

RNA secondary structures can be represented using a graph notation, where nodes represent nucleotides and edges encode the molecule’s backbone or intramolecular base pairs between nucleotides. Below, an RNA molecule graph is depicted that encodes base pairs in blue.

Position 23 represents the 5'-end

**Solution** wrong; We always encode in the 5' (=1) to 3' (=n) direction.

the graph is invalid

1

**Solution** wrong

1c)

contains invalid base pairs

**Hide**

**Solution** wrong; all base pairs depicted in the graph are valid

1d)

contains a pseudoknot

**Hide**

**Solution** wrong; There are no pseudoknot structures in this graph.

1e)

non-crossing

**Hide**

**Solution** correct; There are no pseudoknot structures in this graph.

1f)

nested

**Hide**

**Solution** correct

1g)

contains base pair (5,12)

**Hide**

**Solution** wrong; Position 5 is unpaired.

1h)

contains base pair (4,13)

**Hide**

**Solution** correct

1i)

base pair (1,10) would be crossing

**Hide**

**Solution** correct

1j)

obeys a minimal loop length of 4

**Hide**

**Solution** wrong; The minimum loop length for this graph is 3. (number of unpaired bases in loops)

1k)

encoded by  $((\dots).((((\dots))).))$ .

**Hide**

**Solution** wrong

11)

encoded by  $.(((.((\dots))))).((\dots))$

**Hide**

**Solution** correct

## Exercise 2

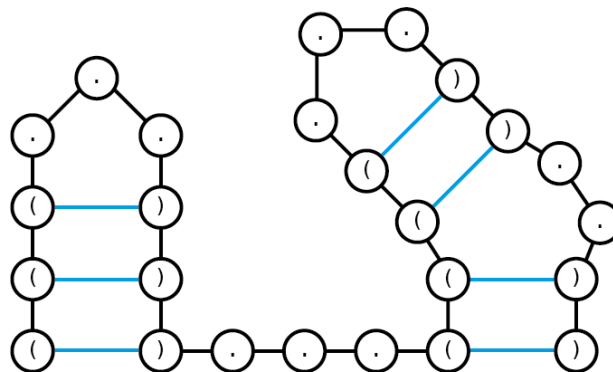
You are given the following dot-bracket string:  $(((\dots)))\dots(((\dots))\dots)$

2a)

Draw graph representations of all nested structures that can be encoded by the dot-bracket string. Assume a minimal loop length of 3.

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**Solution**



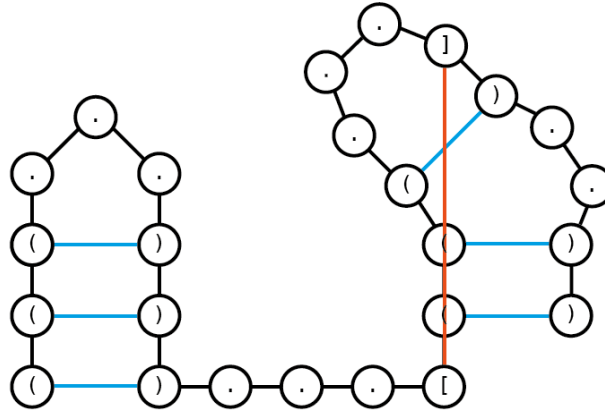
This is the only possible nested structure based on the dot-bracket string given.

2b)

Draw a graph representation of one possible crossing structure that can be encoded by the dot-bracket string. Assume a minimal loop length of 3.

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Solution



Dot-bracket string:  $((((...)))...[(((...))..))$

There are multiple other possible crossing structures. (e.g.  $((((...)))...[(((<...])..>))$  )

### Exercise 3

Given the following partially filled Nussinov matrix  $N$  using a minimal loop length  $l = 0$ , i.e. neighbored nucleotides are allowed to pair.

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

3a)

What are the values of the green and red entry?

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**Solution** green: 2

red: 1

**3b)**

How many tracebacks exist for the red entry using the original recursion by Nussinov?

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**Solution** There exist two tracebacks for the red entry; pairing with either G.

## Exercise 4

Given any matrix  $N$  filled by Nussinov's algorithm for and RNA sequence  $S$  of length  $n$ . Discuss which of the following statements are correct or wrong.

The entry  $N_{1,n}$  of the Nussinov matrix encodes ...

**4a)**

... the optimal structure.

**Hide**

**Solution** wrong; It only encodes the base pair number for the optimal structure.

**4b)**

... the minimum free energy (mfe) structure.

**Hide**

**Solution** wrong; No energy minimization is done.

**4c)**

... the maximal number of base pairs for sequence  $S_1..S_n$ .

**Hide**

**Solution** correct

4d)

... the traceback end.

**Hide**

**Solution** wrong; It encodes the traceback start.

4e)

... the maximal number of base pairs for any structure.

**Hide**

**Solution** correct

4f)

... information for a unique structure.

**Hide**

**Solution** wrong; Typically there is more than one optimal structure with maximal number of base pairs.

## Exercise 5

$$\begin{aligned}
 \text{Diagram 1} &= \max \left\{ \text{Diagram 2}, \text{Diagram 3} \right\} \\
 \text{Diagram 2} &= \begin{cases} \text{Diagram 4} + 1 & \text{if } S_i \text{ and } S_j \text{ are compl.} \\ 0 & \text{else} \end{cases} \\
 \text{Diagram 3} &= \max_{i \leq k < j} \left\{ \text{Diagram 5} \right\}
 \end{aligned}$$

The diagrams represent sequence alignment subproblems. Diagram 1 is a wavy line between points  $i$  and  $j$ . Diagram 2 is a smooth curve between  $i$  and  $j$ . Diagram 3 is a wavy line between  $i$  and  $j$  with a gap. Diagram 4 is a smooth curve between  $i+1$  and  $j-1$ . Diagram 5 shows two subproblems: a smooth curve between  $i$  and  $k$ , and a wavy line between  $k+1$  and  $j$ .

5a)

Provide all recursion and initialization details for the following recursion depictions. Note, also ensure a minimal loop length  $l$  within your recursions.

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Solution

$$\begin{aligned}
 N_{i,i} &= N_{i,i-1} = 0 \quad (\text{no init for } B \text{ and } D \text{ needed}) \\
 \forall 1 \leq i < j \leq n : N_{i,j} &= \max \{B_{i,j}, D_{i,j}\} \\
 B_{i,j} &= \begin{cases} N_{i+1,j-1} + 1 & \text{if } i + l < j \wedge S_i, S_j \text{ compl.} \\ 0 & \text{else} \end{cases} \\
 D_{i,j} &= \max_{i \leq k < j} \{B_{i,k} + N_{k+1,j}\} \quad (\text{only valid for } i < j)
 \end{aligned}$$