Affine Gap Alignment

CS181 Fall 2021

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)

$$
\begin{aligned}
&V(0,0) \leftarrow 0 \\
&\textbf{for } j \leftarrow 1 \textbf{ to } n \textbf{ do} \\
&\quad V(0,j) = E(0,j) \leftarrow -\gamma - j\tau \\
&\textbf{end} \\
&\textbf{for } i \leftarrow 1 \textbf{ to } m \textbf{ do} \\
&\quad V(i,0) = F(i,0) \leftarrow -\gamma - i\tau \\
&\textbf{end} \\
&\textbf{for } i \leftarrow 1 \textbf{ to } m,\ j \leftarrow 1 \textbf{ to } n \textbf{ do} \\
&\quad G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases} \\
&\quad E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases} \\
&\quad F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases} \\
&\quad V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases} \\
&\textbf{end}
\end{aligned}
$$

An Example:

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

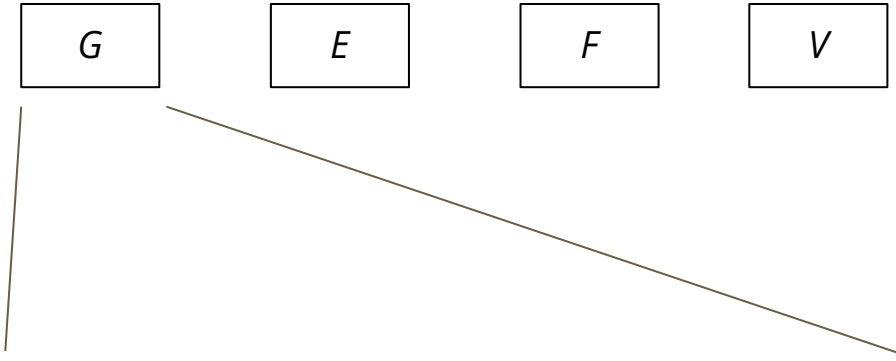
$$
\begin{aligned}
&V(0,0) \leftarrow 0 \\
&\textbf{for } j \leftarrow 1 \textbf{ to } n \textbf{ do} \\
&\quad V(0,j) = E(0,j) \leftarrow -\gamma - j\tau \\
&\textbf{end} \\
&\textbf{for } i \leftarrow 1 \textbf{ to } m \textbf{ do} \\
&\quad V(i,0) = F(i,0) \leftarrow -\gamma - i\tau \\
&\textbf{end} \\
&\textbf{for } i \leftarrow 1 \textbf{ to } m,\ j \leftarrow 1 \textbf{ to } n \textbf{ do} \\
&\quad G(i,j) \leftarrow \begin{cases} V(i-1,j-1) + \alpha & \text{if } x_i = y_j \\ V(i-1,j-1) - \mu & \text{if } x_i \neq y_j \end{cases} \\
&\quad E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases} \\
&\quad F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases} \\
&\quad V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases} \\
&\textbf{end}
\end{aligned}
$$

Tips for Initialization

1. Update the scores with the right recurrence relation math.

2. Update the backpointers to know where the score originated from.

3. The *i* represents the column and the *j* represents a row number in our example.



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

*0th row, 0th column in *G* is unused → initialize with error values

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

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

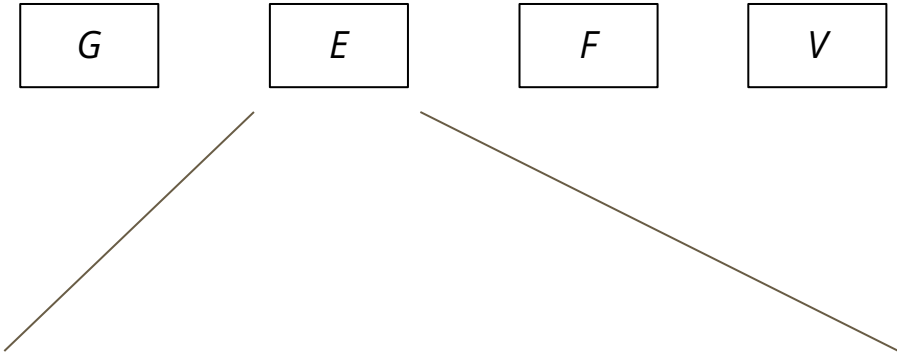
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3						
G	-4						
C	-5						

***0th row in *E* is unspecified → initialize with negative infinity to favor opening gaps from *V* once we start calculating down**

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

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

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

end

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

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

end

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

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

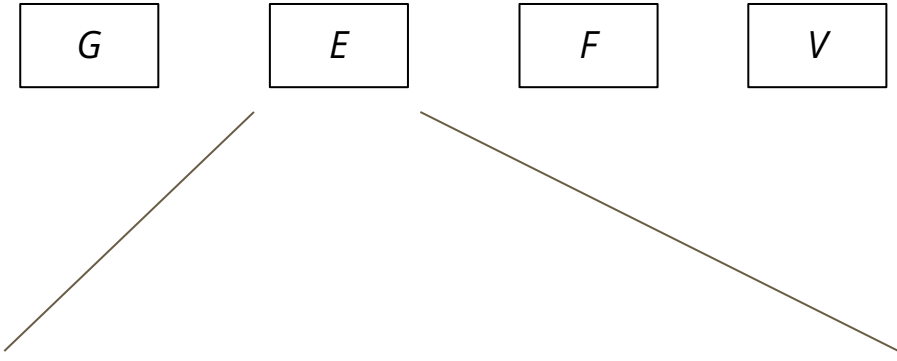
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V						
G	-4_E						
C	-5_E						

***Also keep backpointers to let you know which matrix was used to compute the score in each cell**

$V(0,0) \leftarrow 0$

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

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

end

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

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

end

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

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

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

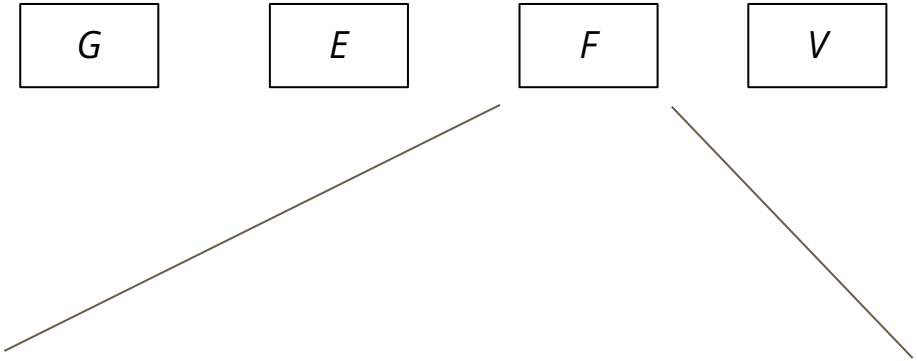
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

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

end

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

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



F		A	T	C	G	G	C
	-∞	-3	-4	-5	-6	-7	-8
A	-∞						
G	-∞						
C	-∞						

***0th column in *F* is unspecified → initialize with negative infinity to favor opening gaps from *V* once we start calculating across**

