Molecular Programming

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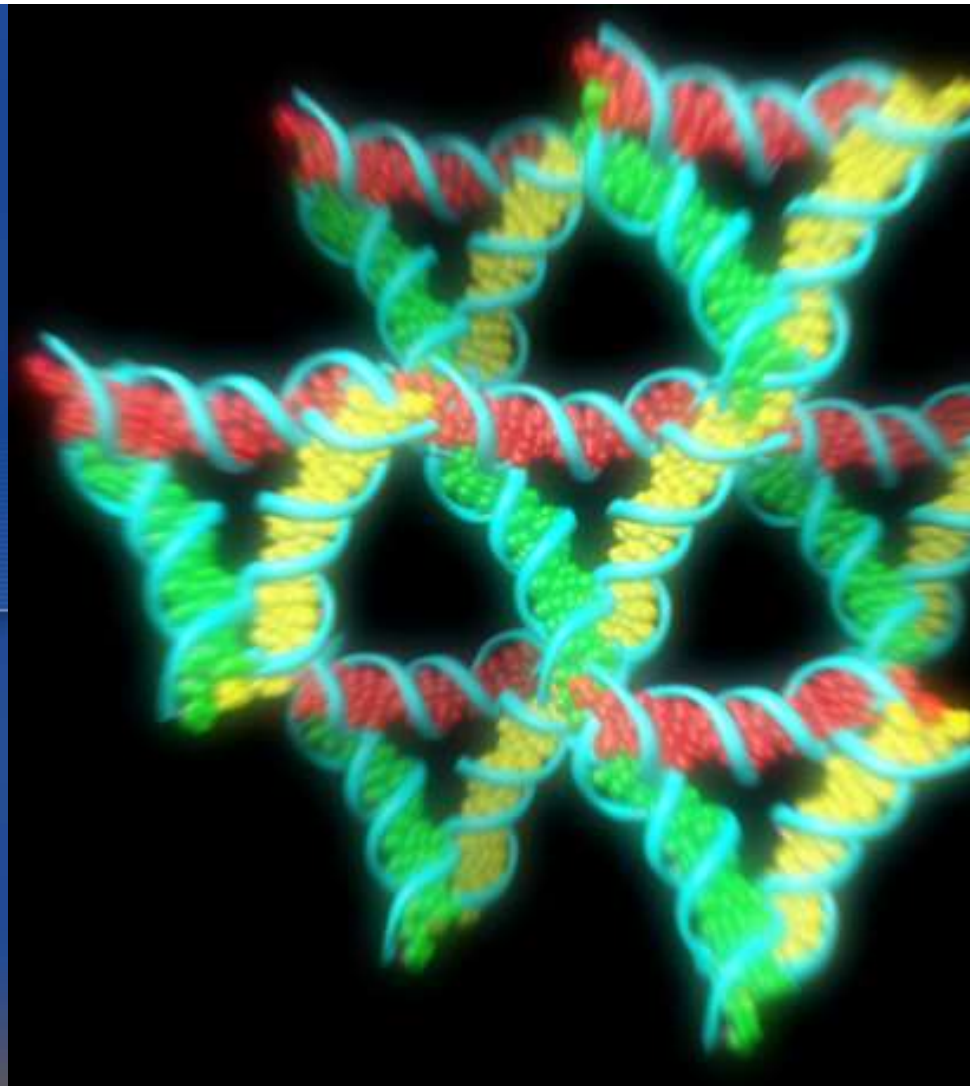
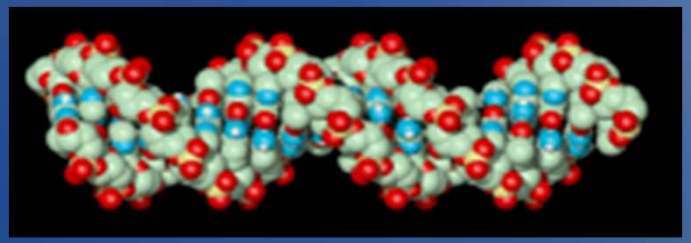
2018-10-10, ECSS Gothenburg



Objectives

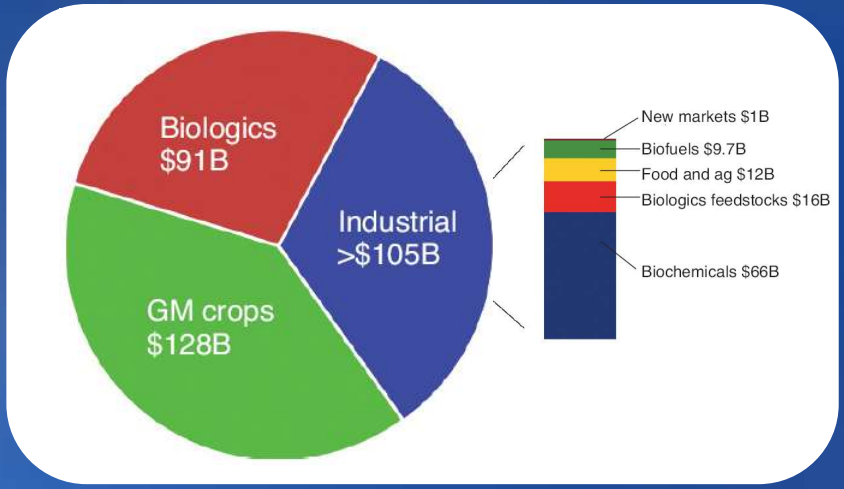
- The promises of Molecular Programming:
  - In Science & Medicine
  - In Engineering
  - In Computing

- The current practice of Molecular Programming
  - DNA technology
  - Molecular languages and tools
  - Molecular algorithms



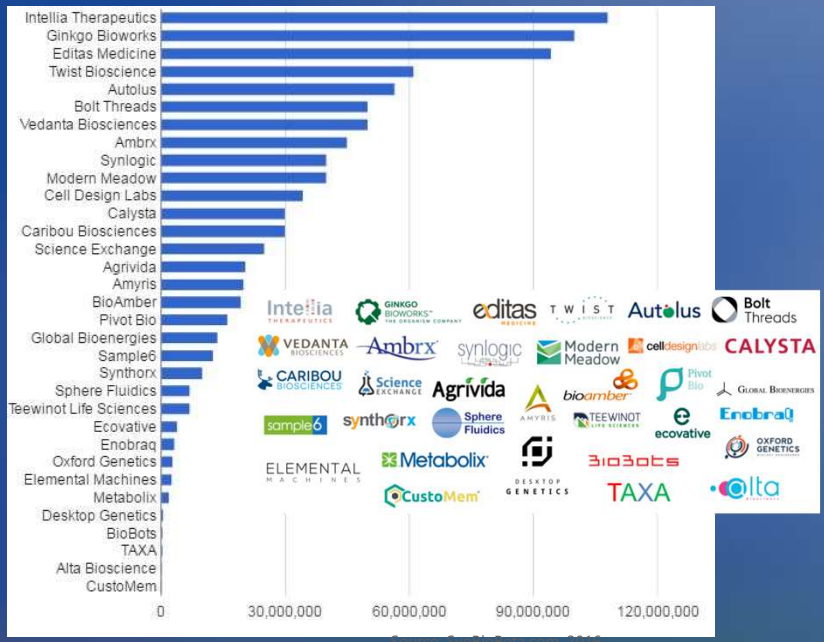
Synthetic Biology Market

Annual revenue from GMOs in the US exceeds $324Bn



Source: Rob Carlson, Nature Biotechnology, 2016

33 Programming Biology companies raised $900M in 2016



Some (ongoing) successes stories

JUNO THERAPEUTICS

- ($4Bn) Reprogram a patient's own blood cells to recognise and destroy specific cancers.
- 90% remission in terminally ill leukemia patients

AMYRIS

- ($300M) Reprogram … to synthesise chemicals
- Antimalarial … tion (with Sanofi)
- Jet f… flights (with Total)

Molecular "hacking"

GINKGO BIOWORKS
THE ORGANISM COMPANY

- Supply custom organisms for bio fabrication

Modern Meadow

- Grow meat, leather ($100Bn market) in the lab
- Proofs of concept already in production

Hacking Yoghurt

Tuur van Balen - Hacking Yoghurt
- genetically modify your yoghurt in your own kitchen

https://www.youtube.com/watch?v=Co8NOnErrPU

Molecular Programming

A *technology* (and theory of computation)
based on information-bearing molecules
of historically biological origin (DNA/RNA)
non necessarily involving living matter

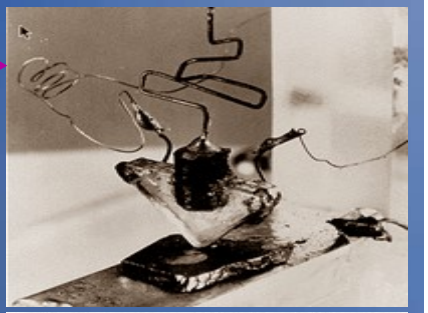
Molecular Programming:
The Hardware Aspect

Smaller and smaller things can be built

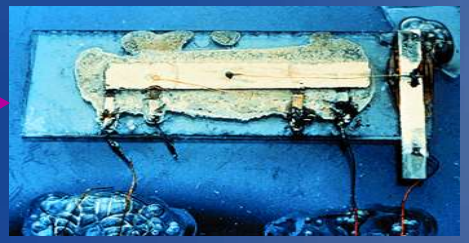
Smaller and Smaller

Very few Moore's cycles left!

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

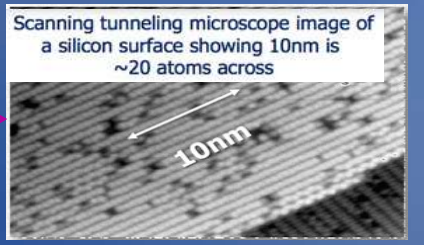


First integrated circuit
Jack Kilby, Sep. 1958.



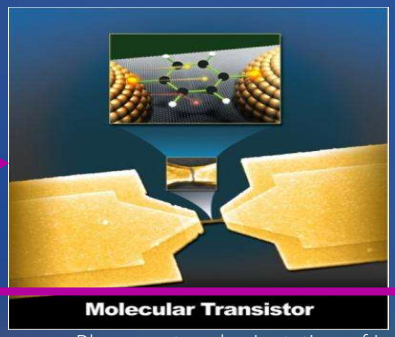
50+ years later

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

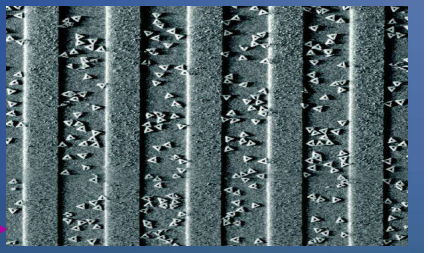


Jun 2018 7nm (54nm pitch)
TSMC, Intel, Samsung, GlobalFoundries - mass production

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



Molecules on a chip



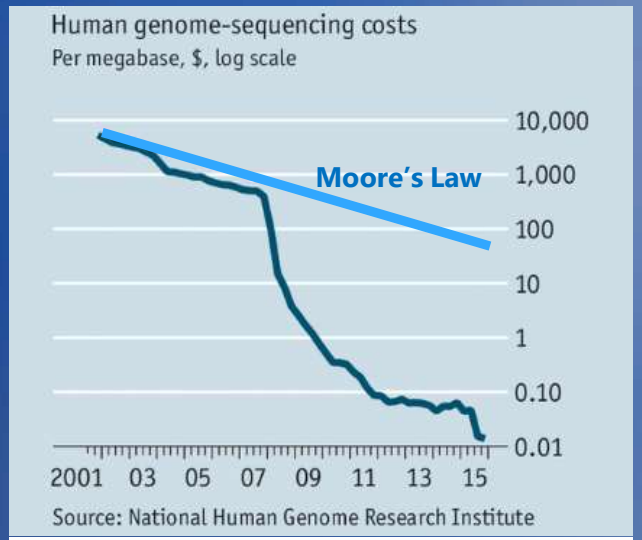
Placement and orientation of individual DNA shapes on lithographically patterned surfaces. Nature Nanotechnology 4, 557 - 561 (2009).

