Tauray 1.0 User Manual

Julius Ikkala

Contents

Chapter 1

Introduction

Figure 1.1: The logo of Tauray.

Tauray 1.0 is a GPU-accelerated rendering software developed at Tampere University. Its focus is on speed and scalability. Tauray can be used for generating datasets as well as developing real-time rendering algorithms. It is primarily used as a command-line program, which makes scripting and remote use over SSH easy.

This file is the end-user manual; it does not describe how to develop new features for tauray. See `DEVELOPERS.md`[1] for details on how to work with Tauray source code.

This document may not always be perfectly up-to-date. You can get the most up-to-date information on all available options through `tauray --help`. That information is gathered in such a way that the developers cannot accidentally miss updating it when they add new options or modify old ones.

In any case, you should install Tauray and prepare a scene first. Then, you should check that the scene works properly, using the interactive mode or a one-off offline rendering. After that, you should read how Tauray is configured and choose the options based on your needs, and render the final results.

[1] DEVELOPERS.md

Chapter 2

Installing Tauray

It is recommended that you run Tauray on a PC running Ubuntu 22.04 LTS with one or more Nvidia RTX GPUs.

2.1 Building Tauray

Tauray has some dependencies, so install them first:

```
sudo apt install libvulkan-dev vulkan-validationlayers vulkan-tools imagemagick libnng-dev \
    libcbor-dev libczmq-dev libglm-dev libsdl2-dev
```

Then, you can build Tauray.

```
cmake -S . -B build
cmake --build build
```

You can use Tauray from `build/tauray` (make sure to run it like this, it won't find its internal `data` folder if you do `./tauray` in the build folder!), or you can install it system-wide with

```
sudo cmake --install build
```

The rest of the manual assumes a system-wide installation.

2.2 Binaries

If you have acquired a `.deb` of Tauray, you can install it system-wide with the following command:

```
sudo dpkg -i tauray.deb
```

Chapter 3

Scene setup

If you want to skip this part, you can just use the included test model `test/test.glb` instead of the `example.glb` shown in example commands.

Tauray only supports glTF 2.0 files as inputs. They must be in the `.glb` binary format. These files can contain almost everything needed, such as the geometry, cameras, lights and even animations.

There are some features missing in glTF 2.0. To work around these limitations, Tauray comes with a Blender plugin. Usage of this plugin is not required, but recommended, as some scene features will not work properly without it. We will be going over how to install this plugin, author a scene in Blender, and export it for Tauray.

3.1 Blender setup

While not the only possible option, Blender[1] is a great open-source 3D authoring tool that we recommend for preparing scenes for Tauray. Start by installing the newest version, if you don't yet have it.

Next, we'll install the Tauray plugin. First, navigate to the Tauray folder and find the `blender` folder. Make a .zip file of the `tr_gltf_extension` file included within (unless it already exists).

Now, you can open Blender. Go to the preferences and open the "Add-ons" section.

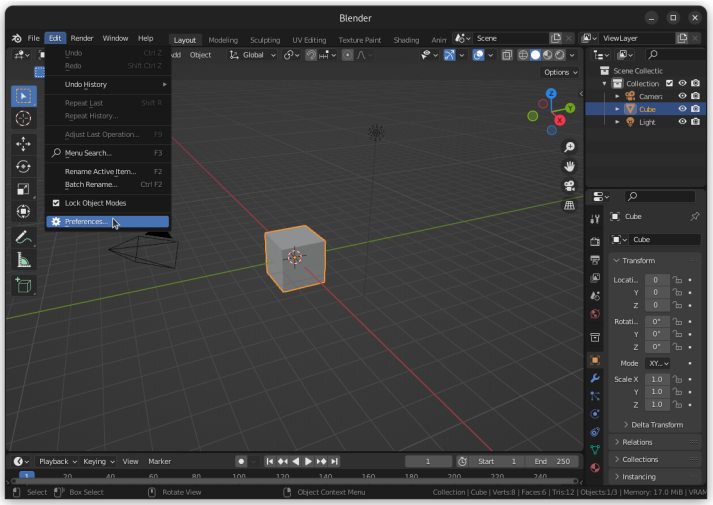


Figure 3.1: Select "Preferences" from the "Edit" drop-down.

Next, press the "Install" button.

From the file dialog that opens, navigate to the Tauray folder. Go to the `blender` directory and find the .zip you just created. Then, click the `Install Add-on` button.

[1] https://www.blender.org/

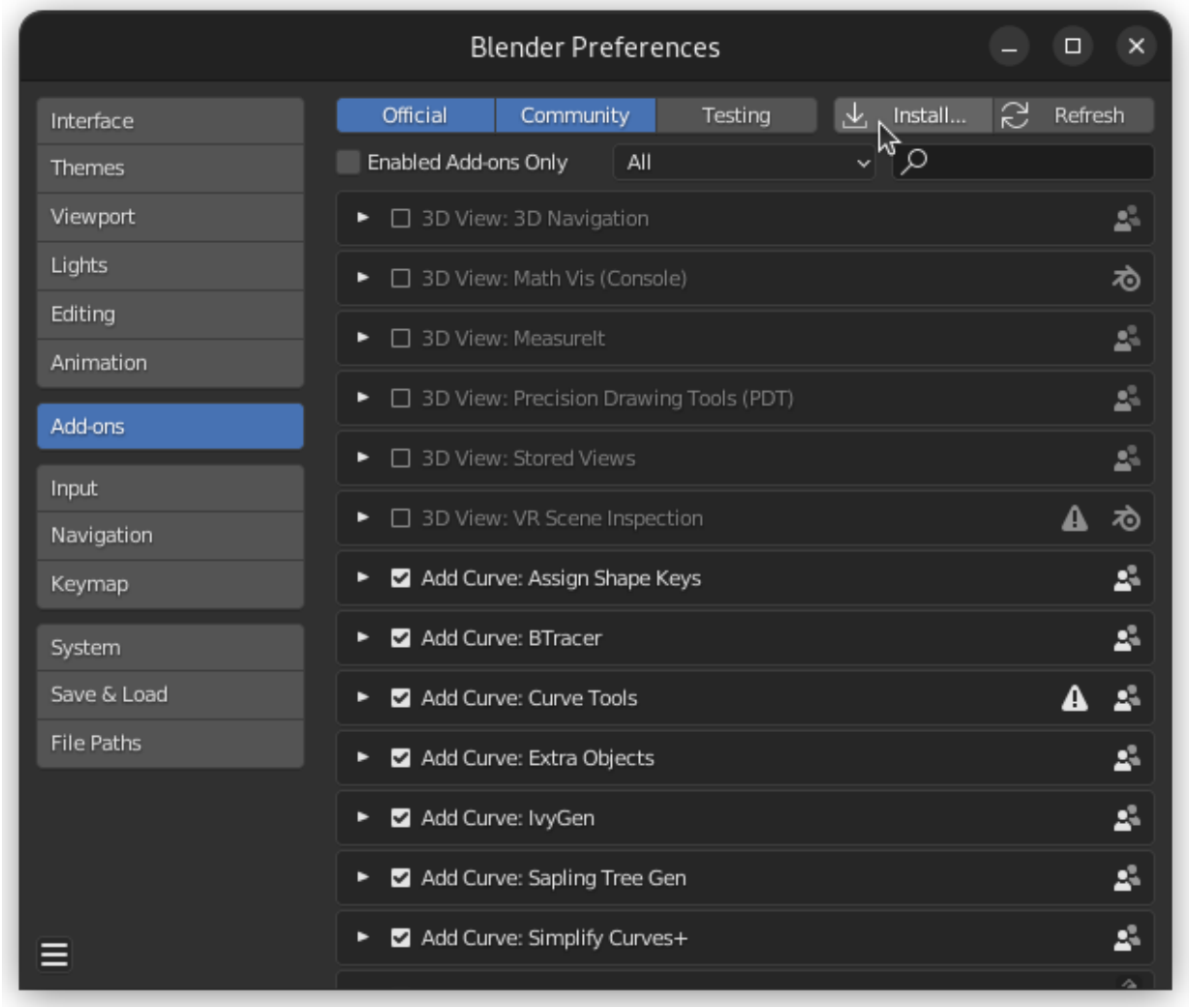


Figure 3.2: Click the “Install...” button in the Add-ons section.

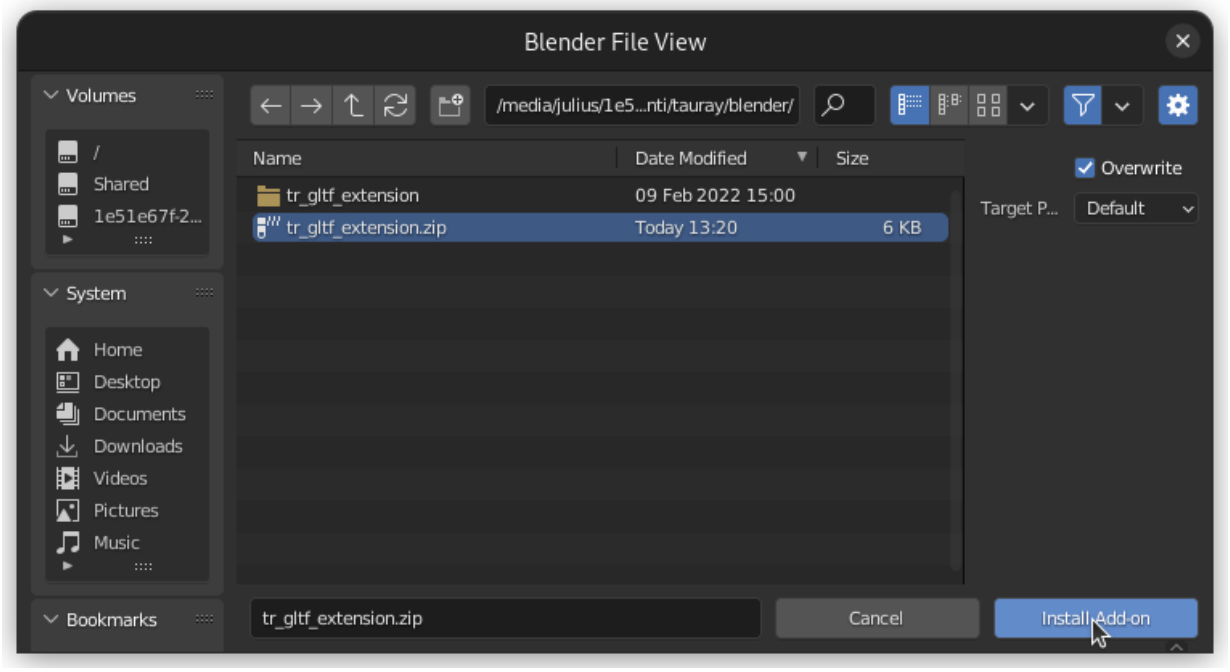


Figure 3.3: Clicking the Install button in the file dialog.

Depending on Blender version and whether you already had the plugin installed, it may be automatically shown in the Add-ons section. If not, search for “tauray”. In any case, enable the “Tauray glTF extension” by checking the checkbox next to the name.

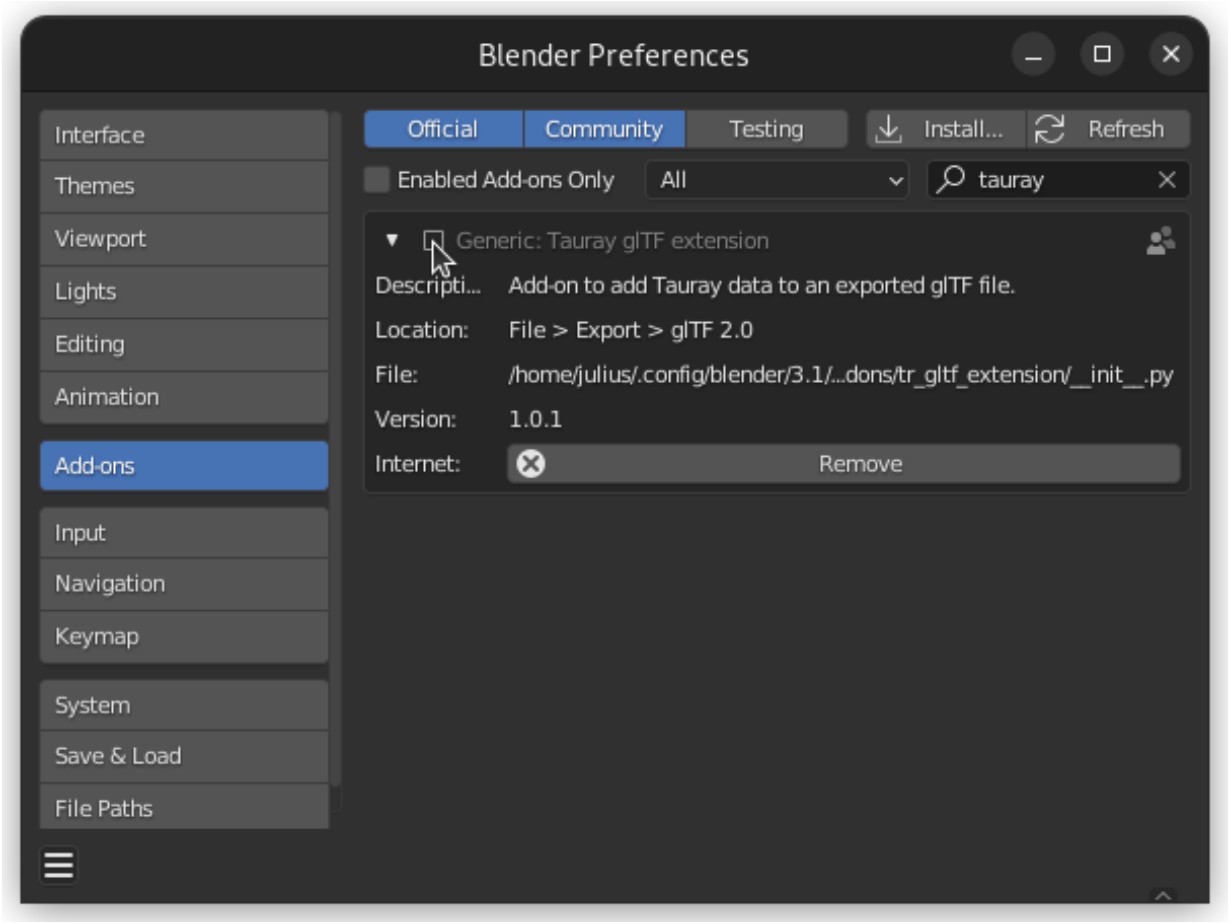


Figure 3.4: Enable the Tauray addon.

