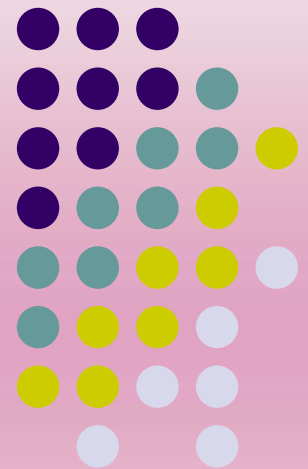
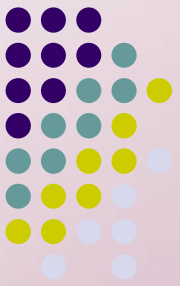


Lecture 7

String similarity and alignments



The edit-distance based similarity metric



S	a	c	c	g	c
S1	a	c		t	c

S	a		c	c		g	c
S2	a	c	c	c	t	g	c

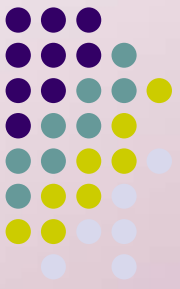
The smaller is the edit distance, the larger is the similarity

The edit distance alone is not always sufficient metric to characterize similarity between strings

In these 2 examples, the edit distance between S and S1 is the same as an edit distance between S and S2, but it is intuitively clear that S is more similar to S2 than to S1, since they share more identical characters

We want to evaluate what was preserved rather than what changed to infer the common pattern

The longest common substring

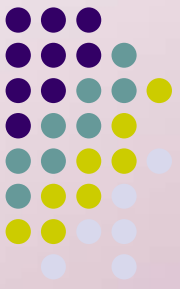


- The longest substring, common to both strings, the longest sequence of consecutive characters which occur in both strings

The longest sequence of ***consecutive matches***

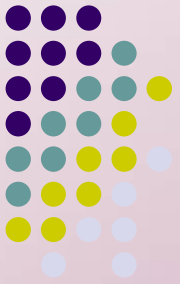
- The linear-time solution via suffix tree

The longest common subsequence



- A **subsequence** of a string S is a subset of characters of S in their original relative order
A subsequence does not need to consist of the consecutive characters of S
- Given 2 strings $S1$ and $S2$, **a common subsequence** for 2 strings is a subsequence which appears both in $S1$ and $S2$
- **The longest common subsequence** is a longest between all possible subsequences of $S1$ and $S2$

Substring vs subsequence



w	i	n	t	e	r	s
---	---	---	---	---	---	---

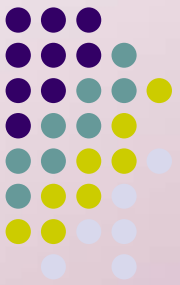
w	i	n	t	e	r	s
---	---	---	---	---	---	---

its – a subsequence of *winters*

w	i	n	t	e	r	s
---	---	---	---	---	---	---

inter – both substring and subsequence of *winters*

Longest Common Subsequence (LCS)

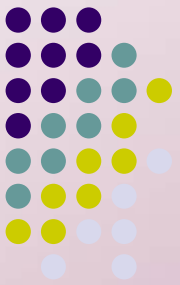


m	a	d	b	u	n	n	y	
b	a	d	m	o	n	e	y	

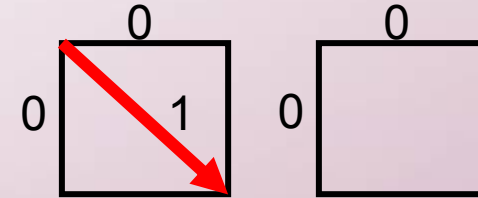
m	a	d	b	u	n	n	y	
b	a	d	m	o	n	e	y	

How can we be sure that **adny** is the longest common subsequence

The Dynamic Programming solution for LCS. Edit graph



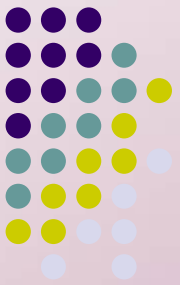
		<i>b</i>	<i>a</i>	<i>d</i>	<i>m</i>	<i>o</i>	<i>n</i>	<i>e</i>	<i>y</i>
	0								
<i>m</i>									
<i>a</i>									
<i>d</i>									
<i>b</i>									
<i>u</i>									
<i>n</i>									
<i>n</i>									
<i>y</i>									



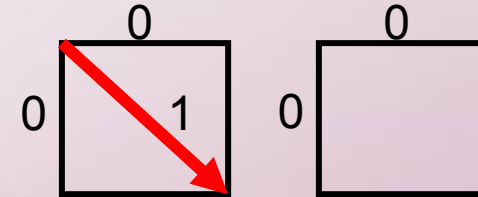
Since we are interested in a longest sequence of matches, we give to the red edges cost 1 and to all the other edges cost 0

Since aligning 2 different characters does not contribute to the total score we do not consider the diagonal edges in case of mismatch

The Dynamic Programming solution for LCS. The greediest path

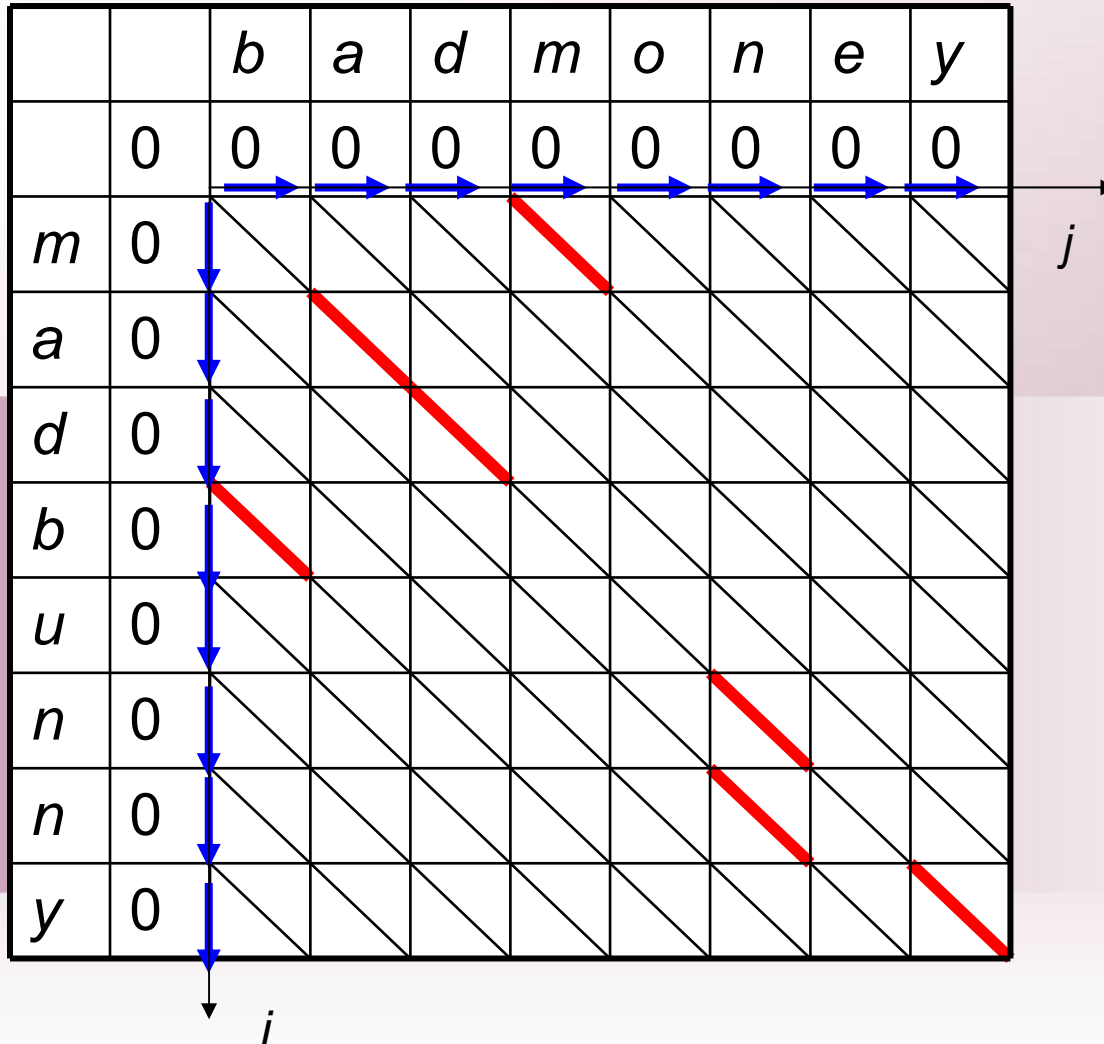
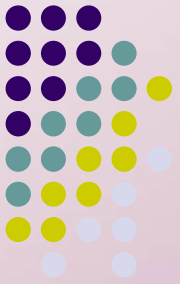


		<i>b</i>	<i>a</i>	<i>d</i>	<i>m</i>	<i>o</i>	<i>n</i>	<i>e</i>	<i>y</i>
	0	0	0	0	0	0	0	0	0
<i>m</i>	0				↘				
<i>a</i>	0		↘						
<i>d</i>	0			↘					
<i>b</i>	0	↘							
<i>u</i>	0								
<i>n</i>	0						↘		
<i>n</i>	0							↘	
<i>y</i>	0								↘

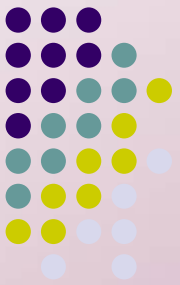


The problem can be reduced to finding the greediest (the longest) path through matches - the path with the largest cost

Base condition



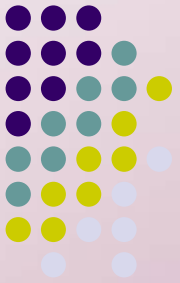
All the black edges are of cost 0, so moving strictly right or down gives paths of a total cost 0



LCS. Recurrence relation

$$\text{COST}(i,j)=\max \begin{cases} \text{COST}(i-1,j) \\ \text{COST}(i,j-1) \\ \text{COST}(i-1,j-1)+1 \text{ if } S1[i]=S2[j] \end{cases}$$

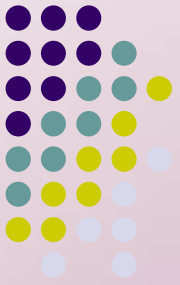
Tabular computation. Row 1



		<i>b</i>	<i>a</i>	<i>d</i>	<i>m</i>	<i>o</i>	<i>n</i>	<i>e</i>	<i>y</i>
	0	0	0	0	0	0	0	0	0
<i>m</i>	0	0	0	0	1	1	1	1	1
<i>a</i>	0	0	1	1	1	1	1	1	1
<i>d</i>	0								
<i>b</i>	0								
<i>u</i>	0								
<i>n</i>	0								
<i>n</i>	0								
<i>y</i>	0								

Diagram illustrating the tabular computation for Row 1. The grid shows the characters *b*, *a*, *d*, *m*, *o*, *n*, *e*, and *y* in the columns and the characters *m*, *a*, *d*, *b*, *u*, *n*, *n*, and *y* in the rows. The top row contains zeros. Blue arrows indicate the direction of computation: vertical arrows pointing down from the top row to the first column, and horizontal arrows pointing right from the first row to the top of the grid. Red diagonal arrows indicate the path of computation for the first row, starting from the top-left cell (0,0) and moving down-right to the bottom-right cell (8,8). The label *j* is positioned to the right of the grid, and the label *i* is positioned below the grid.

