



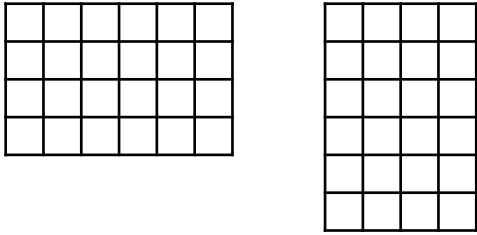
Python Meets Mathematics: **Calculus**

Sunglok Choi, Assistant Professor, Ph.D.
Computer Science and Engineering Department, SEOULTECH
sunglok@seoultech.ac.kr | <https://mint-lab.github.io/>

Building Mathematical Intuition

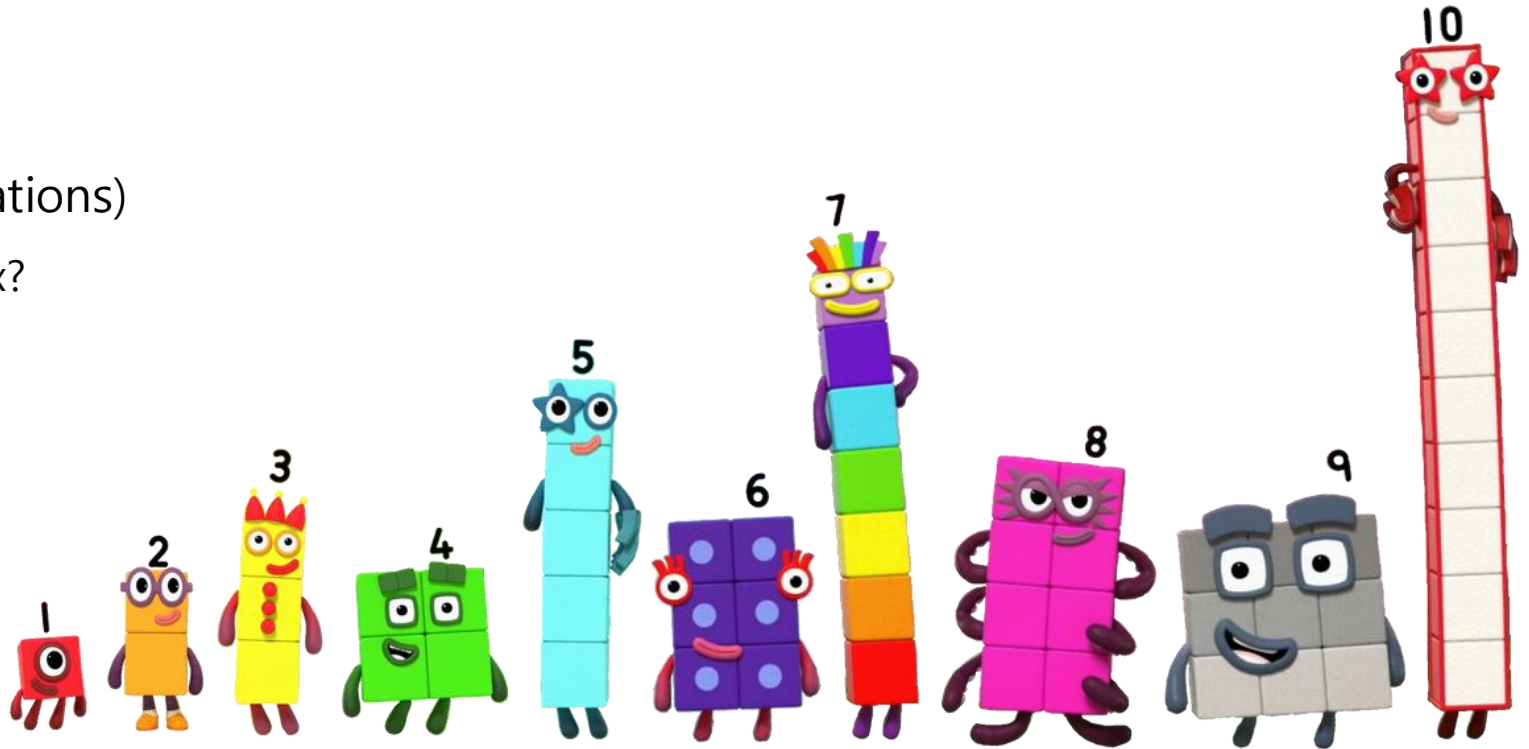
1. Imagine (or visualize)

- e.g. *Numberblocks* (by BBC) [\[YouTube\]](#)
- e.g. Why $4 \times 6 == 6 \times 4$? (for kids without knowledge of a [multiplication table](#) and [commutativity](#))



2. Ask why (or think about its applications)

- e.g. Why did I learn about a matrix?



Tools

- [SciPy](#)

- A python-based open-source ecosystem for mathematics, science, and engineering.
 - An open-source computing tool against the commercial software such as [MATLAB](#)
 - Included in [Anaconda](#) by default
- Major components



NumPy
Base N-dimensional
array package



SciPy library
Fundamental library for
scientific computing



Matplotlib
Comprehensive 2-D
plotting



IPython
Enhanced interactive
console



SymPy
Symbolic mathematics



pandas
Data structures &
analysis

- Online references: [MINT Lab's Know-where](#)

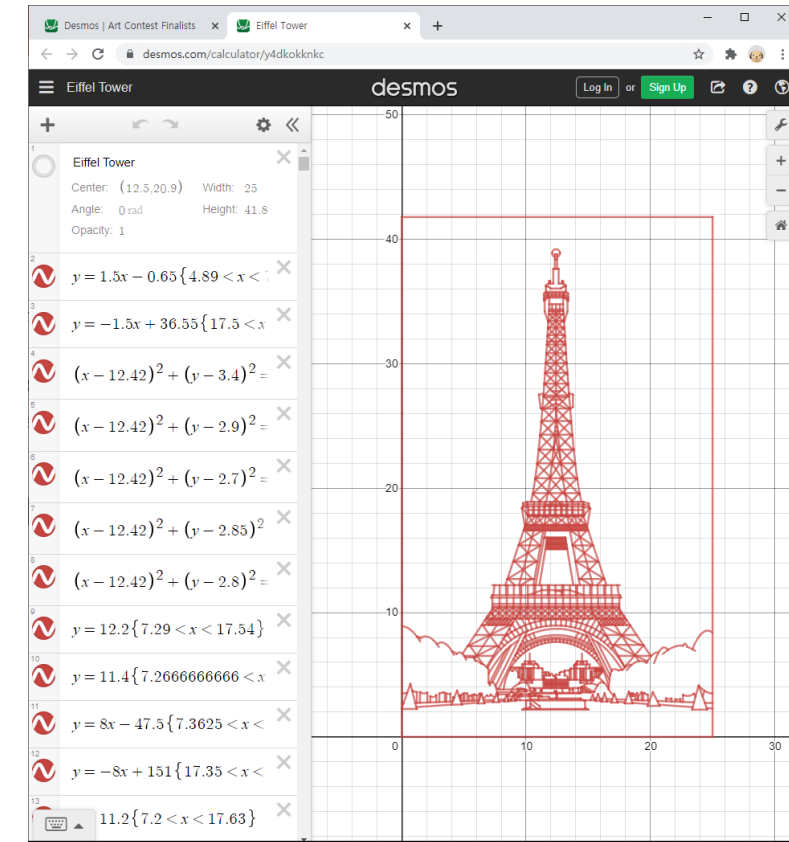
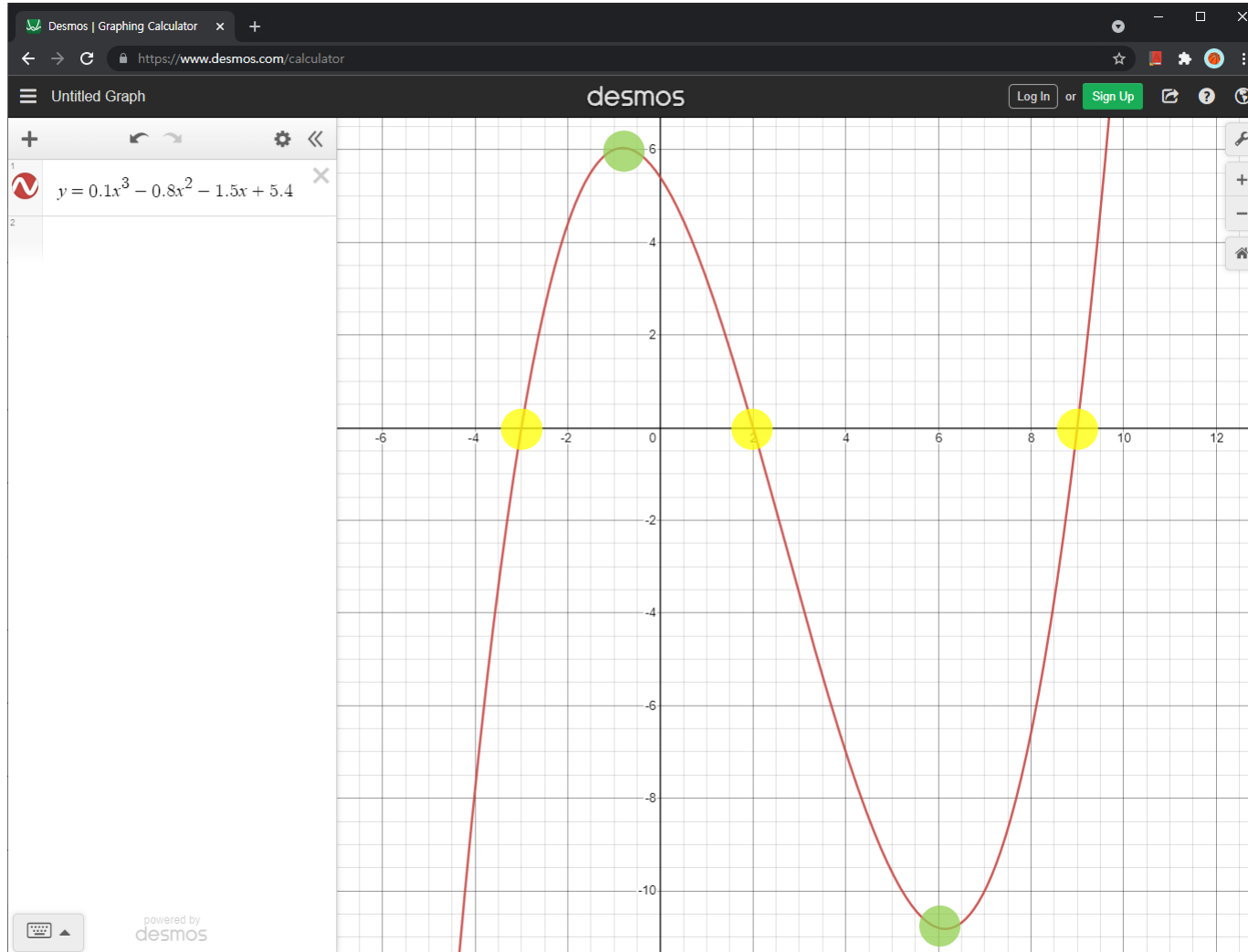
- Please refer *Programming (Python)* category, especially about *P3. NumPy, SciPy, and Matplotlib* section.

