Introduction to DNA data storage

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    - Channel Coders (SFC4 and C3)
    - JPEG-based Image source coders (JPEG DNA SFC4 and JPEG2000 DNA)
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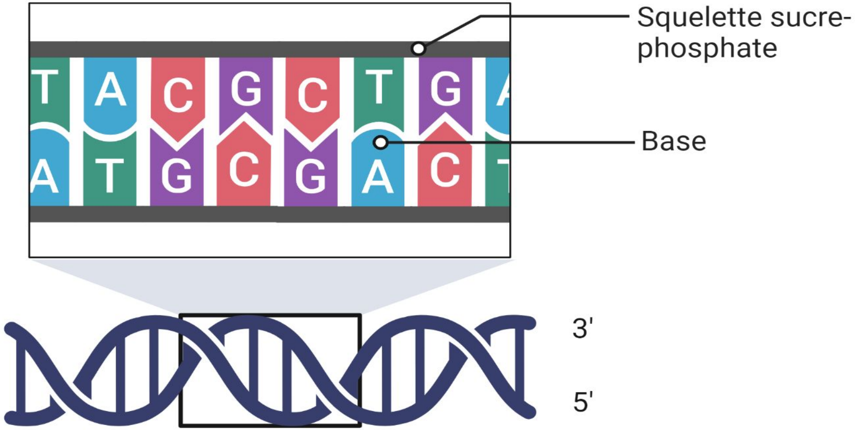
Motivations and principle

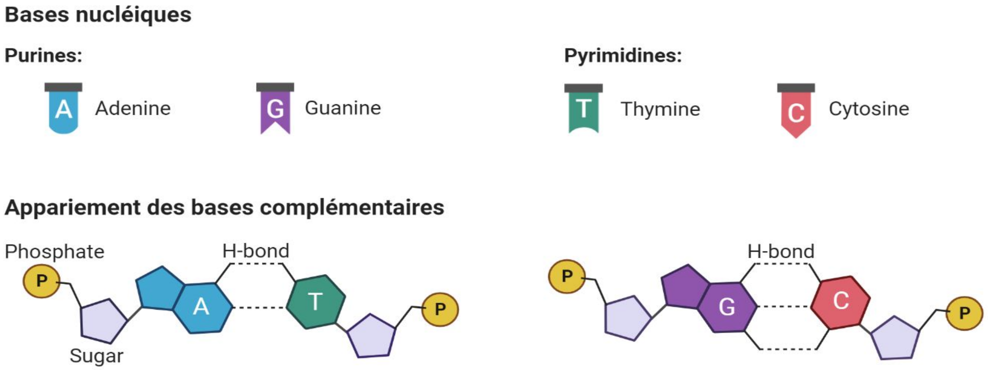
Conventional Storage Infrastructures

- Data storage demand is **ever expanding**
- Conventional Storage **cannot** be produced in **sufficient quantity**
- High **energy consumption**

Source: Data Age 2025, sponsored by Seagate with data from IDC Global DataSphere, Nov 2018

The DNA molecule





Two key biochemical processes

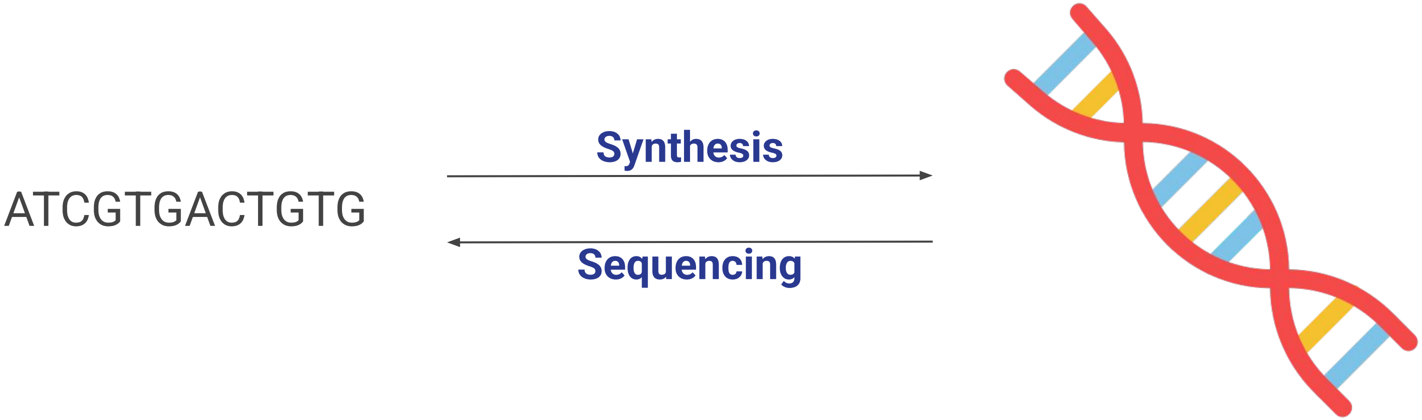
Synthesis:

- **Chemical fabrication** of a DNA molecule
- Composed of nucleotides
- Takes as input **any quaternary sequence** composed of As, Ts, Cs and Gs to synthesize in a molecule

Sequencing:

- **Chemical analysis** of a DNA molecule
- **Extracts** the quaternary **sequence** of As, Ts, Cs and Gs composing the molecule
- Takes as input any DNA molecule
- Outputs the associated quaternary representation

