# ADDRESSABLE CONFIGURATIONS OF DNA NANOSTRUCTURES FOR REWRITABLE MEMORY

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## ABSTRACT

**DNA serves as nature's information storage molecule, and has been the primary focus of engineered systems for biological computing and data storage. Here we combine recent efforts in DNA self-assembly and toehold-mediated strand displacement to develop a rewritable multi-bit DNA memory system. The system operates by encoding information in distinct and reversible conformations of a DNA nanoswitch and decoding by gel electrophoresis. We demonstrate a 5-bit system capable of writing, erasing, and rewriting binary representations of alphanumeric symbols, as well as compatibility with 'OR' and 'AND' logic operations. Our strategy is simple to implement, requiring only a single mixing step at room temperature for each operation and standard gel electrophoresis to read the data. We envision such systems could find use in covert product labeling and barcoding, as well as secure messaging and authentication when combined with previously developed encryption strategies. Ultimately, this type of memory has exciting potential in biomedical sciences as data storage can be coupled to sensing of biological molecules.**

## INTRODUCTION

The inherent nanoscale features and molecular recognition properties of DNA has made it useful for the construction of nanostructures with various applications in biology (1), medicine (2), materials science (3) and information processing and storage (4–6). As an archival storage medium, DNA is highly dense (~1 exabyte/mm$^3$) (7) and long lasting (half-life of 500 years) (8), with recent efforts demonstrating storage of books and images (9) and a Shakespearean sonnet (10), and information retrieval of up to 215 petabytes per gram of DNA (11). However, archival storage systems are rewritable DNA systems providing short-term storage (12). The design of a memory device based on biomolecular interactions has been presented as early as the 1980s (13). DNA-based information processing systems reported so far include single and double stranded DNA (14) as bits '0' and '1', a hairpin-based memory stick with an address site on the loop (15), a three-state nanopatterned device providing eight possible memory states (16), and a translation system based on DNA double crossover (DX) tiles (17) (Supplementary Figure S1). Here, we present a user-friendly DNA-based memory system that can encode multiple bits of information with erasing, rewriting, write-protection and logic functionality.

Our memory system is based on encoding data in discrete conformational states of DNA nanostructures. To demonstrate the concept, we expanded upon previously developed DNA nanoswitches that exhibit binary switching behavior (18,19). The DNA nanoswitches self-assembled using DNA origami approaches (20) and purified from excess strands (21,22), have inducible loops that can be spatially programmed by placement of DNA overhangs at desired locations (23). In those previous works, the DNA nanoswitches were used as on/off sensors for detection and analysis of molecular interactions. In the simplest realization, DNA nanoswitches encode a single bit of information depending on the presence or absence of a single loop (1 or 0, respectively), detectable by gel electrophoresis (Figure 1). The loop is formed when single stranded overhangs on different sections of the nanoswitch are each partially hybridized with an external strand. For the purpose of this work, we will refer to the single stranded extensions as *address sites* and the external strands as *data strands*.

## MATERIALS AND METHODS

### Design and oligonucleotide mixtures

Oligonucleotides were purchased from Integrated DNA Technologies (IDT) with standard desalting. DNA nanoswitches were prepared as previously reported

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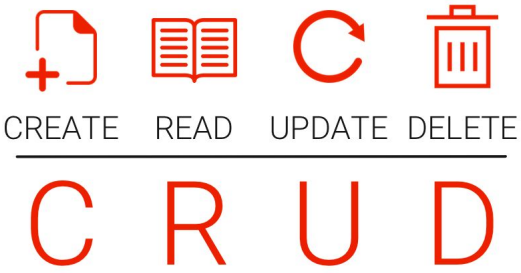
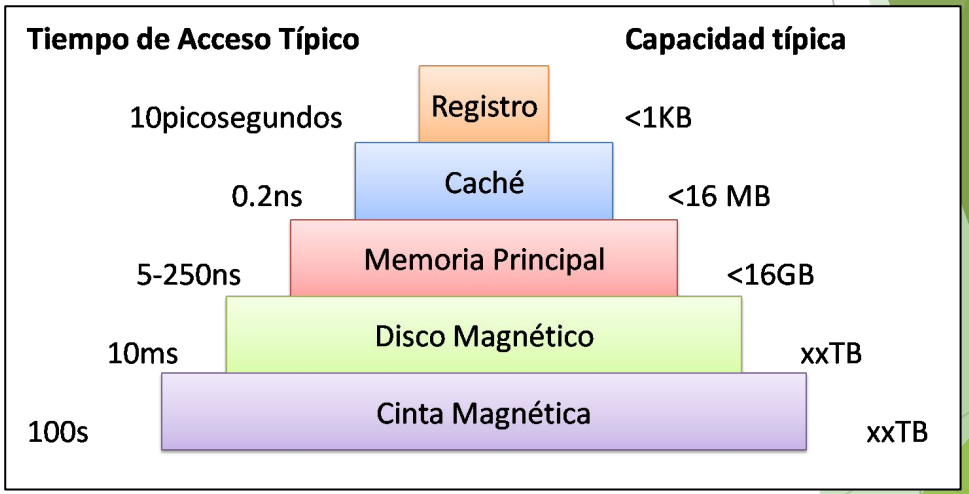
# Objetivo

