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CSCI 351-01 Data Communications and Networks
Programming Project 2 Report

1. Program Inputs, Program Objective, Program Outputs

Chirp.java

This program takes in a character for the type of graph to generate, the number of vertices (or crickets) and the number of time ticks to step through. Then depending on what graph type is used, the program takes in different parameters. When generating a single cycle graph, no further arguments are required to run the program. When generating a k-regular graph, an additional argument ***k***, must be supplied. When generating a scale-free graph, the change in entropy ***ΔE***, must be supplied. When generating a random graph, the edge probability ***p***, and seed value ***seed***, must be supplied. When generating a small-world graph, edge probability ***p***, a seed value ***seed***, and ***k*** must be included. Regardless of what graph type is used, the program simulates the cricket network as a graph of vertices connected to other vertices through unweighted, undirected edges. Each vertex represents a cricket, and each edge (connecting 2 vertices) represents the fact that 2 crickets are near each other. The program's objective is to explore how the topology of a network of chirping crickets effects chirp-synchronization. After the program ensures proper usage, it generates a single graph (according to the type specified), tells cricket number 0 to chirp at ***t=0***, simulates the number of time ticks and generates an image describing the result of the simulation.

2. Exact Command Line

Chirp.java

note: This program accepts numerous amounts of supplied command line arguments due to the differing number of necessary "knobs" needed for each kind of graph.

Cycle Graph Mode

`usage: java Chirp c <num crickets> <num ticks> <output image>`

`c`	- denotes "cycle graph" mode
`<num crickets>`	- number of crickets (vertices) in graph
`<num ticks>`	- number of time steps to simulate the network for
`<output image>`	- name of output image file describing the results

K-Regular Graph Mode

`usage: java Chirp k <num crickets> <num ticks> <output image> <k>`

`k`	- denotes "k-regular graph" mode

<num crickets>	- number of crickets (vertices) in graph
<num ticks>	- number of time steps to simulate the network for
<output image>	- name of output image file describing the results
<k>	- number of vertices to connect a given vertex to (on its left and right)

Scale-free Graph Mode

usage: java Chirp k <num crickets> <num ticks> <output image> <E>

f	- denotes “scale-free graph” mode
<num crickets>	- number of crickets (vertices) in graph
<num ticks>	- number of time steps to simulate the network for
<output image>	- name of output image file describing the results
<E>	- entropy cutoff in graph generation

Random Graph Mode

usage: java Chirp r <num crickets> <num ticks> <output image> <seed> <p>

r	- denotes “random graph” mode
<num crickets>	- number of crickets (vertices) in graph
<num ticks>	- number of time steps to simulate the network for
<output image>	- name of output image file describing the results
<seed>	- seed value for the Pseudorandom Number Generator
<p>	- edge probability of every pair of vertices

Small World Graph Mode

usage: java Chirp s <num crickets> <num ticks> <output image> <k> <seed> <p>

s	- denotes “small world graph” mode
<num crickets>	- number of crickets (vertices) in graph
<num ticks>	- number of time steps to simulate the network for
<output image>	- name of output image file describing the results
<k>	- the type of k-regular graph to mimic before edges are rewired
<seed>	- seed value for the Pseudorandom Number Generator
<p>	- rewiring probability for every edge in the k regular graph

3. Source Code *(See Appendix B for project’s source code)*

4. (Even number cycle graph) Do the networks synchronize? If so, how long do the networks take to synchronize? Why are the networks behaving in this fashion?

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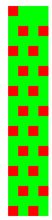
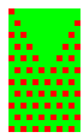
note: Some of the images are very small. When enlarged with Google Drive's image editor, the square pixels are smoothened out. The actual images generated by the program will contain squared off pixels. A green pixel represents a silent cricket, and a red pixel represents a cricket that chirped at that moment in time. Time starts at the top of each image and goes forward towards the bottom of the image.

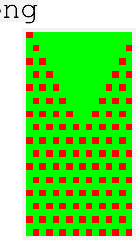
`java Chirp c 4 20 cycle-even-004.png` *- did not synchronize*



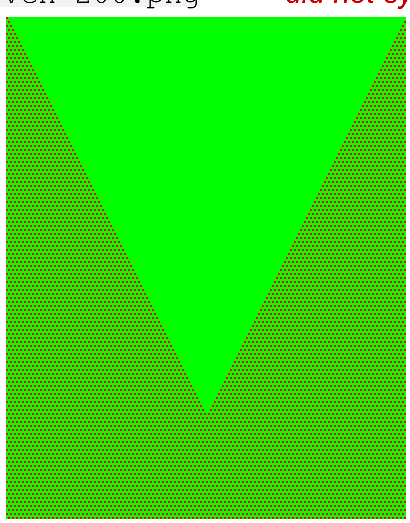
`java Chirp c 12 20 cycle-even-012.png` *- did not synchronize*



`java Chirp c 16 30 cycle-even-016.png` *- did not synchronize*



`java Chirp c 200 250 cycle-even-200.png` *- did not synchronize*



We can see from the images generated that any even amount of crickets that we try will not synchronize. This is due to the fact that an even amount of crickets means at no point will two adjacent crickets chirp at the same time. Consider the Cycle A -> B -> C -> D -> A, with an even amount of vertices. If A chirps at t=0, B and D will chirp at t=2. Then A and C will chirp at t=4, and B and D will chirp at t=6. Since the crickets that are chirping at the exact same time are not adjacent, the synchronization process cannot start. This holds true for any amount of even crickets in the cycle graph.

5. (Odd number cycle graph) Do the networks synchronize? If so, how long do the networks take to synchronize? Why are the networks behaving in this fashion?

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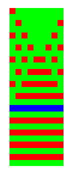
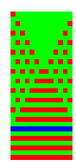
note: The blue horizontal line indicates the time at which the crickets synchronized.

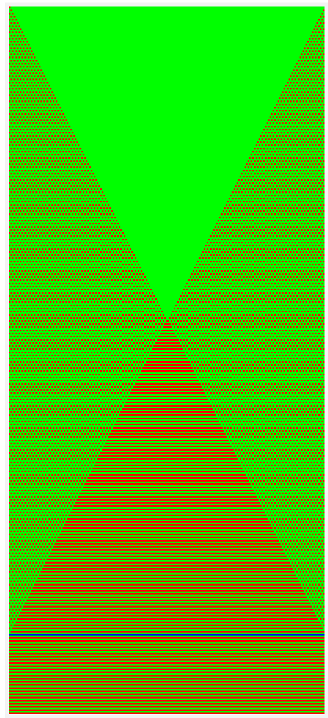
```
java Chirp c 9 25 cycle-odd-009.png
Cycle V = 9: synchronized at t=16.
```



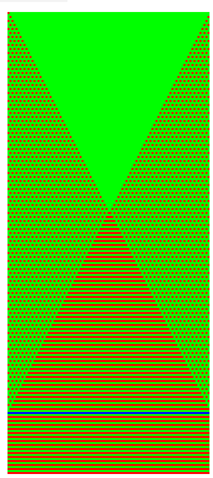
```
java Chirp c 13 30 cycle-odd-013.png
Cycle V = 13: synchronized at t=24.
```



```
java Chirp c 201 450 cycle-odd-201.png
Cycle V = 201: synchronized at t=400.
```



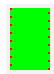
```
java Chirp c 101 230 cycle-odd-101.png
Cycle V = 101: synchronized at t=200.
```



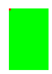
The crickets in every cycle graph with an odd number of vertices synchronizes according to the following equation $\textit{time to synchronize} = (\textit{number of crickets} - 1) * 2$. This is because it takes $(\textit{number of crickets} - 1)\ \textit{ticks}$ for the first chirp to spread to all the crickets in the network. (This is at the bottom of the “green triangle” in the above pictures.) At that point, 2 crickets are guaranteed to chirp at the same time. For instance, A -> B -> C -> A. When A chirps at t=0, B and C will chirp at t=2. Then A, B, and C will chirp at t=4. The initial chirp must travel all the way around the network, meet in the middle with 2 adjacent crickets chirping at the same time, and then travel all the way back to the beginning cricket.

6. (Random graph) Do the networks synchronize? If so, how long do the networks take to synchronize? Why are the networks behaving in this fashion?

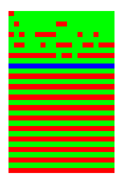
`java Chirp r 20 30 random-20-.08.png 15432 .08` *- did not synchronize*



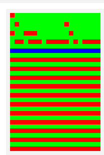
`java Chirp r 20 30 random-20-.1.png 12345 .1` *- did not synchronize*



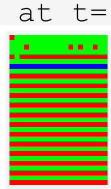
```
java Chirp r 20 30 random-20-.15.png 12359 .15
Random V = 20, p = 0.15: synchronized at t=10.
```



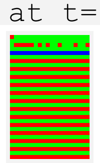
```
java Chirp r 20 30 random-20-.2.png 23451 .2
Random V = 20, p = 0.2: synchronized at t=8.
```



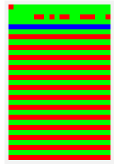
```
java Chirp r 20 30 random-20-.3.png 34512 .3
Random V = 20, p = 0.3: synchronized at t=6.
```



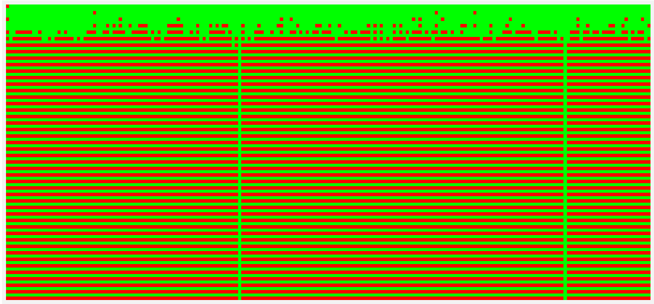
```
java Chirp r 20 30 random-20-.4.png 45123 .4
Random V = 20, p = 0.4: synchronized at t=4.
```



