Plotting Muon Pathways as a Source of Randomness

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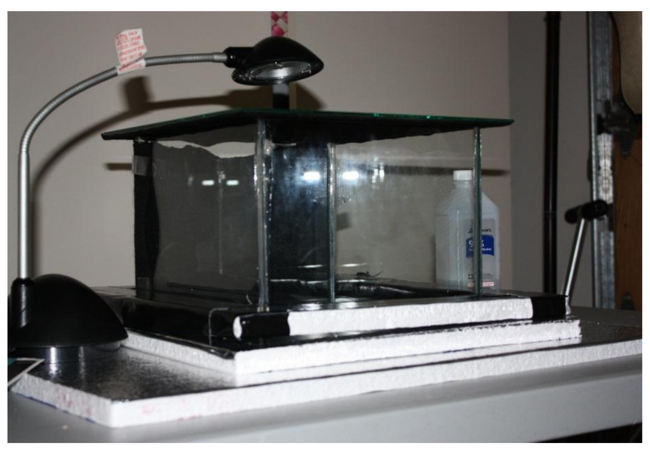
Evolution of the Chamber

1.

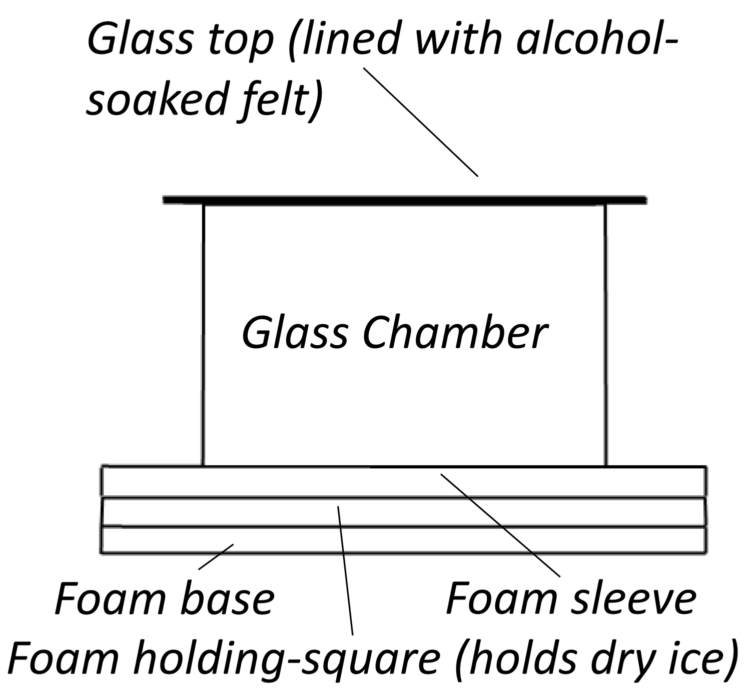
The Initial Chamber:
The initial trials were based off this chamber, which ultimately failed due to the issues with temperature-to-size proportions. The 20 W lamp and dry ice were unable to establish the desired temperature gradient.

2.



The Final Chamber:
The final chamber consists of a 25.4 cm by 25.4 cm by 20.3 cm glass chamber with a metal plate on the bottom and a felt-lined sheet of glass at the top. The temperature gradient was achieved by a 20 W lamp and 2.72 kg of dry ice.

3.



The final schematics of the chamber, adapted from QuarkNet. Final cost: $90.00 for chamber, plus $8.25 per run.

Materials and Methods:
Construction of the Chamber:

- The four pieces of picture-frame **glass** were precisely machined, then glued together with 100 percent silicone sealant.
- The 22 gauge weldable **steel metal plate** was then glued to the bottom, and the resulting chamber was allowed to cure.
- To create the **lid**, a piece of **felt** was glued with sealant to a **glass** plate.
- Two pieces of insulating **foam** were used–one large rectangular one for the **base** and another smaller square one with a hole cut out for the viewing **sleeve**.
- To run the chamber, dry ice is crushed with a hammer and placed on the foam **base**, while **89 mL** of **isopropanol** is poured on the felt and **6 mL** is used to line the base.

Capturing the Image

Goals:
Photographing the chamber was a sensitive process that required four trials. **Photos needed to…**

- Clearly capture muon streaks.
- Focus on the entire chamber.

