DNA provides a solution to our enormous data storage problem

ASU researchers show how molecular structures can store large volumes of data while providing powerful encryption

By Richard Harth, ASU News
January 28, 2026

Since the dawn of the computer age, researchers have wrestled with two persistent challenges: how to store ever-increasing reams of data and how to protect that information from unintended access.

Now, researchers with Arizona State University's Biodesign Institute and their colleagues offer a surprising answer. In a pair of new studies, they show how DNA, the molecule of life, can be harnessed to faithfully store enormous volumes of data and provide powerful encryption.

The findings, appearing in the journals Advanced Functional Materials and Nature Communications respectively, provide a nature-inspired alternative to silicon-based storage and encryption solutions. They could help reshape the design of future microelectronic and molecular information systems for a broad range of applications.

Related research

ASU researchers discover DNA-based electronic storage system

"For decades, information technology has relied almost entirely on silicon," said Hao Yan, a Regents Professor in the School of Molecular Sciences and director of the Biodesign Center for Molecular Design and Biomimetics at Arizona State University. "What we're showing here is that biological molecules, specifically DNA, can be engineered to store and protect information in fundamentally new ways. By treating DNA as an information platform rather than just a genetic material, we can begin to rethink how data is stored, read and secured at the nanoscale."

Yan, along with researchers Chao Wang, associate professor in the School of Electrical, Computer and Energy Engineering, and Rizal Hariadi, associate professor in the Department of Physics, worked together to lead the projects[1].

Big data, tiny molecule

As the world generates tremendous volumes of digital information, today's storage technologies are struggling to keep up. The first study demonstrates a new way to store information using DNA — not by analyzing genetic letters, but by interpreting DNA's physical shape.

DNA is appealing because it can store massive amounts of information in a tiny physical volume, and because it can remain stable for astonishingly long periods. (In 2022, researchers recovered DNA fragments from Greenland sediments dating back roughly 2 million years.)

The new research describes the design and construction of tiny DNA structures that act like physical letters in an alphabet, each carrying a piece of information. As the structures pass through a microscopic sensor, machine learning software records and analyzes subtle electrical signals. Then, the system can translate the data back into readable words and short messages with high accuracy.

The approach offers a powerful alternative to more traditional DNA data storage methods that rely on slow and expensive DNA sequencing. In contrast, the new technique is faster, cheaper and more scalable.

The work points toward a future where DNA could serve as an ultra-dense, long-lasting and secure medium for data storage. It could be useful for archiving massive amounts of information — from scientific records to cultural data — using very little space and energy. It also demonstrates a powerful bridge between synthetic biology and semiconductor technology, opening the door to new kinds of molecular information systems that go beyond conventional electronics.

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> **Hao Yan**
> ASU Regents Professor

Locking down information at the molecular level

While the first study focuses on how DNA can store information efficiently, the second explores how DNA nanostructures could also help protect information through encryption.

In this work, the researchers design intricate DNA origami structures — folded arrangements of DNA strands that form precise two- and three-dimensional shapes. Instead of storing data simply as bits or letters, information is encoded in the arrangement and pattern of these nanoscale structures. This creates a kind of molecular code that is difficult to interpret without the correct tools and reference patterns.

To read the encrypted information, the team uses an advanced form of super-resolution microscopy that can visualize individual DNA structures at extremely high precision. Machine learning software then analyzes thousands of molecular images, grouping similar patterns and translating them back into the original message. Without the correct decoding framework, the patterns are essentially meaningless, adding a layer of built-in security.

The approach greatly increases the number of possible molecular codes that can be created, making unauthorized decoding far more difficult. It also allows information to be packed into three-dimensional DNA structures, which adds even more complexity and security to each molecular key.

“In these studies, our team brings together complementary approaches, including DNA nanotechnology, super-resolution optical imaging, high-speed electronic readout and machine learning, to interrogate DNA nanostructures across multiple spatial and temporal scales,” Wang said. "This integrated strategy helps us better understand the behavior and function of DNA nanostructures.

"This is a very good example of doing research at the intersection of semiconductor technology and biology. In this emerging field, more applications, from advanced biosensing to programmable nanodevices, remain to be explored.”

Bringing storage and security together at the molecular scale

Together, the two studiesBoth studies were funded by the National Science Foundation’s Semiconductor Synthetic Biology Circuits and Communications for Information Storage (SemiSynBio) program. show how DNA can function not only as a compact storage medium, but also as a platform for secure information handling at the nanoscale. One technique emphasizes fast, electronic-style readout of molecular information, while the other demonstrates how molecular patterns themselves can serve as encrypted carriers of data.

