

# Les Acides RiboNucléiques (ARN)

- molécules composées de nucléotides **A**dénine, **C**ytosine, **G**uanine et **U**racile
- transcrits comme des copies de portions de l'ADN

## Tailles très variables :

- de 20 nucléotides (nts) à 3 000 nts environ dans la cellule
- pouvant même atteindre jusqu'à 30 000 nts pour les génomes entiers (virus)

## Grande variété de rôles joués par l'ARN au sein de la cellule :

- Médiateur de l'information génétique (ARN messagers)
- Partie-prenante de la machinerie traductionnelle (ARN ribosomaux, ARN de transfert)
- Acteur de la régulation (interférence par ARN)
- ...

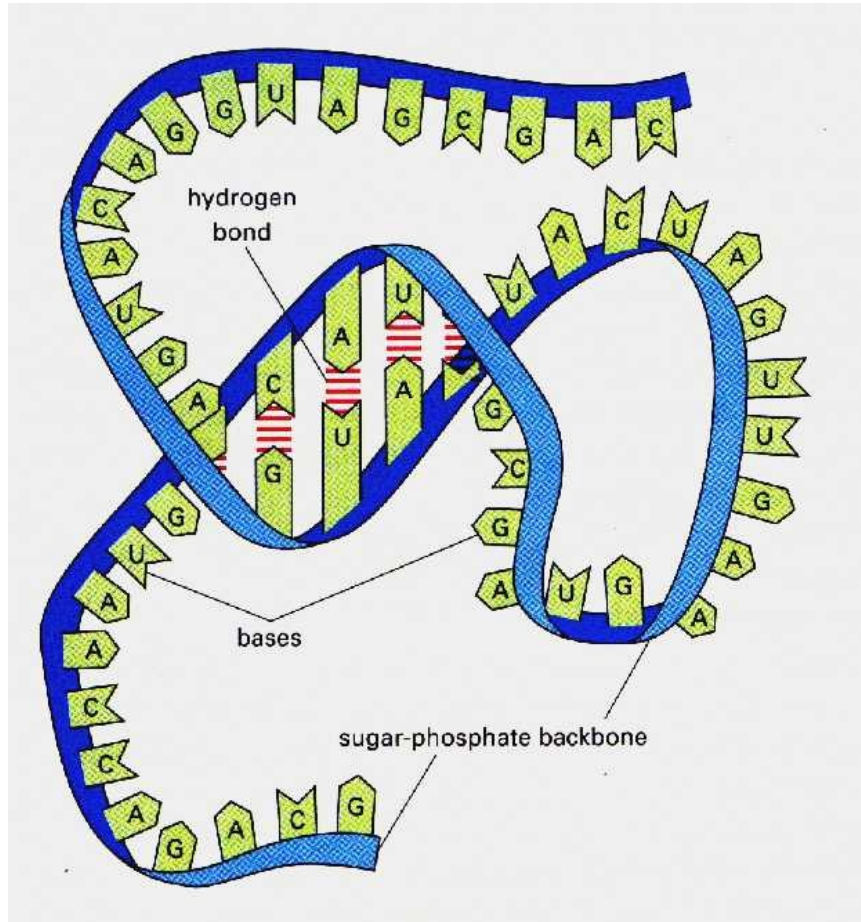
### ARN codants

information nécessaire à la synthèse d'une protéine

### ARN non-codants

se replient sur eux-mêmes pour adopter une conformation spatiale qui **détermine leur fonction**

# Structure des ARN



## Copie simple-brin

**Séquence:** mot sur {A, U, C, G} orienté de 5' en 3'

**Structure:** formation de liaisons hydrogènes entre deux nucléotides

Watson-Crick : A-U, C-G

faible : G-U  
U-C, G-A , . . .

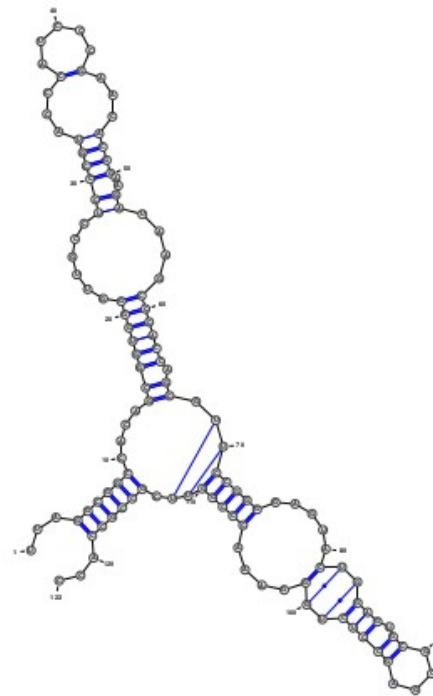
**Pas** de croisement entre les appariements

**La** structure est fonctionnellement importante

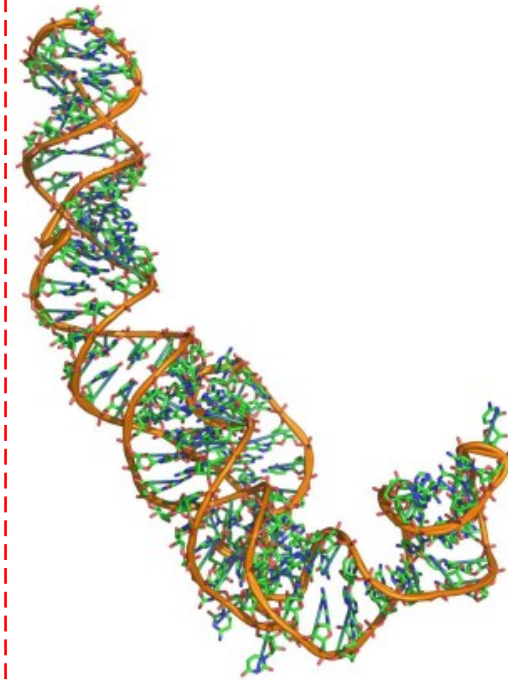
# Structure des ARN 1/4

UUAGGCGGCCACAGC  
GGUGGGGUUGCCUCC  
CGUACCCAUCCCGAA  
CACGGAAGAUAAAGCC  
CACCAGCGUUCCGGG  
GAGUACUGGAGUGCG  
CGAGCCUCUGGGAAA  
CCCGGUUCGCCGCCA  
CC

Structure Primaire  
(Séquence)



Structure Secondaire  
(Couplage partiel)

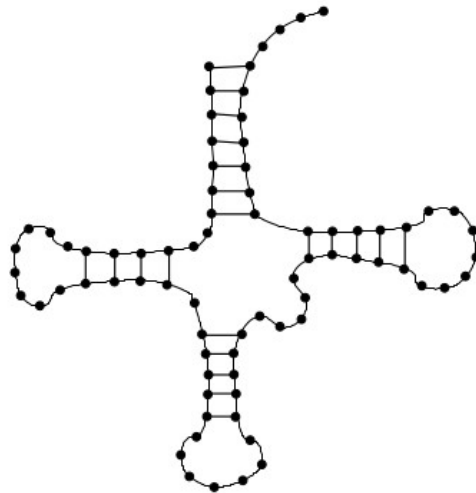
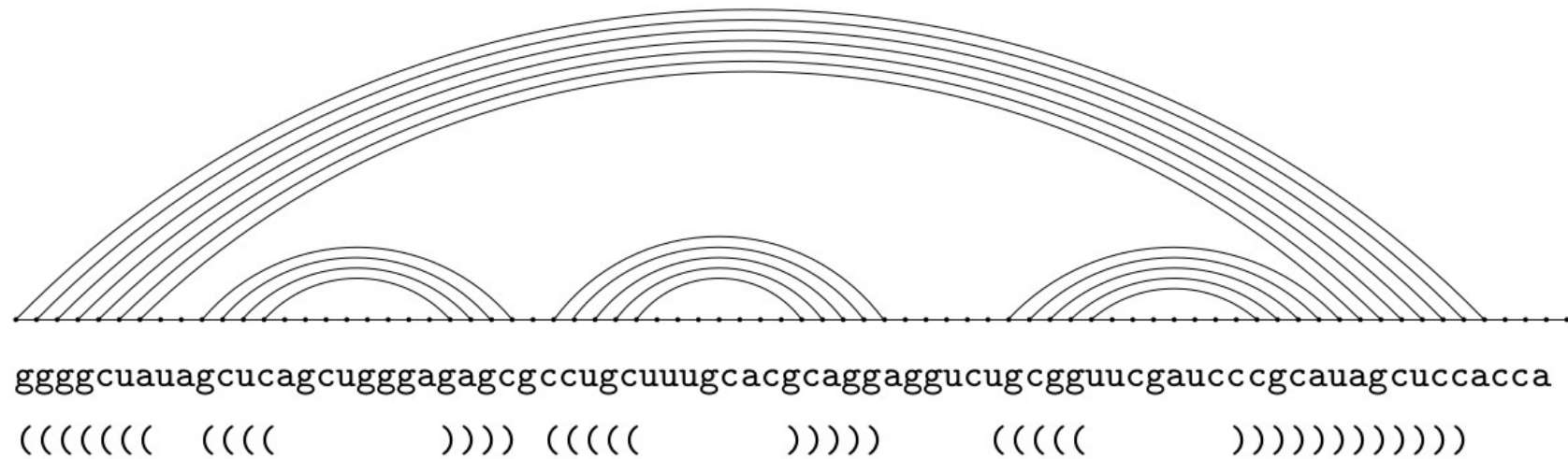


Structure Tertiaire  
(Objet 3D)

