

# Genome 540 Discussion

February 1st, 2024

Clifford Rostomily

# Agenda

- Assignment 4
- Assignment 5




# Assignment 4

# Overview

Part 1: Write a program to find the highest-weight path in a directed acyclic graph using dynamic programming

Part 2: Run your program on a linked list created from DNA sequence

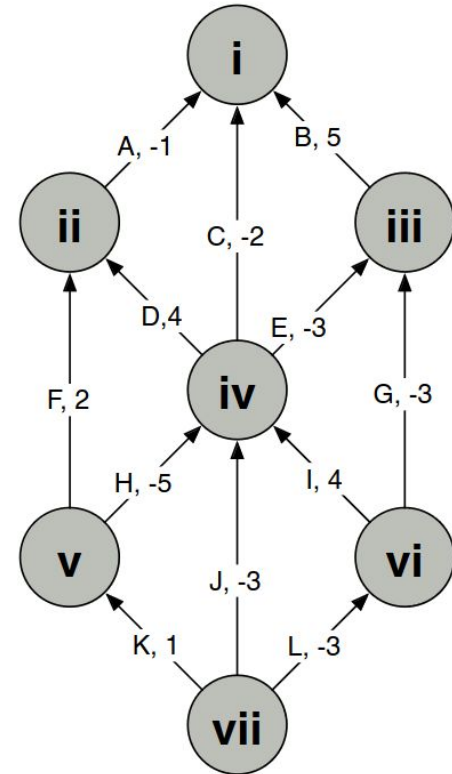
# Program 1: Highest weight path

1. Convert graph to text file of **vertices** and **edges** by hand
2. Use dynamic programming to find the max weight path through the graph (Lectures 7/8)
  - a. Overall
  - b. With constraints (START/END)
3. Output 
  - a. Path Score
  - b. The start/end vertex on the path
  - c. Labels for all the edges on path (in order)

Part 1  
Score: 8.0  
Begin: vi  
End: ii  
Path: ID

Example:  
V vii START  
V vi  
V v  
...  
E A ii i -1  
E B iii i 5

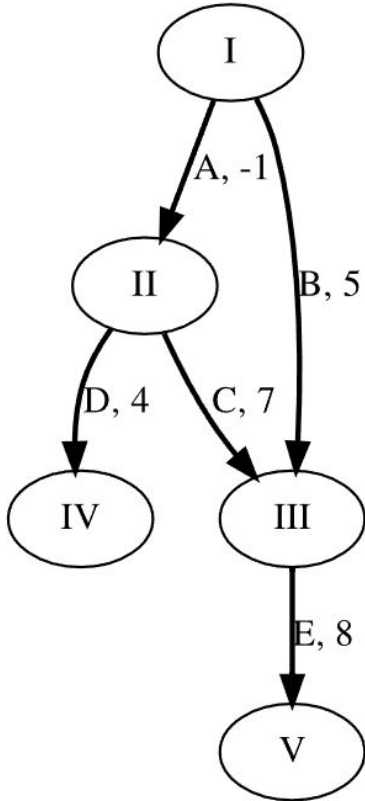
Part 2  
Score: 4.0  
Begin: vii  
End: i  
Path: LIDA



# Example - Dynamic Programming

*my\_graph.txt:*

```
V I  
V II  
V III  
V IV  
V V  
E A I II -1  
E B I III 5  
E C II III 7  
E D II IV 4  
E E III V 8
```



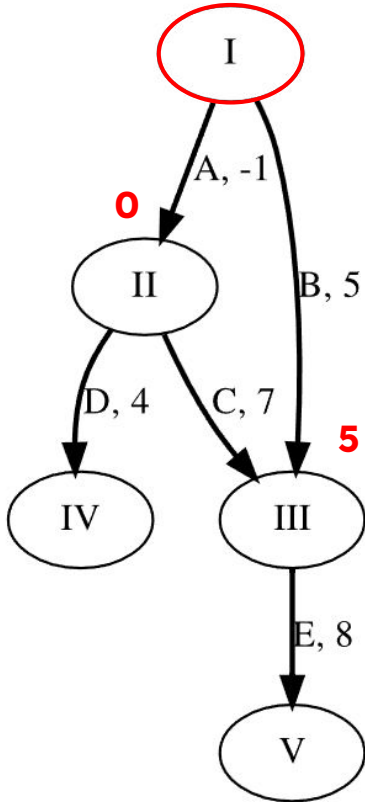
- Assume that graph file is depth ordered
- Vertex I has no parents so points to itself

|                        |   |    |     |    |   |
|------------------------|---|----|-----|----|---|
| Vertex                 | I | II | III | IV | V |
| Highest Weight Parent  | I | II | III | IV | V |
| $w(v)$ (Vertex weight) | 0 | 0  | 0   | 0  | 0 |
| Best Path Start        | I |    |     |    |   |