Two key biochemical processes

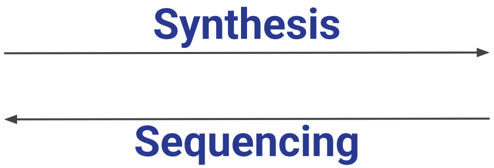


ATCGTGACTGTG

Synthesis →

← **Sequencing**

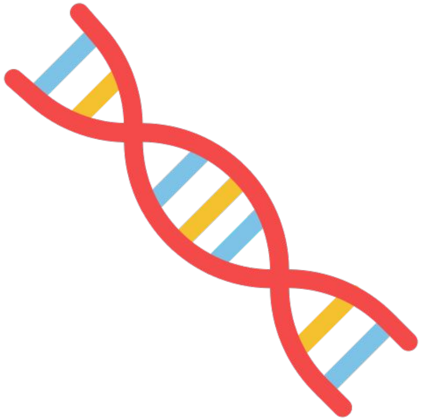
Through the biologist’s lens



ATCGTGACTGTG

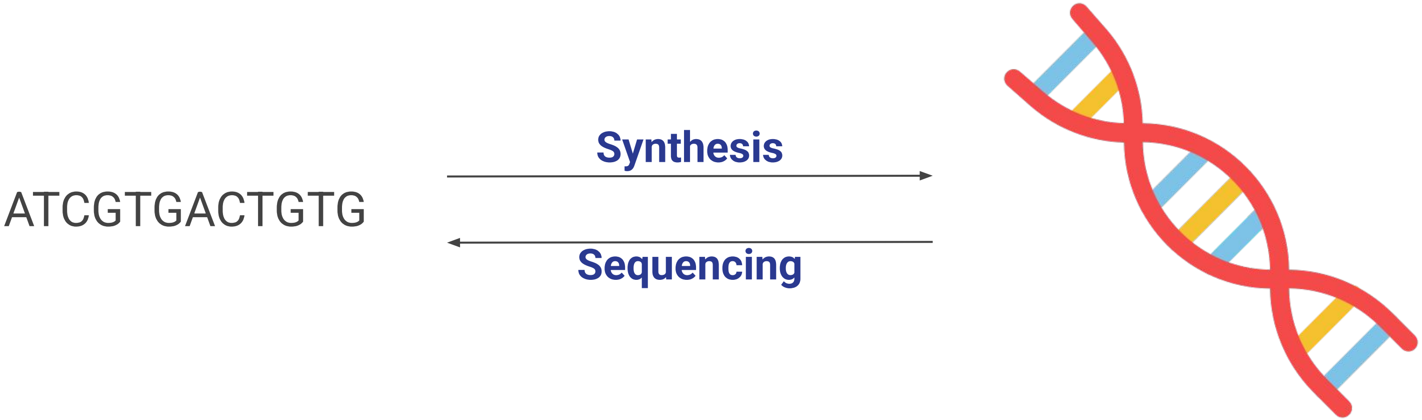
Synthesis

Sequencing



Genome analysis, genetic modification, etc…

Through the computer scientist’s lens

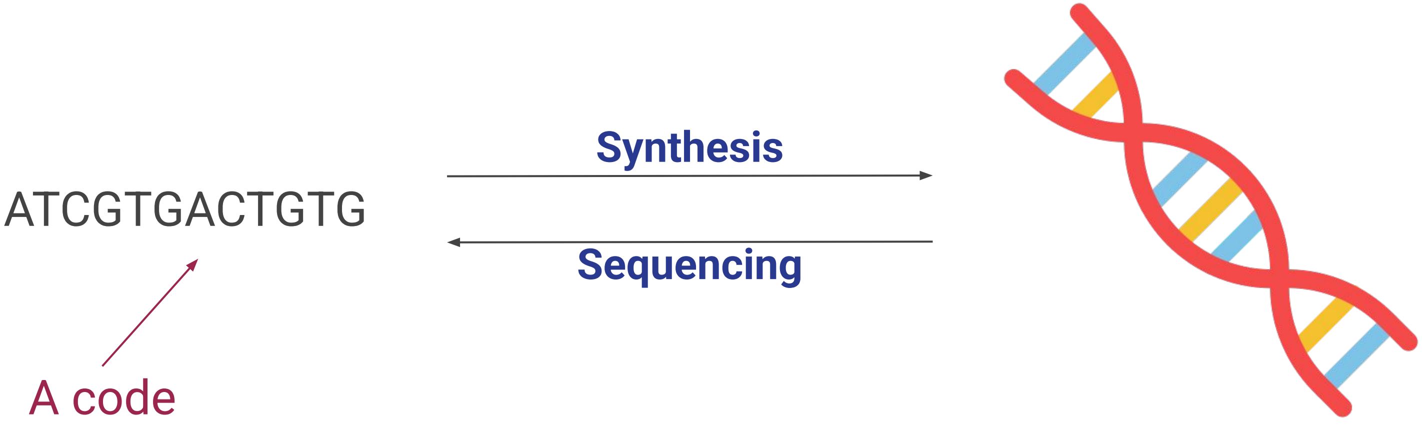


ATCGTGACTGTG

Synthesis

Sequencing

Through the computer scientist’s lens



ATCGTGACTGTG

Synthesis

Sequencing

A code

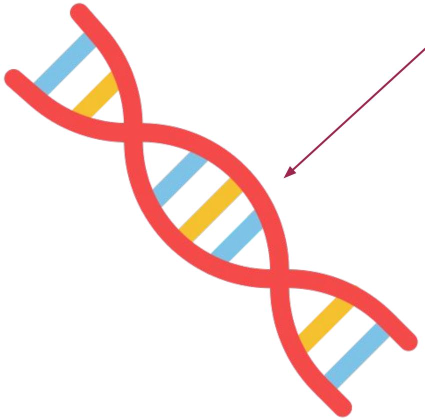
Through the computer scientist's lens

ATCGTGACTGTG

A code

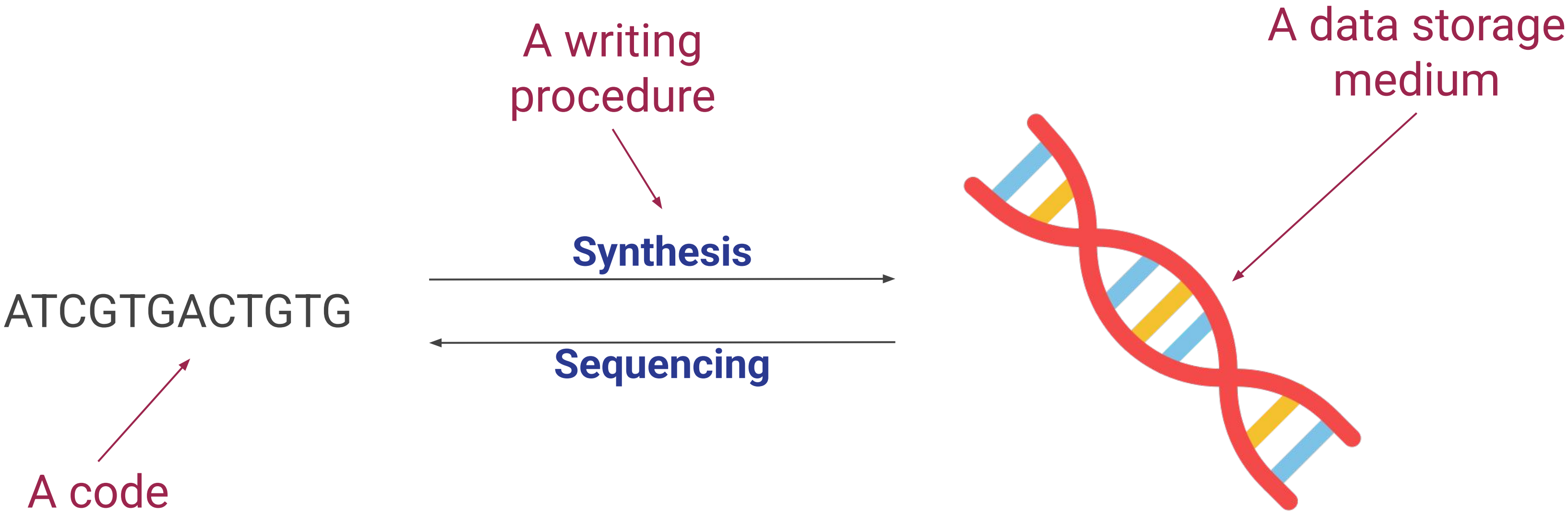
Synthesis

Sequencing



A data storage medium

Through the computer scientist’s lens



A writing procedure

A data storage medium

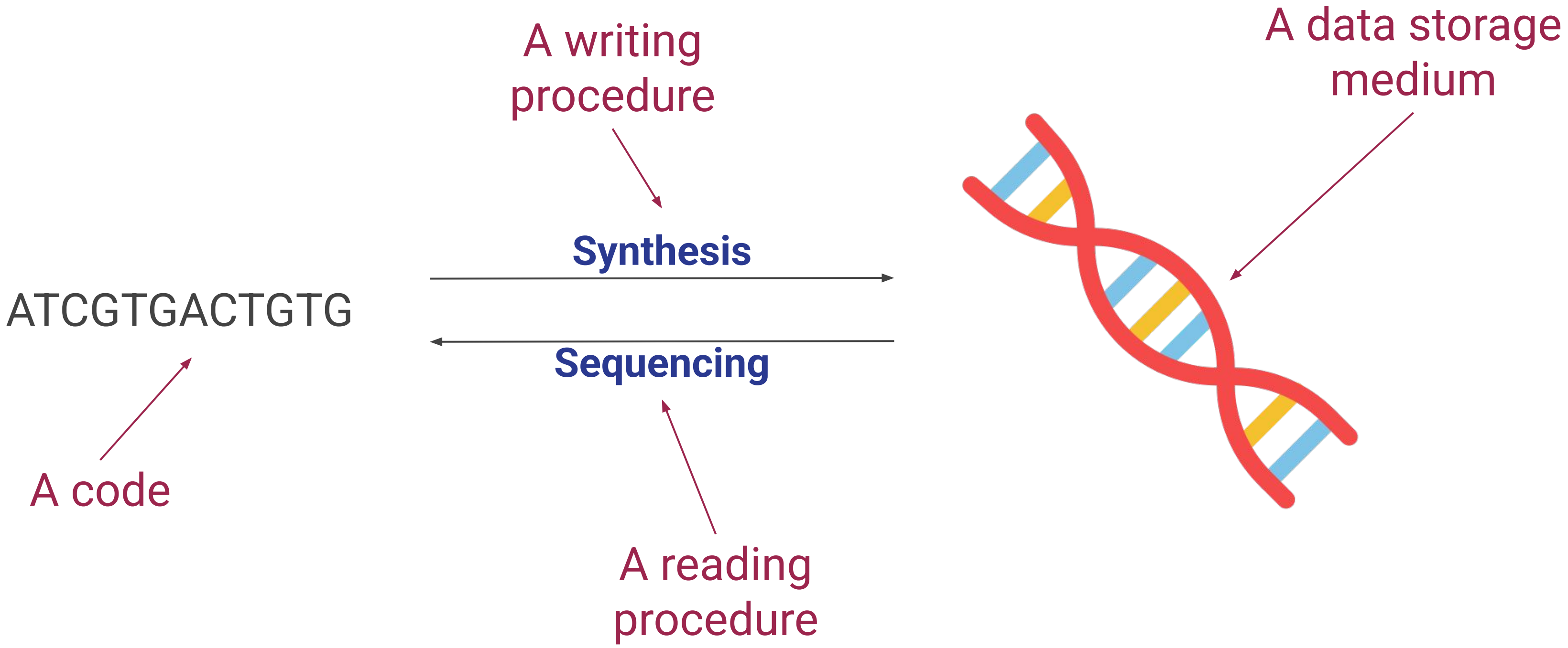
Synthesis

ATCGTGACTGTG

Sequencing

A code

Through the computer scientist’s lens



A writing procedure

A data storage medium

Synthesis

ATCGTGACTGTG

Sequencing

A code

A reading procedure

DNA Data storage - General Principle

- Writing data:
  - Encode a file into a set of quaternary sequences (oligos)
  - Synthesize the DNA molecules represented by these sequences
  - Store the molecules
- Reading data:
  - Retrieve the quaternary sequences from the stored DNA molecules (sequencing)
  - Decode the file from the set of sequenced oligos

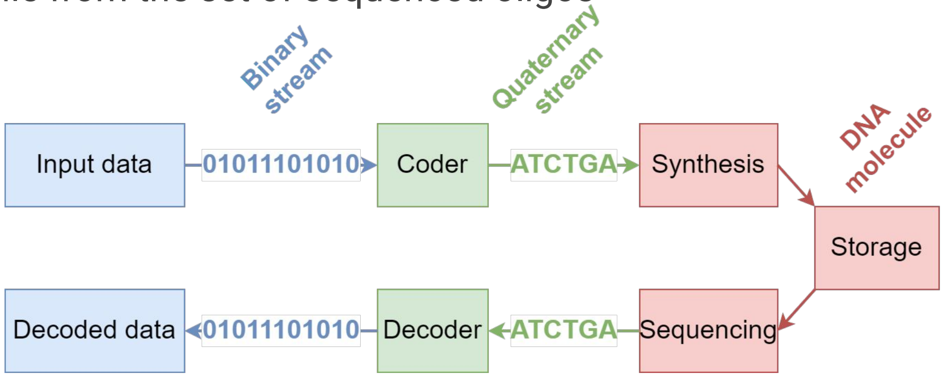


Fig: General workflow of DNA data storage

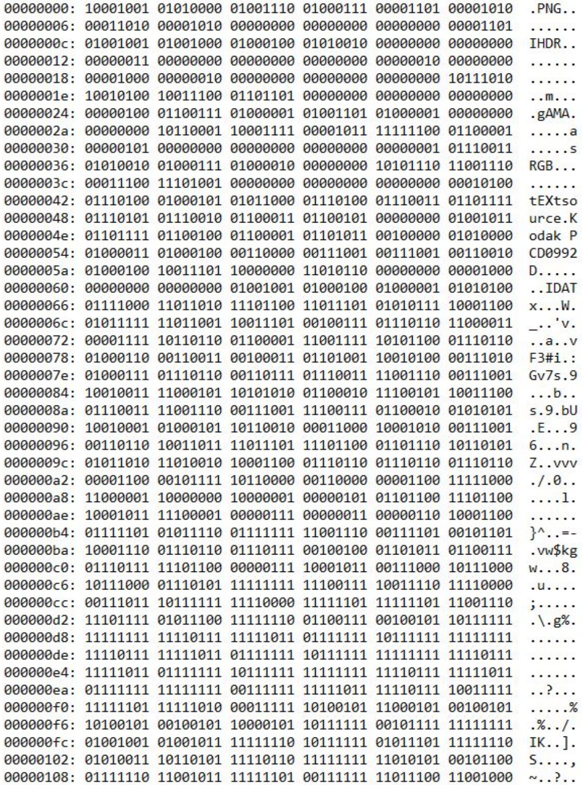
DNA Data storage - Biochemical operations

- Synthesis : Create a set of DNA molecules
- PCR : Copy molecules of DNA
- Sequencing : Read the structure of the DNA molecules

Operation	**Cost**	**Speed**	**Errors**
Synthesis	Very High	Very Slow	Few
PCR	Low	Fast	Low
Sequencing	High	Slow	Many

DNA Coding - Principle

Binary File (.png)



```
00000000: 10001001 01010000 01001110 01000111 00001101 00001010  .PNG..
00000006: 00011010 00001010 00000000 00000000 00000000 00001101  ......
0000000c: 01001001 01001000 01000100 01010010 00000000 00000000  IHDR..
00000012: 00000011 00000000 00000000 00000000 00000010 00000000  ......
00000018: 00001000 00000010 00000000 00000000 00000000 10111010  ......
0000001e: 10010100 10011100 01101101 00000000 00000000 00000000  ..m...
00000024: 00000100 01100111 01000001 01001101 01000001 00000000  .gAMA.
0000002a: 00000000 10110001 10001111 00001011 11111100 01100001  .....a
00000030: 00000101 00000000 00000000 00000000 00000001 01110011  .....s
00000036: 01010010 01000111 01000010 00000000 10101110 11001110  RGB...
0000003c: 00011100 11101001 00000000 00000000 00000000 00010100  ......
00000042: 01110100 01000101 01011000 01110100 01110011 01101111  tEXtso
00000048: 01110101 01110010 01100011 01100101 00000000 01001011  urce.K
0000004e: 01101111 01100100 01100001 01101011 00100000 01010000  odak P
00000054: 01000011 01000100 00110000 00111001 00111001 00110010  CD0992
0000005a: 01000100 10011101 10000000 11010110 00000000 00001000  D.....
00000060: 00000000 00000000 01001001 01000100 01000001 01010100  ..IDAT
00000066: 01111000 11011010 11101100 11011101 01010111 10001100  x...W.
0000006c: 01011111 11011001 10011101 00100111 01110110 11000011  _..'v.
00000072: 00001111 10110110 01100001 11001111 10101100 01110110  ..a..v
00000078: 01000110 00110011 00100011 01101001 10010100 00111010  F3#i.:
0000007e: 01000111 01110110 00110111 01110011 11001110 00111001  Gv7s.9
00000084: 10010011 11000101 10101010 01100010 11100101 10011100  ...b..
0000008a: 01110011 11001110 00111001 11100111 01100010 01010101  s.9.bU
00000090: 10010001 01000101 10110010 00011000 10001010 00111001  .E...9
00000096: 00110110 10011011 11011101 11101100 01101110 10110101  6...n.
0000009c: 01011010 11010010 10001100 01110110 01110110 01110110  Z..vvv
000000a2: 00001100 00101111 10110000 00110000 00001100 11111000  ./.0..
000000a8: 11000001 10000000 10000001 00000101 01101100 11101100  ....l.
000000ae: 10001011 11100001 00000111 00000011 00000110 10001100  ......
000000b4: 01111101 01011110 01111111 11001110 00111101 00101101  }^..=-
000000ba: 10001110 01110110 01110111 00100100 01101011 01100111  .vw$kg
000000c0: 01110111 11101100 00000111 10001011 00111000 10111000  w...8.
000000c6: 10111000 01110101 11111111 11100111 10011110 11110000  .u....
000000cc: 00111011 10111111 11110000 11111101 11111101 11001110  ;.....
000000d2: 11101111 01011100 11111110 01100111 00100101 10111111  .\.g%.
000000d8: 11111111 11110111 11111011 01111111 10111111 11111111  ......
000000de: 11110111 11111011 01111111 10111111 11111111 11110111  ......
000000e4: 11111011 01111111 10111111 11111111 11110111 11111011  ......
000000ea: 01111111 11111111 00111111 11111011 11110111 10011111  ..?...
000000f0: 11111101 11111010 00011111 10100101 11000101 00100101  .....%
000000f6: 10100101 00100101 10000101 10111111 00101111 11111111  .%../.
000000fc: 01001001 01001011 11111110 10111111 01011101 11111110  IK..].
00000102: 01010011 10110101 11110110 11111111 11010101 00101100  S....,
00000108: 01111110 11001011 11111101 00111111 11011100 11001000  ~..?..
```

