Chroma Photon Ray Tracer for Large-Scale Detectors

Benjamin J. Land, Samuel M. M. Naugle, and Joshua R. Klein

University of Pennsylvania, Philadelphia, PA, USA

For *Chroma* Contributors Everywhere

https://github.com/BenLand100/chroma/graphs/contributors

Chroma is a GPU-accelerated optical physics simulation leveraging ray tracing techniques to provide a very fast optical Monte Carlo testbench. As next-generation neutrino detectors rely heavily on detection of scintillation and Cherenkov light, *Chroma* is an attractive option for exploring potential detector configurations and novel photon detection schemes. Here we discuss *Chroma's* capabilities and exhibit how it could be used to simulate large scale neutrino detectors quickly and efficiently.

Contact Information:
Benjamin Land [bland100@sas.upenn.edu]
Joshua Klein [jrk@hep.upenn.edu]

Thematic Areas:
Primary:
(CompF2) Computational Frontier: Theoretical Calculations and Simulation
Secondary:
(NF10) Neutrino Frontier: Neutrino Detectors

As large-scale neutrino detectors become ever larger, photon coverage becomes higher, and photon sensor technology becomes more complex with devices like the ARAPUCA [1], the dichroicon [2], or distributed imaging [3], a major bottleneck in both simulation and reconstruction of physics events is the propagation of photons through the detector geometry. Originally created for the water Cherenkov option for the LBNE experiment, a fast photon ray-tracer was developed by Stan Seibert and Anthony LaTorre [4] that improved photon simulation speeds by a factor of 200 over what GEANT4 itself could do. In order to achieve such high performance, *Chroma* combines techniques from 3D rendering algorithms with the massively parallel calculation hardware inside GPUs. Existing 3D rendering libraries, while quite sophisticated, cannot be used directly for physics simulation purposes, as those libraries tend to rely on physically-unrealistic approximations and shortcuts to improve the appearance of the produced images. Nevertheless, *Chroma* takes similar ideas and applies them within the context of a physics simulation to improve performance without sacrificing precision physics. These techniques map well onto the massively parallel GPUs found in today's workstations. A high-end GPU costs approximately $5000 (twice the cost of a fast consumer-grade CPU), yet provides forty times the raw floating point performance and ten times the memory bandwidth. *Chroma* uses the CUDA toolkit, provided by NVIDIA, to directly access the GPU resources and perform all major calculations. CUDA-compatible GPUs are being used more and more in the construction of large supercomputing clusters, which will make it easier in the future for the work on next-generation neutrino detectors such as Theia [5] to use *Chroma*.

Nearly all fast 3D rendering systems represent the world geometry using a mesh of triangles. Triangle meshes are very simple to represent, and can be used to approximate any surface shape, limited by how much memory can be devoted to triangle storage. With only one surface primitive, there is only code path to optimize. In particular, we have adopted the Bounding Volume Hierarchy (BVH) technique from the graphics world to speed up ray intersection tests with triangle meshes. A BVH is a data structure that organizes a spatial arrangement of shapes (triangles in our case) into a tree of nested boxes. Rather than test for ray intersection with every triangle in a geometry, the photon propagator tests for intersection with boxes in the BVH. If the ray does not intersect the box, then all of the children of that box can be skipped, leading to a large reduction in the number of intersection tests required. For example, a model of a large, 200 kton water Cherenkov detector consists of 62 million triangles, but the BVH reduces a typical propagation step for a photon to 130 box intersection tests and only 2 triangle intersection tests.

Chroma implements the most important physics processes for optical photons, which include:

- Wavelength-dependent index of refraction (chromatic dispersion)
- Absorption in the bulk
- Reemission from a wavelength shifter
- Rayleigh scattering
- Diffuse reflection at surfaces
- Specular reflection at surfaces
- Arbitrary angle, wavelength dependent transmission and reflection (dichroic)
- Standard Fresnel reflection and refraction
- Detection at a photosensitive surface (e.g. a PMT photocathode)

One collateral bonus of *Chroma's* speed is that it provides remarkably beatiful, *realtime* detector displays. It is quite easy to "fly through" a detector and see it rendered in all of its detailed geometry, exactly the way the photons themselves will see the detector. Fig. 1 shows a rendering of the SNO+ [6] detector which, in a static pdf document like this proposal cannot be examined dynamically in realtime, but was created from that realtime fly-through and simply captured by screen-shot. The rendering is in fact a 3D image; with red-blue glasses one can see the relief in the image.

