Übersicht

1. Alignments

   Pairwise Alignments
   - Dot plot
   - Pairwise alignment
   - Scoring matrices
   - Motivation of log-odds
   - Affine gap scores

   Multiple Alignments
   - Motivation and definitions
   - Local multiple alignments
   - Scoring multiple alignments
   - Brute force multiple alignment
   - Progressive alignment
   - Alignment using the fast Fourier transform
References

- Skript von Clemens Gröpl
Evolution of sequences

The genomic sequences that we observe today are the result of a random evolutionary process in which sequences are

- copied with occasional errors,
- stretches of sequence (e.g. gene, chromosome, genome) are duplicated and subsequently modified
- and evolutionary pressure introduces a bias of changes towards a functioning organism.
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Examples of similar sequences

Example (DNA segment of BRCA1 gene from vertebrates)

A dot means that the species has at that position the same nucleotide as human.
Examples of similar sequences

**Example (DNA segment of BRCA1 gene from vertebrates)**

A dot means that the species has at that position the same nucleotide as human.

**Example (A protein family with proteins from human and the plant *Arabidopsis thaliana* (ARATH))**

Proteins are from the SUMO family: Small Ubiquitin-like Modifier
### Standard assumption in genome analysis

#### Conservation of function

Function and 3D structure of proteins with the same origin are often still conserved when sequences are only very weakly similar.

#### Assumption

A statistical highly significant *similarity of sequences* (DNA, RNA, protein) usually *implies* the same evolutionary origin and that there is also *functional or structural similarity*.

#### “Twilight zone” for finding sequence similarity

*(chalk board)*
Standard assumption in genome analysis

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## Sequence homology

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- Alignment using the fast Fourier transform
### A pairwise protein alignment

#### Example (human and shark haemoglobin subunit alpha proteins)

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**Mutation:** A mutation in either lineage has lead to a difference.

**Insertion:** An insertion in the protein from shark with respect to the human protein.

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Note that the terms *insertion* and *deletion* are unclear here. It is not clear from this pairwise alignment whether in the third line there has been a deletion in the shark lineage or an insertion in the human lineage.
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Dot Plot

- simple visualization tool for pairwise sequence comparison
- usually for DNA sequences (e.g. genomes, chromosomes)
- allows to detect repeats and inversions
Example (dot plot)

compare two sequences $S$ and $T$:

$S = \text{YQEWTYIVAREAQYE}$
$T = \text{CIVMREQY}$
Dot Plot

Example (dot plot)

compare two sequences $S$ and $T$:

$S = YQEWTYIVAREAQYE$

$T = CIVMREQY$

Draw a “dot” at $(i, j)$ iff $S[i] = T[j]$. 
Similarities in a Dot Plot

Local similarities appear as diagonal line on the main diagonal...

```
  Y Q E W T Y I V A R E A Q Y E
C I V M R E Q Y
```
Genomanalyse

Mario Stanke

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1.14 Dot Plot

Similarities in a Dot Plot

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Dot Plot

Segmental Duplications

Y Q E W T Y Q E A R E Y Q E I

C I V M R Y Q E
Comparing DNA one has to expect at least 25% of identity. Therefore naive dot plots show a lot of “noise”, which can be suppressed by drawing a dot at \((i, j)\) only if there are at least \(s\) matches in a diagonal of size \(w\) centered around \((i, j)\).
Dot Plot

Example (Two algae (Chlamy vs Volvox))

http://genome.jgi-psf.org/synteny
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Definition: Pairwise Alignment

The purpose of alignments is to softly match sequences, allowing for mutations, insertions and deletions.

Definition (Global Pairwise Alignment)
Let $S$ and $T$ be two strings over an alphabet $\Sigma$. Let $'\cdot'$ denote a special gap symbol that is not in $\Sigma$. For any string $U$ over alphabet $\Sigma \cup \{\cdot\}$, let $g(U)$ denote the string that is obtained when all gap symbols in $U$ are removed. An global pairwise alignment of $S$ and $T$ is then a pair of strings $S'$ and $T'$ over $\Sigma \cup \{\cdot\}$ such that

- $S = g(S')$,
- $T = g(T')$,
- $|S'| = |T'|$ and
- $\not\exists i$ such that $S'[i] = T'[i] = \cdot'$.
Alignment Terms

- the positions of $S'$ and $T'$ are called alignment columns
- $S'$ and $T'$ are called rows
- a match is a column with identical (or similar) letters in both rows
- a mismatch is a column with different (or dissimilar) letters in both rows
- an insertion is a letter in the same column as a gap
- a deletion is a gap in the same column as a letter
- an indel is a column containing a gap
Purpose of Alignments

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Definition: Sequence Identity

“Definition” of sequence identity

Let \((S', T')\) be an alignment of strings \(S\) and \(T\) and let

\[
I := \# \{ i \mid S'[i] = T'[i] \}
\]

be the number of aligned identical characters. Then the sequence identity \(ID\) is the percentage of aligned identical characters.
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and there is no consensus on which to use. Even worse, often the denominator is not stated.
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1. \(ID := \frac{I}{\min(|S|, |T|)}\)
2. \(ID := \frac{I}{|S'|}\)
3. \(ID := \frac{I}{\# \{ i | S'[i] \neq - \neq T'[i] \}}\)

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3. \(ID := I / \#\{i \mid S'[i] \neq T'[i]\}\)
4. \(ID := 2I / (|S| + |T|)\)

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Number of Alignments

**How many alignments are there?**

Let \( m = |S| \) and \( n = |T| \) be the lengths of the two strings. Let \( 0 \leq k \leq \min(m, n) \) be the number of matches (:= no gap) of an alignment \((S', T')\) of \(S\) and \(T\). Then \(S'\) must contain \(m - k\) gaps and \(T'\) must contain \(n - k\) gaps.

The number \(A(m, n)\) of alignments of two strings of lengths \(m\) and \(n\) is therefore

\[
A(m, n) = \sum_{k=0}^{\min(m,n)} \text{number of alignments with } k \text{ matches} \\
= \sum_{k=0}^{\min(m,n)} \text{number of possibilities to distribute } m + n - k \text{ columns to } k \text{ matches, } m - k \text{ gaps on } S' \text{ and } n - k \text{ gaps on } T' \\
= \sum_{k=0}^{\min(m,n)} \frac{(m + n - k)!}{k!(m - k)!(n - k)!} \\
= \Omega(2^{\min(m,n)})
\]
Number of Alignments

For example,

\[ A(10, 10) = 8097453, \]

i.e. there are already more than 8 million alignments of two strings of length 10.
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Typical problem sizes $\min(n, m)$ for alignments are in the order of hundreds and can go up to millions.
How should we pick of all possible alignments a good one that approximately reflects the true history of the sequences (mutations, insertions, deletions)?
Scoring of an alignment

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Scoring scheme

Let $A = (S', T')$ be an alignment of sequences $S$ and $T$. A simple but common way is to assign a score to each column of the alignment and then sum up these scores to score the alignment.

Definition (scoring matrix)

A scoring matrix is a function

$$s : (\Sigma \cup \{-\})^2 \rightarrow \mathbb{R}.$$
Intuition of scoring scheme

A scoring matrix $s$ will typically give

- high values to similar or identical characters: $s(a, a) > 0$

Mismatches, insertions and deletions are punished. More on the topics of scoring matrices later.
Scoring of an alignment

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More on the topics of scoring matrices later.
Scoring of an alignment

**Definition (score of an alignment)**

Given a scoring matrix $s$ the score of an alignment $A = (S', T')$ with $\ell$ columns is defined as

$$s(A) := \sum_{i=1}^{\ell} s(S'[i], T'[i]).$$

**Example (alignment and score)**

*(chalk board)*
Finding a best-scoring alignment

**Needleman-Wunsch Problem**

Find a global alignment of two sequences $S$ and $T$ with maximal score.

- named after two authors who first discussed global alignments in 1970.
- can be solved using Dynamic Programming.
Finding a best-scoring alignment

Definition (DP variables)

Let

\[ M(i, j) := \text{maximal score of an alignment of } S[1..i] \text{ and } T[1..j] \]

for \( i = 1, \ldots, m := |S| \) and \( j = 1, \ldots, n := |T| \).