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

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

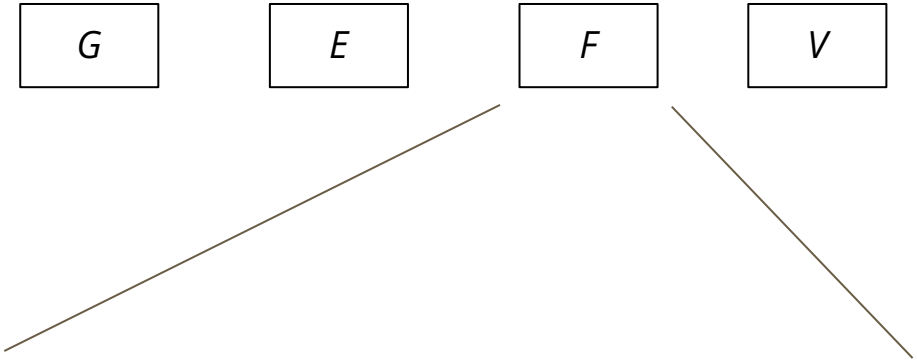
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞						
G	-∞						
C	-∞						

***Also keep backpointers to let you know which matrix was used to compute the score in each cell**

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

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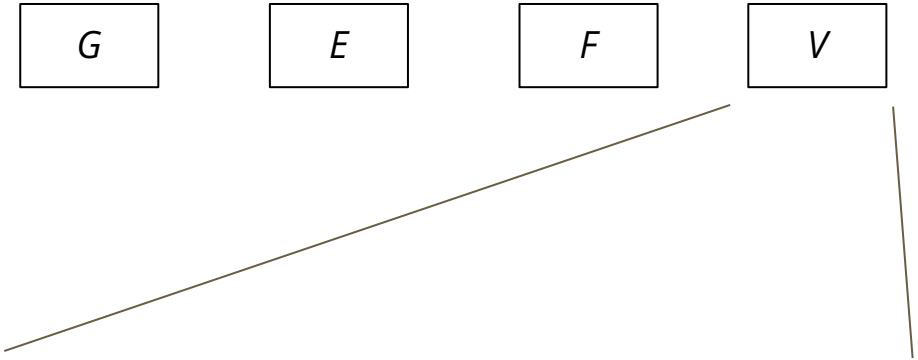
$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

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



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

***In *V*, keep track of which matrix gave you each score**

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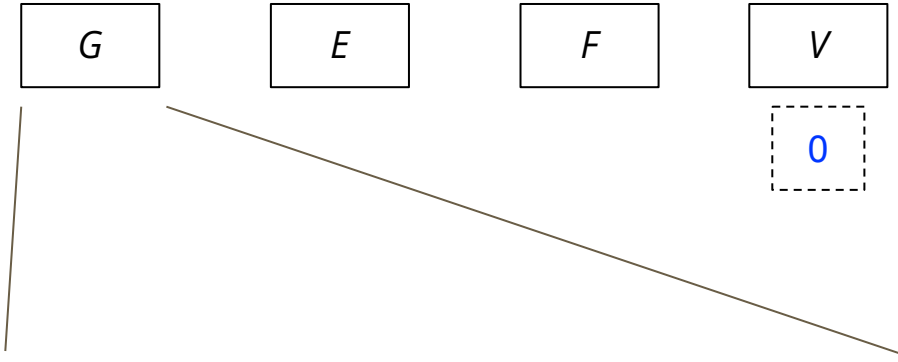
$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

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



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

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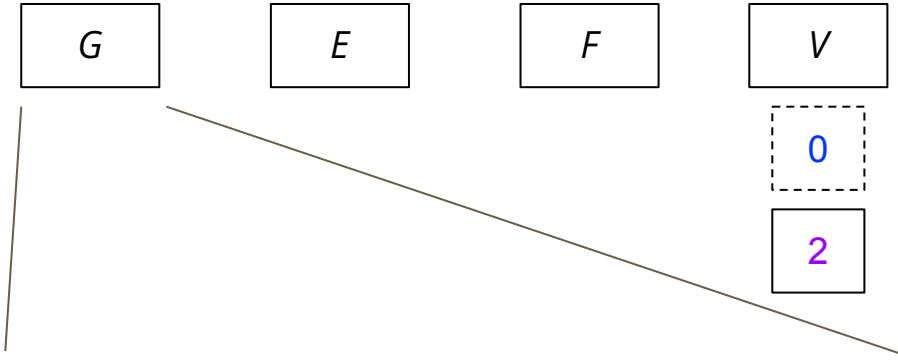
end

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



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

*We don't need backpointers in G because all entries are computed from the same cell in V

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

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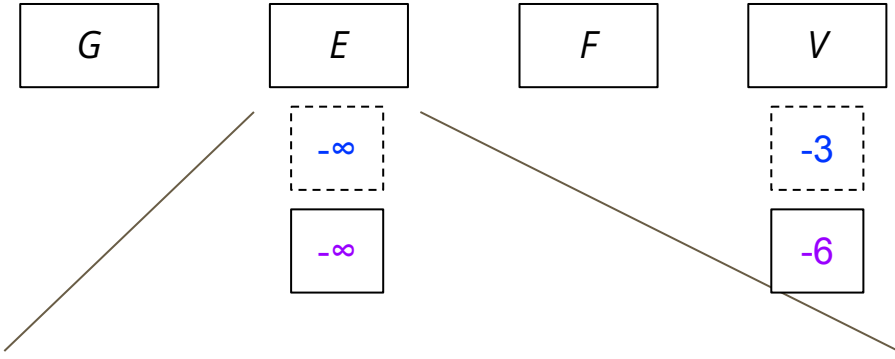
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V						
G	-4_E						
C	-5_E						

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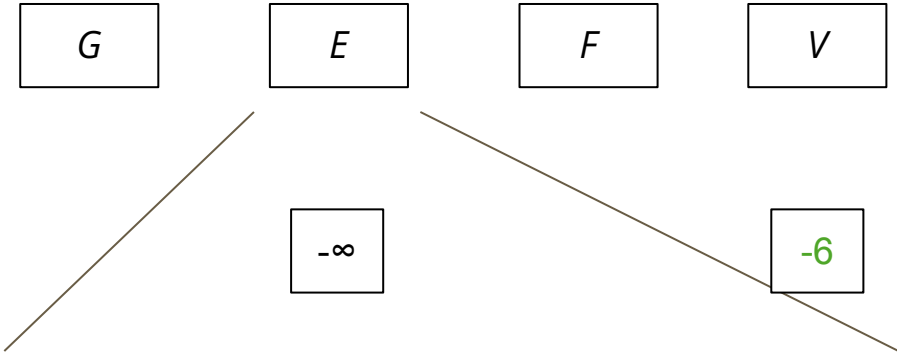
end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V					
G	-4_E						
C	-5_E						

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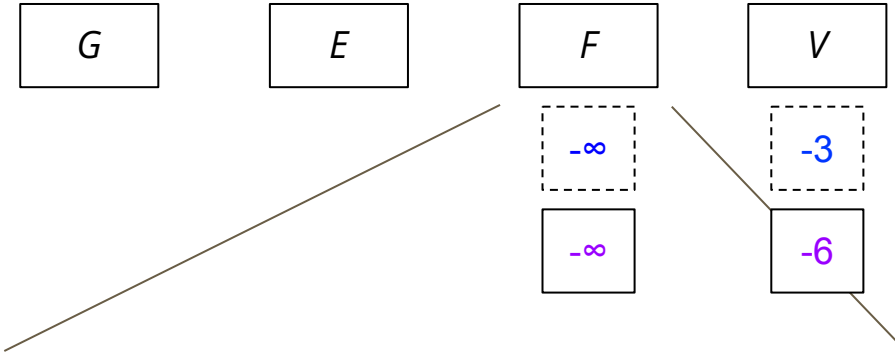
$$V(i,j) \leftarrow \max \begin{cases} G(i,j) \\ E(i,j) \\ F(i,j) \end{cases}$$

