
Digital Innovators
Séminaires d'innovation numérique
L'ADN comme technologie d'archivage des données numériques : état de l'art
Pierre-Yves Burgi
7 décembre 2022
12h30 – 13h30
Webinaire zoom gratuit
http://pin.unige.ch
Accélérateur de Sciences et services numériques
PÔLE INNOVATION NUMÉRIQUE
UNIVERSITÉ DE GENÈVE

Agenda:

- Introduction to long-term data preservation
- Current storage technologies
- Why DNA ?
- Archiving data in DNA molecules
- Viable solutions for legacy archiving?

- Introduction to long-term data preservation

Long-term preservation of electronic documents consists in preserving the document and the information it contains:

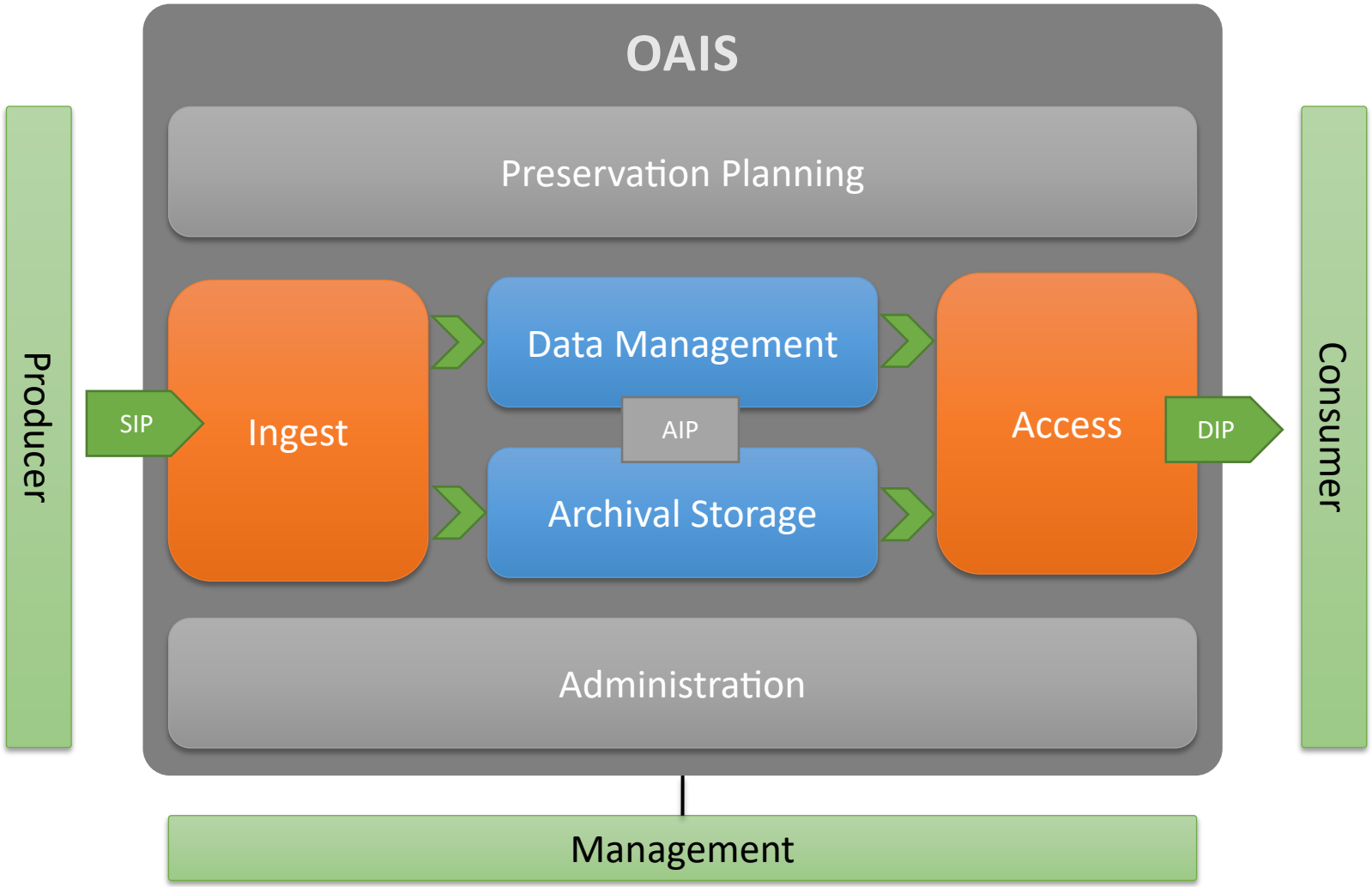
- In its physical and intellectual aspects
- On the very long term (hundreds of years)
- In a way so that it is permanently accessible and understandable

To reach this goal we apply the

Reference Model for an Open Archival Information System (OAIS - ISO 14721)

yareta.unige.ch and olos.swiss are examples of OAIS-compliant archiving systems

Open **A**rchival **I**nformation **S**ystem (ISO 14721)



Backup vs. Archiving

ARCHIVE

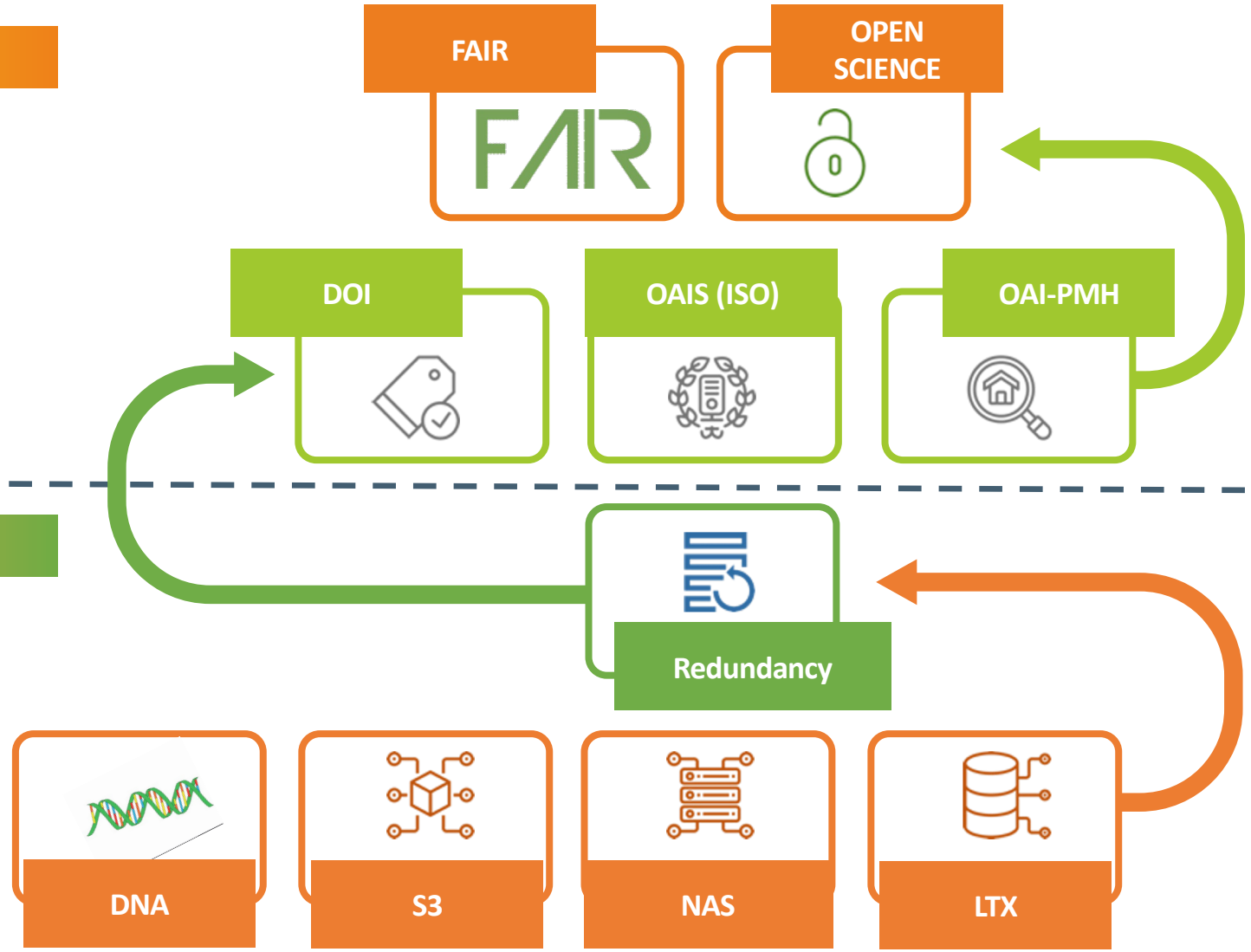
Preserve information as required by regulations and institutional policies

- Auditable
- Follows a life cycle
- Self-described
- Data integrity

BACKUP

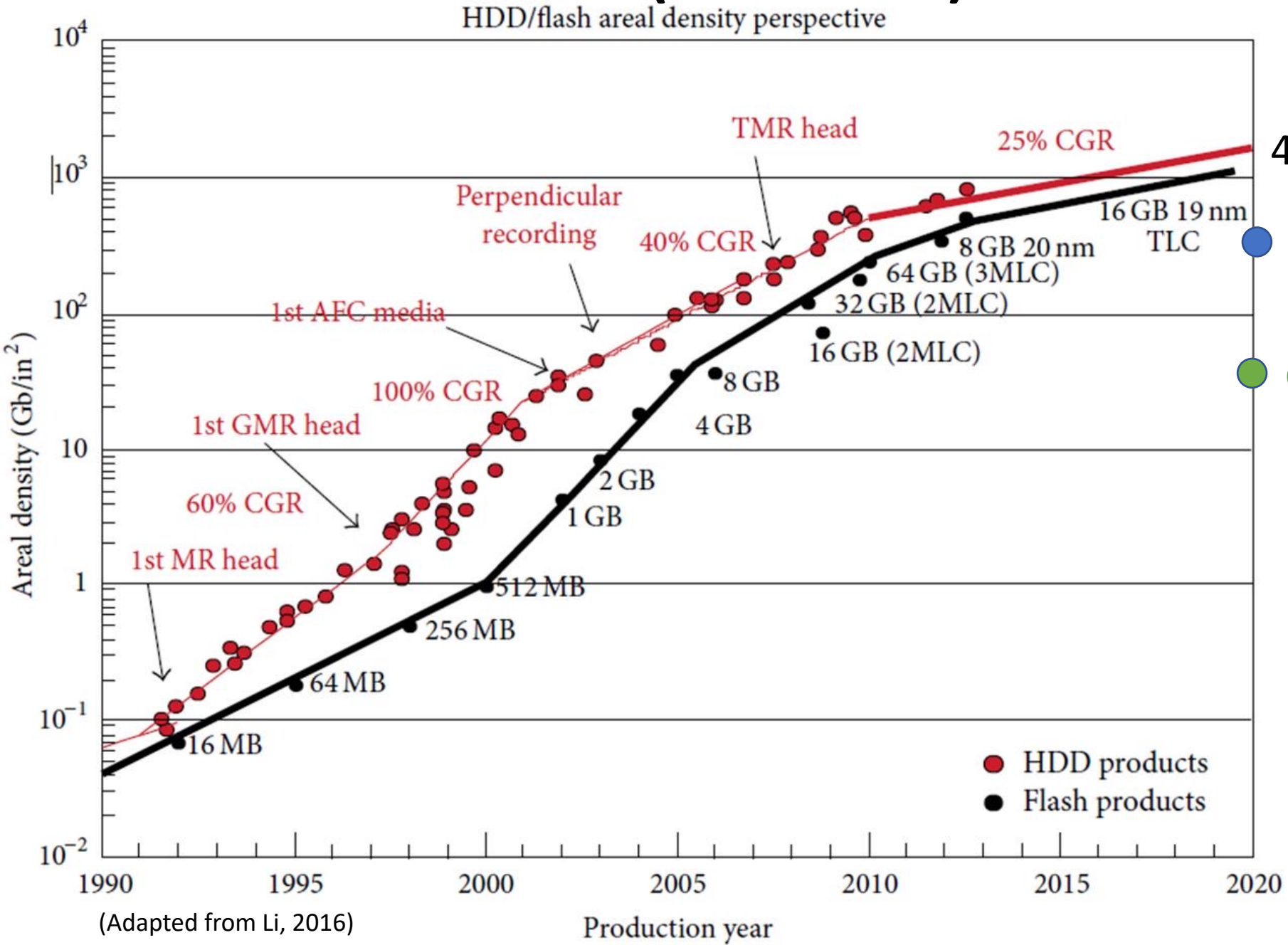
Insurance policy against unforeseen system failures

- Incremental
- Multiple snapshots
- Retained on short periods of time
- Not searchable



