Affine Gap Alignment

CS1810 Fall 2020

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Brown University

PPT created by Sam Maffa, TA, 2020

Definitions: Inputs and Outputs

Inputs: $\langle X, Y, \alpha, \mu, \gamma, \tau \rangle$

- X, Y = strings of length m, n with characters indexed by i, j, respectively
- α = match score
- μ = mismatch penalty
- γ = gap opening penalty
- τ = gap extension penalty (single-letter gap penalty)

Output: An alignment which maximizes the following score:

α(# matches) - μ(# mismatches) - γ(# gap clusters) - τ(# single-letter gaps)

Definitions: Auxiliary Data Structures

Matrices: V, G, E, F

- V = the best-score matrix
- G = the match-mismatch matrix
- E = the X-gap matrix
- F = the Y-gap matrix

The Algorithm:

1) Initialize the matrices
2) Apply the recurrence relations to fill each matrix
3) Traceback through *V* (not shown)

$$
\begin{aligned}
&V(0,0) \leftarrow 0 \\
&\textbf{for } i \leftarrow 1 \textbf{ to } m \textbf{ do} \\
&\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau \\
&\textbf{end} \\
&\textbf{for } j \leftarrow 1 \textbf{ to } n \textbf{ do} \\
&\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau \\
&\textbf{end}
\end{aligned}
$$

$$
\begin{aligned}
&\textbf{for } i \leftarrow 1 \textbf{ to } m,\ j \leftarrow 1 \textbf{ to } n \textbf{ do} \\
&\quad G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases} \\
&\quad E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases} \\
&\quad F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases} \\
&\quad V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases} \\
&\textbf{end}
\end{aligned}
$$

An Example:

- X = ATCGGC
- Y = AGC
- α = 2 (score = +2)
- μ = 1 (penalty = -1)
- γ = 2 (penalty = -2)
- τ = 1 (penalty = -1)

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

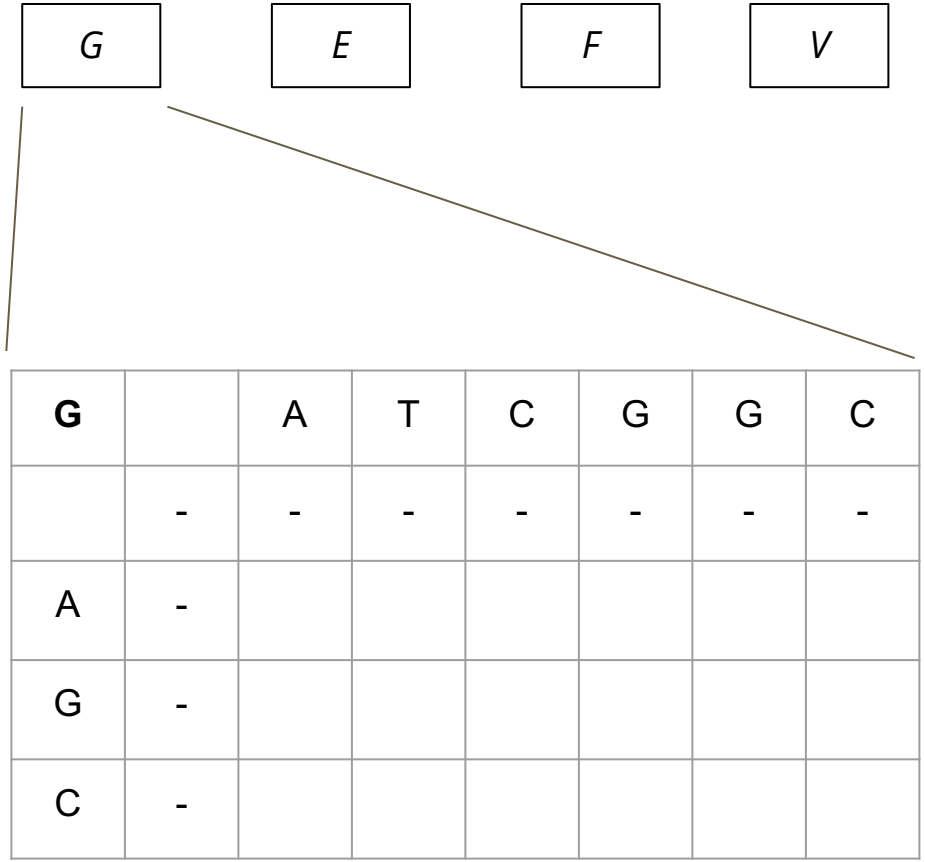
$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end



*We don't use 0th row, 0th column in *G* → initialize with error values

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

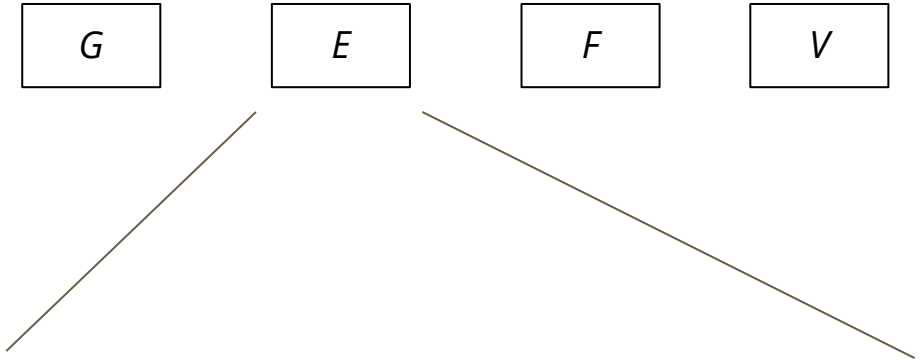
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-						
G	-						
C	-						

*We don't use 0th column in *E* → initialize with error values

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

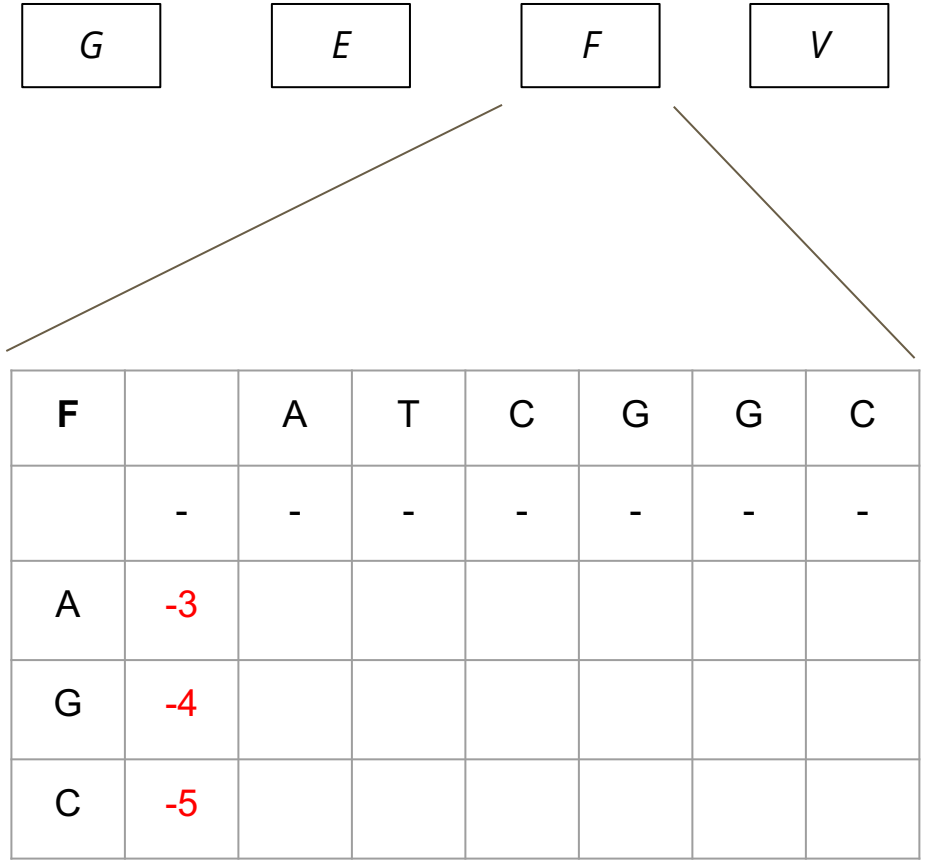
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