Race to the Bottom

Moore's Law is approaching the single-molecule limit

Carlson's Curve is the new exponential growth curve in technology

In both cases, we are now down to *molecules*



The Pace and Proliferation of Biological Technologies

March 4, 2004 by Rob Carlson

The SmidgION: A portable DNA sequencer that runs on an Iphone

Oxford Nanopore

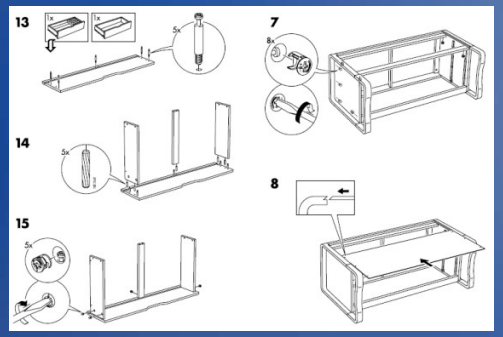
Building the *Smallest* Things

- 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*

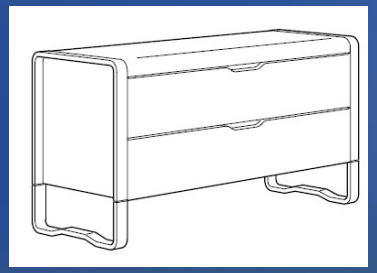
www.youtube.com/watch?v=Ey7Emmddf7Y

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 to each other.
- At the molecular scale many such materials exist…



Add water

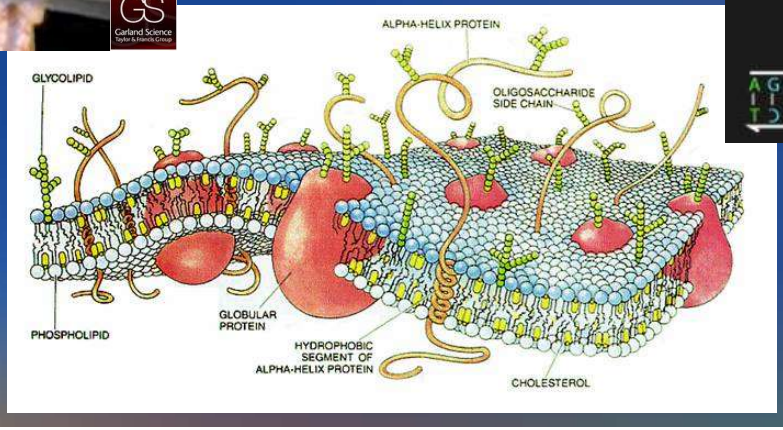


http://www.ikea.com/ms/en_US/customer_service/assembly_instructions.html

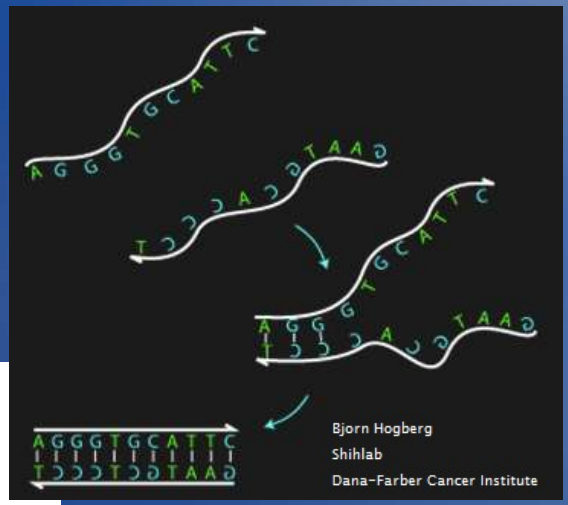
Programmed Self-Assembly

Proteins

Membranes



DNA/RNA

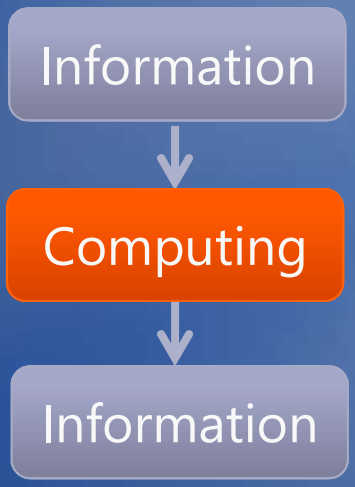


Molecular Programming:
The Software Aspect

Smaller and smaller things can be programmed

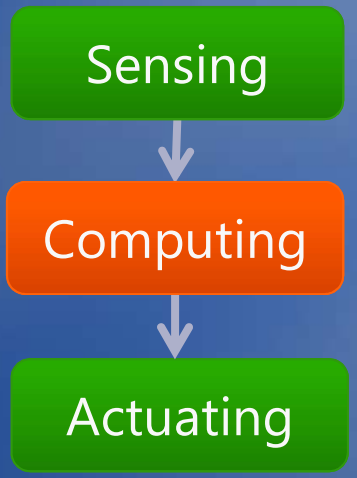
We can program…

- Information
  - Completely!



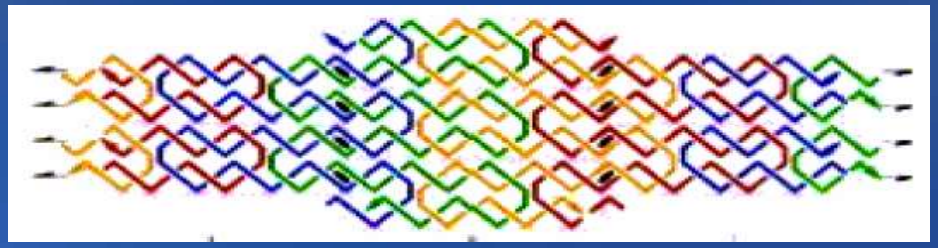
We can program…

- Forces
  - Completely!
    (Modulo sensors/actuators)

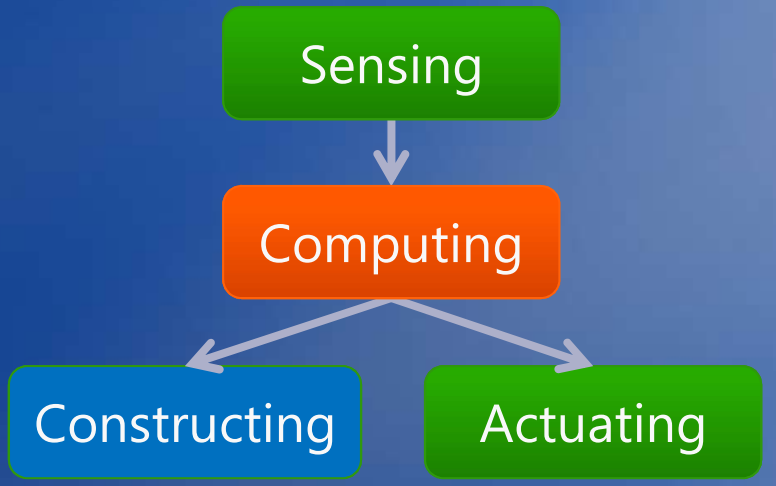


We can program…

- Matter
  - Completely and directly! By self-assembly.
  - Currently: only DNA/RNA.

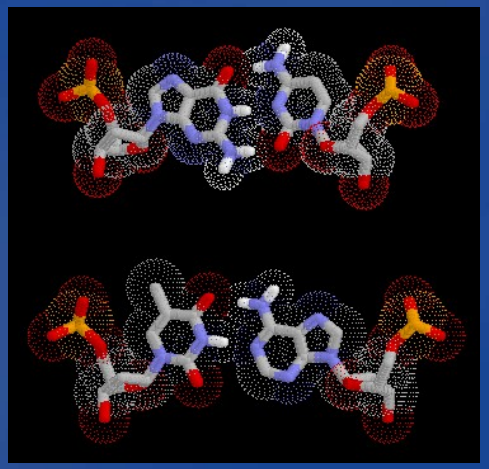


- But DNA is an amazing *material*



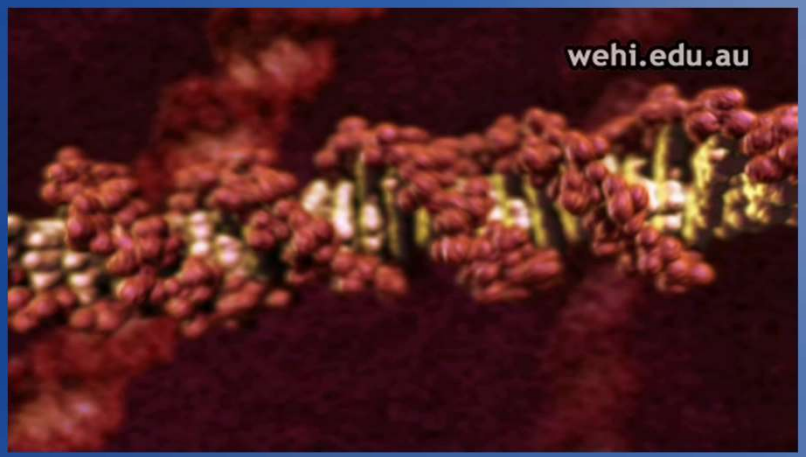
It's like a 3D printer without the printer!
[Andrew Hellington]

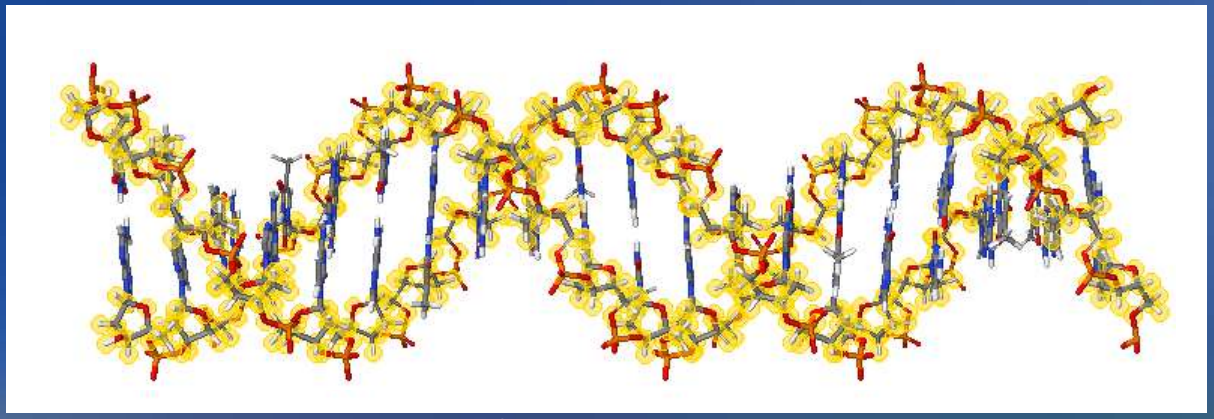
DNA



G-C Base Pair
Guanine-Cytosine

T-A Base Pair
Thymine-Adenine





Sequence of Base Pairs (GACT alphabet)

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

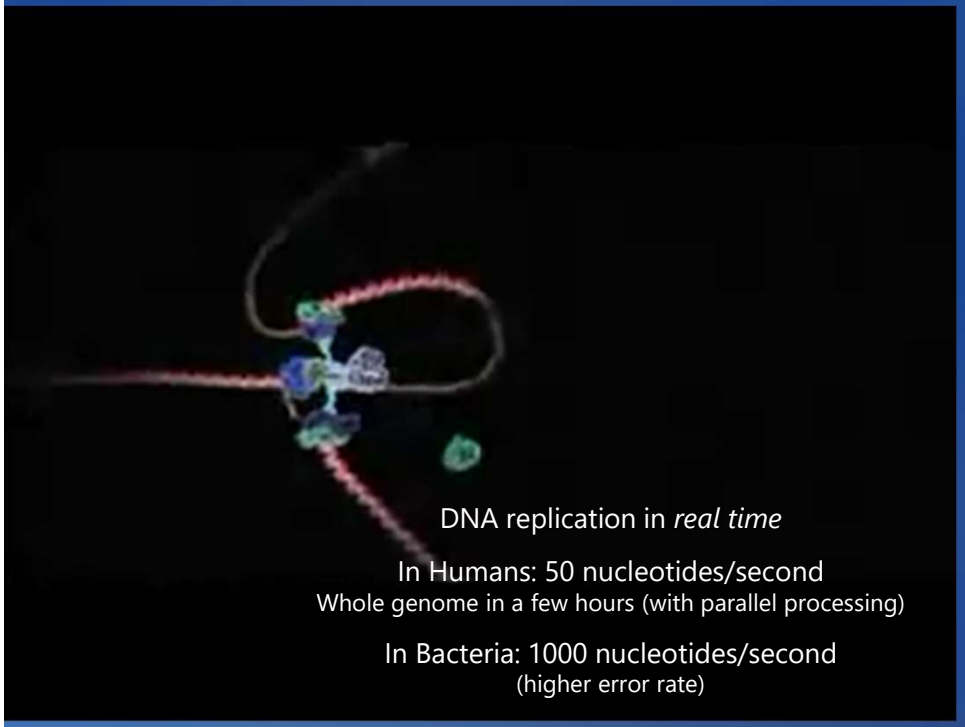
DNA Specs

- DNA in each human cell
  - 3 billion base pairs
  - 2nm thick = 4 silicon atoms!
  - 0.34nm per basepair = 2/3 silicon atom!
  - 2 meters long
    copied in parallel at each cell division!
  - 750 megabytes
    80% functional, but only 1.5% protein coding
  - folded into a 6μm spherical nucleus
    = 140 exabytes (million terabytes)/mm^3
    => *all* the data on the internet fits in a shoebox!
- DNA in each human body
  - 10 trillion cells
  - 133 Astronomical Units long
  - 7.5 octabytes (replicated)
- DNA in human population
  - 20 million light years long

DNA wrapping into chromosomes

Andromeda Galaxy
2.5 million light years away

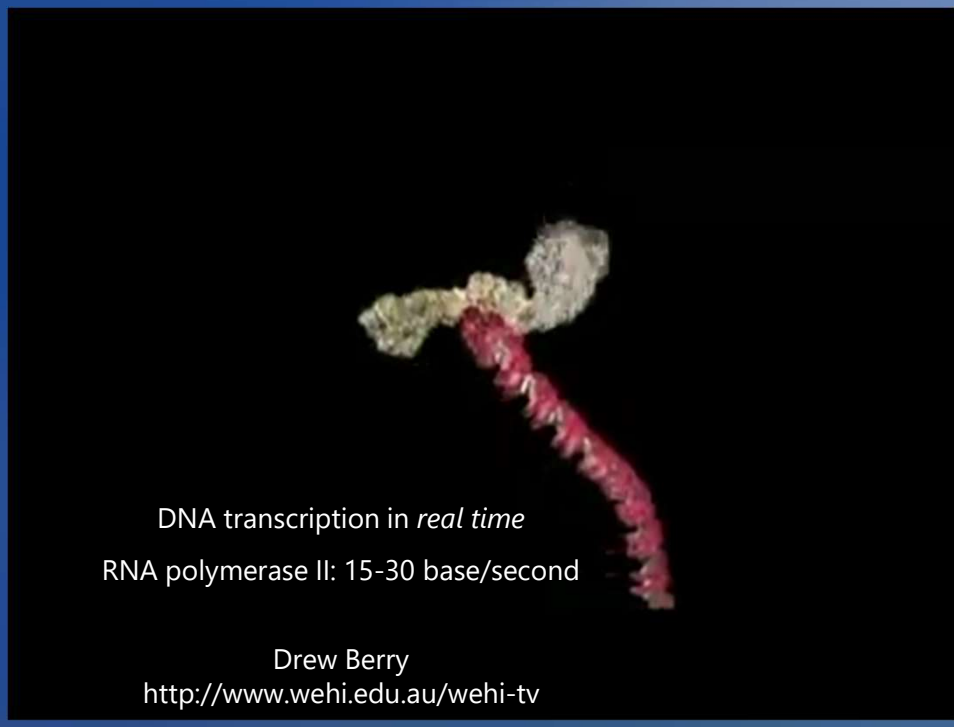
DNA Benchmarks



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)



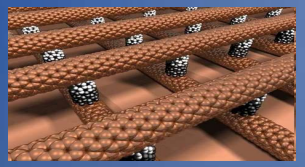
DNA transcription in *real time*

RNA polymerase II: 15-30 base/second

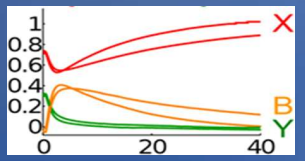
Drew Berry
http://www.wehi.edu.au/wehi-tv

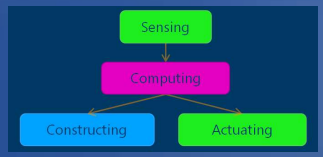
One molecule to rule them all

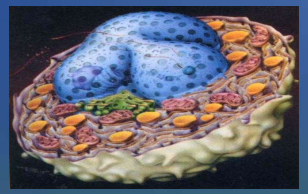
- There are many, many nanofabrication techniques and materials



- But only DNA (and RNA) can:
  - Organize ANY other matter [caveats apply]
  - Execute ANY kinetics [caveats: up to time scaling]
  - Assemble Nano-Control Devices
  - Interface to Biology







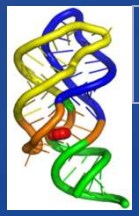
H.Lodish & al. Molecular Cell Biology 4th ed.