~~Programming~~ Python with SciPy meets Mathematics

- Calculus
- Linear Algebra
- Optimization
- Probability
- Information Theory

Getting Started from Drawing an Equation

- Example) Drawing $y = 0.1x^3 - 0.8x^2 - 1.5x + 5.4$
- Visualization with [Desmos Graphing Calculator](https://www.desmos.com/calculator)



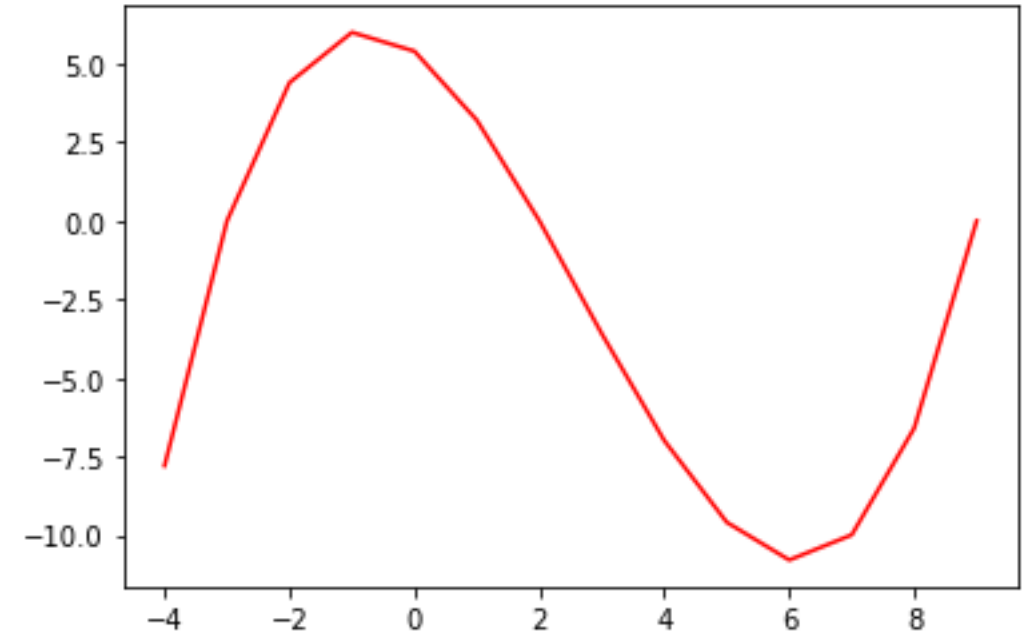
Getting Started from Drawing an Equation

- Example) Drawing $y = 0.1x^3 - 0.8x^2 - 1.5x + 5.4$
- Visualization with [Matplotlib](#)

```
import matplotlib.pyplot as plt
```

```
xs = [x for x in range(-4, 10)]  
ys = [0.1*x**3 - 0.8*x**2 - 1.5*x + 5.4 for x in xs]
```

```
plt.plot(xs, ys, 'r-')  
plt.show()
```

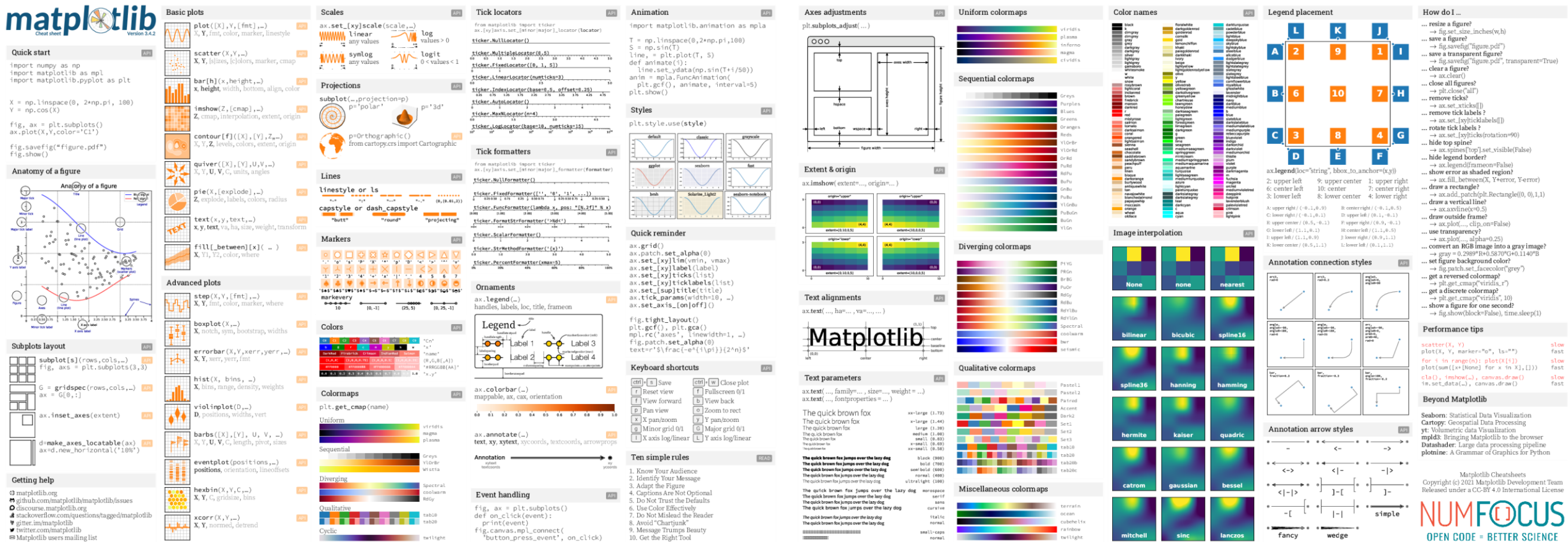


Further improvement)

- How to make the graph smooth?
- How to draw the grid?
- How to display labels on X and Y axes?
- How to make its aspect ratio equal?