# Example - Dynamic Programming

my\_graph.txt:

```
V I  
V II  
V III  
V IV  
V V  
E A I II -1  
E B I III 5  
E C II III 7  
E D II IV 4  
E E III V 8
```



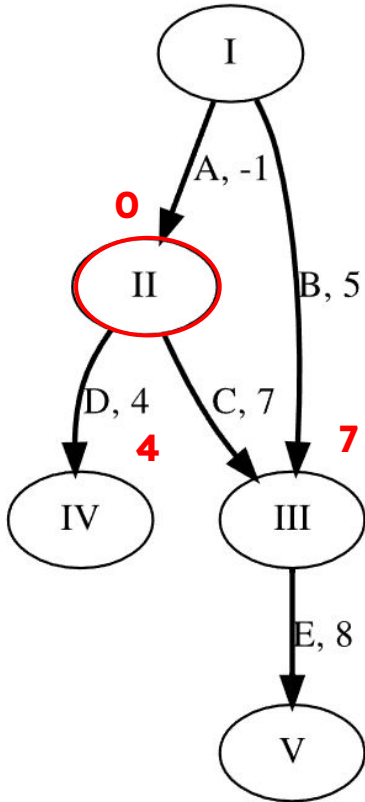
|                       |   |    |     |    |   |
|-----------------------|---|----|-----|----|---|
| Vertex                | I | II | III | IV | V |
| Highest Weight Parent | I | II | I   | IV | V |
| w(v) (Vertex weight)  | 0 | 0  | 5   | 0  | 0 |

Best Path Start III

# Example - Dynamic Programming

my\_graph.txt:

```
V I  
V II  
V III  
V IV  
V V  
E A I II -1  
E B I III 5  
E C II III 7  
E D II IV 4  
E E III V 8
```



|                       |   |    |     |    |   |
|-----------------------|---|----|-----|----|---|
| Vertex                | I | II | III | IV | V |
| Highest Weight Parent | I | II | II  | II | V |
| w(v) (Vertex weight)  | 0 | 0  | 7   | 4  | 0 |

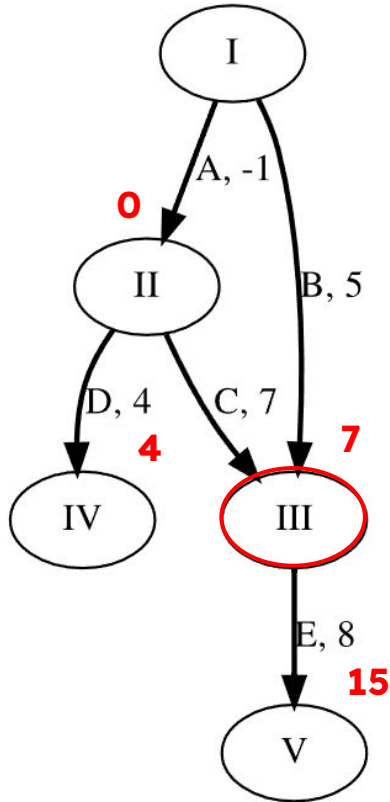
Best Path Start III



# Example - Dynamic Programming

my\_graph.txt:

```
V I
V II
V III
V IV
V V
E A I II -1
E B I III 5
E C II III 7
E D II IV 4
E E III V 8
```

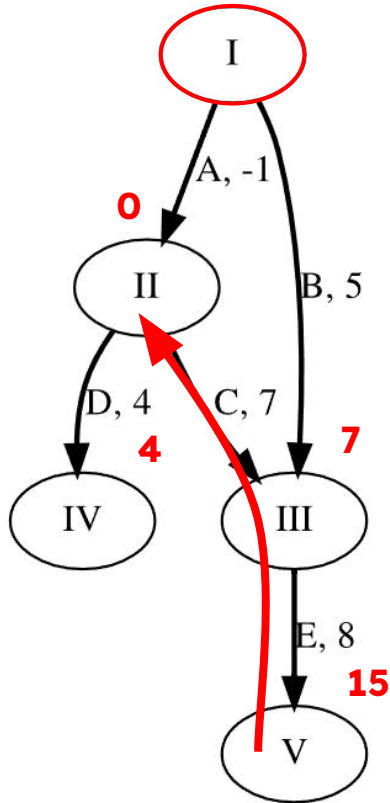


|                       |   |    |     |    |     |
|-----------------------|---|----|-----|----|-----|
| Vertex                | I | II | III | IV | V   |
| Highest Weight Parent | I | II | II  | II | III |
| w(v) (Vertex weight)  | 0 | 0  | 7   | 4  | 15  |
| Best Path Start       | V |    |     |    |     |

# Example - Dynamic Programming

my\_graph.txt:

```
V I  
V II  
V III  
V IV  
V V  
E A I II -1  
E B I III 5  
E C II III 7  
E D II IV 4  
E E III V 8
```



|                       |   |    |     |    |     |
|-----------------------|---|----|-----|----|-----|
| Vertex                | I | II | III | IV | V   |
| Highest Weight Parent | I | II | II  | II | III |
| w(v) (Vertex weight)  | 0 | 0  | 7   | 4  | 15  |

