

CS 466

Introduction to Bioinformatics

Lecture 1

Mohammed El-Kebir

August 26, 2020



Course Staff

Instructor:

- Mohammed El-Kebir (melkebir)
- Office hours: Wednesdays, 3:15-4:15pm via Zoom



Zoom:

- <https://illinois.zoom.us/j/93763998549>

Developing combinatorial algorithms to study all stages of cancer progression.

TA:

- Sarah Christensen (sac2), office hours: Mondays, 3-4pm via Zoom
- Wesley Wei Qian (weiqian3), office hours: Fridays, 9-10am via Zoom

Course Organization

Course website:

www.el-kebir.net/teaching/cs466

Syllabus:

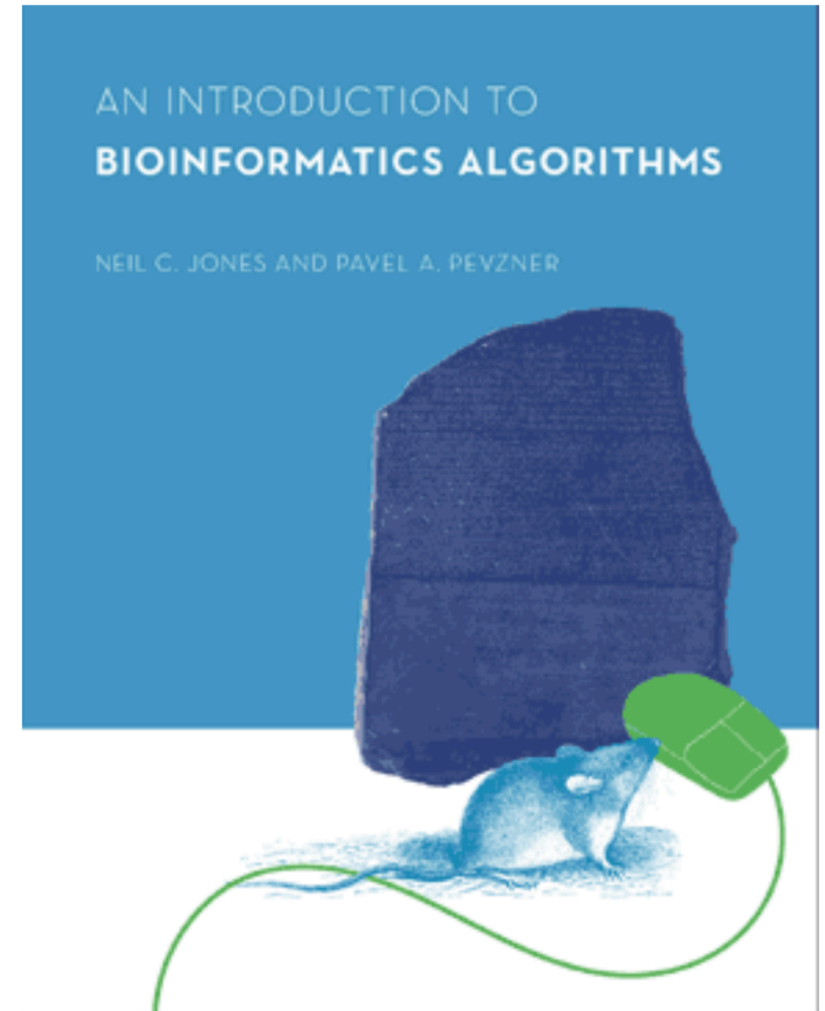
- Prerequisites: CS 225 and its prerequisites
- Textbook

Grading:

- 5 written/programming assignments
- Midterm
- Final
- Research project

Piazza: (please sign up)

- <https://piazza.com/illinois/fall2020/cs466>



Course Objectives

Learn:

- Learn underlying ideas of common algorithms in bioinformatics.
- Learn to translate a biological problem into a computational problem.
- Learn to read scientific papers, propose and conduct independent research.

Not learn:

- Will not learn to run popular bioinformatics packages.
- Will not learn how to program.

Homework Assignments

- 5 homework assignments
- Each homework assignment is a combination of written/programming exercises
- LaTeX highly recommended for homework assignments
- Python for programming exercises

Late policy:

- Students may request one 3-day extension in the semester for full credit
- Late submission within 3 days 80%

Primer on Molecular Biology

Molecular Biology is the field of **biology** that studies the composition, structure and interactions of cellular **molecules** – such as nucleic acids and proteins – that carry out the **biological** processes essential for the cell's functions and maintenance.

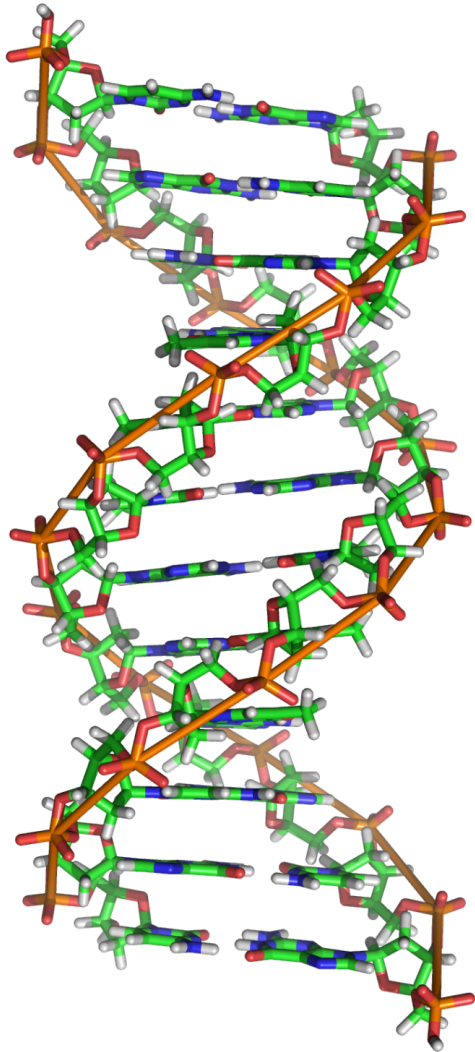
<https://www.nature.com/subjects/molecular-biology>

Cellular molecules:

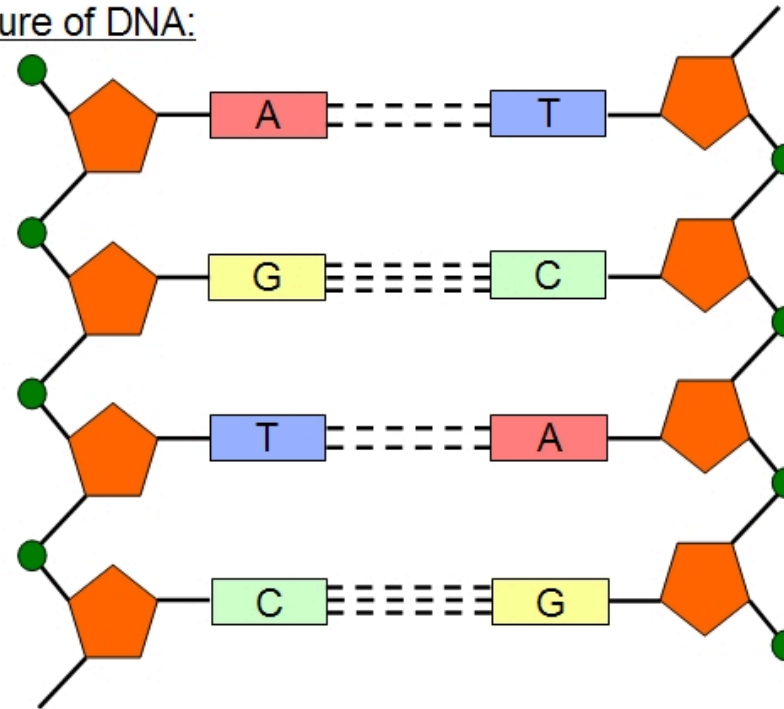
1. DNA
2. RNA
3. Protein

DNA

Each strand composed of sequence of covalently bonded **nucleotides (bases)**.



Structure of DNA:



Four nucleotides:

A (adenine)

C (cytosine)

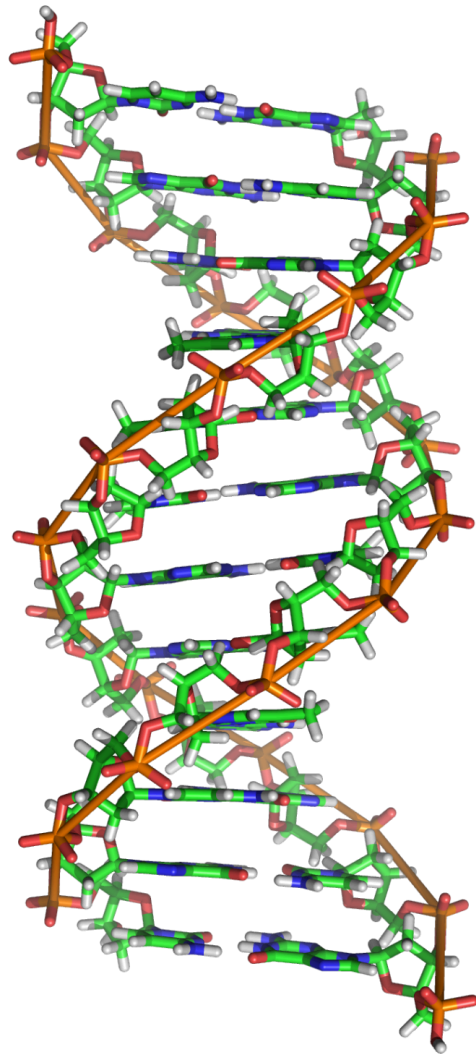
T (thymine)

G (guanine)

$A \leftrightarrow T$, $C \leftrightarrow G$ Watson-Crick base-pairing

DNA

Each strand composed of sequence of covalently bonded **nucleotides (bases)**.



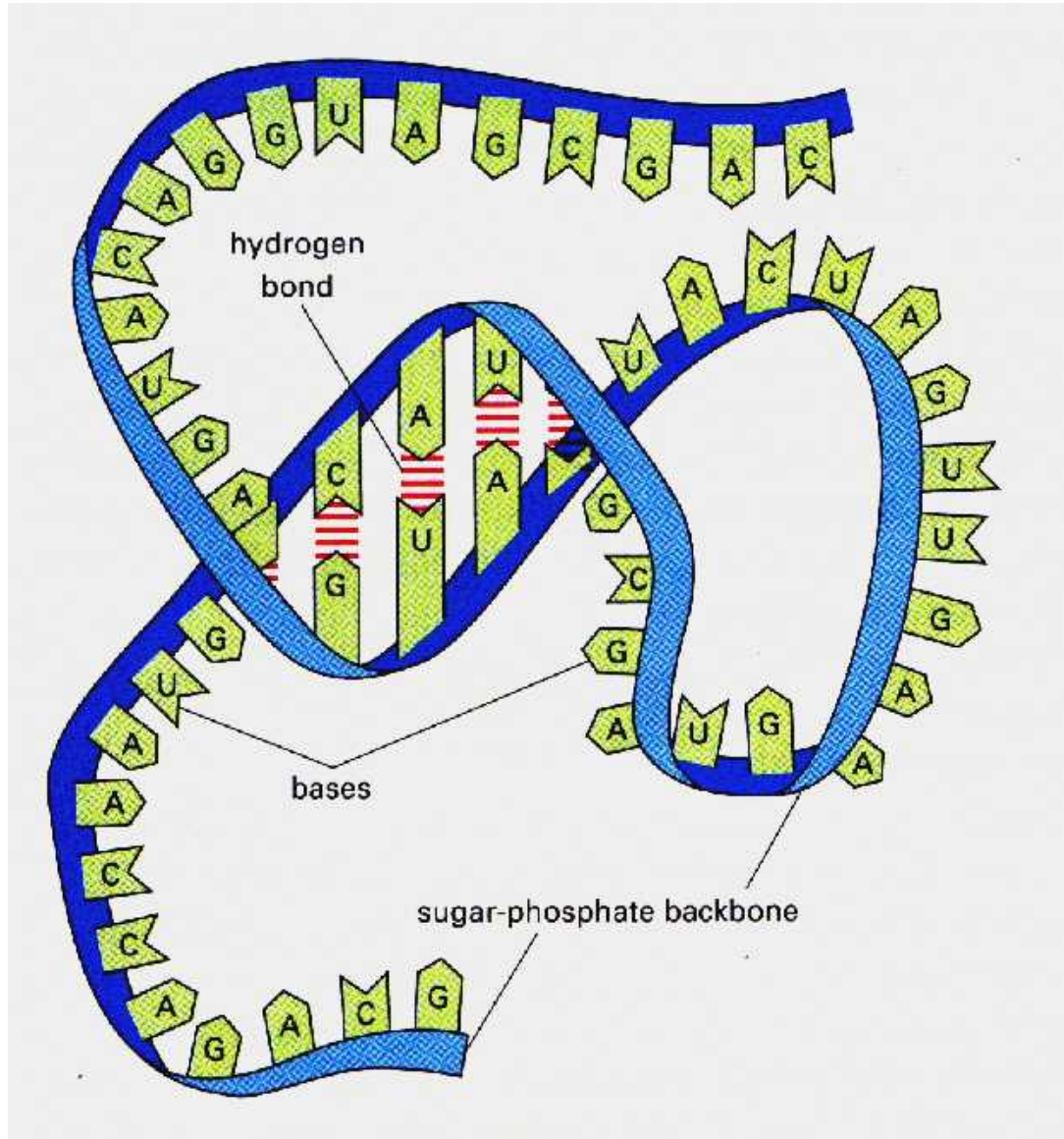
5' ...ACGTGACTGAGGACCGTG... 3'
... |||||
3' ...TGCCTGACTCCTGGCAC... 5'

