DNAmaker
Automating the Storage of Digital Data on Long DNA Molecules

Context

The DNAmaker is an extension of the **dnaXiv** project (2021-2024) that was exploring how digital information can be efficiently stored on DNA molecules. The DNAmaker project run over 18 months, starting from July 2023. Both projects were completed in December 2024. DNAmaker has been organized into several phases of experimentation and progressive technical development. It has been deployed in Rennes, mainly within IRISA/Inria and IGDR laboratories. The automation devices are hosted in Catherine André's laboratory (IGDR). The research team brings together scientists from IRISA/Inria (D. Lavenier, J. Nicolas, O. Boullé, J. Leblanc, G. Andrade-Barosso) and from IGDR (Y. Audic). The project follows the earlier dnarXiv initiative, a scientific effort exploring data storage on DNA molecules.

Objective

The DNAmaker project was aiming to fully automate the design of long DNA molecules for digital data storage, a protocol which was successfully experimented manually in the dnarXiv project. Unlike current DNA synthesis technologies, which only produce short oligonucleotide sequences (< 300 nucleotides), DNAmaker automatically assembles these short fragments into much longer DNA molecules (several thousand nucleotides).

This platform addresses a major challenge: existing biotechnological processes for DNA assembly are fully manual and require 3 to 4 days of work to build a single 25-kilobase molecule. Automation is therefore essential to scale up and make this storage technology operational.

Motivations

DNA-based data storage offers three decisive advantages for future archiving:

- Exceptional density: terabytes of information can be stored inside a tiny capsule
- Outstanding longevity: DNA can remain stable for hundreds of years without special maintenance
- Low total cost of ownership: an economically viable solution for ultra–long-term archiving

Given the exponential growth of global data production, this technology represents a strategic response. In addition, most of the required infrastructure (computing platform, biological

protocols, nanopore sequencing) has already been developed and validated during the dnarXiv project.

The DNAmaker platform

The core of the platform is composed of three robotic devices:

- Opentrons OT-2 robot: a precision pipetting system used for routine laboratory operations. It is programmed to execute the DNA assembly protocols.
- MG400 robotic arm: a modular robotic arm that automatically supplies the Opentrons robot with well plates containing oligonucleotides and chemical reagents.
- Robot-operated refrigerator: a refrigerator that can be controlled automatically to store reagents and products.

These three devices are fully controlled through a Python API, allowing complete synchronization and execution of long, complex experiments without human intervention.

The construction of long DNA molecules involves two major steps: Golden Gate assembly and PCR amplification. This construction method was developed and published as part of the dnarXiv project. This approach allows the progressive assembly of double-stranded DNA molecules, which are much more stable and suitable for storage than the original single-stranded sequences.

The final demonstration consisted of the automated construction of several DNA molecules encoding the 1789 Declaration of the Rights of Man and of the Citizen, stored in three unique copies. A scientific publication is currently being prepared.

Advantages of the DNAmaker Platform

Compared to earlier approaches based solely on short oligonucleotides, assembling long DNA molecules provides several concrete benefits:

- Cost reduction: a major improvement in the ratio of useful data to total data, increasing throughput while lowering costs
- Simplified reconstruction: instead of millions of short fragments, only a few thousand long ones need to be processed, making retrieval easier and faster
- Increased stability: double-stranded DNA is significantly more stable than single-stranded DNA
- Compatibility with next-generation sequencing: nanopore sequencing technologies work best with long molecules several thousand nucleotides long
- Enhanced random-access capabilities: enabling improved design for storage and retrieval systems

Perspectives and Challenges

DNAmaker marks a decisive step toward demonstrating the feasibility of DNA-based data storage using long DNA molecules. Automating the construction process paves the way for storage experiments involving significant data volumes (several megabytes and beyond) and strengthens the credibility of our long-molecule storage approach—an emerging paradigm within the community.

Publications (dnarXiv + DNAmaker)

Journals

- F. De Moor, O. Boullé, D. Lavenier, De-Bruijn graph partitioning for scalable and accurate DNA storage processing, Bioinformatics, Volume 41, Issue 11, November 2025, btaf618
- C. Berton, G. Coatrieux, H. Gasnier, S. Haddad, R. Bellafqira and D. Lavenier, "A Dynamic Sliding Window Encoding for Secured DNA Data Storage Compliant With Biological and Indexing Constraints," in IEEE Access, vol. 13, pp. 66009-66030, 2025
- J. Leblanc, O. Boulle, E. Roux, J. Nicolas, D. Lavenier, Y. Audic", Fully in vitro iterative construction of a 24 kb-long artificial DNA sequence to store digital information", in BioTechniques, vol. 76, no. 5, pp. 203-215, 2024
- B. Hamoum and E. Dupraz, "Channel Model and Decoder With Memory for DNA Data Storage With Nanopore Sequencing," in IEEE Access, vol. 11, pp. 52075-52087, 2023

