DNA Computing With an Associative Memory

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David Turek
CTO
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Based on “Demonstration of a Scalable DNA Computing Platform: Writing and Selection”, Bhatia et al, ACM Journal on Emerging Technologies in Computing Systems, June 2025

Why DNA Computing

“To Out Compete, one must Out Compute”

Council on Competitiveness, 2006

- Computing is a pathway to strategic insight
  - New products
  - New actions/behaviors
  - New insights and theories
- Computing infrastructure is a shared resource
  - You rarely have what you need

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State of Computing-The Virtue of Parallelism (and the “Myth” of Big Data)

- Vocabulary
  - Strong Scaling
    - Addition of more resources reduces the time to solve a fixed problem
      - Ex: doubling processors cuts compute time in half
  - Weak Scaling
    - Increasing resources proportionately (data and compute) maintains solution time
  - Amdahls Law
    - The serial portion of an application is the limiting factor to the impact of parallelism

- Adding resources is complicated and expensive
  - Incremental CapEX
    - Adding one unit of incrementat computing to Summit was $65K for .00025 increase in compute
  - Disruption of integration

Our Core Belief: DNA Computing can add computing capacity cheaply and non-disruptively for strong scaling applications

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Example Applications (the "Myth of Big Data")

Strong Scaling with Small Data

- Molecular Dynamics (drug design, medical research)
  - Few MB of data
  - Computationally intensive (N-Body Problem)
- Cryptographic Key Search
  - Key space is less than an MB
- Graph Optimization (scheduling and routing)
  - 1000 edges is a few MB
- ML Hyperparameter Tuning for Edge Devices
  - Few MB
- CFD (auto and aero)
  - 500MB
- Finite Element Analysis
  - 1GB

Near term DNA Computing opportunities

Strong Scaling with Moderate Data

- Protein Folding: 5-20GB
- Antenna Design 10-40 GB
- Portfolio Analysis 5-30GB
- Clustering Customer data 10-50GB
- Log Analysis for Cyber Forensics 5-40GB
- Supply Chain Optimization 10-30 GB

Intermediate term DNA Computing opportunities

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DNA is one of the mediums that could store and compute data

You can store data in DNA…

DNA storage has been demonstrated by various research organizations and developed

[History of DNA storage]

- **'88** ▪ 5x7 matrix image was stored in a DNA sequence in E.coli
- **'16** ▪ 22 MB of a MPEG compressed movie sequence were stored and recovered from DNA
- **'18** ▪ Method known as DNA Fountain that stored data at a density of 215 petabytes per gram of DNA was published
- **'19** ▪ 16 GB of Wikipedia have been encoded into synthetic DNA by Catalog Technology

…And compute DNA

Concept of DNA computing has been researched and developed, laying the groundwork for commercial viability

[History of DNA computing]

- **'94** ▪ Adelman presented the first prototype of a DNA computer, solving a seven-point Hamiltonian path problem
- **'02** ▪ Created a DNA computer able to play tic-tac-toe against a human player
- **'11** ▪ Developed a DNA-based artificial neural network that can recognize 100-bit hand-written digits.
- **'19** ▪ Produced renewable DNA logic circuit bringing the technology one step closer to the silicon-based computing

DNA Computing Platform

- High data ***density*** and massive ***parallelism*** (the power of "one step") will illuminate "dark data" that would otherwise be in accessible let alone analyzable
- Unlike quantum, DNA computing is ***broadly applicable*** in a variety of latency-tolerant applications

