Stanford CS 106B: Trailblazer

Thanks to Keith Schwarz, Dawson Zhou, Eric Roberts, Julie Zelenski, Nick Parlante, Jerry Cain, and Leonid Shamis (UC Davis) for creating and evolving this assignment and its predecessor, "Pathfinder." BasicGraph class and other modifications by Marty Stepp. Large graph map data added by Chris Gregg and Chris Piech. Alternate path algorithm / description / code by Chris Gregg, Chris Piech, and Nick Troccoli.

Links   Description   Implementation   Style   FAQ   Extras

This assignment focuses on graphs, specifically on searching for paths in a graph.

This is a **pair assignment**. You are allowed to work individually or work with a single partner. If you work as a pair, **comment both members' names** on top of every submitted code file. Only one of you should submit the assignment; do not turn in two copies.

Links:

starter code

We provide a ZIP archive with a starter project that you should download and open with Qt Creator. You will edit and turn in only the following two files. The ZIP contains other files/libraries; do not modify these. Your code must work with the other files unmodified.

- **trailblazer.cpp**, the C++ implementation for your solution
- **map-custom.txt**, a custom world map data file of your own creation
- **map-custom.jpg**, a custom world map image of your own creation

turn in

When you are finished, submit your assignment using our **Paperless** web system. You can turn in all parts of the assignment together, or turn in each problem separately; it is up to you.

output logs:

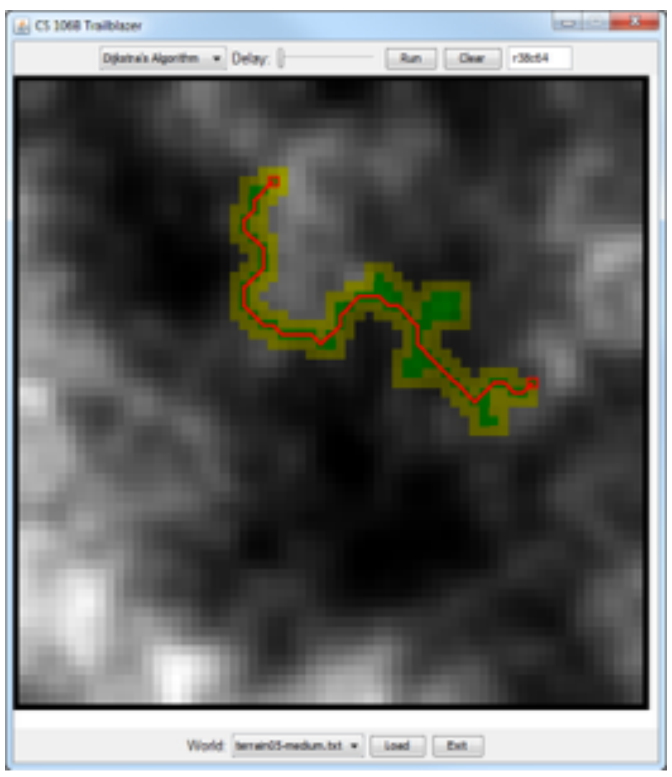
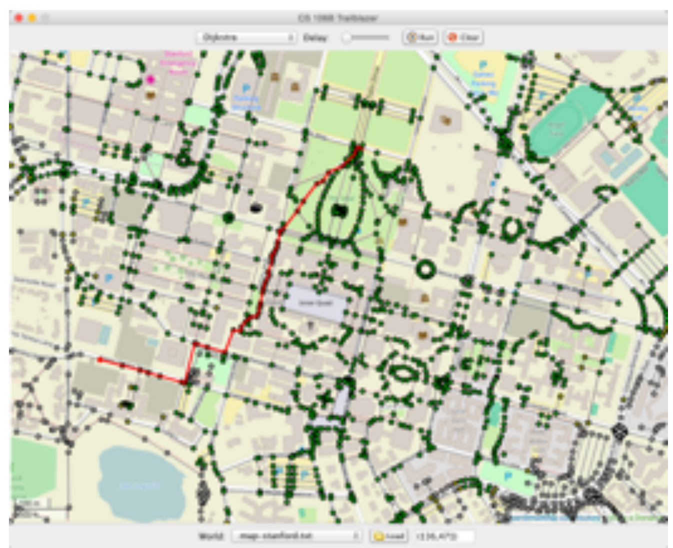
- maze01-tiny: output, DFS, BFS, Dijkstra, A*, Alt.Path (0.2)
- maze04-small: output, DFS, BFS, Dijkstra, A*, Alt.Path (0.2)
- maze05-medium: output, DFS, BFS, Dijkstra, A*, Alt.Path (0.2), Alt.Path (0.5)
- maze10-huge: output, DFS, BFS, Dijkstra, A*
- terrain01-tiny: output, DFS, BFS, Dijkstra, A*, Alt.Path (0.2)
- terrain03-small: output, DFS, BFS, Dijkstra, A*, Alt.Path (0.2), Alt.Path (0.33)
- terrain06-medium: output, DFS, BFS, Dijkstra, A*, Alt.Path (0.2)
- terrain07-large: output, DFS, BFS, Dijkstra, A*, Alt.Path (0.01), Alt.Path (0.2), Alt.Path (0.33)
- map-middleearth: output
- Rauros: DFS, BFS, Dijkstra
- Black Gate: DFS, BFS, Dijkstra, Alt.Path (0.2)
- map-san-francisco: output, Dijkstra A*, Alt.Path (0.2)
- map-stanford: output, DFS, BFS, Dijkstra A*, Alt.Path (0.2), Alt.Path (0.4)
- map-stanford-big: output, Dijkstra A*, Alt.Path (0.2), Alt.Path 2 (0.3)
- map-usa: output
- Portland/NY: DFS, BFS, Dijkstra, Alt.Path (0.2)
- Bismarck/CHI: BFS
- random (medium): output, screenshot

Since this program uses a graphical user interface, its console output appears in the Qt Creator IDE near the bottom in the "**Application Output**" area. You can copy/paste from this area into our Output Comparison Tool to check your output if you like.

