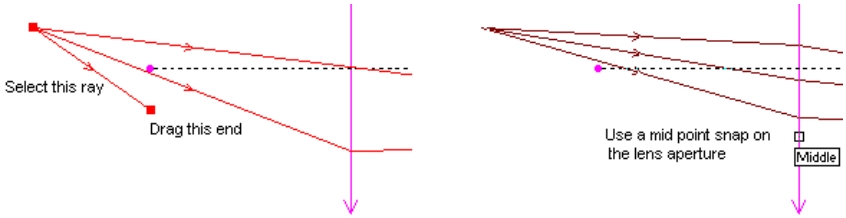
* Select the upper ray coming from the source, click on the drag handle at its end (away from the source centre) and choose **Drag all rays from this source** in the resulting dialog box.

* Once dragging starts, press **L** to invoke a perpendicular snap and click somewhere on the aperture line of the thin lens.

* Select the lower ray coming from the source and repeat the previous step but this time press **M** for a mid point snap rather than **L**.



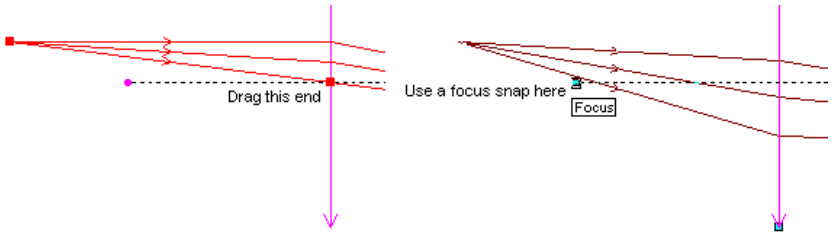
The rays of the source will re-orient to produce the two principal rays - one parallel to the lens and the other through the centre of the lens. The third ray from the source will be somewhere in between. To produce the



three principal rays use the following step.

* Select the lower ray coming from the source (if it is not already selected) and click on the drag handle at its end, press **F** to invoke a focus snap and click on the focus point on the same side of the lens as the source.

Now the source will produce the three principal rays, one through the focus, one through the centre and one parallel to the axis. It may be that the ray through the focus does not strike the lens aperture - you can drag



the lens aperture, focal length or point source position to change this.

Whenever a point source with three or more rays is linked to a par-axial element (thin lens or par-axial mirror) with a perpendicular snap and a mid or focus snap it will generate principal rays. You can use these snaps during the creation of the source or after it is created as was done here.

Adding object and image lines

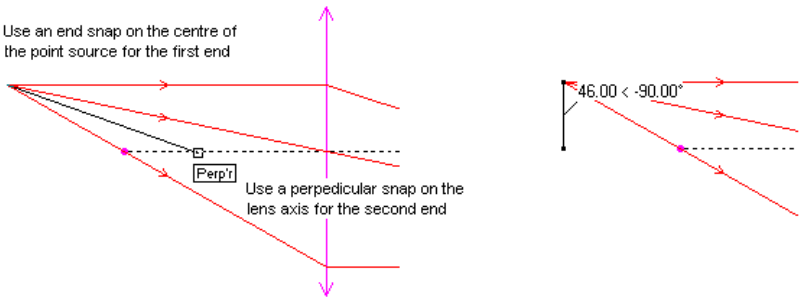
* Choose **Create -- Tape measure**.

* Press **E** to invoke an end snap and click on the centre of the point source.

* Press **L** to invoke a perpendicular snap and click somewhere on the axis line of the thin lens element.

This should produce a tape measure as shown.

* Select the tape measure and choose **Modify -- Tape measure**. Choose the **None** option and uncheck the **Leader** option.



This will leave the tape measure appearing as a simple line - just what you need as an object.
You might like to add an annotation linked to the mid point of the tape measure to indicate that it is the object.

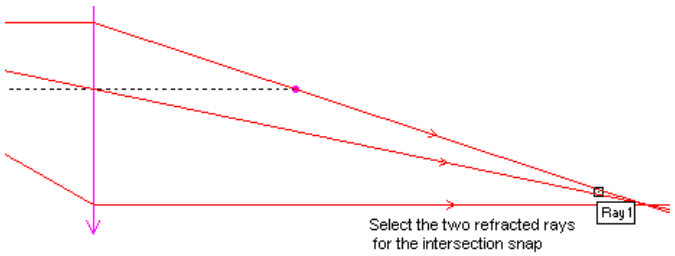
To create the image use another tape measure.

* Choose **Create -- Tape measure**.

This time link the first end to an intersection snap on two of the transmitted rays. An important consideration in choosing the rays is to make sure that they will not disappear when you drag the source around. The ray passing through the focus may not strike the lens for some source positions so choose the refracted rays from the other two source rays for the intersection.

* Press **I** to invoke the ray intersection snap and select the two refracted rays as indicated below.

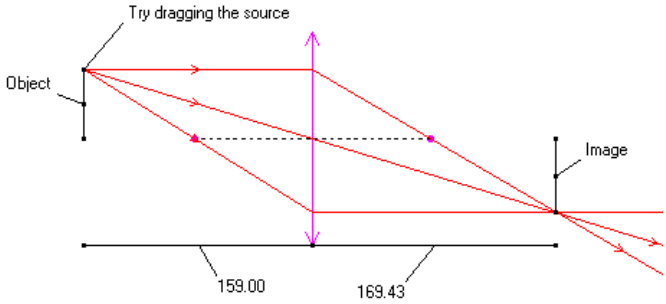
* Link the second end of the tape measure to a perpendicular snap on the lens axis as was done for the object line.



* Select the resulting tape measure and change its options as was done for the object line.

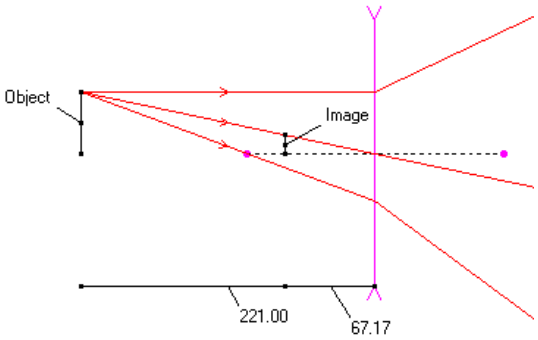
To move the object point, select the source and drag its centre point - dragging the object tape measure will not move the rays since the tape measure is linked to the source not vice versa.

With the addition of a couple more tape measures linked between the lower end of the lens and perpendicular snaps on the object and image tape measures you can come up with the diagram as shown here.



* Select the lens and choose **Modify -- Element > Change to > Diverging**.

This will change the lens to a diverging lens and the ray diagram will be similar to that shown below. You can use **Modify -- Element > Change to > Converging** to go back to a converging lens.



Suggestions for further activities

- Try constructing a multi-lens system and locate the intermediate images

Working with real lenses

It is almost certain that at some stage you will want to investigate lens shapes with Raytrace. This example will show you how to:

- Construct bi-facial lenses
- Modify the lens shapes
- Save a lens shape in a library file
- Position lenses once they are created.

An important tip.

Treat the creation of a lens and its positioning as two separate tasks. You will find it much easier to get a lens in the correct position after it is created rather than trying to create it in the correct place to start with.

Constructing a lens with MAKELENS.

The easiest method of creating a lens is to make use Raytrace's script facility. The script you need is called **makelens.rsc**; it is shipped as standard with Raytrace - it reduces the problem of constructing a bi-facial lens to one of entering some parameters and answering a few questions.

* Run the script **makelens.rsc**. You can do this in one of three ways:

1. Choose the menu item **File -- Run script** and select the file by name.

1. If the button bar is on, you can click on the Run script button - this has the same effect as choosing the menu item just mentioned and you still have to select the file by name.

1. If the button bar is on, you can simply click on the Make Lens button and the script will run immediately.

Once the script starts running you will be given on-screen instructions; simply follow these to construct your lens.

Constructing a lens manually.

Although using the makelens script is quick and simple, constructing lens shapes manually is quite straightforward and can often be quicker than using the script. Also, if you are considering writing or modifying a script to work with real lens shapes then an understanding of how to construct lenses manually is essential.

The following sections will illustrate the construction of lenses using several different techniques as well as some other related issues.

A quick and simple plano-convex lens

* Choose **Create -- Element > Region** and select a start point near where you want the top of the lens.

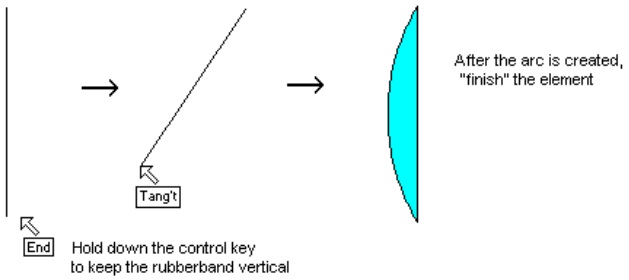
* Click on the secondary mouse button and choose **Circular Arc**. (If you have changed the circular arc options then click on the secondary mouse button, choose **Circular Arc** again and change to the **End/Tangent** option in the second level popup menu.)

* Hold down the control key (to turn on ortho dragging) and drag the cursor so that the rubber band extends a suitable distance vertically below the starting point and select the end point. The distance you drag the cursor will be the height of the lens.