*We don't use 0th row in $F \rightarrow$ initialize with error values

$V(0,0) \leftarrow 0$
for $i \leftarrow 1$ **to** m **do**
  $V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$
end
for $j \leftarrow 1$ **to** n **do**
  $V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$
end
for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

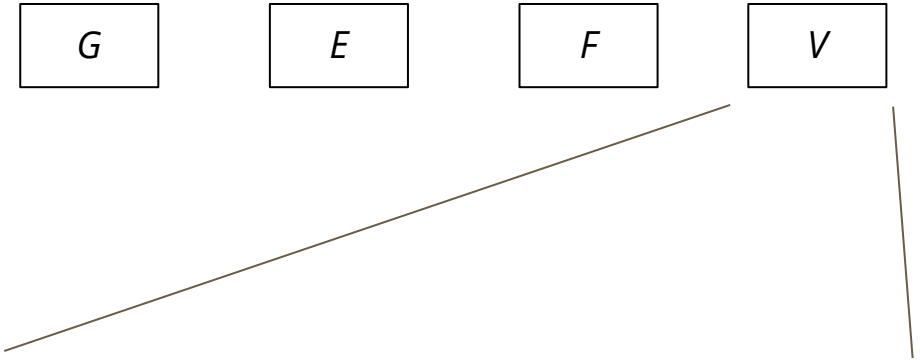
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$
$\mu = 1$ $\tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3						
G	-4						
C	-5						

$V(0,0) \leftarrow 0$
for $i \leftarrow 1$ **to** m **do**
  $V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$
end
for $j \leftarrow 1$ **to** n **do**
  $V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$
end
for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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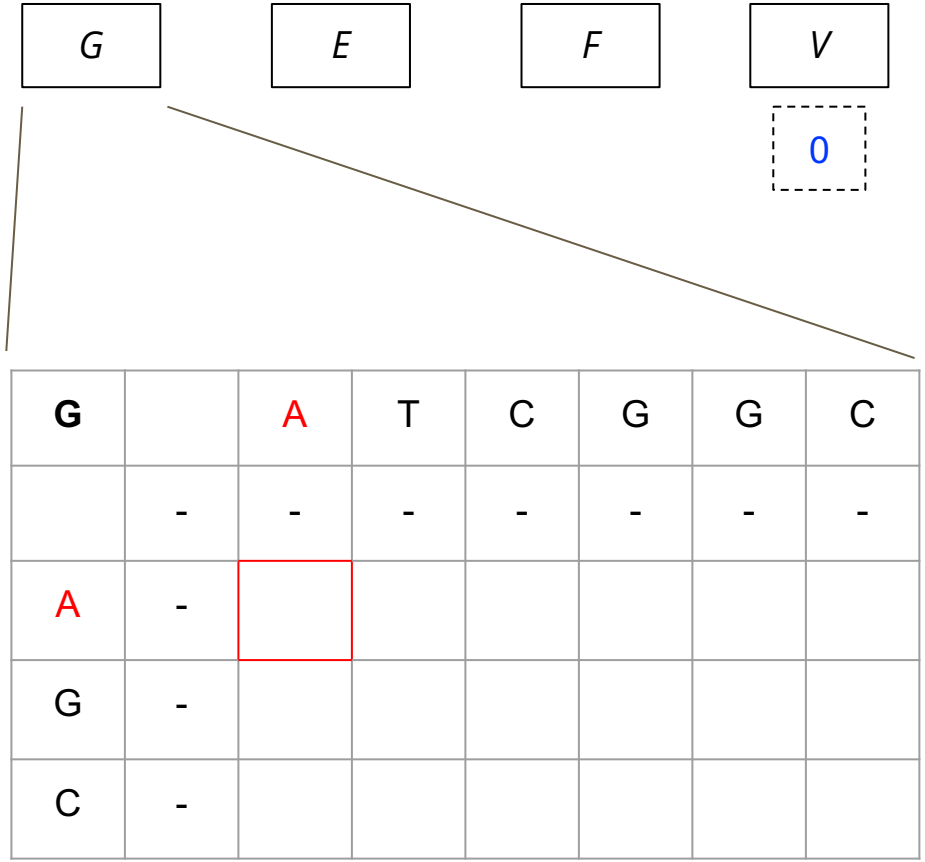
$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$
$\mu = 1$ $\tau = 1$



$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

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for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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end

$\alpha = 2 \quad \gamma = 2$

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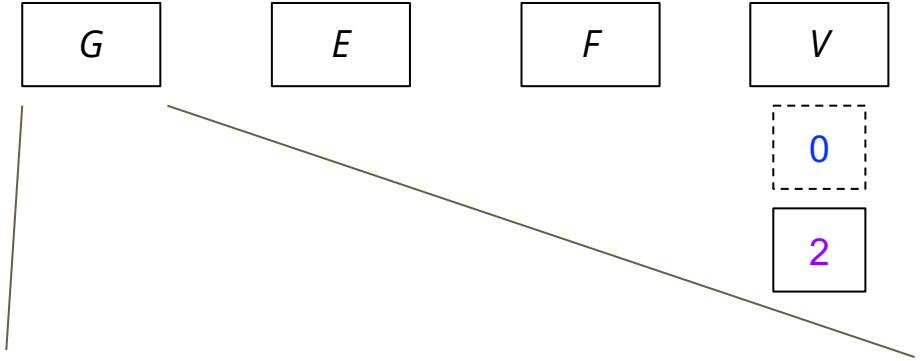

G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2					
G	-						
C	-						

$V(0,0) \leftarrow 0$

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for $j \leftarrow 1$ **to** n **do**

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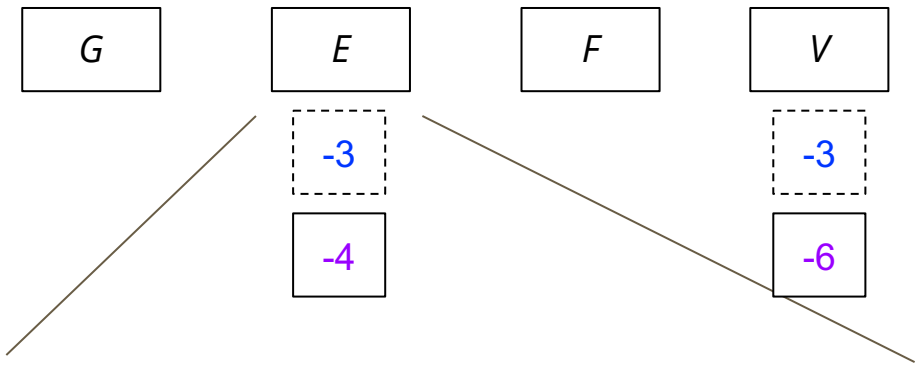

