RADIANCE:
a simulation tool for daylighting systems

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This document serves as course notes. It is intended to complement the RADIANCE original documentation giving more details in some essential areas. Technical terms used within this document come mainly from the lighting domain [CIE87] or the computer graphics domain [Jem92]; the remaining terms are part of the specific jargon employed in the RADIANCE original documentation.

`This character type refers either to a command (a program name) or the content of a file.` *`Adjustable parameters appear in italic.`*

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Introduction

RADIANCE development started in 1984 at the Lawrence Berkeley Laboratory (Berkeley, USA). At the same time, the "radiosity" method was first applied in the computer graphics domain. The "ray tracing" method already used since the 1970s was considered to be incapable of computing interreflections in a reasonable amount of time (note that this idea still perpetuates in some recent publications). The most original part of RADIANCE lies within its interreflection calculation algorithm that uses a backward ray tracing method [War88a&b] [War92a]. As far as we know this is one of the rare (or even the unique) implementations of a purely ray tracing interreflection algorithm in a realistic rendering program; almost all other similar programs are based on radiosity algorithms.

In 1990 the Laboratoire d’Energie Solaire et de Physique du Bâtiment (LESO-PB in Lausanne, Switzerland) initiated a project on daylighting simulation tools [Sca94]. Greg Ward, the principal author of RADIANCE, joined that project for 9 months during which he greatly extended the capabilities of the software especially for daylighting simulation purposes. In parallel, RADIANCE has been included into the ADELINE software developed within an IEA task. Since then, RADIANCE has been available in two versions: the original one as free software for UNIX workstations and a slightly limited MS-DOS version included within ADELINE. The latter is distributed by the research teams that have contributed to ADELINE. This course is based on that version. Differences from the original UNIX version will be highlighted in the text.

RADIANCE is currently a mature ray tracing software package that enables accurate and physically valid lighting and daylighting simulations [War90] [War94b]. It is well established in the research community and has already been used for many projects [War89] [Com92-94] [Pau92] [Fro93] [Lom93] [Nov93] [War94c] [Cla96] [Moe96]. Some validation studies have also been carried out on RADIANCE (see for instance references [Gry88-89] [Com94] and [Mar97]). Due to to the great flexibility of RADIANCE (almost all calculation procedures can be specifically controlled by the users through appropriate parameters), any validation study reflects more the skills of the user who performed it than just the accuracy of the internal algorithms! However, they are many appropriate ways of using RADIANCE and the material presented in this document should not be considered as the unique or best practice for accurate simulation of daylighting systems.

Remarks:

A ray tracing bibliography is maintained on the Internet at:

`http://www.cs.cf.ac.uk/Ray.Tracing/`

A large bibliography on radiosity as well as other very interesting documents regarding this technique are also available on the Internet at:

`http://www.ledalite.com/library-/rrt.htm`

Physical basis

RADIANCE is based on the backward ray tracing algorithm. This means that light rays are traced in the opposite direction to that which they naturally follow. The process starts from the eye (the viewpoint) and then traces the rays up to the light sources taking into account all physical interactions (reflection, refraction) with the surfaces of the objects composing the scene. Polarisation of light rays is not taken into account.

RADIANCE uses a geometrical description of the "scene" based on the boundaries of objects (i.e. their external surfaces). The volumes enclosed by these surfaces are always empty. Surfaces have definite orientation (i.e. a normal vector is attached to each surface).

The objects composing the scene are described using a Cartesian co-ordinate system (X,Y,Z). Originally the X axis is directed towards the East, the Y axis towards the North and the Z axis towards the zenith. It is usually much more convenient to align the principal planes of the scene (e.g. the walls of a rectangular room) along the X,Y,Z axes and then to rotate the sky description around the Z axis in order to correctly orient the scene (this will be explained later).

Co-ordinates can be given in any unit of length. Of course when a single scene is formed by more than one scene file, these must use same unit of length.

Each single ray "carries" a certain amount of radiance (hence the name of the software) expressed in [W/m^{2}sr]. The radiance is divided into three "channels" corresponding to the red, green and blue primary colours (abbreviated as r,g,b). The total radiance R is calculated as a weighted sum of the radiances Rr, Rg and Rb carried by the three channels:

$$R = 0.263 \cdot Rr + 0.655 \cdot Rg + 0.082 \cdot Rb \qquad [W/m^2sr]$$

(note that: 0.263+0.655+0.082 = 1)

The transformation from radiance R (radiometric unit) to luminance L (photometric unit) is given by:

$$L = 179 \cdot R = 47.1 \cdot Rr + 117.2 \cdot Rg + 14.7 \cdot Rb \qquad [cd/m^2]$$

This method of handling colours relates to a perceptual model which is unable to fully account for spectrally dependent properties. Compared to programs where the spectral distribution of the light is modelled using many channels covering narrow wavelength bands, RADIANCE is less precise and is unable to model all possible colours. This disadvantage is far outweighted by the fact that colour data for materials are much more frequently available as colorimetric values (e.g. CIE XYZ tristimulus system). than as detailed spectral curves! In addition, for our type of application spectral effects are rather limited since colours commonly used in buildings are not very saturated (i.e. their spectral reflection curves are smooth).

From the Y,x,y values the reflectances or transmittances C of the corresponding materials are divided into the three red, green and blue channels as follows (see file: `rgb.cal`):

$Cr = 2.739 \cdot X - 1.145 \cdot Y - 0.424 \cdot Z$
$Cg = -1.119 \cdot X + 2.029 \cdot Y + 0.033 \cdot Z$ where: $X = x \cdot Y/y$
$Cb = 0.138 \cdot X - 0.333 \cdot Y + 1.105 \cdot Z$ $Z = (1-x-y) \cdot Y/y$

Exercise:

Start the `gcalc` program by typing the command:

```
gcalc rgb.cal
```

and use it to calculate the reflectances Cr Cg and Cb of some paints whose Y,x,y values are listed in Appendix 1.

Remarks:

In the RADIANCE UNIX original version this program is named `calc` instead of `gcalc` (this latter name has been chosen to avoid conflicts with another program called `calc` originally included on PC systems).

Since version 2.5, RADIANCE uses a slightly different colour model. The corresponding formulas become:

$$R = 0.265 \cdot Rr + 0.670 \cdot Rg + 0.065 \cdot Rb \qquad [W/m^2 sr]$$

$$L = 179 \cdot R = 47.4 \cdot Rr + 119.9 \cdot Rg + 11.7 \cdot Rb \qquad [cd/m^2]$$

$Cr = 2.565 \cdot X - 1.167 \cdot Y - 0.398 \cdot Z$
$Cg = -1.022 \cdot X + 1.978 \cdot Y + 0.044 \cdot Z$
$Cb = 0.075 \cdot X - 0.252 \cdot Y + 1.177 \cdot Z$

The principles of tristimulus colorimetry and the transformations from Y,x,y to Cr, Cg and Cb values are presented in a tutorial fashion in [Mey86]. An annotated bibliography of relevant literature is also provided.

See also the "Frequently Asked Questions about color" document available on the Internet from the page:

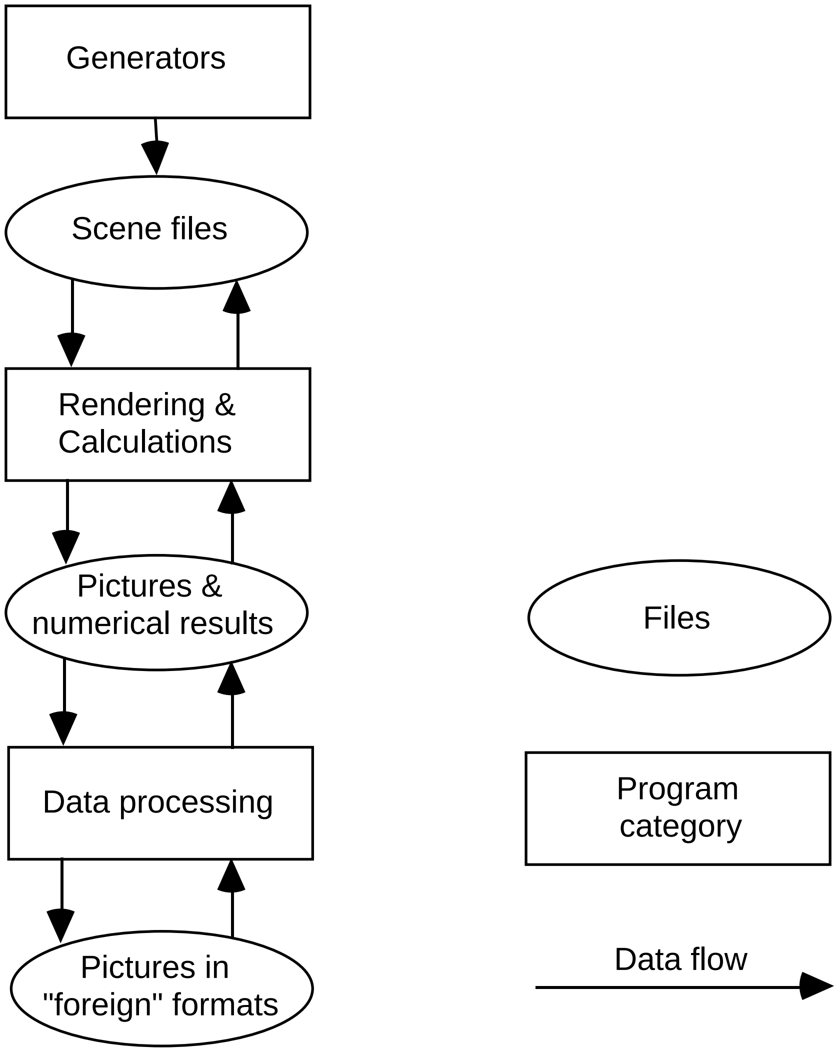
`http://Home.InfoRamp.Net/~poynton/`

"Photometry and Radiometry; a Tour Guide for Computer Graphics Enthusiasts" provides a good tutorial on this subject. It is available on the Internet from the page:

`http://www.ledalite.com/library-/photom.htm`

General structure of the software

RADIANCE software comprises many programs that all perform specific tasks. Depending on the data they handle, these programs can be divided into three distinct categories:



To enable a clear distinction between the various RADIANCE file types a set of conventional extensions have been defined:

File content	Extension	File type
scene (materials and geometry definitions)	.rad	text
numeric data tables	.dat	text
functions	.cal	text
intermediate data to calculate glare indices	.gla	text
progress reports	.log	text
parameters defining a RADIANCE "project"	.rif	text
octree ("compiled" version of a scene)	.oct	binary*
RADIANCE picture	.pic	binary*
ambient illuminance values	.amb	binary*
TIFF format picture	.tif	binary

* Use `getinfo` to view a list of all commands and parameters that have been used to produce these binary files: `getinfo` *`filename`*

Structure of a "scene" file

Scene files can contain four basic types of data described by a simple syntax:

1) comments:

```
# all lines beginning with character #
```

2) primitives:

modifier type identifier
N S1 S2 S3 ... SN
0
M R1 R2 R3 ... RM

where:

modifier	an identifier previously defined or `void` if no modifier has to be applied
type	the primitive type
identifier	the name associated with this primitive
N	the number of string arguments
M	the number of real arguments
Sx Rx	arguments for this specific primitive

Example:

```
# a slightly specular red paint:
void plastic red_paint
0
0
5 1 .02 .02 0.03 0
# sphere centred at location (1,1.5,0) with radius 2
red_paint sphere red_ball
0
0
4 1 1.5 0 2
```

3) calls to external programs:

`!`*program_name parameters*

Remarks: the outputs of the called program have to be formatted according to scene file syntax. In the MS-DOS version, only programs that belong to the RADIANCE software can be called this way!