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞						
G	-∞						
C	-∞						

$V(0,0) \leftarrow 0$
for $j \leftarrow 1$ **to** n **do**
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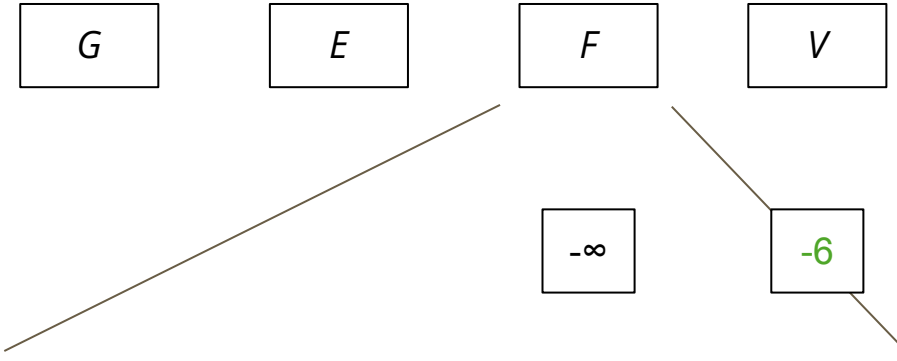
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V					
G	-∞						
C	-∞						

$V(0,0) \leftarrow 0$

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

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

end

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

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

end

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

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

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

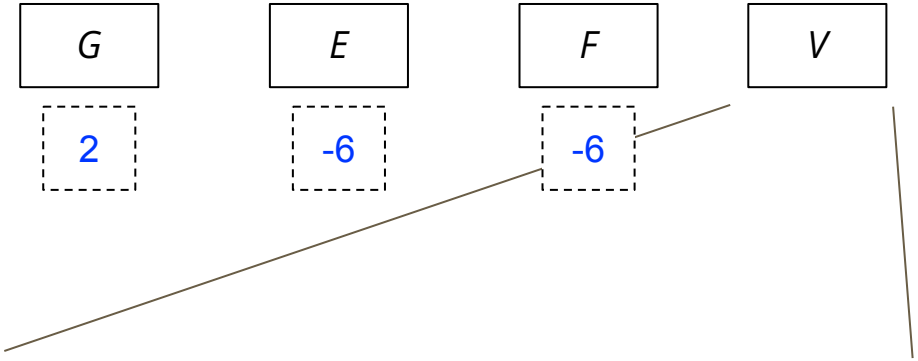
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

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

end

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

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



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

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

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

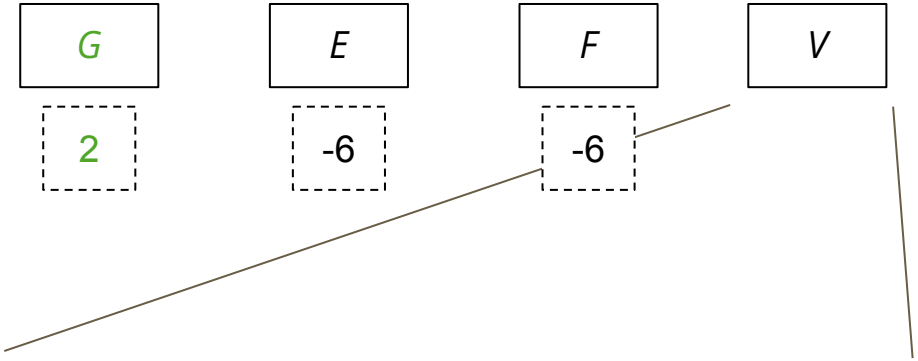
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

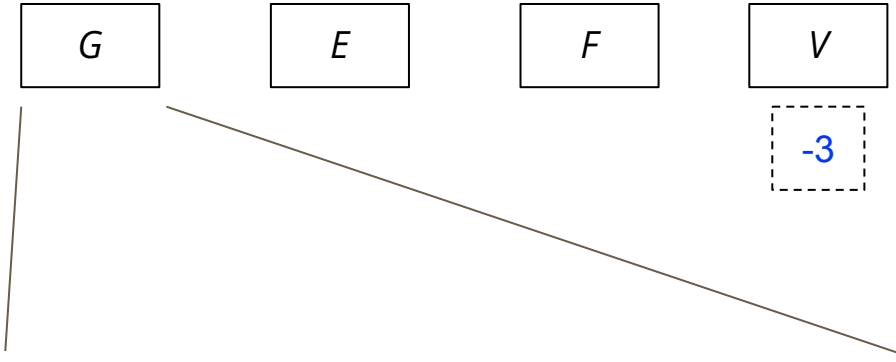
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

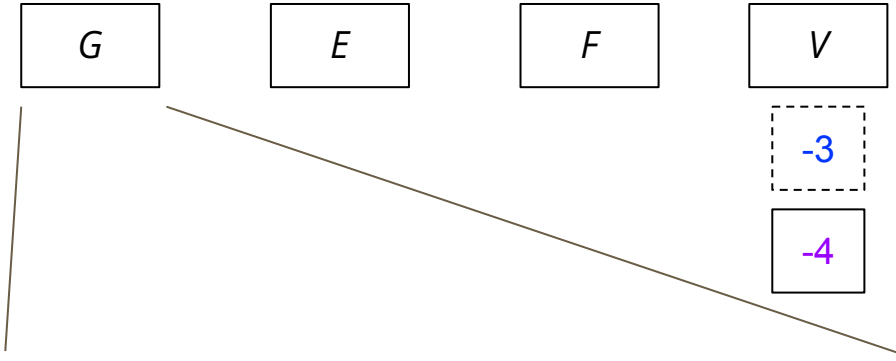
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

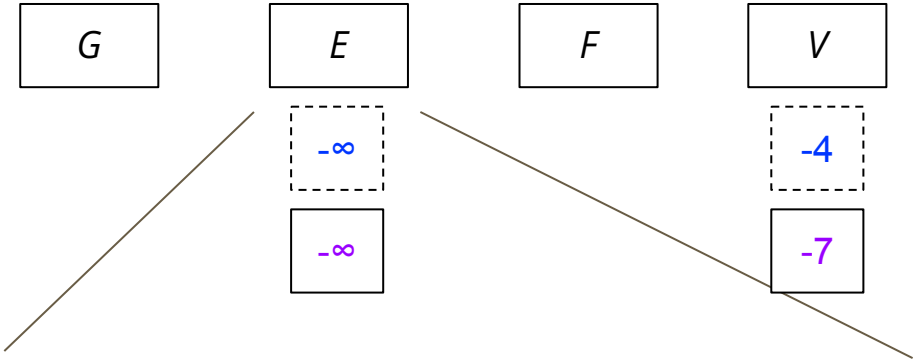
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V					
G	-4_E						
C	-5_E						

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

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

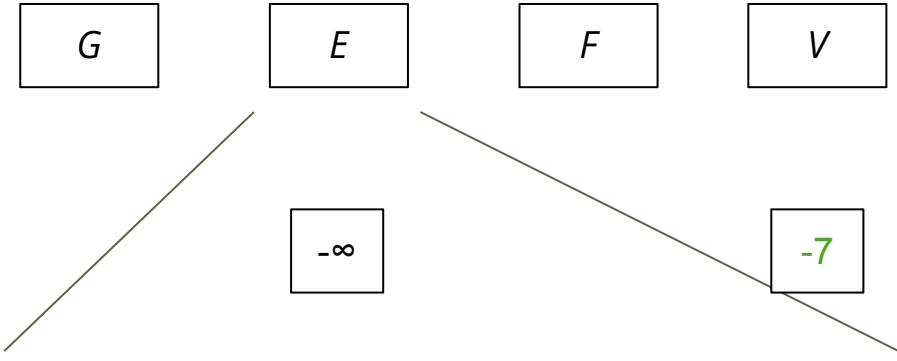
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) & -\tau \\ V(i,j-1) & -\gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V	-7_V				
G	-4_E						
C	-5_E						