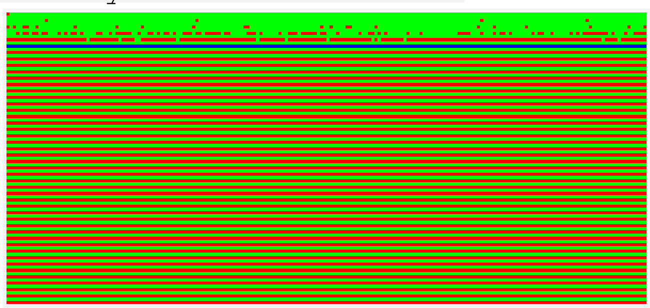
```
java Chirp r 20 30 random-20-.5.png 51234 .5
Random V = 20, p = 0.5: synchronized at t=4.
```



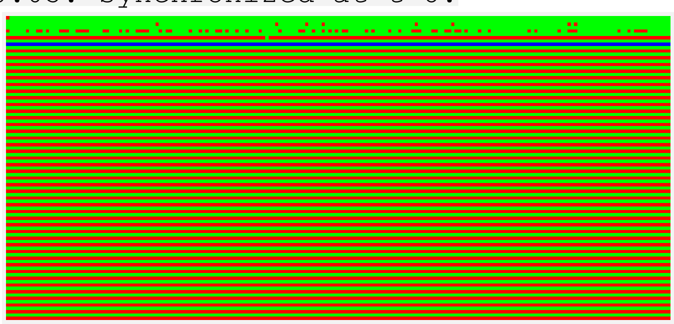
`java Chirp r 200 90 random-200-.02.png -321540 .02`   *- did not synchronize*



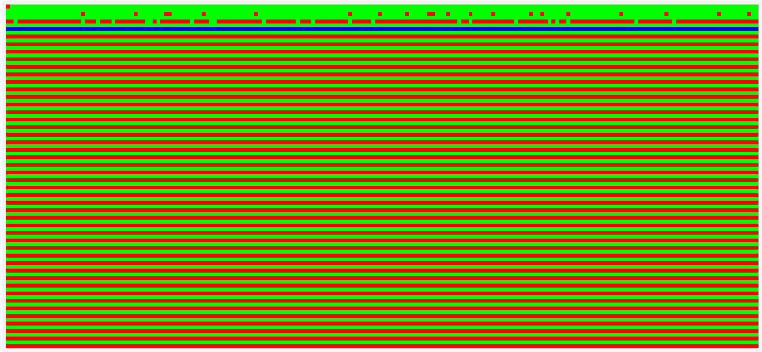
```
java Chirp r 200 90 random-200-.03.png -432150 .03
Random V = 200, p = 0.03: synchronized at t=10.
```



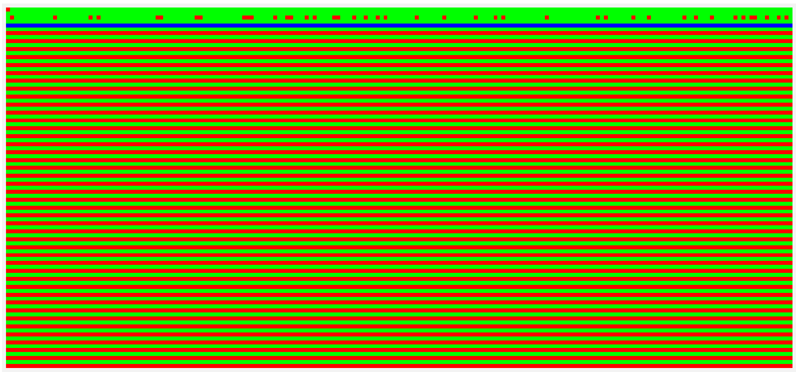
```
java Chirp r 200 90 random-200-.05.png -51234 .05
Random V = 200, p = 0.05: synchronized at t=8.
```



```
java Chirp r 200 90 random-200-.1.png 12345 .1
Random V = 200, p = 0.1: synchronized at t=6.
```



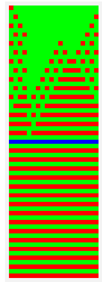
`java Chirp r 200 90 random-200-.2.png 23451 .2`
`Random V = 200, p = 0.2:    synchronized at t=4.`



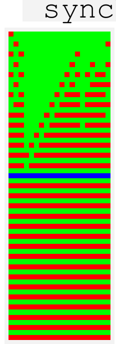
Depending on what parameters are used for random graphs, the crickets will usually synchronize, but not always. Some graphs can have vertices with no edges connected to them when *p* is low enough which means those crickets will never hear other crickets chirp so won't ever chirp themselves. When we have a small amount of crickets, like 20, a low edge probability will cause the crickets to take longer to synchronize. As we saw in the previous project, this combination of vertices and edge probability tends to yield graphs with longer average distances. The cycle graphs mentioned in the first two questions have a pretty high average distance compared to the rest of the graphs generated which is part of the reason those graphs took so long to synchronize, so introducing this aspect into random graphs will produce similar results. We see that the higher and higher edge probability we use with any amount of vertices will take less and less time. This is because we are increasing the connectivity of the graph and adding more and more edges. The more edges the graph has, the higher the chance is that 2 adjacent crickets will chirp at the same time. Once 2 adjacent crickets chirp, they will forever chirp since they are chirping and hearing the other person chirp at the same time. Meanwhile, while these infinitely chirping crickets chirp, their chirps "echo" outwards in the network.

7. (Small-world graph) Do the networks synchronize? If so, how long do the networks take to synchronize? Why are the networks behaving in this fashion?

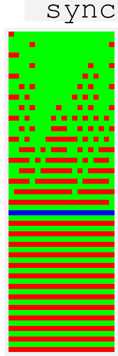
```
java Chirp s 20 60 small-20-k1-.1.png 1 23456 .1
Small-world V = 20, k = 1, p = 0.1:   synchronized at t=30.
```



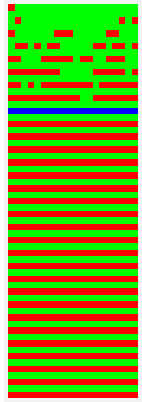
```
java Chirp s 20 60 small-20-k1-.2.png 1 34561 .2
Small-world V = 20, k = 1, p = 0.2:   synchronized at t=28.
```



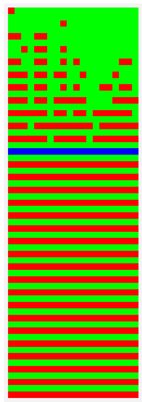
```
java Chirp s 20 60 small-20-k1-.5.png 1 62345 .5
Small-world V = 20, k = 1, p = 0.5:   synchronized at t=34.
```



```
java Chirp s 20 60 small-20-k1-.5n2.png 1 -92245 .5
Small-world V = 20, k = 1, p = 0.5:   synchronized at t=16.
```

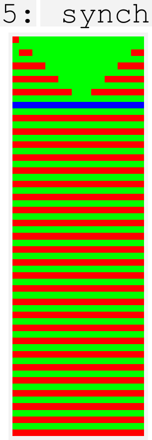


```
java Chirp s 20 60 small-20-k1-.8.png 1 43260 .8
Small-world V = 20, k = 1, p = 0.8:   synchronized at t=22.
```



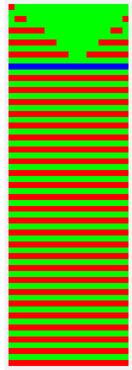
The above graphs begin producing patterns similar to the cycle graph. This is because they are near-k-regular graphs where k=1. The cycle graphs are k-regular where k=1. Looking at the resulting synchronization times, these kinds of graphs don't show a consistent pattern. We see that 2 different trials where k=1 and p=0.5 produce synchronization times of 16 and 34. The element of randomness introduced into the graph is responsible for this and the fact that the graphs are so sparse.

```
java Chirp s 20 60 small-20-k2-.025.png 2 234562 .025
Small-world V = 20, k = 2, p = 0.025: synchronized at t=10.
```



```
java Chirp s 20 60 small-20-k2-.05.png 2 234561 .05
```

Small-world V = 20, k = 2, p = 0.05: synchronized at t=10.

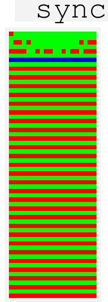


java Chirp s 20 60 small-20-k2-.1.png 2 234560 .1

Small-world V = 20, k = 2, p = 0.1: synchronized at t=8.

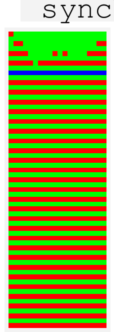
java Chirp s 20 60 small-20-k2-.2.png 2 345610 .2

Small-world V = 20, k = 2, p = 0.2: synchronized at t=6.