Conferences

- J. Mateos, D. Lavenier, M. Dimopoulou, A. Genot, M. Antonini, Primer design for DNA storage random access. CORESA 2024 – 23ème conférence sur COmpression et REprésentation des Signaux Audiovisuels, Nov 2024, Rennes, France. pp.1-3.
- C. Berton, G. Coatrieu, D. Lavenier, S. Haddad, Dynamic sliding window encoding for data storage on DNA under biological and indexing constraints, EUSIPCO2023, 31st European Signal Processing Conference, Helsinki, Finland, September 2023
- B. Hamoum, A. Ezzeddine, E. Dupraz, Synchronization algorithms from high-rate LDPC codes for DNA data storage, Rhodes, 24th International Conference on Digital Signal Processing, Island of Rhodes, Greece, June 2023.
- D. Lavenier, DNA Storage: Synthesis and Sequencing Semiconductor Technologies, 68th Annual IEEE International Electron Devices Meeting, San Francisco, Dec. 2022
- B. Hamoum, E. Dupraz, L. Conde-Canencia, A DNA Data Storage Channel Model Trained on Genomic Data with Nanopore Sequencing, DSMM 2022, 1st International Conference on Data Storage in Molecular Media, 21-23 March 2022, virtual conference
- C. Berton, G. Coatrieux, D. Lavenier, A first proposal for secure data storage into DNA molecules compliant with biological constraints, DSMM 2022, 1st International Conference on Data Storage in Molecular Media, 21-23 March 2022, virtual conference
- O. Boullé, D. Lavenier, Experimental DNA storage platform, DSMM 2022, 1st International Conference on Data Storage in Molecular Media, 21-23 March 2022, virtual conference
- B. Hamoum, E. Dupraz, L. Conde-Canencia, D. Lavenier, Channel Model with Memory for DNA Data Storage with Nanopore Sequencing, 2021 11th International Symposium on Topics in Coding, ISTC 2021

PhD

- Chloé Berton. Sécurité des données stockées sur molécules d'ADN. Informatique [cs]. Ecole nationale supérieure Mines-Télécom Atlantique, 2024

- Belaid Hamoum, DNA data storage algorithms and synchronization, PhD Thesis, UBS, Dec. 15, 2022

Talks

- D. Lavenier, Information Storage on DNA, Journée scientifique du L2TI, Paris, déc. 2024
- E. Dupraz, Codage canal pour le stockage de données dans l'ADN, Cérémonie de remise des prix IMT-Académie des sciences, octobre 2024
- D. Lavenier, DNA Storage, CORESA 2024, Rennes, nov. 2024.
- E. Dupraz, An accurate channel Model with memory for DNA data storage, Journée GdR IASIS, Juillet 2023
- D. Lavenier, Tutoriel: DNA Storage Overview, Journée GdR IASIS, Paris, Juillet 2023
- D. Lavenier, Data Storage on DNA, Big Day 2022, Journée Master Bio-informatique de Rennes, nov. 2022
- D. Lavenier, Data Storage on Synthetic DNA, Séminire IRSET, Rennes, mars 2023
- D. Lavenier, Data Storage on DNA, Invited Speaker, IDA 2022, Symposium on Intelligent Data Analysis, 20-22 April 2022, Rennes, France
- D. Lavenier, Stockage d'information sur ADN, Séminaires IBNM (Institut Brestois du Numérique et des Mathématiques), 18 novembre 2021, Brest, France
- D. Lavenier, Le projet dnarXiv : archivage de l'information sur ADN, Colloque ADN, polymères et big data, 26 octobre 2020, Paris, France

Reports

- D. Lavenier, Constrained Consensus Sequence Algorithm for DNA Archiving, arXiv, May 2021
- A. Badoual, Stockage d'information sur ADN, Rapport stage M1, Univ. Rennes 1, Juin 2019
- B. Hamoum, Systèmes de stockage de données sur ADN, Rapport stage M2, UBS, Juin 2019