* Select the tangent point some distance to the left of the end point you just selected.

* Choose **Create -- Element > Finish Element** or click on the secondary mouse button and choose **Finished** from the popup menu.

You will now have a plano-convex lens. The next steps show you how to add a plane source striking the lens at a specific angle to the axis.



Attaching a plane source to a lens

In some of the examples in this manual the grid has been used to specify the dimensions of an element. If this had been done here then the grid could be used to specify the points of a source so that the source was aligned with the lens in some way. In creating the lens above no regard was given to the position or size of the lens yet it is a simple matter to add a source in a specific orientation.

* Choose **Create -- Source > Plane** and enter the number of rays you want, 10 for example.

* In response the base point cursor click on the secondary mouse button and choose **Rel Coords** from the popup or press **R** to select a relative co-ordinate snap.

Although the cursor remains in the base point form you are now being prompted to select the base point for the relative co-ordinate snap not the base point for the source.

* Press **E** to select an end snap, and click on the upper end of the lens as indicated here.

The relative displacement entry dialog box will then appear. The following steps make a source which strikes the lens from the left at an angle of 2 degrees above the axis but you can choose any orientation.

* In the **Radius** box enter the value 200 and in the **Angle** box enter 178 then click on **Ok**.

The cursor will change to the aperture 1 form.

* Link the first aperture point to the upper end of the lens and the second aperture point to the lower end using end snaps (press **E**) in each case.

The source will then appear and it will have the exact alignment that was specified - no guess work!

If you just want a source without regard to the exact positioning, perhaps for a quick demonstration where you are going to drag the source about, then don't bother with the relative co-ordinates snap, just select a suitable point free-hand.

Attaching a point source to a lens

You can use a relative coords snap to position a point source in a similar manner to that just described for the plane source. In this case you would probably want to specify the base point for the relative co-ordinate snap as the mid point of the lens arc (or perhaps the plane face).

* Delete the plane source created above by selecting one of its rays and pressing **Del**.

* Choose **Create -- Source > Point** and enter the number of rays you want from the source.

* In response to the centre point cursor press **R** for a relative coordinate snap.

* In response to the base point cursor press **M** for a mid point snap and click on the arc of the lens.

* In the relative displacement entry dialog box enter the **X** and **Y** displacements and click on **Ok**. For example, for a point source 20 units off axis and 300 unit left of the lens face enter x = 20 and y = -300.

* Link the aperture points of the source to the upper and lower vertices of the lens arc as before and your source is complete.

Plano-convex lens with specific dimensions

The previous lens was made without regard to its dimensions. This might be fine for a quick example on some aspect of the lens but if the dimensions of the lens are important then you might like to use the following steps.

* Choose **Create -- Element > Region** and select a suitable starting point as before.

* Click on the secondary mouse button and choose **Circular Arc** (and **End**/**Tangent** option if necessary, i.e. if you have changed it from the default startup setting).

* To specify the end of the arc press **R** for a relative coordinate snap and in response to the base point cursor click anywhere in the Raytrace window.

* When the relative displacement entry dialog box appears click on the **Base = Previous point** button.

This changes the base point for the relative co-ordinate snap from the point you clicked on with the base point cursor to the last point selected prior to this, i.e. the starting point of the element. That is why you can click anywhere in the Raytrace window with the base point cursor.

* Enter the height you want for the lens in the **Y** box and click on **Ok**.

* Select the tangent point somewhere on the side of the lens that you want to be convex then click on the secondary mouse button and choose **Finished** to complete the element.

* Select the element and click on the tangent control point of the arc to start dragging it, then click on the secondary mouse button, choose **Set arc radius** and enter the value you want for the radius of curvature, e.g. 300.

An alternative sequence which avoids the need for setting the arc radius at the end is to choose the **Radius**/**End** option when creating the arc segment and use the relative co-ordinate snap to specify points for both the radius and the end. However the ambiguity of arc direction when using **Radius**/**End** usually makes the sequence just described easier.

Now you have the lens with the exact dimensions that you require, all that remains is to position it where you want in the diagram.

Positioning the lens...

There are basically two ways to move the lens into the desired position. You can either drag it there or use the **Modify -- Move** menu item. In both cases you need to select a reference point on the lens and a target point onto which it will be moved. Snaps will play a vital role in selecting these points.

By dragging

In this example the mid point of the arc will be used as the reference point on the lens however you could use another point like the mid point of the plane surface or the centre of the arc.

* If the lens is not already selected then select it by clicking on its outline somewhere.

* Press **M** to invoke the mid point snap then click anywhere on the arc of the lens.

This starts the dragging with the cursor attached exactly on the mid point of the arc.

Since there are no other objects in your diagram to position the lens relative to this example will position the lens at a specified set of co-ordinates using an absolute co-ordinate snap.

* Press **A** to invoke the absolute coordinate entry dialog and enter the coordinates, for example **X** = -100 and **Y** = 0 then click on **Ok**. This will position the lens and stop the dragging operation. (Note that when Raytrace starts the origin is centred in the window and 1 drawing unit = 1 display pixel.)

Using this method you can only move the one lens (unless you have other lenses grouped with it - see **Modify -- Element > Group**).

*Using **Modify -- Move***

* Select the lens and then choose **Modify -- Move**.

* In response to the base point cursor select the point on the lens using a snap, e.g. press **M** and click on the arc to select the mid point of the arc.

* In response to the point cursor select the point where you want the lens to be position, for example an absolute coordinate snap or, if there are other objects in the diagram, a relative coordinate snap.

Using this method you can move several lenses and any attached sources together simply by selecting them all before choosing **Modify -- Move**.

Creating a minimum thickness bi-convex lens

You can quickly create a bi-convex lens in a similar manner to the previous plano-convex lens simply by adding another arc segment. However you need to be able to specify the end point of the second arc as the same point as the original start point. This is easily achieved by using a grid snap for the start point.

* Choose **Create Element > Region**, click on the secondary mouse button and choose **Grid Snap** then select an appropriate starting point.

* Click on the secondary mouse button and choose **Circular arc** (and **End/Tangent** if necessary).

* Specify the arc end point vertically below the start point either with a relative coords snap or using the ortho drag facility.

* Specify the tangent point somewhere to the left of this end point.

* Click on the secondary mouse button and choose **Grid Snap** again then click close to the original starting point - the grid snap will ensure you select exactly the same point. Remember, if something goes wrong when creating a segment, press **U** to undo the last segment.

* Specify the tangent point for the second arc somewhere to the right of this end point then finish the element in the normal manner.

You should now have a bi-convex lens and you can set the arc radii using the **Set arc radius** function as described in the previous examples.

Note the use of "single point" grid snap which is invoked using the secondary mouse button popup menu. This is simply an alternative to toggling the permanent grid snap on and off by pressing **S** - you can use either, just remember that a grid snap is indicated by the cross in the cursor rather than an arrow.

Creating a bi-convex, bi-concave or concave/convex lens

The lenses constructed so far are "minimum thickness" lenses. A more flexible lens shape is one in which linear segments are added between the arc segments to allow you to change the separation of the arcs. Lenses constructed using the makelens script are always of this type. Here a lens of specific dimensions will be constructed (Height = 200, R_1 = 300, R_2 =250 and thickness = 100).

* Choose **Create -- Element > Region** and select a suitable starting point. Click on the secondary mouse button and choose **Circular Arc** from the popup menu.

* Press **R** for a relative coordinate snap, click at any point. When the Relative Coordinate Entry dialog box starts, click on the **Base = Previous point** button and enter a value of -200 for the **Y** value then click on **Ok**.

* Select the arc tangent point somewhere on the left side of and below the starting point.

* Click on the secondary mouse button and select **Line segment** from the popup menu.

* Hold down the control key while you select a point a short distance to the right of the arc end point.

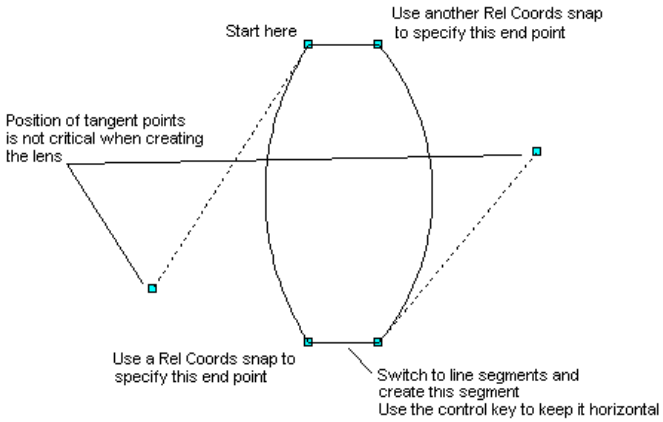
Holding down the control key invokes the ortho drag and keeps the line segment horizontal.

* Click on the secondary mouse button and choose **Circular arc** from the menu again. Use another relative coordinate snap as above to specify the arc end point a distance of 200 units above this point.

* Select the tangent control point for this arc out to the right of the lens somewhere.

* Click on the secondary mouse button and choose **Finished** to complete the lens.

* Select the lens and click on the left hand arc tangent control point - click on the secondary mouse button and use the **Set arc radius** item to set the radius to the required value of 300.



* In a similar manner set the radius of the right hand arc to 250.

All that remains to make the lens shape that was specified is to change the thickness of the lens.