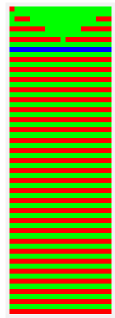
java Chirp s 20 60 small-20-k2-.3.png 2 456230 .3

Small-world V = 20, k = 2, p = 0.3: synchronized at t=8.



java Chirp s 20 60 small-20-k3-.025.png 3 234562 .025

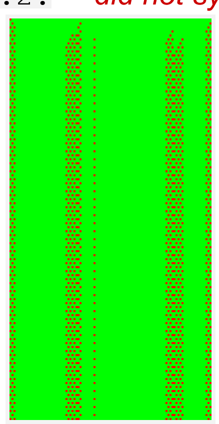
Small-world V = 20, k = 3, p = 0.025: synchronized at t=8.



```
java Chirp s 20 60 small-20-k3-.3.png 3 456230 .3
Small-world V = 20, k = 3, p = 0.3:   synchronized at t=6.
```

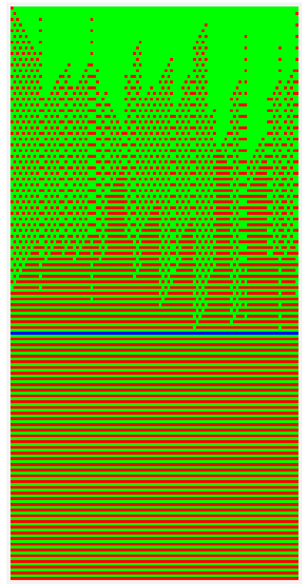
We see that increasing k lowers the synchronization time. This is because we are drastically increasing the number of edges in the graph. Increasing rewire probability, *p*, also decreases the sync time because of the added entropy into the graph. If rewire probability is low, we are left with a graph that is similar to a cycle graph, and as we saw, those took very long to synchronize. But when we mix a few edges around, it increases entropy and instead of the initial chirp having to wait for the effect to propagate around the entire cycle, a rewired edge can short circuit this chirp to the other side of the cycle and decrease sync time.

```
java Chirp s 101 200 small-101-k1-.2.png 1 34561 .2
Small-world V = 101, k = 1, p = 0.2:
```
- did not synchronize

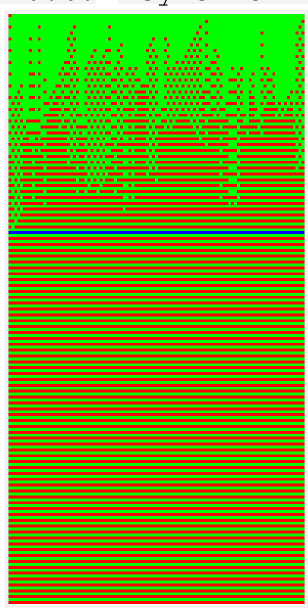


The network here did not synchronize due to the limited connectivity of the graph.

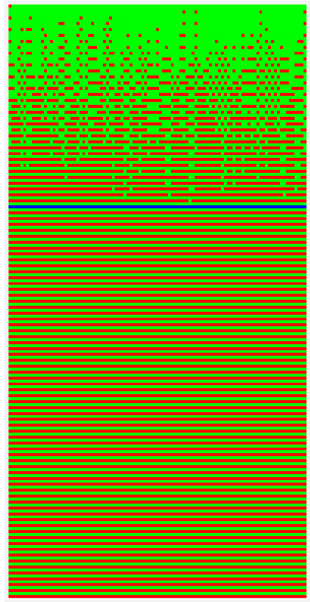
```
java Chirp s 101 200 small-101-k1-.3.png 1 45623 .3
Small-world V = 101, k = 1, p = 0.3:  synchronized at t=114.
```



java Chirp s 101 200 small-101-k1-.6.png 1 65423 .6
Small-world V = 101, k = 1, p = 0.6: synchronized at t=74.

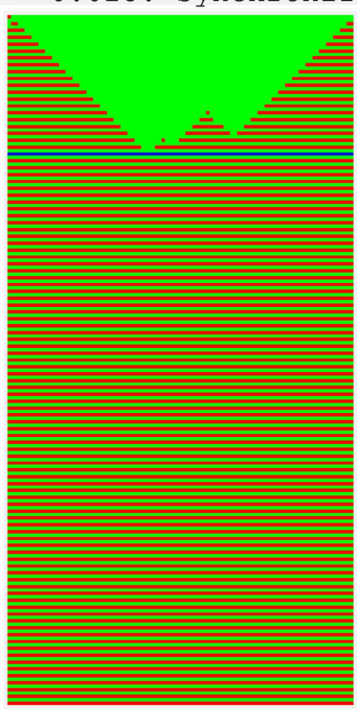


java Chirp s 101 200 small-101-k1-.9.png 1 32645 .9
Small-world V = 101, k = 1, p = 0.9: synchronized at t=68.

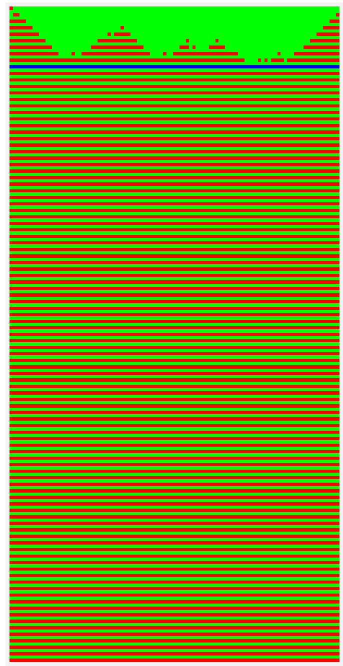


Above, we see the same effect we talked about with k=1 amplified with more vertices. The more edges we rewire, the more entropy we introduce into the network which decreases sync time because we increase the chances that 2 or more adjacent crickets will begin chirping at the same time.

```
java Chirp s 101 200 small-101-k2-.025.png 2 234562 .025
Small-world V = 101, k = 2, p = 0.025: synchronized at t=40.
```

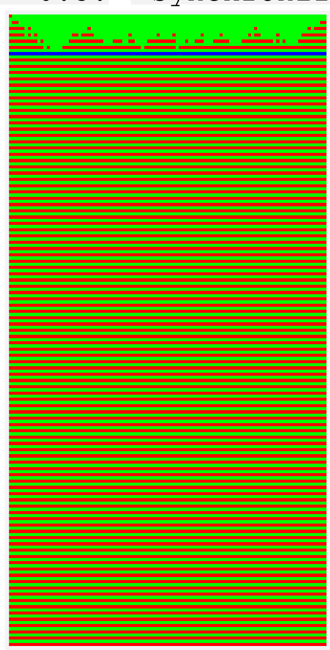


```
java Chirp s 101 200 small-101-k2-.05.png 2 234561 .05
Small-world V = 101, k = 2, p = 0.05:  synchronized at t=18.
```



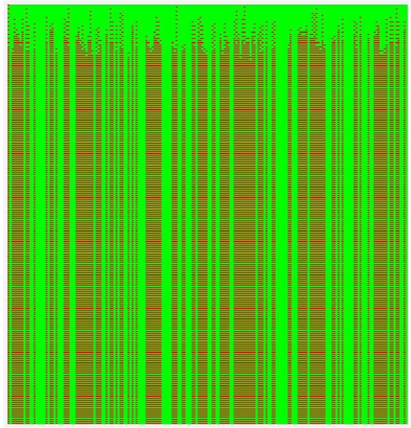
`java Chirp s 101 200 small-101-k2-.3.png 2 456230 .3`

`Small-world V = 101, k = 2, p = 0.3:` `synchronized at t=12.`



`java Chirp s 200 400 small-200-k1-.9.png 1 32645 .9`

`Small-world V = 200, k = 1, p = 0.9:` *- did not synchronize*



```
java Chirp s 200 400 small-200-k1-1.png 1 26543 1
Small-world V = 200, k = 1, p = 1.0:  synchronized at t=112.
```

8. (Scale-free graph) Do the networks synchronize? If so, how long do the networks take to synchronize? Why are the networks behaving in this fashion?

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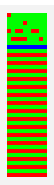
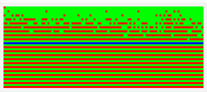
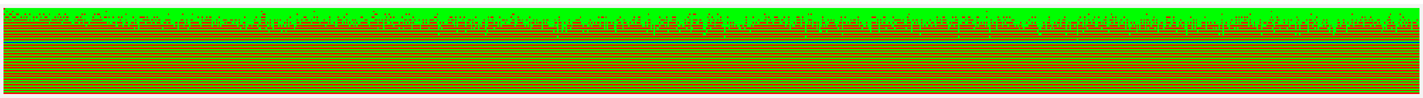
note: Some of these images are too large to include in this report.

```
java Chirp f 10 40 scale-free-10-1.png 1 19429
java Chirp f 100 40 scale-free-100-1.png 1 23456
java Chirp f 1000 60 scale-free-1000-1.png 1 238910
java Chirp f 10000 60 scale-free-10000-1.png 1 1938
```

```
Scale-free V = 10, dE = 1:        synchronized at t=8.
Scale-free V = 100, dE = 1:       synchronized at t=18.
Scale-free V = 1000, dE = 1:      synchronized at t=24.
Scale-free V = 10000, dE = 1:     synchronized at t=32.
```