ENCODING

DECODING

DNA File (.fasta)

```
>Oligo0
ATGTGCAGAATTCCGTTGAATTCCCACAAAGAGAATTCAAGAGAAGAGCGTCTCGACTATCGAGATCACATGTGCTGTGTGTAGTACTATACTGTC
>Oligo1
AATAATAAATAATAAATAATAACCGGATACTGGCTAATACCAAATAATAAATAATAAATAATAAATAATAAATAATAAATAATAAATAATAAATAA
>Oligo2
AATATATCGTAGTGTAGCTGCACGTACGACTCACGACAGCTGCACGTGCGCGAGTCGTGCATCTGATGCAGACAGCAGCAGCGATCGCGCTAGTCG
>Oligo3
AATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAACTATTCATAATATAAGCAAATAATTCACAATAATAATAAATAATAATAAA
>Oligo4
AACAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAGGATCAAATAATTCACAAT
>Oligo5
AAAATACTTCATAATAATATTGAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATA
>Oligo6
AAATAATAATAAATAATAATAAATAATAATAAATATTATTGAATAATAATGAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAA
>Oligo7
AATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAAGATCGAATAATAATGAATAATAATAAATAAT
>Oligo8
ATAATAATCAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAACA
>Oligo9
AAATAATAAATAATAATAAATAACACGTAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAA
>Oligo10
AATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATCCACAATAATAATAAATAATAATAAATAATAATAAATAATAAT
>Oligo11
ATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATATCGAATAATAATA
>Oligo12
AAATAAATAATTCTCAATCCGCTTAAATATACGAGAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAA
>Oligo13
AATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAGATAATAATAATAAATAATAATAAATAATAATAAA
>Oligo14
ATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATATTAAAT
>Oligo15
AAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATA
>Oligo16
AAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAA
>Oligo17
AATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAAT
>Oligo18
ATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATA
>Oligo19
AAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAA
>Oligo20
AATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAAT
>Oligo21
ATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATAAATAATAATA
```

DNA Coding - Constraints

The following operations can increase the errors in biochemical processes (synthesis, PCR, sequencing):

- Homopolymers (repetition of the same nucleotide)
- Motifs (patterns)
- Unbalanced GC content
- Large sequences (>300 nts)
- Undesired sequences

↓

ADAPT AND CONSTRAIN THE CODING SYSTEM

DNA Coding - Why do we need to compress the data?

Errors can occur in the biochemical processes (synthesis, sequencing, PCR):

- High sequencing cost
- Very high synthesis cost
- Low synthesis and sequencing speed (writing and reading cost)

REDUCE THE SIZE OF THE ENCODED DNA FILES

Examples of DNA coders

Summary of the presentation - DNA coding methods

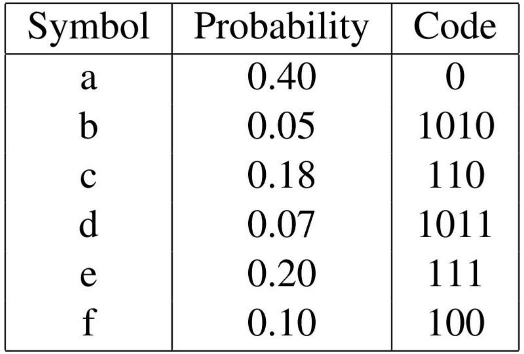
- DNA Adapted Channel coders:
    - SFC4
    - C3
    - CMOSS
- Image coders adapted to DNA:
    - JPEG DNA VM
    - JPEG DNA SFC4
    - JPEG 2000 DNA
    - HiDNA

Examples of DNA Channel Coders

SFC4

DNA Channel Coders - Entropy coder

- **Variable length** coder
- Adapted to **i.i.d. sources**
- Length of the codeword depends on the **probability of appearance** of the associated symbol
- Better performance for compression



Symbol	Probability	Code
a	0.40	0
b	0.05	1010
c	0.18	110
d	0.07	1011
e	0.20	111
f	0.10	100

Fig: Example of a binary Huffman code

DNA Channel Coders - The Goldman Coder

- Ternary Huffman Entropy Coder
- No repeated nucleotides (no homopolymers)

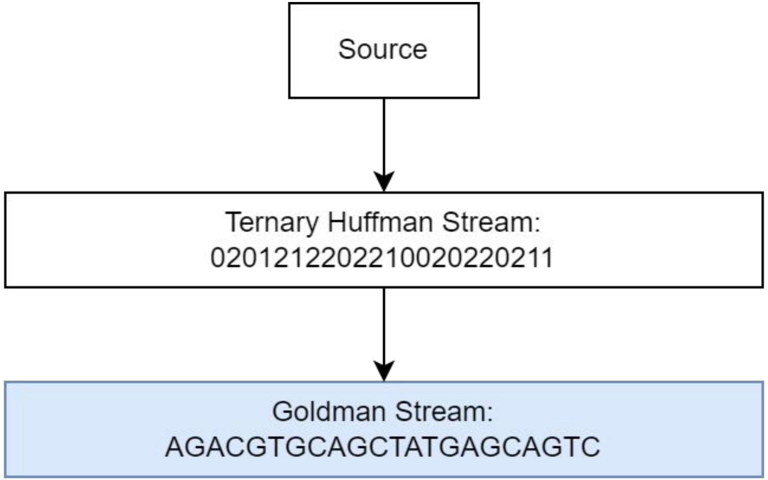
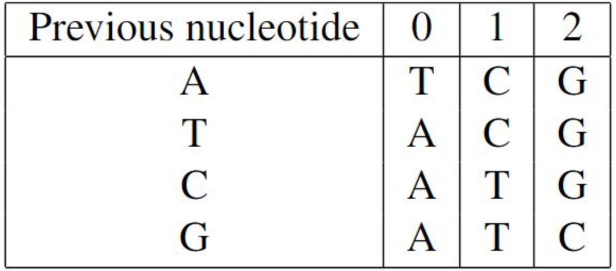


Fig: The data is first encoded into a ternary code



Previous nucleotide	0	1	2
A	T	C	G
T	A	C	G
C	A	T	G
G	A	T	C

Fig: Ternary to DNA translation table

N. Goldman, P. Bertone, and S. Chen, “Towards practical, high-capacity, low-maintenance information storage in synthesized dna,” *Nature*, 2013.

Performance metrics - DNA entropy coders

Expected length:

$$\mathcal{L}(C) = \sum_{x \in \Omega} p(X = x) l(C_x)$$

Ω - The set of symbols in the source

C_x - The codeword associated to the symbol

$l(C_x)$ - The length of a codeword

The **average size of a code** output by the entropy coder for a source

In the case of DNA coding, it is expressed in **nucleotides per symbol**

SFC4 - Characterization of the source and principle

- A source *S* composed of elements of an alphabet *A* has to be encoded
- The frequency of appearance of each element of *A* in *S* is computed
- A tree *T* is initialized as a single node (the root) where all the symbols are allocated
- The Shannon Fano tree is built by subdividing the leaves of the tree