Changing the thickness of a lens

The central thickness of a lens constructed either using the script makelens or the steps given in the preceding section can be changed by dragging one of the faces of the lens as described below. The thickness of a plano-convex or minimum thickness bi-convex lens constructed in previous sections cannot be changed using this method.

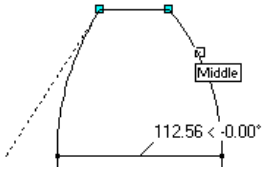
First create a tape measure to indicate the thickness of the lens.

* Choose **Create -- Tape measure** and use mid point snaps to link the ends of the tape measure to the mid points of the two arc segments.

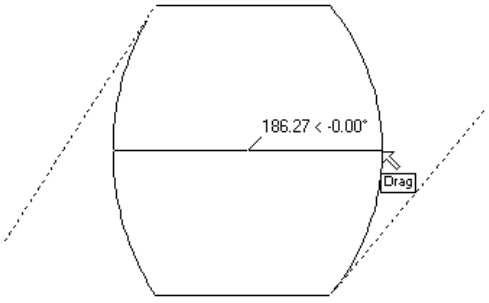
* Select the lens if it is not already selected, and make sure that the tape measure is not selected.

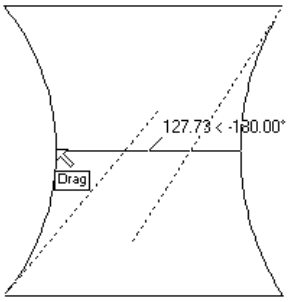
* Click on the secondary mouse button and choose **Mid point Snap** from the popup. Hold down the control key for the next two steps. Click somewhere on the right-hand arc segment of the lens with the mid point select cursor.

* Keep the control key down and move the mouse left and right and you will see that you can change the thickness of the lens.



Notice the drag cursor snapped to the middle of the arc segment because of the mid point snap. Holding down the control key causes the drag to affect the segment not the entire element and keeping it down causes the ortho drag to keep the arc in the same vertical position as you drag it about.



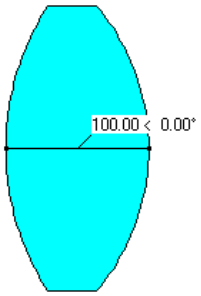


The tape measure should change to indicate the lens thickness. You could just drag the lens to the desired thickness or...

* Click on the secondary mouse button and choose **Rel Coords** from the popup menu. You can release the control key now.

* Press **R** for an end snap and click on the left hand end of the tape measure. In the relative displacement dialog box enter the desired thickness of 100 in the **X** box and click on **Ok**.

The lens will now be the correct thickness. The tape measure served an important purpose here: as well as indicating the thickness of the lens it served to mark the middle of the left hand arc segment so that you could use the end snap during the relative co-ordinates snap. This was necessary because you cannot snap to a point on an element that you are dragging. An alternative would be to move the lens so that the mid point of the left hand arc segment was on a grid snap and use that grid point as the base for the relative co-ordinate snap when adjusting the thickness.



The mid point snap, used when starting the drag operation on the segment, was also important since it specified the point on the right hand arc that would be positioned relative to the middle of the left hand arc. If you just wanted to drag the thickness free-hand without specifying an exact dimension then you could omit the mid point snap.

A final note: After you finish dragging you will notice that the tape measure is also selected. This is because the mid point snap used on the arc segment caused the mouse click to act exactly as it would have if you if you had actually clicked on the arc mid point.

Saving the lens to a library file

Once you've gone to all the trouble of creating the lens shape you should save it in a library file so that you can paste it into any diagram in the future. First you can create your own library file.

* Choose **Edit -- Library > Manager**. and click on the **Create Library...** button in the resulting dialog box. When the Save As dialog box appears choose a filename for your library (use the extension .elb) and click on **Ok**.

When the Save As dialog box closes the Library Manager dialog should display the name of the library file that you chose.

* Click on the **Close** button.

* Select the lens element that you want to save in the library.

* Choose **Edit -- Library > Save to...**

* In the Save Element to Library dialog box type a name for the lens into the edit box in the top right hand corner.

* Once you have entered the name you want, click on the **Save** button.

That's it. Your lens has been saved in the new library file. You can use **Edit -- Library > Paste from...** to paste this lens into any diagram now.

You don't have to create a new library file, you can use on of the ones supplied with Raytrace and simply add your lens to the elements already there. Simple select the element and **choose Edit -- Library > Save to...** and then use the **Change library...** button to select the library file you want.

Making the radii of curvature equal

Raytrace provides you with a facility for forcing a lens like the one just created to have equal radii of curvature. You do this using the **Modify -- Link segments** menu item as described below.

* Choose **Modify -- Link segments**.

* Click on one of the arc segments of the lens

A rubberband will then stretch from the middle of that arc to the cursor position.

* Click on the other arc of the lens.

The second arc will then change to have the same radius of curvature as the first arc. Now if you drag the tangent control point of the first arc selected above then both arcs will change. If you drag the tangent control point of the second arc selected then nothing will change since it now takes its radius dimension from the first arc.

Principal “planes” of a thick lens

In this example you will:

- Paste and scale a lens from an element library
- Use trails to identify the principal planes of a lens
- Use Copy and Paste to duplicate some objects.

The principal plane of a thick lens is the plane in which an ideal thin lens of the correct focal length would have to be placed to have the same effect as the thick lens. There are two principal planes depending upon the direction in which the light passes through the lens. The ray diagram described by this example can be used to illustrate the principal "planes" of a thick lens and the departures from the ideal behaviour.

Pasting and scaling the lens

* Choose **File -- New** to clear the workspace.

* Choose **Edit -- Library > Paste from...**

* When the **Paste Library Element** dialog box appears, click on the **Change Library...** button and select the file LENSES.ELB using the **Open Raytrace Element Library** dialog box.

* Check the **Scale on paste** option in the **Paste Library Element** dialog box .

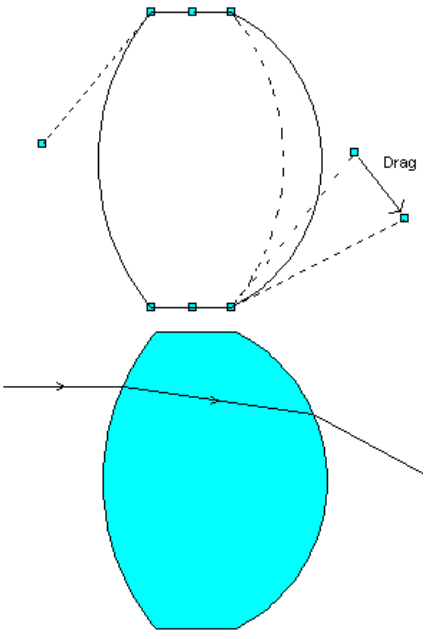
* Click on the entry, **Thick bi-convex**, in the element list box to see the preview of the lens that will be pasted.

* Click on the **Paste** button.

When pasting an element with the **Scale on paste** option set you must specify two corner points of a rectangle. The rectangle is constrained to have the aspect ratio of a rectangle that just bounds the element so all you have to concentrate on is where you want one corner and how big the rectangle should be.

* Select the upper left corner of the rectangle you want the lens to fit in and then drag the scaling rectangle out to the size you want and click with the primary mouse button.

The lens will appear in the diagram once you select the second corner.



* Click on the **Close** button in the minimized **Paste Library Element** dialog box to remove it.

* Select the lens and drag the tangent control point of the right hand arc to make the lens asymmetrical.

* Create a ray that strikes the lens horizontally from the left side as shown. (Hold down the control key when specifying the end point to force it to be horizontal.)

If you made the radius of the right hand arc too small and created the ray too close to the top of the lens then you might find the ray is internally reflected in the lens. If this happens then increase the radius of the right hand arc until you get a result similar to that shown on the right.

* Select the ray you just created and turn on its forward projection either by pressing the **F6** key or using **Modify -- Rays...** and the dialog box.

* Select the forward projected ray and press **F6** to turn off the projection beyond the second lens surface.

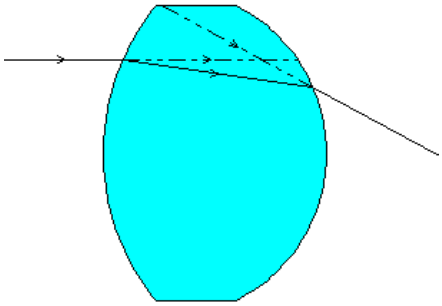
* Select the refracted ray that traverses the lens and press **F3** to turn off its **Reflect if no refraction** fertility option.

This will prevent internal reflections if you drag the ray too close to the periphery of the lens.

* Select the ray that exits the right hand side of the lens and turn on its back projection by pressing **F7**.

* Select the back projected ray within the lens and press **F7** to turn off the projection beyond the lens.

You should now have a set of rays as shown on the right.



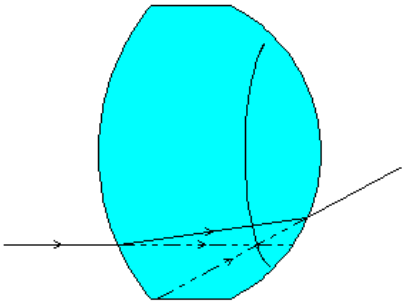
Locating the principal "plane"

The intersection point of the forward and back projected rays lies on one of the principal surfaces of the lens. To define the surface make use of a trail object.

