Molecular Programming
The systematic manipulation of matter

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Objectives

• The promises of Molecular Programming:
  • In Science & Medicine
  • In Engineering
  • In Computing

• The current practice of Molecular Programming
  • DNA technology
  • Molecular languages and tools
  • Example of a molecular algorithm
Nanotechnology and the Double Helix
How it all started.
Ned Seeman, now at New York University, pioneered the field of structural DNA nanotechnology when he realized in 1979 that covalent phosphate linkages that connect two DNA duplex strands upon homologous recombination during cell division (so-called Holliday junctions) and that usually freely slide along the two connected DNA double helices can be immobilized and thus be used to create a spatially fixed connection between the two DNA duplex molecules—such feat is an elementary requirement for all kind of construction. He even went on and other discoveries to that made and how they started an entire new field of applied sciences that deals with building things using DNA as construction material. The article also

Universal computing by DNA origami robots in a living animal
Yaniv Amir1, Eldad Ben-Ishay2, Daniel Levner3, Shmulik Ittah1, Almogit Abu-Horowitz3 and Ido Bachelet*
The Hardware Argument

Smaller and smaller things can be built
Smaller and Smaller

First working transistor
John Bardeen and Walter Brattain, Dec. 23, 1947

First integrated circuit

50 years later

25nm NAND flash
Intel&Micron, Jan. 2010. ~50 atoms

Single molecule transistor
Observation of molecular orbital gating
Nature, 2009; 462 (7276): 1039

Molecules on a chip

~10 Moore’s Law cycles left!

Building the *Smallest* Things

- How do we build structures that are by definition smaller than your tools?
- Basic answer: you can’t. Structures (and tools) should build themselves!
- By *programmed self-assembly*

www.youtube.com/watch?v=Ey7Emmddf7Y
Molecular IKEA

- Nature can self-assemble. Can we?
- “Dear IKEA, please send me a chest of drawers that assembles itself.”
- We need a magical material where the pieces are pre-programmed to fit into each other.
- At the molecular scale many such materials exist...

Programmed Self-Assembly

Proteins

Membranes

DNA/RNA

![Image of proteins and membranes](image1.png)

![Image of DNA/RNA sequences](image2.png)
The Software Argument

Smaller and smaller things can be programmed
We can program...

- Information
  - Completely!
We can program...

- Forces
  - Completely!
    (Modulo sensors/actuators)
We can program...

• Matter
  • Completely and directly!
  • Currently: only DNA/RNA.

It's like a 3D printer without the printer!
[Andrew Hellington]
DNA

Sequence of Base Pairs (GACT alphabet)

GC Base Pair
Guanine-Cytosine

TA Base Pair
Thymine-Adenine

Interactive DNA Tutorial
(http://www.biosciences.bham.ac.uk/labs/minchin/tutorials/dna.html)
Robust, and Long

- DNA in each human cell:
  - 3 billion base pairs
  - 2 meters long, 2nm thick
  - folded into a 6µm ball
  - 750 MegaBytes

- A huge amount for a cell
  - Every time a cell replicates it has to copy 2 meters of DNA reliably.
  - To get a feeling for the scale disparity, compute:

- DNA in human body
  - 10 trillion cells
  - 133 Astronomical Units long
  - 7.5 OctaBytes

- DNA in human population
  - 20 million light years long
Zipping Along

- DNA can support structural and computational complexity.

DNA replication in *real time*

In Humans: 50 nucleotides/second  
Whole genome in a few hours (with parallel processing)

In Bacteria: 1000 nucleotides/second  
(higher error rate)

DNA transcription in *real time*

RNA polymerase II: 15-30 base/second

Drew Berry
http://www.wehi.edu.au/wehi-tv
What can we do with “just” DNA?

- Organize ANY matter [caveats apply]
- Execute ANY kinetics [caveats: up to time scaling]
- Build Nano-Control Devices
- Interface to Biology
Organizing Any Matter

- Use one kind of programmable matter (e.g. DNA).
- To organize (almost) ANY matter through it.

"What we are really making are tiny DNA circuit boards that will be used to assemble other components."

Greg Wallraff, IBM

6 nm grid of individually addressable DNA pixels

Executing Any Kinetics

- The kinetics of any finite network of chemical reactions, can be implemented (physically) with especially programmed DNA molecules.

- Chemical reactions as an executable programming language for dynamical systems!

DNA as a universal substrate for chemical kinetics

David Soloveichik, Georg Seelig, and Erik Winfree

PNAS
Building Nano-Control Devices

- All the components of nanocontrollers can already be built entirely and solely with DNA, and interfaced to the environment.

DNA Aptamers
Sensing
DNA Logical Gates
Computing
Actuating
DNA Walkers & Tweezers
Self-assembling DNA Tiles
Constructing
Constructing
Crosslinking
Crosslinking
Crosslinking
Crosslinking
Crosslinking

In nature, crosslinking is deadly (blocks DNA replication).