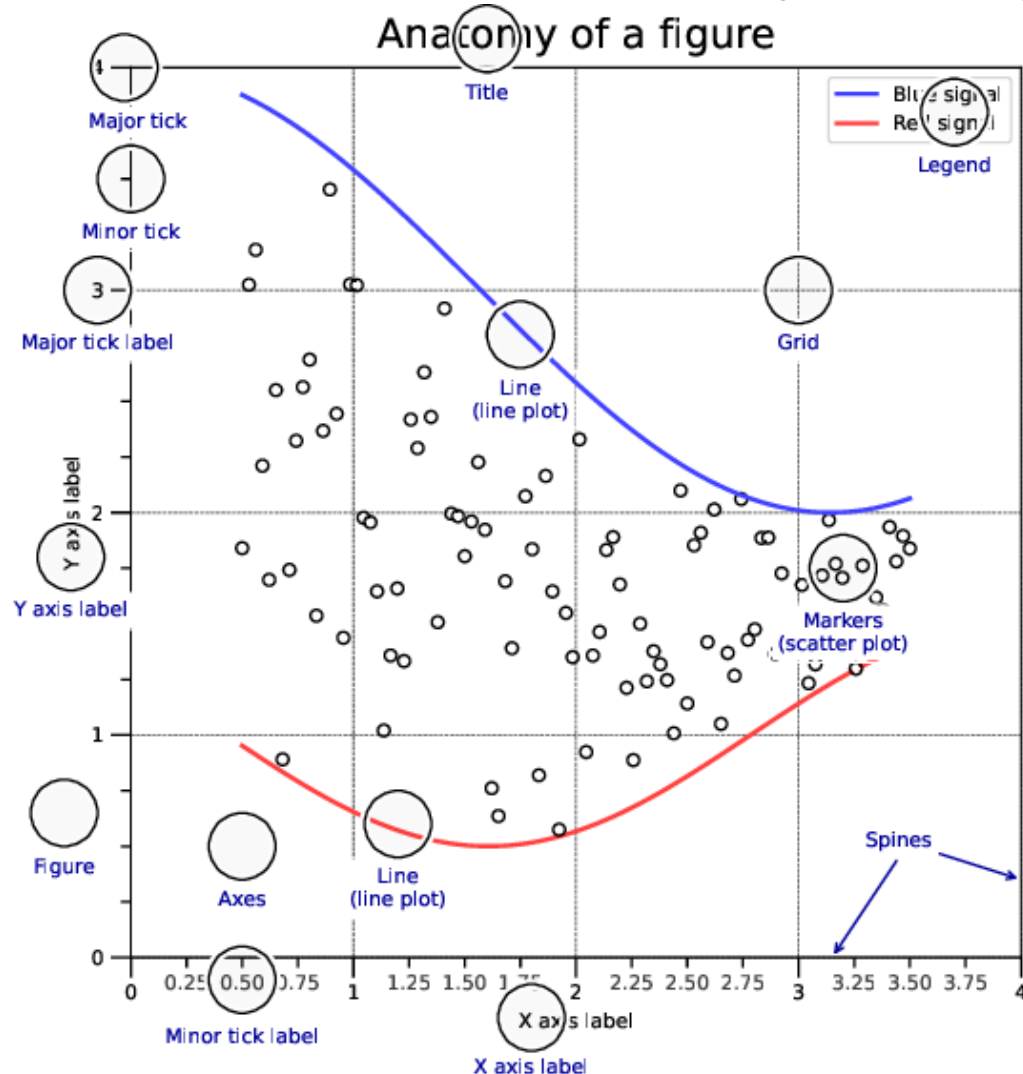
Matplotlib: A Plotting Library in Python

- [Matplotlib](#) is a plotting library for creating static, animated, and interactive visualization in Python.
- References: [Documentation](#), [Examples](#) (Gallery), [Tutorials](#), and [Cheatsheets](#) (made by Matplotlib)



Matplotlib: A Plotting Library in Python

- [Matplotlib](#) is a plotting library for creating static, animated, and interactive visualization in Python.
- References: [Documentation](#), [Examples](#) (Gallery), [Tutorials](#), and [Cheatsheets](#) (made by Matplotlib)



Basic plots

	<code>plot([X], Y, [fmt], ...)</code> X, Y, fmt, color, marker, linestyle	API
	<code>scatter(X, Y, ...)</code> X, Y, [s]izes, [c]olors, marker, cmap	API
	<code>bar[h](x, height, ...)</code> x, height, width, bottom, align, color	API
	<code>imshow(Z, [cmap], ...)</code> Z, cmap, interpolation, extent, origin	API
	<code>contour[f]([X], [Y], Z, ...)</code> X, Y, Z, levels, colors, extent, origin	API
	<code>quiver([X], [Y], U, V, ...)</code> X, Y, U, V, C, units, angles	API
	<code>pie(X, [explode], ...)</code> Z, explode, labels, colors, radius	API
	<code>text(x, y, text, ...)</code> x, y, text, va, ha, size, weight, transform	API
	<code>fill[_between][x](...)</code> X, Y1, Y2, color, where	API

Advanced plots

	<code>step(X, Y, [fmt], ...)</code> X, Y, fmt, color, marker, where	API
	<code>boxplot(X, ...)</code> X, notch, sym, bootstrap, widths	API
	<code>errorbar(X, Y, xerr, yerr, ...)</code> X, Y, xerr, yerr, fmt	API
	<code>hist(X, bins, ...)</code> X, bins, range, density, weights	API
	<code>violinplot(D, ...)</code> D, positions, widths, vert	API
	<code>barbs([X], [Y], U, V, ...)</code> X, Y, U, V, C, length, pivot, sizes	API
	<code>eventplot(positions, ...)</code> positions, orientation, lineoffsets	API
	<code>hexbin(X, Y, C, ...)</code> X, Y, C, gridsize, bins	API
	<code>xcorr(X, Y, ...)</code> X, Y, normed, detrend	API

Matplotlib: A Plotting Library in Python

- [Matplotlib](#) is a plotting library for creating static, animated, and interactive visualization in Python.
- References: [Documentation](#), [Examples](#) (Gallery), [Tutorials](#), and [Cheatsheets](#) (made by Matplotlib)
- API examples @ [matplotlib.pyplot](#) **module** (a state-based interface; ~ [MATLAB](#))
 - `plot([x], y, [fmt], ...)`: Plot y versus x as lines and/or markers
 - `hist(x, bins=None, range=None, ...)`: Plot a [histogram](#)
 - `contour([X, Y,] Z, [levels], ...)`: Plot [contour lines](#)
 - `imshow(X, cmap=None, ...)`: Display data as an image (a 2D regular [raster](#))
 - `title(label, ...)`: Set a title for the Axes
 - `axis(...)`: Get or set axis properties (e.g. 'on'/'off', 'equal', and range of X/Y axes)
 - `legend(...)`: Place a legend on the Axes
 - `grid(...)`: Configure the grid lines
 - `xlabel(label, ...)`, `xlim(left, right)`, ...: Set the label and limit for the x-axis
 - `figure(num=None, ...)`: Create a new figure or activate an existing figure
 - `show(...)`: Display all open figures
 - `savefig(filename, ...)`: Save the current figure

Matplotlib: A Plotting Library in Python

- Usage example) Drawing $y = 0.1x^3 - 0.8x^2 - 1.5x + 5.4$

```
import matplotlib.pyplot as plt
```

```
scale = 10
```

```
xs = [x/scale for x in range(-4*scale, 10*scale)]
```

```
ys = [0.1*x**3 - 0.8*x**2 - 1.5*x + 5.4 for x in xs]
```

```
plt.title('$y = 0.1x^3 - 0.8x^2 - 1.5x + 5.4$') # LaTeX style
```

```
plt.plot(xs, ys, 'r-')
```

```
plt.xlabel('x')
```

```
plt.ylabel('y')
```

```
plt.grid()
```

```
plt.axis('equal')
```

```
plt.show()
```



Further improvement)

- ✓ How to make the graph smooth?
- ✓ How to draw the grid?
- ✓ How to display labels on X and Y axes?
- ✓ How to make its aspect ratio equal?