Define \( M(0, 0) := 0 \).
Finding a best-scoring alignment

DP recursion

\[
M(i, j) = \max \left\{ 
\begin{align*}
M(i - 1, j - 1) &+ s(S[i], T[j]) \\
M(i - 1, j) &+ s(S[i], -) \\
M(i, j - 1) &+ s(-, T[j])
\end{align*}
\right. \quad (4)
\]

\[
M(i, 0) = M(i - 1, 0) + s(S[i], -) \quad (5)
\]

\[
M(0, j) = M(0, j - 1) + s(-, T[j]) \quad (6)
\]

for \(i, j > 0\).
**Explanation of recursion**

Let $i, j > 0$. There are three possibilities for the *last column* of an optimal alignment of $S[1..i]$ and $T[1..j]$:
DP recursion

Explanation of recursion

Let $i, j > 0$.
There are three possibilities for the last column of an optimal alignment of $S[1..i]$ and $T[1..j]$:

- **no gap:**
  - $S[i]$ and $T[j]$ are aligned
  - $M(i, j) = M(i-1, j-1) + s(S[i], T[j])$

- **gap in $T$:**
  - $S[i]$ is aligned to a gap
  - $M(i, j) = M(i-1, j) + s(S[i], -)$

- **gap in $S$:**
  - $T[j]$ is aligned to a gap
  - $M(i, j) = M(i, j-1) + s(-, T[j])$

Since $M(i, j)$ is the score of the optimal alignment it is the maximum of the three and therefore we have (4).

(5) and (6) are special cases in which only the second or third possibility is possible.
DP recursion

Explanation of recursion

Let \( i, j > 0 \).
There are three possibilities for the \textit{last column} of an optimal alignment of \( S[1..i] \) and \( T[1..j] \):

- **no gap:**
  \( S[i] \) and \( T[j] \) are aligned

\[
M(i, j) = M(i-1, j-1) + s(S[i], T[j])
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- **gap in \( T \):**
  \( S[i] \) is aligned to a gap

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M(i, j) = M(i-1, j) + s(S[i], -)
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- **gap in \( S \):**
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Let $i, j > 0$.
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<tbody>
<tr>
<td>$S[i]$ and $T[j]$ are aligned</td>
<td>$M(i, j) = M(i-1, j-1) + s(S[i], T[j])$</td>
<td>$M(i, j) = M(i-1, j) + s(S[i], -)$</td>
<td>$M(i, j) = M(i, j-1) + s(-, T[j])$</td>
</tr>
</tbody>
</table>

Since $M(i, j)$ is the score of the optimal alignment it is the maximum of the three and therefore we have (4).

(5) and (6) are special cases in which only the second or third possibility is possible.
Needleman-Wunsch algorithm

<table>
<thead>
<tr>
<th>Line</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:</td>
<td>$M(0, 0) \leftarrow 0$ // initialization of boundary case</td>
</tr>
<tr>
<td>2:</td>
<td>for $i = 1$ to $m$ do</td>
</tr>
<tr>
<td>3:</td>
<td>for $j = 1$ to $n$ do</td>
</tr>
<tr>
<td>4:</td>
<td>compute $M(i, j)$ according to DP recursion</td>
</tr>
<tr>
<td>5:</td>
<td>set $p(i, j)$ to either $(i - 1, j - 1)$, $(i - 1, j)$ or $(i, j - 1)$ corresponding to the entry of $M$ that was used in line 4</td>
</tr>
<tr>
<td>6:</td>
<td>end for</td>
</tr>
<tr>
<td>7:</td>
<td>end for</td>
</tr>
<tr>
<td>8:</td>
<td>output $M(m, n)$ as optimal global alignment score</td>
</tr>
<tr>
<td>9:</td>
<td>// backtracking starts</td>
</tr>
<tr>
<td>10:</td>
<td>$A \leftarrow \langle$ empty alignment $\rangle$</td>
</tr>
<tr>
<td>11:</td>
<td>$(i, j) \leftarrow (m, n)$</td>
</tr>
<tr>
<td>12:</td>
<td>repeat</td>
</tr>
<tr>
<td>13:</td>
<td>depending on whether $p(i, j)$ is $(i - 1, j - 1)$, $(i - 1, j)$ or $(i, j - 1)$ add alignment column $\left( \begin{array}{c} S[i] \ T[j] \end{array} \right)$, $\left( \begin{array}{c} S[i] \ - \end{array} \right)$ or $\left( \begin{array}{c} - \ T[j] \end{array} \right)$, respectively, to left of $A$</td>
</tr>
<tr>
<td>14:</td>
<td>$(i, j) \leftarrow p(i, j)$</td>
</tr>
<tr>
<td>15:</td>
<td>until $(i, j) = 0$</td>
</tr>
<tr>
<td>16:</td>
<td>output $A$ as optimal alignment</td>
</tr>
</tbody>
</table>
Needleman-Wunsch algorithm

<table>
<thead>
<tr>
<th>Complexity</th>
</tr>
</thead>
</table>
| • **running time:** $O(mn)$  
| • **memory:** $O(mn)$ |
Needleman-Wunsch algorithm

### Complexity

- **running time:** $O(mn)$
- **memory:** $O(mn)$

### Variant of the algorithm

- do not store the matrix $p(\cdot, \cdot)$ of backtracking pointers
- instead, recompute the maximum each time during traceback
### Needleman-Wunsch algorithm

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We add only $O(m + n)$ steps.
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### Variant of the algorithm

- do not store the matrix $p(\cdot, \cdot)$ of backtracking pointers
- instead, recompute the maximum each time during traceback

The running time of this variant is still $O(mn)$:

We add only $O(m + n)$ steps.
We save the space for $p(\cdot, \cdot)$. Depending on the representation of $p(\cdot, \cdot)$ and $M(\cdot, \cdot)$ this may be up to half the space.
Local alignment

**Definition (local alignment problem)**

Given two strings $S$ and $T$, find substrings $s$ of $S$ and $t$ of $T$, whose similarity (= optimal global alignment score) is maximal over all pairs of substrings from $S$ and $T$. 

**Motivation**
When comparing long sequences often only a smaller part is conserved or alignable. E.g.:
- protein domain
- cDNA to genome alignment
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When comparing long sequences often only a smaller part is conserved or alignable. E.g.

- protein domain
- cDNA to genome alignment
**Local alignment**

Example (DNA alignment)

**global alignment:**

```
--T--CC-C-AGT--TATGT-CAGGGGACACG-A-GCATGCAGA-GAC
   |   |   |   |   |   |   |   |   |   |   |   |   |   |
AATTGCCGCC-GTCGT-T-TTCAG-----CA-GTTATG-T-CAGAT--C
```

**local alignment:**

```
tccCAGTTATGTCAGgggacacgagcatgcagagac
   |   |   |   |   |   |   |   |   |   |   |   |   |   |
aattgccgccccgtcgttttccagCAGTTATGTCAGatc
```

toy example from Clemens Gröpl
Smith-Waterman algorithm

Finding a best-scoring *local* alignment

- can be done using a DP algorithm
Smith-Waterman algorithm

Finding a best-scoring *local* alignment

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- a local alignment can now **start and end at any position** in the “alignment space” \([1..m] \times [1..n]\)
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Finding a best-scoring *local* alignment

- can be done using a DP algorithm
- which is a variant of the Needleman-Wunsch algorithm
- a local alignment can now start and end at any position in the “alignment space” $[1..m] \times [1..n]$
- an arbitrary start can be achieved by adding an option to 0 to the recursion
- an arbitrary end can be achieved by maximizing over all entries of the DP-matrix
Local pairwise alignment

Definition (DP variables)

Let

\[ N(i, j) := \text{maximal score of a global alignment of a suffix of } S[1..i] \text{ and a suffix of } T[1..j] \]  

(7)

for \( i = 1, \ldots, m := |S| \) and \( j = 1, \ldots, n := |T| \).

Define \( N(0, 0) = N(i, 0) = N(0, j) := 0 \).

Remarks

- String \( a \) is called a suffix of string \( b \) of length \( n \) if \( a = b[i..n] \) for some \( i \).
- We assume that indels have a negative score, so that an optimal local alignment will never start with an indel.
Local pairwise alignment

**DP recursion**

\[
N(i, j) = \max \begin{cases} 
0 \\
N(i - 1, j - 1) + s(S[i], T[j]) \\
N(i - 1, j) + s(S[i], -) \\
N(i, j - 1) + s(-, T[j]) 
\end{cases}
\]

(8)

\(1 \leq i \leq m, 1 \leq j \leq n\)
Smith-Waterman algorithm

1: \( M(0, 0) \leftarrow 0 \) // initialization of boundary case
2: \( p(0, 0) \leftarrow (-1, -1) \) // initialization of predecessor pointer to undefined value
3: for \( i = 1 \) to \( m \) do
4:   for \( j = 1 \) to \( n \) do
5:     compute \( N(i, j) \) according to DP recursion (8)
6:     set \( p(i, j) \) to either \((-1, -1), (i-1, j-1), (i-1, j) \) or \((i, j-1) \)
8:       corresponding to whether the first, second, third or fourth argument of \( \max \)
8:       in (8) is maximal
7: end for
8: end for
9: \( (i, j) \leftarrow \text{argmax}\{N(a, b) \mid 1 \leq a \leq m, 1 \leq b \leq n\} \)
10: output \( N(i, j) \) as optimal local alignment score
11: // backtracking starts
12: \( A \leftarrow \langle \text{empty alignment} \rangle \)
13: while \( p(i, j) \neq (-1, -1) \) do
14:   depending on whether \( p(i, j) \) is \((i-1, j-1), (i-1, j) \) or \((i, j-1) \) add
15:     alignment column \((S[i], T[j])\), \((S[i], \cdot)\) or \(( \cdot, T[j])\), respectively, to left of \( A \)
16: \( (i, j) \leftarrow p(i, j) \)
17: end while
18: output \( A \) as optimal alignment
Alignments