E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-						
G	-						
C	-						

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end

$\alpha = 2$ $\gamma = 2$

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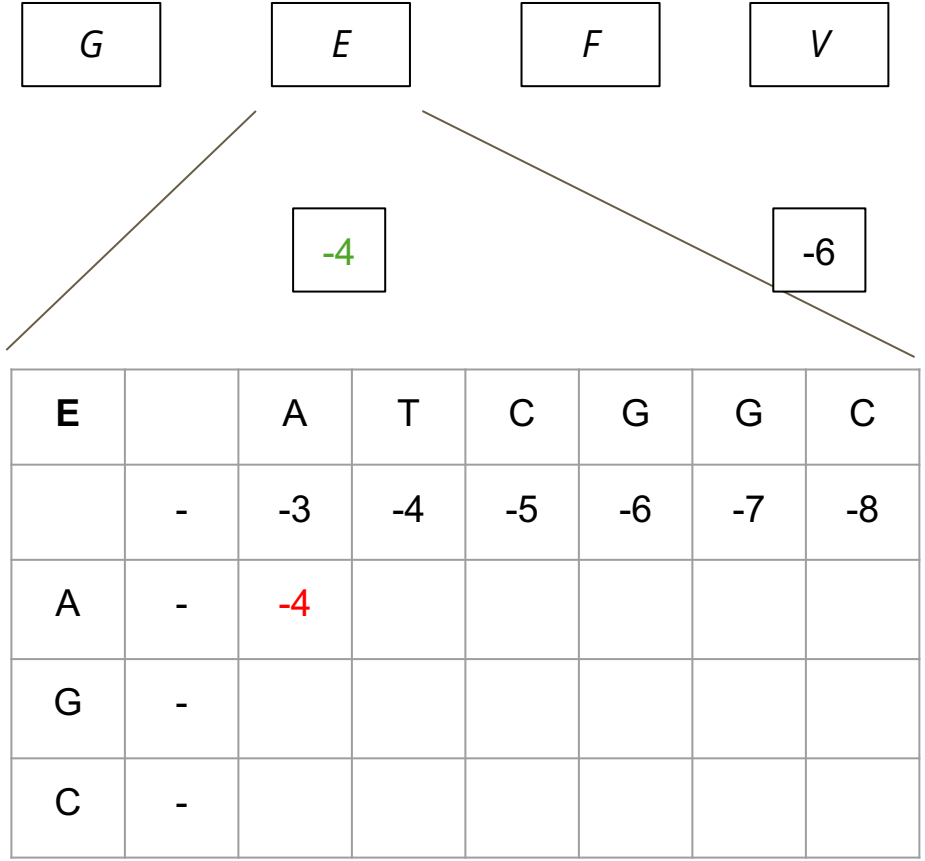

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$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

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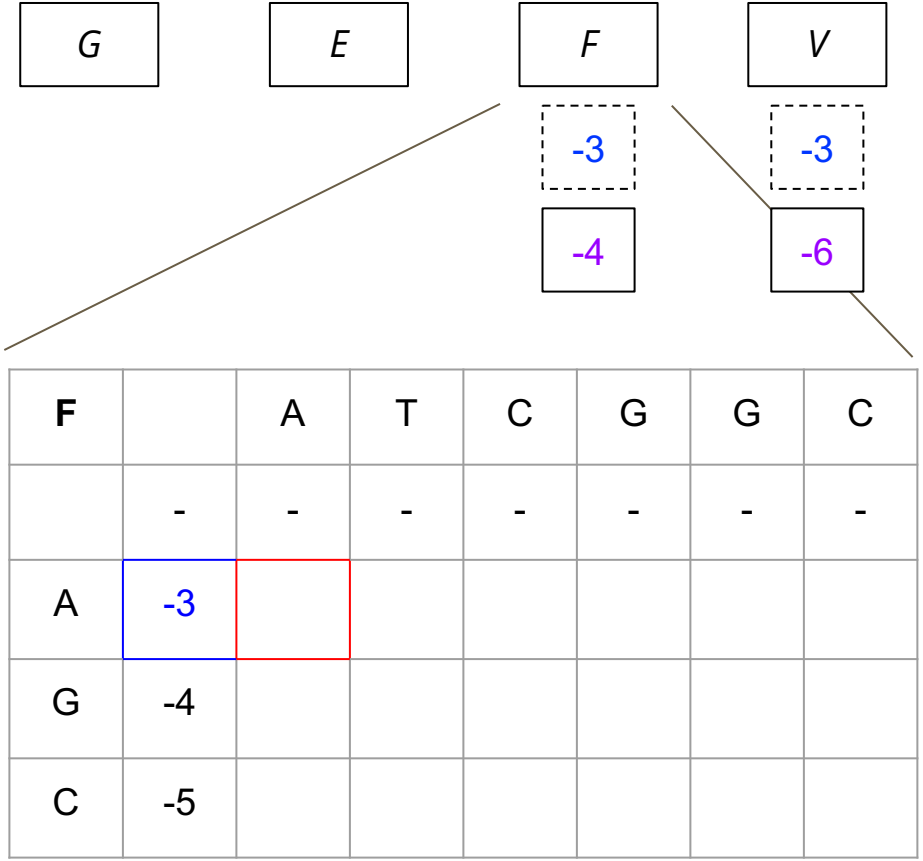
end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



$$V(0,0) \leftarrow 0$$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

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for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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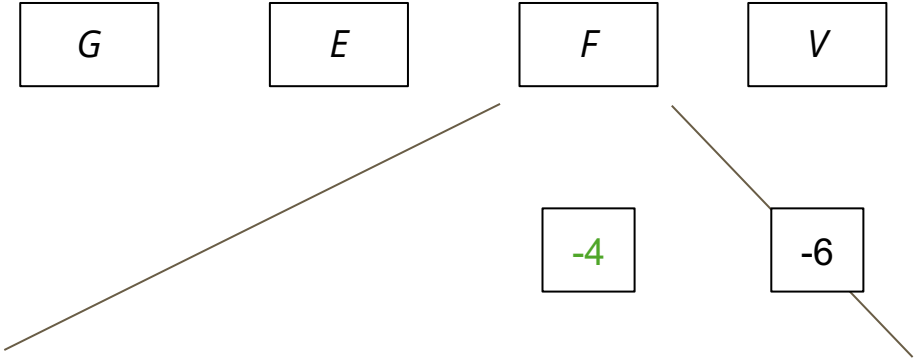
$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4					
G	-4						
C	-5						

$$V(0,0) \leftarrow 0$$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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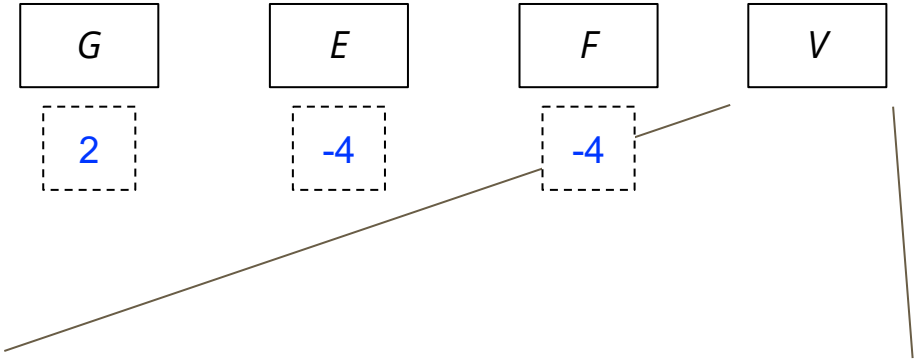
$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3						
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$

G	E	F	V
2	-4	-4	

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G					
G	-4						
C	-5						

*Keep track of which matrix gave you the max score!

