shapely

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1 Introduction to Shapley

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We begin our series on geospatial data analysis with a look at the library Shapely. Shapely supports the creation, manipulation, and analysis of planar geometric objects. Its role in the Python geospatial ecosystem is to provide fundamental support for vector data models, which in turn are built up from points, lines, and polygons.

1.0.1 Objectives

- Understand the purpose of Shapely
- Gain familiarity with core geometric types (Point, LineString, Polygon, and their collection types)
- Explore deterministic spatial analysis and relationships

1.0.2 Basic Imports

We will utilize a common set of imports across notebooks to facilitate plotting:

```
In [1]: import matplotlib
        import matplotlib.pyplot as plt
        import numpy as np
        %matplotlib inline
```

Matplotlib is the workhorse of visualization in Python so we import it first. We also alias `matplotlib's` `pyplot` module as `plt`. `numpy` is the core mathematical library for Python and we alias it as `np`. Finally, we use the Jupyter *magic* `%matplotlib inline` to ensure that any plots we generate are shown within the notebook itself (i.e., inline).

2 Basic Geometric Types

2.1 Points

Our first primitive geometry type is a **Point**. We import the class for creating point objects from shapely's `geometry` module:

```
In [2]: from shapely.geometry import Point
```

With the class imported, we can instantiate two example points:

```
In [3]: p_1 = Point((2.0, 5.0))
        p_2 = Point((4.0, 7,0))
```

and inspect their values:

```
In [4]: p_1
```

```
Out[4]:
```

and here:

```
In [5]: p_2
```

```
Out[5]:
```

As we see, the inspection generates a plot of the point object. Shapely is a geometric library so this makes sense.

We can introspect the point object to learn more:

```
In [6]: p_1.xy
```

```
Out[6]: (array('d', [2.0]), array('d', [5.0]))
```

and we learn that the coordinates for `p_1` are stored in an attribute that is of type `numpy array`.

If we want to check the `type` of of Python object we do so as follows:

```
In [7]: type(p_1)
```

```
Out[7]: shapely.geometry.point.Point
```

So points are straightforward, we pass in a tuple of x,y coordinates and we get back a point object.

While simple, they are useful in that they can do things. Things like measure the distance from each other:

```
In [8]: p_1.distance(p_2)
```

```
Out[8]: 2.8284271247461903
```

and

```
In [9]: p_2.distance(p_1)
```

```
Out[9]: 2.8284271247461903
```

Points are zero-dimensional geometric objects, meaning they do not have area or length.

2.2 LineStrings

Our next geometric type is a `LineString`. This is a sequence of points connected with a segment. We import the class in the same way we did for our `Point` class:

```
In [10]: from shapely.geometry import LineString
```

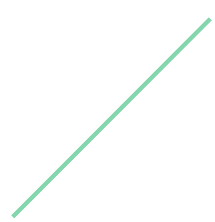
Let's now reuse our two point objects as arguments to construct the first `LineString`:

```
In [11]: l_1 = LineString([(2.0, 5.0), (4.0,7.0)])
```

and we get:

```
In [12]: l_1
```

```
Out[12]:
```



which plots the single segment for our `LineString` object.

`LineStrings` are one-dimensional, and that dimension is *length*:

```
In [13]: l_1.length
```

```
Out[13]: 2.8284271247461903
```

And, again, we can check the objects type:

```
In [14]: type(l_1)
```

```
Out[14]: shapely.geometry.linestring.LineString
```

Like, points, `LineStrings` also have a distance method:

```
In [15]: p_3 = Point(3, 5)
         l_1.distance(p_3)
```

```
Out[15]: 0.7071067811865476
```

Note, this is the minimum distance between `l_1` and `p_3`:

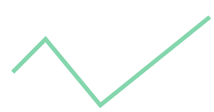
```
In [16]: p_3.distance(p_1) > l_1.distance(p_3) and p_3.distance(p_2) > l_1.distance(p_3)
```

```
Out[16]: True
```

LineStrings can have more than a single pair of points:

```
In [17]: l_2 = LineString([(2.0, 4.0), (5.0, 7.0), (10,1), (20,9)])
         l_2
```

```
Out[17]:
```



and this is a longer object:

```
In [18]: l_2.length > l_1.length
```

```
Out[18]: True
```

A very useful construct is a *bounding rectangle* which is a rectangle that contains a geometric object. We can get the coordinates for the bounding rectangle for `l_2` as follows:

```
In [19]: l_2.bounds
```

```
Out[19]: (2.0, 1.0, 20.0, 9.0)
```

Bounding rectangles are used to filter objects when testing for different types of spatial relationships, such as containment, intersection, touching, and more. We will return to these below.