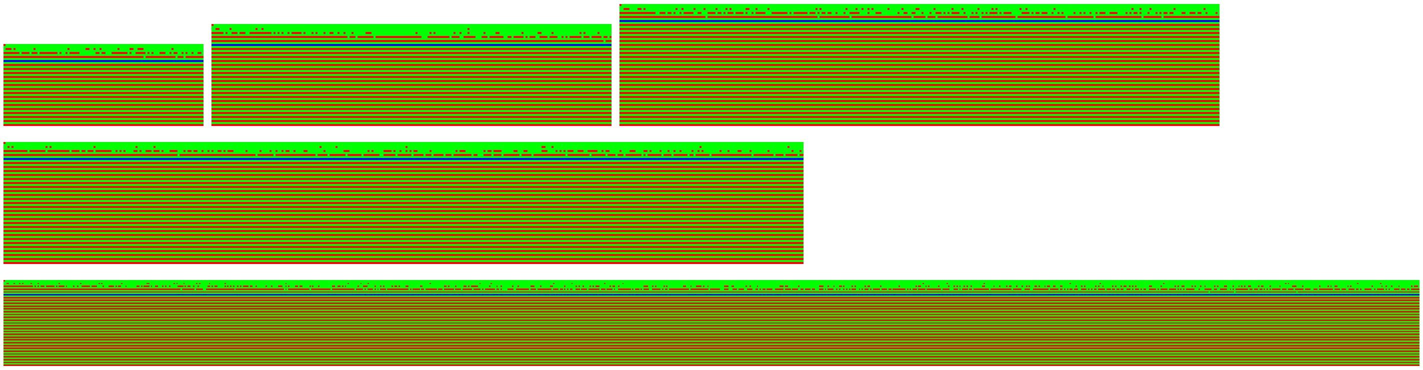





Observe an interesting phenomenon above. When dE is 1 and V is increased by a power of 10, the time to synchronize increases nearly linearly. Recall that Scale-free graphs produce some vertices that are hubs. A hub is a vertex with a relatively large number of edges connected to it. When dE is 1, there are only *V* edges added to the graph. This means the average distance from a vertex (that is not a hub) to a hub is longer compared to a Scale-free graph with a higher dE value. Chirps will therefore take longer to reach a hub the higher *V* is because the ratio of hubs to non-hubs decreases as *V* increases. It's not hard to realize that once a hub cricket hears a chirp and chirps 2 ticks later, that chirp will reach a large percentage of the network. Since the ratio of hubs to regular vertices decreases as *V* increases, paths to these hubs will be longer with larger *V* values, thus taking more time to synchronize since the key to synchronizing a scale-free graph is to get some of the hubs chirping.

```
java Chirp f 100 40 scale-free-100-2.png 2 34567
java Chirp f 200 50 scale-free-200-2.png 2 02341
java Chirp f 300 60 scale-free-300-2.png 2 43829
java Chirp f 400 60 scale-free-400-2.png 2 33939
java Chirp f 1000 60 scale-free-1000-2.png 2 100283
```

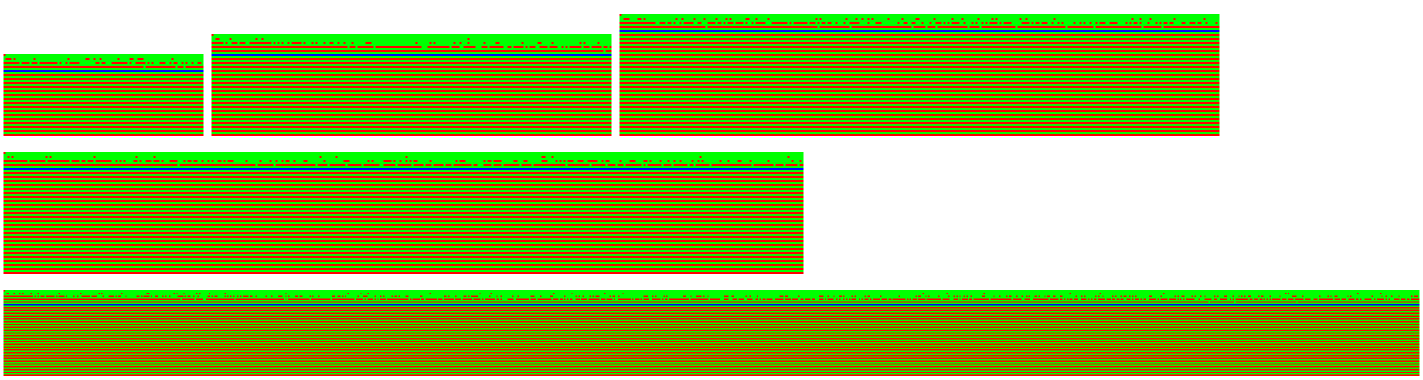
```
Scale-free V = 100, dE = 2:       synchronized at t=8.
Scale-free V = 200, dE = 2:       synchronized at t=8.
Scale-free V = 300, dE = 2:       synchronized at t=8.
Scale-free V = 400, dE = 2:       synchronized at t=10.
Scale-free V = 1000, dE = 2:      synchronized at t=10.
```



When dE is 2, we add approximately $V * 2$ edges to the graph. This means the average distance of these graphs will be much shorter than the average distance in a dE = 1 graph. The shorter the average distance is, the sooner a hub will chirp which means the sooner the network will synchronize. This is why we see a drastically lower synchronization time for dE = 2 than we did with dE = 1.

```
java Chirp f 100 40 scale-free-100-3.png 3 45678
java Chirp f 200 50 scale-free-200-3.png 3 34120
java Chirp f 300 60 scale-free-300-3.png 3 38294
java Chirp f 400 60 scale-free-400-3.png 3 39393
java Chirp f 1000 60 scale-free-1000-3.png 3 108392
java Chirp f 10000 12 scale-free-10000-3.png 3 19928
java Chirp f 50000 20 scale-free-50000-3.png 3 814832
```

```
Scale-free V = 100, dE = 3:       synchronized at t=8.
Scale-free V = 200, dE = 3:       synchronized at t=8.
Scale-free V = 300, dE = 3:       synchronized at t=6.
Scale-free V = 400, dE = 3:       synchronized at t=8.
Scale-free V = 1000, dE = 3:      synchronized at t=8.
Scale-free V = 10000, dE = 3:     synchronized at t=8.
Scale-free V = 50000, dE = 3:     synchronized at t=10.
```



We observe even smaller synchronization times for dE = 3 for the same reason we did for dE = 2: more edges. These graphs have even shorter average distances which means hubs are found very quickly which causes the entire network to light up with chirps fairly quickly. The increase in dE will continue to produce graphs with a smaller and smaller synchronization time.

9. Compare and contrast the results from Questions 6–8. Discuss what is causing the differences in behavior between random, small-world, and scale-free graphs.

We saw that some random graphs produced relatively low synchronization times compared to small-world graphs and some scale-free graphs. We also saw that we are not guaranteed that the network will synchronize if the connectivity of the graph is too low. This is caused by having an edge probability that is too low causing some vertices to be left out of the graph.

In small-world graphs, depending on the parameters, k and p, the synchronization times were longer than random graphs in some cases and shorter in others. Like random graphs, we are not guaranteed that the graph will synchronize because the rewiring process can sever off a section of a graph and result in a disconnected graph. We saw that when $k = 1$, the small world graphs take exceptionally longer than other k values. These graphs also took longer than random graphs to synchronize. This is because the entropy in random graphs is much greater than small world graphs with low k values and low p values. Small world graphs with $k = 1$ are essentially cycles with a certain number of edges rewired (depending on p). The lower p is, the lower the entropy therefore increasing synchronization time.

With scale-free graphs, we observed guaranteed synchronization. This is due to the fact that all scale free graphs generated in this simulation have at least 1 cycle with an odd number of vertices (3 to be exact), and all scale-free graphs generated are fully connected. The method of scale-free graph generation we used guarantees this. We saw that with the odd numbered cycles in the questions earlier, they all synchronized. Since we know this sub-graph-cycle will synchronize, and every other node in the graph has a path to this synchronized sub-graph, the entire graph will synchronize. Scale-free graphs have hubs which spread out chirps quickly once they're reached; random graphs & small-world graphs do not have hubs.

The major differences in behavior between random, small-world, and scale-free graphs is the underlying topology. Small-world graphs are composed of a cycle with a certain number of "short-cuts" or rewired edges and synchronize quicker than regular cycles because of these shortcuts. Scale-free graphs synchronize quickly once their hubs are reached because of the numerous connections in these hubs. Most of the random graphs we studied synchronized as long as they were connected enough, and depended on having a shorter average distance of the graph for quicker network synchronization.

10. Write a paragraph describing what you learned from this project.

I learned that the kind of graph used to simulate network synchronization drastically affects the outcome of the synchronization behavior. Small-world graphs are relatively efficient (compared to other graphs studied in this project) in network synchronization in terms of the maximum vertex degree of the graph and the time needed to synchronize. I gained an appreciation for small-world graphs in how they accurately model some real world applications. Websites can be described by using scale-free graphs where search engines like Google and news sites are hubs and other pages like blogs or recipe sites are non-hubs and edges represent a website containing a link or info about another page/website on the internet.