Tabular computation. Row 2



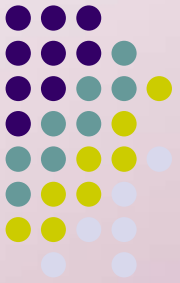
		<i>b</i>	<i>a</i>	<i>d</i>	<i>m</i>	<i>o</i>	<i>n</i>	<i>e</i>	<i>y</i>
	0	0	0	0	0	0	0	0	0
<i>m</i>	0	0	0	0	1	1	1	1	1
<i>a</i>	0	0	1	1	1	1	1	1	1
<i>d</i>	0								
<i>b</i>	0								
<i>u</i>	0								
<i>n</i>	0								
<i>n</i>	0								
<i>y</i>	0								

i (vertical axis label)

j (horizontal axis label)

→ Alternative path

Tabular computation. Row 3

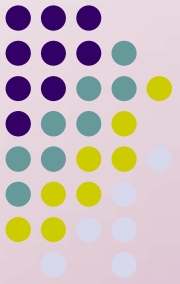


		<i>b</i>	<i>a</i>	<i>d</i>	<i>m</i>	<i>o</i>	<i>n</i>	<i>e</i>	<i>y</i>
	0	0	0	0	0	0	0	0	0
<i>m</i>	0	0	0	0	1	1	1	1	1
<i>a</i>	0	0	1	1	1	1	1	1	1
<i>d</i>	0	0	1	2	2	2	2	2	2
<i>b</i>	0								
<i>u</i>	0								
<i>n</i>	0								
<i>n</i>	0								
<i>y</i>	0								

i (vertical axis label)

j (horizontal axis label)

Tabular computation. Row 4

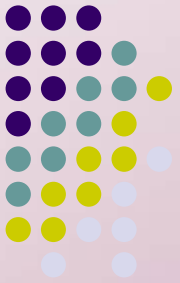


		<i>b</i>	<i>a</i>	<i>d</i>	<i>m</i>	<i>o</i>	<i>n</i>	<i>e</i>	<i>y</i>
	0	0	0	0	0	0	0	0	0
<i>m</i>	0	0	0	0	1	1	1	1	1
<i>a</i>	0	0	1	1	1	1	1	1	1
<i>d</i>	0	0	1	2	2	2	2	2	2
<i>b</i>	0	1	1	2	2	2	2	2	2
<i>u</i>	0								
<i>n</i>	0								
<i>n</i>	0								
<i>y</i>	0								

i (vertical axis label)

j (horizontal axis label)

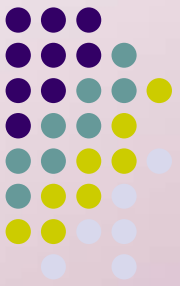
Tabular computation. Rows 5,6z



		<i>b</i>	<i>a</i>	<i>d</i>	<i>m</i>	<i>o</i>	<i>n</i>	<i>e</i>	<i>y</i>
	0	0	0	0	0	0	0	0	0
<i>m</i>	0	0	0	0	1	1	1	1	1
<i>a</i>	0	0	1	1	1	1	1	1	1
<i>d</i>	0	0	1	2	2	2	2	2	2
<i>b</i>	0	1	1	2	2	2	2	2	2
<i>u</i>	0	1	1	2	2	2	2	2	2
<i>n</i>	0	1	1	2	2	2	3	3	3
<i>n</i>	0								
<i>y</i>	0								

i (vertical axis label)
 j (horizontal axis label)

Tabular computation. Rows 7,8

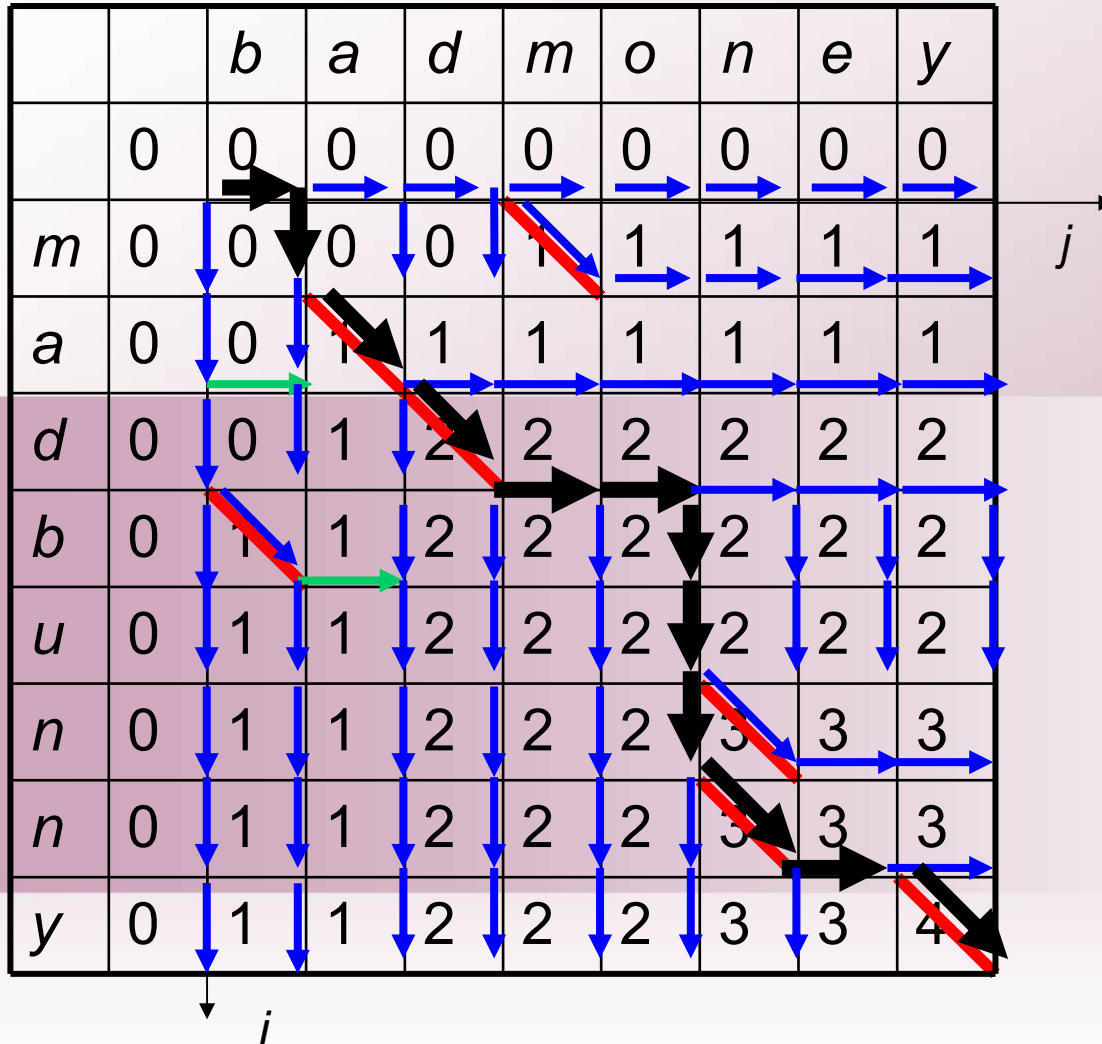
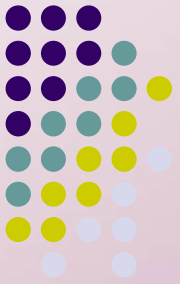


		<i>b</i>	<i>a</i>	<i>d</i>	<i>m</i>	<i>o</i>	<i>n</i>	<i>e</i>	<i>y</i>
	0	0	0	0	0	0	0	0	0
<i>m</i>	0	0	0	0	1	1	1	1	1
<i>a</i>	0	0	1	1	1	1	1	1	1
<i>d</i>	0	0	1	2	2	2	2	2	2
<i>b</i>	0	1	1	2	2	2	2	2	2
<i>u</i>	0	1	1	2	2	2	2	2	2
<i>n</i>	0	1	1	2	2	2	3	3	3
<i>n</i>	0	1	1	2	2	2	3	3	3
<i>y</i>	0	1	1	2	2	2	3	3	4

i (vertical axis, pointing down)
 j (horizontal axis, pointing right)