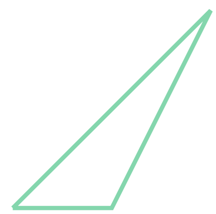
2.3 LinearRings

An ordered sequence of point tuples can be used to construct a `LinearRing`. At first glance this seems redundant, since a `LineString` is an ordered sequence of point tuples. However, a `LinearRing` is distinct from a `LineString` in four ways:

- The sequence will be closed (i.e., the first and last point will be equal)
- It does not cross itself
- It does not touch itself at a single point

```
In [20]: from shapely.geometry.polygon import LinearRing
         r1 = LinearRing([(2.0, 5.0), (4.0, 7.0), (3.0, 5.0)])
         r1
```

Out[20]:



We see that the ring is closed even though the last point tuple we passed in was not equal to the first.

Although the ring looks like a polygon (our next geometric primitive), it isn't one as the ring has zero-area:

```
In [21]: r1.area
```

```
Out[21]: 0.0
```

but it does have length:

```
In [22]: r1.length
```

```
Out[22]: 6.06449510224598
```

and its coordinates can be obtained as:

```
In [23]: list(r1.coords)
```

```
Out[23]: [(2.0, 5.0), (4.0, 7.0), (3.0, 5.0), (2.0, 5.0)]
```

Again, note the additional point tuple beyond what we passed in when creating the ring above.

2.4 Polygons

Our fourth geometry type is a **Polygon**:

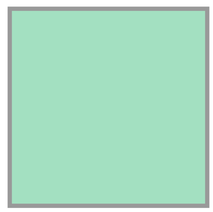
```
In [24]: from shapely.geometry import Polygon
```

`Polygon` takes two positional arguments, where the first is a sequence of ordered point tuples that define the polygon's exterior ring, and the second is a sequence of interior rings that define holes.

For example, let's start with a simple polygon with a single exterior ring:

```
In [25]: poly_1 = Polygon([(0, 0), (10, 0), (10, 10), (0, 10)])
         poly_1
```

Out[25]:



Like the `LinearRing` the polygon will be closed if we don't do so explicitly. However, unlike the `LinearRing` the `Polygon` will have non-zero area:

```
In [26]: poly_1.area

Out[26]: 100.0
```

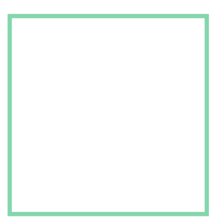
`Polygons` have length:

```
In [27]: poly_1.length

Out[27]: 40.0
```

and an exterior:

```
In [28]: poly_1.exterior
```

Out[28]:



which is a LinearRing:

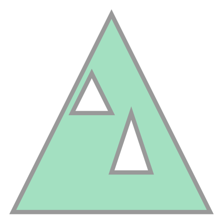
```
In [29]: type(poly_1.exterior)
```

```
Out[29]: shapely.geometry.polygon.LinearRing
```

A more complex polygon is one with holes:

```
In [30]: poly_2 = Polygon([(10, 0), (20,0), (15, 10)],
                          [[(13, 5), (14,7), (15,5) ],
                           [(15, 2),  (16, 5), (17, 2)]])
         poly_2
```

```
Out[30]:
```



The holes do not count toward the polygon's area:

```
In [31]: poly_2.area
```

```
Out[31]: 45.0
```

whereas:

```
In [32]: Polygon(poly_2.exterior.coords).area
```

```
Out[32]: 50.0
```

and

```
In [33]: h1, h2 = [Polygon(h) for h in list(poly_2.interiors)]
         h1.area + h2.area + poly_2.area
```

```
Out[33]: 50.0
```

3 Container (Multi) Types

In addition to these primitive geometric types, Shapely provides what are known as *collection types*. These serve two purposes. First, as we will see below, certain *spatial operations* can result in a collection of geometric objects, and thus there is a need to have a structure to hold these collections. Second, within GIS applications, it is sometimes necessary to represent a single feature as a collection of geometric objects. For example, think of the state of California which is composed of one mainland polygon and eight polygons for the Channel Islands. The state feature would be represented as a collection of these nine polygons.