Appendix A (Output):

```
#####################################
# CRICKET CHIRPING AUTOMATION FILE  #
#####################################
# author: Jimi Ford
# version: 3-12-15
#####################################
# EVEN NUMBER VERTICES CYCLE GRAPHS #
#####################################

Cycle V = 2:  did not synchronize.
Cycle V = 4:  did not synchronize.
Cycle V = 6:  did not synchronize.
Cycle V = 8:  did not synchronize.
Cycle V = 10: did not synchronize.
Cycle V = 12: did not synchronize.
Cycle V = 14: did not synchronize.
Cycle V = 16: did not synchronize.
Cycle V = 200:      did not synchronize.

####################################
# ODD NUMBER VERTICES CYCLE GRAPHS #
####################################

Cycle V = 3:  synchronized at t=4.
Cycle V = 5:  synchronized at t=8.
Cycle V = 7:  synchronized at t=12.
Cycle V = 9:  synchronized at t=16.
Cycle V = 11: synchronized at t=20.
Cycle V = 13: synchronized at t=24.
Cycle V = 15: synchronized at t=28.
Cycle V = 101:      synchronized at t=200.
Cycle V = 201:      synchronized at t=400.

#################
# RANDOM GRAPHS #
#################

############## 20 CRICKETS #############
```

```
Random V = 20, p = 0.07:    did not synchronize.
Random V = 20, p = 0.08:    did not synchronize.
Random V = 20, p = 0.09:    did not synchronize.
Random V = 20, p = 0.1:     did not synchronize.
Random V = 20, p = 0.15:    synchronized at t=10.
Random V = 20, p = 0.2:     synchronized at t=8.
Random V = 20, p = 0.3:     synchronized at t=6.
Random V = 20, p = 0.4:     synchronized at t=4.
Random V = 20, p = 0.5:     synchronized at t=4.
Random V = 20, p = 0.6:     synchronized at t=4.
Random V = 20, p = 0.7:     synchronized at t=4.
Random V = 20, p = 0.8:     synchronized at t=4.
Random V = 20, p = 0.9:     synchronized at t=4.
Random V = 20, p = 1.0:     synchronized at t=4.

############# 200 CRICKETS #############

Random V = 200, p = 0.02:   did not synchronize.
Random V = 200, p = 0.03:   synchronized at t=10.
Random V = 200, p = 0.04:   synchronized at t=10.
Random V = 200, p = 0.05:   synchronized at t=8.
Random V = 200, p = 0.06:   synchronized at t=6.
Random V = 200, p = 0.07:   synchronized at t=6.
Random V = 200, p = 0.08:   synchronized at t=6.
Random V = 200, p = 0.09:   synchronized at t=6.
Random V = 200, p = 0.1:    synchronized at t=6.
Random V = 200, p = 0.2:    synchronized at t=4.
Random V = 200, p = 0.3:    synchronized at t=4.
Random V = 200, p = 0.4:    synchronized at t=4.
Random V = 200, p = 0.5:    synchronized at t=4.

######################
# SMALL-WORLD GRAPHS #
######################

######## 20 CRICKETS | k=1 #############

Small-world V = 20, k = 1, p = 0.05:     synchronized at t=32.
Small-world V = 20, k = 1, p = 0.1:      synchronized at t=30.
Small-world V = 20, k = 1, p = 0.2:      synchronized at t=28.
Small-world V = 20, k = 1, p = 0.3:      synchronized at t=32.
Small-world V = 20, k = 1, p = 0.4:      synchronized at t=30.
Small-world V = 20, k = 1, p = 0.5:      synchronized at t=34.
Small-world V = 20, k = 1, p = 0.5:      synchronized at t=16.
Small-world V = 20, k = 1, p = 0.6:      synchronized at t=20.
Small-world V = 20, k = 1, p = 0.7:      synchronized at t=30.
Small-world V = 20, k = 1, p = 0.8:      synchronized at t=22.
Small-world V = 20, k = 1, p = 0.9:      synchronized at t=24.
Small-world V = 20, k = 1, p = 1.0:      synchronized at t=20.
```

```
######## 20 CRICKETS | k=2 #############

Small-world V = 20, k = 2, p = 0.025:    synchronized at t=10.
Small-world V = 20, k = 2, p = 0.05:     synchronized at t=10.
Small-world V = 20, k = 2, p = 0.1:      synchronized at t=8.
Small-world V = 20, k = 2, p = 0.2:      synchronized at t=6.
Small-world V = 20, k = 2, p = 0.3:      synchronized at t=8.
Small-world V = 20, k = 2, p = 0.4:      synchronized at t=8.
Small-world V = 20, k = 2, p = 0.5:      synchronized at t=6.
Small-world V = 20, k = 2, p = 0.6:      synchronized at t=10.
Small-world V = 20, k = 2, p = 0.7:      synchronized at t=8.
Small-world V = 20, k = 2, p = 0.8:      synchronized at t=6.
Small-world V = 20, k = 2, p = 0.9:      synchronized at t=6.
Small-world V = 20, k = 2, p = 1.0:      synchronized at t=8.

######## 20 CRICKETS | k=3 #############

Small-world V = 20, k = 3, p = 0.025:    synchronized at t=8.
Small-world V = 20, k = 3, p = 0.05:     synchronized at t=8.
Small-world V = 20, k = 3, p = 0.1:      synchronized at t=8.
Small-world V = 20, k = 3, p = 0.2:      synchronized at t=6.
Small-world V = 20, k = 3, p = 0.3:      synchronized at t=6.
Small-world V = 20, k = 3, p = 0.4:      synchronized at t=6.
Small-world V = 20, k = 3, p = 0.5:      synchronized at t=6.
Small-world V = 20, k = 3, p = 0.6:      synchronized at t=6.
Small-world V = 20, k = 3, p = 0.7:      synchronized at t=6.
Small-world V = 20, k = 3, p = 0.8:      synchronized at t=6.
Small-world V = 20, k = 3, p = 0.9:      synchronized at t=6.
Small-world V = 20, k = 3, p = 1.0:      synchronized at t=6.

######## 101 CRICKETS | k=1 #############

Small-world V = 101, k = 1, p = 0.1:     did not synchronize.
Small-world V = 101, k = 1, p = 0.2:     did not synchronize.
Small-world V = 101, k = 1, p = 0.3:     synchronized at t=114.
Small-world V = 101, k = 1, p = 0.4:     did not synchronize.
Small-world V = 101, k = 1, p = 0.5:     did not synchronize.
Small-world V = 101, k = 1, p = 0.6:     synchronized at t=74.
Small-world V = 101, k = 1, p = 0.7:     did not synchronize.
Small-world V = 101, k = 1, p = 0.8:     did not synchronize.
Small-world V = 101, k = 1, p = 0.9:     synchronized at t=68.
Small-world V = 101, k = 1, p = 1.0:     did not synchronize.

######## 101 CRICKETS | k=2 #############

Small-world V = 101, k = 2, p = 0.025:   synchronized at t=40.
Small-world V = 101, k = 2, p = 0.05:    synchronized at t=18.
Small-world V = 101, k = 2, p = 0.1:     synchronized at t=16.
Small-world V = 101, k = 2, p = 0.2:     synchronized at t=14.
Small-world V = 101, k = 2, p = 0.3:     synchronized at t=12.
```

```
Small-world V = 101, k = 2, p = 0.4:     synchronized at t=12.
Small-world V = 101, k = 2, p = 0.5:     synchronized at t=12.
Small-world V = 101, k = 2, p = 0.6:     synchronized at t=12.
Small-world V = 101, k = 2, p = 0.7:     synchronized at t=12.
Small-world V = 101, k = 2, p = 0.8:     synchronized at t=12.
Small-world V = 101, k = 2, p = 0.9:     synchronized at t=12.
Small-world V = 101, k = 2, p = 1.0:     synchronized at t=12.

######## 101 CRICKETS | k=3 #############

Small-world V = 101, k = 3, p = 0.025:   synchronized at t=24.
Small-world V = 101, k = 3, p = 0.05:    synchronized at t=12.
Small-world V = 101, k = 3, p = 0.1:     synchronized at t=14.
Small-world V = 101, k = 3, p = 0.2:     synchronized at t=10.
Small-world V = 101, k = 3, p = 0.3:     synchronized at t=8.
Small-world V = 101, k = 3, p = 0.4:     synchronized at t=8.
Small-world V = 101, k = 3, p = 0.5:     synchronized at t=8.
Small-world V = 101, k = 3, p = 0.6:     synchronized at t=8.
Small-world V = 101, k = 3, p = 0.7:     synchronized at t=8.
Small-world V = 101, k = 3, p = 0.8:     synchronized at t=8.
Small-world V = 101, k = 3, p = 0.9:     synchronized at t=10.
Small-world V = 101, k = 3, p = 1.0:     synchronized at t=8.


######## 200 CRICKETS | k=1 #############

Small-world V = 200, k = 1, p = 0.1:     did not synchronize.
Small-world V = 200, k = 1, p = 0.2:     did not synchronize.
Small-world V = 200, k = 1, p = 0.3:     did not synchronize.
Small-world V = 200, k = 1, p = 0.4:     did not synchronize.
Small-world V = 200, k = 1, p = 0.5:     did not synchronize.
Small-world V = 200, k = 1, p = 0.6:     did not synchronize.
Small-world V = 200, k = 1, p = 0.7:     did not synchronize.
Small-world V = 200, k = 1, p = 0.8:     did not synchronize.
Small-world V = 200, k = 1, p = 0.9:     did not synchronize.
Small-world V = 200, k = 1, p = 1.0:     synchronized at t=112.

######## 200 CRICKETS | k=2 #############

Small-world V = 200, k = 2, p = 0.025:   synchronized at t=58.
Small-world V = 200, k = 2, p = 0.05:    synchronized at t=22.
Small-world V = 200, k = 2, p = 0.1:     synchronized at t=22.
Small-world V = 200, k = 2, p = 0.2:     synchronized at t=16.
Small-world V = 200, k = 2, p = 0.3:     synchronized at t=12.
Small-world V = 200, k = 2, p = 0.4:     synchronized at t=14.
Small-world V = 200, k = 2, p = 0.5:     synchronized at t=12.
Small-world V = 200, k = 2, p = 0.6:     synchronized at t=12.
Small-world V = 200, k = 2, p = 0.7:     synchronized at t=14.
Small-world V = 200, k = 2, p = 0.8:     synchronized at t=12.
Small-world V = 200, k = 2, p = 0.9:     synchronized at t=14.
```

```
Small-world V = 200, k = 2, p = 1.0:     synchronized at t=12.

######## 200 CRICKETS | k=3 #############

Small-world V = 200, k = 3, p = 0.025:   synchronized at t=24.
Small-world V = 200, k = 3, p = 0.05:    synchronized at t=16.
Small-world V = 200, k = 3, p = 0.1:     synchronized at t=12.
Small-world V = 200, k = 3, p = 0.2:     synchronized at t=12.
Small-world V = 200, k = 3, p = 0.3:     synchronized at t=10.
Small-world V = 200, k = 3, p = 0.4:     synchronized at t=10.
Small-world V = 200, k = 3, p = 0.5:     synchronized at t=10.
Small-world V = 200, k = 3, p = 0.6:     synchronized at t=8.
Small-world V = 200, k = 3, p = 0.7:     synchronized at t=8.
Small-world V = 200, k = 3, p = 0.8:     synchronized at t=10.
Small-world V = 200, k = 3, p = 0.9:     synchronized at t=10.
Small-world V = 200, k = 3, p = 1.0:     synchronized at t=10.


#####################
# SCALE-FREE GRAPHS #
#####################


# f 10 15 scale-free-010-2.png 2 12345
######## dE=1 #########################
Scale-free V = 10, dE = 1:  synchronized at t=8.
Scale-free V = 100, dE = 1:       synchronized at t=18.
Scale-free V = 1000, dE = 1:      synchronized at t=24.
Scale-free V = 10000, dE = 1:     synchronized at t=32.
# f 50000 60 scale-free-50000-1.png 1 138
# synchronized at t=36
######## dE=2 #########################
Scale-free V = 100, dE = 2:       synchronized at t=8.
Scale-free V = 200, dE = 2:       synchronized at t=8.
Scale-free V = 300, dE = 2:       synchronized at t=8.
Scale-free V = 400, dE = 2:       synchronized at t=10.
Scale-free V = 1000, dE = 2:      synchronized at t=10.
######## dE=3 #########################
Scale-free V = 100, dE = 3:       synchronized at t=8.
Scale-free V = 200, dE = 3:       synchronized at t=8.
Scale-free V = 300, dE = 3:       synchronized at t=6.
Scale-free V = 400, dE = 3:       synchronized at t=8.
Scale-free V = 1000, dE = 3:      synchronized at t=8.
Scale-free V = 10000, dE = 3:     synchronized at t=8.
Scale-free V = 50000, dE = 3:     synchronized at t=10.
```

