

# 3D Graphics Module

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## **Abstract**

The purpose of this research project is to find a way to maximize the speed of a 3D graphics program. To change the runtime speeds, I used different methods to store the matrices used for graphics-related operations (such as rotations, translations, etc.). The slowest version of my program involved a matrix expression tree where all the points were recalculated with each rotation and were stored as column vectors. Calculating the points once at the beginning of the program seemed to make no appreciable difference in speed, but storing them as row vectors did. The change that seemed to make the biggest difference was to get rid of the matrix trees completely and hard-code the rotation formulas.

## **1 Introduction**

### **1.1 Scope of Study**

The scope of this program is to allow the user to graph functions of two variables. The program uses homogeneous coordinates and matrices to perform rotations on the graphs while viewing. The function and the bounds of the viewing window are inputted by the user. In order to store the function, the program creates a binary expression tree and substitute in values of the independent variables to determine the value of the function at various points. I used this program to test the speeds of the various data storage methods.

Another area of my program involved a matrix editor, which I used to test my matrix expression tree class. This editor allows the user to set the

size of a matrix and input data into the cells. After editing the matrix, the user can then perform various operations on it, such as matrix multiplication, Gauss-Jordan elimination, matrix inversion, etc.

After creating these two programs, I used them to test the data structures. The first data storage scheme that I used involved a matrix expression tree. This data structure is similar to a binary expression tree, but it stores matrices instead of numbers. The tree would be used to store the matrix expressions needed to rotate my graphs, and it would be evaluated whenever I needed to plot points. The original, unrotated points would be recalculated each time the viewing window updates itself to take into account any changes in screen size. The original data points would also be stored as column vectors.

My second data storage scheme was similar to the first one. However, the points would be stored as row vectors instead of column vectors because of the way Java stores arrays. My third data storage scheme involved calculating the original data points only once at the beginning of the program. Other than that, this storage scheme was similar to my second one. My final data storage scheme involved hard-coding the rotation formulas instead of using matrices. The original data would only be calculated once at the beginning. Once the testing phase is finished, the programs that I wrote will be put up on the TJ Intranet for others to use, so my program involves the use of modular programming as well.

## **1.2 Purpose/Relevance**

The purpose of this research project is to compare different data structures in order to maximize the speed of a 3D graphics program. To do this, I first had to create a binary expression tree class to store expressions. Then, I had to expand this class so that it'd store matrix expressions. Next, I had to create a class that allowed the user to perform matrix operations in order to test my matrix expression tree. Finally, I had to create a class that graphed functions of two variables in order to test my data storage schemes. This research is important to others because it's trying to find a way to optimize the processes involved in 3D graphics.

## 2 Background

Previous projects concerning this area of research include The Investigation of Graphics in the Processing Language by J. Trent, CityBlock Project: Multi-perspective Panoramas of City Blocks by M. Levoy, and TJForge Iodine for the modular programming component. The 3D graphics projects used rotation matrices, such as the 2D matrix  $\begin{bmatrix} \cos(a) & -\sin(a) \\ \sin(a) & \cos(a) \end{bmatrix}$ , to rotate graphs by an angle  $a$  (Levoy, Trent). However, they didn't seem to indicate how these matrices were stored. Other sources specific to Java programming suggested the use of the format  $xB$  instead of  $Ax$  for linear transformations, where both the column vector and the matrix get transposed. The purpose of this was to take advantage of the way arrays are stored in Java and to reduce errors (Ameraal). Iodine used HTML to program in the modules. Possible state-of-the art programs could be MatLab or other computer algebra systems or even the 3D-graphing feature of the TI-89.

One algorithm that was used in my program was infix traversal. My binary expression trees consisted of a String and two other binary expression trees. The String represented the operation that was being stored, while the subtrees were the two operands. In my infix evaluation, the two subtrees would be evaluated, and the results would be used as inputs to the specified operation. In order to create the binary expression trees, I split up my Strings in the reverse of my order of operations. They would be split up first based on addition and subtraction, then by multiplication and division, then by exponentiation, etc. That way, my order of operations would be preserved when I evaluated the trees.