You only need to install and enable the addon once, Blender will remember it across projects. You can now close the preferences window and start working with the scene.

3.2 Scene preparation

This is not really the proper place for a full Blender modeling tutorial. If you need to make models yourself, you can use any tutorial you find, but please only use the “Principled BSDF” material. Also, make sure that the scene has a light source! Otherwise, you won’t see anything. Setting up a camera is also important, otherwise you may only get a poorly placed default camera.

You can find high-quality ready-made models with good free licenses from Poly Haven[2], some Sketchfab collections[3], and danish museum scans[4]. You can import some of these in Blender, move them around, add a camera and a light, then export.

Reusing random models found online in the `.blend` format is often problematic as they tend to use complicated Blender-specific material nodes and features; it’s best to import general-purpose models instead.

Tauray supports rigid and skeletal animations. Morph targets are not supported, so scenes relying on those will not work properly. You should also ensure that all meshes are triangulated, especially if they use normal maps.

[2] https://polyhaven.com/models
[3] https://sketchfab.com/nebulousflynn/collections/cc0
[4] https://www.myminifactory.com/users/SMK%20-%20Statens%20Museum%20for%20Kunst

3.3 Exporting from Blender

Once you've designed a suitable scene, it's time to export it from Blender. From the File dropdown, select the Export > glTF 2.0 option.

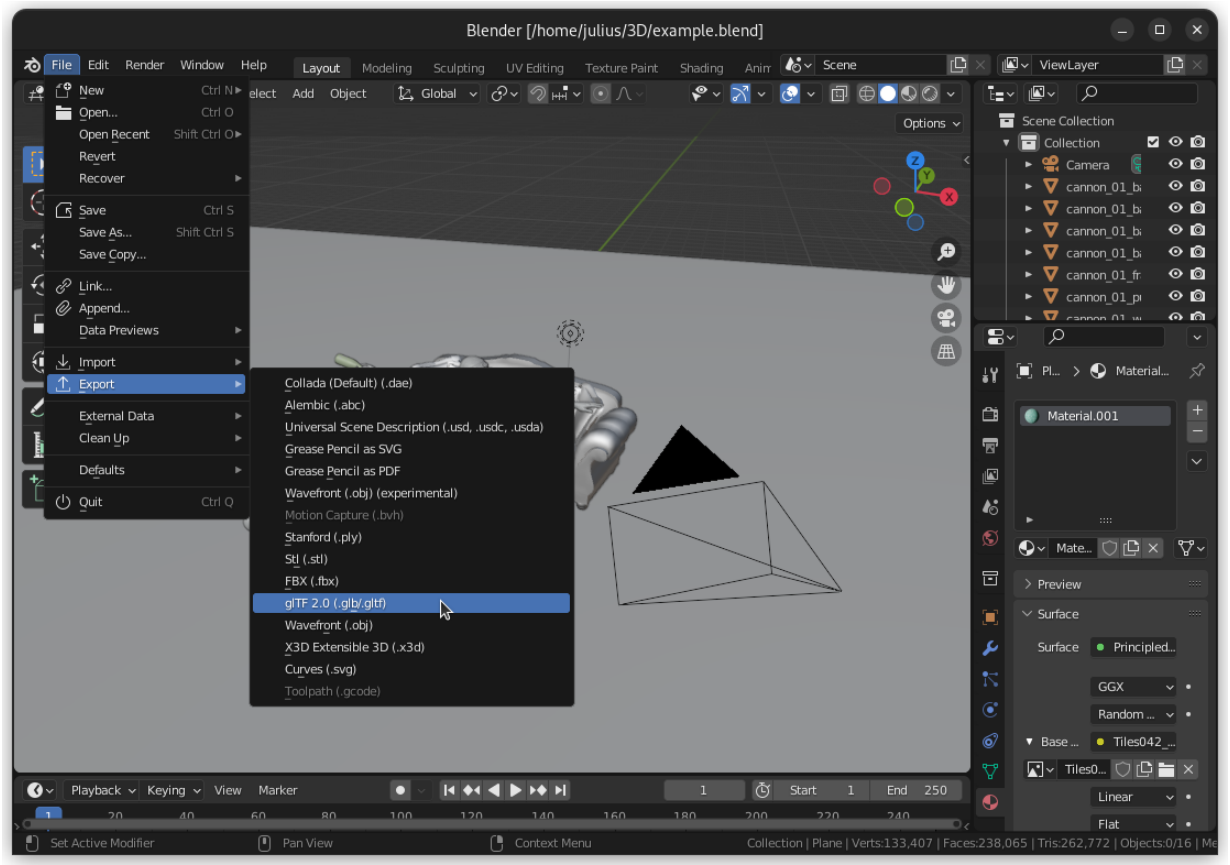


Figure 3.5: Finding the correct export format.

Now, export the model with the settings shown in the image below. You must enable exporting tangents if your scene uses normal maps (and they don't harm you in any case), and cameras and punctual lights.

You can now click the "Export glTF 2.0" button. We are now done with Blender for the extent of this manual.

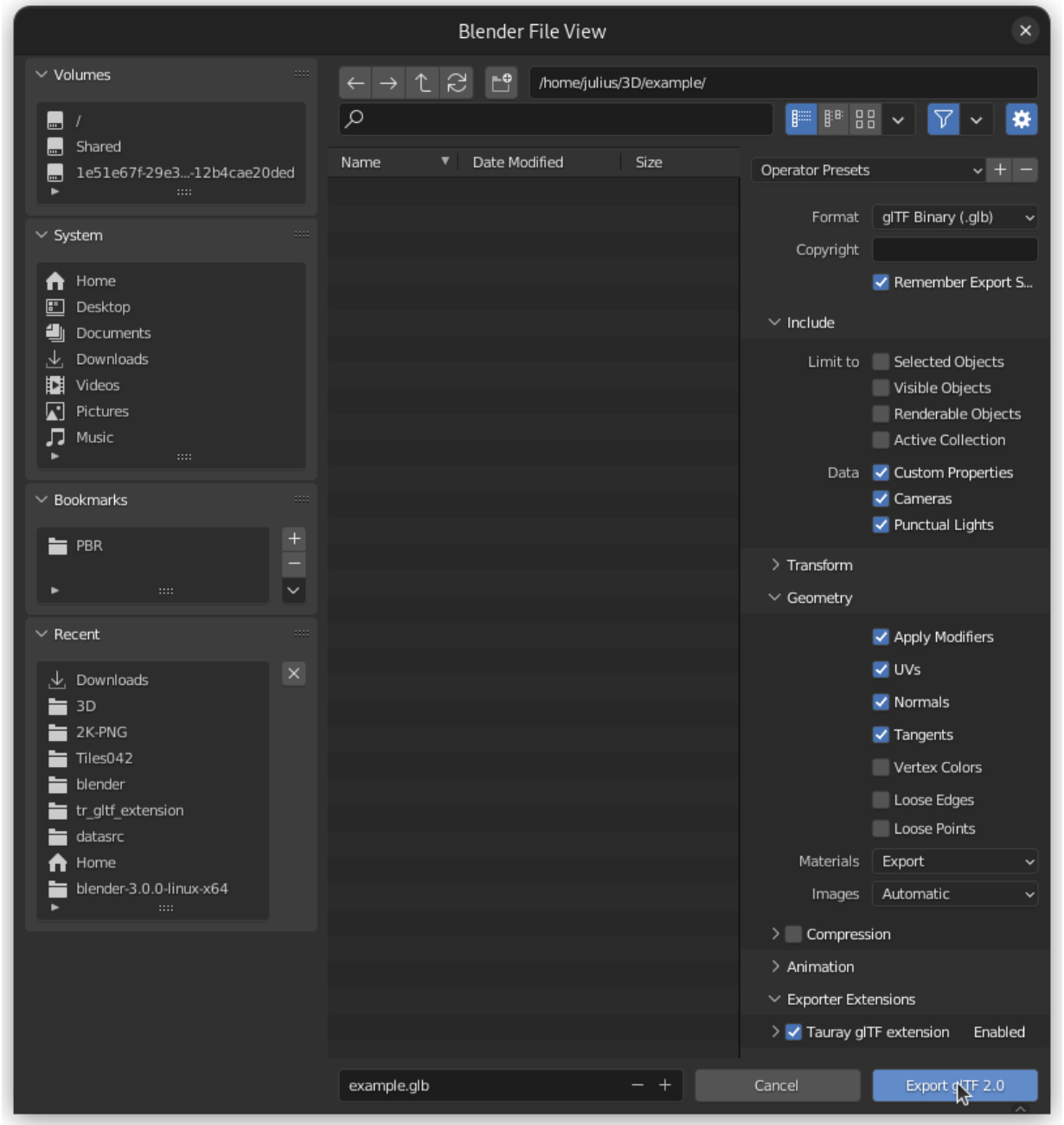


Figure 3.6: You must enable exporting cameras, punctual lights and tangents.

Chapter 4

Interactive rendering

The interactive mode allows you to fly around in your scene in real-time. It is the default mode in Tauray, so you don't have to set any extra parameters to use it!

```
tauray /path/to/example.glb
```

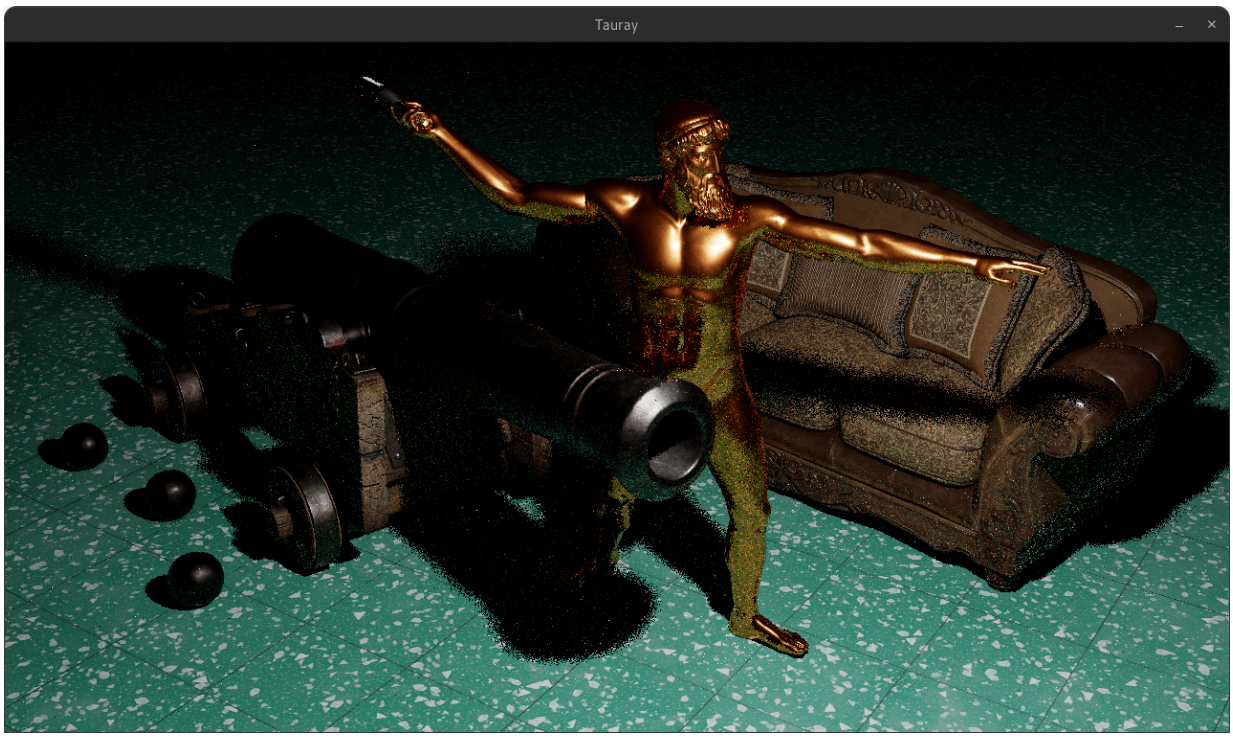


Figure 4.1: Tauray running in interactive mode.