3.1 MultiPoints

For `Points`:

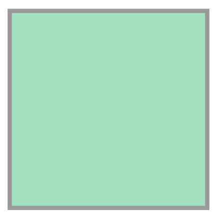
```
In [34]: from shapely.geometry import MultiPoint
         mp_1 = MultiPoint([p_1, p_2])
```

MultiPoints have a number of useful attributes:

```
In [35]: mp_1.bounds

Out[35]: (2.0, 5.0, 4.0, 7.0)
```

and

```
In [36]: mp_1.envelope

Out[36]:
```



Let's create a new collection:

```
In [37]: mp_2 = MultiPoint([p_1, p_2, Point(-7, 2)])
```

and inspect:

```
In [38]: mp_2.bounds

Out[38]: (-7.0, 2.0, 4.0, 7.0)
```

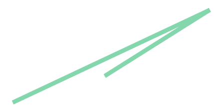
The `MultiPoint` is cleary distnct from its component `Points`

```
In [39]: p_1.bounds

Out[39]: (2.0, 5.0, 2.0, 5.0)
```

3.2 MultiLineStrings

```
In [40]: from shapely.geometry import MultiLineString

         l_2 = LineString([(0, 0), (15, 7), (7, 2)])
         l_2
```

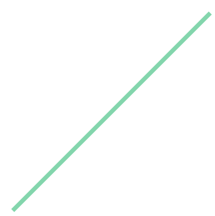
Out[40]:



Recall our earlier `LineString`:

```
In [41]: l_1
```

Out[41]:



and put them together into a `MultiLineString`:

```
In [42]: mls_1 = MultiLineString((l_1, l_2))
```

If we want the bounding rectangle for the pair of `LineStrings` we can query the `MultiLineString`:

```
In [43]: mls_1.bounds

Out[43]: (0.0, 0.0, 15.0, 7.0)
```

which is different from the individual bounds:

```
In [44]: l_1.bounds

Out[44]: (2.0, 5.0, 4.0, 7.0)
```

and

```
In [45]: l_2.bounds

Out[45]: (0.0, 0.0, 15.0, 7.0)
```

3.3 MultiPolygons

```
In [46]: from shapely.geometry import MultiPolygon
```

4 Spatial Relationships

Shapely supports a number of natural language relationships between geometric objects.

4.1 Intersects

```
In [47]: l_1 = LineString( ( (10,5), (10,15) ) )
         l_2 = LineString( ( (5,8), (12, 9) ) )
         l_3 = LineString( ( (11, 15), (17, 8) ) )
```

Do `l_1` and `l_2` intersect?

```
In [48]: l_1.intersects(l_2)

Out[48]: True
```

How about `l_1` and `l_3`?

```
In [49]: l_1.intersects(l_3)

Out[49]: False
```

Intersects works for different geometric types as well:

```
In [50]: poly_1 = Polygon(((9, 6), (12, 8), (12, 1), (9, 1)))
         l_1.intersects(poly_1)

Out[50]: True
```

4.2 Contains and Within

```
In [51]: p_1 = Point(11, 7)
         poly_1.contains(p_1)

Out[51]: True
```

And from the perspective of `p_1` it is *within* `poly_1`:

```
In [52]: p_1.within(poly_1)

Out[52]: True
```

4.3 Crosses

`poly_1` crosses `l_1`

```
In [53]: poly_1.crosses(l_1)
```

```
Out[53]: True
```

because its interior intersects, but does not contain, the interior of `l_1`:

```
In [54]: poly_1.contains(l_1)
```

```
Out[54]: False
```

