

Lab 3: Frugal Maps

The questions below are due on Friday February 28, 2020; 04:00:00 PM.

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1) Preparation

This lab assumes you have Python 3.6 or later installed on your machine.

The following file contains code and other resources as a starting point for this lab: [lab3.zip](#)

Most of your changes should be made to `lab.py`, which you will submit at the end of this lab. Importantly, you should not add any imports to the file.

You can also see and participate in online discussion about this lab in the ["Lab 3" Category](#) in the forum.

This lab is worth a total of 4 points. Your score for the lab is based on:

- correctly answering the questions throughout this page (1 point)
- passing the `test.py` tests on the server (1 point, see below), and
- a brief "checkoff" conversation with a staff member to discuss your work, and a review of your code's clarity/style (2 points).

Note that passing all of the tests on the server will require that your code runs reasonably efficiently, and that it makes reasonably efficient use of memory.

The questions in section 2 on this page are due before lecture, at 1:30pm on Monday, 24 Feb. The remaining questions on this page (including your code submission) are due at 4pm on Friday, 28 Feb. Checkoffs are due at 10pm on Wednesday, 4 Mar.

2) Introduction

In this lab, you will be working with freely-available¹ real-world mapping data to solve the realistic large problem of finding the shortest (or fastest) path between two points on a map. You will implement the backend for a route-finding application, which we will be able to use to plan paths around Cambridge.

2.1) The Data

The data we'll use for this lab comes from [OpenStreetMap](#), and for the bulk to this lab, we are working with data about Cambridge and the surrounding area (about 650 MB of data). While the raw data (downloaded from [here](#)) was specified in the [OSM XML Format](#), we have done a little bit of pre-processing to convert the data to a format that is slightly easier to work with.

As in the original format, we have divided the data into two separate pieces: a list of "nodes" (representing individual locations), and a list of "ways" (representing roads or other kinds of connections between nodes). We have stored these data in large files that contain many [pickled](#) Python objects, one for each node/way (the function we used to do this is made available to you in the `util.py` file as `osm_to_serial_pickles`, in case you want to try it on your own data).

The Cambridge data set stores these in two files, which are available in the code distribution: `resources/cambridge.nodes` and `resources/cambridge.ways`.

We have also provided a helper function in `util.py` called `read_osm_data` (which has been imported into `lab.py` for you). Calling `read_osm_data` with a filename will produce an object over which you can loop to examine each node/way in turn. For example, you could use the following code to print all of the nodes in this database:

```
for node in read_osm_data('resources/cambridge.nodes'):
    print(node)
```

One important thing worth noting is that this object can only be looped over once (looping over the same data again would require calling `read_osm_data` again).

Each node (representing a location) is represented as a dictionary containing the following keys:

- `'id'` maps to an integer ID number for the node
- `'lat'` maps to the node's latitude (in degrees)
- `'lon'` maps to the node's longitude (in degrees)
- `'tags'` maps to a dictionary containing additional information about the node, including information about the type of object represented by the node (traffic lights, speed limit signs, etc).

Each way (representing an ordered sequence of connected nodes) is represented as a dictionary with the following keys:

- `'id'` maps to an integer ID number for the way
- `'nodes'` maps to a list of integers representing the nodes that comprise the way (in order)
- `'tags'` maps to a dictionary containing additional information about the way (e.g., is this a one-way street? is it a highway or a pedestrian path? etc.)

Try printing out the nodes and ways to get a sense for the kind of information that is available there, and then use Python to answer the following questions about the database.

How many total **nodes** are in the database?

(Hint: it may take a long time and use a large amount of memory to make a big list containing all the nodes; try looping over the result from `read_osm_data` instead).

This question is due on Monday February 24, 2020 at 01:30:00 PM.

Some of the nodes have a name associated with them (by virtue of having a `'name'` entry in their `'tags'` dictionary). How many of the nodes have a name?

This question is due on Monday February 24, 2020 at 01:30:00 PM.

What is the ID number of the node named `'77 Massachusetts Ave'`?

This question is due on Monday February 24, 2020 at 01:30:00 PM.

How many total **ways** are in the database?

This question is due on Monday February 24, 2020 at 01:30:00 PM.

How many of these are one-way streets? (Hint: look at the 'oneway' key in the 'tags' dictionary if it exists to make a decision; if that key doesn't exist, assume the road is two-way)

This question is due on Monday February 24, 2020 at 01:30:00 PM.

