

Data-analysis and Retrieval

Case study k-grams:

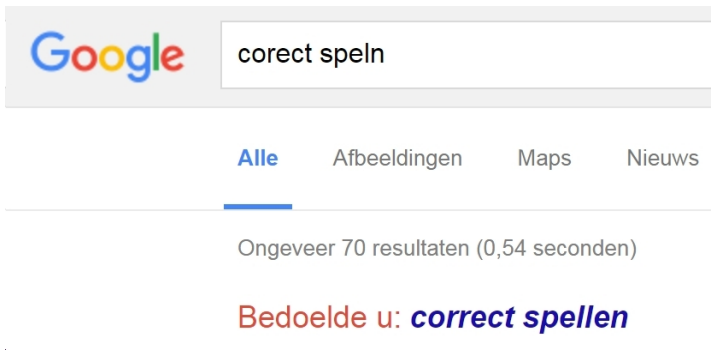
Biological sequence alignment

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Text search

- So far, we considered exact text search ...
- ... supported by indexing techniques ...
- ... and possibly with wildcards
- But (almost) everyone knows this phenomenon:



Approximate string matching

- Application: automatic spelling correction
- Can be solved using dynamic programming techniques
- But in large scale applications, this may be computationally (too) heavy
- Heuristic indexing techniques based on k-grams
- Application: biological sequence alignment

	AGU1	left	chr_3	RP1818	AGU2	left	chr_3	AGU3	left	chr_3	AGU4	left	chr_3	AGU5	left	chr_3	AGU6	left	chr_3	AGU7	left	chr_3	AGU8	left	chr_3	AGU9	left	chr_3	AGU10	left	chr_3	AGU11	left	chr_3	AGU12	left	chr_3	AGU13	left	chr_3	AGU14	left	chr_3	AGU15	left	chr_3	AGU16	left	chr_3	AGU17	left	chr_3	AGU18	left	chr_3	AGU19	left	chr_3	AGU20	left	chr_3	AGU21	left	chr_3	AGU22	left	chr_3	AGU23	left	chr_3	AGU24	left	chr_3	AGU25	left	chr_3	AGU26	left	chr_3	AGU27	left	chr_3	AGU28	left	chr_3	AGU29	left	chr_3	AGU30	left	chr_3	AGU31	left	chr_3	AGU32	left	chr_3	AGU33	left	chr_3	AGU34	left	chr_3	AGU35	left	chr_3	AGU36	left	chr_3	AGU37	left	chr_3	AGU38	left	chr_3	AGU39	left	chr_3	AGU40	left	chr_3	AGU41	left	chr_3	AGU42	left	chr_3	AGU43	left	chr_3	AGU44	left	chr_3	AGU45	left	chr_3	AGU46	left	chr_3	AGU47	left	chr_3	AGU48	left	chr_3	AGU49	left	chr_3	AGU50	left	chr_3	AGU51	left	chr_3	AGU52	left	chr_3	AGU53	left	chr_3	AGU54	left	chr_3	AGU55	left	chr_3	AGU56	left	chr_3	AGU57	left	chr_3	AGU58	left	chr_3	AGU59	left	chr_3	AGU60	left	chr_3	AGU61	left	chr_3	AGU62	left	chr_3	AGU63	left	chr_3	AGU64	left	chr_3	AGU65	left	chr_3	AGU66	left	chr_3	AGU67	left	chr_3	AGU68	left	chr_3	AGU69	left	chr_3	AGU70	left	chr_3	AGU71	left	chr_3	AGU72	left	chr_3	AGU73	left	