In engineering, crosslinking is the key to using DNA as a construction material.
DNA Tiling

4 sticky ends
crosslinking

Construction and manipulation of DNA tiles in free space
Praktali
2D DNA Lattices

Chengde Mao
Purdue University, USA

N-point Stars
3D DNA Structures

Ned Seeman
NYU

Andrew Tuberfield
Oxford

3D Crystal

Tetrahedron
CADnano

William Shih
Harvard

S.M. Douglas, H. Dietz, T. Liedl, B. Högberg, F. Graf and W. M. Shih
Self-assembly of DNA into nanoscale three-dimensional shapes, Nature (2009)
**DNA Origami**

*Folding* long (7000bp) naturally occurring (viral) ssDNA
By lots of short ‘staple’ strands that constrain it

Paul W K Rothemund
California Institute of Technology

Black: long viral strand
Color: short staple strands

Paul Rothemund’s “Disc with three holes” (2006)
"What we are really making are tiny DNA circuit boards that will be used to assemble other components."
--Greg Wallraff, IBM
Sensing
Aptamers

Artificially evolved DNA molecules that stick to anything you like highly selectively
Pathogen Spotlights

- DNA aptamer binds to:
  - A) a pathogen
  - B) a molecule our immune system already hates and immediately removes (eats) along with anything attached to it

- Result: instant immunity
  - Mice poisoned with Anthrax plus aptamer (100% survival)
  - Mice poisoned with Anthrax (not so good)

Kary Mullis (incidentally, also Nobel prize for inventing the Polymerase Chain Reaction)
Actuating
DNA Tweezers

Hybridization

Strand Displacement

Waste

Open

Set strand

Closed

DNA tweezers
Jonathan Bath & Andrew J. Turberfield
doi:10.1038/nnano.2007.124
DNA Walkers
Hybridization Chain Reaction

Triggered amplification by hybridization chain reaction

Robert M. Dirks and Niles A. Pierce®
Polymerization Motor

Rickettsia (spotted fever)

An autonomous polymerization motor powered by DNA hybridization

[Diagram]

C

Downloaded Acute Polymorphonuclear Associated With Spotted Fever Group Rickettsia Infection of Vero Cells

[Image]
Curing
Computational Drugs

- An automaton sequentially reading the string PPAP2B, GSTP1, PIM1, HPS (known cancer indicators) and sequentially cutting the DNA hairpin until a ssDNA drug (Vitravene) is released.
Interfacing to Biology

- A doctor in each cell

*Fig. 1 Medicine in 2050: “Doctor in a Cell”*
The Biological Argument

Biological systems are already ‘molecularly programmed’
Abstract Machines of Biology

- **Gene Machine**
  - Nucleotides
  - Make proteins
  - Send signals
  - Direct construction and regulators
  - Hold receptors, host reactions

- **Protein Machine**
  - Amino acids
  - Metabolism, Propulsion
  - Signaling, Transport

- **Membrane Machine**
  - Phospholipids
  - Enact fusion, fission

- **Regulation**
  - Confinement, Storage
  - Bulk Transport

Additional features:
- **Glycan Machine**
  - Surface and Extracellular Features
Biological Languages

Gene Machine

Protein Machine

Membrane Machine

Molecular Interaction Maps

Gene Networks

Transport Networks

A

B

C

x

y

P

Q
But ...  

- Biology is programmable, but (mostly) not by us!

- Still work in progress:
  - Gene networks are being programmed in synthetic biology, but using existing ‘parts’
  - Protein networks are a good candidate, but we cannot yet effectively design proteins
  - Transport networks are being investigated for programming microfluidic devices that manipulate vesicles
Molecular Languages

... that we can execute
Our Assembly Language: Chemistry

- A Lingua Franca between Biology, Dynamical Systems, and Concurrent Languages

- Chemical Reaction Networks
  - $A + B \rightarrow C + D$ (the program)

- Ordinary Differential Equations
  - $\frac{d[A]}{dt} = -r[A][B]$ ... (the behavior)

- Rich analytical techniques based on Calculus

- But prone to combinatorial explosion
  - E.g., due to the peculiarities of protein interactions
How do we “run” Chemistry?