$V(0,0) \leftarrow 0$
for $i \leftarrow 1$ **to** m **do**
  $V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$
end
for $j \leftarrow 1$ **to** n **do**
  $V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$
end
for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$
$\mu = 1$ $\tau = 1$

G	E	F	V
			-3

G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2					
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$

G	E	F	V
			-3
			-4

G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2	-4				
G	-						
C	-						

$$V(0,0) \leftarrow 0$$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

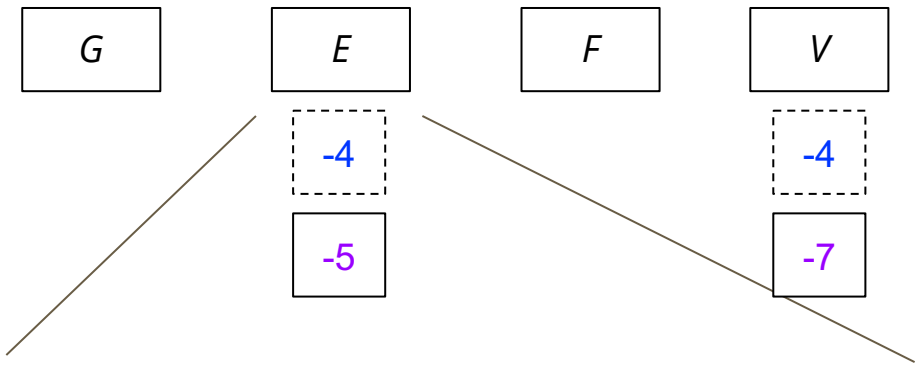
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4					
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

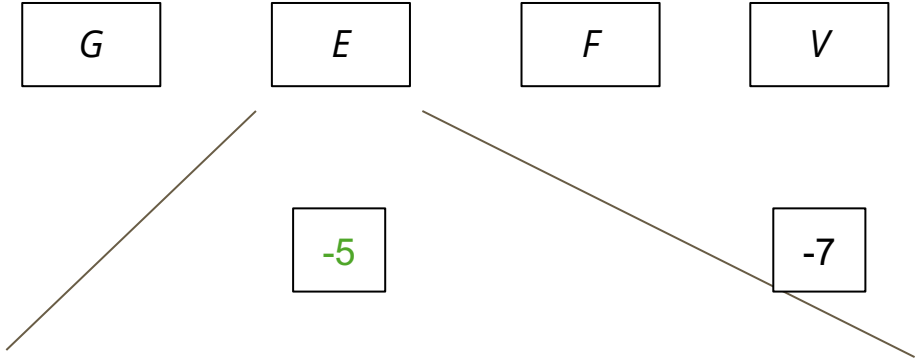
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4	-5				
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

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$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

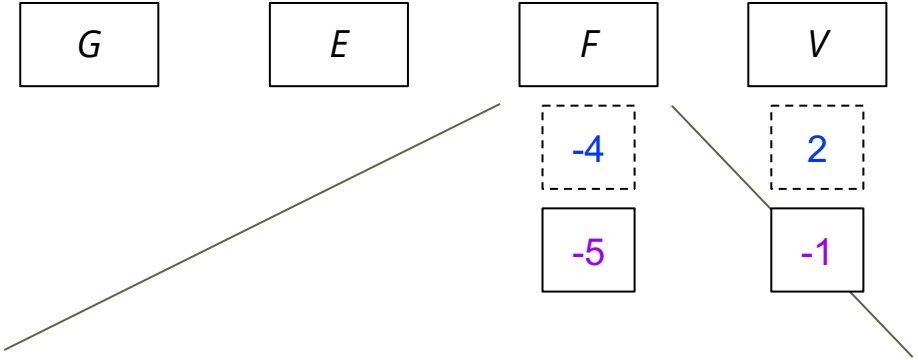
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4					
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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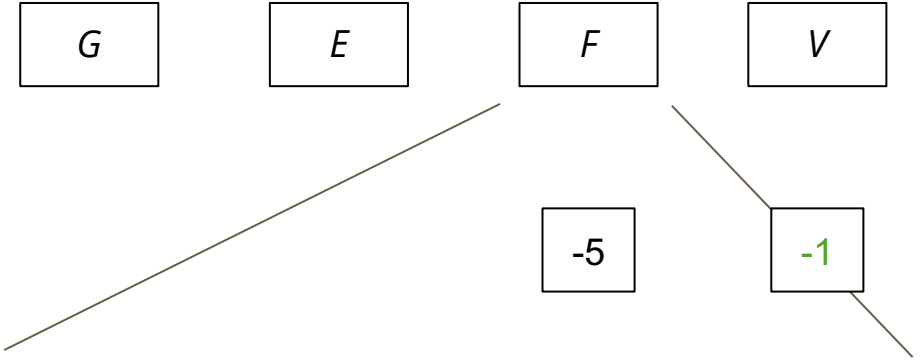
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4	-1				
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

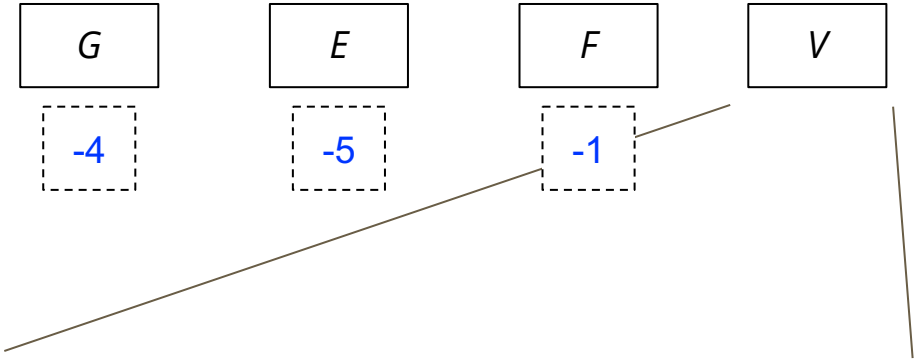
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G					
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

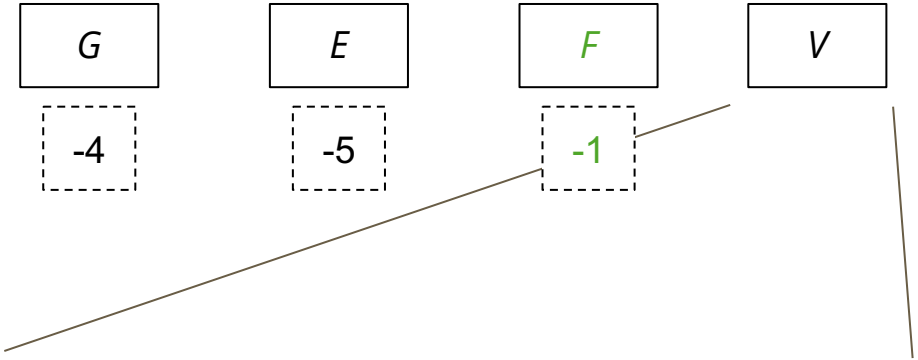
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F				
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$

G	E	F	V
			-4

G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2	-4				
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

