Lesson 10

August 7, 2020

1 Lesson 10: Carbon Dating

1.1 Chemical Kinetics

What are Chemical Kinetics?

Have you ever wondered why explosions happen very quickly? Or why if you leave your bike in the rain it rusts so slowly you can't even see it happening? And how do scientists know how old ancient manuscripts or prehistoric skeletons are anyway?

These are all questions of chemical kinetics. Chemists can measure how much of a reacting chemical is present over time. Take a look at the information in the file carbon_data.cvs. Notice how the amount of Carbon-14 in the sample is decaying over time.

```python
[1]: import pandas
     carbon_decay=pandas.read_csv("carbondecay.csv")
     print(carbon_decay)
```

```
     Time    C14_Con
0       0   1.000000
1      20   0.997603
2      40   0.995212
3      60   0.992826
4      80   0.990446
5     100   0.988072
6     120   0.985703
7     140   0.983340
8     160   0.980983
9     180   0.978632
10    200   0.976286
11    220   0.973945
12    240   0.971611
13    260   0.969282
14    280   0.966958
15    300   0.964640
16    320   0.962328
17    340   0.960021
18    360   0.957720
19    380   0.955424
20    400   0.953134
```

```
21      420   0.950849
22      440   0.948570
23      460   0.946296
24      480   0.944027
25      500   0.941765
26      520   0.939507
27      540   0.937255
28      560   0.935008
29      580   0.932767
..      …       …
575   11500   0.251579
576   11520   0.250975
577   11540   0.250374
578   11560   0.249774
579   11580   0.249175
580   11600   0.248578
581   11620   0.247982
582   11640   0.247387
583   11660   0.246794
584   11680   0.246203
585   11700   0.245613
586   11720   0.245024
587   11740   0.244436
588   11760   0.243850
589   11780   0.243266
590   11800   0.242683
591   11820   0.242101
592   11840   0.241521
593   11860   0.240942
594   11880   0.240364
595   11900   0.239788
596   11920   0.239213
597   11940   0.238640
598   11960   0.238068
599   11980   0.237497
600   12000   0.236928
601   12020   0.236360
602   12040   0.235793
603   12060   0.235228
604   12080   0.234664

[605 rows x 2 columns]
```

What is happening here? When scientists talk about carbon dating, they are referring to a specific reaction. This reaction is the nuclear decay of an unstable species of carbon, called carbon-14 because it has a total of 14 protons and neutrons in its nucleus. Each year a little bit of carbon-14 decays, converting a neutron into a proton, giving off a beta particle, and leaving behind a nitrogen atom. When an plant or animal is alive it replaces the carbon-14 from the carbon dioxide

it photosynthesizes or the food it eats respectively, but once it dies it begins to slowly lose its carbon 14.
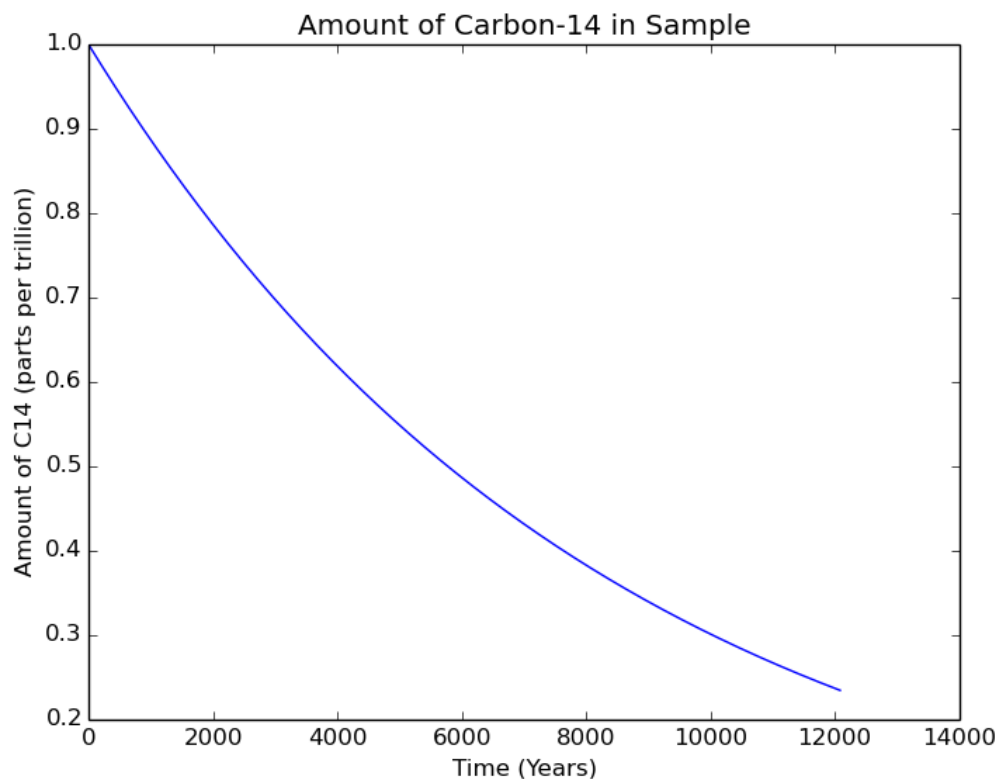
1.2 Analyze Rate Data