- Current storage technologies

Hard Disk and Flash (and other) Devices



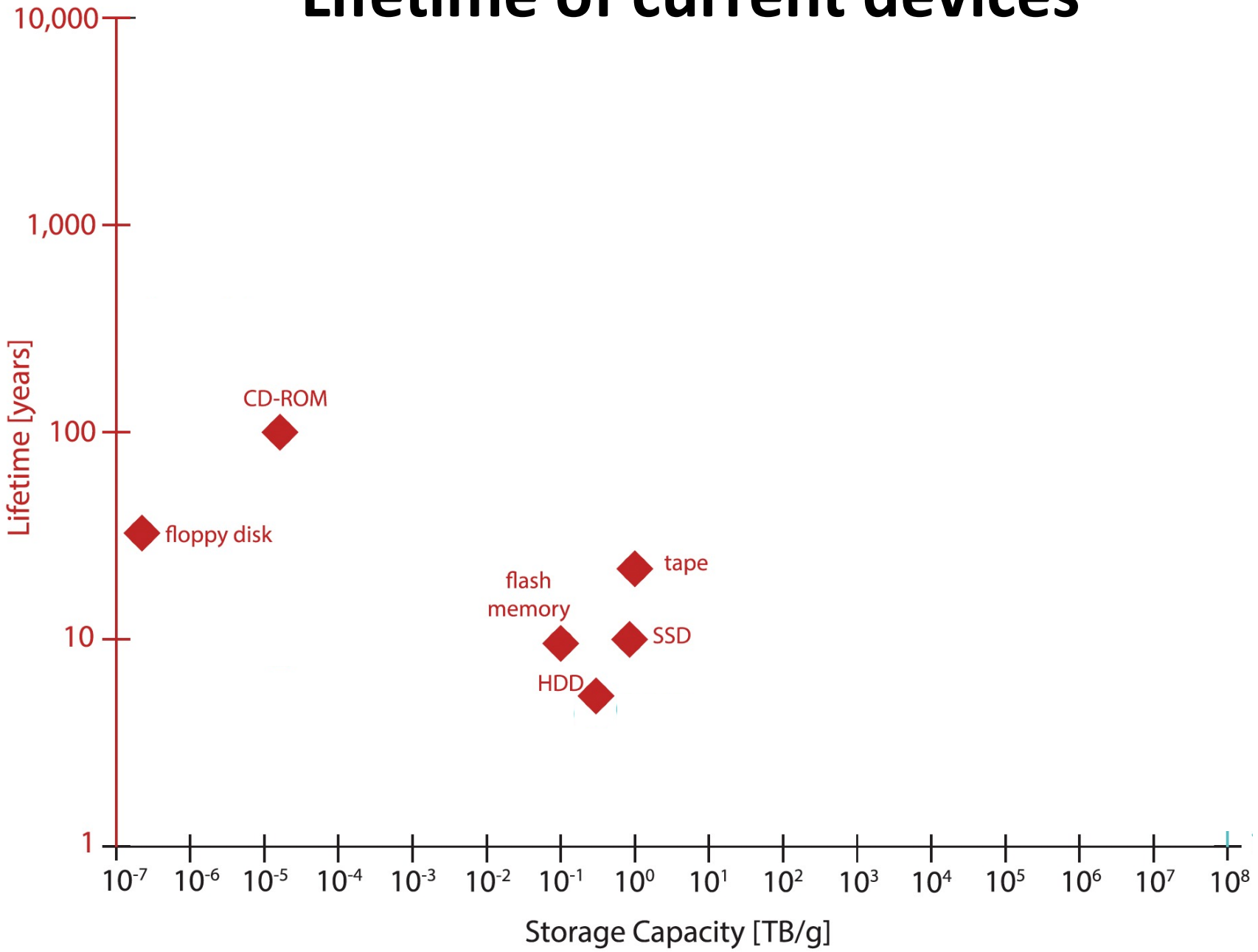
(Adapted from Li, 2016)

4 Gb/mm^2

Tapes

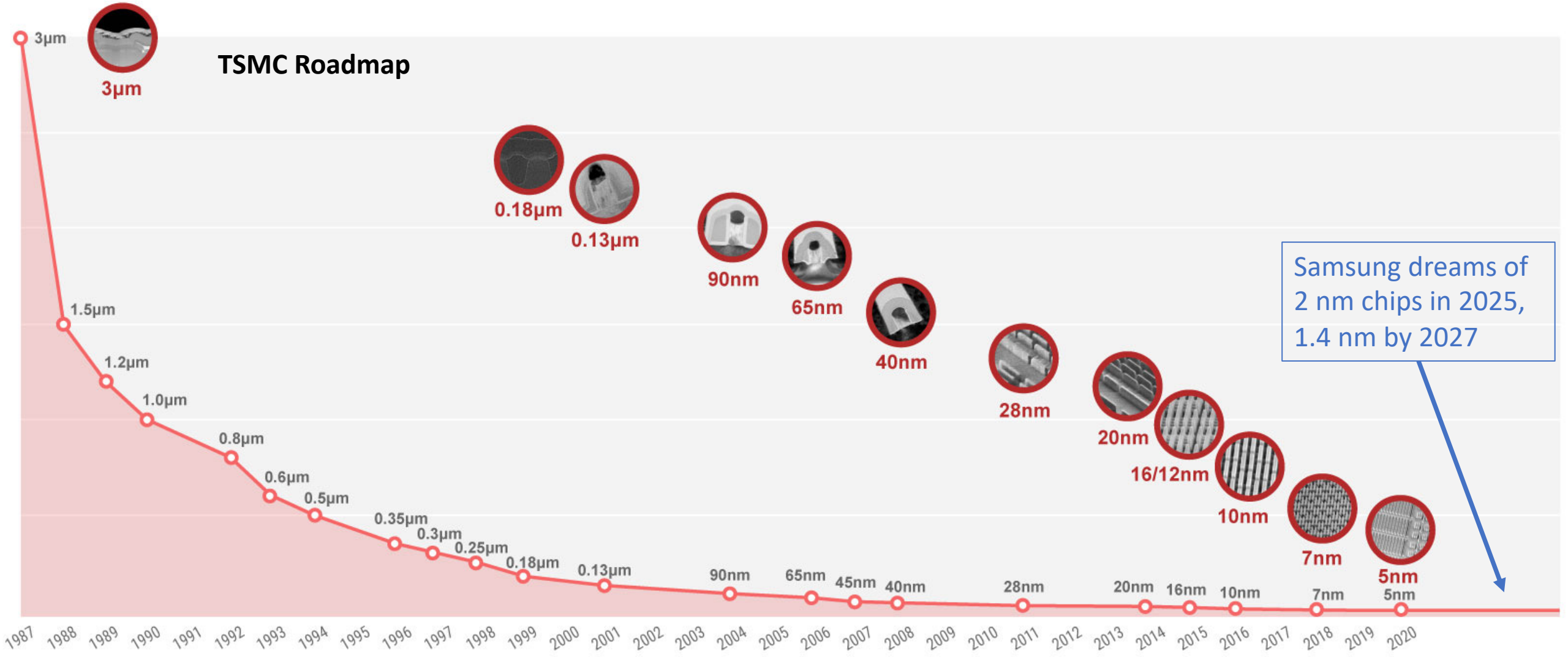
Optical disks

Lifetime of current devices



(Meiser et al., 2022)

Technology reaches its limits



Under 10-15 nm the quantum tunnelling effect affects storage reliability

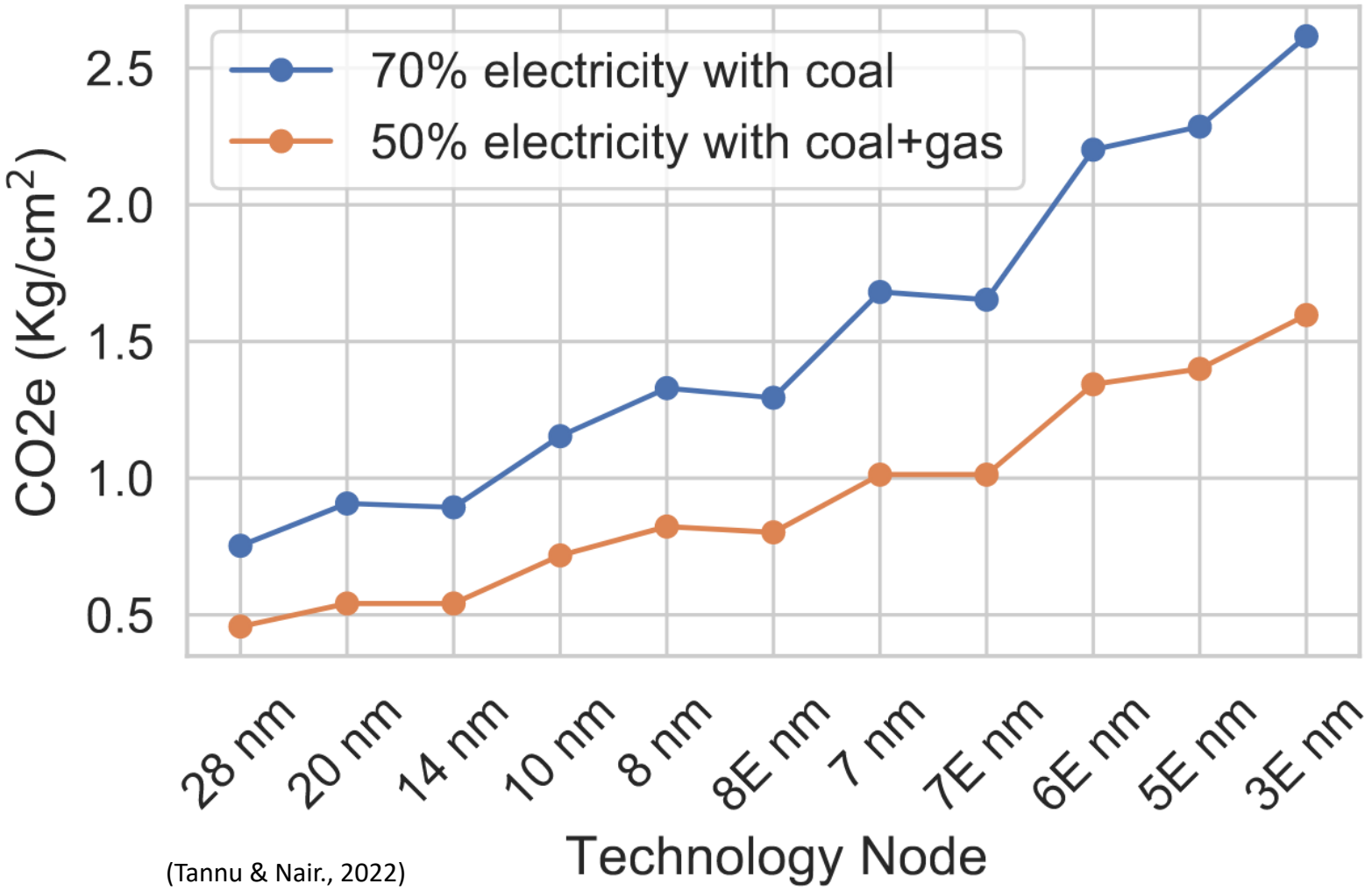
Environmental Impacts

Taiwan Semiconductor Manufacturing Company uses almost 5% of all Taiwan's electricity, predicted to rise to 10% by 2030, and it used about 63 million tons of water in 2019.

Advanced technologies, such as the Extreme Ultraviolet Lithography (EUV) tools that TSMC bought in 2019, consume 20 times as much power as previous generations of production tech.

Media and hardware used to store and manage the data will be changed every 5-10 years, with the old media/hardware either recycled, incinerated, or dumped in a landfill.

Environmental Impacts



(Tannu & Nair., 2022)

- Why DNA ?