4) identifier aliases:

modifier `alias` *new_identifier old_identifier*

Long input may extend over multiple lines using the \ continuation character (see for example `genprism` calls in the `chair.rad` file).

Model of a sky

Example: a CIE overcast sky (`cie.rad`)

```
# CIE overcast sky (Horizontal illuminance: 10000 Lux)
# Ground reflectance: 0.1

!gensky 1 1 1 -c -b 22.8634396 -g 0.1

skyfunc glow sky_glow
0
0
4 1 1 1 0
sky_glow source sky
0
0
4 0 0 1 180

skyfunc glow ground_glow
0
0
4 1 1 1 0
ground_glow source ground
0
0
4 0 0 -1 180
```

Remarks:

The `gensky` program prepares the radiance distribution of the sky and assigns the `skyfunc` identifier to it. In order to produce a sky giving a specified horizontal illuminance Eh (in [lux]), the zenith radiance Rz has been explicitly given using option `-b`. The following formulas serve for that purpose:

CIE overcast sky: $$Rz = \frac{9}{7} \cdot \frac{Eh}{\pi \cdot 179}$$

Uniform overcast sky: $$Rz = \frac{Eh}{\pi \cdot 179}$$

To specify colours for the sky and the ground while preserving the radiance values imposed by `skyfunc` it is necessary to normalise (R = 1 [W/m^{2}sr]) the radiances Rr Rg and Rb passed as arguments to the `glow` material type. The Crn Cgn and Cbn values defined in the `rgb.cal` file serve for this prupose.

Similarly the radiances Rr Rg and Rb of a light source of luminance L [cd/m2] are calculated as:

$$Rr = \frac{Crn \cdot L}{179} \qquad Rg = \frac{Cgn \cdot L}{179} \qquad Rb = \frac{Cbn \cdot L}{179}$$

Exercise:

Modify the file `wsol12.rad` in order to model a spring equinox sky (21st of March) at 13h00 (local time) and save it as a new file named `equ13.rad`
Give appropriate colours to the sky and the ground (use colours listed in Appendix 1).

Interactive visualisation using `rview`

The `rview` program produces a picture that is displayed on the screen while the calculations are performed. It mainly serves to detect errors in a scene file and to choose appropriate view points.

Exercise:

Convert `equ13.rad` into an "octree" (compiled version of a scene) using the `oconv` program:

```
oconv equ13.rad > equ13.oct
```

Choose a viewpoint (x,y,z coordinates) and a view direction (a vector dx,dy,dz). Define the field of view of the picture by an horizontal angle (vh) and a vertical angle (vv) (see Appendix 3). Start `rview` with the appropriate options and their corresponding arguments (an option is a parameter of a program that is specified by a name that begins with a character '-' and that is followed by its argument value).

```
rview -vp x y z -vd dx dy dz -vh vh -vv vv  equ13.oct
```

Remarks:

In this case the view point has absolutely no importance since the scene only comprises two infinitely remote sources!

The programs that read octrees (e.g. `rview`) also access the original `.rad` files. Therefore these original scene files should not be deleted after they have been converted into an octree! For the same reason if an octree is moved from one directory to another, the scene files that were merged into it need also to be moved.

To following command prints a list of default values assumed for each option:

```
rview -defaults
```

The "exposure" of a RADIANCE picture

The picture produced by `rview` first appears totally white! This is due to the limited luminance range of the VDU screen: the upper luminance that can be displayed is about 100 [cd/m^2] while a real sky can well reach luminances around 10000 [cd/m^2]. To solve this problem an "exposure" factor (e) is attached to each RADIANCE picture. For a pixel that has to depict a luminance L, the screen displays it with a fraction P of its maximum reachable luminance:

$$P = e \cdot \frac{L}{179}$$

P varies between 0 (pixel off) and 1 (pixel glowing at its maximum value).

The exposure e can be calculated by specifying a maximum luminance Lmax over which a white coloured pixel will glow at its maximum value:

$$e = \frac{179}{Lmax}$$

By default (e.g. when the calculation starts with `rview`) e = 1.

A specified exposure can be set to a picture by passing it through the `pfilt` filter program:

pfilt -1 -e *exposure_value orig.pic* > *final.pic*

`pfilt` is also able to set an automatic exposure that is appropriate for the picture:

pfilt *orig.pic* > *final.pic*

The exposure of a picture appears in the output of the `getinfo` program as a line formatted like:

EXPOSURE=*xxxxx*

IMPORTANT! : the exposure is a multiplying factor. If `getinfo` outputs multiple `EXPOSURE` lines for the same picture, its real exposure is the PRODUCT of all these values. For the same reason, if a picture has an exposure e1 that has to be adjusted to a new value e2, the exposure parameter to specify when starting `pfilt` is the ratio e2/e1 instead of e2 only!

A proper exposure can be calculated from the accomodation level of the eye. See reference [War94a] for details. From release 3.1, the UNIX RADIANCE version also contains a very useful program called `pcond` which can filter a picture according to human visual perception characteristics. The reference [War97] gives full details about the features offered by `pcond`.

Rendering a picture using `rpict`

The usual way of computing RADIANCE pictures is to start the `rpict` program in "background" mode (on a UNIX workstation) or in a MS-DOS window (on a PC running Windows95) and wait for the final result while performing other tasks...

Exercise:

Use `rpict` to produce a picture of the `equ13.rad` sky (the following command must be given on a single line):

```
rpict -x X_#pixels -y Y_#pixels -t 60 -vd dx dy dz
-vh vh -vv vv equ13.oct > equ13.pic
```

The output of `rpict` is stored into the "picture file" `equ13.pic`
Option `-t 60` specifies that a progress report is requested every 60 seconds. Once the picture is ready, the `vgaimage` program (MS-DOS version) or the `ximage` program (UNIX version) can be used to display the picture on the screen:

`vgaimage equ13.pic`   or   `ximage equ13.pic`

By clicking on a pixel and then pressing the "L" key, its luminance value is displayed on the screen. Using this feature, devise an appropriate exposure for the picture. Then use `pfilt` to adjust the exposure and put the result into `nequ13.pic`

Special projections using `rtrace`

The `rtrace` program is able to trace rays in a scene from any point in any direction. It is especially useful to produce numerical values (e.g. illuminance profiles) or to render picture using special projections (e.g. stereographic or cylindrical projections).

Exercise

How is it possible to produce a cylindrical projection of the sky defined in `equ13.rad` ?
First a direction vector must be computed for each pixel composing the picture. This is defined by formulas contained in the `pcyl.cal` file. The picture size is defined by the parameters *XD* (number of horizontal pixels) and *YD* (number of vertical pixels). The bottom line of the picture will be associated to an altitude specified by the *AM* parameter (suggestion: use an altitude just below the horizon like `AM=-10`). The top of the picture will always be associated to the zenith (altitude=90°).

The rendering of the picture makes use of a series of programs linked by "pipes". Note that this is a typical way of working on UNIX system!. The following command must be given on a single line:

```
cnt YD XD |
rcalc -f pcyl.cal -e XD=XD;YD=YD;AM=AM |
rtrace -x XD -y YD -fac equ13.oct |
pfilt -1 -e .0179 > pcyl.pic
```

The `cnt` program produces a series of successive integer values grouped in pairs, giving the x,y position of each pixel. Then these positions are converted into direction vectors by `rcalc`. Each output line of `rcalc` contains six values:

Xorig Yorig Zorig dx dy dz

These lines "feed" the `rtrace` program that will then trace rays starting from points (*Xorig,Yorig,Zorig*) (in our case positioned at the origin 0,0,0) in the directions given by the vectors (*dx,dy,dz*). Finally the exposure is set by `pfilt`.

Picture processing

A RADIANCE picture can be considered as a matrix of positive real values on which mathematical operations can be performed. Note that the RADIANCE picture format does not allow pixels with negative values since negative radiances have no physical meaning! [War91c]

They are many ways of transforming RADIANCE pictures using the `pcomb` program which enables operations to be made over one or many pictures at a time. As an example the following command superimposes azimuth and altitude axes on `pcyl.pic` :

`pcomb -f axis.cal -e XD=`*XD*`;YD=`*YD*`;AM=`*AM* `pcyl.pic > npcyl.pic`

This command tells `pcomb` to compute output radiances according to the formulas specified in the `axis.cal` file. These formulas use the `axe` variable defined so that `axe=1` for pixels located on the axis and `axe=0` otherwise. The `if` functions indicate that the output radiances are set to `ro=go=bo=1` on the axis (this means that the axis will appear a white line). Everywhere else the output radiances are set to the original values `ri(1),gi(1)` and `bi(1)` of the input picture.

It is sometimes useful to assemble multiple pictures into a single one by juxtaposition. The `pcompos` program serves for this purpose. In order to have a resulting picture that fits within the screen limits, the input pictures should first be reduced in size using the `pfilt` program. For instance to assemble two pictures by juxtaposition their size are first reduced by a factor of 2:

`pfilt -1 -x /2 -y /2` *orig.pic* `>` *reduced.pic*

Note that here `pfilt` does not perform any exposure adjustment since the `-1` option is set without any `-e` option specified.

Then the two reduced pictures are assembled either vertically (i.e. in a single column):

`pcompos -a 1 -s 5` *first.pic second.pic* `>` *result.pic*

or horizontally (i.e. in two columns):

`pcompos -a 2 -s 5` *first.pic second.pic* `>` *result.pic*

Remarks:

The radiances R obtained by `pcomb` or `pcompos` are calculated from input values that INCLUDE the specific exposure of each input picture:

`R = f(e1·R1, e2·R2,... en·Rn)`

instead of:

`R = f(R1,R2,...Rn)`

with `Ri` the radiance of the input picture `i` and `ei` its exposure.

The output pictures of these programs always have an exposure `e=1.` The multiple `EXPOSURE` values obtained from `getinfo` refer to the original input pictures only! This means that without special procedures, the radiance or luminance values obtained from `vgaimage` or `ximage` will no longer be valid for such pictures!

The `getinfo` program can also be used to get the pixel dimensions of a picture: `getinfo -d` *`picture.pic`*

To export a RADIANCE picture to other programs it is necessary to convert it to a more standard picture format (usually the TIFF format serves for this purpose). The `ra_tiff` program performs this transformation:

`ra_tiff -g` *`gamma_value picture.pic picture.tif`*

By experience a gamma value of 1.8 is usually appropriate. For more details regarding gamma correction see the FAQ documentation available on the Internet at:

`http://Home.InfoRamp.Net/~poynton/GammaFAQ.html`

The program `pvalue` is able to extract the radiances Rr, Rg and Rb of each pixel of a RADIANCE picture and convert them into an ASCII tabular format that is then easy to read by any other application. To ensure that `pvalue` outputs the radiance values without taking into account the exposure, option `-o` must be used!