Appendix B (Source code):

```java
//*************************************************************************
//
// File:    Automator.java
// Package: ---
// Unit:    Class Automator
//
//*************************************************************************

import java.io.IOException;
import java.nio.charset.Charset;
import java.nio.file.Files;
import java.nio.file.Paths;
import java.util.List;

/**
 * This class automates many calls to the Chirp main method
 * by using command line arguments from an automation file.
 *
 * Each line in the file must either be commented out with
 * a '#', or be a valid command for Chirp.java.
 *
 * @author Jimi Ford (jhf3617)
 * @version 3-31-2015
 */
public class Automator {

    /**
     *
     * @param args command line arguments
     * args[0] = automation file
     */
    public static void main(String[] args) {
        if(args.length != 1) {
            usage();
        }
        try {
            List<String> lines = Files.readAllLines(Paths.get(args[0]),
                    Charset.defaultCharset());
            String[] lineArr;
            int lineCount = 0;
            boolean skip, comment;
            for (String line : lines) {
                ++lineCount;
                line = line.trim();
                lineArr = line.split(" ");
                skip = lineArr[0].equals(line);
                comment = lineArr[0].startsWith("#");
                if(skip || comment) {
                    if(comment) {
                        if(line.equals("#")) {
                            System.out.println();
                        } else {
                            System.out.println(line);
                        }
                    }
                    continue;
                }
                Chirp.main(lineArr);
```

```java
            }
        } catch (IOException e) {
            error("Error reading automation file");
        }
    }

    /**
     * display usage message and exit
     */
    private static void usage() {
        System.err.println("usage: java Automator <automation file>");
        System.exit(1);
    }

    /**
     * print error message and call usage()
     * @param msg
     */
    private static void error(String msg) {
        System.err.println(msg);
        usage();
    }
}
```

```java
//****************************************************************************
//
// File:    Chirp.java
// Package: ---
// Unit:    Class Chirp
//
//****************************************************************************

import java.io.IOException;

/**
 * Chirp runs a simulation of crickets chirping at night. The phenomenon we are
 * interested in studying is that some types of networks synchronize in how they
 * chirp. Based on the command line parameters, chirp tests the type of network
 * and determines what time the crickets syncrhonize.
 *
 * @author Jimi Ford (jhf3617)
 * @version 3-31-2015
 */
public class Chirp {

    private static final int GRAPH_TYPE_INDEX = 0,
                             NUM_VERTICES_INDEX = 1,
                             NUM_TICKS_INDEX = 2,
                             OUTPUT_IMAGE_INDEX = 3,
                             SEED_INDEX = 4,
                             K_INDEX = 4,
                             DE_INDEX = 4,
                             DE_SEED_INDEX = 5,
                             EDGE_PROBABILITY_INDEX = 5,
                             K_SEED_INDEX = 5,
                             REWIRE_PROBABILITY_INDEX = 6;

    /**
     * main method
     * @param args command line arguments
     */
    public static void main(String[] args) {
        if(args.length != 4 && args.length != 5 &&
                args.length != 6 && args.length != 7) usage();
        int crickets = 0, ticks = 0, k = 0, dE = 0;
        long seed = 0;
        double prob = 0;
        char mode;
        String outputImage = args[OUTPUT_IMAGE_INDEX];

        try {
            crickets = Integer.parseInt(args[NUM_VERTICES_INDEX]);
        } catch (NumberFormatException e) {
            error("<num vertices> must be a number");
        }
        try {
            ticks = Integer.parseInt(args[NUM_TICKS_INDEX]) + 1;
        } catch (NumberFormatException e) {
            error("<num ticks> must be numeric");
        }
        mode = args[GRAPH_TYPE_INDEX].toLowerCase().charAt(0);
        if(!(mode == 'c' || mode == 'r' || mode == 'k' ||
```

```java
                mode == 's' || mode == 'f')) {
            error("<graph type> must be either 'c' for cycle, "
                    + "'r' for random, "
                    + "'k' for k-regular, "
                    + "'s' for small-world, "
                    + "'f' for scale-free");
        }
        UndirectedGraph g = null;
        CricketObserver o = new CricketObserver(crickets, ticks);
        switch(mode) {
        case 'r': // RANDOM GRAPH
            try {
                seed = Long.parseLong(args[SEED_INDEX]);
                prob = Double.parseDouble(args[EDGE_PROBABILITY_INDEX]);
                g = UndirectedGraph.randomGraph(
                        new Random(seed), crickets, prob, o);
            } catch(NumberFormatException e) {
                error("<seed> and <edge probability> must be numeric");
            } catch(IndexOutOfBoundsException e) {
                error("<seed> and <edge probability> must be included with "
                        + "random graph mode");
            }
            break;
        case 'c': // CYCLE GRAPH
            g = UndirectedGraph.cycleGraph(crickets, o);
            break;
        case 'k': // K-REGULAR GRAPH
            try {
                k = Integer.parseInt(args[K_INDEX]);
                g = UndirectedGraph.kregularGraph(crickets, k, o);
            } catch (NumberFormatException e) {
                error("<k> must be an integer");
            } catch (IllegalArgumentException e) {
                error("<k> must be < the number of crickets");
            }
            break;
        case 's': // SMALL WORLD GRAPH
            try {
                k = Integer.parseInt(args[K_INDEX]);
                prob = Double.parseDouble(args[REWIRE_PROBABILITY_INDEX]);
                seed = Long.parseLong(args[K_SEED_INDEX]);
                g = UndirectedGraph.smallWorldGraph(
                        new Random(seed), crickets, k, prob, o);
            } catch (NumberFormatException e) {
                error("<k> must be an integer < V, <rewire probability> "
                        + "must be a number "
                        + "between 0 and 1, and <seed> must be numeric");
            } catch (IllegalArgumentException e) {
                error("<k> must be < the number of crickets");
            }
            break;
        case 'f': // SCALE-FREE GRAPH
            try {
                dE = Integer.parseInt(args[DE_INDEX]);
                seed = Long.parseLong(args[DE_SEED_INDEX]);
                g = UndirectedGraph.scaleFreeGraph(
                        new Random(seed), crickets, dE, o);
            } catch (NumberFormatException e) {
```

```java
                error("<dE> and <seed> must be numeric");
            } catch (IndexOutOfBoundsException e) {
                error("<dE> and <seed> must be supplied");
            }
        }

        g.vertices.get(0).forceChirp();
        Ticker.tick(g, ticks);



        try {
            ImageHandler.handle(o, outputImage);
        } catch (IOException e) {
            error("Problem writing image");
        }
        int sync = o.sync();
        String description;
        switch(mode) {
        case 'c': // CYCLE GRAPH
            description = "Cycle V = " + crickets +":";
            handleOutput(description,sync);
            break;
        case 'r': // RANDOM GRAPH
            description = "Random V = " + crickets +", p = " + prob + ":";
            handleOutput(description,sync);
            break;
        case 'k': // K-REGULAR GRAPH
            description = "K-regular V = " + crickets +", k = " + k + ":";
            handleOutput(description,sync);
            break;
        case 's': // SMALL-WORLD GRAPH
            description = "Small-world V = " + crickets + ", k = " + k +
                ", p = " + prob + ":";
            handleOutput(description,sync);
            break;
        case 'f': // SCALE-FREE GRAPH
            description = "Scale-free V = " + crickets +", dE = " + dE + ":";
            handleOutput(description,sync);
            break;
        }

    }

    /**
     * handle printing the results of the simulation
     * @param description the description of what kind of graph is being printed
     * @param sync time at which the network synchronized
     *      (-1 for not synchronized)
     */
    private static void handleOutput(String description, int sync) {
        System.out.print(description);
        if(sync >= 0) {
            System.out.println("\t"+" synchronized at t="+sync+".");
        } else {
            System.out.println("\t "+(char)27+"[31m"+  "did not synchronize." +
                    (char)27 + "[0m");
        }
```

```
    }

    /**
     * print an error message and call usage()
     * @param msg
     */
    private static void error(String msg) {