The screenshots are taken on a variety of different operating systems, so your output may not match exactly. Depending on the path algorithm being used, some other paths may be equally correct to the ones shown in our output. See later in spec for discussion of "correct" output. We do not provide any tool for graphically comparing your output to our screenshots; you will have to do so manually.

Problem Description:

This program displays various 2-dimensional worlds that represent either maps, mazes, or terrain and allows the user to generate paths in a world from one point to another. When you start up the program, you will see a graphical window containing a 2D maze, where white squares are open and black ones represent walls. The program is also able to display terrain, where bright colors indicate higher elevations and darker colors represent lower elevations. Mountain ranges appear in bright white, while deep canyons are closer to black.

If you click on any two points in the world, the program will find a path from the starting position to the ending position. As it does so, it will color the vertexes green, yellow, and gray based on the colors assigned to them by the algorithm. Once the path is found, the program will highlight it and display information about the path weight in the console. The user can select one of five path-searching algorithms in the top menu:

- depth-first search (DFS)
- breadth-first search (BFS)
- Dijkstra's algorithm
- A* search
- Alternate Path

The window also contains several controls. You can load mazes and terrains of different sizes (tiny, small, medium, large, and huge) from the bottom drop-down menu and then clicking the "Load" button.

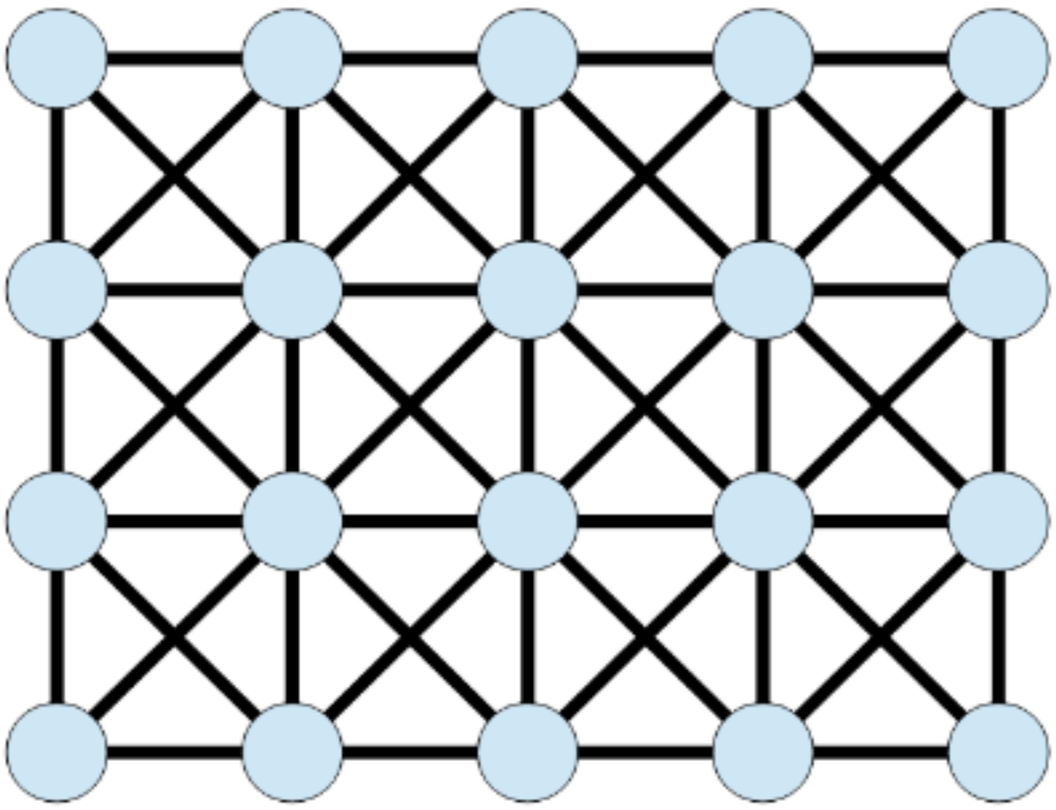
In your **trailblazer.cpp** file, you must write the following six functions for finding paths and creating mazes in a graph:

```
// functions you must write for this assignment
Vector<Vertex*> depthFirstSearch(BasicGraph& graph, Vertex* start, Vertex* end)
Vector<Vertex*> breadthFirstSearch(BasicGraph& graph, Vertex* start, Vertex* end)
Vector<Vertex*> dijkstrasAlgorithm(BasicGraph& graph, Vertex* start, Vertex* end)
Vector<Vertex*> aStar(BasicGraph& graph, Vertex* start, Vertex* end)
Vector<Vertex*> alternatePath(BasicGraph& graph, Vertex* start, Vertex* end, double difference)
Set<Edge*>      kruskal(BasicGraph& graph)
```

Each of the first four implements a path-searching algorithm taught in class. You should search the given graph for a path from the given start vertex to the given end vertex. If you find such a path, the path you return should be a list of all vertexes along that path, with the starting vertex first (index 0 of the vector) and the ending vertex last. The alternate path function is a variation of A* described later in this document that finds a second path similar to the one that A* would find.