1. Pairwise Alignments
   - Dot plot
   - Pairwise alignment
   - Scoring matrices
     - Motivation of log-odds
     - Affine gap scores

2. Multiple Alignments
   - Motivation and definitions
   - Local multiple alignments
   - Scoring multiple alignments
   - Brute force multiple alignment
   - Progressive alignment
   - Alignment using the fast Fourier transform
## Amino Acid Properties

### Amino Acids

<table>
<thead>
<tr>
<th>amino acid</th>
<th>3 letter</th>
<th>1 letter</th>
<th>polarity</th>
<th>charge</th>
<th>hydro-path index</th>
<th>average res. mass [daltons]</th>
<th>accessible surface area [Å²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alanine</td>
<td>Ala</td>
<td>A</td>
<td>nonpolar</td>
<td>neutral</td>
<td>1.8</td>
<td>71.1</td>
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<tr>
<td>Arginine</td>
<td>Arg</td>
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<td>positive</td>
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<td>196</td>
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<td>Asparagine</td>
<td>Asn</td>
<td>N</td>
<td>polar</td>
<td>neutral</td>
<td>-3.5</td>
<td>114.1</td>
<td>113</td>
</tr>
<tr>
<td>Aspartic acid</td>
<td>Asp</td>
<td>D</td>
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<td>Cysteine</td>
<td>Cys</td>
<td>C</td>
<td>nonpolar</td>
<td>neutral</td>
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<td>103.1</td>
<td>104</td>
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<tr>
<td>Glutamic acid</td>
<td>Glu</td>
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<td>negative</td>
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<td>129.1</td>
<td>138</td>
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<td>Gln</td>
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<td>polar</td>
<td>neutral</td>
<td>-3.5</td>
<td>128.1</td>
<td>144</td>
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<td>Gly</td>
<td>G</td>
<td>nonpolar</td>
<td>neutral</td>
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<td>57.1</td>
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<td>His</td>
<td>H</td>
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<td>positive</td>
<td>-3.2</td>
<td>137.1</td>
<td>151</td>
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<tr>
<td>Isoleucine</td>
<td>Ile</td>
<td>I</td>
<td>nonpolar</td>
<td>neutral</td>
<td>4.5</td>
<td>113.2</td>
<td>140</td>
</tr>
<tr>
<td>Leucine</td>
<td>Leu</td>
<td>L</td>
<td>nonpolar</td>
<td>neutral</td>
<td>3.8</td>
<td>113.2</td>
<td>137</td>
</tr>
<tr>
<td>Lysine</td>
<td>Lys</td>
<td>K</td>
<td>polar</td>
<td>positive</td>
<td>-3.9</td>
<td>128.2</td>
<td>167</td>
</tr>
<tr>
<td>Methionine</td>
<td>Met</td>
<td>M</td>
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<td>neutral</td>
<td>1.9</td>
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<tr>
<td>Phenylalanine</td>
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<td>80</td>
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<td>Threonine</td>
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<td>T</td>
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<td>neutral</td>
<td>-0.7</td>
<td>101.1</td>
<td>102</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>Trp</td>
<td>W</td>
<td>nonpolar</td>
<td>neutral</td>
<td>-0.9</td>
<td>186.2</td>
<td>217</td>
</tr>
<tr>
<td>Tyrosine</td>
<td>Tyr</td>
<td>Y</td>
<td>polar</td>
<td>neutral</td>
<td>-1.3</td>
<td>163.2</td>
<td>187</td>
</tr>
<tr>
<td>Valine</td>
<td>Val</td>
<td>V</td>
<td>nonpolar</td>
<td>neutral</td>
<td>4.2</td>
<td>99.1</td>
<td>117</td>
</tr>
</tbody>
</table>
Amino Acid Properties

Amino Acid Venn Diagram
Amino Acid Properties

For the purpose of this class we need not know any particular amino acid properties.
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3. simplifying, we can define an “overall similarity” for each pair of amino acids

4. Remark: Later, we will also use a more detailed model that takes into account that a residue may have a certain property, that can not be defined through pairwise similarity
Score of a protein alignment

Reminder:
Neglect gaps for now.
The score of an alignment \( A = (S', T') \) of two protein sequences \( S \) and \( T \) is the sum of the scores of the alignment columns:

\[
s(A) = \sum_i s(S'[i], T'[i])
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Score of a protein alignment

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$$s(A) = \sum_i s(S'[i], T'[i])$$

Scoring Matrix Principle
For two amino acids $a, b$, the score $s(a, b)$ is usually defined through

$$s(a, b) = \log \frac{p(a, b)}{q(a)q(b)}, \quad (9)$$

where $p(a, b)$ is the probability of observing $a$ aligned to $b$ in correct alignments and $q(a), q(b)$ are the relative overall frequencies of amino acids $a$ and $b$, respectively.
**Score of a protein alignment**

### Pairwise Scores

Some intuitive properties of (9):

- $s(\cdot, \cdot)$ is symmetric

<table>
<thead>
<tr>
<th>Pairwise Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Some intuitive properties of (9):</td>
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Score of a protein alignment

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- \( q(a)q(b) \) is the probability of pairings \((a, b)\) in random alignments of unrelated sequences
- the score is positive iff \( p(a, b) > q(a)q(b) \), i.e. if \( a, b \) co-occur more often than expected by chance
- normalizing with \( q(a)q(b) \) has the effect that rare amino acids can have high scores
- \( s(a, a) > 0 \) and, usually, \( a \) is the amino acid that is most similar to \( a \)
Score of a protein alignment

Pairwise Scores

Must satisfy

$$
\sum_{a,b} s(a, b)q(a)q(b) < 0.
$$

Interpretation: The expected score of two random unrelated amino acids must be negative. If this was not satisfied, then local alignments would not be meaningful: Long unrelated stretches were likely to be aligned.
## Example of a Scoring Matrix

### BLOSUM62

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

BLOSUM\(x\)

- example \(x = 62\) on previous slide
- made from alignment "BLOCKS", in which any two sequences are less than \(x\)% percent identical
- \(p(\cdot, \cdot), q(\cdot)\) estimated using observed relative frequencies in alignment BLOCKS
- scaled and rounded to integers
1 Alignments

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- Alignment using the fast Fourier transform
Test of a simple hypothesis against a simple alternative

Suppose, we want to test a (simple) hypothesis $H_0$ against a (simple) alternative $H_1$. E.g.

$H_0 : \text{alignment column } x = \begin{pmatrix} a \\ b \end{pmatrix}$ is "not correct"

$H_1 : \text{alignment column } x \text{ is "correct"}

In other words, $H_0$ is the *null-hypothesis* that residues $a$ and $b$ are unrelated. $H_1$ is the alternative that residues $a$ and $b$ stem from a common ancestor residue.
Decision Function, Type 1 error, power

Let $\phi = \phi(x) \in \{0, 1\}$ be a decision function that assigns to an observation $x$ one of the hypotheses ($H_0, H_1$).
Statistical Test

### Decision Function, Type 1 error, power

Let $\phi = \phi(x) \in \{0, 1\}$ be a decision function that assigns to an observation $x$ one of the the two hypotheses ($H_0, H_1$). Let

$$P(\phi(x) = 1 \mid H_0) = \text{prob. that we decide for } H_1 \text{ although } H_0 \text{ is true}$$

be the type 1 error. In our example, the type 1 error is that we conclude that $a$ and $b$ are related although they are not. We want to chose a $\phi$ that keeps the probability of this error low.
Statistical Test

**Decision Function, Type 1 error, power**

Let $\phi = \phi(x) \in \{0, 1\}$ be a decision function that assigns to an observation $x$ one of the two hypotheses ($H_0, H_1$). Let

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be the **type 1 error**. In our example, the type 1 error is that we conclude that $a$ and $b$ are related although they are not. We want to choose a $\phi$ that keeps the probability of this error low. Let

$$P(\phi(x) = 1 \mid H_1) = \text{prob. that we decide for } H_1 \text{ if } H_1 \text{ is true}$$

be the **power**. In our example, the power is the probability that we predict $a$ and $b$ to be related if they really are related. We want to choose a $\phi$ with high power.
Neyman-Pearson-Lemma

Among all decision functions that satisfy an upper bound for the type 1 error, a decision function of the following form has maximal power:

\[ \phi(x) = 1 \iff \frac{P(x|H_1)}{P(x|H_0)} > t \quad (10) \]

for some constant threshold \( t \).
Neyman-Pearson-Lemma

Among all decision functions that satisfy an upper bound for the type 1 error, a decision function of the following form has maximal power:

$$\phi(x) = 1 \iff \frac{P(x|H_1)}{P(x|H_0)} > t$$

(10)

for some constant threshold $t$.