The rebranding 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

Building Nano-Control Devices

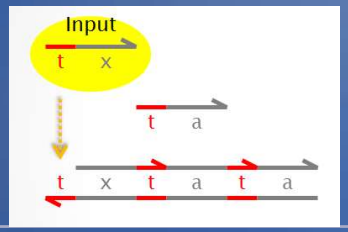
All the components of nanocontrollers can already be built entirely and solely with DNA, and interfaced to the environment



DNA Aptamers

Sensing

Computing

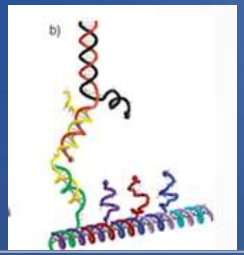


DNA Logical Gates

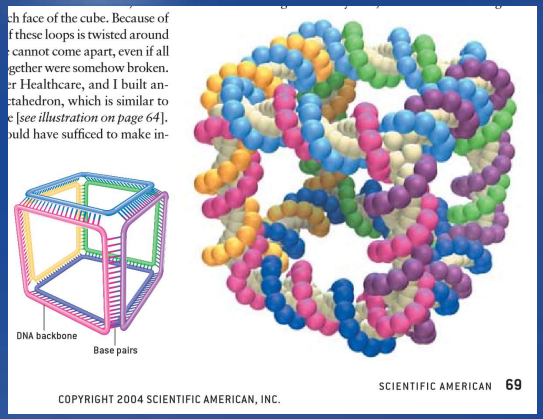
Constructing

Actuating

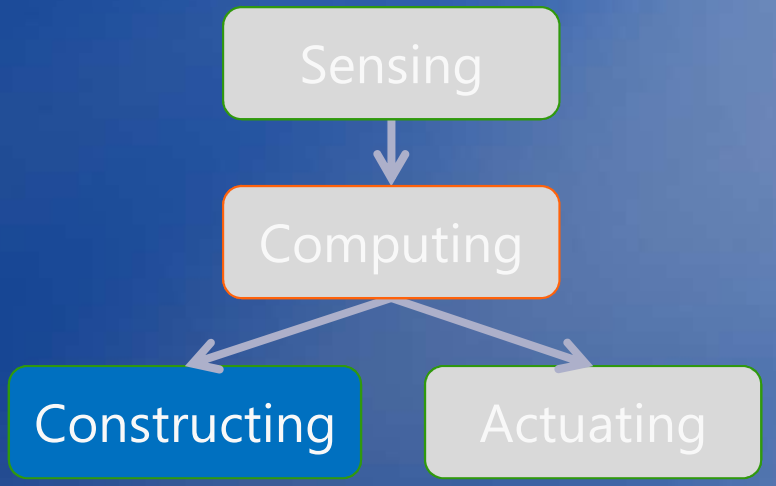
Self-assembling DNA Tiles



DNA Walkers & Cages



Constructing



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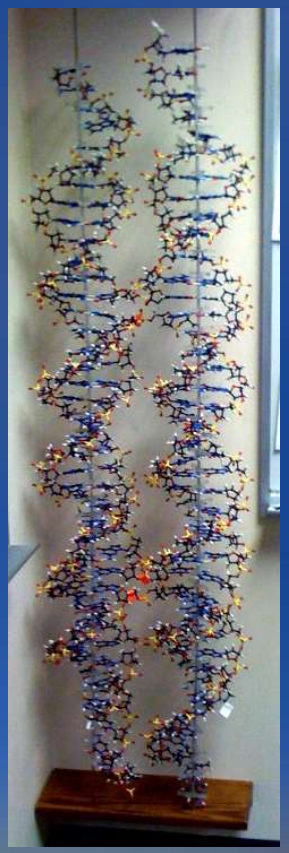
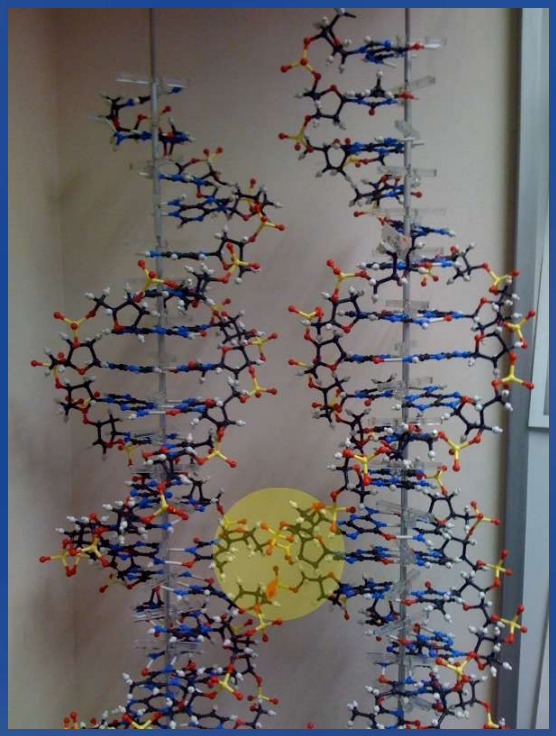
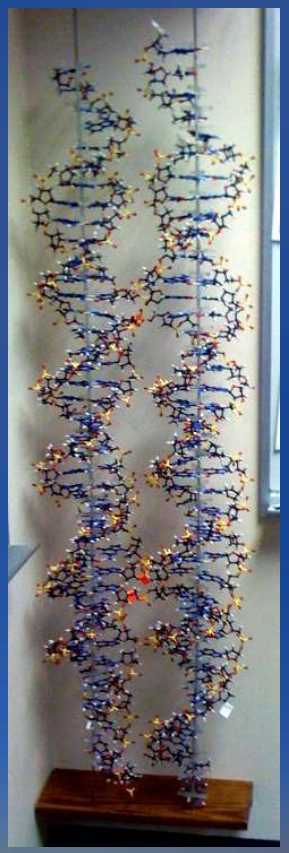
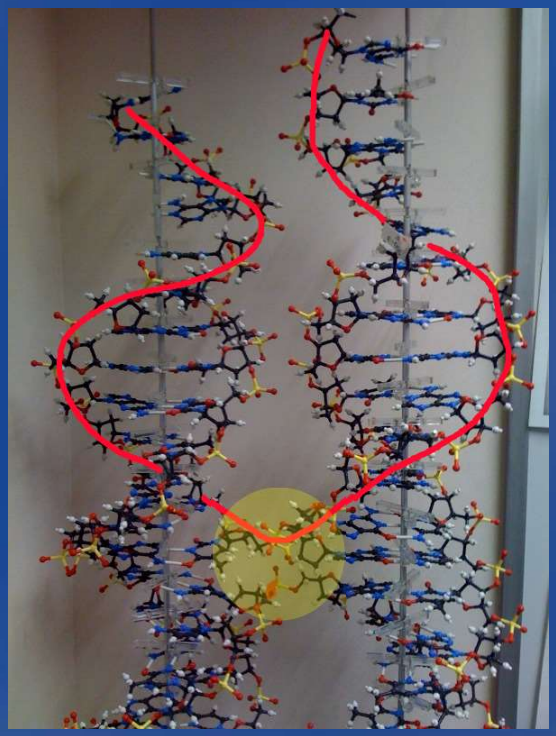




the dawn of structural DNA nanotechnology

Crosslinking





the dawn of structural DNA nanotechnology

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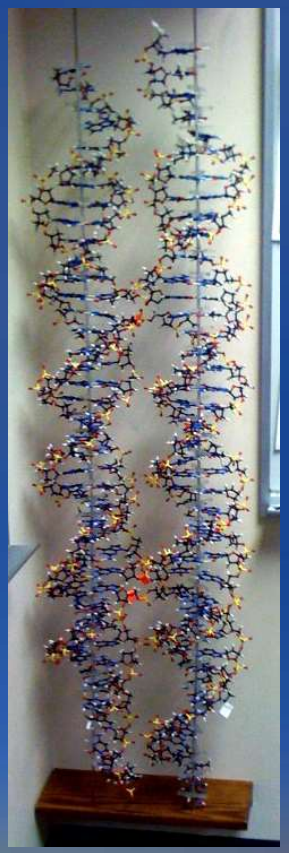

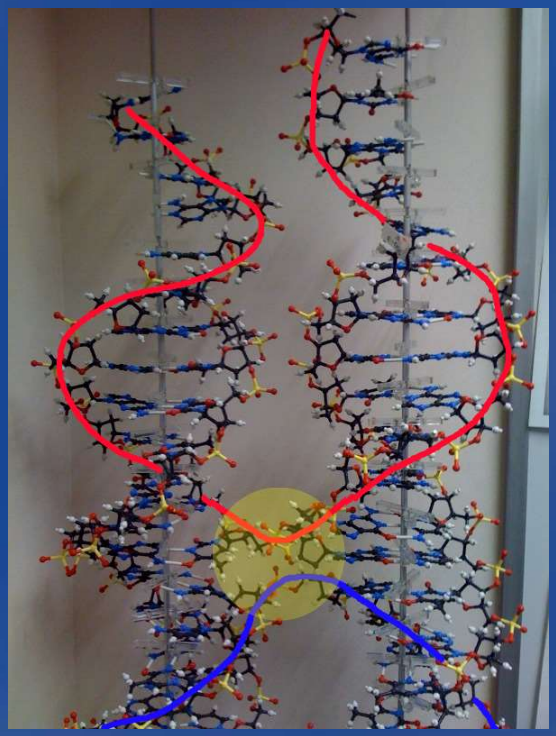

the dawn of structural DNA nanotechnology

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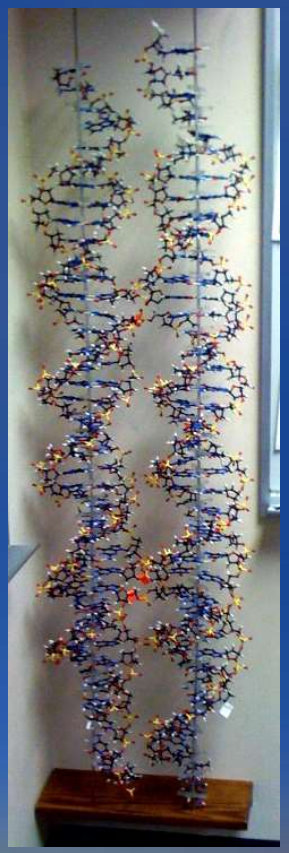

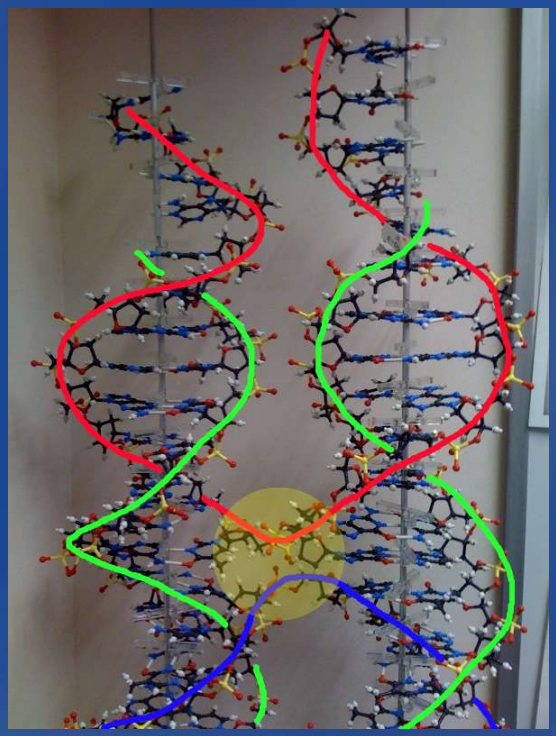

the dawn of structural DNA nanotechnology

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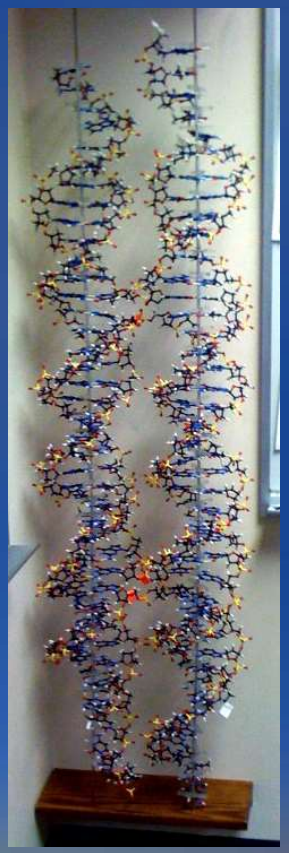
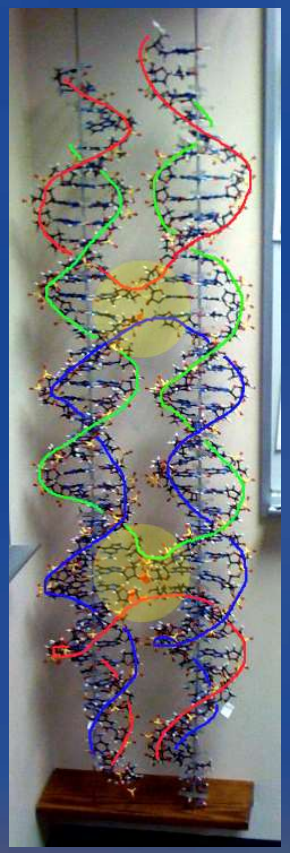
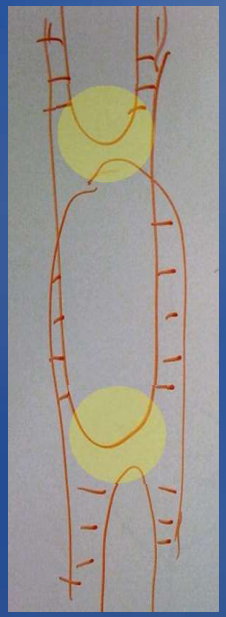