Matplotlib: A Plotting Library in Python

- Example) Plotting midterm and final scores
 - The given data (file: data/class_score_en.csv)
midterm (max 125), final (max 100)

113, 86

104, 83

110, 78

101, 79

101, 77

103, 76

71, 94

102, 71

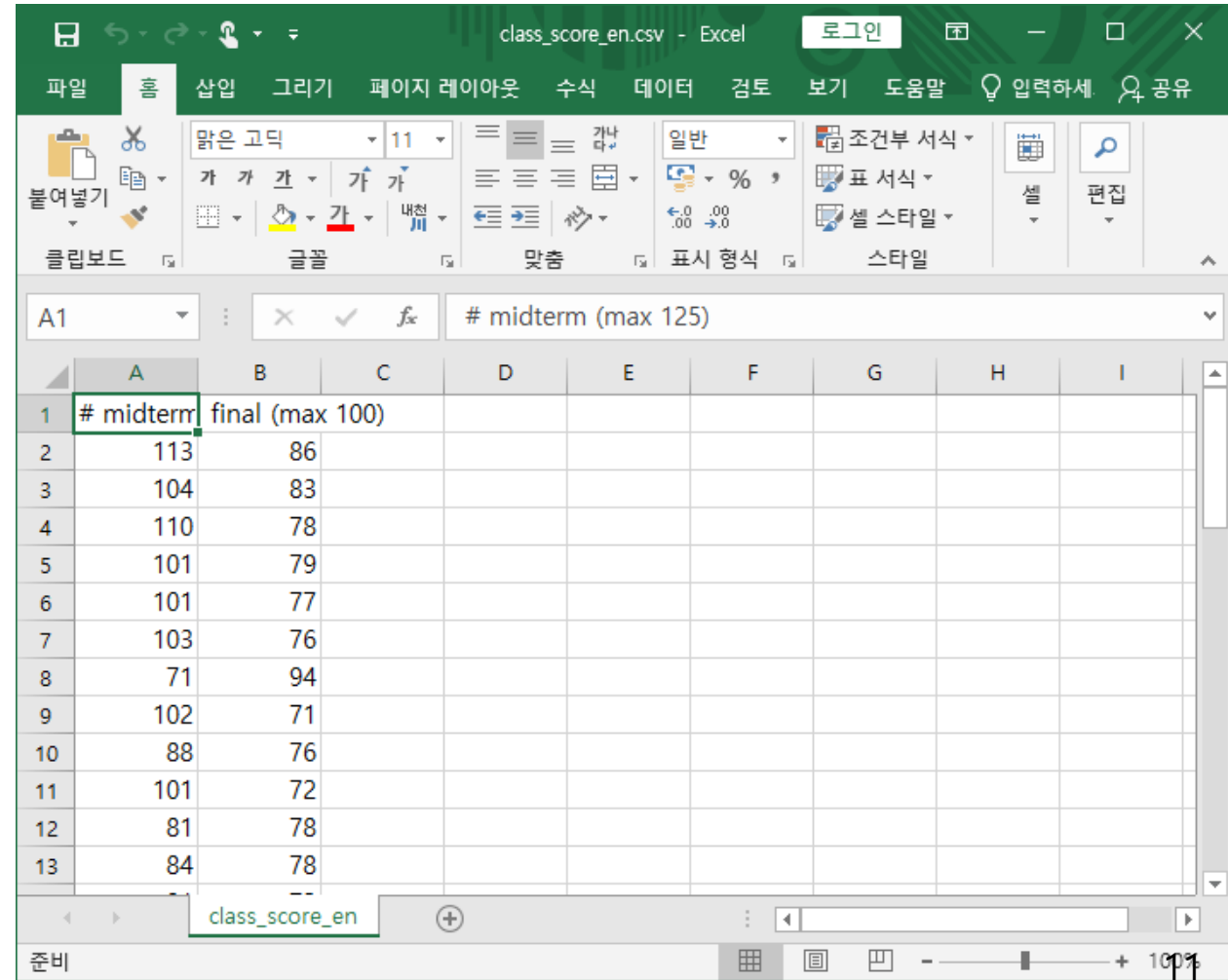
88, 76

101, 72

81, 78

84, 78

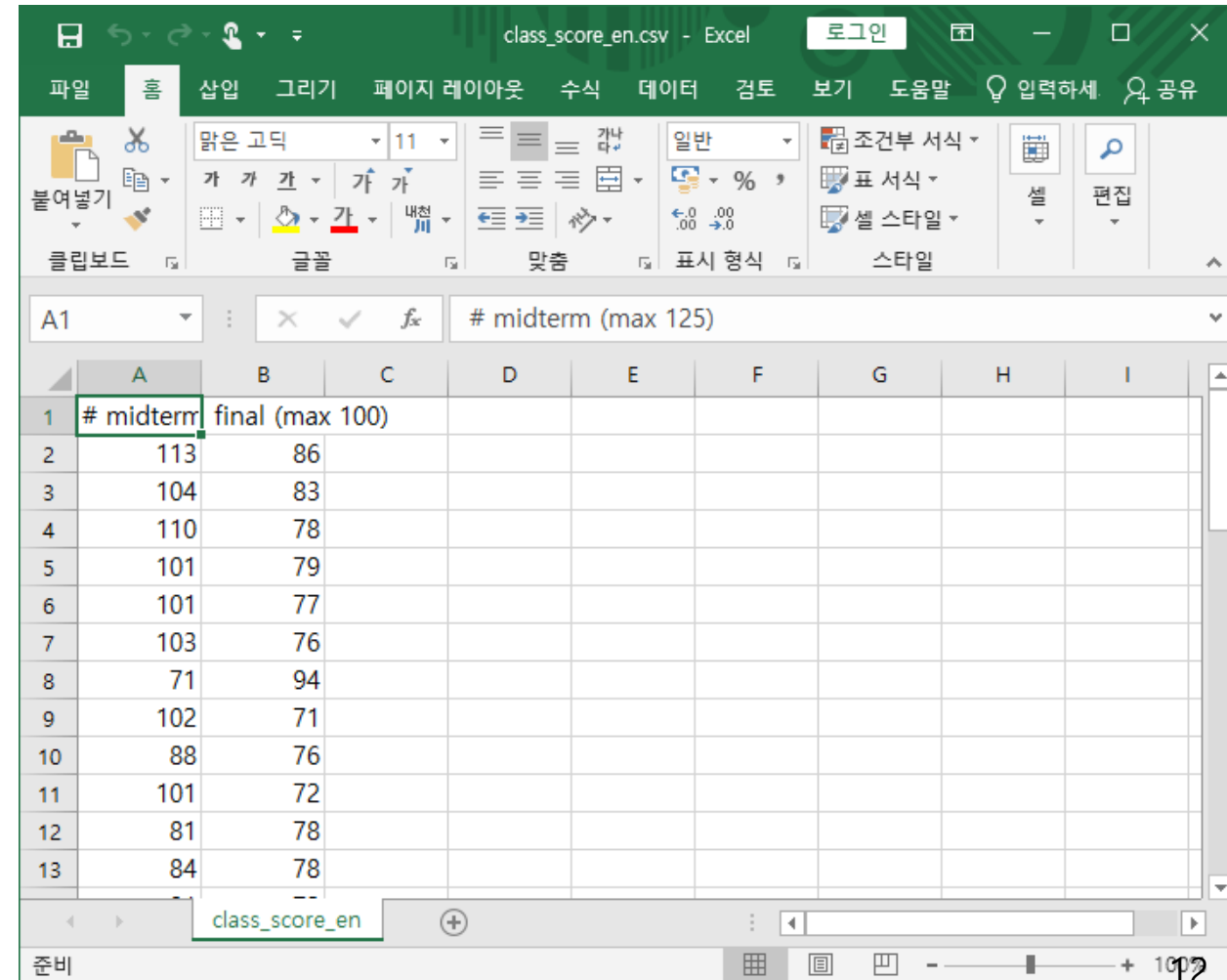
. . .



	# midterm (max 125)	final (max 100)
1	113	86
2	104	83
3	110	78
4	101	79
5	101	77
6	103	76
7	71	94
8	102	71
9	88	76
10	101	72
11	81	78
12	84	78
13		

Matplotlib: A Plotting Library in Python

- Example) Plotting midterm and final scores
 - Analysis using representative values (e.g. mean, median, ...; [대표값](#) in Korean)
 - Midterm
 - Mean: **74.209**
 - Variance: 632.817
 - Median: **72.000**
 - Min/Max: (21.000, 117.000)
 - Final
 - Mean: **58.674**
 - Variance: 618.545
 - Median: **66.000**
 - Min/Max: (0.000, 94.000)
 - Total
 - Mean: **58.952**
 - Variance: 423.546
 - Median: **65.000**
 - Min/Max: (6.720, 87.760)