Intuitively, this means that we should decide for the alternative, if the observation $x$ is such that it is relatively likely in case $H_1$ is true (the denominator), compared to when $H_0$ is true (the nominator).
Connection between the Neyman-Pearson-Lemma and Scoring Matrices

In the alignment problem we are considering $H_0$ : the two sequences are unrelated and $H_1$ : the two sequences are evolutionary related and want to effectively decide among the two.
Connection between the Neyman-Pearson-Lemma and Scoring Matrices

In the alignment problem we are considering $H_0$ : the two sequences are unrelated and $H_1$ : the two sequences are evolutionary related and want to effectively decide among the two. Using a scoring matrix $s(\cdot, \cdot)$ as and a DP-algorithm as above we are finding an alignment which maximizes

$$\sum_i s(S'[i], T'[i]) = \sum_i \log \frac{p(S'[i], T'[i])}{q(S'[i])q(T'[i])} = \log \prod_i \frac{p(S'[i], T'[i])}{q(S'[i])q(T'[i])}$$
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\[
\sum_i s(S'[i], T'[i]) = \sum_i \log \frac{p(S'[i], T'[i])}{q(S'[i])q(T'[i])}
\]

\[
= \log \prod_i \frac{p(S'[i], T'[i])}{q(S'[i])q(T'[i])}
\]

As the logarithm is a monotonous function, this is equivalent to

\[
\prod_i \frac{p(S'[i], T'[i])}{q(S'[i])q(T'[i])} = \frac{\left(\prod_i p(S'[i], T'[i])\right)}{\prod_i q(S'[i]) \prod_i q(T'[i])} \rightarrow \text{max} \quad (11)
\]
Connection between the Neyman-Pearson-Lemma and Scoring Matrices

The expression in (11) can be interpreted under an independence assumption as

\[ \frac{P(S,T \mid H_1)}{P(S,T \mid H_0)} . \]  

(12)

By the Neyman-Pearson-Lemma, we find the most truely related sequences (decide for \( H_1 \) if \( H_1 \) is true) under the constraint that the type 1 error is bounded (not too many false positives = unrelated sequences that we think are related), when using (12) as criterion. In that sense, the scoring matrix approach is optimal.

We just have to balance out a high power against a low probability of a type 1 error by considering a low alignment score threshold or a higher one.
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Example (beetle - bee)

section from an alignment between a protein from the red flour beetle and from honey bee:

```
VNIDGTNCPIKKTFVVPPKSPNDLDVYN----WRLSFQEQEELLHNYKNMKSSIRLIK
+++D C KT+F +P D D+ N WRLSF QE+E+L Y +K IR +KK
IHVDLAPCR-NKTWFAPLPLPLTDDDINNKNFYWRLSFSCQEKELTGYGRIKPVRQMKK
```
Gap Scores Revisited

**Example (beetle - bee)**

Section from an alignment between a protein from the red flour beetle and from honey bee:

```
VNIDGTNCPIKKTFVVVKSPNLDVYN----WRLSFQEQEREELLHYKKNKSSIRLIK
+++DCKT+F+PDND+NWRLSFQE+EL Y+KIR+KK
IHVDLAPCRNKTWFAPLPLPLDDINNKNFYWRLSFSCQEKEILTKYGRKIPVIRQMKK
```  

**Example (chicken - opossum)**

Another alignment between chicken and opossum proteins:

```
FSPTKVADWFYDSISIVLSEIQKKPQRGMPKVEKVEKNGTIIISIIIL---GVGSSRMLYDI
LCPTQVASWFFSSLSAVAVSTLTPTP---GAPRLVHAARHAGVTIILLSTPGGPRLLLLFDL

VPVVSFKGWPAVAQSWLMENHFWDGKITEEEEVISGFLVPCSYKGGKDNEWRLSFARSE
VPGISVTGWPERTRT-----HAWMGPLAAGP---TSYYLVPFGAGKEEDGLCWRICFARQE
```
Gap lengths

Example

<table>
<thead>
<tr>
<th>Compare</th>
<th>with</th>
</tr>
</thead>
<tbody>
<tr>
<td>AATCGGACTGGTAA AA-------TGGCAA</td>
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</tr>
</tbody>
</table>

Under a typical linear scoring scheme, the right alignment scores better. But it’s less plausible: 3 indel events instead of 1 longer indel and 1 mutation.

Observations/Conclusions

- indels are not distributed homogenously over alignment
Gap lengths

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- indel columns tend to cluster
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- indels are not distributed homogenously over alignment
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- whether there is an insertion (deletion) at alignment position \( i \) is not independent from the event whether we observe one at, say, position \( i + 1 \)
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Example

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</table>

with

<table>
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<th>AATCGGACTGGTAA</th>
</tr>
</thead>
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Observations/Conclusions

- indels are not distributed homogenously over alignment
- indel columns tend to cluster
- whether there is an insertion (deletion) at alignment position $i$ is not independent from the event whether we observe one at, say, position $i + 1$
- neighboring indels could reflect an insertion or deletion event during evolution of more than 1 amino acid in one step
Scoring a gap

Gap penalty function

- let $p(n) < 0$ be the score associated with a gap of length $n$
Scoring a gap

Gap penalty function

- let $p(n) < 0$ be the score associated with a gap of length $n$
- $-p(n)$ is also called a penalty
Scoring a gap

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- let $p(n) < 0$ be the score associated with a gap of length $n$
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- a simple scoring scheme as introduced above scores an indel position independently on the length of the complete gap.
  It has linear gap penalties if, as usual, $s(a, -) = s(-, a)$ is independent of $a$:

$$p(n) = c \cdot n$$
### Scoring a gap

**Gap penalty function**

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\[
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\]

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- linear gap penalties are not realistic and may lead to too many (short) gaps
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It has **linear gap penalties** if, as usual, $s(a, -) = s(-, a)$ is independent of $a$:

$$p(n) = c \cdot n$$

- linear gap penalties are not realistic and may lead to too many (short) gaps
- good/true alignments should have rather fewer longer gaps than many short gaps
Affine gap penalties

A scoring scheme in which the costs of a gap of length \( n \) is of the form

\[
p(n) = -g - e \cdot n
\]

with constants \( g, e \geq 0 \) is said to have **affine gap penalties**.

- \( g \) can be interpreted as the penalty for creating a gap at all and is called **gap opening penalty**
- \( e \) can be interpreted as the penalty for any gap position and is called **gap extension penalty**
Affine gap penalties

- affine gap penalties usually model the evolution of gaps more realistically than linear gap penalties
Affine gap penalties

- **affine gap penalties** usually model the evolution of gaps more realistically than linear gap penalties
- algorithms that find a best alignment in a scoring scheme with affine gap penalty require more time than algorithms under a linear gap model
Affine gap penalties

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- Algorithms that find a best alignment in a scoring scheme with affine gap penalty **require more time** than algorithms under a linear gap model.
- With a suitable DP algorithm, a best-scoring alignment under an affine gap penalties model can be found in time $O(nm)$ (same complexity as linear gap penalties).
Affine gap penalties

- **affine gap penalties** usually model the evolution of gaps more realistically than linear gap penalties.
- Algorithms that find a best alignment in a scoring scheme with affine gap penalty require more time than algorithms under a linear gap model.
- With a suitable DP algorithm, a best-scoring alignment under an affine gap penalties model can be found in time $O(nm)$ (same complexity as linear gap penalties).
- Affine gap penalties constitute a good compromise between speed and accuracy and are most often used in practice.
**DP variables for affine gap penalties**

Consider again the **global pairwise alignment problem** for two strings $S$ and $T$ over alphabet $\Sigma$ and a given scoring matrix $s : \Sigma \times \Sigma \rightarrow \mathbb{R}$. Each gap of length $d$ should be scored using gap opening penalty $g$ and gap extension penalty $e$. 
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**Idea**

- Here: have different DP variables for solutions to subproblems depending on whether a gap in $S$ or $T$ has already been opened (and therefore only needs to be extended)
- In general: “Remember” properties of solution to subproblem by defining variants of DP variables.
### DP variables for affine gap penalties

**Definition (DP variables)**

Let

- $G(i, j) :=$ maximum score of any alignment of $S[1..i]$ and $T[1..j]$ that aligns $S[i]$ with $T[j]$  
- $E(i, j) :=$ maximum score of any alignment of $S[1..i]$ and $T[1..j]$ that ends with a gap in $S$  
- $F(i, j) :=$ maximum score of any alignment of $S[1..i]$ and $T[1..j]$ that ends with a gap in $T$  
- $V(i, j) :=$ maximum score of any alignment of $S[1..i]$ and $T[1..j]$
DP recursion for affine gap penalties