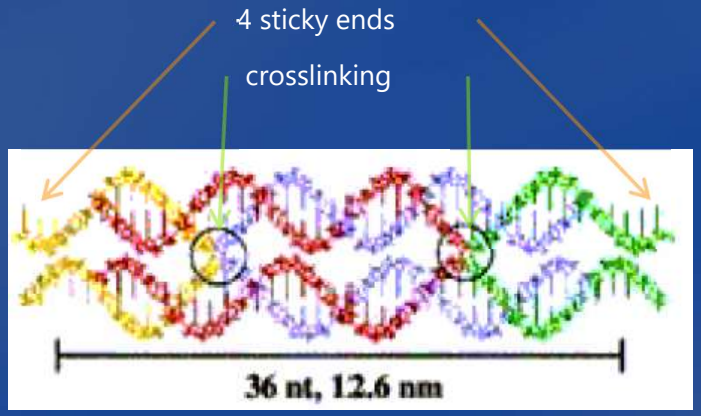


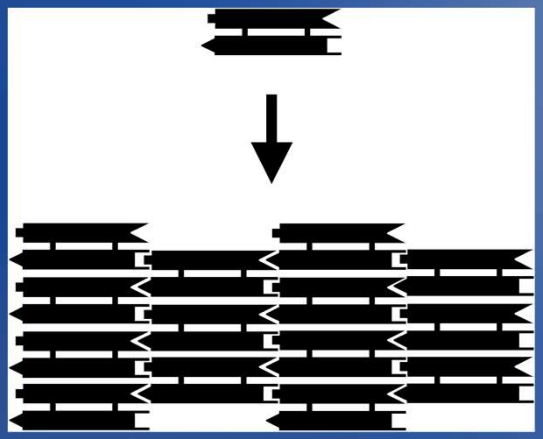
In nature, crosslinking is deadly (blocks DNA replication).

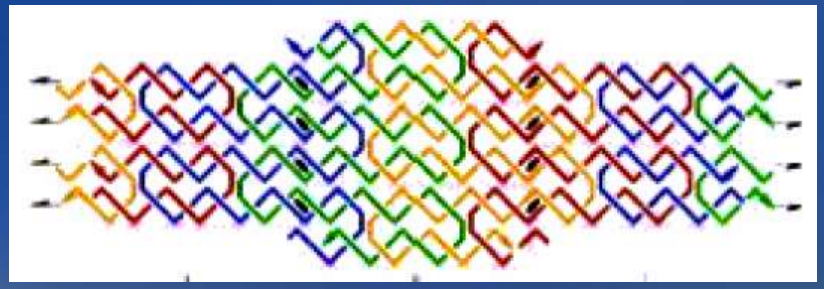


In engineering, crosslinking is the key to using DNA as a construction material.

DNA Tiling



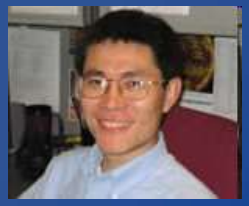




Construction and manipulation of DNA tiles in free space

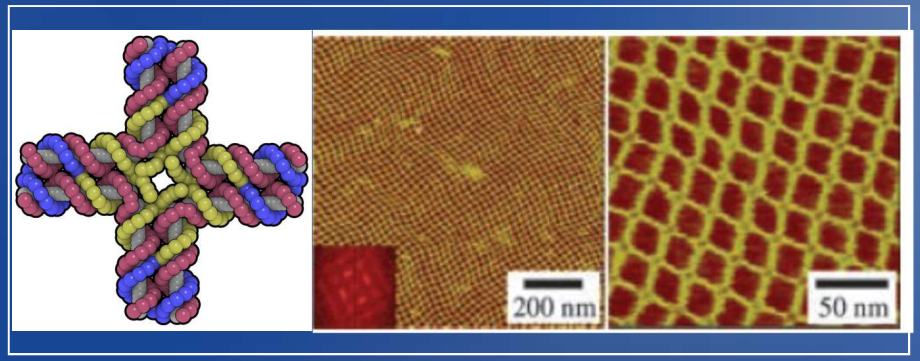
Pankhudi

2D DNA Lattices

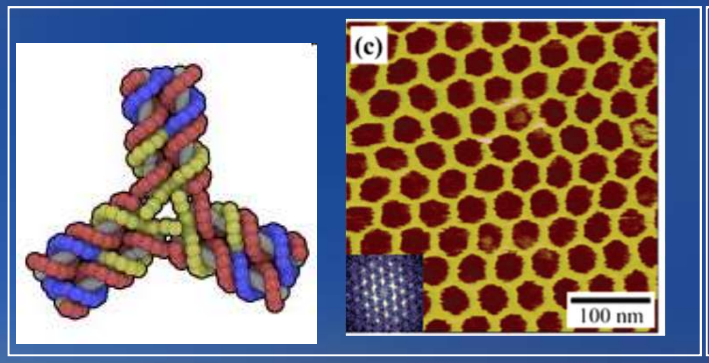


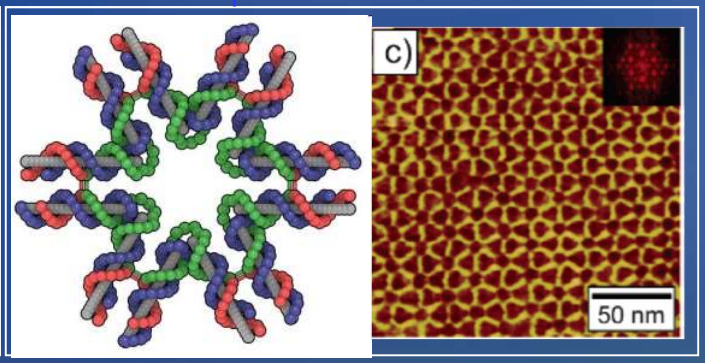
Chengde Mao

Purdue University, USA



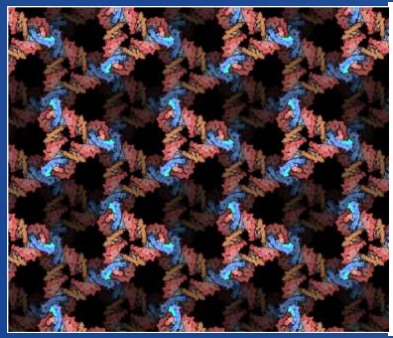
N-point Stars



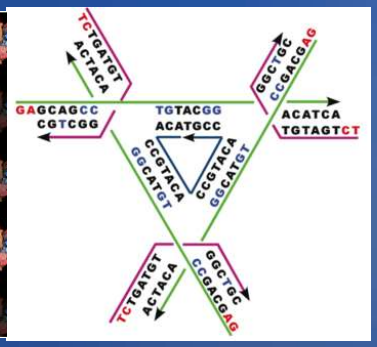


3D DNA Structures

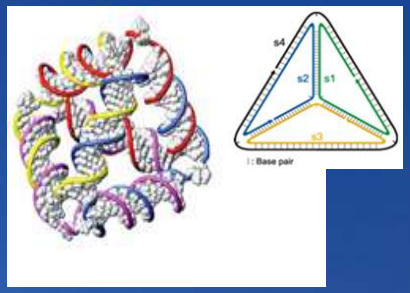
Ned Seeman
NYU



3D Cyrstal

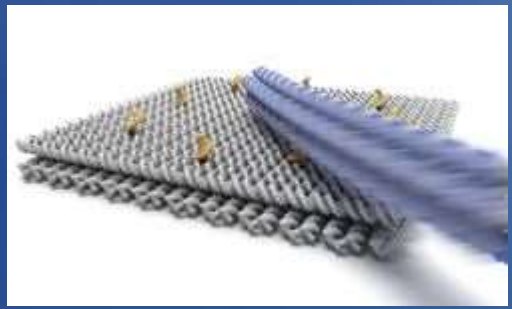


Andrew Tuberfield
Oxford



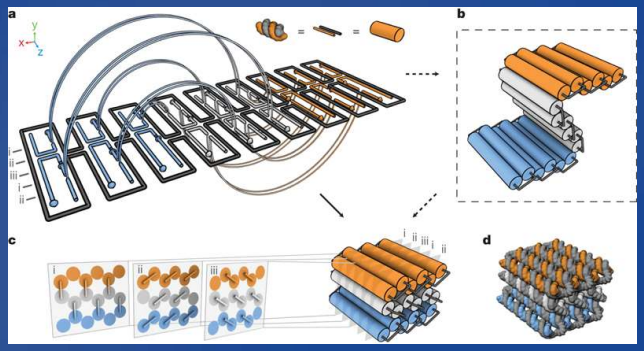
Tetrahedron

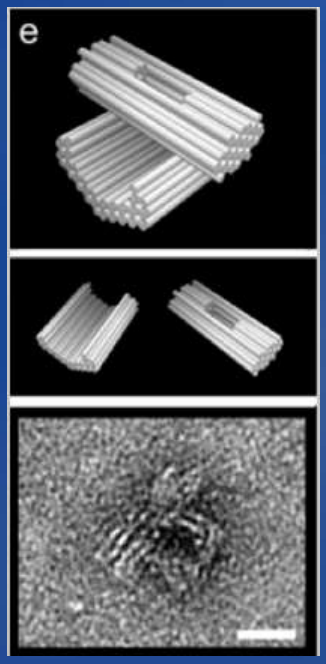
Friedrich Simmel
Munich

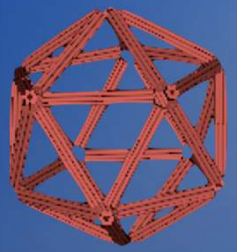


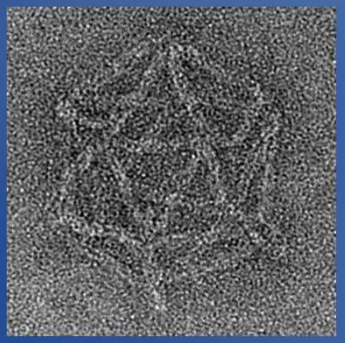
Robotic Arm

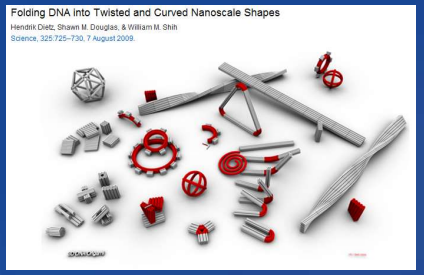
CADnano











William Shih
Harvard

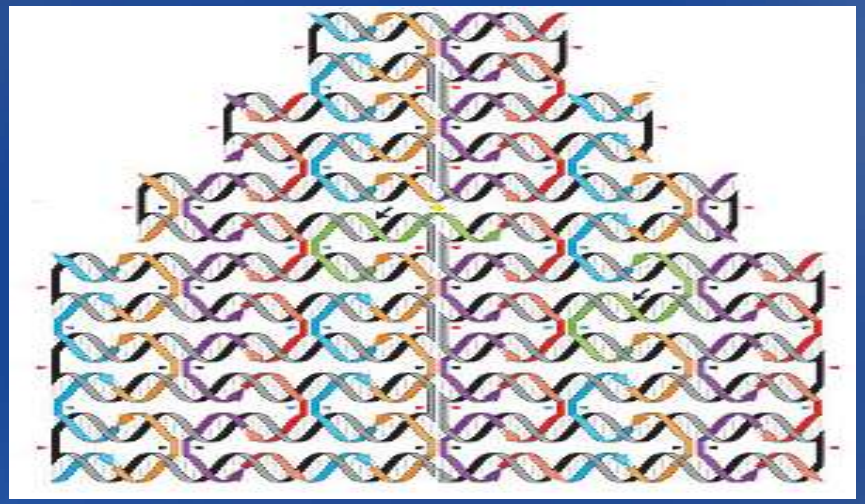
https://www.youtube.com/watch?v=Ek-FDPymyyg

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

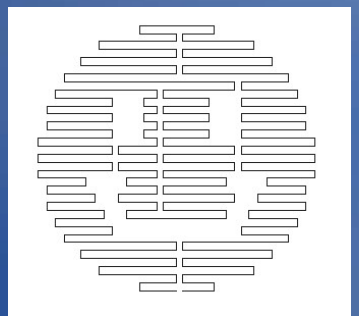
Folding long (7000bp) naturally occurring (viral) ssDNA via lots of short 'staple' strands that constrain it

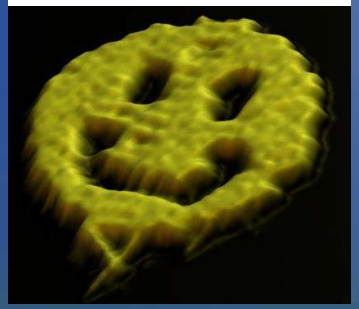
Paul W K Rothemund
California Institute of Technology



PWK Rothemund, *Nature* 440, 297 (2006)

Black/gray: 1 long viral strand (natural DNA)
Color: many short staple strands (synthetic DNA)

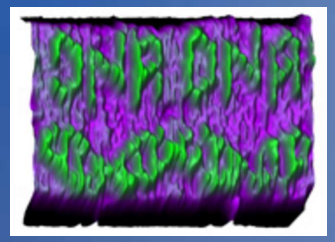




Paul Rothemund's "Disc with three holes" (2006)

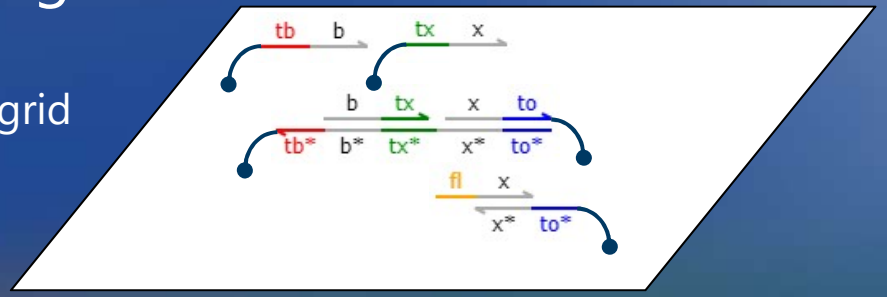
DNA Circuit Boards

- DNA origami are arrays of uniquely-addressable locations
  - Each staple is different and binds to a unique location on the origami
  - It can be extended with a unique sequence so that something else will attach uniquely to it.