Using Python to Analyze Rate Data

It will be easier to visualize if we display it as a graph. Review Lesson Five: Intro to Statistics to recall how to save the CVS data in a python variable. Then go ahead and practice in the code box below. Remember the data file is called carbondata.csv. If you get stuck, I've included the answer in a second box below.

```python
import pandas
import matplotlib.pyplot as plt
carbon_decay=pandas.read_csv("carbondecay.csv")

fig1 = plt.figure()
plt.plot(carbon_decay.Time, carbon_decay.C14_Con)
plt.title('Amount of Carbon-14 in Sample')
plt.xlabel('Time (Years)')
plt.ylabel('Amount of C14 (parts per trillion)')
plt.savefig('C14.png')
```


If we look at this graph closely we can see that the decay is fairly rapid at first but slows down

over time. This makes sense. Remember that a certain percentage of carbon-14 decays each year. If you start a year with most of the carbon-14 already gone, there will be less left to decay.

You might recognize this graph from your math classes. This shape describes an exponential decay. We could write a mathematical equation that models this data like this:

$$\ln[C\text{-}14]_t = -k*t + \ln[C\text{-}14]_0$$

You can read that as "The amount of C-14 present at some time t, is equal to the original amount of C-14 at time 0 times e to the negative k times t." k is called a rate constant and we will talk about that in the next section.

1.3 Rate Constant

What is a rate constant?

I mentioned earlier that reactions occur at different rates. An explosion from setting hydrogen on fire may last only a couple of seconds. The reactions involved in baking a cake might take a few minutes to a few hours. The chemistry that rusts your bike can take months or years. In our example above, the decay of carbon-14 takes thousands of years.

A rate constant tells you how fast a reaction goes. We might expect our explosion to have a very large rate constant, while carbon-14 might have a very small one. But how do we find out what this rate constant is?

A neat trick that scientists often use is to linearlize data. Remember that exponential decay from before? If we take the natural log of both sides with can get a new equation that looks like this:

$$\ln[C\text{-}14]_t = -k*t + \ln[C\text{-}14]_0$$

If you look closely you should be able to see that plotting ln[C-14]t on the y-axis and t on the x-axis should give a straight line with an intercept of ln[C-14] at time 0 and a slope of k. That allows us to find our rate constant! But first let's program this linear data in python. Remember our data file is called carbondecay.csv

```python
#We will need to import numpy this time to calculate the natural log
import pandas
import matplotlib.pyplot as plt
import numpy

#Load the data file
carbon_decay=pandas.read_csv('carbondecay.csv')
```
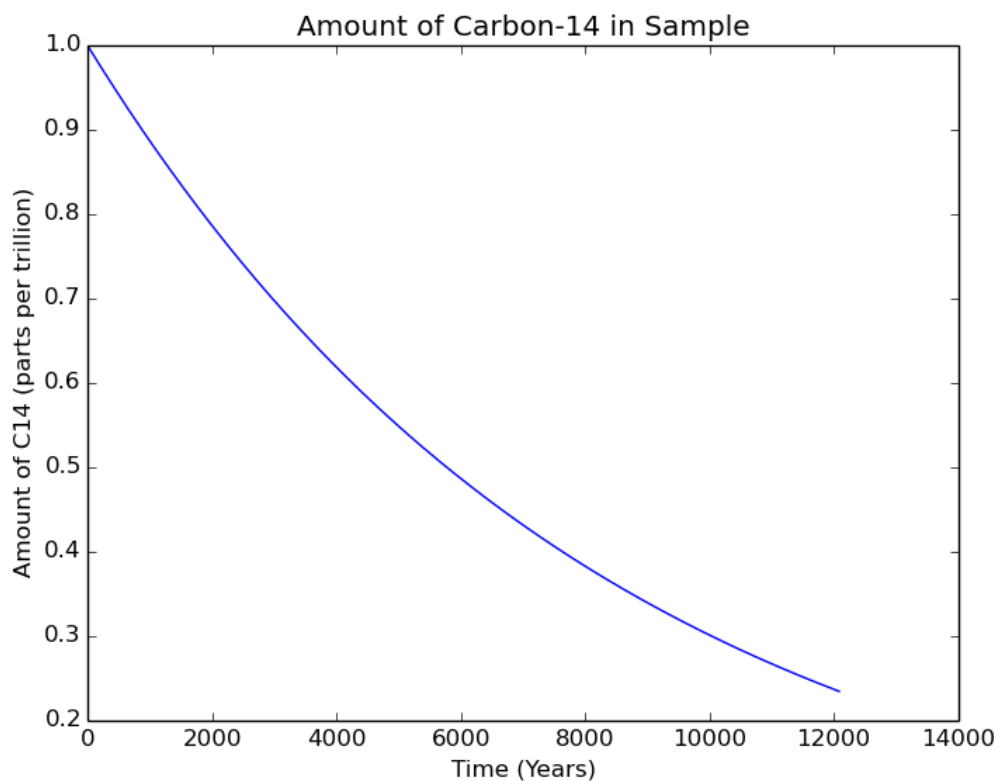
```
#If you look at the carbondecay file you will see it has two columns labeled␣
 →"Time" and "C14_Con" the following line takes the natural log of every entry␣
 →in the C14_Con column and then prints it. Note that in python the command␣
 →"log" means natural log, and not log base 10. I will use log to mean natural␣
 →log for the remainder of this lesson
logC_14=numpy.log(carbon_decay.C14_Con)
print(logC_14)

#Now we want to plot time v our new data to get a linear plot
plt.plot(carbon_decay.Time, logC_14)
plt.title('Amount of Carbon-14 in Sample') # this is the title of the graph␣
 →(note it's a string)
plt.xlabel('Time (years)') # this is the label for the x-axis
plt.ylabel('log of Amount of Carbon-14 (parts per trillion)') # this is the␣
 →label for the y-axis
plt.savefig('C14-2.png') ## CHANGE
```


You should be getting a graph that looks like the one below. We will talk about how to calculate the rate constant from this graph in the next section.

1.4 Equation of a line

You learned about libraries in lesson 4. We can use the scipy library to find the equation of this line. This function will return the values for the slope, the y-intercept, and a value called R^2. R^2 is always a number between zero and one. A value of zero tells you that your data doesn't remotely follow a line while a value of 1 means your data lies on a perfect line.

What do you think the R^2 value for the data you graphed in part 2 is? [Exactly 1 , because the data formed a perfect line]