Pair of strings
from 4-character
alphabet

5' ...ACGTGACTGAGGACCGTG
CGACTGAGACTGACTGGGT
CTAGCTAGACTACGTTT
TATATATATACGTCGTCGT
ACTGATGACTAGATTACAG
TGATTTTAAAAAATATT... 3'

Single string
from 4-character
alphabet

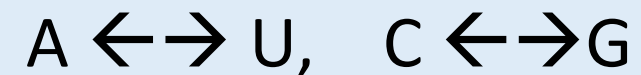
RNA



- **Single-stranded**

- A (adenine)
- C (cytosine)
- U (uracil)
- G (guanine)

- Can fold into **structures** due to base complementarity.



- Comes in many flavors:

mRNA, rRNA, tRNA, tmRNA, snRNA,
snoRNA, scaRNA, aRNA, asRNA, piwiRNA, etc.

Protein

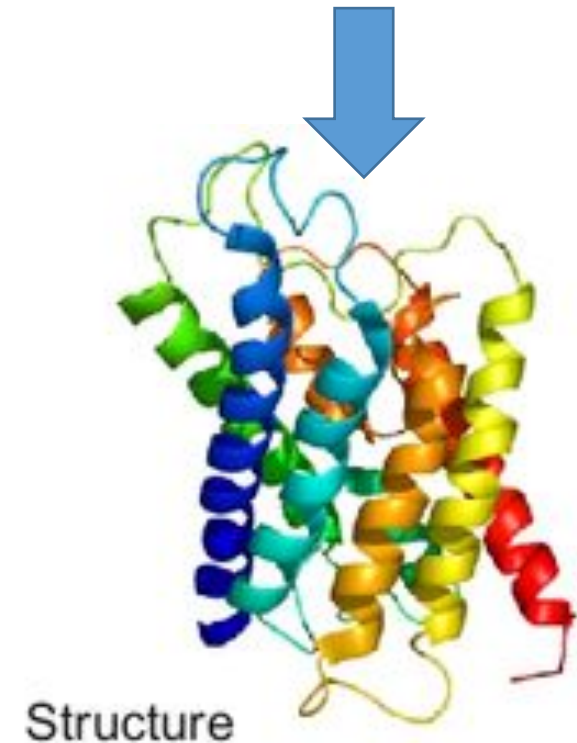
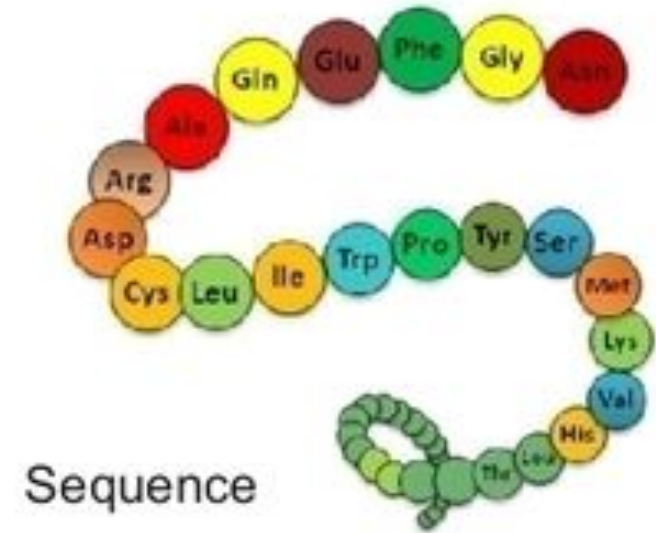
- String of amino acids: 20 letter alphabet

...DTIGDWNSPSFFGIQLVSSVHT
TLWYRENAFPVLGGFSWLSWFNW
HNMGYYPVYHIGYPMIRCGTHL
VPMQFAFQSIARSFALVHWNAPM
VLKINPHERQDPVFWPCLYYSVD
IRSMHIGYPMIRCYQA...

Amino Acid	3-Letters	1-Letter
Alanine	Ala	A
Arginine	Arg	R
Asparagine	Asn	N
Aspartic acid	Asp	D
Cysteine	Cys	C
Glutamic acid	Glu	E
Glutamine	Gln	Q
Glycine	Gly	G
Histidine	His	H
Isoleucine	Ile	I
Leucine	Leu	L
Lysine	Lys	K
Methionine	Met	M
Phenylalanine	Phe	F
Proline	Pro	P
Serine	Ser	S
Threonine	Thr	T
Tryptophan	Trp	W
Tyrosine	Tyr	Y
Valine	Val	V

Protein

- String of amino acids: 20 letter alphabet
- Folds into 3D structures to perform various functions in cells



Primer on Molecular Biology

Three fundamental molecules:

1. DNA

Information storage.

