Examining and Visualizing NMR Kinetics Data

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Overview

Questions:

- How can I use pandas to process data?
- How can I visualize relationships between different parts of my data?

Objectives:

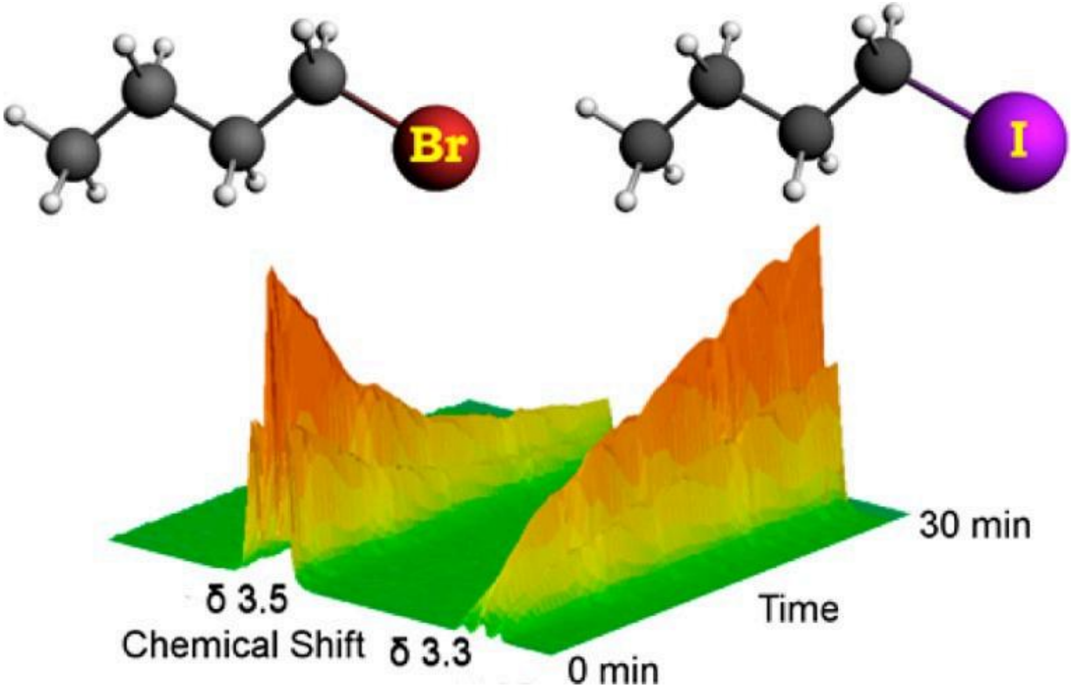
- Use pandas and scipy to load and analyze NMR kinetics data
- Determine the reaction order and rate constant (k) from NMR reaction monitoring data

NMR kinetics: S_N2

The SN2 reaction between 1-bromobutane (BuBr) and iodide ion (I–) proceeds via a single-step bimolecular mechanism.

Using NMR spectroscopy, the reaction's progress can be monitored by observing the disappearance of the BuBr signal (δ3.5) and the appearance of the BuI signal (δ3.3).

Reagents	Concentration
BuBr	0.6 M
NaI	0.6 M



Source: NMR Kinetics of the SN2 Reaction between BuBr and I–: An Introductory Organic Chemistry Laboratory Exercise

Let's dive into the data and compute the rate constant!

Import packages/libraries

In [14]:

```python
from rdkit import Chem
from rdkit.Chem import Draw, AllChem
```

Draw a reaction using RDKit

`rdkit.AllChem.ReactionFromSmarts()` can draw reactions from SMILES strings formatted using these rules:

- Separate molecules using: `.`
- Separate reactants from products using arrows: `>>`
- (Optional) place solvent molecules between the arrows: `>solvent1.solvent2>`

Examples:

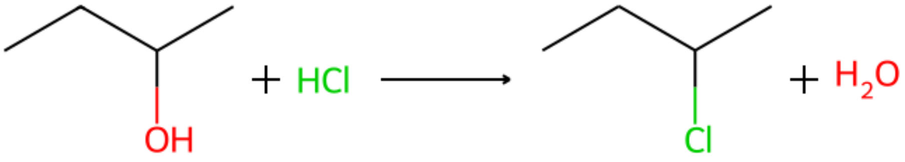
```
'reactant1.reactant2>>product1.product2'
or
'reactant1.reactant2>solvent1.solvent2>product1.product2'
```

Let's draw a substitution reaction!

In [15]:

```python
reaction_smiles = 'CCC(O)C.Cl>>CCC(Cl)C.O'
AllChem.ReactionFromSmarts(reaction_smiles, useSmiles=True)
```

Out[15]:



Challange

Draw the S_N2 reaction for butyl bromide `CCCCBr` and iodide `[I-]` in acetone `CC(=O)C`.

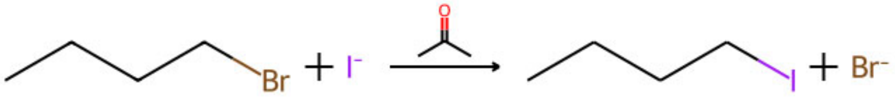
- **Reactants**: `CCCCBr` and `[I-]`
- **Solvent**: `CC(=O)C`
- **Products**: `CCCCI` and `[Br-]`

Tip: In SMILES strings ions are drawn inside `[]` (eg. `[Na+]`, `[I-]`)

In [16]:

```python
reaction_smiles = 'CCCCBr.[I-]>CC(=O)C>CCCCI.[Br-]'
AllChem.ReactionFromSmarts(reaction_smiles, useSmiles=True)
```

Out[16]:



Visualizing protons and chemical shifts

We can monitor the progress of our reaction via NMR because the reactant and product have unique chemical shifts.