* Choose **Create -- Trail**.

* Press the **I** key to specify a ray intersection snap; position the Ray 1 cursor select box over the intersection of the two projected rays and click the primary mouse button.

* Drag the whole incident ray down the lens and see the trail trace out the locus of the intersection. Finish dragging the ray in a position as shown on the right.



Notice that the locus the intersection traces out is not a straight line. This is because the concept of a principal plane depends upon the par-axial approximation being valid - you can see that the locus that was traced out is nearly straight near the axis of the lens where this approximation holds.

Duplicating the rays

* Select the incident ray if it is not already selected and then choose **Edit -- Select Child Rays**.

This will select all the rays stemming from the incident ray. (In this diagram, where there is only one incident ray, you could have used **Edit -- Select all > Rays** to accomplish the same thing.)

* Choose **Edit -- Copy**.

The cursor will change to the "base point" form as a prompt for you to select the reference point for the copy operation.

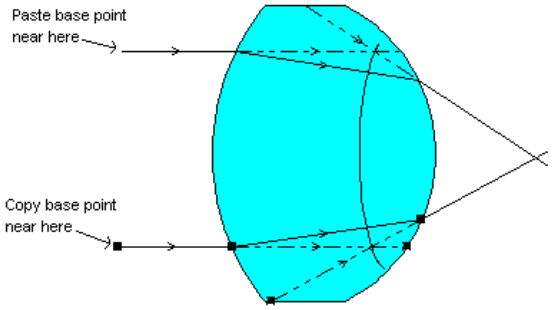
* Specify the copy base point somewhere near the start of the incident ray; the exact position is not critical.

* Choose **Edit -- Paste**.

The cursor will change to the "base point" form again. The reference point that was selected for the copy operation will be mapped onto the point you select now when the objects are pasted in.

* Specify the paste base point near where you started the original incident ray.

Once you specify the paste base point a copy of the original ray and all its children will be pasted into the ray diagram. Copying the rays like this means all the child rays with the correct fertilities will be generated immediately; if you created a new incident ray then you would have to repeat all the steps involved in setting the fertilities.



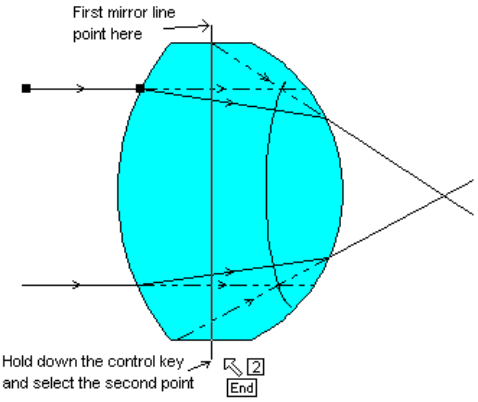
The next step is to flip the new incident ray over to the other side of the lens.

* Select the new incident ray and choose **Modify -- Mirror**.

Now you need to specify two points on a line about which the selected objects will be "mirrored".

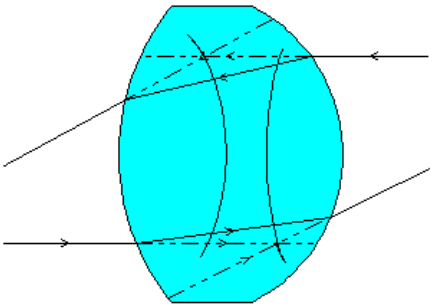
* Position the cursor somewhere near the middle of the top edge of the lens and click the primary mouse button.

* Hold down the control key, drag the cursor down towards the bottom of the lens then click the primary mouse button again.



This will flip the incident ray over to the other side of the lens and the child rays will update automatically.

* Create a second trail object attached to the intersection of the two new projected rays and then drag the second incident ray up and down the second principal plane of the lens will be traced out as shown on the right.



Notice the principal planes are not the same distance from the centre of the lens; this is generally true for non-symmetrical lenses.

Suggestions for further activities

- Change the lens shape (e.g. bi-concave, meniscus, thicker or thinner), reset the trails and trace out the new principal planes. Don't delete the lens, simply change its shape by dragging.

- Create a plane source incident on the lens and determine the focal lengths of the lens as measured from the principle planes and compare it to result of the lens makers equation.

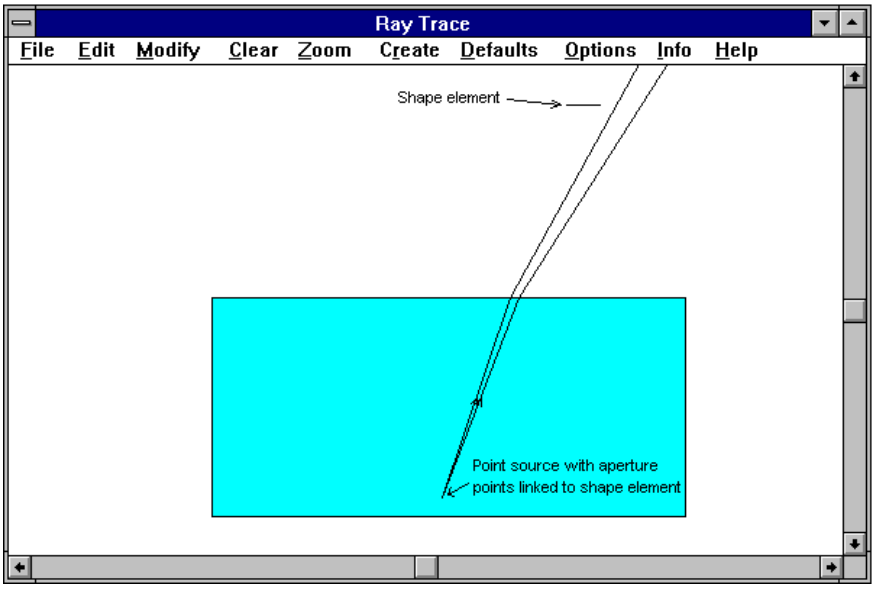
Real and apparent depth

In this example you will:

- Investigate the apparent depth of an object immersed in a refractive medium
- Learn how to link a point source using its child rays
- Use the "Auto drag" function to tabulate readouts from tape measures and protractors

The first few steps will result in a diagram as shown below.

* Choose **File -- New** to clear the workspace



Either:

* Draw the refracting region manually.

Or:

* Choose **Edit -- Library > Paste from...**
* Click on the **Change Library...** button and select the library file PRISMS.ELB.
* Check the **Scale on paste** option and paste in the rectangular prism so that it occupies a large portion of the lower half of the Raytrace window as shown above.

The small horizontal line labeled "Shape element" in the diagram above will be used to represent the entrance pupil of an observer's eye. Raytrace has a script which will draw an eye shape for you but to keep the example simple use the simple shape shown here.

* Create the short horizontal line shape element about in the position shown above - this will be called the "target" element.
* Create the point source, with 2 rays, centred near the bottom of the rectangular region; link its first aperture point to the right hand end of the target element and the second aperture point to the left hand end using end snaps.

If you link the aperture points to the ends of the target element in the reverse sense then the rays from the source will extend almost horizontally to left and right rather than almost vertically. If this happens then simply select one of the rays from the source and choose **Modify -- Source > Flip point sources** to reverse the aperture points.

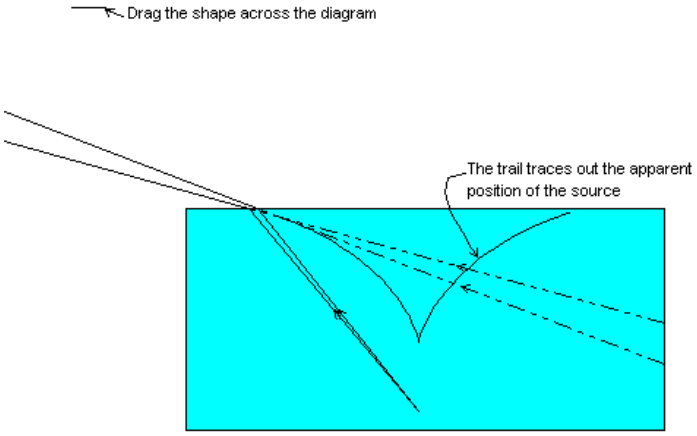
* Select both of the refracted rays above the rectangle and press the **F7** key to turn on their back projections.

* Create a trail object linked to the intersection of the two back projected rays.

* Select the shape element and drag it horizontally, as a whole, across the window.

This should result in a diagram similar to that shown on the right.

The trail traces out the apparent position of the point source as the angle of view of an observer outside the refracting medium changes.



Obtaining apparent depth as a function of viewing angle

* Choose **Create -- Tape measure**.
Specify the first end of the tape measure as the intersection of the back projected rays and the second end as a perpendicular snap to the upper edge of the rectangle.

* In a similar manner, create another tape measure to indicate the depth of the point source.

* Choose **Edit -- Select All > Tape measures** then use **Modify -- Tape measures...** and set the **Distance**, **Use leader** and **Leader fixed** options.