chr_3	AGU74	left	chr_3	AGU75	left	chr_3	AGU76	left	chr_3	AGU77	left	chr_3	AGU78	left	chr_3	AGU79	left	chr_3	AGU80	left	chr_3	AGU81	left	chr_3	AGU82	left	chr_3	AGU83	left	chr_3	AGU84	left	chr_3	AGU85	left	chr_3	AGU86	left	chr_3	AGU87	left	chr_3	AGU88	left	chr_3	AGU89	left	chr_3	AGU90	left	chr_3	AGU91	left	chr_3	AGU92	left	chr_3	AGU93	left	chr_3	AGU94	left	chr_3	AGU95	left	chr_3	AGU96	left	chr_3	AGU97	left	chr_3	AGU98	left	chr_3	AGU99	left	chr_3	AGU100	left	chr_3	AGU101	left	chr_3	AGU102	left	chr_3	AGU103	left	chr_3	AGU104	left	chr_3	AGU105	left	chr_3	AGU106	left	chr_3	AGU107	left	chr_3	AGU108	left	chr_3	AGU109	left	chr_3	AGU110	left	chr_3	AGU111	left	chr_3	AGU112	left	chr_3	AGU113	left	chr_3	AGU114	left	chr_3	AGU115	left	chr_3	AGU116	left	chr_3	AGU117	left	chr_3	AGU118	left	chr_3	AGU119	left	chr_3	AGU120	left	chr_3	AGU121	left	chr_3	AGU122	left	chr_3	AGU123	left	chr_3	AGU124	left	chr_3	AGU125	left	chr_3	AGU126	left	chr_3	AGU127	left	chr_3	AGU128	left	chr_3	AGU129	left	chr_3	AGU130	left	chr_3	AGU131	left	chr_3	AGU132	left	chr_3	AGU133	left	chr_3	AGU134	left	chr_3	AGU135	left	chr_3	AGU136	left	chr_3	AGU137	left	chr_3	AGU138	left	chr_3	AGU139	left	chr_3	AGU140	left	chr_3	AGU141	left	chr_3	AGU142	left	chr_3	AGU143	left	chr_3	AGU144	left	chr_3	AGU145	left	chr_3	AGU146	left	chr_3	AGU147	left	chr_3	AGU148	left	chr_3	AGU149	left	chr_3	AGU150	left	chr_3	AGU151	left	chr_3	AGU152	left	chr_3	AGU153	left	chr_3	AGU154	left	chr_3	AGU155	left	chr_3	AGU156	left	chr_3	AGU157	left	chr_3	AGU158	left	chr_3	AGU159	left	chr_3	AGU160	left	chr_3	AGU161	left	chr_3	AGU162	left	chr_3	AGU163	left	chr_3	AGU164	left	chr_3	AGU165	left	chr_3	AGU166	left	chr_3	AGU167	left	chr_3	AGU168	left	chr_3	AGU169	left	chr_3	AGU170	left	chr_3	AGU171	left	chr_3	AGU172	left	chr_3	AGU173	left	chr_3	AGU174	left	chr_3	
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Sequence alignment: searching for homologies