Trois principaux niveaux de représentation pour un ARN ribosomal

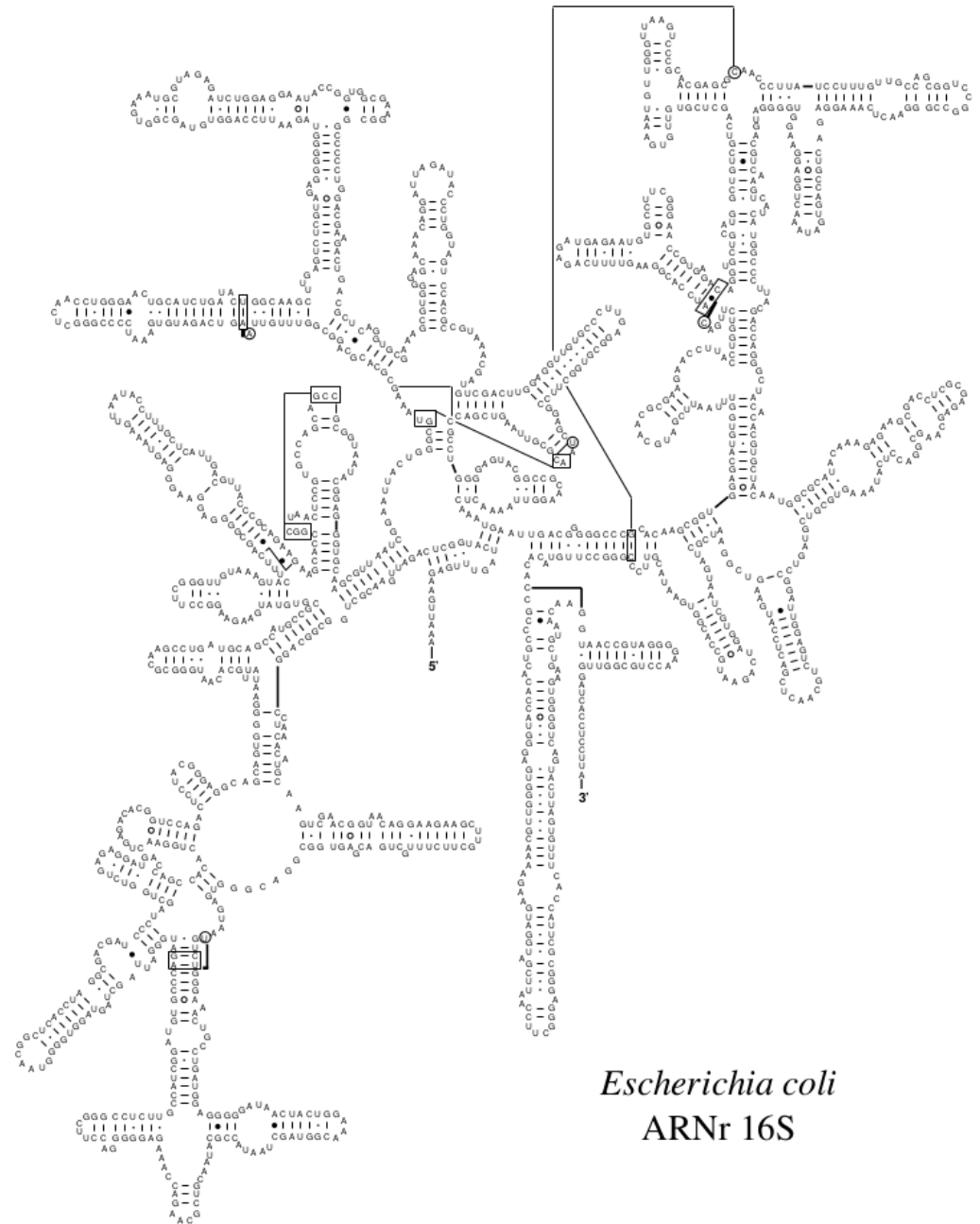
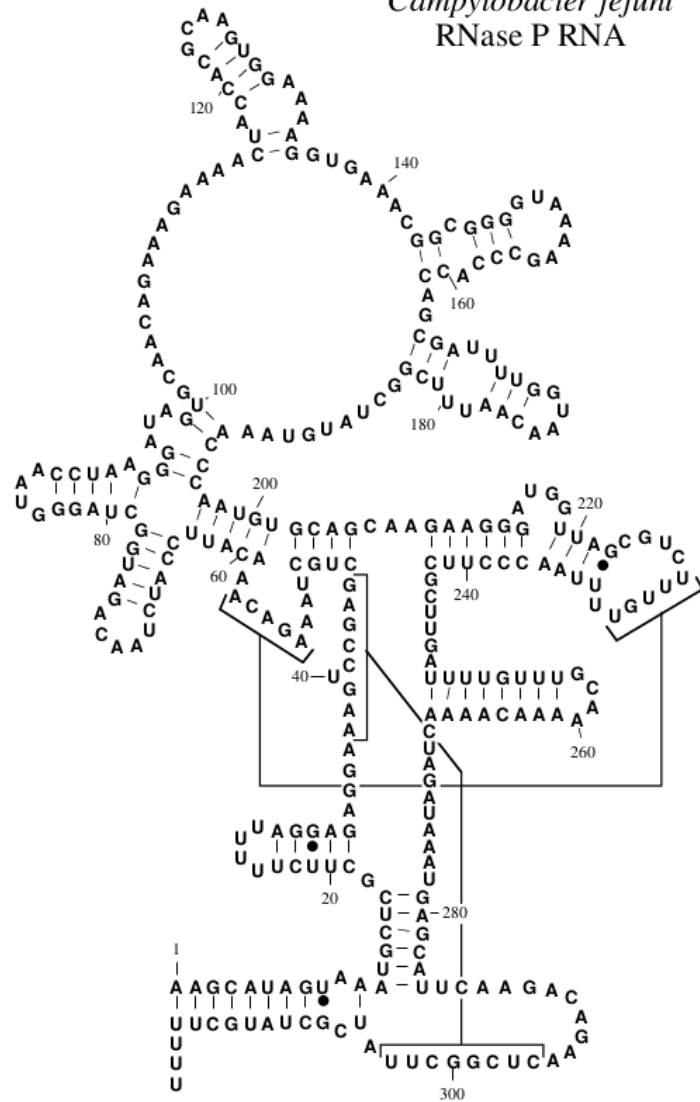
# Structure des ARN 2/4

**Exemple :** ARN de transfert (Alanine – E. coli)



# Structure des ARN 3/4

*Campylobacter jejuni*  
RNase P RNA



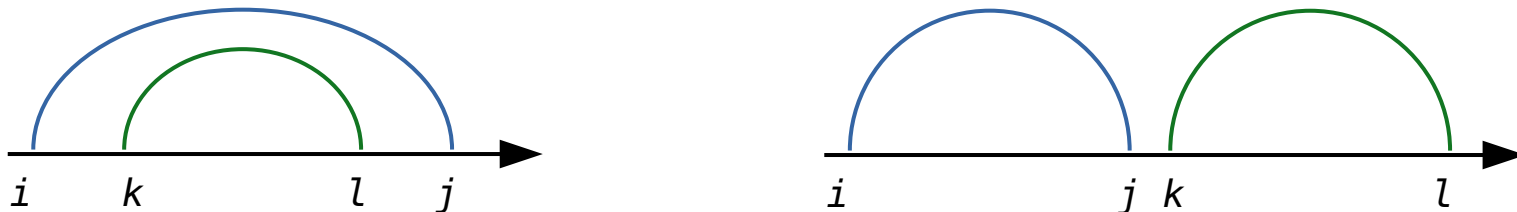
*Escherichia coli*  
ARNr 16S

# Structure des ARN 4/4

Formellement, une **structure secondaire** est un ensemble  $S$  de paires de bases satisfaisant les contraintes suivantes :

1. **Distance minimale  $\theta$**  : Si  $(i, j) \in S$ , alors on a  $j - i > \theta$
2. **Monogamie** : Toute position est impliquée dans *au plus* une paire de  $S$
3. **Croisements interdits** : Si  $(i, j), (k, l)$  telles que  $i < k$ , alors on a

$$i < k < l < j \quad \text{ou} \quad i < j < k < l$$





# Formats de fichiers pour stocker les structures

## Format parenthésé

```
>RA7680
GGGGGCGUAGCUCAGAUGGUAGAGCGCUCGCUUgGCgUGUGAGAGGUACCGGGAUCGaUACCCGGCGCCUCCACCA
(((((((..((((.....))))).((((.....))))). ....((((.....)))))))). ....
>sequence_test
ggggaaaccagguucguuucggucaagacaaccc
((((.....))).(((((((.....))((.....)))))).
>sequence_test2
GCAAAAAGCUUAAGGGAAAACCUCCAUAUCCCC
((((.....))..((((.....))(.))))....
>sequence_test3
CAGAGUAUGAUCACGGUUUCACCUUGGUACAGGGCGUCCACUGCACUCUG
(((((((..((((.(.....)).))))).((((.....)).)).)).))))))
```

GGCUUUUGCAUACCCUCGG  
(((.....))..(.....)).. => **OK**

GGCUUUUGCAUACCCUCGG  
((((.....))..(.)).. => **PAS OK**

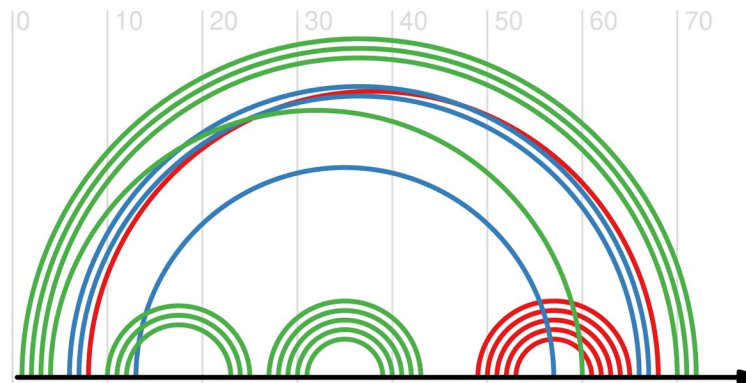
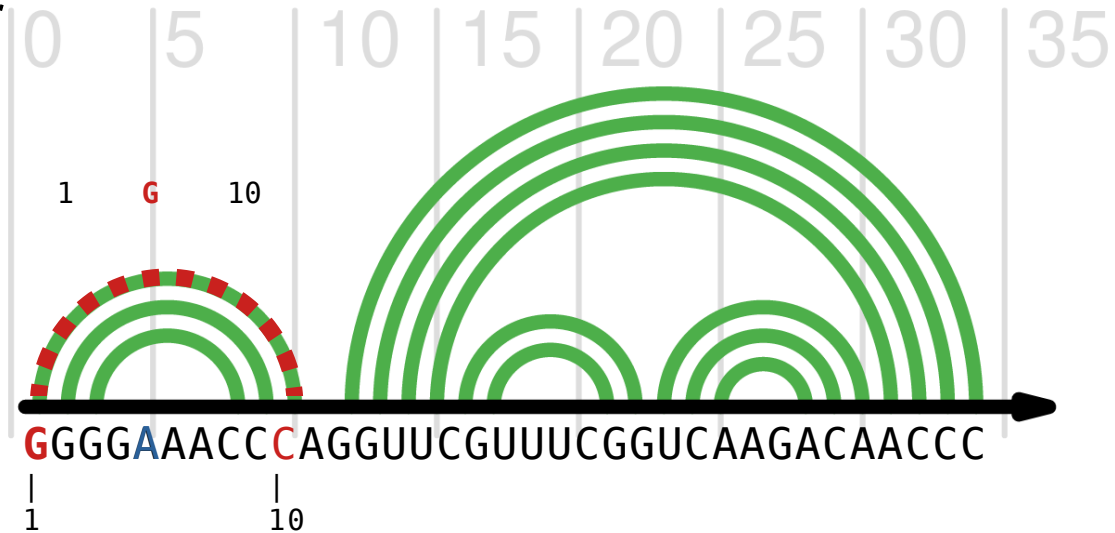
G**G**CUUUUG**G**AUACCCUCGG  
(((.....))..(.....)).. => **PAS OK**