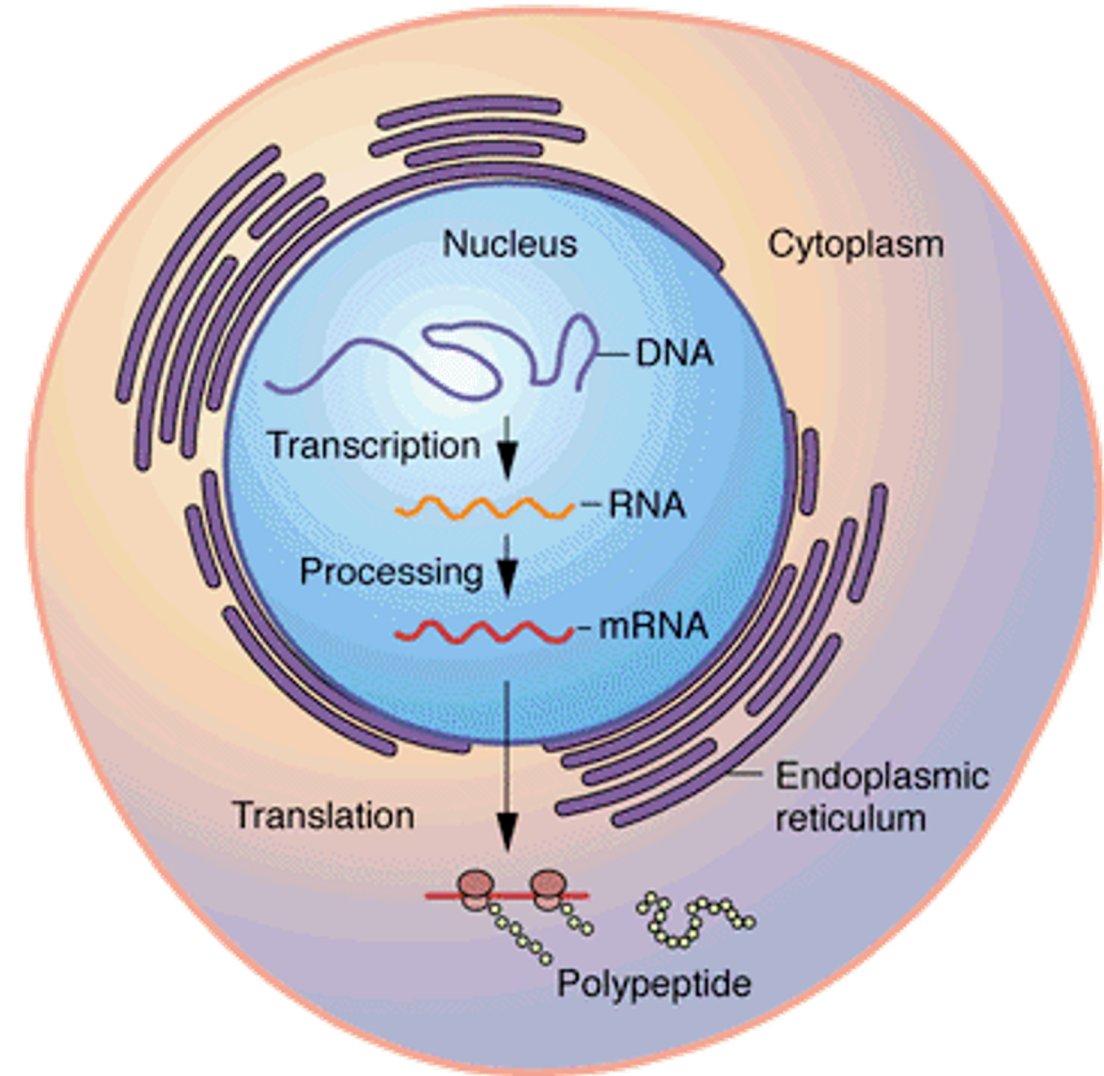
2. RNA

Old view: Mostly a “messenger”.

New view: Performs many important functions.

3. Protein

Perform most cellular functions
(biochemistry, signaling, control, etc.)