Best Path Start V

- Now traceback to find highest weight path

# Program 2: DNA Linked List

1. Create a linked list from a DNA sequence and a scoring scheme
  - a. Positions are vertices
  - b. Bases are edges
2. Run your program from part 1 on the graph

## Example:

Scores            Sequence: AGCT

A = -1.49

T = -1.49

G = .74

C = .74

Graph:

V 0

V 1

V 2

V 3

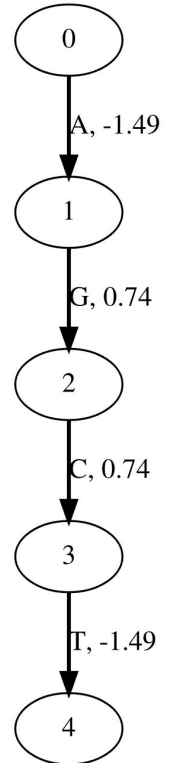
V 4

E A 0 1 -1.49

E G 1 2 .74

E C 2 3 .74

E T 3 4 -1.49



# Questions?

## **Program 1:**

Use dynamic programming to find the highest weight path in an arbitrary WDAG



## **Program 2:**

Make a linked list from a fasta and run program 1 on it



# Homework 5

# Overview

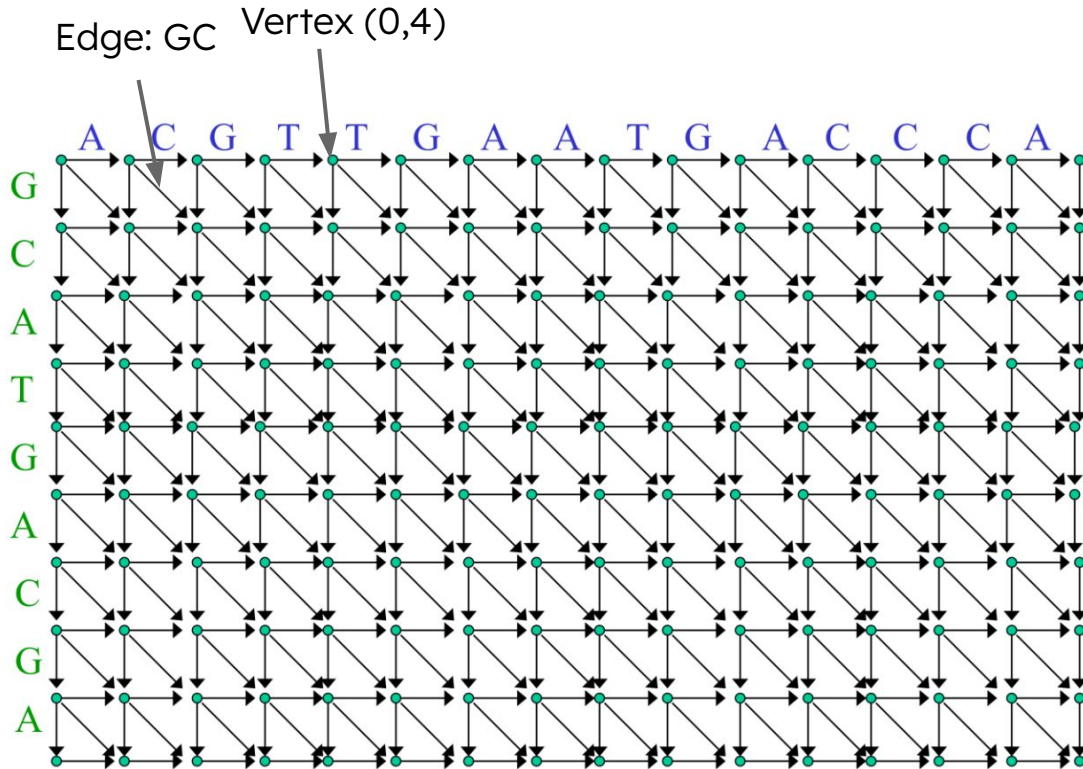
## ■ Part 1

- Build a weighted edit graph for 3 amino acid sequences of the insulin protein (human, frog, water buffalo) using the BLOSUM62 scoring matrix and save it as a text file

## ■ Part 2:

- Use your program from HW4 to find the max weight path through the edit graph

# The edit graph for 2 sequences



Vertices

(0,0) (0,1) (0,2) ... (0,N2)  
(1,0) (1,1)  
(2,0) ...  
...  
(N1,0) (N1,N2)

Edges are alignments

(0,0) (0,1) weight ( $\_A$ )

(0,0) (1,0) weight ( $G\_$ )

(0,0) (1,1) weight (GA)