Some staples are attached to "green blobs" (as part of their synthesis) Other staples aren't

- More generally, we can bind "DNA gates" to specific locations
  - And so connect them into "DNA circuits" on a grid
  - Only neighboring gates will interact

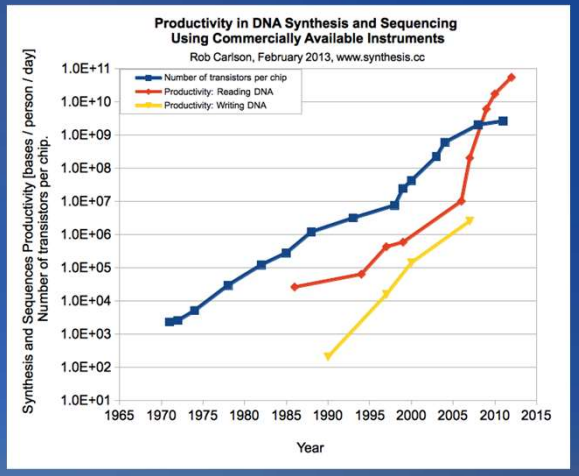


Dalchau, Chandran, Gopalkrishnan, Reif, Phillips. 2014

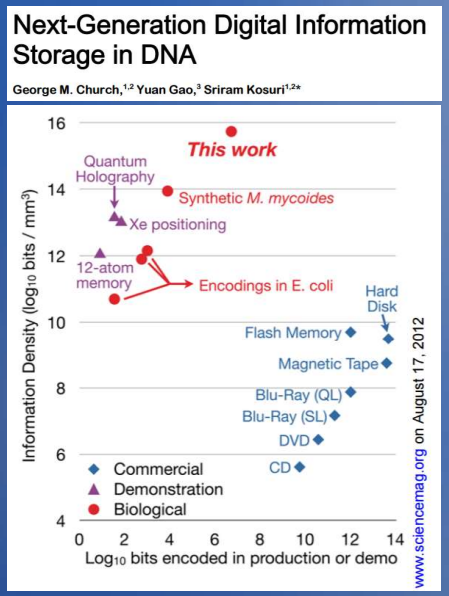
DNA Storage (Read/Write)

Information-rich physical structures can be used for storage.

DNA has a data density of 140 exabytes (1.4×10^{20} bytes) per mm^3 compared to state-of the art storage media that reaches ~500 megabytes (5×10^{8} bytes) per mm^3
DNA has been shown to be stable for millions of years



The Pace and Proliferation of Biological Technologies
March 4, 2004 by Rob Carlson



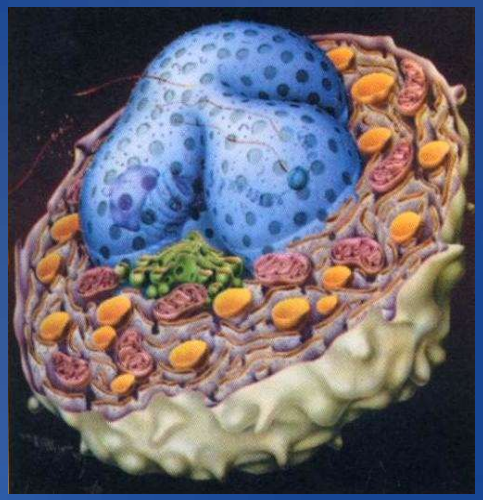
We have machines that can read (sequence) and write (synthesize) DNA. The Carslon Curve of "productivity" is growing much faster than Moore's Law.

Cost of sequencing is decreasing rapidly ($1000 whole human genome), while cost of synthesis is decreasing very slowly.
[Rob Carlson, www.synthesis.cc]

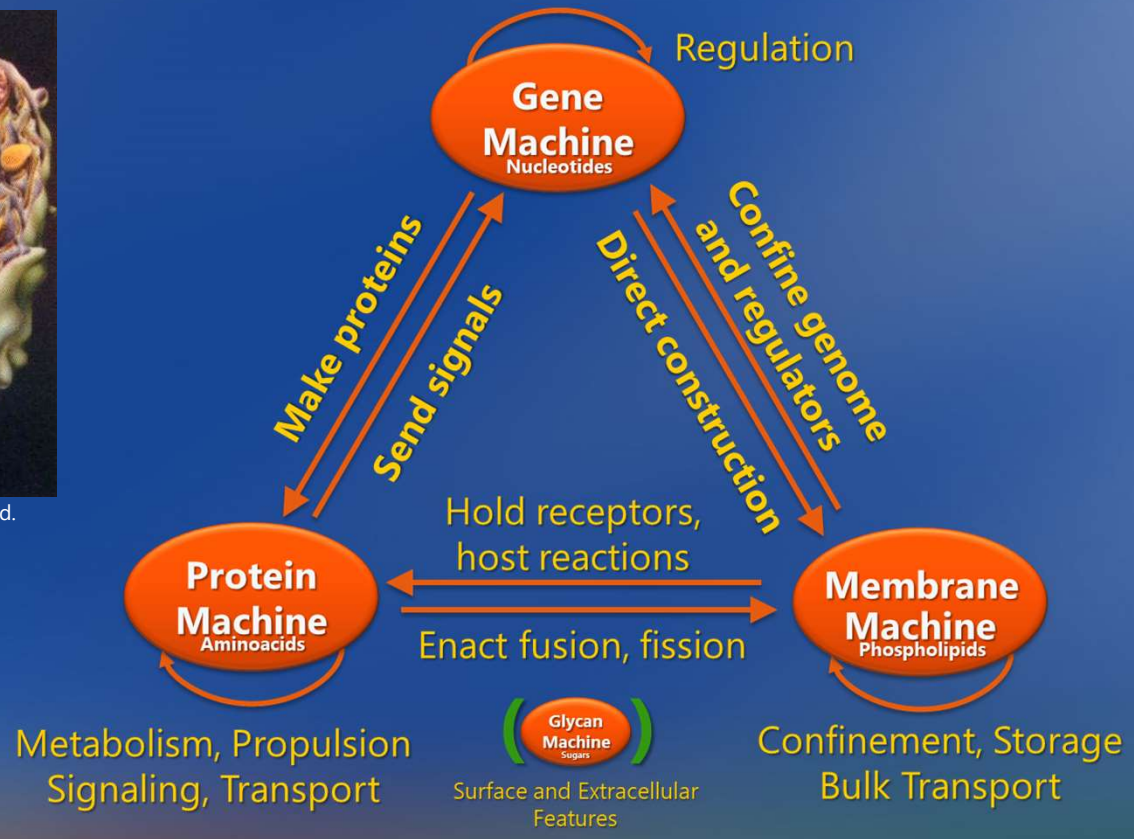
Molecular Programming:
The Biological Aspect

Biological systems are already
'molecularly programmed'

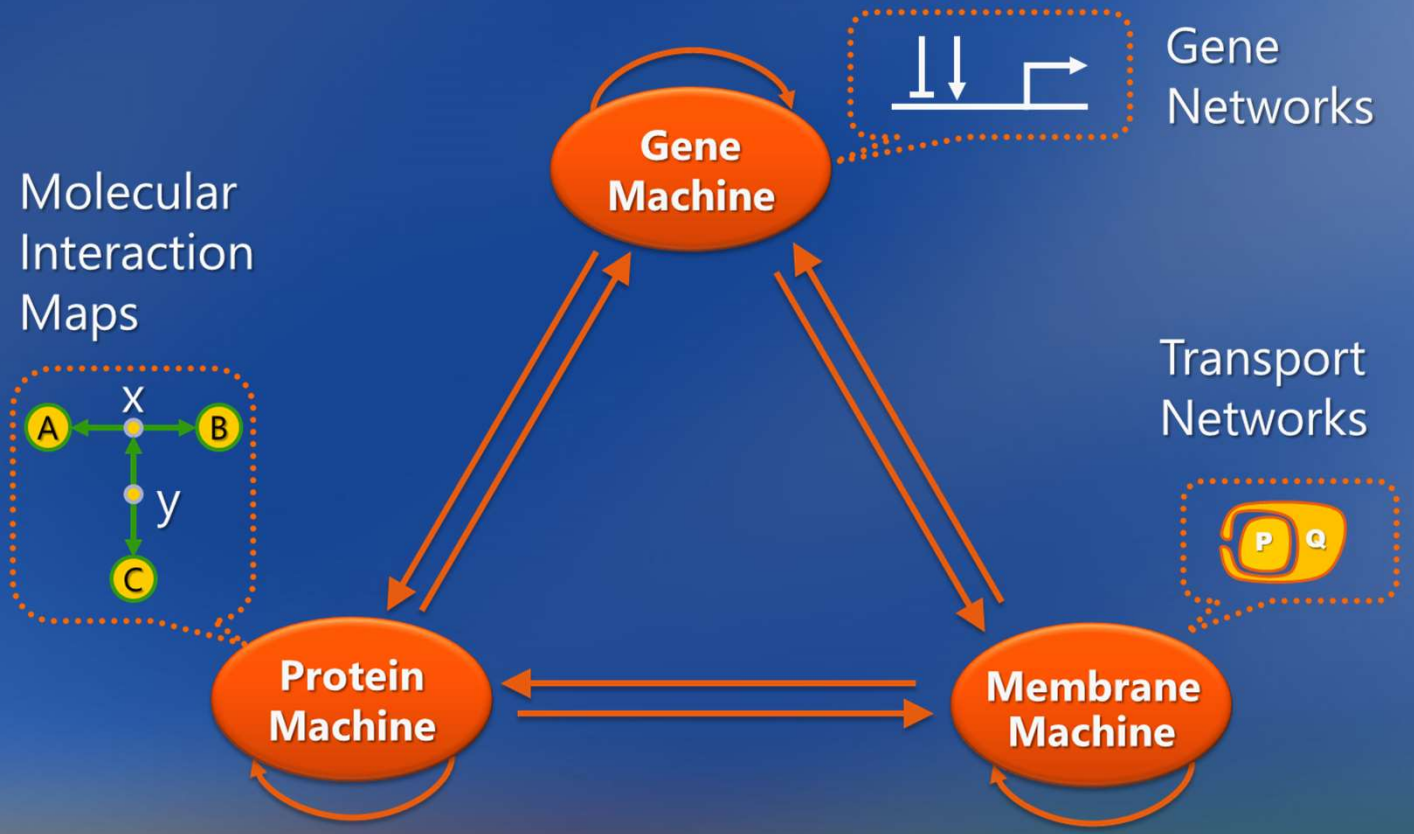
Abstract Machines of Biology



H.Lodish & al. Molecular Cell Biology 4th ed.



Biological Languages



Interfacing to Biology

- A doctor in each cell

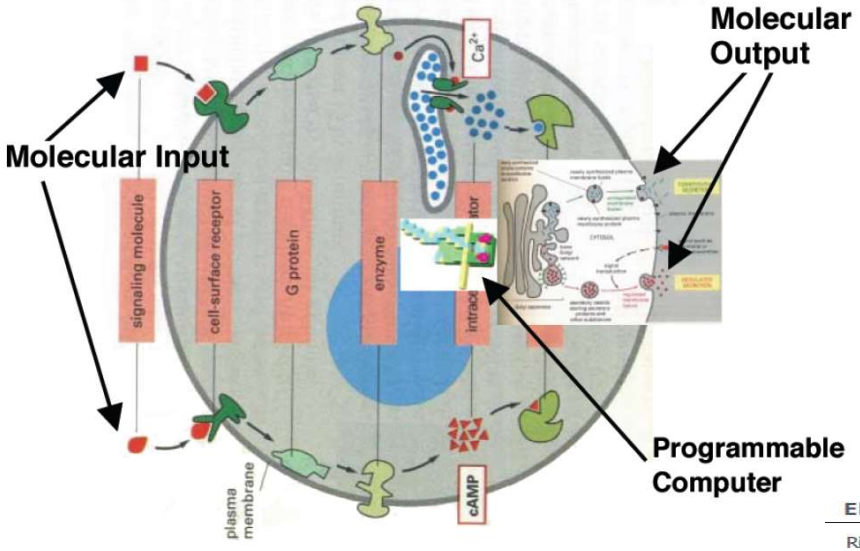


Fig. 1 Medicine in 2050: "Doctor in a Cell"

Ehud Shapiro

Rivka Adar
Kobi Benenson
Gregory Linshitz
Aviv Regev
William Silverman

Molecules and computation

~2002

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 Programming:
The Execution Aspect

How do you "run" a molecular program?