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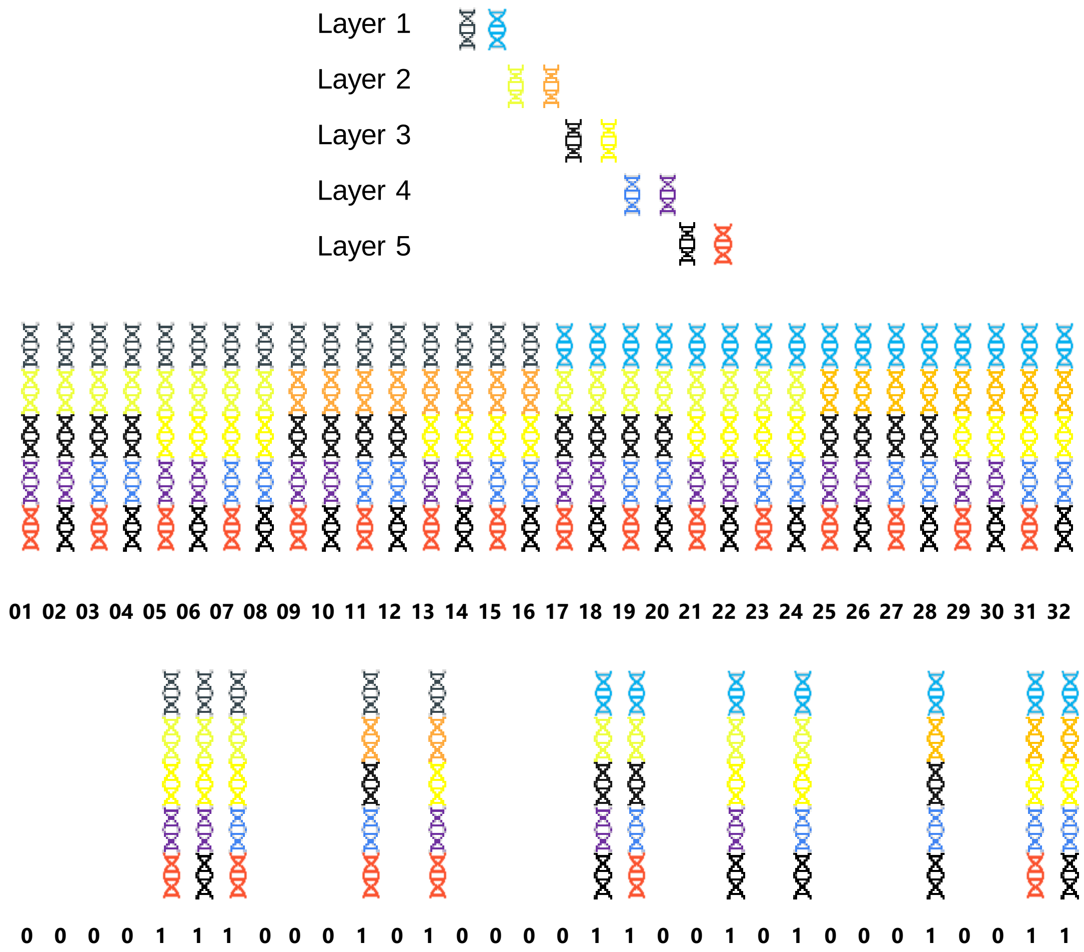
How CATALOG encodes information in DNA



Pre-made short pieces of DNA are combined into longer molecules

All possible assemblies of the DNA sequences create an ordered **combinatorial space**

Use DNA sequences analogously to characters in a typesetting machine

https://koreajoongangdaily.joins.com/2023/04/12/culture/koreanHeritage/jikji-bnf-gutenberg/20230412195850132.html