# Computing edge weights

## BLOSUM62

|   | A  | R  | N  | D  | C  | Q  | E  | G  | H  | I  | L  | K  | M  | F  | P  | S  | T  | W  | Y  | V  | B  | Z  | X  | *  |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| A | 4  | -1 | -2 | -2 | 0  | -1 | -1 | 0  | -2 | -1 | -1 | -1 | -1 | -2 | -1 | 1  | 0  | -3 | -2 | 0  | -2 | -1 | 0  | -4 |
| R | -1 | 5  | 0  | -2 | -3 | 1  | 0  | -2 | 0  | -3 | -2 | 2  | -1 | -3 | -2 | -1 | -1 | -3 | -2 | -3 | -1 | 0  | -1 | -4 |
| N | -2 | 0  | 6  | 1  | -3 | 0  | 0  | 0  | 1  | -3 | -3 | 0  | -2 | -3 | -2 | 1  | 0  | -4 | -2 | -3 | 3  | 0  | -1 | -4 |
| D | -2 | -2 | 1  | 6  | -3 | 0  | 2  | -1 | -1 | -3 | -4 | -1 | -3 | -3 | -1 | 0  | -1 | -4 | -3 | -3 | 4  | 1  | -1 | -4 |
| C | 0  | -3 | -3 | -3 | 9  | -3 | -4 | -3 | -3 | -1 | -1 | -3 | -1 | -2 | -3 | -1 | -1 | -2 | -2 | -1 | -3 | -3 | -2 | -4 |
| Q | -1 | 1  | 0  | 0  | -3 | 5  | 2  | -2 | 0  | -3 | -2 | 1  | 0  | -3 | -1 | 0  | -1 | -2 | -1 | -2 | 0  | 3  | -1 | -4 |
| E | -1 | 0  | 0  | 2  | -4 | 2  | 5  | -2 | 0  | -3 | -3 | 1  | -2 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 1  | 4  | -1 | -4 |
| G | 0  | -2 | 0  | -1 | -3 | -2 | -2 | 6  | -2 | -4 | -4 | -2 | -3 | -3 | -2 | 0  | -2 | -2 | -3 | -3 | -1 | -2 | -1 | -4 |
| H | -2 | 0  | 1  | -1 | -3 | 0  | 0  | -2 | 8  | -3 | -2 | -1 | -2 | -1 | -2 | -1 | -2 | -2 | 2  | -3 | 0  | 0  | -1 | -4 |
| I | -1 | -3 | -3 | -3 | -1 | -3 | -3 | -4 | -3 | 4  | 2  | -3 | 1  | 0  | -3 | -2 | -1 | -3 | -1 | 3  | -3 | -3 | -1 | -4 |
| L | -1 | -2 | -3 | -4 | -1 | -2 | -3 | -4 | -3 | 2  | 4  | -2 | 2  | 0  | -3 | -2 | -1 | -2 | -1 | 1  | -4 | -3 | -1 | -4 |
| K | -1 | 2  | 0  | -1 | -3 | 1  | 1  | -2 | -1 | -3 | -2 | 5  | -1 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 0  | 1  | -1 | -4 |
| M | -1 | -1 | -2 | -3 | -1 | 0  | -2 | -3 | -2 | 1  | 2  | -1 | 5  | 0  | -2 | -1 | -1 | -1 | -1 | 1  | -3 | -1 | -1 | -4 |
| F | -2 | -3 | -3 | -3 | -2 | -3 | -3 | -3 | -1 | 0  | 0  | -3 | 0  | 6  | -4 | -2 | -2 | 1  | 3  | -1 | -3 | -3 | -1 | -4 |
| P | -1 | -2 | -2 | -1 | -3 | -1 | -1 | -2 | -2 | -3 | -3 | -1 | -2 | -4 | 7  | -1 | -1 | -4 | -3 | -2 | -2 | -1 | -2 | -4 |
| S | 1  | -1 | 1  | 0  | -1 | 0  | 0  | 0  | -1 | -2 | -2 | 0  | -1 | -2 | -1 | 4  | 1  | -3 | -2 | -2 | 0  | 0  | 0  | -4 |
| T | 0  | -1 | 0  | -1 | -1 | -1 | -1 | -2 | -2 | -1 | -1 | -1 | -1 | -2 | -1 | 1  | 5  | -2 | -2 | 0  | -1 | -1 | 0  | -4 |
| W | -3 | -3 | -4 | -4 | -2 | -2 | -3 | -2 | -2 | -3 | -2 | -3 | -1 | 1  | -4 | -3 | -2 | 11 | 2  | -3 | -4 | -3 | -2 | -4 |
| Y | -2 | -2 | -2 | -3 | -2 | -1 | -2 | -3 | 2  | -1 | -1 | -2 | -1 | 3  | -3 | -2 | -2 | 2  | 7  | -1 | -3 | -2 | -1 | -4 |
| V | 0  | -3 | -3 | -3 | -1 | -2 | -2 | -3 | -3 | 3  | 1  | -2 | 1  | -1 | -2 | -2 | 0  | -3 | -1 | 4  | -3 | -2 | -1 | -4 |
| B | -2 | -1 | 3  | 4  | -3 | 0  | 1  | -1 | 0  | -3 | -4 | 0  | -3 | -3 | -2 | 0  | -1 | -4 | -3 | -3 | 4  | 1  | -1 | -4 |
| Z | -1 | 0  | 0  | 1  | -3 | 3  | 4  | -2 | 0  | -3 | -3 | 1  | -1 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 1  | 4  | -1 | -4 |
| X | 0  | -1 | -1 | -1 | -2 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -2 | 0  | 0  | -2 | -1 | -1 | -1 | -1 | -1 | -4 |
| * | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | 1  |

