

Backbone Determination in a Wireless Sensor Network

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Abstract

A report on implementing algorithms to partition a random geometric graph into bipartite subgraphs. Three different graph geometries are explored: unit square, unit disk, and unit sphere. Nodes are uniformly distributed in the geometry. Then the edges are determined and the vertices are colored using smallest-last vertex ordering.

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1 Executive Summary

1.1 Introduction

Random geometric graphs (RGGs) are useful for simulating wireless sensor networks placed in different topologies. This project examines three different geometries: Square, Disk, and Sphere. The user supplies parameters for how many nodes they want in the network and how many connections they want for each node. Then, the simulation finds the average radius needed for that number of connections, finds multiple backbones for the RGG, and displays the results graphically.

1.2 Environment Description

The data structures and topologies for this simulation are implemented in Python2.7. The graphics are done using Processing.py. All development and benchmarking has been done on a 2014 MacBook Pro with a 3 GHz Intel Core i7 processor and 16 GB of DDR3 RAM running macOS High Sierra 10.13.3.

A separate data generation script was used to generate the graphs using matplotlib. This library, and a variety of others, could not be imported into Processing.py because the jython interpreter used by Processing only accepts libraries written in raw Python.

The different geometries were implemented in a stand alone Python file and imported into the Processing.py script or the data generation script depending on what was being run. Because there is no intermediary file to hold the generated nodes and edges, there is no additional disk space needed to run the simulation. Everything can be done in system memory managed by Processing.

2 Reduction to Practice

2.1 Data Structure Design

The primary data structure used for this project is an adjacency list. However, to allow for constant time lookup of edges of a node, I used a Python dictionary where the keys are nodes and the values are a list of adjacent nodes. The space needed by the adjacency list is $\Theta(2n)$ where $n = |E|$. Two entries are used for each edge because they are undirected. This is superior to the adjacency matrix data structure which would require $\Theta(n^2)$ space where $n = |E|$.

In order to make this project maintainable as it is developed along the semester, I used the object-oriented capabilities Python has to offer to design the different geometries. I start with a base Topology class that creates the interface Processing uses to draw the graphs. This base class implements all of the methods needed for node placement and edge detection in 2D graphs. Then, I create three subclasses: Square, Disk, and Sphere.

The Square and Disk topologies simply need to override the methods for generating nodes and calculating the node radius needed for the desired average degree. The Sphere subclass needs to override a few additional functions because it exists in a 3D space. Other than the methods for generating nodes and calculating the node radius, it also needs to override the function used to draw the graph so that Processing will render the graph properly in 3D.

2.2 Algorithm Descriptions

2.2.1 Node Placement

A different node placement algorithm is required for each of the geometries. For the Square, the coordinates for each node are generated as two random numbers taken from a uniform distribution on the range $[0, 1]$. All of these points are guaranteed to be in the unit square.

For the Disk, a similar method is used. The coordinates for nodes are randomly sampled from a uniform distribution; however, if a node has a distance from the center of the Disk greater than the radius of 1, the coordinates for that node are resampled.

For the Sphere a different method must be used so that all of the nodes are placed on the surface of the Sphere and the volume is vacant. For this geometry, I used the following equations:

$$x = \sqrt{1 - u^2} \cos \theta \tag{1}$$

$$y = \sqrt{1 - u^2} \sin \theta \tag{2}$$

$$z = u \tag{3}$$

where $\theta \in [0, 2\pi]$ and $u \in [-1, 1]$. This is guaranteed to uniformly distribute nodes on the surface area of the sphere [1].

All of these algorithms can be solved in $\Theta(n)$ where $n = |V|$ because each node only needs to be assigned a position once.

2.2.2 Edge Determination

There are several methods for finding the edges in the graph. The brute force method checks every node, and for each node checks all other nodes to see if they are close enough to form an edge. The brute force method is $\Theta(n^2)$ where $n = |V|$.

The second method to find the edges is the sweep method. This method first sorts the nodes along the x-axis. Then, for any node, we only need to search left and right until the distance along the x-axis is greater than the connection radius for the nodes. This dramatically reduces the search space. The sweep method is $O(n \lg(n) + 2rn^2)$ where $n = |V|$ and r is the connection radius. The $n \lg(n)$ portion is for the sorting and the $2rn^2$ portion is for measuring the distance between nodes in a sweep step.

The final method to find edges is the cell method. This method places the nodes into cells of area $r \times r$ based on their position in the topology. When the edge detection runs, each node needs to be visited once, but only the cell the node populates and the neighboring cells need to be searched for connections.

The only method that needs to be adjusted for the Sphere is the cell method. Instead of using a two dimensional grid of cells, a three dimensional mesh is needed to divide the topology. The cells then have volume $r \times r \times r$. Only the current cell and the neighboring cells need to be searched.

2.2.3 Graph Coloring

Two algorithms are used for coloring the graphs. The first is smallest-last vertex ordering, which sorts the vertices based on the number of degrees they have. The second is the greedy graph coloring algorithm.

Smallest-last vertex ordering is used to order the nodes for coloring. The steps to this algorithm are as follows [3]:

1. Initialize a representation of your target graph
2. Find the vertex v_j of minimum degree in your representation
3. Update your representation to simulate deleting v_j
4. If there are still vertices in the representation, return to step 1, otherwise terminate with the sequence of vertices removed

This algorithm is linear if each of the above steps is linear. Step 1 is linear if we can build a representation of the graph in linear time. For this, we can use an array of buckets, where each bucket holds the vertices that have the same number of edges as the position of the bucket in the array of buckets. To build this data structure, each node only needs to be visited once, making this linear in both space and time. Next, finding the vertex of minimum degree simply requires finding the lowest index bucket that has a node. This is bounded by the number of buckets, which is bounded by the number of nodes, making Step 2 linear. Next, we have to update the representation of the graph. To do this, we have to look at each node that shares an edge with v_j and move it to the bucket for nodes with one fewer degree. This requires traversing the list of edges for v_j which means Step 3 is linear. Since this is repeated for each node, the runtime of this program is $\Theta(|E| + |V|)$ and the space needed is $\Theta(|V|)$.

After this, a single traversal of the smallest-last vertex ordering is needed to color the graph. As we traverse this list, we check to see if the nodes before it (that are already colored) share an edge with the current node. The node can then be colored with any color it does not share an edge with or, if it shares an edge with all currently used colors, it is assigned a new color. This algorithm is also linear. Each node needs to be visited once and when a node is visited, all previous nodes are checked to see if they are in the edge list of the current node. Because we used smallest last vertex ordering, as we have to check more and more nodes, we get to check fewer and fewer edges. This makes the greedy coloring algorithm $O(|V| + |E|)$.

2.3 Algorithm Engineering

2.3.1 Node Placement

It is easy to implement the algorithms for placing nodes in the different geometries using Python's math library. This library offers functions for sampling points on a uniform distribution. For the Square,

sampling on a range $[0, 1]$ is sufficient for all of the nodes. Since each node only needs to be placed once, this runs at $\Theta(n)$ where $n = |V|$.

For the Disk, the node needs to be resampled if it is too far from the center. To do this, the distance function is used to find the distance between the node and the center. If the node is further than 1 from the center, node generation falls into a while loop which iterates until the node is within the unit circle. Since nodes are taken from a uniform distribution, the number of nodes that will need to be resampled is approximately equal to the ratio of the area of the square that circumscribes the unit circle which falls outside of the unit circle to the total area of the square. This is given by:

$$\frac{(2r)^2 - \pi r^2}{(2r)^2} = \frac{4 - \pi}{4} = 0.2146 \quad (4)$$

Since the placement algorithm for each node of the Disk will iterate until the node falls within the unit circle, the total number of iterations N can be found as the sum of the geometric series:

$$N = \sum_{k=0}^{\infty} n(0.2146)^k = \frac{n}{1 - 0.2146} = 1.273n \quad (5)$$

where $n = |V|$. This shows this implementation is $\Theta(n)$.

For the node placement algorithm of the Sphere, again the math library in Python makes this easy. Each node needs two random values pulled from a uniform distribution, two square root operations, one sine operation, and one cosine operation. Each node only needs to be placed once so the runtime of this algorithm is $\Theta(n)$ where $n = |V|$.

2.3.2 Edge Determination

Each method implemented for finding edges has a different time complexity. The brute force method uses an outer loop and an inner loop, which each iterate over every node in the graph. An edge is saved to the adjacency list if the nodes are not the same and the distance between them is less than or equal to the calculated node radius. This is guaranteed to run in $\Theta(n^2)$ where $n = |V|$. The number of times the distance needs to be calculated is $n \times (n - 1)$ because it will not be calculated when the nodes are the same (distance would be zero, but no edge is drawn here). No additional space is needed for the brute force method so the space complexity is $O(1)$.

The implementation of sweep starts by sorting the nodes along the x-axis. Python lists have a built-in sort function that has $O(n \lg(n))$ time complexity [2]. After this stage, it iterates over every node building a search space which will be scanned for edges. For each node, the list of nodes is searched left and right $r \times n$ nodes to find those within one radius length of the current node. With the search space built, the search space is iterated over once to find nodes that have a distance less than or equal the node radius. My implementation of this runs in $O(n \lg(n) + 4rn)$ where $n = |V|$ and r is the node connection radius. Because the list sort method sorts in-place, the only additional space needed is for the search space. This saves $O(2rn)$ nodes and is reset after every iteration.

The cell method implementation works in linear time. In the first step of the method, the cells are initialized as a list of empty lists. There are $(1/r + 1)^2$ cells. The nodes are then iterated over and assigned a cell by dividing their x and y coordinates by the node radius. At this point, the cells are iterated over and, for each node in the cell, the nodes in the current cell and the eight adjacent cells and the are checked to see if they fall within the node radius of the current node. All together, this implementation runs at $O(n + n + 9nr^2) = O((2 + 9r^2)n)$ where $n = |V|$. The amount of additional space needed is equal to the number of nodes because they are copied into their respective cells. This places the space complexity at $\Theta(n)$.

