Parallelization of Air Shower Simulation with IceCube

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Overview

• Introduction to IceCube Neutrino Observatory
• IceCube’s old simulation chain for cosmic-ray air showers
• Improvements to the simulation chain
• Results
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW-Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

50 m
1450 m
2450 m

86 strings of DOMs, set 125 meters apart

60 DOMs on each string

DOMs are 17 meters apart

Antarctic bedrock

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
IceCube Needs a Lot of Background Simulation

- Cosmic-ray air showers occur at a rate of about 3kHz
- Neutrinos at a rate of about 2mHz
- An event selection that keeps 1 in $10^6$ means we need a lot of background simulation
- Old simulation chain suffered from low CPU utilization, IO bottlenecks, and memory spikes
- Trend in Computing centers less Memory per CPU core
Old Simulation Chain

- Simulates the development of Cosmic-ray air showers
- The energy distribution of daughter particles is highly stochastic
- Muons are the only daughter particle which is relevant for simulating IceCube’s deep ice detectors
- CORSIKA is a single 100k fortran file that has to be compiled as a separate binary
Old Simulation Chain

CORSIKA Executable

ICECUBE

PROPOSAL

“PROPOSAL” is the name of a software package not an actual proposal
• Propagates muons as they travel through ice
• Muons energy loss is also highly stochastic and non-parallelizable
• All muons will lose a significant fraction of their energy before making it to the deep ice detector
• Only muons with very high energy will make it to the detector
Old Simulation Chain

CORSIKA Executable

- CORSIKA
- CPU
- Air shower simulation

IceTray - IceCube's processing framework

- CORSIKA BINARY FORMAT
- CPU
- Propagate Muons
- GPU
- Propagate Photons
- Detector Response

Photon Propagation

- Light emitted by muons is propagated through the Ice
- Layers of different concentrations of dust cause the scattering and absorption of the ice to be different at different heights
- Photon propagation is highly parallelizable and can only be effectively performed on GPUs with OpenCL/CUDA
Old Simulation Chain

CORSIKA Executable

CORSIKA

CPU

Air shower simulation

CORSIKA BINARY FORMAT

IceTray - IceCube's processing framework

PROPOSAL

CPU

Propagate Muons

OpenCL

GPU

Propagate Photons

Detector Simulation

I3MCTree

I3Photon

CPU

Detector Response

Detector Response/Reconstruction

- Simulates DOM Photomultiplier tube and front-end electronics
- Simulates noise
- Simulates the data acquisition system and trigger
- Performs all reconstructions the same as if it were experimental data

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Problems with Old Simulation Chain

**CORSIKA Executable**

- CORSIKA
- CPU
- Air shower simulation

**IceTray - IceCube's processing framework**

- CORSIKA BINARY FORMAT
- PROPOSAL
- CPU
- Propagate Muons
- I3MC
- GPU
- Propagate Photons
- I3Photon
- CPU
- Detector Simulation

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- IO Bottleneck
  - CORSIKA needs to write all the events to a file
  - Almost all air shower muons don’t have sufficient energy to reach the IceCube active volume

- Inclined showers have a much higher threshold to make it to the detector

- Memory Limits Exceeded
  - The memory needed for each event is highly stochastic
  - Storing all photons from event results in brief memory allocations which exceed this limit and kill the job

- Efficient use of resources
  - GPU is underutilized because the previous stages do not produce results fast enough to keep the GPU busy

- Memory per CPU core is expected to decrease in computing environments in the future

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Most air showers don’t produce muons that have enough energy to make it to the detector: Low energy showers have very small chance of producing a high energy muon. Inclined showers have a much higher threshold to make it to the detector.
**New Simulation Chain**

- Move to a Client/Server model for Air Shower, Muon, and Photon propagators
  - Each client has a work queue can span multiple events
  - 1 instance of CORSIKA Server for air showers propagation
  - 1 instance OpenCL Server collects work units and sends them to the GPU
  - 8 instances of PROPOSAL for muon propagation
  - 8 instances of the simulation chain are used in parallel to connect to the propagation servers
  - Keeps the GPU fully utilized

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New Simulation Chain

I3PrimaryInjector

- Primaries are now sampled from new IceTray module rather than hard coded functions in CORSIKA
- Primaries are generated on directly on the detector surface with arbitrary energy and spatial distributions
- Allows for future schemes for oversampling regions that produce more background
New Simulation Chain

**CORSIKA Server**

- CORSIKA was modified to run as a server which can be configured with individual primaries (thanks to D. Baack)
- Different CORSIKA cards for different showers
  - The energy needed to reach the detector is highly dependent on the inclination of the shower
  - The energy at which CORSIKA will stop propagating particles is now higher for inclined showers
- Showers with higher energy leading edge muons are undersampled:
  - Showers with low energy muons are killed before the rest of the shower is calculated
  - Since individual particles are sent over IPC no files are written avoiding IO bottleneck

More inclined showers encounter more matter between the surface and the detector and require higher energy muons to reach the detector.

New CORSIKA Server will set the minimum muon energy higher for more inclined showers.
New Simulation Chain

Memory Resources

- Memory is saved with more efficient dataclass for storing photons: I3MCPE
- The Propagation Client’s work queue doesn’t have to store intermediate data for the entire event reducing memory usage
- The memory is amortized across the 8 instances of icetray
  - 8 instance sharing 8GB are much less likely to be taken down by a memory spike than 8 jobs with 1GB each
Optimizing Leading Muon Undersampling

Air showers are undersampled based on the energy of the first muon to appear in the shower.

This undersampling based on leading muon energy results in a 20x increase in the simulated lifetime per GPU time.

Undersampling also takes primary energy and zenith into consideration.
Comparison Between New and Old Simulation

Good agreement is seen between old and new
## Performance

<table>
<thead>
<tr>
<th></th>
<th>Old Simulation Chain</th>
<th>New Simulation Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time Per Shower</strong></td>
<td>101 µs</td>
<td>3.70 µs</td>
</tr>
<tr>
<td><strong>Memory/Core</strong></td>
<td>7GB</td>
<td>1GB</td>
</tr>
<tr>
<td><strong>Walltime of Completed Jobs/Total WallTime</strong></td>
<td>60%</td>
<td>84%</td>
</tr>
<tr>
<td><strong>GPU utilization</strong></td>
<td>45%</td>
<td>80%</td>
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