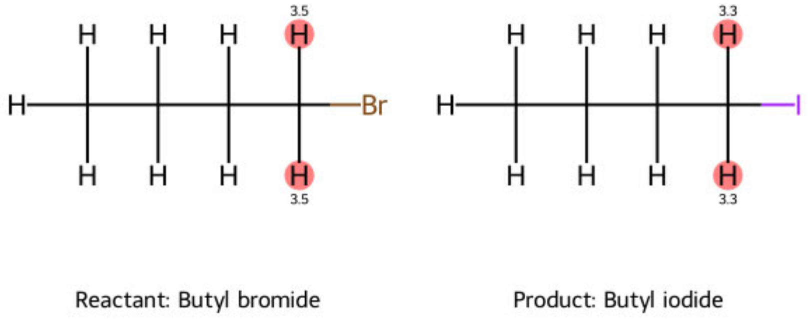
Let's visualize which protons we will be integrating to monitor our reaction!

In [17]:

```python
# Define the molecules
butyl_bromide = Chem.MolFromSmiles("CCCCBr")
butyl_iodide = Chem.MolFromSmiles("CCCCI")

# Add explicit hydrogens
butyl_bromide = Chem.AddHs(butyl_bromide)
butyl_iodide = Chem.AddHs(butyl_iodide)

# Annotate chemical shifts into unique protons
butyl_bromide.GetAtomWithIdx(12).SetProp('atomNote', '3.5')
butyl_bromide.GetAtomWithIdx(13).SetProp('atomNote', '3.5')
```

```python
butyl_iodide.GetAtomWithIdx(12).SetProp('atomNote', '3.3')
butyl_iodide.GetAtomWithIdx(13).SetProp('atomNote', '3.3')

# Create a combined image
Draw.MolsToGridImage(
    [butyl_bromide, butyl_iodide],
    legends=['Reactant: Butyl bromide', 'Product: Butyl iodide'],
    highlightAtomLists=[[12, 13], [12, 13]],
    molsPerRow=2,
    subImgSize=(300, 300),
)
```

Out[17]:



Pandas: Data manipulation and analysis

Pandas is very powerful Python library used for data analysis and manipulation. Pandas is ubiquitous in the world of data science and today we will use it to examine and analyze data from a photo NMR experiment.

For more information on pandas, refer to the pandas documentation or the 10 minutes to pandas guide.

Dataframe

The central data structure of pandas is a `pandas.DataFrame`.

You can think of a Dataframe as an Excel spreadsheet that contains data in columns and rows.

	index	column_1	column_2	...
row_1	0	data	data	...
row_2	1	data	data	...
row_3	2	data	data	...
...	...	...	...	...

Import packages/libraries

Let's import `pandas`, `numpy`, and the plotting package `matplotlib` using their standard abbreviations `pd`, `np`, and `plt`.

In [18]:
```python
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
```

Reading a CSV File

Pandas makes it simple to read and work with datasets in spreadsheets (CSV or Excel formats).

- read CSV files: `pd.read_csv()`
- read Excel files: `pd.read_excel()`

Let's create a Dataframe using our NMR kinetics data.

In [19]:
```python
kinetics_data = pd.read_csv('data/kinetics_data_condition3.csv')
```

Examining Data with `.head()` and `.tail()`

You can see a preview of your Dataframe using the `.head()` or `.tail()` method. By default `.head()` or `.tail()` display the first or last 5 rows of the Dataframe. You can display more rows by passing an `int` as an argument to either method.

Let's look at the first 10 rows of our `kinetics_data` DataFrame.

In [20]:

```
kinetics_data.head(10)
```

Out[20]:

	Timepoint	Integration_3.5_ppm	Integration_3.3_ppm
0	1	16591300000	1850710000
1	2	16816100000	2118990000
2	3	15617800000	2828960000
3	4	14513500000	3507860000
4	5	13819000000	4019790000
5	6	13263100000	4462330000
6	7	12892100000	4802640000
7	8	12476000000	5104320000
8	9	12095700000	5287240000
9	10	11728300000	5430190000

Challange

Use the `tail()` method to display the last 8 rows of our `kinetics_data` DataFrame.

In [21]:

```
kinetics_data.tail(8)
```

Out[21]:

	Timepoint	Integration_3.5_ppm	Integration_3.3_ppm
52	53	5799200000	11437600000
53	54	5761140000	11487500000
54	55	5731440000	11508000000
55	56	5682460000	11549200000
56	57	5663930000	11573900000
57	58	5619960000	11609200000
58	59	5587810000	11641900000
59	60	5548890000	11682000000

Getitem (`[ ]`): selecting data in a DataFrame

You can index data in a DataFrame by column or row. This process looks similar to indexing or slicing a list.