The cell method needs to be updated for the Sphere. To do this, an extra dimension is added to the cells, creating a 3D mesh. The only changes needed from the 2D method is that another loop is needed to iterate over the added dimension, and the search space turns into a 3x3 cube with the current cell at the center. Each node is still only visited once as the edges are determined. The runtime for this algorithm is $O(n + n + 27nr^3) = O((2 + 27r^3)n)$ where $n = |V|$. Again, the space complexity is $\Theta(n)$.

2.4 Verification

2.4.1 Node Placement

The nodes can be verified to be distributed uniformly if the distribution of degrees follows a normal distribution. To show that the distribution of degrees for each of my geometries are following a normal

Benchmark #	Num. Nodes	Avg. Degree	Distribution	Run Time (s)
1	1000	32	Square	0.430
2	8000	64	Square	2.157
3	16000	32	Square	1.926
4	64000	64	Square	9.960
5	64000	128	Square	14.543
6	128000	64	Square	17.258
7	128000	128	Square	28.460
8	8000	64	Disk	1.402
9	64000	64	Disk	8.908
10	64000	128	Disk	18.700
11	16000	64	Sphere	22.627
12	32000	128	Sphere	86.638
13	64000	128	Sphere	177.856

Table 1: Benchmark Data and Run Times

distribution, I plotted degree histograms for each of the geometries with 32,000 nodes and an average degree of 16. The histogram for Square is given in Figure 1, Disk is given in Figure 2, and Sphere is given in Figure 3. These histograms clearly follow a normal distribution.

2.4.2 Edge Determination

The runtime for the edge detection methods can be varified by varying the number of nodes and measuring the runtime of each algorithm. By looking at how the runtime grows, we can calculate the trendline that best fits the growth rate. For the first comparison, I vary the number of nodes from 4,000 to 64,000 in steps of 4,000, while holding the desired average dgree constant at 16. As we can see in Figure 4, the growth rates of the brute force and sweep methods are quadratic, while the growth rate of the cell method. The trendline functions are given on the graph.

For the second metric, I held the number of nodes constant at 32,000 and varied the desired average degree from 2 to 32 in steps of 2. The graph is given in Figure 5. The cell method clearly grows linearly, but the sweep method is harder to gauge. Since varying the desired average degree should only change the node radius, I would expect this to grow linearly as well. However, because each graph is randomly generated, some graphs can have nodes that are closer to sorted order than others. This can effect the measured runtime. It would be easier to gauge the trend if it I ran the data collection multiple times and averages the results.

References

- [1] Weisstein, Eric W., Wolfram MathWorld
Sphere Point Picking
<http://mathworld.wolfram.com/SpherePointPicking.html>
- [2] Peters, Tim
Timsort
<http://svn.python.org/projects/python/trunk/Objects/listsort.txt>
- [3] Matula, David and Beck, Leland
Smallest-Last Ordering and Clustering and Graph Coloring Algorithms
- [4] Johnson, Ian
Linear-Time Computation of High-Converage Backbones for Wireless Sensor Networks
<https://github.com/ianjohnson/SensorNetwork/blob/master/Report/Report.pdf>

3 Appendix A - Figures

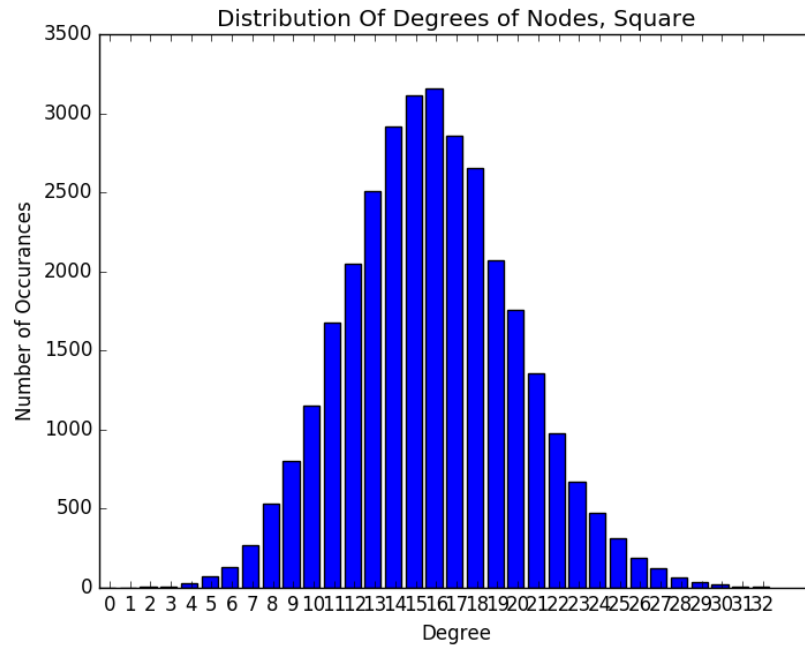


Figure 1: Distribution of Degree counts for Square. 32,000 Nodes, Average Degree of 16

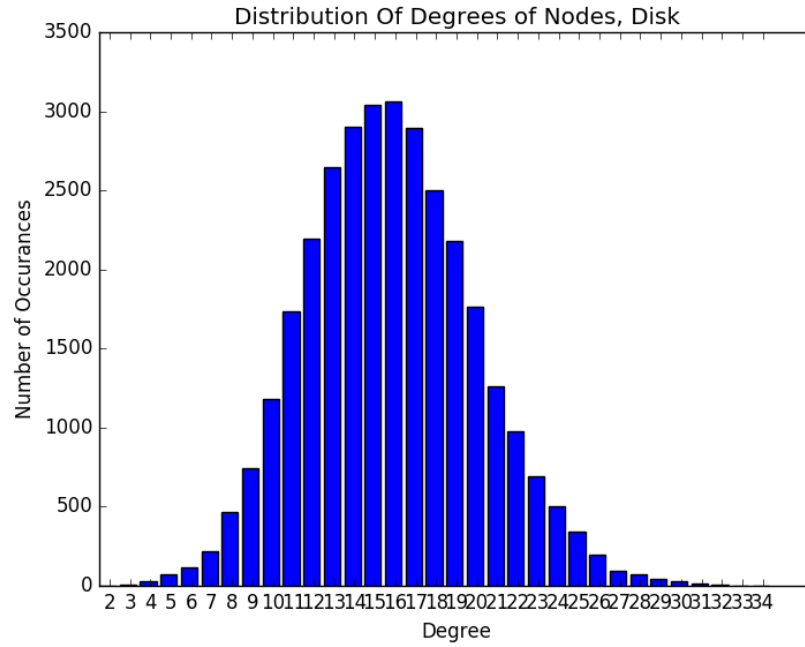


Figure 2: Distribution of Degree counts for Disk. 32,000 Nodes, Average Degree of 16

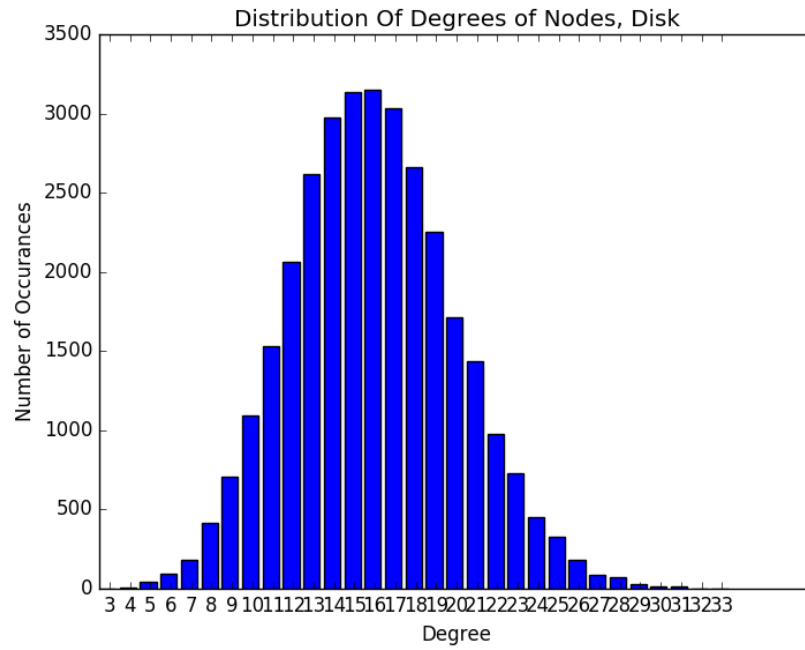


Figure 3: Distribution of Degree counts for Sphere. 32,000 Nodes, Average Degree of 16