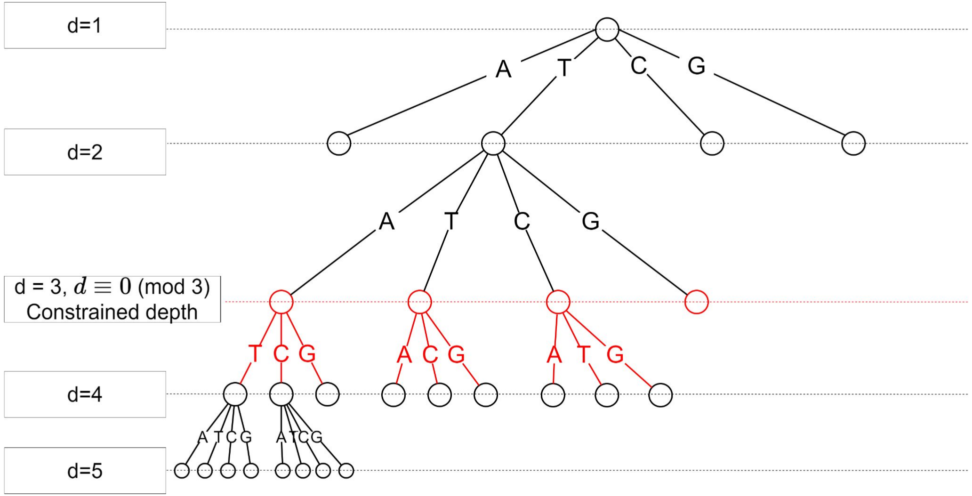


Fig.: Example of an SFC4 coding tree, constrained at depths multiples of 3

SFC4 - Coding tree

Fig.: Example of an SFC4 coding tree, constrained at depths multiples of 3

SFC4 - Coding tree

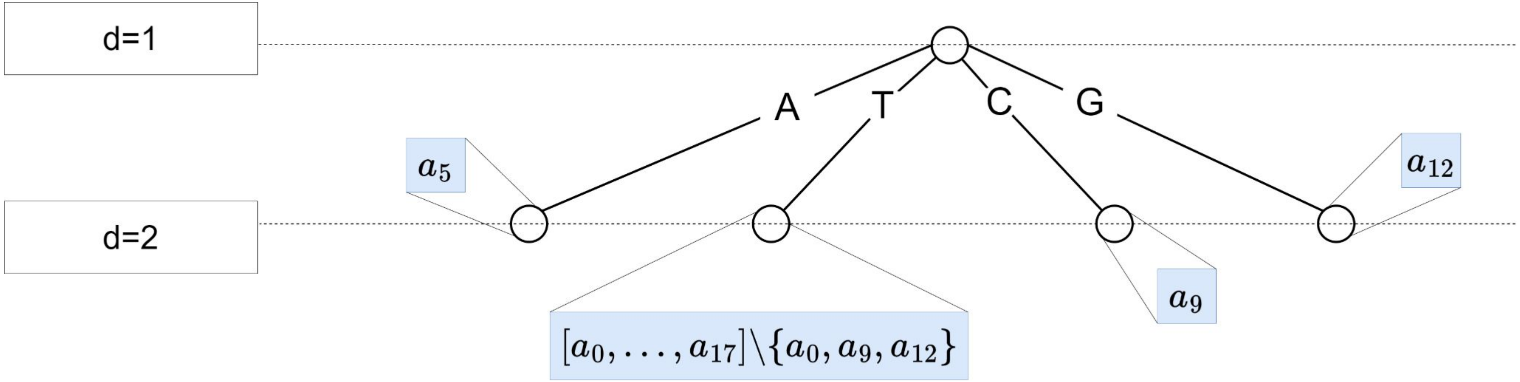


Fig.: Example of an SFC4 coding tree, constrained at depths multiples of 3

SFC4 - Coding tree

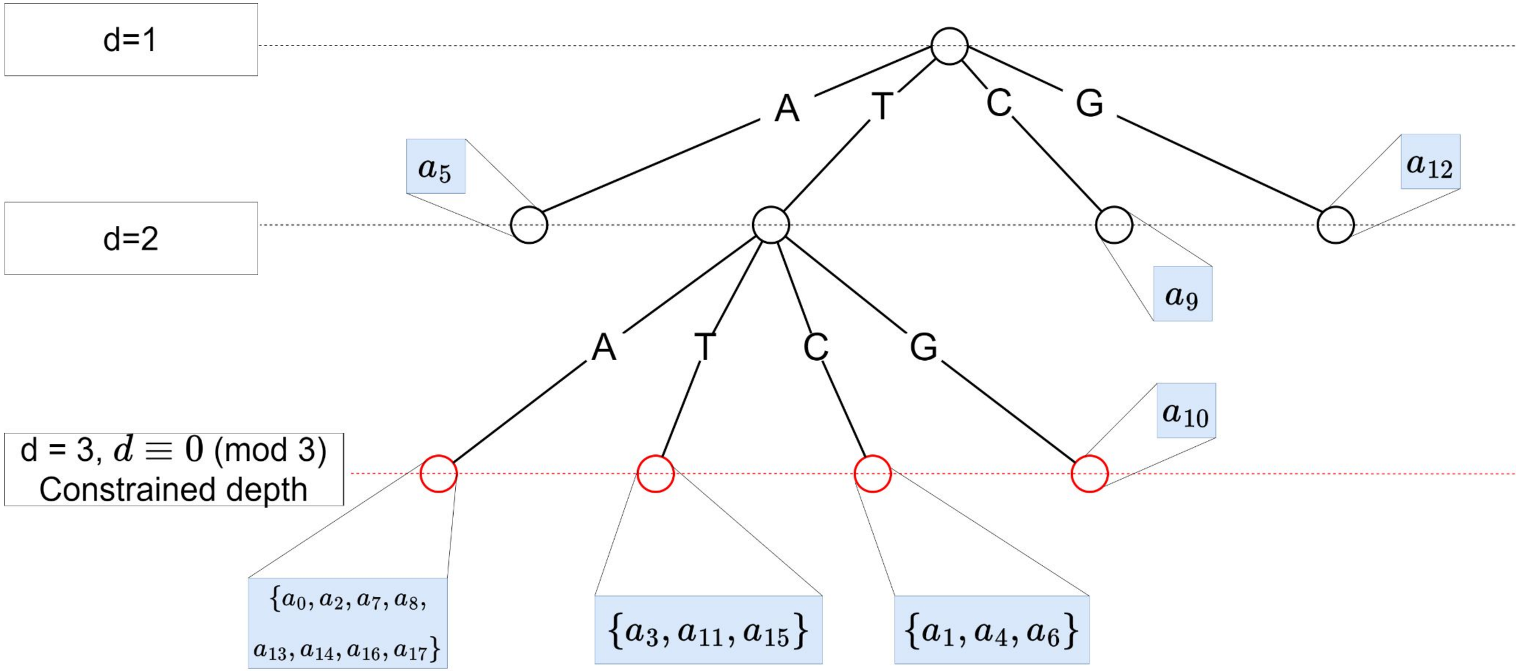
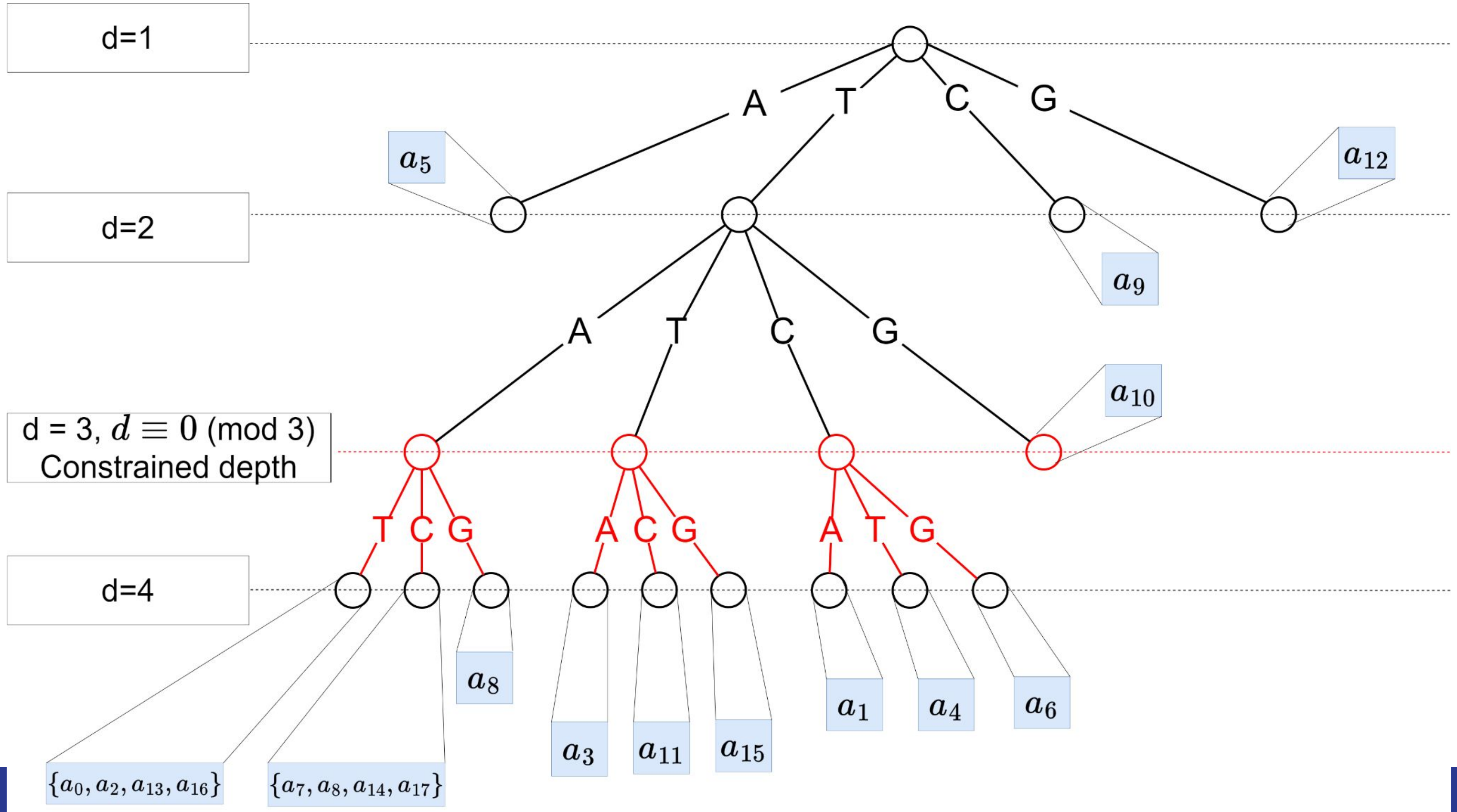


Fig.: Example of an SFC4 coding tree, constrained at depths multiples of 3

SFC4 - Coding tree



SFC4 - Coding tree

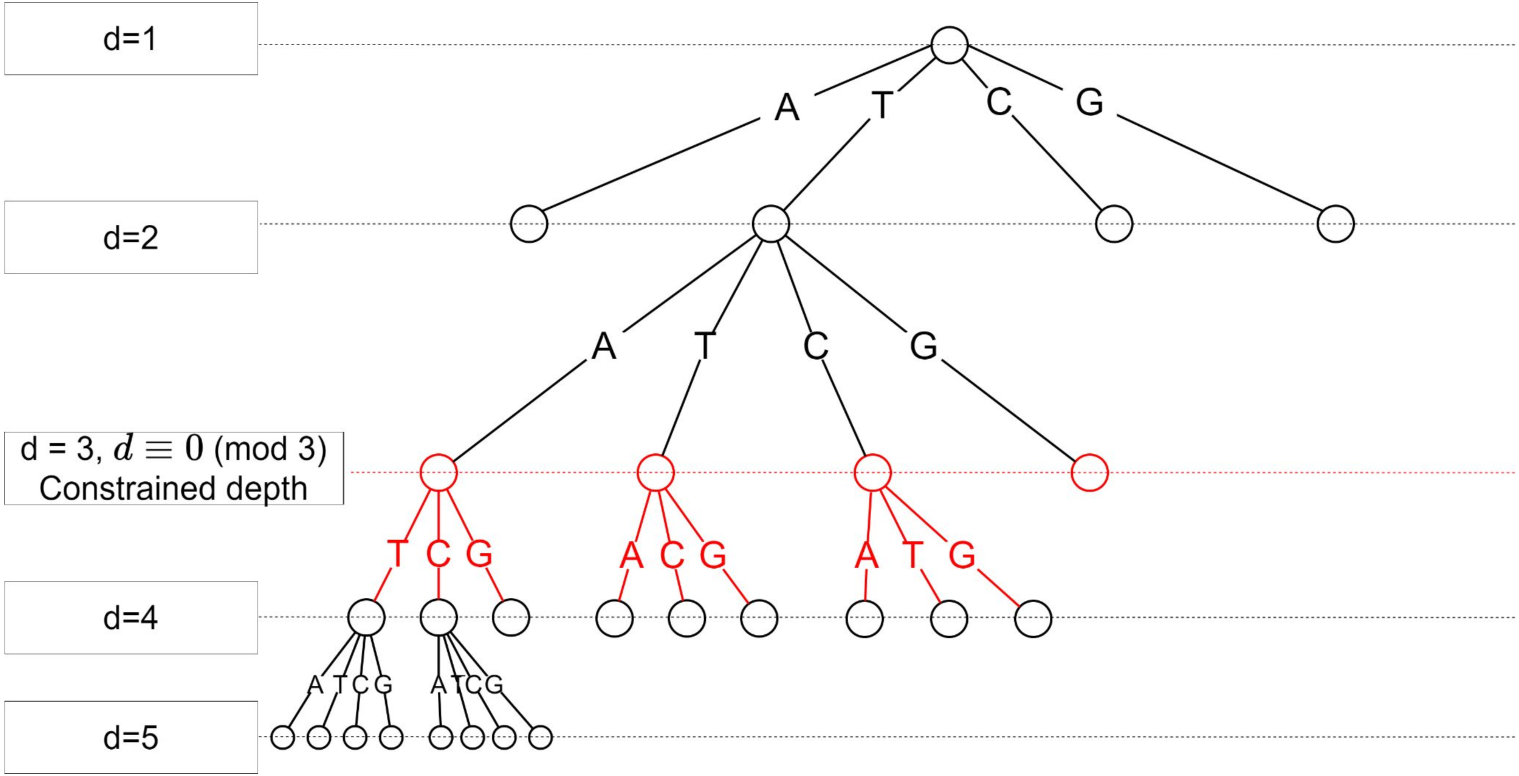
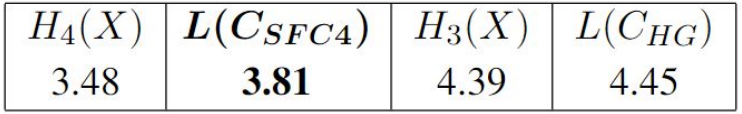


Fig.: Example of an SFC4 coding tree, constrained at depths multiples of 3

SFC4 - Results on I.I.D. Gaussian Sources

Expected length:

- Average results on a series of **100 i.i.d. gaussian sources**
- Each source contained **10000 samples**
- Quantized to the **nearest integer**



$H_4(X)$	$\boldsymbol{L(C_{SFC4})}$	$H_3(X)$	$L(C_{HG})$
3.48	**3.81**	4.39	4.45

Fig: Ternary to DNA translation table

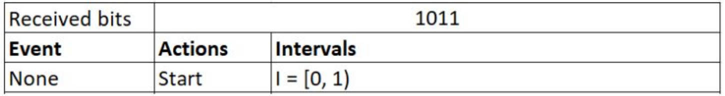
Kodak dataset, weblink: https://r0k.us/graphics/kodak/