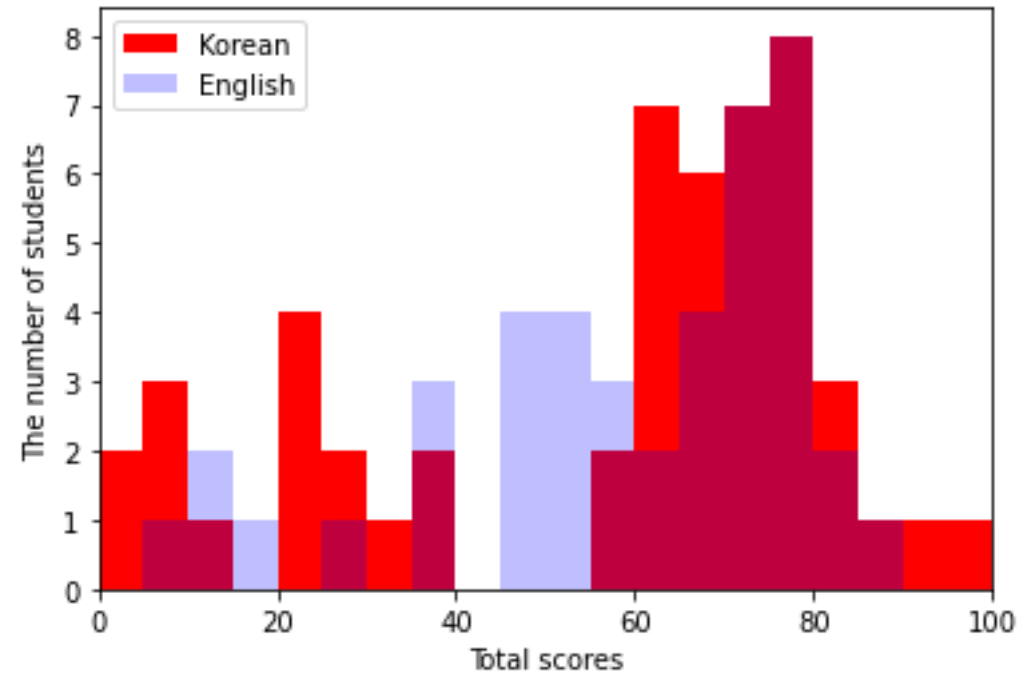
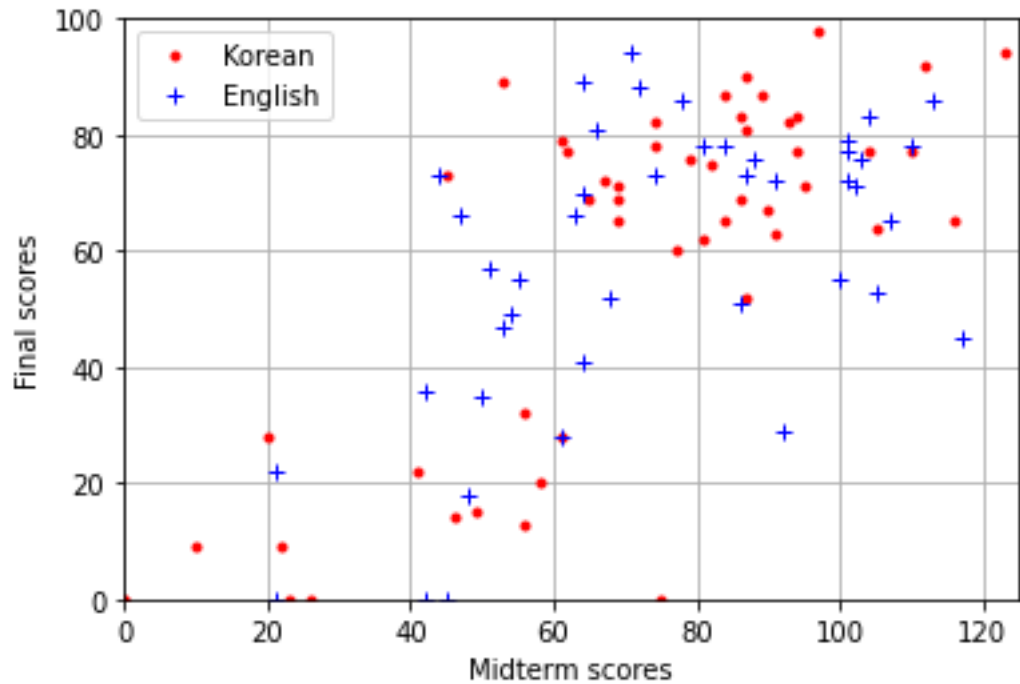


The screenshot shows an Excel spreadsheet titled 'class_score_en.csv'. The data is organized into two columns: '# midterm' and 'final (max 100)'. The first column is highlighted with a green border. The data is as follows:

	# midterm	final (max 100)
1	113	86
2	104	83
3	110	78
4	101	79
5	101	77
6	103	76
7	71	94
8	102	71
9	88	76
10	101	72
11	81	78
12	84	78
13		

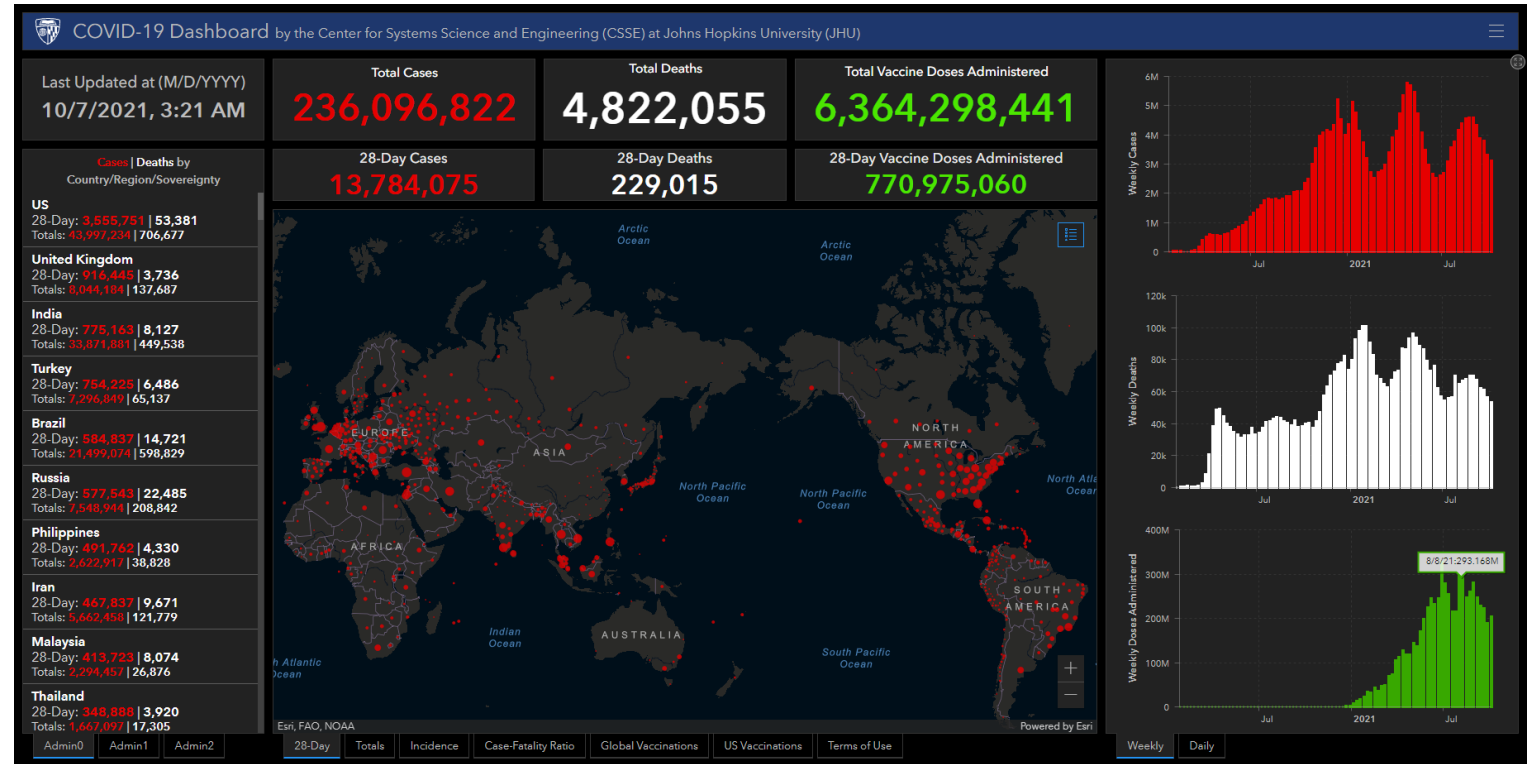
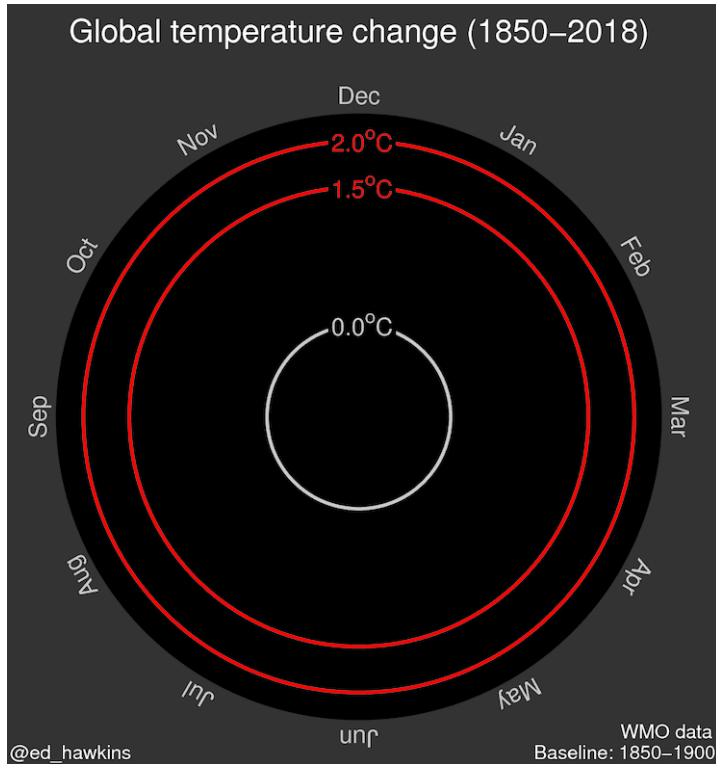
Matplotlib: A Plotting Library in Python