Density

- 14 atoms / bit
- No tunneling effect because made of molecules
- Created on demand
- About 200 Tb/mm^2 (vs. 4 Gb/mm^2 HDD)
- All human-made digital data stored in less than 100 g of DNA
- Human genome: 3.59 pg

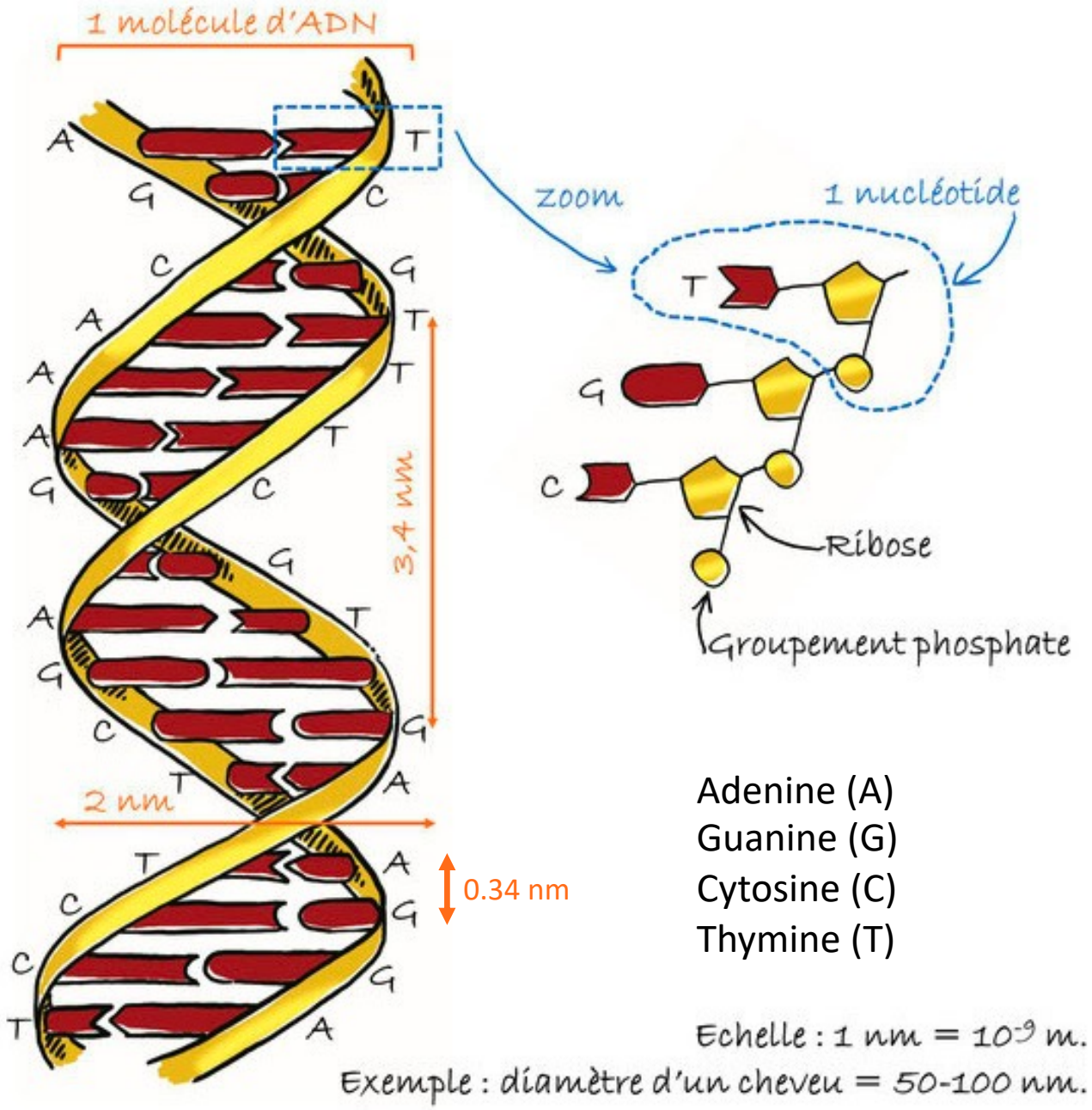
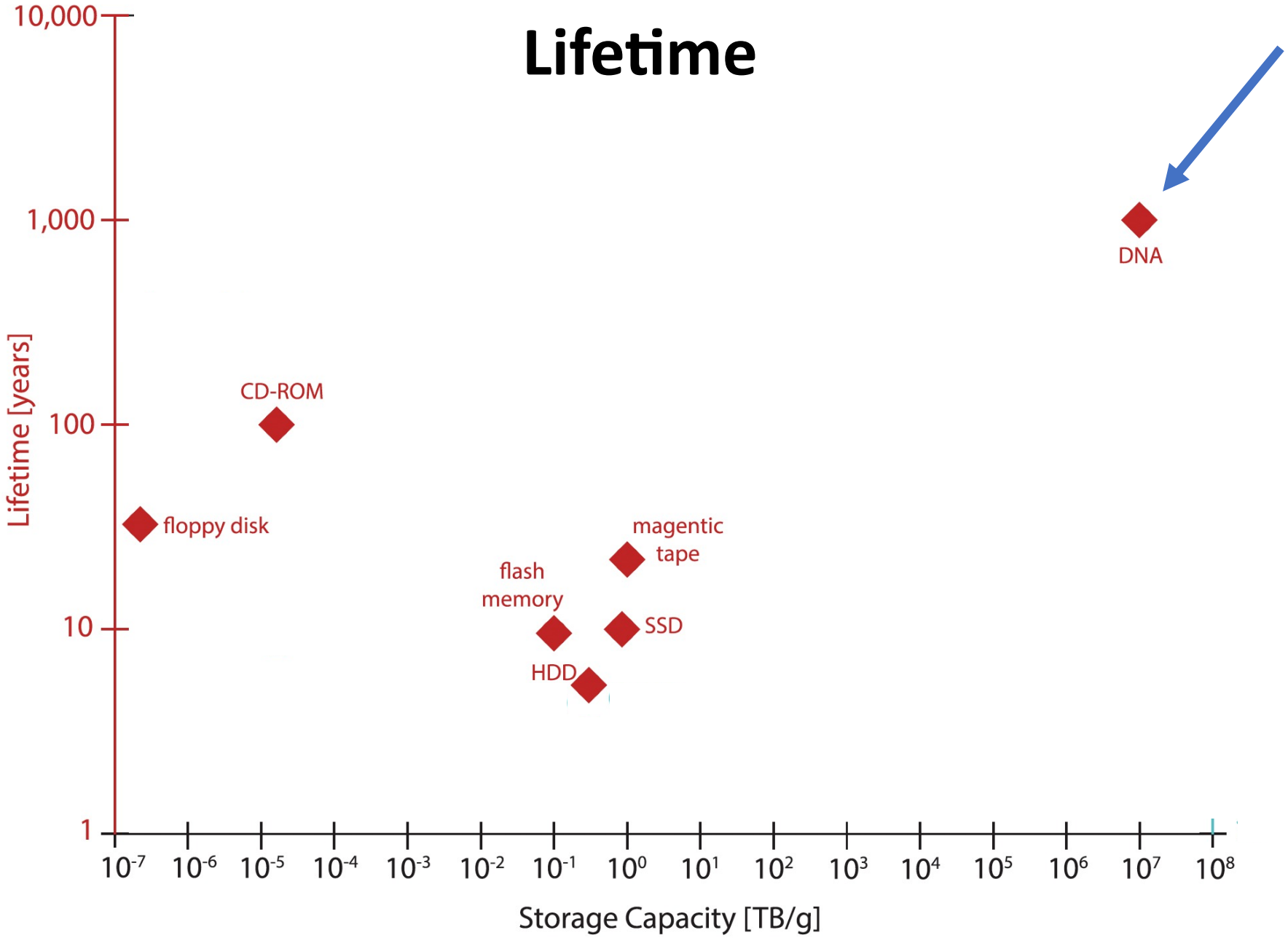


Illustration de Jeanne Le Peillet

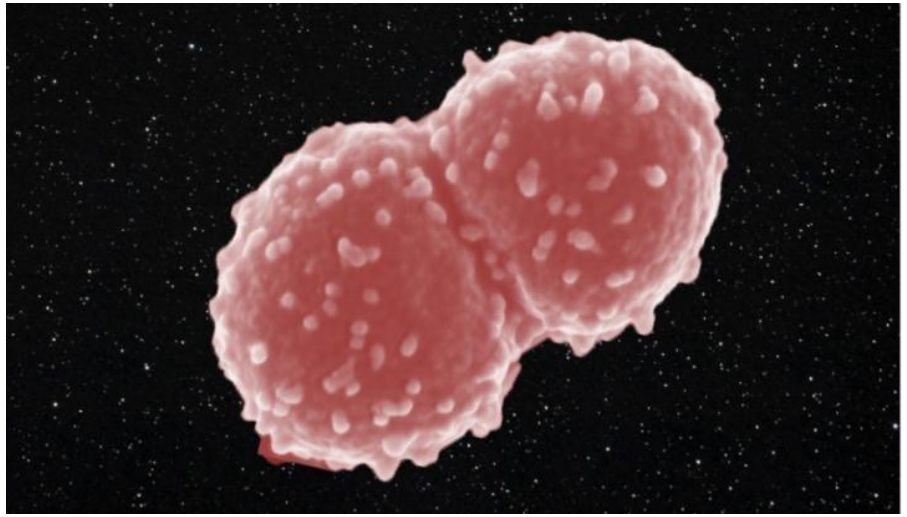
Lifetime



(L. Meiser et al., 2022)

No obsolescence (fabric of life)

Thermus aquaticus, up to 85 °C and in very acidic environments



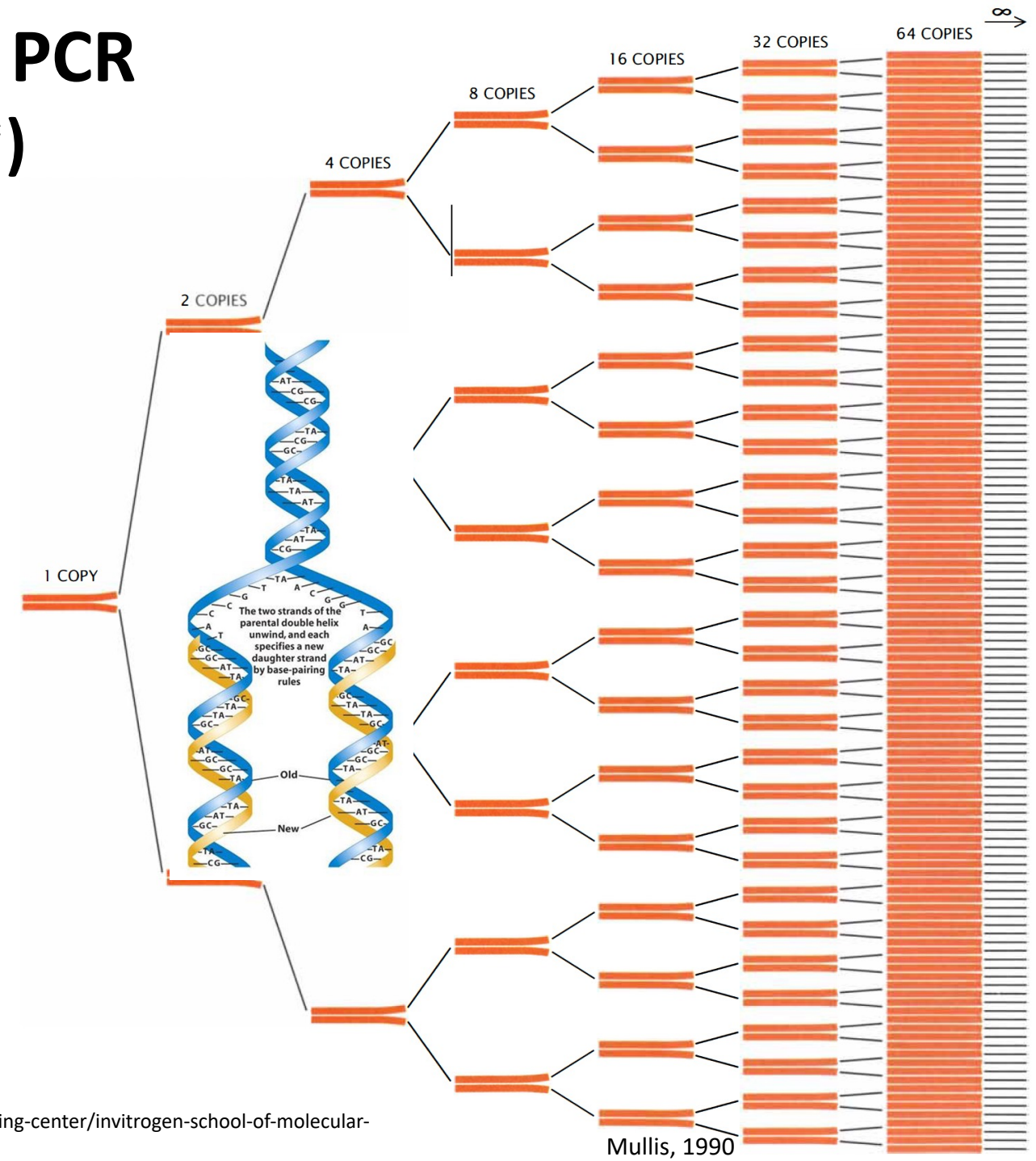
Space traveler Deinococcus radiodurans recovered after 1 year of exposure to low Earth orbit (LEO) outside the International Space Station

Resistance to ionization and extreme environments

Science Photo Library

Low-cost copies based on PCR (Polymerase Chain Reaction*)

- Fixed time process (few minutes) : does not depend on the volume of data
- Average power of approximately 1.0 W per PCR cycle !