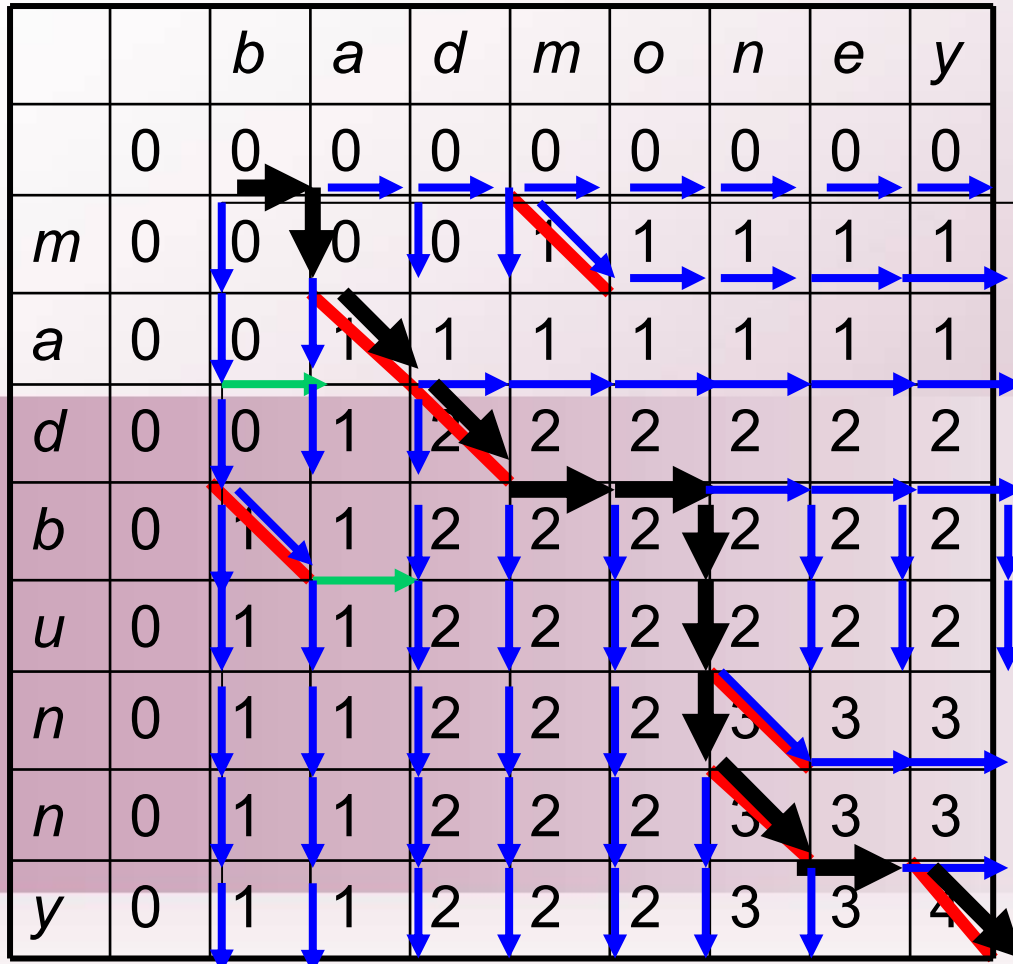
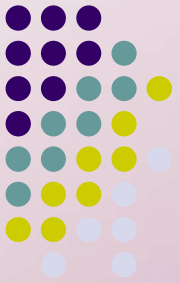
Read the length of the longest common subsequence in cell $[N][M]$

LCS. Traceback



Find the subsequence itself following the sequence of matches backwards

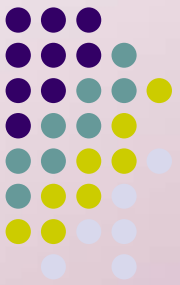
LCS. Alignment



Note, that only the matches are aligned, since this is the problem we are solving – finding the longest sequence of matches

We don't count the number of edit operations, since their cost in this model is 0

<i>i</i>	S1	-	m	a	d	-	-	b	u	n	n	-	y
	S2	b	-	a	d	m	o	-	-	-	n	e	y



The LCS based similarity metric

S	a	c	c	c
S1	a	c	-	c

S	a	-	c	c	-	-	c
S2	a	c	c	-	t	g	c

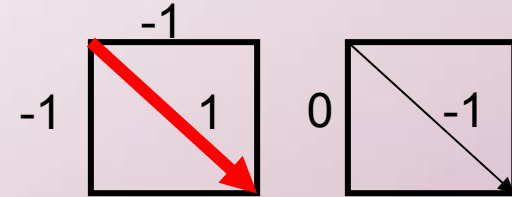
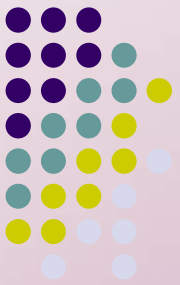
The longer is the LCS, the more similar are the strings

The LCS alone is not sufficient similarity metric

In these 2 examples, the LCS of S and S1 is the same as the LCS of S and S2, but it is intuitively clear that S is more similar to S1 than to S2, since they have more different characters

We want to score both the matches and the differences

Basic optimal alignment scores



	S2	t	g	c	a	t	a
S1							
a							
t							
c							
t							
g							
a							
t							

Let us set the simplest weights of the edges:

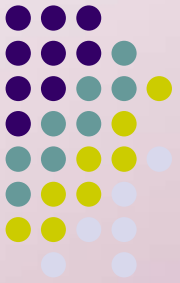
For a match: award of 1

For a mismatch: penalty of -1

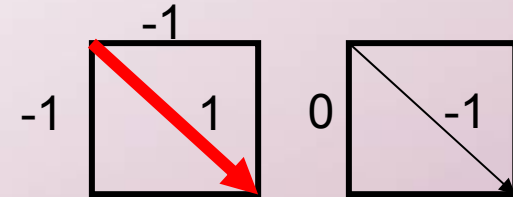
For a gap: penalty of -1

Then the maximum cost of the path in the edit graph will give a numerical score of the similarity between S1 and S2: large positive values – two strings are similar, negative or low positive values – the strings are different

Optimal alignment. Base condition

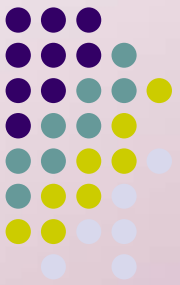


	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1						
t	-2						
c	-3						
t	-4						
g	-5						
a	-6						
t	-7						



Since moving from point (0,0) strictly to the right or to the bottom corresponds to a series of gaps, we initialize the 0-column and 0-row with consecutive negative integers

Optimal alignment. Recurrence relation



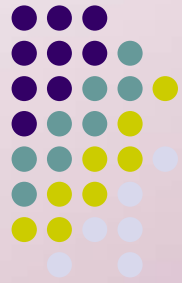
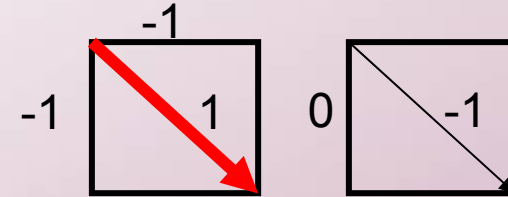
$$\text{COST}(i,j)=\max \begin{cases} \text{COST}(i-1,j) - 1 \\ \text{COST}(i,j-1) - 1 \\ \text{COST}(i-1,j-1)+\text{diagonal}(i,j) \end{cases}$$

$$\text{diagonal}(i,j)= \begin{cases} 1 \text{ if } S1[i]=S2[j] \\ -1 \text{ if } S1[i]\neq S2[j] \end{cases}$$

Optimal alignment. Row 1

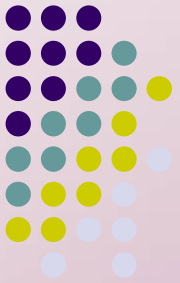
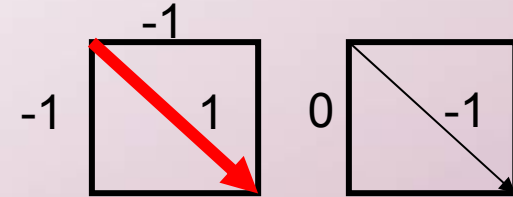
	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1	-1	-2	-3	-2	-3	-2
t	-2						
c	-3						
t	-4						
g	-5						
a	-6						
t	-7						

The table shows a dynamic programming matrix for sequence alignment. The first row (S1) contains values from 0 to -6. The first column (S2) contains values from -1 to -7. Blue arrows indicate the optimal path: a vertical path down the first column from (0,0) to (7,0), followed by a horizontal path from (7,0) to (7,7), and a diagonal path from (7,7) to (0,7). Red arrows indicate alternative paths: a diagonal path from (0,0) to (7,7), and a path that goes down the first column to (7,0), then horizontally to (7,4), and finally diagonally to (0,7).

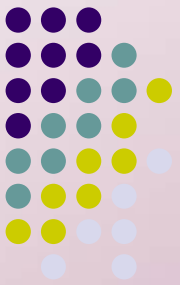


Optimal alignment. Row 2

	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1	-1	-2	-3	-2	-3	-2
t	-2	0	-1	-2	-3	-1	-2
c	-3						
t	-4						
g	-5						
a	-6						
t	-7						

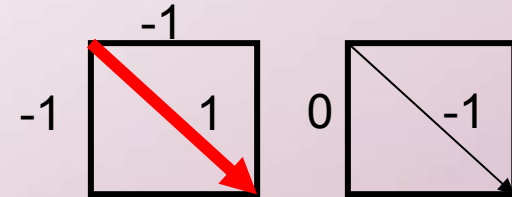


Optimal alignment. Row 3

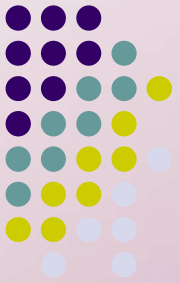


	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1	-1	-2	-3	-2	-3	-2
t	-2	0	-1	-2	-3	-1	-2
c	-3	-1	-1	0	-1	-2	-2
t	-4						
g	-5						
a	-6						
t	-7						

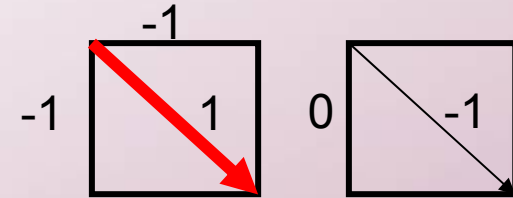
The table shows a dynamic programming matrix for sequence alignment. The top row (S1) and left column (S2) contain the sequence elements. The matrix cells contain numerical values representing the cost of alignments. Blue arrows indicate the path of the optimal alignment, starting from the top-left cell (0) and moving through the cells (a, a), (t, t), (c, c), (t, t), (g, g), (a, a), and (t, t). Red arrows indicate the path of a sub-optimal alignment, starting from the top-left cell (0) and moving through the cells (a, t), (t, c), (c, a), (t, t), (g, g), (a, a), and (t, t).