How Genetically Related Are We to Bananas?

Share



https://www.pfizer.com/news/articles/how_genetically_related_are_we_to_bananas

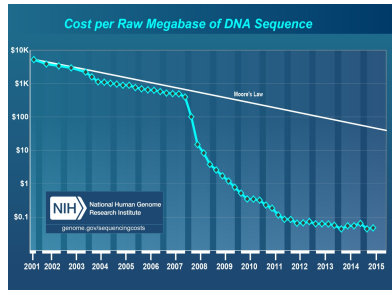
Sequence alignment: searching for homologies

Queries in context:

- *We have a number of patients with disease X. Can we find a sequence that is common in their genomes and that is different from corresponding sequences in genomes of non-patients?*
- *We have a new virus that has a lot properties in common with some known viruses. Can we find the differences in genetic properties? Can these differences be the result of a plausible sequence of spontaneous mutations, or is it likely to be engineered?*

DNA sequencing: milestones

- 1953 Crick & Watson discover the molecular structure of DNA (double helix)
- 1977 Sanger pioneers with sequencing techniques
- 2000-2003 human genome sequenced
- 2008-2015 dramatic decrease of sequencing cost
- Currently: e.g. individual DNA analysis

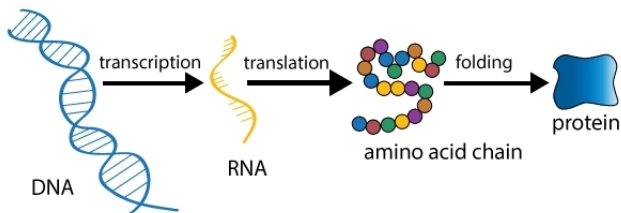


Some genetics

- The Model: a DNA sequence is a string over the alphabet $\{A,C,G,T\}$
- Each of the letters represents a *base*, in the chemical sense
- A = adenine, G = guanine, C = cytosine and T = thymine
- T in DNA corresponds to U (uracil) in RNA
- A gene is a part of the genome that codes for a specific protein
- The length of a gene varies from a few hundreds to several thousands characters
- Example: ATGGGCGTGATCAAGCCCGACATGAAGATC...
- Background reading: *Altman, Computer Applications in Molecular Biology*

Some genetics

- Gene expression: a part of the genome is copied as messenger-RNA (transcription)
- The ribosome translates the mRNA code into a protein



Genetics: protein coding

- A protein is represented by a sequence of amino acids. On earth, 20 different amino acids are known. Each of the amino acids is identified by a unique letter.
- A codon is a triplet of base characters. There are $4^3 = 64$ different codons
- Each codon determines an amino acid. Most amino acids are represented by more than codon
- A DNA/RNA string that encodes a protein is can be seen as a sequence of codons, for instance ATGACCAGGATCTTTAAGTGA ...
- ... can be read as ATG-ACC-AGG-ATC-TTT-AAG-TGA

Reference: https://en.wikipedia.org/wiki/Genetic_code

- A DNA/RNA string that encodes a protein is can be seen as a sequence of codons, for instance
ATG-ACC-AGG-ATC-TTT-AAG-TGA
- ATG is start codon; TGA is stop codon
- translated to amino acids: methionine-threonine-arginine...
- encoded to string representing amino acids: MTR...

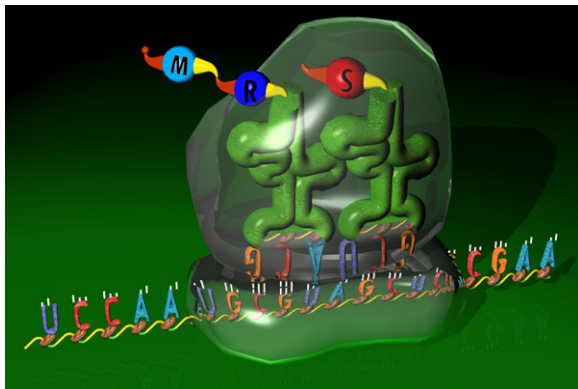
Reference: https://en.wikipedia.org/wiki/DNA_codon_table

Genetics: the codon table

		Second letter				
		U	C	A	G	
First letter	U	UUU } Phe UUC } UUA } Leu UUG }	UCU } UCC } Ser UCA } UCG }	UAU } Tyr UAC } UAA Stop UAG Stop	UGU } Cys UGC } UGA Stop UGG Trp	U C A G
	C	CUU } CUC } Leu CUA } CUG }	CCU } CCC } Pro CCA } CCG }	CAU } His CAC } CAA } Gln CAG }	CGU } CGC } Arg CGA } CGG }	U C A G
	A	AUU } AUC } Ile AUA } AUG Met	ACU } ACC } Thr ACA } ACG }	AAU } Asn AAC } AAA } Lys AAG }	AGU } Ser AGC } AGA } Arg AGG }	U C A G
	G	GUU } GUC } Val GUA } GUG }	GCU } GCC } Ala GCA } GCG }	GAU } Asp GAC } GAA } Glu GAG }	GGU } GGC } Gly GGA } GGG }	U C A G

Some genetics

- The ribosome translates the mRNA triplet code into a protein



- SWISSPROT, GENBANK
- Contain both protein sequences and base sequences
- Generic query:
Find protein sequences similar to
MKYMTVTDLNNAGATV...