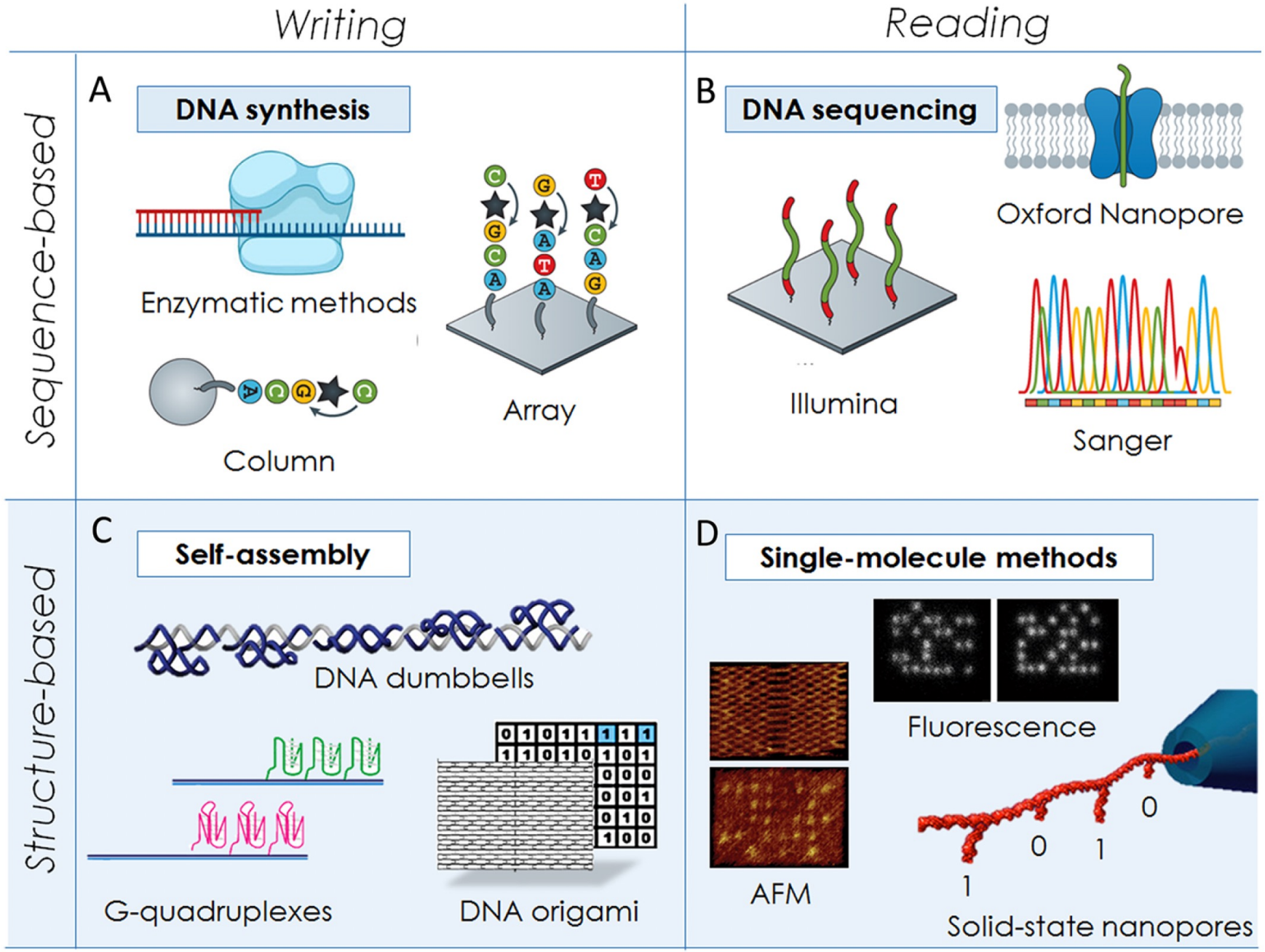


Mullis, 1990

* Use the DNA polymerase enzyme e.g., isolated from the *Thermus aquaticus*

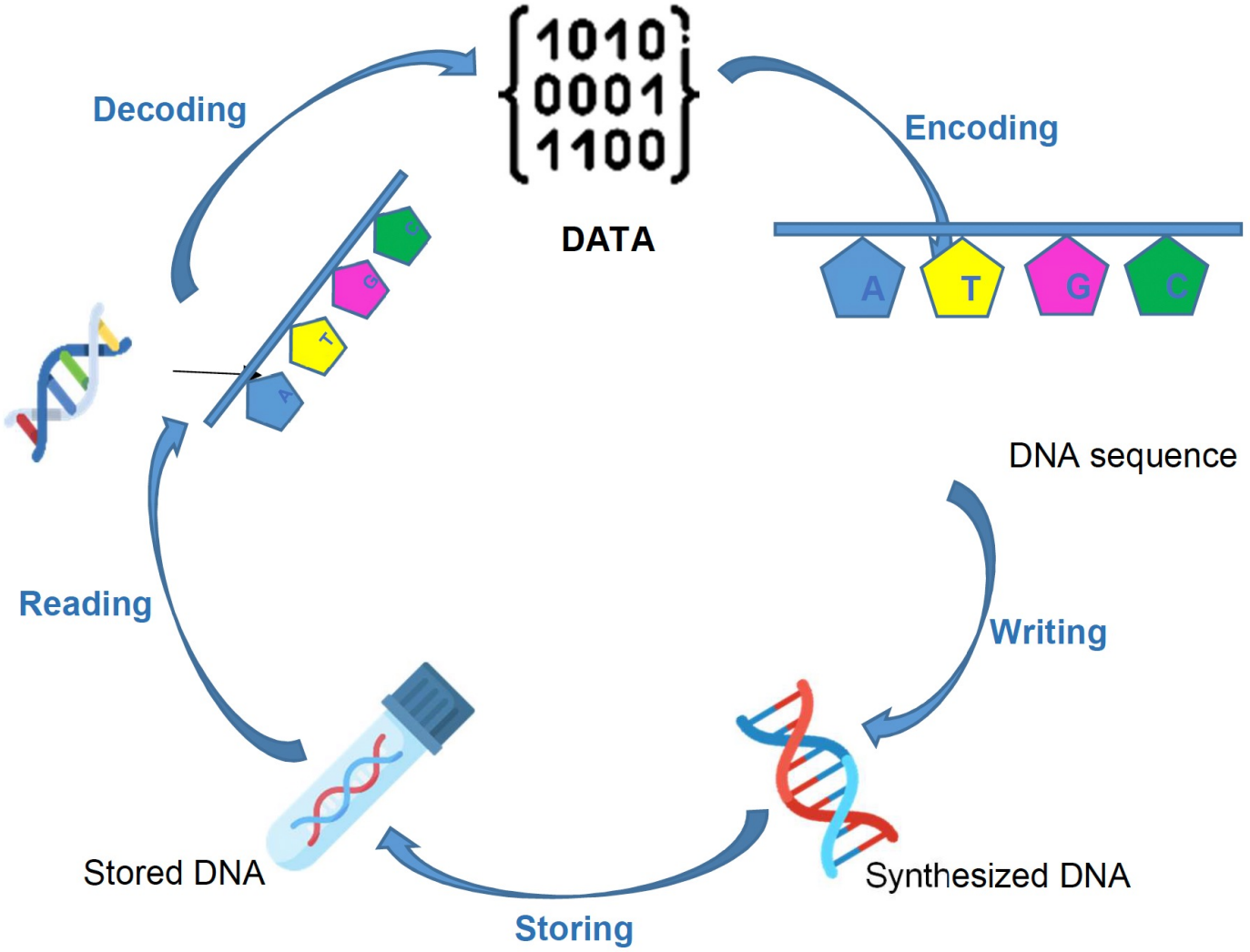
See for instance https://www.thermofisher.com/ch/en/home/life-science/cloning/cloning-learning-center/invitrogen-school-of-molecular-biology/pcr-education/pcr-reagents-enzymes/pcr-cycling-considerations.html

- Archiving data in DNA molecules



(Doricchi et al. 2022)

I. Sequenced-based archiving



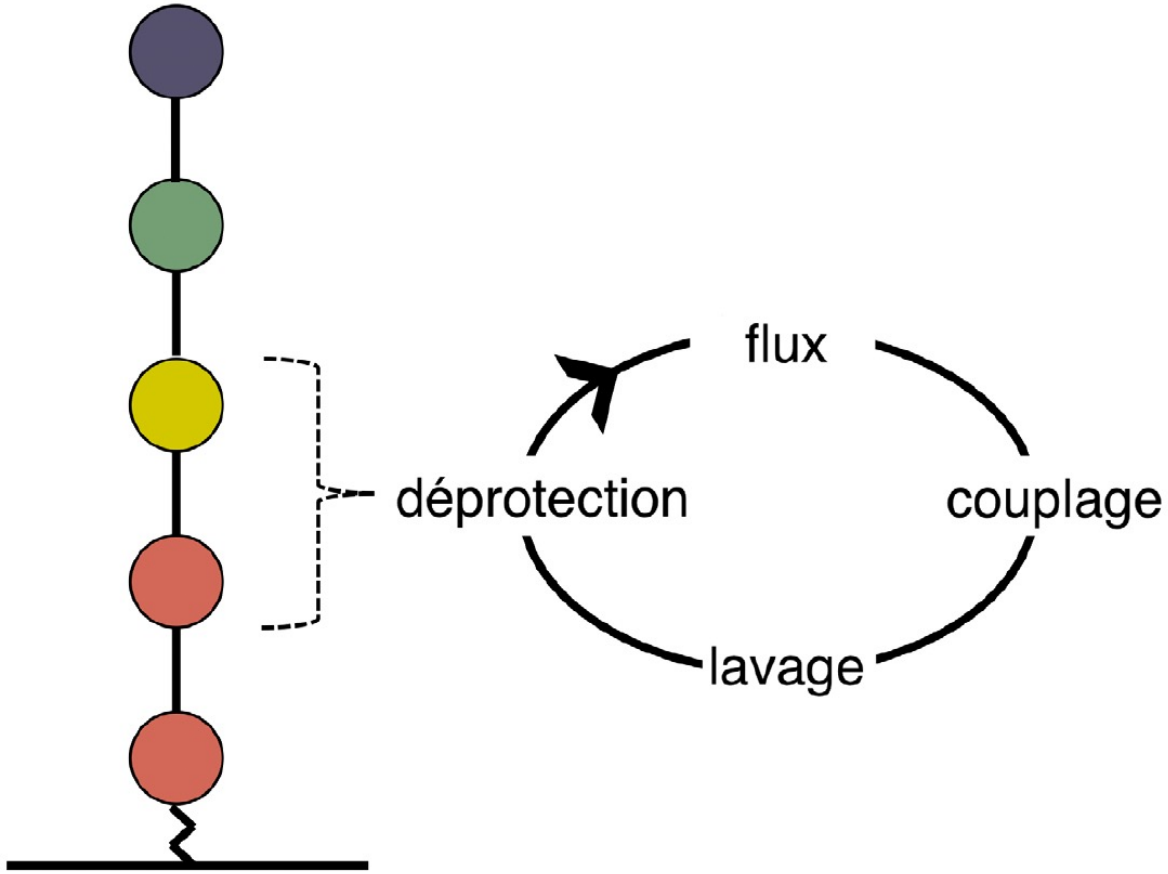
(Andriamahady 2021)

1 Writing

A = 00 T = 01 C = 10 G = 11

Une seule synthèse

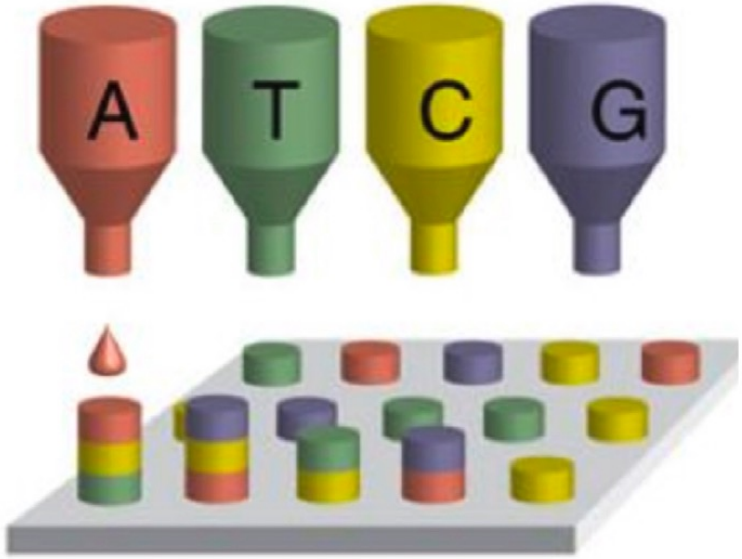
00 00 10 01 11



Adapté par François Képès depuis la présentation de Nick Gold (Catalog DNA)

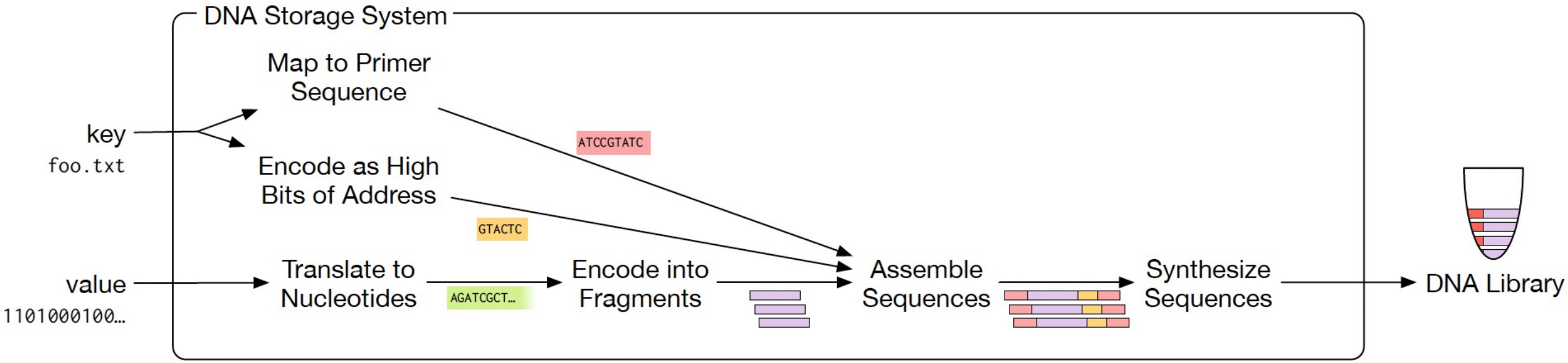
Synthèses en parallèle

01 10 00 01 11 01
00 10 11 01 11 10
10 01 00 10 10 …



About 1 error(s) per 500-2000 nucleotides (nts) (0.2 - 0.05 %)