DNA-based systems could one day support ultra-dense storage for scientific data, medical records or cultural archives. Molecular encryption could provide new ways to secure sensitive information in environments where conventional electronics struggle, such as extreme temperatures, radiation or long-term preservation.

The research highlights a growing convergence between biology, materials science, computation and electronics. By treating DNA as both a biological molecule and an information platform, researchers are opening new ways to store, protect and access data at scales far smaller and potentially far more durable than today’s digital devices.

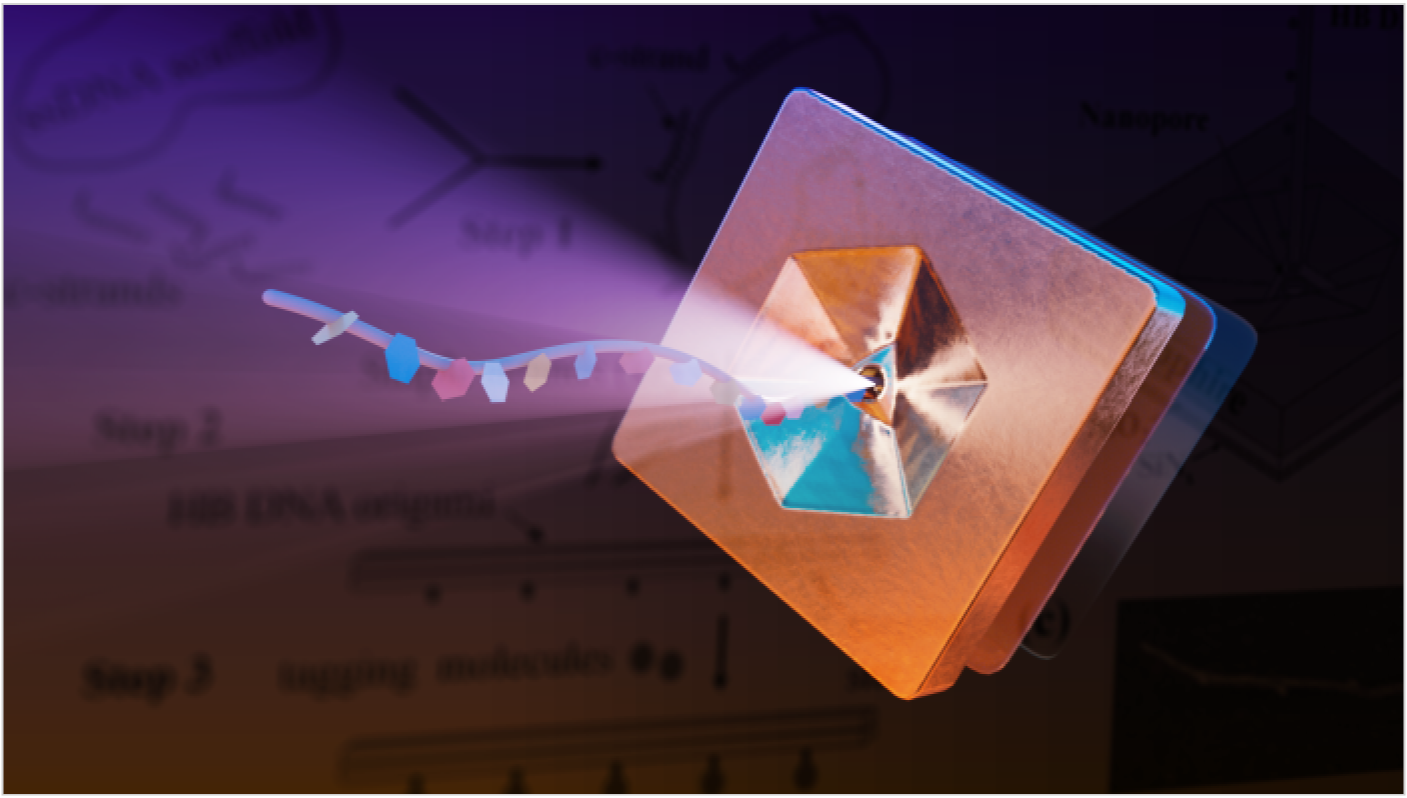
Why this research matters

This story originally appeared on ASU News.

[1] The team co-authored the two studies with other ASU collaborators. The two first authors of those papers are Gde Bimananda Mahardika Wisna and Penkun Xia.

[2] Both studies were funded by the National Science Foundation’s Semiconductor Synthetic Biology Circuits and Communications for Information Storage (SemiSynBio) program.

Main image



An illustration shows a strand of engineered DNA passing through a nanoscale sensor, where its physical structure can be decoded as digital information. DNA nanostructures could one day serve as ultra-dense carriers of digital information and advance the field of data encryption. Graphic by Jason Drees/ASU