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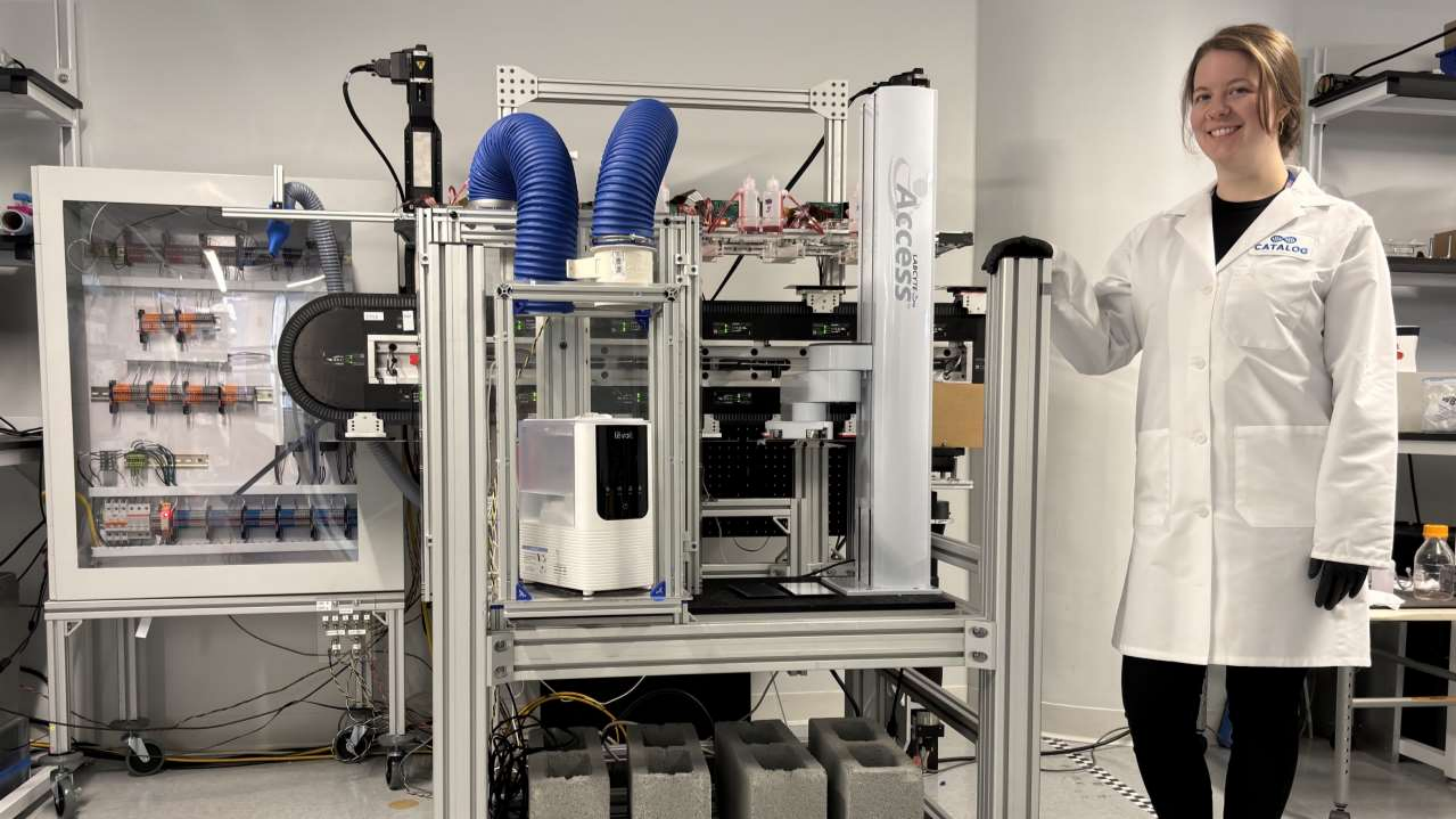
CAUTION