- Sistema de memoria ADN multi-bit.
- Sistema multi-bit de 5-bit capaz de:
  - Escribir
  - Borrar
  - Reescribir
- Protección contra escritura

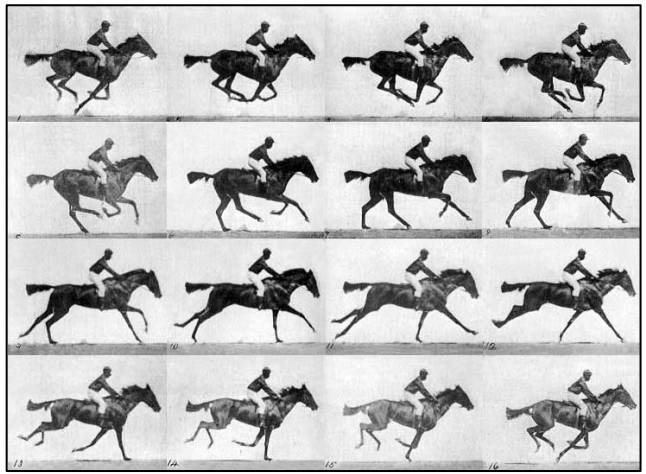


# Jerarquía de Memoria

- Un disco
  - Terabytes
  - 10 años
- Una célula
  - ~1 exabyte/mm3
  - 500 años de vida
- 215 petabytes por gramo de ADN



# Experimentos previos

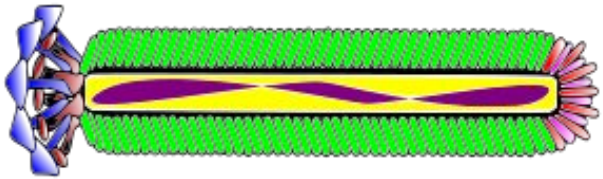


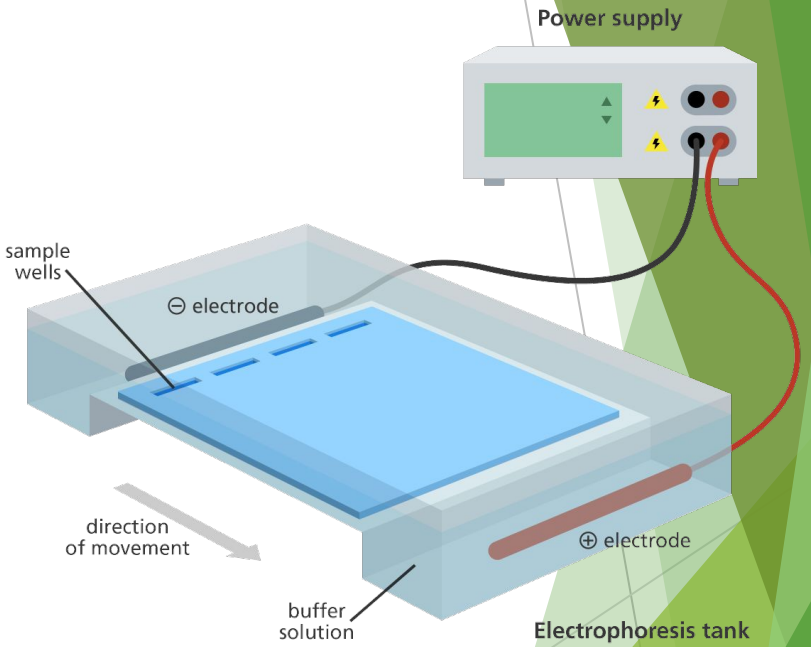
- Se han guardado
  - Imágenes
  - Libros
  - Sonetos de Shakespear
- Visto en clase
  - GIF de caballos de Eadweard Muybridge
  - 5-6 frames