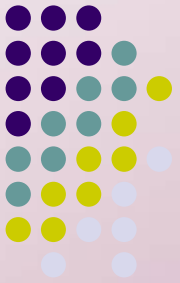
Optimal alignment. Row 4



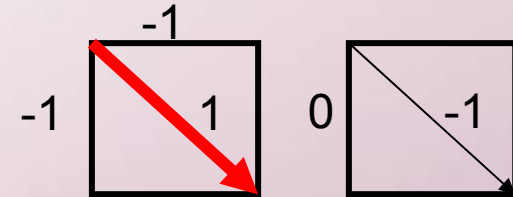
	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1	-1	-2	-3	-2	-3	-2
t	-2	0	-1	-2	-3	-1	-2
c	-3	-1	-1	0	-1	-2	-2
t	-4	0	-1	-1	-1	0	-1
g	-5						
a	-6						
t	-7						



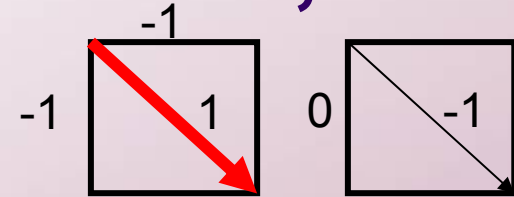
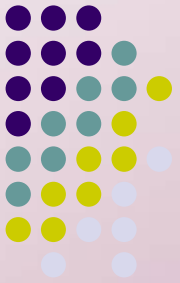
Optimal alignment. Row 5



	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1	-1	-2	-3	-2	-3	-2
t	-2	0	-1	-2	-3	-1	-2
c	-3	-1	-1	0	-1	-2	-2
t	-4	-2	-1	-1	-1	0	-1
g	-5	-1	-1	-2	-2	-1	-1
a	-6						
t	-7						

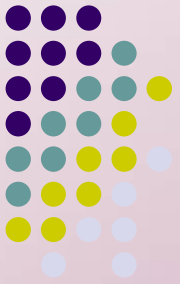


Optimal alignment. Rows 6,7



	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1	-1	-2	-3	-2	-3	-2
t	-2	0	-1	-2	-3	-1	-2
c	-3	-1	-1	0	-1	-2	-2
t	-4	-2	-1	-1	-1	0	-1
g	-5	-1	-1	-2	-2	-1	-1
a	-6	-2	-2	-2	-1	-2	0
t	-7	-3	-3	-3	-2	0	-1

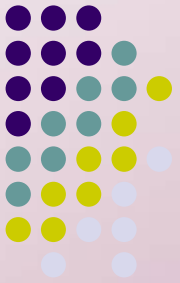
Optimal alignment. Traceback



	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1	-1	-2	-3	-2	-3	-2
t	-2	0	-1	-2	-3	-1	-2
c	-3	-1	-1	0	-1	-2	-2
t	-4	-2	-1	-1	-1	0	-1
g	-5	-1	-1	-2	-2	-1	-1
a	-6	-2	-2	-2	-1	-2	0
t	-7	-3	-3	-3	-2	0	-1

The table shows a dynamic programming matrix for sequence alignment. The columns represent sequence S2 (t, g, c, a, t, a) and the rows represent sequence S1 (a, t, c, t, g, a, t). The diagonal elements are 0. The matrix is filled with values representing the cost of alignments. Blue arrows indicate the path of the optimal alignment, starting from the bottom-right cell (S1=t, S2=a) and moving towards the top-left cell (S1=S2=0). Red arrows indicate alternative paths. Black arrows highlight the optimal path: (S1=t, S2=a) to (S1=t, S2=t) to (S1=g, S2=a) to (S1=g, S2=g) to (S1=c, S2=g) to (S1=c, S2=c) to (S1=t, S2=c) to (S1=t, S2=a) to (S1=a, S2=a) to (S1=a, S2=t) to (S1=a, S2=g) to (S1=a, S2=c) to (S1=a, S2=t) to (S1=a, S2=a).

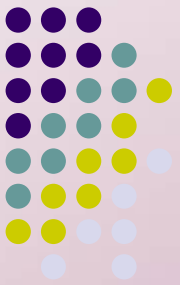
Optimal alignment. Alignment



	S2	t	g	c	a	t	a
S1	0	-1	-2	-3	-4	-5	-6
a	-1	-1	-2	-3	-2	-3	-2
t	-2	0	-1	-2	-3	-1	-2
c	-3	-1	-1	0	-1	-2	-2
t	-4	-2	-1	-1	-1	0	-1
g	-5	-1	-1	-2	-2	-1	-1
a	-6	-2	-2	-2	-1	-2	0
t	-7	-3	-3	-3	-2	0	-1

The table above shows a dynamic programming matrix for sequence alignment. It includes blue arrows indicating the path of the optimal alignment, red arrows indicating alternative paths, and black arrows indicating the final optimal path from the bottom-right cell (S1=t, S2=t) to the top-left cell (S1=S2, S2=t).

S1	a	t	c	t	g	-	a	t	-
S2	-	t	-	-	g	c	a	t	a



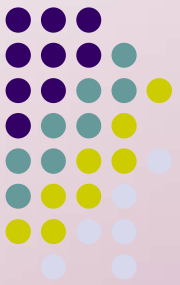
General scoring schemes

$$\text{COST}(i,j)=\max \begin{cases} \text{COST}(i-1,j) + \text{gapCost} \\ \text{COST}(i,j-1) + \text{gapCost} \\ \text{COST}(i-1,j-1)+\text{score}(S1[i], S2[j]) \end{cases}$$

Here the *gapCost* is the cost of aligning each character with a gap, and it should be negative in order to penalize

score depends on the characters placed opposite to each other. It is always positive for a pair of matching characters

The total score is a summative score of aligning the characters in S1 and S2, maximized over all the combinations of possible alignments



The scoring matrix

For an alphabet Σ of size σ add one more artificial character '-'.
Then the scoring matrix is a $(\sigma+1) \times (\sigma+1)$ table, where for each character of Σ plus '-' there is a cost of aligning this character with each other character.

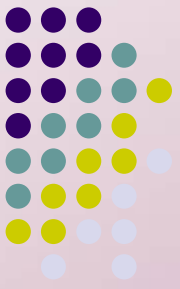
If an optimal alignment has been computed according to a given scoring matrix, the total score of an alignment is the sum of scores of the columns of an alignment table

Our scoring matrix

	a	c	g	t	-
a	1	-1	-1	-1	-1
c	-1	1	-1	-1	-1
g	-1	-1	1	-1	-1
t	-1	-1	-1	1	-1
-	-1	-1	-1	-1	n/a

S1	a	t	c	t	g	-	a	t	-
S2	-	t	-	-	g	c	a	t	a
	-1	1	-1	-1	1	-1	1	1	-1

Total score is -1



The sequence of mutations

S1	a	t	c	t	g	-	a	t	-
S2	-	t	-	-	c	c	a	t	a

This alignment suggests that S1 was transformed into S2 by the following sequence of evolutionary events:

Deletion of nucleotide a

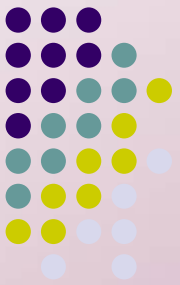
Deletion of nucleotides c and t

Substitution of nucleotide g by c

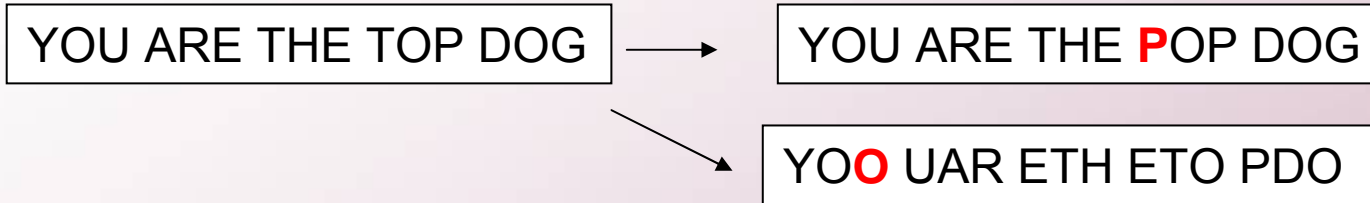
Insertion of nucleotide c

Deletion of nucleotide a

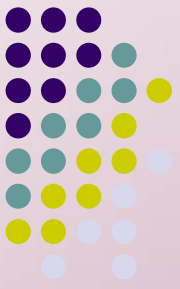
Since an optimal alignment is not unique, this sequence of mutations is only one of many possible explanations



Mutations



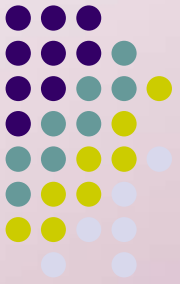
- Mutagenesis (causes of mutations)
 - Wrong base-pairing during replication - point
 - Damage from the environmental agents - point
 - Unequal crossing-over - macromutations
 - Insertions from mobile genes (transposons) – macromutations
- Point mutations can be as deleterious as the macromutations, since they can break the reading frame or introduce a stop codon in the middle of the reading frame