Access
LABCYTE
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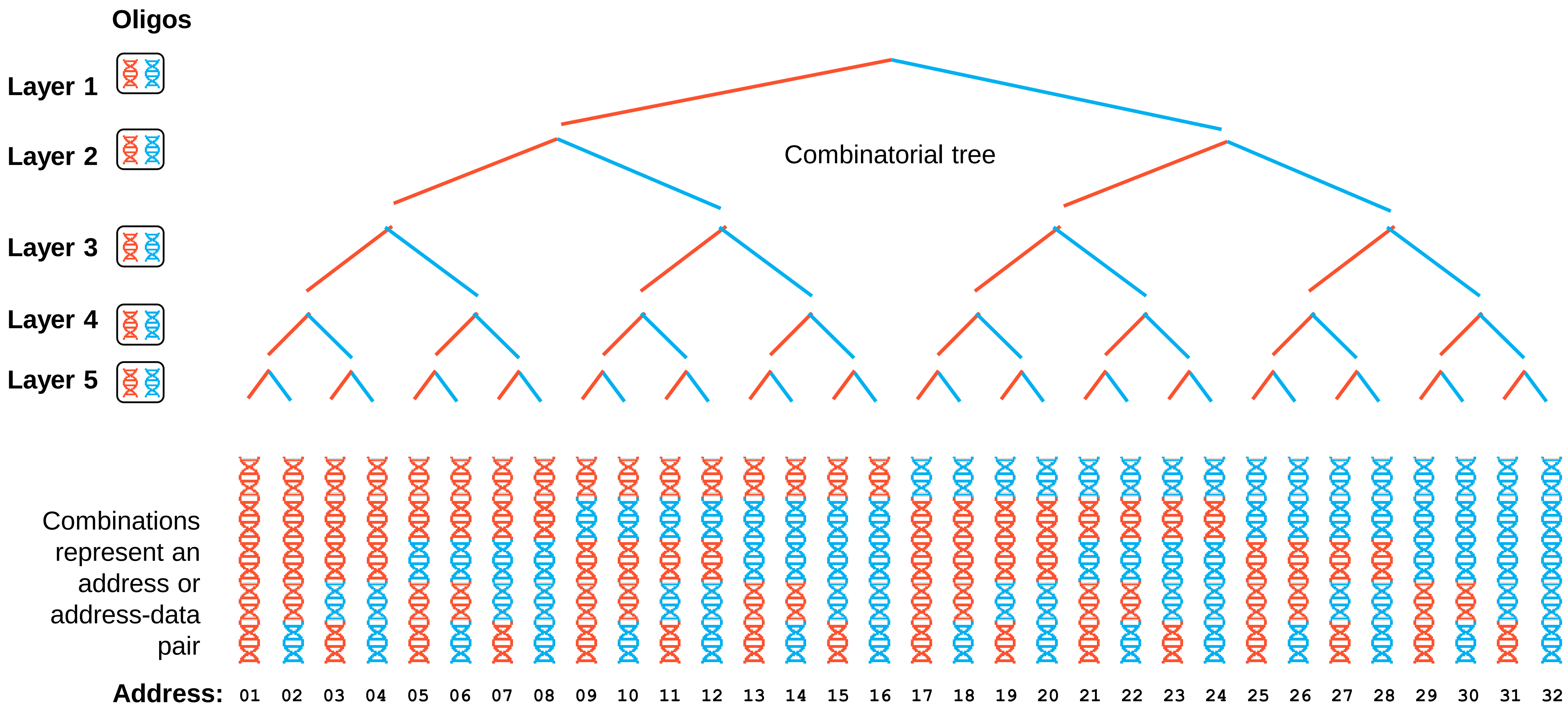
What is a Parallel Energy-Efficient In-Memory DNA Computer?