4.4 Touches

```
In [55]: poly_2 = Polygon([(0, 0), (0, 2), (2, 2), (2, 0) ])
         line_2 = LineString([ (0, 1), (-1, 2) ] )
         line_3 = LineString([ (2, 1), (1, 1) ] )
         line_2.touches(poly_2)
```

```
Out[55]: True
```

but:

```
In [56]: line_3.touches(poly_2)
```

```
Out[56]: False
```

because:

```
In [57]: line_3.within(poly_2)
```

```
Out[57]: True
```

while

```
In [58]: line_2.within(poly_2)
```

```
Out[58]: False
```

5 Spatial Operations

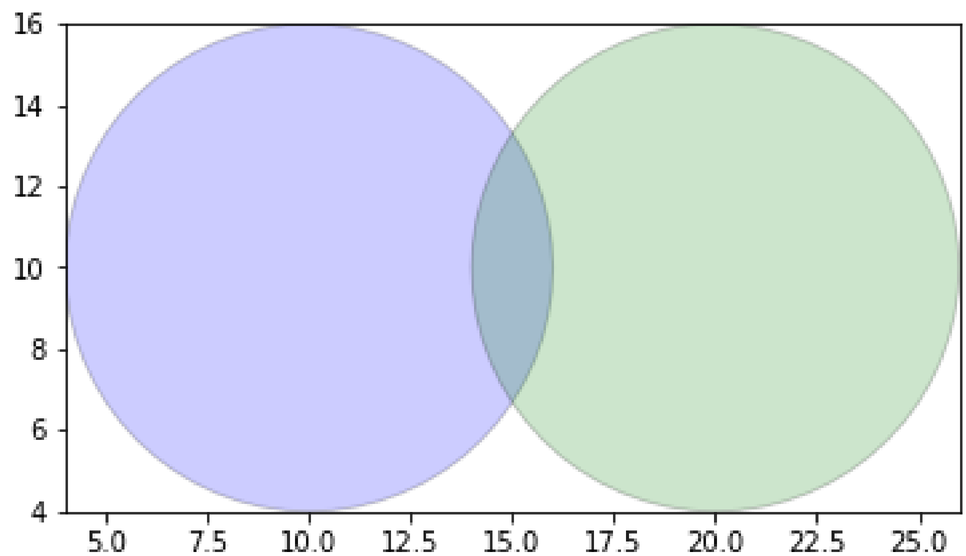
Many times we are not only interested in testing for a geometrical relationship between two objects, but also in obtaining a new geometric object that results from that relationship. **Spatial Operations** accomplish this for us.

5.1 Intersections

In [59]:
```
poly_1 = Point((10, 10)).buffer(6)
poly_2 = Point((20, 10)).buffer(6)
mp = MultiPolygon((poly_1, poly_2))
```

We will import the library `decartes` to facilitate visualization of these operations:

In [60]:
```
import descartes
ax = plt.gca()
ax.add_patch(descartes.PolygonPatch(poly_1, fc='b', ec='k', alpha=0.2))
ax.add_patch(descartes.PolygonPatch(poly_2, fc='g', ec='k', alpha=0.2))
minx, miny, maxx, maxy = mp.bounds
ax.set_xlim(minx, maxx); ax.set_ylim(miny, maxy)
ax.set_aspect('equal')
plt.show()
```



Testing the relationships we see:

In [61]:
```
poly_1.intersects(poly_2)
```

Out[61]: True

and

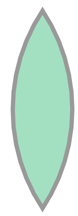
In [62]:
```
poly_2.intersects(poly_1)
```

Out[62]: True

Getting the object from this relationship is done as follows:

```
In [63]: int_1_2 = poly_1.intersection(poly_2)
         int_1_2
```

Out[63]:



And its type is:

```
In [64]: type(int_1_2)
```

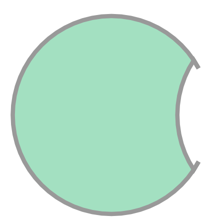
```
Out[64]: shapely.geometry.polygon.Polygon
```

5.2 Difference

Continuing on with set theoretic operations:

```
In [65]: poly_1.difference(int_1_2)
```

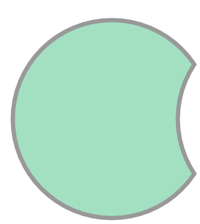
Out[65]:



and

```
In [66]: poly_1.difference(poly_2)
```

Out[66]:



but

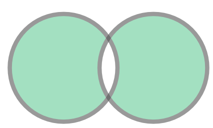
```
In [67]: type(int_1_2)
```

```
Out[67]: shapely.geometry.polygon.Polygon
```