### DP recursion

<table>
<thead>
<tr>
<th>Expression</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V(i, j) )</td>
<td>( \max{ G(i, j), E(i, j), F(i, j) } )</td>
</tr>
<tr>
<td>( G(i, j) )</td>
<td>( V(i - 1, j - 1) + s(S[i], T[j]) )</td>
</tr>
<tr>
<td>( E(i, j) )</td>
<td>( \max{ E(i, j - 1), V(i, j - 1) - g } - e )</td>
</tr>
<tr>
<td>( F(i, j) )</td>
<td>( \max{ F(i - 1, j), V(i - 1, j) - g } - e )</td>
</tr>
</tbody>
</table>

**boundary cases:**

<table>
<thead>
<tr>
<th>Expression</th>
<th>Equation</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V(i, 0) )</td>
<td>( E(i, 0) = -g - ei )</td>
<td>( 1 \leq i \leq</td>
</tr>
<tr>
<td>( V(0, j) )</td>
<td>( F(0, j) = -g - ej )</td>
<td>( 1 \leq j \leq</td>
</tr>
<tr>
<td>( V(0, 0) )</td>
<td>( 0 )</td>
<td></td>
</tr>
</tbody>
</table>
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Global multiple alignment

Definition (global multiple alignment)

A global (multiple) alignment of $k$ strings $S = \{S_1, S_2, \ldots, S_k\}$ is an array $(S'_1, S'_2, \ldots, S'_k)$ of strings possibly including gap characters, such that

- all $S'_i$ have the same length $\ell$
- removing all gap characters from $S'_i$ yields $S_i$ for all $i$
- $(S_1[j], S_2[j], \cdots, S_k[j]) \neq (\text{--}, \text{--}, \cdots, \text{--})$ for all $1 \leq j \leq \ell$

Example

- NCDKLGWY-INS-ZQLP
  SHCDQ-GWY-LG--EQLZ
  -YCDKIGWY-IA--EQLP
  SHCDELGWYEIGLGLGKQLP
Multiple versus pairwise alignment in “twilight zone”

“...two homologous sequences wisper ... a full multiple alignment shouts out lout” (Arthur Lesk, 1996)
**Multiple versus pairwise alignment in “twilight zone”**

excerpt from a multiple alignment

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Alignment</th>
<th>Sequence</th>
<th>Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A8B7S5_GIALA/381-716</td>
<td>FPDMIPETDGS...KRFLKLINSAPSFICPGAYSD...IKTLGGLLOCFGGVQ...K...D...S...YRGQIHVLVGDGP</td>
<td>Q8S5SE5_ENCCU/304-622</td>
<td>PIDKIDEL.RKRP...DYVIELANSVAPSVC...MED...TKKALVLQLFGGVR...K...ELGS...SR...LRLGINILLAGDP</td>
</tr>
<tr>
<td>MCM4_DROME/447-772</td>
<td>RVEEQLL.AKRP...DIYDRLARAIAPSYE...NDD...IKKGLLQLQLFGGTK...K...KHAM...LFRQNFRESPHLLCQGDGP</td>
<td>Q95XQ8_CAEEL/404-730</td>
<td>RIQQIEL.SKRP...DIMDALQSIAPSYE...HDD...VKRGLLCLLQFGGTR...KDDETTN...KTK...LRLSEVINLLCGDGP</td>
</tr>
<tr>
<td>Q86IF1DICIDI/469-792</td>
<td>KREIIEIL.YKRP...DIYDIVTKSIAPNIE...LED...IKKGLQICLFQGSS...K...SYQDYGGK...FRQDGINILLGDGP</td>
<td>Q75SH5_NEURC/580-912</td>
<td>EEERIKET.AARP...DIYDLSRSIAPSYE...VDD...VKKGGQLQLQGGTN...K...TFE...GSS...K...FRQDGINILLGDGP</td>
</tr>
<tr>
<td>CDC54_YEAST/505-834</td>
<td>DLAKIREV.AARE...DIYDLRSARIAPSYE...LED...KKGLQQLQGGTN...K...TFTK...GGR...GR...LRLGINILLGDGP</td>
<td>MCM4_SCHPO/480-811</td>
<td>EVEKIQQV.SKRD...DIYDLRSLSIAPSYE...VDD...VKKGLLQLQGQGT...K...SFHK...GSPYRGRGINILLGDGP</td>
</tr>
<tr>
<td>MCM3_ENTHI/167-531</td>
<td>DKNIKKK.MKEE...NPNLFSKSIAPSYE...HSD...KKAKLLMLVGGAT...K...IRLR...SR...LRLGINHVLCGDGP</td>
<td>A8B7J1_GIALA/302-626</td>
<td>LATDLVSL.REKA...IPLHVLSFAPRPRIHG...RED...EKLACLCLS1VGGNE...I...VVPD...M...K...VRGNINTLFGDGP</td>
</tr>
<tr>
<td>Q9U1E0_LEIMA/317-646</td>
<td>QVDIRDY.PDRE...AVIELKTRSIAPYE...W...VKKALCLQLVGGSS...IAN...GIR...IRSDINIFMDGP</td>
<td>Q7RJM3_PLAYO/402-752</td>
<td>IMEEVQKL.KSSP...NYLRLAYNIGPEIY...HED...KKKLLQQLQGGCT...K...KKDD...GDL...IRGDHILLGDGP</td>
</tr>
<tr>
<td>PROL_ARATH/313-638</td>
<td>EEEOIARL.AE0...DIYKNSLSIAPSYE...HED...IKKALLQQLQGDAP...R...QLK...G...IRGDHNHCLMGDGP</td>
<td>CDC47_YEAST/397-725</td>
<td>VEERWME...TSG...DYVNRKLAIPEIY...NLD...VKKALLQQLQVGVD...K...RVGD...G...IRGDINVLMCGDGP</td>
</tr>
<tr>
<td>Q70QK1_ANOGA/318-640</td>
<td>TQEELDEL.AKRD...DFYTRIASSLPEIY...V...VKKALLQQLQVGVD...V...RSPD...G...IRGDINVLMCGDGP</td>
<td>016297_CAEEL/328-652</td>
<td>QSAEEVL.RKKG...DNYEETLASAPFHI...GHD...VKKALLQQLQVGVD...N...SSN...G...IRGDINVLMCGDGP</td>
</tr>
<tr>
<td>Q7YY63_CRYPV/268-626</td>
<td>SFRKFLIE...SOPH...NGNMLKAYVPVHYG...YSG...LKKGILQQLQGGVE...K...RTKD...N...IRGDINVCVGDGP</td>
<td>Q71DF0_PLAF7/423-751</td>
<td>DLKWLRID.AHMP...NIDILACIAPIKW...N...IKKGLAMQMTGGQ...K...ITSN...C...IRGDINMCVGDGP</td>
</tr>
<tr>
<td>Q8BLX7_GIALA/424-793</td>
<td>YREAVSNM...RNPD...NIVSNLVASFAPHIY...HET...VKGILQQLQGGGI...K...IRTE...EHL...IRSDINILLGDGP</td>
<td>MCM6_CAEEL/333-660</td>
<td>DRAILKMK...SDKK...KIEKIVDSLFPNIY...NHE...VKKGILMNLMLVAVKAK...SRDE...GTS...IRGDINVCVGDGP</td>
</tr>
<tr>
<td>MCM6_DROME/325-649</td>
<td>EWHKIIYM...SKDR...NLQYNLSLCLPFIY...NDE...VKKGILQOFQGGVA...K...TDE...KTS...IRGDINVCVGDGP</td>
<td>MCM6_RAT/19-343</td>
<td>EWEKVFEN...SQDQ...NLQYNLCLSLPFIY...NDE...VKKGILQOFQGGVP...K...TTE...GTS...IRGDINVCVGDGP</td>
</tr>
<tr>
<td>MCM6_DICIDI/407-731</td>
<td>EKDSLKKM...IKSK...KIQYQNYNNCSAPFIY...HEE...IKKGVQLMLLGQVHQ...K...KTPE...K...IRGDINVCVGDGP</td>
<td>MCM6_YEAST/512-836</td>
<td>EINLKG...VKA...HDY...KIQVYNSIAPAVFG...HEA...VKKGILQOMMGGH.V...STVE...GIK...IRGDINVCVGDGP</td>
</tr>
<tr>
<td>MCM6_SCHPO/413-737</td>
<td>EIDDLRAM...VHSD...HIYSLTSLAPSVY...HEI...IKKGVQLOMMGGVH...K...LTE...G...IRGDINVCVGDGP</td>
<td>Q8H1A3_PEA/330-654</td>
<td>ELDEVQRM...RNTP...DFFTKLVSEPVTIF....HOD...IKRAILMLMGGV.H...SST...G...IRGDINVCVGDGP</td>
</tr>
<tr>
<td>pairwise alignment</td>
<td>multiple alignment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------</td>
<td>--------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• two sequences are aligned</td>
<td>• more than two sequences are aligned</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• degree of sequence similarity is measured</td>
<td>• can also work with relatively low sequence similarity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• requires higher similarity for statistical significance</td>
<td>• often done with sequences that are known to be homologous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• often done to decide whether they are homologous</td>
<td>• to predict which residues share common ancestry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• used as a tool for database search</td>
<td>• to construct a phylogenetic tree</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• to detect residues that are particularly conserved through evolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• to infer which residues are important for function</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Local multiple alignment

Definition (local multiple alignment)

A local (multiple) alignment of $k$ strings $\{S_1, S_2, \ldots, S_k\}$ is a global alignment of substrings $\{s_1, s_2, \ldots, s_k\}$ ($s_i$ substring of $S_i$).
Local multiple alignment

Definition (local multiple alignment)

A local (multiple) alignment of \( k \) strings \( \{ S_1, S_2, \ldots, S_k \} \) is a global alignment of substrings \( \{ s_1, s_2, \ldots, s_k \} \) (\( s_i \) substring of \( S_i \)).