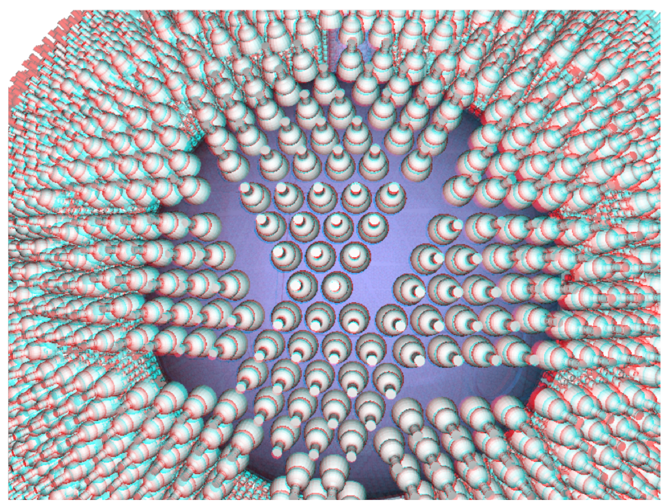

FIG. 1. A screen capture from a realtime, three-dimensional "movie" of the SNO+ [6] detector created with *Chroma*, which is best viewed with red-blue 3D glasses. The model shown is exactly the model used by *Chroma*'s physics simulation, albeit with false-color optics for the display rather than the complete physics the simulation uses. The PMTs are fully rendered, including their Winston-cone light concentrators.

The choice of representing geometries in *Chroma* as triangle mesh makes it straightforward to import CAD drawings into the optical simulation, as shown in Fig. 2. All that is required is that the triangles on the mesh have optical properties assigned to them, which is a trivial operation in the case of a CAD model with uniform properties over its entire surface, but allows for fine-grain

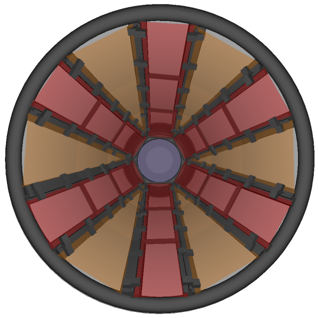

FIG. 2. The CAD drawing for the 3D-printed dichroic filter holder for the dichroicon [2] was directly imported into *Chroma*, and used to accurately simulate the orientations of the dichroic filters (shown in red and orange) with respect to the benchtop experiment.

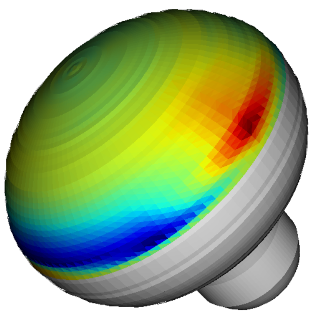

FIG. 3. From [4], a visualization of per-triangle control of the PMT transit time property, which represents the delay in detection of a photon due to the time it takes the photoelectron to travel from the photocathode to the first dynode. Red areas are up to 3 ns late, and blue areas 3 ns early, relative to the mean detection time. All *Chroma* properties can be defined at this level.

position dependent control of material properties as well, as shown in Fig. 3. This allows anyone with CAD experience to quickly create an arbitrarily complicated simulation without having to learn a new way to represent geometries. The ability to rapidly prototype designs makes *Chroma* well suited for benchtop studies as well, as can be seen in Fig. 4, which shows preliminary application of the dichroicon to the CHESS [7] experiment. Combining these features allows easy modeling of new photon-detector technologies, as shown in Fig. 5, which includes 3D Large Area Picosecond Photodetectors (LAPPD) [8] mixed with standard PMTs in a *Chroma* model of the Theia25 [5] detector.

Chroma was designed to be easy to use, is now maintained in a public Github repository [9] complete with Docker containers for easy deployment. Primarily written in Python, *Chroma* interfaces well with popular data-science packages in that ecosystem (Matplotlib, Scipy, Tensorflow, etc.), allowing for rapid development of ideas with minimal overhead. *Chroma* is also well connected to GEANT4, which it uses to simulate physical interactions that produce photons, and ROOT, which serializes *Chroma* events allowing for traditional ROOT-style analyses of the simulations. If you have a use case for a GPU-accelerated, physically-accurate, optical simulation, give *Chroma* a try!