Biological sequence databases

SWISSPROT example entries (FASTA format):

```
>gi|1171675|sp|P42268|NDD_BPR70 NUCLEAR DISRUPTION PROTEIN
MKYMTVTDLNNAGATVIGTIKGGEWFLGTPHKDILSKPGFYFLVSEFDGSCV
SARFYVGNQRSKQGFSAVLSHIRQRSQLARTIANNNMAYTVFYLPASKMKP
LTTGFGKGQLALAFTRNHHSEYQTLEEMNRMLADNFKFVLQAY
```

```
>gi|123527|sp|P05228|HRP2_PLAFA HISTIDINE-RICH PROTEIN PRECURSOR
(CLONE PFHRP-III)
MVSFSKNKVLAAVFASVLLLDNNNSEFNNNLFSKNAKGLNSNKRL LHESQA
HAGDAHHAHHVADAHHAHHVADAHHAHHAANAHHAANAHHAANAHHAANAHH
AANAHHAANAHHAANAHHAANAHHAANAHHAANAHHAANAHHAANAHHAANA
HHAADANHG FHFNLHDNNSHTLHHA KANACFDDSHHDDAHHDGAHHDDAHHD
GAHHDDAHHDGAHHDDGAHHDDGAHHNATTHHLHMKYMTVTDLNNAGATV
```

Protein based sequence similarity

- Two DNA fragments are *homologous* if they show similarities based on common descent
- Below left, we see two homologous fragments. Not only do we have eight matching letters, also the S-N, Q-K and G-A pairings are likely (+) due to electrochemical properties of the amino acids
- We are looking for a formal notion of *sequence similarity* that comprises *letter distance* and *gapping*

seq1:	GSAQVKGHGKKVA	seq3:	HV---D--DMPNAL
mtch:	G+ +VK+HGKKV	mtch:	++ +L
seq2:	GNPKVKAHGKKVL	seq4:	QLQVTGVVVTDATL

- There exists a classic solution for approximate string matching based on dynamic programming and edit distance
- We will refine this approach according to the specific properties of this domain, especially the letter distance
- Analysis of collections of protein strings provides us with probabilities of letters, when picking them randomly
- Analysis of collections of protein strings that represent known homologies provides us with probabilities of letter pairings

Reference: http://en.wikipedia.org/wiki/Edit_distance

- Each string x consists of a list of symbols x_i
- Symbol a has probability q_a , based on relative frequency
- A pair of symbols a, b has combined probability p_{ab} under the Match assumption, expressing the probability to be seen together in case of homology

- According to the *Random Model* R , the probability to observe x and y is

$$P(x, y|R) = \prod_i q_{x_i} \prod_i q_{y_i}$$

- According to the *Match Model* M , the probability to observe x and y is related to the probability of the pairings

$$P(x, y|M) = \prod_i p_{x_i y_i}$$

- The *odds-ratio*

$$\frac{P(x, y|M)}{P(x, y|R)} = \prod_i \frac{p_{x_i y_i}}{q_{x_i} q_{y_i}}$$

is an indicator for homology

- For mathematical reasons, we prefer to do our calculations in log-space

Scoring model: log space

- The *odds-ratio*

$$\frac{P(x, y|M)}{P(x, y|R)} = \prod_i \frac{p_{x_i y_i}}{q_{x_i} q_{y_i}}$$

- The *log-odds ratio* for character pairs

$$s(a, b) = \log\left(\frac{p_{ab}}{q_a q_b}\right)$$

- The *log-odds ratio* for strings x and y

$$S(x, y) = \sum_i s(x_i, y_i)$$

Scoring model: Blocks Substitution Matrix (BLOSUM)

- BLOSUM matrices represent log-odds ratios
- Several variants, for instance:
 - BLOSUM80: used for strongly related proteins
 - BLOSUM62: midrange
 - BLOSUM45: distantly related proteins
- Below you see a part of the BLOSUM50 matrix
- D, E and K charged; V, I and L hydrophobe