Examples of DNA Channel Coders

C3DNA

C3 - Principle of the MQ coder’s arithmetic coder

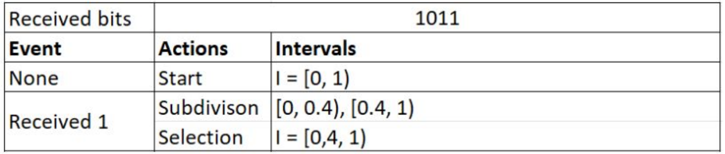
- Source: [1,0,1,1]
- Initialize an interval to [0, 1]



Received bits	1011	
Event	**Actions**	**Intervals**
None	Start	I = [0, 1)

C3 - Principle of the MQ coder’s arithmetic coder

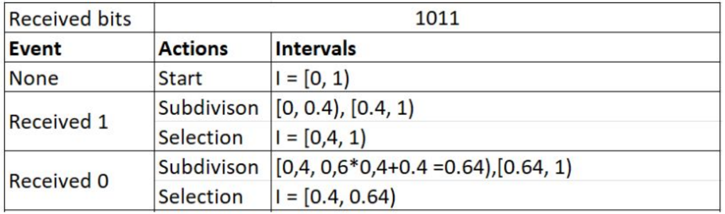
- Source: [1,0,1,1]
- Initialize an interval to [0, 1]
- First received bit: 1
    - Subdivide the interval into two smaller intervals of size relative to the probability of appearance of a zero or a one.
    - Select the subdivision associated to the received bit (1)



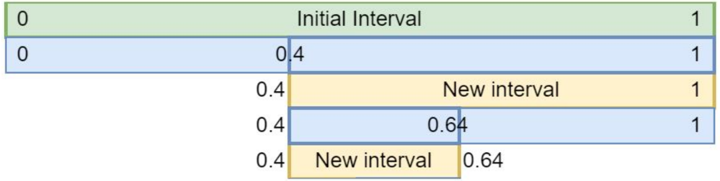
Received bits	1011	
Event	**Actions**	**Intervals**
None	Start	I = [0, 1)
Received 1	Subdivison	[0, 0.4), [0.4, 1)
	Selection	I = [0,4, 1)

C3 - Principle of the MQ coder’s arithmetic coder

- Source: [1,0,1,1]
- Initialize an interval to [0, 1]
- First received bit: 1
- Second received bit: 0
  - Subdivide the interval into two smaller intervals of size relative to the probability of appearance of a zero or a one.
  - Select the subdivision associated to the received bit (0)

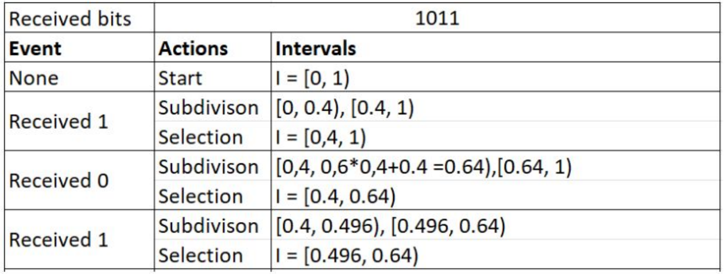


Received bits	1011	
Event	**Actions**	**Intervals**
None	Start	I = [0, 1)
Received 1	Subdivison	[0, 0.4), [0.4, 1)
	Selection	I = [0,4, 1)
Received 0	Subdivison	[0,4, 0,6*0,4+0.4 =0.64),[0.64, 1)
	Selection	I = [0.4, 0.64)

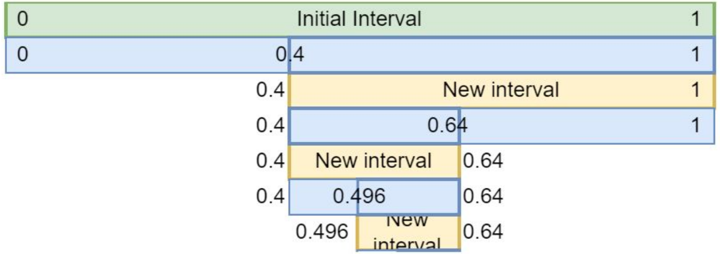


C3 - Principle of the MQ coder’s arithmetic coder

- Source: [1,0,1,1]
- Initialize an interval to [0, 1]
- First received bit: 1
- Second received bit: 0
- Third received bit: 1
    - Subdivide the interval into two smaller intervals of size relative to the probability of appearance of a zero or a one.
    - Select the subdivision associated to the received bit (1)

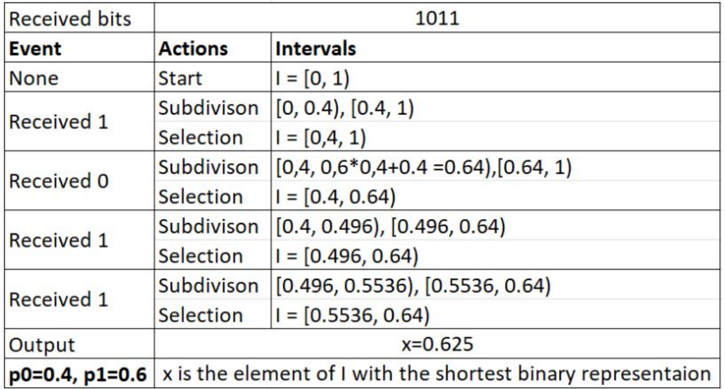


Received bits	1011	
Event	**Actions**	**Intervals**
None	Start	I = [0, 1)
Received 1	Subdivison	[0, 0.4), [0.4, 1)
	Selection	I = [0,4, 1)
Received 0	Subdivison	[0,4, 0,6*0,4+0.4 =0.64),[0.64, 1)
	Selection	I = [0.4, 0.64)
Received 1	Subdivison	[0.4, 0.496), [0.496, 0.64)
	Selection	I = [0.496, 0.64)

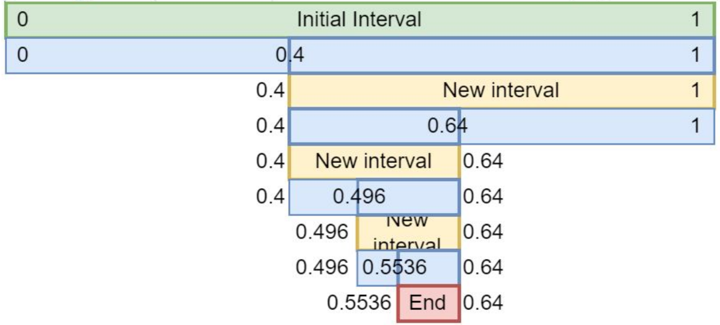


C3 - Principle of the MQ coder’s arithmetic coder

- Source: [1,0,1,1]
- Initialize an interval to [0, 1]
- First received bit: 1
- Second received bit: 0
- Third received bit: 1
- Final received bit: 1



Received bits	1011	
Event	**Actions**	**Intervals**
None	Start	I = [0, 1)
Received 1	Subdivison	[0, 0.4), [0.4, 1)
	Selection	I = [0,4, 1)
Received 0	Subdivison	[0,4, 0,6*0,4+0.4 =0.64),[0.64, 1)
	Selection	I = [0.4, 0.64)
Received 1	Subdivison	[0.4, 0.496), [0.496, 0.64)
	Selection	I = [0.496, 0.64)
Received 1	Subdivison	[0.496, 0.5536), [0.5536, 0.64)
	Selection	I = [0.5536, 0.64)
Output	x=0.625	
p0=0.4, p1=0.6	x is the element of I with the shortest binary representaion	



The **final interval** represents the whole input source [1, 0, 1, 1]

C3 - MQ coder-based arithmetic coder for DNA

- Transcode the registries of the binary MQ-coder
- Constrained fixed length code of length 3 (48 elements)
- Transcode integers into a base 48 representation
- Code the coefficients of this representation

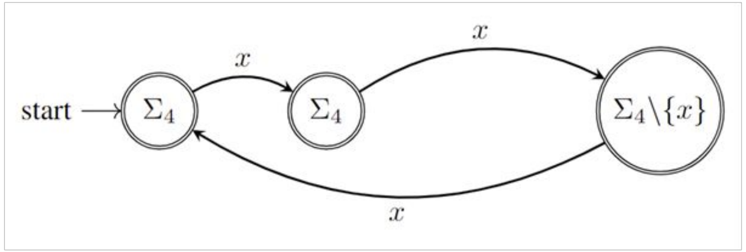


Fig. Automata generating the coding dictionary: **homopolymers are avoided**

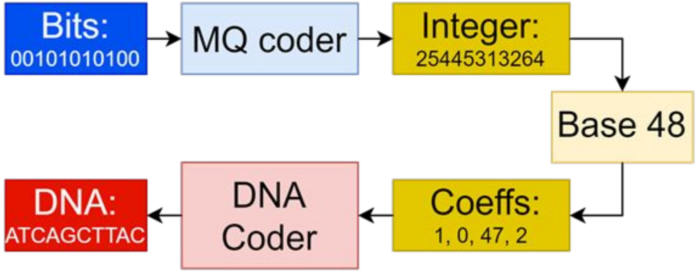

Bits: 00101010100
MQ coder
Integer: 25445313264
Base 48
Coeffs: 1, 0, 47, 2
DNA Coder
DNA: ATCAGCTTAC

Fig. Adaptation of the MQ-coder to DNA

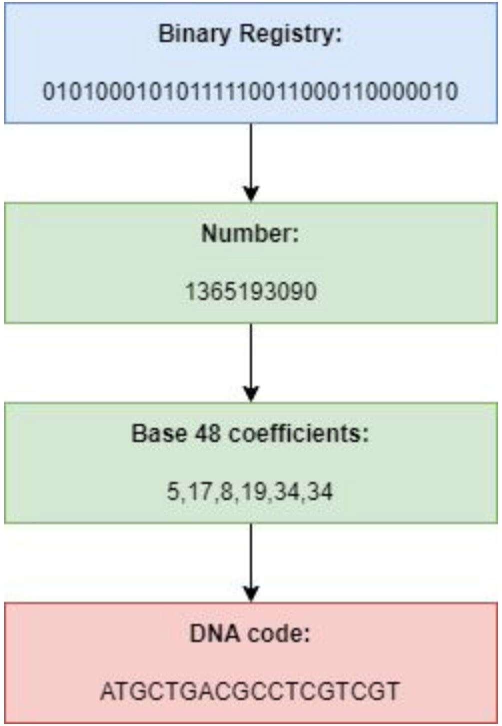
$$C_3 = \{AAT, AAC, AAG, ATA, ATC, ATG, ACA, \ ..., \ GCT, GCG, GGA, GGT, GGC\}$$

X. Pic, M. Dimopoulou, E. Gil San Antonio and M. Antonini, “MQ-Coder inspired Arithmetic Coder for Synthetic DNA data storage”, ICIP 2023

C3 - Encoding a registry

- The registry is first converted into a number
- The number is represensented into base 48
- The coefficients in base 48 are encoded into DNA, one by one, with the C3 coder:

$$C_3 = \{AAT, AAC, AAG, ATA, ATC, ATG, ACA,\ ...,\ GCT, GCG, GGA, GGT, GGC\}$$



Binary Registry:

01010001010111110011000110000010

Number:

1365193090

Base 48 coefficients:

5,17,8,19,34,34

DNA code:

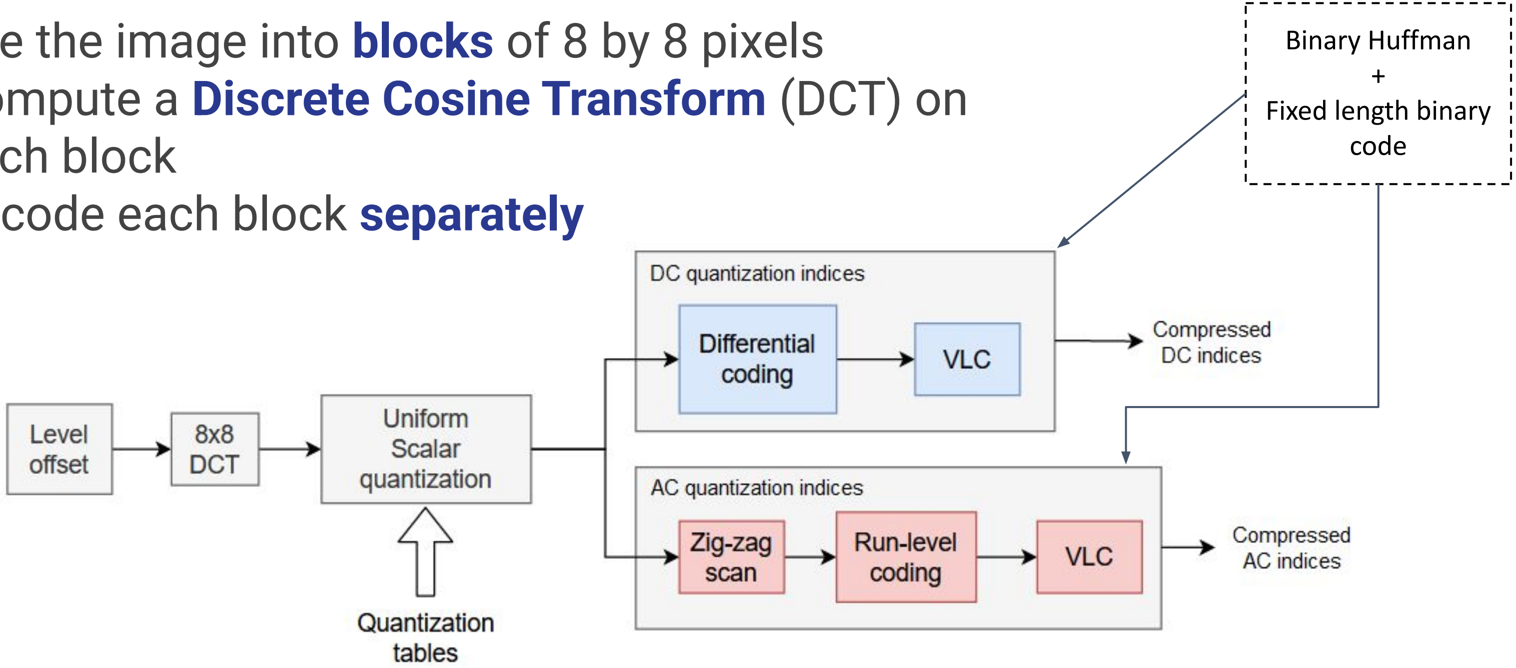
ATGCTGACGCCTCGTCGT

Examples of DNA Image Coders

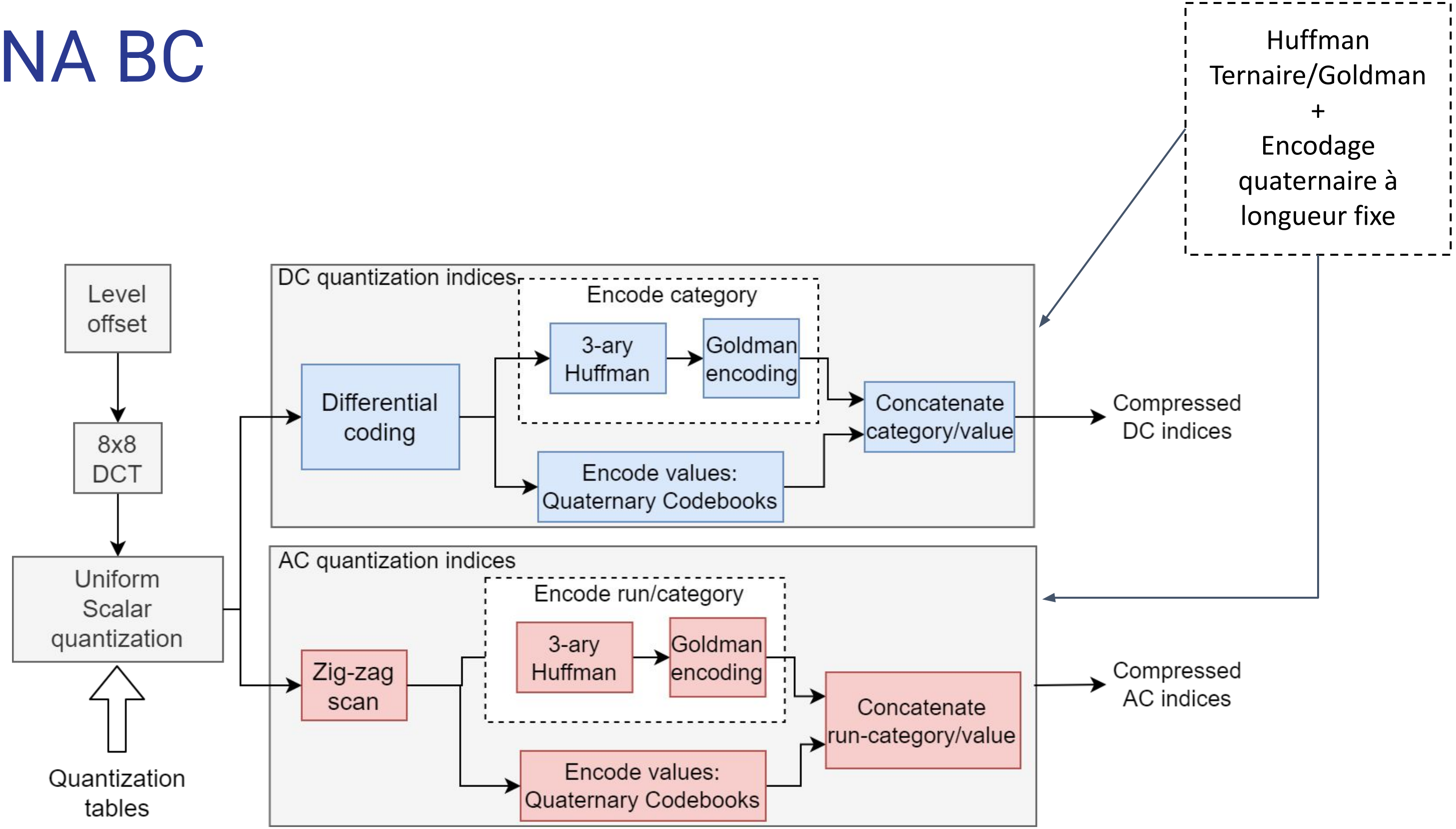
JPEG DNA SFC4 and JPEG2000 DNA

Image coders - JPEG

- Tile the image into **blocks** of 8 by 8 pixels
- Compute a **Discrete Cosine Transform** (DCT) on each block
- Encode each block **separately**

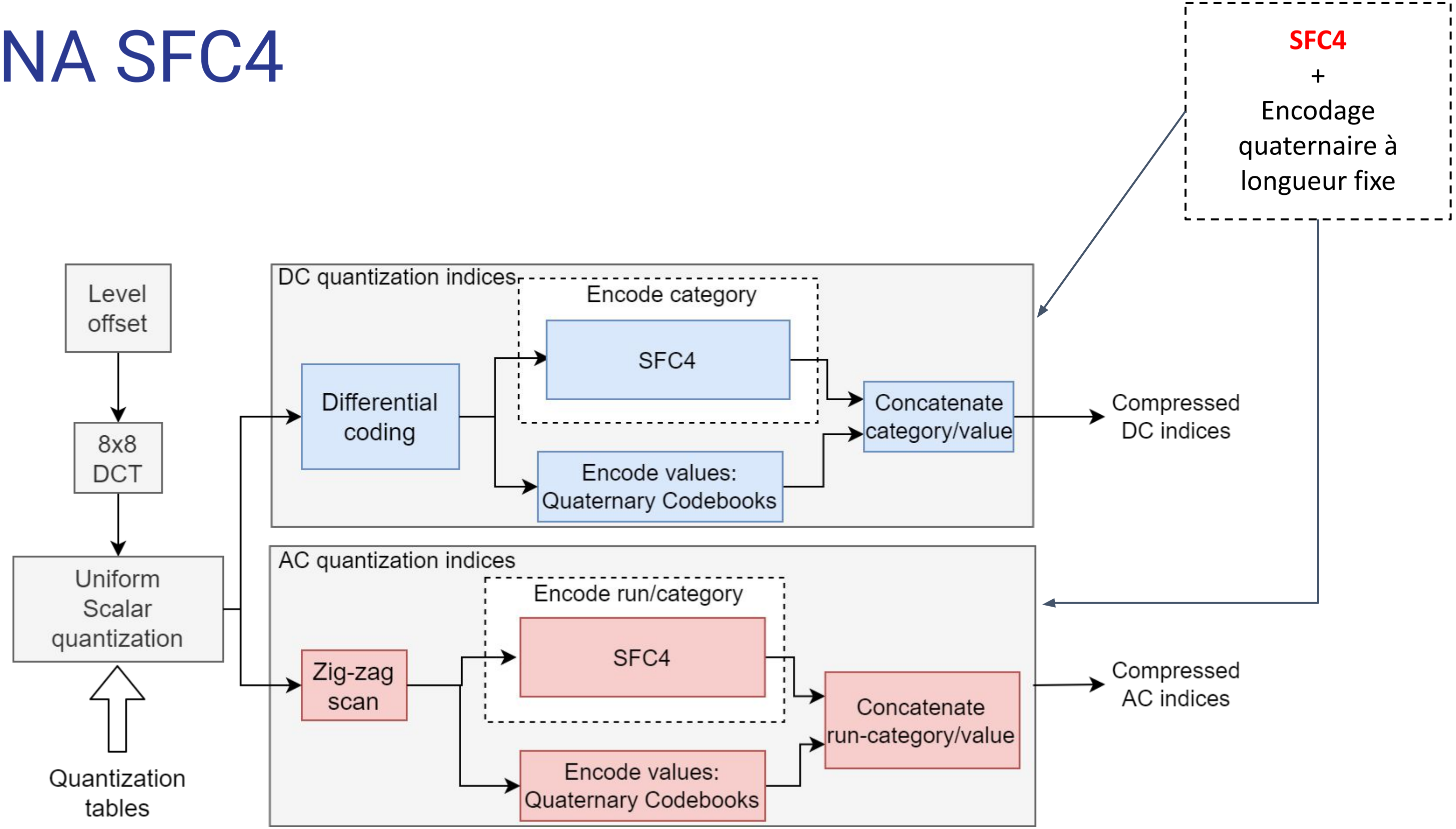


JPEG DNA BC



1. M. Dimopoulou, E. Gil San Antonio, M. Antonini, “A JPEG-based image coding solution for data storage on DNA”, *EUSIPCO*, 2021.
2. X. Pic, E. Gil San Antonio, M. Dimopoulou, M. Antonini, M93103 - JpegDNA Python Library

JPEG DNA SFC4



X. Pic and M. Antonini, “A constrained shannon-fano entropy coder for image storage in synthetic DNA”, EUSIPCO 2022

Metrics for DNA coding

Performance metrics - DNA Channel coders

Compression rate:

$$cr_{btsnt} = \frac{\#bits}{\#nucs}$$

The **number of bits** in the source that can be encoded in a **single nucleotide**