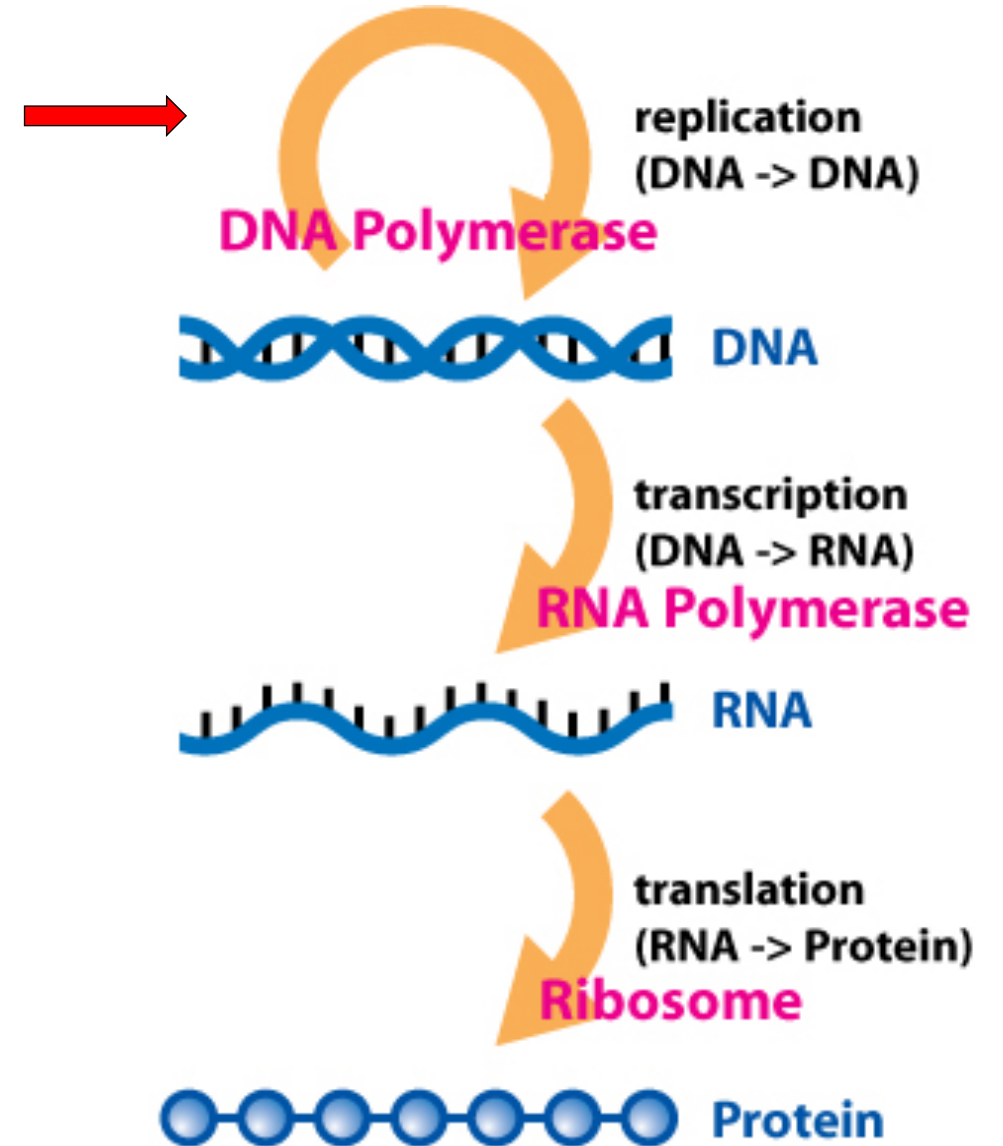


Central Dogma of Molecular Biology

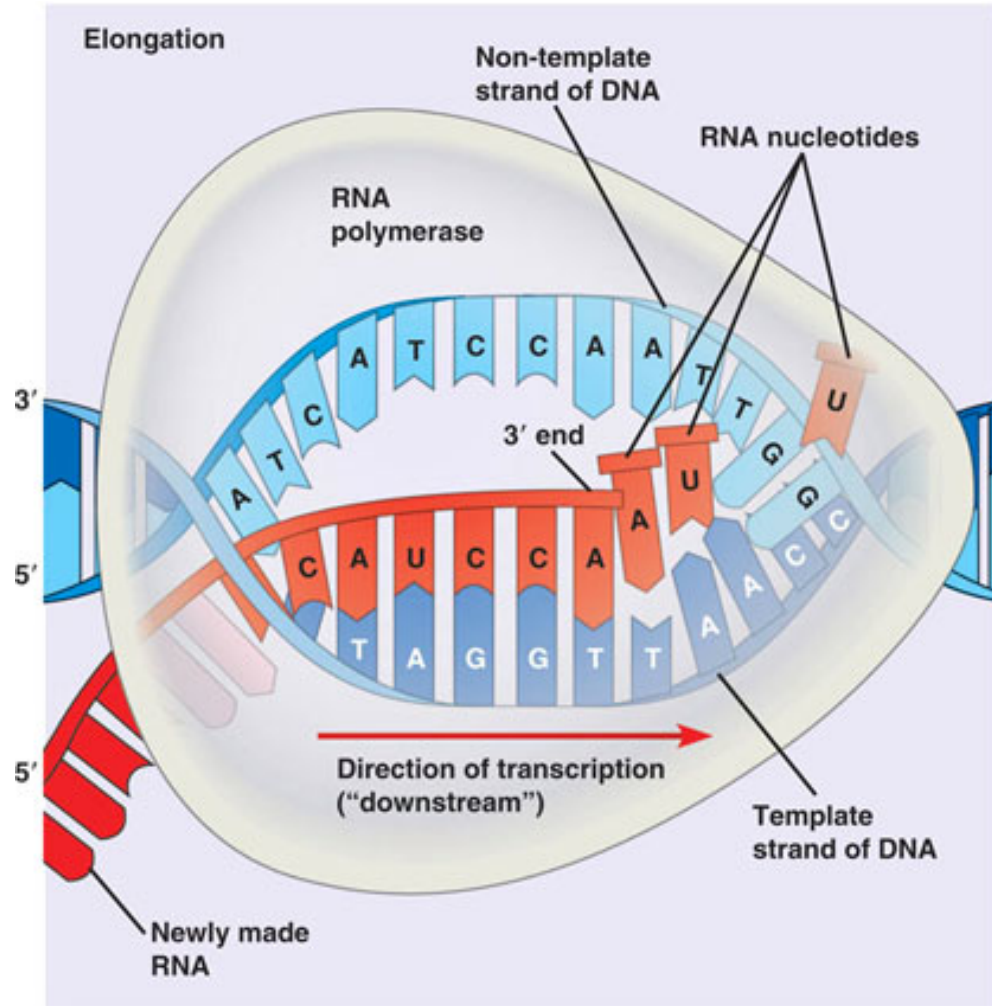
DNA → RNA → Protein:
The process by which cells
“read” the genome

First proposed by Francis Crick in 1956.