G=C  
A=U  
G=U

# Formats de fichiers pour stocker les structures

Format CT (connect)

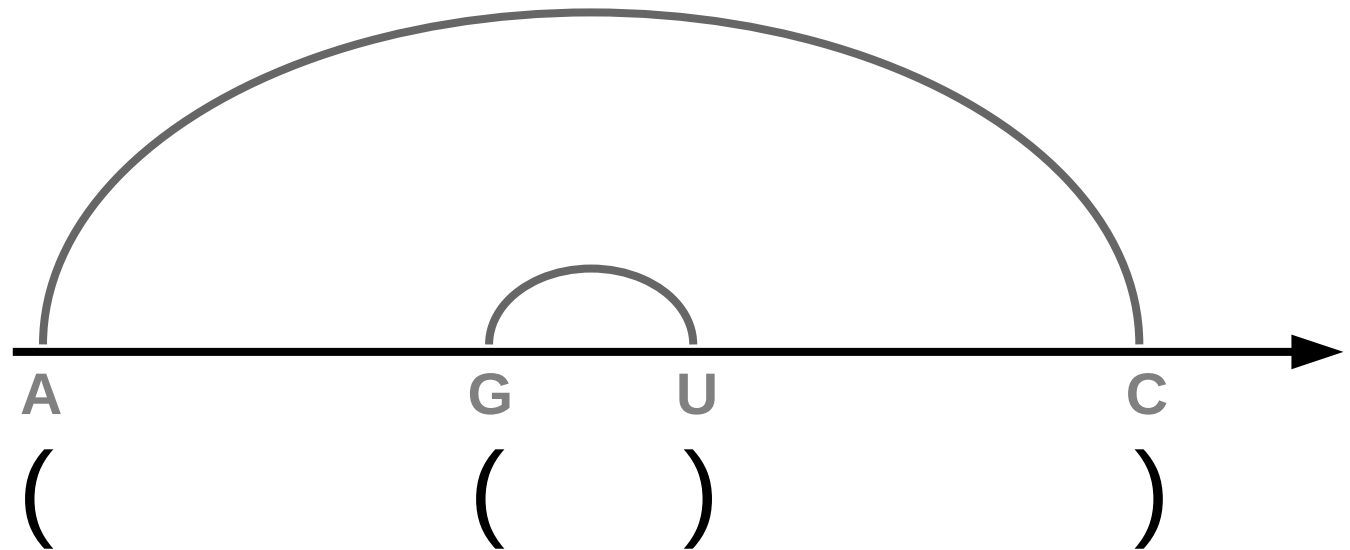
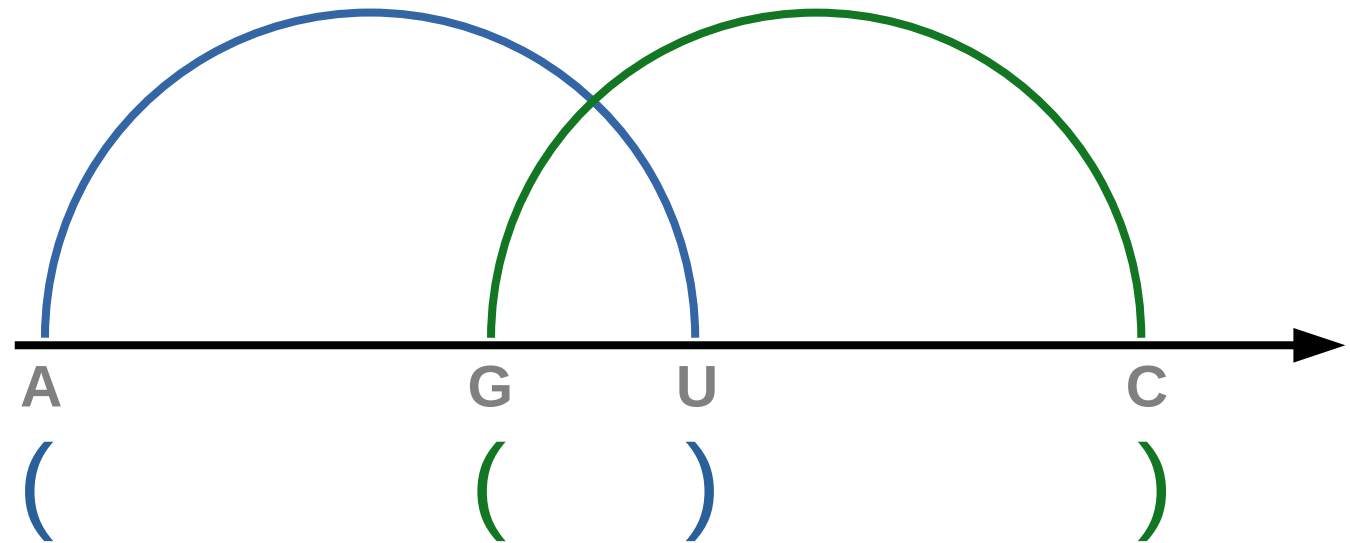
|    |   |    |
|----|---|----|
| 1  | g | 10 |
| 2  | g | 9  |
| 3  | g | 8  |
| 4  | g | 0  |
| 5  | a | 0  |
| 6  | a | 0  |
| 7  | a | 0  |
| 8  | c | 3  |
| 9  | c | 2  |
| 10 | c | 1  |
| 11 | a | 0  |
| 12 | g | 34 |
| 13 | g | 33 |
| 14 | u | 32 |
| 15 | u | 31 |
| 16 | c | 22 |
| 17 | g | 21 |
| 18 | u | 0  |
| 19 | u | 0  |
| 20 | u | 0  |
| 21 | c | 17 |
| 22 | g | 16 |
| 23 | g | 30 |
| 24 | u | 29 |
| 25 | c | 28 |
| 26 | a | 0  |
| 27 | a | 0  |
| 28 | g | 25 |
| 29 | a | 24 |
| 30 | c | 23 |
| 31 | a | 15 |
| 32 | a | 14 |
| 33 | c | 13 |
| 34 | c | 12 |
| 35 | c | 0  |



Vérifier la distance minimale entre  
deux positions appariées > 3



# Formats de fichiers pour stocker les structures



# Comment déterminer la structure d'une molécule ?

→ **Structure primaire** : séquençage

→ **Structure secondaire et tertiaire**

→ Expérimentalement : cristallographie par diffraction à rayons X,

résonance magnétique nucléaire (RMN)

Long, difficile et coûteux

→ Par bio-informatique: algorithmes de prédiction de structures secondaires

**Approche thermodynamique**

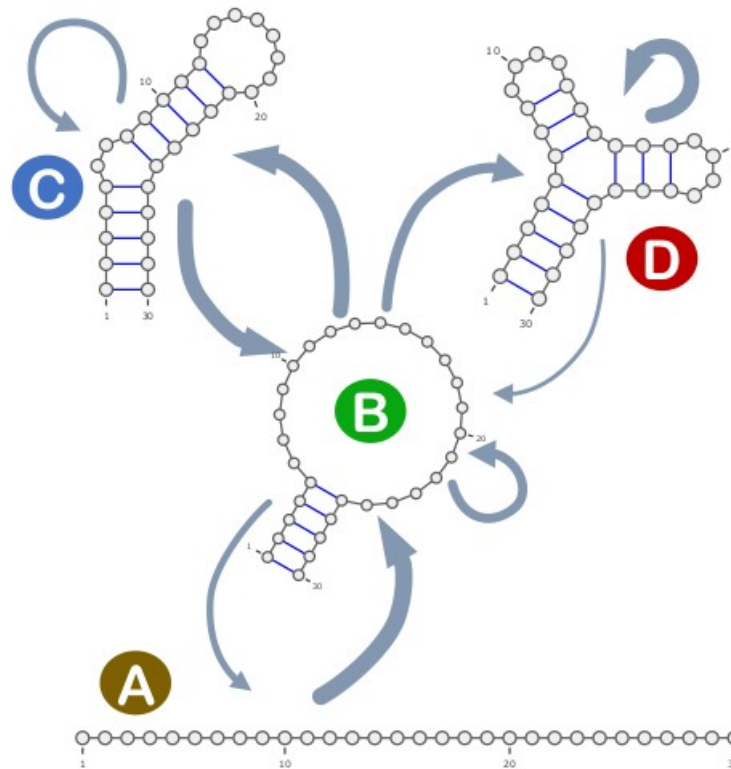
# Approche thermodynamique

- **Trois hypothèses :**

- À chaque configuration de la molécule correspond un nombre de liaisons hydrogènes (*quantité d'énergie libre*).
- La configuration la plus stable est celle qui maximise le nombre de liaisons hydrogènes (*minimise l'énergie libre*).
- La molécule, en se repliant, adopte la configuration la plus stable.

- On s'est ramené à un problème combinatoire : trouver la structure dont le nombre de liaisons hydrogènes (*l'énergie*) est optimale.

# Approche thermodynamique



1. **A** ARN transcrit sous une forme essentiellement déstructurée
2. Fluctue alors de façon stochastique entre ses différents états
3. Le système finit par atteindre l'équilibre thermodynamique => **D**

## Modèle initial (Nussinov - 1978)

→ L'énergie de la molécule est la somme des liaisons hydrogènes (*énergies*) de chaque paire de bases.

→  $\alpha(r_i, r_j)$  : nombre de liaisons hydrogènes (*énergie libre*) de l'appariement  $(r_i, r_j)$

$$\alpha(G, C) = 3 \qquad G \equiv C$$

$$\alpha(A, U) = 2 \qquad A = U$$

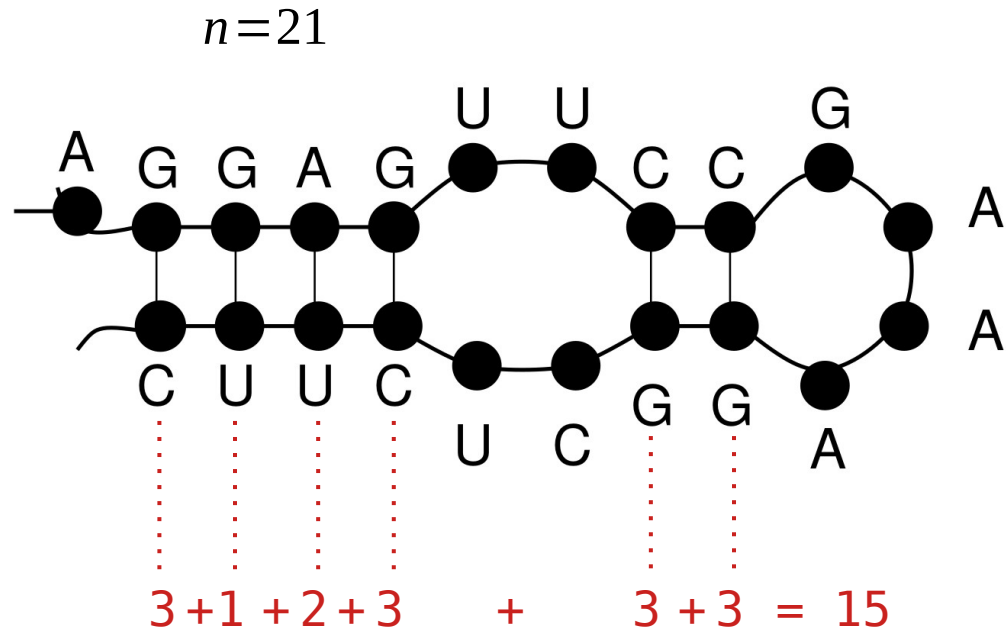
$$\alpha(G, U) = 1 \qquad G - U$$

→ Nombre de liaisons hydrogènes (énergie libre) de la structure secondaire  $S$

$$L(S) = \sum_{(r_i, r_j) \in S} \alpha(r_i, r_j)$$

Minimisation de l'énergie  $\Leftrightarrow$  **Maximisation** du nombre de paires de bases.