Performance metrics - DNA image coders

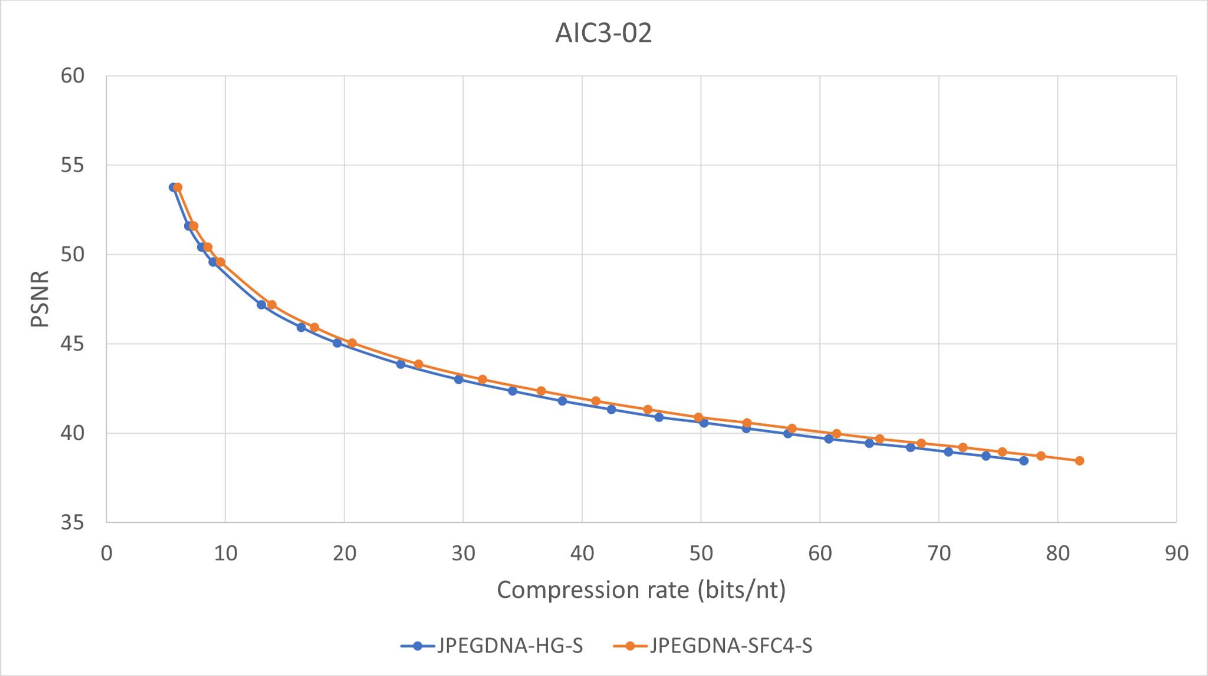
Nucleotide rate:

$$r_{ntpp} = \frac{\#nucs}{H \times W}$$

The **average number of nucleotides** to encode a **pixel**

JPEG DNA SFC4 - Results

- Novel codec improves the rate by 5% on average
- Tested on different datasets (kodak and JPEG AIC 03)



1. Kodak dataset, weblink: https://r0k.us/graphics/kodak/
2. M. Testolina, V. Hosu, M. Jenadeleh, D. Lazzarotto, D. Saupe, T. Ebrahimi, “JPEG AIC-3 Dataset: Towards Defining the High Quality to Nearly Visually Lossless Quality Range”, *2023 15th International Conference on Quality of Multimedia Experience (QoMEX)*, Ghent, Belgium, 2023

JPEG2000 DNA - Principle

- The **binary MQ coder** is associated to the new **C3 coder**
- The **overheads** are transcoded into DNA using a **fixed length** DNA adapted coder
- The decoder consists in reverting all previous operations
- **Closed loop modification** of JPEG2000

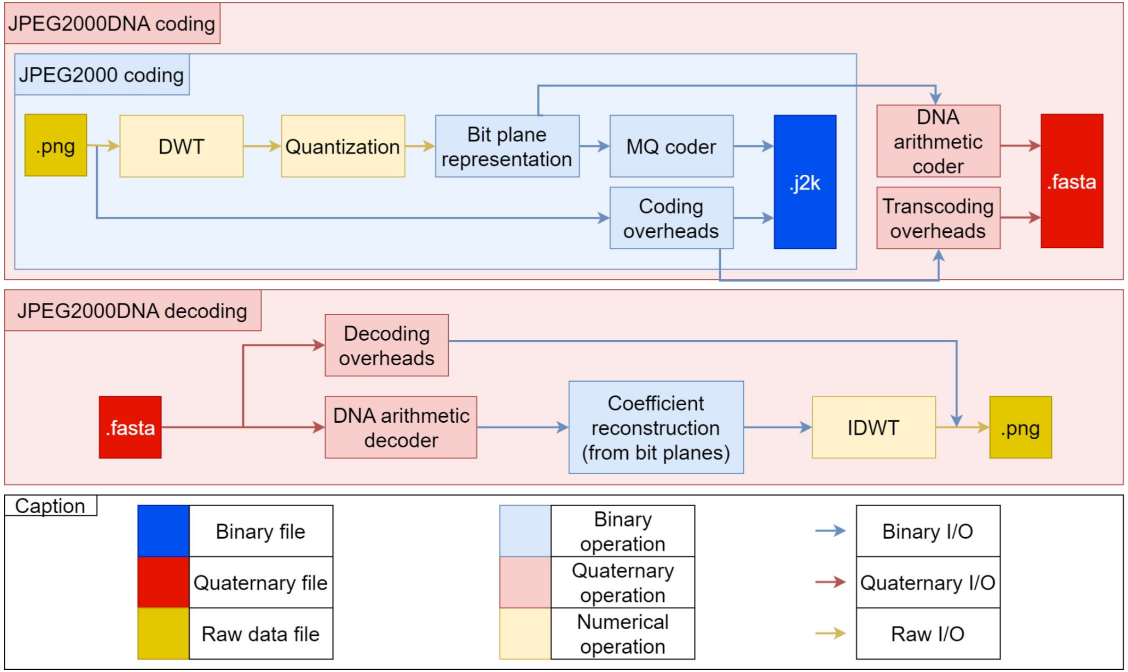
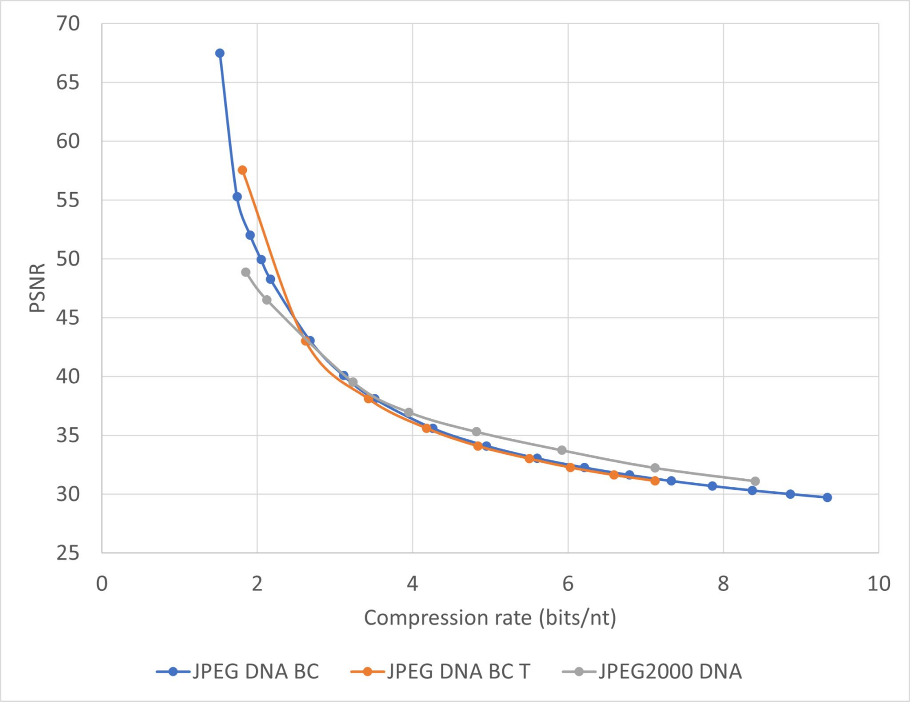


Fig: Adaptation to DNA of the JPEG2000 codec

X. Pic, M. Dimopoulou, E.G. San Antonio and M. Antonini, “MQ-Coder Inspired Arithmetic Coder for Synthetic DNA Data Storage”, ICIP 2023

JPEG2000 DNA - Results

- Tested across the kodak dataset
- On the right, an example of encoding one image of the kodak dataset (kodim7) using the JPEG DNA 2000 codec
- Performance mostly similar with the original JPEG DNA BC software



Kodak dataset, weblink: https://r0k.us/graphics/kodak/

Examples of DNA Channel Coders

JPEG DNA VM

DNA Fountain Codes - Raptor Code

- **Cut** the memory into bytes
- Randomly **Select and sum** a fixed number of these bytes
- Seed and **encode** into DNA
- **Repeat** the bytes **selection**, **sum** and **encoding** until all bytes are encoded

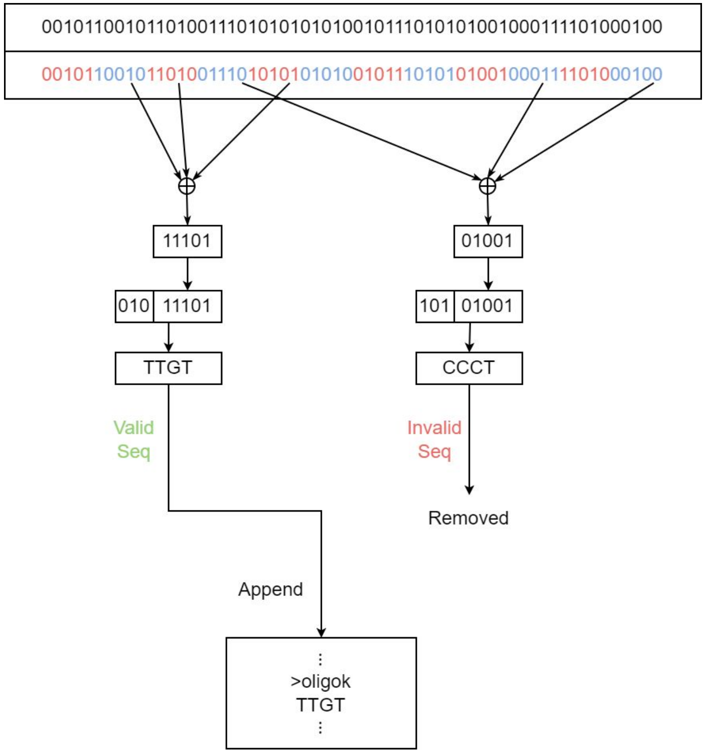


Fig: A DNA adapted fountain code

Y. Erlich and D. Zielinski, “DNA fountain enables a robust and efficient storage architecture” *Science*, vol. 355, no. 6328, pp.950–954, 2017

Fountain code adapted to DNA

- Fountain code
- Encode the XORed chunks into DNA with the following table:

Input bits	DNA code
00	A
01	T
10	C
11	G

Selection of the oligos

- Code is **not constrained**
- Some generated oligos will not respect the constraints
- **Remove all the oligos** that don't respect the constraints
- Check that there is still enough **redundancy**, otherwise:
  - Start the whole process all over
  - Change the seed for the random selection of chunks

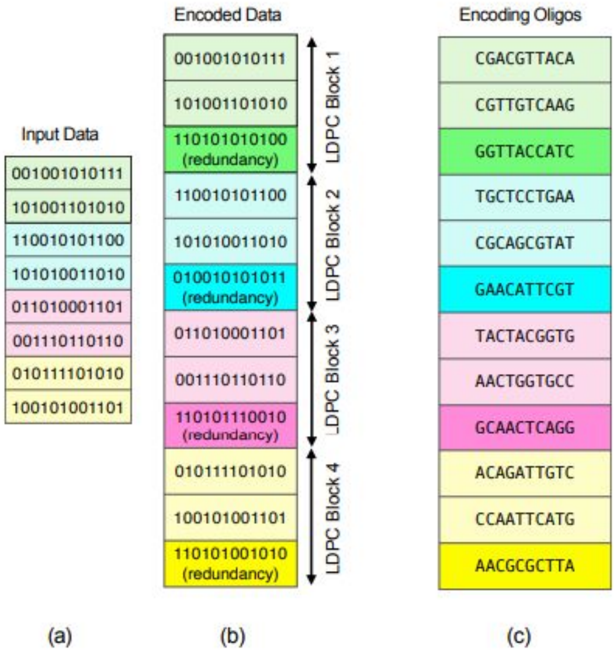
Davi Lazzarotto, Jorge Encinas Ramos, Michela Testolina, Touradj Ebrahimi, "Storing images and point clouds on DNA support with fountain codes", Applications of Digital Image Processing XLVII

