Information Processing with DNA

By Jordan Osborn

Intro

- Perform computations using biological molecules rather than silicon.
- DNA has 4 distinct bases TACG so can be thought of as a base 4 number system. With the added caveat that T & A and C & G are complementary base pairs.
- DNA forms a double helix when two complementary strands of DNA bind together with Hydrogen bonds between the base pairs (2 TA) (3 CG)
- Inputs are represented by single strands of DNA with specific sequences.

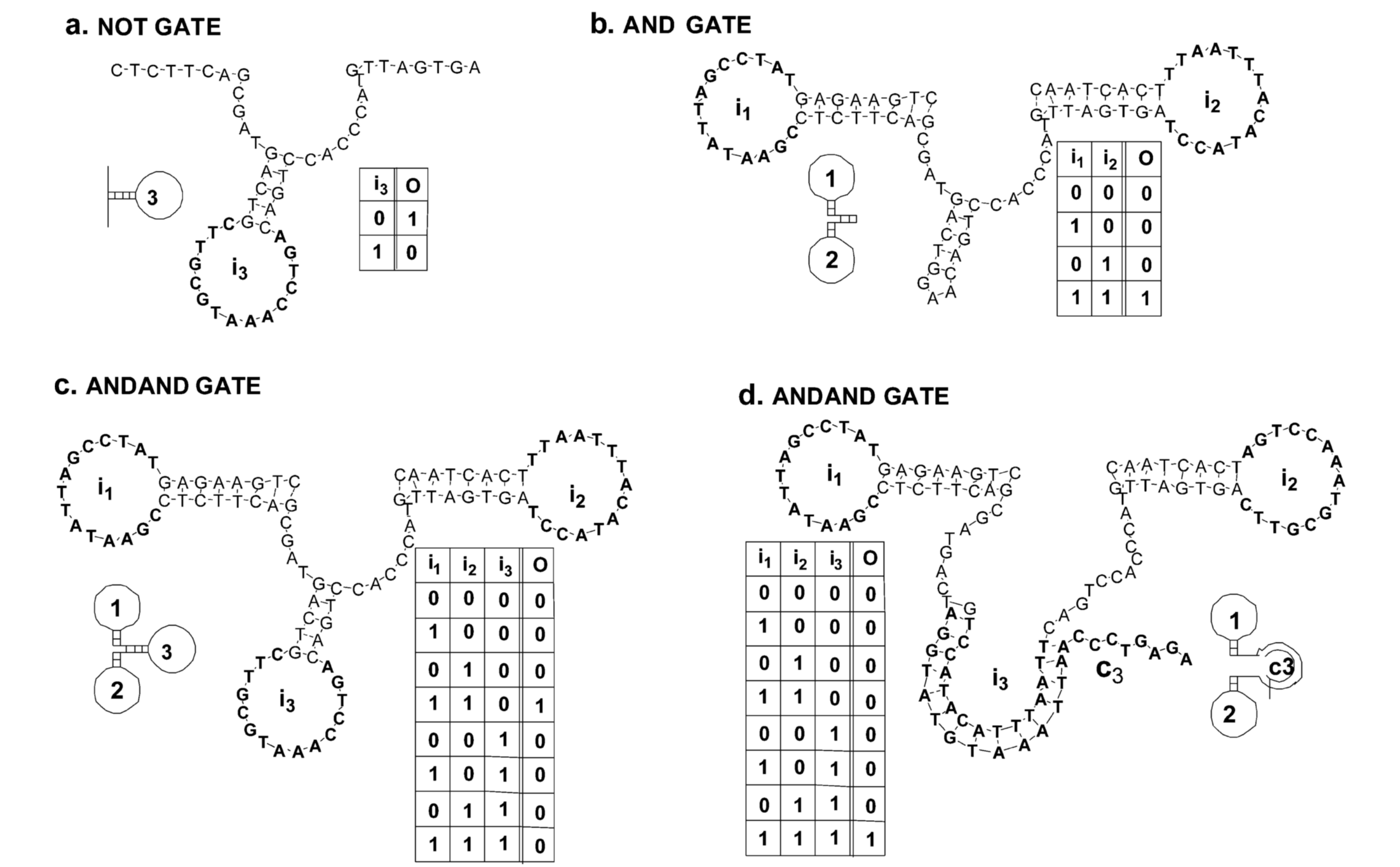
History

- 1950s Feynman proposes the idea that computation could be achieved at the molecular level.
- 1994 Adleman (Regarded as start of DNA computing) solved a special case (Directed Hamiltonian Path Problem) of the travelling salesperson problem, to find the shortest route between 7 cities.
- 1997 Ogihara & Ray describe ways to implement Boolean circuits (logic gates AND, OR etc.)
- 2013 Researchers manage to encode 739kBs of data in to DNA and were able to synthesize and reconstruct that data with 100% accuracy.
- 2013 Researchers create a transistor like device from DNA & RNA "transcriptor". A group of which can carry out typical computational tasks.

How

- Many techniques that utilise DNA as a tool for information processing.
- Deoxyribozyme based. Catalyse reactions when interacting with an input oligonucleotide. Used to build logic gates, when correct inputs attached they change shape and release a fluorescent substrate which can then catalyse a reaction. Single use only.
- Enzyme based. Can create a simple Turing machine where DNA acts as the software and the enzymes act as hardware.
- Toehold Exchange. An input DNA strand binds to a sticky end (unpaired nucleotides on end of DNA molecule) which then displaces another DNA segment. Can create modular logic gate components.

Examples of logic gates made from Deoxyribozymes



Pros

- Much more energy efficient (during computation) than traditional computers. (Adleman 1994 2*10^19 Operations / Joule)
- Biologically compatible, can be used in fluids such as blood.
- Can be made much smaller than (current) traditional computers.
- DNA has a very large memory density (lots of information can be stored in a small volume). 1000s TB per cm^3.
- Carry out a large amount of parallel (at the same time) computations, this means in general that a complex problem should take the same order of time as a simple problem.
- Can compute all possibilities at the same time.

Cons

- Has a slow processing speed with response times of order minutes, hours and days. In comparison traditional computers can complete billions of operations each second.
- It is harder to analyse the results given by a DNA computer (Use fluorescence etc.).
- Can’t solve any problems that traditional computers can’t, use cases are limited to places traditional computers perform poorly.
- Error rates higher than traditional computers.

Interesting Developments

- 2002 Macdonald, Stefanovic, Stojanovic created a DNA computer capable of playing Tic-Tac-Toe against a human opponent.
- 2011 Qian, Winfree create a ”circuit” from 130 DNA strands that can compute the square root of 4 bit numbers (0,15)
- 2013 Transcriptor base component which can be used to construct logic gates
- 2013 DNA AND gate that can respond to specific RNA sequences inside a live mammalian cell.

Applications

- Solving NP-complete problems (no polynomial time solution using traditional computers) time required to solve exponential. Examples include many optimisation problems scheduling, travelling salesperson. Try's all solutions.
- Making large addressable associative storage. (Can search to find closest match, do not need to know exact memory location).
- Small scale computation for nanotechnology. For use in biological context.