This might give you a sense of the scale of the database we're working with; there's a lot of information here!

2.2) Testing

We have provided three datasets for you to work with as you are testing your code, and also a visualization (see [section 3.3](#)).

As you are debugging, you may wish to primarily make use of the `mit` data set (which contains some manually-constructed nodes and ways), which is relatively small compared to the others (to the extent that it should be possible to manually compute some relevant results after printing out the nodes and ways contained therein).

`midwest` is quite a bit larger, so it may not be possible to manually compute results from it, but it should load relatively quickly, so it can be used for testing on a slightly larger scale (using the visualization, for example).

`cambridge` is *really* big, and so working with it can take a while. As such, you may not want to do too much testing with it until you are reasonably sure that things are working. However, once things *are* working, it can be neat to plan paths through Cambridge and the surrounding area using the visualization.

3) Shortest Paths

Now that we've had a chance to get used to the format of the data set, we'll embark on our first of two tasks for the lab: finding the shortest path between two locations. Ultimately, we will implement this as a function `find_short_path` in `lab.py`. This function takes three arguments:

- `aux_structures`: some structures of your creation (see below)
- `loc1`: a tuple of (latitude, longitude) of our starting location
- `loc2`: a tuple of (latitude, longitude) of our ending location

We are interested in returning the shortest path (in miles) between those two locations.

Ultimately, `find_short_path` should return a list of (latitude, longitude) tuples (each corresponding to a single node) representing a path between the two given locations, where each pair of adjacent nodes must be connected by a way. If no such path exists, you should return `None`.

You can make use of the ideas introduced in lecture on 24 Feb, or look [here](#) for a brief overview of one appropriate algorithm.

3.1) Design Considerations

This procedure is fairly complicated, and so are the data we're given, so we'll clarify a few things and make a few small simplifying assumptions, as indicated below.

3.1.1) Road Types

The datasets we're working with contain information not only about roadways, but also about bicycle paths, pedestrian paths, buildings, etc. Since we are (for now, at least) planning paths for cars only, we will only consider a way to be valid for our purposes if it is a roadway (we're responsible citizens of the world, so we won't drive on a bike path or a pedestrian-only walkway).

Some ways in the dataset have a tag called 'highway', indicating that the path represents a path people can use to travel (as opposed to the outline of a building, a river, the outline of a park, etc). We will use this tag to decide what kinds of ways to include in our results.

In particular, we'll only consider a way as part of our path-planning process if:

- it has a 'highway' tag, **and**
- its 'highway' tag is in the `ALLOWED_HIGHWAY_TYPES` set that is defined at the top of `lab.py`.

(Ways that don't have these properties should be ignored completely)

3.1.2) Connectedness

We will assume that we can travel from a node to another node if and only if there is a way that connects them. For example, if we have the following two ways in the database:

```
w1 = {'id': 1, 'nodes': [1, 2, 3], 'tags': {}}
w2 = {'id': 2, 'nodes': [5, 6, 7], 'tags': {'oneway': 'yes'}}
```

then moving from node 1 to node 2, from 2 to 3, from 3 to 2, or from 2 to 1 are all OK because `w1` represents a bidirectional street. But, while moving from 5 to 6 or from 6 to 7 are OK, moving from 7 to 6 or from 6 to 5 are **not** OK because `w2` represents a one-way street (we're responsible citizens of the world, so we respect one-way restrictions).

Note that moving directly from node 1 to node 3 is **not** possible given the above, unless there is another way that directly connects those two nodes.

As we're planning paths between nodes, we'll want to make sure that we only consider a node as a possibility if it exists as part of a way (we can ignore all other nodes in the database).

3.1.3) Distance Measure

Throughout this lab, we will use an approximation for distance (in miles) that takes into account the approximate curvature of the earth. This approximation has been defined as a function `great_circle_distance` in `util.py` (and it has been imported into `lab.py` for your use).

You should not use any other distance measure for this lab, as the test cases expect you to use this measure of distance.

What is the distance (in miles) between the following two locations, specified in terms of latitude and longitude?

Location 1: (42.363745, -71.100999)

Location 2: (42.361283, -71.239677)

Enter your answer as accurately as Python provides it to you; don't round!

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In the `midwest` dataset, what is the distance (in miles) between the nodes with the following ID numbers?

ID 1: 233941454

ID 2: 233947199

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In the `midwest` dataset, there is a way with ID number 21705939. If we were to follow that way from its beginning node to its ending node (and through all the intermediate nodes), how many miles would we have traveled?