1 Writing



(Bornholt et al 2016)

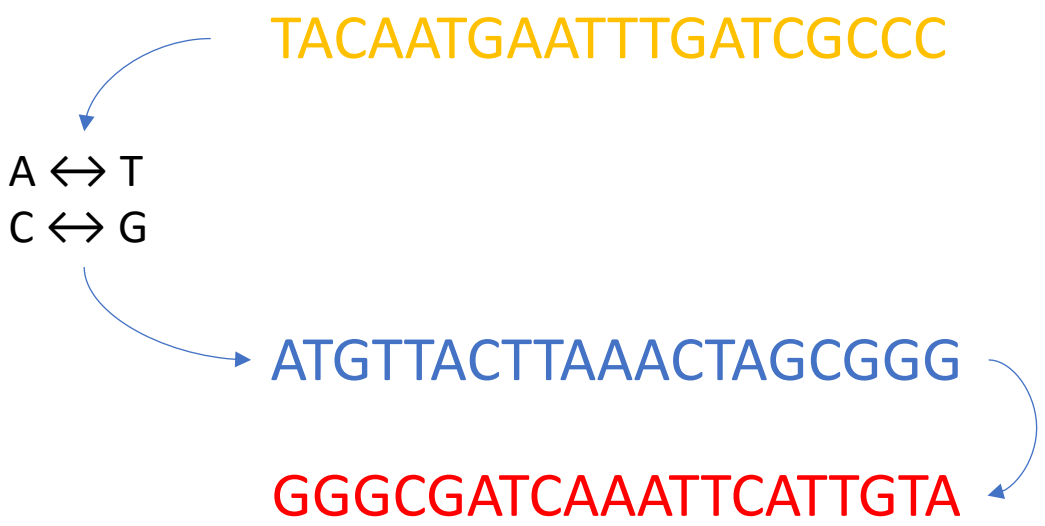
The logical structure

Primer

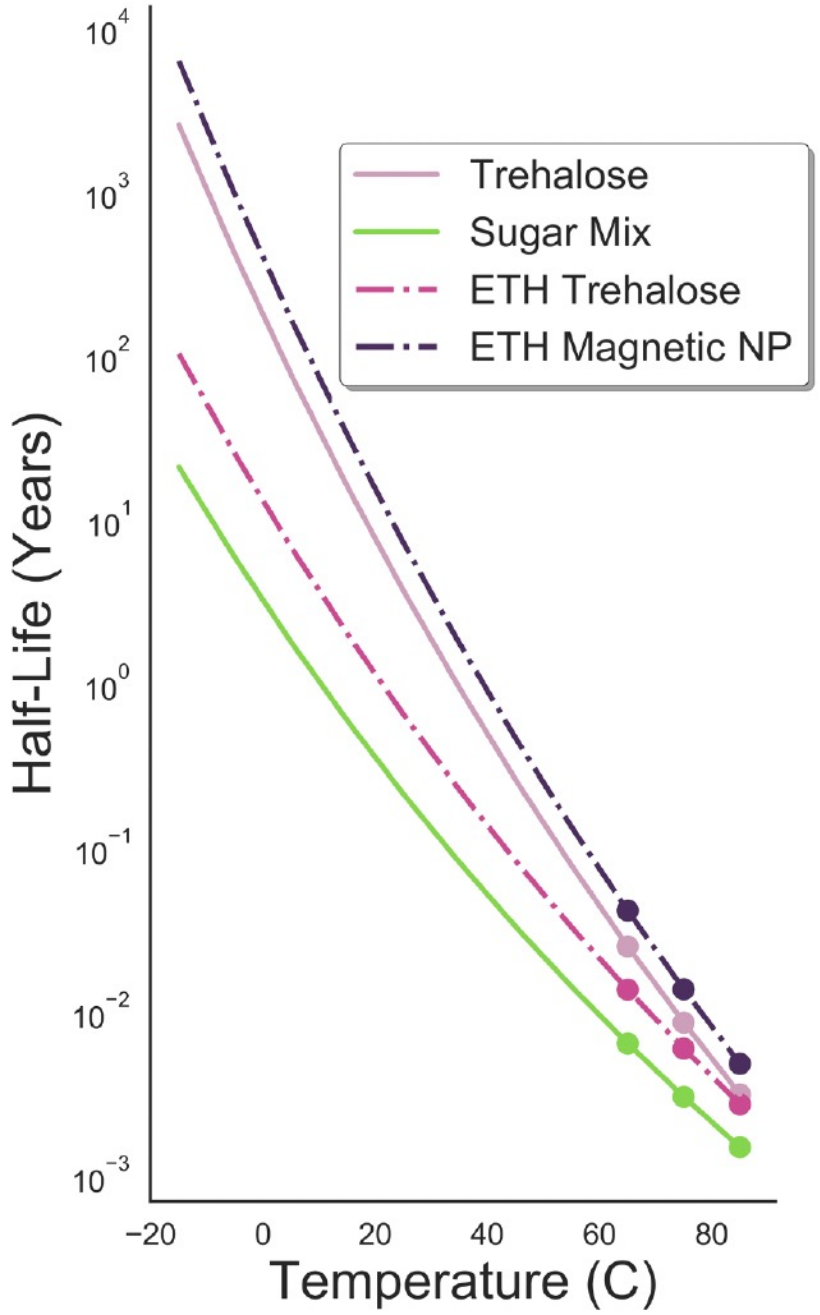
Payload (including index and code redundancy)

TACAATGAATTTGATCGCCCCGAAAGCAAGAAGATCGGACAAGCCCGGCGGTCCCGGCCAGCTCTGAGTCGCGGGTCGTCTCGGCCTAA
TATGTTAGGTCCCTGATTACCTGATAGCGCTTAGCTTTCCCGAGATTCGACAAAGGTCTTTGTACATGGGCGATCAAATTCATTGTA

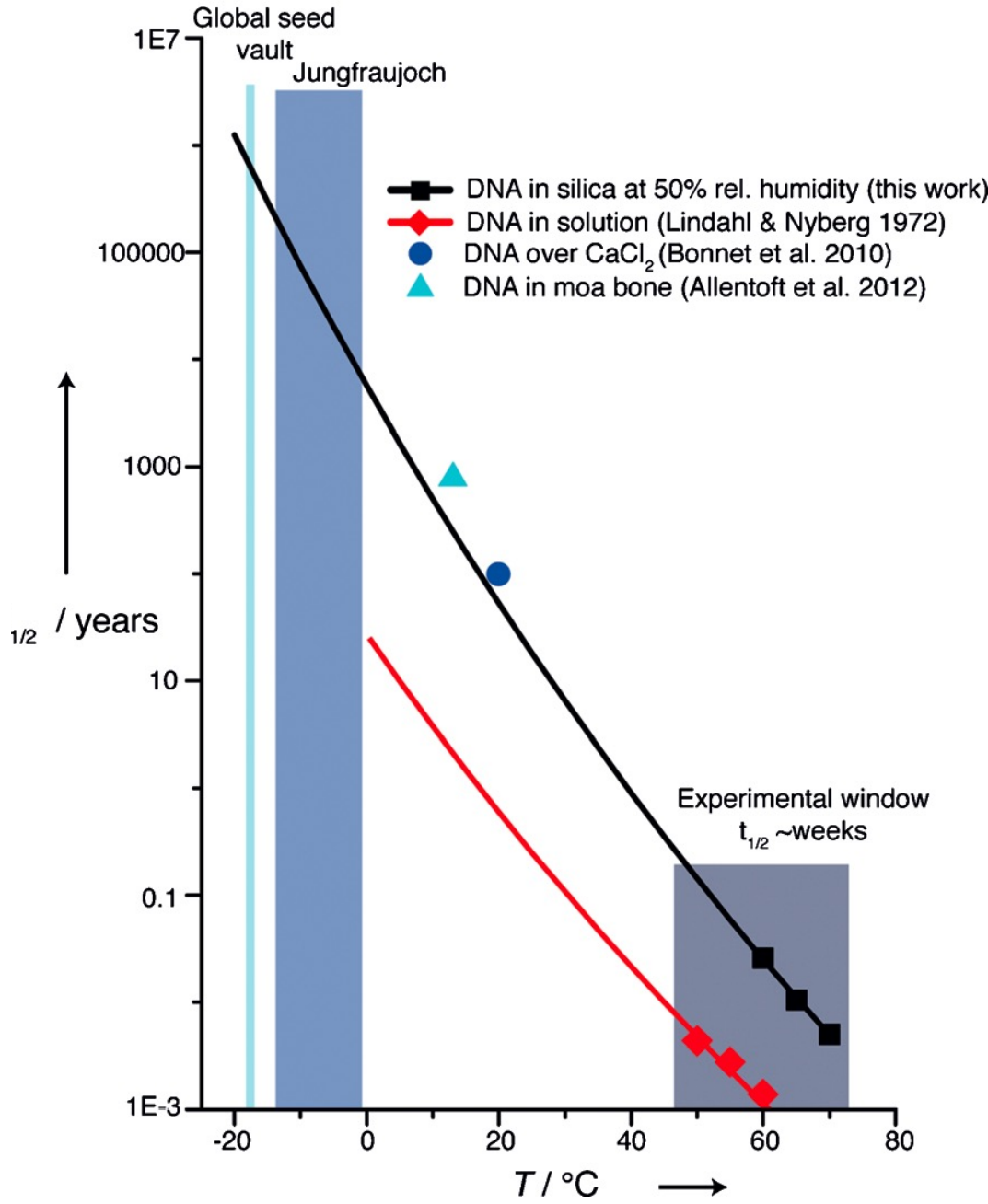
Primer



2 Preserving

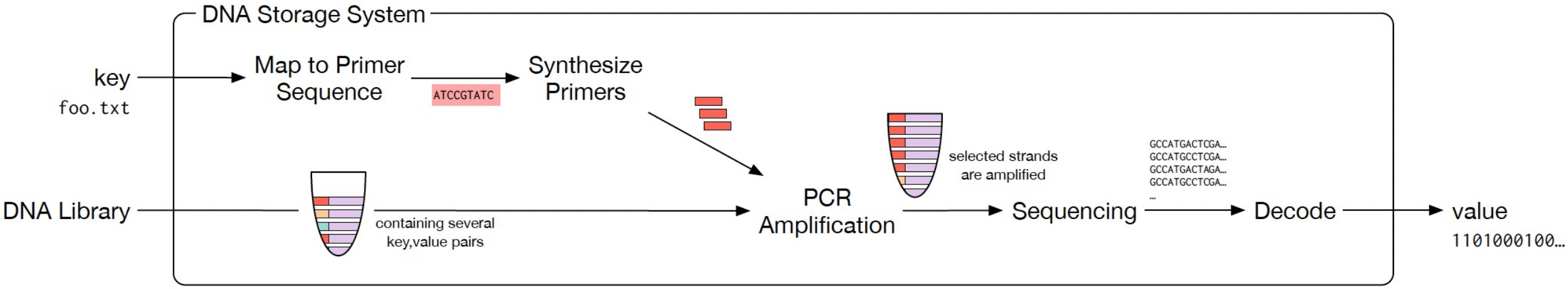


(Organick et al. 2020)