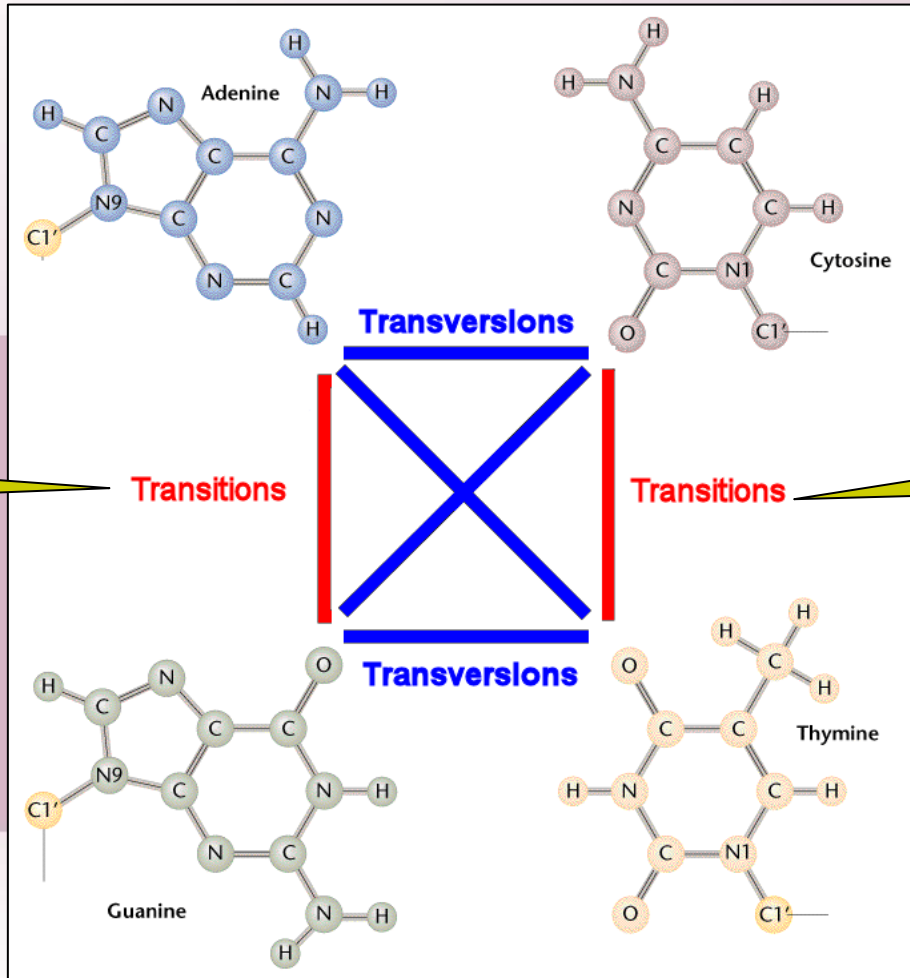
Mutations

- Regulatory mechanisms of DNA repair try to undo the mutations
- Despite this, all cells possess a spontaneous mutation rate defined as a number of mutations which normally occur in each genome over a particular time
- This allows to infer the evolutionary distance between species diverged from a common ancestor

Some mutations are more likely than the others



A



C

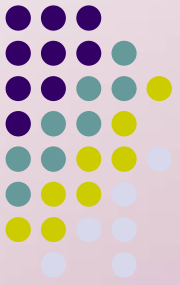
More likely

More likely

G

T

The first scoring matrix for a real DNA



A, G – 2-ring bases

T, C – 1-ring bases

Mutation which preserves rings number is much more likely than changing the number of rings.

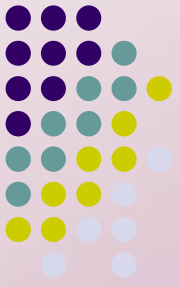
The score of exact matches: + 3

	a	c	g	t	-
a	3	0	2	0	-1
c	0	3	0	2	-1
g	2	0	3	0	-1
t	0	2	0	3	-1
-	-1	-1	-1	-1	

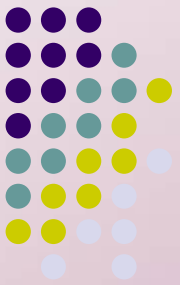
The score of transitions A->G, G->A and T->C, C->A: + 2

The score of any other mismatch (transversions) is 0

Gaps



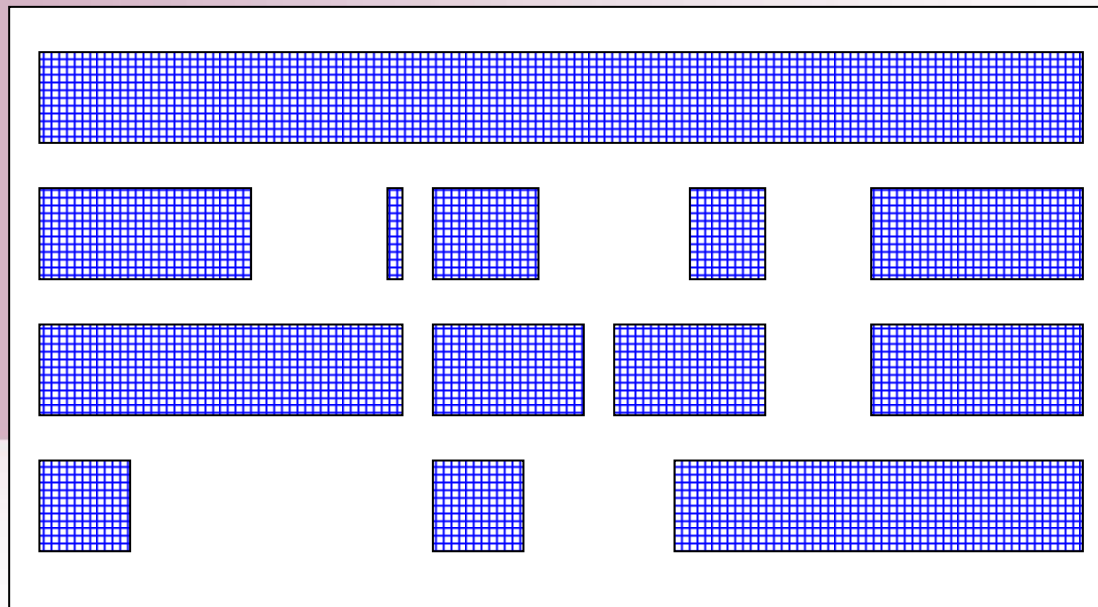
- The deletion or insertion of a single nucleotide is often called *indel* (insertion/deletion)
- In real molecular life, the insertions/ deletions occur in a consecutive block, rather than at the level of single nucleotides
- The deletion/insertion of an entire substring occurs as a single mutational event
- The sequence of consecutive insertions/deletions is called a *gap*

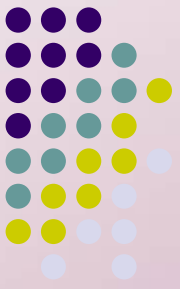


Scoring gaps

Each row represents a part of the genomic sequence of a different strain of HIV virus. 3 bottom rows represent mutated genotypes with an ancestral sequence in the top row.

How many evolutionary events did really occur in each of these 3 cases?

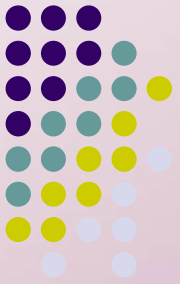




Scoring gaps

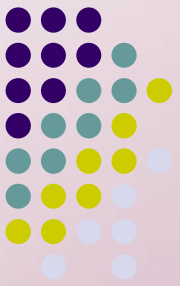
- An optimal alignment of two biological sequences is intended to reflect the likelihood of mutational events.
- Since a gap of more than 1 space can be created by a single mutational event, the alignment model should reflect the true distribution of indels in gaps, not merely the number of indels in an alignment

Scoring gaps



- Constant gap weights
 - Give score -1 for each gap independently of its length
- Affine gap weights
 - Give score $\rho + \mu M$ for a gap of length M
 - ρ is comparatively large (for example, -1)
 - μ is comparatively small (for example -0.01)
- In this way we count each gap as a single mutational event, but we take into account that longer gaps are less likely to occur than the shorter gaps

The recurrence relation for affine gap weights



$$\downarrow \text{COST}(i,j)=\max \left\{ \begin{array}{l} \downarrow \text{COST}(i-1,j) - 0.01 \\ \text{COST}(i-1,j) - 1 - 0.01 \end{array} \right.$$

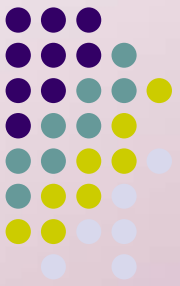
$$\rightarrow \text{COST}(i,j)=\max \left\{ \begin{array}{l} \rightarrow \text{COST}(i,j-1) - 0.01 \\ \text{COST}(i,j-1) - 1 - 0.01 \end{array} \right.$$

When we compute the cost of moving from the top, we distinguish 2 cases:

1. if the top character was already a part of a gap, we just penalize for the extension of the gap.
2. Otherwise, we penalize for the opening of a new gap of length 1

The same when computing the cost of moving from the left to the current cell

The recurrence relation for affine gap weights



$$\swarrow \\ \text{COST}(i,j) = \text{COST}(i-1,j-1) + \text{score}(S1[i], S2[j])$$

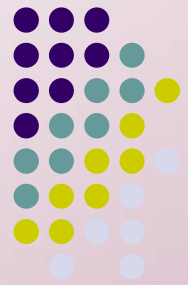
When computing the cost of moving from a diagonal cell,

we account only for a score of aligning characters at current positions $S1[i]$ and $S2[j]$, as we did before

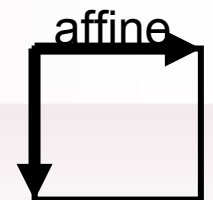
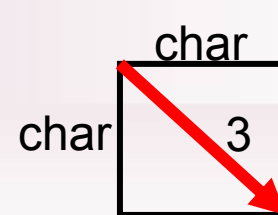
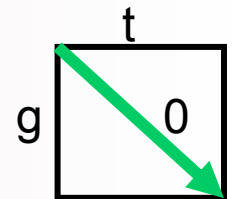
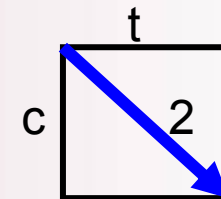
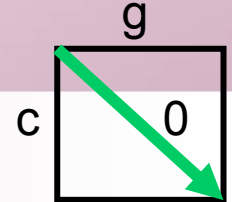
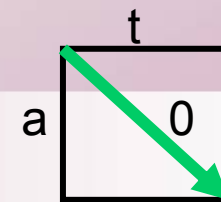
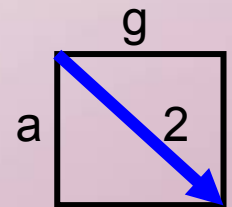
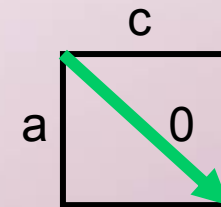
$$\text{COST}(i,j) = \max \left\{ \begin{array}{l} \downarrow \\ \text{COST}(i,j) \\ \rightarrow \\ \text{COST}(i,j) \\ \swarrow \\ \text{COST}(i,j) \end{array} \right.$$

Then we take the max of these 3 values

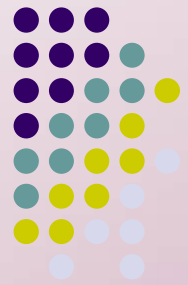
Optimal alignment with affine gap weights and the DNA scoring matrix