Index a list

```
first_value = list[0]
or
first_five_values = list[0:5]
```

Getitem in a DataFrame

```
column = DataFrame['column_name']
or
first_five_rows = DataFrame[0:5]
```

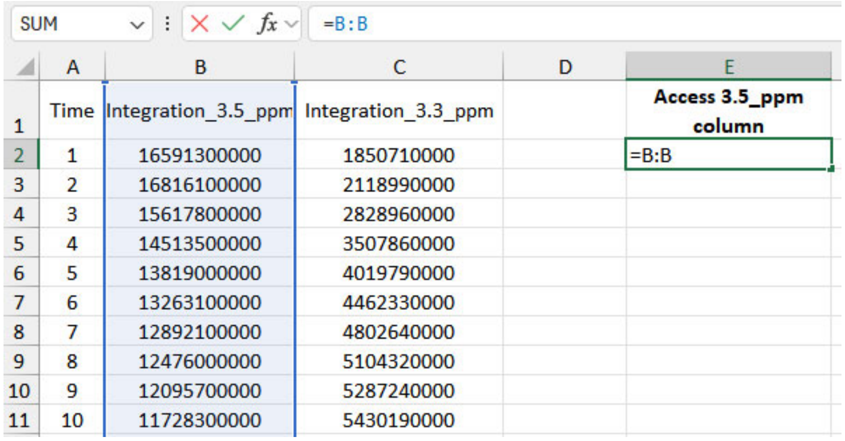
Let's see how we access data in the `Integration_3.5_ppm` column.

```
In [22]: kinetics_data['Integration_3.5_ppm']
```

```
Out[22]: 0     16591300000
         1     16816100000
         2     15617800000
         3     14513500000
         4     13819000000
         5     13263100000
         6     12892100000
         7     12476000000
         8     12095700000
         9     11728300000
         10    11465800000
         11    11315500000
         12    11045900000
         13    10808900000
         14    10480900000
         15    10181500000
         16     9918420000
         17     9643220000
         18     9432790000
         19     9194070000
         20     8971060000
         21     8781150000
         22     8597770000
         23     8414760000
         24     8247250000
         25     8079540000
         26     7921860000
         27     7788600000
         28     7647310000
         29     7512990000
         30     7405860000
         31     7299280000
         32     7191940000
         33     7096840000
         34     6995360000
         35     6898390000
         36     6807320000
         37     6724690000
         38     6629830000
         39     6567130000
         40     6487630000
         41     6388700000
         42     6318880000
         43     6258190000
         44     6198780000
         45     6146410000
         46     6091320000
         47     6038290000
         48     5980180000
         49     5929910000
         50     5882500000
         51     5845120000
         52     5799200000
         53     5761140000
         54     5731440000
         55     5682460000
         56     5663930000
         57     5619960000
         58     5587810000
         59     5548890000
         Name: Integration_3.5_ppm, dtype: int64
```

`kinetics_data['Integration_3.5_ppm']` displays every value in the `Integration_3.5_ppm` column.

In Excel this operation would look something like this:



SUM =B:B

	A	B	C	D	E
1	Time	Integration_3.5_ppm	Integration_3.3_ppm		Access 3.5_ppm column
2	1	16591300000	1850710000		=B:B
3	2	16816100000	2118990000		
4	3	15617800000	2828960000		
5	4	14513500000	3507860000		
6	5	13819000000	4019790000		
7	6	13263100000	4462330000		
8	7	12892100000	4802640000		
9	8	12476000000	5104320000		
10	9	12095700000	5287240000		
11	10	11728300000	5430190000		

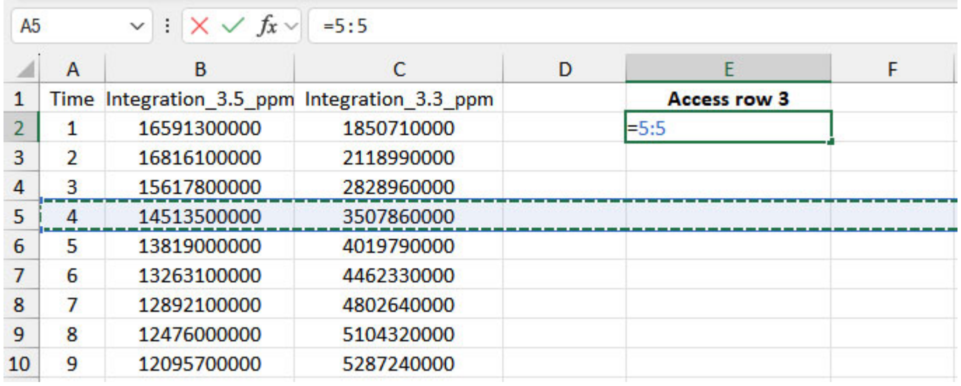
Let's see how we access data in the 5th row.

```
In [23]: kinetics_data[4:5]
```

```
Out[23]:
     Timepoint  Integration_3.5_ppm  Integration_3.3_ppm
4            5          13819000000           4019790000
```

`kinetics_data[4:5]` displays every value in the 5th row.

In Excel this operation would look something like this:



A5 =5:5

	A	B	C	D	E	F
1	Time	Integration_3.5_ppm	Integration_3.3_ppm		Access row 3	
2	1	16591300000	1850710000		=5:5	
3	2	16816100000	2118990000			
4	3	15617800000	2828960000			
5	4	14513500000	3507860000			
6	5	13819000000	4019790000			
7	6	13263100000	4462330000			
8	7	12892100000	4802640000			
9	8	12476000000	5104320000			
10	9	12095700000	5287240000			

Setting a new column

You can create a new column in a DataFrame by performing mathematical operations (`+` , `-` , `*` , `/` , ect.) on an existing column. This is the equivalent of using a function for perform an operation in Excel.