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for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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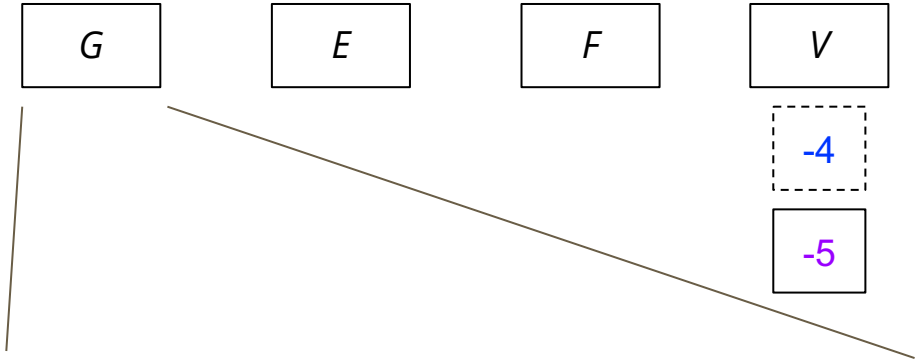
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2	-4	-5			
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

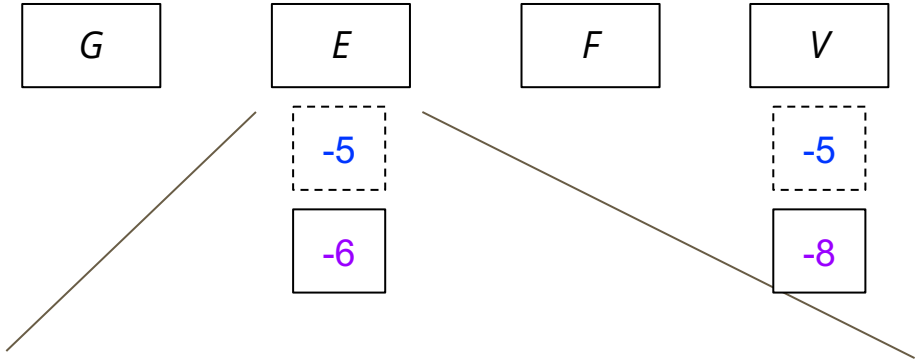
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4	-5				
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

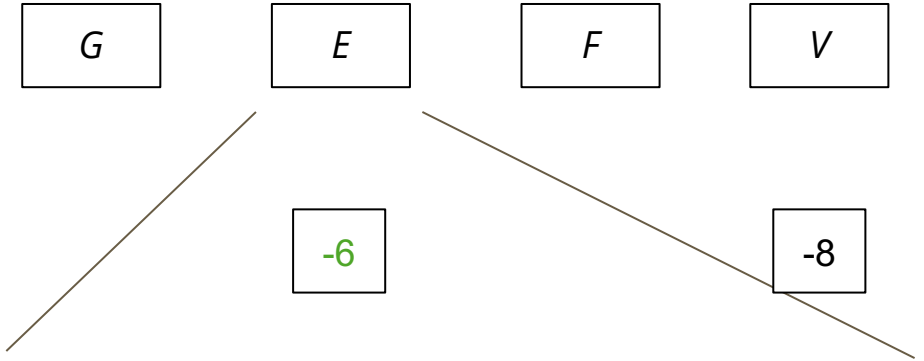
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4	-5	-6			
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

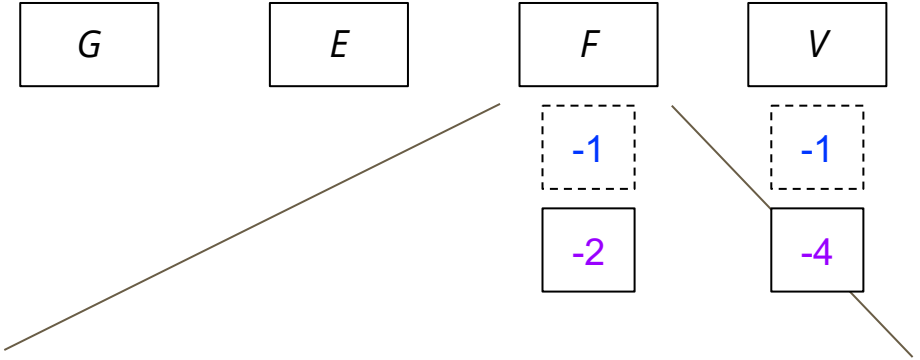
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4	-1				
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

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$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

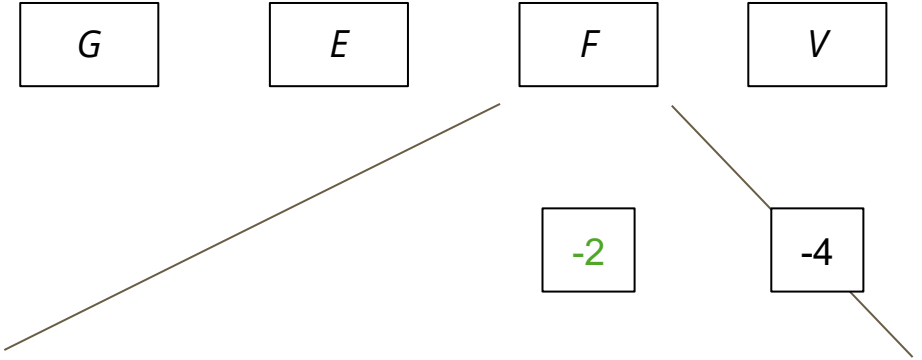
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4	-1	-2			
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

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$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

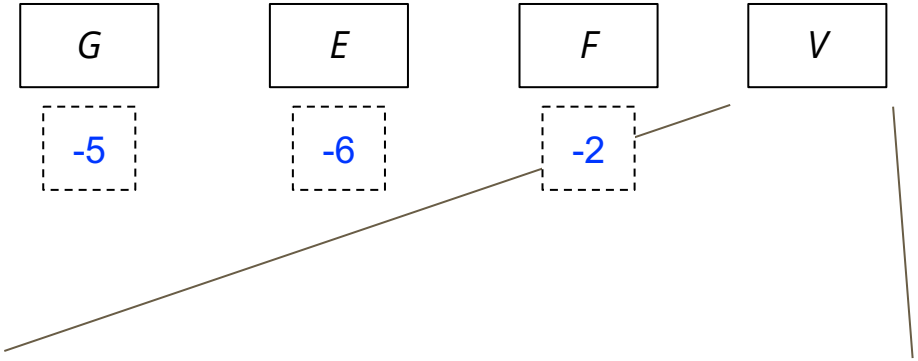
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F				
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

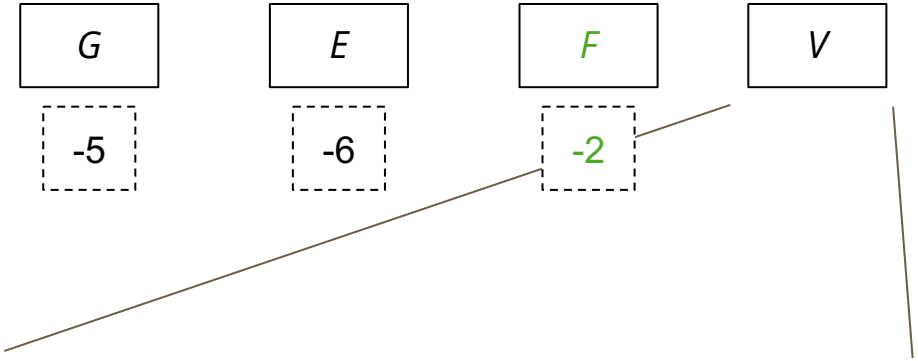
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F			
G	-4						
C	-5						

$V(0,0) \leftarrow 0$
for $i \leftarrow 1$ **to** m **do**
  $V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$
end
for $j \leftarrow 1$ **to** n **do**
  $V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$
end
for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$
$\mu = 1$ $\tau = 1$

And so on...