        System.err.println(msg);
        usage();
    }

    /**
     * usage message called when program improperly used
     */
    private static void usage() {
        System.err.println(
                "usage: java Chirp <graph type> <num vertices> <num ticks> "
                + "<output image> {(<seed> <edge probability>), or "
                + "(<k>), or "
                + "(<k> <seed> <rewire probability>), or "
                + "(<dE> <seed>)}");
        System.exit(1);
    }
}
```

```java
//****************************************************************************
//
// File:    Cricket.java
// Package: ---
// Unit:    Class Cricket
//
//****************************************************************************

/**
 * This class models a cricket that will chirp at time t + 2 if it hears a chirp
 * at time t. It inherits from vertex so that it can be connected to other
 * crickets through undirected edges.
 *
 * @author Jimi Ford (jhf3617)
 * @version 3-31-2015
 */
public class Cricket extends Vertex {

    private boolean[] chirp = new boolean[2];
    private boolean willChirp;
    private int currentTick = 0;
    private final CricketObserver observer;

    /**
     * Construct a cricket
     * @param n the unique integer identifier
     * @param o the cricket observer this cricket should report to
     */
    public Cricket(int n, CricketObserver o) {
        super(n);
        this.observer = o;
    }

    /**
     * force a cricket to chirp at the next time tick
     */
    public void forceChirp() {
        willChirp = chirp[0] = true;
    }

    /**
     * will chirp only if it is being forced to, or if it has heard a chirp
     * 2 time ticks ago
     */
    public void emitChirp() {
        if(willChirp) {
            willChirp = false;
            int n = super.degree();
            for(int i = 0; i < n; i++) {
                edges.get(i).other(this).hearChirp();
            }
            observer.reportChirp(currentTick, super.n);
        }
    }

    /**
     * hear another chirp from an adjacent cricket
     */
```

```java
    private void hearChirp() {
        chirp[1] = true;
    }

    /**
     * simulate time passing by letting the cricket know what time it is
     *
     * @param tick the current time tick for this cricket
     */
    public void timeTick(int tick) {
        currentTick = tick;
        willChirp = chirp[0];
        chirp[0] = chirp[1];
        chirp[1] = false;
    }

    /**
     * determine if a given cricket is directly connected to this cricket
     * @param other the given cricket to check
     * @return true if this cricket as a single edge that connects the two
     */
    public boolean directFlight(Cricket other) {
        boolean retval = false;
        if(equals(other)) return true;
        int e = super.degree();
        Cricket o;
        for(int i = 0; i < e && !retval; i++) {
            o = super.edges.get(i).other(this);
            retval = o.equals(other);
        }
        return retval;
    }

    /**
     * determine if another object is equal to this cricket
     * @param o the other object
     * @return true if the other object is equal to this cricket
     */
    public boolean equals(Object o) {
        if( !(o instanceof Cricket)) {
            return false;
        }
        if(o == this) {
            return true;
        }
        Cricket casted = (Cricket) o;

        return casted.n == this.n;
    }
}
```

```java
//***************************************************************************
//
// File:    CricketObserver.java
// Package: ---
// Unit:    Class CricketObserver
//
//***************************************************************************

/**
 * Class observes a group of crickets for a given number of time ticks and
 * keeps track of whether or not they have chirped or not.
 *
 * @author Jimi Ford (jhf3617)
 * @version 3-31-2015
 */
public class CricketObserver {

    /**
     * the number of crickets being observed
     */
    public final int crickets;

    /**
     * the number of time ticks observing for
     */
    public final int ticks;

    // private data members
    private boolean[][] chirps;

    /**
     * Construct a cricket observer
     * @param crickets the number of crickets to observe
     * @param ticks the number of time ticks observing for
     */
    public CricketObserver(int crickets, int ticks) {
        this.crickets = crickets;
        this.ticks = ticks;
        chirps = new boolean[ticks][crickets];
    }

    /**
     * called by a cricket to inform the observer that he has chirped
     * @param tick the time tick at which the cricket is chirping
     * @param n the unique identifier of the cricket
     */
    public void reportChirp(int tick, int n) {
        chirps[tick][n] = true;
    }

    /**
     * lookup a given time and cricket to see if it chirped at that moment
     * @param tick the moment in time to lookup
     * @param cricket the unique identifier of the cricket to check
     * @return true if it chirped
     */
    public boolean chirped(int tick, int cricket) {
        return chirps[tick][cricket];
```

```java
    }

    /**
     * get the time tick at which all the crickets being observed synchronized
     * @return a number >= to 0 if they synchronized, -1 if they didn't
     */
    public int sync() {
        int row = 0;
        while(row < ticks) {
            if(sync(row)) return row;
            row++;
        }
        return -1;
    }

    /**
     * determine whether the crickets were synchronized at a given time tick or
     * not
     * @param tick the time tick to test
     * @return true if every cricket at this time tick chirped
     */
    private boolean sync(int tick) {
        boolean retval = true;
        for(int i = 0; i < crickets && retval; i++) {
            retval = chirps[tick][i];
        }
        return retval;
    }
}
```

```java
//***************************************************************************
//
// File:    ImageHandler.java
// Package: ---
// Unit:    Class ImageHandler
//
//***************************************************************************

import java.io.BufferedOutputStream;


/**
 * Class takes care of saving the results of the simulation as an image
 *
 * @author Jimi Ford (jhf3617)
 * @version 3-31-2015
 */
public class ImageHandler {

    // private data members
    private static final byte SILENT = 0,
                              CHIRPED = 1,
                              SYNC = 2;

    /**
     *
     * @param o the cricket observer that holds the results of the simulation
     * @param out the name of the image file to save
     * @throws FileNotFoundException if there was an error writing to the given
     * file
     */
    public static void handle(CricketObserver o, String out)
            throws FileNotFoundException {
        AList<Color> palette = new AList<Color>();
        Color green = new Color().rgb(0, 255, 0);// green
        Color red = new Color().rgb(255, 0, 0); // red
        Color blue = new Color().rgb(0,0,255); // blue
        palette.addLast (green);
        palette.addLast (red);
        palette.addLast (blue);


        OutputStream imageout =
                new BufferedOutputStream (new FileOutputStream (new File(out)));
        IndexPngWriter imageWriter = new IndexPngWriter
                (o.ticks, o.crickets, imageout, palette);
        ByteImageQueue imageQueue = imageWriter.getImageQueue();
        byte[] bytes;
        boolean chirped;
        int sync = o.sync();
        for(int i = 0; i < o.ticks; i++) {
            bytes = new byte[o.crickets];
            for(int j = 0, cricket = 0; j < bytes.length; j++, cricket++) {
                if(i != sync) {
                    chirped = o.chirped(i, cricket);
                    bytes[j] = chirped ? CHIRPED : SILENT;
                } else {
                    bytes[j] = SYNC;
```

```
                }
            }
            try {
                imageQueue.put(i, bytes);
            } catch (InterruptedException e) {
                // TODO Auto-generated catch block
                e.printStackTrace();
            }
        }
        try {
            imageWriter.write();
        } catch (IOException e) {
            // TODO Auto-generated catch block
            e.printStackTrace();
        } catch (InterruptedException e) {
            // TODO Auto-generated catch block
            e.printStackTrace();
        }
    }
}
```

```java
//**************************************************************************
//
// File:    Ticker.java
// Package: ---
// Unit:    Class Ticker
//
//**************************************************************************

/**
 * Class simulates a number of time ticks on a given network of crickets
 * @author Jimi Ford (jhf3617)
 * @version 3-31-2015
 */
public class Ticker {

    /**
     * tick a number of time ticks on a given network of crickets
     * @param g the network of crickets to tick
     * @param ticks the number of ticks to simulate
     */
    public static void tick(UndirectedGraph g, int ticks) {
        for(int i = 0; i < ticks; i++) {
            g.tick(i);
        }
    }
}