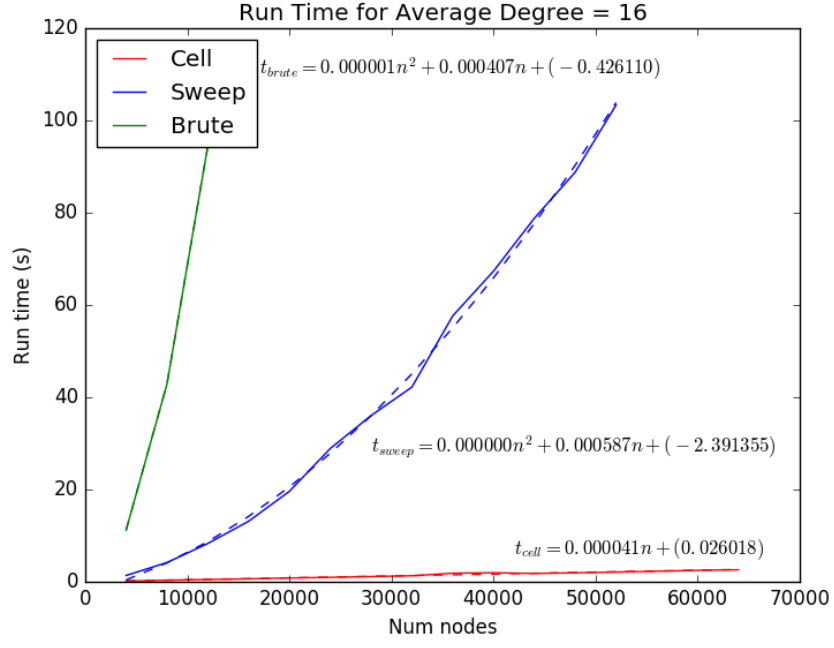


Figure 4: Runtime for Each Edge Detection Method, Average Degree of 16

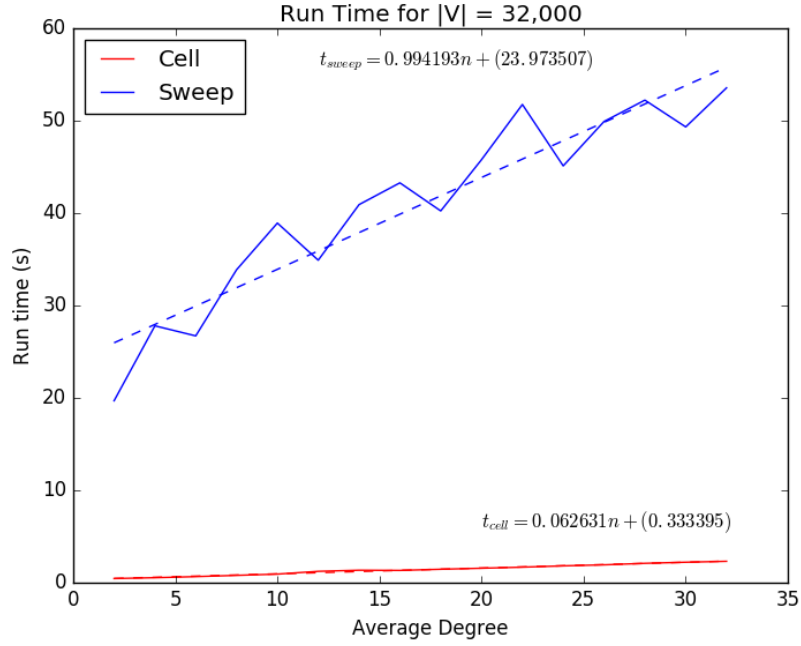


Figure 5: Runtime for Cell and Sweep Edge Detection, Variable Average Degree

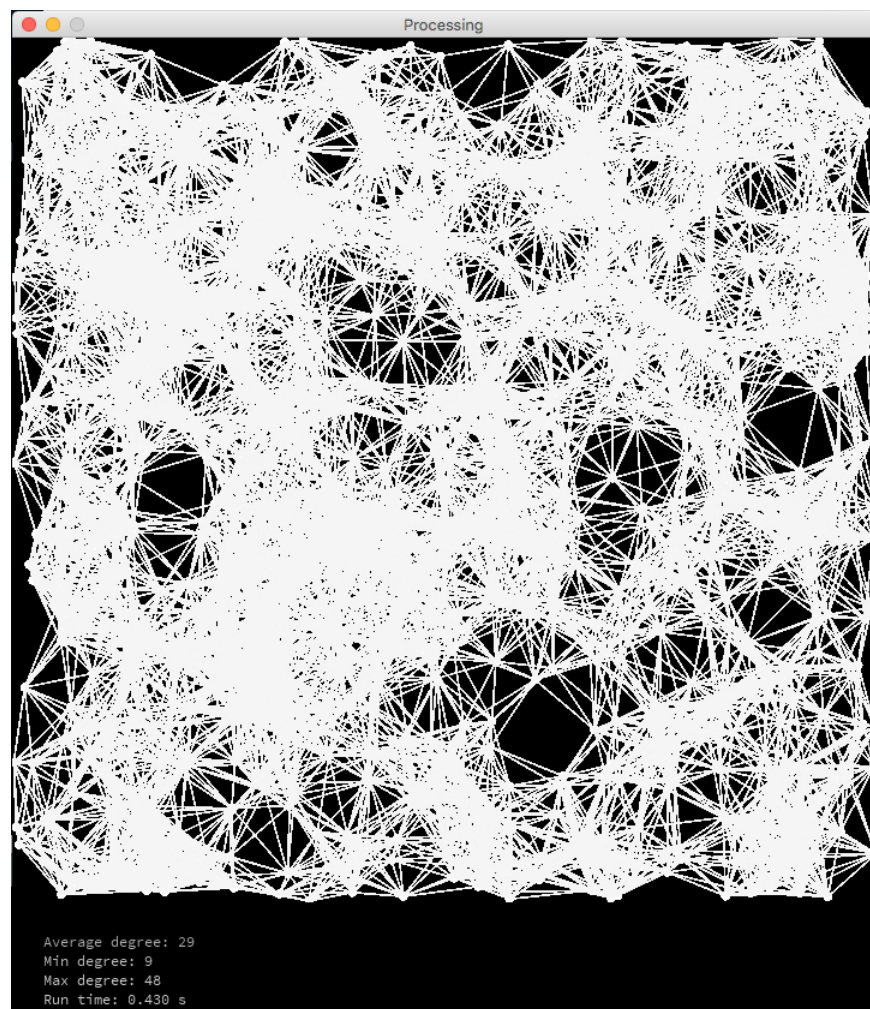


Figure 6: Square Benchmark Number 1. 1000 Nodes, Average Degree of 32

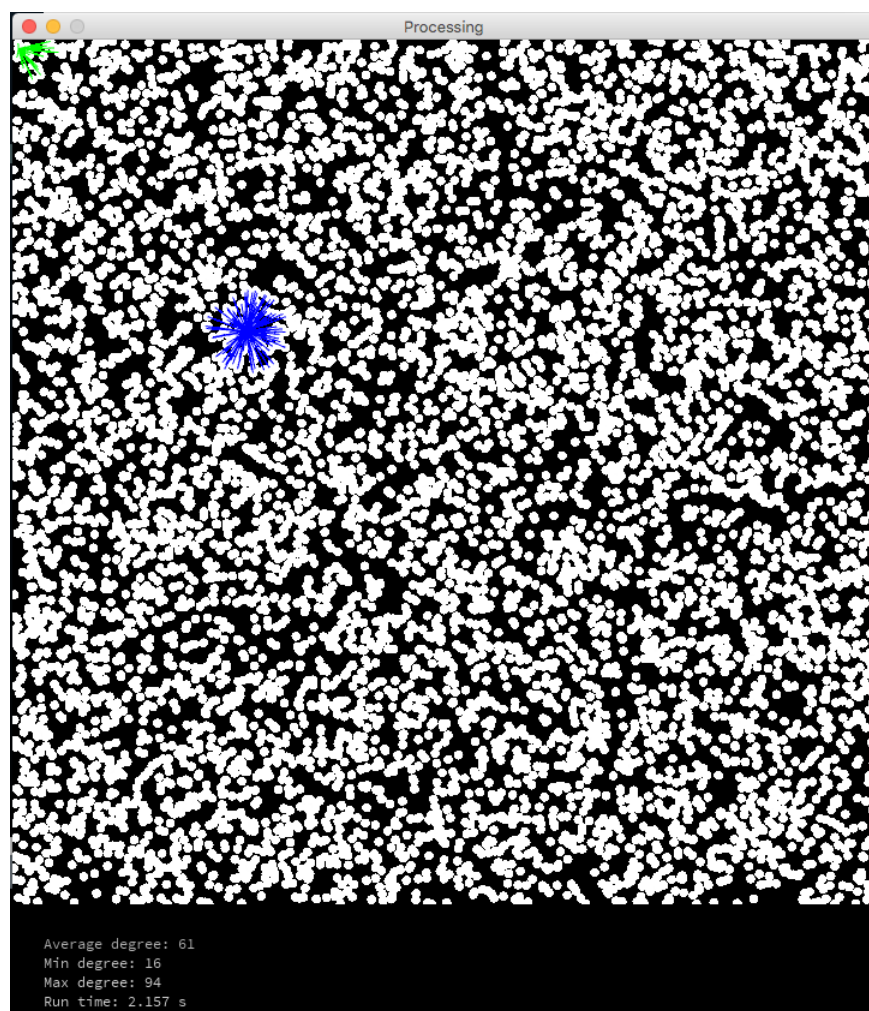


Figure 7: Square Benchmark Number 2. 8000 Nodes, Average Degree of 64

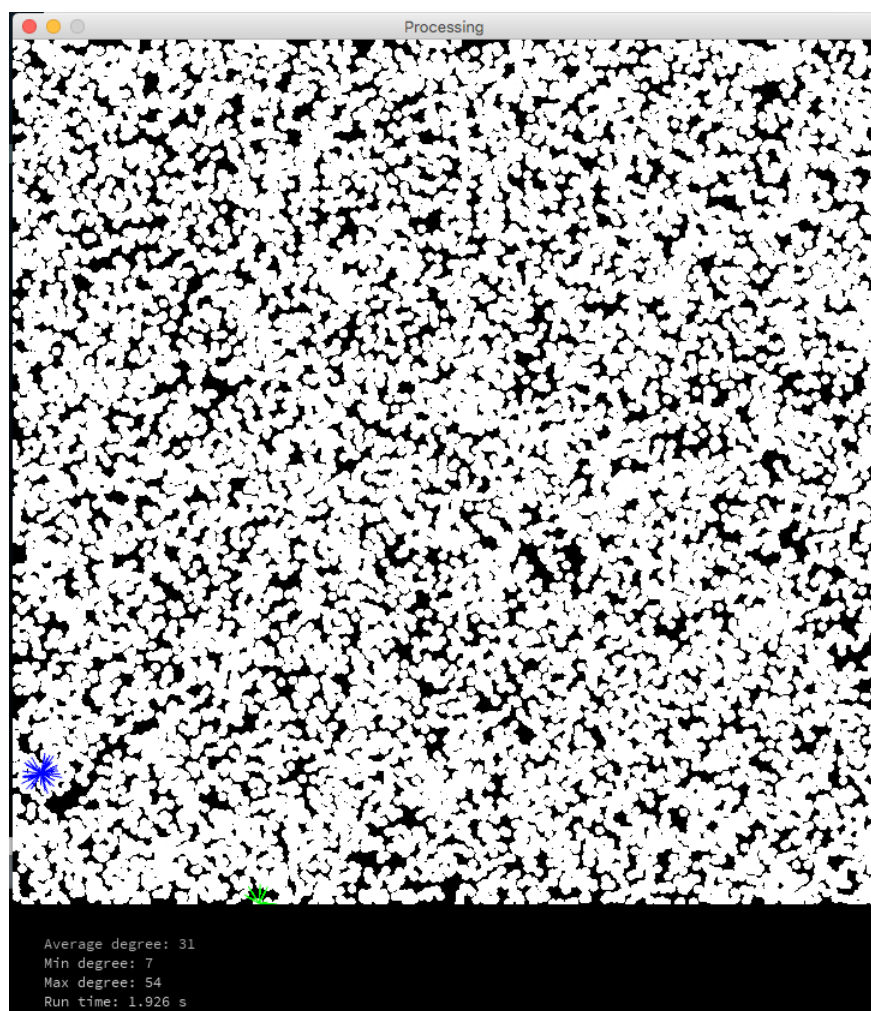


Figure 8: Square Benchmark Number 3. 16000 Nodes, Average Degree of 32

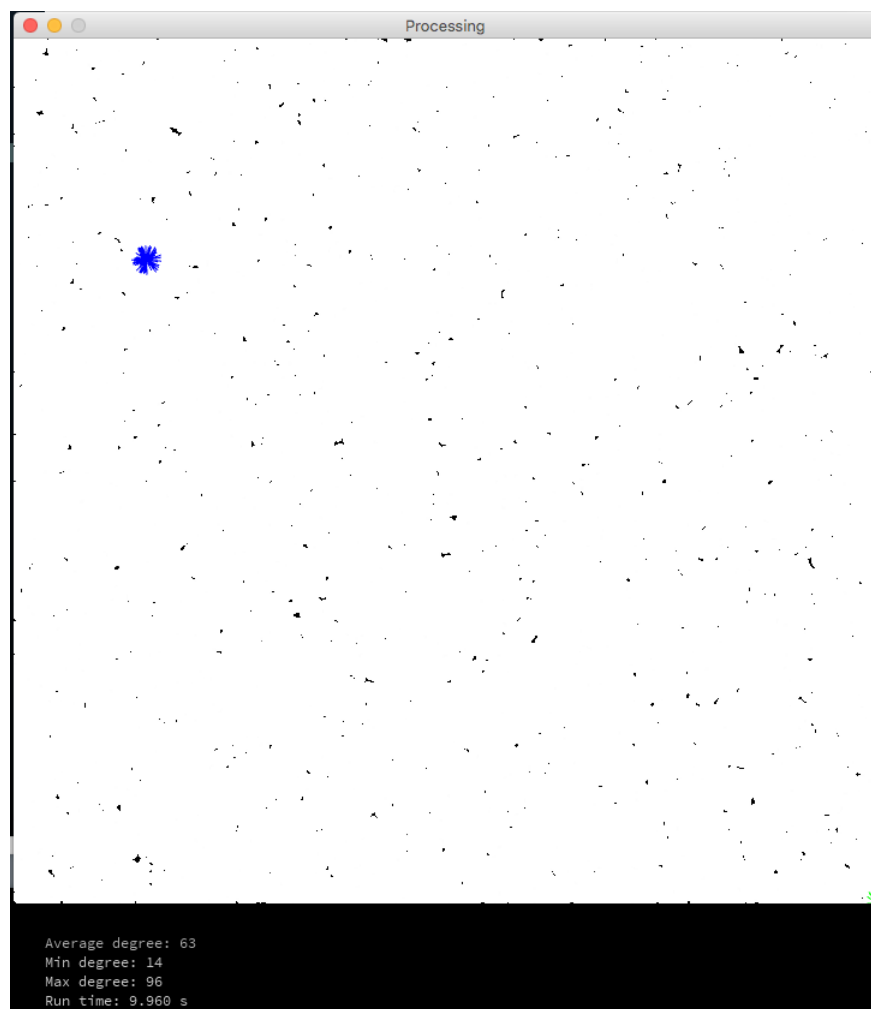


Figure 9: Square Benchmark Number 4. 64000 Nodes, Average Degree of 64

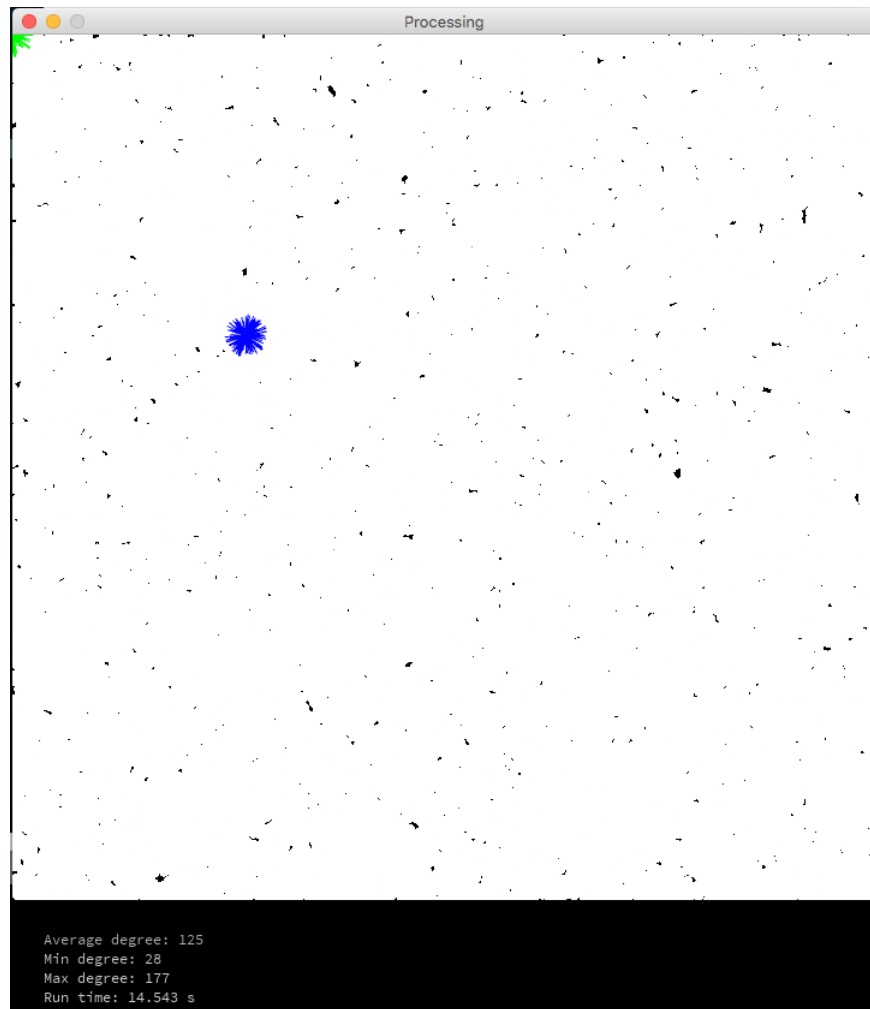


Figure 10: Square Benchmark Number 5. 64000 Nodes, Average Degree of 128

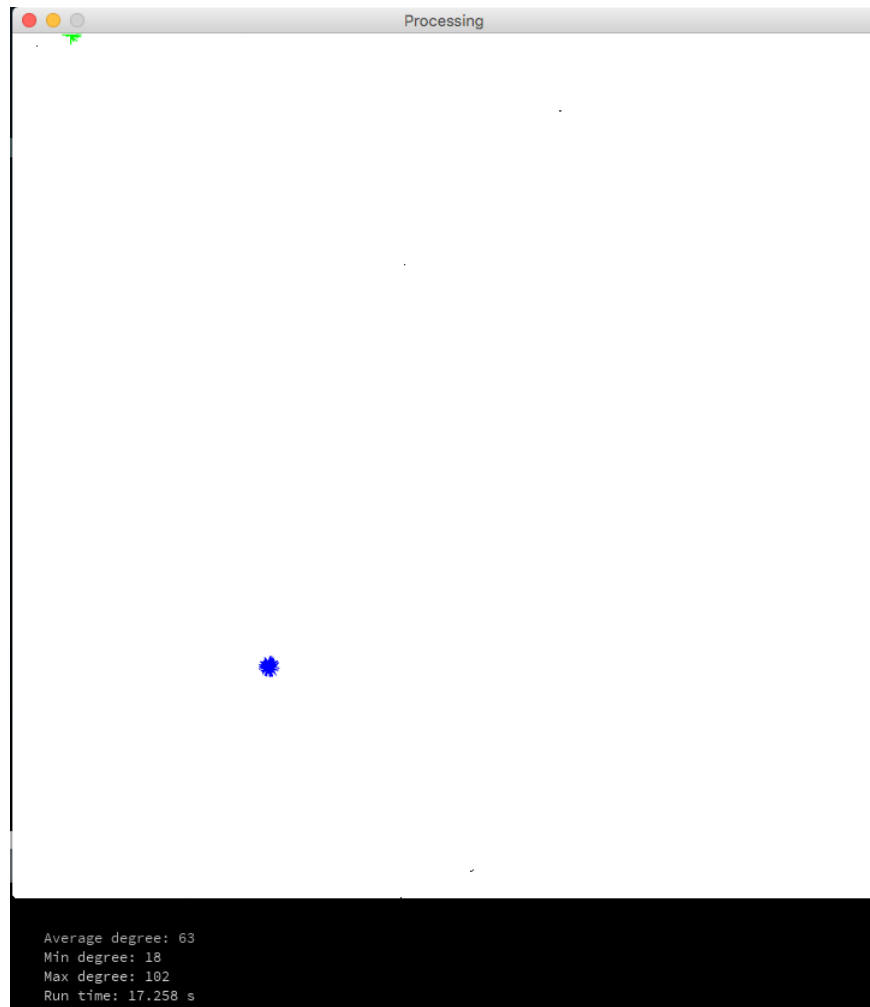


Figure 11: Square Benchmark Number 6. 128000 Nodes, Average Degree of 64

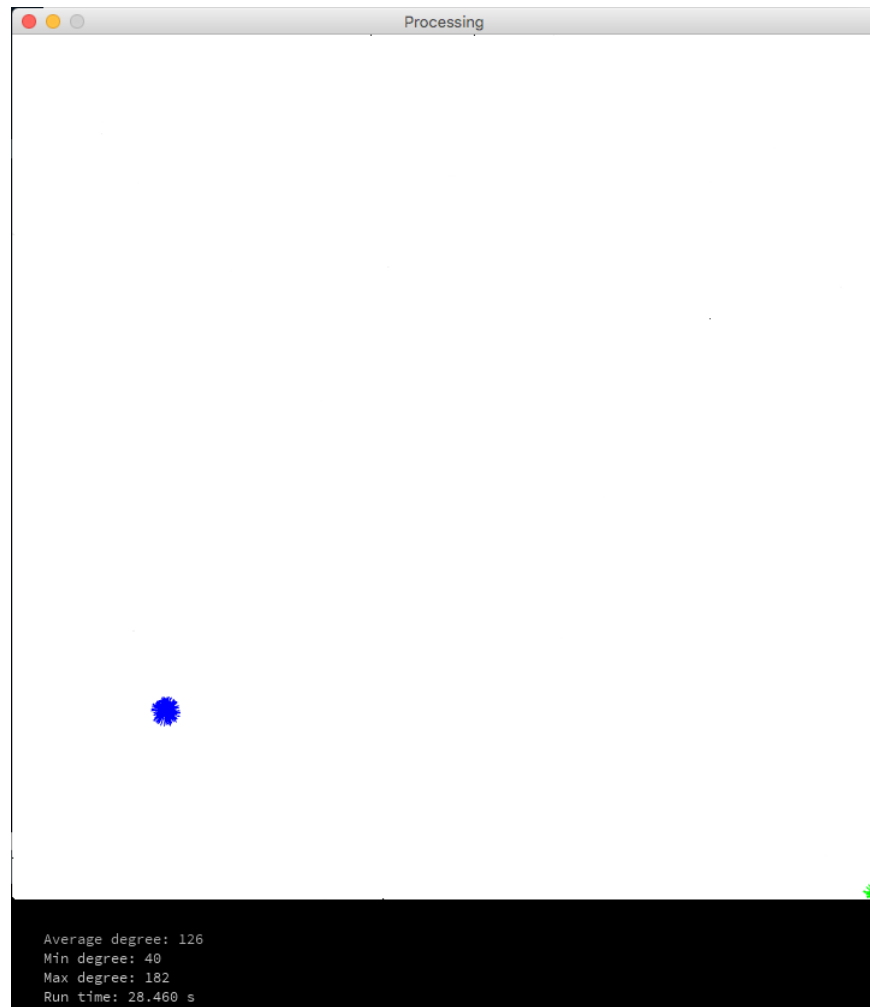


Figure 12: Square Benchmark Number 7. 128000 Nodes, Average Degree of 128

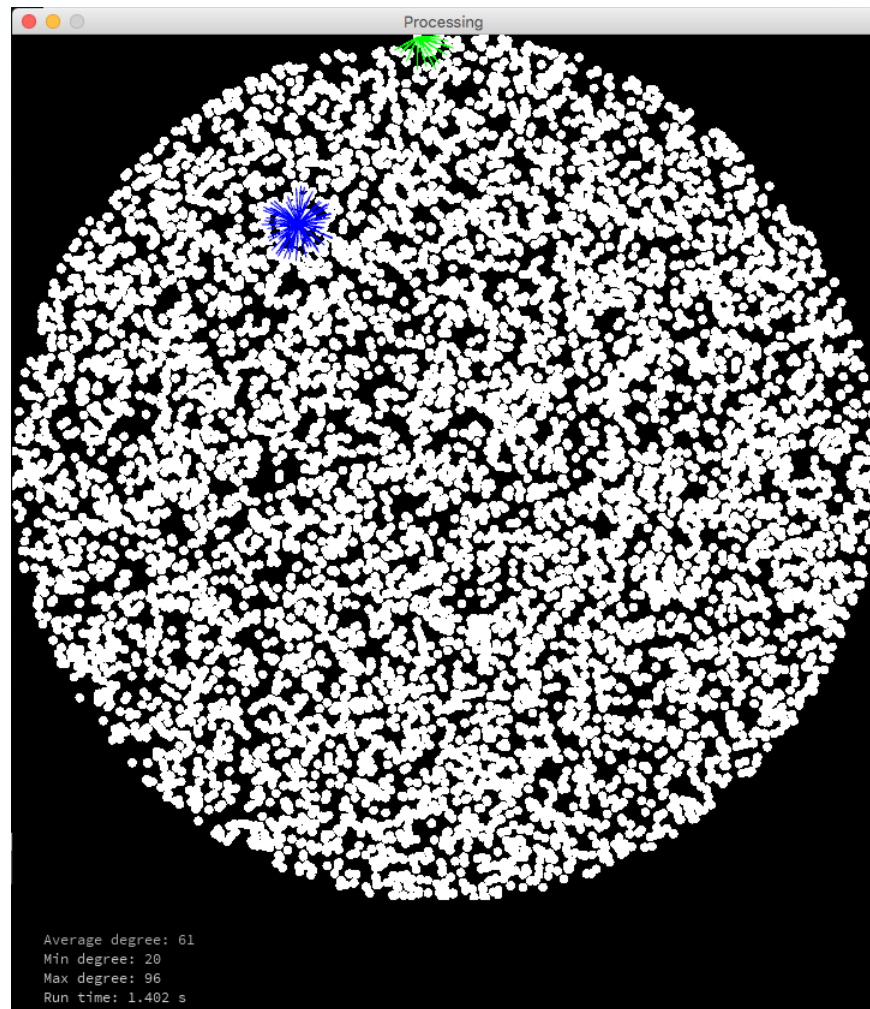


Figure 13: Disk Benchmark Number 1. 8000 Nodes, Average Degree of 64

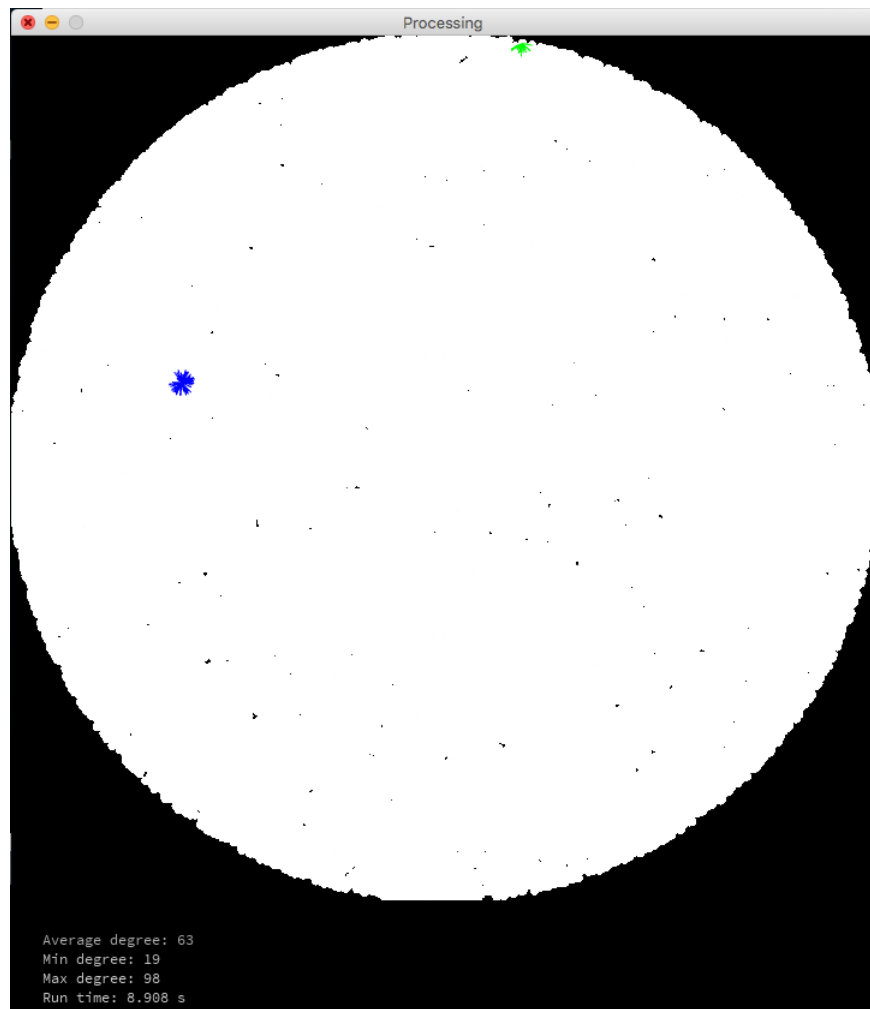


Figure 14: Disk Benchmark Number 2. 64000 Nodes, Average Degree of 64

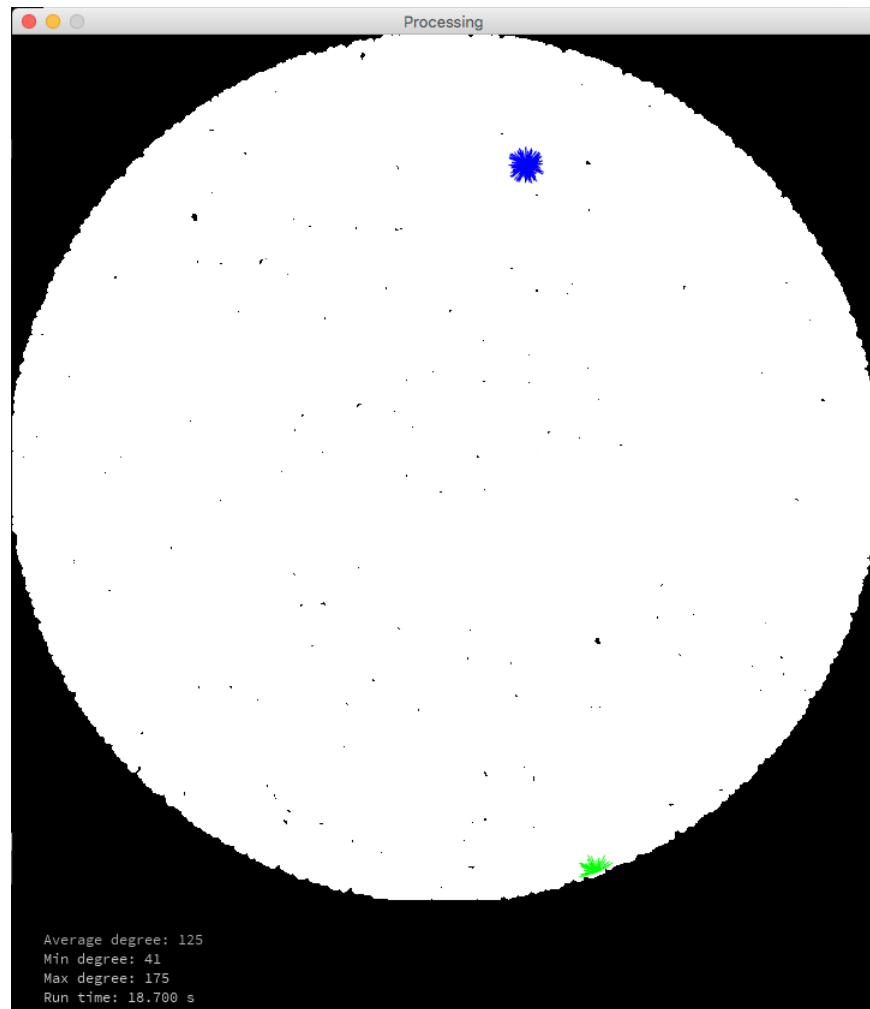


Figure 15: Disk Benchmark Number 3. 64000 Nodes, Average Degree of 128

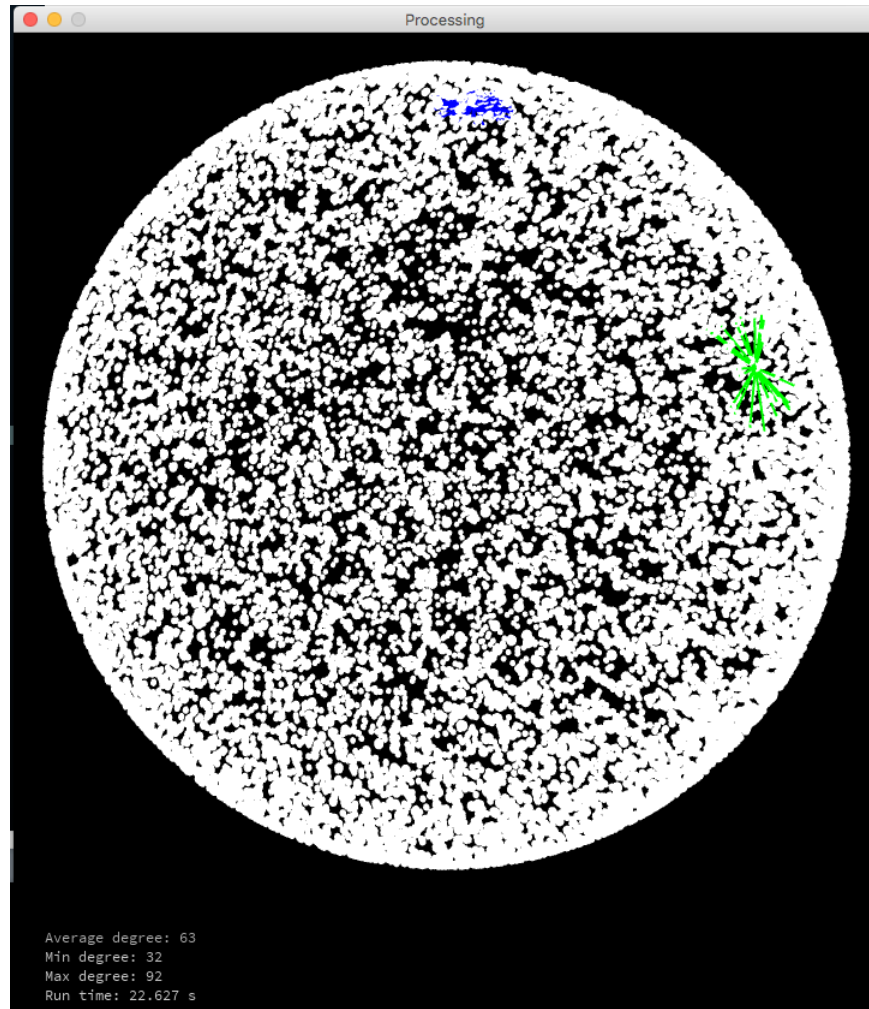


Figure 16: Sphere Benchmark Number 1. 16000 Nodes, Average Degree of 64

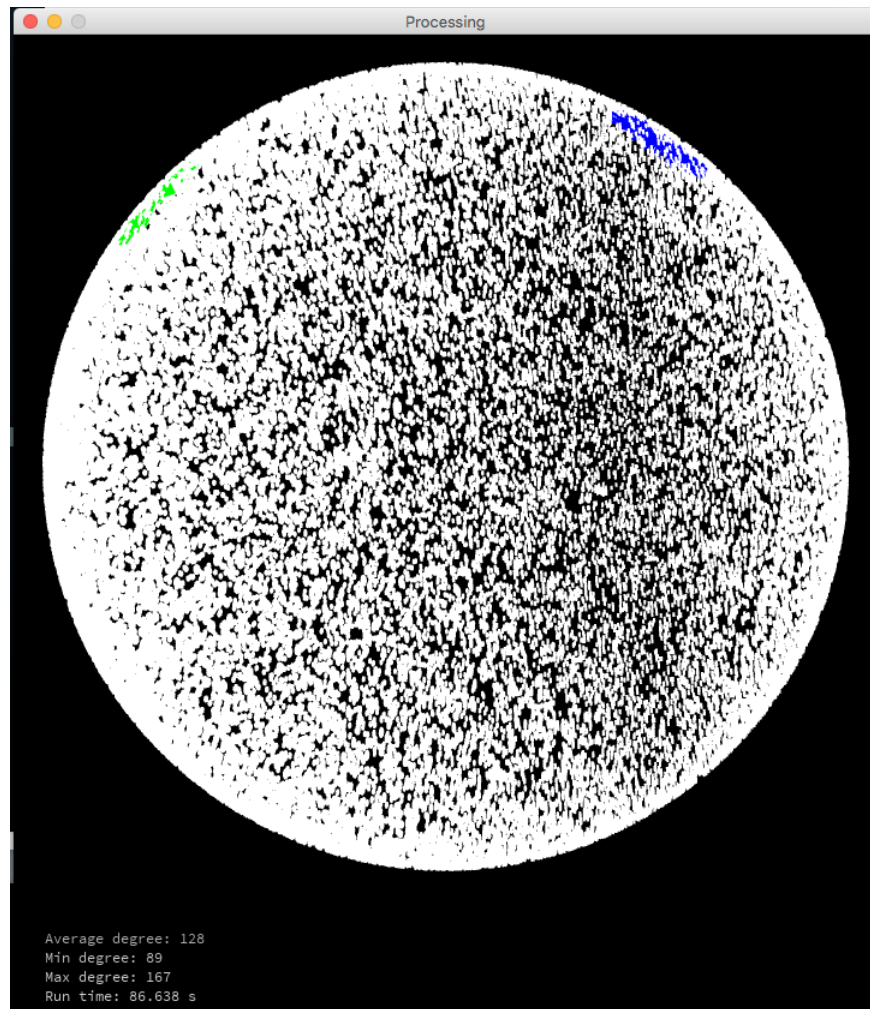


Figure 17: Sphere Benchmark Number 2. 32000 Nodes, Average Degree of 128

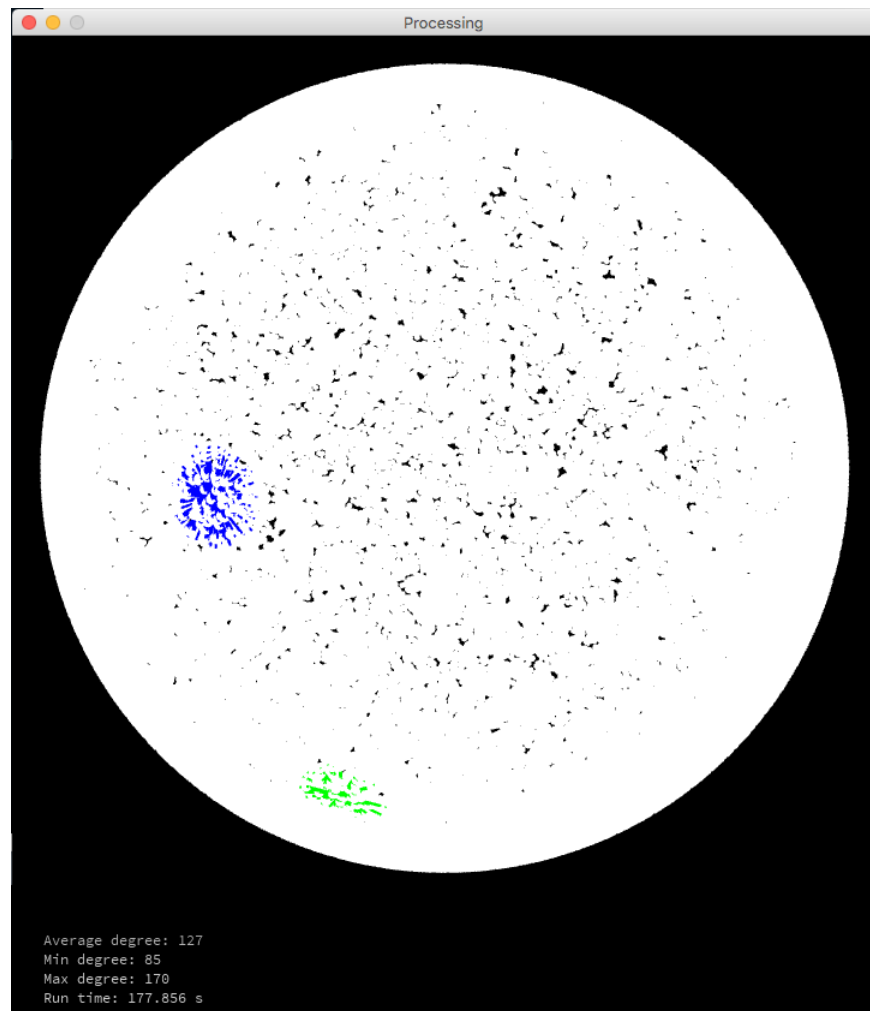


Figure 18: Sphere Benchmark Number 3. 64000 Nodes, Average Degree of 128

4 Appendix B - Code Listings

Listing 1: Processing driver

```
1 import random
2 import time
3 import math
4 from objects.topology import Square, Disk, Sphere
5
6 CANVAS_HEIGHT = 720
7 CANVAS_WIDTH = 720
8
9 NUMNODES = 1000
10 AVG_DEG = 16
11
12 MAX_NODES_TO_DRAW_EDGES = 8000
13
14 RUN_BENCHMARK = False
15
16 def setup():
17     size(CANVAS_WIDTH, CANVAS_HEIGHT, P3D)
18     background(0)
19
20 def draw():