Programming Language: Chemistry

- A Lingua Franca between Biology, Dynamical Systems, and Concurrent Languages
- Chemical Reaction Networks
  - $A + B \rightarrow_r C + D$ (the program)
- Ordinary Differential Equations
  - $d[A]/dt = -r[A][B]$ … (the behavior)
- Rich analytical techniques based on Calculus and more recently on stochastic models

Chemical Programming Examples

specification

Y := min(X1, X2)

Y := max(X1, X2)

program

X1 + X2 -> Y

X1 -> L1 + Y
X2 -> L2 + Y
L1 + L2 -> K
Y + K -> 0

max(X1,X2)=
(X1+X2)-min(X1,X2)

(but is not computed "sequentially": it is a form of concurrent computation)

chemical reaction network

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Chemical Reaction Networks

- Finite list of chemical reactions over a finite set of species
  - N.B.: "abstract" species, not specific atoms/molecules that physically exist
- Computationally Powerful
  - Turing-complete up to an arbitrarily small error
- Full Turing Completeness
  - When including complexation (polymerization), which DNA enables (complexation encodes an actual infinity of chemical reactions by finite means)

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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?

DNA Strand Displacement

An "unnatural" use of DNA for emulating *any* system of chemical reactions

Domains

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

oriented DNA single strand

- 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.

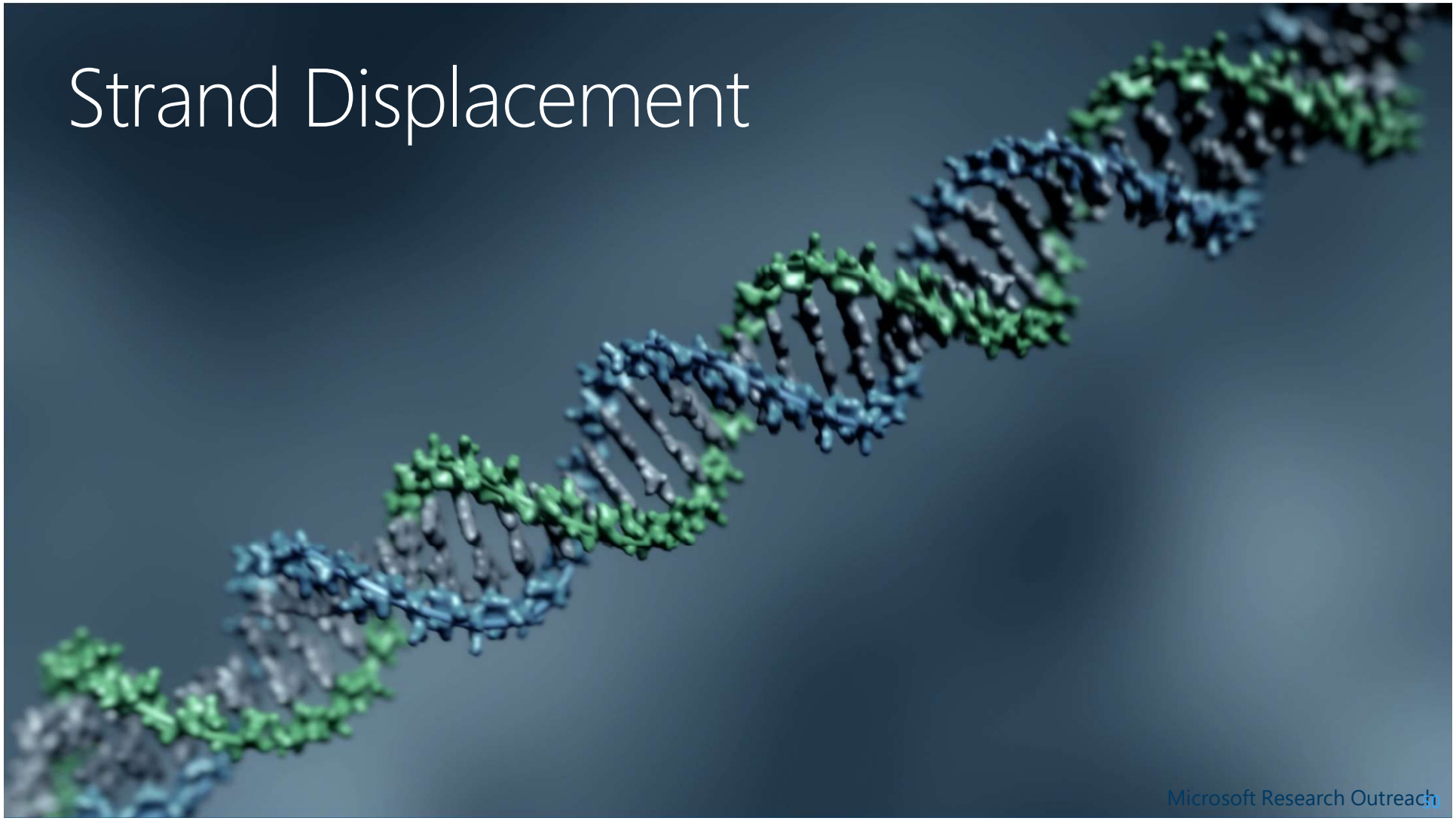
Short Domains

Reversible Hybridization

Long Domains

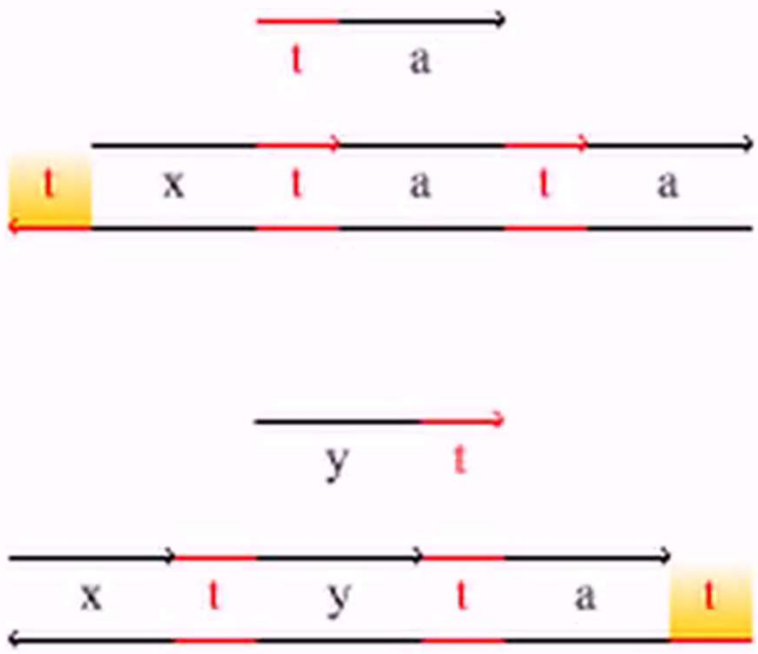
Irreversible Hybridization

Strand Displacement



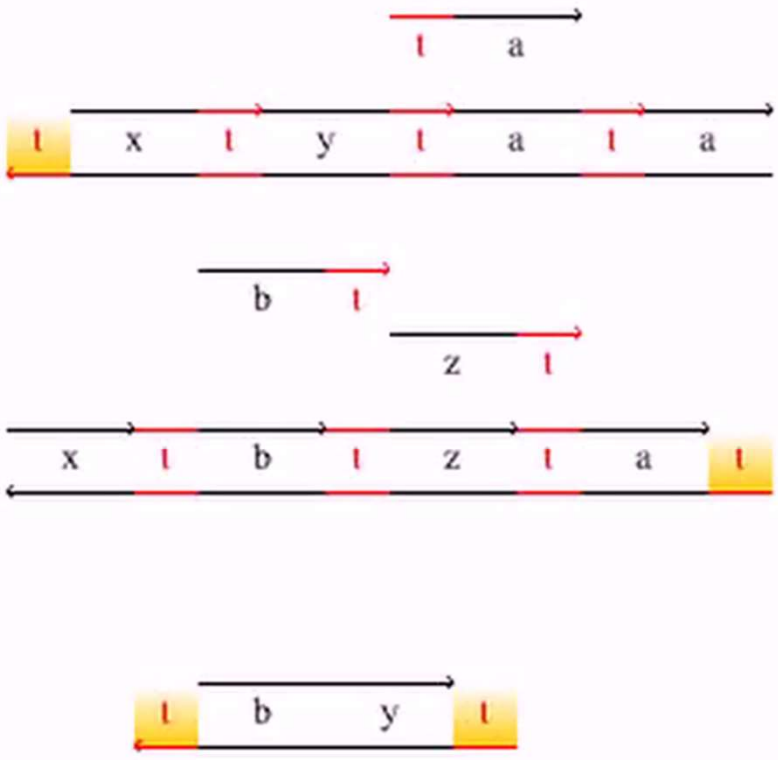
Powered by Sothink

Transducer x → y



Powered by Sothink

Join x+y → z

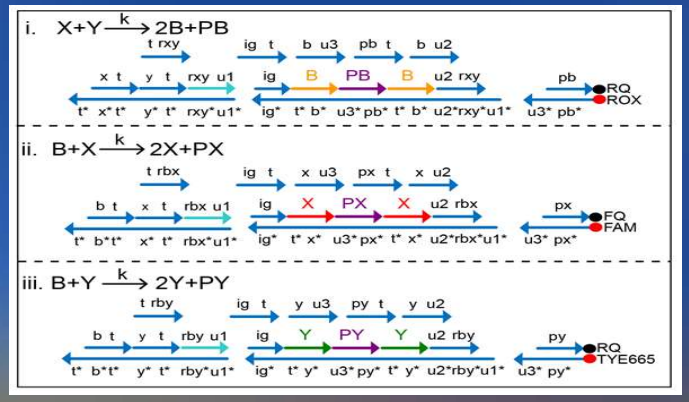


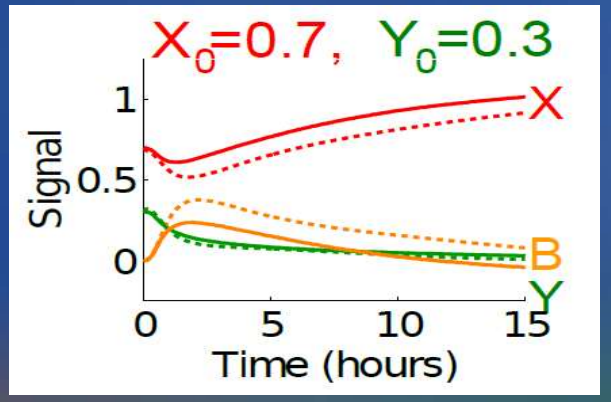
DNA Implementation of the Approximate Majority algorithm

nature nanotechnology

Programmable chemical controllers made from DNA

Yuan-Jyue Chen, Neil Dalchau, Niranjan Srinivas, Andrew Phillips, Luca Cardelli, David Soloveichik & Georg Seelig



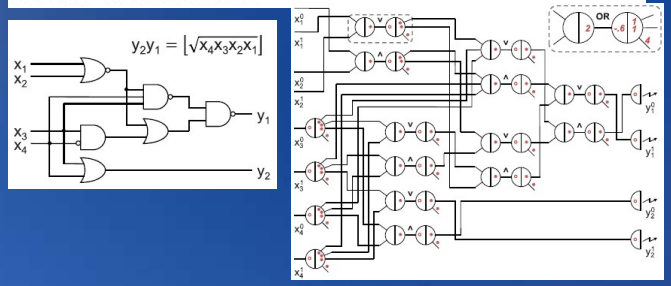


Large-scale Circuits (so far…)

3 JUNE 2011 VOL 332 SCIENCE

Scaling Up Digital Circuit Computation with DNA Strand Displacement Cascades

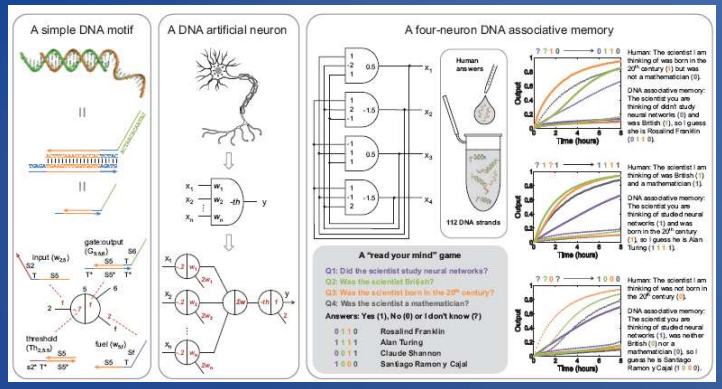
Lulu Qian[1] and Erik Winfree[1,2,3]*



368 | NATURE | VOL 475 | 21 JULY 2011

Neural network computation with DNA strand displacement cascades

Lulu Qian[1], Erik Winfree[1,2,3] & Jehoshua Bruck[3,4]



Scaling up: DNA Circuit Boards

ARTICLES
PUBLISHED ONLINE: 24 JULY 2017 | DOI: 10.1038/NNANO.2017.127
nature nanotechnology

A spatially localized architecture for fast and modular DNA computing

Gourab Chatterjee[1], Neil Dalchau[2], Richard A. Muscat[3], Andrew Phillips[2]* and Georg Seelig[3,4]*