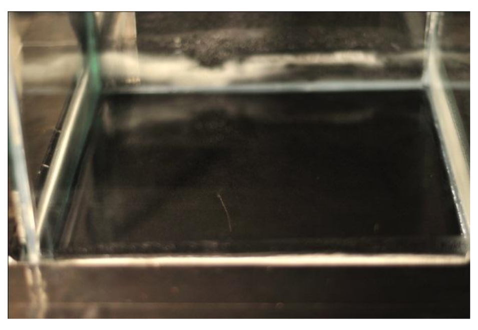
General Methods:

- Photos were taken at **regular intervals** using automatic timers.
- Sets of at least 200 photographs were taken in each trial in order to provide sufficiently large data pools.
- Photos were saved as RAW.

The Trials:

- A Nikon D5000 was used for the first, second, and fourth trials.
- A Canon EOS 5D Mark II was used for the third trial.
- Trials were repeated until the images clearly focused upon the entire chamber.

1.



Photograph from trial 1.

Acknowledgements:
Photography was facilitated with the help of Christophe Haubursin, photographer of the first, second and fourth trials, and Gennadiy Magidin, photographer of the third trial.

Image Processing

Computer Vision Goals:

- Attenuation of high frequency components to **eliminate noise**.
- **Isolation of streaks** through Canny edge detection.

1.

```
// Perform edge detection if threshold is not 0
if (m_cannythreshold1 != 0) {
    Canny(m_imgGrayFilter, m_imgFilter, m_cannythreshold1,
          m_cannythreshold2, m_cannyApertureSize, true);
} else {
    m_imgFilter = m_imgGrayFilter.clone();
}
```

Snippet of code that calls Canny.

Implementation:

- The necessary methods were provided by OpenCV, a set of open-source libraries.
- The program was written in C++ using Microsoft Visual Studio.

Image Filtering

- Various filters were implemented, including box, Gaussian, and bilateral.
- Convolution using **Gaussian kernels** proved most successful.

Edge Detection

- **Canny edge detection** was used to isolate the streaks.
- Appropriate hysteresis threshold values were experimentally determined for each image.

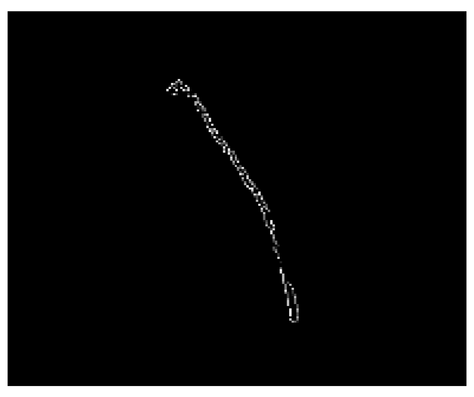
Creation of GUI

- A custom-built Windows GUI was written.
- The GUI allowed for experimentation with kernel size, threshold values, etc.

2.

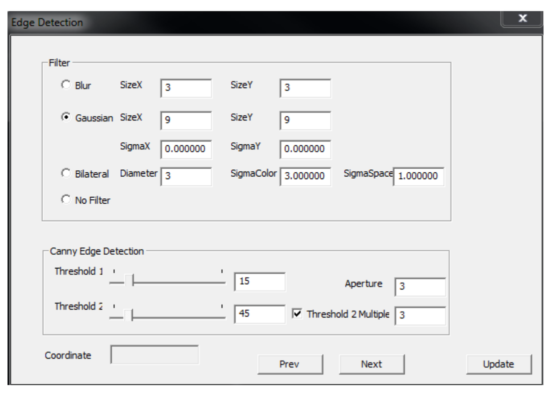
Streak before image processing.

3.



Streak after Gaussian blur and edge detection.

4.



GUI interface for configuration of values.

Collection of Data

- After analysis of each picture, values of the kernel size, sigma, threshold, etc. were recorded.

X and Y Extraction:

- X and Y coordinate extraction was facilitated through the GUI.

Acknowledgements:
Image processing procedure advised by Ajay Agrawal, Ram Charan, Ph.D Computer Vision, and Narendra Ahuja, Professor of Computer Engineering at Urbana-Champaign.

Statistical Tests

Statistical Goals:
This final step focused on evaluating the data for randomness. **This involved…**

- Utilization of a **test suite** that would test the data effectively.
- **Interpretation of results** to determine whether to accept or reject the null hypothesis; that is, whether the data would be random.

Implementation:

- Data was subjected to the Statistical Test Suite provided by the National Institute of Standards and Technology (NIST), judged to be the standard for statistical tests.
- All values were converted from decimal to binary, as required by the NIST suite.
- The tests were performed on Mac OS X.

Testing:

- 10 tests were run to analyze the data.
- The tests output a *p*-value, which denotes the probability that a perfect RNG will generate less random numbers than the generator being tested.
- *P*-values greater than or equal to .01 indicated randomness.
- All tests indicated that the collected data was random.