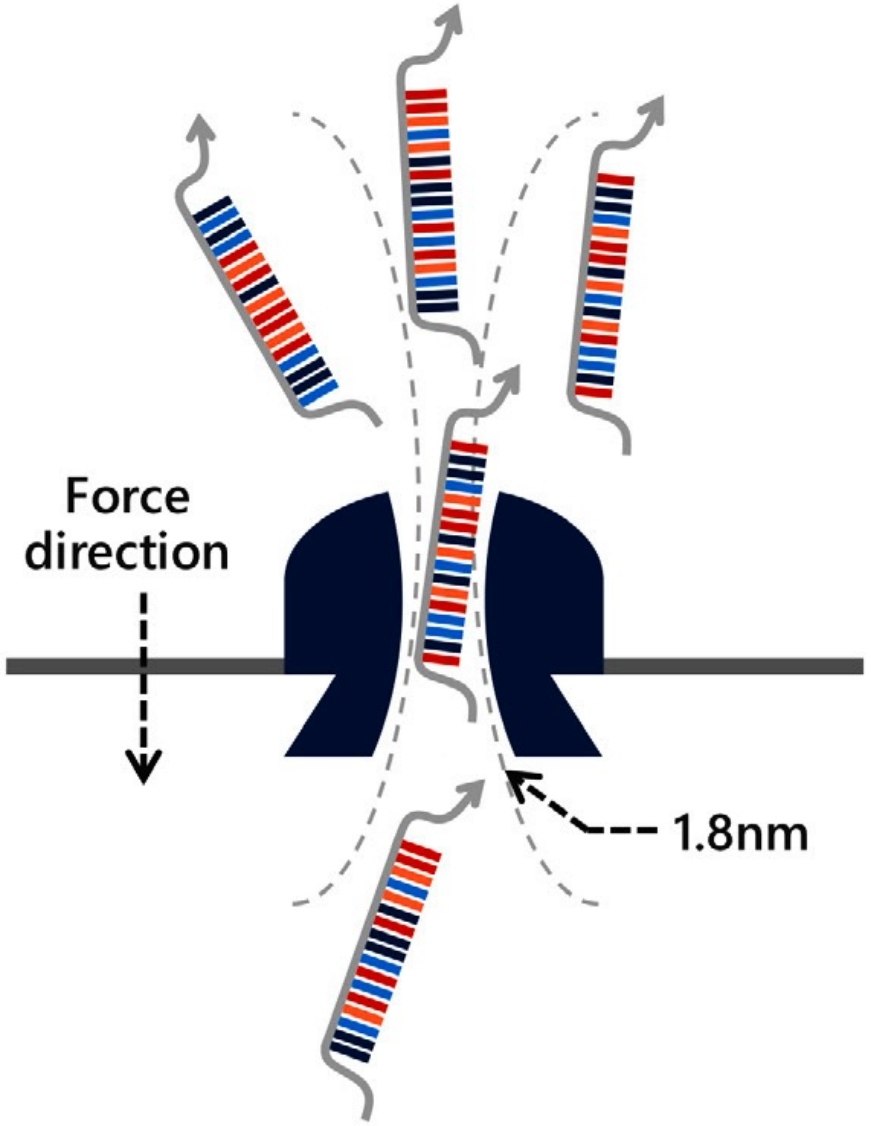
(Grass et al. 2015)

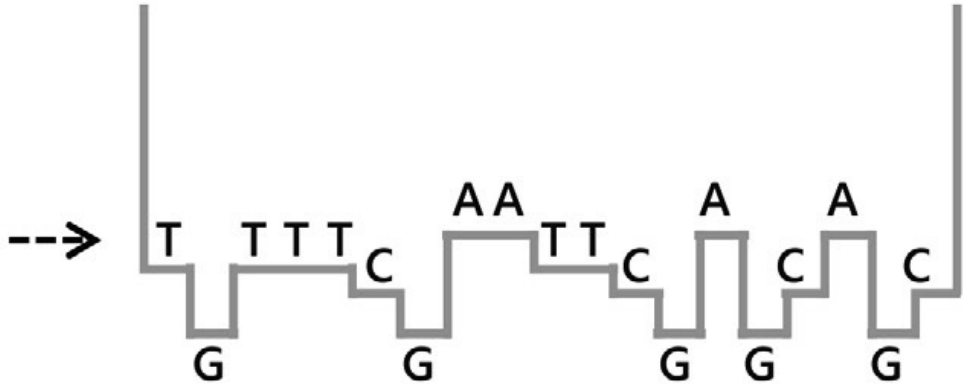
3 Reading process



(Bornholt et al 2016)

3 Reading through nanopore technologies



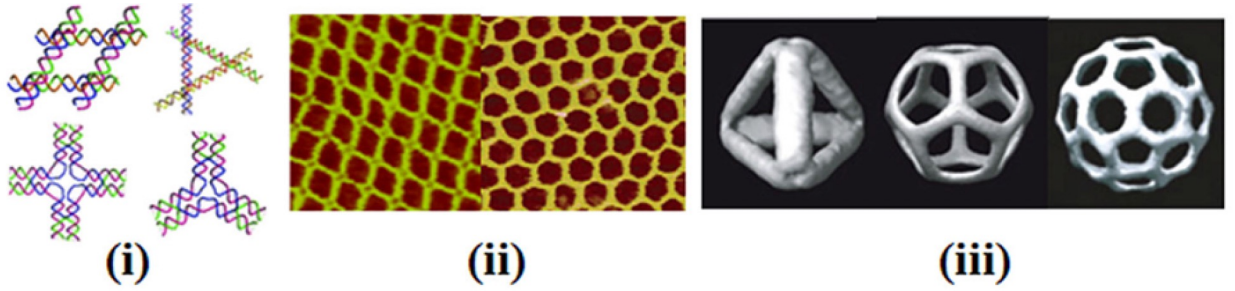


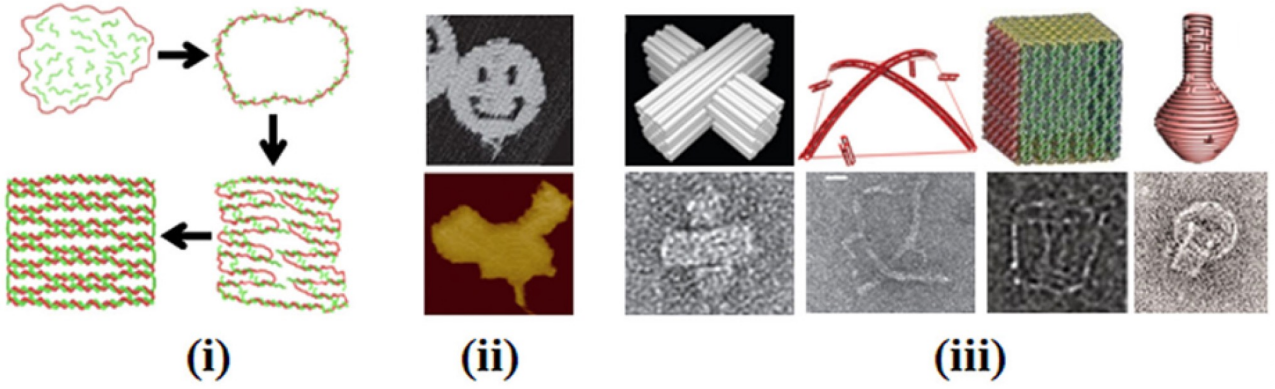
Error rate: 5-15%
Transition A-G more error prone than A-T

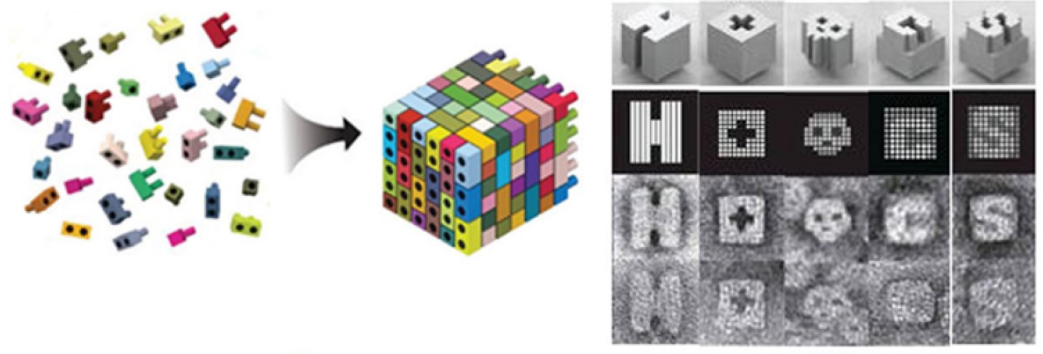
Oxford Nanopore Technologies

II. Structure-based archiving

DNA Origami



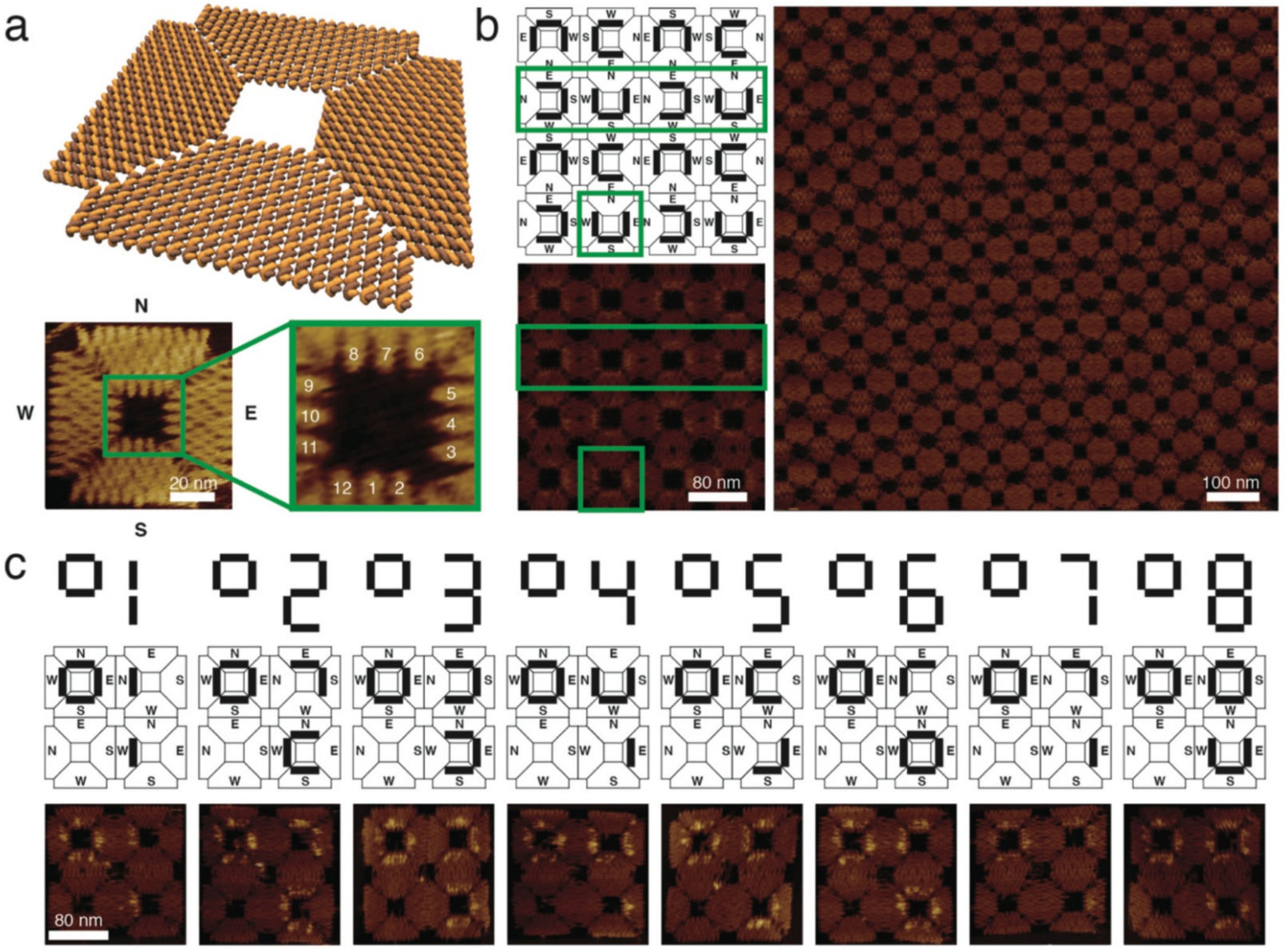




(Wang & Ding, 2022)

DNA Origami Method

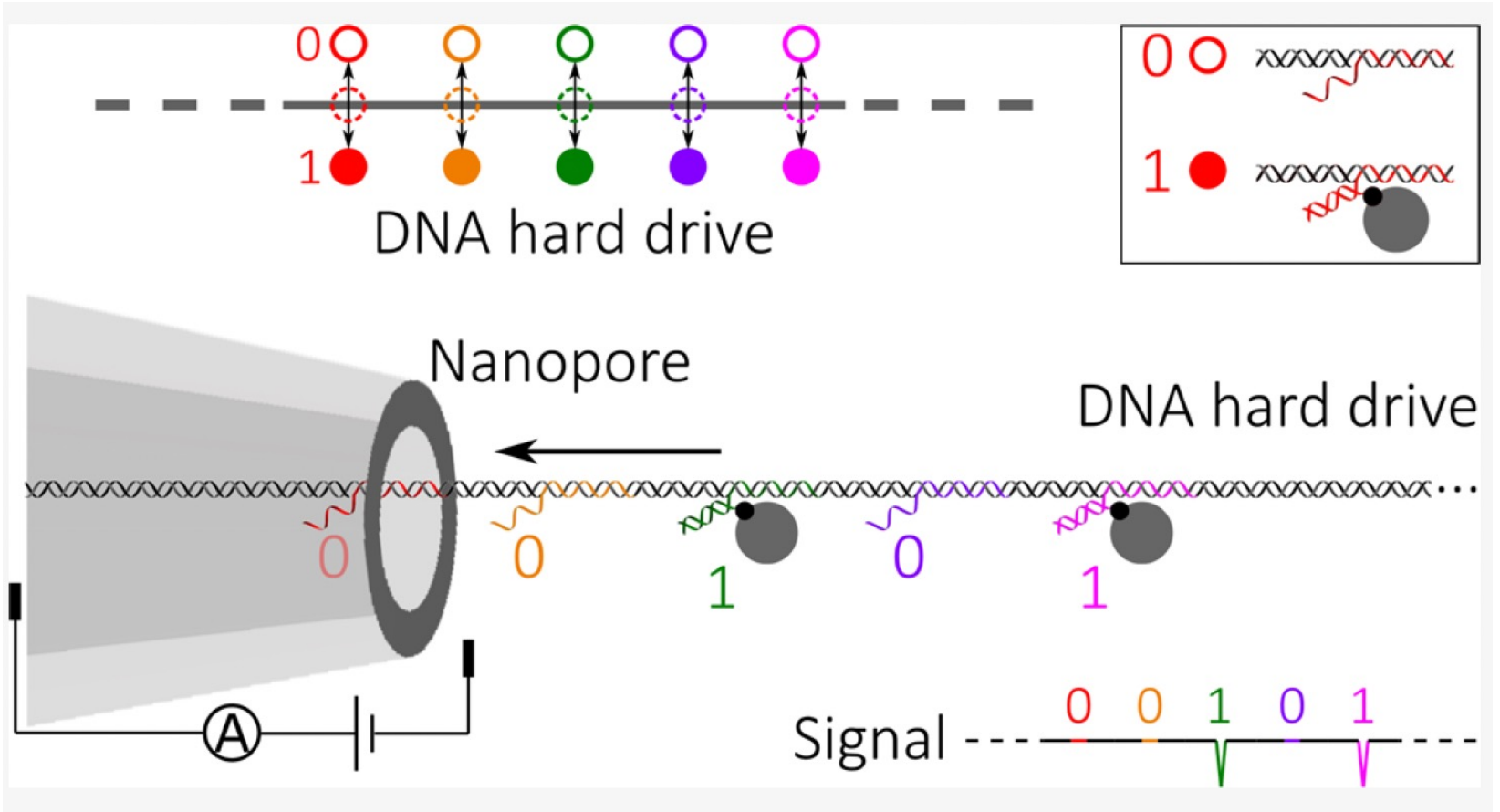
- Short DNA staple strand (< 20 nt) can be configured (e.g. orientation) and regarded as pixels (voxels in 3D).
- "Pixel" size ≈ 5 nm, about 330 Gbit/cm^2
- Reading through AFM or optical methods