## 3 Development

### 3.1 Development Plan

My project uses the staged delivery development process, since I have a different plan for each quarter. Every quarter, I have a specific version in mind that has specific functionality. For the first quarter, I planned to just implement a regular calculator module to make sure my infix evaluation algorithms were functioning properly. These recursive algorithms would be used again for my graphing calculator, since the equations would be read in and stored in binary expression trees before graphing. During second quarter, I planned

to implement a matrix editing module since the 3D graphics component required the use of matrices. For third quarter, I planned to actually implement my graphing module so that I could test the various data structures.

## 3.2 Testing Requirements

The implementation of the binary expression trees was pretty straightforward, so my first criteria for determining success involved the actual parsing of Strings. I had to make sure that the listeners associated with the "Enter" button followed the correct order of operations and created binary expression trees based on that order. To test the accuracy of my program, I used the TI-83 evaluation algorithm as a standard. My second criteria was to make sure the matrix editing panel and the matrix operations panel interacted correctly so that matrices could be inputted without losing data. For the graphing panel, I had to see whether the program could plot points according to a right-handed set of coordinate axes and apply the relevant matrix operations to rotate the graphs. My final test was to measure the amount of lag that resulted for each data storage scheme and see which one resulted in the shortest waiting time.

## 3.3 Research Theory and Design Criteria

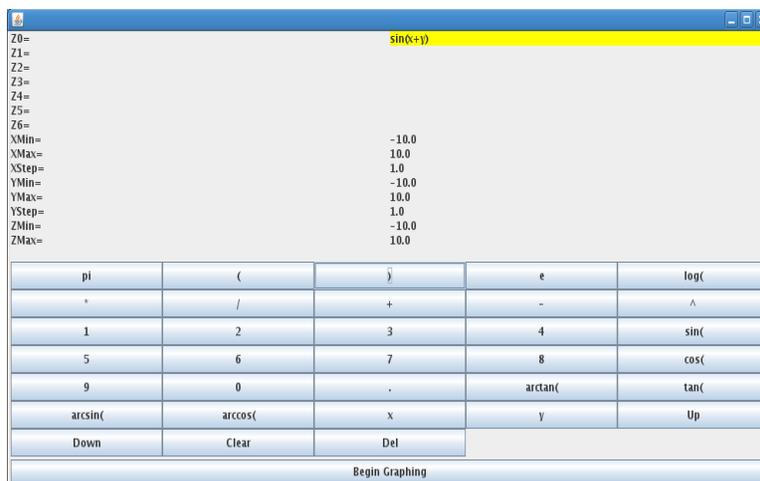
To find out the quickest way to store data, I used four different data structures when graphing my functions. The first data storage scheme that I used involved a matrix expression tree. The tree was used to store the matrix expressions needed to rotate my graphs, and it was evaluated whenever I needed to plot points. The original, unrotated points were recalculated each time the viewing window updated itself to take into account any changes in screen size. The original data points were to be stored as column vectors. My second data storage scheme was similar to the first one. However, the points were to be stored as row vectors instead of column vectors. My third data storage scheme involved calculating the original data points only once at the beginning of the program and using row vectors. My final data storage scheme involved hard-coding the rotation formulas and calculating the original points only once.

In order to gather my data, I modified one of the listeners for my graphing calculator so that whenever you pressed one of the "Rotate" buttons, it changes the viewing angles and re-rotates the graph 10,000,000 times. Each

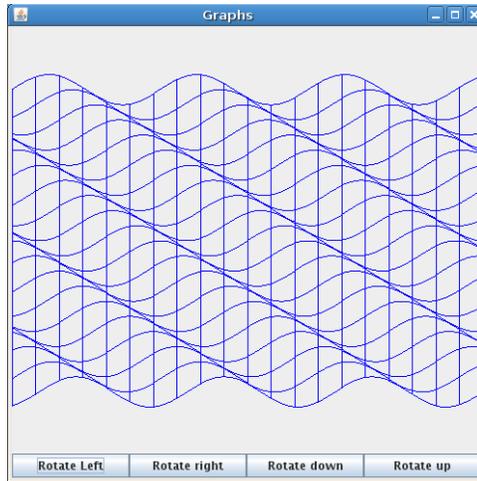
time, it executes the method `System.nanoTime()` before and after repainting the graphing window, since it is in the `repaint()` process that it performs the viewing transformations. Then, it prints out the elapsed time to a text file. After gathering data for each different data storage scheme, I ran another program to analyze this data. This program ignored the first million data points for each scheme, since the programs tended to run slower at the beginning of the trial period and then reached a "steady state" after multiple iterations. The analyzer program calculated the average runtime for the remaining 9,000,000 iterations and printed out the results. I decided to go with 9,000,000 iterations to "dilute" the effects of outliers on the averages. All programs were run on a 1.2 gigahertz processor, with no other programs running except for the NetBeans IDE v. 4.1. The version of Java used was J2SE 1.5.