For any of the path searching functions, if no path is found, you should return an **empty vector**. If the start and end vertexes are the same, return a one-element vector containing only that vertex. Though the mazes and terrains in our main app are **undirected** graphs (all edges go both ways), your code should not assume this. You may assume that the graph passed has a valid state.

Our provided main client program will allow you to test each algorithm one at a time before moving on to the next. You can add more functions as helpers if you like, particularly to help you implement any recursive algorithms and/or to remove redundancy between some algorithms containing similar code.



The 2D world is represented by a `BasicGraph`, where each vertex represents a specific location on the world. If it is a maze, each location represents one square in the maze's grid-like world. Open squares are connected by edges to any other neighboring open squares that are directly adjacent to them (differ by +/- 1 row or column exactly). Black "wall" squares are not connected as neighbors to any other squares; no edges touch them. If the world is a terrain rather than a maze, each location represents some elevation between 0 (lowland) and 1 (high mountain peak). Terrain locations are connected to neighbors in all 8 directions including diagonal neighbors, but maze locations are only connected to neighbors directly up, down, left, and right.

Your code can treat maps, mazes, and terrains exactly the same. You should just think of each kind of world as a graph with vertexes and edges that connect neighboring vertexes. In the case of mazes, vertexes happen to represent 2D locations and neighbors happen to be directly up, down, left, right, etc., but your code does not utilize or rely on that information. Your path-searching algorithms will work on any kind of graph that might be passed to them.

Provided Code:

We provide you with a lot of starter code for this assignment. Here is a quick breakdown of what each file contains, though you do not need to examine or know about each file or its contents in order to complete the assignment.

- **trailblazer.h/.cpp**: We provide a skeleton version of these files where you will write your path-searching code for the assignment.
- **color.h/.cpp**: Constants representing colors of vertexes.
- **trailblazergui.h/.cpp**: The app's graphical user interface, and the `main` function that launches the application.
- **world(abstract,grid,map,maze,terrain).h/.cpp**: Hierarchy of types of world graphs.

Each vertex in the graph is represented by an instance of the `Vertex` structure, which has the following members:

`Vertex` member	**Description**
`v->name`	vertex's name, such as `"r34c25"` or `"vertex17"` (a `string`)
`v->edges`	edges outbound from this vertex (a `Set<Edge*>`)
`v->setColor(c)`	sets this vertex to be drawn in the given color in the GUI; set it to one of the following constants: `UNCOLORED`, `WHITE`, `GRAY`, `YELLOW`, or `GREEN`
`v->getColor()`	returns the color you set previously using setColor; initially `UNCOLORED`
`v->toString()`	returns a printable `string` representation of the vertex for debugging

Each edge in the graph is represented by an instance of the `Edge` structure, which has the following members:

Edge member	**Description**
`e->start`	pointer to the starting vertex of this edge (a `Vertex*`)
`e->finish`	pointer to the ending vertex of this edge; i.e., `finish` is a neighbor of `start` (a `Vertex*`)
`e->weight`	weight or cost to traverse this edge (a `double`)
`e->toString()`	returns a printable `string` representation of the edge for debugging

The vertexes and edges are contained inside a `BasicGraph` object passed to each of your algorithm functions. See the Stanford C++ library documentation for descriptions of the members of the `BasicGraph` class. In addition to those members, `BasicGraph` includes all of the public members from its parent class `Graph`.

`BasicGraph` has a useful public member named `resetData`. You must call `resetData` on the graph at the start of any path-searching algorithm that wants to store data in the vertexes, to make sure that no stale data is left in the vertexes from some prior call. Call it at the start of your algorithm and not at the end, to ensure that any old state (such as vertex colors) is cleaned out before your algorithm begins. If you don't call it, your algorithms may fail for subsequent calls.

Graph Algorithm Details:

Coloring: In addition to searching for a path in each algorithm, we also want you to add some code to give colors to various vertexes at various times. This coloring information is used by the GUI to show the progress of your algorithm and to provide the appearance of animation. To give a color to a vertex, call the `setColor` member function on that vertex's `Vertex` object, passing it a global color constant such as `GRAY`, `YELLOW`, or `GREEN`. For example:

```
Vertex* myVertex = graph.getVertex("foo");
myVertex->setColor(GREEN);                    // set the vertex's color to green
```

Here is a listing of colors available and when you should use them:

- **enqueued = yellow:** Whenever you enqueue a vertex to be visited for the first time, such as in BFS and Dijkstra's algorithm when you add a vertex to a data structure for later processing, color it yellow (`YELLOW`).
- **visited = green:** Whenever your algorithm directly visits and examines a particular vertex, such as when it is dequeued from the processing queue in BFS or Dijkstra's algorithm, or when it is the starting vertex of a recursive call in DFS, color it green (`GREEN`).
- **eliminated = gray:** Whenever your algorithm has finished exploring a vertex and did not find a path from that vertex, and therefore is "giving" up on that vertex as a candidate, color it gray (`GRAY`). The only algorithm that explicitly "backtracks" like this is depth-first search (DFS). You don't need to set any vertexes to gray in any other path-searching algorithms besides DFS.

The provided GUI has an animation **slider** that you can drag to set a delay between coloring calls. If the slider is not all the way to its left edge, each call to `setColor` on a vertex will pause the GUI briefly, causing the appearance of animation so that you can watch your algorithms run.