# El experimento

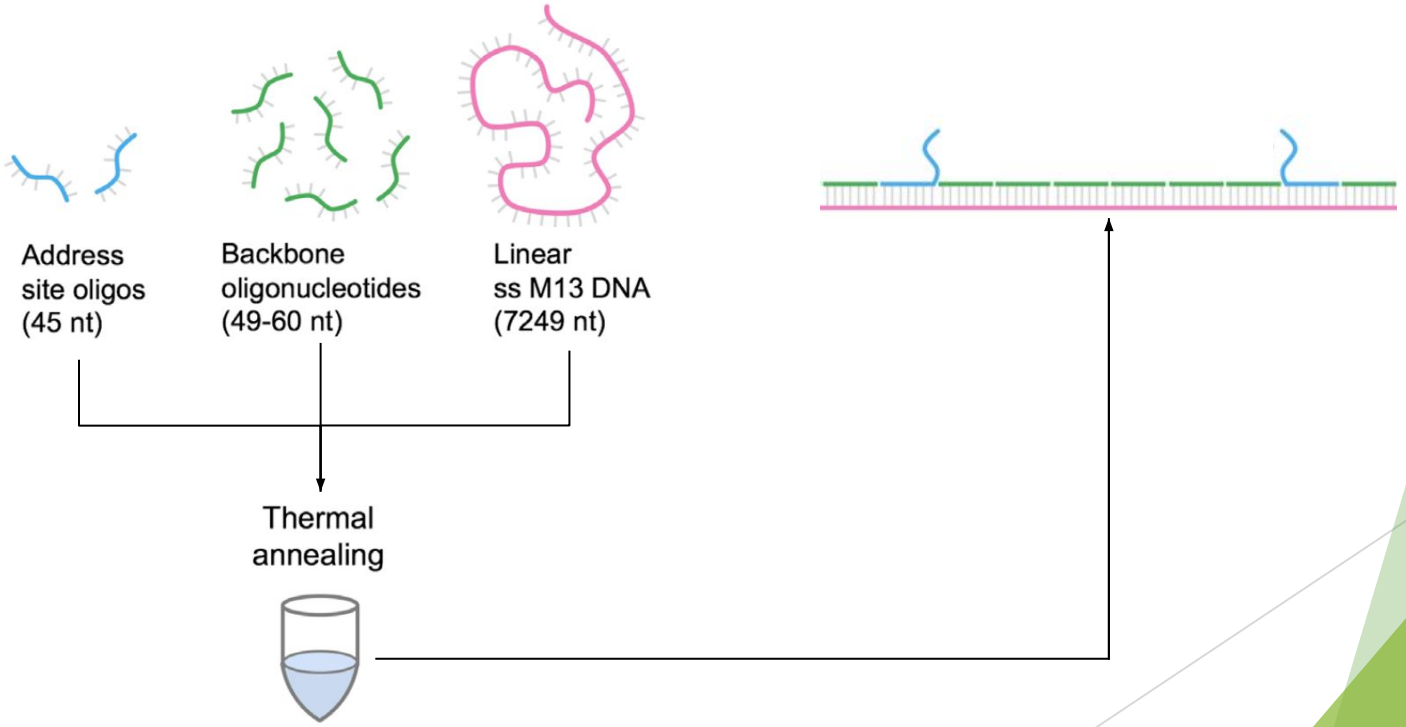
# Experimento

- Oligonucleótidos
  - Integrated DNA Technologies (IDT)
  - Una secuencia corta de ADN o ARN, con cincuenta pares de bases o menos.
- Gel electrophoresis
- “Linearization of M13 DNA”



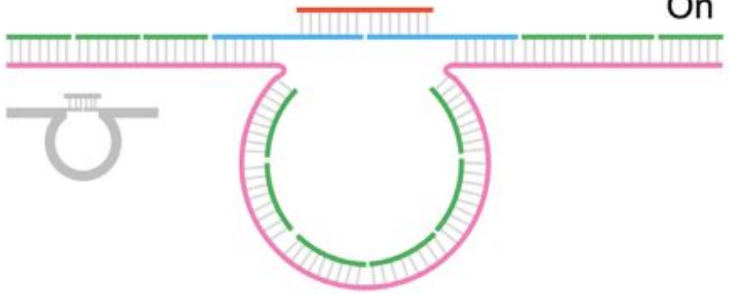


# Experimento



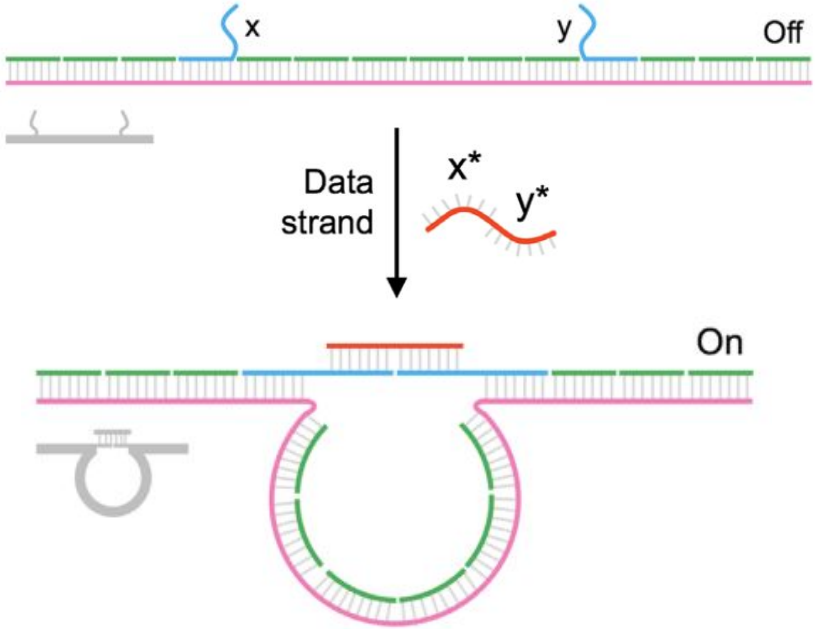
# ¿Cómo crear un 0 o un 1 lógico?