## Exemple



$$\alpha(G, C) = 3$$

$$\alpha(A, U) = 2$$

$$\alpha(G, U) = 1$$

**Nombre total de liaisons hydrogènes : 15**

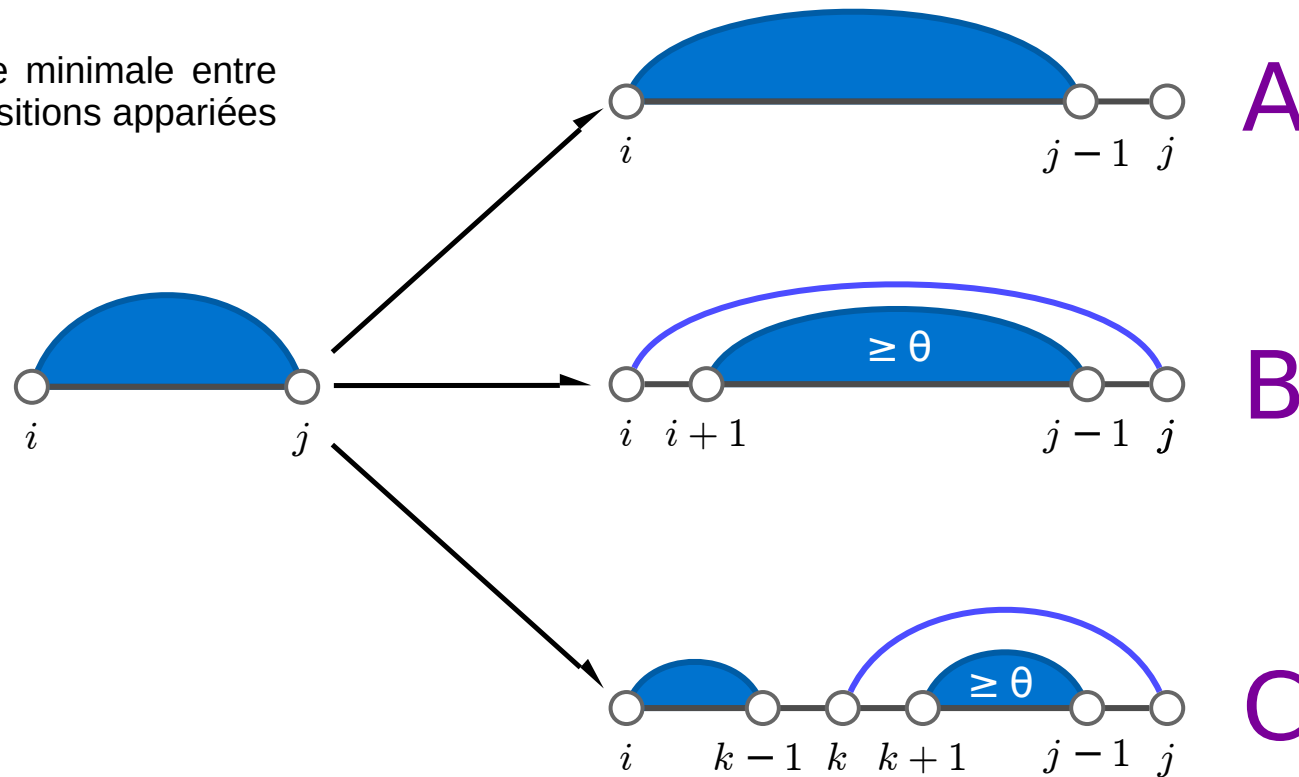
→ **Comment calculer la structure optimale ?**

le nombre de structures secondaires compatibles avec un ARN est, en moyenne, exponentiel sur la taille de celui-ci. **L'énumération des structures candidates est impossible !!**

**=> Programmation dynamique**

# Décomposition du problème en instance plus petites 1/2

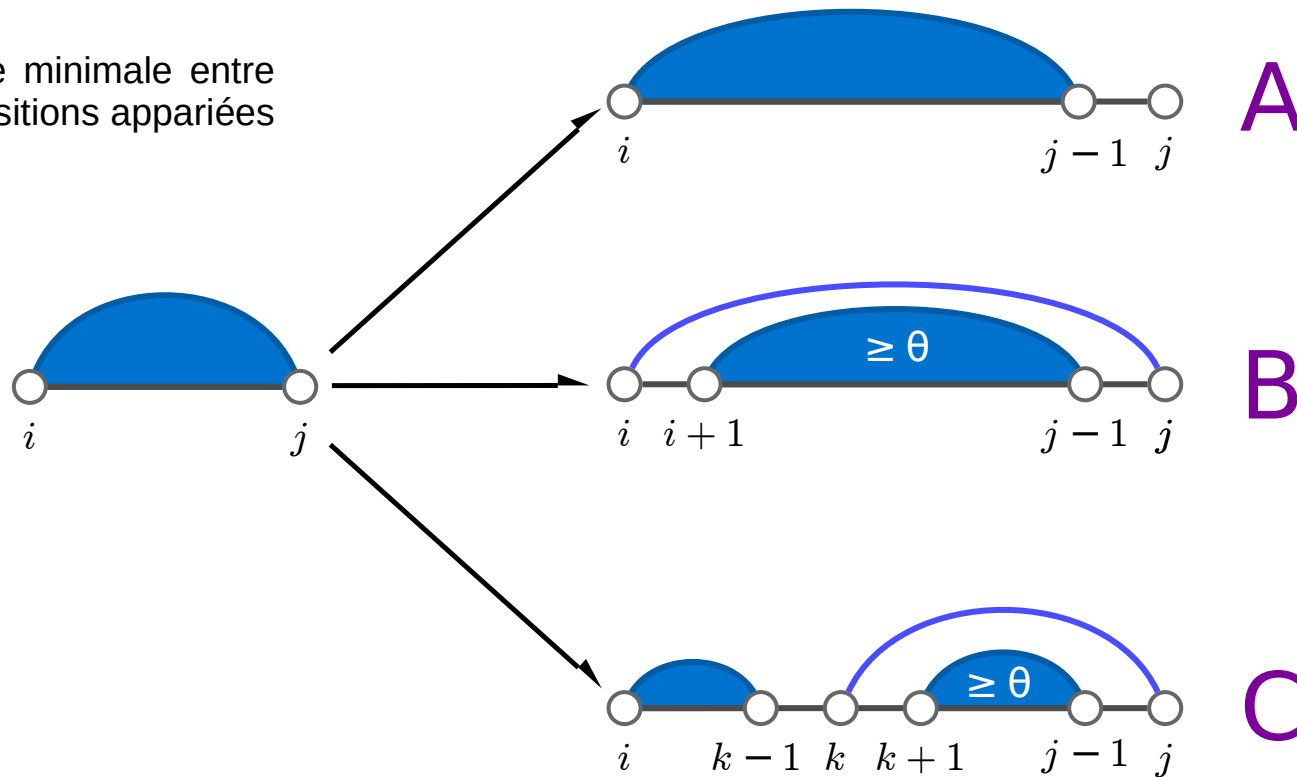
$\theta \Rightarrow$  distance minimale entre deux positions appariées



- **Cas A** Soit  $j$  libre, et précédé par une structure secondaire formée indépendamment sur la région  $[i, j-1]$
- **Cas B** Soit  $j$  est apparié à la position  $i$ ,  $j - i > \theta$ , et alors il se forme une structure secondaire sur la région  $[i + 1, j - 1]$
- **Cas C** Soit  $j$  est apparié à une position  $k$  avec  $i < k < j$ ,  $j - k > \theta$ , et des structures se forment alors dans les régions  $[i, k - 1]$  et  $[k + 1, j - 1]$ . Celles-ci sont indépendantes, du fait de l'interdiction des croisements

# Décomposition du problème en instance plus petites 2/2

$\theta \Rightarrow$  distance minimale entre deux positions appariées



- **Cas A**  $L(S_{i,j}) = L(S_{i,j-1})$
- **Cas B**  $L(S_{i,j}) = L(S_{i+1,j-1}) + \alpha(r_i, r_j)$
- **Cas C**  $L(S_{i,j}) = \max \{ L(S_{i,k-1}) + \alpha(r_k, r_j) + L(S_{k+1,j-1}), k \in ]i, j[ \}$



# construction de la table de programmation dynamique

→ Une table  $T$ , de dimension 2:  $T(i, j) = L(S_{i,j})$

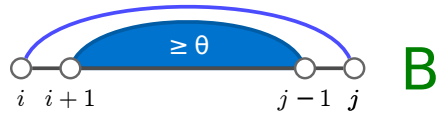
$$T(i, j) = \max \left\{ \begin{array}{l} T(i, j-1) \\ T(i+1, j-1) + \alpha(r_i, r_j) \\ \max \{ T(i, k-1) + \alpha(r_k, r_j) + T(k+1, j-1) \} \end{array} \right.$$

**Étape suivante** : construction de la structure secondaire optimale,  
par retour arrière

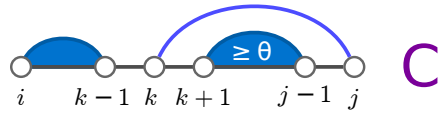
$$L(S_{i,j})=14 \quad \text{avec } i=0 \text{ et } j=17$$



**A**



**B**



**C**

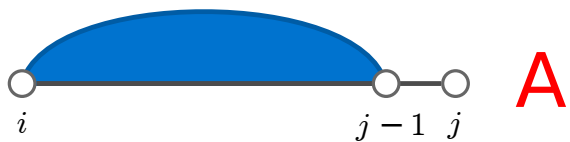
|    | j | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|----|---|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6 | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6 | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5 | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0 | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  |