- Example) Plotting midterm and final scores
 - Practice) Plot the [scatter plot](#) of midterm and final scores
 - Practice) Plot the [histogram](#) of total scores
 - What can you discover from two graphs?



Visualization

- Visualization is very important not only for your data but also for your programs, systems, and society.

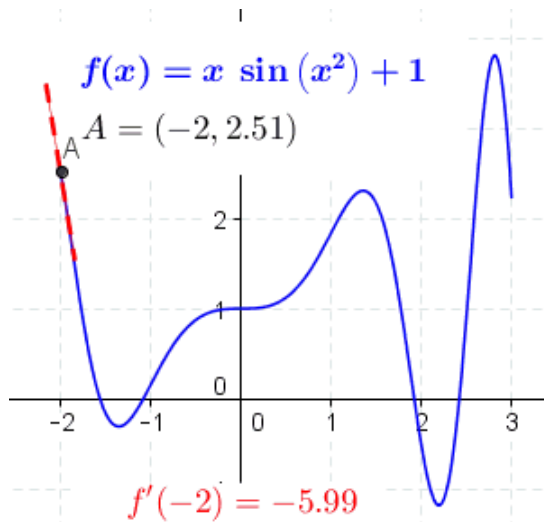


Calculus

- Calculus (originally called *infinitesimal calculus*, 미적분학 in Korean) is the mathematical study of continuous change.
- Two major tools

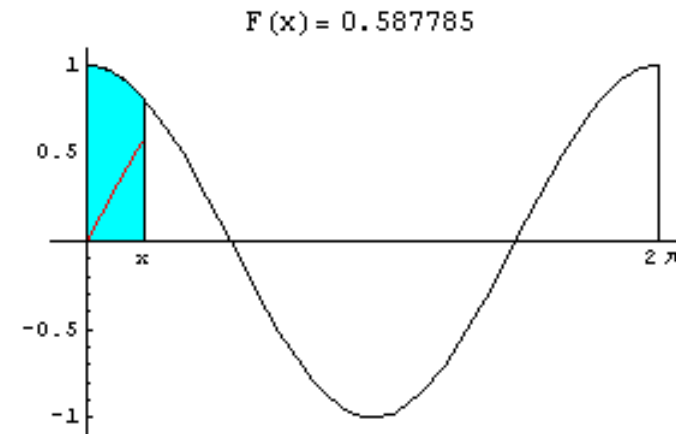
Differentiation:

Finding a derivative of a function



Integration:

Calculating numbers to a function
by combining infinitesimal increments



Calculus Differentiation

- [Differentiation](#) is the process of finding a **derivative** of a function.

- **Derivative** [\[Wikipedia\]](#)

- Definition

- Change of the function value (**output value**) with respect to a change in its argument (**input value**)

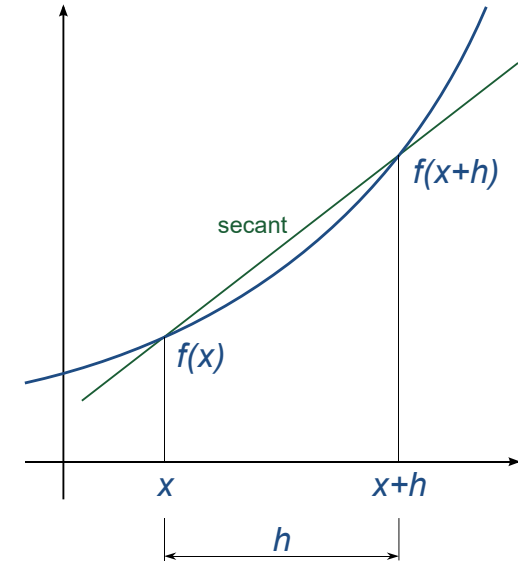
$$f'(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}$$

- Meaning

- The **slope** of a tangent line (plane) to the given function
- The tangent line ~ **linear approximation** (Note: 1st-order [Taylor series](#))

- Notation

- Leibniz's notation: $\frac{df}{dx}(x), \frac{d^2f}{dx^2}(x)$
- Lagrange's notation: $f'(x), f''(x)$
- Newton's notation: \dot{y}, \ddot{y} where $y = f(x)$
- Euler's notation: $D_x f(x), D_x^2 f(x)$



Differentiation

- Rules of computing a derivative [\[Wikipedia\]](#)
 - The polynomial functions such as $f(x) = x^n$
 - $f'(x) = nx^{n-1}$
 - Logarithmic and exponential functions
 - $\frac{d}{dx} \ln x = \frac{1}{x}$
 - $\frac{d}{dx} (e^x) = e^x$ (Note: e - [Euler's number](#), 자연상수 in Korean)
 - Too many functions ...
 - Differentiation is linear.**
 - $(f(x) + g(x))' = f'(x) + g'(x)$ and $(af(x))' = af'(x)$
 - The **product rule** of $h(x) = f(x)g(x)$
 - $h'(x) = f'(x)g(x) + f(x)g'(x)$
 - The **chain rule** of $h(x) = f(g(x))$
 - $h'(x) = \frac{dh(x)}{dx} = \frac{df(g(x))}{dg(x)} = f'(g(x)) \cdot g'(x) = \frac{df(g(x))}{dg(x)} \cdot \frac{dg(x)}{dx}$