- Un 0 lógico

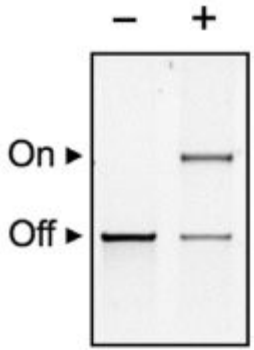



- Un 1 lógico

# ¿Cómo crear un 0 o un 1 lógico?



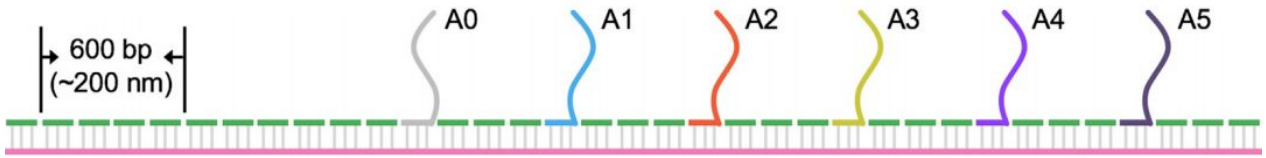
# ¿Cómo leer un 0 o un 1 lógico?

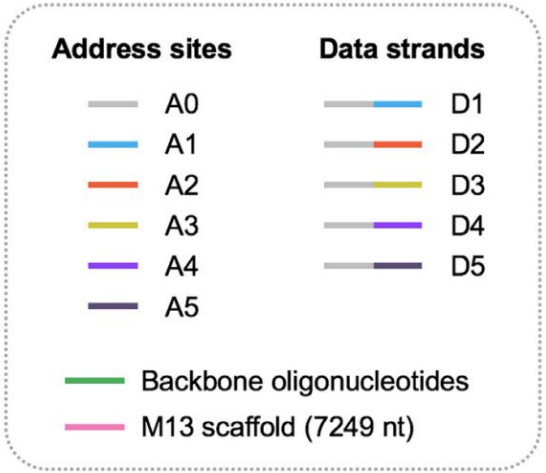


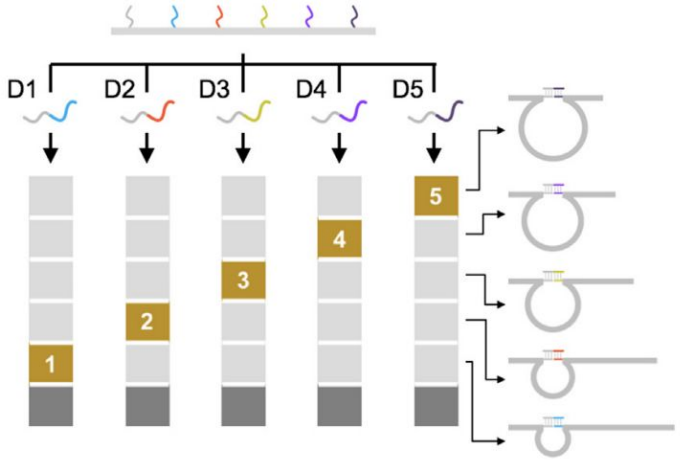

- Gel electrophoresis para la lectura de los bits en la secuencia de ADN

# La construcción del sistema multi-bit

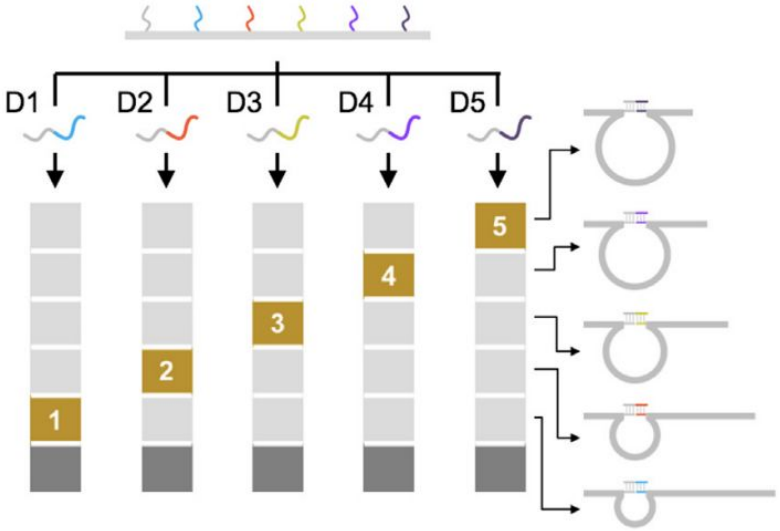
# Sistema multi-bit

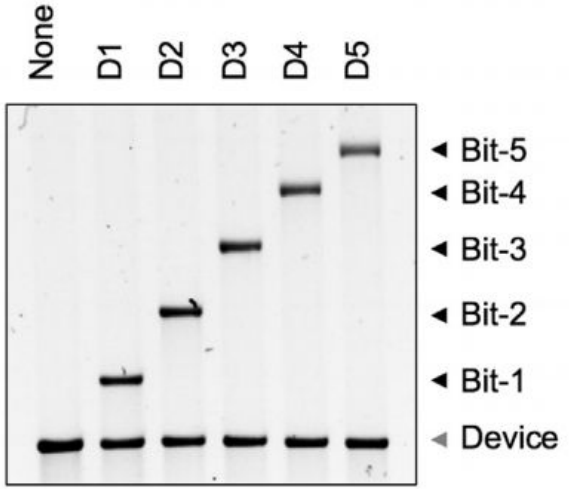


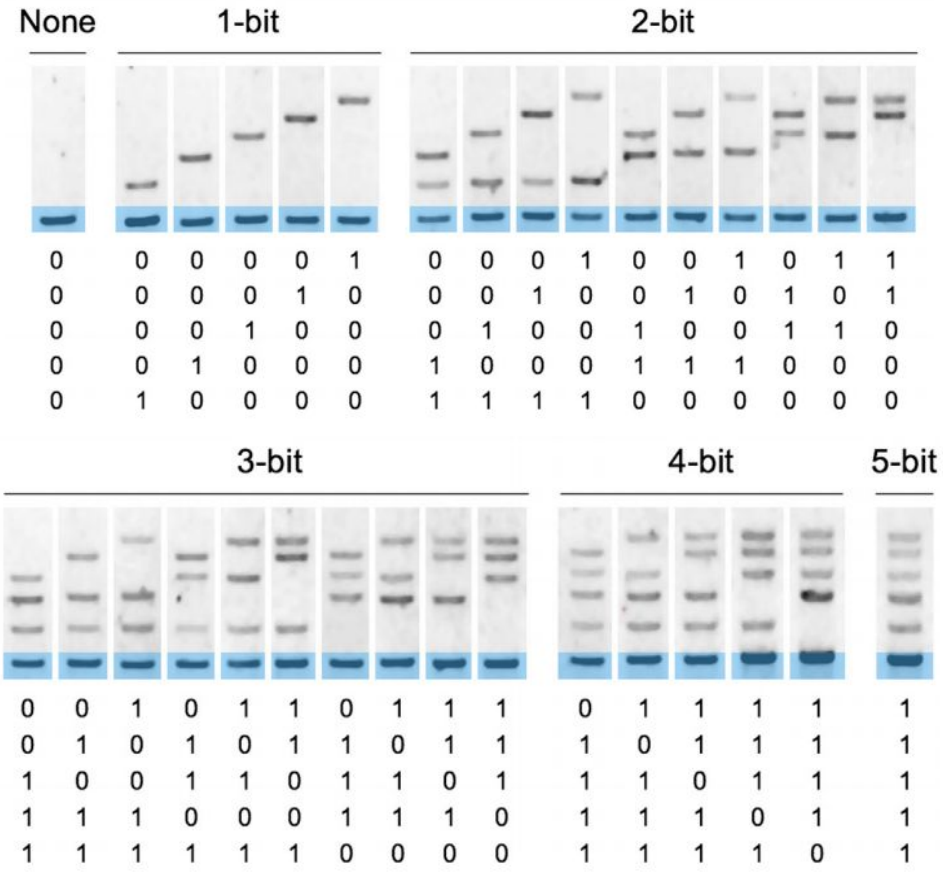