Let's test it. I've shown the code below. Remember that the slope of the line is the rate constant, which we call k.

```python
import pip
import numpy
import scipy
from scipy import stats
import pandas

# We start by loading the excel file.
carbon_decay_2=pandas.read_csv('carbondecaywithnoise.csv')
logC_14=numpy.log(carbon_decay_2.C14_Con)

#The best fit function returns values in what is called an array. The first
 →value is the slope, the second is the y-intercept of the best fit line, and
 →the third is the r^2 value. It also returns some other data we will ignore
 →for now and prints them on the screen to the right.
best_fit = scipy.stats.linregress(carbon_decay_2.Time, logC_14)

#If we want to, we can assign each of the values in the array individual
 →variables by using square brackets with the number of the position of the
 →value we care about. Note that computer languages start counting at zero. So
 →the slope is position 0 of the best_fit we created above.
slope=best_fit[0]
intercept=best_fit[1]
r_square=best_fit[2]

print(slope)

print(intercept)

print(best_fit)
```
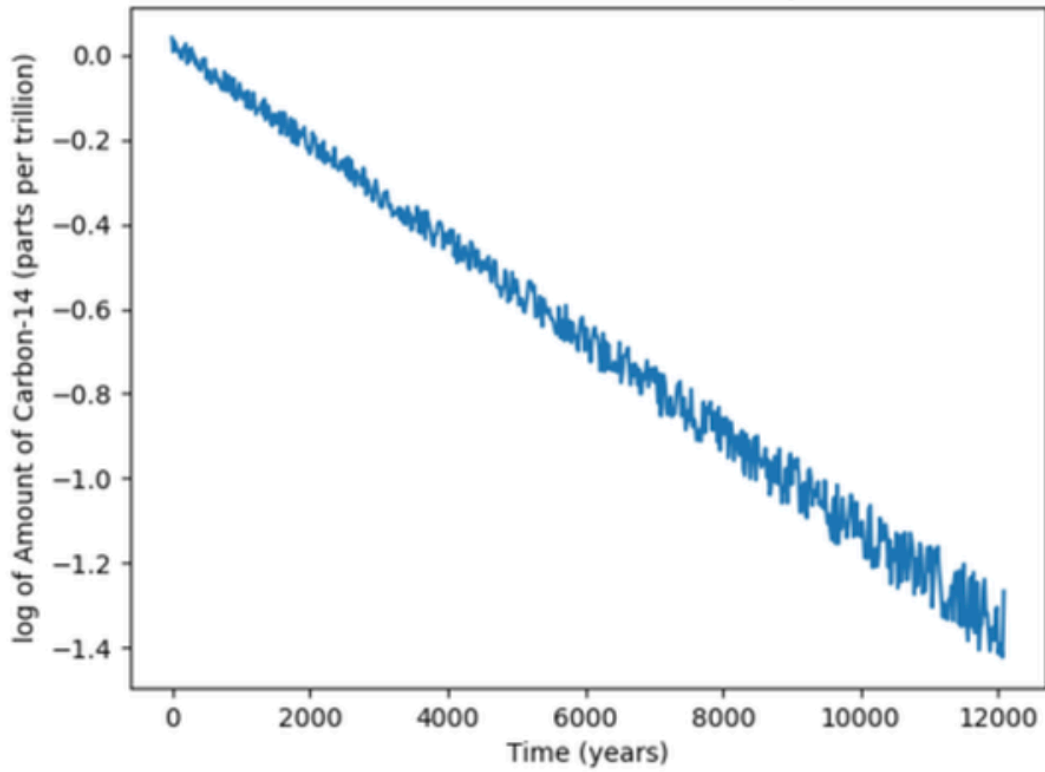
In real science, things aren't quite this nice. Even the most careful scientists with the best instruments don't measure exactly accurate values every time. There is some uncertainty in all measurements, and we call this noise. The third column of the cvs file (called C14_Con_noisy) has some uncertainty built into the measurements. Try repeating the steps you've already done for this data. What does the curve of C-14 concentration v time look like? What does the best-fit line look like? What is the new R-squared value? What about your rate constant? Make a prediction,
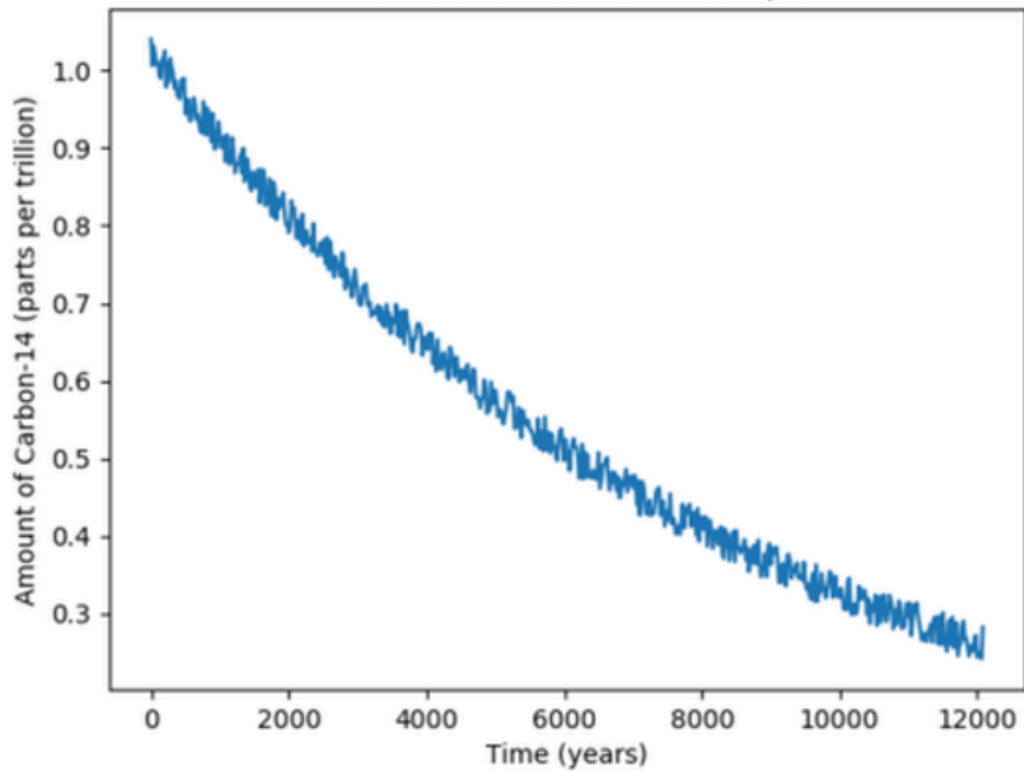
and then try figuring it out below!

```
[ ]: ### INSERT CODE HERE
```