5.3 Union

```
In [68]: u_1_2 = poly_1.union(poly_2)

         u_1_2

         d_1_2 = poly_1.difference(poly_2)
         d_2_1 = poly_2.difference(poly_1)

         d_1_2

         d_2_1

         d_1_2.union(d_2_1)
```

```
Out[68]:
```



5.4 Cascaded Union

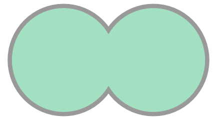
Let's use another special operation:

```
In [69]: from shapely.ops import cascaded_union
```

Putting things back together:

```
In [70]: cu = cascaded_union([d_1_2, d_2_1, int_1_2])
         cu
```

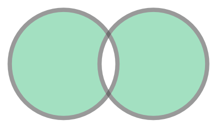
```
Out[70]:
```



Putting things partially back together:

```
In [71]: d_1_2_d_2_1 = d_1_2.union(d_2_1)
         d_1_2_d_2_1
```

Out[71]:



A testing point:

```
In [72]: p = Point(15, 10)
         d_1_2_d_2_1.contains(p)
```

Out[72]: False

but:

```
In [73]: cu.contains(p)
```

Out[73]: True

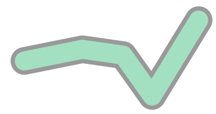
5.5 Buffers

We already saw the use of the `buffer` method above in constructing circles, which were nothing more than a `Polygon` that results from a `Point` calling its `buffer` method. `buffer` is a method that all primitives and collection types poses.

LineString:

```
In [74]: l_3 = LineString([(20, 5), (30, 7), (37, 6), (42, -1), (50, 12)])
         buf_l_3 = l_3.buffer(2)
         buf_l_3
```

Out[74]:



And it is a `Polygon`

```
In [75]: type(buf_l_3)
```

```
Out[75]: shapely.geometry.polygon.Polygon
```

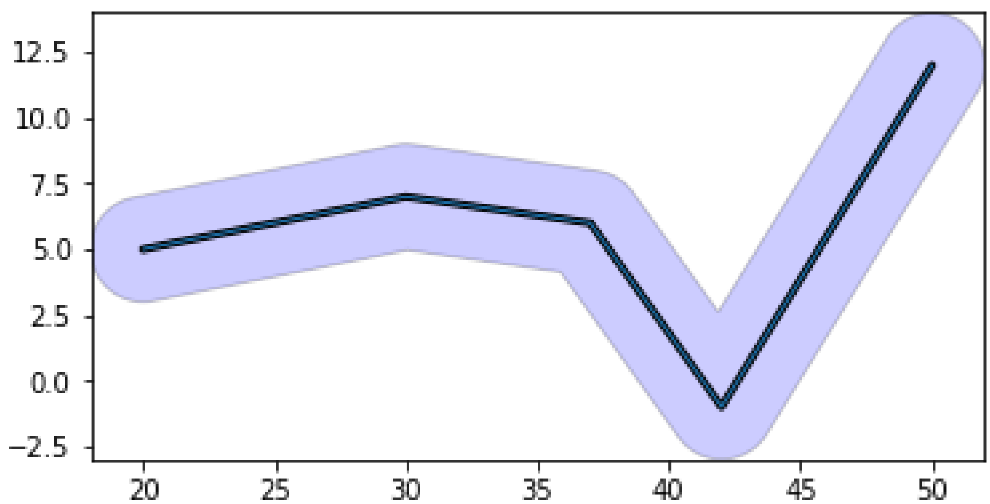
while the calling object was a `LineString`:

```
In [76]: type(l_3)
```

```
Out[76]: shapely.geometry.linestring.LineString
```

The relation between the buffer and the original object looks like:

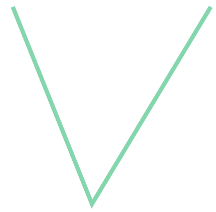
```
In [77]: ax = plt.gca()
         ax.add_patch(descartes.PolygonPatch(buf_l_3, fc='b', ec='k', alpha=0.2))
         ax.add_patch(descartes.PolygonPatch(l_3.buffer(0.1)))
         minx, miny, maxx, maxy = buf_l_3.bounds
         ax.set_xlim(minx, maxx); ax.set_ylim(miny, maxy)
         ax.set_aspect('equal')
         plt.show()
```