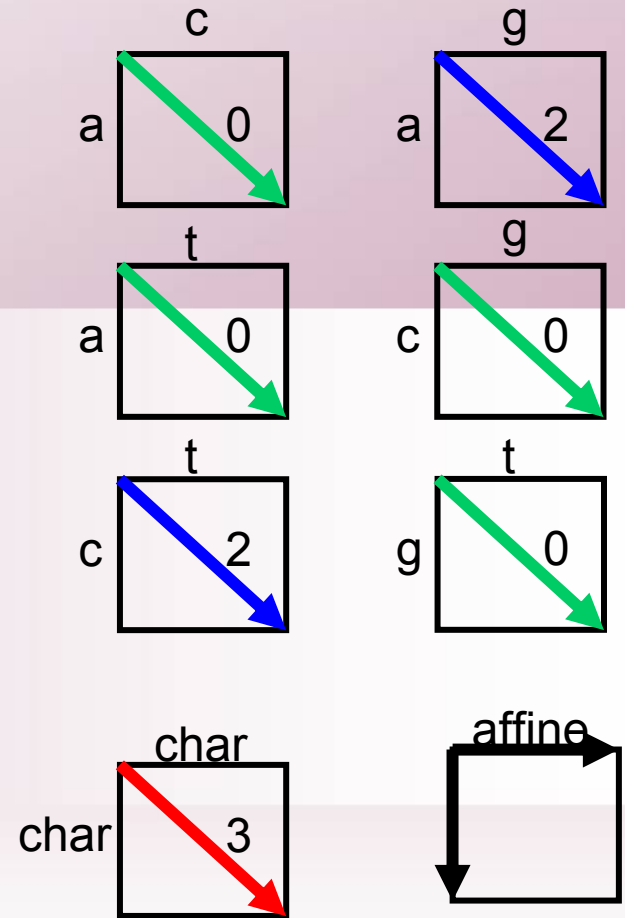
	S2	t	g	c	a	t	a
S1	0						
a							
t							
c							
t							
g							
a							
t							



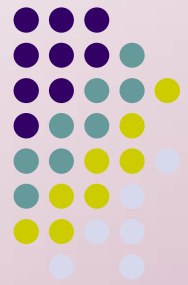
Optimal alignment with affine gap weights and the DNA scoring matrix. Base condition



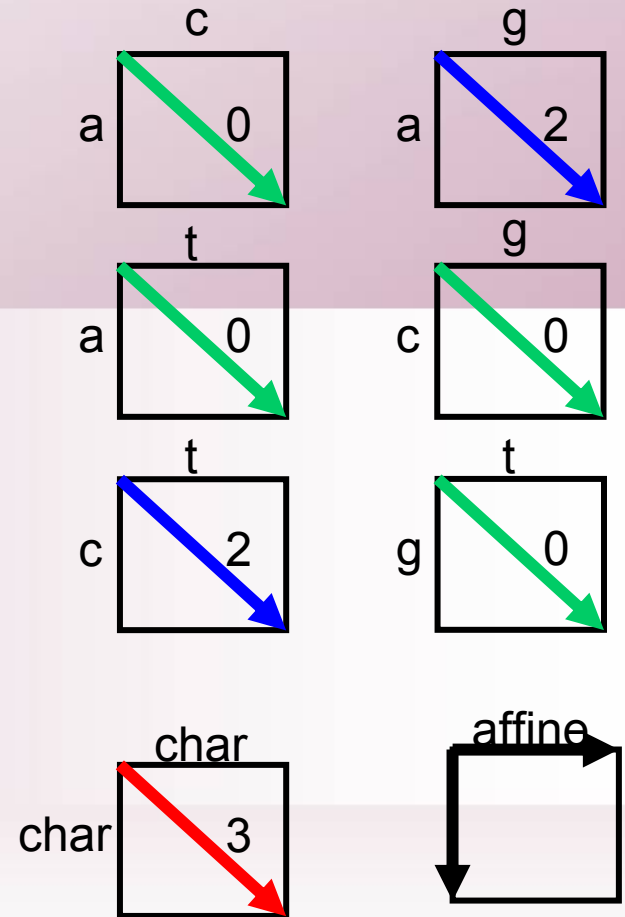
	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓						
t	-1.02 ↓						
c	-1.03 ↓						
t	-1.04 ↓						
g	-1.05 ↓						
a	-1.06 ↓						
t	-1.07 ↓						



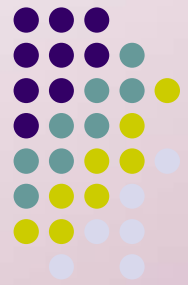
Optimal alignment with affine gap weights and the DNA scoring matrix. Row 1



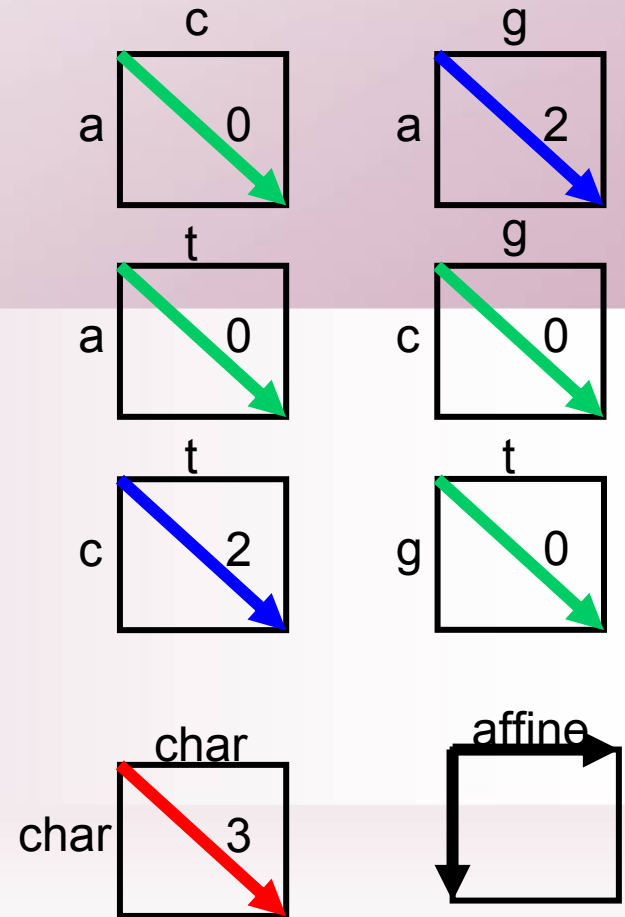
	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓	0 ↘	0.99 ↘	0.02 →	1.97 ↘	0.96 →	1.95 ↘
t	-1.02 ↓						
c	-1.03 ↓						
t	-1.04 ↓						
g	-1.05 ↓						
a	-1.06 ↓						
t	-1.07 ↓						



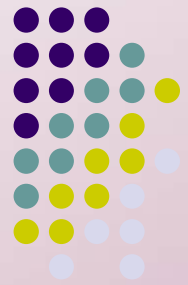
Optimal alignment with affine gap weights and the DNA scoring matrix. Row 2



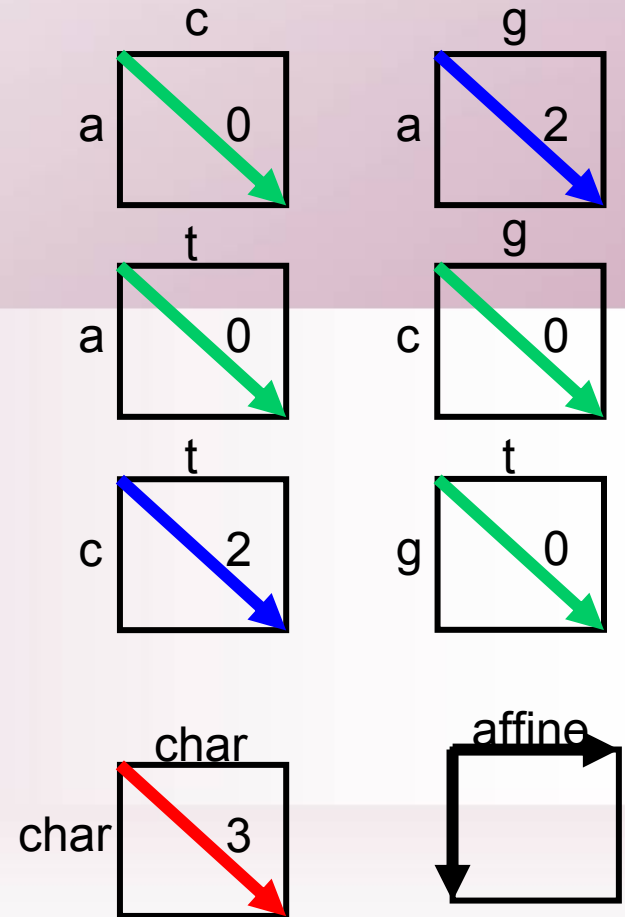
	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓	0 ↘	0.99 ↘	0.02 →	1.97 ↘	0.96 →	1.95 ↘
t	-1.02 ↓	1.99 ↘	0.98 →	2.99 ↘	1.98 →	4.97 ↘	3.96 →
c	-1.03 ↓						
t	-1.04 ↓						
g	-1.05 ↓						
a	-1.06 ↓						
t	-1.07 ↓						



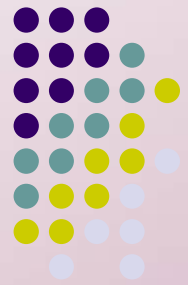
Optimal alignment with affine gap weights and the DNA scoring matrix. Row 3