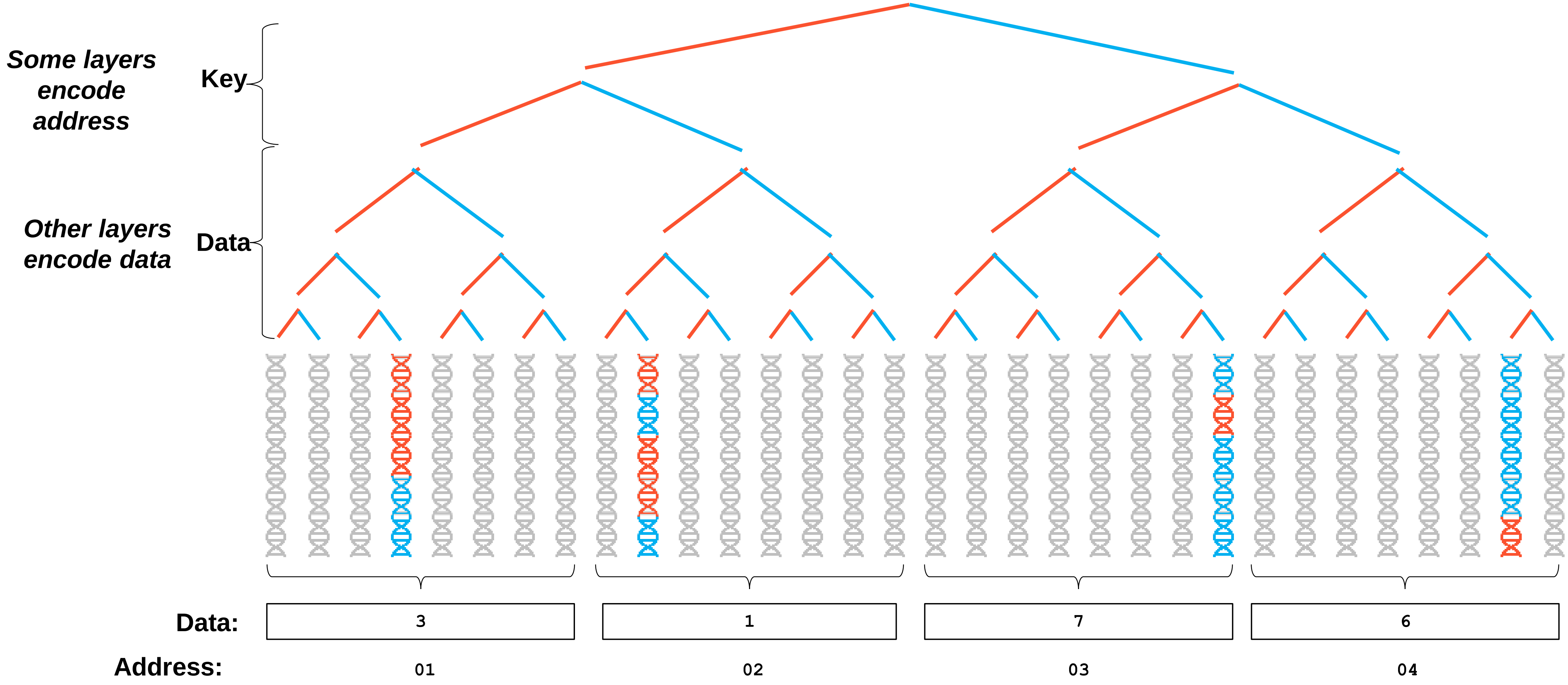
- Uses synthetic DNA to encode input, memory, and output
  - High density and longevity: inputs, memory, and output can be stored at micron scale for 1000s of years at ~zero energy cost without bit rot
- Uses DNA chemistry to transform inputs to outputs
  - Chemistry is executed on inputs encoded in DNA by automated robots or fluidic chips
- Computation happens within DNA memory without any fetch/store
- An instruction can be applied to all desired bits in parallel
  - Unlocks million- to billion-fold parallelism
- Instructions manipulate DNA, an energy-efficient molecule
  - Theoretically, a petabyte in DNA can be copied with only 55 J of energy (< J in 1 MLB pitch)
- Higher latency, of the order of minutes to hours
  - Great for latency-tolerant applications on high value data, and high throughput

CATALOG writes data using combinations of DNA oligos



Scales exponentially: ***L* layers of *N* components enables N^L bits of information with only LN oligos**