21     topology.drawGraph(MAX_NODES_TO_DRAW_EDGES)
22
23 def main():
24     global topology
25     topology = Square()
26     # topology = Disk()
27     # topology = Sphere()
28
29     topology.num_nodes = NUMNODES
30     topology.avg_deg = AVG_DEG
31     topology.canvas_height = CANVAS_HEIGHT
32     topology.canvas_width = CANVAS_WIDTH
33
34     if RUN_BENCHMARK:
35         n_benchmark = 0
36         topology.prepBenchmark(n_benchmark)
37
38     run_time = time.clock()
39
40     topology.generateNodes()
41     topology.findEdges(method="sweep")
42     topology.colorGraph()
43
44     print "Average degree: {}".format(topology.findAvgDegree())
45     print "Min degree: {}".format(topology.getMinDegree())
46     print "Max degree: {}".format(topology.getMaxDegree())
47
48     run_time = time.clock() - run_time
49     print "Run time: {0:.3f} s".format(run_time)
50
51 main()
```

Listing 2: Topology class and subclasses

```
1 import random
2 import math
3
4 # benchmarks (num_nodes, avg_deg)
5 SQUARE_BENCHMARKS = [(1000,32), (8000,64), (16000,32), (64000,64), (64000,128),
6                       (128000,64), (128000,128)]
7 DISK_BENCHMARKS = [(8000,64), (64000,64), (64000,128)]
8 SPHERE_BENCHMARKS = [(16000,64), (32000,128), (64000,128)]
9
10 """
```



```

11 Topology – super class for the shape of the random geometric graph
12 """
13 class Topology(object):
14
15     num_nodes = 100
16     avg_deg = 0
17     canvas_height = 720
18     canvas_width = 720
19
20     def __init__(self):
21         self.nodes = []
22         self.edges = {}
23         self.node_r = 0.0
24         self.minDeg = ()
25         self.maxDeg = ()
26
27     # public function for generating nodes of the graph, must be subclassed
28     def generateNodes(self):
29         print "Method for generating nodes not subclassed"
30
31     # public function for finding edges
32     def findEdges(self, method="brute"):
33         self._getRadiusForAverageDegree()
34         self._addNodesAsEdgeKeys()
35
36         if method == "brute":
37             self._bruteForceFindEdges()
38         elif method == "sweep":
39             self._sweepFindEdges()