# Sistema multi-bit

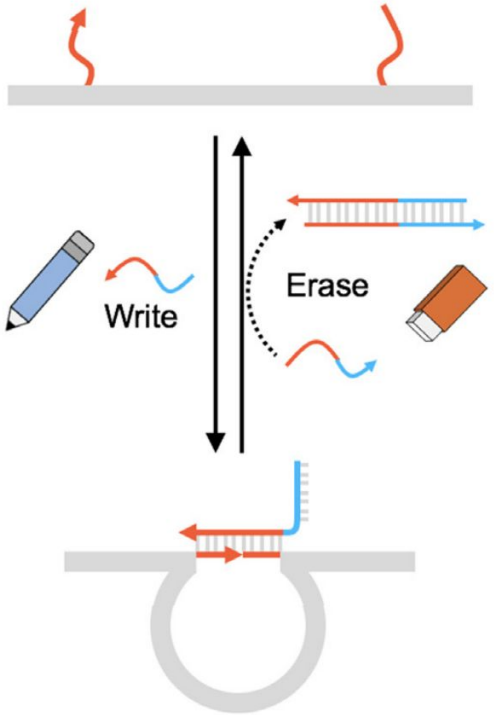


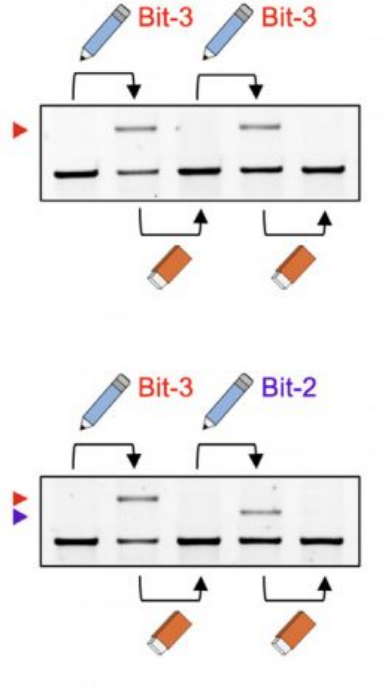



# Sistema multi-bit

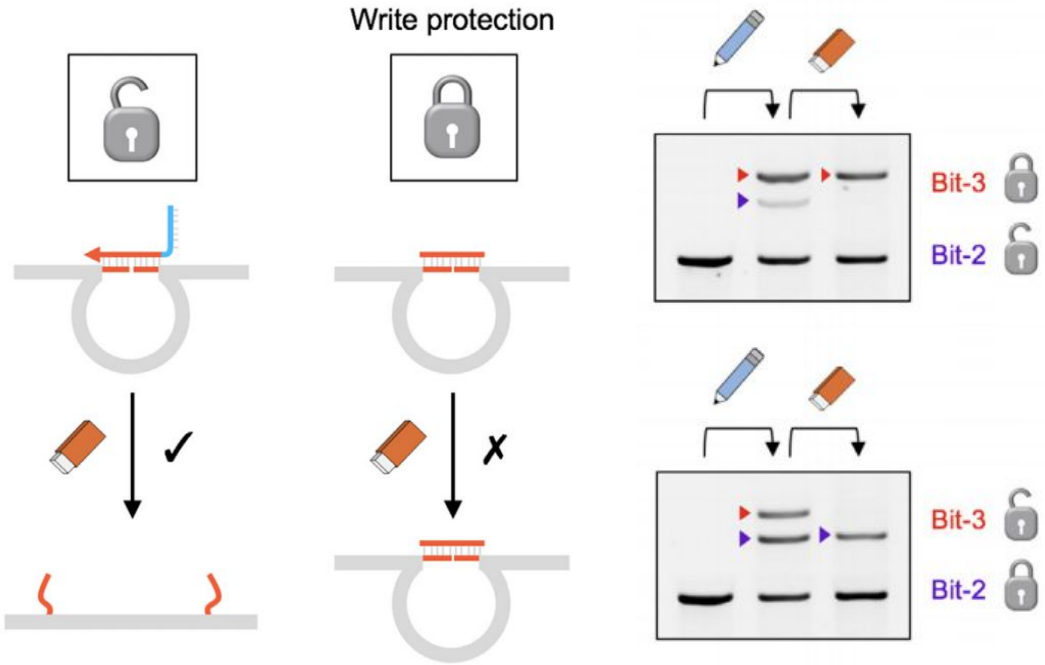


# Borrado y reescritura

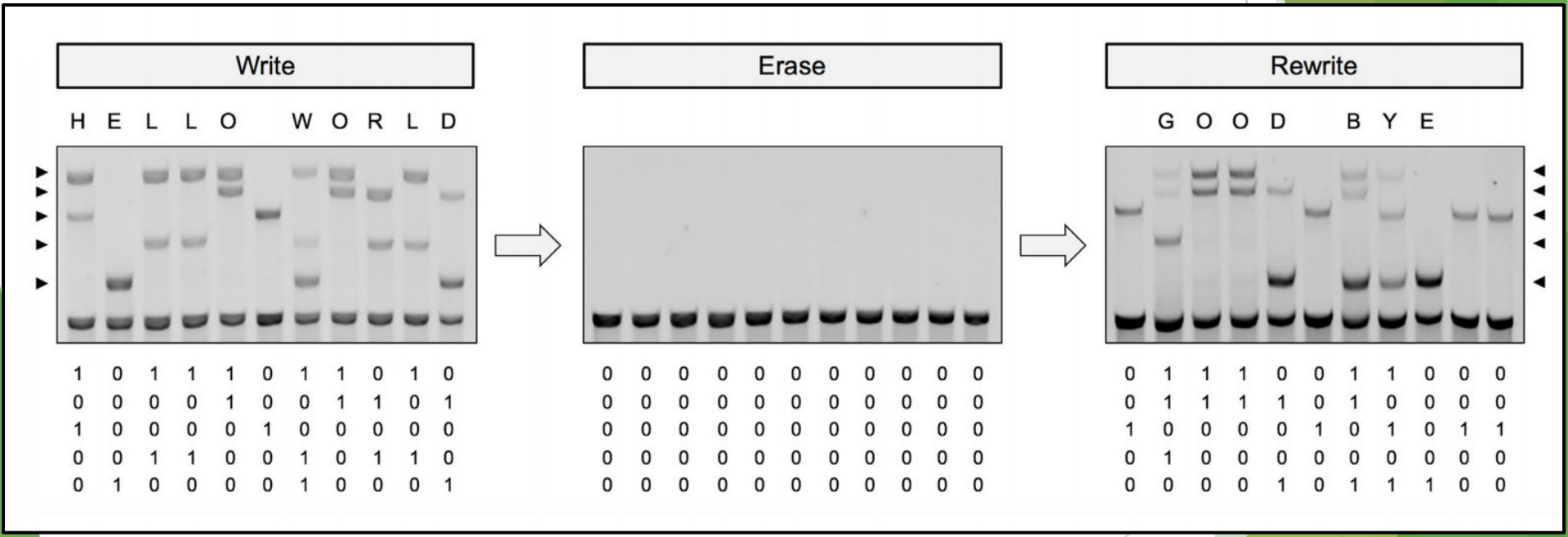


# Protección contra escritura

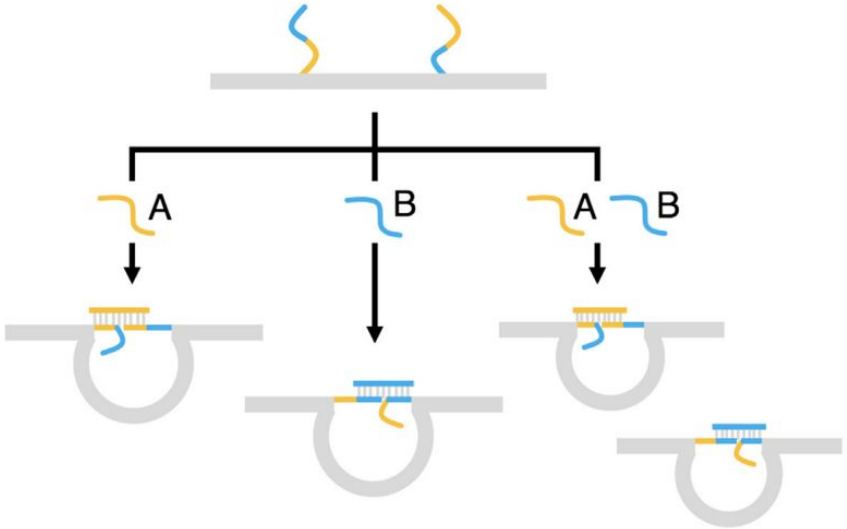


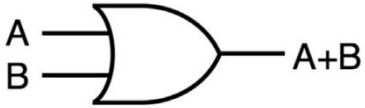
# Escritura, borrado y reescritura



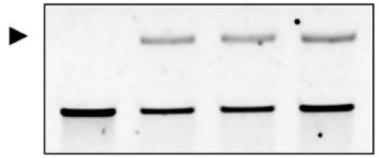
# La construcción de puertas lógicas

# Puertas OR

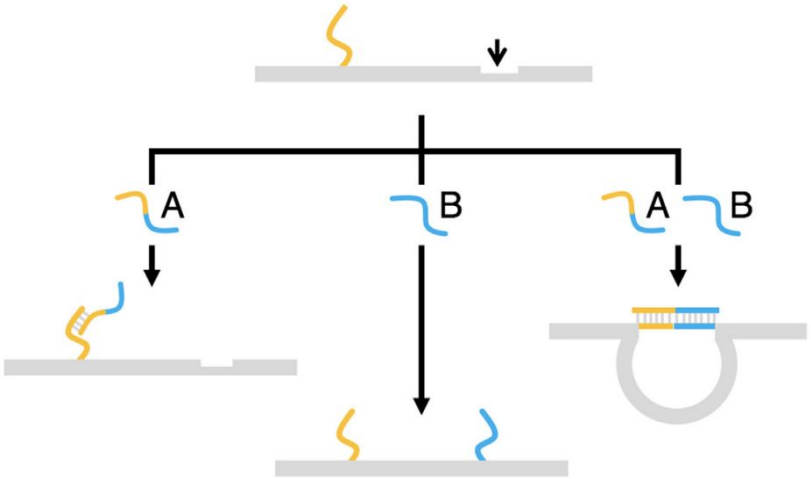



| | | | | |
|---|---|---|---|---|