As a more complicated example consider two sections of a road network, the sections are `LineStrings`:

```
In [78]: l_1 = LineString([(5, 10), (7, 5), (10, 10)])
         l_1
```

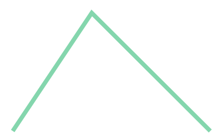
Out[78]:



and

```
In [79]: l_2 = LineString([(5, 0), (7, 3), (10, 0)])
         l_2
```

Out[79]:



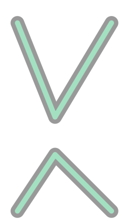
and they are combined into the network as a `MultiLineString`:

```
In [80]: ml = MultiLineString([l_1, l_2])
```

We can buffer the `MultiLineString`, but the result will depend on the size of the buffer:

```
In [81]: b1 = ml.buffer(0.25)
         b1
```

Out[81]:



with:

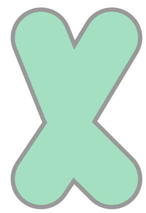
```
In [82]: type(b1)
```

```
Out[82]: shapely.geometry.multipolygon.MultiPolygon
```

If we increase the size of the buffer:

```
In [83]: b2 = ml.buffer(2.0)
         b2
```

```
Out[83]:
```



we get a single `Polygon`

```
In [84]: type(b2)
```

```
Out[84]: shapely.geometry.polygon.Polygon
```

6 Shapely as a Simple GIS

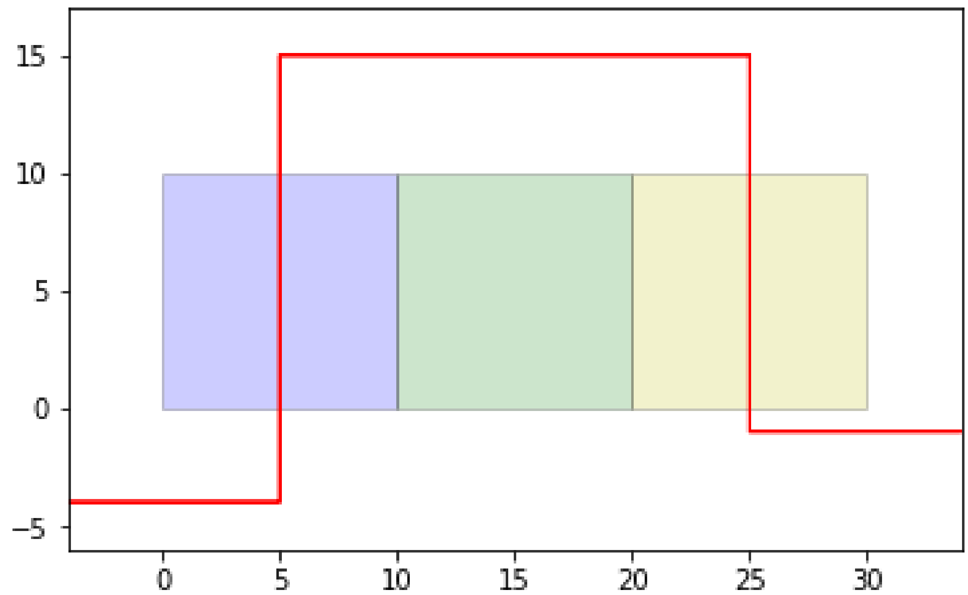
As a precursor for the rest of this workshop series, let's consider how Shapely might be used as a simple GIS.

Consider the simple landscape below that has three census tracks (as `Polygons`) and a highway (a `LineString`):

```
In [85]: tract_1 = Polygon([(0, 0), (0, 10), (10, 10), (10, 0)])
         tract_2 = Polygon([(10, 0), (10, 10), (20, 10), (20, 0)])
         tract_3 = Polygon([(20, 0), (20, 10), (30, 10), (30, 0)])
         highway = LineString( [(-4, -4), (5, -4), (5, 15),
                               (25, 15), (25, -1), (34,-1)]).buffer(0.01)
```