Tauray does not have a loading screen, so large scenes will simply show a black screen until it's done loading.

You can fly around with typical FPS controls. For this reason, Tauray will also grab your cursor while running. The controls are summarized below.

Table 4.1: Controls of Tauray's interactive mode.

Control	Function
Escape	Close the program
W	Fly forwards
S	Fly backwards

Control	Function
A	Fly to the left
D	Fly to the right
Left shift	Descend
Space	Ascend
Mouse move	Turn camera
Scroll up	Speed up flight
Scroll down	Slow down flight
Page up	Switch to next camera
Page down	Switch to previous camera
0	Reset camera to origin
F1	Detach cursor from window
F5	Reload all shaders
T	Print timing info
Return	Pause all animations

You may want to start experimenting with different options now. They are outlined in the Options chapter. Certain (but very few) options are specific to the interactive mode. They are mostly related to windowing.

Chapter 5

Offline rendering

Offline rendering means that instead of an interactive session, you want to leave the computer rendering high-quality images over a long time, ranging from seconds to days. This is what you want to do when you wish to generate datasets, for example.

Offline rendering can be done with the headless mode. This mode does not open a window and doesn't even require a desktop session to exist - it's very suitable for running on a server.

This command will render the same example image as in interactive mode, but as a still image.

```
tauray /path/to/example.glb --filetype=png --headless=output
```

You may want to start experimenting with different options now. They are outlined in the Options chapter. Certain (but very few) options are specific to the headless mode. They are mostly related to the output format and animations.

Chapter 6

Configuration

Configuration of Tauray can be done in a three ways: command-line parameters, configuration files and the command-line interface.

The command-line parameters you've already seen earlier in this document: `--filetype=png` is one of these. In general, most command-line parameters start with `--` and have an equals-sign for specifying the value. There's also no whitespace. Then there's also the short flags: `-f`, enables fullscreen mode, for example.

Configuration files have all of the same parameters available, but they use a slightly different syntax. Preceding dashes are omitted, and the equals sign is optional. Whitespace is allowed! Short flags also do not exist in configuration files, so you'll need to use their long names instead (e.g. `fullscreen` instead of `f`). An example configuration file could look as follows:

```
# Let's call this file my_config.cfg
# This is a comment!
film blackman-harris
force-double-sided on
max-ray-depth 5
accumulation on
renderer path-tracer
sampler sobol-z3
samples-per-pixel 1
regularization 0.2

# Config files are also allowed to load each other like this, but please avoid
# creating cycles.
config base_config.cfg
```

If you saved this file as `my_config.cfg`, you can load it in Tauray using the `--config=my_config.cfg` parameter.

Finally, there's the command-line interface (CLI). It is only available in interactive mode. You can access it by detaching control of the Tauray window with F1 and alt-tabbing to the console/terminal where you launched Tauray. Now, you can type in commands with the same syntax as in the configuration files, but they will take place while the program is running!

You can use the CLI to experiment with options without having to restart Tauray constantly. There's also some extra features in the CLI that are not present elsewhere. You can get help for one specific command with the `help command-name` command, close the program with `quit` and print current configuration with `dump`.

A few parameters cannot be changed while the program is running; generally, these are related to windowing or how the scene is loaded. You cannot switch into headless mode, re-select involved GPUs, change display type, etc. without restarting Tauray.

Chapter 7

Options

Tauray has a **lot** of options and most things are customizable. Here, we've gathered the most important ones with example images of their function where applicable. Remember that, you can always get the most up-to-date information with `tauray --help`.

In general, options are documented with a list of possible values for them. For example, `--some-algorithm-selection=<algo-a|algo-b|algo-c>` means that `--some-algorithm-selection=algo-b` would select the `algo-b` option of the listed three. Boolean flags (`--some-boolean-flag=<on|off>`) also have a short form: You can simply use `--some-boolean-flag` to set the value to `on`.

While everything here is documented with the command-line parameter syntax (with the `--`, etc.), these options are also usable in configuration files. Just drop the `--` and replace the equals-sign with a space.

7.1 Presets

`--preset=<preset-name>` loads the given preset. "Presets" are configuration files that are shipped with Tauray (in `data/presets/preset-name.cfg`) and can be loaded with a shorthand name.

Preset	Image
`accumulation`: Interactive renderer that slowly reduces noise when not moving.	
`ddish-gi`: Interactive rendering with a fast global illumination approximation.	
`denoised`: Interactive renderer that produces denoised images.	

Preset	Image
`quality`: Offline renderer that creates high-quality images fairly quickly.	
`reference`: Reference renderer that avoids biased images.	

Presets are subject to minor changes every now and then, so don't rely on specific behaviour (except for the `reference` preset).

7.2 Fullscreen

`-f` or `--fullscreen=<on|off>` enable fullscreen mode. Runs the interactive Tauray session in fullscreen at the native resolution. By default, Tauray runs in a window instead.

7.3 Output resolution

`-h=<integer>` and `--height=<integer>` set the output height, `-w=<integer>` and `--width=<integer>` set the output width, The default output size is 1280x720. The output size is the window size in interactive mode and the output image file size in offline rendering.

7.4 Replay mode

`-r` or `--replay=<on|off>` enable the replay mode. This means that even in the interactive mode, the user does not have camera control. Instead, it follows the animation, if present. This option is also forced on by the headless rendering mode.

7.5 Timing

`-t` or `--timing=<on|off>` make Tauray print timing information on every frame. If you are benchmarking Tauray performance, please only use this with interactive mode. If you need to use headless mode regardless,

ensure that its output filetype is `none`, so that your benchmark doesn't end up just measuring your disk speed instead.

The timing information is printed in a similar format as presented below, by default:

```
FRAME 617:
    DEVICE 0:
        [skinning] 0.001856 ms
        [scene update] 0.051872 ms
        [light BLAS update] 0.026624 ms
        [path tracing (1 viewports)] 1.55018 ms
        [distribution frame from host] 0.283552 ms
        [stitch (1 viewports)] 0.047136 ms
        [tonemap (1 viewports)] 0.032608 ms
    DEVICE 1:
        [skinning] 0.001568 ms
        [scene update] 0.050688 ms
        [light BLAS update] 0.02576 ms
        [path tracing (1 viewports)] 1.1321 ms
        [distribution frame to host] 1.26109 ms
    HOST: 3.64286 ms
```

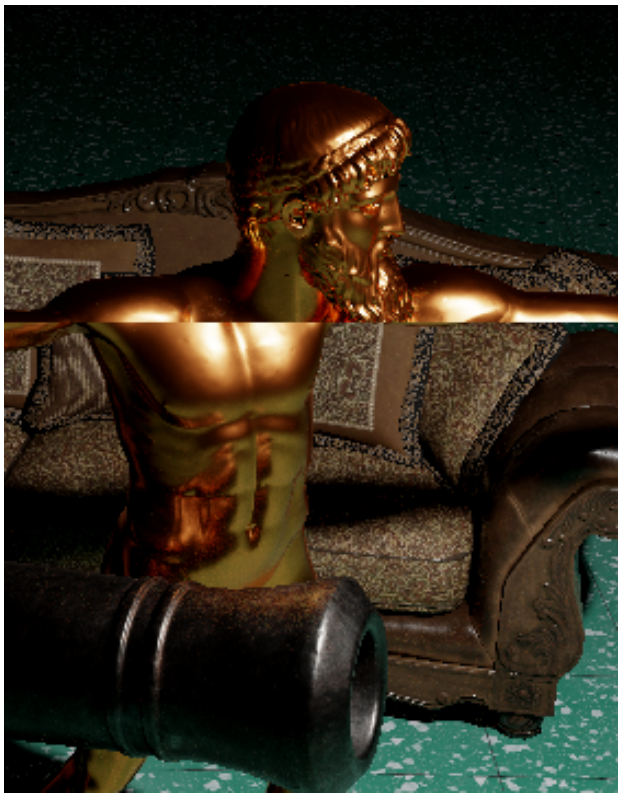
You get the frame index (the first frame is `FRAME 0`) and timing for each rendering stage on every device. The `HOST` timing means the overall frametime as measured on the CPU: this is what you want to use for benchmarks, excluding the first and last few values which wind the in-flight frames up and down.

You can also press the `T` key while Tauray is running to print the same timing info for one frame only.

Additionally, you can change the timing output format into "Trace Event Format" with `--trace=trace-event-format`. The output can be viewed in Chrome's `about://tracing`.

7.6 Vertical synchronization

`-s` or `--vsync=<on|off>` can be used to enable vertical synchronization. This is only meaningful in interactive mode and is used to combat display tearing artifacts occurring in motion:



Tearing with `--vsync=off`.

No tearing with `--vsync=on`

These artifacts are not any Tauray-specific issue, they occur in any program that doesn't do vertical synchronization. It's caused by the image being only partially updated when the display is refreshing.

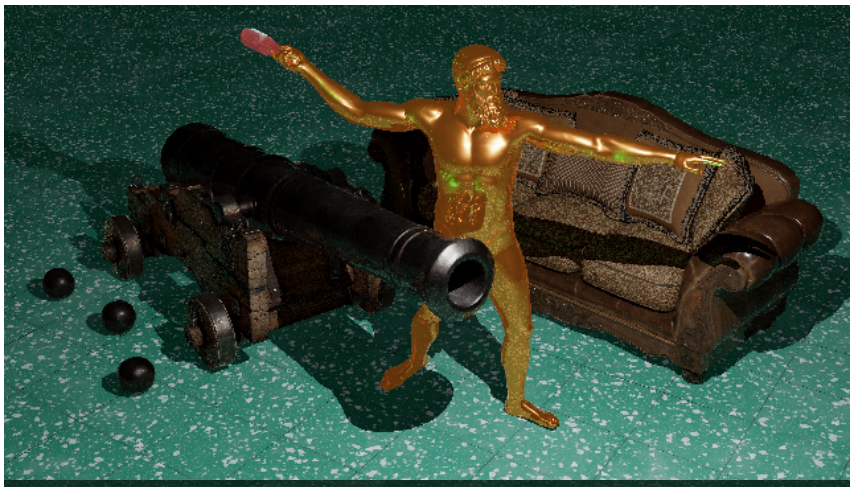
Important! Do not benchmark Tauray with vertical sync enabled! It intentionally limits the framerate!

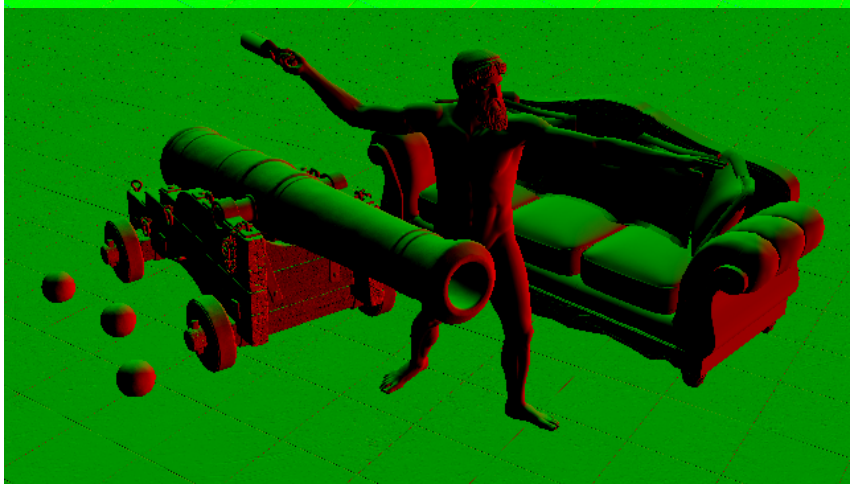
7.7 Renderer

`--renderer=<renderer-name>` sets the renderer used by Tauray. Tauray comes with many different renderers. Below is a table of each, with example images. The default renderer is the path tracer.

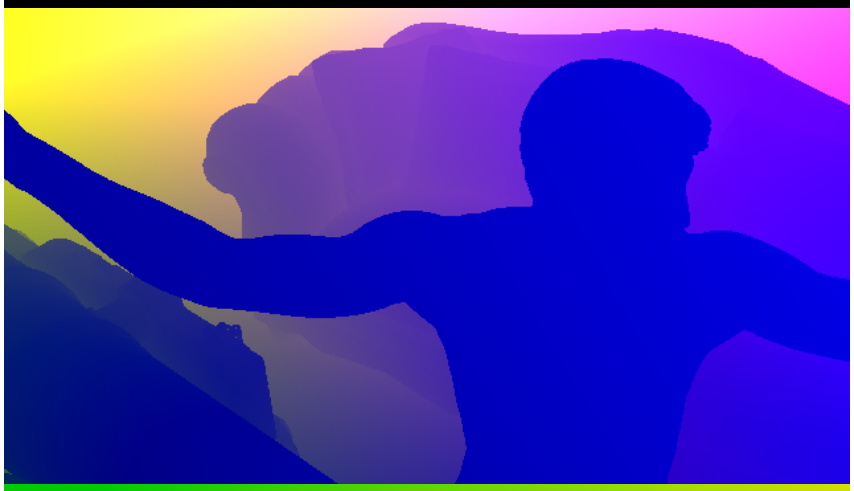
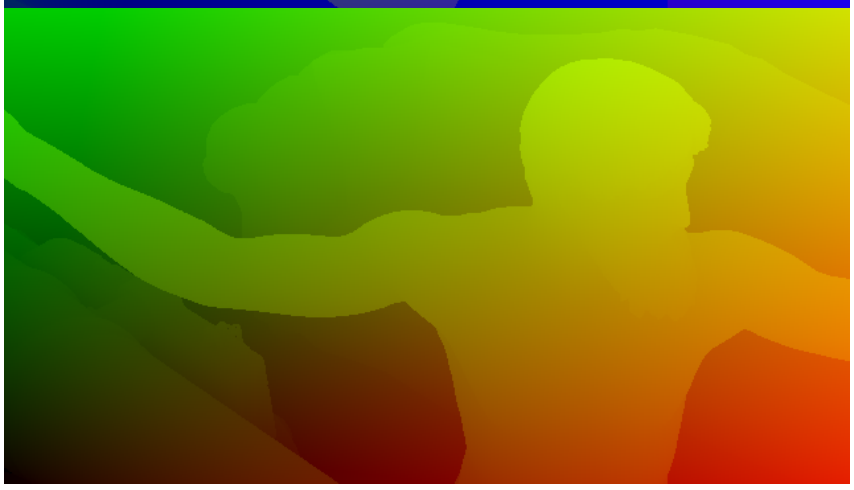
Table 7.3: Summary of renderers included in Tauray.