	D	E	K	V	I	L
D	8	2	-1	-4	-4	-4
E	2	6	1	-3	-4	-3
K	-1	1	6	-3	-3	-3
V	-4	-3	-3	5	4	1
I	-4	-4	-3	4	5	2
L	-4	-3	-3	1	2	5

Reference: <https://en.wikipedia.org/wiki/BLOSUM>

Scoring model: gaps

seq1:	GSAQVKGHGKKVA		seq3:	HV---D--DMPNAL
mtch:	G+ +VK+HGKKV		mtch:	++ +L
seq2:	GNPKVKAHGKKVL		seq4:	QLQVTGVVVTDATL

- We give a penalty for gaps with length g

$$\gamma(d) = -gd$$

- Based on empirical tuning, $d = 8$ is often suggested

Intermezzo: example alignments

Using BLOSUM50 and $\gamma(d) = -gd$, $d = 8$, calculate the scores for the following alignments:

seq1:	GSAQVKGHGKKVA	seq3:	HV---D--DMPNAL
mtch:	G+ +VK+HGKKV	mtch:	++ +L
seq2:	GNPKVKAHGKKVL	seq4:	QLQVTGVVVTDATL

Intermezzo: example alignments

Using BLOSUM50 and $\gamma(d) = -gd$, $d = 8$, calculate the scores for the following alignments:

seq1: GSAQVKGHGKKVA
mtch: G+ +VK+HGKKV
seq2: GNPKVKAHGKKVL

$$8+1-1+2+5+6+0+10+8+6+6+5-2 \\ = 54$$

seq3: HV---D--DMPNAL
mtch: ++ +L
seq4: QLQVTGVVVTDATL

$$1+1-24-1-16-4-1-1-1+0+5 \\ = -41$$

Alignment algorithms

- Gapping enlarges the search space dramatically
- But, we can apply *dynamic programming*
- The optimal alignment between strings $x = x_1 \dots x_m$ and $y = y_1 \dots y_n$ can be expressed in the optimal alignments of subsequences of x and y

Alignment algorithms: Needleman-Wunsch

- Suppose we know optimal alignments for
 - $x_1 \dots x_{m-1}$ and $y_1 \dots y_{n-1}$
 - $x_1 \dots x_m$ and $y_1 \dots y_{n-1}$
 - $x_1 \dots x_{m-1}$ and $y_1 \dots y_n$
- The optimal alignment for $x_1 \dots x_m$ and $y_1 \dots y_n$ can be determined by choosing the best option from:
 - solution for $x_1 \dots x_{m-1}$ and $y_1 \dots y_{n-1}$;
pair x_m with y_n
 - solution for $x_1 \dots x_{m-1}$ and $y_1 \dots y_n$;
pair x_m with gap
 - solution for $x_1 \dots x_m$ and $y_1 \dots y_{n-1}$;
pair y_n with gap

- Now we can fill the dynamic programming matrix from upper left to bottom right
- The score F for entry i, j can be calculated as follows:

$$F(i, j) = \max \begin{cases} F(i-1, j) - d \\ F(i, j-1) - d \\ F(i-1, j-1) + s(x_i, y_j) \end{cases}$$

- Arrows indicate which of the three options was chosen for the calculation of $F(i, j)$

Needleman-Wunsch: example

Align HEAGAWGHEE with PAWHEAE

$$\gamma(d) = -gd, d = 8$$

Initialized matrix:

	-	H	E	A	...
-	0	← -8	← -16	← -24	
P	↑ -8				
A	↑ -16				
W	↑ -24				
...					

Needleman-Wunsch: example

Align HEAGAWGHEE with PAWHEAE

$$\gamma(d) = -gd, d = 8$$

One step:

	-	H	E	A	...
-	0	← -8	← -16	← -24	
P	↑ -8	↖ -2			
A	↑ -16				
W	↑ -24				
...					

Needleman-Wunsch: example

Align HEAGAWGHEE with PAWHEAE

$$\gamma(d) = -gd, d = 8$$

Two more steps:

	-	H	E	A	...
-	0	← -8	← -16	← -24	
P	↑ -8	↖ -2	↖ -9		
A	↑ -16	↑ -10			
W	↑ -24				
...					