Syntax

```
DataFrame_name['Grams'] = DataFrame_name['Kilograms'] / 1000
```

A time point was taken every 30 seconds in our reaction monitoring data.

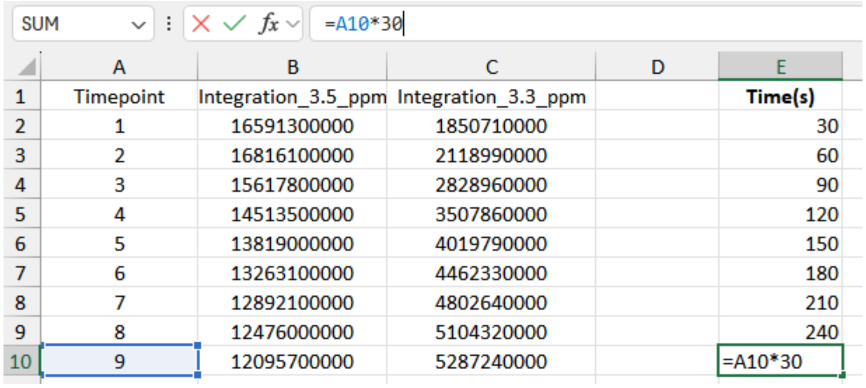
Let's convert our `kinetics_data['Timepoint']` column into seconds and save the results to new column called `kinetics_data['Time(s)']` !

```
In [24]: kinetics_data['Time(s)'] = kinetics_data['Timepoint'] * 30
         kinetics_data.head()
```

Out[24]:

	Timepoint	Integration_3.5_ppm	Integration_3.3_ppm	Time(s)
0	1	16591300000	1850710000	30
1	2	16816100000	2118990000	60
2	3	15617800000	2828960000	90
3	4	14513500000	3507860000	120
4	5	13819000000	4019790000	150

In Excel this operation would look something like this:



=A10*30

	A	B	C	D	E
1	Timepoint	Integration_3.5_ppm	Integration_3.3_ppm		**Time(s)**
2	1	16591300000	1850710000		30
3	2	16816100000	2118990000		60
4	3	15617800000	2828960000		90
5	4	14513500000	3507860000		120
6	5	13819000000	4019790000		150
7	6	13263100000	4462330000		180
8	7	12892100000	4802640000		210
9	8	12476000000	5104320000		240
10	9	12095700000	5287240000		=A10*30

We need to create several new columns in our `kinetics_data` DataFrame to help us determine the reaction rate constant (k):

- `kinetics_data['Normalized_BuBr]` : Mol fraction of butylbromide.
- `kinetics_data['Normalized_BuI]` : Mol fraction of butyliodide.
- `kinetics_data['[BuBr]']` : Concentration of butylbromide (M).
- `kinetics_data['[BuI]']` : Concentration of butyliodide (M).
- `kinetics_data['ln[BuBr]']` : Natural log of the concentration of butylbromide (M).
- `kinetics_data['1/[BuBr]']` : Inversion concentration of butylbromide (M^{-1}).

Let's create these new columns now!

In [25]:

```
kinetics_data['Normalized_BuBr'] = kinetics_data['Integration_3.5_ppm'] / (kinetics_data['Integration_3.5_ppm'] + kinetics_dat
kinetics_data['Normalized_BuI'] = kinetics_data['Integration_3.3_ppm'] / (kinetics_data['Integration_3.5_ppm'] + kinetics_data
kinetics_data['[BuBr]'] = kinetics_data['Normalized_BuBr'] * 0.6
kinetics_data['[BuI]'] = kinetics_data['Normalized_BuI'] * 0.6
kinetics_data['ln[BuBr]'] = np.log(kinetics_data['[BuBr]'])
```

Challange

Create new column `kinetics_data['1/[BuBr]']` (M^{-1}) by taking the inverse of `kinetics_data['[BuBr]']` (M).

In [26]:

```
kinetics_data['1/[BuBr]'] = 1 / kinetics_data['[BuBr]']
```

Examining Data Part 2

Pandas has additional useful methods for quickly examining and summarizing date.

- `info()` : Provides a summary of the DataFrame, including data types and non-null counts.
- `describe()` : Generates descriptive statistics for numeric columns.

Now that we have more data in our DataFrame, let's use the `describe()` method to examine how our DataFrame has changed:

In [27]:

```
kinetics_data.describe()
```

Out[27]:

	Timepoint	Integration_3.5_ppm	Integration_3.3_ppm	Time(s)	Normalized_BuBr	Normalized_BuI	[BuBr]	[BuI]	ln[Bu
count	60.000000	6.000000e+01	6.000000e+01	60.000000	60.000000	60.000000	60.000000	60.000000	60.000(
mean	30.500000	8.563993e+09	8.897774e+09	915.000000	0.488243	0.511757	0.292946	0.307054	-1.275(
std	17.464249	2.996777e+09	2.749852e+09	523.927476	0.161350	0.161350	0.096810	0.096810	0.304(
min	1.000000	5.548890e+09	1.850710e+09	30.000000	0.322032	0.100353	0.193219	0.060212	-1.643!
25%	15.750000	6.185688e+09	7.231048e+09	472.500000	0.358699	0.413501	0.215219	0.248101	-1.536
50%	30.500000	7.459425e+09	9.992435e+09	915.000000	0.427429	0.572571	0.256457	0.343543	-1.360
75%	45.250000	1.025635e+10	1.105912e+10	1357.500000	0.586499	0.641301	0.351899	0.384781	-1.044
max	60.000000	1.681610e+10	1.168200e+10	1800.000000	0.899647	0.677968	0.539788	0.406781	-0.616!