```

```java
//***************************************************************************
//
// File:    UndirectedEdge.java
// Package: ---
// Unit:    Class UndirectedEdge
//
//***************************************************************************

/**
 * Class UndirectedEdge represents an edge in a graph that connects two
 * vertices. It's important to note that the edge does not have a direction nor
 * weight.
 *
 * @author Jimi Ford
 * @version 2-15-2015
 */
public class UndirectedEdge {

    // private data members
    private Cricket a, b;

    // future projects may rely on a unique identifier for an edge
    private final int id;

    /**
     * Construct an undirected edge
     * @param id a unique identifier to distinguish between other edges
     * @param a one vertex in the graph
     * @param b another vertex in the graph not equal to <I>a</I>
     */
    public UndirectedEdge(int id, Cricket a, Cricket b) {
        this.id = id;
        // enforce that a.n is always less than b.n
        if(a.n < b.n) {
            this.a = a;
            this.b = b;
        } else if(b.n < a.n) {
            this.a = b;
            this.b = a;
        } else {
            throw new IllegalArgumentException("Cannot have self loop");
        }
        this.a.addEdge(this);
        this.b.addEdge(this);
    }

    /**
     * Get the <I>other</I> vertex given a certain vertex connected to
     * this edge
     *
     * @param current the current vertex
     * @return the other vertex connected to this edge
     */
    public Cricket other(Cricket current) {
        if(current == null) return null;
        return current.n == a.n ? b : a;
    }
}
```

```java
//*****************************************************************************
//
// File:    UndirectedGraph.java
// Package: ---
// Unit:    Class UndirectedGraph
//
//*****************************************************************************

import java.util.ArrayList;
import java.util.LinkedList;
import edu.rit.pj2.vbl.DoubleVbl;
import edu.rit.util.Random;
import edu.rit.util.Searching;

/**
 * Class UndirectedGraph represents an undirected graph meaning that if
 * there exists an edge connecting some vertex A to some vertex B, then
 * that same edge connects vertex B to vertex A.
 *
 * @author Jimi Ford
 * @version 2-15-2015
 */
public class UndirectedGraph {

    // private data members
    private ArrayList<UndirectedEdge> edges;
    public ArrayList<Cricket> vertices;
    private int v;


    /**
     * Private constructor used internally by the static random graph
     * method
     * @param v the number of vertices in the graph
     */
    private UndirectedGraph(int v, CricketObserver o) {
        this.v = v;
        vertices = new ArrayList<Cricket>(v);
        edges = new ArrayList<UndirectedEdge>();
        for(int i = 0; i < v; i++) {
            vertices.add(new Cricket(i,o));
        }
    }

    /**
     * Perform a BFS to get the distance from one vertex to another
     *
     * @param start the id of the start vertex
     * @param goal the id of the goal vertex
     * @return the minimum distance between the two vertices
     */
    private int BFS(int start, int goal) {
        return BFS(vertices.get(start), vertices.get(goal));
    }

    /**
     * Perform a BFS to get the distance from one vertex to another
     *
```

```
     * @param start the reference to the start vertex
     * @param goal the reference to the goal vertex
     * @return the minimum distance between the two vertices
     */
    private int BFS(Cricket start, Cricket goal) {
        int distance = 0, verticesToProcess = 1, uniqueNeighbors = 0;
        LinkedList<Cricket> queue = new LinkedList<Cricket>();
        boolean[] visited = new boolean[v];
        visited[start.n] = true;
        Cricket current, t2;
        queue.add(start);
        while(!queue.isEmpty()) {
            current = queue.removeFirst();
            if(current.equals(goal)) {
                return distance;
            }
            for(int i = 0; i < current.degree(); i++) {
                t2 = current.getEdges().get(i).other(current);
                if(!visited[t2.n]) {
                    visited[t2.n] = true;
                    queue.add(t2);
                    uniqueNeighbors++;
                }
            }
            verticesToProcess--;
            if(verticesToProcess <= 0) {
                verticesToProcess = uniqueNeighbors;
                uniqueNeighbors = 0;
                distance++;
            }

        }
        return 0;
    }

    /**
     * Accumulate the distances of each pair of vertices into
     * a "running total" to be averaged
     *
     * @param thrLocal the reference to the "running total"
     * Prof. Alan Kaminsky's library handles averaging this
     * accumulated value.
     */
    public void accumulateDistances(DoubleVbl.Mean thrLocal) {
        for(int i = 0; i < v; i++) {
            for(int j = i + 1; j < v; j++) {
                int distance = BFS(i, j);
                // only accumulate the distance if the two vertices
                // are actually connected
                if(distance > 0) {
                    thrLocal.accumulate(distance);
                }
            }
        }
    }

    /**
     * simulate time passing
```

```java
     * @param tick the current time tick
     */
    public void tick(int tick) {
        Cricket c;
        for(int i = 0; i < v; i++) {
            c = vertices.get(i);
            c.timeTick(tick);
        }
        for(int i = 0; i < v; i++) {
            c = vertices.get(i);
            c.emitChirp();
        }
    }

    /**
     * Generate a random graph with a PRNG, a specified vertex count and
     * an edge probability
     *
     * @param prng Prof. Alan Kaminsky's Perfect Random Number Generator
     * @param v number of vertices to use
     * @param p edge probability between vertices
     * @return the randomly generated graph
     */
    public static UndirectedGraph randomGraph(Random prng, int v, double p,
            CricketObserver o) {
        UndirectedGraph g = new UndirectedGraph(v, o);
        UndirectedEdge edge;
        Cricket a, b;
        int edgeCount = 0;
        for (int i = 0; i < v; i++) {
            for (int j = i + 1; j < v; j++) {
                // connect edges
                // always order it `i` then `j`
                if(prng.nextDouble() <= p) {
                    a = g.vertices.get(i);
                    b = g.vertices.get(j);
                    edge = new UndirectedEdge(edgeCount++, a, b);
                    g.edges.add(edge);
                }
            }
        }
        return g;
    }

    /**
     * create a cycle graph
     * @param v number of vertices
     * @param o cricket observer crickets should report to
     * @return constructed cycle graph
     */
    public static UndirectedGraph cycleGraph(int v, CricketObserver o) {
        return kregularGraph(v, 1, o);
    }

    /**
     * create a k-regular graph
     * @param v number of vertices
     * @param k number of adjacent vertices left and right of given vertex to
```

```java
     * connect to
     * @param o cricket observer the crickets should report to
     * @return the constructed k-regular graph
     */
    public static UndirectedGraph kregularGraph(int v, int k,
            CricketObserver o) {
        return smallWorldGraph(null, v, k, 0, o);
    }

    /**
     * create a small-world graph
     * @param prng pseudorandom number generator
     * @param v number of vertices
     * @param k the initial k-regular graph to modify
     * @param p edge rewire probability
     * @param o cricket observer the crickets should report to
     * @return the constructed small-world graph
     */
    public static UndirectedGraph smallWorldGraph(Random prng, final int v,
            int k, double p, CricketObserver o) {
        UndirectedGraph g = new UndirectedGraph(v, o);
        UndirectedEdge edge;
        Cricket a, b, c;
        int edgeCount = 0;
        for(int i = 0; i < v; i++) {
            a = g.vertices.get(i);
            for(int j = 1; j <= k; j++) {
                b = g.vertices.get((i + j) % v);
                if(prng != null && prng.nextDouble() < p) {
                    do {
                        c = g.vertices.get(prng.nextInt(v));
                    } while(c.n == a.n || c.n == b.n || a.directFlight(c));
                    b = c;
                }
                edge = new UndirectedEdge(edgeCount++, a, b);
                g.edges.add(edge);
            }
        }
        return g;
    }

    /**
     * create a scale-free graph
     * @param prng psuedorandom number generator to use
     * @param v number of vertices
     * @param dE number of edges to add to each additional vertex
     * @param o cricket observer the crickets should report to
     * @return the scale-free graph generated
     */
    public static UndirectedGraph scaleFreeGraph(Random prng, final int v,
            final int dE, CricketObserver o) {
        UndirectedGraph g = new UndirectedGraph(v, o);
//      boolean[]
        int edgeCount = 0;
        int c0 = prng.nextInt(v);
        int c1 = (c0 + 1) % v;
        int c2 = (c1 + 1) % v;
        Cricket a = g.vertices.get(c0), b = g.vertices.get(c1),
```

```java
                c = g.vertices.get(c2);
        UndirectedEdge edge = new UndirectedEdge(edgeCount++, a, b);
        g.edges.add(edge);
        edge = new UndirectedEdge(edgeCount++, b, c);
        g.edges.add(edge);
        edge = new UndirectedEdge(edgeCount++, a, c);
        g.edges.add(edge);
        // we have 3 fully connected vertices now
        Cricket[] others = new Cricket[v-3];
        for(int other = 0, i = 0; i < v; i++) {
            if(i != c0 && i != c1 && i != c2) {
                others[other++] = g.vertices.get(i);
            }
        }
        // the rest are contained in others
        double[] cum = new double[v];
        double[] deg = new double[v];
        Cricket next, temp;
        ArrayList<Cricket> existing = new ArrayList<Cricket>();
        existing.add(a); existing.add(b); existing.add(c);
        Searching.Double h = new Searching.Double();
        for(int i = 0; i < others.length; i++) {
            next = others[i];
            existing.add(next);
            if(existing.size() <= dE) {
                for(int e = 0; e < existing.size(); e++) {
                    temp = existing.get(e);
                    if(next.equals(temp)) continue;
                    edge = new UndirectedEdge(edgeCount++, temp, next);
                    g.edges.add(edge);
                }
            } else {
                setDegreeDistribution(g, deg);
                for(int e = 0; e < dE; e++) {
                    setProbabilityDistribution(deg, cum);
                    double nr = prng.nextDouble();
                    double ch = cum[cum.length-1]*nr;
                    int vertex = Searching.searchInterval(cum, ch, h);
                    deg[vertex] = 0;
                    temp = g.vertices.get(vertex);
                    edge = new UndirectedEdge(edgeCount++, next, temp);
                    g.edges.add(edge);
                }
            }
        }

        return g;
    }

    /**
     * set the degree distribution of a given graph
     * @param g the given graph
     * @param deg the degree distribution of the graph
     */
    private static void setDegreeDistribution(UndirectedGraph g, double[] deg) {
        for(int i = 0; i < g.v; i++) {
            deg[i] = g.vertices.get(i).degree();
        }
```

```
    }

    /**
     * set the cumulative sum of the degree array
     * @param deg degrees of a graph
     * @param cum cumulative sum of the degree
     */
    private static void setProbabilityDistribution(double deg[], double[] cum) {
        double cumulative = 0;
        for(int i = 0; i < deg.length; i++) {
            cum[i] = cumulative += deg[i];
        }
    }
}
```

```java
//****************************************************************************
//
// File:    Vertex.java
// Package: ---
// Unit:    Class Vertex
//
//****************************************************************************

import java.util.ArrayList;

/**
 * Class Vertex represents a single vertex in a graph. Vertices can be connected
 * to other vertices through undirected edges.
 *
 * @author Jimi Ford
 * @version 2-15-2015
 */
public class Vertex {

    // private data members
    protected ArrayList<UndirectedEdge> edges = new ArrayList<UndirectedEdge>();

    /**
     * The unique identifier for this vertex
     */
    public final int n;

    /**
     * Construct a vertex with a unique identifier <I>n</I>
     *
     * @param n the unique identifier to distinguish this vertex from
     *          all other vertices in the graph
     */
    public Vertex(int n) {
        this.n = n;
    }

    /**
     * Get the number of edges connected to this vertex
     *
     * @return the number of edges connected to this vertex
     */
    public int degree() {
        return edges.size();
    }

    /**
     * Get the reference to the collection of edges connected to
     * this vertex.
     *
     * @return the reference to the collection of edges
     */
    public ArrayList<UndirectedEdge> getEdges() {
        return this.edges;
    }

    /**
     * Add an edge to this vertex
```

```
     *
     * @param e the edge to add
     */
    public void addEdge(UndirectedEdge e) {
        this.edges.add(e);
    }

    /**
     * Compare another object to this one
     *
     * @param o the other object to compare to this one
     * @return true if the other object is equivalent to this one
     */
    public boolean equals(Object o) {
        if( !(o instanceof Vertex)) {
            return false;
        }
        if(o == this) {
            return true;
        }
        Vertex casted = (Vertex) o;

        return casted.n == this.n;
    }
}
```