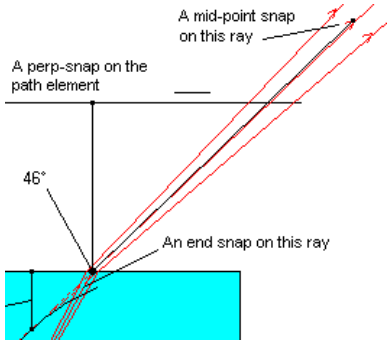
* Drag the tape measure readouts to convenient locations.

* Create a shape element consisting of a single horizontal line segment about the same length as the rectangular element and about the same distance above the rectangle as the target element previously constructed. (See the diagram on the next page.) This element will be referred to as the "path" element.

* Select one of the rays coming from the point source then use **Modify -- Source > Ray count...** to change the number of rays from the source to 3.

* Choose **Create -- Protractor** and attach the centre of the protractor to the end of the middle ray coming from the source (use the fine select facility, Shift+F4, to aid selection of the end of the middle ray). Attach the first end of the protractor to the mid point of the middle refracted ray and attach the second end to a perpendicular snap to the path element just created.

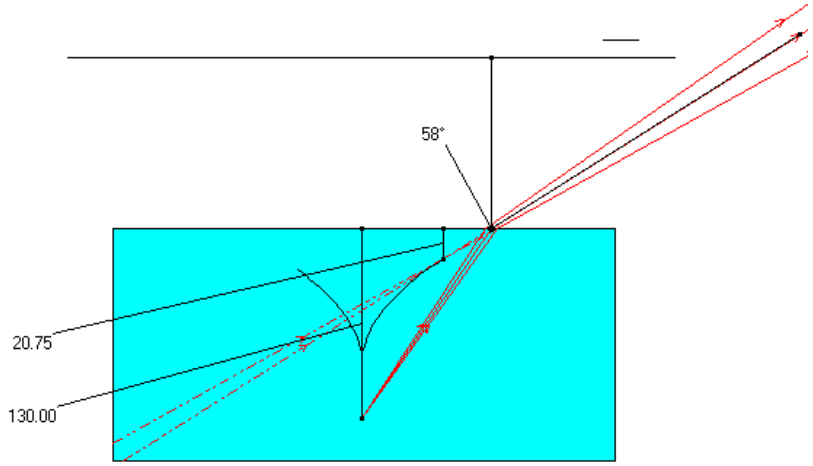
* Select the protractor and use **Modify -- Protractors** to change the number of decimal places in the readout if you want and drag the leader at a convenient point.



The protractor indicates the angle at which the image of the source is viewed. The third ray was added so that the angle would be measured half way between the two rays being used to locate the image.

Your diagram should now look similar to this:

* Choose **Defaults -- Auto drag settings...**



* Check the **Press space to step** option and click on **Ok** in the dialog box.

* Choose **Modify -- Reset Trails**.

* Select the target element and then click on it again to start dragging it as a whole.

* While dragging the target element, click on the secondary mouse button and choose **Auto Drag** from the popup menu.

The cursor will now change back to the select form.

* Position the select cursor box over the path element and click the primary mouse button.

The target element will be moved to one end of the path element. (The end to which it moves to depends on whether you drew the path element from left to right or right to left.)

* Press the space bar and the small element will be moved one step along the path element.

* Continue pressing the space bar and watch the small shape element move across the length of the path element.

If you clicked with the cursor exactly on the target element when you started dragging then it will overlay exactly on the path element and you won't be able to see it; you will only see the effect of it moving.

When the auto drag function finishes it returns you to normal drag mode.

* Move the target element to some convenient location and finish dragging.

Why use this auto drag function? Well if you open the Windows clipboard viewer you will see it contains three columns of numbers. The first two numbers are the readouts of the two tape measures at each position the short element occupied as it was moved along the longer shape element. One of these is constant since it is the depth of the source which was not moved. The vertical bar character, |, is a separator; the number following it is the readout of the protractor at the same locations.

You can now paste these numbers into a spread sheet and plot the apparent depth as a function of viewing angle or perform some other action on them.

Whenever the **Modify -- Auto Trace** or **Auto Drag** functions are used, all the tape measure and protractor readouts are copied to the clipboard like this for you to use in other programs.

The number of steps that are taken along the path element can be changed using the **Defaults -- Auto drag settings...** dialog box. Also, if you uncheck the **Press space to step** option in the **Auto drag settings** dialog box then the automatic dragging will proceed as fast as the calculations can be done. This setting also applies to the **Auto trace** function which was used in a previous example.

Linking the source via its child rays

You might find it dissatisfying that the refracted rays in this diagram do not actually pass through the "observer's eye" (the target element). Raytrace includes a facility for fixing this; known as "linking via child rays". At present the point source is linked directly to the target shape element. Change this as follows.

* Select one or more of the source rays, hold down the control key and select the two refracted rays coming from the extreme rays of the source.

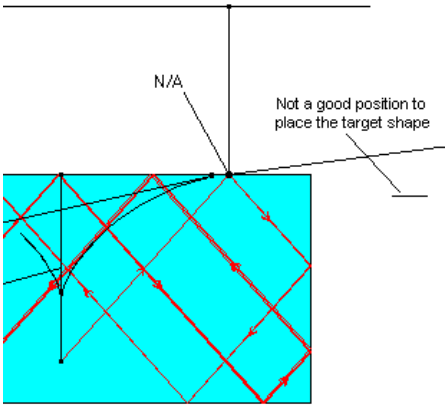
* Choose the menu item **Modify -- Source > Link point source via child rays**.

The cursor will change to the "aperture 1 point" form - just as it did when you were creating the source.

* Use an end snap to link to the first aperture point to the right hand end of the target shape and then again to link the second aperture point to the left hand end of the target shape.

The source will now be re-oriented so that the child rays that you selected pass through these aperture points. When you drag the target shape the source will automatically be adjusted to maintain this relationship.

You need to exercise a little bit of caution with the **Link point source via child rays** option. Raytrace uses a numerical algorithm to search for the possible ray paths that will lead to the child rays passing through the requested points. If you drag the target element so that no such path exists then the results are undefined and you may find that you end up a strange result. Simply reversing the drag will probably not correct the problem. This is illustrated here - if you drag the target down to the side of the refracting region the source is totally internally reflected and can not reach the target; dragging the target back does not result in the original paths re-establishing because the refracted rays no longer exist and Raytrace has no way of knowing which way to go. If this happens use the **Edit -- Undo** to correct it.



Linking a point source this way lets you examine cross sections as the of images that the eye actually sees. Raytrace comes with several script examples illustrating this; try running fisheye.rsc, mansview.rsc or magfier.rsc.

Finding the real depth if the apparent depth is known.

You can create a ray diagram so that the apparent depth is fixed and the real depth changes as viewing angle is changed.

* Choose **Clear -- Trails**, **Clear -- Rays**, **Clear -- Tape measures**, and **Clear -- Protractors**.

This should leave you with only the rectangular region and the shape elements:

* Choose **Defaults -- Child Rays...** and uncheck all the fertility options.

* Create a new point source with two rays and aperture points linked to the target element as before but this time position it closer to the top edge of the rectangular region.

Don't worry if the rays are totally internally reflected.

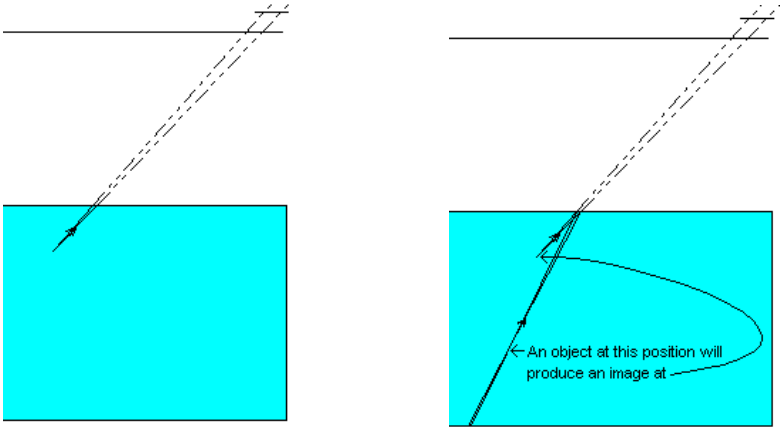
* Select the two rays coming from the source and press **F3**, **F4** and **F6** so that they only produce forward projection child rays.

You should have a diagram like that shown below on the left at this stage.

* Select the two forward projected rays and press **F9** or choose **Modify -- Rays** and check the **Parent by refraction** option.

This step will add two rays as shown below on the right.

These new rays are "parent by refraction" rays. They are child rays of the forward projected rays and are simply the refracted rays that would exist if the forward projected rays were reversed. An object at the



intersection of these last two rays would produce an image at the position of the point source.

A disadvantage of this ray diagram is that the rays that would enter the eye are drawn as dash-dot lines and the imaginary rays (those coming directly from the point source) are drawn as solid lines. However, it does allow you to fix the image depth, vary the viewing angle and find the object depth.

* Create tape measures to indicate the image and object depths and a protractor to indicate the viewing angle.

* Create a trail attached to the intersection of the two "parent by refraction" rays.

* Drag the target element around

See how the real depth depends upon the viewing angle. Notice that for angles close to normal incidence the ratio of the real and apparent depths is given by the ratio of the refractive indices of the two media; 1.5:1 for the default refractive indices for red rays in Raytrace. As the viewing angle increases the real depth increases rapidly and quickly moves beyond the bounds of the rectangular region - this is the asymptote along which rays from within the medium are totally internally reflected.