Needleman-Wunsch: example

Align HEAGAWGHEE with PAWHEAE

$$\gamma(d) = -gd, d = 8$$

Six more steps:

	-	H	E	A	...
-	0	← -8	← -16	← -24	
P	↑ -8	↖ -2	↖ -9	↖ -17	
A	↑ -16	↑ -10	↖ -3	↖ -4	
W	↑ -24	↑ -18	↑ -11	↖ -6	
...					

Needleman-Wunsch: example

Align HEAGAWGHEE with PAWHEAE
default is ↖

$$\gamma(d) = -gd, d = 8$$

	-	H	E	A	G	A	W	G	H	E	E
-	0	< -8	< -16	< -24	< -32	< -40	< -48	< -56	< -64	< -72	< -80
P	↑ -8	-2	-9	-17	< -25	-33	< -42	< -49	< -57	-65	-73
A	↑ -16	↑ -10	-3	-4	< -12	-20	< -28	< -36	< -44	< -52	< -60
W	↑ -24	↑ -18	↑ -11	-6	-7	-15	-5	< -13	< -21	< -29	< -37
H	↑ -32	-14	-18	-13	-8	-9	↑ -13	-7	-3	< -11	< -19
E	↑ -40	↑ -22	-8	< -16	↑ -16	-9	-12	↑ -15	-7	3	-5
A	↑ -48	↑ -30	↑ -16	-3	< -11	-11	-12	-12	↑ -15	↑ -5	2
E	↑ -56	↑ -38	↑ -24	↑ -11	-6	-12	-14	-15	-12	-9	1

Needleman-Wunsch: example

- Alignment is finished when lower right field is reached
- This field contains the alignment score: +1
- Time complexity is $O(mn)$
- Backward arrows indicate the **alignment path**
- Corresponding alignment ?

Needleman-Wunsch: example

- Alignment is finished when lower right field is reached
- This field contains the alignment score: +1
- Time complexity is $O(mn)$
- Backward arrows indicate the alignment path
- Corresponding alignment:

seq1: HEAGAWGHE-E

seq2: --P-AW-HEAE

Global versus local alignment

- Global alignment: score = +1:

seq1: HEAGAWGHE-E

seq2: --P-AW-HEAE

- Local alignment: score = +21:

seq1: HEA

seq2: HEA

- Local matches are much more interesting, especially when comparing a relatively short query string to a long database string

Local alignment: Smith-Waterman

- Question: How do you adapt Needleman-Wunsch to find local matches?
- Remember: the score F according to N-W for entry i, j can be calculated as follows:

$$F(i, j) = \max \begin{cases} F(i-1, j) - d \\ F(i, j-1) - d \\ F(i-1, j-1) + s(x_i, y_j) \end{cases}$$

Local alignment: Smith-Waterman

- Question: How do you adapt Needleman-Wunsch to find local matches?
- Make it possible to start anywhere in the matrix from scratch, i.e. with score = 0
- Make it possible to stop anywhere in the matrix
- The score F for entry i, j can be calculated as follows:

$$F(i, j) = \max \begin{cases} 0, & (\text{start new alignment}) \\ F(i-1, j) - d \\ F(i, j-1) - d \\ F(i-1, j-1) + s(x_i, y_j) \end{cases}$$

Smith-Waterman: example

Align HEAGAWGHEE with PAWHEAE

$$\gamma(d) = -gd, d = 8$$

A less exciting start:

	-	H	E	A	...
-	0	0	0	0	
P	0	0	0	0	
A	0	0	0		
W	0	0			

Smith-Waterman: example

Align HEAGAWGHEE with PAWHEAE

$$\gamma(d) = -gd, d = 8$$

	-	H	E	A	...
-	0	0	0	0	
P	0	0	0	0	
A	0	0	0	5	
W	0	0	0	0	

Smith-Waterman: example

Align HEAGAWGHEE with PAWHEAE

$$\gamma(d) = -gd, d = 8$$

default is ↖; backpointer irrelevant for zero fields

	-	H	E	A	G	A	W	G	H	E	E
-	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0
A	0	0	0	5	0	5	0	0	0	0	0
W	0	0	0	0	2	0	20	< 12	< 4	0	0
H	0	10	< 2	0	0	0	↑ 12	18	22	< 14	< 6
E	0	↑ 2	16	< 8	0	0	↑ 4	↑ 10	18	28	20
A	0	0	↑ 8	21	< 13	5	0	4	↑ 10	↑ 20	27
E	0	0	6	↑ 13	18	12	< 4	0	4	16	26

Alignment = ?