Depth-first search implementation notes: You can implement it recursively as shown in lecture, or non-recursively. The choice is up to you. A recursive solution can sometimes run slowly or crash on extremely large worlds; this is okay. You do not need to modify your DFS implementation to avoid crashes due to excessive call stack size.

Breadth-first search implementation notes: Your code will need to regenerate the path that it finds, so look at the version of the algorithm pseudo-code from lecture that keeps track of paths along the way. One interesting note is that BFS and Dijkstra's algorithm behave exactly the same when run on a maze, but differently on a terrain. (Why?)

Dijkstra's algorithm implementation notes: The version of Dijkstra's algorithm suggested in the course textbook is slightly different than the version we discussed in lecture and is less efficient. Your implementation of Dijkstra's algorithm should follow the version we discussed in lecture. The priority queue should store vertexes to visit, and once you find the destination, you should reconstruct the shortest path back. See the lecture slides for more details.

Our pseudocode for Dijkstra's algorithm occasionally refers to **"infinity"** as an initial value when talking about the cost of reaching a vertex. If you want to refer to infinity in your code, you can use the `double` constant `POSITIVE_INFINITY` that is visible to your code.

Both Dijkstra's algorithm and A* involve a priority queue of vertexes to process, and furthermore, they each depend on the ability to alter a given vertex's priority in the queue as the algorithm progresses. Use the Stanford library's `PriorityQueue` class (documentation) for this. To do this, call the `changePriority` member function on the priority queue and pass it the new priority to use. It is important to use this function here because otherwise there is no way to access an arbitrary element from the priority queue to find the one whose priority you want to change. You would have to remove vertexes repeatedly until you found the one you wanted, which would be very expensive and wasteful. The new priority you pass must be at least as urgent as the old priority for that vertex (because the function bubbles a value upward in the priority queue's internal heap structure).

Note that the notion of a given vertex's current priority might be stored in two places in your code: in your own record-keeping about each `Vertex`, and in the priority queue's ordering. You'll have to keep these two in sync yourself; if you update just your own records, the priority queue won't know about it if you don't call `changePriority`, and vice versa. If the two values get out of sync, this can lead to bugs in your program.

A* implementation notes: As discussed in class, the A* search algorithm is essentially a variation of Dijkstra's algorithm that uses heuristics to fine-tune the order of elements in its priority queue to explore more likely desirable elements first. So when you are implementing A*, you need a **heuristic function** to incorporate into the algorithm. We supply you with a global function called `heuristicFunction` that accepts a pointer to two vertexes ***v1*** and ***v2*** and returns a heuristic value from ***v1*** to ***v2*** as a `double`. You can assume that this is an admissible heuristic, meaning that it never overestimates the distance to the destination (which is important for A*). For example:

```
Vertex* v1 = graph.getVertex("foo");
Vertex* v2 = graph.getVertex("bar");
double h = heuristicFunction(v1, v2);    // get an A* heuristic between these vertexes
```

You can compare the behavior of Dijkstra's algorithm and A* (or any pair of algorithms). First try performing a search between two points using Dijkstra's algorithm, then select A* and press the "Run" button at the top of the GUI window. This will repeat the same search using the currently selected algorithm. Run a search using Dijkstra's algorithm, switch the algorithm choice to "A*," then run that search to see how much more efficient A* is.

Your A* search algorithm should always return a path with the **same weight** as the path found by Dijkstra's algorithm. If you find that the algorithms give paths of different weights, it probably indicates a bug in your solution. For mazes, all three of BFS, Dijkstra's algorithm, and A* should return paths with the same length and weight.

The A* algorithm performs no better than Dijkstra's algorithm when run on most **maps** because many maps disable the heuristic.

Several expected output files have been posted to the class web site. If you have implemented each path-searching algorithm correctly, for DFS you should get any valid path from the start to the end; for BFS you should get the same path lengths as shown in the expected outputs posted on the class web site. For Dijkstra's and A* you should get the same path weights as shown in the expected outputs. But you do *not* need to exactly match our path itself, nor its "locations visited", so long as your path is a correct one. For Kruskal's algorithm (described next), your code must find a valid minimum spanning tree on the given graph. If there are several of equal total weight, any will suffice.

As mentioned previously, your code should *not* assume that the graph is undirected; we will test your code with directed graphs as well as undirected ones.

Alternate Path implementation notes: When travelling between two points on a map, you may want to take the fastest route, but if there is a reasonable alternative you might prefer that instead. For example, though Highway 101 is often the slightly faster way to get to San Francisco from the peninsula, Highway 280 is more beautiful. You must implement the Alternate Path search algorithm, which is a slight variation of Dijkstra's and A*.

In this example the shortest path between the oval and the back of MemChu is shown in red, and a next best alternative is shown in blue:

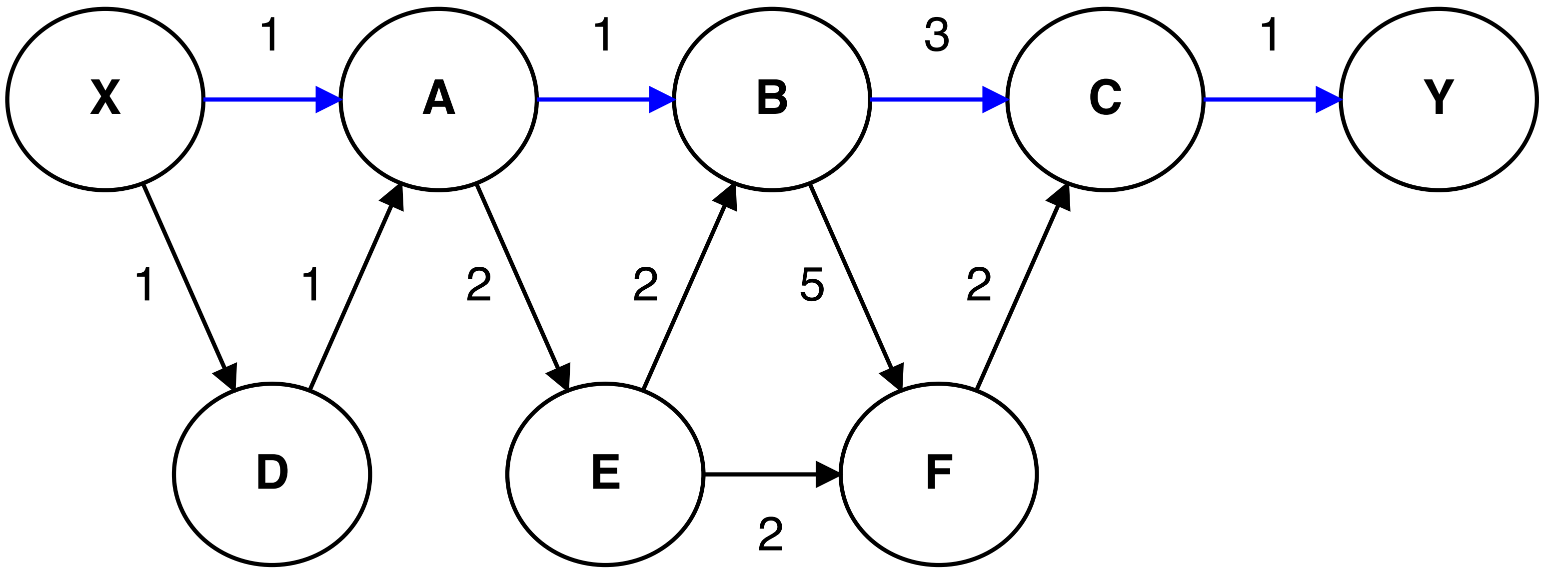
We already know how to find a shortest path from a start to a goal. How do we find an alternate route? First we are going to calculate the minimum-weight path between the start and end, using our A* algorithm. Then, for each edge in the best path we are going to calculate the minimum-weight path from start to end that ignores that edge. Each search will thus return a candidate alternate route. **Your function should return the lowest weight alternate route that is sufficiently different from the original best path.** When we say "sufficiently different," we mean according to a `difference` parameter that we will pass to your function, whose default value is `0.2` representing 20%.

To calculate the difference between two paths: we define the difference of an alternate path P from the best path B to be the number of nodes that are in P but are not in B, divided by the number of nodes in B:

$$\text{difference}(P, B) = \frac{\text{\# nodes in P that are not in B}}{\text{\# nodes in B}}$$

For each edge in the best path you will produce one candidate alternate route. Your function should choose, from those candidates, the shortest path (by total edge weight) that has a difference score greater than 0.2 when compared to the original best path (i.e. strictly greater than the `difference` parameter).

Example of alternative route calculation: In the graph below, the minimum weight path from vertex X to Y has four edges. For each edge we compute a candidate alternate route:



The best A* path is X → A → B → C → Y, which has a total weight of 6.

Excluded Edge	Alternate Path	Weight	Difference
X → A	X → **D** → A → B → C → Y	7	1 / 5 (0.2)
A → B	**X → A → E → F → C → Y**	**8**	**2 / 5 (0.4)**
B → C	X → A → B → **F** → C → Y	8	1 / 5 (0.2)
C → Y	no path	∞	N/A

The minimum-weight alternate route is the path X → D → A → B → C → Y. However it has a difference score of 0.2 (recall that we are looking for a path with difference score *greater than* 0.2). The shortest alternative that also has a difference greater than 0.2, and therefore the path that your alternative path algorithm should return, is:

X → A → E → F → C → Y

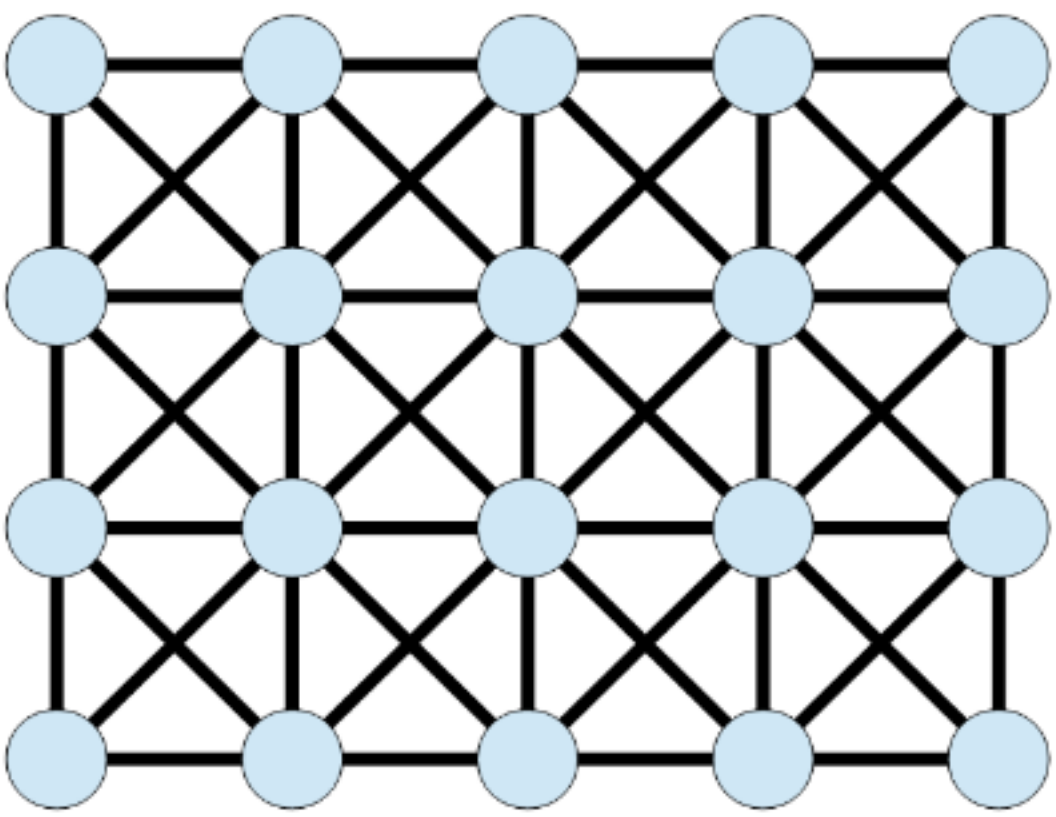
There are different ways to accomplish this modification to your path algorithm. One option is to simply write a separate and modified Dijkstra or A* function that can ignore or exclude an edge, but this duplicates a lot of code. A better option would be to refactor your code and write a modified function that performs A* and can either perform the standard algorithm or can ignore a given edge.

Random Maze Generation (Kruskal's Algorithm)

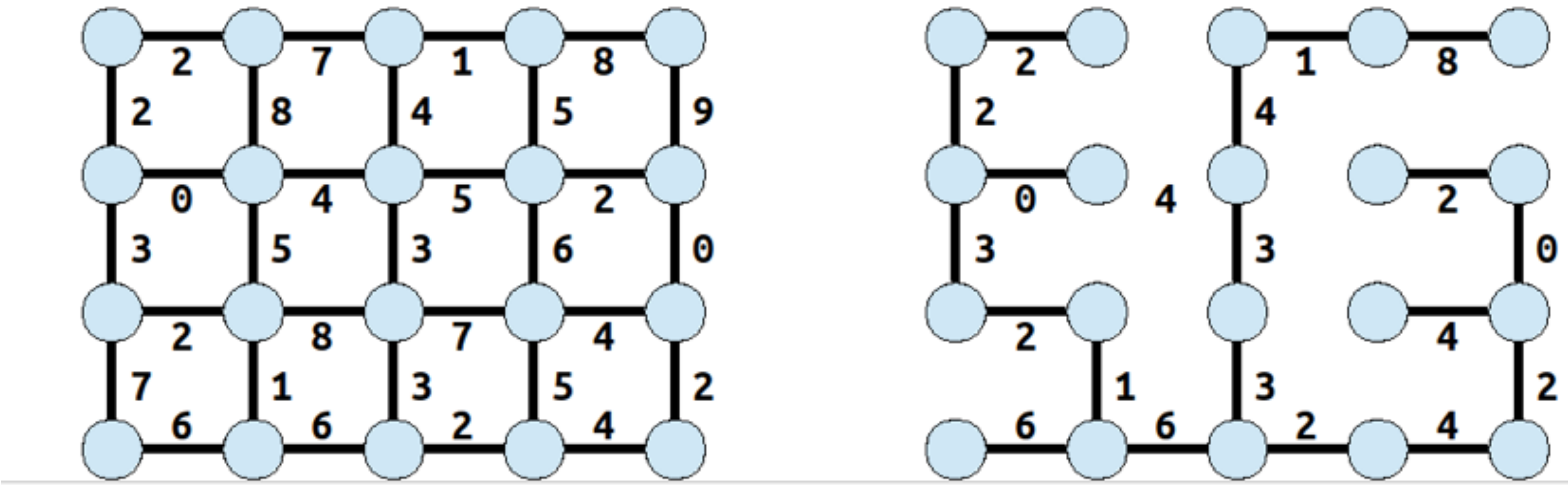
Your final task in this assignment is to implement **Kruskal's algorithm** for finding a minimum spanning tree. Your function should accept a graph as a parameter, and you should return a set of pointers to edges in the graph such that those edges would connect the graph's vertexes into a minimum spanning tree. (Don't actually add/remove edges from the graph object passed in by calling `addEdge`, `removeEdge`, etc. on it. Just return the set of edges separately.) Specifically, your task is to write a function with the following signature:

```
Set<Edge*> kruskal(BasicGraph& graph)
```