| **A** | 0 | 0 | 1 | 1 |
| **B** | 0 | 1 | 0 | 1 |
| **O** | 0 | 1 | 1 | 1 |

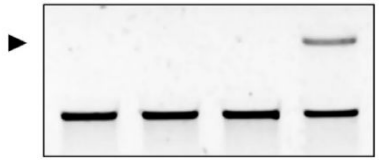


# Puertas AND



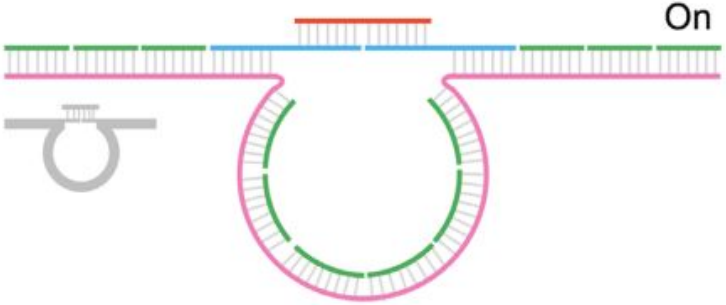


| | | | | |
|---|---|---|---|---|
| **A** | 0 | 0 | 1 | 1 |
| **B** | 0 | 1 | 0 | 1 |
| **O** | 0 | 0 | 0 | 1 |



# Conclusiones

# Resumen

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  - Escribir
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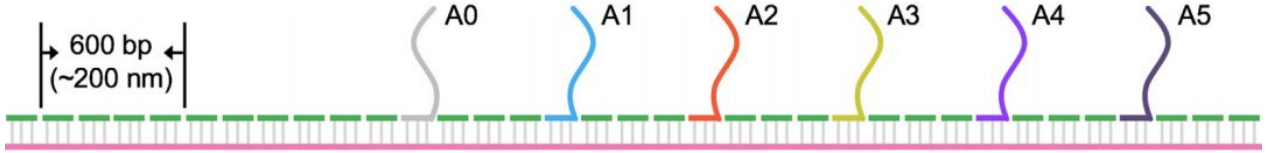
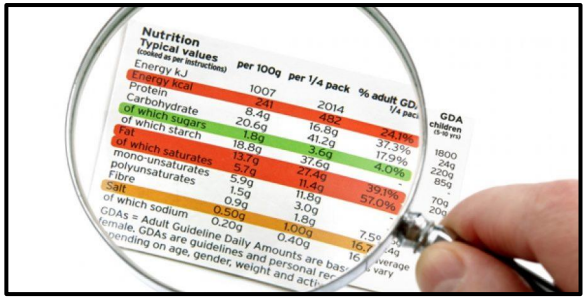
- Protección contra escritura