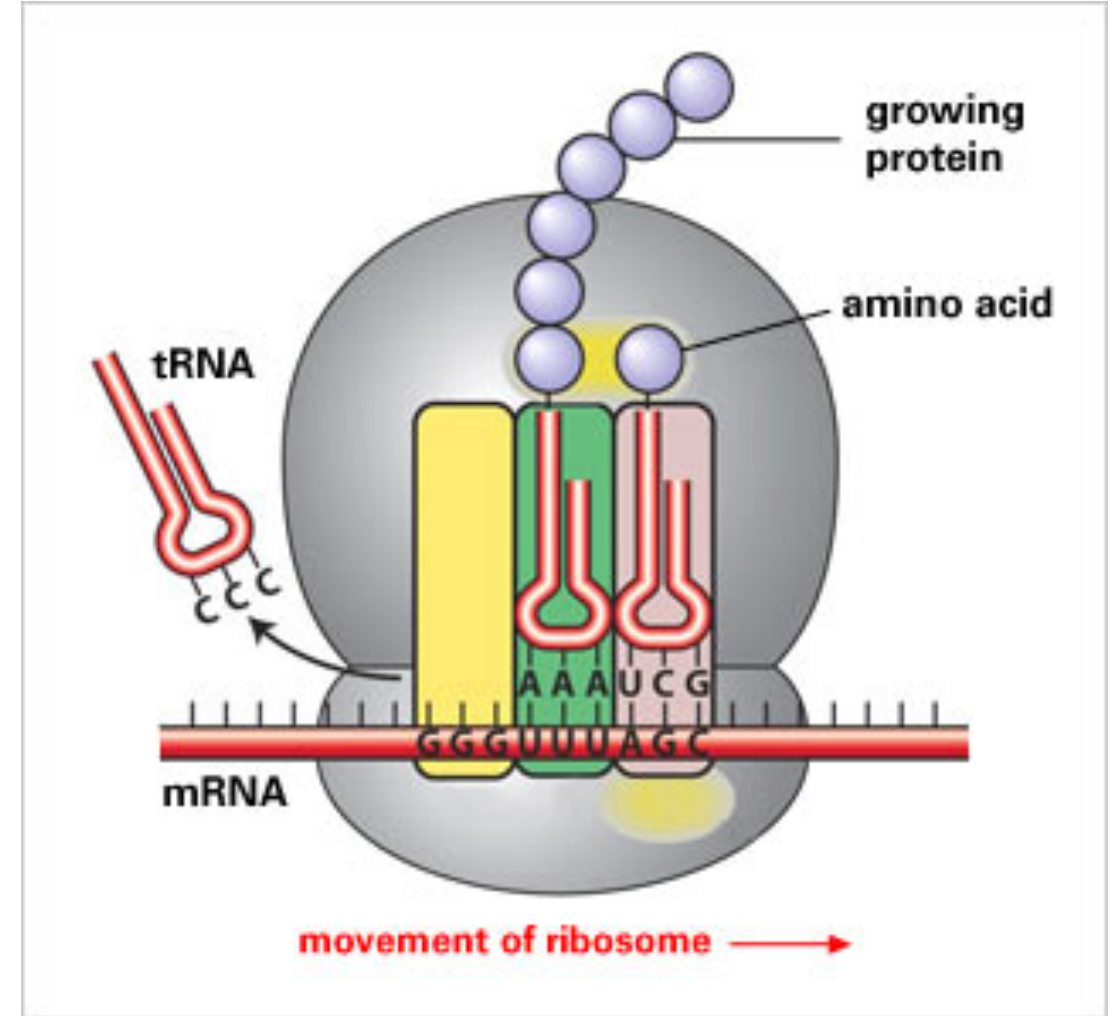
Start here



Transcription and Translation

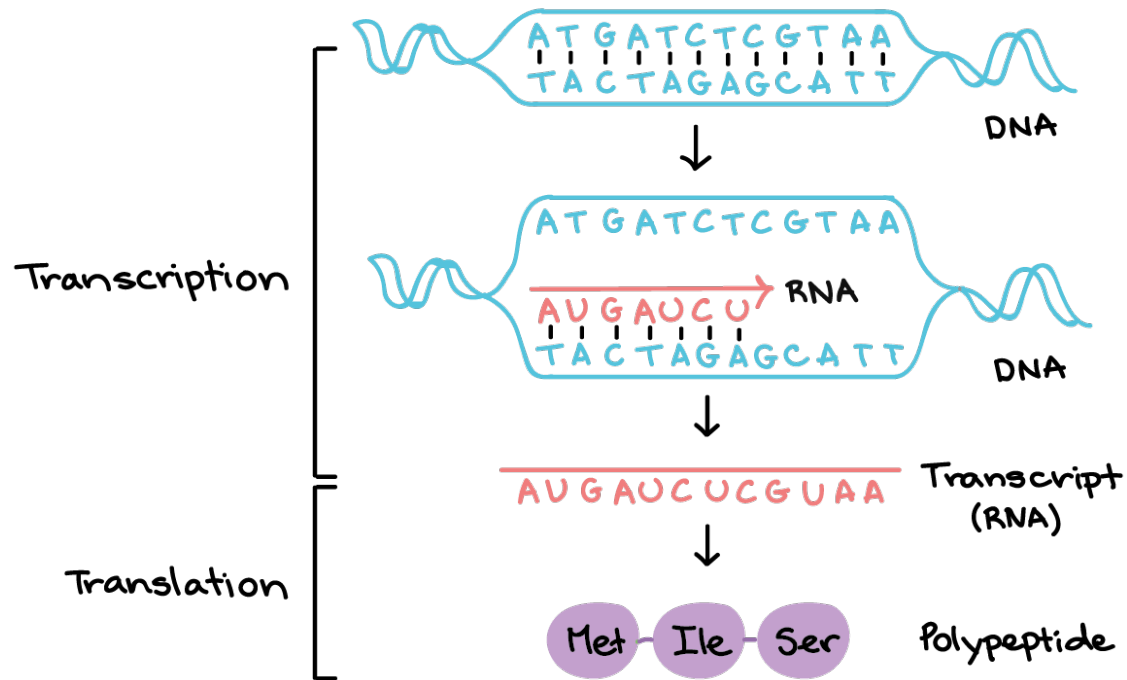


<http://dna-rna.net/wp-content/uploads/2011/08/rna-transcription2.jpg>



http://www.frontiers-in-genetics.org/en/pictures/translation_1.jpg

Transcription and Translation



		Second base				
		U	C	A	G	
First base	U	UUU } Phenyl-alanine F UUC } UUA } Leucine L UUG }	UCU } Serine S UCC } UCA } UCG }	UAU } Tyrosine Y UAC } UAA } Stop codon UAG } Stop codon	UGU } Cysteine C UGC } UGA } Stop codon UGG } Tryptophan W	U C A G
	C	CUU } Leucine L CUC } CUA } CUG }	CCU } Proline P CCC } CCA } CCG }	CAU } Histidine H CAC } CAA } Glutamine Q CAG }	CGU } Arginine R CGC } CGA } CGG }	U C A G
	A	AUU } Isoleucine I AUC } AUA } AUG } Methionine start codon M	ACU } Threonine T ACC } ACA } ACG }	AAU } Asparagine N AAC } AAA } Lysine K AAG }	AGU } Serine S AGC } AGA } Arginine R AGG }	U C A G
	G	GUU } Valine V GUC } GUA } GUG }	GCU } Alanine A GCC } GCA } GCG }	GAU } Aspartic acid D GAC } GAA } Glutamic acid E GAG }	GGU } Glycine G GGC } GGA } GGG }	U C A G

<https://www.khanacademy.org/science/biology/gene-expression-central-dogma/transcription-of-dna-into-rna/a/overview-of-transcription>

<http://bioinfo.bisr.res.in/project/crat/pictures/codon.jpg>

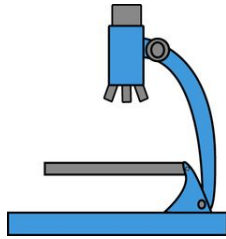
What is Computational Biology/Bioinformatics?

Computational biology and **bioinformatics** is an interdisciplinary field that develops and applies **computational methods** to analyze large collections of biological data, such as genetic sequences, cell populations or protein samples, to make new predictions or **discover new biology**.