Visualizing data with Pandas

Pandas makes data visualization easy with its built-in `DataFrame.plot()` method that can make plots directly from a DataFrame object.

Why plot with Pandas?

- **Ease of Use**: Quickly create line plots, bar charts, scatter plots, and more.
- **Built for DataFrames**: Automatically uses column names as labels and handles indexing seamlessly.

`DataFrame.plot()`

Make plots of a DataFrame.

Parameters

- **x** : `str` of column name, *(default: `None`)*

  The column to use for the x-axis (independent variable).

- **y** : `str` or `list` of column name(s), *(default: `None`)*

  The column(s) to use for the y-axis (dependent variable).

- **kind** : `str` , *(Default: `'line'`)*

  The kind of plot to produce (e.g., `'bar'` , `'hist'` , `'scatter'`)

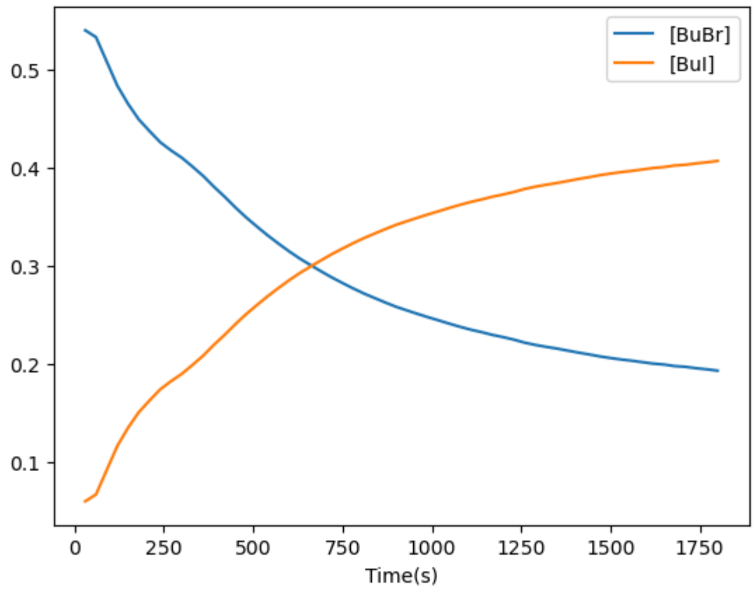
Let's plot our reaction over time!

In [28]:

```
kinetics_data.plot(x='Time(s)', y=['[BuBr]', '[BuI]'])
```

Out[28]:

```
<Axes: xlabel='Time(s)'>
```



Introduction to Matplotlib

Matplotlib is a popular Python library used for creating static, interactive, and animated visualizations. It is especially useful in scientific computing for generating publication-quality graphs and plots. Matplotlib works seamlessly with NumPy, pandas, and other data-handling libraries, making it an excellent choice for visualizing chemical data.

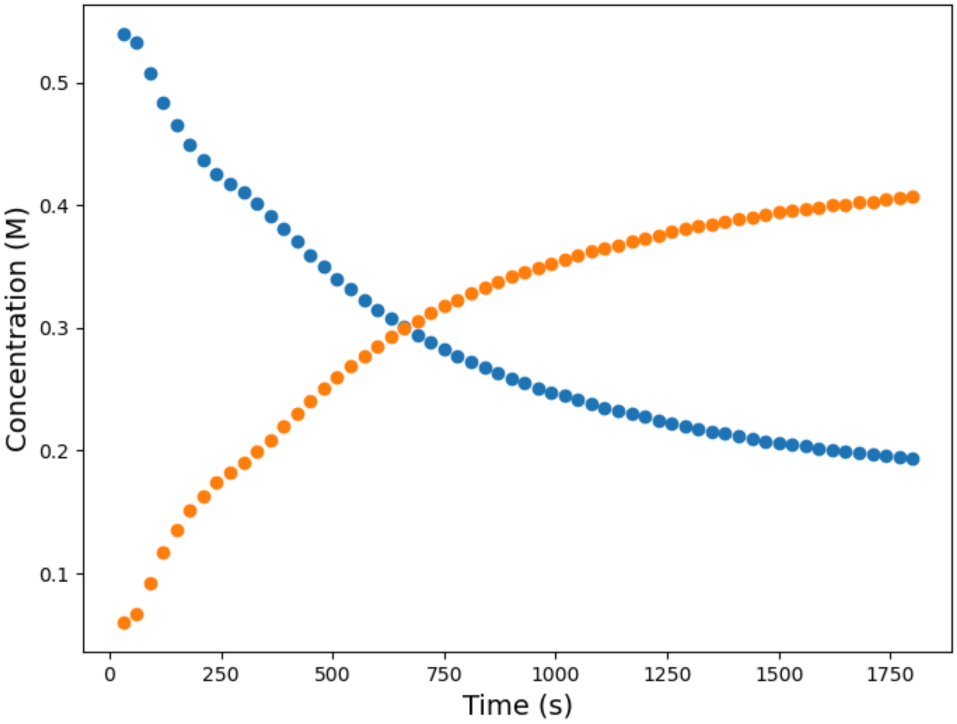
Why plot with Matplotlib?