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3.1.4) Starting and Ending Points

It is entirely possible that the locations passed to `find_short_path` will not correspond exactly to a node in the dataset. As such, we will instead plan our shortest paths as follows, where a "relevant" way refers to any way that we will actually consider in our path planning (i.e., one that has not been ignored by the rules in [section 3.1.1](#)):

- finding the nearest node to `loc1` that is part of a relevant way (call this node n_1)
- finding the nearest node to `loc2` that is part of a relevant way (call this node n_2)
- finding the shortest path from n_1 to n_2 (in terms of miles)

After finding n_1 and n_2 , we will ignore `loc1` and `loc2` completely during the search process. They should not show up in the path, and they should not be considered when computing the total distance represented by the path.

In the `midwest` dataset, what is the ID number of the nearest relevant node to location (41.4452463, -89.3161394), i.e., the nearest node to that location that is part of a way we'll actually consider in our path-planning?

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3.2) Auxiliary Data Structures

As we saw in lab 2, the choice of internal data structures is going to be important (in fact, this is even more true in this lab, which makes use of a *lot* more data than lab 2).

As such, you are free to create whatever data structures you like by filling in the `build_auxiliary_structures` function in `lab.py`. The object returned by this function will be passed in as the first argument to your path finding functions.

The ultimate goal of these auxiliary structures is to be able to quickly answer questions about the data that we'll need to answer repeatedly (without looping over the whole dataset). We set things up this way so that we can build these structures once, and then use them multiple times to compute various results. As such, it is OK for this function to be a bit slow, so long as it saves time during the actual search process.

However, it may not be possible to store all of the nodes or all of the ways in memory (so if there are nodes and/or ways that you know will be irrelevant, you should not store them in memory).

3.3) Visualization

As with the last lab, we have provided a web-based interface that acts as a visualization for your code.

Here, we use [leaflet](#) to display map data from the Wikimedia foundation (more information about their Maps service is available [here](#)).

You can start the server by running `server.py` but providing the filename of one of the datasets as an argument, for example:

```
python3 server.py midwest
```

or

```
python3 server.py cambridge
```

(if you are not using a terminal to run your code, you can replace `sys.argv[1]` in `server.py` with a hard-coded name of a dataset, like `'midwest'`, which you can then change later to load in different datasets).

This process will first build up the necessary auxiliary structures for pathfinding by calling your `build_auxiliary_structures` function, and then it will start a server. After the server has successfully started, you can interact with this application by navigating to `http://localhost:6009/` in your web browser. In that view, you can double-click on two locations to find and display a path between them.

Alternatively, you can manually call your path-finding procedure to generate a path, and then pass its path to the provided `to_local_kml_url` function to receive a URL that will initialize to display the resulting path. For example, to show a path from Adam's high school to Timber Edge Alpaca Farms (where Adam worked in high school), you could run the following:

```
phs = (41.375288, -89.459541)
timber_edge = (41.452802, -89.443683)
aux = build_auxiliary_structures('resources/midwest.nodes', 'resources/midwest.ways')
print(to_local_kml_url(find_short_path(aux, phs, timber_edge)))
```

which should print out a URL that, when pasted into the browser, shows the path you found (assuming the server is running). If you started the server with the `midwest` dataset loaded, you can then double-click around that area to find other paths.

4) Improving Runtime With Heuristics

By now, your code should be working for planning paths, and it should be passing the test cases associated with `find_short_path`. In this section, we'll introduce an optimization that will allow us to speed up our searches while retaining the optimality of the paths we return.

The method for finding minimum-cost paths described on the page linked above involves searching radially outward from a starting point in terms of increasing cost, but it does not take into account information about where the goal is, and so it can waste time considering paths that don't really make sense (for example, paths that move off in the wrong direction, away from the goal position).

We consider those paths because our search process was deciding which paths to consider based on the total cost of the path so far, let's call it $g(n)$:

$g(n)$ = the path cost from the starting node to node n

When we have multiple paths we could consider, we always start with the one that has the smallest $g(n)$ value (the shortest total distance in miles), with no regard for whether that path was moving in a sensible direction or not. While this does guarantee that we end up with an optimal path, it wastes time.