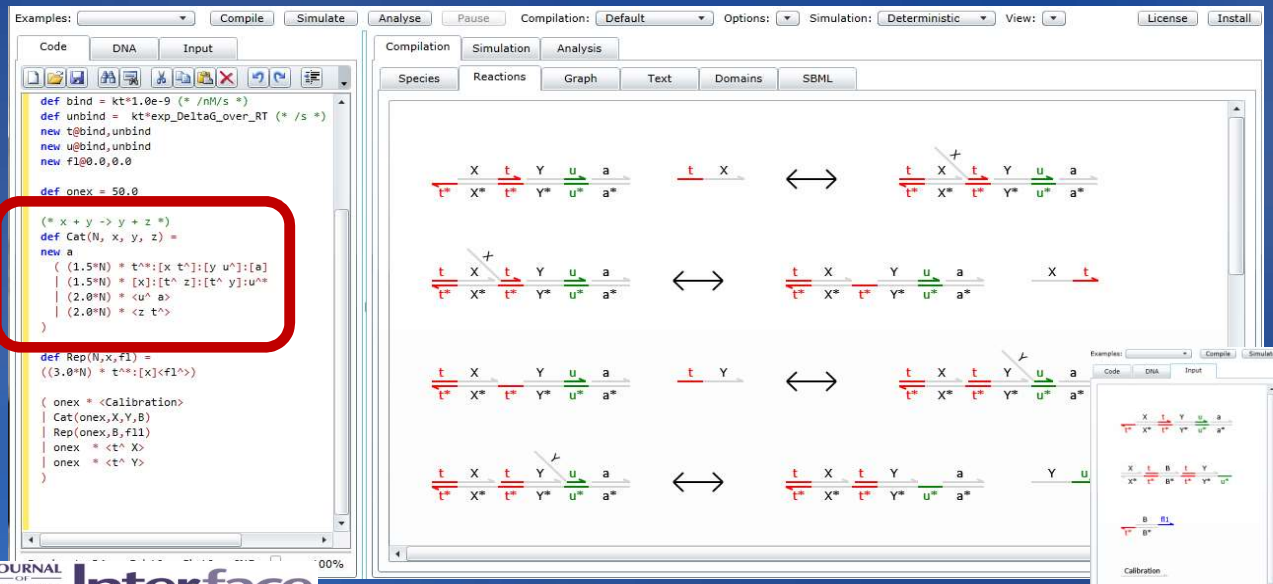
The first computational circuit boards made of DNA
https://www.microsoft.com/en-us/research/blog/researchers-build-nanoscale-computational-circuit-boards-dna

Physical Execution

A wetlab pipeline for Molecular Programming

Computer Aided Design

MSRC Biological Computation Group



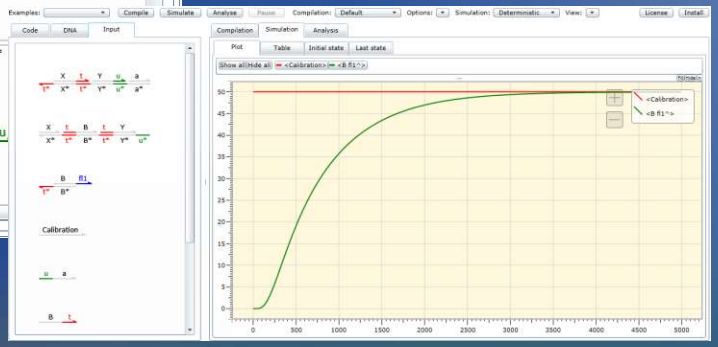
JOURNAL OF THE ROYAL SOCIETY Interface

A programming language for composable DNA circuits

Andrew Phillips and Luca Cardelli

Visual DSD

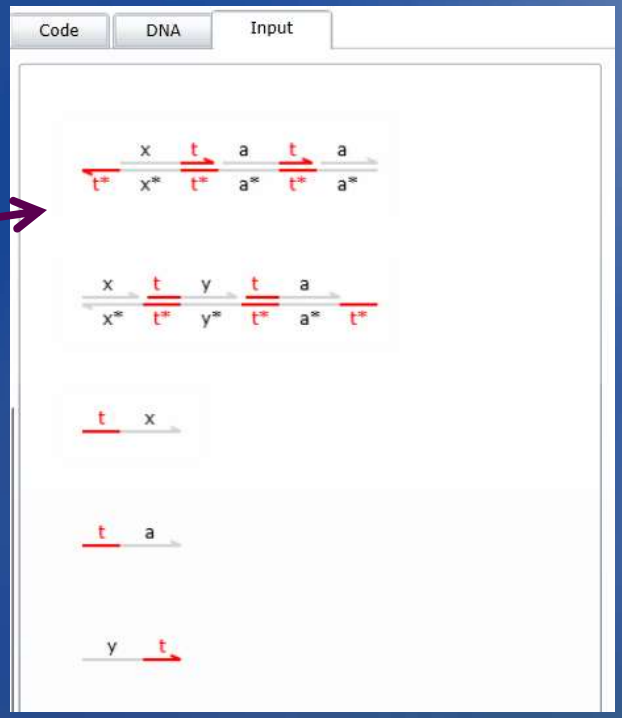
A Development Environment for DNA Strand Displacement



Output of Design Process

- Domain structures
  - (DNA sequences to be determined)

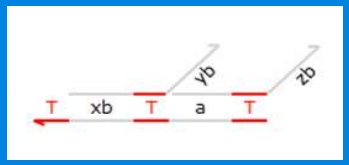
"Ok, how do I run this for real"

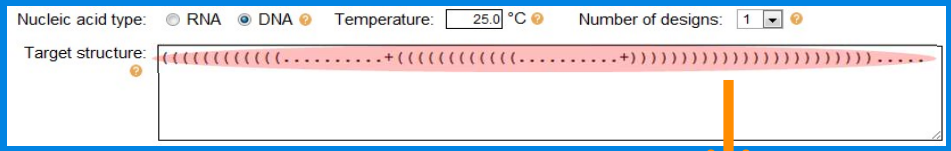


From Structures to Sequences

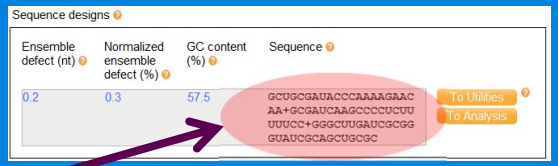
www.nupack.org

DSD Structure → "Dot-Paren" representation

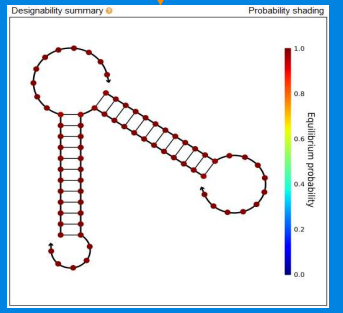




Output Sequences

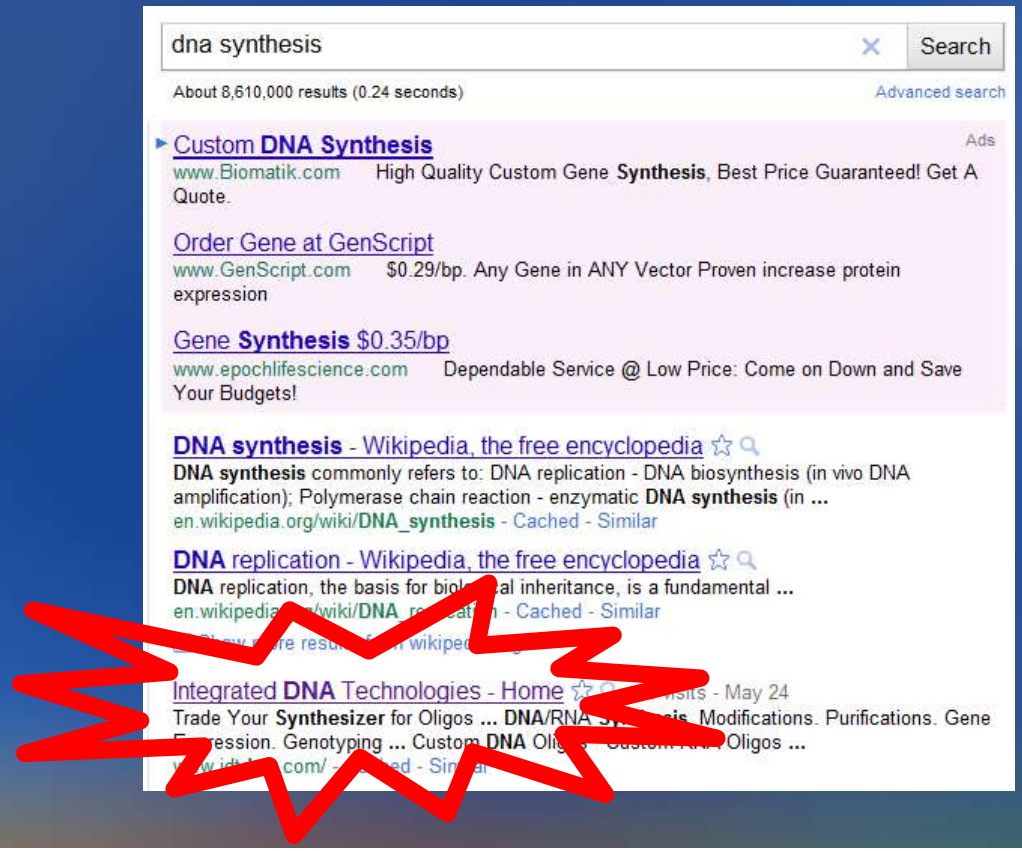


Thermodynamic Synthesis



"Ok, where do I buy these?"

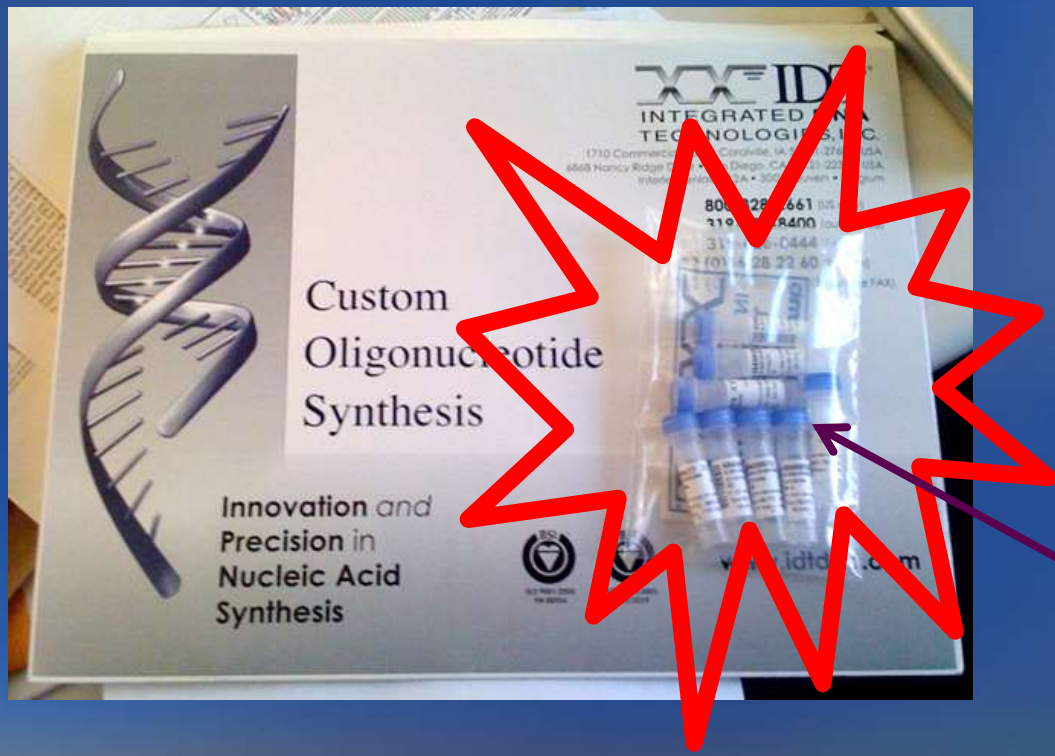
"DNA Synthesis"



From Sequences to Molecules

- Copy&Paste from nupack

Molecules by FedEx

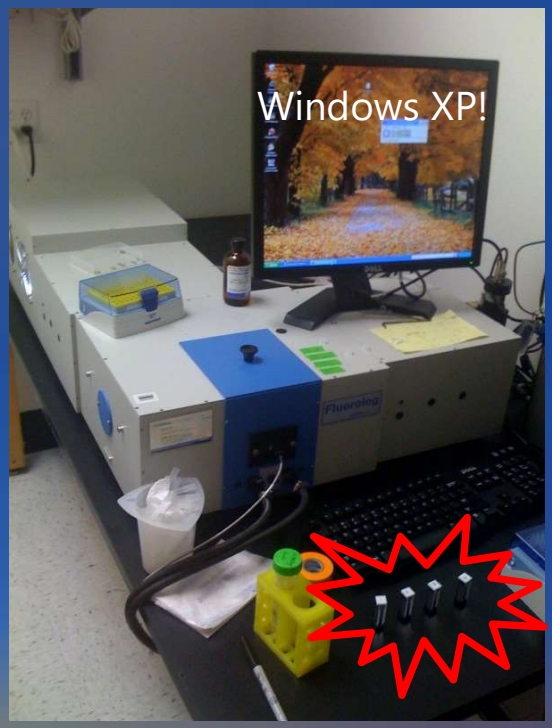


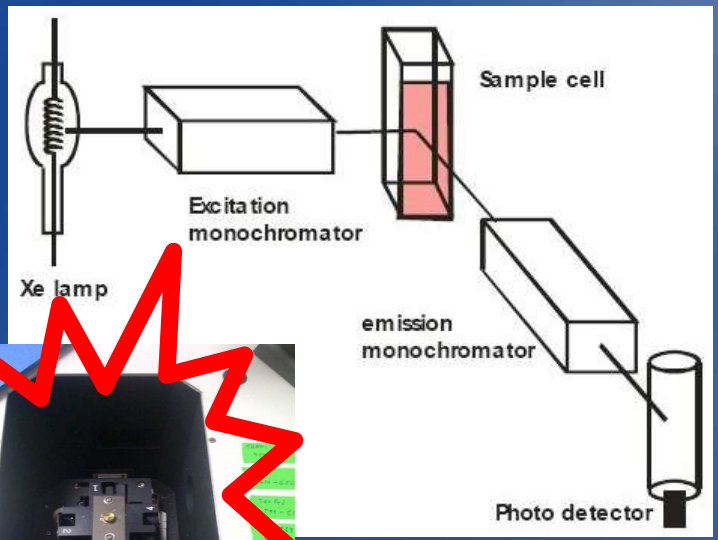
"Ok, how do I run these?"