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

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

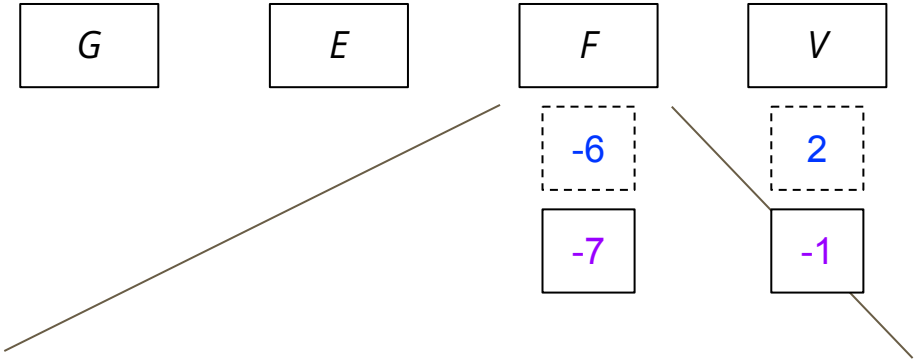
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V					
G	-∞						
C	-∞						

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

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

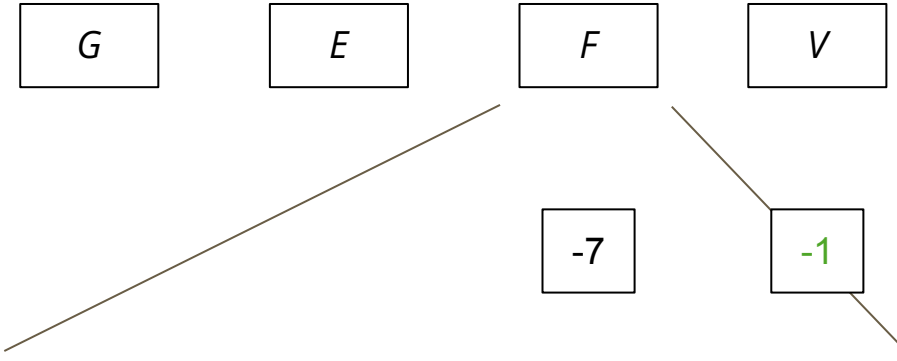
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V				
G	-∞						
C	-∞						

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

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

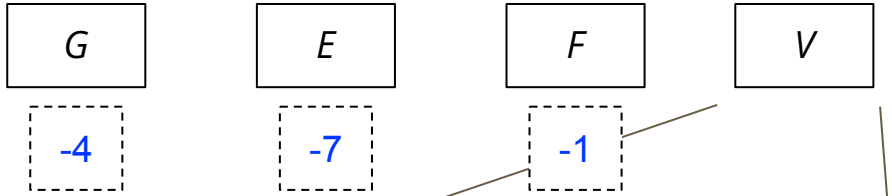
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

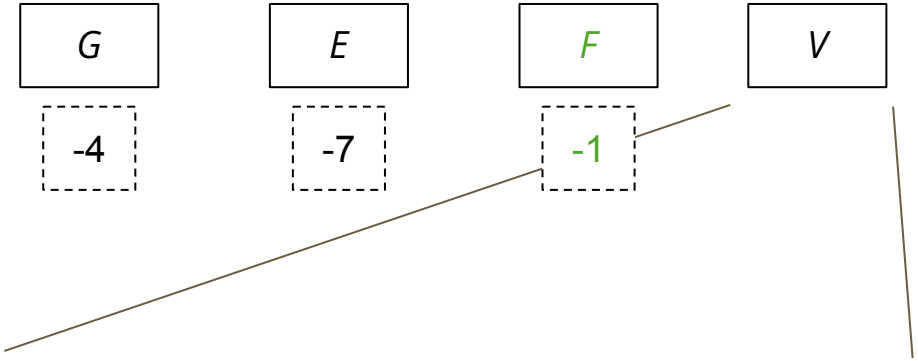
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

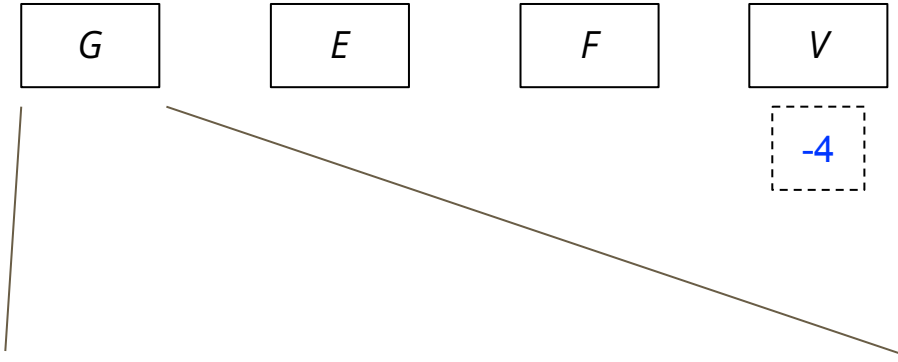
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

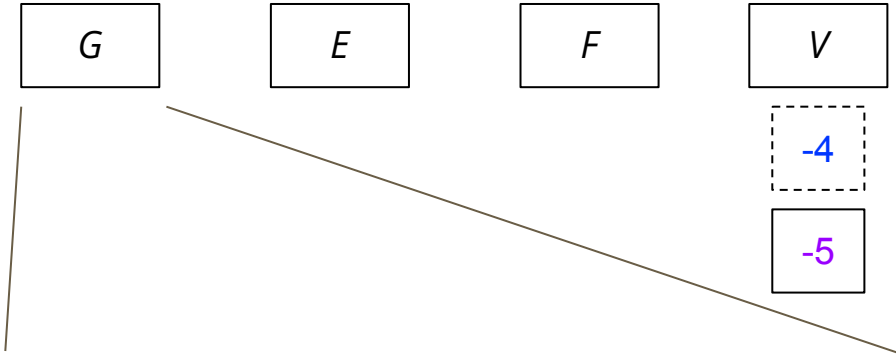
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

$V(0,0) \leftarrow 0$

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

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

end

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

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

end

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

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

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

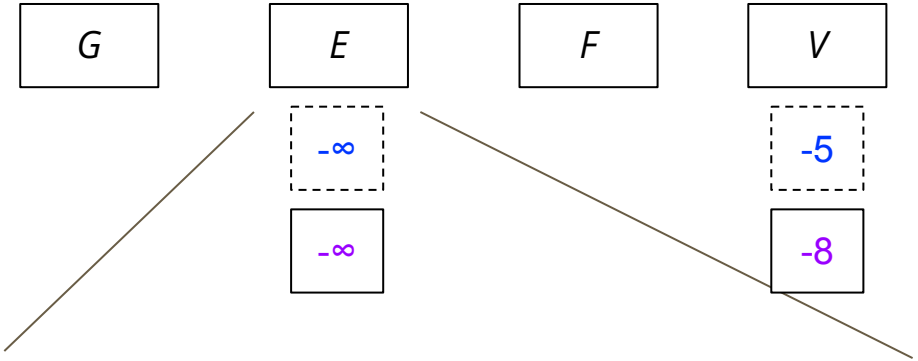
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