(Rafta et al, 2020)

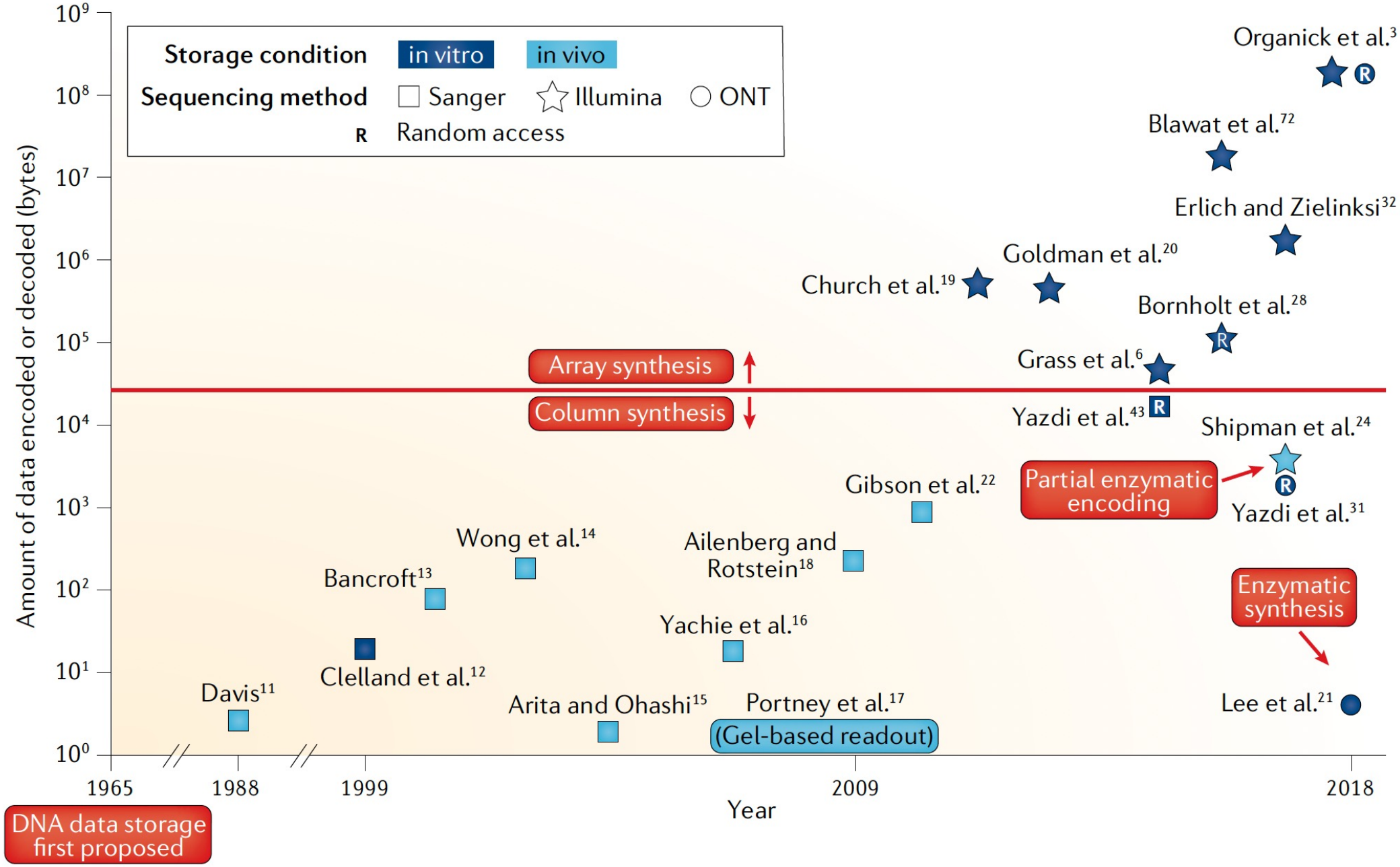
Nanopore-Based DNA Hard Drives (structured-based)

- A DNA strand (20 nt) is defined as «0» without a binding protein and «1» otherwise
- Nanopores are sensitive to the DNA configuration shape
- The protein can be removed (erase operation) and added (write operation)
- DNA molecules can move through microfluidics channels
- About 100 nt per bit
- Possibility to chemically encrypt the information



(Chen et al, 2020)

- Viable solutions for legacy archiving ?



200 MB

today

(Ceze et al. 2019)

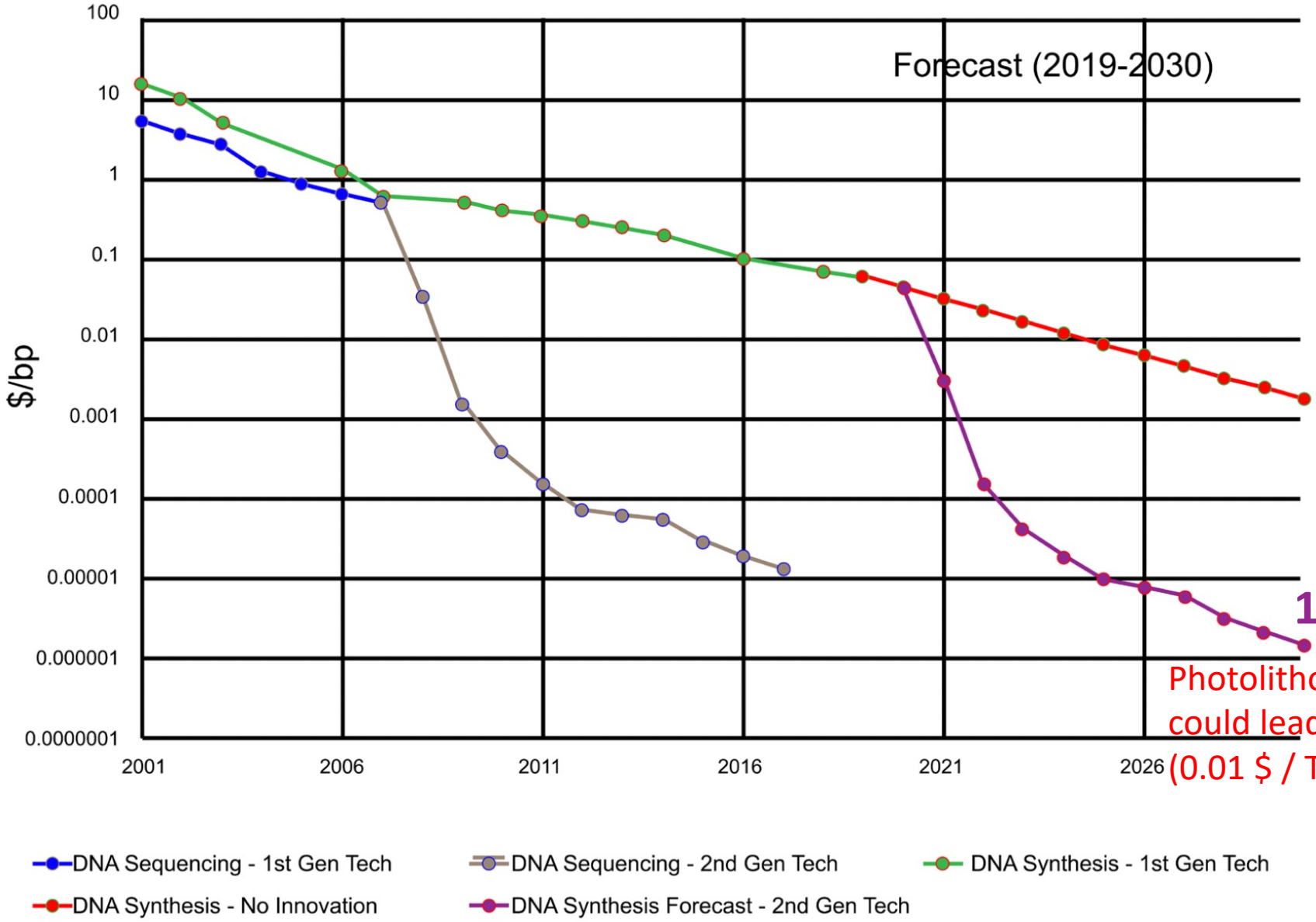
Costs

Today about 1’000 CHF/MB

But 2 main reasons not to worry…

Forecast of DNA Synthesis Cost

1 DNA Technology is advancing 7.5 times faster than Moore's Law

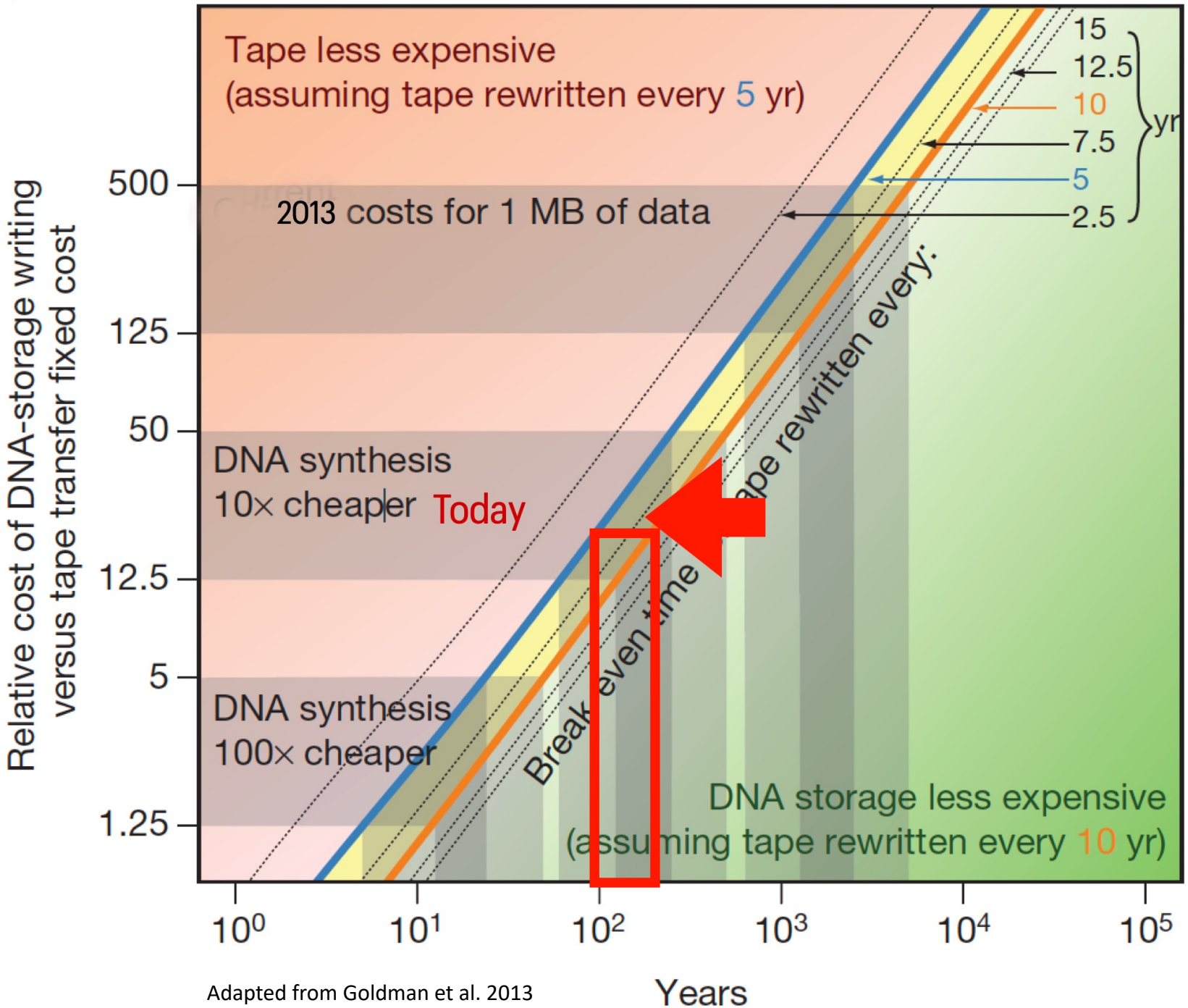


1 $ / MByte

Photolithographic DNA could lead to 10^{-8} $ / MB (0.01 $ / TB)