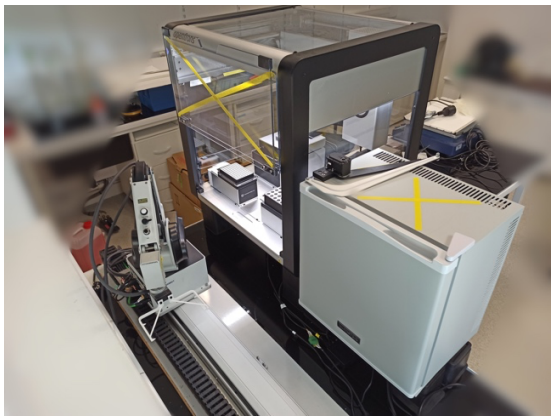
Posters

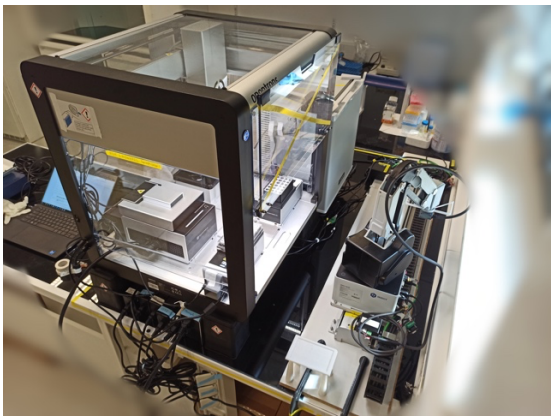
- J. Leblanc, D. Lavenier, O. Boullé, Y. Audic, G. Andrade-Barosso, DNAmaker: High-Throughput Automated Construction of Multi-Kilobase DNA Molecules for Digital Data, MoleculArXiv Autumn School, IESC Cargèse, Corse, 2025
- O. Boullé, F. De Moor, J. Leblanc, D. Lavenier, De Bruijn Graph Partitioning for Scalable and accurate DNA Storage Processing, MoleculArXiv Autumn School, IESC Cargèse, Corse, 2025
- C. Berton, G. Coatrieux, D. Lavenier, Secure data storage into DNA molecules compliant with biological constraints. Ensuring the confidentiality of data stored into DNA molecules, Journées RITS, Recherche en Imagerie et Technologies pour la Santé, Brest, Mai 2022
- C. Berton, G. Coatrieux, D. Lavenier, Secure data storage into DNA molecules compliant with biological constraints, Colloque gestion de crise et numérique : nouvelles menaces et nouvelles solutions, mars 2022, IMT, Palaiseau
- L. Conde-Canencia, B. Hamoum, D. Lavenier, Error Correction Schmes for DNA Storage with Nanopore Sequencing, JOBIM 2019, Jul. 2019, Nantes
- L. Conde-Canencia, B. Hamoum, D. Lavenier, E. Roux, Advanced Coding Schemes for DNA-based storage using nanopore sequencing technologies, CominLabs days, Nov. 2019

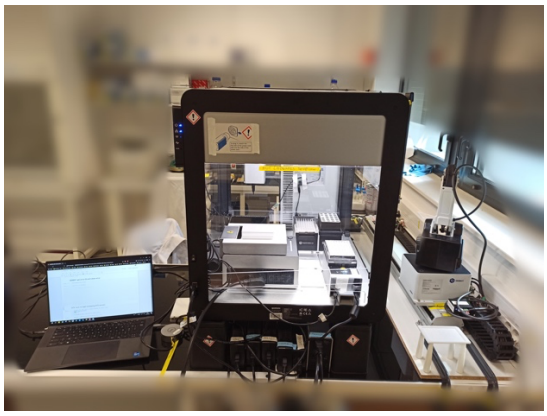
Popularisation article

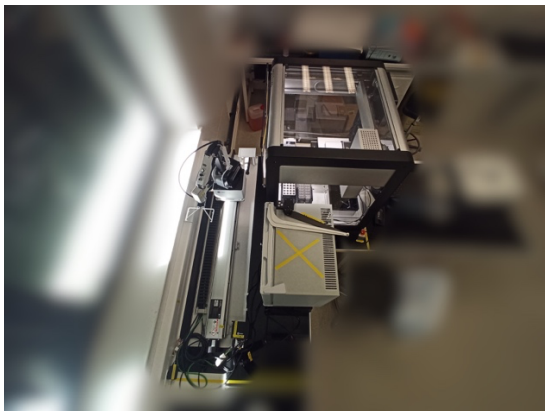
- D. Lavenier, M. Antonini, A. Genot, Y. Rondelez, Stocker les données : la piste prometteuse de l'ADN, Interstices, Janvier 2023
- D. Lavenier, M. Antonini. Stockage d'information sur ADN. Le calcul à découvert, CNRS Editions, 2025, 978-2-271-15373-9

Annexes









https://www.youtube.com/watch?v=VA38WajV7hc