- Puertas lógicas



# Utilidad

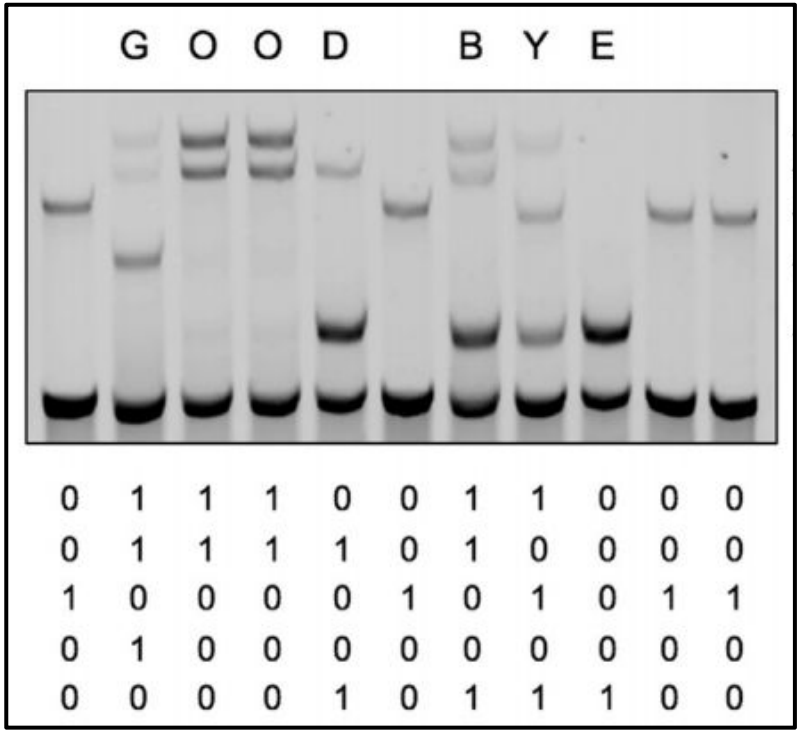
- Código de barras
- Etiquetado

# Referencias


- Erlich,Y. and Zielinski,D. (2017) DNA Fountain enables a robust and efficient storage architecture. Science, 355, 950–954. https://www.biorxiv.org/content/biorxiv/early/2016/12/04/074237.full.pdf
- Church,G.M., Gao,Y. and Kosuri,S. (2012) Next-generation digital information storage in DNA. Science, 337, 1628–1628. http://arep.med.harvard.edu/pdf/Church_Science_12.pdf
- https://wyss.harvard.edu/media-post/dna-nanoswitches/
- Koussa,M.A., Sotomayor,M. and Wong,W.P. (2014) Protocol for sortase-mediated construction of DNA–protein hybrids and functional nanostructures. Methods, 67, 134–141. http://wonglab.tch.harvard.edu/images/koussa_wong_sortase_methods_2014.pdf
- Wikipedia para cosas elementales para biólogos https://es.wikipedia.org/wiki/Fago_M13 o https://en.wikipedia.org/wiki/Gel_electrophoresis

# ¡Gracias!


G O O D B Y E
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0 1 1 1 1 0 1 0 0 0 0
1 0 0 0 0 1 0 1 0 1 1
0 1 0 0 0 0 0 0 0 0 0
0 0 0 0 1 0 1 1 1 0 0