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

end

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

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V	-7_V				
G	-4_E						
C	-5_E						

$V(0,0) \leftarrow 0$

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

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

end

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

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

end

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

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

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

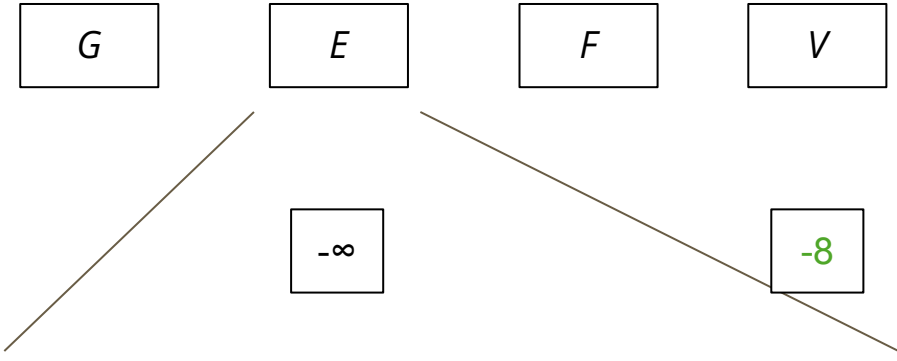
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

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

end

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

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



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

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

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

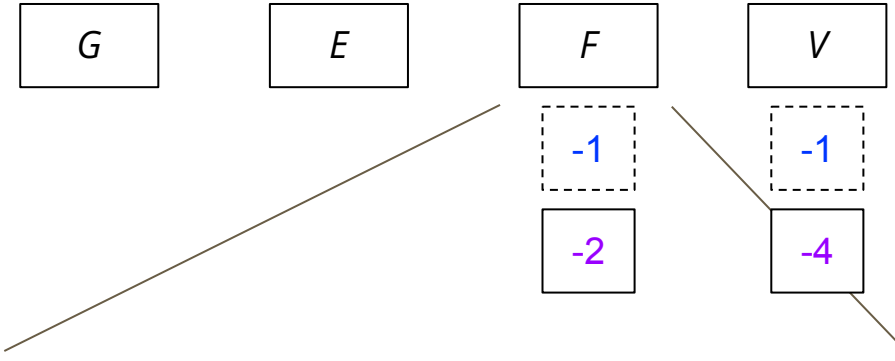
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V				
G	-∞						
C	-∞						

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

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

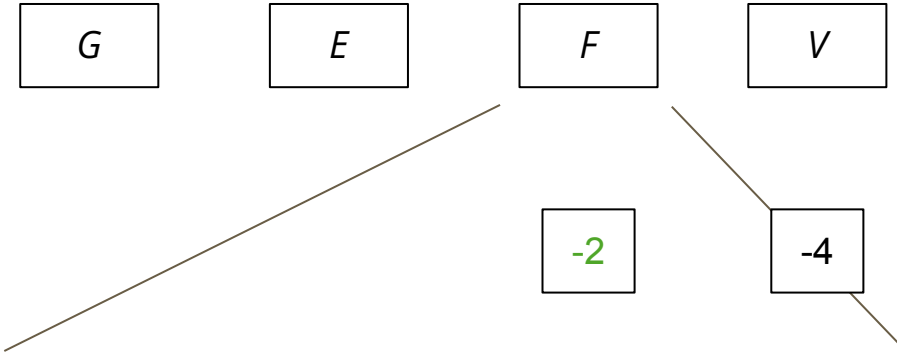
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F			
G	-∞						
C	-∞						

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

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

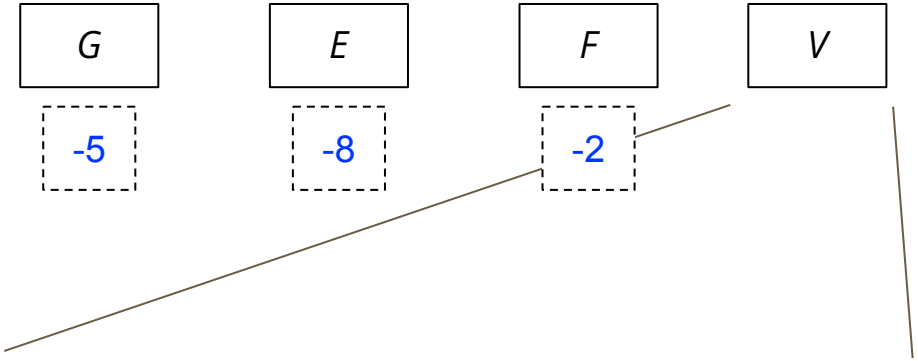
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

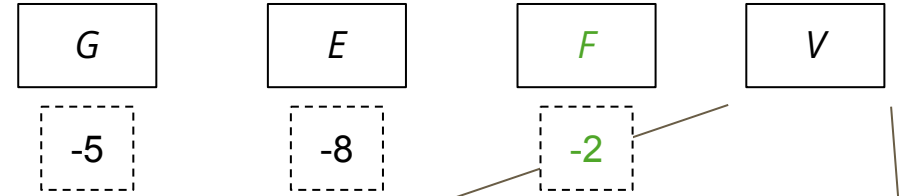
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

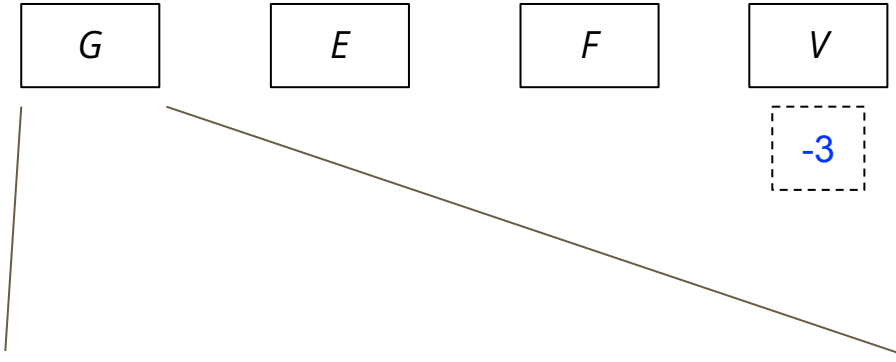
$\alpha = 2 \quad \gamma = 2$
$\mu = 1 \quad \tau = 1$

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

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

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

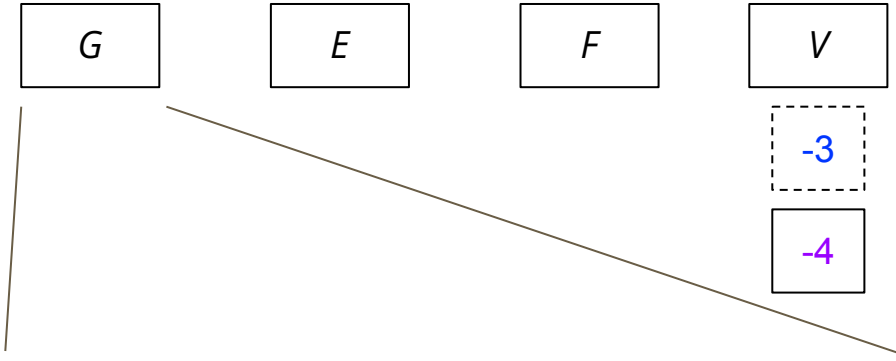
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