Theoretical Computer Science Cheat Sheet	
π	Calculus
Wallis' identity: $\pi = 2 \cdot \frac{2}{1} \cdot \frac{2}{3} \cdot \frac{4}{5} \cdot \frac{4}{7} \cdot \frac{6}{9} \cdots$ Brouncker's continued fraction expansion: $\frac{\pi}{4} = 1 + \frac{1^2}{2 + \frac{3^2}{2 + \frac{5^2}{2 + \frac{7^2}{2 + \cdots}}}}$ Gregory's series: $\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \cdots$ Newton's series: $\frac{\pi}{6} = \frac{1}{2} + \frac{1}{2 \cdot 3 \cdot 2^3} + \frac{1 \cdot 3}{2 \cdot 4 \cdot 5 \cdot 2^5} + \cdots$ Sharp's series: $\frac{\pi}{6} = \frac{1}{\sqrt{3}} \left(1 - \frac{1}{3^1 \cdot 3} + \frac{1}{3^2 \cdot 5} - \frac{1}{3^3 \cdot 7} + \cdots \right)$ Euler's series: $\frac{\pi^2}{6} = \frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \frac{1}{5^2} + \cdots$ $\frac{\pi^2}{6} = \frac{1}{1^2} + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \frac{1}{9^2} + \cdots$ $\frac{\pi^2}{12} = \frac{1}{1^2} - \frac{1}{2^2} + \frac{1}{3^2} - \frac{1}{4^2} + \frac{1}{5^2} - \cdots$	Derivatives: 1. $\frac{d(cu)}{dx} = c \frac{du}{dx}$, 2. $\frac{d(u+v)}{dx} = \frac{du}{dx} + \frac{dv}{dx}$, 3. $\frac{d(uv)}{dx} = u \frac{dv}{dx} + v \frac{du}{dx}$, 4. $\frac{d(u^n)}{dx} = nu^{n-1} \frac{du}{dx}$, 5. $\frac{d(u/v)}{dx} = \frac{v \frac{du}{dx} - u \frac{dv}{dx}}{v^2}$, 6. $\frac{d(e^{cu})}{dx} = ce^{cu} \frac{du}{dx}$, 7. $\frac{d(c^u)}{dx} = (\ln c)c^u \frac{du}{dx}$, 8. $\frac{d(\ln u)}{dx} = \frac{1}{u} \frac{du}{dx}$, 9. $\frac{d(\sin u)}{dx} = \cos u \frac{du}{dx}$, 10. $\frac{d(\cos u)}{dx} = -\sin u \frac{du}{dx}$, 11. $\frac{d(\tan u)}{dx} = \sec^2 u \frac{du}{dx}$, 12. $\frac{d(\cot u)}{dx} = -\csc^2 u \frac{du}{dx}$, 13. $\frac{d(\sec u)}{dx} = \tan u \sec u \frac{du}{dx}$, 14. $\frac{d(\csc u)}{dx} = -\cot u \csc u \frac{du}{dx}$, 15. $\frac{d(\arcsin u)}{dx} = \frac{1}{\sqrt{1-u^2}} \frac{du}{dx}$, 16. $\frac{d(\arccos u)}{dx} = \frac{-1}{\sqrt{1-u^2}} \frac{du}{dx}$, 17. $\frac{d(\arctan u)}{dx} = \frac{1}{1+u^2} \frac{du}{dx}$, 18. $\frac{d(\operatorname{arccot} u)}{dx} = \frac{-1}{1+u^2} \frac{du}{dx}$, 19. $\frac{d(\operatorname{arcsec} u)}{dx} = \frac{1}{u\sqrt{1-u^2}} \frac{du}{dx}$, 20. $\frac{d(\operatorname{arccsc} u)}{dx} = \frac{-1}{u\sqrt{1-u^2}} \frac{du}{dx}$, 21. $\frac{d(\sinh u)}{dx} = \cosh u \frac{du}{dx}$, 22. $\frac{d(\cosh u)}{dx} = \sinh u \frac{du}{dx}$, 23. $\frac{d(\tanh u)}{dx} = \operatorname{sech}^2 u \frac{du}{dx}$, 24. $\frac{d(\coth u)}{dx} = -\operatorname{csch}^2 u \frac{du}{dx}$, 25. $\frac{d(\operatorname{sech} u)}{dx} = -\operatorname{sech} u \tanh u \frac{du}{dx}$, 26. $\frac{d(\operatorname{csch} u)}{dx} = -\operatorname{csch} u \coth u \frac{du}{dx}$, 27. $\frac{d(\operatorname{arcsinh} u)}{dx} = \frac{1}{\sqrt{1+u^2}} \frac{du}{dx}$, 28. $\frac{d(\operatorname{arccosh} u)}{dx} = \frac{1}{\sqrt{u^2-1}} \frac{du}{dx}$, 29. $\frac{d(\operatorname{arctanh} u)}{dx} = \frac{1}{1-u^2} \frac{du}{dx}$, 30. $\frac{d(\operatorname{arccoth} u)}{dx} = \frac{1}{u^2-1} \frac{du}{dx}$, 31. $\frac{d(\operatorname{arsech} u)}{dx} = \frac{-1}{u\sqrt{1-u^2}} \frac{du}{dx}$, 32. $\frac{d(\operatorname{arcsch} u)}{dx} = \frac{-1}{ u \sqrt{1+u^2}} \frac{du}{dx}$.
Partial Fractions Let $N(x)$ and $D(x)$ be polynomial functions of x . We can break down $N(x)/D(x)$ using partial fraction expansion. First, if the degree of N is greater than or equal to the degree of D , divide N by D , obtaining $\frac{N(x)}{D(x)} = Q(x) + \frac{N'(x)}{D(x)},$ where the degree of N' is less than that of D . Second, factor $D(x)$. Use the follow-	

Note) The quotient rule of $h(x) = \frac{f(x)}{g(x)} = f(x)g(x)^{-1}$

$$\bullet \quad h'(x) = \frac{f'(x)g(x) - g'(x)f(x)}{g^2(x)}$$

Differentiation

- Example) Finding the slope and tangent line of $y = 0.1x^3 - 0.8x^2 - 1.5x + 5.4$ at $x = 2$ ($y = 0$)
 - Derivative function: $\frac{dy}{dx}(x) = 0.3x^2 - 1.6x - 1.5$
 - Derivative value at $x = 2$ ($y = 0$): $\frac{dy}{dx}(2) = -3.5$
 - Tangent line at $x = 2$ ($y = 0$): $y - 0 = -3.5(x - 2) \rightarrow y = -3.5x + 7$

- Example) Plotting the above results

```
import matplotlib.pyplot as plt
```

```
scale = 10
```

```
xs = [x/scale for x in range(-4*scale, 10*scale)]
```

```
ys = [0.1*x**3 - 0.8*x**2 - 1.5*x + 5.4 for x in xs]
```

```
yt = [-3.5*x + 7 for x in xs]
```

```
plt.plot(xs, ys, 'r-', label='y')
```

```
plt.plot(xs, yt, 'b--', label='tangent line at x=2')
```

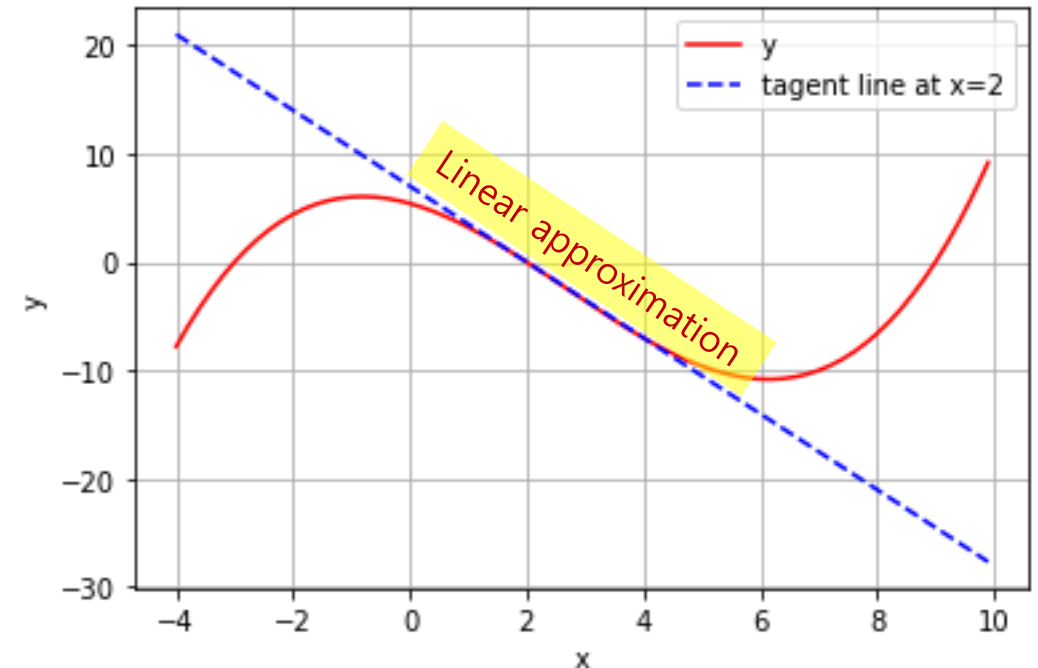
```
plt.xlabel('x')
```

```
plt.ylabel('y')
```

```
plt.grid()
```

```
plt.legend()
```

```
plt.show()
```



Differentiation

- Example) A turtle moving on $y = 0.1x^3 - 0.8x^2 - 1.5x + 5.4$ (turtle_animation.py)