<https://www.nature.com/subjects/computational-biology-and-bioinformatics>

Technology and Bioinformatics are Transforming Biology

Until late 20th Century



Hypothesis Generation
and Validation

21th Century and Beyond



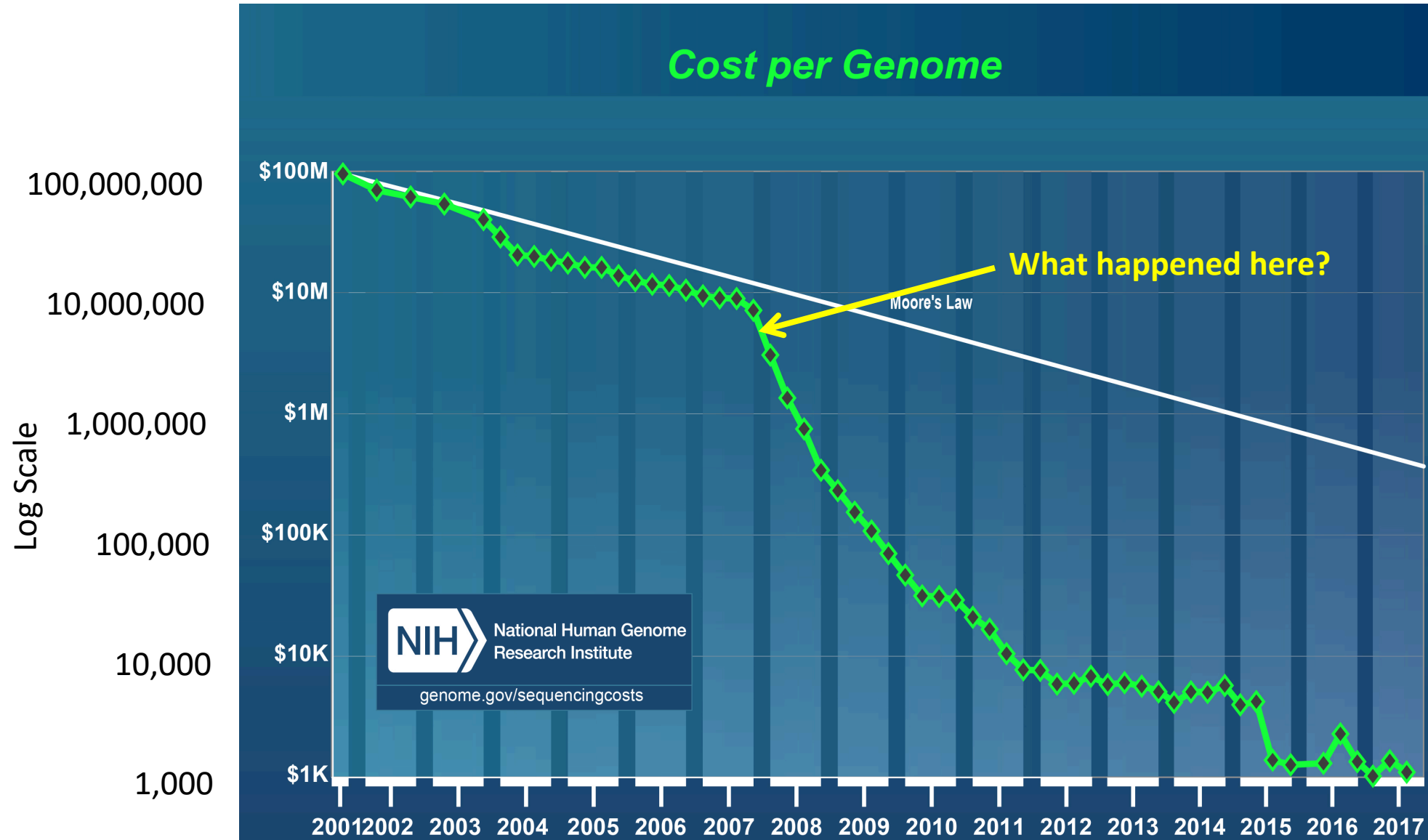
Algorithms



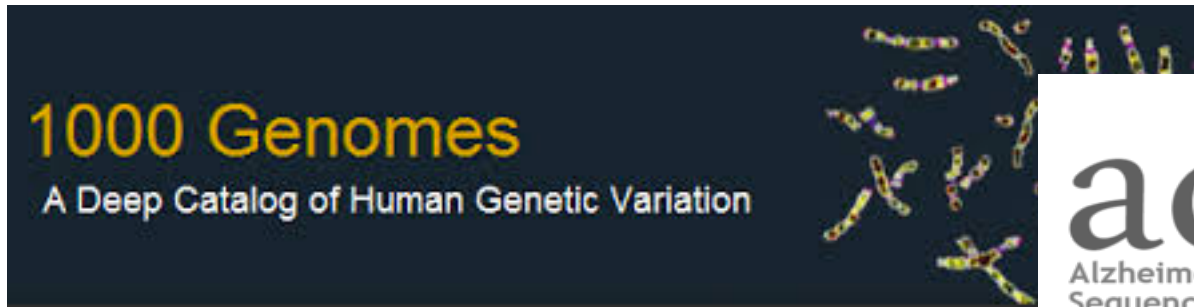
Hypothesis Generation
and Validation

High throughput technologies

A Deluge of Data



A Deluge of Data



1000 Plant Genomes



International Cancer Genome Consortium



NIH HUMAN MICROBIOME PROJECT



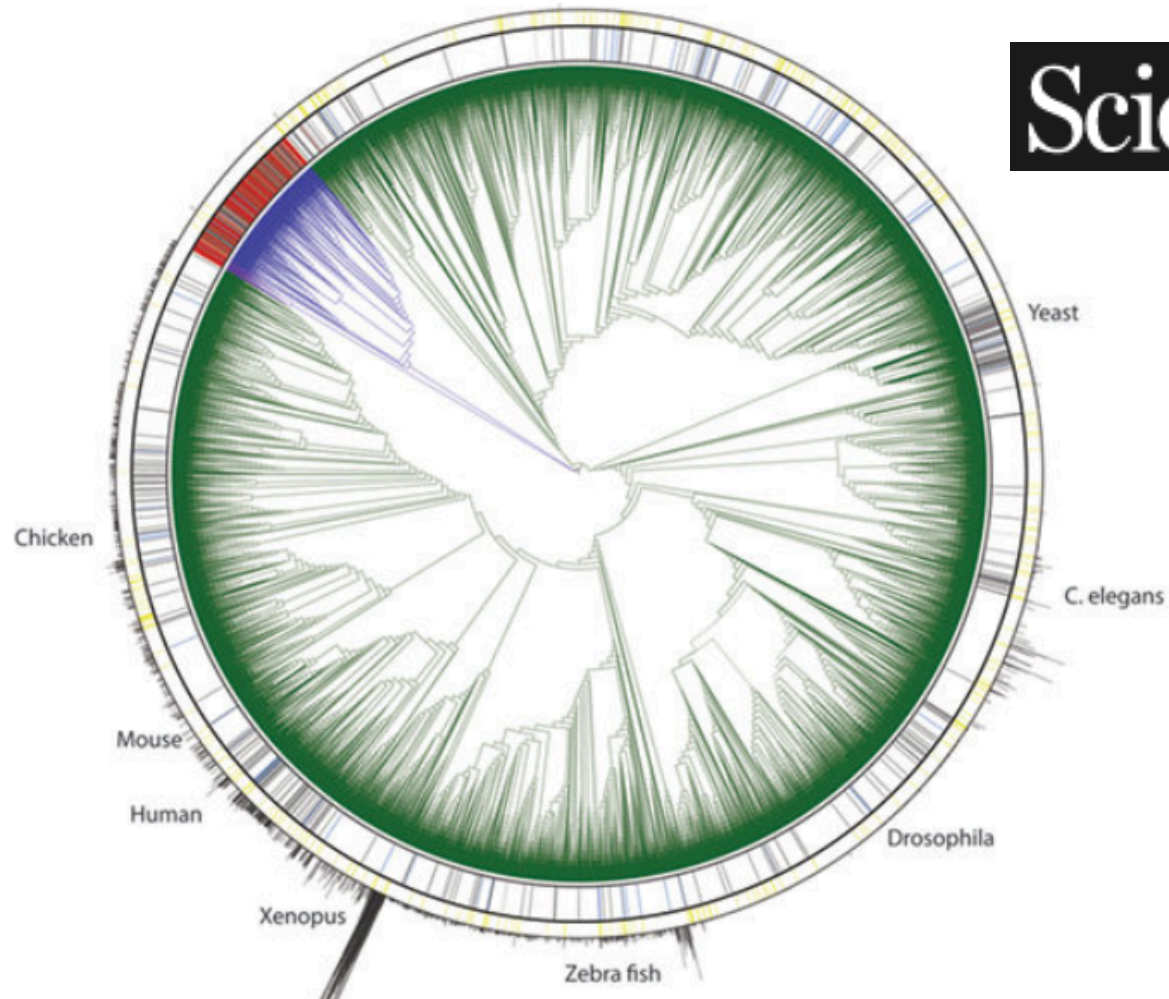
A Deluge of Data

Biologists propose to sequence the DNA of all life on Earth

By [Elizabeth Pennisi](#) | Feb. 24, 2017, 1:15 PM

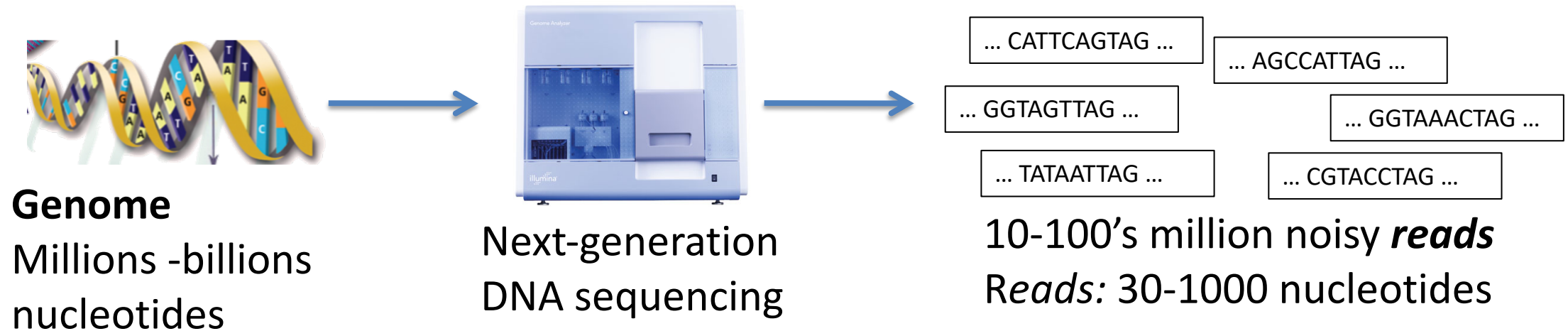
Science

Outer ring color scheme:
Red: Completed genome
Light Blue: Low resolution genome



Question: What does it mean that we can sequence a genome?

No technology exists that can sequence a complete (human) genome from end to end!