Amount of Carbon-14 in Sample

Amount of Carbon-14 in Sample

Notice how the noise gets bigger by 12,000 years. As the sample gets older, you are measuring smaller and smaller amounts of carbon-14. That makes it harder to tell how much of your measurement is "real" and how much is just noise. On samples that are too old, scientists can't use carbon dating to tell the age at all, and have to use other techniques. Next we will talk about half-lives and how they can help us carbon-date old samples.

1.5 Checkpoint

```
[ ]: # TBD
```

1.6 Half Life

So, how does this relate to how scientist can date old materials? One of the interesting features of reactions whose concentrations decrease with exponential decay, which we call first order reactions, is that they have a constant half life. As you might have guessed, the half life is the time it takes to lose one half of the carbon-14. You might be surprised to learn that it takes the same amount of time to go from 100% of the original amount of C-14 to 50% as it does to go from 50% to 25% the original amount, or from 25% to 12.5%.

We can calculate the half life as:

$$half\ life = \frac{\ln(2)}{k}$$

Remember, k is the rate constant and the slope of the best fit line you found on the last page. Be careful though. When you are calculating half-lives, remember that the curve of carbon-14 concentration v time is an exponential decay. You lose carbon-14 more slowly has time goes on. This means you can't, for example, calculate a "forth-life" that is half the length of time as a half life because it takes less than 50% of a half life to lose 1/4 of your carbon-14. Check this out on the graph you made in part 1 and convince yourself this is true. How long does it take to lose half of your C-14? How long to lose 1/4? I've reproduced the graph below the answer keys.