Renderer	Image
`path-tracer`: Photorealistic algorithm susceptible to noise.	

Renderer	Image
`whitted`: Noise-free oldskool ray tracing.	
`raster`: Naive rasterization with shadow mapping.	
`dshgi`: DDISH-GI.	

Renderer	Image
`albedo`: Albedo of the first intersection.	
`world-normal`: World-space of the first intersection.	
`view-normal`: View-space normal of the first intersection.	

Renderer	Image
`world-pos`: World-space position of the first intersection.	
`view-pos`: View-space position of the first intersection.	
`distance`: Distance to the first intersection.	

Renderer	Image
`world-motion`: World-space movement between frames.	
`view-motion`: View-space movement between frames.	
`screen-motion`: Screen coordinate of intersection in previous frame.	

Renderer	Image
`instance-id`: Color channels are geometry-dependent IDs.	

7.7.1 Primary renderers

These are the `path-tracer`, `whitted`, `raster` and `dshgi` renderers. Many further options only affect some of these renderers.

Most of the time, you want to be running `path-tracer`, as it is the most realistic rendering algorithm provided in Tauray.

The `whitted`-style renderer isn't particularly useful from an end-user's point of view, unless you are trying to replicate vintage 90s ray tracing art.

If you can't run Tauray normally due to missing ray tracing support, you may still be able to run the `raster` renderer. But in that case, there's hardly any reason to be running Tauray, anyway...

Note that when creating scenes for DDISH-GI (`dshgi`), you should place an "Irradiance Volume" that covers the scene in Blender. DDISH-GI will use this volume for its probe placement. The resolution selected in Blender for the irradiance volume will also be used by Tauray.

7.7.2 Feature buffer / AOV renderers

These are the `albedo`, `world-normal`, `view-normal`, `world-pos`, `view-pos`, `distance`, `world-motion`, `view-motion`, `screen-motion`, and `instance-id` renderers. They all use a common backend, which is why most options affecting feature buffers tend to affect all of them equally.

In the table above, many color channels appear black or extremely bright. This is because the PNG files cannot preserve the entire range of values. Feature buffers are internally rendered to floating-point buffers, so you probably don't want to be using `.png` files for feature buffer datasets.

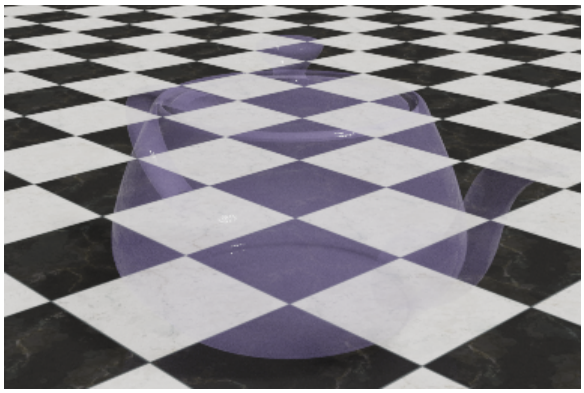
Instead, use `.exr`, which preserves negative and values larger than 1. `.exr` is the default image type in Tauray so that you wouldn't accidentally lose data if you forgot to specify the filetype.

Particularly, the `instance-id` renderer places the instance ID in the red color channel, triangle index in the green color channel, and mesh index in the blue color channel. They are all integers, so `.png` will not suffice!

7.8 Alpha to transmittance

`--alpha-to-transmittance=<on|off>`

A crude approximation that turns alpha + albedo color into colored transmittance for all materials in the scene whose constant alpha factor is below 1.0. It is disabled by default. You can use this to get transmittance with some .glb files that have not been exported with Tauray's Blender plugin.



A scene with an alpha blended teapot.

The same scene with `--alpha-to-transmittance`.

`--transmittance-to-alpha=<number>` is simply the inverse operation, but it has very few use cases. The value is the minimum alpha assigned to materials converted this way.

7.9 Ambient

`--ambient=<r,g,b>`

The `raster` and `whitted` renderers do not properly estimate surrounding indirect lighting. Instead, they apply a constant light, called "ambient light", to every surface in the scene. You can adjust that ambient light's color and intensity with this parameter.

`raster` rendering with `--ambient=0,0,0`.

The same scene with `--ambient=0.1,0.2,0.4`.

Setting ambient to zero is equivalent to simulating direct light only. Note that this parameter does nothing in the `dshgi` or `path-tracer` renderers, as they don't use an ambient light.

7.10 Animation

`--animation` or `--animation=<name>`

Tauray supports animations, but they are not running by default. You can add the `--animation` flag to play animations. Without a string parameter, the flag just plays the first found animation for everything in the scene. If you give a string, it tries to play animations with that name.

Both rigid and skeletal animations are supported. The camera and lights can be animated as well. Note that camera animation will not work in interactive mode, because the camera is controlled by the user instead. If you want to preview an animation, you can use the `-r` flag (replay mode) to forego user control of the camera.

By default, `headless` mode (offline rendering) will render all frames of the full animation with this flag specified. You can limit the number of frames to something lower with `--frames=<integer>`.

If your animation render is interrupted without finishing, you can easily continue from the frame you left off with `--skip-frames=<integer>`.

In replay and offline rendering modes, you can set the simulated framerate for the animation with `--framerate=<number>`. It defaults to 60 fps.

7.11 Aspect ratio

`--aspect-ratio=<number>`

By default, Tauray assumes that pixels are square. If you want them to be something else, you can force the image aspect ratio with `--aspect-ratio`.

The default aspect ratio, which is 1.5 in this case.

The same scene with `--aspect-ratio=0.75`.

7.12 Camera

There's many ways to modify the camera included in a scene with command line options, because it's often faster to compare different views this way instead of re-exporting the scene with a different camera from Blender.

7.12.1 Camera selection

`--camera=<name>`

If there are multiple cameras in the scene, you can choose which one to use by specifying `--camera=nameofthecamera`. The default camera is the first one.

7.12.2 Camera position

`--camera-offset=<x,y,z>`

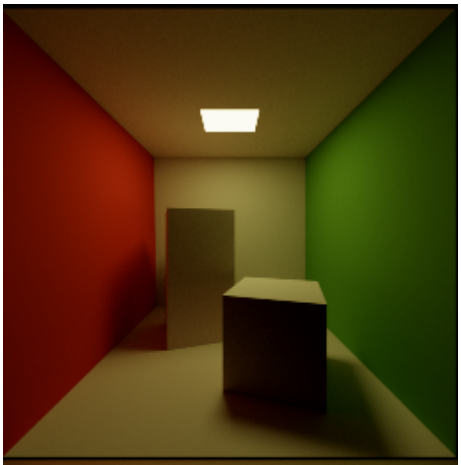
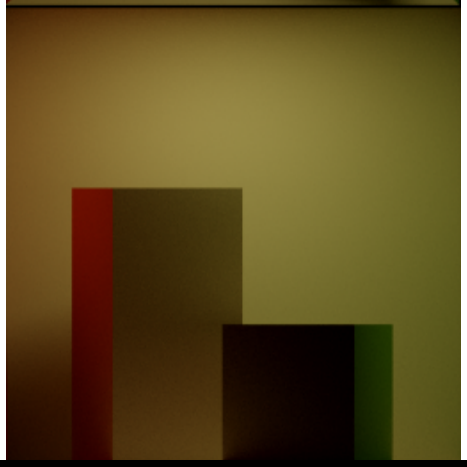
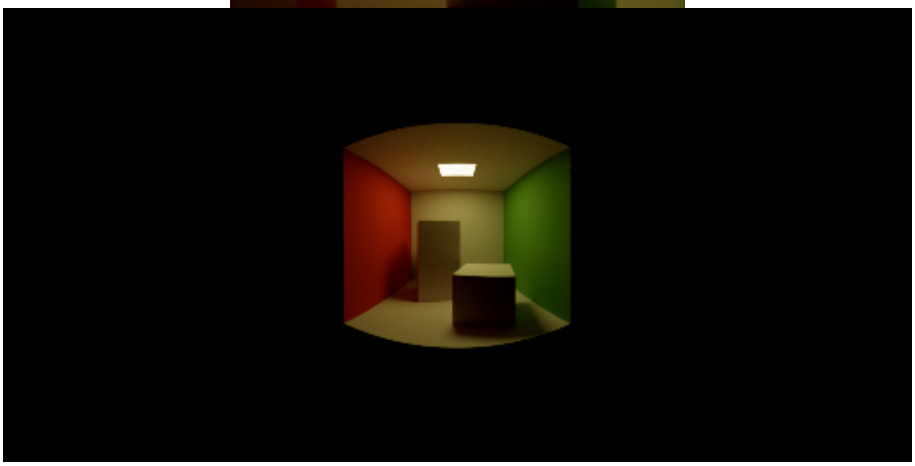
You can also move the camera a bit from its original position with `--camera-offset=<x,y,z>`.

7.12.3 Camera projection

`--force-projection=<perspective|orthographic|equirectangular>`

It's possible to force a different camera projection than specified in the scene. Note that the `equirectangular` projection only works with ray tracing!

Table 7.7: Summary of available camera projections.

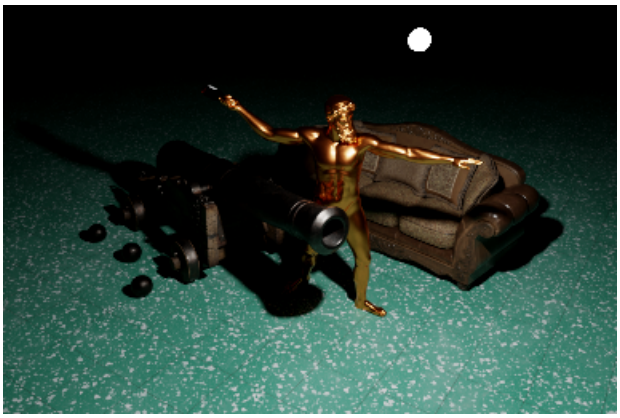
Projection	Image
`perspective`	
`orthographic`	
`equirectangular`	

7.12.4 Field of view (FOV)

`--fov=<number>`

If you want to force a different field of view than the original, you can do so with `--fov`. Adjusting FOV is just like adjusting zoom on a camera. Lower FOV = more zoomed in.

`--fov=30`



`--fov=40`

7.12.5 Camera grid / simple light fields

`--camera-grid=<w,h,x,y>`

`--camera-grid-roll=<degrees>`

`--camera-recentering-distance=<distance>`

If you want to render a grid of views instead of just one, you can easily turn one camera into many with the `--camera-grid` option. It takes four numbers: `w` and `h` specify the view grid size horizontally and vertically; `x` and `y` specify the distance between views horizontally and vertically. If you want the grid to be rotated (without rotating the cameras themselves!), you can use `--camera-grid-roll=<degrees>`.

`--camera-recentering-distance` is used to set the distance to the zero-disparity plane. In other words, objects at that depth appear at the exact same screen coordinates on all cameras of the grid. This parameter is commonly needed for VR and light field setups.

7.12.6 Camera logging

`--camera-log=<path-to-log>`

You can write a log of camera matrices from an animation using this flag. The data will be in the JSON format.

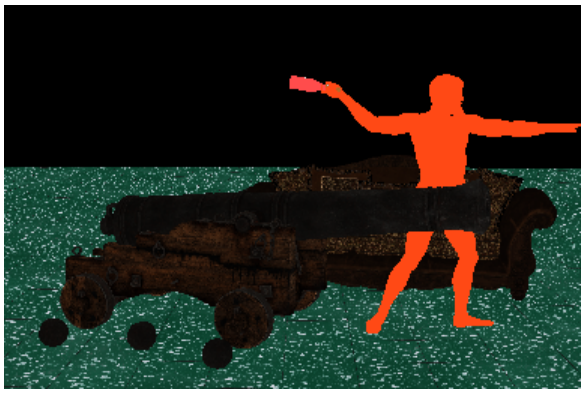
7.13 Networking

There are certain setups in Tauray that require networking. There's always a server and a client. The server will bind to a port (default is 3333, you can set it with `--port=<integer>`. The client will connect to a server with an address that can be specified with `--connect=<address:port>` (default is localhost:3333).