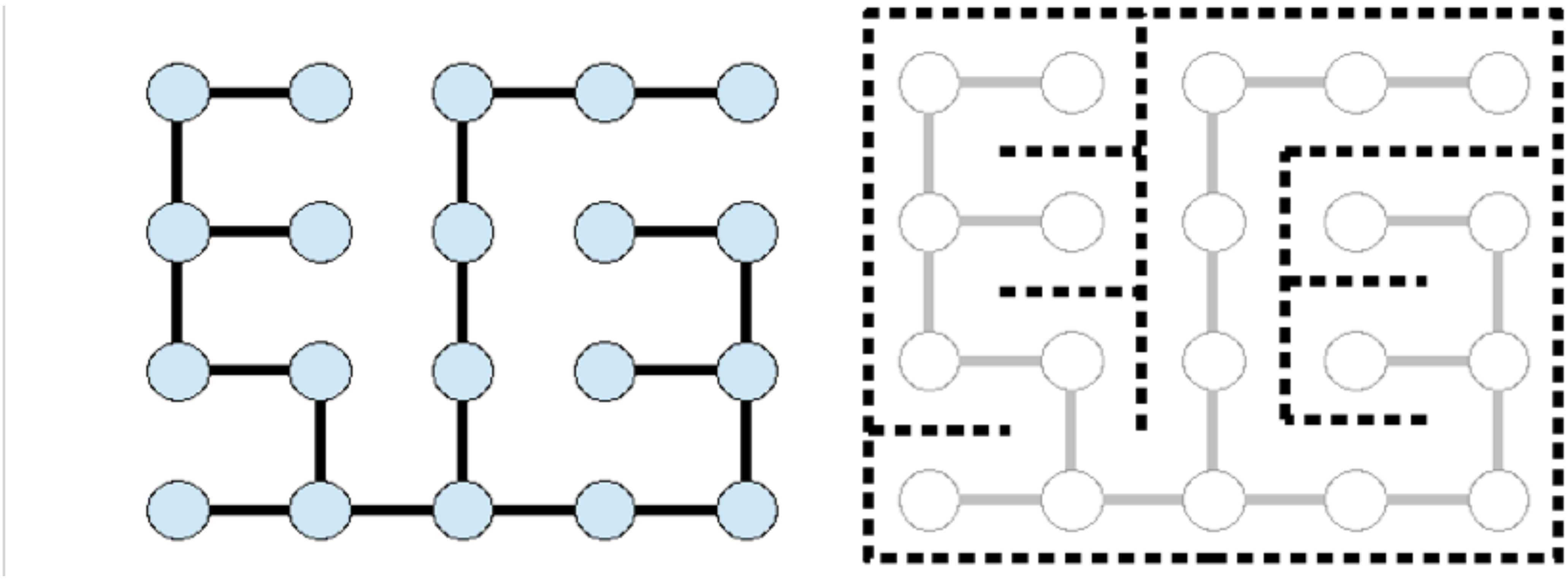
The specific application we'll Kruskal's algorithm to solve is the problem of generating new random mazes. As discussed earlier in this handout, you can think of a maze as a graph, where the vertexes are connected as follows. The following figure would be a fully connected maze with no walls:



If you assign each edge a random weight and then run Kruskal's algorithm on the resulting graph, you will end up with a spanning tree; there will be exactly one path between each pair of vertexes. For example, assigning the edges in the above graph weights as follows and running Kruskal's algorithm would produce the following result:



In the above tree, lines represent edges between connected neighbors, which are passable. Neighbors that are not connected by an edge can be thought of as having an impassable "wall" between them. You can turn the above tree into a maze by drawing lines in all of the empty space, as shown here:



Whenever you click the GUI's "Load" button with one of the "Random" options selected, our starter code will generate a maze of the given size with every vertex connected to all of its neighbors, as in the "fully connected" maze figure above. **Our code will randomly assign weights to each edge for you**; you shouldn't change the weights we pass in. Then we will pass the graph to your algorithm for you to find the minimum spanning tree. Once you return your set of edges, our starter code will process your set and fill in "walls" between any neighbors that are not directly connected by an edge. The resulting maze will show in the GUI. Once you've made a maze, you can run your path-finding algorithms to locate paths between points in the maze. Implementing this function raises questions such as:

- How will you keep track of which nodes are in each cluster?
- How will you determine which cluster a node belongs to?
- How will you merge together two clusters?

Think about these issues yourself and come up with a clean and efficient way of solving the problem. Our own sample solution is able to generate "Large" sized mazes in a few seconds' time at most, and you should strive for similar efficiency. If your maze generation algorithm takes, say, close to a minute or more to finish, optimize it.

Creative Aspect (map-custom.txt and map-custom.jpg):

Turn in files **map-custom.txt** and map-custom.jpg representing a map graph of your own. Put the files into the **res/** folder of your project. The text file contains information about the graph's vertexes and edges. The graph can be whatever you want, so long as it is not essentially the same as any of the provided graphs. Your image can be any (non-offensive) JPEG image you like; we encourage you to use a search engine like Google Image Search to find an interesting background. The text file's format should exactly match the following example, from **map-small.txt**. For full credit, your file should load successfully into the program without causing an error and be searchable by the user.

```
IMAGE
map-usa.jpg                                 ←      image file name
654                                         ←      image width, in pixels
399                                                image height, in pixels

VERTEXES
Washington, D.C.;536;176                    ←      vertex format is: name;x;y
Minneapolis;349;100
San Francisco;26;170

EDGES
Minneapolis;San Francisco;1777              ←      edge format is: vertex1;vertex2;weight
Minneapolis;Washington, D.C.;1600                  (or, for a directed one-way edge:
San Francisco;Washington, D.C.;2200                vertex1;vertex2;weight;true )
```

Development Strategy and Hints:

- **Trace through the algorithms** by hand on small sample graphs before coding them.
- **Work step-by-step.** Complete each algorithm before starting the next one. You can test each individually even if others are incomplete. We suggest doing DFS/BFS, then Dijkstra's, then A*, and finally Kruskal's.
- **Start out with tiny worlds first.** It is much easier to trace your algorithm and/or print every step of its execution if the world is small. Once your output matches perfectly on tiny files, go to small, medium, large.
- In Dijkstra's algorithm, you cannot call `changePriority` on a vertex that is not already in the queue. You also cannot call changePriority with a priority less urgent (greater) than the existing priority in the queue.
- Remember that edge weights are `doubles`, not `ints`.
- In A* search, when storing the candidate distance to a vertex, *do not* add the heuristic value in. The heuristic is only used when setting the priorities in the priority queue.
- Don't forget to keep your record of each vertex's "previous" neighbor up-to-date in Dijkstra's algorithm or A* search. Otherwise, though you'll dequeue the vertexes in the proper order, your resulting path might end up incorrect.
- In Dijkstra's algorithm, don't stop your algorithm early when you enqueue the ending vertex; stop it when you *dequeue* the ending vertex (that is, when you color the vertex green).
- When merging clusters together in Kruskal's algorithm, remember that every vertex in the same cluster as either endpoint (not just the endpoints themselves) should be merged together into one resulting cluster.

Style Details:

As in other assignments, you should follow our **Style Guide** for information about expected coding style. You are also expected to follow all of the general style constraints emphasized in the Homework 1-6 specs, such as the ones about good problem decomposition, parameters, redundancy, using proper C++ idioms, and commenting. The following are additional points of emphasis and style contraints specific to this problem.

Graph algorithms: Part of your grade will come from appropriately utilizing the graph objects passed to your function. You will also be graded on whether you properly implement the various path-searching algorithms and Kruskal's algorithm as described in class. Many algorithms ask you to mark various vertexes as being "visited" or as having a certain "cost" or "weight", etc.; it is up to you to write an elegant and efficient representation of such state in your algorithms.

Memory usage: Your code should have no memory leaks. Free the memory associated with any new objects you allocate on the heap.

Frequently Asked Questions (FAQ):

For each assignment problem, we receive various frequent student questions. The answers to some of those questions can be found by clicking the link below.

Trailblazer FAQ (click to show)
Trailblazer FAQ (click to show)

Possible Extra Features:

Here are some ideas for extra features that you could add to your program for a small amount of extra credit:

- **Implement bidirectional search:** A common alternative to using A* search is to use a bidirectional search algorithm, in which you search outward from both the start and end vertexes simultaneously. As soon as the two searches find a vertex in common, you can construct a path from the start vertex to the end vertex by joining the two paths to that vertex together. Try coding this algorithm up as a fifth algorithm choice.
- **Implement a disjoint-set forest:** When implementing Kruskal's algorithm, you need a way to keep track of which vertexes in the graph are connected to one another. While it's possible to do this using the standard collections types, there is a much faster way to do this using a *disjoint-set forest*, a specialized data structure that makes it easy to determine if two vertexes are connected and to connect pairs of vertexes. It is not particularly hard to code up a disjoint-set forest, and doing so can dramatically reduce time required to create a maze.
- **Make a new world type:** The existing code has several classes that extend a superclass World to represent maps, mazes, and terrains. Add your own new subclass for a type of world that we didn't include.
- **Write better heuristics:** The heuristics we have provided for estimating terrain weights and map / maze distances are simple admissible heuristics that work reasonably well. Try seeing if you can modify these functions to produce more accurate heuristics. If you do this correctly, you can cut down on the amount of unnecessary searching required. However, make sure that your heuristics are admissible; that is, they should never overestimate the distance from any starting vertex to any destination vertex.
- **Write another maze-generation algorithm:** Kruskal's algorithm is only one of many ways to generate a random maze. Another minimum spanning tree algorithm called Prim's algorithm can also be used here to generate random mazes. Try adding Prim's algorithm in addition to Kruskal's algorithm for maze generation. Can you generate more complicated mazes and maps?
- **Write a better terrain generator:** Our starter code generates terrain uses the diamond-square algorithm, coupled with a Gaussian blur. Many other algorithms exist that can generate random terrains, such as the 2D Perlin Noise algorithm. Try implementing a different terrain generator and see if it produces better results.
- **Better alternate path:** The alternate route algorithm is slow and not guaranteed to find the best alternate. Can you come up with a different algorithm that is faster or that uses a more realistic measure of path distance?
- **Other:** If you have your own creative idea for an extra feature, ask your SL and/or the instructor about it.

Indicating that you have done extra features: If you complete any extra features, then in the comment heading on the top of your program, please list all extra features that you worked on and where in the code they can be found (what functions, lines, etc. so that the grader can look at their code easily).

Submitting a program with extra features: Since we use automated testing for part of our grading process, it is important that you submit a program that conforms to the preceding spec, even if you want to do extra features. If your feature(s) cause your program to change the output that it produces in such a way that it no longer matches the expected sample output test cases provided, you should submit two versions of your program file: a first one with the standard file name without any extra features added (or with all necessary features disabled or commented out), and a second one whose file name has the suffix **-extra.cpp** with the extra features enabled. Please distinguish them in by explaining which is which in the comment header. Our turnin system saves every submission you make, so if you make multiple submissions we will be able to view all of them; your previously submitted files will not be lost or overwritten.

Survey: After you turn in the assignment, we would love for you to fill out our anonymous CS 106B homework survey to tell us how much you liked / disliked the assignment, how challenging you found it, how long it took you, etc. This information helps us improve future assignments.

Honor Code Reminder: Please remember to follow the **Honor Code** when working on this assignment. Submit your own work and do not look at others' solutions. Also please do not give out your solution and do not place a solution to this assignment on a public web site or forum. If you need help, please seek out our available resources to help you.