Examples of DNA Channel Coders

CMOSS

CMOSS - Encoding in columns

- Data is first organized in columns
- Each line in the column has a set number of bits
- Lines are grouped in blocks
- Redundancy is introduced (LDPC block)
- Each line is encoded into DNA using a motif



Input Data

001001010111
101001101010
110010101100
101010011010
011010001101
001110110110
010111101010
100101001101

(a)

Encoded Data

001001010111
101001101010
110101010100 (redundancy)
110010101100
101010011010
010010101011 (redundancy)
011010001101
001110110110
110101110010 (redundancy)
010111101010
100101001101
110101001010 (redundancy)

(b)

Encoding Oligos

CGACGTTACA
CGTTGTCAAG
GGTTACCATC
TGCTCCTGAA
CGCAGCGTAT
GAACATTCGT
TACTACGGTG
AACTGGTGCC
GCAACTCAGG
ACAGATTGTC
CCAATTCATG
AACGCGCTTA

(c)

Eugenio Marinelli, Yiqing Yan, Lorenzo Tattini, Virginie Magnone, Pascal Barbry, Raja Appuswamy, “CMOSS: A Reliable, Motif-based Columnar Molecular Storage System”, 17th ACM International Systems and Storage Conference

CMOSS - A motif-based coding system

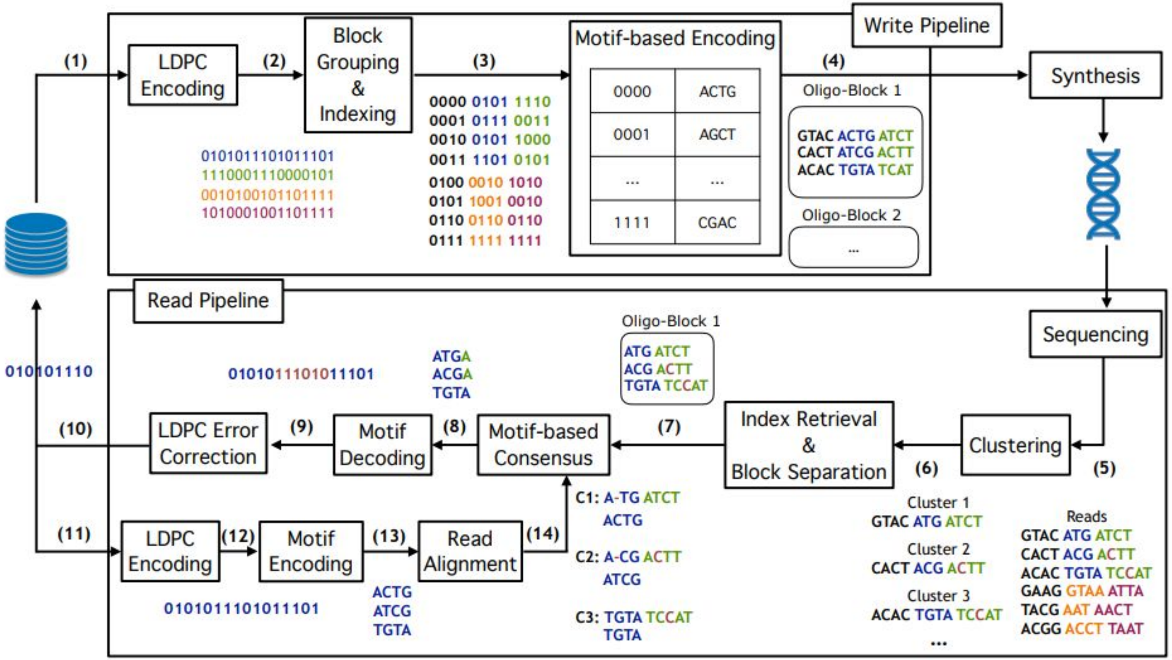
- Preconstructed set of motifs that can be used to encode data
- Translation table
- Motifs are synthesized in large numbers
- Ligated (concatenated) into larger oligos

Eugenio Marinelli, Yiqing Yan, Lorenzo Tattini, Virginie Magnone, Pascal Barbry, Raja Appuswamy, “CMOSS: A Reliable, Motif-based Columnar Molecular Storage System”, 17th ACM International Systems and Storage Conference

CMOSS - A consensus-driven coding system

- PCR allows the cheap copy of DNA molecules
- Easier to decode noised data when you have a lot of copies of it
    - Try to sequence all of the molecules
    - Operate a clusterization and consensus (merge the data from all the copies)
- Compute the minimal coverage (average number of copies) necessary to read, to be sure to decode the data

CMOSS - General workflow



Eugenio Marinelli, Yiqing Yan, Lorenzo Tattini, Virginie Magnone, Pascal Barbry, Raja Appuswamy, “CMOSS: A Reliable, Motif-based Columnar Molecular Storage System”, 17th ACM International Systems and Storage Conference

Examples of DNA Image Coders

AI-based Image coder (HiDNA)

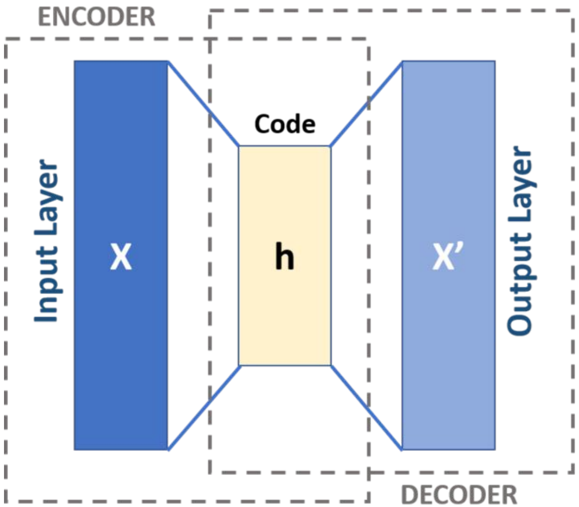
Motivations

- Learning-based models such as JPEG AI are very promising
- AI-based methods can be used to adapt to noise

T. Ladune, P. Philippe, F. Henry, G. Clare, T. Leguay, “COOL-CHIC: Coordinate-based Low Complexity Hierarchical Image Codec”, ICCV 2023

Principle - Synthesis Model

- The model learns to represent an image into a latent space (encoder side)
- Reconstruct the same image from the latent space (decoder side)
- Latent space is a tensor of fixed dimensions



Synthesis model - Training phase

A loss based on the minimization of the **rate** of the latent space and the **reconstruction quality** of the image:

$$L = D(I, \hat{I}) + \lambda \times H(y)$$

where:

- I: Input image
- $\hat{I}$: Reconstructed image
- y: Latent space
- D: Distortion metric
- H: Entropy

Principle - Latent Space Coding

- Fully connected neural network (ARM Model)
- Learns the Probability Density Function of each element of the latent space, depending on its context
- The PDF is used to instantiate an arithmetic, binary entropy coder, associated with a DNA adapted coder

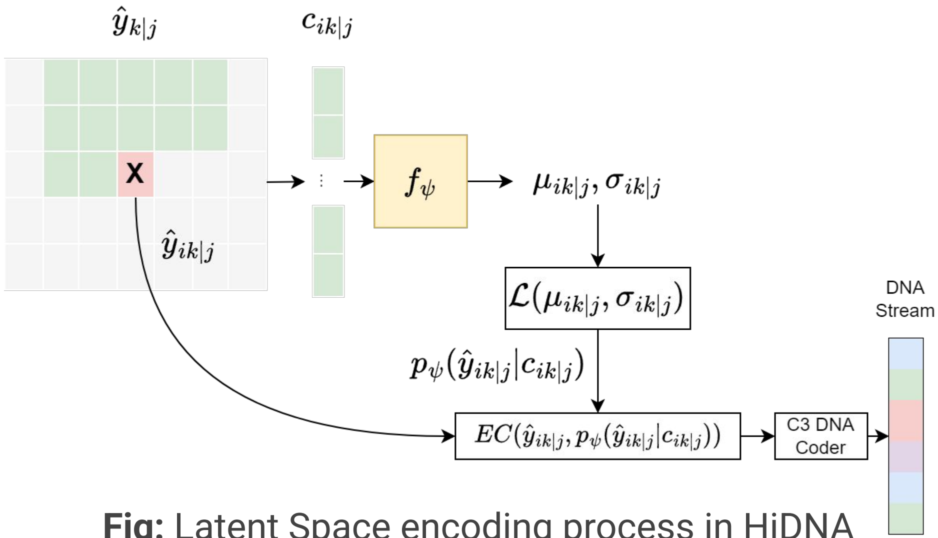
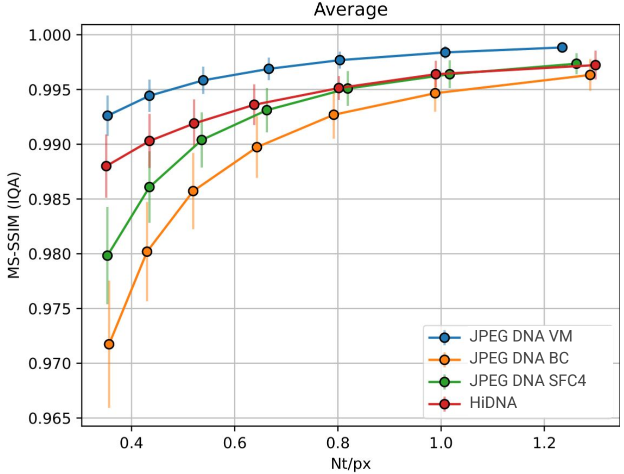


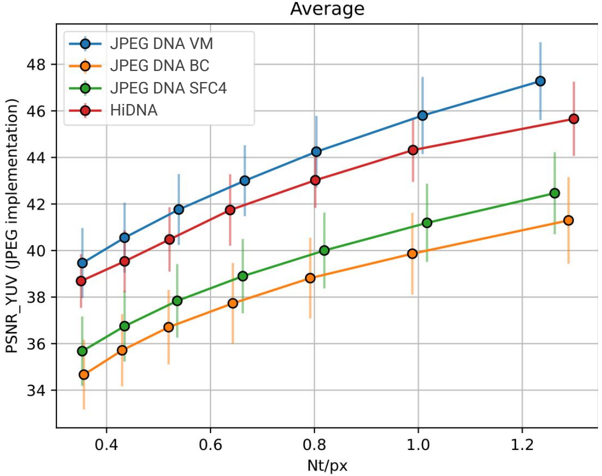
Fig: Latent Space encoding process in HiDNA

Results

- HiDNA overperforms all other state of the art source coders

- Only the JPEG DNA VM (**open loop** adaptation of JPEG XL to DNA) performs better





M. Testolina, V. Hosu, M. Jenadeleh, D. Lazzarotto, D. Saupe, T. Ebrahimi, “JPEG AIC-3 Dataset: Towards Defining the High Quality to Nearly Visually Lossless Quality Range”, *2023 15th International Conference on Quality of Multimedia Experience (QoMEX)*, Ghent, Belgium, 2023

Conclusion

- A series of coding softwares have been adapted to DNA data storage or implemented
  - For images (source coders and joint source/channel coders):
    - JPEG DNA SFC4, JPEG 2000 DNA, HiDNA
  - For any kind of data (channel coders):
    - C3, SFC4, Raptor Code
- Fairly new field of research -> Still opportunities for improvement in several fields (coding theory, information theory)

References

- PEPR MoleculArxiv (French Gvt - ANR)
- Molecular-Scale Data Storage and Archiving (USA - IARPA)
- DNA Data Storage Alliance (SNIA Technology Groups)
- Companies and labs: Wyss Institute, Twist Bioscience, Catalog DNA, Biomemory, PearCode

Thank you !

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EURECOM - Data Science

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