1.

```
1000111111101010000011100
1010100100010100000110011
1111001101100111010000000
1010010110010001111000110
1000111001100000011110010
1001111010001101001000111
1111100000100011001010100
1111100110101110000010
1010011110010000101001100
1000100000110010100011000
1000101111001011111100101
1001011000101011111101101
1011000111001010101100100
1010010101010111011111110
1001100100010001111101111
1010011101111010000100111
100101011100000111101001001
```

Subset of binary data.

Frequency Test

- Most fundamental of 10 tests run.
- Counts the frequency of each bit.
- If frequency significantly differs from ½, the *p*-value is less than .01 and the sequence is not random.

Introduction

True random numbers are integral to various mathematical fields, ranging from cryptography to statistics; however, such numbers can only be extracted from physical phenomena. Many purported true random number generators (TRNGs) carry some intrinsic bias, undermining their viabilities as sources of random numbers.

The focus of this engineering project is to create a novel TRNG by analyzing the positions of muon pathways in a cloud chamber.

Background

The inspiration for this project came while viewing a cloud chamber at the San Francisco Exploratorium. The cloud chamber's apparently random muon pathways piqued our interest in creating a TRNG that would utilize the behavior of muons.

Muons ionize gaseous particles in the chamber, around which supercooled isopropanol vapor condenses. These streaks' pathways ought to emulate a random distribution.

Current utilization of physical phenomena as sources for TRNGs is often susceptible to outside interference and are thus unreliable. Cosmic ray emission, however, is noted to be truly random, as rays bombard earth from all directions at velocities near the speed of light, rendering their pathways unpredictable.

This engineering project aims to investigate the viability of cosmic radiation, specifically muons, as the foundation of a TRNG.

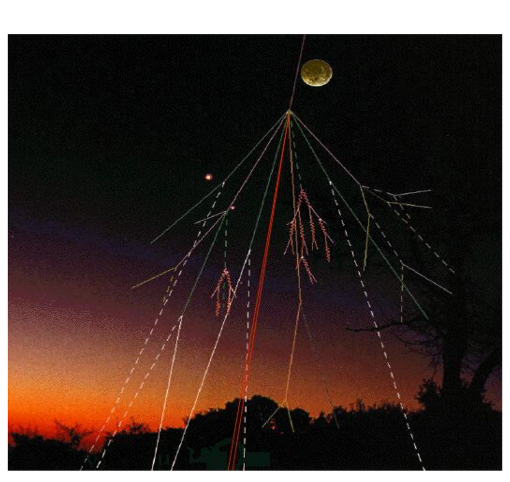
Key Sources:

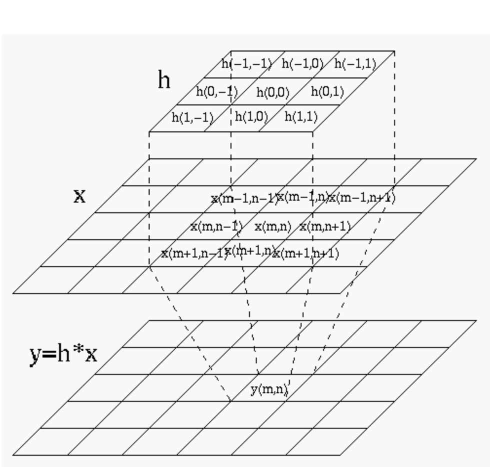
- Paschke, Jeremy, and Anne Mary Teichert. "How to Build a Cosmic-Ray Cloud Chamber." *QuarkNet*. Oct. 2008. Web. 15 Feb. 2011.<http://quarknet.fnal.gov/resources/QN_CloudChamberV1_4.pdf>.
- Cornell University. "Cloud Chambers and Cosmic rays." *Laboratory for Elementary-Particle Physics*. 2006. Web. 17 Feb. 2011.
- Watkins, Christopher, Alberto Sadun, and Stephen Marenka. *Modern Image Processing: Warping, Morphing, and Classical Techniques*. Cambridge: Academic Press Professional, 1993. Print.
- Bradski, Gary, and Adrian Kaehler. *Learning OpenCV: Computer Vision with the OpenCV Library*. Sebastopol: O'Reilly Media, Inc., 2008. Print.
- Close, Frank. *Particle Physics: A Very Short Introduction*. Oxford: Oxford University Press, 2004. Print.
- NIST. "Guide to the Statistical Tests." *Computer Security Division*. U.S. Dept. of Commerce, 14 Apr. 2008. Web. 16 Feb. 2011. <http://csrc.nist.gov/groups/ST/toolkit/rng/stats_tests.html>.