We can do a bit better by introducing the notion of a *heuristic function* $h(n)$:

$h(n)$ = the estimated cost of the lowest-cost path from node n to the goal node

From this, we can derive a new function:

$$f(n) = g(n) + h(n)$$

Because $g(n)$ represents the path cost from the start node to node n , and $h(n)$ is the estimated cost of the lowest-cost path from n to the goal, we have:

$f(n)$ = the estimated cost of the lowest-cost solution involving n

Because the total cost of the path is the thing we're trying to optimize, we can make a slight change to the algorithm from above: when we have multiple paths to consider, we should always choose the one with the lowest $f(n)$ value as the next path to be considered (i.e., the one with the lowest estimated total path cost). By so doing, we can focus our attention on paths that kind of move toward the goal, and avoid wasting time considering other paths. The most effective heuristics will be easy to compute but will be reasonably accurate estimates of the cost of the optimal path to the goal.

Note that the introduction of a heuristic does not change the **cost** of the paths, only the order in which we consider the various paths.

4.1) Heuristics and Optimality

Interestingly, as long as we're careful with the design of our heuristics, we can get this benefit without sacrificing the optimality of the path we return, so long as our heuristic has a couple of properties, which we call *admissibility* and *consistency*:

- a heuristic is *admissible* if it never overestimates the cost of the optimal path from any node to the goal, i.e., for all nodes n :

$$h(n) \leq c^*(n)$$

where $c^*(n)$ represents the actual cost of the least-cost path to the goal.

- a heuristic is *consistent* if the value of the heuristic never increases as we get closer to the goal. More precisely, a heuristic is consistent if, for each node n and each successor n' of that node, the heuristic evaluated at n is no more than the heuristic evaluated at n' plus the cost of traveling directly from n to n' :

$$h(n) \leq c(n, n') + h(n')$$

If these two properties hold for our heuristic function $h(n)$, then we are guaranteed that we will still find an optimal path if we sort our agenda according to $f(n) = g(n) + h(n)$.

4.2) A Heuristic For This Problem

Given the above, a reasonable heuristic in this domain is the distance directly from the given node to the goal node:

$$h(n) = \text{great_circle_distance}(n, \text{goal})$$

This function provides a decent estimate of our overall cost, it is admissible and consistent, and it is pretty fast to compute. As such, we should expect that it will do a decent job of improving the efficiency of our search procedure.

To test this theory, try running a search between the following two locations using the `cambridge` dataset, both *with* and *without* the heuristic, and make note of *the total number of paths we pull off of the agenda in each case*. How do those two numbers differ?

- Location 1: (42.3858, -71.0783)
- Location 2: (42.5465, -71.1787)

Be prepared to discuss these results, including how you computed them, during your checkoff conversation.

5) Need for Speed (Limits)

So far, our planning has been based purely on distance, but oftentimes, when planning a route between two locations, we are actually interested in the amount of *time* it will take to move from one location to another.

For the last part of this lab, you should implement `find_fast_path`, which, unlike `find_short_path`, should take into account speed limits (we're responsible citizens of the world, so we won't drive over the speed limit).

Some ways in the dataset store information about the speed limit along that way. That said, unfortunately, speed limit information is somewhat sparse in OSM data (at least in these datasets), and so we'll have to guess a little bit for some of

the roads. We have done a little bit of preprocessing of the data for you, to make extracting this information a little bit easier than it would otherwise be.

For each way, we'll determine the speed limit as follows:

- if the way has the 'maxspeed_mph' tag, the corresponding value (an integer) represents the speed limit in miles per hour
- if that tag does not exist, look up the way's 'highway' type in the `DEFAULT_SPEED_LIMIT_MPH` dictionary and use the corresponding value.

If two nodes are connected by more than one way with distinct speed limits, you should always prefer higher of the two speed limits.

Note that implementing this new function might require changing or reorganizing your code for `find_short_path` and/or for `build_auxiliary_structures`. Even if it isn't required for functionality, you may also be presented with opportunities to refactor your `lab.py` to avoid duplicated code.

5.1) Heuristics

With this new notion of optimality, the heuristic function from earlier is no longer admissible (so we are no longer guaranteed to return an optimal path!).

As such, for this part of the lab, it is fine not to use a heuristic; but you may find it interesting to try to come up with an effective heuristic that is admissible and consistent given this new measure of cost, in order to speed up your search.

5.2) Visualization

If, after starting `server.py`, you open the following URL in your browser (note the difference from above), the web UI will use your `find_fast_path` instead of `find_short_path` for pathfinding when double-clicking:

```
http://localhost:6009/?type=fast
```

Try using both this and the shortest-path metric between a few different points on the Cambridge map. How would you expect those to differ? Do your results match your expectation?