· Chemistry is not easily executable
  · “Please Mr Chemist, execute me this bunch of reactions that I just made up”

· Most molecular languages are not executable
  · They are descriptive (modeling) languages

· How can we execute molecular languages?
  · With real molecules?
  · That we can design ourselves?
  · And that we can buy on the web?
Molecular Programming with DNA

Building the cores of programmable molecular controllers
The role of DNA Computing

- **Non-goals**
  - Not to solve NP-complete problems with large vats of DNA
  - Not to replace silicon

- **Bootstrapping a carbon-based technology**
  - To precisely control the organization and dynamics of matter and information at the molecular level
  - DNA is our engineering material
    - Its biological origin is “accidental” (but convenient)
    - It is an information-bearing programmable material
    - Other such materials will be (are being) developed
Domains

- Subsequences on a DNA strand are called **domains**
  - *provided* they are “independent” of each other

- Differently named domains must not **hybridize**
  - With each other, with each other’s complement, with subsequences of each other, with concatenations of other domains (or their complements), etc.
Short Domains

Reversible Hybridization

DNA double strand
Long Domains

Irreversible Hybridization
Strand Displacement

“Toehold Mediated”
Strand Displacement

Toehold Binding
Strand Displacement

Branch Migration
Strand Displacement

Displacement
Strand Displacement

Irreversible release
Bad Match

\[ t \quad x \quad z \]

\[ t \quad x \quad y \]
Bad Match
Bad Match
Bad Match

Cannot proceed
Hence will undo
Two-Domain Architecture

- Signals: 1 toehold + 1 recognition region

- Gates: “top-nicked double strands” with open toeholds

Garbage collection “built into” the gate operation

Two-Domain DNA Strand Displacement

*Luca Cardelli*

Plasmidic Gate Technology

- Synthetic DNA is length-limited
  - Finite error probability at each nucleotide addition, hence ~ 200nt max
- Bacteria can replicate plasmids for us
  - Loops of DNA 1000’s nt, with extremely high fidelity
  - Practically no structural limitations on gate fan-in/fan-out

Only possible with two-domain architecture
Transducer
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$

$ta$ is a \textit{private} signal (a different ‘a’ for each $xy$ pair)

Built by self-assembly!
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$

So far, a tx signal has produced an at cosignal. But we want signals as output, not cosignals.
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$
Here is our output \textbf{ty signal}.
But we are not done yet:
1) We need to make the output irreversible.
2) We need to remove the garbage.
We can use (2) to achieve (1).
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$
Transducer $x \rightarrow y$

Done.

N.B. the gate is consumed: it is the energy source
(no proteins, no enzymes, no heat-cycling, etc.; just DNA in salty water)
Transducer \( x \rightarrow y \)
Join $x + y \rightarrow z$
Tools and Techniques

A software pipeline for Molecular Programming
Development Tools

MSRC Biological Computation Group

Visual DSD
A Development Environment for DNA Strand Displacement

A programming language for composable DNA circuits
Andrew Phillips and Luca Cardelli
Execution

A wetlab pipeline for Molecular Programming
Output of Design Process

- Domain structures
  - (DNA sequences to be determined)

“Ok, how do I run this for real”
From Structures to Sequences

DSD Structure \[ \rightarrow \] "Dot-Paren" representation

Output Sequences

Thermodynamic Synthesis

"Ok, where do I buy these?"

www.nupack.org
“DNA Synthesis”

DNA synthesis commonly refers to DNA replication - DNA biosynthesis (in vivo DNA amplification); Polymerase chain reaction - enzymatic DNA synthesis (in vitro). DNA replication, the basis for biological inheritance, is a fundamental concept in biology. DNA synthesis is also used in genetic engineering and biotechnology research.
From Sequences to Molecules

- Copy&Paste from nupack
Molecules by FedEx

"Ok, how do I run these?"
Add Water
Execute (finally!)

- Fluorescence is your one-bit ‘print’ statement
Output
Debugging

- A core dump

DNA strand length

Various processing stages

Calibration scale
Delivery!
A Molecular Algorithm
Running something interesting with DNA
Approximate Majority Algorithm

• Given two populations of agents (or molecules)
  • Randomly communicating by radio (or by collisions)
  • Reach an agreement about which population is in majority
  • By converting all the minority to the majority
  [Angluin et al., Distributed Computing, 2007]

• 3 rules of agent (or molecule) interaction
  • $X + Y \rightarrow B + B$
  • $B + X \rightarrow X + X$
  • $B + Y \rightarrow Y + Y$

“our program”
DNA Implementation, at U.W.

- Programmable chemical controllers made from DNA
  [Yuan-Jyue Chen, Neil Dalchau, Niranjan Srinivas, Andrew Phillips, Luca Cardelli, David Soloveichik and Georg Seelig]
Final Remarks
A Brief History of DNA

Turing Machine, 1936

Transistor, 1947

Computer programming

20th century

Systematic manipulation of information

DNA, -3,800,000,000

DNA Algorithm, 1994

Systematic manipulation of matter

Molecular programming

21st century

Structural DNA Nonotech, 1982
Acknowledgments

- Microsoft Research
  - Andrew Phillips, Biological Computation Group

- Caltech
  - Winfree Lab

- U.Washington
  - Seelig Lab
Questions?
Resources

• Visual DSD at MSR

• Molecular Programming Project at Caltech
  http://molecular-programming.org/

• Georg Seelig’s DNA Nanotech Lab at U.W. CS&E
  http://homes.cs.washington.edu/~seelig/