Example (protein domain Hexokinase_2 (PF03727))
Local multiple alignment

Definition (local multiple alignment)

A local (multiple) alignment of $k$ strings $\{S_1, S_2, \ldots, S_k\}$ is a global alignment of substrings $\{s_1, s_2, \ldots, s_k\}$ ($s_i$ substring of $S_i$).

Example (protein domain Hexokinase_2 (PF03727))

Pfam-seed alignment for PF03727

<table>
<thead>
<tr>
<th>Pfam ID</th>
<th>E-value</th>
<th>Accession</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P33284</td>
<td>224-472</td>
<td>QTKGIIITGVNGAYDVSQIEKLGLLLP..EDIGPDSPMAINCEYGFSDNHLVLPRTKYDVIDEESPRPGQOFEFKMTSGYGLGEIMRLVLDD</td>
<td></td>
</tr>
<tr>
<td>P50521</td>
<td>213-449</td>
<td>DFMGIIITGGTYVECMNQPKLACK...CTCDHLMINMEGWATDFSCHLHSTR...YDLLLHDTPNACQIFEKRYGGMYLGEFLRALFH</td>
<td></td>
</tr>
<tr>
<td>P35557</td>
<td>219-458</td>
<td>QCEGMIVGTTGACNYEMHQMVELVEG...DEGRNCNTWQAFDGSDELDFLLYDRLVESANSQPQLYELLPGKYMELVRLVLRR</td>
<td></td>
</tr>
<tr>
<td>P52789</td>
<td>223-462</td>
<td>NCEGLIVTGNCSACNMHEDVHMVEG...DEGRMCINWQAFDGGSLNDIRTEFDQEDIMGSLNPGKQLEFKMSQGMYELVRLVLK</td>
<td></td>
</tr>
<tr>
<td>P27595</td>
<td>223-462</td>
<td>HCEVLIGITGTNACMEELRQDFTGWG...DDGRCINTWQFDGGSLEDIKFEDFEDFRRGSLNPGQKRFEMVSQVYMEDVYRLVLK</td>
<td></td>
</tr>
<tr>
<td>P17709</td>
<td>243-500</td>
<td>EPVIGCGIFGTGNTGYCEINKITKLPQELRD handjob...KTHPIINIMYWYFSLNKLAPFIMFHELKVFFSVGMFMFLLGDVLNRNILVD</td>
<td></td>
</tr>
<tr>
<td>P50506</td>
<td>224-469</td>
<td>EAKGLFSGTGCGAYVDVNDKLPKLEGKV...DDIKSSSPAINCCEYGFSDNEHILPRKTYDIQIDEEERPRPGQAFEFKMSQGMYELVRLVID</td>
<td></td>
</tr>
<tr>
<td>P04807</td>
<td>225-473</td>
<td>ETKLGVIITGTGNYAYVGSDDIEKQNLS.DDIPSAPMAINCEYGFSDNEHVLPRKTYDIQIIDEESPRPGQQAFEFKMSQGMYELVRLVID</td>
<td></td>
</tr>
<tr>
<td>P27595</td>
<td>671-910</td>
<td>TCEVLIGTGCSACNEEMKVEMVEG...NQFQCNINQAGFNGCDDDIRTFDKVYDEEYSLNNGNQFENMISQGMYELVRLVID</td>
<td></td>
</tr>
<tr>
<td>Q9756</td>
<td>228-469</td>
<td>TGEYGIITGTGNCYEMEIEKFPSEIPLKHY...DFPENDNNIINCEYGFSDNEHVLPRKTYDIQIDDEESPRPGQQAFEFKMSQGMYELVRLVID</td>
<td></td>
</tr>
<tr>
<td>P04806</td>
<td>225-472</td>
<td>ETKLGVIITGTGNYAYVGSDDIEKQNLS.DDIPSAPMAINCEYGFSDNEHVLPRKTYDIQIDDEESPRPGQQAFEFKMSQGMYELVRLVID</td>
<td></td>
</tr>
<tr>
<td>P52789</td>
<td>236-475</td>
<td>PCEVLIGTITGTNCACMEEARHVAVLDEE...DGRVCVCSVWSOFSDDPLGAPVLTFDHTLDHS.LNPGAQDQFEKMSQGMYELVRLVLH</td>
<td></td>
</tr>
<tr>
<td>P52789</td>
<td>677-916</td>
<td>RCEVLIGTITGTNCACMEELRQDFTGWG...DSGRCINTWQFDGGSLEDIKFEDFEDFRRGSLNPGQKRFEMVSQVYMEDVYRLVLK</td>
<td></td>
</tr>
<tr>
<td>Q02155</td>
<td>259-485</td>
<td>PCYGIIILITGSGCQYPECWKKKYKYG...KIINGHGFSDK...DLPTPQIDLVMYANSDQRQFEMTSGYELVRLVID</td>
<td></td>
</tr>
<tr>
<td>P52789</td>
<td>671-910</td>
<td>HCEVLIGITGTGCSACNEEMKVEMVEG...EERFCVCSVWSODDDLLDFTEDFEDFEDFRRGSLNPGQKRFEMVSQVYMEDVYRLVLK</td>
<td></td>
</tr>
</tbody>
</table>
Example for local multiple alignment

**Example (protein domain Hexokinase_2 (PF03727))**

### Domain organisation

Below is a listing of the unique domain organisations or architectures in which this domain is found. [More...](#)  

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Example</th>
<th>Description</th>
<th>No. of Residues</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hexokinase_1, Hexokinase_2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HXK1_ARATH [Arabidopsis thaliana (Mouse-ear cress)]</td>
<td>Hexokinase-1 EC=2.7.1.1 (496 residues)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hexokinase_1, Hexokinase_2, Hexokinase_1, Hexokinase_2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HXK1_BOVIN [Bos taurus (Bovine)]</td>
<td>Hexokinase-1 EC=2.7.1.1 (918 residues)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hexokinase_1, Hexokinase_2, Hexokinase_1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q0CPV0 ASPTN [Aspergillus terreus (strain NIH 2624 / FGSC A1156)]</td>
<td>Putative uncharacterized protein (339 residues)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hexokinase_1, Hexokinase_2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2W6G6 PYRTR [Pyrenophora tritici-repentis (strain Pt-1C-BFP) (Wheat tan spot fungus) (Drechslera tritici-repentis)]</td>
<td>Glucokinase GLK1 (632 residues)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hexokinase_1 x 2, Hexokinase_2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q74996_YARLI [Yarrowia lipolytica (Candida lipolytica)]</td>
<td>Hexokinase (534 residues)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hexokinase_2, Hexokinase_1, Hexokinase_2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q53QX9_HUMAN [Homo sapiens (Human)]</td>
<td>Putative uncharacterized protein HK2 (Fragment) (573 residues)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hexokinase_1, Hexokinase_2, Hexokinase_1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Induced pairwise alignment

**Definition (induced pairwise alignment)**

Given a multiple alignment $\mathcal{M}$, the induced pairwise alignment of two strings $S_i$ and $S_j$ is obtained from $\mathcal{M}$ by removing all rows except the two rows for $S_i$ and $S_j$ and removing all columns that contain only gaps.
**Induced pairwise alignment**

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Given a multiple alignment $\mathcal{M}$, the induced pairwise alignment of two strings $S_i$ and $S_j$ is obtained from $\mathcal{M}$ by removing all rows except the two rows for $S_i$ and $S_j$ and removing all columns that contain only gaps.