- **Cas A**  $L(S_{i,j-1})=14$
- **Cas B**  $L(S_{i+1,j-1})+\alpha(r_i,r_j)=11$
- **Cas C**  $\max\{L(S_{i,k-1})+\alpha(r_k,r_j)+L(S_{k+1,j-1}), k \in ]i,j[ \} = 11 \quad \text{pour } k=8$

|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |

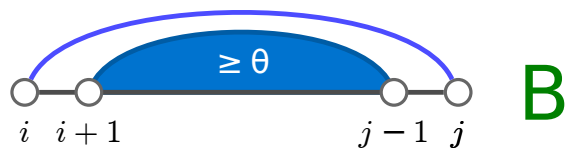
| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |



|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |

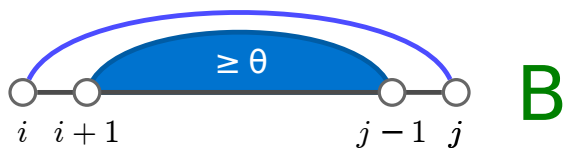
|    | j | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|----|---|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6 | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6 | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5 | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0 | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  |



|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( |   |   |   |   |   |   |   |   |    |    |    |    |    | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |

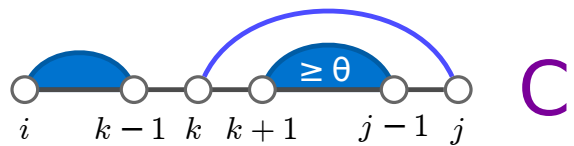
| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |



|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( |   |   |   |   |   | ( |   |   |    |    |    |    | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |
| k |

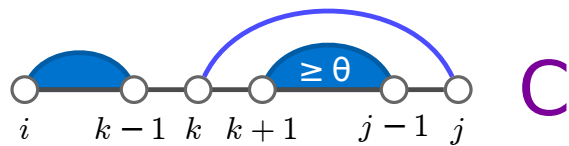
| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |



|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( |   |   |   |   |   | ( |   | ( |    |    |    | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

i  
j  
k

| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |



|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( |   |   |   |   |   | ( | . | ( |    |    |    | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

$i=j$

i  
j  
k

| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |

$$j-i \leq \theta \quad \text{avec } \theta=3$$



|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( |   |   |   |   |   | ( | . | ( |    |    | .  | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |
| k |

| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |

$$j-i \leq \theta \quad \text{avec } \theta=3$$

|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( |   |   |   |   |   | ( | . | ( |    | .  | .  | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |
| k |

| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |

$$j-i \leq \theta \quad \text{avec } \theta=3$$

|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( |   |   |   |   |   | ( | . | ( | .  | .  | .  | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

$i=j$

|   |
|---|
| i |
| j |
| k |

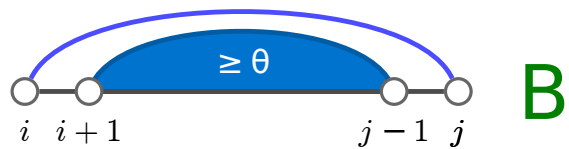
| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |

$$j-i \leq \theta \quad \text{avec } \theta=3$$

|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( | ( |   |   |   | ) | ( | . | ( | .  | .  | .  | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |
| k |

| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |



|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( | ( |   |   | . | ) | ( | . | ( | .  | .  | .  | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |
| k |

| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 0  | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |

$$j-i \leq \theta \quad \text{avec } \theta=3$$

|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( | ( |   | . | . | ) | ( | . | ( | .  | .  | .  | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

|   |
|---|
| i |
| j |
| k |

| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |    |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |    |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |    |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |    |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |

$$j-i \leq \theta \quad \text{avec } \theta=3$$

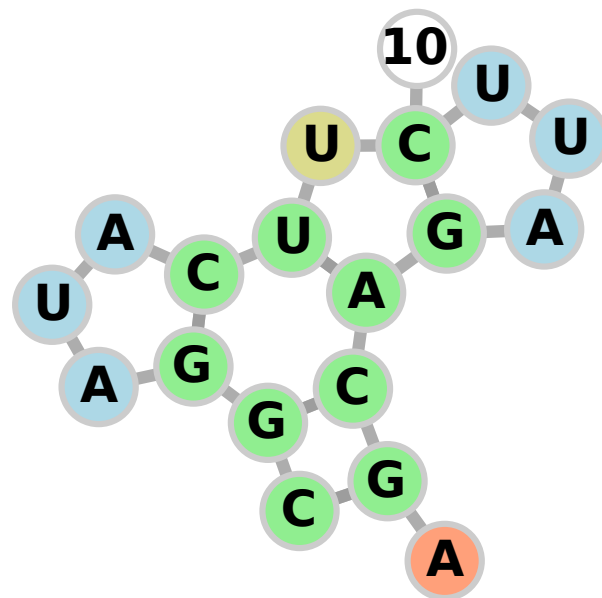
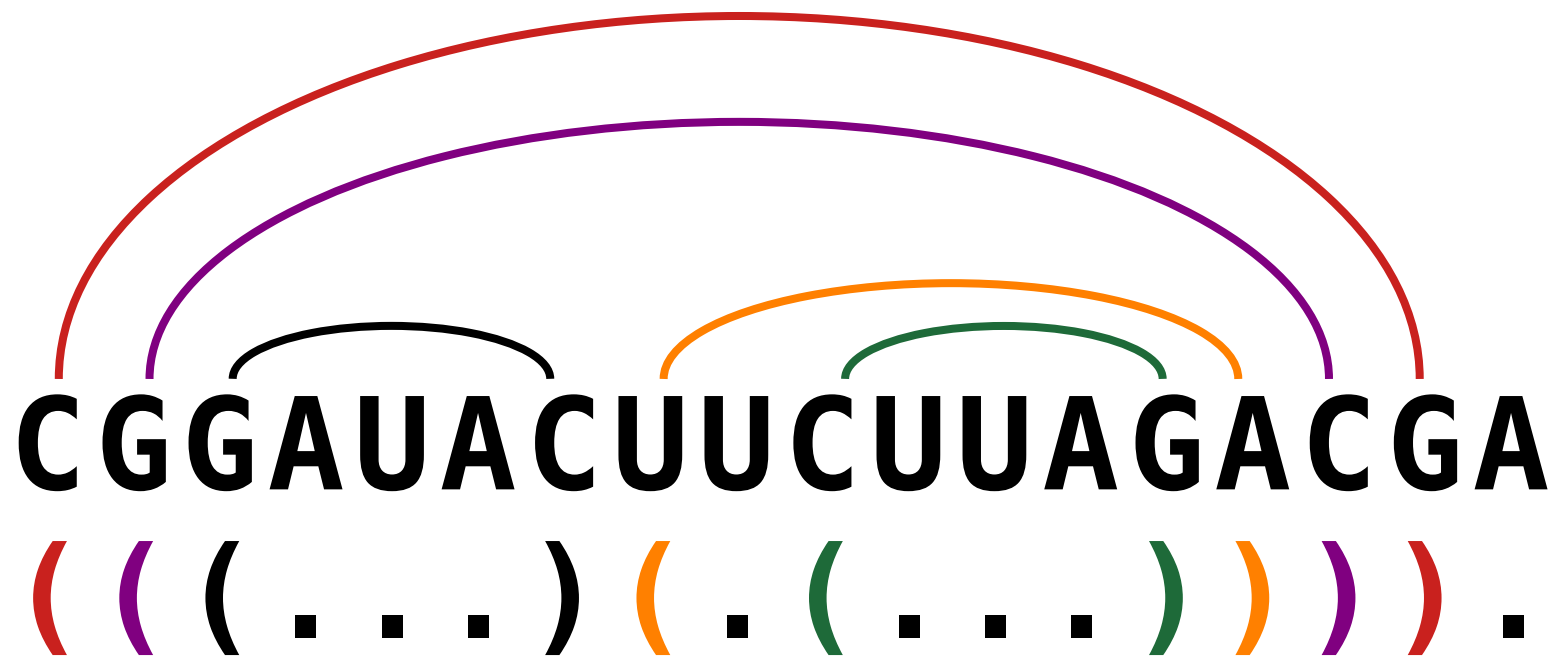
|   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|
| ( | ( | ( | . | . | . | ) | ( | . | ( | .  | .  | .  | )  | )  | )  | )  | .  |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |

$i=j$

|   |
|---|
| i |
| j |
| k |

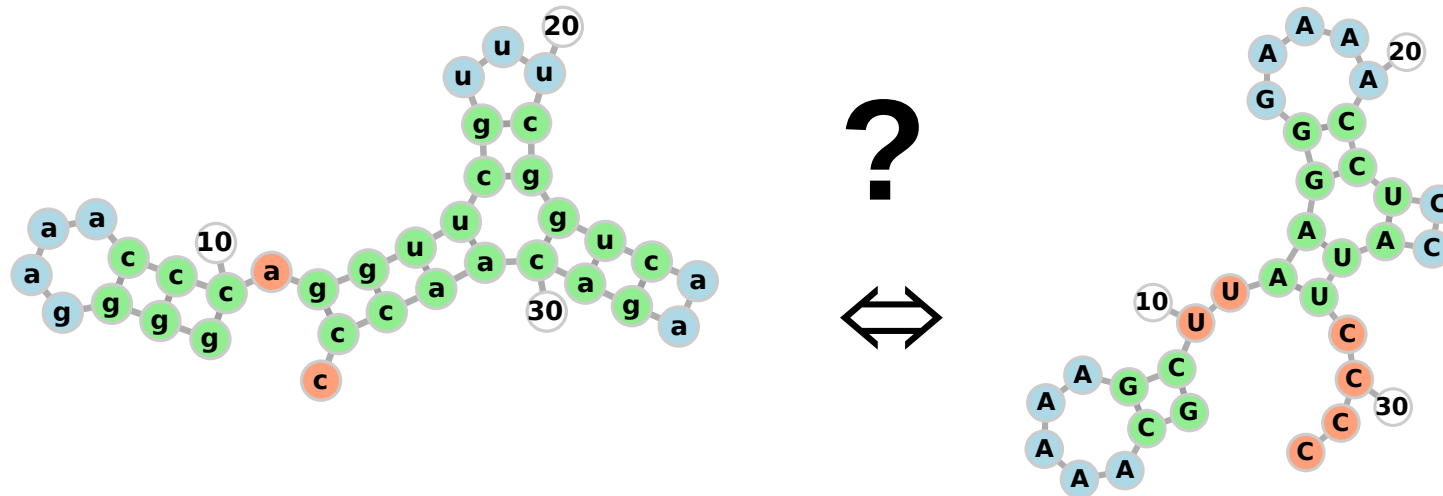
| j  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |    |
|----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| i  |   | C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| 0  | C | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 9  | 9  | 11 | 14 | 14 |
| 1  | G |   | 0 | 0 | 0 | 0 | 0 | 3 | 4 | 4 | 6  | 6  | 6  | 6  | 7  | 9  | 11 | 11 | 11 |
| 2  | G |   |   | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 5  | 5  | 5  | 5  | 6  | 8  | 10 | 10 | 10 |
| 3  | A |   |   |   | 0 | 0 | 0 | 0 | 2 | 2 | 2  | 2  | 4  | 4  | 5  | 7  | 7  | 8  | 10 |
| 4  | U |   |   |   |   | 0 | 0 | 0 | 0 | 0 | 2  | 2  | 4  | 5  | 7  | 7  | 8  | 10 |    |
| 5  | A |   |   |   |   |   | 0 | 0 | 0 | 0 | 2  | 2  | 2  | 5  | 5  | 5  | 8  | 8  |    |
| 6  | C |   |   |   |   |   |   | 0 | 0 | 0 | 0  | 0  | 2  | 5  | 5  | 5  | 8  | 8  |    |
| 7  | U |   |   |   |   |   |   |   | 0 | 0 | 0  | 0  | 2  | 3  | 5  | 5  | 6  | 7  |    |
| 8  | U |   |   |   |   |   |   |   |   | 0 | 0  | 0  | 2  | 3  | 5  | 5  | 5  | 7  |    |
| 9  | C |   |   |   |   |   |   |   |   |   | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 5  | 5  |
| 10 | U |   |   |   |   |   |   |   |   |   |    | 0  | 0  | 0  | 0  | 2  | 2  | 2  | 3  |
| 11 | U |   |   |   |   |   |   |   |   |   |    |    | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 12 | A |   |   |   |   |   |   |   |   |   |    |    |    | 0  | 0  | 0  | 0  | 0  | 0  |
| 13 | G |   |   |   |   |   |   |   |   |   |    |    |    |    | 0  | 0  | 0  | 0  | 0  |
| 14 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    | 0  | 0  | 0  | 0  |
| 15 | C |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    | 0  | 0  | 0  |
| 16 | G |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    | 0  | 0  |
| 17 | A |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    | 0  |