Exercise:

Use `pcomb` to draw axes on `pcyl.pic`. Then assemble the resulting picture with `pcyl.pic` into a new composed picture and finally transform it into a TIFF format picture.

Model of a room daylit by an anidolic light-shelf

The basic principles of RADIANCE have been introduced. Now we consider a more detailed example of a rectangular simple room (length=7 [m], width=5 [m], height=3 [m]) daylit from the south facade by two openings (see Appendix 2). The lower window offers a direct view to the outside. The upper opening is equipped with an anidolic internal light-shelf [Com93b] [Com94]. For convenience, these elements and their materials are defined in separate `.rad` files:

`cie.rad`	a CIE overcast sky
`mat.rad`	definitions of the materials
`room.rad`	the room with empty openings
`system.rad`	the daylighting system alone (window glasses and the anidolic light-shelf)

Remarks:

The `system.rad` file calls the genrator program `genprism` to build the curved anidolic reflector at the line:

```
!genprism reflector ashelf ashelf.dat -c -e -l 0 0 5 | \
xform -rx 90 -rz 90 -t 0 0 3
```

The reflector profile is given in two dimensions as U,V coordinate pairs in the `ashelf.dat` file. The output of `genprism` is then passed through the filter program `xform` that enables the positioning of a scene using translations (option `-t`) and/or rotations around the axes of the space (options `-rx -ry` and `-rz`). The transformations are applied in the same order as they appear on the command line.
Caution!

command:	`xform -t 1 0 0 -rz 90`
is NOT equivalent to:	`xform -rz 90 -t 1 0 0`

To get the extreme dimensions of a scene file (i.e. its bounding box in the X,Y,Z space), use the following command:

`getbbox` *`filename.rad`*

Exercise:

Prepare the required transformations in order to position a desk (file `desk.rad`) and a chair (file `chair.rad`) somewhere in the room. Write the corresponding calls to `xform` in a new `furnish.rad` file. Then put the required scene files together in an octree named `model0.oct` and make a picture of this model using `rview` and the following view options:
-vp (viewpoint), -vd (view direction), -vh (horizontal view angle) and -vv (vertical view angle).

Important: choose a view point and a view direction in order to have the openings in the field of view!

To check the relative positions of the desk and the chair, use the `objview` program that will quickly display the scene:

```
objview furnish.rad
```

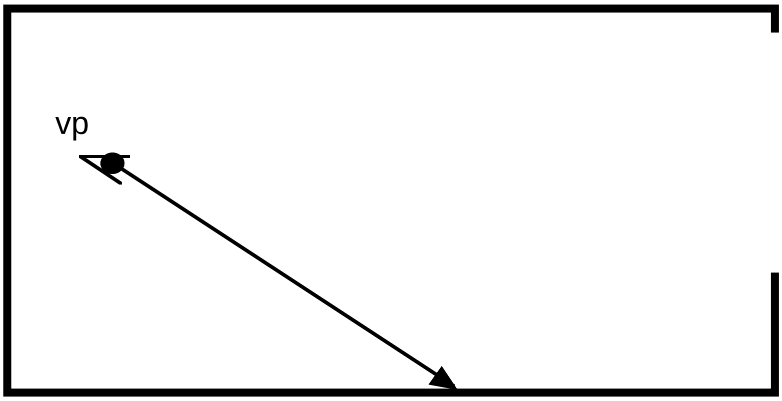
How ray tracing works within RADIANCE

The first results are not really convincing. This points out the main difficulty of using RADIANCE: how to control the ray tracing process in order to obtain good results. Many adjustable parameters have to be properly set to achieve this goal and the following section will explain, step by step, how the principal parameters modify the ray tracing process. The symbols used in the graphics are defined in Appendix 5.

STEP 1:

In the preceding example, `rview` was started without specifying any ray tracing parameter; this means that neither light coming through interreflections nor a constant ambient illuminance is taken into account (by default `rview` uses options `-ab 0` and `-av 0 0 0`). In addition the model does not include any light source (the `glow` material type used to model the sky is usually not considered as a light source!). Finally the sky seen through the openings is the only thing that appears in the picture.

-ab 0 (no interreflections)
-av 0 0 0 (no ambient value)



STEP 2:

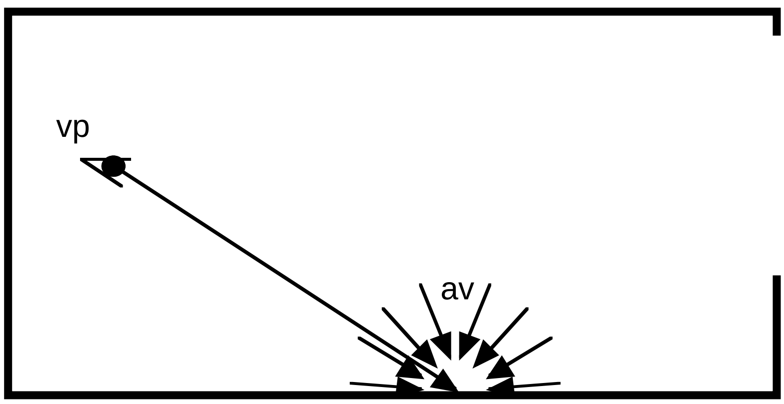
Now in a second attempt an ambient value is set and is supposed constant over the entire scene. This value is specified using option -av that needs three radiances Rr, Rg and Rb as parameters. Usually the ambient value is not coloured so that Rr=Rg=Rb=Ramb. Assuming a constant ambient illuminance Eamb expressed in [lux], Ramb is calculated as:

$$Ramb = \frac{Eamb}{179 \cdot \pi}$$

Exercise:

Calculate an appropriate ambient value for the scene and start `rview` again adding the corresponding `-av` option after the same view options as before.

-ab 0
-av .889 .889 .889 (ambient value set to 500 lux)



Now the objects of the scene appear uniformly lit and can be distinguished by their respective colours. This simple method of illuminating a scene using a constant ambient value is quite crude but very efficient since a single ray is traced for each pixel.

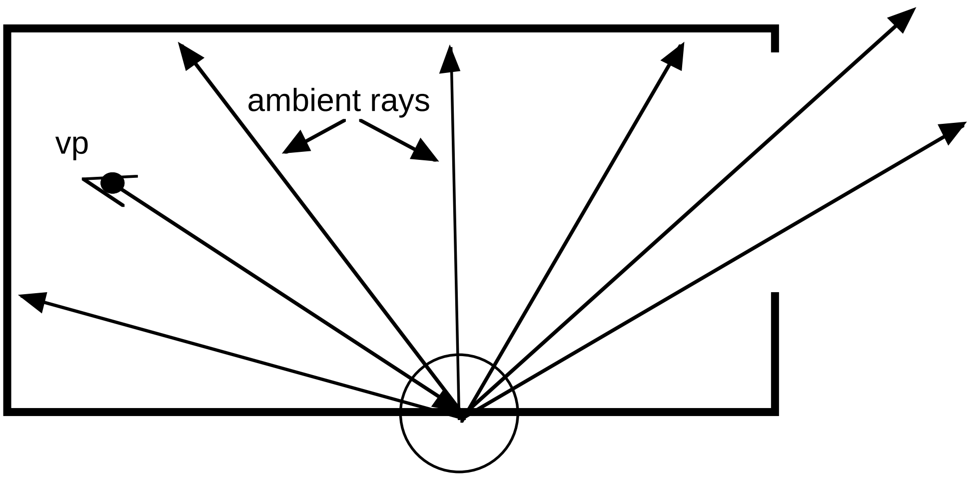
STEP 3:

To calculate a better value of the ambient illuminance falling on a point, RADIANCE is able to send additional rays (named "ambient" rays) in random directions. By specifying option `-ab 1` the first interreflection is taken into account. The number of ambient rays that will be traced is specified using option `-ad` (see Appendix 4).

Exercise:

Turn on the ambient calculation by specifying `-ab 1` and `-ad 64` to `rview` but cancel any ambient value (`-av 0 0 0`). Observe the resulting picture and then restart it by specifying an ambient value.

-ab 1 (one interreflection)
-ad 64 (64 ambient rays)
-av 0 0 0 (no ambient value)



Since a limited number of ambient rays are traced, a small fraction of them will by chance reach the openings and then the sky. Therefore the resulting picture shows high contrasts where they are not really expected.

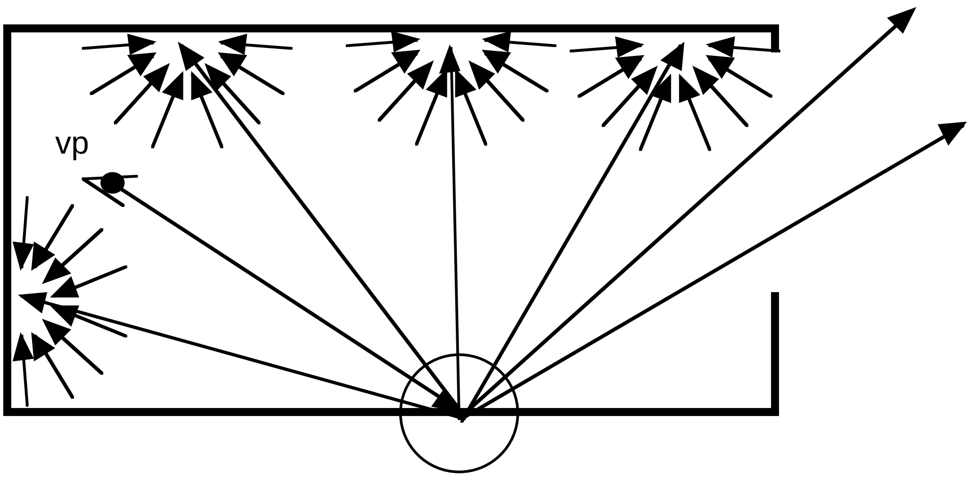
Note that the luminous patches appear more or less of spherical shape. This is due to the "sphere of influence" attached to each ambient value. For all points located in such a zone, RADIANCE will optimise its workload by evaluating the ambient values from interpolations instead tracing many additional ambient rays (see details in [War88a&b] [War92a]). The extent of these spheres of influence (i.e. their radius) is determined according to the rate of variation expected for the ambient value around the point where it has been calculated. Where high variations are expected the radius is set at its minimum value Rmin calculated as:

$$Rmin = Max\_Size \cdot \frac{aa}{ar}$$

where Max_Size is the largest width occupied by the scene either on the X,Y or Z axis (use `getbbox` to get it).
aa and *ar* are the values attached to the corresponding `-aa` and `-ar` options.

Even with a constant ambient value, the spherical luminous patches do not disappear. To solve this problem, one solution would be to greatly increase the number of ambient rays (option `-ad`). For simple cases this is worth trying. Appendix 4 can help in choosing an appropriate number of ambient rays.

-ab 1 (one interreflection)
-ad 64 (64 ambient rays)
-av .889 .889 .889 (ambient value set to 500 lux)



STEP 4:

A far better and more general solution is to make RADIANCE aware that the openings are the effective sources of light for the indoor scene. This means that the openings will then always be sampled by "direct rays".