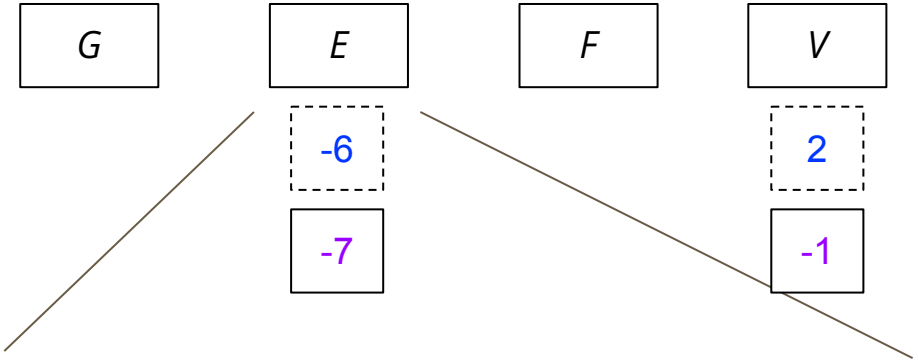
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V	-7_V	-8_V	-9_V	-10_V	-11_V
G	-4_E						
C	-5_E						

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

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

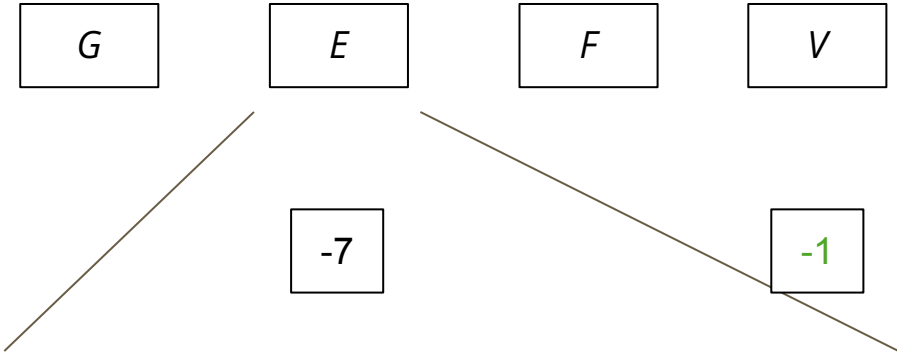
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V	-7_V	-8_V	-9_V	-10_V	-11_V
G	-4_E	-1_V					
C	-5_E						

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

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

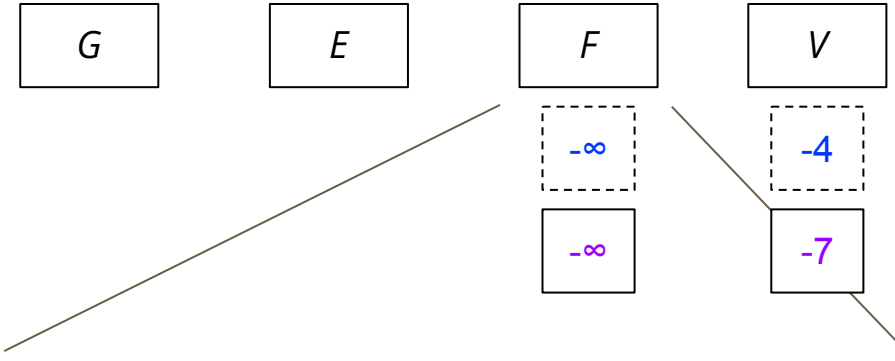
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

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

end



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞						
C	-∞						

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

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

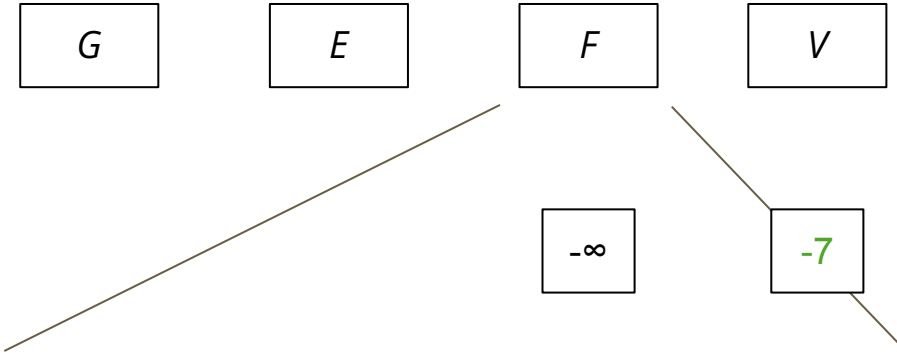
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V					
C	-∞						

$V(0,0) \leftarrow 0$

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

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

end

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

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

end

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

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

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

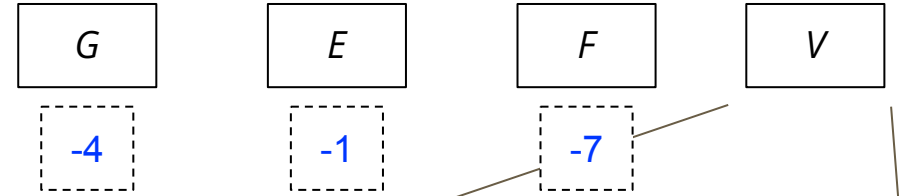
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

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

end

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

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



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

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

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

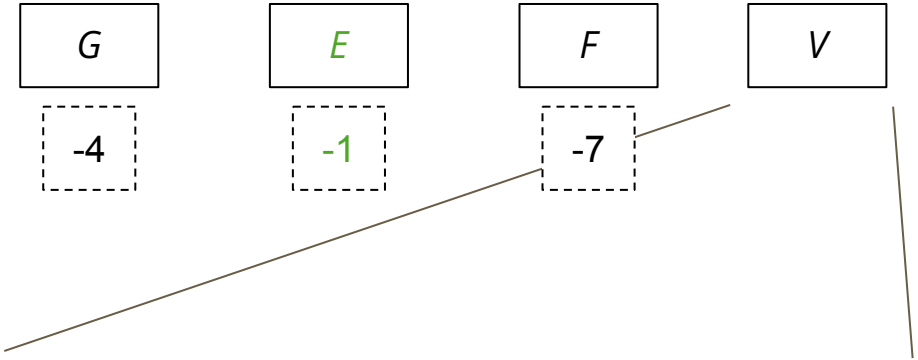
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

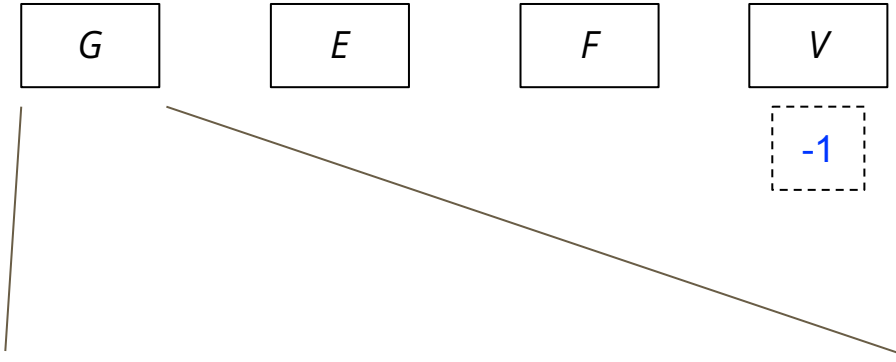
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