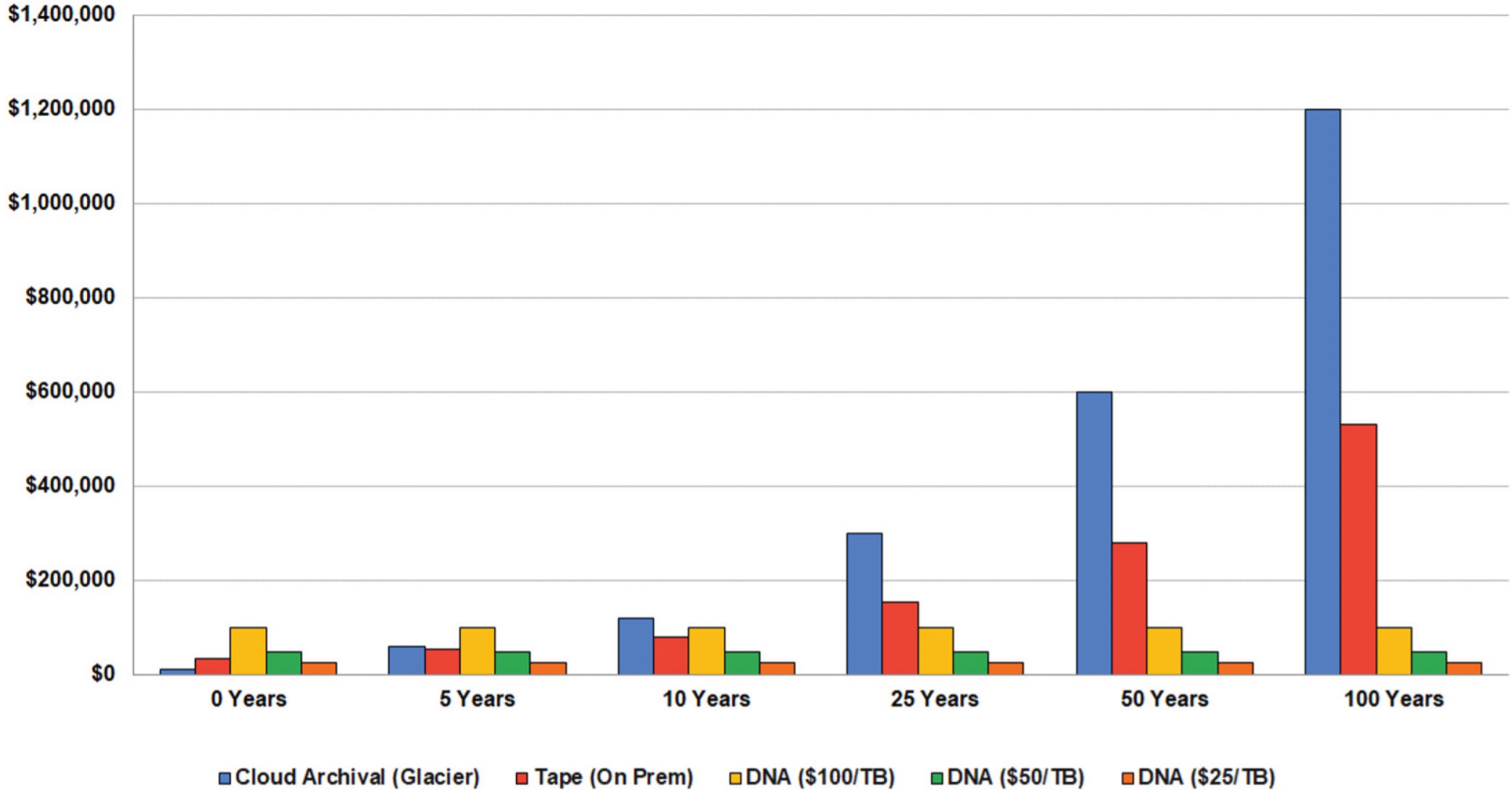
The future of DNA storage (sept. 2018)

2 Technology obsolescence requires recurrent investments



Adapted from Goldman et al. 2013

Estimated Cost of Writing and Storing 1PB - Cloud Archival (Glacier Deep Archive), Tape (On-Prem) and DNA



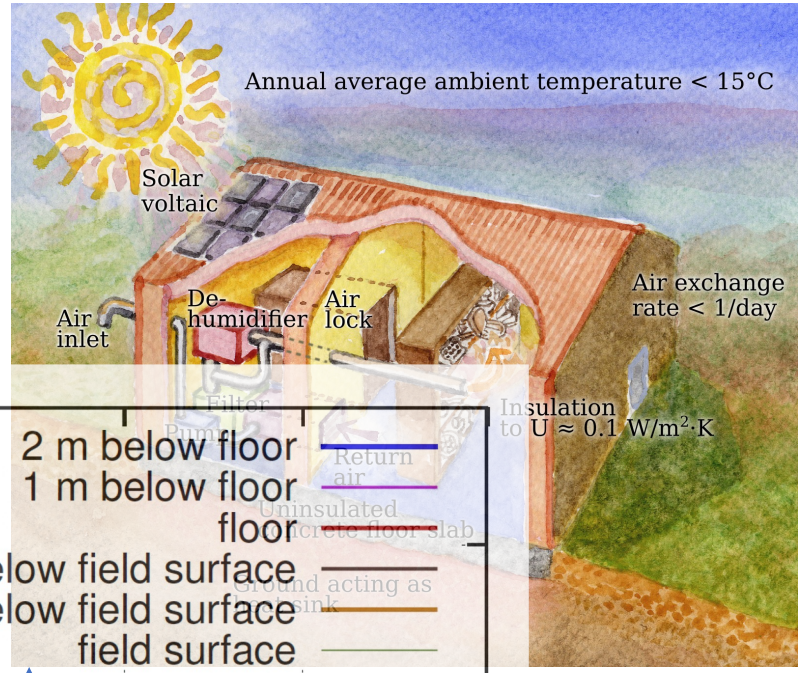
From: The future of DNA storage, DNA Storage Alliance (sept. 2018)

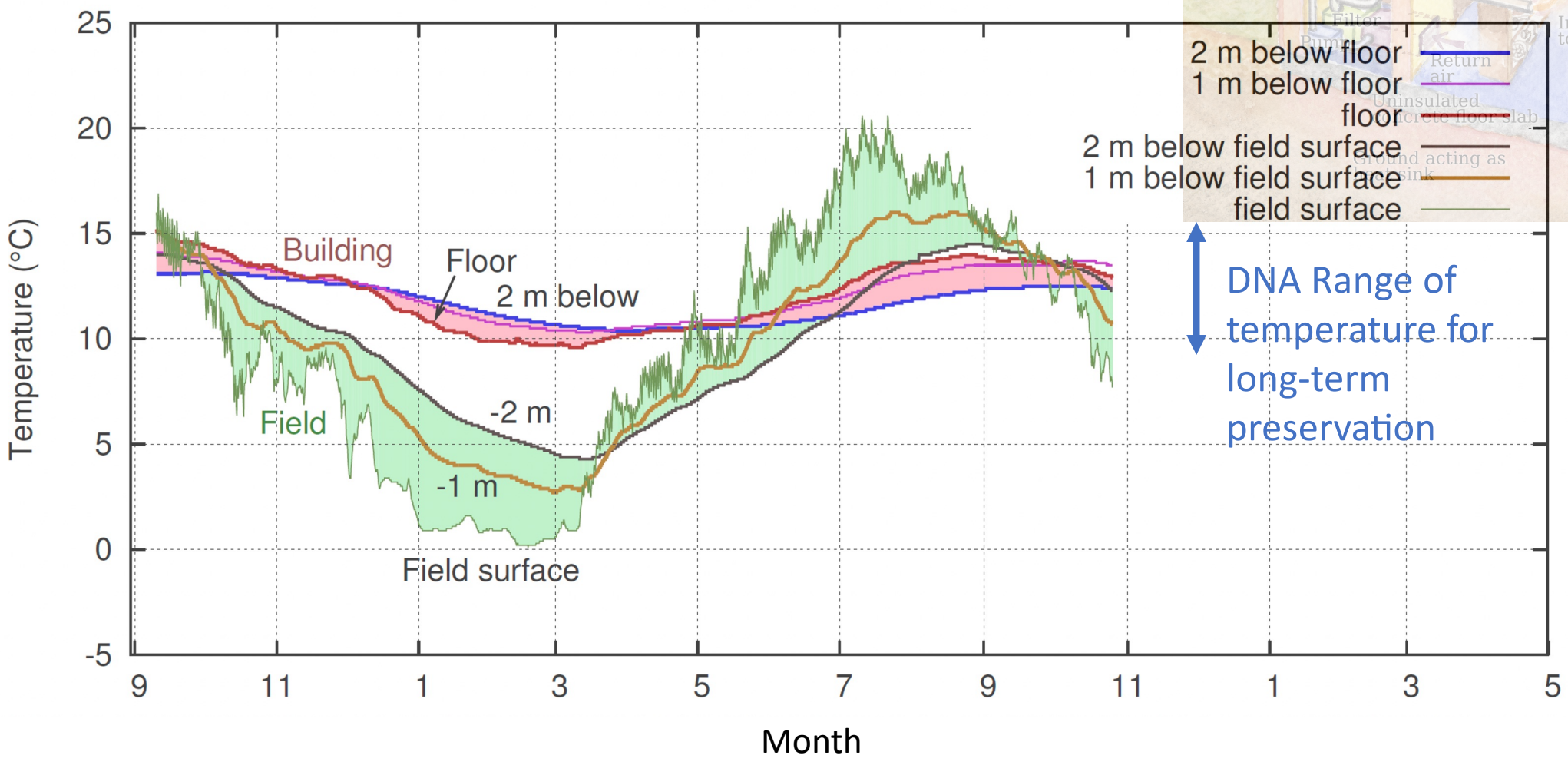
Error correction is still an ongoing research field

Generating a library of orthogonal primers for very large datasets is not obvious

The density of information in DNA is enormous, but “only” a small part is currently feasible, so far about 200 PB/g

No energy to keep information


Annual average ambient temperature < 15°C
Solar voltaic
Air inlet
De-humidifier
Air lock
Air exchange rate < 1/day
Insulation to U ≈ 0.1 W/m²·K
Filter
Return air
Uninsulated concrete floor slab
Ground acting as heat sink


Temperature (°C)
25
20
15
10
5
0
-5
9
11
1
3
5
7
9
11
1
3
5
Month
Building
Floor
2 m below
Field
-2 m
-1 m
Field surface
2 m below floor
1 m below floor
floor
2 m below field surface
1 m below field surface
field surface
DNA Range of temperature for long-term preservation

Conclusions

The environmental impacts of DNA storage are not commensurate with those of silicon/electronic technologies

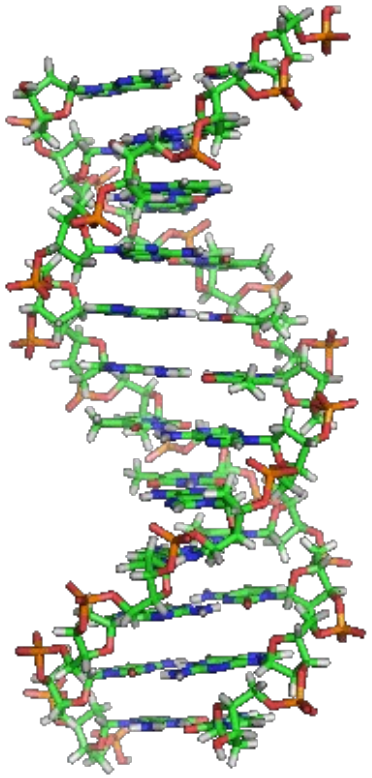
Six to eight orders of magnitude more dense than traditional storage media

Is already being made available to institutions aiming at very long-term preservation

Its technology is evolving faster than Moore's Law, so will soon be available to legacy archiving institutions

Get ready for the next storage revolution !

Thanks for your attention !



Interested in a collaboration ?

Contact us:

pierre-yves.burgi@unige.ch

lamia.friha@unige.ch

To know more on our DNA project:
Burgi et al. (2022) OAIS-Compliant digital archiving of research and patrimonial data in DNA. *Proc. iPres22, pp. 220-224*