A preprocessing of the scene file through the `mkillum` program is first necessary. The surfaces that need to be transformed as secondary sources must be identified. In our case we choose the view window and an invisible surface located over the anidolic light-shelf. It is important to select surfaces whose indicatrix of diffusion can be assumed to be reasonably constant over their entire areas. In addition it is essential that these surfaces have their normal pointing towards the right direction (in this case towards the interior of the room).

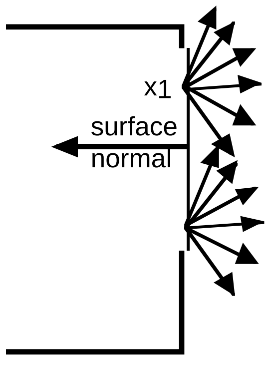
The two surfaces to transform are described in the `system.rad` file:

```
#@mkillum i=trans80 d=223 s=115 m=window
trans80 polygon view_window
0
0
12
   4.8 0 1
   0.2 0 1
   0.2 0 2
   4.8 0 2

#@mkillum i=void d=1100 s=202 m=illum
void polygon illuminator
0
0
12
    0.2 1.52412861 2.12004394
    0.2 0 3
    4.8 0 3
    4.8 1.52412861 2.12004394
#@mkillum n
```

The lines beginning with `#@mkillum` specifies some parameters for the `mkillum` program. `#@mkillum n` tells the program not to transform anything before being told to. The parameter `i=` specifies the modifier of the surfaces to be transformed. The parameter `m=` allows a specific name to be given to the indicatrix of diffusion and to the data files that will store its values.

The parameter `d=` specifies the number of directions randomly sampled per unit of projected solid angle. This parameter relates to the angular resolution of the indicatrix of diffusion (see Appendix 4). The parameter `s=` serves to specify the number of points randomly sampled over the surface when producing the indicatrix. Depending on the geometry of the elements located behind the surfaces that have to be transformed, the parameters `d` and `s` have to be carefully adjusted! Otherwise undersampling effects may strongly affect the accuracy of the resulting indicatrix of diffusion.



Remark: "indicatrix of diffusion" or "scattering indicatrix" is defined by the CIE as: the representation in space, in the form of a surface expressed in polar coordinates, of the angular distribution function of luminance of an element of surface of a medium that diffuses light by reflection or transmission [CIE87].

Now the `mkillum` filter program can be started:

```
mkillum -ab 0 model0.oct < system.rad >isystem.rad
```

This process may take a long time. Therefore the resulting file `isystem.rad` has already been computed. The definition of the window material has for instance been transformed as:

```
void brightdata window.dist
5 noneg window.dat
     illum.cal il_alth il_azih
0
9
     -1.000000 0.000000  0.000000
     0.000000  0.000000  1.000000
     0.000000  1.000000  0.000000

window.dist illum window
1 trans80
0
3 5.626943 5.626943 5.626943
```

It is this `illum` material type that is treated as a secondary light source. When it is directly seen (for instance when a ray is traced from the viewpoint directly towards the window), this material behaves as its previous original material (here `trans80`). Otherwise, this material behaves as a light source whose total luminous flux density M can be calculated as:

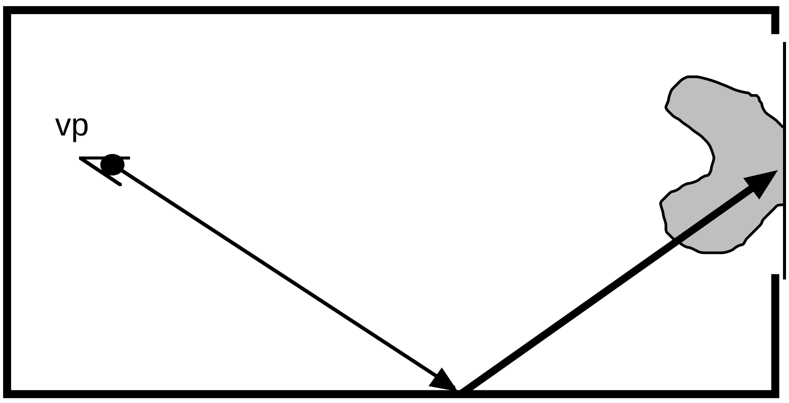
$$M = R \cdot 179 \cdot \pi \qquad [\text{lumen/m}^2]$$

where R is obtained from the three parameters Rr, Rg and Rb of the `illum` material.

Exercise:

Create a new octree (named `model1.oct`) that comprises the secondary sources and restart `rview` without any ambient calculation. Add the `-dr 0` option when calling rview (the reason will be explained later).

-ab 0 (no interreflections)
-av 0 0 0 (no ambient value)
-ds 0 (no large source subdivision)



The resulting picture is far better! But the light seems to emerge from the centre of the window only. And note that for now, the direct illumination only is taken into account!

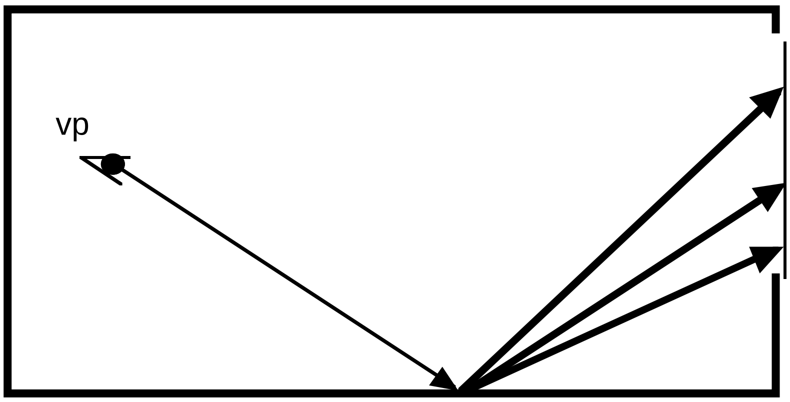
STEP 5:

To correctly treat the window as a large source RADIANCE will automatically split the area of the window into many smaller sources (see detailed explanations in [War94b]). This process is controlled by the option `-ds` (see Appendix 4 to set an appropriate value).

Exercise:

Turn on the automatic subdivision of large sources by specifying a value >0 for option `-ds` and restart the rendering process.

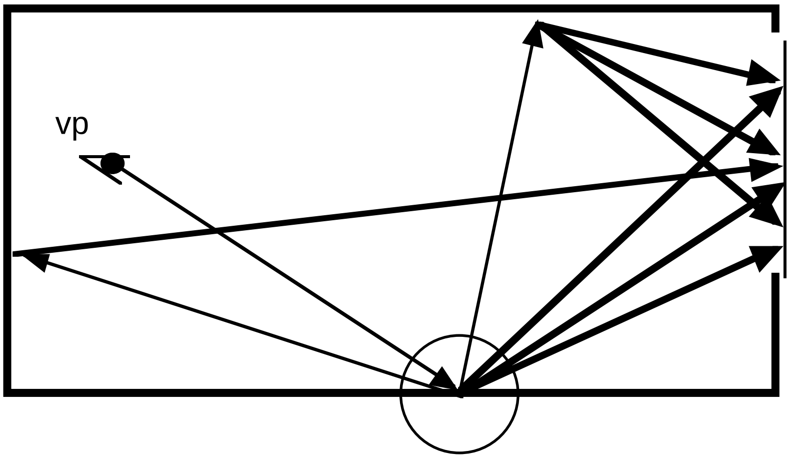
-ab 0 (no interreflections)
-av 0 0 0 (no ambient value)
-ds 0.3 (large source subdivisions on)



STEP 6:

Finally the interreflections should also be taken into account in order to compute an accurate picture.

-ab 1 (one interreflection)
-ad 64 (64 ambient rays)
-av 0 0 0 (no ambient value)
-ds 0.3 (large source subdivisions on)



Exercise:

Use `rpict` with all required options set at their appropriate values to produce an accurate picture of the model!

Illuminance calculations

RADIANCE is able to compute pictures whose pixels are irradiance values instead of radiance. The option `-i` of the rendering programs `rview` and `rpict` act as switch to this kind of calculation. When looking these pictures using `vgaimage` or `ximage`, the values obtained by clicking on specific pixels are either irradiance [W/m^2] or illuminance [lux]. Note that this type of picture is totally virtual since it is impossible to produce in the real world.

For such pictures, the exposure factor (e) is calculated from a maximum illuminance level Emax in [lux]:

$$e = \frac{179}{Emax}$$

But why spending much time to get a full irradiance picture ? Usually the illuminance falling on a relatively limited number of points is sufficient to know (for instance along an axis in the middle section of the room). The `rtrace` program called with option `-I` serves for this purpose. As input it needs a list of the points and orientations where illuminance measurement will be performed. These are provided one per line as two vectors:

X Y Z Xdir Ydir Zdir

Finally the results of the `rtrace` program are piped to `rcalc` in order to compute illuminance values from the three red, green and blue irradiances. In the RADIANCE MS-DOS version, this typical series of programs "`rtrace -I | rcalc`" has been merged into a new single program called `rillum`. Its parameters are exactly the same as those for the `rtrace` program but the output results are illuminance levels in [lux]. The call to `rillum` looks like:

```
rillum (rtrace options) model.oct <points.xyz >lux.dat
```

where `points.xyz` is a file containing the measurement points (the sign "<" means that this file serves as the standard input of the `rillum` program). The results are written in the output file `lux.dat`.

Exercise

Produce an irradiance picture with the same view and ray tracing options as the one just produced before.

For the same model use `rillum` to compute a profile of illuminance levels in the middle section of the room at an height level of 0.8 [m].

False colour pictures

It is often a good idea to present numerical results using a false colour scale. The `falsecolor` program is able to perform this task on a RADIANCE picture colouring each pixel according to its radiance value R. The values are mapped to a nice rainbow coloured scale with its lower bound coloured in blue and its upper bound coloured in red. To produce such a picture with a linear scale (always starting from 0), the `falsecolor` command looks like:

```
falsecolor -i input.pic
           -s Max_scale -l label -n #divisions >result.pic
```

(This command must be given on a single line)

where:

input.pic	is the picture containing the values that will be mapped to the coloured scale
Max_scale	is the luminance or illuminance value of the upper bound of the scale (every pixel that has higher values will be coloured in red)
label	is the title that will appear on the top of the coloured scale appended at the left of the original picture (usually the label refers to the unit of the scale such as [cd/m^2] or [lux])
#divisions	specifies the number of numerical labels that will be superimposed on the coloured scale

With option `-cl` the program will instead superimpose *#divisions* coloured contour lines onto a background picture (specified by option `-p`):

```
falsecolor -cl -i input.pic -p background.pic
           -s Max_scale -l label -n #divisions >result.pic
```

This command is very convenient for instance to superimpose isolux curves onto a normal picture of a daylit space. This means that *input.pic* and *background.pic* must be of the same size and rendered with the same view parameters but as an illuminance picture for the former (using option `-i` of either `rview` or `rpict`) and as a normal luminance picture for the latter. This kind of resulting picture is of great value because it combines quantitative information (the isolux curves) onto a picture of the space that is less objective (since its exposure can be arbitrarily changed to obtain the desired appearance).

Exercise

Experience `falsecolor` using the pictures produced so far.