- **Versatility:** Supports various types of plots like scatter, line, bar, and histogram.
- **Customization:** You can control every aspect of the figure, such as colors, labels, and markers.

Let's replot our reaction progress over tim using matplotlib!

In [29]:

```
# Create a blank figure
plt.figure(figsize=(8, 6))  # Set the figure size

# Plot [BuBr] as a scatter plot
plt.scatter(
    x=kinetics_data['Time(s)'],
    y=kinetics_data['[BuBr]'],
    label='[BuBr]'
)

# Plot [BuI] as a scatter plot
plt.scatter(
    x=kinetics_data['Time(s)'],
    y=kinetics_data['[BuI]'],
    label='[BuI]'
)

# Add labels, title, and legend
plt.xlabel('Time (s)', fontsize=14)
plt.ylabel('Concentration (M)', fontsize=14)

# Show the plot
plt.show()
```



Customize scatter plots with Matplotlib

Matplotlib offers tons of customization. Here is a summary of some of the methods and arguments we can use to modify our scatter plot.

`plt.scatter()`

A scatter plot of y vs. x with varying marker size and/or color.

Parameters

- **s** : `float` , *(default:* `20` *)*

  The size of the markers.

- **color** : `str` of color, *(default:* `None` *)*

  The marker colors (e.g., `'red'` , `'blue'` , `'green'` , `'yellow'`).

- **marker** : `str` of marker style, *(default:* `'o'` *)*

  The style of the markers (e.g., `'o'` , `'v'` , `'s'` , `'*'`).

- **edgecolors** : `str` of color, *(default:* `'face'` *)*

  The edge color of the markers. Use `'face'` to match the face color or `'none'` for no edge.

- **alpha** : `float` , *(default:* `None` *)*

  The alpha blending value for markers, between 0 (transparent) and 1 (opaque).

- **label** : `str` , *(default:* `None` *)*

  A label for the legend.

`plt.title()`

Set a title for the plot.

Parameters

- **label** : `str` , *(default:* `None` *)*

The title text to display at the top of the plot.

- **loc** : `str` , one of `'center'` , `'left'` , or `'right'` , *(default: `'center'`)*

  The alignment of the title relative to the plot.

`plt.legend()`

Place a legend on the Axes.

Parameters

- **loc** : `str` , *(default: `'best'`)*

  The location of the legend (e.g., `'upper right'` , `'center'` , or `'best'`).

- **title** : `str` , *(default: `None`)*

  The title of the legend box.

- **fontsize** : `int` or `str` , *(default: `None`)*

  The size of the legend text.

`plt.grid()`

Configure the grid lines.

Parameters

- **visible** : `bool` , *(default: `None`)*

  Whether to show (`True`) or hide (`False`) the grid.

- **color** : `str` of color, *(default: `None`)*

  The color of the grid lines.

- **linestyle** : `str` of line style, *(default: `None`)*

  The style of the grid lines (e.g., `'solid'` , `'dotted'` , or `'dashed'`).

`plt.xlim()`

Set the x limits of the current Axes.

Parameters

- **left** : `float` or `None` , *(default: `None`)*

  The lower limit of the x-axis.

- **right** : `float` or `None` , *(default: `None`)*

  The upper limit of the x-axis.

`plt.ylim()`

Set the y limits of the current Axes.

Parameters

- **bottom** : `float` or `None` , *(default: `None`)*

  The lower limit of the y-axis.

- **top** : `float` or `None` , *(default: `None`)*

  The upper limit of the y-axis.