Try applying this information for yourself! I've listed some questions below. Try to answer them before looking at the answers underneath.
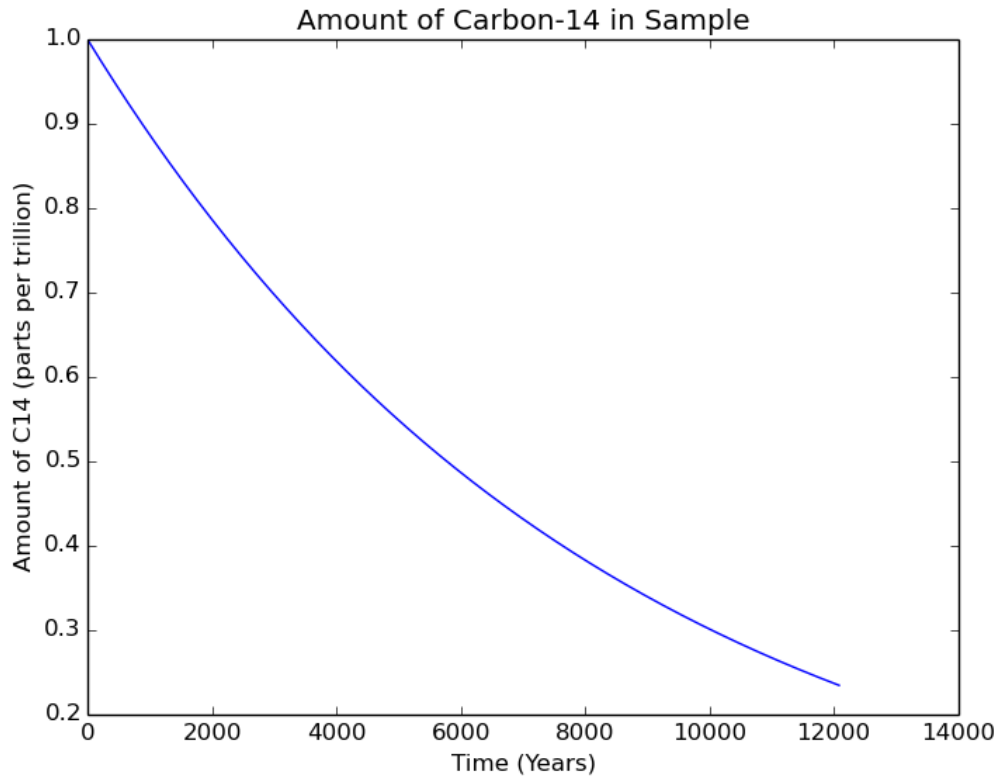
1. What is the half life of carbon 14?

2. How long would it take to lose 87.5% of the original C-14? Does this match what your grap

3. Scientists have trouble carbon dating things more than 50,000 years old. Can you think of

1. The k value you found was about 0.00012 per year. You can plug that k value in to the half life equation above and find that the half life is about 5,600 years.

2. 87.5% of the original C-14 is lost after three half lives. The first half-life takes you from 100->
   50% of your original C-14. The second half life cuts that 50% to 25% and after the third
   half-life you have only one half of that 25% left, or 12.5%. If you have 12.5% left, that means
   you have lost 87.5% of your original C-14.

Three half lives is 5600*3=16,800 years.

If you found a substance that had lost 87.5% of its original C-14, it would be from a time when
homo sapiens had just recently become the only humans on the planet, but several thousand years
before we developed agriculture, domesticated animals, or started to move to the Americas.

Your graph in part 1 looked like this

This graph only went out 12,000 years. However, after 12,000 years we still had a bit over 20% of
our original C-14 and the line was starting to flatten out. It makes sense that in 6000 more years
we'd have 12.5% of the original C-14 left.

3. After many half lives, very little C-14 is left. The noise from the measurements becomes
   almost as large as the signal itself. There are many ways of dating older objects, the easiest
   is perhaps to use a compound that decays with a longer half life.

Extra Challenge: The Smithsonian has a timeline of major events in human history. Can you figure
out approximately how many half lives of C-14 have past for different events? How much C-14 is
left from the artifacts humans left during these events?

http://humanorigins.si.edu/human-characteristics/humans-change-world

1.7 Summary

```
[ ]:  # TBD
```

You should now understand the following:

Graph data using appropriate Python 3 synthax

Find best-fit lines using python

Manipulate chemical rate data to find a rate constant

Use first-order rate constants to find a half-life

```
[ ]:
```

```
[ ]:
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