Assessing discomfort glare

Discomfort glare is experienced when excessively bright areas are perceived in the field of view. To quantify the sensation of discomfort glare, many "glare indices" have been defined. Nevertheless they are all based on the same kind of parameters. Basically, each excessively bright area is considered as a "source". In fact this reflects the origins of the methods involved which mainly concentrated on artificial lighting installations where each luminaire (= an obvious light source) might create discomfort glare. For daylit scenes, the selection of the parts of the field of view that have to be considered as "sources" is less straightforward.

To compute glare indices using RADIANCE, two steps are involved. First the relevant parameters are computed from a calculated picture (or directly from an octree, see [War91b] for details) by the `findglare` program. The computed parameters are then passed to the `glarendx` program.

First step:

`findglare -p` *`input.pic`* `-t` *`L_threshold`* `-v >`*`result.gla`*

where:

input.pic	is a calculated picture taken from the point of view for which discomfort glare has to be assessed
L_threshold	is the threshold luminance value in [cd/m^2]

The threshold value is used by the program to devise which parts must be treated as "sources". Briefly explained, every pixel whose luminance exceed the threshold will first be pinpointed and later merged with neighbouring similar pixels to form individual sources. The resulting parameters describing the positions of the sources found in the picture, the angular extents they subtend (solid angles) and their luminances are finally passed to the output file *`result.gla`*. Option `-v` simply asks the program to print progress reports while running.

Second step:

`glarendx -t` *`index_type input.gla`*

where:

index_type	is the name of the discomfort glare index to be computed (to get a list of available indices call `glarendx` without any argument).

The output of `glarendx` will comprise two numbers: the first column gives the angle between the view direction for which the glare index has been calculated and the original view direction of the input picture (in our case it will always be 0) and the second column is the requested discomfort glare index value. Note that by using option `-t vert_ill` the `glarendx` program will return the illuminance measured at the eye level in [lux].

The UNIX RADIANCE version includes a very convenient program called `xglaresrc` that displays a picture (using `ximage`) and superimposes circles around each of the sources identified by `findglare`.

Remarks:

There is no definitive method to devise appropriate values for the threshold luminance. However, the resulting final discomfort glare indices that strongly depend on the threshold do not have great significance by themselves. They are much more valuable when analysed by comparison with other cases.

One possible way of devising a non arbitrary luminance threshold is given by a graph found in reference [Hop70] showing the approximate upper luminance limit under which discomfort glare is not experienced. The corresponding fitted function `ulim(La)` is the following (contained in the `ulim.cal` file):

```
fl2cd(v)=3.426*v;
cd2fl(v)=.292*v;
ulim(La)=fl2cd(10^(5.731+(log10(cd2fl(La))+5)*
                    (0.3376+(log10(cd2fl(La))+5)*0.0189)-6));
```

The `ulim` function takes the adaptation luminance `La` in [cd/m^2] as its argument and returns a threshold luminance also in [cd/m^2]. The adaptation luminance is not easy to devise for a complex scene since this notion is mainly relevant for experiments on vision where a small target is presented against a background of uniform luminance to which the eyes are adapted. For complex scenes, the adaptation is probably also dependent on the details on which the attention is focused. This is a domain where further reserach is still needed. Anyway, it is common to assume that the illuminance E_{eye} measured in the scene at eye level is in fact due to a uniform adaptation luminance L_a over the whole field of view:

$$L_a = \frac{E_{eye}}{\pi} \qquad [cd/m^2]$$

Then the threshold value can be calculated using the piped commands (given on a single line):

```
findglare -p input.pic -t 100000 | glarendx -h -t vert_ill
| rcalc -f ulim.cal -e $1=ulim($2/PI)
```

At this stage the very high threshold value used with `findglare` just ensures that the program does not spend time searching for sources since we just need an illuminance value.

Since `findglare` should normally analyse pictures covering the whole field of view, it is recommended to use hemispherical input pictures (rendered with options `-vth -vh 180 -vv 180`). Nevertheless, `findglare` is able to handle pictures covering smaller portions of the field of view.

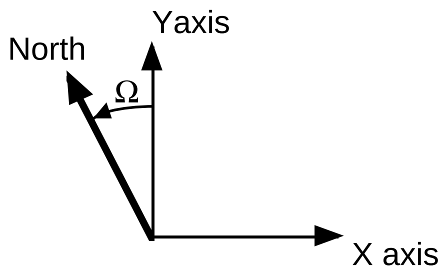
Exercise:

Experience discomfort glare calculations using the pictures produced so far.

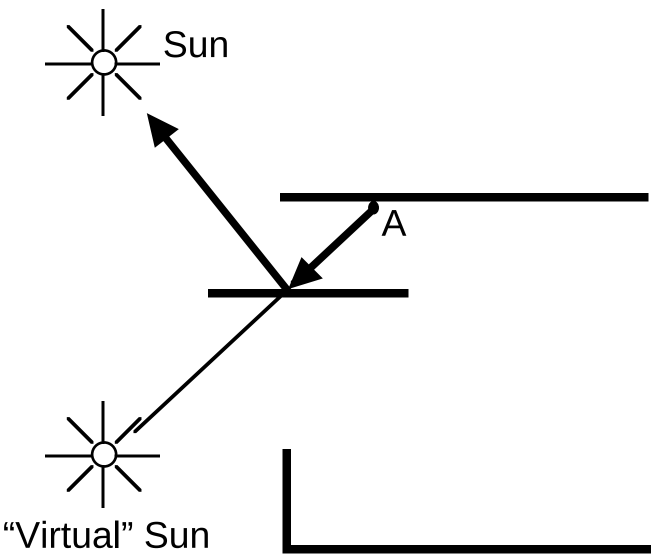
Simulations with sunny skies

The orientation of the building becomes of great importance with sunny skies since, unlike the standard overcast skies, their luminance distributions have no circular symmetry around the zenith (Z axis). This means that if the scene describing the building is, for convenience, kept aligned along the principal axes (X,Y,Z), the file describing the sky should be orientated by a proper rotation. If the North direction makes an angle Ω (degrees) with the Y axis (as illustrated below the angle is counted positively in the anticlockwise direction), the corresponding rotation of the sky is obtained by the command:

```
xform -rz Ω orig_sky.rad > oriented_sky.rad
```



Now see what happens when using sunny skies with models comprising materials of `mirror` or `prism` type. For instance consider a horizontal specular light-shelf where the point A is clearly lit by the sun after a reflection on the light-shelf.



Without precautions, RADIANCE will not take this illumination into account. The sun is defined as a light source that attracts direct rays but because the sun is located behind the opaque surface on which point A lies, no direct rays will be traced! Then the ambient rays may try to reach the sun after reflection by the light-shelf, but this is unlikely to happen because of the limited number of ambient rays and the very small solid angle covered by the sun.

This means that a "trick" has to be devised to force RADIANCE to trace direct rays towards the light-shelf and then towards the sun. This is automatically done at the beginning of the calculations by creating "virtual" light sources for each real source reflected by a mirror or refracted by a prismatic element. Then RADIANCE is somehow "cheated": from point A a direct ray will be traced towards the virtual sun but along its path this ray will encounter the light-shelf and will then continue towards the real sun!

The option `-dr 1` instructs the ray-tracing program to build virtual sources of 1st order. When direct rays may encounter more than one specular reflection or refraction before being redirected towards the true sun, virtual sources of 2nd generation (virtual sources of virtual sources) have also to be created and would require a `-dr 2` option. See [War94b] for additional details.

Up to now it was recommended to use option `-dr 0` when doing the exercises. This is because in our case, the anidolic curved light-shelf is composed of many small flat reflectors and therefore, when starting the calculations, it would take a very long time for the program to figure out that no virtual sources need to be created since all sources we have in our scene (remember that we use an overcast sky and that we have two secondary sources namely the lower window and the "illuminator") do not reflect through the reflector (this becomes clear when looking at the geometrical arrangement of the sources relatively to the reflector).

Of course if a sunny sky is used with our scene, then `-dr 1` is essential to generate a virtual sun for each facet of the reflector. But at this stage we reach a fundamental limitation of RADIANCE: since curved surface are approximated by small flat facets, the reflections appear as discontinuous bands instead of a single bright continuous area.

A few words on textures and patterns

In the RADIANCE context a **"**texture" is a local perturbation of the surface normal and a "pattern" is a local perturbation of the surface colour. They are usually defined on a smaller scale than that of the model (typically 1/10 to 1/100). Both have considerable impacts on the realistic appearance of the renderings. However, they can be considered as of secondary importance when using RADIANCE mainly for computing lighting performances of spaces. For instance it is far simpler and numerically equivalent to take the patterns into account using mean reflectances and to use the corresponding uniformly coloured materials.

The file `pmat.rad` gives some examples:

- a skirting_board is defined for the walls by defining a pattern that changes the colour of the walls on the first 6 [cm] above floor level;
- a parquet pattern is defined for the floor by applying a ±30% random variation on the original reflectance of the floor on small 20[cm]x5[cm] rectangular patches;
- a texture is used to define 2[cm] wide joins between rectangular plates of 25 [cm] width positioned on the ceiling. This texture only modifies the surface normal along the Y axis for the positions located on the joins. The perturbation is calculated by the `y_pert` function defined in the `plate.cal` file.

Exercise:

Rebuild a new octree for the model but replace the file `mat.rad` by `pmat.rad` that comprises the definitions of the skirting_board and parquet patterns and plate texture. Render new pictures using this octree.

Automation of the rendering process using `rad`

The purpose of the `rad` program is to automate the rendering process. In particular it relieves the user from the painful task of setting appropriate values for all the options that control the ray-tracing process. The user only needs to prepare a "project" file specifiying the name of the involved scene files, the view parameters for the pictures to produce, and some additional intuitive control variables either of qualitative (e.g. the quality level expected for the resulting pictures: either low, medium or high) or quantitative nature (e.g. the zone of interest in the scene defined by the coordinates of the bounding cube enclosing the zone). See reference [War95] for details.

Nevertheless, users who master the setting of the RADIANCE ray-tracing options can specify their values explicitely (hopefully these tutorial notes will help in reaching this level...). Then `rad` can be considered as a convenient automated rendering process. Long command lines are avoided and thus the risk of making typing errors is highly reduced. To generate all pictures that are described in a project file *input.rif* the command to issue is simply:

rad *input.rif*

Before starting the calculations, it is sometimes very useful to find out which commands `rad` will issue or to check which values have been assigned to the ray-tracing options. This can simply be done using `rad` with its `-n` option:

rad -n *input.rif*

`rad` is clever enough to check the dependencies between various files. For instance if `rad` is asked to produce a picture after it has already completed a preceding one, the octree that already exists will not be rebuilt unless some of the scene files have been edited in the meantime. This feature is comparable to the `make` utility program common to UNIX systems [Tal89].

Illuminance profiles, the production of false colour pictures and the calculation of discomfort glare indices are not supported by the `rad` program.

Exercise:

Have a look at the `cell.rif` project file and try using it with `rad`

RADIANCE distribution and user support

The RADIANCE UNIX version is freely available on the Internet. The latest version is available by anonymous ftp from one of these WWW servers:

`http://lesowww.epfl.ch/radiance/radiance.html`

or

`http://radsite.lbl.gov/radiance/`

Only the source code is distributed. That means that some computer skills are then necessary to compile and install the software (although an interactive automatic installation procedure is provided).

It is worth looking at the RADIANCE-DIGEST (available from the WWW sites) which is a compilation of questions asked by RADIANCE users and the answers given to them.