Each combination represents an address-data pair



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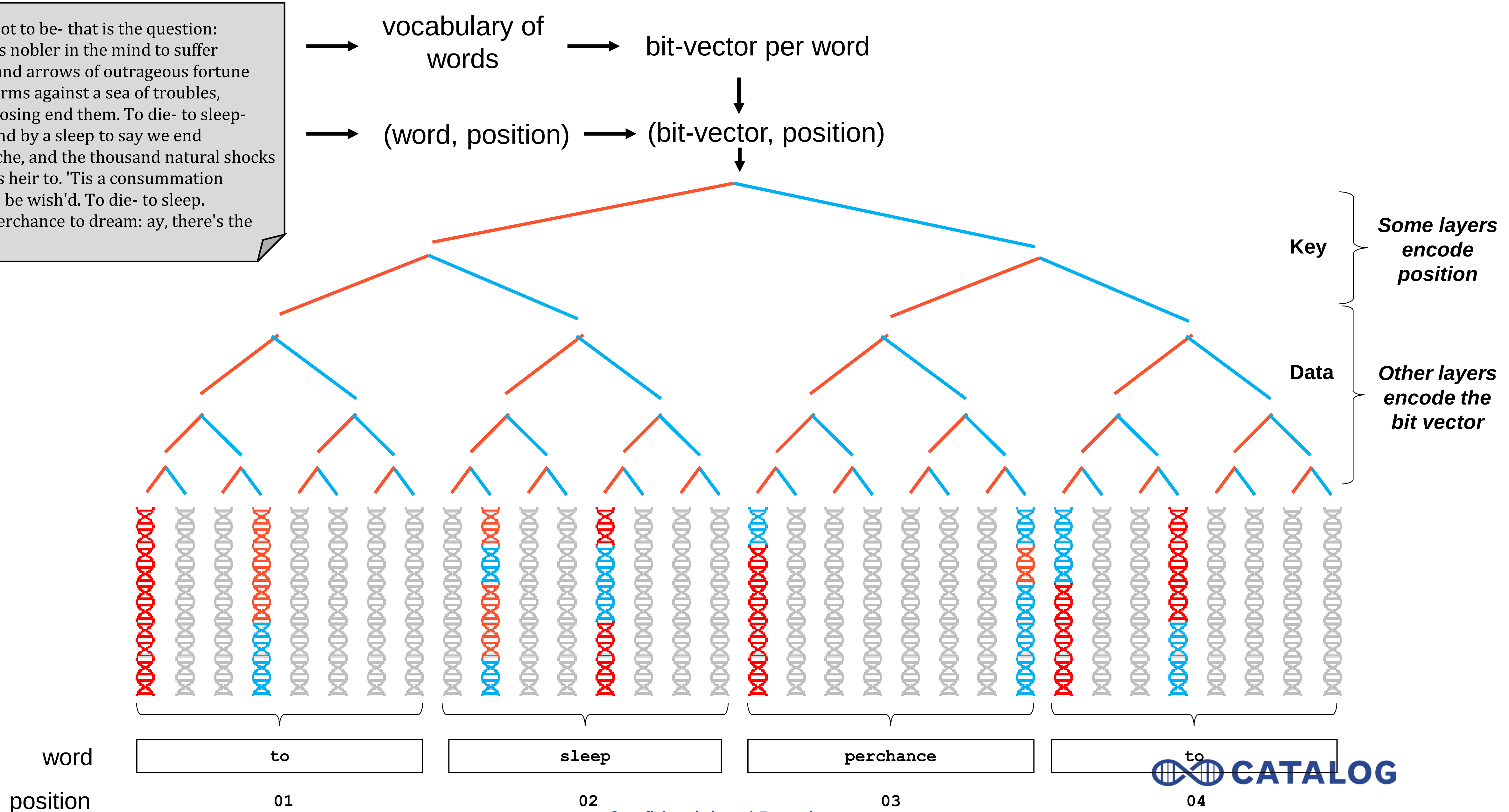
Demonstration of the *select* instruction in a parallel text search example

"To be, or not to be- that is the question:
Whether 'tis nobler in the mind to suffer
The slings and arrows of outrageous fortune
Or to take arms against a sea of troubles,
And by opposing end them. To die- to sleep-
No more; and by a sleep to say we end
The heartache, and the thousand natural shocks
That flesh is heir to. 'Tis a consummation
Devoutly to be wish'd. To die- to sleep.
To sleep- perchance to dream: ay, there's the
rub!"



