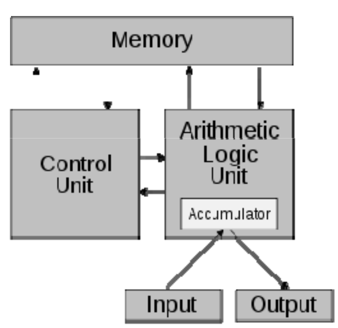
Computing with DNA
&
Review and Study Suggestions

Wednesday, April 29, 2009

1

von Neumann Architecture

- Refers to the existing computer architectures consisting of
  - a processing unit
  - a single separate storage structure to hold both instructions and data
- Implements a Turing Machine



2

DNA Computing

- Existing genetic engineering tools can slice, create, and rebuild DNA sequences:
  - Custom sequences can be made "to order".
  - Duplication, replication, and selection operations exist for DNA sequences.
- Many ($\approx 10^{15}$) different DNA sequences can be operated on at the same time in a single test tube.
- DNA acts as memory; computation is carried out by complementary bases

How can DNA manipulations lead to computation?

In 1993, Leonard Adleman (USC) proposed DNA computing

- Storage
  - DNA and binary strings encode information
- Alphabet
  - DNA has a 4-letter alphabet: A, C, G, T
  - Computers have a 2-letter alphabet: 0, 1
- Operations
  - We can synthesize any strand of DNA
  - We can generate any binary sequence

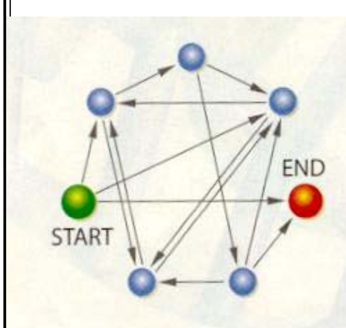
How can DNA strings carry out computation?

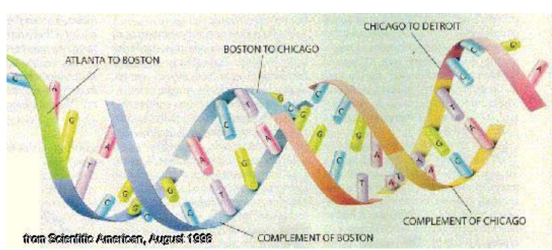
DNA strings attach to each other (twist into a double helix) if they have complementary elements in corresponding positions.

- A and T are complements
- C and G are complements

Adleman devised a DNA manipulation technique to solve the Hamiltonian Path (HP) problem.

- DNA sequences were created
- They allowed the execution of trillions of operations in parallel





From Adleman's '98 Scientific American paper

Adleman's first DNA computation operated on a 7-node, 14-edge directed graph.

The algorithm is probabilistic.

- With high probability it will generate a Hamiltonian path, if one exists.

It is a hard-wired, not a programmed solution.

- The setup is for one graph.
- It needs to be repeated from scratch for another graph.

Demonstrated feasibility and started a new area:
DNA Computing

Overview of the HP DNA algorithm

Given is a directed graph G and nodes s and t

1. Generate DNA sequences to represent nodes and edges.
2. Generate DNA strands representing paths.
3. From among the paths, select a path that:
    - begins at s and ends at t
    - has length $n-1$
    - is a simple path

Encoding of nodes and edges

For every node v_i:

generate a random DNA strand R_i of length 20

For every edge (v_i, v_j):

create the string S(i,j), which consists of the first half of R_i and the second half of R_j.

Example:

v_2 as R_2 = **ATCGAACGTT**TTAACGTAGT

v_3 as R_3 = *TCGAATTACG***TAGAACGTTT**

edge (v_2,v_3) as **TTAACGTAGT***TCGAATTACG*

9 Wednesday, April 29, 2009

Initial conditions

Start node s has strand R_s and end node t has strand R_t

For every edge (s, v_i), create the edge strand consisting of R_s and the first half of R_i

For every edge (v_i, t), create the edge strand consisting of the second half of R_i followed by R_t

Consider a path < s, v_1, v_2, … >

R_s = TTCATTCGCCTTAAAGGACT

R_1 = GTAGTACGTTTCGGCGTAGA

R_2 = ATCGAACGTATTAACGTAGT

TTCATTCGCCTTAAAGGACT**GTAGTACGTTTCGGCGTAGA**ATCGAACGTATTA …

10 Wednesday, April 29, 2009 10

What goes on in the test tube?

- Complement of the node strands – lots of them
- Edge strands – lots of them

DNA strands attach to form double strands if they have complementary elements in the corresponding positions.