A discussion list is also organised where people using RADIANCE share their problems and (sometimes...) solutions. To subscribe to the list send a request to: `radiance-request@radsite.lbl.gov`

The references [War88b] [War91a] [War92a] [War92b] [War94b] [War95] and [War97] are available on the Internet from:

`http://radsite.lbl.gov/radiance/papers/`

The ADELINE package also has dedicated WWW servers but it is not available for free (its price is around 450 US$):

`http://www.ibp.fhg.de/wt/adeline/adeline.htm`

or

`http://radsite.lbl.gov/adeline/`

Each distribution site defines its own policy regarding the user support it offers.

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WWW sites of the above mentioned research groups:

Martin Centre, Cambridge (UK):

`http://www.arct.cam.ac.uk/mc/index.html`

LEARN, London (UK):

`http://www.unl.ac.uk/LEARN/`

LESO-PB, Lausanne (Switzerland):

`http://lesowww.epfl.ch/`

Architecture et Climat, Louvain-la Neuve (Belgium):

`http://www.gc.ucl.ac.be/arch/index.html`

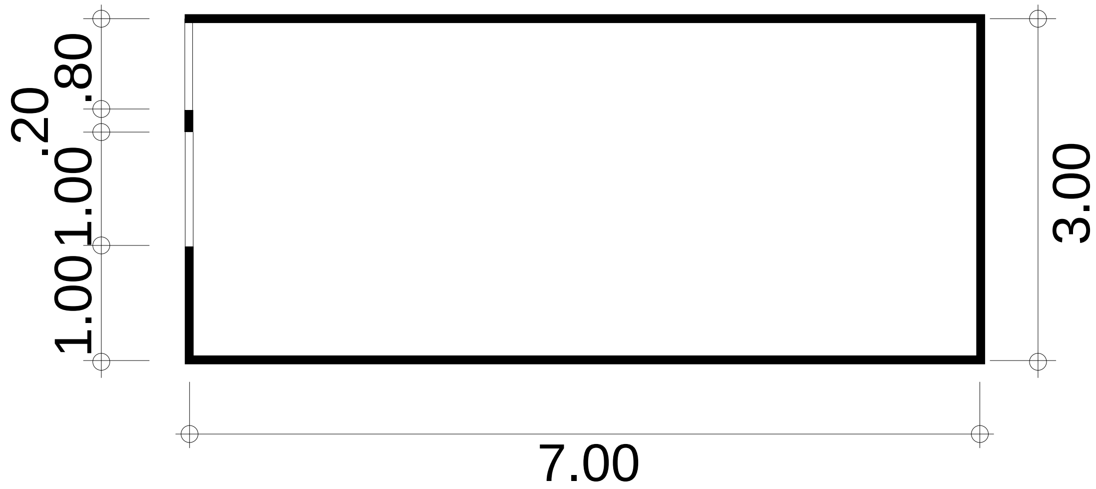
Appendix 1

Colour "trade" name	Visual appearance	Y	x	y
RAL9010	pure white	0.835	0.328	0.335
2k216	beige	0.71	0.331	0.353
2k218	beige	0.696	0.344	0.369
1k117	off-white	0.688	0.32	0.341
2k217	yellowish	0.683	0.341	0.362
2k205	off-white	0.675	0.33	0.347
6k605	light_gray	0.674	0.317	0.34
4e400	sulfur-yellow	0.673	0.417	0.436
RAL1016	sulfur-yellow	0.673	0.417	0.436
1k105	light_gray	0.667	0.32	0.336
1e101	white-gray	0.666	0.328	0.336
RAL9002	white-gray	0.666	0.328	0.336
1k101	light_gray	0.665	0.323	0.342
2k206	cream	0.665	0.345	0.363
2k201	beige	0.664	0.328	0.349
2k208	beige	0.659	0.352	0.369
7k701	pastel green	0.656	0.316	0.341
1k122	light_gray	0.647	0.322	0.336
2k219	ivory	0.644	0.335	0.359
4k403	beige	0.64	0.362	0.378
7k707	pastel green	0.634	0.327	0.352
1k109	light_gray	0.633	0.314	0.33
4k401	light_yellow	0.629	0.36	0.389
1k113	light_gray	0.628	0.311	0.33
7k709	greenish-white	0.623	0.326	0.349
4k402	yellow	0.621	0.39	0.417
8k801	yellow-green	0.621	0.375	0.431
2k202	beige	0.595	0.336	0.357
6k601	light_blue	0.587	0.307	0.33
2k209	beige	0.584	0.344	0.354
2k220	cream	0.578	0.351	0.375
4k407	yellow	0.572	0.362	0.377
7k710	light_green	0.572	0.322	0.358
1k102	light_gray	0.57	0.322	0.341
4k405	yellow	0.568	0.372	0.39
7k702	green	0.565	0.303	0.343
1k106	light_gray	0.563	0.316	0.332
4k404	yellow	0.56	0.382	0.399
7k704	green	0.55	0.316	0.341
6k608	light_blue	0.548	0.301	0.32
8k804	yellow	0.548	0.449	0.455
1k119	green-gray	0.546	0.318	0.348
6k609	blue-gray	0.541	0.303	0.321
RAL1023	traffic-yellow	0.541	0.449	0.443
1k114	gray	0.533	0.306	0.327
4k408	yellow	0.532	0.375	0.384
1k110	light_gray	0.531	0.312	0.331
2k203	cream	0.527	0.347	0.367
2k222	beige	0.52	0.35	0.373
4k406	ochre-yellow	0.512	0.394	0.399
6k602	light_blue-gray	0.512	0.299	0.32
1k111	light_gray	0.505	0.311	0.329
7k708	green	0.497	0.331	0.373
1k103	light_gray	0.496	0.324	0.343
1k125	beige-gray	0.471	0.339	0.356
3k305	beige-gray	0.464	0.325	0.345

1k120	green-gray	0.462	0.318	0.345
8k802	green	0.462	0.385	0.455
4k409	yellow	0.46	0.397	0.425
2k221	greenish-yellow	0.459	0.366	0.392
3k301	light_gray	0.451	0.331	0.345
2k204	beige	0.45	0.351	0.372
2k210	beige	0.443	0.359	0.367
1e123	pebble-gray	0.432	0.337	0.346
RAL7032	pebble-gray	0.432	0.337	0.346
1k107	light_gray	0.432	0.317	0.336
1k104	light_gray	0.43	0.327	0.345
2k213	beige	0.428	0.363	0.376
3k308	beige	0.427	0.344	0.36
7k705	green-blue	0.422	0.31	0.342
1k115	blue-gray	0.418	0.299	0.319
2k223	yellow	0.413	0.358	0.384
7k711	green	0.412	0.315	0.367
6k603	light_blue	0.407	0.286	0.314
2k214	yellow	0.406	0.379	0.395
2k212	brownish-beige	0.398	0.379	0.378
1k124	gray	0.395	0.324	0.337
1k112	gray	0.393	0.306	0.323
1k108	light_gray	0.388	0.317	0.335
2k215	yellow	0.379	0.377	0.397
1k116	blue-gray	0.378	0.298	0.318
4e404	chrome-yellow	0.377	0.464	0.433
RAL1007	chrome-yellow	0.377	0.464	0.433
2k225	brown	0.375	0.377	0.391
4k410	yellow	0.374	0.432	0.413
1k126	gray	0.368	0.335	0.354
1k127	beige	0.367	0.345	0.364
4k411	ochre	0.351	0.426	0.391
2k211	brownish-yellow	0.337	0.37	0.379
7k713	light_green	0.334	0.362	0.4
6k604	blue	0.326	0.281	0.309
RAL2008	light_red-orange	0.323	0.469	0.408
7k712	green	0.315	0.337	0.381
3k306	gray	0.312	0.324	0.346
4k412	orange-beige	0.307	0.427	0.396
7k706	green-blue	0.305	0.309	0.35
3k309	gray	0.3	0.329	0.344
1e121	silver-gray	0.298	0.311	0.321
RAL7001	silver-gray	0.298	0.311	0.321
2k224	olive	0.292	0.368	0.399
7e712	pale green	0.287	0.341	0.364
RAL6021	pale green	0.287	0.341	0.364
2k229	green	0.282	0.352	0.378
2k228	brown	0.28	0.382	0.384
1k128	beige	0.278	0.344	0.363
2k227	brown	0.278	0.385	0.387
2k226	brown	0.264	0.386	0.384
1e122	stone-gray	0.259	0.332	0.34
RAL7030	stone-gray	0.259	0.332	0.34
4k413	orange-brown	0.253	0.441	0.391
8k803	olive	0.251	0.403	0.468
1k129	gray	0.249	0.338	0.362
3k302	light_gray	0.246	0.32	0.341
3k311	gray	0.245	0.326	0.343
4k414	light_brown	0.231	0.423	0.383
5k505	red-brown	0.23	0.391	0.353
7k714	green	0.22	0.354	0.409

RAL6018	yellow-green	0.218	0.376	0.45
3k303	gray	0.217	0.321	0.343
8k806	blue	0.209	0.242	0.263
1e105	concrete-gray	0.201	0.332	0.341
RAL7023	concrete-gray	0.201	0.332	0.341
8k805	orange-red	0.197	0.467	0.361
3k310	gray	0.184	0.331	0.346
3k312	brown-gray	0.179	0.347	0.356
3k313	beige-brown	0.179	0.349	0.359
7e704	reseda-green	0.169	0.349	0.379
RAL6011	reseda-green	0.169	0.349	0.379
5e520	lilac-blue	0.169	0.277	0.264
RAL4005	lilac-blue	0.169	0.277	0.264
3k307	gray	0.169	0.328	0.35
RAL2002	blood-orange	0.162	0.485	0.392
3k304	dark_gray	0.149	0.329	0.346
1k130	gray	0.147	0.308	0.337
1k134	dark_gray	0.138	0.302	0.315
RAL6024	traffic-green	0.133	0.318	0.398
1e119	blue-gray	0.121	0.304	0.317
RAL7031	blue-gray	0.121	0.304	0.317
5e509	fire-red	0.119	0.473	0.381
RAL3000	fire-red	0.119	0.473	0.381
7e706	emerald-green	0.086	0.351	0.427
RAL6001	emerald-green	0.086	0.351	0.427
RAL6016	turquoise-green	0.079	0.285	0.364
7e711	olive-green	0.071	0.36	0.381
RAL6003	olive-green	0.071	0.36	0.381
RAL5017	traffic-blue	0.069	0.177	0.199
5e504	ruby-red	0.065	0.488	0.376
RAL3003	ruby-red	0.065	0.488	0.376
6e610	gentian-blue	0.052	0.183	0.196
RAL5010	gentian-blue	0.052	0.183	0.196
RAL4004	bordeaux-violet	0.042	0.408	0.32
5e505	red-brown	0.042	0.467	0.368
RAL3004	red-brown	0.042	0.467	0.368
RAL5002	ultramarine	0.039	0.171	0.162
3e311	mahogany-brown	0.032	0.415	0.381
RAL8016	mahogany-brown	0.032	0.415	0.381
5e506	wine-red	0.029	0.45	0.359
RAL3005	wine-red	0.029	0.45	0.359
RAL4007	purple-violet	0.027	0.342	0.291
6e605	sapphire-blue	0.026	0.202	0.207
RAL5003	sapphire-blue	0.026	0.202	0.207
RAL5022	midnight-blue	0.023	0.197	0.184

Appendix 2



Vertical section of the room defined in `room.rad` (dimensions in [m]).