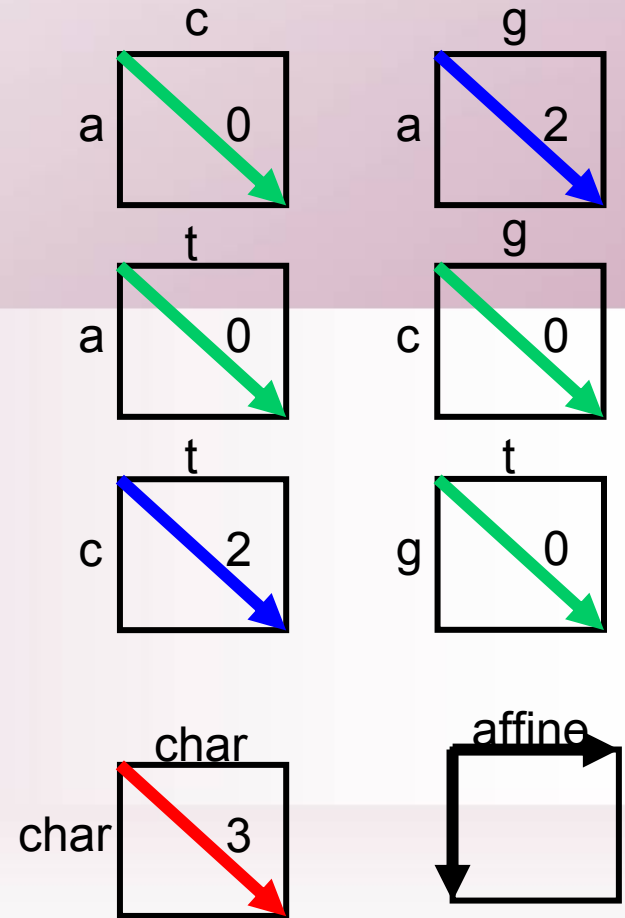
	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓	0 ↘	0.99 ↘	0.02 →	1.97 ↘	0.96 →	1.95 ↘
t	-1.02 ↓	1.99 ↘	0.98 →	2.99 ↘	1.98 →	4.97 ↘	3.96 →
c	-1.03 ↓	0.88 ↘	1.99 ↘	3.98 ↘	2.97 →	3.98 ↘	4.97 →
t	-1.04 ↓						
g	-1.05 ↓						
a	-1.06 ↓						
t	-1.07 ↓						



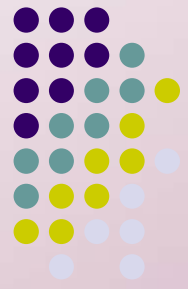
Optimal alignment with affine gap weights and the DNA scoring matrix. Rows 4,5



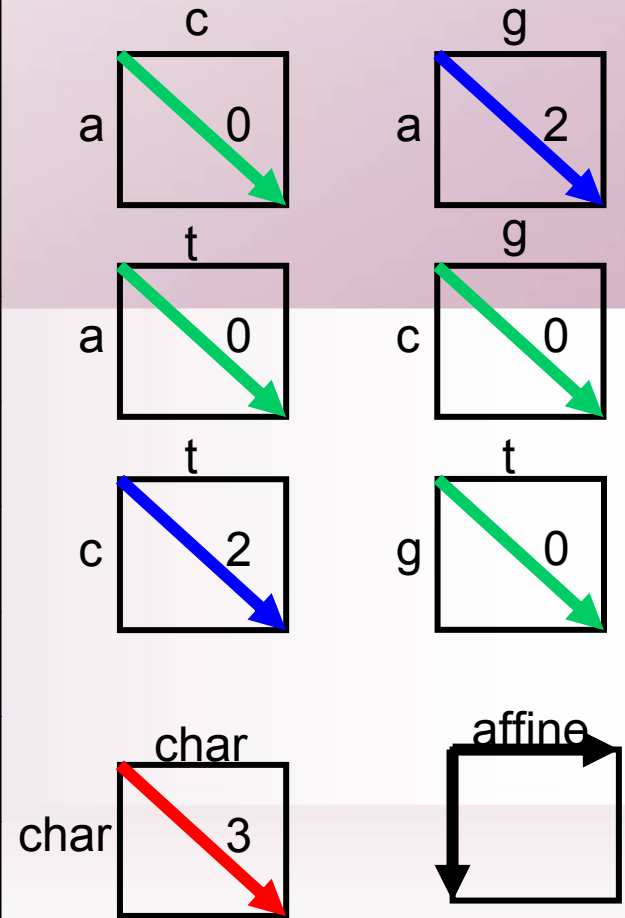
	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓	0 ↘	0.99 ↘	0.02 →	1.97 ↘	0.96 →	1.95 ↘
t	-1.02 ↓	1.99 ↘	0.98 →	2.99 ↘	1.98 →	4.97 ↘	3.96 →
c	-1.03 ↓	0.88 ↘	1.99 ↘	3.98 ↘	2.97 →	3.98 ↘	4.97 →
t	-1.04 ↓	1.97 ↘	0.98 →	3.99 ↘	3.98 →	5.97 ↘	4.96 →
g	-1.05 ↓	0.96 ↘	4.97 ↘	3.96 →	5.99 ↘	4.98 →	7.97 ↘
a	-1.06 ↓						
t	-1.07 ↓						



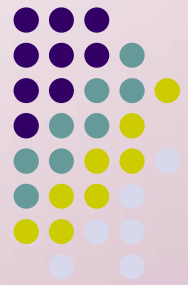
Optimal alignment with affine gap weights and the DNA scoring matrix. Rows 6,7



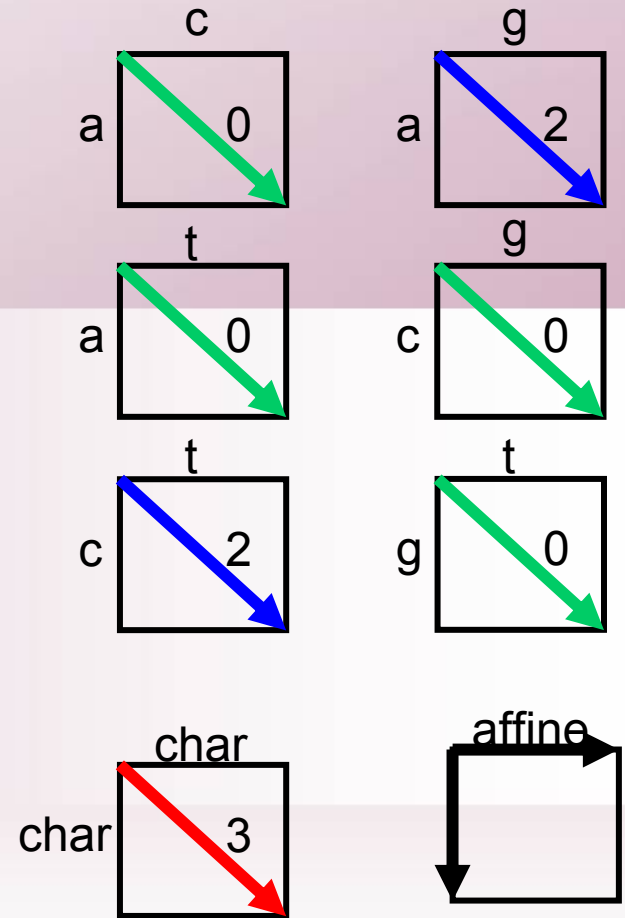
	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓	0	0.99	0.02	1.97	0.96	1.95
t	-1.02 ↓	1.99	0.98	2.99	1.98	4.97	3.96
c	-1.03 ↓	0.88	1.99	3.98	2.97	3.98	4.97
t	-1.04 ↓	1.97	0.98	3.99	3.98	5.97	4.96
g	-1.05 ↓	0.96	4.97	3.96	5.99	4.98	7.97
a	-1.06 ↓	0.14	3.96	4.97	6.96	5.99	7.98
t	-1.07 ↓	1.94	2.95	5.96	5.95	9.96	8.95



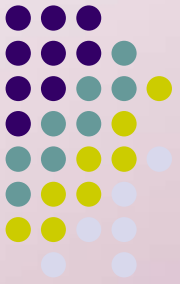
Optimal alignment with affine gap weights and the DNA scoring matrix. Row 7



	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓	0 ↘	0.99 ↘	0.02 →	1.97 ↘	0.96 →	1.95 ↘
t	-1.02 ↓	1.99 ↘	0.98 →	0.99 ↘	0.96 →	4.97 ↘	3.96 →
c	-1.03 ↓	0.98 ↘	1.99 ↘	4.98 ↘	3.97 →	3.96 ↘	4.97 ↘
t	-1.04 ↓	1.97 ↘	0.98 →	3.99 ↘	4.98 ↘	6.97 ↘	5.96 →
g	-1.05 ↓	0.96 ↘	4.97 ↘	3.96 →	5.99 ↘	5.96 ↘	8.97 ↘
a	-1.06 ↓	0.95 ↘	3.96 ↘	4.97 ↘	6.96 ↘	5.99 ↘	8.96 ↘
t	-1.07 ↓	1.94 ↘	3.95 ↘	5.96 ↘	5.95 ↘	9.96 ↘	8.95 →



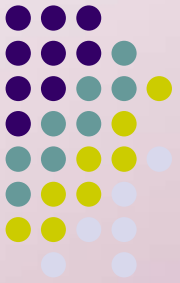
Optimal alignment with affine gap weights and the DNA scoring matrix. Traceback



	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓	0	0.99	0.02	1.97	0.96	1.95
t	-1.01 ↓	1.99	0.98	0.99	0.96	4.97	3.96
c	-1.01 ↓	0.98	1.99	4.98	3.97	3.96	4.97
t	-1.04 ↓	1.97	0.98	3.99	4.98	6.97	5.96
g	-1.05 ↓	0.96	4.97	3.96	5.99	5.96	8.97
a	-1.06 ↓	0.95	3.96	4.97	6.96	5.99	8.96
t	-1.07 ↓	1.94	3.95	5.96	5.95	9.96	8.95

The table displays a dynamic programming matrix for sequence alignment. The rows represent sequence S1 (S2, a, t, c, t, g, a, t) and the columns represent sequence S2 (S2, t, g, c, a, t, a). The diagonal path of the optimal alignment is highlighted with colored arrows: red for matches, green for mismatches, and blue for gaps. The path starts at (S2, S2) and ends at (t, a). The scores along the path are: 0, 1.99, 3.96, 5.96, 8.96, 8.95.