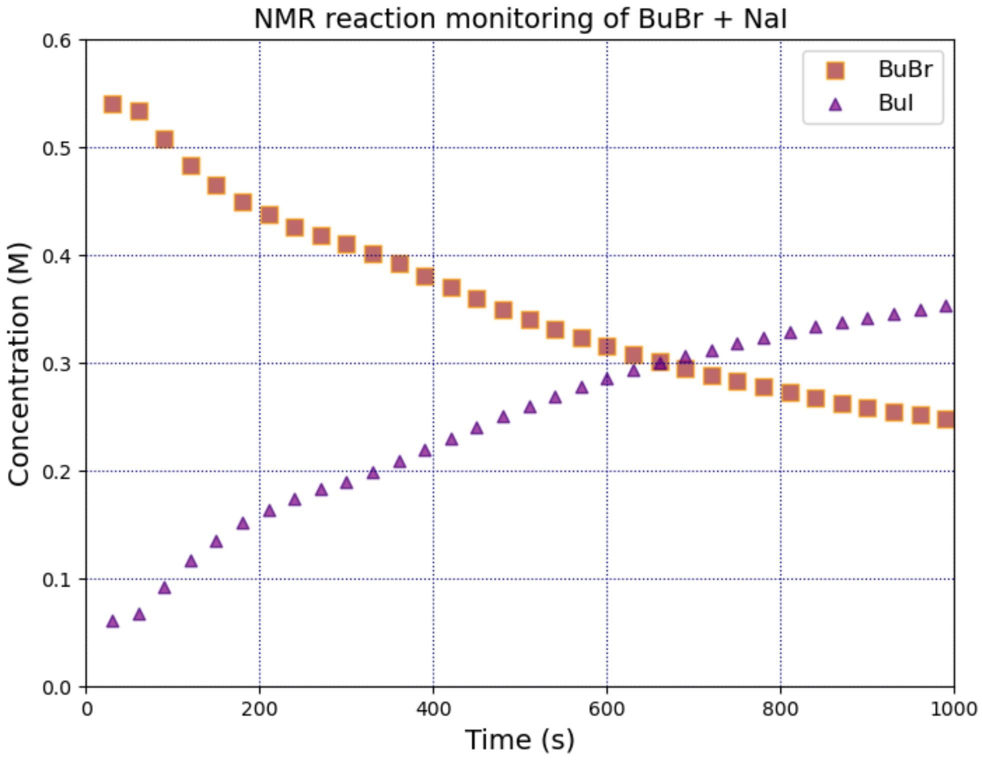
Challange

Use the documentation summary above to customize your own scatter plot.

Make a few modification to the code below and run the cell to view your new scatter plot.

In [30]:

```python
# Create a blank figure
plt.figure(figsize=(8, 6))  # Set the figure size

# Plot [BuBr] as a scatter plot
plt.scatter(
    x=kinetics_data['Time(s)'],
    y=kinetics_data['[BuBr]'],
    s=75,
    color='brown',
    marker='s',
    alpha=0.7,
    edgecolor='orange',
    label='BuBr',
)

# Plot [BuI] as a scatter plot
plt.scatter(
    x=kinetics_data['Time(s)'],
    y=kinetics_data['[BuI]'],
    color='purple',
    edgecolor='indigo',
    marker='^',
    label='BuI',
    alpha=0.7,
)

# Add labels, title, and legend
plt.xlim(left=0, right=1000)
plt.ylim(top=0.6, bottom=0)
plt.xlabel('Time (s)', fontsize=14)
plt.ylabel('Concentration (M)', fontsize=14)
plt.title('NMR reaction monitoring of BuBr + NaI', fontsize=14)
plt.legend(fontsize=12)

# Show the plot
plt.grid(visible=True, color='darkblue', linestyle='dotted')  # Add a grid for better readability
plt.show()
```



Determining Reaction Order and Rate Constant

We can determine the reaction order and rate constant (k) of our reaction by analyzing the data and constructing specific plots.

Reaction order

The reaction order is determined by finding which plot gives the best linear regression.

- **First-order**: Plot ln[reactant] vs. time.
- **Second-order**: Plot 1/[reactant] vs. time.

Rate constant

The rate constant (k) can be determined from the slope of the linear regression.

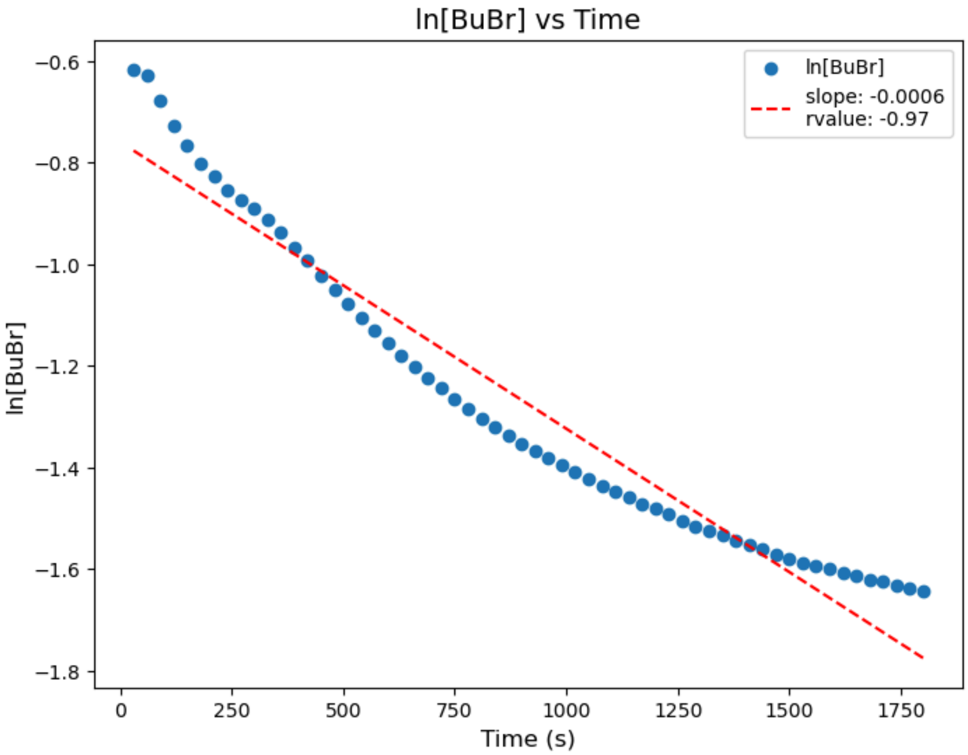
- **First-order**: slope = -k
- **Second-order**: slope = k

Summary

	First-order	Second-order
Rate Law	$Rate = k[reactant]$	$Rate = k[reactant]^2$
Integrated Form	$ln[reactant] = -kt + ln[reactant_o]$	$1/[reactant] = kt + 1/[reactant_o]$
Linear Plot	ln[reactant] vs. time (slope = -k)	1/[reactant] vs. time (slope = k)