Appendix 3

VDU screens have usually a 4/3 (width/height) aspect ratio while photographic films and slides have a 3/2 aspect ratio. To make a perspective view (option -vtv) with one of these specific aspect ratios, the vertical view angle (option -vv) must be adjusted to the chosen horizontal view angle (option -vh) according to the following table:

-vh (degrees)	-vv (degrees) 4/3 aspect ratio	-vv (degrees) 3/2 aspect ratio
5	3.75	3.33
10	7.51	6.68
15	11.28	10.03
20	15.07	13.41
25	18.88	16.81
30	22.73	20.26
35	26.61	23.74
40	30.54	27.28
45	34.52	30.87
50	38.55	34.54
55	42.65	38.28
60	46.83	42.1
65	51.08	46.02
70	55.41	50.05
75	59.84	54.18
80	64.37	58.45
85	69	62.84
90	73.74	67.38
95	78.6	72.07
100	83.58	76.93
105	88.69	81.97
110	93.93	87.19
115	99.31	92.6
120	104.82	98.21
125	110.47	104.03
130	116.26	110.06
135	122.18	116.29
140	128.23	122.73
145	134.4	129.38
150	140.68	136.21
155	147.07	143.21
160	153.54	150.37
165	160.09	157.66
170	166.69	165.05
175	173.34	172.51

The same field of view as a 24x36 camera with a lens of a specific focal length can be obtained using a perspective view (option -vtv) with the view angles adjusted according to this table:

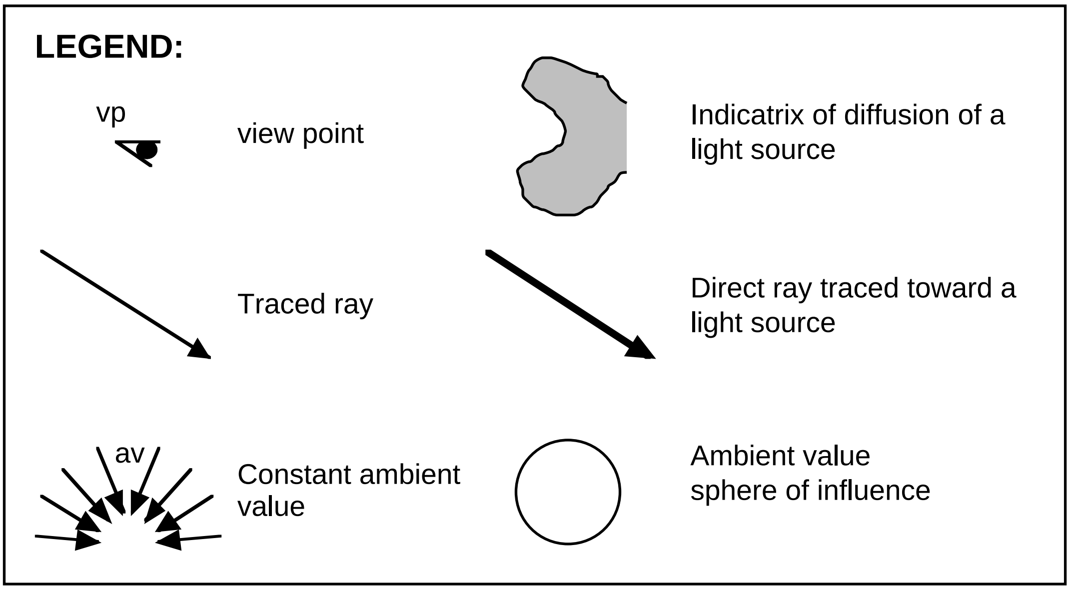
Focal length of camera lens (mm)	-vh (degrees)	-vv (degrees)
17	93.27	70.44
28	65.47	46.40
35	54.43	37.85
50	39.60	26.99
85	23.91	16.07
135	15.19	10.16
300	6.87	4.58

Appendix 4

Table of values for ray tracing parameters as function of the required angular resolution:

Angular resolution (degrees)	option -ad	parameter "d" of mkillum	option -ds
1	33863247	10779006	0.02
2	2117743	674098	0.03
3	418745	133291	0.05
4	132682	42234	0.07
5	54446	17331	0.09
6	26315	8376	0.1
7	14242	4533	0.12
8	8374	2666	0.14
9	5246	1670	0.16
10	3455	1100	0.17
11	2370	754	0.19
12	1681	535	0.21
13	1227	391	0.23
14	917	292	0.25
15	700	223	0.26
16	544	173	0.28
17	430	137	0.3
18	345	110	0.32
19	280	89	0.33
20	230	73	0.35
21	190	61	0.37
22	160	51	0.39
23	135	43	0.41
24	115	37	0.43
25	98	31	0.44
26	85	27	0.46
27	74	24	0.48
28	65	21	0.5
29	57	18	0.52
30	50	16	0.54

Appendix 5


LEGEND:
vp
view point
Indicatrix of diffusion of a light source
Traced ray
Direct ray traced toward a light source
av
Constant ambient value
Ambient value sphere of influence

Appendix 6

Example files are listed in the following pages:

Note that the data files `ashelf.dat illum.dat` and `window.dat` that are also necessary for the exercises are not listed hereafter. However, they are stored with all other example files in the archive files: `rc97tut.tar.Z` or `rc97tut.zip`

rgb.cal

```
{ Colour model transformation from Yxy to rgb
  R. Compagnon, Martin Centre, Cambridge UK, 04/JUN/97

  Input data: Y x y
  Output data: Cr Cg Cb or normalized values Crn Cgn Cbn
}

X=x*Y/y;
Z=(1-x-y)*Y/y;

r=  2.739*X -1.145*Y -0.424*Z;
g= -1.119*X +2.029*Y +0.033*Z;
b=  0.138*X -0.333*Y +1.105*Z;

Cr=floor(1000*r+0.5)/1000;
Cg=floor(1000*g+0.5)/1000;
Cb=floor(1000*b+0.5)/1000;

n=.263*r+.655*g+.082*b;

Crn=floor(1000*r/n+.5)/1000;
Cgn=floor(1000*g/n+.5)/1000;
Cbn=floor(1000*b/n+.5)/1000;
```

cie.rad

```
# CIE overcast sky
# Horizontal illuminance: 10000 Lux
# Ground reflectance: 0.1

!gensky 1 1 1 -c -b 22.8634396 -g 0.1

skyfunc glow sky_glow
0
0
4 1 1 1 0

sky_glow source sky
0
0
4 0 0 1 180

skyfunc glow ground_glow
0
0
4 1 1 1 0

ground_glow source ground
0
0
4 0 0 -1 180
```

wsol12.rad

```
# Intermediate sky with sun
# Winter solstice (21 decembre) at 12:00 (local time)

# Parametres for Louvain-la-Neuve (Belgium):
#       latitude: -a 50.67
#       longitude: -o -4.6
#       meridian: -m -15
#                 Note that the meridian is given in degrees!
#                 For summer time it would be -m -30
#       ground reflectance: -g 0.1

!gensky 12 21 12 +i -a 50.67 -o -4.6 -m -15 -g 0.1

skyfunc glow sky_glow
0
0
4 1 1 1 0

sky_glow source sky
0
0
4 0 0 1 180

skyfunc glow ground_glow
0
0
4 1 1 1 0

ground_glow source ground
0
0
4 0 0 -1 180
```

pcyl.cal

```
{ Definitions for cylindrical projection
  R. Compagnon, Martin Centre, Cambridge UK, 04/JUN/97 }

{ Parameters defined externaly:
   XD : horizontal picture dimension (pixels)
   YD : vertical picture dimension (pixels)
   AM : altitude at the bottom line of the picture (degrees) }

{ Direction of the current pixel (angles in radians)  }
px=$2;
py=YD-$1;
altitude=(AM+py*(90-AM)/YD)*PI/180;
azimut=((px-XD/2)*360/XD)*PI/180;

{ Transformation into a direction vector }
n=sqrt(1+sin(altitude)^2);
dx=-sin(azimut)*cos(altitude);
dy=-cos(azimut)*cos(altitude);
dz=sin(altitude);

{ Output line to rtrace }
$1=0;$2=0;$3=0;
$4=dx;$5=dy;$6=dz;
```

axis.cal

```
{ Axis for cylindrical projection
  R. Compagnon, Martin Centre, Cambridge UK, 04/JUN/97 }

{ Parameters defined externaly:
   XD : horizontal picture dimension (pixels)
   YD : vertical picture dimension (pixels)
   AM : altitude at the bottom line of the picture (degrees) }

{ Position of the axis }
div_H=15; { division between altitude lines (in degrees) }
div_V=30; { division between azimuth lines (in degrees) }
h1=AM+y*(90-AM)/YD;
h2=AM+(y+1)*(90-AM)/YD;
axe_h=if(floor(h2/div_H)-floor(h1/div_H),1,0);
a1=x*360/XD;
a2=(x+1)*360/XD;
axe_v=if(floor(a2/div_V)-floor(a1/div_V),1,0);
axe=if(axe_h+axe_v,1,0);

{ pcomb output radiances }
ro=if(axe,1,ri(1));
go=if(axe,1,gi(1));
bo=if(axe,1,bi(1));
```

mat.rad

```
void plastic walls_mat
0
0
5 .6 .6 .6 0 0

void plastic south_wall_mat
0
0
5 .6 .6 .6 0 0

void plastic frame_mat
0
0
5 .683 .476 .261 0 0

void plastic ceiling_mat
0
0
5 0.8 0.8 0.8 0 0

void plastic floor_mat
0
0
5 0.433 0.118 0.073 0.03 0.1

void mirror reflector
0
0
3 .8 .8 .8

# 80 % transmittance glass
void glass trans80
0
0
3 .8715 .8715 .8715

# 90 % transmittance glass
void glass trans90
0
0
3 .98 .98 .98
```

room.rad

```
ceiling_mat polygon ceiling
0
0
12
    0 7 3
    5 7 3
    5 0 3
    0 0 3

floor_mat polygon floor
0
0
12
    0 0 0
    5 0 0
    5 7 0
    0 7 0

walls_mat polygon wall_W
0
0
12
   0.001 0 0
   0.001 7 0
   0.001 7 3
   0.001 0 3

walls_mat polygon wall_N
0
0
12
   0 7 0
   5 7 0
   5 7 3
   0 7 3

walls_mat polygon wall_E
0
0
12
   4.999 7 0
   4.999 0 0
   4.999 0 3
   4.999 7 3

frame_mat polygon wall_S
0
0
12
   5 0 0
   0 0 0
   0 0 1
   5 0 1
```

```
frame_mat polygon frame_E
0
0
12
   5 0 1
   4.8 0 1
   4.8 0 3
   5 0 3

frame_mat polygon frame_W
0
0
12
   0.2 0 1
   0 0 1
   0 0 3
   0.2 0 3

frame_mat polygon frame_S
0
0
12
   4.8 0 2
   0.2 0 2
   0.2 0 2.2
   4.8 0 2.2

south_wall_mat polygon tablette
0
0
12
   0 0 .8
   5 0 .8
   5 .2 .8
   0 .2 .8

south_wall_mat polygon contre-coeur
0
0
12
  0 .2 0
  0 .2 .8
  5 .2 .8
  5 .2 0
```