**Example**

$\begin{align*}
S_1 & \quad -NCDKLGWY-INS-ZQLP \\
S_2 & \quad SHCDQ-GWY-LG--EQLZ \\
S_3 & \quad -YCDKIGWY-IA--EQLP \\
S_4 & \quad SHCDELGWEIGLGKQLP
\end{align*}$

induces the pairwise alignment

$\begin{align*}
S_1 & \quad NCDKLGWYINSZQLP \\
S_3 & \quad YCDKIGWYIA--EQLP
\end{align*}$

on $S_1$ and $S_3$. 
How to score a multiple alignment?

**Definition (sum-of-pairs score)**

The *sum-of-pairs* score of a multiple alignment $\mathcal{M}$ is the sum of the scores of all pairwise alignments induced by $\mathcal{M}$.

**Example**

*(chalk board)*
How to score a multiple alignment?

**Definition (sum-of-pairs score)**

The *sum-of-pairs* score of a multiple alignment \( \mathcal{M} \) is the sum of the scores of all pairwise alignments induced by \( \mathcal{M} \).

**Example**

*(chalk board)*

**Other scoring methods for multiple alignments**

- weighted sum-of-pairs score \( \sum_{i<j} w(i, j)d(S_i, S_j) \) with \( d(S_i, S_j) \) being the score of the induced pairwise alignment of \( S_i \) and \( S_j \) and \( w(i, j) \) being a weight reflecting evolutionary distance of \( S_i \) and \( S_j \)
- scoring along a phylogenetic tree
- (Steiner) consensus string
Generalize from pairwise alignments

- Consider a global multiple alignment problem of \( r=3 \) sequences \( S_1, S_2, \ldots, S_r \) using the sum-of-pairs score.
Brute Force DP-Algorithm for Multiple Alignment

Generalize from pairwise alignments

- Consider a global multiple alignment problem of $r=3$ sequences $S_1, S_2, \ldots, S_r$ using the sum-of-pairs score.
- Let $s(a, b, c) = s(a, b) + s(a, c) + s(b, c)$ be the score of an alignment column in which $a, b, c \in \Sigma \cup \{-\}$ are aligned with each other.
Brute Force DP-Algorithm for Multiple Alignment

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- The score of a multiple alignment \( A = (S'_1, S'_2, S'_3) \) of length \( \ell \) of three sequences \( S_1, S_2 \) and \( S_3 \) is then

\[
s(A) = \sum_{i=1}^{\ell} s(S'_1[i], S'_2[i], S'_3[i]).
\]
Brute Force DP-Algorithm for Multiple Alignment

Generalize from pairwise alignments

- Consider a global multiple alignment problem of \( r = 3 \) sequences \( S_1, S_2, \ldots, S_r \) using the sum-of-pairs score.
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  \[
  s(A) = \sum_{i=1}^{\ell} s(S'_1[i], S'_2[i], S'_3[i]).
  \]
- We want to find a multiple alignment with maximal score.
Brute Force DP-Algorithm for Multiple Alignment

Generalize from pairwise alignments

Idea: Same, same, but different.
### Brute Force DP-Algorithm for Multiple Alignment

#### Generalize from pairwise alignments

**Idea:** *Same, same, but different.*

Let

**Definition (DP variables)**

Let

\[ M(i, j, k) \] \[=\] maximal score of an alignment of \( S_1[1..i], S_2[1..j] \) and \( S_3[1..k] \)

for \( i = 1, \ldots, |S_1|, j = 1, \ldots, |S_2|, k = 1, \ldots, |S_3| \).
### Brute Force DP-Algorithm for Multiple Alignment

#### DP recursion for 3 sequences

$$M(i, j, k) = \max \begin{cases} 
M(i - 1, j - 1, k - 1) + s(S_1[i], S_2[j], S_3[k]) \\
M(i - 1, j - 1, k) + s(S_1[i], S_2[j], -) \\
M(i - 1, j, k - 1) + s(S_1[i], -, S_3[k]) \\
M(i, j - 1, k - 1) + s(-, S_2[j], S_3[k]) \\
M(i - 1, j, k) + s(S_1[i], -, -) \\
M(i, j, k - 1) + s(-, -, S_3[k]) \\
M(i, j - 1, k) + s(-, S_2[j], -) 
\end{cases}$$

for $i = 1, \ldots, |S_1|$, $j = 1, \ldots, |S_2|$, $k = 1, \ldots, |S_3|$.
Brute Force DP-Algorithm for Multiple Alignment

DP recursion for 3 sequences

\[
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M(i, j, k - 1) + s(-, -, S_3[k]) \\
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\end{cases}
\]

for \( i = 1, \ldots, |S_1|, j = 1, \ldots, |S_2|, k = 1, \ldots, |S_3| \).

The 7 arguments of “max” correspond to the 7 possibilities for the gap characters in the last column of an optimal alignment of \( S_1[1..i], S_2[1..j] \) and \( S_3[1..k] \).
Brute Force DP-Algorithm for Multiple Alignment

DP recursion for 3 sequences

\[
M(i, j, k) = \max \begin{cases} 
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M(i - 1, j, k) + s(S_1[i], S_2[j], -) \\
M(i - 1, j - 1, k) + s(\ - , \ - , S_3[k]) \\
M(i, j - 1, k - 1) + s(\ - , S_2[j], S_3[k]) \\
M(i, j, k - 1) + s(S_1[i], \ - , \ - ) \\
M(i, j - 1, k) + s(\ - , \ - , \ - ) \\
\end{cases}
\]

for \( i = 1, \ldots, |S_1|, j = 1, \ldots, |S_2|, k = 1, \ldots, |S_3| \).

The 7 arguments of “max” correspond to the 7 possibilities for the gap characters in the last column of an optimal alignment of \( S_1[1..i] \), \( S_2[1..j] \) and \( S_3[1..k] \).

Boundary cases for \( i = 0, j = 0 \) or \( k = 0 \) can also be found (exercise).
Brute Force DP-Algorithm for Multiple Alignment

**Algorithm sketch**

1. compute $M$ for boundary cases ($i = 0, j = 0$ or $k = 0$)
2. compute $M(i, j, k)$ for increasing $i, j, k$ using recursion
3. $M(|S_1|, |S_2|, |S_3|)$ is the score of the best alignment
4. backtrack
## Brute Force DP-Algorithm for Multiple Alignment

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### Time and space requirements

- running time: $O(|S_1| \cdot |S_2| \cdot |S_3|)$, “cubic” running time
Brute Force DP-Algorithm for Multiple Alignment

Algorithm sketch

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Time and space requirements

- running time: $O(|S_1| \cdot |S_2| \cdot |S_3|)$, “cubic” running time
- memory: $O(|S_1| \cdot |S_2| \cdot |S_3|)$
Brute Force DP-Algorithm for Multiple Alignment

**Generalization for** \( r > 3 \) **sequences**

Let \( n_1, n_2, \ldots, n_r \) be the lengths of \( r \) sequences that are to be aligned.

Further generalization like above possible.
Brute Force DP-Algorithm for Multiple Alignment

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Further generalization like above possible.

- Required running time and space with generalization: $O(n_1 \cdot n_2 \cdot \ldots \cdot n_r)$
Brute Force DP-Algorithm for Multiple Alignment

**Generalization for \( r > 3 \) sequences**

Let \( n_1, n_2, \ldots, n_r \) be the lengths of \( r \) sequences that are to be aligned.

Further generalization like above possible.

- Required running time and space with generalization: \( O(n_1 \cdot n_2 \cdot \ldots \cdot n_r) \)
- Not feasible with typical problem sizes: \( n_i, r \) a few hundreds each
Progressive Alignment Heuristic

**Idea**

- find a multiple alignment using a *stepwise* heuristic
Progressive Alignment Heuristic

**Idea**

- find a multiple alignment using a **stepwise** heuristic
- do at most $r$ steps, each step relatively simple (polynomial time)
Progressive Alignment Heuristic

Idea

- find a multiple alignment using a stepwise heuristic
- do at most \( r \) steps, each step relatively simple (polynomial time)
- from small to big: start by aligning only some sequences to each other
Progressive Alignment Heuristic

Idea

- find a multiple alignment using a stepwise heuristic
- do at most $r$ steps, each step relatively simple (polynomial time)
- from small to big: start by aligning only some sequences to each other
- progressively add more sequences to alignments
### Idea

- find a multiple alignment using a **stepwise** heuristic
- do at most $r$ steps, each step relatively simple (polynomial time)
- from small to big: start by aligning only some sequences to each other
- progressively add more sequences to alignments
- until all sequences are aligned
Sequence Profile

Definition (Profile)

Let \( A = (S'_1, \ldots, S'_k) \) be a multiple alignment of strings \( S_1, \ldots, S_k \) over an alphabet \( \Sigma \) of length \( \ell \).