Gap penalty: -6

What is the weight for edge DR?

What is the edge weight of \_A?



# Computing edge weights

## BLOSUM62

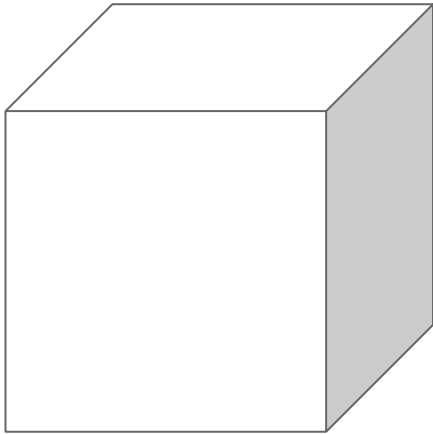
|   | A  | R  | N  | D  | C  | Q  | E  | G  | H  | I  | L  | K  | M  | F  | P  | S  | T  | W  | Y  | V  | B  | Z  | X  | *  |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| A | 4  | -1 | -2 | -2 | 0  | -1 | -1 | 0  | -2 | -1 | -1 | -1 | -1 | -2 | -1 | 1  | 0  | -3 | -2 | 0  | -2 | -1 | 0  | -4 |
| R | -1 | 5  | 0  | -2 | -3 | 1  | 0  | -2 | 0  | -3 | -2 | 2  | -1 | -3 | -2 | -1 | -1 | -3 | -2 | -3 | -1 | 0  | -1 | -4 |
| N | -2 | 0  | 6  | 1  | -3 | 0  | 0  | 0  | 1  | -3 | -3 | 0  | -2 | -3 | -2 | 1  | 0  | -4 | -2 | -3 | 3  | 0  | -1 | -4 |
| D | -2 | -2 | 1  | 6  | -3 | 0  | 2  | -1 | -1 | -3 | -4 | -1 | -3 | -3 | -1 | 0  | -1 | -4 | -3 | -3 | 4  | 1  | -1 | -4 |
| C | 0  | -3 | -3 | -3 | 9  | -3 | -4 | -3 | -3 | -1 | -1 | -3 | -1 | -2 | -3 | -1 | -1 | -2 | -2 | -1 | -3 | -3 | -2 | -4 |
| Q | -1 | 1  | 0  | 0  | -3 | 5  | 2  | -2 | 0  | -3 | -2 | 1  | 0  | -3 | -1 | 0  | -1 | -2 | -1 | -2 | 0  | 3  | -1 | -4 |
| E | -1 | 0  | 0  | 2  | -4 | 2  | 5  | -2 | 0  | -3 | -3 | 1  | -2 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 1  | 4  | -1 | -4 |
| G | 0  | -2 | 0  | -1 | -3 | -2 | -2 | 6  | -2 | -4 | -4 | -2 | -3 | -3 | -2 | 0  | -2 | -2 | -3 | -3 | -1 | -2 | -1 | -4 |
| H | -2 | 0  | 1  | -1 | -3 | 0  | 0  | -2 | 8  | -3 | -2 | -1 | -2 | -1 | -2 | -1 | -2 | -2 | 2  | -3 | 0  | 0  | -1 | -4 |
| I | -1 | -3 | -3 | -3 | -1 | -3 | -3 | -4 | -3 | 4  | 2  | -3 | 1  | 0  | -3 | -2 | -1 | -3 | -1 | 3  | -3 | -3 | -1 | -4 |