The algorithm continues like so until all the matrices are filled.

We'll skip ahead, stopping at some interesting intermediate states which cover new branches in the algorithm.

As an exercise, try filling out these matrices on your own and checking the values against our final solution!

G	E	F	V
			-3

G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2	-4	-5	-6	-7	-8
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

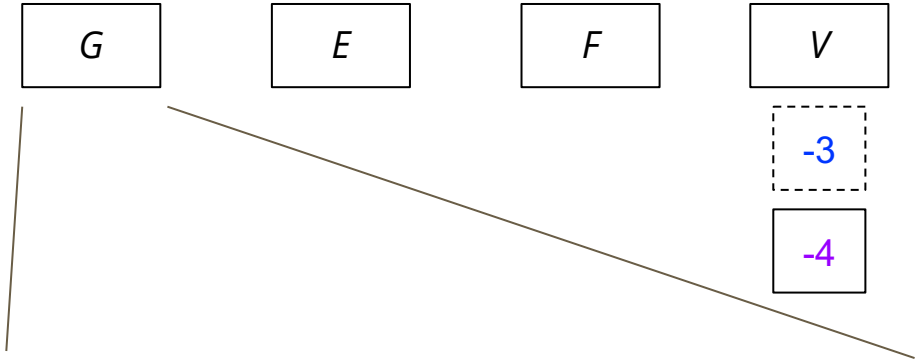
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2	-4	-5	-6	-7	-8
G	-	-4					
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

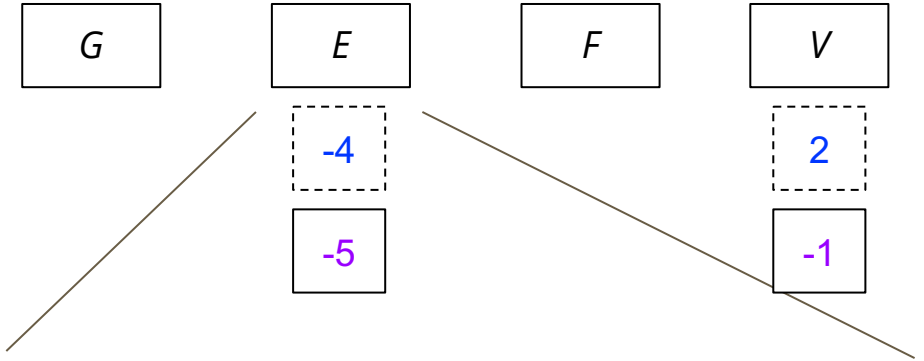
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4	-5	-6	-7	-8	-9
G	-						
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

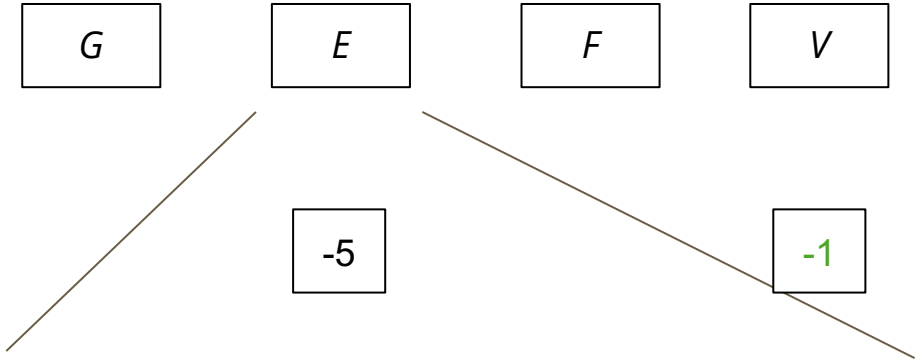
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4	-5	-6	-7	-8	-9
G	-	-1					
C	-						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

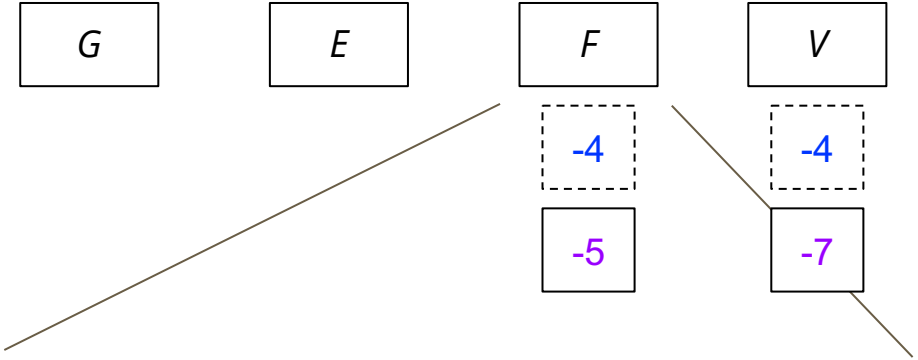
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4	-1	-2	-3	-4	-5
G	-4						
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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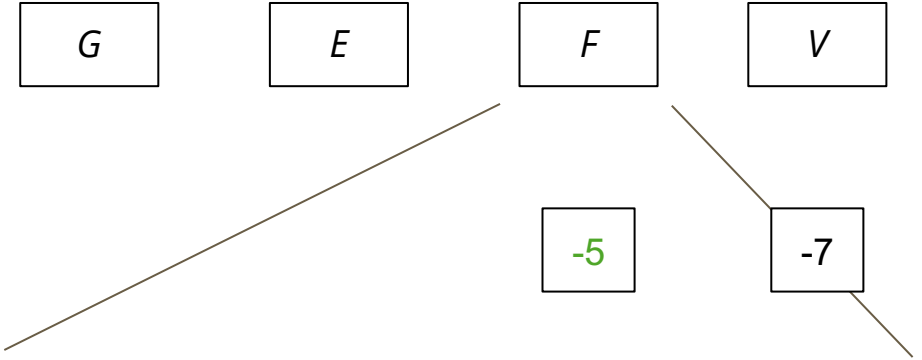
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4	-1	-2	-3	-4	-5
G	-4	-5					
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

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for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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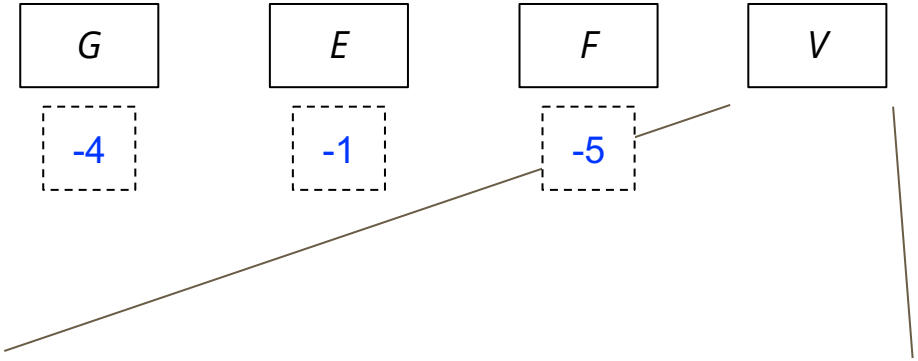
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4						
C	-5						

$V(0,0) \leftarrow 0$
for $i \leftarrow 1$ **to** m **do**
  $V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$
end
for $j \leftarrow 1$ **to** n **do**
  $V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$
end
for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$
$\mu = 1$ $\tau = 1$

G	E	F	V
-4	-1	-5	

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E					
C	-5						

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$

...