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					

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

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

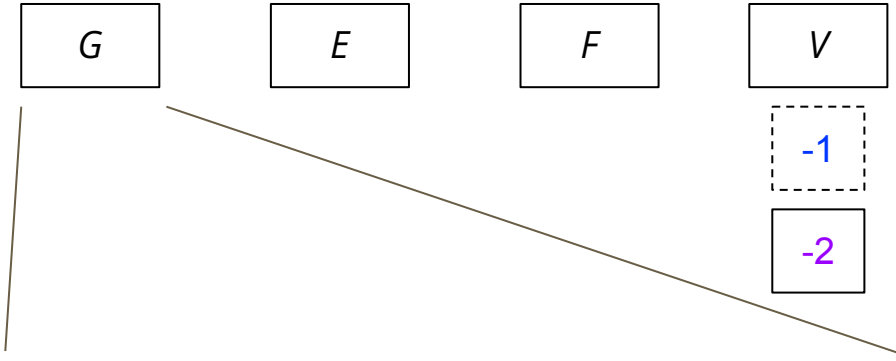
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

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

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

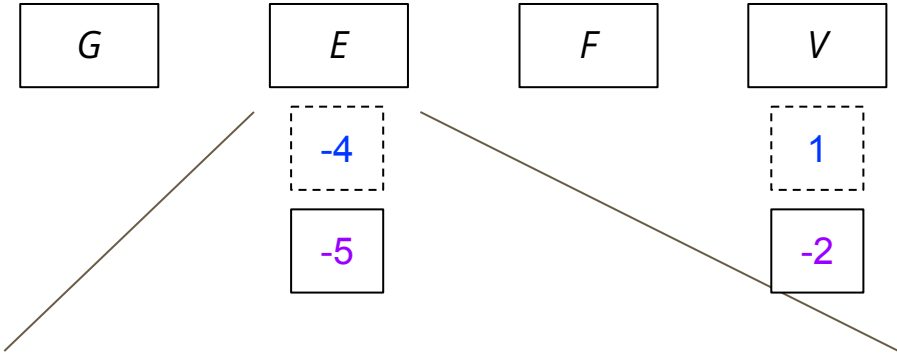
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V	-7_V	-8_V	-9_V	-10_V	-11_V
G	-4_E	-1_V	-4_V	-5_V	-6_V	-7_V	-8_V
C	-5_E	-2_E					

$V(0,0) \leftarrow 0$

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

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

end

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

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

end

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

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

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

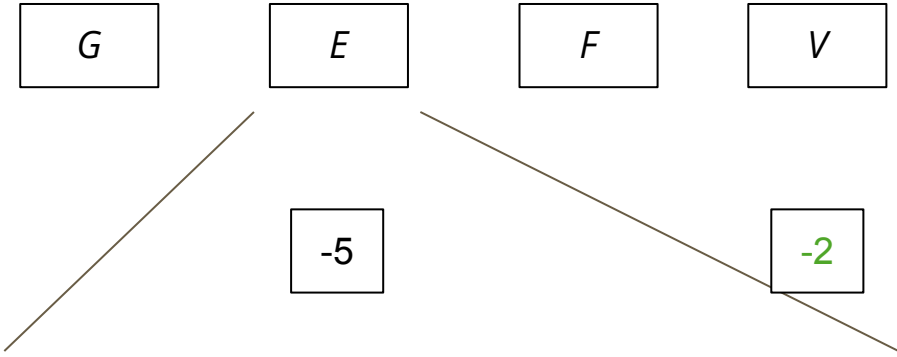
$$F(i,j) \leftarrow \max \begin{cases} F(i-1,j) - \tau \\ V(i-1,j) - \gamma - \tau \end{cases}$$

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

end

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

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V	-7_V	-8_V	-9_V	-10_V	-11_V
G	-4_E	-1_V	-4_V	-5_V	-6_V	-7_V	-8_V
C	-5_E	-2_E	-2_V				

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

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

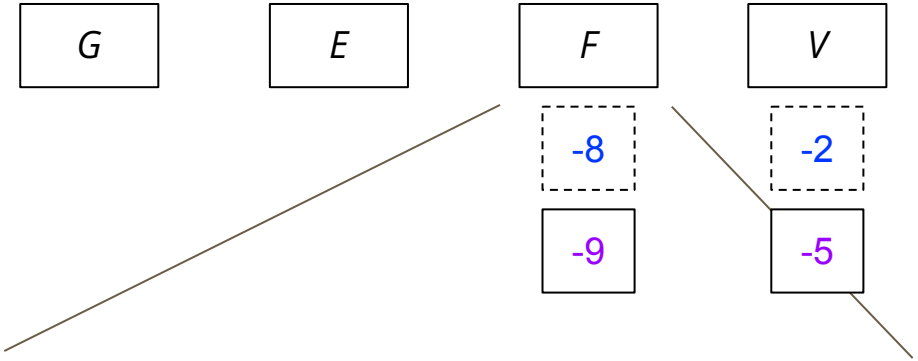
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V	-4_V	-2_V	-3_F	-3_V	-4_V
C	-∞	-8_V					

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

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

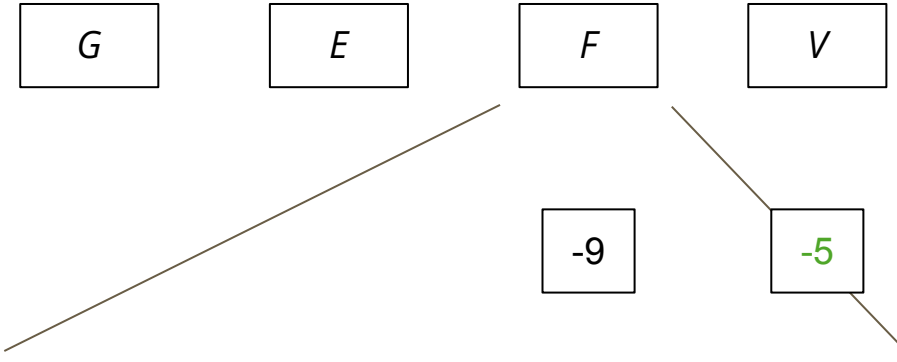
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V	-4_V	-2_V	-3_F	-3_V	-4_V
C	-∞	-8_V	-5_V				

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

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

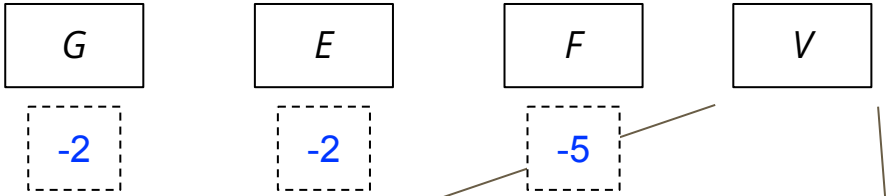
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

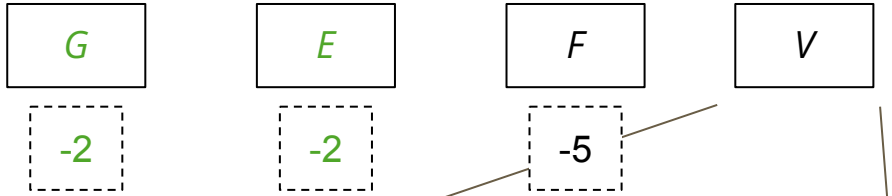
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