$$j-i \leq \theta \quad \text{avec } \theta=3$$





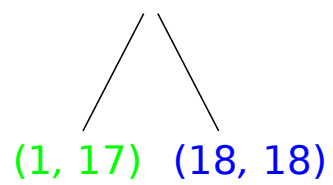
# Comparaison de structures



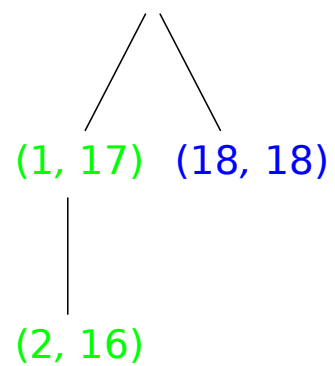
Comparer les structures :

- Avec le format parenthésé
- À l'aide d'une représentation sous forme d'arbre

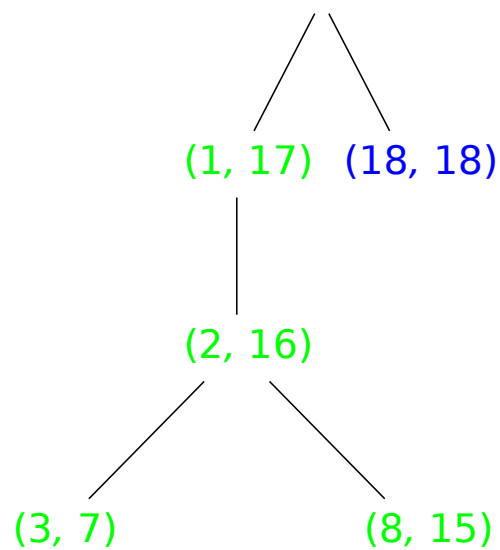
|   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| ( | ( | ( | . | . | . | ) | ( | . | (  | .  | .  | .  | )  | )  | )  | )  | .  |



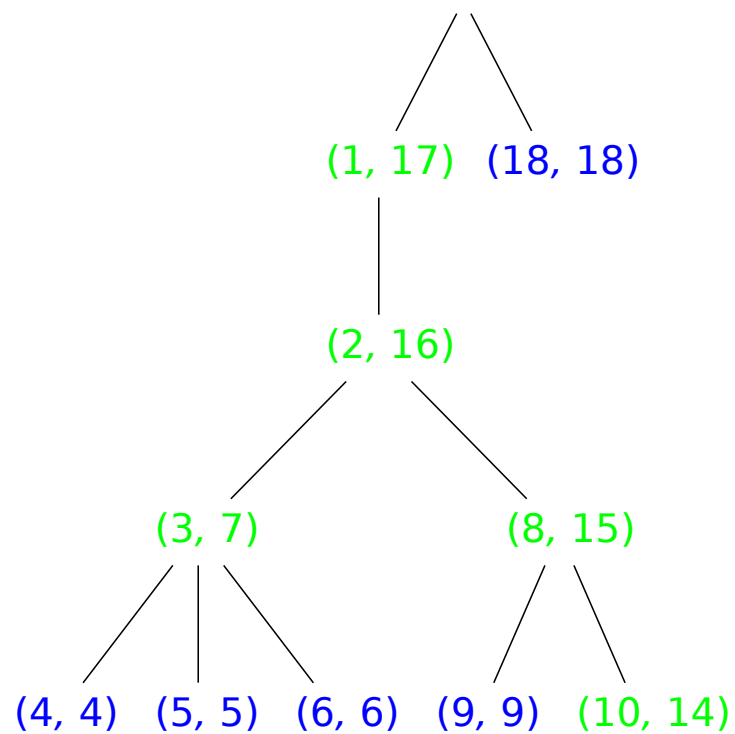
|   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| ( | ( | ( | . | . | . | ) | ( | . | (  | .  | .  | .  | )  | )  | )  | )  | .  |



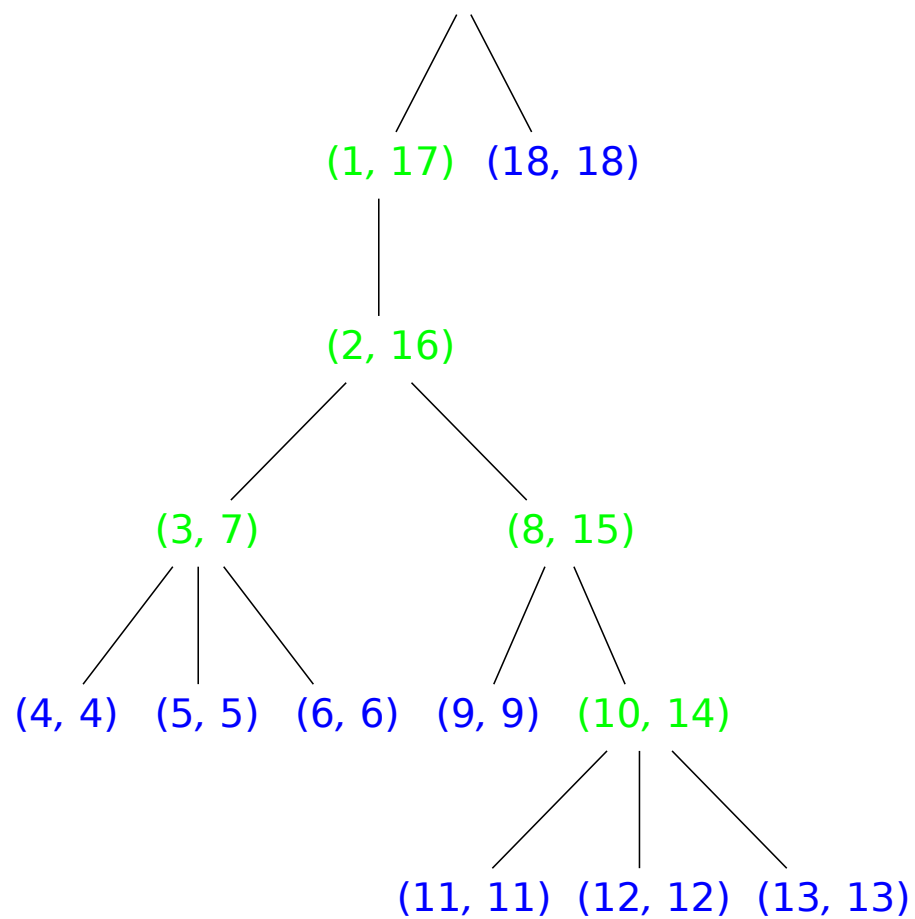
|   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| ( | ( | ( | . | . | . | ) | ( | . | (  | .  | .  | .  | )  | )  | )  | )  | .  |



|   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| ( | ( | ( | . | . | . | ) | ( | . | (  | .  | .  | .  | )  | )  | )  | )  | .  |



|   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |
|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| C | G | G | A | U | A | C | U | U | C  | U  | U  | A  | G  | A  | C  | G  | A  |
| ( | ( | ( | . | . | . | ) | ( | . | (  | .  | .  | .  | )  | )  | )  | )  | .  |