40         elif method == "cell":
41             self._cellFindEdges()
42         else:
43             print "Find edges method not defined: {}".format(method)
44
45         self._findMinAndMaxDegree()
46
47     # brute force edge detection
48     def _bruteForceFindEdges(self):
49         for n in self.nodes:
50             for m in self.nodes:
51                 if n != m and self._distance(n, m) <= self.node_r:
52                     self.edges[n].append(m)
53
54     # sweep edge detection (2D)
55     def _sweepFindEdges(self):
56         self.nodes.sort(key=lambda x: x[0])
57
58         for i, n in enumerate(self.nodes):
59             search_space = []
60             for j in range(1, i+1):
61                 if abs(n[0] - self.nodes[i-j][0]) <= self.node_r:
62                     search_space.append(self.nodes[i-j])
63             else:
64                 break
65             for j in range(1, self.num_nodes-i):
66                 if abs(n[0] - self.nodes[i+j][0]) <= self.node_r:
67                     search_space.append(self.nodes[i+j])
68             else:
69                 break
70             for m in search_space:
71                 if self._distance(n, m) <= self.node_r:
72                     self.edges[n].append(m)
73
74     # cell edge detection (2D)
75     def _cellFindEdges(self):
76         num_cells = int(1/self.node_r) + 1
77         cells = []
78         for i in range(num_cells):

```

```

79         cells.append([[j for j in range(num_cells)])
80
81     for n in self.nodes:
82         cells[int(n[0]/self.node_r)][int(n[1]/self.node_r)].append(n)
83
84     for i in range(num_cells):
85         for j in range(num_cells):
86             for n in cells[i][j]:
87                 for c in self._findAdjCells(i, j, num_cells):
88                     for m in cells[c[0]][c[1]]:
89                         if n != m and self._distance(n, m) <= self.node_r:
90                             self.edges[n].append(m)
91
92     # cell edge detection helper function (2D)
93     def _findAdjCells(self, i, j, n):
94         result = []
95         xRange = [(i-1)%n, i, (i+1)%n]