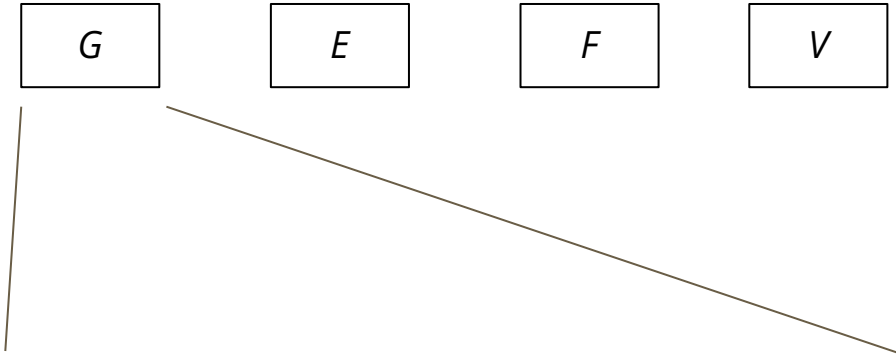
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

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	3	-3	-1	1

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

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

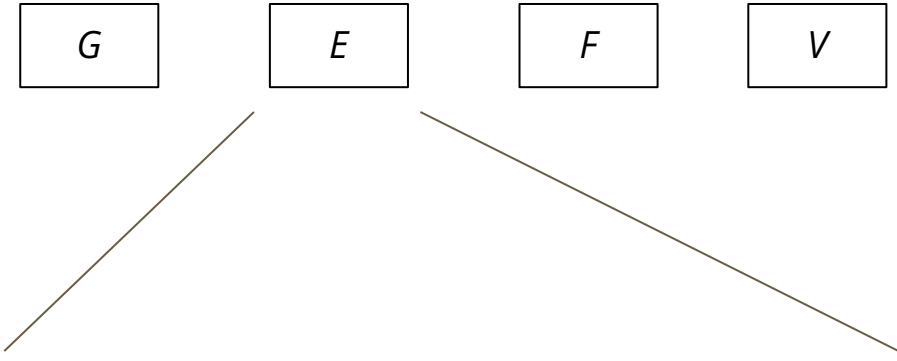
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



E		A	T	C	G	G	C
	-∞	-∞	-∞	-∞	-∞	-∞	-∞
A	-3_V	-6_V	-7_V	-8_V	-9_V	-10_V	-11_V
G	-4_E	-1_V	-4_V	-5_V	-6_V	-7_V	-8_V
C	-5_E	-2_E	-2_V	-5_V	-3_V	-4_V	-7_V

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

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

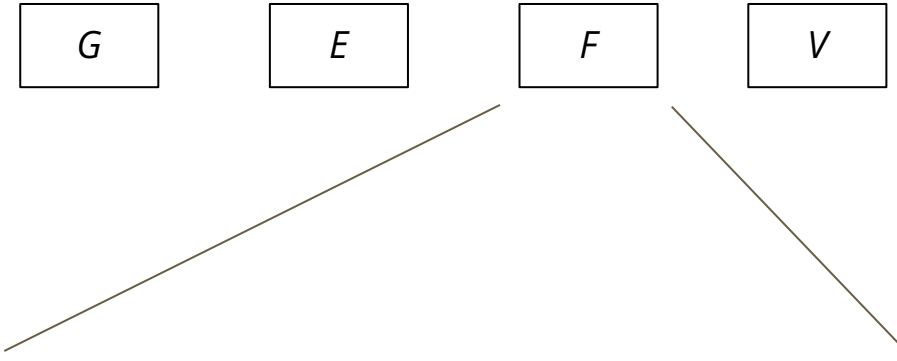
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V	-4_V	-2_V	-3_F	-3_V	-4_V
C	-∞	-8_V	-5_V	-5_V	0_V	-1_F	-2_F

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

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

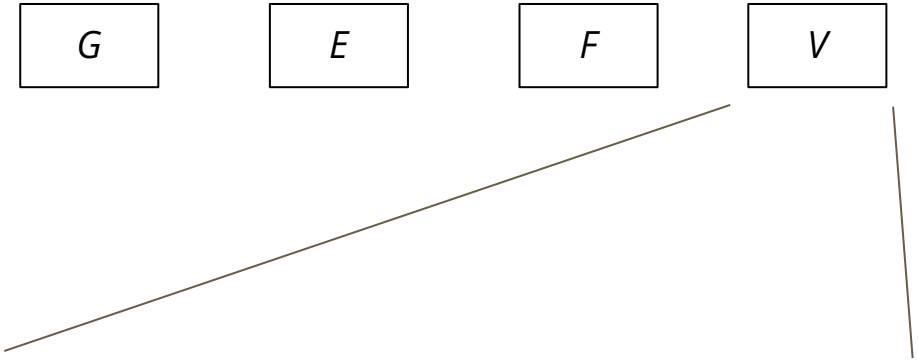
$$E(i,j) \leftarrow \max \begin{cases} E(i,j-1) - \tau \\ V(i,j-1) - \gamma - \tau \end{cases}$$

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

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

end

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



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

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

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

Traceback

We use the backpointers in our matrices 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* → recover a match/mismatch; recurse on *V(i-1, j-1)*
- If argmax = *E* → recover a gap in *X*; follow the backpointers of *E(i,j)* recursively, inserting gaps in *X* until we return to *V*; recurse
- If argmax = *F* → recover a gap in *Y*; follow the backpointers of *F(i,j)* recursively, inserting gaps in *Y* until we return to *V*; recurse

X sequence

Y sequence

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

Score:

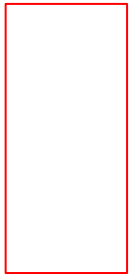
+1

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



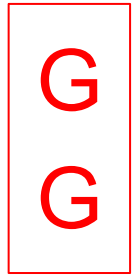
C

C

Score:

+1

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



C

C

Score:

+1

Here you hit the backpointer referencing *F* matrix. So you must continue backtracking through the *F* matrix.

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

G C

G C

Score:

+1

We switched to the *F* matrix.

F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V	-4_V	-2_V	-3_F	-3_V	-4_V
C	-∞	-8_V	-5_V	-5_V	0_V	-1_F	-2_F

G C

G C

Score:

+1

F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V	-4_V	-2_V	-3_F	-3_V	-4_V
C	-∞	-8_V	-5_V	-5_V	0_V	-1_F	-2_F

G G C

– G C

Score:

+1

F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V	-4_V	-2_V	-3_F	-3_V	-4_V
C	-∞	-8_V	-5_V	-5_V	0_V	-1_F	-2_F

G G C

– G C

Score:

+1

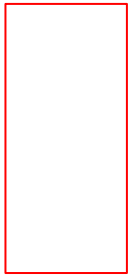
F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V	-4_V	-2_V	-3_F	-3_V	-4_V
C	-∞	-8_V	-5_V	-5_V	0_V	-1_F	-2_F

C	G	G	C
–	–	G	C

Score:
+1

Here you hit the backpointer referencing *V* matrix. So you must continue backtracking through the *V* matrix

F		A	T	C	G	G	C
	-∞	-3_V	-4_F	-5_F	-6_F	-7_F	-8_F
A	-∞	-6_V	-1_V	-2_F	-3_F	-4_F	-5_F
G	-∞	-7_V	-4_V	-2_V	-3_F	-3_V	-4_V
C	-∞	-8_V	-5_V	-5_V	0_V	-1_F	-2_F



C G G C

– – G C

Score:

+1

We switched to the *V* matrix.

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

A	T	C	G	G	C	Score:
A	–	–	–	G	C	+1

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

A	T	C	G	G	C	Score:
A	–	–	–	G	C	+1

Results:

A	T	C	G	G	C
A	–	–	–	G	C

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