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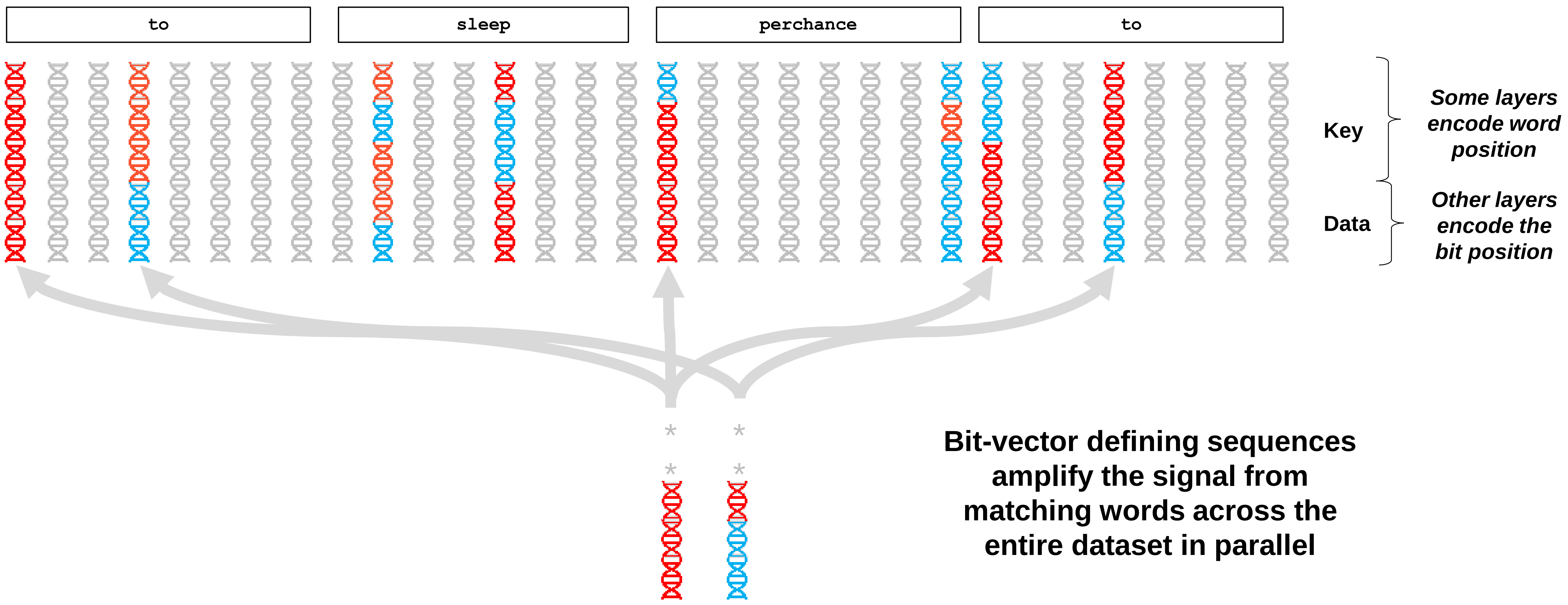

Bit-vector defining sequences amplify the signal from matching words across the entire dataset in parallel

query word → bit-vector → DNA sequences defining bit vector

"to" (10010000) (10010000)