| L | -1 | -2 | -3 | -4 | -1 | -2 | -3 | -4 | -3 | 2  | 4  | -2 | 2  | 0  | -3 | -2 | -1 | -2 | -1 | 1  | -4 | -3 | -1 | -4 |
| K | -1 | 2  | 0  | -1 | -3 | 1  | 1  | -2 | -1 | -3 | -2 | 5  | -1 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 0  | 1  | -1 | -4 |
| M | -1 | -1 | -2 | -3 | -1 | 0  | -2 | -3 | -2 | 1  | 2  | -1 | 5  | 0  | -2 | -1 | -1 | -1 | -1 | 1  | -3 | -1 | -1 | -4 |
| F | -2 | -3 | -3 | -3 | -2 | -3 | -3 | -3 | -1 | 0  | 0  | -3 | 0  | 6  | -4 | -2 | -2 | 1  | 3  | -1 | -3 | -3 | -1 | -4 |
| P | -1 | -2 | -2 | -1 | -3 | -1 | -1 | -2 | -2 | -3 | -3 | -1 | -2 | -4 | 7  | -1 | -1 | -4 | -3 | -2 | -2 | -1 | -2 | -4 |
| S | 1  | -1 | 1  | 0  | -1 | 0  | 0  | 0  | -1 | -2 | -2 | 0  | -1 | -2 | -1 | 4  | 1  | -3 | -2 | -2 | 0  | 0  | 0  | -4 |
| T | 0  | -1 | 0  | -1 | -1 | -1 | -1 | -2 | -2 | -1 | -1 | -1 | -1 | -2 | -1 | 1  | 5  | -2 | -2 | 0  | -1 | -1 | 0  | -4 |
| W | -3 | -3 | -4 | -4 | -2 | -2 | -3 | -2 | -2 | -3 | -2 | -3 | -1 | 1  | -4 | -3 | -2 | 11 | 2  | -3 | -4 | -3 | -2 | -4 |
| Y | -2 | -2 | -2 | -3 | -2 | -1 | -2 | -3 | 2  | -1 | -1 | -2 | -1 | 3  | -3 | -2 | -2 | 2  | 7  | -1 | -3 | -2 | -1 | -4 |
| V | 0  | -3 | -3 | -3 | -1 | -2 | -2 | -3 | -3 | 3  | 1  | -2 | 1  | -1 | -2 | -2 | 0  | -3 | -1 | 4  | -3 | -2 | -1 | -4 |
| B | -2 | -1 | 3  | 4  | -3 | 0  | 1  | -1 | 0  | -3 | -4 | 0  | -3 | -3 | -2 | 0  | -1 | -4 | -3 | -3 | 4  | 1  | -1 | -4 |
| Z | -1 | 0  | 0  | 1  | -3 | 3  | 4  | -2 | 0  | -3 | -3 | 1  | -1 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 1  | 4  | -1 | -4 |
| X | 0  | -1 | -1 | -1 | -2 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -2 | 0  | 0  | -2 | -1 | -1 | -1 | -1 | -1 | -4 |
| * | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | 1  |