### 3.4 Runtime Process

During the runtime of my third quarter version, the user starts out with this window:



Here, the user can input equations to graph and change the window bounds. After pressing the "Begin Graphing" button, a graph of the function is displayed. The "Rotate" buttons allow the user to rotate the graph in the specified directions.



## 4 Results, Conclusion, and Discussion

The purpose of this research project is to find a way to maximize the speed of a 3D graphics program. To change the runtime speeds, I used different methods to store the matrices used for graphics-related operations. This research is important to others because it's trying to find a way to optimize the processes involved in 3D graphics. I consider my project to be a success since I obtained enough to compare the performances of each data structure.

So far, I have managed to create a working binary expression trees class that can handle logarithmic functions, exponential functions, trigonometric operations, inverse trigonometric operations, and regular arithmetic operations. The trees for non-arithmetic operations only have one subtree since they only take one argument. I created a class that parsed input Strings and broke them up based on an order of operations that I determined. My matrix editor also uses binary expression trees, except this time, the arguments are matrices instead of doubles. It can handle addition, subtraction, multiplication, and other operations such as matrix inversion and Gauss-Jordan elimination. I also have a working graphing calculator that can store functions in binary expression trees, apply the rotations that are necessary to view the object, and display the data points on the screen.

The slowest version of my program involved a matrix expression tree where all the points were recalculated with each rotation and were stored as column vectors (Scheme 1). Each iteration, this scheme took 2685 nanosec-

onds to rotate a single graph. Storing the points as row vectors instead of column vectors made a significant difference, since this scheme only took 2513 nanoseconds (Scheme 2). Calculating the points once at the beginning of the program seemed to make no appreciable difference in speed, since the runtime per iteration was 2592 nanoseconds (Scheme 3). The change that seemed to make the biggest difference was to get rid of the matrix trees completely and hard-code the rotation formulas, since this scheme only took 2440 nanoseconds per iteration (Scheme 4). I will not include the data points that were collected in this paper, since there are 40 million of them and they took up a total of 240 megabytes.

However, there are anomalies in the data. Scheme 3 took longer than Scheme 2, even though it performed fewer flops per iteration. A closer analysis of the data I collected revealed that the runtimes did not stay constant. At the beginning, each program took over 10,000 nanoseconds per iteration to run. After a few iterations, the runtime length would spike, and then it would decrease to 9,000 nanoseconds. After running at 9,000 nanoseconds, the runtime length would spike again and then plateau at an even lower value. This process continued until the programs reached a steady-state. By iteration number 20,000, the runtimes would alternate between 2235 ns and 2514 ns. An calculation of the mode data point confirmed this operation: Schemes 1 and 2 had modes of 2514 ns, while Schemes 3 and 4 had modes of 2235 ns.

One possible explanation for the spike-and-plateau pattern involves the use of memory. Every time I ran the `repaint()` method, my program left data in the computer's memory. As the Java Virtual Machine started to run out of RAM, it would "ask" the system for more, which explains the spikes. This increase in RAM allocation allows the program to run faster, which explains the plateaus. One possible solution to this problem would be to run the garbage collector (`System.gc()`) every iteration so that the amount of RAM usage stays constant. The preliminary data that I have managed seems to confirm this fact, since the programs do not speed up when the garbage collector is run.

The conclusion that I can draw is that the type of data structure being used has a significant impact on the runtime efficiency of the program. Although the use of a binary search tree allows the user to write neater code, it results in considerable lag when the program runs. The best way to store a matrix is to hard-code the formulas. Areas for future research would involve investigating the effects of the garbage collector. The `repaint()` method was

only meant to be executed once when a "rotate" button was pressed, so the end user would therefore be more interested in the behavior of the program before more RAM is allocated.

## References

- [1] M. Levoy, "CityBlock Project: Multi-perspective Panoramas of City Blocks," 2006.
- [2] J. Trent, "The Investigation of Graphics in the Processing Language," 2006.
- [3] L. Amaraal, Computer Graphics for Java Programmers, 1998.