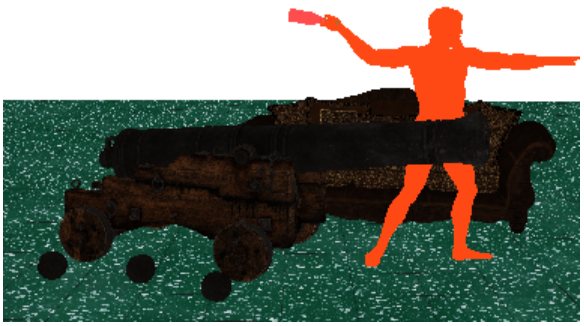
7.14 Default value

`--default-value=<number>`

You can set the default value to be used in feature renderers when the ray misses geometry. The default is NaN, which can be stored and detected in .exr images.



An `albedo` render, with `--default-value=0`.

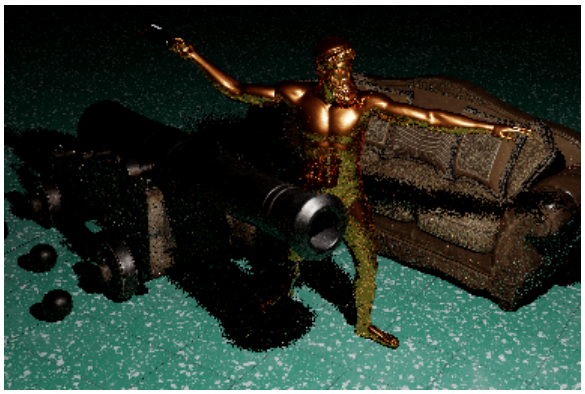


The same scene, with `--default-value=1`.

7.15 Denoising

`--denoiser=<none|svgf|bmfr>`

Denoising can be used with the `path-tracer` renderer in order to reduce noise from the images. You basically only want this when very few samples per pixel are taken, which causes massive noise.



A path traced rendering with `--denoiser=none`.

The same scene, with `--denoiser=svgf`.

You may want to use `--warmup-frames=<number>` for offline rendering use cases in order to get some temporal history before starting actual rendering. Doing so will reduce noise. Usually, you also use denoising in conjunction with temporal anti aliasing.

7.16 Multi-device rendering

`--devices=<int,int,...>`

You can define which devices to use with the `--devices` argument. By default, it uses all ray tracing-capable GPUs that are found. If you only want one GPU, you can use `--devices=-1` (which picks the default GPU) or `--devices=0` (which picks the first one) and so on. You can also give a list of integers to define a subset of GPUs to use.

7.17 Display

`--display=<headless|window|openxr|looking-glass>`

Display type. If you use `--headless`, the `headless` display is forced on. Otherwise, you can pick whether you want to output to a window, to a VR HMD with OpenXR or a Looking Glass light field display.

7.17.1 Looking Glass

`--lkg-params=<viewports,midplane,depthiness,relative_view_distance>`

You can set the parameters for rendering to a Looking Glass display with the `--lkg-params` option. `viewports` is the number of discrete viewports to render, this would usually be between 48 to 128. `midplane` is the plane of convergence, i.e. which scene depth corresponds to the actual physical distance of the display from the viewer's eye. `depthiness` can be used to adjust the distance between viewports, and `relative_view_distance` is the distance of the user's eye relative to the size of the display (this is needed for the Y axis, as the Looking Glass displays only have multiple horizontal views.)

7.18 Environment map

`--envmap=<path-to-envmap>`

Environment maps are among one of the only things that glTF 2.0 files cannot contain. If you want your scene to have a "background image" instead of floating in an infinite black void, you need to specify an environment map with the `--envmap` parameter. You can find free CC0-licensed environment maps from Poly Haven[1].

A path traced rendering with no envmap.

The same scene, with an environment map.

Environment maps make it easier to generate realistic-looking images of individual objects, as you don't have to model proper surrounding geometry. They are also nice in larger scenes as well.

By default, environment maps are importance sampled. This has a noticeable performance impact and you may want to disable the importance sampling sometimes. You can do this with `--importance-sample-envmap=off`. Note that this importance sampling is basically required if your environment map includes the sun or any other small and bright light source:

[1] https://polyhaven.com/hdris

`--importance-sample-envmap=off`

`--importance-sample-envmap=on` (default)

7.19 Tone mapping

`--tonemap=<filmic|gamma-correction|linear|reinhard|reinhard-luminance>`

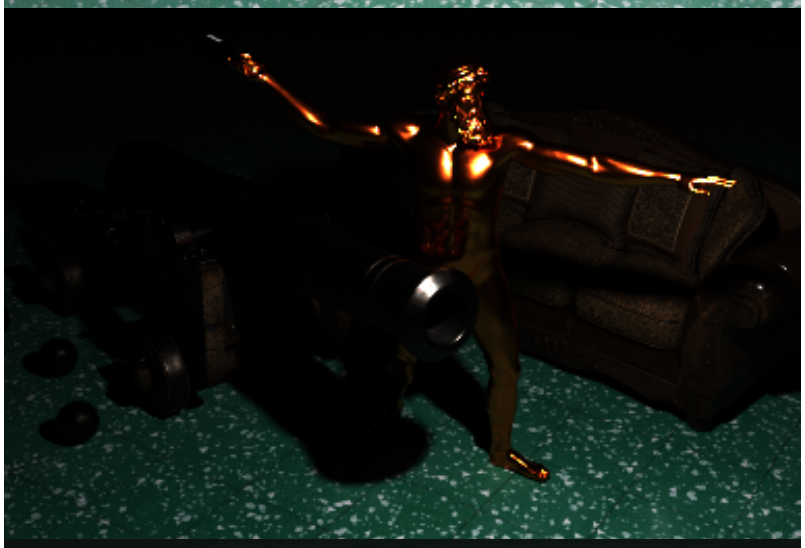
`--gamma=<number>`

`--exposure=<number>`

If you want to affect the final look of the render, you can adjust the tonemapping parameters. Firstly, you'll want to pick a tonemapping operator with `--tonemap`.

Table 7.13: Summary of available tonemapping operators.

Operator	Image
`filmic`: Looks generally good, but has relatively stark contrast for an HDR operator.	

Operator	Image
`gamma-correction`: Plain and susceptible to clipping, but sometimes required for science.	
`linear`: Looks wrong on regular displays, but is useful if you intend to do math with the output.	
`reinhard`: A bit plain, but works well with HDR. Often seen in literature.	

Operator	Image
`reinhard-luminance`: Reinhard done on luminance instead of color channels. Technically incorrect, but preserves saturation better.	

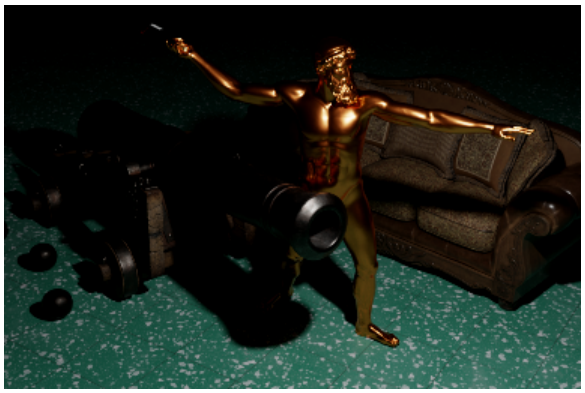
Then, you can adjust `gamma`, to change the gamma curve[2]. It affects every operator except `linear`. It's usually best to leave this as the default value 2.2 unless your display expects a different gamma value.

Filmic tonemapping with `--gamma=1.5`.

The same scene, with `--gamma=2.5`.

`exposure` should be used to adjust the overall brightness of the image. It works just like adjusting exposure on a real camera, although it's defined in relative terms. `--exposure=1` is the default exposure that is expected by glTF files. `--exposure=2` doubles the brightness *before* tonemapping.

[2] https://en.wikipedia.org/wiki/Gamma_correction



Filmic tonemapping with `--exposure=0.5`.

The same scene, with `--exposure=2.0`.

7.20 Output file

7.20.1 File format

`--filetype=<exr|png|raw|none>`

You can change the file format for the output data of headless mode with `--filetype`. The default is .EXR, which may be hard to view without an EXR viewer application, but it will not lose data. If you intend to generate images just to be looked at, you probably want to specify `--filetype=png` instead. Tauray's PNG output is limited to 8-bits-per-channel color, clipped between 0 to 1.

The `raw` file format just dumps 4 floating point numbers per pixel to the disk as-is. This can be easy to load in your own programs consuming Tauray data, as you don't have to deal with image formats. However, you must know the size of the image yourself, as no metadata is included.

The `none` format just means that no output is actually written. This can be useful for benchmarking Tauray on a server, so you don't end up benchmarking disk and EXR compression speed instead.

7.20.2 Pixel format

`--format=<rgb16|rgb32|rgba16|rgba32>`

This flag sets the pixel format for EXR files. All are floating point formats, you can only choose whether you want 3 (`rgb`) or 4 (`rgba`) color channels and half floating point values (`16`) or regular floating point values (`32`).

7.20.3 Compression

`--compression=<zip|zips|rle|piz|none>`

Currently, this parameter only sets the compression scheme for the EXR format. All schemes are lossless, but may not be supported by every EXR viewer. For example, a 384x256 image of the example scene used in this manual takes 594 kilobytes with `--compression=none`, and 403 kilobytes with `--compression=piz`. The PIZ compression scheme is used by default.

7.21 Anti-aliasing

There's many parameters controlling how anti-aliasing is done, as it's generally a bit different between path tracing and rasterization-based methods. By default, anti-aliasing is **disabled** because it makes it harder to post-process images afterwards. However, if you just want to show pretty pictures, you most definitely want to enable it.

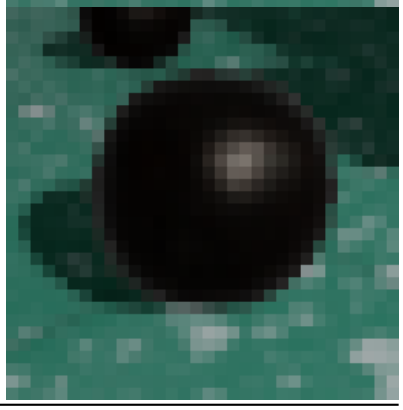
7.21.1 Rasterization

In rasterization (i.e. `raster` and `dshgi` renderers), two related anti-aliasing methods are available: MSAA[3] and SSAA[4].

Both are enabled by setting `--samples-per-pixel=<integer>`, where the integer is a power-of-two number between 1 and 8. 1 corresponds to no anti-aliasing and is the default, whereas 8 is the slowest and prettiest anti-aliasing.

MSAA is used by default. It only anti-aliases geometric edges, so shading details such as sharp shadows may still appear aliased. SSAA is enabled by setting `--sample-shading=on`. This method is very slow, as it linearly increases the workload by your `--samples-per-pixel` value. However, it generally works the best.

Table 7.16: Comparison between anti-aliasing methods for rasterization.

Anti-aliasing mode	Image
No anti-aliasing	
8 x MSAA	
8 x SSAA	

[3]https://en.wikipedia.org/wiki/Multisample_anti-aliasing
[4]https://en.wikipedia.org/wiki/Supersampling

7.21.2 Path tracing

`--film=<point|box|blackman-harris>`

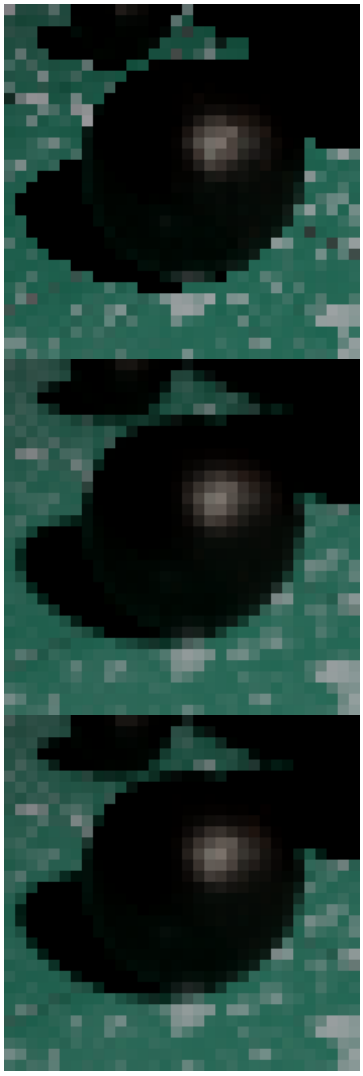
With `path-tracer`, you can set the film filtering scheme. This jitters the origin of the ray according to a filter function, in order to cause anti-aliasing with a method that is fairly physically correct. You can set the filter shape with `--film`. `box` looks like the anti-aliasing methods available in rasterization, but `blackman-harris` has fewer artifacts and is recommended instead. `point` is the default, which means that all rays start from the center of the pixel and there is no anti-aliasing.

`--film-radius=<number>`

For the `box` and `blackman-harris` filters, you can set the filter radius `--film-radius`. The default is usually good, but you can make the image appear even less aliased (and blurrier) if needed. Higher radius = blurrier image.

Note that the anti-aliasing starts to appear once you have multiple samples per pixel. So you'll want to set `--samples-per-pixel` to something higher than 1.

Table 7.17: Comparison between film filters for anti-aliasing path traced images.