Gap penalty: -6

What is the weight for edge DR? **-2**

What is the edge weight of A? **-6 (Gap)**

# Now do it for 3 sequences



G P A T W  
T W A P G  
T Y W P P



$$\text{weight}(PWY) = \text{score}(PW) + \text{score}(WY) + \text{score}(PY)$$

# Computing edge weights

## BLOSUM62

|   | A  | R  | N  | D  | C  | Q  | E  | G  | H  | I  | L  | K  | M  | F  | P  | S  | T  | W  | Y  | V  | B  | Z  | X  | *  |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| A | 4  | -1 | -2 | -2 | 0  | -1 | -1 | 0  | -2 | -1 | -1 | -1 | -1 | -2 | -1 | 1  | 0  | -3 | -2 | 0  | -2 | -1 | 0  | -4 |
| R | -1 | 5  | 0  | -2 | -3 | 1  | 0  | -2 | 0  | -3 | -2 | 2  | -1 | -3 | -2 | -1 | -1 | -3 | -2 | -3 | -1 | 0  | -1 | -4 |
| N | -2 | 0  | 6  | 1  | -3 | 0  | 0  | 0  | 1  | -3 | -3 | 0  | -2 | -3 | -2 | 1  | 0  | -4 | -2 | -3 | 3  | 0  | -1 | -4 |
| D | -2 | -2 | 1  | 6  | -3 | 0  | 2  | -1 | -1 | -3 | -4 | -1 | -3 | -3 | -1 | 0  | -1 | -4 | -3 | -3 | 4  | 1  | -1 | -4 |
| C | 0  | -3 | -3 | -3 | 9  | -3 | -4 | -3 | -3 | -1 | -1 | -3 | -1 | -2 | -3 | -1 | -1 | -2 | -2 | -1 | -3 | -3 | -2 | -4 |
| Q | -1 | 1  | 0  | 0  | -3 | 5  | 2  | -2 | 0  | -3 | -2 | 1  | 0  | -3 | -1 | 0  | -1 | -2 | -1 | -2 | 0  | 3  | -1 | -4 |
| E | -1 | 0  | 0  | 2  | -4 | 2  | 5  | -2 | 0  | -3 | -3 | 1  | -2 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 1  | 4  | -1 | -4 |
| G | 0  | -2 | 0  | -1 | -3 | -2 | -2 | 6  | -2 | -4 | -4 | -2 | -3 | -3 | -2 | 0  | -2 | -2 | -3 | -3 | -1 | -2 | -1 | -4 |
| H | -2 | 0  | 1  | -1 | -3 | 0  | 0  | -2 | 8  | -3 | -3 | -1 | -2 | -1 | -2 | -1 | -2 | -2 | 2  | -3 | 0  | 0  | -1 | -4 |
| I | -1 | -3 | -3 | -3 | -1 | -3 | -3 | -4 | -3 | 4  | 2  | -3 | 1  | 0  | -3 | -2 | -1 | -3 | -1 | 3  | -3 | -3 | -1 | -4 |
| L | -1 | -2 | -3 | -4 | -1 | -2 | -3 | -4 | -3 | 2  | 4  | -2 | 2  | 0  | -3 | -2 | -1 | -2 | -1 | 1  | -4 | -3 | -1 | -4 |
| K | -1 | 2  | 0  | -1 | -3 | 1  | 1  | -2 | -1 | -3 | -2 | 5  | -1 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 0  | 1  | -1 | -4 |
| M | -1 | -1 | -2 | -3 | -1 | 0  | -2 | -3 | -2 | 1  | 2  | -1 | 5  | 0  | -2 | -1 | -1 | -1 | -1 | 1  | -3 | -1 | -1 | -4 |
| F | -2 | -3 | -3 | -3 | -2 | -3 | -3 | -3 | -1 | 0  | 0  | -3 | 0  | 6  | -4 | -2 | -2 | 1  | 3  | -1 | -3 | -3 | -1 | -4 |
| P | -1 | -2 | -2 | -1 | -3 | -1 | -1 | -2 | -2 | -3 | -3 | -1 | -2 | -4 | 7  | -1 | -1 | -4 | -3 | -2 | -2 | -1 | -2 | -4 |
| S | 1  | -1 | 1  | 0  | -1 | 0  | 0  | 0  | -1 | -2 | -2 | 0  | -1 | -2 | -1 | 4  | 1  | -3 | -2 | -2 | 0  | 0  | 0  | -4 |
| T | 0  | -1 | 0  | -1 | -1 | -1 | -1 | -2 | -2 | -1 | -1 | -1 | -1 | -2 | -1 | 1  | 5  | -2 | -2 | 0  | -1 | -1 | 0  | -4 |
| W | -3 | -3 | -4 | -4 | -2 | -2 | -3 | -2 | -2 | -3 | -2 | -3 | -1 | 1  | -4 | -3 | -2 | 11 | 2  | -3 | -4 | -3 | -2 | -4 |
| Y | -2 | -2 | -2 | -3 | -2 | -1 | -2 | -3 | 2  | -1 | -1 | -2 | -1 | 3  | -3 | -2 | -2 | 2  | 7  | -1 | -3 | -2 | -1 | -4 |
| V | 0  | -3 | -3 | -3 | -1 | -2 | -2 | -3 | -3 | 3  | 1  | -2 | 1  | -1 | -2 | -2 | 0  | -3 | -1 | 4  | -3 | -2 | -1 | -4 |
| B | -2 | -1 | 3  | 4  | -3 | 0  | 1  | -1 | 0  | -3 | -4 | 0  | -3 | -3 | -2 | 0  | -1 | -4 | -3 | -3 | 4  | 1  | -1 | -4 |
| Z | -1 | 0  | 0  | 1  | -3 | 3  | 4  | -2 | 0  | -3 | -3 | 1  | -1 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 1  | 4  | -1 | -4 |
| X | 0  | -1 | -1 | -1 | -2 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -2 | 0  | 0  | -2 | -1 | -1 | -1 | -1 | -1 | -4 |
| * | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | 1  |

Gap penalty: -6

What is the weight for edge DR\_?