Smith-Waterman: example

Align HEAGAWGHEE with PAWHEAE

	-	H	E	A	G	A	W	G	H	E	E
-	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0
A	0	0	0	5	0	5	0	0	0	0	0
W	0	0	0	0	2	0	20	< 12	< 4	0	0
H	0	10	< 2	0	0	0	↑ 12	18	22	< 14	< 6
E	0	↑ 2	16	< 8	0	0	↑ 4	↑ 10	18	28	20
A	0	0	↑ 8	21	< 13	5	0	4	↑ 10	↑ 20	27
E	0	0	6	↑ 13	18	12	< 4	0	4	16	26

Alignment: seq1: AWGHE
seq2: AW-HE

- Complexity of dynamic programming algorithms is $O(mn)$, where m = length of query string and n = length of database
- Unsatisfying for large databases, heuristic required
- Two step approach
 - step 1 (filtering): select a number of promising candidate sections in the database
 - step 2 (expansion): apply further analysis to select best matches to query
- *Blast*-approach: heuristic based on k-gram filtering
- $k = 3$ for protein string matching (20 char alphabet)
- $k = 11$ for base string matching (ACGT alphabet)

- Example: 3-gram match (a *hit*) between HEAGAWGHEE and PAWHEAE
- A hit points to positions in x and y that are candidates for further processing by an expansion algorithm
- First observation: if size of k
 - increases, then precision increases, recall decreases
 - decreases, then precision decreases, recall increases

BLAST Protein search

- Blast uses 3-grams for protein matching and 11-gram for base string matching
- Having just one 3-gram match (hit) between two strings gives a lot of false positives
- Blast applies other techniques to influence precision and recall

BLAST increasing precision

- *Two hit diagonal* principle
- A database string is a candidate when it shares two hits with the query string *on the same diagonal*, i.e. with the same distance between the hits
- OK: qu: CWYWRWYYC
 db: RRWYWAWYYRR
- Wrong: qu: CWYWRWYYC
 db: RRWYWABCWYYRR

BLAST increasing recall

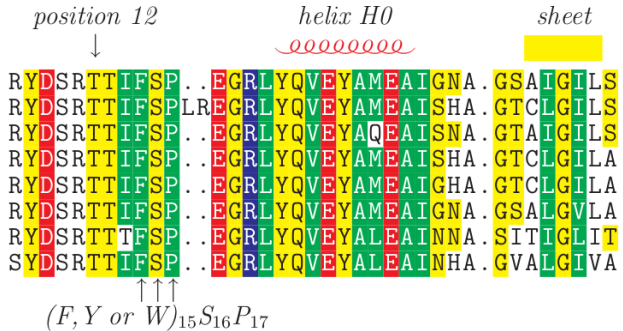
- Extended version of hit notion
- Two 3-grams match if their score exceeds a threshold (default = 11)
- Example: HEAGAWGHEE and PAWHEAE
- Score for GAW - PAW is $-2 + 5 + 15 = +18$

BLAST scores & probabilities

- Intuitively, it is clear that a high score ($\gg 0$) indicates a homology, ...
- ... whereas a negative score makes it unlikely.
- Altschul (see references) gives a way to calculate probabilities from raw scores, ...
- ... but we will not go into further detail here.

Looking further...

- Multiple sequence alignment



- Durban, Eddy e.a., *Biological Sequence Analysis*
- Altschul e.a., *Gapped BLAST and PSI-BLAST: a new generation of protein database search programs*