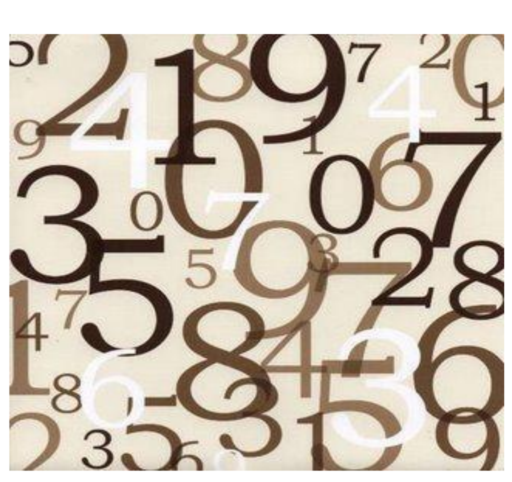
Engineering Goal

The primary goal of this project is to develop a **true random number generator** based upon the position of **muon pathways** in an isopropanol cloud chamber. Furthermore, since the sources of cosmic radiation cannot be determined, the TRNG this project aims to construct ought to be a consistently reliable source of random numbers.

Parsing the positions of the streaks will require a novel implementation of **computer vision** algorithms to successfully isolate individual streaks while attenuating higher frequency components. **OpenCV**, a set of open-source computer vision libraries, will provide the necessary low-pass spatial filters and edge detection methods to achieve the aforementioned goal. Standard **statistical tests** will be utilized to analyze the randomness of the obtained coordinates.







Interpretation of Data

- Of the 15 tests available, only 10 were applicable; the remaining five required larger data pools.
- All 10 tests passed, outputting a wide-range of *p*-values greater than or equal to .01, suggesting that the data is random.
- The high success rate illustrates that muons are a prime source of random numbers and verifies the viability of this project as a true random number generator.

```
                    BLOCK FREQUENCY TEST
          ---------------------------------------------
          COMPUTATIONAL INFORMATION:
          ---------------------------------------------
          (a) Chi^2             = 7.200000
          (b) # of substrings = 10
          (c) block length     = 10
          (d) Note: 0 bits were discarded.
          ---------------------------------------------
SUCCESS   p_value = 0.706438
                    BLOCK FREQUENCY TEST
          ---------------------------------------------
          COMPUTATIONAL INFORMATION:
          ---------------------------------------------
          (a) Chi^2             = 5.600000
          (b) # of substrings = 10
          (c) block length     = 10
          (d) Note: 0 bits were discarded.
          ---------------------------------------------
SUCCESS   p_value = 0.847676

                         RUNS TEST
          ------------------------------------------
          COMPUTATIONAL INFORMATION:
          ------------------------------------------
          (a) Pi                         = 0.480000
          (b) V_n_obs (Total # of runs) = 50
          (c) V_n_obs - 2 n pi (1-pi)
              -----------------------    = 0.011332
                2 sqrt(2n) pi (1-pi)
          ------------------------------------------
SUCCESS   p_value = 0.987214
                         RUNS TEST
          ------------------------------------------
          COMPUTATIONAL INFORMATION:
          ------------------------------------------
          (a) Pi                         = 0.480000
          (b) V_n_obs (Total # of runs) = 47
          (c) V_n_obs - 2 n pi (1-pi)
              -----------------------    = 0.413612
                2 sqrt(2n) pi (1-pi)
          ------------------------------------------
SUCCESS   p_value = 0.558591
```

Conclusion

- This engineering project created a true random number generator based on the intrinsic random behavior of muon pathways in an isopropanol cloud chamber.
- A novel implementation of computer vision algorithms was used to eliminate noise and isolate the muon pathways.
- A combination of a Gaussian blur algorithm and edge detection algorithm highlighted the streaks.
- Standard statistical tests packaged by NIST verified the randomness of the generated data.
- This TRNG marks the first time that ionizing radiation in cloud chambers has been used to generate random values.
- By creating an affordable and reliable TRNG, this project has not only increased accessibility to random numbers, but has also provided insight into the nature of cosmic radiation.

Further Research

This project successfully utilized the random behavior of muons to create a TRNG. Future research will focus on automating the entire process to increase the rate at which random numbers are generated.

The chamber will be rendered self-sustainable to increase efficiency. Research will revolve around discovering a non-degradable yet affordable cooling source and a recycling system for the alcohol that would continually replenish the chamber with vapor.

Furthermore, the method of capturing images will also be automated by placing a camera in an optimal position and hooking it up to a computer, expediting the transfer of photos.

The image processing will continue to be perfected until the computer vision algorithms can quickly isolate the streaks and extract their x and y coordinates. This may require research into the implementation of new filtering and edge detection methods.