96         yRange = [(j-1)%n, j, (j+1)%n]
97         for x in xRange:
98             for y in yRange:
99                 result.append((x,y))
100
101     return result
102
103     # function for finding the radius needed for the desired average degree
104     # must be subclassed
105     def _getRadiusForAverageDegree(self):
106         print "Method for finding necessary radius for average degree not
107         subclassed"
108
109     # helper function for findEdges, initializes edges dict
110     def _addNodesAsEdgeKeys(self):
111         self.edges = dict((n, []) for n in self.nodes)
112
113     # calculates the distance between two nodes (2D)
114     def _distance(self, n, m):
115         return math.sqrt((n[0] - m[0])**2+(n[1] - m[1])**2)
116
117     # public function for finding the average degree of nodes
118     def findAvgDegree(self):
119         sigma_degree = 0
120         for k in self.edges.keys():
121             sigma_degree += len(self.edges[k])
122
123         return sigma_degree/len(self.edges.keys())
124
125     # helper function for finding nodes with min and max degree
126     def _findMinAndMaxDegree(self):
127         self.minDeg = self.edges.keys()[0]
128         self.maxDeg = self.edges.keys()[0]
129
130         for k in self.edges.keys():
131             if len(self.edges[k]) < len(self.edges[self.minDeg]):
132                 self.minDeg = k
133             if len(self.edges[k]) > len(self.edges[self.maxDeg]):
134                 self.maxDeg = k
135
136     # public function for getting the minimum degree
137     def getMinDegree(self):
138         return len(self.edges[self.minDeg])
139
140     # public function for getting the maximum degree
141     def getMaxDegree(self):
142         return len(self.edges[self.maxDeg])
143
144     # public function for setting up the benchmark to run, must be subclassed
145     def prepBenchmark(self, n):
146         print "Method for preparing benchmark not subclassed"

```

```

146
147 # public function for drawing the graph
148 def drawGraph(self, n_limit):
149     self._drawNodes()
150     if self.num_nodes <= n_limit:
151         self._drawEdges()