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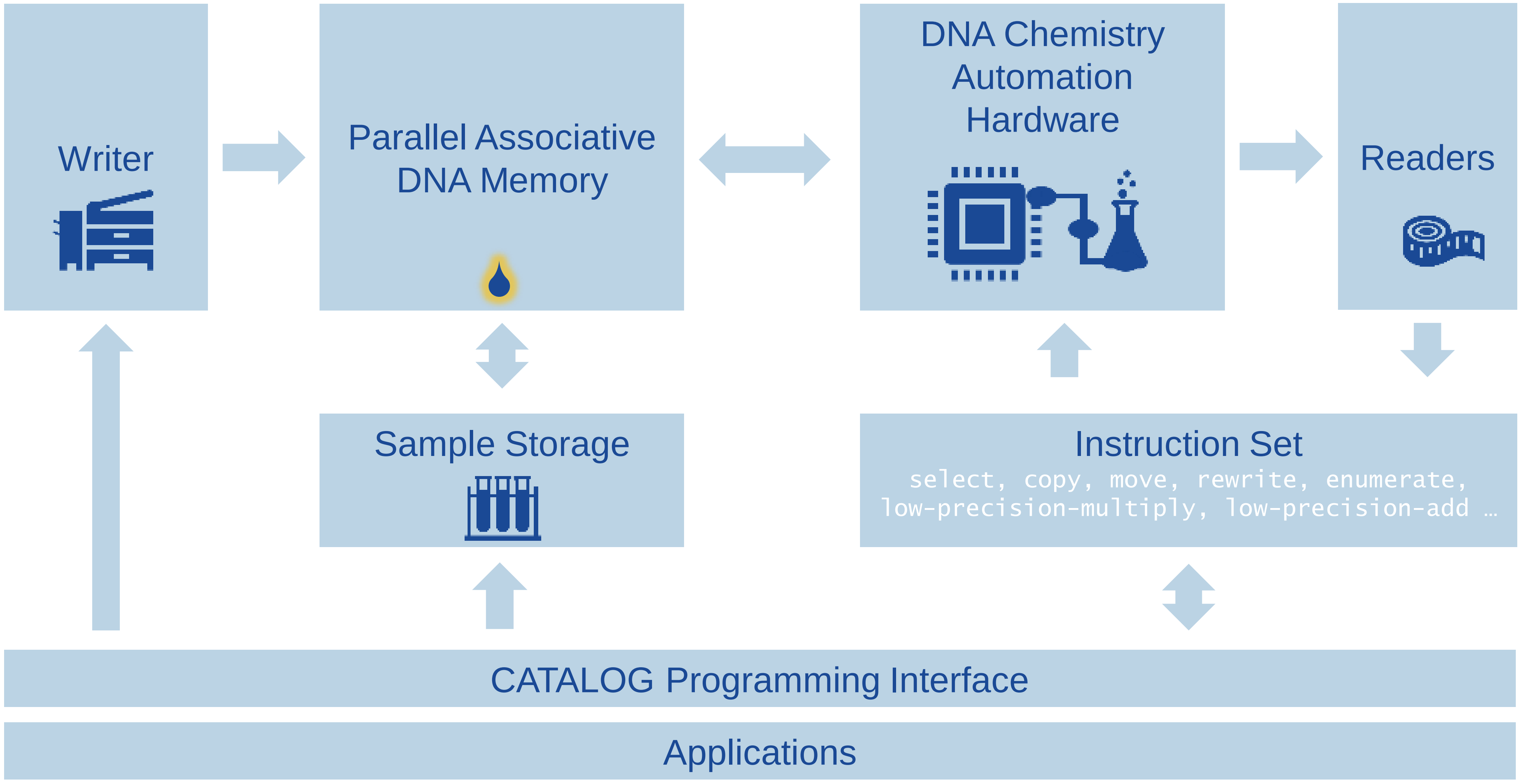
A Data Parallel Energy Efficient In-Memory DNA Computer



Summary

- DNA Computing can beat conventional computers on *operations per joule* because DNA is amenable to more efficient transformation and preservation than electromagnetic symbols. DNA Storage beats conventional storage on *longevity, density, and energy consumption* because DNA is error-resistant, information-dense, and energy efficient
- Together DNA-based storage and computing can beat conventional computing on energy-efficiency, density, and longevity (*e.g.*, a 10-year-old petabyte can be searched with a few ~KJ in a small DNA computing lab)
- DNA Computing is broadly applicable to applications with
  - long-term valuable data
  - latency-tolerant
  - sufficiently large scale of data
  - addressable with CATALOG's growing instruction set
- Current applications include search, inference, and signal processing, intractable problems, and ML training

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