A profile (also sequence profile, weight matrix) for \( A \) specifies for each column \( i \) of \( A \) the frequency of the characters in that column (a probability distribution over \( \Sigma \cup \{-\} \)):

\[
p(y, i) \quad (1 \leq i \leq \ell, y \in \Sigma \cup \{-\})
\]
**Sequence Profile**

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$$p(y, i) \quad (1 \leq i \leq \ell, y \in \Sigma \cup \{-\})$$

**Example (profile)**

<table>
<thead>
<tr>
<th></th>
<th>T</th>
<th>A</th>
<th>C</th>
<th>-</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>G</td>
<td>C</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>G</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>T</td>
<td>-</td>
<td>-</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td>T</td>
<td></td>
</tr>
</tbody>
</table>

$p$:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0.2</td>
<td>0.6</td>
<td>0.6</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>0.2</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Aligning a Sequence against a Profile

Definition

Score for aligning a character to a profile position

Let \( s(x, y) \) denote the score for aligning two characters (or gaps) \( x \) and \( y \). The score for aligning a character \( x \) to position \( j \) of profile \( p \) is defined as

\[
S(x, j) := \sum_{y \in \Sigma \cup \{-\}} s(x, y)p(y, j).
\]
Aligning a Sequence against a Profile

Definition

Score for aligning a character to a profile position Let $s(x, y)$ denote the score for aligning two characters (or gaps) $x$ and $y$. The score for aligning a character $x$ to position $j$ of profile $p$ is defined as

$$S(x, j) := \sum_{y \in \Sigma \cup \{-\}} s(x, y)p(y, j).$$

- $S(x, j)$ can be interpreted as the average score of $x$ with a random character of the $j$th profile position.
- The score of a sequence-to-profile alignment is the sum of the scores of the columns.
Aligning a Sequence against a Profile

Example (Sequence-Profile Alignment)

Consider the scoring scheme

\[
s(x, y) = \begin{cases} 
2 , & \text{if } x = y \neq - \\
-2 , & \text{if } (x = - \text{ and } y \neq -) \text{ or } (y = - \text{ and } x \neq -) \\
0 , & \text{if } x = y = - \\
-1 , & \text{otherwise.}
\end{cases}
\]

We set \( s(-, -) = 0 \) in order to generalize for profiles.
Aligning a Sequence against a Profile

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\end{cases}
\]

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An alignment between the sequence \( T = \text{ATACT} \) and profile \( p \):

<table>
<thead>
<tr>
<th>( p )</th>
<th>-</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>A</td>
<td>T</td>
<td>A</td>
<td>-</td>
<td>C</td>
<td>T</td>
</tr>
<tr>
<td>score</td>
<td>-1</td>
<td>1.4</td>
<td>0</td>
<td>-0.8</td>
<td>0.8</td>
<td>1.4</td>
</tr>
</tbody>
</table>

This alignment has total score 1.8.
Aligning a Sequence against a Profile

### DP variables

Let

\[ V(i, j) := \text{value of an optimal alignment of substring } T[1..i] \text{ with the first } j \text{ columns of } p \]
Aligning a Sequence against a Profile

DP variables

Let

\[ V(i, j) := \text{value of an optimal alignment of substring } T[1..i] \text{ with the first } j \text{ columns of } p \]

DP recursion

\[ V(i, j) = \max \begin{cases} 
V(i - 1, j - 1) + S(T[i], j) \\
V(i - 1, j) + s(T[i], -) \\
V(i, j - 1) + S(-, j) 
\end{cases} \]
Aligning a Sequence against a Profile

**DP variables**

Let

\[ V(i, j) := \text{value of an optimal alignment of substring } T[1..i] \text{ with the first } j \text{ columns of } p \]

**DP recursion**

\[ V(i, j) = \max \left\{ V(i - 1, j - 1) + S(T[i], j), V(i - 1, j) + s(T[i], -), V(i, j - 1) + S(-, j) \right\} \]

**Sequence-profile alignment...**

... can be done using DP in time and space \( O(mn) \) if \( m \) and \( n \) are the length of the sequence and profile, respectively (details very similar to Needleman-Wunsch)
Aligning a Profile against a Profile

Profile-Profile Alignment

- Using a straightforward generalization we can define alignments between two profiles and their score.
Aligning a Profile against a Profile

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- Gaps can be inserted in both profiles.
Aligning a Profile against a Profile

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- Scores are again defined as averages

\[ S(i, j) = \sum_{x,y} s(x, y)p_1(x, i)p_2(y, j). \]
Aligning a Profile against a Profile

**Profile-Profile Alignment**

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- This problem will be used as subtask for progressive multiple alignment.
Aligning a Profile against a Profile

Profile-Profile Alignment

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- Gaps can be inserted in both profiles.
- Scores are again defined as averages
  \[ S(i, j) = \sum_{x, y} s(x, y) p_1(x, i) p_2(y, j). \]
- This problem will be used as subtask for progressive multiple alignment.
- An alignment between two profiles (or between a profile and a sequence) representing alignments of sequences in disjoint sets \( M \) and \( N \) naturally defines a multiple alignment of all sequences in \( M \cup N \).

(chalk board)
Progressive Alignment Heuristic

Guide tree

- a binary tree $G$ with the sequences $S_1, \ldots, S_k$ as leaves
- determines the order of pairwise alignment steps
- an internal node $u$ represents an alignment of all leaves in the subtree rooted at $u$
- if $v$ and $w$ are children of $u$ then to get the alignment associated with $u$ we align the profiles or sequences associated with $v$ and $w$
- makes the progressive alignment method generic: methods differ in how the guide tree is constructed
Progressive Alignment Heuristic

Example

```
WCEAQTKnQGWVPSNYITPvN
WWRLNDKEGyVPRNLLGLYP
AVVIQDNSDIKVVPKAKIIRD
YAVESEAHPGSFQPVAALERIN
WLNYNETTGERGDFPGTYVEYIGRKKISP
```
Progressive Alignment Heuristic

Example

```
WCEAQTKNGQGWVPSNYITPVN
WW--RLNDKEGYVPRNLLGLYP--AVVIQDNSDIKVVP--KAKIIRD
YAVESEASFQPVAALERIN
WLNYNEERGDFPGTYVEYIGRKKISP
⇒ first align 2nd and 3rd sequence
```
Progressive Alignment Heuristic

Example

WCEAQT KNGQGWVPSNYITPVN

WW--RLNDKEGYVPRNLLGLYP--AVVIQDNSDIKVVP--KAKIIRD

YAVESEAVQ--PVAALERIN--------WLN--YNEERGDFPGTYVEYIGRKKISP

⇒ then 4th and 5th
Progressive Alignment Heuristic

Example

\[
\begin{align*}
WCEAQTKNGQGWVPSNYITPVN- \\
WW--RLNDKEGYVPRNLLGLYP- \\
AVVIQDNSDIKVVP--KAKIIRD
\end{align*}
\]

\[
\begin{align*}
YAVESEASVQ--PVAALERIN------
WLN-YNEERGDFPGTYVEYIGRKKISP
\end{align*}
\]

⇒ then the 1st to the profile of the alignment of \{2, 3\}
Progressive Alignment Heuristic

Example

```
WCEAQT KNGQ GWVPSNYITPVN----------
WW--R LNDKEGYVPRN LLGLYP----------
AVV IQDNSDIKV V P--KAKIIRD--------
YA VESEA----SVQ--PVAALERIN--------
WL N--YNE---ERGDFPGTYVEYIGRKKISP
```

⇒ Lastly, the two profiles of alignments of \{1, 2, 3\} and \{4, 5\}
Progressive Alignment Heuristic

Algorithm complexity

Let $k$ be the number of sequences and let $n$ be the maximal length of any sequence.
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Let $k$ be the number of sequences and let $n$ be the maximal length of any sequence. In each pairwise alignment step we require time and space $O(n^2)$. 

**Progressive Alignment Heuristic**
Progressive Alignment Heuristic

Algorithm complexity

Let \( k \) be the number of sequences and let \( n \) be the maximal length of any sequence.  
In each pairwise alignment step we require time and space \( O(n^2) \).
There are \( k - 1 \) inner vertices in a binary tree with \( k \) vertices.
**Progressive Alignment Heuristic**

### Algorithm complexity

Let \( k \) be the number of sequences and let \( n \) be the maximal length of any sequence. In each pairwise alignment step we require time and space \( O(n^2) \).

There are \( k - 1 \) inner vertices in a binary tree with \( k \) vertices. Therefore, the overall requirements are:

\[
\text{time} = O(kn^2) \\
\text{space} = O(n^2 + kn) \quad \text{(reuse space for DP matrix, input size = } O(kn)\text{)}
\]
Problem of Progressive Alignments

“Once a gap – always a gap”

- Problem of greedy heuristic: false decisions are not taken back later
- Gap characters that are introduced will never disappear no matter what the evidence is.
- (chalk board)
Alignment using the fast Fourier transform

omitted