Add Water

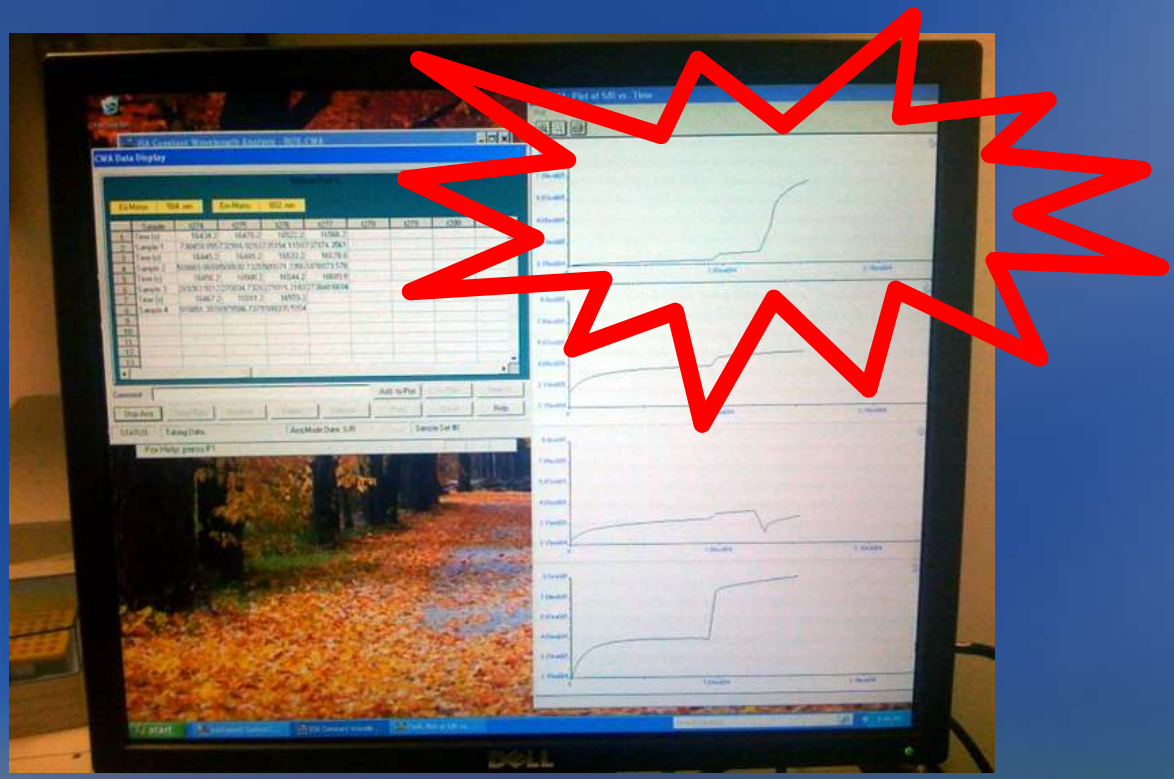
Execute (finally!)

- Fluorescence is your one-bit ‘print’ statement





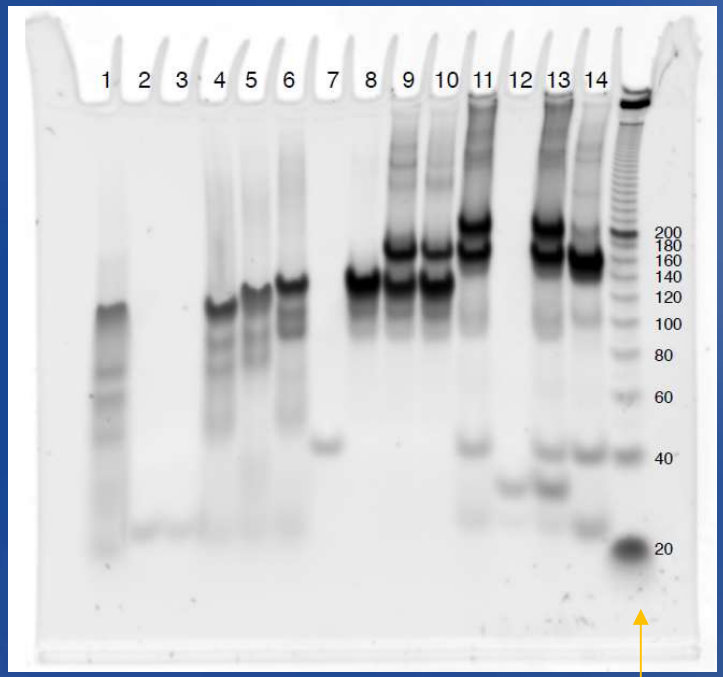
Output



Debugging

- A core dump

polyacrylamide gel electrophoresis



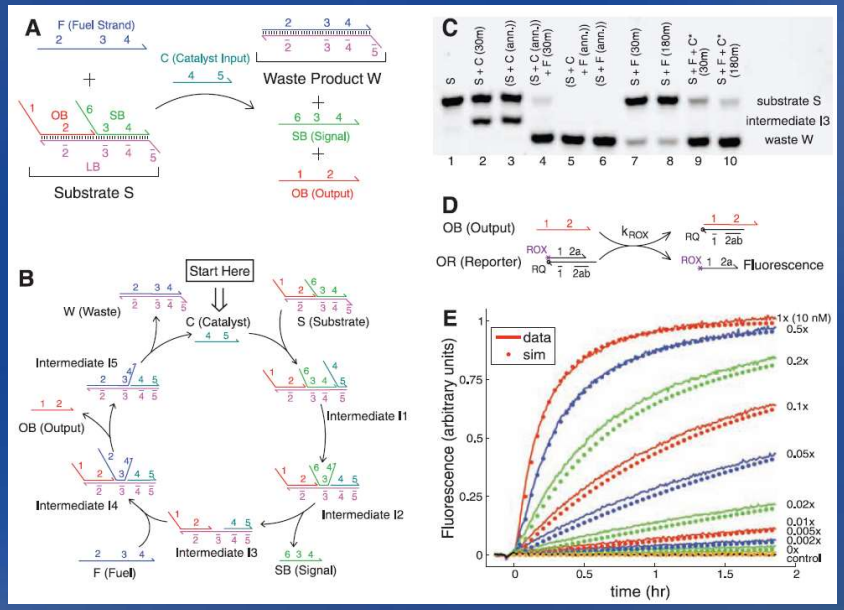
DNA strand length

Various processing stages

Calibration scale

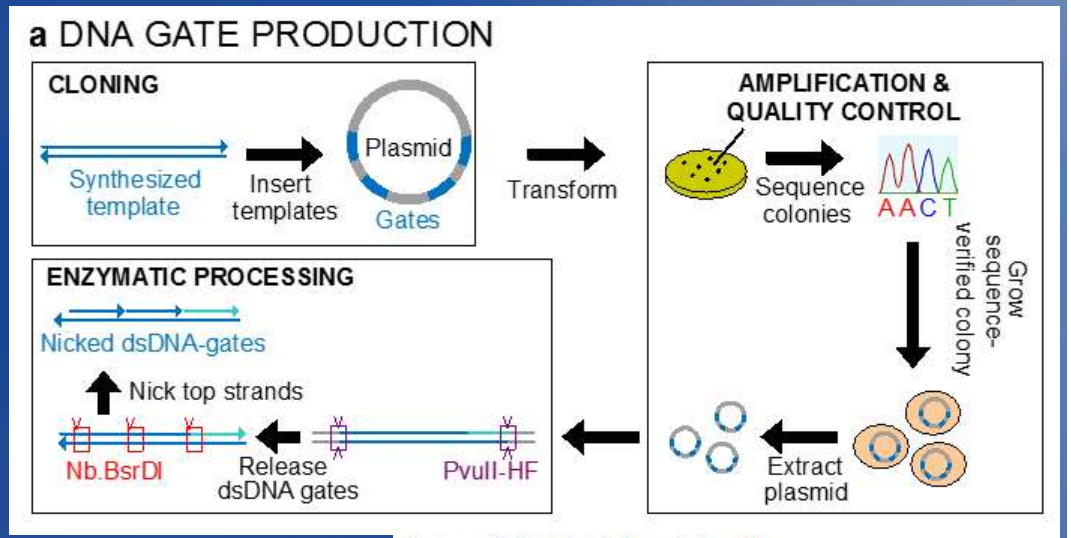
Delivery!

Engineering Entropy-Driven Reactions and Networks Catalyzed by DNA
David Yu Zhang, *et al.*
Science **318**, 1121 (2007);
DOI: 10.1126/science.1148532



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

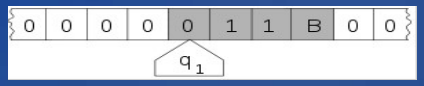
Final Remarks

State of the art

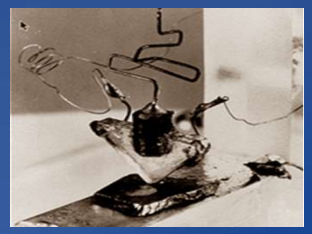
- Building a full software/hardware pipeline for a new fundamental technology
  - Mathematical Foundations [~ concurrency theory in the 80's]
  - Programming Languages [~ software engineering in the 70's]
  - Analytical Methods and Tools [~ formal methods in the 90's]
  - Device Architecture and Manufacturing [~ electronics in the 60's]
- To realize the potential of Molecular Programming
- "With *no alien technology*" [David Soloveichik]
- We have some good strategies. Device design is now largely a 'software problem' but with a significant 'engineering scaleup and integration' problem

A Brief History of DNA

Turing Machine, 1936

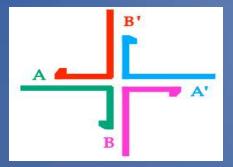


Transistor, 1947

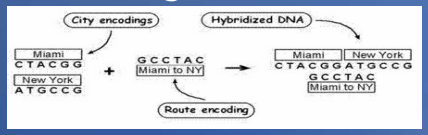


DNA, -3,800,000,000

Structural DNA Nonotech, 1982



DNA Algorithm, 1994



Computer programming

Systematic manipulation of information

Systematic manipulation of matter

Molecular programming

20th century

21th century

Resources

- DNA Computing and Molecular Programming Conference - incarnations since 1995
  http://www.dna-computing.org/
- Molecular Programming Project (Caltech - U.W. - Harvard - UCSF)
  http://molecular-programming.org/ (2008-2018 NSF Expeditions in Computing)
- Georg Seelig's DNA Nanotech Lab at U.W. CS&E
  http://homes.cs.washington.edu/~seelig/
- Biological Computation Group at Microsoft
  https://www.microsoft.com/en-us/research/group/biological-computation/

Questions?

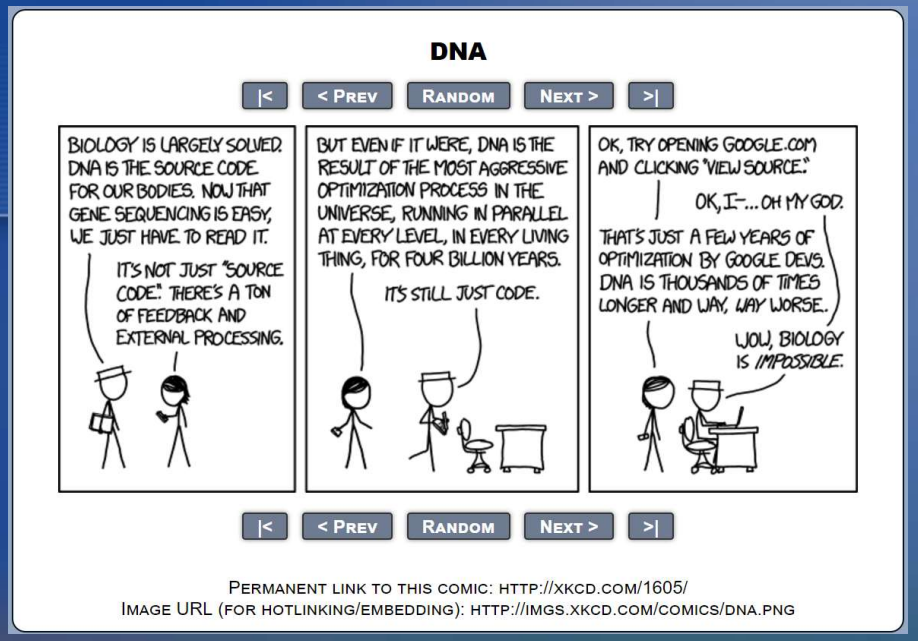

DNA
|< < Prev Random Next > >|
BIOLOGY IS LARGELY SOLVED. DNA IS THE SOURCE CODE FOR OUR BODIES. NOW THAT GENE SEQUENCING IS EASY, WE JUST HAVE TO READ IT.
IT'S NOT JUST "SOURCE CODE." THERE'S A TON OF FEEDBACK AND EXTERNAL PROCESSING.
BUT EVEN IF IT WERE, DNA IS THE RESULT OF THE MOST AGGRESSIVE OPTIMIZATION PROCESS IN THE UNIVERSE, RUNNING IN PARALLEL AT EVERY LEVEL, IN EVERY LIVING THING, FOR FOUR BILLION YEARS.
IT'S STILL JUST CODE.
OK, TRY OPENING GOOGLE.COM AND CLICKING "VIEW SOURCE."
OK, I-... OH MY GOD.
THAT'S JUST A FEW YEARS OF OPTIMIZATION BY GOOGLE DEVS. DNA IS THOUSANDS OF TIMES LONGER AND WAY, WAY WORSE.
WOW, BIOLOGY IS IMPOSSIBLE.
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Image URL (for hotlinking/embedding): http://imgs.xkcd.com/comics/dna.png