G	E	F	V
			-1

G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2	-4	-5	-6	-7	-8
G	-	-4	1	-2	0	-1	-5
C	-	-5					

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

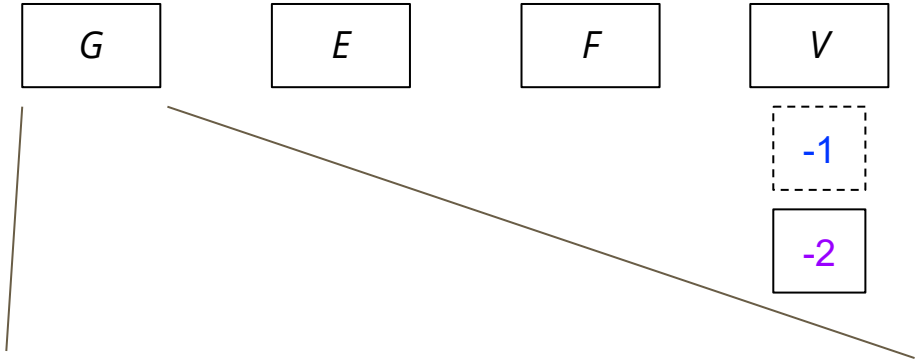
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2	-4	-5	-6	-7	-8
G	-	-4	1	-2	0	-1	-5
C	-	-5	-2				

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

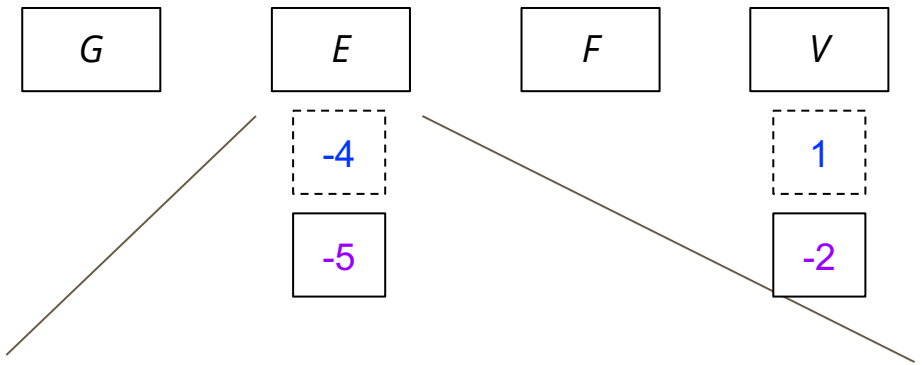
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4	-5	-6	-7	-8	-9
G	-	-1	-4	-5	-6	-7	-8
C	-	-2					

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

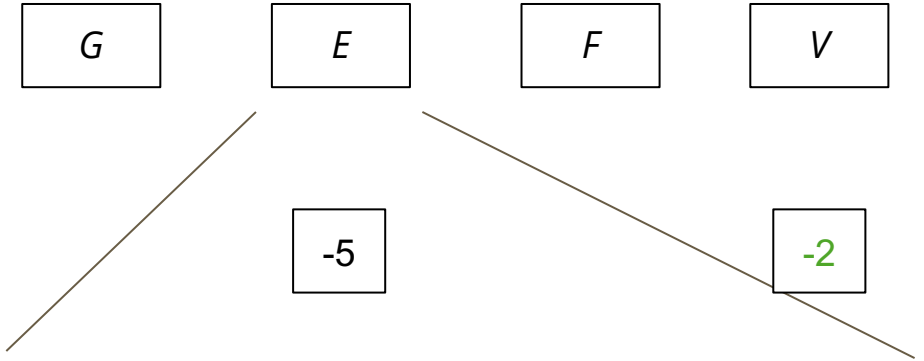
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4	-5	-6	-7	-8	-9
G	-	-1	-4	-5	-6	-7	-8
C	-	-2	-2				

$V(0,0) \leftarrow 0$
for $i \leftarrow 1$ **to** m **do**
  $V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$
end
for $j \leftarrow 1$ **to** n **do**
  $V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$
end
for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

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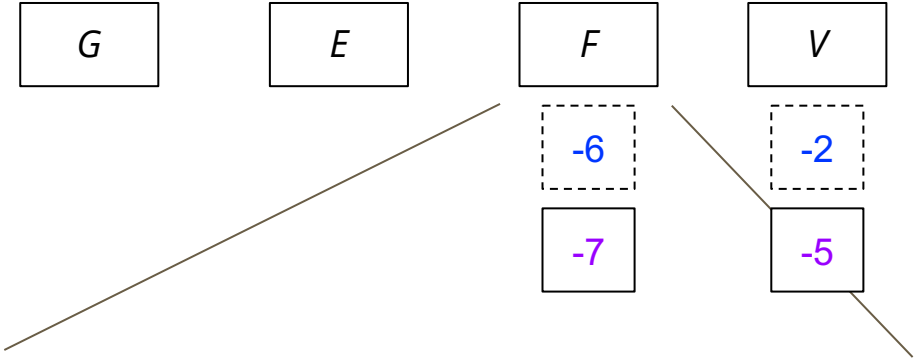
$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$
$\mu = 1$ $\tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4	-1	-2	-3	-4	-5
G	-4	-5	-4	-2	-3	-3	-4
C	-5	-6					

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

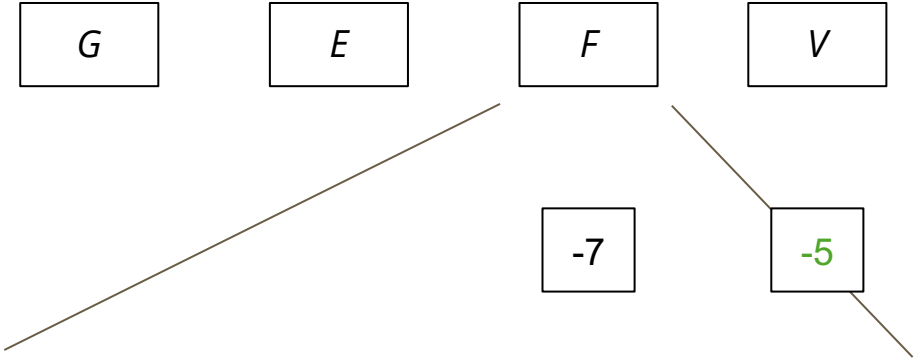
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$

$\mu = 1$ $\tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4	-1	-2	-3	-4	-5
G	-4	-5	-4	-2	-3	-3	-4
C	-5	-6	-5				

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

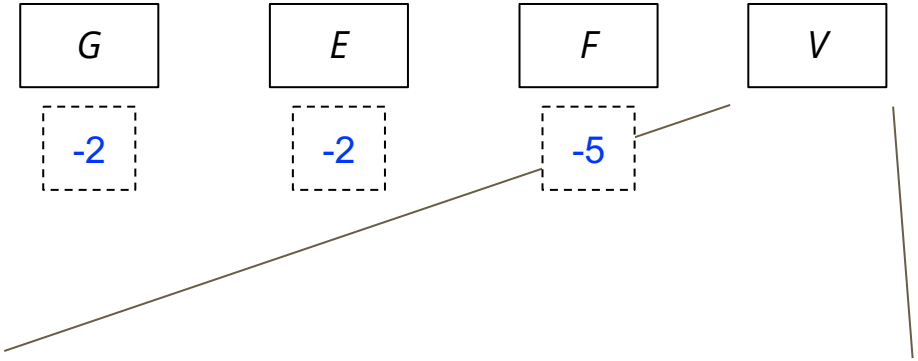
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E					

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

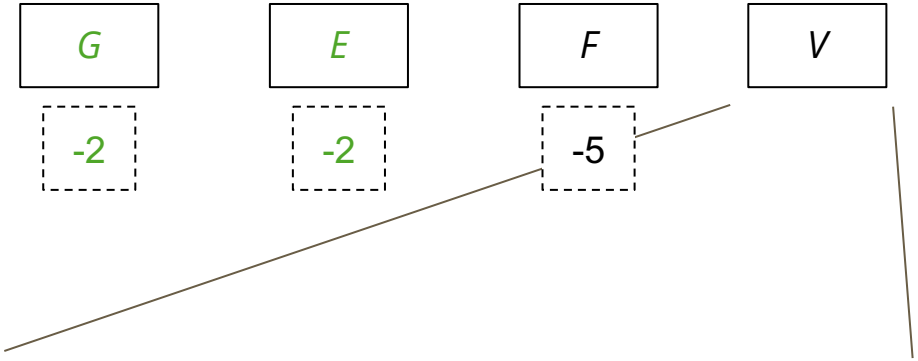
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$				

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$

...