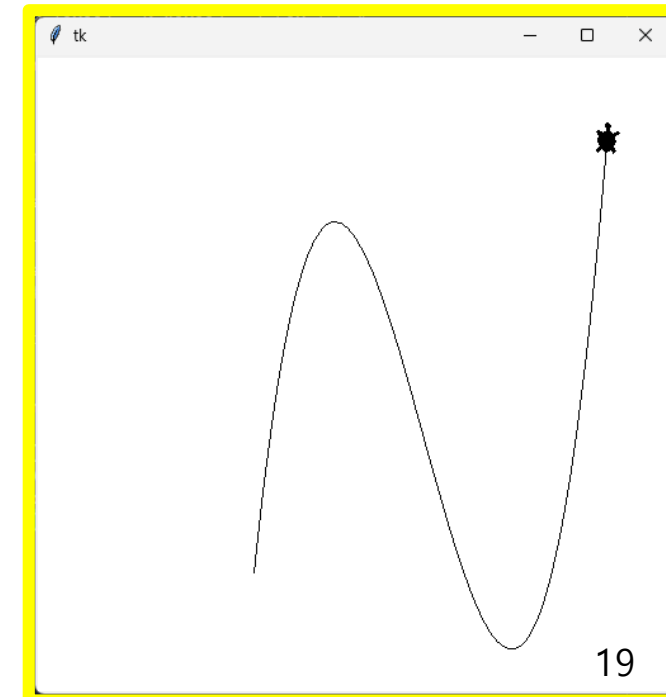
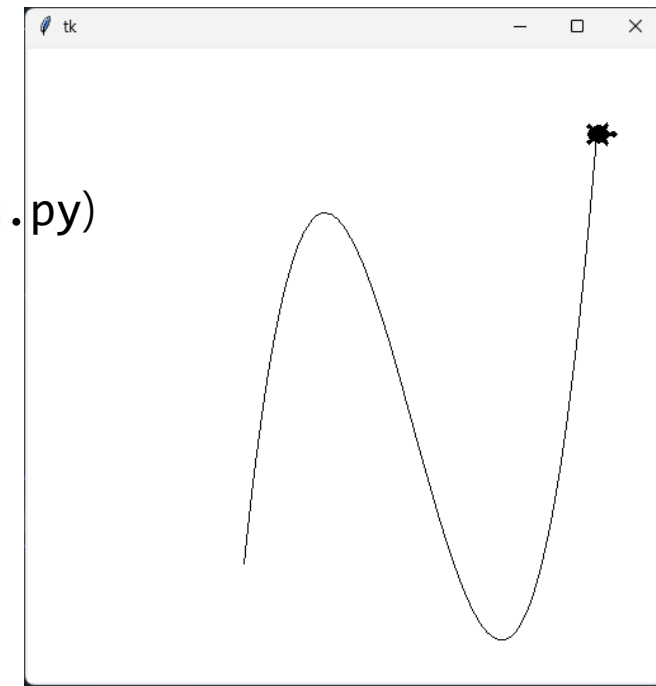
```
import tkinter as tk
import turtle, math

# Generate 'y = 0.1*x**3 - 0.8*x**2 - 1.5*x + 5.4'
scale = 10
xs = [x/scale for x in range(-4*scale, 10*scale)]
ys = [0.1*x**3 - 0.8*x**2 - 1.5*x + 5.4 for x in xs]
yd = [0.3*x**2 - 1.6*x - 1.5 for x in xs]

# Prepare 'screen' and 'actor'
root = tk.Tk()
canvas = tk.Canvas(root, width=500, height=500)
canvas.pack()
screen = turtle.TurtleScreen(canvas)
actor = turtle.RawTurtle(screen, 'turtle')
actor.radians() # Use radian unit for angle and rotation

# Draw the function
zoom = 20
actor.penup()
actor.setpos(zoom*xs[0], zoom*ys[0]) # Put at the initial point
actor.pendown()
for (x, y, slope) in zip(xs, ys, yd):
    actor.setpos(zoom*x, zoom*y)
    actor.setheading(math.atan2(slope, 1))
screen.mainloop()
```

How to derive a **derivative function** of
a complex function?



Differentiation

- Example) Finding the derivative function of $y = 0.1x^3 - 0.8x^2 - 1.5x + 5.4$ using [SymPy](#)

```
import sympy as sp
```

```
x, y = sp.symbols('x y')
```

```
y = 0.1*x**3 - 0.8*x**2 - 1.5*x + 5.4
```

```
yd = sp.diff(y, x)
```

```
print(yd)
```

```
# 0.3*x**2 - 1.6*x - 1.5
```

```
print(float(yd.subs({x: 2})))
```

```
# -3.5 / Casting from Float object to float
```

Note) More Examples with [SymPy](#)

- Example) Solve the above equation (find x when $y = 0$) using [SymPy](#)

```
roots = sp.solve(y, x)
print(roots) # FiniteSet(-3.0, 2.0, 9.0)
r0 = float(roots[0]) # -3.0 / Casting from Float object to float
```

- Example) Factorize the above equation using [SymPy](#)

```
sp.pprint(sp.factor(y)) # 5.4*(0.11...x - 1.0)*(0.33...x + 1.0)*(0.5x - 1.0)

y = (x**3 - 8*x**2 - 15*x + 54)/10 # Make the coefficients rational numbers
sp.pprint(sp.factor(y)) # (x - 9)*(x - 2)*(x + 3)
# -----
# 10
# (x - 9)*(x - 2)*(x + 3)/10

print(sp.factor(y))
```

Differentiation

- Example) Finding the derivative function of a composite function using [SymPy](#)

```
import sympy as sp
```

```
from random import random
```

```
perceptron = lambda x, w, b: sp.tanh(w * x + b)
```

```
f = lambda x: perceptron(x, random(), random())
```

```
x, y = sp.symbols('x y')
```

```
y = f(f(f(f(f(f(f(x)))))))
```

```
yd = sp.diff(y, x)
```

```
print(yd)
```

```
#0.005*
```

```
 #(1 - tanh(0.12*x + 0.81)**2)*
```

```
 #(1 - tanh(0.97*tanh(0.12*x + 0.81) + 0.62)**2)*
```

```
 #(1 - tanh(0.75*tanh(0.97*tanh(0.12*x + 0.81) + 0.62) + 0.97)**2)*
```

```
 #(1 - tanh(0.68*tanh(0.75*tanh(0.97*tanh(0.12*x + 0.81) + 0.62) + 0.97) + 0.38)**2)*
```

```
 #(1 - tanh(0.99*tanh(0.68*tanh(0.75*tanh(0.97*tanh(0.12*x + 0.81) + 0.62) + 0.97) + 0.38) + 0.91)**2)*
```

```
 #(1 - tanh(0.49*tanh(0.99*tanh(0.68*tanh(0.75*tanh(0.97*tanh(0.12*x + 0.81) + 0.62) + 0.97) + 0.38) + 0.91) + 0.27)**2)*
```

```
 #(1 - tanh(0.16*tanh(0.49*tanh(0.99*tanh(0.68*tanh(0.75*tanh(0.97*tanh(0.12*x + 0.81) + 0.62) + 0.97) + 0.38) + 0.91) + 0.27) + 0.07)**2)*
```


Differentiation

- [Numerical differentiation](#) is an algorithm to approximate a derivative value of a function using values of the function. (Note: It does not derive a derivative function.)

- The definition of derivative: $f'(x) = \lim_{\Delta x \rightarrow 0} \frac{f(x+\Delta x) - f(x)}{\Delta x}$
- Two-point estimation: $f'(x_0) = \frac{f(x_0+h) - f(x_0)}{h}$ or $f'(x_0) = \frac{f(x_0+h) - f(x_0-h)}{2h}$

- Example) Finding the slope and tangent line of $y = 0.1x^3 - 0.8x^2 - 1.5x + 5.4$ at $x = 2$

- Derivative at $x = 2$ ($y = 0$): -3.5

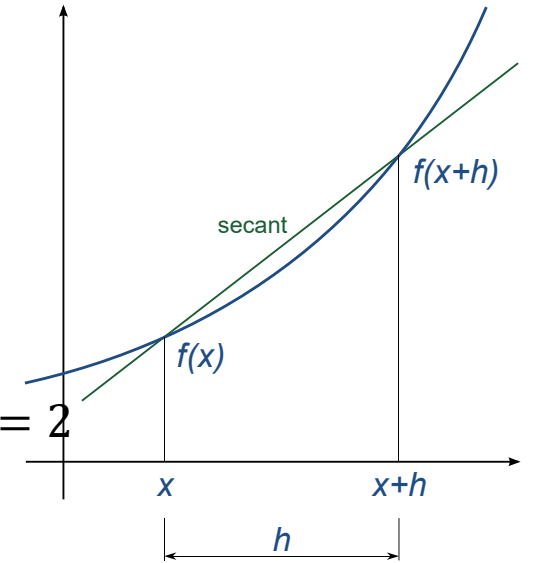
```
y = lambda x: 0.1*x**3 - 0.8*x**2 - 1.5*x + 5.4
```

```
x0 = 2
```

```
h = 0.001
```

```
d1 = (y(x0+h) - y(x0)) / h # -3.5002
```

```
d2 = (y(x0+h/2) - y(x0-h/2)) / h # -3.5000
```



Summary

- Building **mathematical intuition**: 1) **Imagine**, 2) **Ask why**
- Visualization
 - [Matplotlib](#): A plotting library in Python
 - **Visualization is very important** not only for your data but also for your programs, systems, and society.

~~▪ Calculus~~ Differentiation

- Derivative definition: $f'(x) = \lim_{\Delta x \rightarrow 0} \frac{f(x+\Delta x) - f(x)}{\Delta x}$
- Meaning
 - The **slope** of a tangent line (plane) to the given function
 - The tangent line ~ **linear approximation**
- How to get a derivative
 - ~~▪ Your hand-on derivation using [rules](#)~~
 - Analytical differentiation using [SymPy](#) (a symbolic mathematical engine in Python)
 - Numerical differentiation (two-point estimation)