Film filtering	Image	Explanation
`point`		No anti-aliasing.
`box`		Anti-aliased. This case doesn't show major issues with the box filter.
`blackman-harris`		Less blurry than `box` but still well anti-aliased.

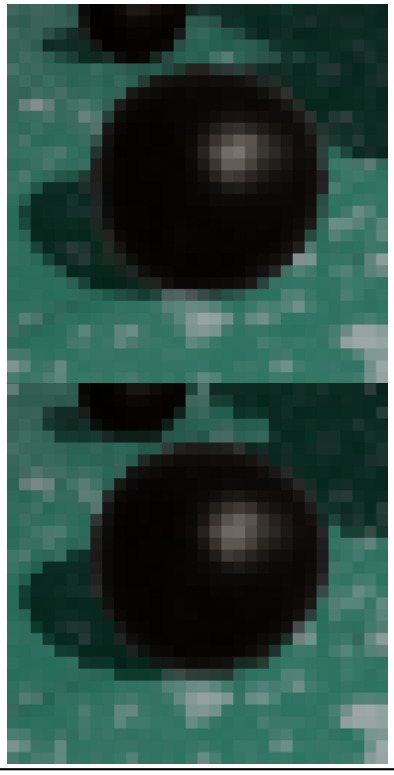
Film filtering	Image	Explanation
`blackman-harris` with `--film-radius=4`		Who smudged the lens?

7.21.3 Temporal anti-aliasing

`--taa=<integer>`

Tauray also implements Temporal Anti-Aliasing[5]. This works with all renderers, but isn't recommended with path tracing unless you also use a denoiser. The integer corresponds to the equivalent SSAA sample quality that it aims for. TAA can cause some flickering in shiny edges and in certain rare cases, ghosting. Smaller values suffer less from these issues, but don't anti-alias quite as well.

Table 7.18: Comparison between supersampling anti-aliasing with temporal anti-aliasing.

Anti-aliasing mode	Image	Explanation
8 x SSAA		The aimed quality of SSAA.
8 x TAA		TAA generally works well when there is little motion.

7.22 Sidedness

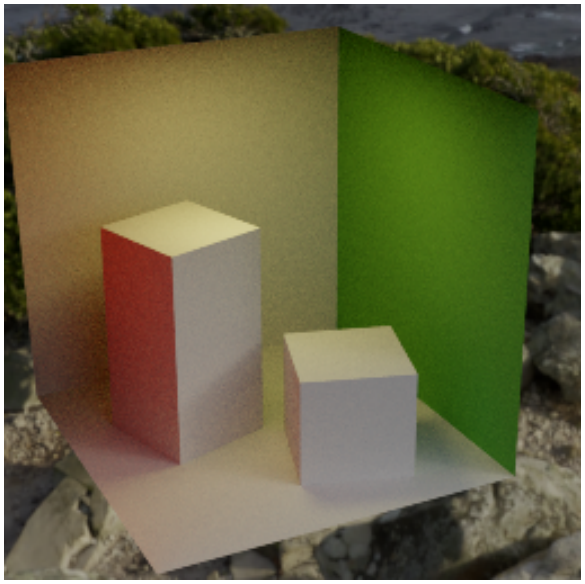
`--force-double-sided=<on|off>`

[5]https://en.wikipedia.org/wiki/Temporal_anti-aliasing

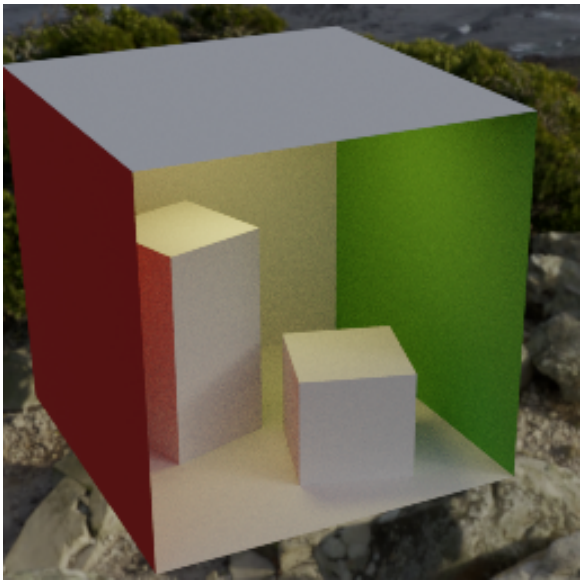
`--force-single-sided=<on|off>`

Usually, Tauray follows what each glTF 2.0 material has specified as the "sidedness" of the surface. Many models are marked as single-sided, simply because that is faster in rasterization-based methods. However, this is not true in ray tracing, where double-sided surfaces are faster. The options `--force-double-sided` and `--force-single-sided` can be used to force the desired kind of sidedness.

Single-sided surfaces are also known as **Backface culling**.



Cornell box with the original single-sided behaviour.



The same scene with `--force-double-sided`

If you want to improve ray tracing performance, use `--force-double-sided`!

7.23 HDR

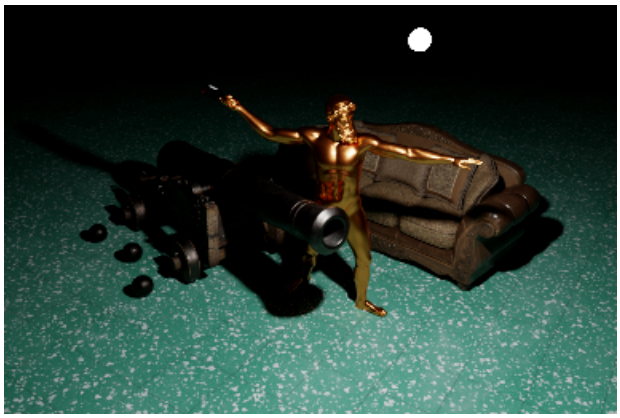
`--hdr=<on|off>`

If you have an HDR display, you can make use of it with `--hdr`. You probably want to use a tonemapping that doesn't target values between 0 to 1, so you probably should simply use `--tonemap=gamma-correction`. *note*: VR HMDs usually specify HDR support and you want to enable this with them!

7.24 Hide lights

`--hide-lights=<on|off>`

In path tracing, light sources are also rendered. For example, a spherical light will appear as a bright sphere. You can disable this from primary rays with `--hide-lights`.



Note how the light source is visible.

With `--hide-lights`, it's hidden!

7.25 Firefly mitigation (path space regularization & indirect clamping)

`--regularization=<number>` `--indirect-clamping=<number>`

If your image suffers from fireflies, you have two ways to get rid of them: path space regularization with `--regularization` and indirect clamping with `--indirect-clamping`.

Path space regularization is the recommended way to do this. It biases the image by strategically adjusting roughness for indirect bounces such that fireflies cannot occur. Good values for real-time renders are between 0.1-0.5. Higher values make caustics appear blurrier.

Indirect clamping is the older but powerful way to reduce or remove firelies. However, it's a fairly aggressive method that causes more biasing and loss of energy than path space regularization. Usually, good indirect clamping values are around 10-100, lower values start to affect the image too much.

Fireflies can be seen in the cannon's shadow.

The same scene with `--indirect-clamping=5`.

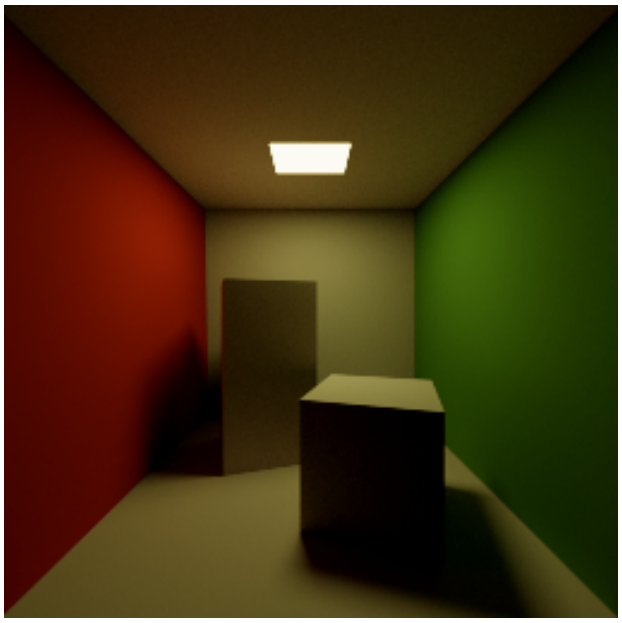
The same scene with `--regularization=0.5`.

7.26 Ray bounces

`--max-ray-depth=<integer>`

The maximum number of bounces the ray can make can be set with `--max-ray-depth`. Higher numbers are generally slower, but are more realistic and brighter. While the default is 8, you should usually be fine with just 3-4. Especially in bright outdoor areas, you can get away with a low number of bounces.

The name of the flag refers to recursion depth, as it also affects refraction and alpha blending.



`--max-ray-depth=3`

`--max-ray-depth=8`

7.27 Minimum ray distance

`--min-ray-dist=<number>`

To prevent self-intersections, rays must have a minimum distance that they will travel. You can set the distance with this flag. In massive scenes, you may encounter precision issues if it's too small, and in small scenes, you may see light leaking a short distance past walls. The default value of 0.0001 is generally fairly good.

7.28 Shadow mapping

In the `raster` and `dshgi` renderers, shadows are implemented using shadow mapping[6]. There are multiple parameters controlling them.

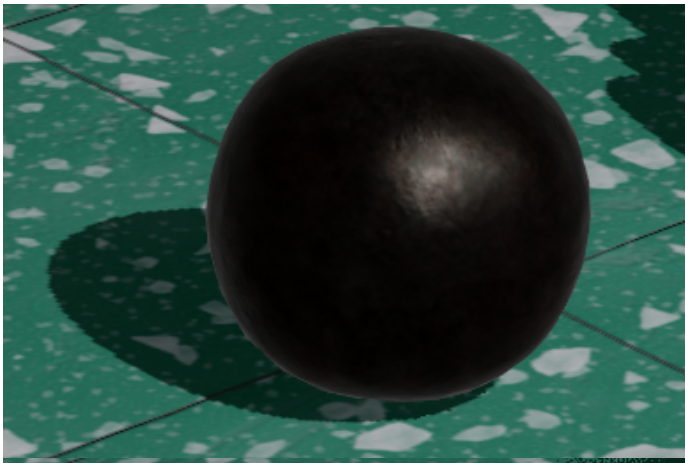
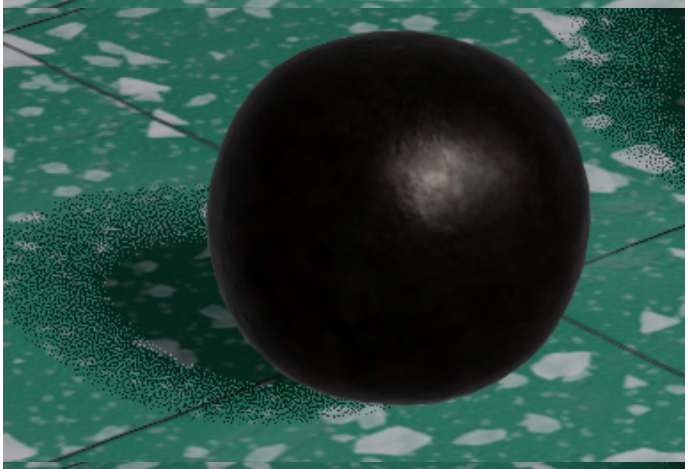
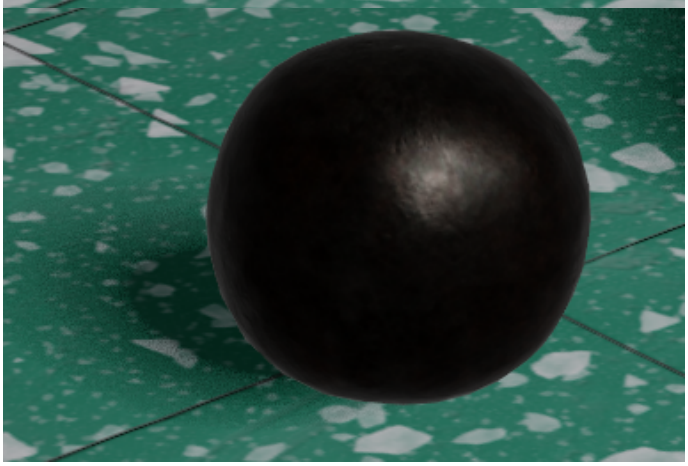
7.28.1 Percentage Closer Filtering

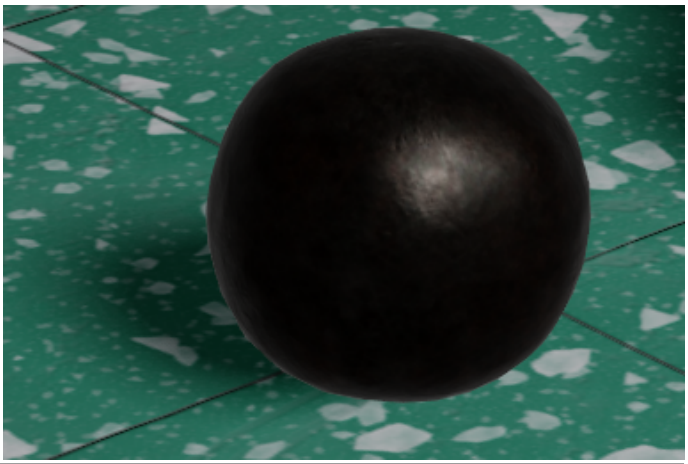
`--pcf=<integer>`

The Percentage Closer Filtering (PCF) technique makes shadows appear smoother. You can set the number of PCF samples taken. Low values have more noise but are faster. `--pcf=0` disables PCF and uses bilinear interpolation instead. It's set to 64 by default, which is pretty slow, but mostly noise-free. Without PCSS, PCF uses a constant blur radius relative to the size of the light source.