# Comparaison de structures

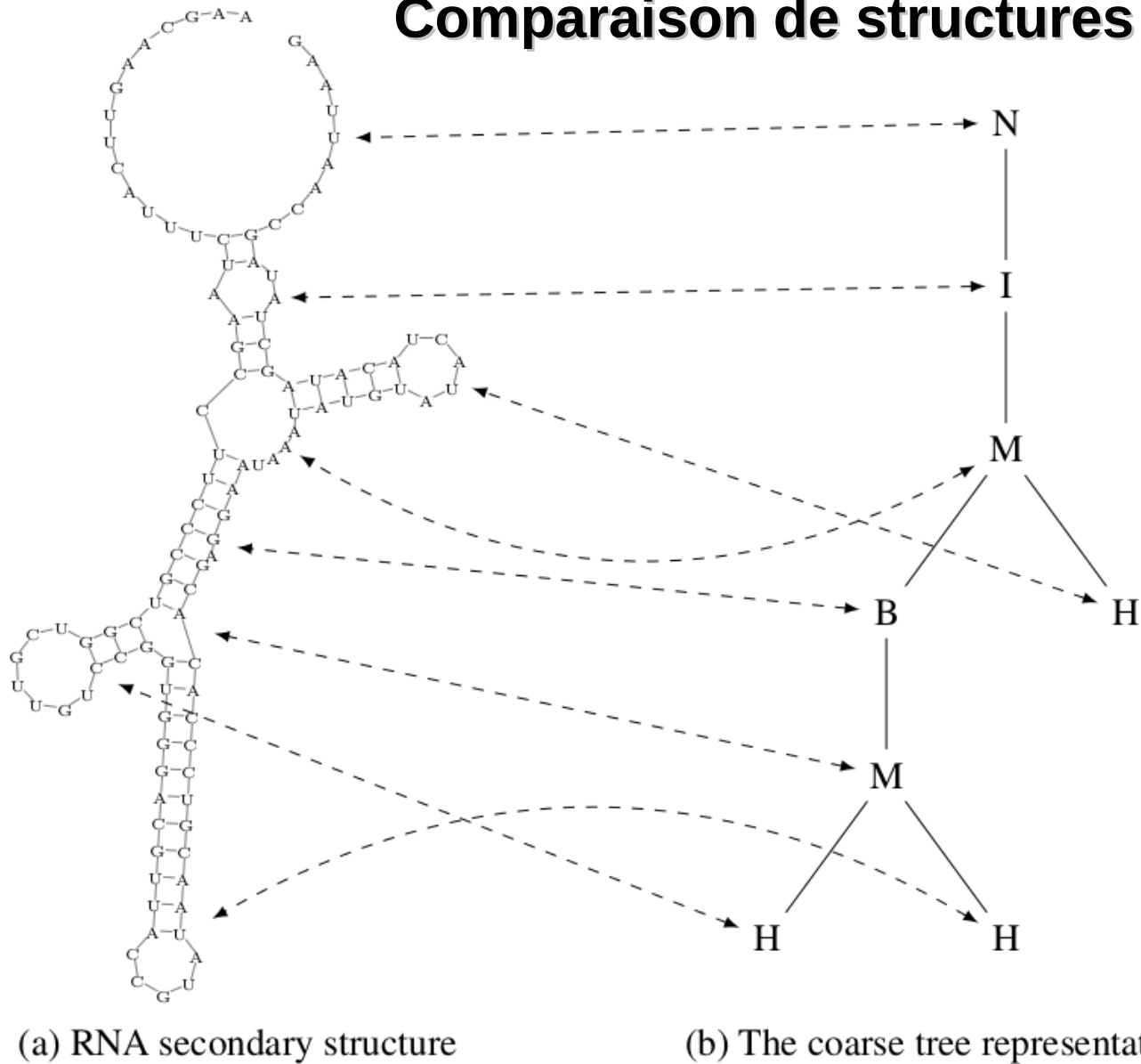
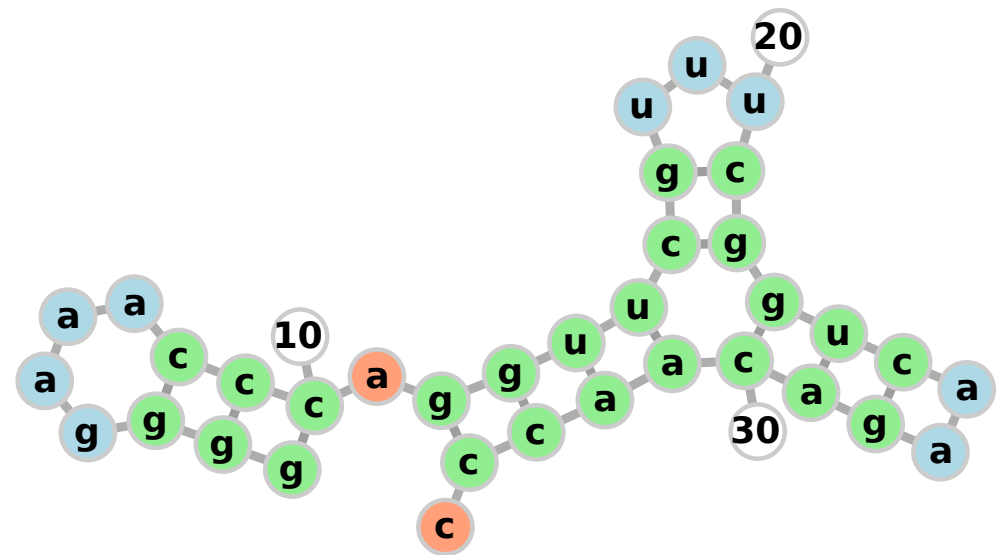
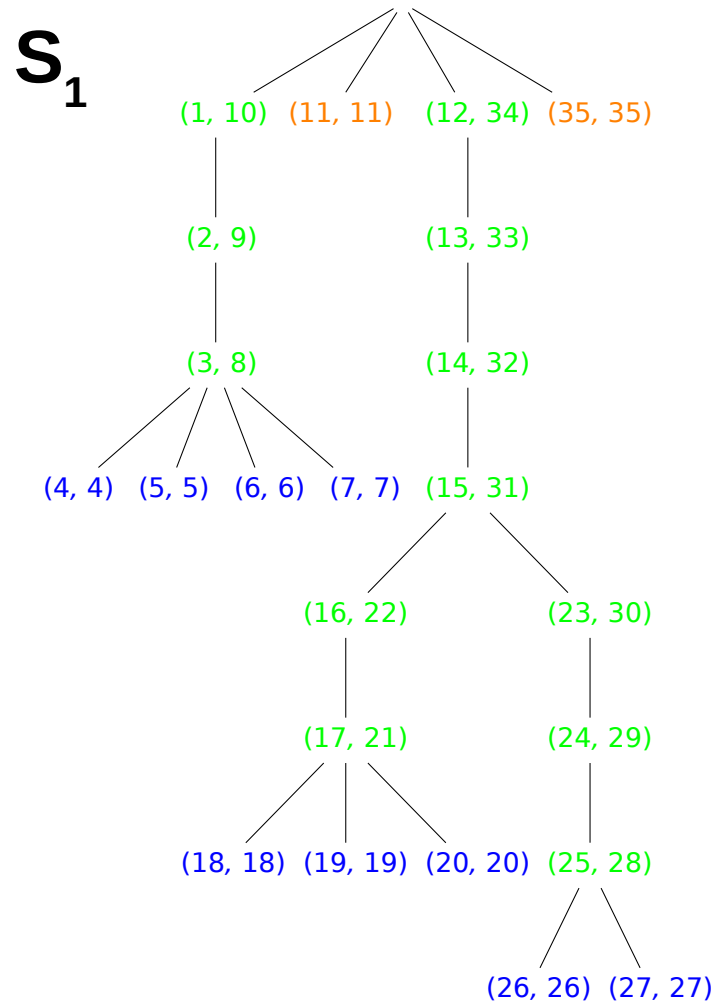


Fig. 4: Coarse grained tree representation, which represents an RNA secondary structure as a tree of structural building blocks such as hairpin loops (H), multiloops (M), bulges (B), internal loops (I). Node N does not represent a structural element, it closes the secondary structure and makes sure the representation forms a tree.

# Comparaison de structures

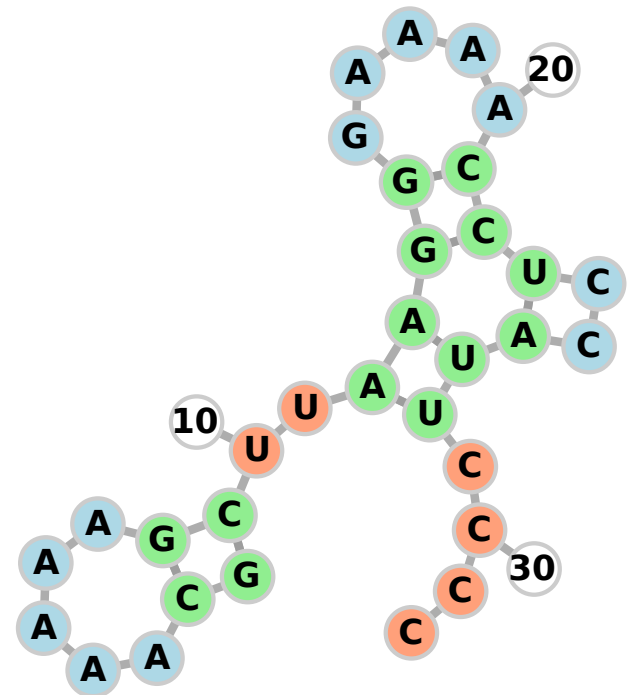
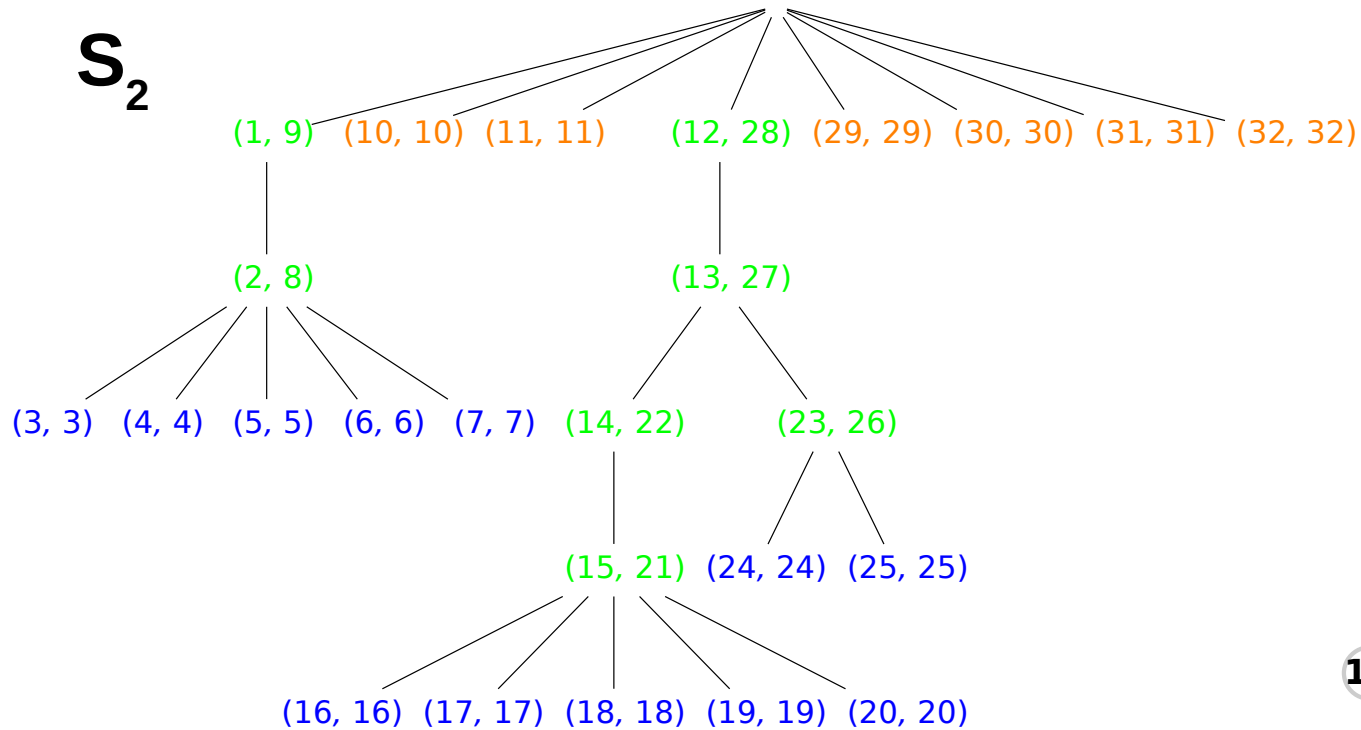
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| G | G | G | G | A | A | A | C | C | C  | A  | G  | G  | U  | U  | C  | G  | U  | U  | U  | C  | G  | G  | U  | C  | A  | A  | G  | A  | C  | A  | A  | C  | C  | C  |
| ( | ( | ( | . | . | . | . | ) | ) | )  | .  | (  | (  | (  | (  | (  | (  | .  | .  | .  | )  | )  | (  | (  | (  | .  | .  | )  | )  | )  | )  | )  | )  | )  | .  |