Suggestions for further activities

- Use **Auto drag** to generate real depths as a function of viewing angle in a similar manner as was done for apparent depth as a function of viewing angle. You may need to define a more appropriate path shape for the auto drag to follow.

- Investigate how apparent/real depths changes as the refractive index of the rectangular element is changed.

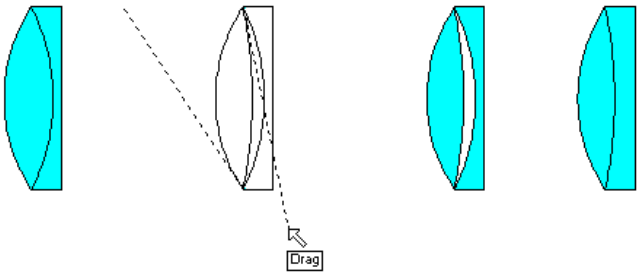
Creating a “cemented” doublet lens

In this example you will:

- Link segments of two different lenses
- Examine and minimize the longitudinal chromatic aberration of a doublet lens

A lens system with very little chromatic aberration can be made using doublets - two lenses in series. A cemented doublet is one in which the lenses share a common surface. You can easily draw two lenses with matching surfaces in Raytrace using object snaps but this presents another problem. Suppose you had created two lenses with matched surfaces as shown below on the left. Suppose you then wanted to change the radius of curvature of the matched surfaces to that shown on the right below. To do this you would have to drag two surfaces, first the right hand surface of the left lens and then the left hand surface of the right lens. Part way through this process you would have a gap in the lens as shown second from the right below.

For some applications this might not matter. However, if you were trying to find the focal length of the lens as the radius of the intermediate surface was changed this would be a real nuisance since you could not use



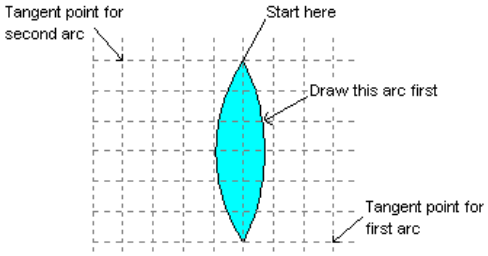
the auto drag facility but would have to perform the sequence of drags by hand.

Raytrace allows you to overcome this problem by linking segments from different elements.

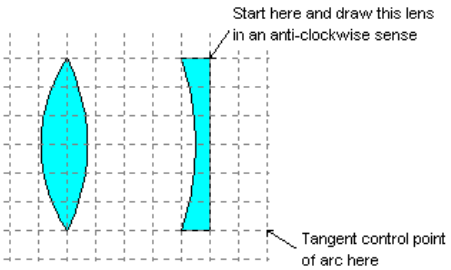
* Clear the workspace with **File -- New**.

* Turn on the grid and snap to grid options.

* Create a simple bi-convex lens as shown on the right. Use the **End/Tangent** method of specifying the arcs with the sequence of points as indicated.



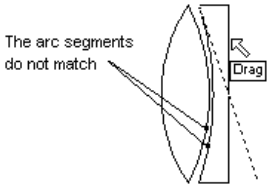
* Create a plano-concave lens a few grid spacings to the right of this as shown below.



Since the first element was created in a clockwise sense it is important that you create the second element in an anti-clockwise sense. This is because the two segments which are to be matched must be drawn in the same direction; in this example the two arcs to be matched are drawn downwards.

* Select the second lens and drag it up to near the first lens and notice that the arc segments are not the same shape.

* Put the second lens back near where you created it and finish dragging.



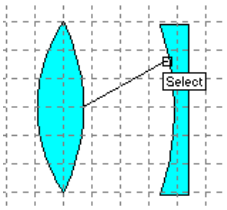
* Choose **Modify -- Link segments**.

* Position the select cursor box somewhere over the right hand arc of the bi-convex lens and click the primary mouse button.

A rubberband will attach itself to the middle of the arc.

* Move the select cursor box to a point over the arc of the second lens and click the primary mouse button.

A dialog box with two options "Stretch" and "Move" will appear.

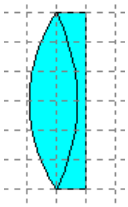


* Click on the **Move** button.

The second lens will then be moved up against the first lens and the shape of the arc will be adjusted to match the first lens exactly.

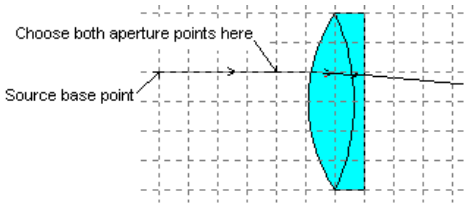
* Select the left hand lens and drag the tangent control point of the right hand arc segment.

You will see that a gap never appears between the two lens shapes. The arc of the second lens changes shape to match the first lens at all times.



Minimising chromatic aberration

* Create a plane source with three rays using the points as shown on the right (use the snap to grid).



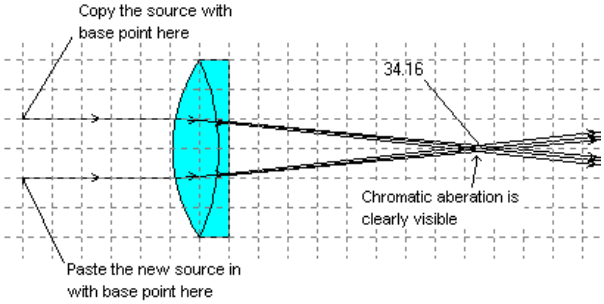
* Select the rays making up the source and make a white ray (as was done in the example on dispersion) by changing the colours of the second and third ray to green and blue respectively.

* While the source rays are still selected choose **Edit -- Copy** and specify the copy base point as the grid intersection where the source starts.

* Choose **Edit -- Paste** and specify the paste base point two grid spacings lower down so that a new source will be pasted in symmetrically with respect to the lens axis as shown below.

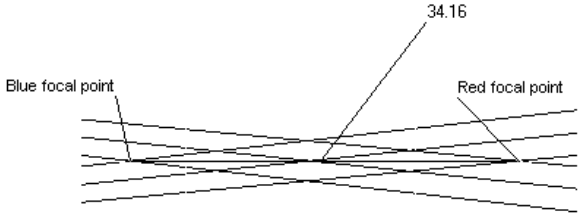
The chromatic aberration of the lens is clearly significant.

* Zoom in on the region where the rays are focused and create a tape measure that measures the distance



between the focal point of the blue rays (use a ray intersection snap) and the focal point of the red rays (use another ray intersection snap) as shown below.

* Select the tape measure and use **Modify -- Tape measure...** to turn on the **Distance** and **Leader fixed** options.



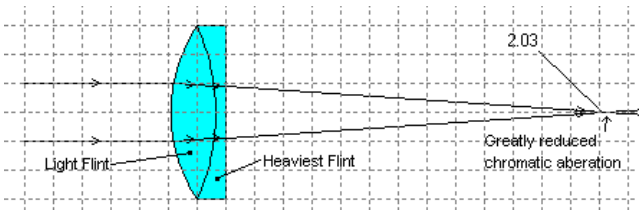
* Use **Zoom -- Previous** to return to the previous scale and drag the tape measure readout to a convenient location.

* Select the left hand lens and choose **Modify -- Element > Refractive index...**. Click on the **Material...** button and choose **Light Flint** then click on **Ok** in the **Select Material** and **Refractive Index** dialog box.

* Select the right hand lens and change its refractive indices to those of **Heaviest Flint** in the same manner as above.

The chromatic aberration of the doublet combination will be greatly reduced now as shown below.

You can reduce the chromatic aberration still more by changing the radius of the boundary between the two parts of the doublet.



* Select the left hand lens and then begin dragging the tangent control point of the right hand arc segment.

You will see that dragging the arc can produce significant changes in the degree of chromatic aberration.

* Drag the tangent control point and try and minimize the distance between the red and blue focal points. When you get close to the minimum, hold down the shift key to turn on the fine drag mode. This allows you to make finer adjustments as the mouse movements are scaled down by a factor of 10 before they are applied to the drag.

You should be able to reduce the distance to less than 0.01 drawing units without too much trouble. For finer control in changing the arc radius, move the tangent control point as far from the arc starting point as possible in the desired direction and use the shift key for fine dragging.

Suggestions for further activities

- Try and set the focal length of the lens to a specific value (add a tape measure to show the focal length) and reduce chromatic aberration at the same time. You'll need to adjust the front surface of the lens as well so some trial and error will be needed.

- Unlink the segments (by selecting one of the elements and using Modify -- Unlink segments). Move the right hand lens away from the bi-convex lens and re-link the segments but this time use the **Stretch** option and see what the difference is.

An introduction to conic sections

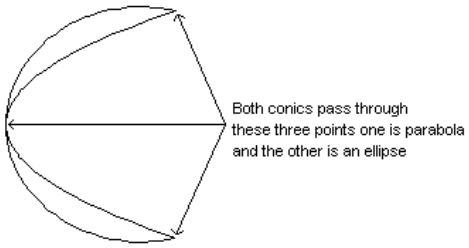
Raytrace allows you to create elements which contain segments that are conic sections, i.e. ellipses, parabolas and hyperbolas.