[6] https://en.wikipedia.org/wiki/Shadow_mapping

Table 7.23: Images visualizing the effects of increasing PCF samples.

PCF	Image
`--pcf=0`	
`--pcf=1`	
`--pcf=8`	

PCF	Image
`--pcf=64`	

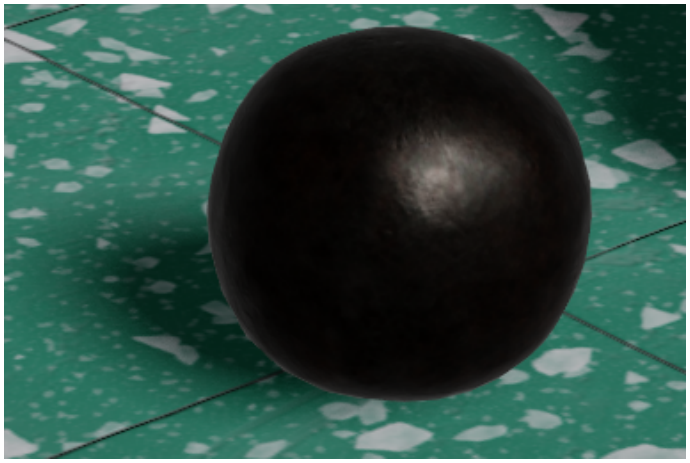
7.28.2 Percentage Closer Soft Shadows

`--pcss=<integer>`

Percentage Closer Soft Shadows (PCSS) works in conjuction with Percentage Closer Filtering in order to create realistic shadow penumbrae. `--pcss=0` disables it, low values are noisy, the default is 32. Note that you have to have `--pcf` as something other than 0 for PCSS to work!

Unfortunately, PCSS only works with directional lights (like the sun), so point lights do not work. For the table below, the point light in the scene has been swapped for a directional light.

Table 7.24: Images visualizing the effects of increasing PCSS samples.

PCSS	Image
`--pcss=0`	

PCSS	Image
`--pcss=1`	
`--pcss=8`	
`--pcss=32`	

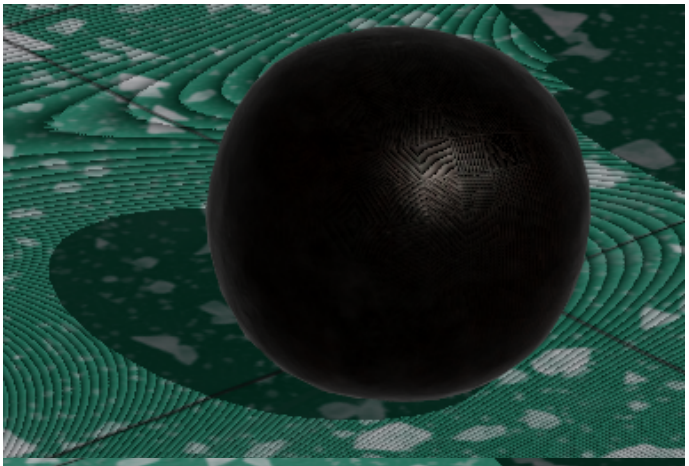
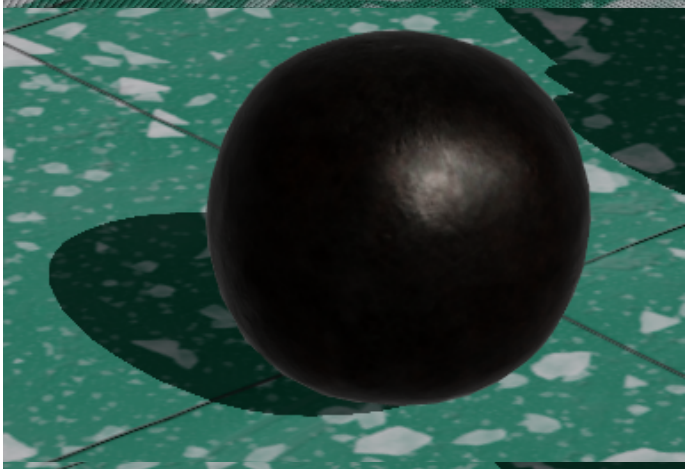
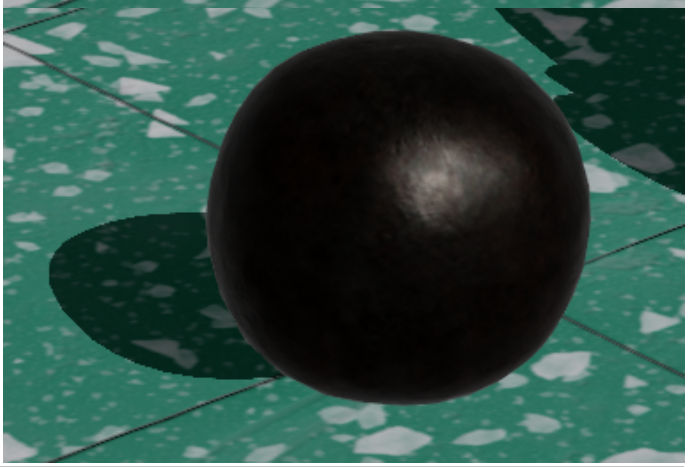
If you want to avoid ever going too sharp with the PCSS shadows, you can use `--pcss-minimum-radius=<number>` to force a minimum radius instead of being arbitrarily sharp.

7.28.3 Shadow map bias

`--shadow-map-bias=<number>`

Shadow map biasing is a technique that removes the "shadow acne" artefacts caused by precision issues. High bias values remove the acne effectively, but also cause "peter panning", i.e. shadows detached from their casters. The default is 0.05.

Table 7.25: Comparison of a few different bias values. Note how the highest bias causes notable peter panning (i.e. shadow detached from caster) and the lowest bias causes "shadow acne."

PCSS	Image
Bias = 0.0	
Bias = 0.05	
Bias = 0.5	

7.28.4 Shadow map cascades

`--shadow-map-cascades=<integer>`

Tauray implement cascaded shadow maps for directional lights. This means that the same shadow map is rendered at multiple different zoom levels. Nearby areas are shown with the highest zoom level, while areas further away get successively less precise shadow maps. This lets the shadow map cover very large distances.

For small scenes, you may want to disable cascades by setting `--shadow-map-cascades=1`.

7.28.5 Shadow map depth

`--shadow-map-depth=<number>`

If your scene is very large, the default shadow map distance range of 100 may not be enough. If you notice that the shadow cuts off, you should increase the range.

7.28.6 Shadow map radius

`--shadow-map-radius=<number>`

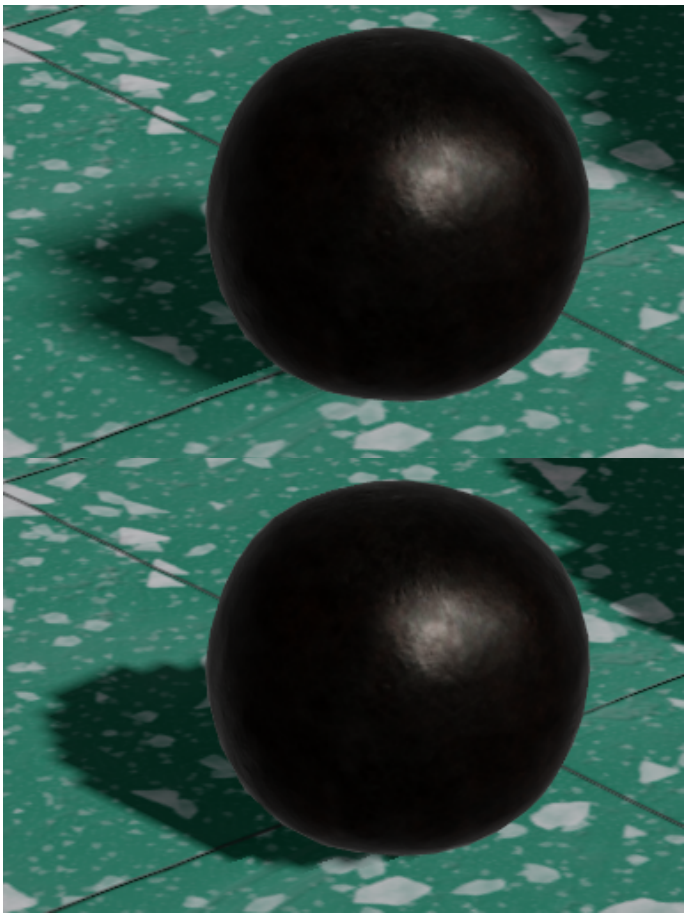
You usually don't have to change this unless you want to disable shadow map cascades. If so, you'll have to find a radius that is large enough to cover your scene. Lower radius values let you distribute the shadow map resolution to a smaller area, which makes it look more precise.

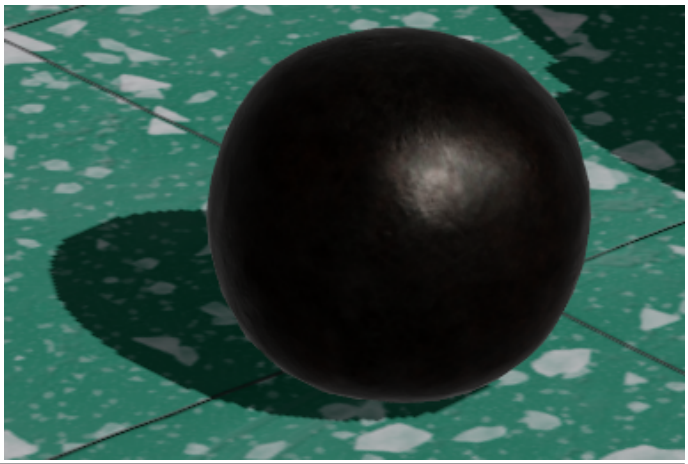
7.28.7 Shadow map resolution

`--shadow-map-resolution=<integer>`

In Tauray, shadow maps are simply square images. You can set the size of the square with this parameter. Higher resolutions allows you to preserve more details in the shadows, but are also slower to render. Lower resolutions are also more susceptible to shadow acne.

Table 7.26: Effects of resolution to shadow map quality. Bias was manually adjusted to barely avoid shadow acne in each case.

Resolution	Image
256	
1024	

Resolution	Image
4096	

7.29 Random number seed

`--rng-seed=<integer>`

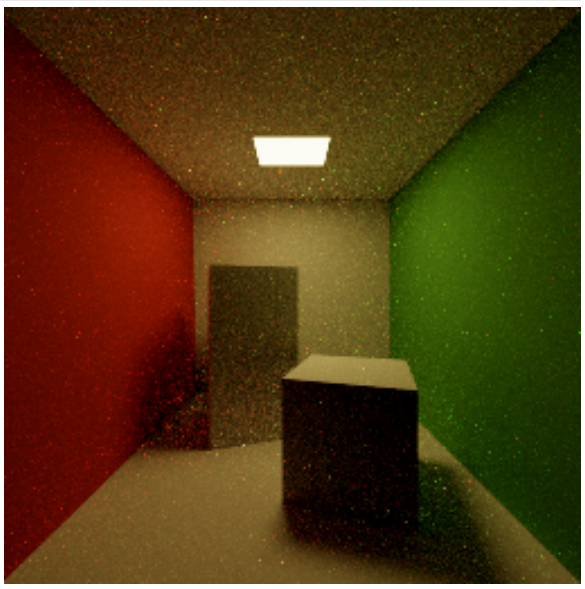
Typically, Tauray renders are reproducible in that the RNG seed will always be the same. If you want to have different noise in the otherwise same render, you should set the random number generator seed with `--rng-seed`.

7.30 Russian roulette sampling

`--russian-roulette=<number>`

Russian Roulette sampling is a method that randomly kills off deep rays in the scene. It is typically used when you need lots of light bounces, but still want to render the image reasonably quickly. Higher numbers raise the odds of rays losing the roulette. You can think of the number as the number of chambers in the revolver, and only one of them *doesn't* have a bullet...

100 bounces, 100k spp, no russian roulette: 22s



Same, but with `--russian-roulette=4` : 3s

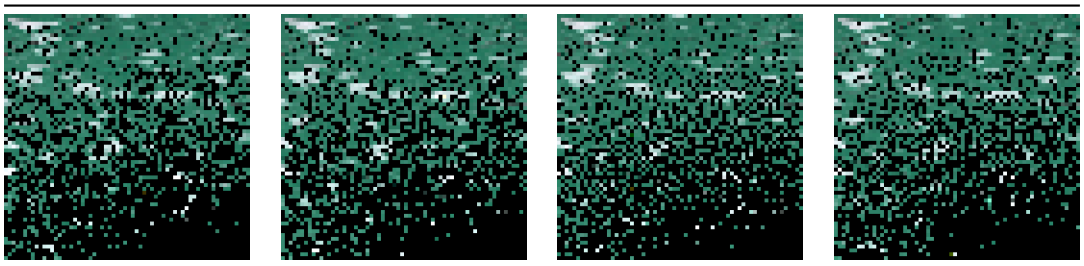
Note: because this method relies on causing certain samples to have higher weight than usual, it responds poorly to `--indirect-clamping`!