Generate

R_s = TTCATTCGCCTTAAAGGACT

R_1 = GTAGTACGTTTCGGCGTAGA

R_2 = ATCGAACGTATTAACGTAGT

What goes into the tube

$c(R_s)$ = AAGTAAGCGGAATTTCCTGA

$c(R_1)$ = CATCATGCAAAGCCGCAACA

$c(R_2)$ = TAGCTTGCATAATTGCATCA

edge (s, v_1): TTCATTCGCCTTAAAGGACTGTAGTACGTT

edge (v_1, v_2): TCGGCGTAGAATCGAACGTA

Reaction

TTCATTCGCCTTAAAGGACTGTAGTACGTTTCGGCGTAGAATCGAACGTA
AAGTAAGCGGAATTTCCTGACATCATGCAAAGCCGCAACATAGCTTGCATAATTGCATC

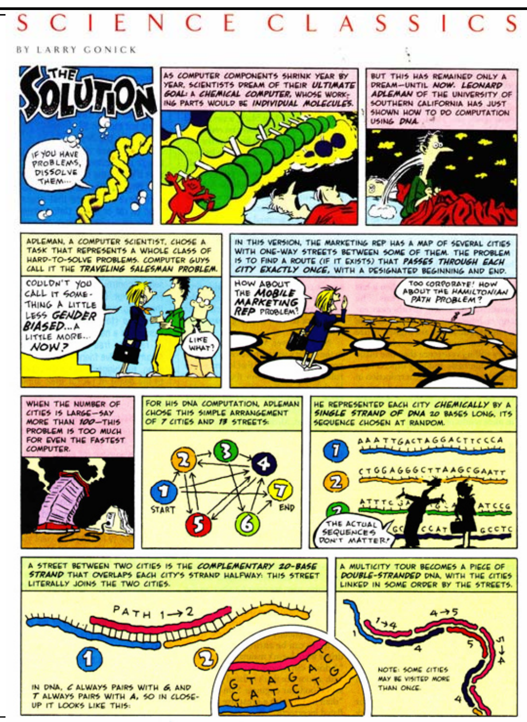
Putting it all together

1. Generate DNA sequences representing nodes and edges.
2. Mix to generate the paths.
3. From among the paths, select a path that
   - begins at s and ends at t
   - has length n−1
   - is a simple path

Step 3 involves operations like merge, amplify, test-if-empty, separate, separate-by-length, separate-by-positions.

13

Wednesday, April 29, 2009



http://www.msri.org/ext/larryg/pages/11.htm

14

Progress since 1993

Other problems were solved using Adleman's approach (formula satisfiability, factoring numbers, combinatorial problems with a large solution space).

It was shown that DNA computation does not provide additional computational power beyond that of a Turing machine.

Between 2002-04, researchers from the Weizmann Institute of Science (Israel) developed a programmable molecular computing machine composed of enzymes (hardware) and DNA molecules (data).

What about quantum computing?

- A quantum computer uses quantum mechanical phenomena - superposition and entanglement - to perform operations on data.
  - Quantum properties are used to represent data and perform operations.
- Quantum computing has the potential to support a new kind on computation
  - A system with n qubits can perform 2^n calculations at one
- The technology supporting quantum computation has not yet been developed

Quantum Computing

- Quantum computers would be different from traditional computers as well as DNA computers.
- A quantum computer could not solve unsolvable problems (like the Halting Problem)
- But, exponential time algorithms may have feasible solutions.
  - Fast integer factorization would break cryptographic systems
  - Security of existing methods for public key encryption (RSA systems) would no longer be guaranteed

17

Wednesday, April 29, 2009

Review and study suggestions

- Exam will have some programming questions, some explain questions
- Sample questions will be posted on Blackboard this week
- Programming questions
  - Write one line statements achieving what is specified
  - Write small programs (like in exam 2)
  - Know how to generate plots/visuals (not Cytoscape)
- Explain Questions
  - Give short answers addressing the point
  - Don't reproduce material from sources

18

Wednesday, April 29, 2009

Review and study suggestions

- Work through lab material and lab problems
  - Understand what the focus of the lab was
  - Read posted solutions
  - Re-solve problems
- Understand code posted in association with lectures
  - Change it, break it …
- Make sure to review …
  - Recursion
  - Graph operations
  - Dictionaries
  - Be able to read class definitions and methods

19

Review and study suggestions

- **Chapters covered from Zelle**
  - 1, 2, 3, 4
  - 6, 7, 8, 11
  - 13 (except 13.3)
- **Software packages (basic uses)**
  - MatPLotLib, VPython, NetworkX, NumPy
- **Learning Python Book**
  - Mainly for looking up material and seeing different examples
  - There are a number of Python features we did not cover

20

Wednesday, April 29, 2009