# Computing edge weights

## BLOSUM62

|   | A  | R  | N  | D  | C  | Q  | E  | G  | H  | I  | L  | K  | M  | F  | P  | S  | T  | W  | Y  | V  | B  | Z  | X  | *  |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| A | 4  | -1 | -2 | -2 | 0  | -1 | -1 | 0  | -2 | -1 | -1 | -1 | -2 | -1 | 1  | 0  | -3 | -2 | 0  | -2 | -1 | 0  | -4 |    |
| R | -1 | 5  | 0  | -2 | -3 | 1  | 0  | -2 | 0  | -3 | -2 | 2  | -1 | -3 | -2 | -1 | -1 | -3 | -2 | -3 | -1 | 0  | -1 | -4 |
| N | -2 | 0  | 6  | 1  | -3 | 0  | 0  | 0  | 1  | -3 | -3 | 0  | -2 | -3 | -2 | 1  | 0  | -4 | -2 | -3 | 3  | 0  | -1 | -4 |
| D | -2 | -2 | 1  | 6  | -3 | 0  | 2  | -1 | -1 | -3 | -4 | -1 | -3 | -3 | -1 | 0  | -1 | -4 | -3 | -3 | 4  | 1  | -1 | -4 |
| C | 0  | -3 | -3 | -3 | 9  | -3 | -4 | -3 | -3 | -1 | -1 | -3 | -1 | -2 | -3 | -1 | -1 | -2 | -2 | -1 | -3 | -3 | -2 | -4 |
| Q | -1 | 1  | 0  | 0  | -3 | 5  | 2  | -2 | 0  | -3 | -2 | 1  | 0  | -3 | -1 | 0  | -1 | -2 | -1 | -2 | 0  | 3  | -1 | -4 |
| E | -1 | 0  | 0  | 2  | -4 | 2  | 5  | -2 | 0  | -3 | -3 | 1  | -2 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 1  | 4  | -1 | -4 |
| G | 0  | -2 | 0  | -1 | -3 | -2 | -2 | 6  | -2 | -4 | -4 | -2 | -3 | -3 | -2 | 0  | -2 | -2 | -3 | -3 | -1 | -2 | -1 | -4 |
| H | -2 | 0  | 1  | -1 | -3 | 0  | 0  | -2 | 8  | -3 | -3 | -1 | -2 | -1 | -2 | -1 | -2 | -2 | 2  | -3 | 0  | 0  | -1 | -4 |
| I | -1 | -3 | -3 | -3 | -1 | -3 | -3 | -4 | -3 | 4  | 2  | -3 | 1  | 0  | -3 | -2 | -1 | -3 | -1 | 3  | -3 | -3 | -1 | -4 |
| L | -1 | -2 | -3 | -4 | -1 | -2 | -3 | -4 | -3 | 2  | 4  | -2 | 2  | 0  | -3 | -2 | -1 | -2 | -1 | 1  | -4 | -3 | -1 | -4 |
| K | -1 | 2  | 0  | -1 | -3 | 1  | 1  | -2 | -1 | -3 | -2 | 5  | -1 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 0  | 1  | -1 | -4 |
| M | -1 | -1 | -2 | -3 | -1 | 0  | -2 | -3 | -2 | 1  | 2  | -1 | 5  | 0  | -2 | -1 | -1 | -1 | -1 | 1  | -3 | -1 | -1 | -4 |
| F | -2 | -3 | -3 | -3 | -2 | -3 | -3 | -3 | -1 | 0  | 0  | -3 | 0  | 6  | -4 | -2 | -2 | 1  | 3  | -1 | -3 | -3 | -1 | -4 |
| P | -1 | -2 | -2 | -1 | -3 | -1 | -1 | -2 | -2 | -3 | -3 | -1 | -2 | -4 | 7  | -1 | -1 | -4 | -3 | -2 | -2 | -1 | -2 | -4 |
| S | 1  | -1 | 1  | 0  | -1 | 0  | 0  | 0  | -1 | -2 | -2 | 0  | -1 | -2 | -1 | 4  | 1  | -3 | -2 | -2 | 0  | 0  | 0  | -4 |
| T | 0  | -1 | 0  | -1 | -1 | -1 | -1 | -2 | -2 | -1 | -1 | -1 | -1 | -2 | -1 | 1  | 5  | -2 | -2 | 0  | -1 | -1 | 0  | -4 |
| W | -3 | -3 | -4 | -4 | -2 | -2 | -3 | -2 | -2 | -3 | -2 | -3 | -1 | 1  | -4 | -3 | -2 | 11 | 2  | -3 | -4 | -3 | -2 | -4 |
| Y | -2 | -2 | -2 | -3 | -2 | -1 | -2 | -3 | 2  | -1 | -1 | -2 | -1 | 3  | -3 | -2 | -2 | 2  | 7  | -1 | -3 | -2 | -1 | -4 |
| V | 0  | -3 | -3 | -3 | -1 | -2 | -2 | -3 | -3 | 3  | 1  | -2 | 1  | -1 | -2 | -2 | 0  | -3 | -1 | 4  | -3 | -2 | -1 | -4 |
| B | -2 | -1 | 3  | 4  | -3 | 0  | 1  | -1 | 0  | -3 | -4 | 0  | -3 | -3 | -2 | 0  | -1 | -4 | -3 | -3 | 4  | 1  | -1 | -4 |
| Z | -1 | 0  | 0  | 1  | -3 | 3  | 4  | -2 | 0  | -3 | -3 | 1  | -1 | -3 | -1 | 0  | -1 | -3 | -2 | -2 | 1  | 4  | -1 | -4 |
| X | 0  | -1 | -1 | -1 | -2 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -2 | 0  | 0  | -2 | -1 | -1 | -1 | -1 | -1 | -4 |
| * | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | 1  |

Gap penalty: -6

What is the weight for edge DR\_?

$$\text{DR} + \text{R}_- + \text{D}_- \\ -2 + -6 + -6 = -14$$

# Reminders

- HW4 due this Sunday, 11:59pm
- Please have your name in the filename of your homework assignment and match the template