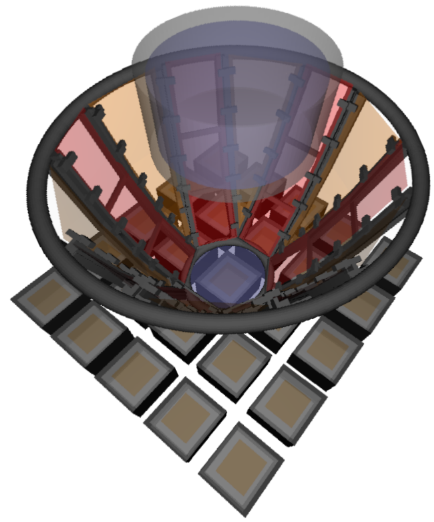

FIG. 4. *Chroma* is also applicable to benchtop-scale experiments like CHESS [7] where application of the Cherenkov/scintillation separation with the dichroicon [2] is being explored. A preliminary geometry is shown here with a liquid scintillator target, a dichroicon, and an array of fast PMTs from CHESS. GEANT4 is used to simulate cosmic muons traversing this geometry, while *Chroma* simulates the optical and PMT response, all within the framework of *Chroma*.

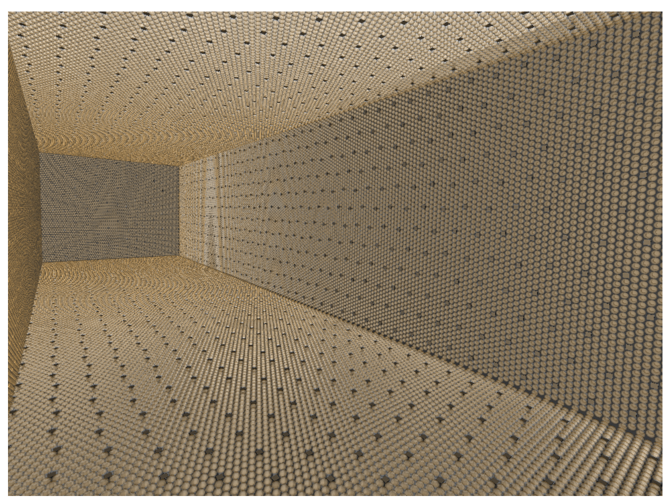

FIG. 5. Next-generation photon detectors like LAPPDs [8] are straightforward to simulate and include in larger geometries, as shown in this internal view of a Theia25 [5] model made with *Chroma*, which has mixed PMTs and LAPPDs for detecting photons. The *Chroma* framework makes it quick and easy to explore new detector geometries and photon detecting devices.

[1] A. Machado and E. Segreto, Journal of Instrumentation **11** (02), C02004.

[2] T. Kaptanoglu, M. Luo, B. Land, A. Bacon, and J. R. Klein, Phys. Rev. D **101**, 072002 (2020).

[3] J. Dalmasson, G. Gratta, A. Jamil, S. Kravitz, M. Malek, K. Wells, J. Bentley, S. Steven, and J. Su, Phys. Rev. D **97**, 052006 (2018).

[4] S. Seibert and T. LaTorre, Fast optical MonteCarlo simulation with surface-based geometries using Chroma.

[5] M. Askins *et al.*, Eur. Phys. J. C **80** (2020).

[6] S. Andringa *et al.* (SNO+), Adv. High Energy Phys. **2016**, 6194250 (2016).

[7] J. Caravaca, F. B. Descamps, B. J. Land, J. Wallig, M. Yeh, and G. D. Orebi Gann, Phys. Rev. C **95**, 055801 (2017).

[8] B. W. Adams, A. Elagin, H. J. Frisch, R. Obaid, E. Oberla, A. Vostrikov, R. G. Wagner, J. Wang, and M. Wetstein, Nucl. Instrum. Meth. A **795**, 1 (2015).

[9] B. J. Land, Chroma3 GitHub repository.