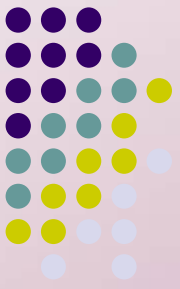
The global alignment



	S2	t	g	c	a	t	a
S1	0	-1.01 →	-1.02 →	-1.03 →	-1.04 →	-1.05 →	-1.06 →
a	-1.01 ↓	0	0.99	0.02	1.97	0.96	1.95
t	-1.02 ↓	1.99	0.98	0.99	0.96	4.97	3.96
c	-1.03 ↓	0.98	1.99	4.98	3.97	3.96	4.97
t	-1.04 ↓	1.97	0.98	3.99	4.98	6.97	5.96
g	-1.05 ↓	0.96	4.97	3.96	5.99	5.96	8.97
a	-1.06 ↓	0.95	3.96	4.97	6.96	5.99	8.96
t	-1.07 ↓	1.94	3.95	5.96	5.95	9.96	8.95

This alignment is called **global** since it represents an alignment with the best overall cost for entire strings S1 and S2

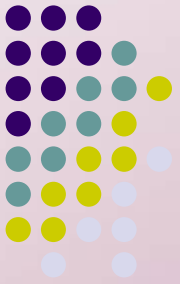
S1	a ↓	t ↓	c ↓	t ↘	g ↘	- →	a ↘	t ↘	- →
S2	-	-	-	t	g	c	a	t	a



The local alignment

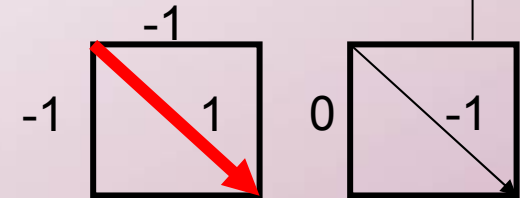
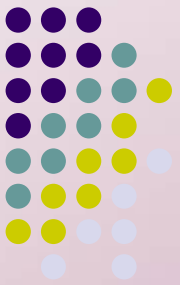
- The similarity of biological strings rarely extends through the entire length of these strings
- Example: homeodomain of the homeobox genes is a very conserved substring in overall very different sequences
- How to detect the regions of local similarity?

The local alignment problem



- Find a pair $(S1[i1\dots i2], S2[j1\dots j2])$ of substrings of $S1$ and $S2$ such that the global alignment score between these substrings is maximal among all possible pairs of substrings of $S1$ and $S2$
- In terms of paths, find the path with the best cost between any pair of vertices

The solution to the local alignment problem. Simple scoring example



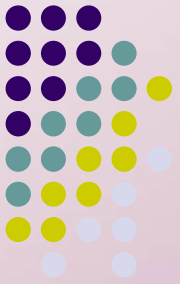
	S2	t	g	c	a	t	a
S1			0				
a					0		
t							
c							
t							
g							
a							
t							

The table shows a sequence alignment between S1 and S2. Red diagonal lines represent the alignment path. Blue arrows indicate the local alignment path starting from (0,0) and ending at (3,3). The cost of the local alignment is 0.

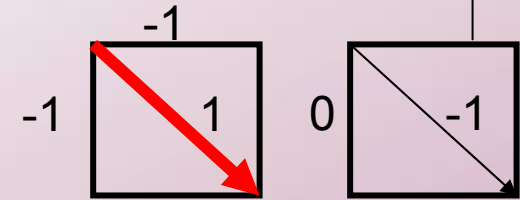
When choosing the best move through the next cell, take into account an additional possibility to start from vertex (0,0) with an overall 0-cost

This means that if the cost of some path drops below 0, we abandon this path and restart the cost to find a better local path starting from the current position.

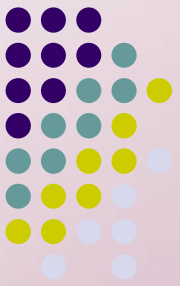
The local alignment. Base condition



	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0						
t	0						
c	0						
t	0						
g	0						
a	0						
t	0						



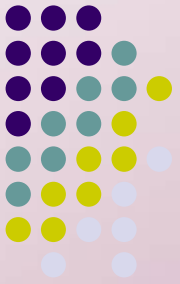
The local alignment. Recurrence relation



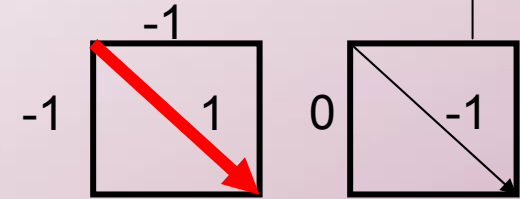
$$\text{COST}(i,j)=\max \begin{cases} 0 \\ \text{COST}(i-1,j) + \text{gapCost} \\ \text{COST}(i,j-1) + \text{gapCost} \\ \text{COST}(i-1,j-1)+\text{score}(S1[i], S2[j]) \end{cases}$$

The cost never drops below 0. if it is negative, we start a new path from the same point with a cost 0

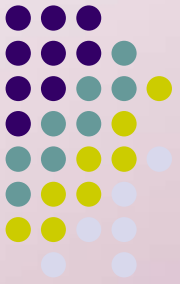
The local alignment. Row 1



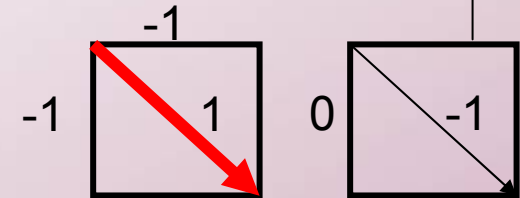
	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0	0	0	0	1	0	1
t	0						
c	0						
t	0						
g	0						
a	0						
t	0						



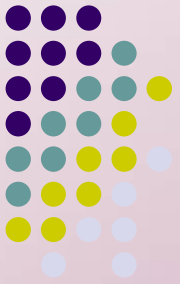
The local alignment. Row 2



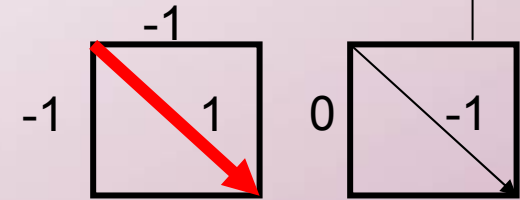
	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0	0	0	0	1	0	1
t	0	1	0	0	0	2	0
c	0						
t	0						
g	0						
a	0						
t	0						



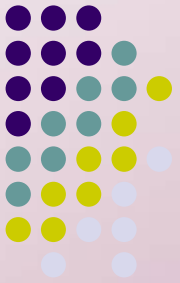
The local alignment. Row 3



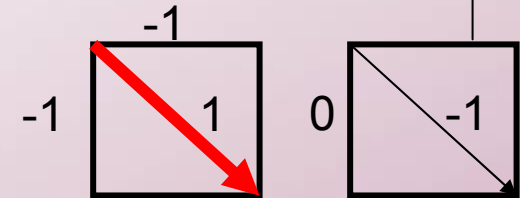
	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0	0	0	0	1	0	1
t	0	1	0	0	0	2	0
c	0	0	0	1	0	1	1
t	0						
g	0						
a	0						
t	0						



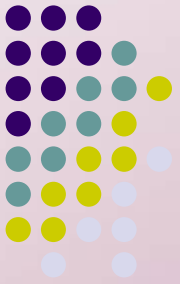
The local alignment. Row 4



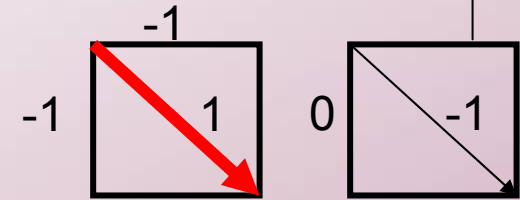
	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0	0	0	0	1	0	1
t	0	1	0	0	0	2	0
c	0	0	0	1	0	1	1
t	0	1	0	0	0	1	0
g	0						
a	0						
t	0						



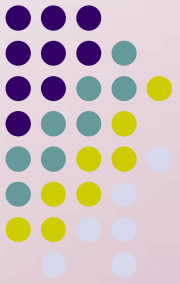
The local alignment. Row 5



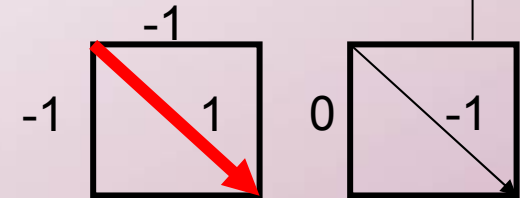
	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0	0	0	0	1	0	1
t	0	1	0	0	0	2	0
c	0	0	0	1	0	1	1
t	0	1	0	0	0	1	0
g	0	0	2	1	0	0	0
a	0						
t	0						



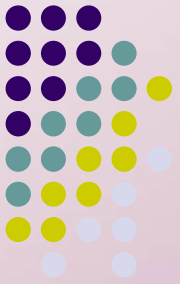
The local alignment. Row 6



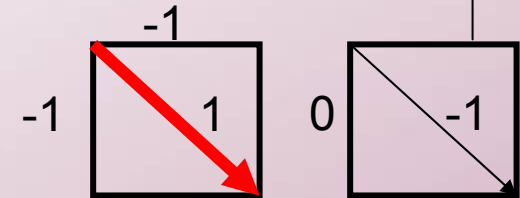
	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0	0	0	0	1	0	1
t	0	1	0	0	0	2	0
c	0	0	0	1	0	1	1
t	0	1	0	0	0	1	0
g	0	0	2	1	0	0	0
a	0	0	1	1	2	1	1
t	0						



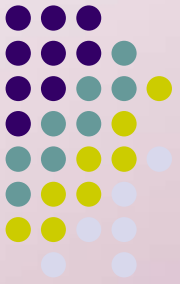
The local alignment. Row 7



	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0	0	0	0	1	0	1
t	0	1	0	0	0	2	0
c	0	0	0	1	0	1	1
t	0	1	0	0	0	1	0
g	0	0	2	1	0	0	0
a	0	0	1	1	2	1	1
t	0	1	0	0	1	3	2



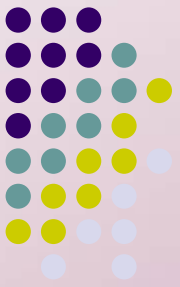
The local alignment. Alignment



	S2	t	g	c	a	t	a
S1	0	0	0	0	0	0	0
a	0	0	0	0	1	0	1
t	0	1	0	0	0	2	0
c	0	0	0	1	0	1	1
t	0	1	0	0	0	1	0
g	0	0	2	1	0	0	0
a	0	0	1	1	2	1	1
t	0	1	0	0	1	3	2

S1	a	t	c	t	g	-	a	t	-
S2	-	-	-	t	g	c	a	t	a

The local alignment. Running time



- $O(NM)$
- If we want to find the regions of high similarity between a new sequence of size M and all G genes of size N each in the database, we need to perform $O(MNG)$ operations