In this example you will:

- Learn how to create conic segments and constrain their shapes
- Create a parabolic reflector and examine the properties of the focus
- Create an elliptical lens region that is free from spherical aberration
- Use the “join” facility to connect separated elements

Conic segment options

In general you can define a conic section with the equivalent of three points and the eccentricity of the conic. The fact that you need the eccentricity is illustrated on the right where a parabola (eccentricity = 1) and an ellipse (eccentricity = 0.5) both pass through the same three points.



When you draw a conic you are always required to define four points: the start point, the focus, the vertex and the end point. The vertex point is the point of intersection of the conic and its axis. How these points are used in defining the shape of the conic depends upon the **Conic Settings** that are in force at the time.

* Choose **Defaults -- Conics Settings**.

This starts a dialog box giving you five options for constraining a conic. How these options constrain the shape of the conic is explained below.

Focus, End, Axis
The start, focus and end points remain fixed where specified. The line joining the focus and vertex points only defines the axis direction. The actual vertex point is shifted along the axis to be consistent with the other points and the axis direction.

Focus, Vertex, End Angle
The start, focus and vertex points will remain fixed where specified. The actual end point is moved to the point where the conic crosses a line joining the focus and the specified end point. This is the default option when you start Raytrace.

Vertex, Axis, Eccentricity
The start and vertex points remain fixed. The focus point is used to determine the direction of the axis relative to the vertex point and the end point defines the direction from the focus to the actual end point. The eccentricity remains fixed at the value shown in the **Conic Segment Options** dialog box.

Vertex End, Eccentricity
The start, vertex and end points remain fixed. The specified focus point is not used at all. The axis direction and focus point will be determined from the other parameters. The eccentricity remains fixed at the value shown in the **Conic Segment Options** dialog box.

Focus, End, Eccentricity
The start, focus and end points remain fixed. The vertex point is not used. The axis direction and vertex point will be determined from the other parameters. The eccentricity remains fixed at the value shown in the **Conic Segment Options** dialog box.

Note that the start point always remains at the specified point no matter which option you choose.

A parabolic reflector

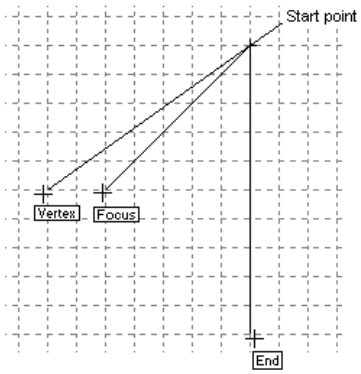
* In the **Conic Segment Options** dialog box, choose the **Vertex, End, Eccentricity** option and make sure the value in the **Eccentricity** edit box is 1 the click on **Ok**.

* Turn on the grid and snap to grid options.

* Choose **Create -- Element** and select a starting point about one third of the way down and half way across the Raytrace window.

* Click on the secondary mouse button and choose **Conic Segment** from the popup menu.

* Specify the focus, vertex and end points relative to the starting point as here.



Note the rubberband which remains anchored to the start point throughout.

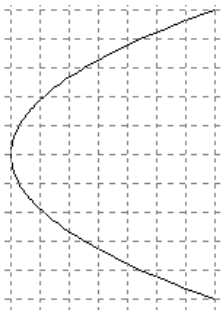
When you finish this the parabola will be drawn shown below.

* Turn off the grid and snap to grid options.

* Choose **Create -- Source > Point...** and enter 10 as the number of rays.

* Press the **F** key or click on the secondary mouse button and choose **Focus Snap** from the popup menu.

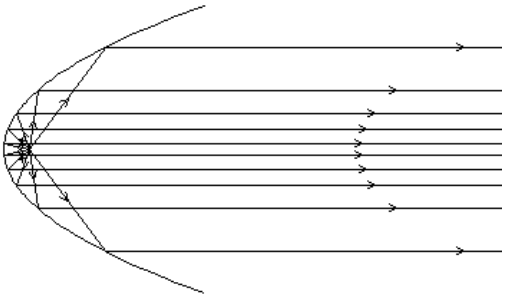
* Position the focus select box somewhere over the parabola and click the primary mouse button.



This links the source centre point to the focus of the conic (parabola).

* Anchor the first aperture point to the upper end of the parabola using an end snap and similarly for the second aperture point and the lower end of the parabola.

This should result in a ray diagram as shown on the right.



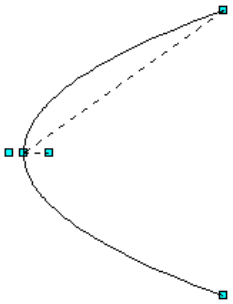
Note:

- All the rays are reflected parallel to the axis of the parabola.
- The focus point of the conic (same point as the centre of the source) is not where you originally selected the focus point.

* Uncheck the menu item **Options -- Show > Red Rays** to temporarily hide the rays.

* Select the parabola and notice the five drag handles that appear.

* Try dragging the drag handle at the focus.

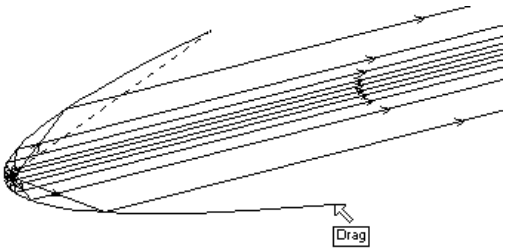


Nothing will happen since with the **Vertex End, Eccentricity** option the focus point is determined from the other three points and the eccentricity.

* Check the menu item **Options -- Show > Red Rays** and try dragging the start, vertex and end points.

For example if you drag the end point you could end up with something like that shown below.

If the point source "flips over" during this then stop dragging, select one of the source rays and use **Modify -- Source > Flip point sources** to flip it back onto the reflector.



The fifth drag handle

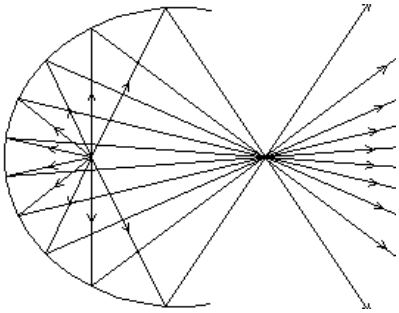
You should have noticed the fifth drag handle which always appears near the vertex of the parabola. This drag handle gives you access to changing the conic segment options for this particular segment.

* Click on the fifth drag handle.

The **Conic Segment Options** dialog box will appear and you can now change how the focus, vertex and end points will be used or change the eccentricity. These changes only apply to this particular conic however the option you choose will also become the default for new conics.

* Choose the **Vertex, Axis, Eccentricity** option and change the eccentricity value to 0.5 then click on **Ok**.

The curve will change to an elliptical shape and you can see the property of an ellipse: rays leaving one focus are reflected back to the other focus.



Elliptical lens

An elliptically shaped refracting region will focus parallel rays to a point without spherical aberration provided the eccentricity of the ellipse is equal to the reciprocal of the refractive index.

* Choose **File -- New**.

Creating the ellipse

* Choose **Defaults -- Conic Settings...** and choose the **Vertex, Axis, Eccentricity** option and change the eccentricity value to 0.8 then click on **Ok**.

* Turn on the grid and snap to grid options.

* Choose **Create -- Element > Surface** and specify a start point about half way down and three quarters of the way across the Raytrace window.

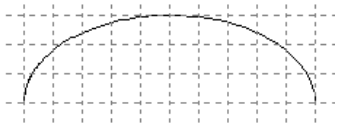
* Click on the secondary mouse button and choose **Conic segment** from the popup menu.

* Select the focus point a few grid spacings horizontally to the left of the start point. The exact distance from the start point is not important only the direction.

* Select both the vertex and end points as the same point 10 grid spacings horizontally to the left of the start point.

* Click on the secondary mouse button and choose **Finished** from the popup menu.

This will produce a half ellipse as shown here.

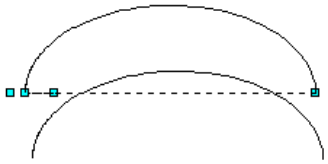


* Turn off the grid and snap to grid options.

* Select the half ellipse then choose **Edit -- Copy** and specify a base point somewhere near the end of the element.

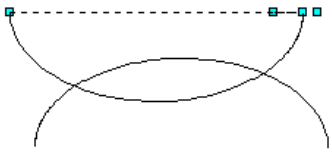
* Choose **Edit -- Paste** and specify a base point a bit lower down the Raytrace window.

You will now have two identical elliptical arcs one of which is still selected.



* Choose **Modify -- Rotate**, enter 180 degrees as the rotation angle in the resulting dialog box then, when the cursor changes to the centre point form, specify the centre of the rotation somewhere near the middle of the selected elliptical arc.

This will flip the selected elliptical arc over.



* Select the second arc as well then use **Modify -- Element > Join** followed by **Modify -- Element > Change to > Region** to form a complete elliptical region from the two halves.

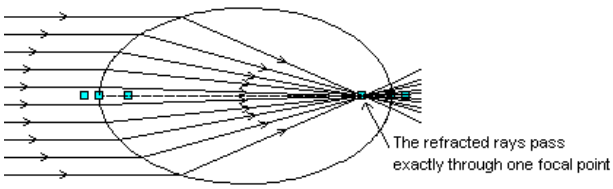
You cannot create a completely closed ellipse using a single conic segment in Raytrace since the start and end points would not be distinct and you need to resort to making the complete ellipse from two halves as was done here.