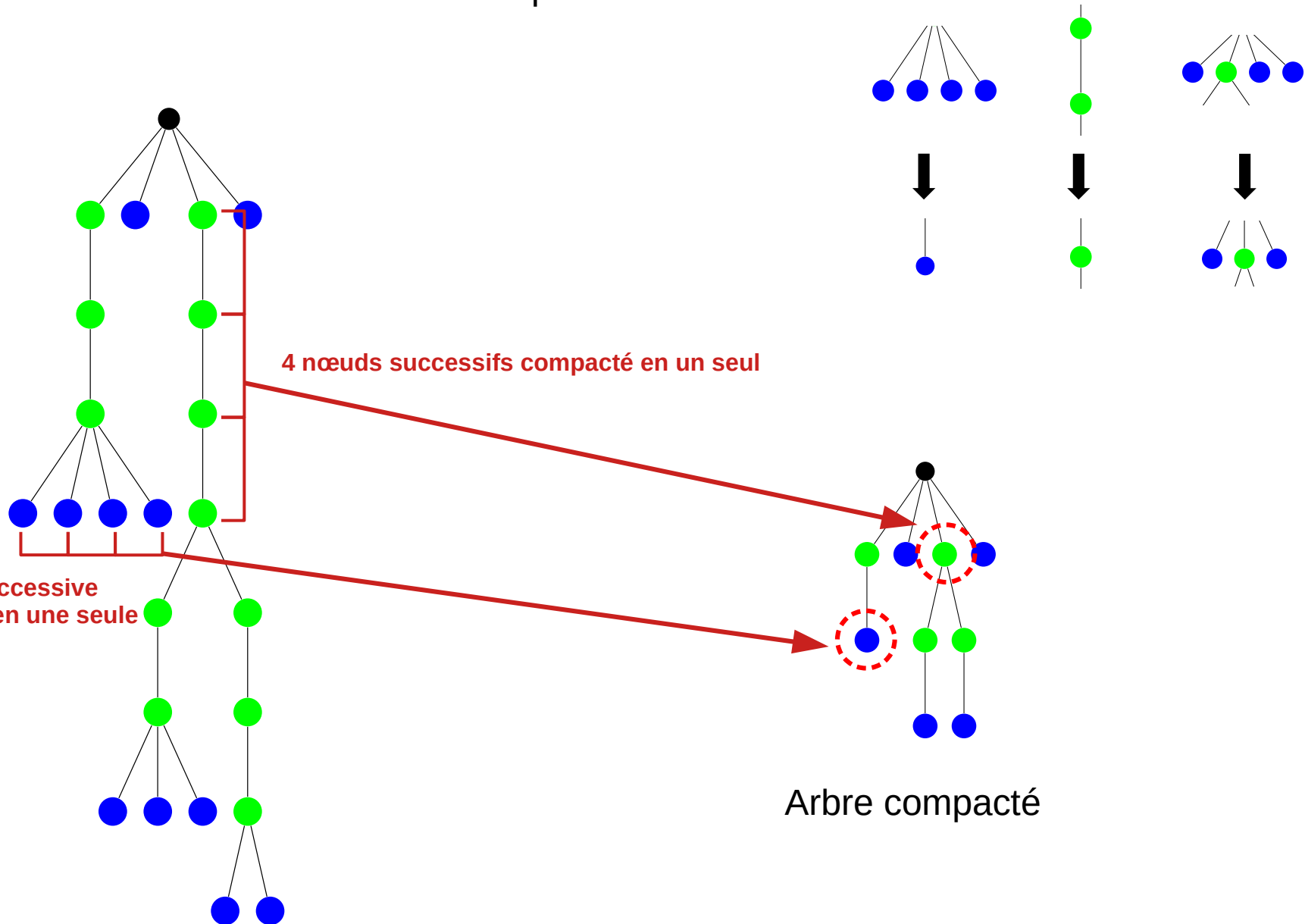
# Comparaison de structures

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| G | C | A | A | A | A | A | G | C | U | U  | A  | A  | G  | G  | G  | A  | A  | A  | A  | C  | C  | U  | C  | C  | A  | U  | U  | C  | C  | C  | C  |
| ( | ( | . | . | . | . | . | ) | ) | . | .  | (  | (  | (  | (  | .  | .  | .  | .  | .  | )  | )  | (  | .  | .  | )  | )  | )  | .  | .  | .  | .  |



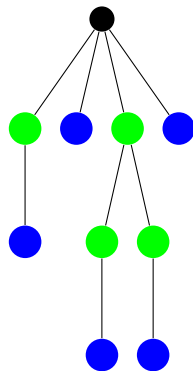
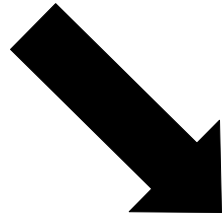
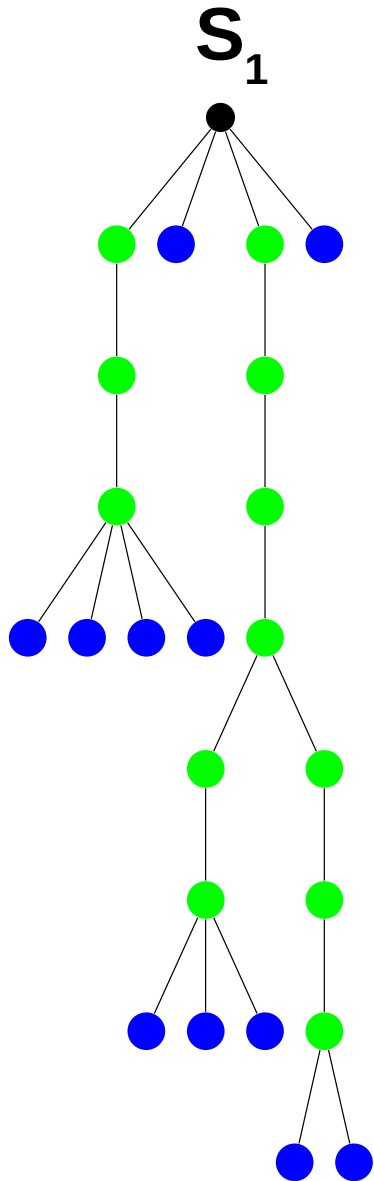
# Comparaison de structures

Compacter un arbre



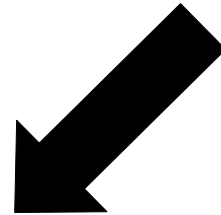
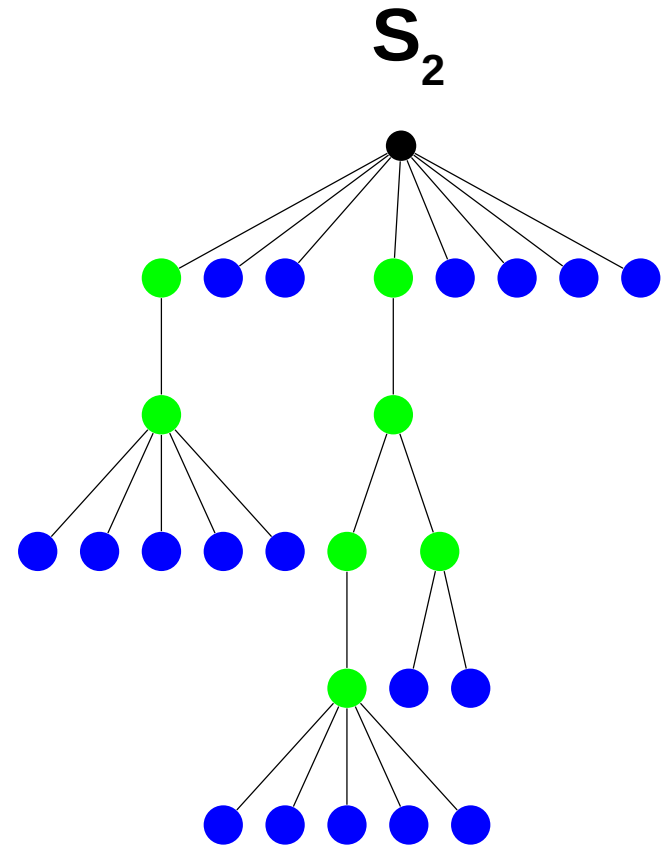
# Comparaison de structures

$$S_1 \Leftrightarrow S_2 ?$$



Architecture identiques

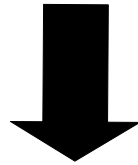
$$S_1 \Leftrightarrow S_2$$



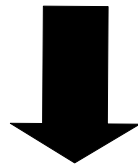
# Comparaison de structures

Compacter les structures au format parenthésé

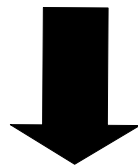
((...))..(((...))(...))...



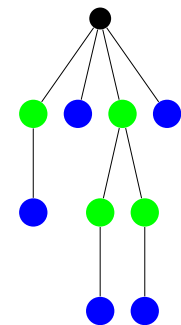
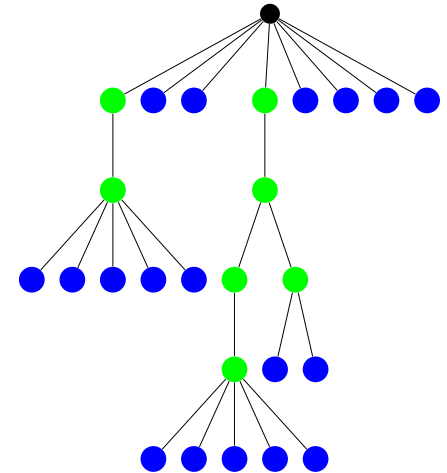
((.))..(((.))(...))..



((.))..(((.))(...))..



((.))..(((.))(...))..

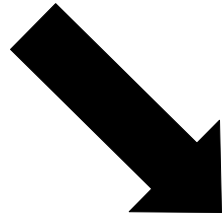


# Comparaison de structures

$$S_1 \Leftrightarrow S_2 ?$$

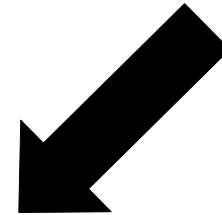
$S_1$

$(((((\dots))) \cdot ((((((\dots))) (((\dots)))))))).$



$S_2$

$((\dots)) \dots ((((\dots)) (\dots))) \dots$



$(\cdot) \cdot ((\cdot)(\cdot)) \cdot$

$$S_1 \Leftrightarrow S_2$$