Let's use Matplotlib to create the first-order plot (ln[reactant] vs. time) and linregress from the scipy library to perform a linear regression.

```
In [31]: # Import linregress method
from scipy.stats import linregress

# Create a blank figure
plt.figure(figsize=(8, 6))

# Plot ln([BuBr]) vs Time
plt.scatter(
    x=kinetics_data['Time(s)'],
    y=kinetics_data['ln[BuBr]'],
    label="ln[BuBr]",
)

# Use scipy to perform linear regression
slope, intercept, rvalue, _, _ = linregress(
                                    kinetics_data['Time(s)'],
                                    kinetics_data['ln[BuBr]']
)

# Add linear regression line (line = kt + ln[reactantₒ])
regression_line = slope * kinetics_data['Time(s)'] + intercept

# Plot the linear regression line
plt.plot(
    kinetics_data['Time(s)'],
    regression_line,
    label=f"slope: {slope:.4f}\nrvalue: {rvalue:.2f}",
    color='red',
    linestyle='--'
)

# Add labels, title, and legend
plt.title("ln[BuBr] vs Time", fontsize=14)
plt.xlabel("Time (s)", fontsize=12)
plt.ylabel("ln[BuBr]", fontsize=12)
plt.legend()

# Show plot
plt.show()
```



Challange

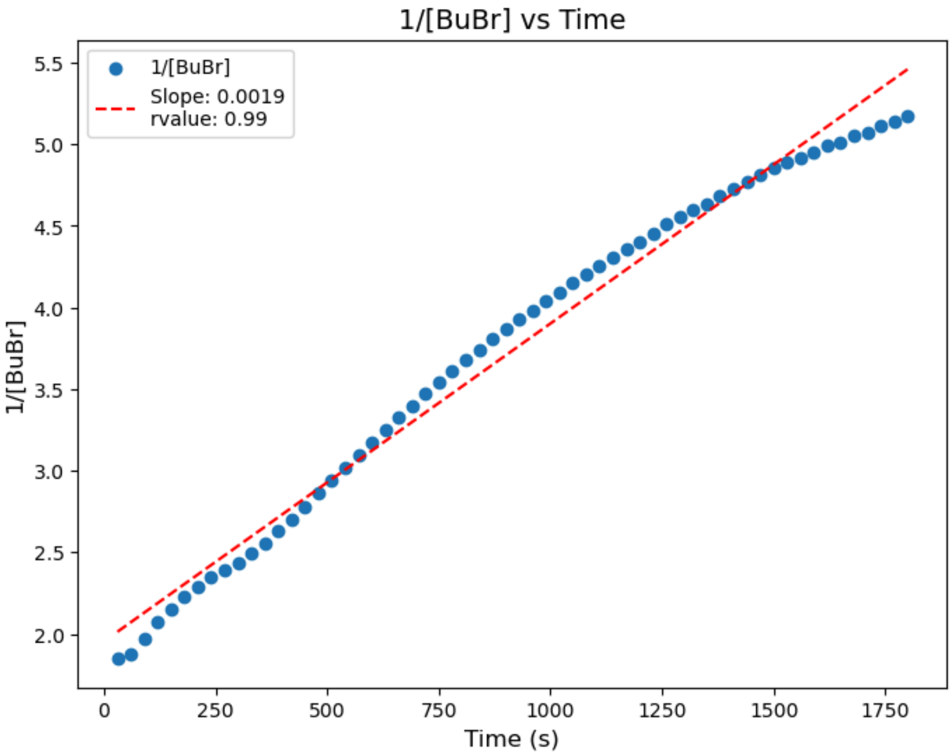
Use Matplotlib to create the second-order plot (1/[reactant] vs. time).

- x: `kinetics_data['Time(s)']`
- y: `kinetics_data['1/[BuBr]']`

In [32]:

```
# Import linregress method
from scipy.stats import linregress

# Create a blank figure
plt.figure(figsize=(8, 6))

# Plot ln([BuBr]) vs Time
plt.scatter(
    x=kinetics_data['Time(s)'],
    y=kinetics_data['1/[BuBr]'],
    label="1/[BuBr]",
)

# Use scipy to perform linear regression
slope, intercept, rvalue, _, _ = linregress(
                                    kinetics_data['Time(s)'],
                                    kinetics_data['1/[BuBr]']
)

# Add linear regression line (line = kt + ln[reactantₒ])
regression_line = slope * kinetics_data['Time(s)'] + intercept

# Plot the linear regression line
plt.plot(
    kinetics_data['Time(s)'],
    regression_line,
    label=f"Slope: {slope:.4f}\nrvalue: {rvalue:.2f}",
    color='red',
    linestyle='--'
)

# Add labels, title, and legend
plt.title("1/[BuBr] vs Time", fontsize=14)
plt.xlabel("Time (s)", fontsize=12)
plt.ylabel("1/[BuBr]", fontsize=12)
plt.legend()
```

```
# Show plot
plt.show()
```



Challange

Use the plots and linear regressions to:

1. Determine the reaction order.
2. Determine the rate constant (k).

Write your answer in the Markdown cell below.

- Reaction order: 2nd order
- rate constant (k): 0.0019 s^-1