* The ellipse should still be selected so use **Modify -- Element > Refractive Index...** to change its refractive index to red rays to 1.25 (the reciprocal of 0.8).

* Create a plane source striking the ellipse parallel to the major axis as shown below. (Use the snap to grid option to align the source.)

* Select the ellipse and you will see that the refracted rays pass through one of the foci of the ellipse.

Although this is an interesting piece of geometry it is pretty useless as a lens since the focal point lies within



the refracting medium. To overcome this, a spherical surface needs to be added with its centre on the focus of the ellipse. Raytrace comes with an example script file which illustrates such an elliptical lens with a spherical back surface, the script is called elliplen.rsc.

Customising the button bar

The Raytrace button bar gives you the facility to make menu items and scripts easily accessible. This can make it faster and easier for novice users to access the key features necessary for a specific task. You can create different button bars and load the one which best suits the task at hand.

In this example you will:

- Learn how to control and edit the button bar
- Create a new button for the button bar
- Link a button to a script or menu item

The button bar is controlled by items in the menu **File -- Button Bar >**. Some of the menu items are self explanatory e.g. turning the button bar on or off and switching between a vertical arrangement down the left-hand side of the window or a horizontal arrangement across the top of the window.

If the button bar is not visible then perform the following step.

* Choose **File -- Button Bar > Load** and select the file raytrace.rbb in the Load button bar dialog box which appears.

A button linked to a menu item

This example will start by creating a new button to invoke the menu item **Zoom -- In**.

* Choose **File -- Button Bar > Add a button**.

A dialog box will appear giving you two options: **Run a script** or **Choose a menu item**. Click on the **Choose a menu item** button.

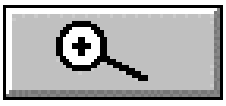
* Choose **Zoom -- In**.

This does not invoke the **Zoom -- In** function; it simply selects that menu item as the one to be a linked to the button. An "Open file" style dialog box will appear.

* Scroll through the list of files and select zoomin.bmp then click on **Ok**.

The new button will appear at the bottom of the button bar with the magnifier symbol as shown on the right. You can move it to a new position by choosing **File -- Button Bar > Move a button** and following the directions presented to you.

If you go to the trouble of creating new buttons you will want to save the modified button bar.



* Choose **File -- Button Bar > Save,** enter a name for the new button bar in the dialog box which appears and click on **Ok**.

When Raytrace starts, it loads the button bar file most recently loaded using **File -- Button bar > Load**. If no button bar has been loaded manually then it loads the button bar contained in the file raytrace.rbb file as a default. If, after saving your new button bar, you do not explicitly load it using this menu item then the next time Raytrace starts it will return to the previous button.

Creating your own button bitmaps

The file zoomin.bmp is supplied for the purposes of this example. You can create your own button bitmaps by using a bitmap editor such as Windows PaintBrush.

* Start PaintBrush or a similar bitmap editor program and open the file zoomin.bmp.

You will see that the file contains the central grey area of the button and the magnifier icon. The easiest way to create a new button bitmap is to edit one of the existing .bmp files supplied with Raytrace and save it under a new name. For example you could easily change the zoomin bitmap into a zoomout bitmap by changing the plus symbol to a minus symbol (zoom in PaintBrush to make it easier if you try this), save the modified bitmap in a new file called zoomout.bmp and create another button to invoke the **Zoom - Out** menu as described above.

The bitmap files are not required once you create the new button bar; the bitmap information is included in the button bar file when it is saved. The .bmp files supplied with Raytrace are for you to use in designing your own buttons.

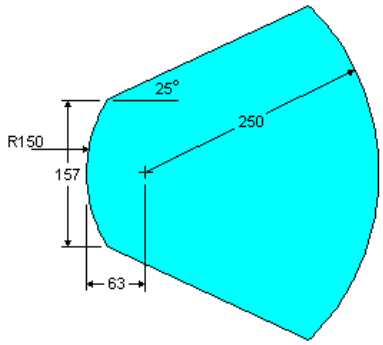
A button linked to a script

You can make a button run a Raytrace script simply by choosing the **Run a script** option after choosing **File -- Button Bar > Add a button.** In this case you will be presented with two “open file” type dialog boxes in sequence. In the first, select the script file that you want to run, in the second select the bitmap file for the button. The rest is the same as for a button linked to a menu item.

Solving a geometry problem

This example is included to illustrate the fact that you can make use of Raytrace's powerful editing facilities and, perhaps surprisingly, it's ray tracing ability, to solve geometrical intersection problems. One of the uses for this is to construct elements where the positions of all the vertices are not known.

As an example, consider the a shape like the one shown on the right where you know only the following information:



- Left hand arc radius = 150 units
- Chord length of left hand arc = 157 units
- Right hand arc radius = 250 units
- Axial thickness of element = 313 units
- Taper between arcs 25°

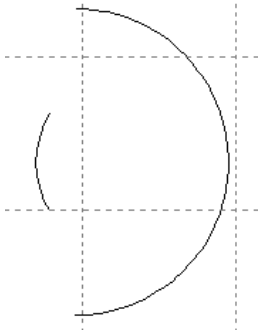
To draw this element you basically need to solve for the intersection between the tapered edges and the right hand arc. If you did this you could then enter the coordinates manually. However Raytrace can do this for you as shown below. You need to be familiar with the basic operations of drawing arcs and using snaps before you embark on a task like this one.

* Create the left hand arc first, drawing in an anti-clockwise direction (start at the top). Use either the **Radius/End** or the **End/Tangent** method and **Rel Coords** snaps to specify its chord length and radius.

* Set the grid spacing to 250 units, zoom out and use the **End/Tangent** method to create a semi-circular arc (in an anti-clockwise sense - start at the bottom) with radius 250 units somewhere nearby. (To make a semi circular arc use snap to grid and specify the tangent point at a point 90° to the chord direction).

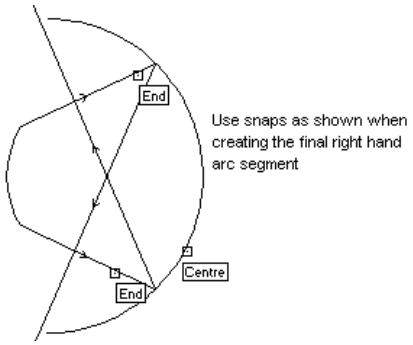
* Select the large arc and choose **Modify -- Move**. In response to the base point cursor, use a centre snap on the large arc. In response to the "point cursor" use a **Rel Coords** snap to pick a point 63 units to the right of the mid point of the small arc.

Now you should have the two arcs positioned as shown on the right.

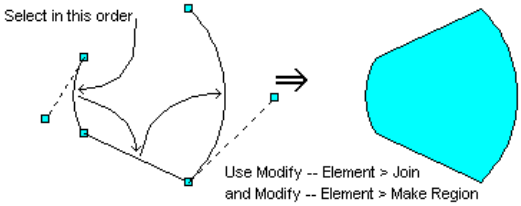


* Draw a horizontal ray from the bottom of the left hand arc towards the right and then use **Modify -- Rotate** to rotate it 25° clockwise about its starting point. (Or use a **Rel coords** snap to create it 25° to start with.) Create a similar ray starting at the top of the left hand arc.

* Now draw another arc (anti-clockwise) overlaying the right hand arc but this time use the **Centre/End** option and specify the arc start, end and centre by snapping to the ends of the rays and the centre of the existing large arc (as indicated on the right). When you have finished delete the semi-circular arc and the rays.



* Draw a connecting surface element between the lower ends of the two arcs, select the left hand arc, the line segment and the right hand arc in that order then choose **Modify -- Element > Join** and **Modify -- Element > Make Region** to create the final element as shown here.



Shortcut keys

Snap actions

These keys allow you to select a snap without having to click the secondary mouse button.

E	---	End snap
C	---	Centre snap
T	---	Tangent snap
M	---	Mid point snap
F	---	Focus point snap
V	---	Conic Vertex snap
I	---	Ray intersection snap
L	---	Perpendicular snap
Z	---	Terminal snap
A	---	Absolute coords entry
R	---	Relative coords entry
N	---	None (Cancels an unwanted snap if you change your mind)

Grid actions

G	---	Toggles the display of the grid on and off
S	---	Toggles the snap to grid option on and off

Fertility actions

Pressing these keys changes the setting of the fertility option indicated for all selected rays.

F2	---	Reflect always
F3	---	Reflect if no refraction
F4	---	Refract
F5	---	Show normal
F6	---	Forward project
F7	---	Back project
F8	---	Parent by reflection
F9	---	Parent by refraction

Ray colour change

Shift + F2	---	Change the colour of all selected rays in the cyclic order of Red → Green → Blue → Red

Selecting

Shift + F3	---	Starts an extended select operation (Same as menu item **Edit -- Select extended**)
Shift + F4	---	Fine select - toggles a pixel level zoom box centred on the current cursor position so that you can select at the pixel resolution

Miscellaneous

P	---	Toggles the pause state for trail updating. (Same as menu item **Modify -- Pause Trail update**)
ESC	---	Aborts most operations
Del	---	Same as choosing **Edit -- Delete**.