152     else:
153         self._drawMinMaxDegNodes()
154
155 # responsible for drawing the nodes in the canvas
156 def _drawNodes(self):
157     strokeWeight(2)
158     stroke(255)
159     fill(255)
160
161     for n in range(self.num_nodes):
162         ellipse(self.nodes[n][0]*self.canvas_width, self.nodes[n][1]*self.
canvas_height, 5, 5)
163
164 # responsible for drawing the edges in the canvas
165 def _drawEdges(self):
166     strokeWeight(1)
167     stroke(245)
168     fill(255)
169
170     for n in self.edges.keys():
171         for m in self.edges[n]:
172             line(n[0]*self.canvas_width, n[1]*self.canvas_height, m[0]*self.
canvas_width, m[1]*self.canvas_height)
173
174 # responsible for drawing the edges of the min and max degree nodes
175 def _drawMinMaxDegNodes(self):
176     strokeWeight(1)
177     stroke(0,255,0)
178     fill(255)
179     for n in self.edges[self.minDeg]:
180         line(self.minDeg[0]*self.canvas_width, self.minDeg[1]*self.
canvas_height, n[0]*self.canvas_width, n[1]*self.canvas_height)
181
182     stroke(0,0,255)
183     for n in self.edges[self.maxDeg]:
184         line(self.maxDeg[0]*self.canvas_width, self.maxDeg[1]*self.
canvas_height, n[0]*self.canvas_width, n[1]*self.canvas_height)
185
186 # uses smallest last vertex ordering to color the graph
187 def colorGraph(self):
188     self.s_last = self._smallestLastVertexOrdering()
189     print "Terminal clique size:", self.term_clique_size
190
191     self.node_colors = self._assignNodeColors(self.s_last)
192     print "Number of colors:", len(set(self.node_colors))
193
194 # constructs a degree structure and determines the smallest last vertex
ordering
195 def _smallestLastVertexOrdering(self):
196     deg_list = [[] for _ in range(len(self.edges[self.maxDeg])+1)]
197
198     for n in self.nodes:
199         deg_list[len(self.edges[n])].append(n)
200
201     smallest_last_ordering = []
202
203     clique_found = False
204     j = len(self.nodes)
205     while j > 0:
206         # get the current smallest bucket
207         curr_bucket = 0
208         while curr_bucket < len(deg_list) and len(deg_list[curr_bucket]) == 0:

```

```

209         curr_bucket += 1
210
211     # if all the remaining nodes are connected we have the terminal clique
212     if not clique_found and len(deg_list[curr_bucket]) == j:
213         clique_found = True
214         smallest_last_ordering.extend(deg_list[curr_bucket])
215         self.term_clique_size = curr_bucket
216
217     # get node with smallest degree
218     v = deg_list[curr_bucket].pop()
219     smallest_last_ordering.append(v)
220
221     # decrement position of nodes that shared an edge with v
222     for n in self.edges[v]:
223         for i in range(len(deg_list)):
224             to_decrement = True
225             try:
226                 deg_list[i].remove(n)
227             except:
228                 to_decrement = False
229
230             if to_decrement:
231                 deg_list[i-1].append(n)
232
233     j -= 1
234
235     # reverse list since it was built shortest-first
236     return smallest_last_ordering[::-1]
237
238 # assigns the colors to nodes given in a smallest-last vertex ordering as a
239 # parallel array
240 def _assignNodeColors(self, s_last):
241     colors = [0 for _ in range(len(s_last))]
242     for i in range(1, len(s_last)):
243         adj_colors = [colors[j] for j in range(i) if s_last[j] in self.edges[
244             s_last[i]]]
245         color = 0
246         while color in adj_colors:
247             color += 1
248         colors[i] = color
249
250     return colors
251
252 """
253 Square — inherits from Topology, overloads generateNodes and
254 _getRadiusForAverageDegree
255 for a unit square topology
256 """
257 class Square(Topology):
258
259     def __init__(self):
260         super(Square, self).__init__()
261
262     # places nodes uniformly in a unit square
263     def generateNodes(self):
264         for i in range(self.num_nodes):
265             self.nodes.append((random.uniform(0,1), random.uniform(0,1)))
266
267     # calculates the radius needed for the requested average degree in a unit
268     # square
269     def _getRadiusForAverageDegree(self):
270         self.node_r = math.sqrt(self.avg_deg/(self.num_nodes * math.pi))
271
272     # gets benchmark setting for square
273     def prepBenchmark(self, n):
274         self.num_nodes = SQUARE_BENCHMARKS[n][0]
275         self.avg_deg = SQUARE_BENCHMARKS[n][1]

```

```

273 """
274 Disk – inherits from Topology, overloads generateNodes and
      _getRadiusForAverageDegree
275 for a unit circle topology
276 """
277 class Disk(Topology):
278
279     def __init__(self):
280         super(Disk, self).__init__()
281
282     # places nodes uniformly in a unit square and regenerates the node if it falls
283     # outside of the circle
284     def generateNodes(self):
285         for i in range(self.num_nodes):
286             p = (random.uniform(0,1), random.uniform(0,1))
287             while self._distance(p, (0.5,0.5)) > 0.5:
288                 p = (random.uniform(0,1), random.uniform(0,1))
289             self.nodes.append(p)
290
291     # calculates the radius needed for the requested average degree in a unit
292     # circle
293     def _getRadiusForAverageDegree(self):
294         self.node_r = math.sqrt((self.avg_deg + 0.0)/self.num_nodes)/2
295
296     # gets benchmark setting for disk
297     def prepBenchmark(self, n):
298         self.num_nodes = DISK_BENCHMARKS[n][0]
299         self.avg_deg = DISK_BENCHMARKS[n][1]
300 """
301 Sphere – inherits from Topology, overloads generateNodes,
      _getRadiusForAverageDegree,
302 and _distance for a unit sphere topology. Also updates the drawGraph function for
303 a 3D canvas
304 """
305 class Sphere(Topology):
306
307     # adds rotation and node limit variables
308     def __init__(self):
309         super(Sphere, self).__init__()
310         self.rot = (0,math.pi/4,0) # this may move to Topology if rotation is
311         # used to control _drawNodes functionality
312         self.n_limit = 8000
313
314     # places nodes in a unit cube and projects them onto the surface of the sphere
315     def generateNodes(self):
316         for i in range(self.num_nodes):
317             # equations for uniformly distributing nodes on the surface area of
318             # a sphere: http://mathworld.wolfram.com/SpherePointPicking.html
319             u = random.uniform(-1,1)
320             theta = random.uniform(0, 2*math.pi)
321             p = (
322                 math.sqrt(1 - u**2) * math.cos(theta),
323                 math.sqrt(1 - u**2) * math.sin(theta),
324                 u
325             )
326             self.nodes.append(p)
327
328     # overrides cell for 3D topology, uses 3D mesh of buckets
329     def _cellFindEdges(self):
330         num_cells = int(1/self.node_r) + 1
331         cells = []
332         for i in range(num_cells):
333             cells.append([[] for k in range(num_cells)] for j in range(num_cells)
334 ])
335
336         for n in self.nodes:

```

```

336         cells[int(n[0]/self.node_r)][int(n[1]/self.node_r)][int(n[2]/self.
node_r)].append(n)
337
338     for i in range(num_cells):
339         for j in range(num_cells):
340             for k in range(num_cells):
341                 for n in cells[i][j][k]:
342                     for c in self._findAdjCells(i, j, k, num_cells):
343                         for m in cells[c[0]][c[1]][c[2]]:
344                             if n != m and self._distance(n, m) <= self.node_r:
345                                 self.edges[n].append(m)
346
347     # overrides adjacent cell finding for 3x3 surrounding buckets
348     def _findAdjCells(self, i, j, k, n):
349         result = []
350         xRange = [(i-1)%n, i, (i+1)%n]
351         yRange = [(j-1)%n, j, (j+1)%n]
352         zRange = [(k-1)%n, k, (k+1)%n]
353         for x in xRange:
354             for y in yRange:
355                 for z in zRange:
356                     result.append((x,y,z))
357
358     return result
359
360     # calculates the radius needed for the requested average degree in a unit
sphere
361     def _getRadiusForAverageDegree(self):
362         self.node_r = math.sqrt((self.avg_deg + 0.0)/self.num_nodes)*2
363
364     # calculates the distance between two nodes (3D)
365     def _distance(self, n, m):
366         return math.sqrt((n[0] - m[0])**2+(n[1] - m[1])**2+(n[2] - m[2])**2)
367
368     # gets benchmark setting for sphere
369     def prepBenchmark(self, n):
370         self.num_nodes = SPHERE_BENCHMARKS[n][0]
371         self.avg_deg = SPHERE_BENCHMARKS[n][1]
372
373     # public function for drawing graph, updates node limit if necessary
374     def drawGraph(self, n_limit):
375         self.n_limit = n_limit
376         self._drawNodesAndEdges()
377
378     # responsible for drawing nodes and edges in 3D space
379     def _drawNodesAndEdges(self):
380         # positions camera
381         camera(self.canvas_width/2, self.canvas_height/2, self.canvas_width*-2,
0.5,0.5,0, 0,1,0)
382
383         # updates rotation
384         self.rot = (self.rot[0], self.rot[1]-math.pi/100, self.rot[2])
385
386         background(0)
387         strokeWeight(2)
388         stroke(255)
389         fill(255)
390
391         for n in range(self.num_nodes):
392             pushMatrix()
393
394             # sets new rotation
395             rotateZ(self.rot[2])
396             rotateY(-1*self.rot[1])
397
398             # sets drawing origin to current node
399             translate((self.nodes[n][0])*self.canvas_width, (self.nodes[n][1])*
self.canvas_height, (self.nodes[n][2])*self.canvas_width)

```

```

400
401     # places ellipse at origin
402     ellipse(0, 0, 10, 10)
403
404     # draw all edges
405     if self.num_nodes <= self.n_limit:
406         for e in self.edges[self.nodes[n]]:
407             # draws line from origin to neighboring node
408             line(0,0,0, (e[0] - self.nodes[n][0])*self.canvas_width, (e[1]
- self.nodes[n][1])*self.canvas_height, (e[2] - self.nodes[n][2])*self.
canvas_width)
409         # draw edges for min degree node
410         elif self.nodes[n] == self.minDeg:
411             stroke(0,255,0)
412             for e in self.edges[self.nodes[n]]:
413                 # draws line from origin to neighboring node
414                 line(0,0,0, (e[0] - self.nodes[n][0])*self.canvas_width, (e[1]
- self.nodes[n][1])*self.canvas_height, (e[2] - self.nodes[n][2])*self.
canvas_width)
415             stroke(255)
416         # draw edges for max degree node
417         elif self.nodes[n] == self.maxDeg:
418             stroke(0,0,255)
419             for e in self.edges[self.nodes[n]]:
420                 # draws line from origin to neighboring node
421                 line(0,0,0, (e[0] - self.nodes[n][0])*self.canvas_width, (e[1]
- self.nodes[n][1])*self.canvas_height, (e[2] - self.nodes[n][2])*self.
canvas_width)
422             stroke(255)
423
424     popMatrix()

```