system.rad

```
#@mkillum n

!genprism reflector ashelf ashelf.dat -c -e -l 0 0 5 | \
xform -rx 90 -rz 90 -t 0 0 3

ceiling_mat polygon cache_H
0
0
12
    5 1.52412861 2.1
    5 0 2.1
    0 0 2.1
    0 1.52412861 2.1

frame_mat polygon cache_V
0
0
12
   5 1.52412861 2.1
   0 1.52412861 2.1
   0 1.52412861 2.12004394
   5 1.52412861 2.12004394

frame_mat polygon side1
0
0
12
 0 1.52412861 2.1
 0 1.52412861 3
 0.2 1.52412861 3
 0.2 1.52412861 2.1

frame_mat polygon side2
0
0
12
 5 1.52412861 2.1
 4.8 1.52412861 2.1
 4.8 1.52412861 3
 5 1.52412861 3

reflector polygon side_refl1
0
0
12
 0.2 0 2.12004394
 0.2 1.52412861 2.12004394
 0.2 1.52412861 3
 0.2 0 3

reflector polygon side_refl2
0
0
12
 4.8 0 2.12004394
 4.8 0 3
 4.8 1.52412861 3
 4.8 1.52412861 2.12004394
```

```
trans80 polygon upper_window
0
0
12
   4.8 0 2.12004394
   0.2 0 2.12004394
   0.2 0 3
   4.8 0 3

trans90 polygon interior_window
0
0
12
   4.8 1.52412861 2.12004394
   0.2 1.52412861 2.12004394
   0.2 1.52412861 3
   4.8 1.52412861 3

#@mkillum i=trans80 d=223 s=115 m=window
trans80 polygon view_window
0
0
12
   4.8 0 1
   0.2 0 1
   0.2 0 2
   4.8 0 2

#@mkillum i=void d=1100 s=202 m=illum
void polygon illuminator
0
0
12
    0.2 1.52412861 2.12004394
    0.2 0 3
    4.8 0 3
    4.8 1.52412861 2.12004394

#@mkillum n
```

desk.rad

```
#
# Office desk 1.6x0.8 M
#

#@mkillum n

void plastic colour_grey
0
0
5 0.4 0.4 0.4 0.03 0.1

!genbox colour_grey tiroir 0.45 0.8 0.605 | xform -t 1.12 0 .13
!genbox colour_grey tiroir 0.45 0.8 0.605 | xform -t .03 0 .13
!genbox colour_grey plateau 1.6 .8 .025 | xform -t 0 0 .775

void metal metal_noir
0
0
5 0.1 0.1 0.1 0.03 0

!genprism metal_noir cadre 4 0 0 1.6 0 1.6 .8 0 .8 -e -l 0 0 .04 | \
 xform -t 0 0 .735
!genprism metal_noir pied 4 0 0 .03 0 .03 .03 0 .03 -e -l 0 0 .77
!genprism metal_noir pied 4 0 .77 .03 .77 .03 .8 0 .8 -e -l 0 0 .77
!genprism metal_noir pied 4 1.57 0 1.6 0 1.6 .03 1.57 .03 -e \
 -l 0 0 .77
!genprism metal_noir pied 4 1.57 .77 1.6 .77 1.6 .8 1.57 .8 -e \
 -l 0 0 .77

void plastic ral3004
0
0
5 0.09 0.026 0.014 0.03 0.1

!genbox ral3004 sousmain 0.8 0.6 0.001 | xform -t .4 .1 .8
```

chair.rad

```
#
# Office chair
#
void metal chrome
0
0
5 0.5 0.5 0.5 0.6 0

void plastic noir
0
0
5 0.1 0.1 0.1 0.03 0

void plastic tissu
0
0
5 0.09 0.026 0.014 0 0

!genprism chrome prism 4 0 0 0 .05 .27 .03 .27 0 -l 0 0 .02 | \
 xform -rx 90 -t 0.035 -0.01 0.06

noir sphere roulette
0
0
4 0.305 0 0.03 0.03

!genprism chrome prism 4 0 0 0 .05 .27 .03 .27 0 -l 0 0 .02 | \
 xform -rx 90 -t 0.035 -0.01 0.06 -rz 72

noir sphere roulette
0
0
4 0.094 0.290 0.03 0.03

!genprism chrome prism 4 0 0 0 .05 .27 .03 .27 0 -l 0 0 .02 | \
 xform -rx 90 -t 0.035 -0.01 0.06 -rz 144

noir sphere roulette
0
0
4 -0.247 0.179 0.03 0.03

!genprism chrome prism 4 0 0 0 .05 .27 .03 .27 0 -l 0 0 .02 | \
 xform -rx 90 -t 0.035 -0.01 0.06 -rz 216

noir sphere roulette
0
0
4    -0.247 -0.179 0.03 0.03

!genprism chrome prism 4 0 0 0 .05 .27 .03 .27 0 -l 0 0 .02 | \
 xform -rx 90 -t 0.035 -0.01 0.06 -rz 288
```

```
noir sphere roulette
0
0
4 0.094 -0.290 0.03 0.03

noir cone cylindre
0
0
8
        0       0       0.06
        0       0       0.41
        0.035   0.04

!genbox chrome lien .03 .0015 .3 | \
 xform -t -0.015 -0.2 0.41

!genbox tissu coussin .4 .4 .04 -r .01 | \
 xform -t -0.2 -0.2 0.41

!genbox tissu dossier .4 .04 .22 -r .01 | \
 xform -t -0.2 0 -0.11 -rx 15 -t 0 -0.2 0.71
```

isystem.rad

```
# mkillum -ab 0 modele0.oct
#@mkillum !
# mkillum n

!genprism reflector ashelf ashelf.dat -c -e -l 0 0 5 | \
xform -rx 90 -rz 90 -t 0 0 3

ceiling_mat polygon cache_H
0
0
12
                  5        1.52412861              2.1
                  5                 0              2.1
                  0                 0              2.1
                  0        1.52412861              2.1

frame_mat polygon cache_V
0
0
12
                  5        1.52412861              2.1
                  0        1.52412861              2.1
                  0        1.52412861       2.12004394
                  5        1.52412861       2.12004394

frame_mat polygon side1
0
0
12
                  0        1.52412861              2.1
                  0        1.52412861                3
                0.2        1.52412861                3
                0.2        1.52412861              2.1

frame_mat polygon side2
0
0
12
                  5        1.52412861              2.1
                4.8        1.52412861              2.1
                4.8        1.52412861                3
                  5        1.52412861                3

reflector polygon side_refl1
0
0
12
                0.2                 0       2.12004394
                0.2        1.52412861       2.12004394
                0.2        1.52412861                3
                0.2                 0                3

reflector polygon side_refl2
0
0
12
                4.8                 0       2.12004394
                4.8                 0                3
                4.8        1.52412861                3
                4.8        1.52412861       2.12004394
```

```
trans80 polygon upper_window
0
0
12
                4.8                  0         2.12004394
                0.2                  0         2.12004394
                0.2                  0                  3
                4.8                  0                  3

trans90 polygon interior_window
0
0
12
                4.8         1.52412861         2.12004394
                0.2         1.52412861         2.12004394
                0.2         1.52412861                  3
                4.8         1.52412861                  3
# mkillum i=trans80 d=223 s=115 m=window

void brightdata window.dist
5 noneg window.dat
        illum.cal il_alth il_azih
0
9
        -1.000000       0.000000        0.000000
        0.000000        0.000000        1.000000
        0.000000        1.000000        0.000000

window.dist illum window
1 trans80
0
3 5.626943 5.626943 5.626943

window polygon view_window
0
0
12
                4.8                  0                  1
                0.2                  0                  1
                0.2                  0                  2
                4.8                  0                  2

# mkillum i=void d=1100 s=202 m=illum

void brightdata illum.dist
5 noneg illum.dat
        illum.cal il_alth il_azih
0
9
        -1.000000       0.000000        0.000000
        0.000000        -0.866025       0.500000
        0.000000        0.500000        0.866025

illum.dist illum illum
0
0
3 1.453124 1.453124 1.453124
```

```
illum polygon illuminator
0
0
12
                0.2         1.52412861          2.12004394
                0.2                  0                   3
                4.8                  0                   3
                4.8         1.52412861          2.12004394
# mkillum n
```

ulim.cal

```
{ Approximate upper limit without glare related to adaptation level

  RC @ Martin Centre, Cambridge UK, 26/FEB/97
}

{ footlambert to cd/m2 conversion }
fl2cd(v)=3.426*v;
cd2fl(v)=.292*v;

{ Approximate upper limit without glare }
ulim(La)=fl2cd(10^(5.731+(log10(cd2fl(La))+5)*
                  (0.3376+(log10(cd2fl(La))+5)*0.0189)-6));
```

pmat.rad

```
void colorfunc skirting_board
4 if(Pz-0.06,1,0.309/0.6) if(Pz-0.06,1,0.165/0.6)
  if(Pz-0.06,1,0.083/0.6) .
0
0

skirting_board plastic walls_mat
0
0
5 .6 .6 .6 0 0

skirting_board plastic south_wall_mat
0
0
5 .6 .6 .6 0 0

void plastic frame_mat
0
0
5 .683 .476 .261 0 0

void texfunc plate
4 0 y_pert 0 plate.cal
0
2 .25 .02

plate plastic ceiling_mat
0
0
5 0.8 0.8 0.8 0 0

void brightfunc parquet
2 0.6*rand(floor(Px/0.2)*floor(Py/0.05))+0.7 .
0
0

parquet plastic floor_mat
0
0
5 0.433 0.118 0.073 0.03 0.1

void mirror reflector
0
0
3 .8 .8 .8

# 80 % transmittance glass
void glass trans80
0
0
3 .8715 .8715 .8715

# 90 % transmittance glass
void glass trans90
0
0
3 .98 .98 .98
```

plate.cal

```
{ Definition of ceiling plates texture
  RC LESO-PB 16/JAN/96
  Parameters: A1= total length
              A2= empty space width between plates }

l=A1;
lb=A2;
la=l-lb;

position=Py-floor(Py/l)*l;
y_pert=if(la-position,
                        0, { no perturbation on the plate }
                        if(position-la-lb/2,
                                                -1, { face 2 }
                                                +1  { face 1 }
                        )
        );
```

cell.rif

```
OCTREE= model.oct

scene= cie.rad room.rad
material= pmat.rad

illum=system.rad
mkillum=-ab 0

objects=ashelf.dat

ZONE= I 0 5 0 7 0 3

EXPOSURE= 1.79

QUALITY= M

RESOLUTION= 480

INDIRECT= 1

AMBFILE= cell.amb

render= -dr 0 -av .01 .01 .01

view= v1 -vp 4.5 6.5 1.5 -vd -1 -2 0 -vh 90 -vv 67.4
view= v1i -i -vp 4.5 6.5 1.5 -vd -1 -2 0 -vh 90 -vv 67.4
view= fe -vth -vp 2.5 4.9 1.5 -vd 0 -1 0 -vh 180 -vv 180
view= p -vtl -vp 2.5 3.5 1.5 -vd 0 0 -1 -vu -1 0 0 -vh 7 -vv 5
```