G	E	F	V

G		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-	2	-4	-5	-6	-7	-8
G	-	-4	1	-2	0	-1	-5
C	-	-5	-2	3	-3	-1	1

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

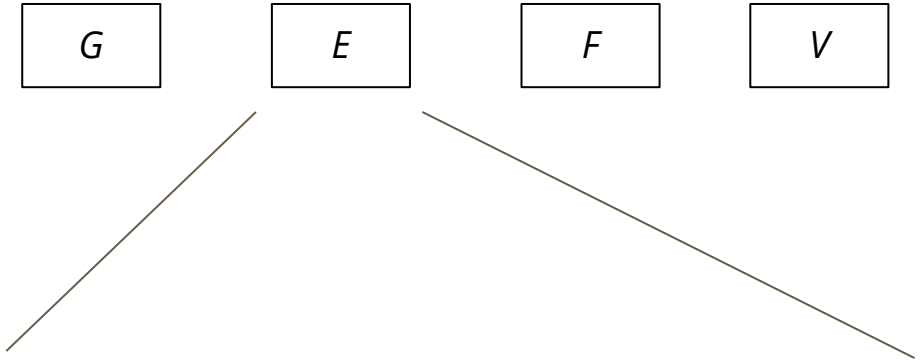
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



E		A	T	C	G	G	C
	-	-3	-4	-5	-6	-7	-8
A	-	-4	-5	-6	-7	-8	-9
G	-	-1	-4	-5	-6	-7	-8
C	-	-2	-2	-5	-3	-4	-7

$V(0,0) \leftarrow 0$

for $i \leftarrow 1$ **to** m **do**

$\quad V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$

end

for $j \leftarrow 1$ **to** n **do**

$\quad V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$

end

for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

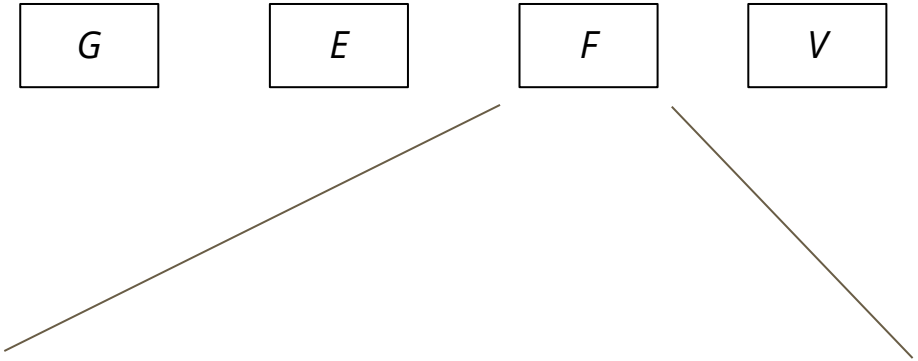
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2 \quad \gamma = 2$

$\mu = 1 \quad \tau = 1$



F		A	T	C	G	G	C
	-	-	-	-	-	-	-
A	-3	-4	-1	-2	-3	-4	-5
G	-4	-5	-4	-2	-3	-3	-4
C	-5	-6	-5	-5	0	-1	-2

$V(0,0) \leftarrow 0$
for $i \leftarrow 1$ **to** m **do**
  $V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$
end
for $j \leftarrow 1$ **to** n **do**
  $V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$
end
for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

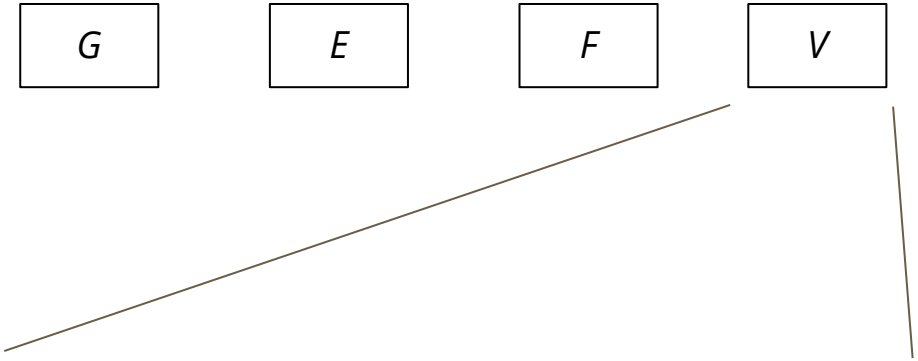
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$
$\mu = 1$ $\tau = 1$



V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

$V(0,0) \leftarrow 0$
for $i \leftarrow 1$ **to** m **do**
  $V(i,0) = E(i,0) \leftarrow -\gamma - i\tau$
end
for $j \leftarrow 1$ **to** n **do**
  $V(0,j) = F(0,j) \leftarrow -\gamma - j\tau$
end
for $i \leftarrow 1$ **to** m, $j \leftarrow 1$ **to** n **do**

$$G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases}$$

$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

$\alpha = 2$ $\gamma = 2$
$\mu = 1$ $\tau = 1$

Traceback

We use the backpointers in our *V* matrix to reconstruct our alignment.

At each position, we can recover the single-letter alignment of the prior two characters based on which matrix produced our maximum score.

Starting from $V(m,n)$, at every $V(i,j)$:

- If argmax = $G \rightarrow$ recover a match/mismatch; recurse on $V(i-1, j-1)$
- If argmax = $E \rightarrow$ recover a gap in X; recurse on $V(i, j-1)$
- If argmax = $F \rightarrow$ recover a gap in Y; recurse on $V(i-1, j)$

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

C
C

Score:
+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

C

C

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

G C

G C

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

G C

G C

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

G	G	C
–	G	C

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

G G C

– G C

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

C	G	G	C
–	–	G	C

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

C G G C

– – G C

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

T	C	G	G	C
–	–	–	G	C

Score:
+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

T C G G C

– – – G C

Score:

+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

A	T	C	G	G	C
A	–	–	–	G	C

Score:
+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

A	T	C	G	G	C
A	–	–	–	G	C

Score:
+1

V		A	T	C	G	G	C
	0	-3	-4	-5	-6	-7	-8
A	-3	2_G	-1_F	-2_F	-3_F	-4_F	-5_F
G	-4	-1_E	1_G	$-2_{G/F}$	0_G	-1_G	-4_F
C	-5	-2_E	$-2_{G/E}$	3_G	0_F	$-1_{G/F}$	1_G

A	T	C	G	G	C
A	–	–	–	G	C

Score:
+1

Results:

A	T	C	G	G	C
A	–	–	–	G	C

...is our optimal alignment with score **+1**!