Our urban landscape looks like:

```
In [86]: ax = plt.gca()
         ax.add_patch(descartes.PolygonPatch(tract_1, fc='b', ec='k', alpha=0.2))
         ax.add_patch(descartes.PolygonPatch(tract_2, fc='g', ec='k', alpha=0.2))
         ax.add_patch(descartes.PolygonPatch(tract_3, fc='y', ec='k', alpha=0.2))
         ax.add_patch(descartes.PolygonPatch(highway, fc='k', ec='red'))
         minx, miny, maxx, maxy = highway.bounds
         ax.set_xlim(minx, maxx); ax.set_ylim(miny-2, maxy+2)
         ax.set_aspect('equal')
         plt.show()
```



We combine the three polygons inside a `MultiPolygon` object as this will simplify some bounds checking.

```
In [87]: city = MultiPolygon([tract_1, tract_2, tract_3])
```

For example, let's test if the highway intersects the collection of tracts - think of the collection as say a city, so we are in effect asking if the network intersects the city:

```
In [88]: highway.intersects(city)
```

```
Out[88]: True
```

Since it does intersect the city, we might be interested in determining how much of the network is within the city boundaries:

```
In [89]: highway_in_city = highway.intersection(city)
         lic = highway_in_city.length
         ltot = highway.length
         print("The city contains %2.2f miles or %f of the network."%(lic, lic/ltot))
```

```
The city contains 40.08 miles or 0.274435 of the network.
```

and we can see the segments in the city:

```
In [90]: highway_in_city
```

```
Out[90]:
```

We may also be interested in identifying which tracts within the city intersect the network:

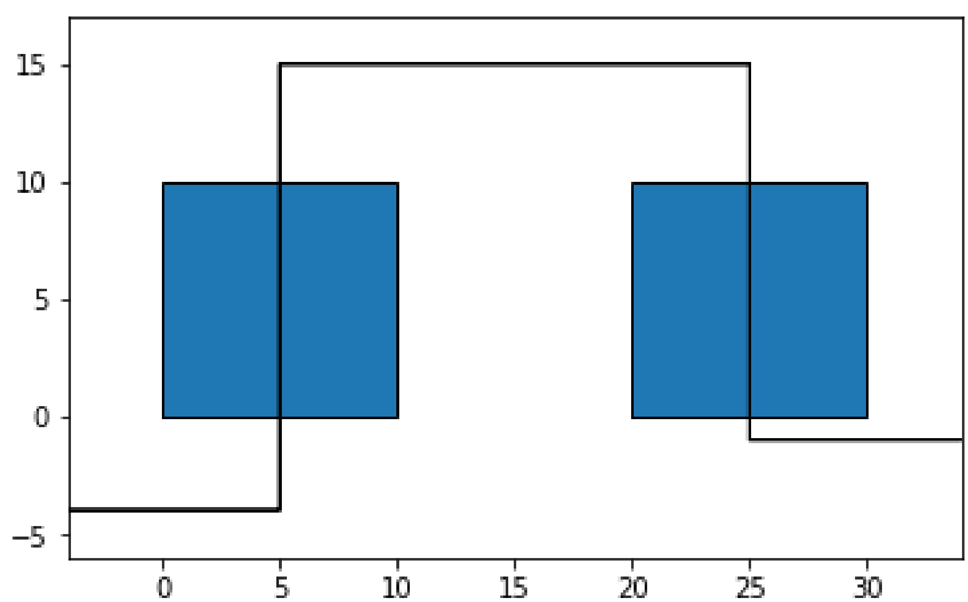
```
In [91]: hit = [tract for tract in [tract_1, tract_2, tract_3] if highway.intersects(tract)]
```

`hit` is a list of the two tracts that intersect with the network:

```
In [92]: hit

Out[92]: [<shapely.geometry.polygon.Polygon at 0x7f60de4c8198>,
          <shapely.geometry.polygon.Polygon at 0x7f60de4be400>]
```

as can be seen below:

```
In [93]: hit.append(highway)
         ax = plt.gca()
         for feature in hit:
             ax.add_patch(descartes.PolygonPatch(feature))
         ax.set_xlim(minx, maxx); ax.set_ylim(miny-2, maxy+2)
         ax.set_aspect('equal')
         plt.show()
```



Later on, we will utilize similar functionality to add attributes to the tracts to distinguish those that intersect a network from tracts that do not intersect the network. This is known as a *spatial join* since we are joining information from the network to the tracts.