During the checkoff, you will be asked to demonstrate your code running in the UI by finding both the shortest and fastest paths from Waltham, MA (west of Cambridge on the map) to Salem, MA (north and east of Cambridge) using the cambridge data set. As such, please make sure that you've got the server running with the cambridge dataset loaded when you ask for your checkoff.

6) Code Submission

When you have tested your code sufficiently on your own machine, submit your modified `lab.py` below. Note that your checkoff (including style considerations) will be based on your most recent submission, and that all aspects of the file will be considered in terms of style, including those that are not explicitly tested in `test.py` (for example, any helper functions you write).

When submitting `lab.py`, the server will run the tests and report back the results (including timing). Submit your `lab.py` in the box below:

No file selected

This question is due on Friday February 28, 2020 at 04:00:00 PM.

7) Checkoff

When you are ready, please come to a lab session or office hour and add yourself to the queue asking for a checkoff. **You must be ready to discuss your code in detail before asking for a checkoff.** Since the clarity of your code will be evaluated as part of the checkoff, you may wish to take some time to comment your code, use good variable names, avoid repetitive code (create helper methods), etc.

Be prepared to discuss:

- What auxiliary data you stored in `build_auxiliary_structures`, and why.
- Your implementation of `find_short_path`.
- Imagine using a BFS (as discussed in tutorial 2) to find shortest paths, instead of this method. What might we expect to be different about the paths returned from BFS, versus the paths we're returning here?
- Your implementation of the heuristic function, and the effect that it had on the number of total paths we considered in the course of our search.
- Your implementation of `find_fast_path`, and how it differs from `find_short_path`.
- Demonstrate your code running in the UI by finding both the shortest and fastest paths from Waltham, MA (west of Cambridge on the map) to Salem, MA (north and east of Cambridge) using the `cambridge` data set. What differentiates these paths? Why do they look the way they do?

7.1) Grade

You have not yet received this checkoff. When you have completed this checkoff, you will see a grade here.

8) (Optional) Extra Pieces

If you are interested, there are a number of ways you could modify or build on the code from this lab to do some other kinds of cool things! Here are a few ideas, and we're happy to help if you're interested to work on any of these (or on other ideas of your own!):

1. Import data from your own home state / home country! You can download data from <http://download.bbbike.org/osm/> or <https://download.geofabrik.de/> and use the `osm_to_serial_pickle` function in `util.py` to get convert the data to the format used in this lab.

But be warned that if you're importing data from a country that uses a sensible measure of speed like `kph`, the speed limit calculations might be a bit off, since they assume `MPH`...so that might require some other adjustments.

2. Implement an admissible heuristic for the version of the code that takes speed limits into account.
3. Use the route planning for bicycles or pedestrians rather than motorists by modifying the "highway" types that are allowed. See [this page](#) for a list of "highway" types, and note also that many ways contain information about bicycle travel.

Note that you probably won't be able to implement the 'speed limit' behavior in this case :)

4. Often times, there are considerations other than speed limit that factor in to what makes a path desirable. You could take this into account by introducing a penalty (in terms of cost) for paths that move through nodes that are labeled as traffic lights, or for any time we transition between ways, or something like that.
5. Depending on how you implemented your search process, you might have been storing (cost, path) tuples or something like that, and using `sort` to sort that list each time through a loop. While this definitely works, there are ways to make that process much more efficient, in particular by using the structures from the [heapq](#) module, which provides a nice set of abstractions for maintaining a sorted list of items efficiently (you are welcome to import this module if you wish).
6. Depending on how you implemented things, you may find that a lot of the time spent planning paths between two locations is actually spent looking up the two nodes that we want to use as our starting and ending points. So you might try to find a way to speed that process up.
7. As it currently stands, we are ignoring a large class of tags called "relations" in the OSM data, which include restrictions on driving such as "no left turns." You could try modifying your code to take these relations into account.

Footnotes

¹ In fact, all of the software and data we are working with in this lab is freely available, including the mapping data, the images used to render the maps, and the software used to control the map display! In fact, a lot of the world's most-widely-used software is created in this same spirit of sharing and community. If you are interested in exploring the philosophical ideas behind these movements, a place to start would be the Wikipedia articles on the [Free/Libre Software](#) and [Free-culture](#) movements. Or talk with Adam (who is passionately interested in these ideas).