7.31 Sampler

`--sampler=<uniform-random|sobol-owen|sobol-z2|sobol-z3>`

A sampler picks the samples for Monte Carlo integration in the path tracer. `uniform-random` is just regular random values, `sobol-owen` implements Practical Hash-based Owen Scrambling[7]. `sobol-z2` and `sobol-z3` are related to Screen-Space Blue-Noise Diffusion of Monte Carlo Sampling Error via Hierarchical Ordering of Pixels[8]. The difference between them is that `sobol-z2` is using a typical 2D Morton curve, while `sobol-z3` is using a 3D Morton curve where frame index/time is the third axis.

`sobol-z3` is the default, as it seems to perform fairly well in most cases. For low-spp renders, you may want to go for `sobol-z2` instead. For maximum performance, `uniform-random` is the fastest.



`uniform-random`	`sobol-owen`	`sobol-z2`	`sobol-z3`

7.32 Samples per pixel

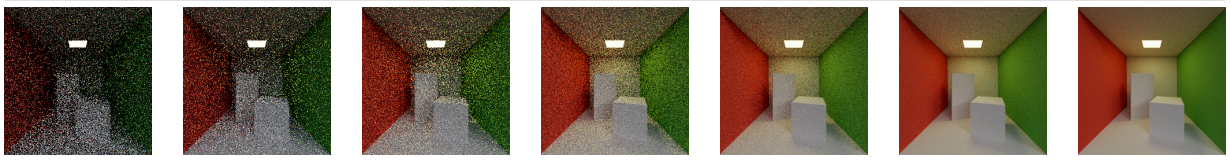
`--samples-per-pixel=<integer>`

This flag has two meanings depending on the renderer, but they are both somewhat related. For rasterization-based renderers (such as `raster` and `dshgi`), it's the number of anti-aliasing samples to take per pixel.

For path tracing, it's the number of Monte Carlo samples to take. Lower numbers are fast, but noisy. High numbers are slow, but don't have much noise.

Usually, `--samples-per-pixel=4096` is suitable for offline rendering. The default value is 1, which is suitable real-time use.

Table 7.29: Effects of samples per pixel (SPP) counts to noise in path tracing.



1 SPP	4 SPP	16 SPP	64 SPP	256 SPP	1024 SPP	4096 SPP

7.33 DDISH-GI

Many parameters affect DDISH-GI (`--renderer=dshgi`) alone.

7.33.1 Temporal reuse

`--dshgi-temporal-ratio=<number>`

[7] https://jcgt.org/published/0009/04/01/
[8] http://abdallagafar.com/publications/zsampler/

To adjust the temporal reuse, which affects visible flickering in probe data, you can use the `--dshgi-temporal-ratio` parameter. The argument is between 0 and 1, where 1 means all data comes from the current frame and values approaching zero use increasingly more data from previous frames.

7.33.2 Samples per probe

`--samples-per-probe=<integer>`

This parameter adjusts how many paths are traced per probe during each frame. Higher values make the update slower, but reduce flickering.

7.33.3 Spherical harmonics order

`--sh-order=<integer>`

By default, spherical harmonics up to L2 are used for the probe data. You can select orders between 1 and 4. Higher orders store more detailed information, which can be visible in reflections, but are increasingly slower.

DDISH-GI with `--sh-order=2`.

Same, but with `--sh-order=4`.

7.33.4 Probe visibility approximation

`--use-probe-visibility=<on|off>`

This flag can reduce light leaking from probes, but can also cause odd artefacts and slow down rendering significantly. It's disabled by default.

DDISH-GI with `--use-probe-visibility=off`.

Same, but with `--use-probe-visibility=on`.

7.34 Reprojection

Reprojection can be used with path tracing to re-use data from previous frames or other viewports. These are the *temporal* and *spatial* reprojection, respectively.

7.34.1 Spatial reprojection

`--spatial-reprojection=<int,int,...>`

This type of reprojection is only useful for light-field rendering. You list the viewport indices that are rendered, and the rest are then reprojected from those.

7.34.2 Temporal reprojection

`--temporal-reprojection=<number>`

Temporal reprojection can be used with regular renders as well, though it's most useful in interactive mode. This method re-uses pixel values from the previous frame to deliver a more noise-free image. The given number affects the ratio of data re-used from the previous frame, where 0 is no re-use and 0.5 is 50/50 new and old frame.

7.35 Accumulation

`--accumulation=<on|off>`

Enables accumulation in the interactive path tracer, meaning that new frames are blended with previous frames until you move. This lets you quickly and interactively preview scenes with high SPP counts, as you can fly around normally, then stop to accumulate a high-SPP image. Do not use accumulation in headless mode.

7.36 Transparent background

`--transparent-background=<on|off>`

If you want to render cut-out images where the background is transparent, you can use `--transparent-background` to achieve just that.

7.37 Depth of field

`--depth-of-field=<f-stop,distance,sensor-size,sides,angle>`.

You can enable simulation of a simplistic non-pinhole camera with the thin-lens model, by using the `--depth-of-field` option. `f-stop` controls the aperture size[9], `distance` sets the distance to the plane of focus, `sensor-size` sets the camera sensor size (default: 0.036), `sides` sets the shape of the aperture (0 = circle, 3 and above: polygonal), `angle` sets the angle of a polygonal aperture.

7.38 Force white albedo for first bounce

`--use-white-albedo-on-first-bounce=<on|off>`

This flag has a very specific use case in mind: denoising research. You can force the albedo of every material to be white on the first intersection, which lets you observe the lighting arriving at the surface without meddling textures. On further bounces, the materials are back to their usual colors, so you still get color bleeding!

[9] https://en.wikipedia.org/wiki/F-number

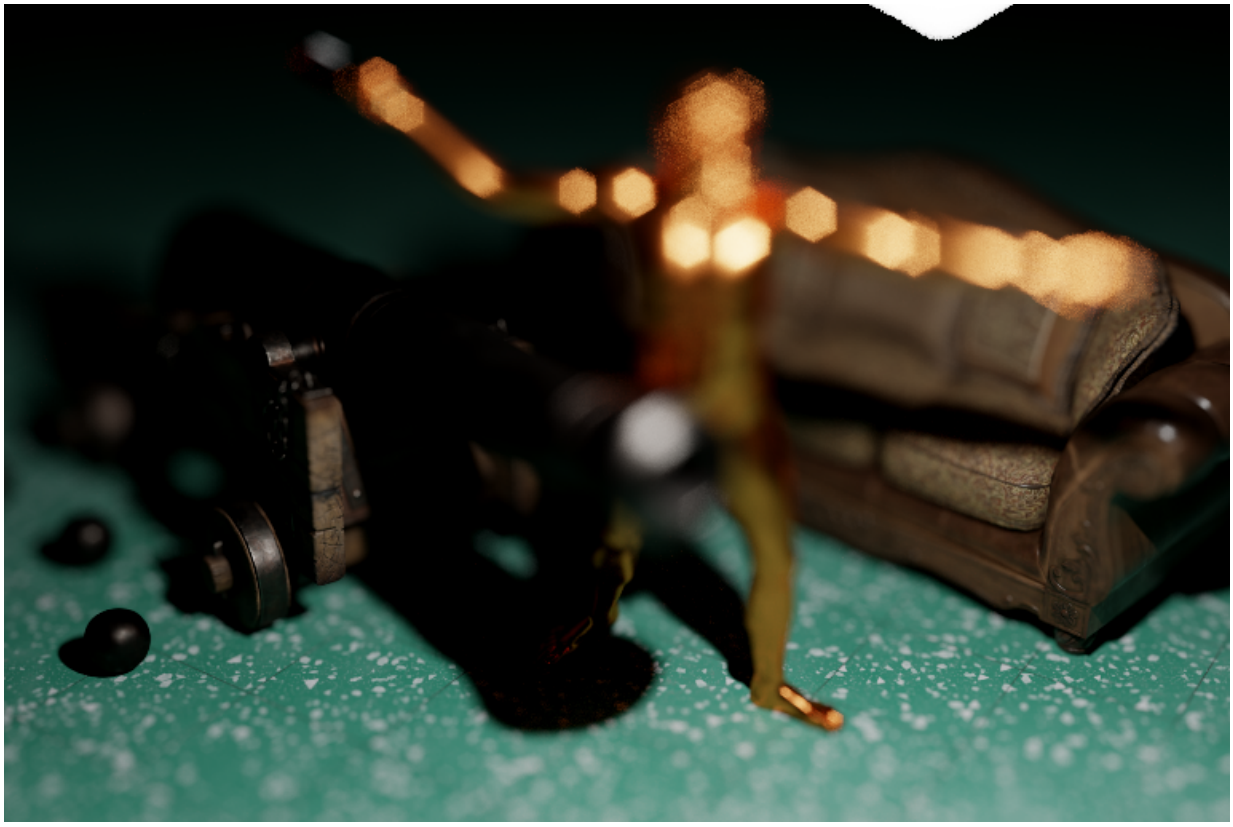


Figure 7.1: The usual scene, but with `--depth-of-field=0.05,10,0.036,6`.

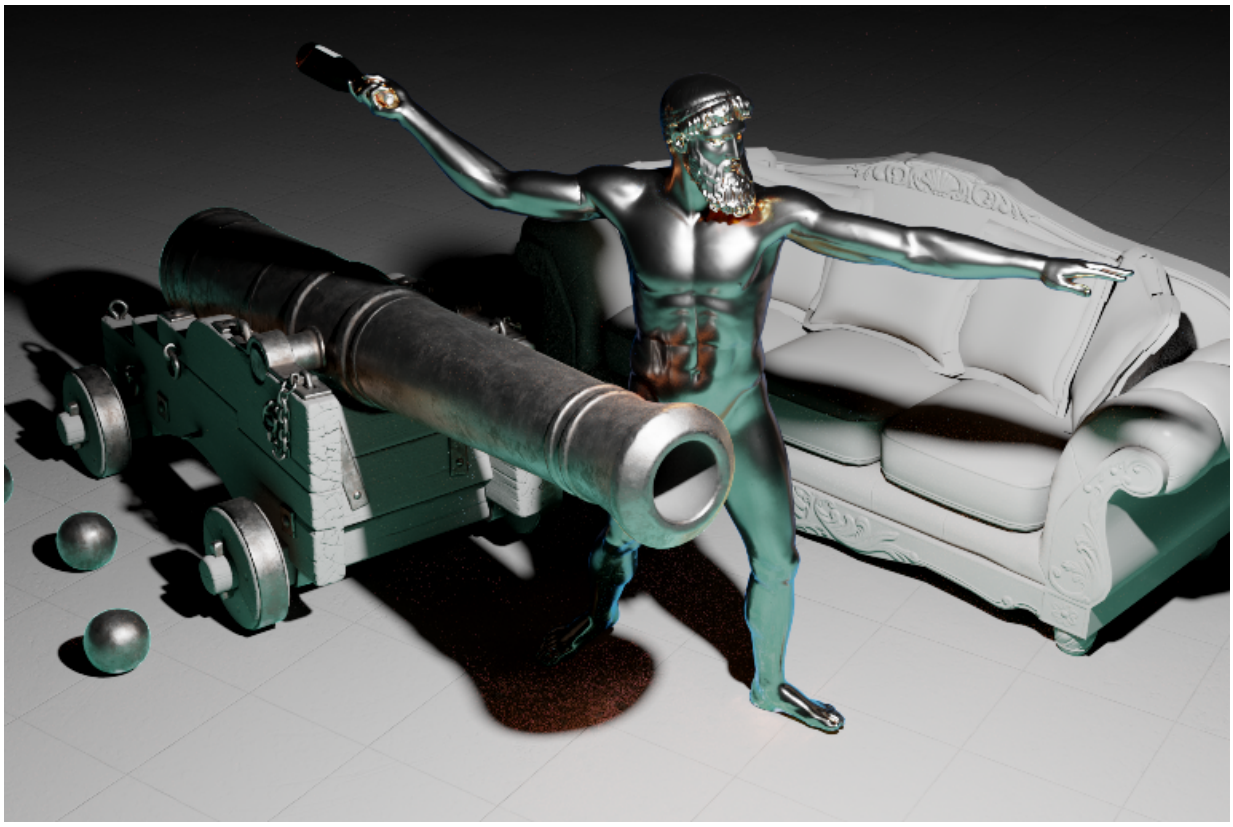


Figure 7.2: The usual scene, but with `--use-white-albedo-on-first-bounce`.

Chapter 8

Limitations

There are things that Tauray does not handle well. In such cases, you may want to use some other tool instead. This list of limitations may also change in the future, as we work on implementing more missing features. Namely:

- Poor sampling of non-spherical area lights (i.e. emissive volumes). There is no importance sampling for these yet, so the image will be pretty noisy.
- Morph target animations are not supported.
- Advanced material models are not yet supported, only the basic GGX metallic-roughness + transmission.
- Noisy caustics, due to the forward path tracing algorithm.

Chapter 9

Conclusion

Thank you for using Tauray.