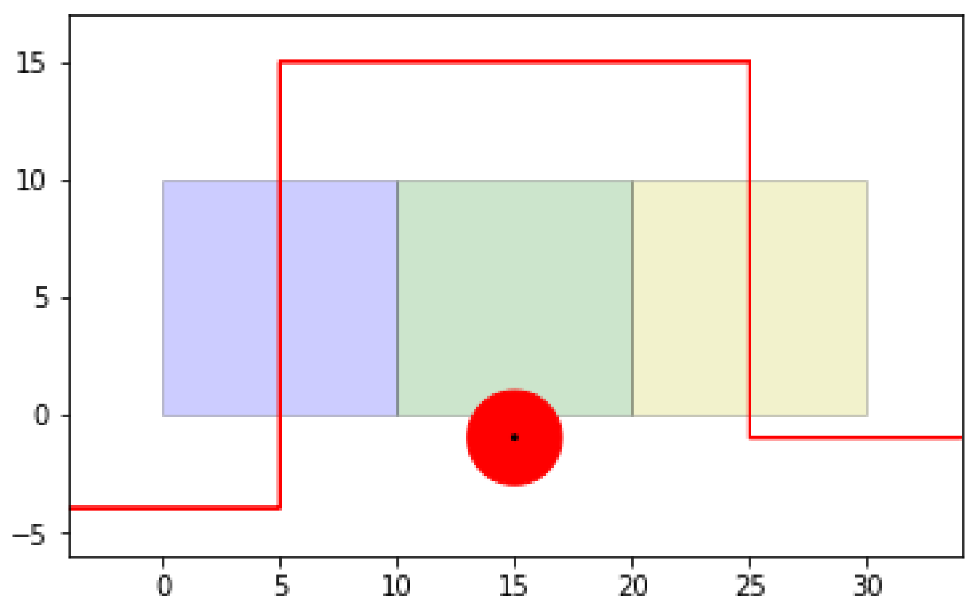
6.1 Using a Buffer

Let's make our city a little bit more interesting. Suppose a state government agency has discovered a toxic waste site located 1 mile south of the city. State regulations are such that any residents within 2 miles of the newly discovered site have to be notified.

To determine what residents need to be notified, we will first create a *buffer* around the hazard location, and then test for the intersection of the buffer with the tracts.

Step 1: we create the point and its buffer:

```
In [94]: hazard_point = Point(15, -1)
         buffer = hazard_point.buffer(2)
         ax = plt.gca()
         ax.add_patch(descartes.PolygonPatch(tract_1, fc='b', ec='k', alpha=0.2))
         ax.add_patch(descartes.PolygonPatch(tract_2, fc='g', ec='k', alpha=0.2))
         ax.add_patch(descartes.PolygonPatch(tract_3, fc='y', ec='k', alpha=0.2))
         ax.add_patch(descartes.PolygonPatch(highway, fc='k', ec='red'))
         ax.add_patch(descartes.PolygonPatch(buffer, fc='r', ec='red'))
         ax.add_patch(descartes.PolygonPatch(hazard_point.buffer(0.1), fc='k', ec='k'))
         minx, miny, maxx, maxy = highway.bounds
         ax.set_xlim(minx, maxx); ax.set_ylim(miny-2, maxy+2)
         ax.set_aspect('equal')
         plt.show()
```



Step 2, we find out which tracts intersect with the buffer:

```
In [95]: to_warn = [tract for tract in [tract_1, tract_2, tract_3] if buffer.intersects(tract)]
         to_warn

Out[95]: [<shapely.geometry.polygon.Polygon at 0x7f60de4c8320>]
```

7 Summary

We have touched on only the more commonly encountered features of Shapely when dealing with geospatial data. Before moving on to other parts of the Python geospatial stack, it is important to note several things.

First, shapely does not support coordinate system transformations, and all of its functionality assumes features exist in the same Cartesian plane. Second, we will see that other popular packages in the geospatial Python stack actually use Shapely as a dependency and they themselves deal with coordinate transformations. Third, we will introduce other Shapely operations later on in this series as we have need. Finally, readers are encouraged to more fully explore the The Shapely User Manual.