Making sense of this data absolutely requires the use and development of **algorithms**!

Why Study Computational Biology?

Interdisciplinary

Biology

Computer Science

Mathematics

Statistics

= FUN!



Why choose just 1?

Best Jobs

1. Actuary
2. Audiologist
3. Mathematician
4. Statistician
5. Biomedical Engineer
6. Data Scientist
7. Dental Hygienist
8. Software Engineer
9. Occupational Therapist
10. Computer Systems Analyst

Worst Jobs

200. Newspaper reporter
199. Lumberjack
198. Enlisted Military Personnel
197. Cook
196. Broadcaster
195. Photojournalist
194. Corrections Officer
193. Taxi Driver
192. Firefighter
191. Mail Carrier



Donald Knuth

Professor emeritus of Computer Science at Stanford University

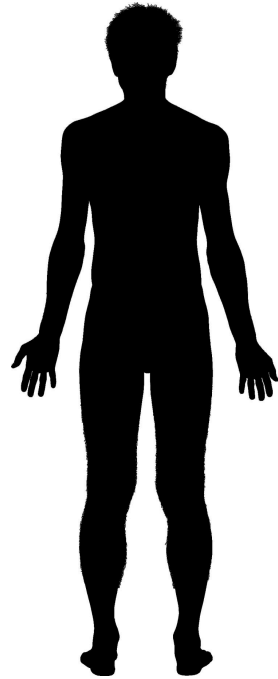
Turing Award winner

“father of the analysis of algorithms.”

*“I can’t be as confident about computer science as I can about biology. **Biology easily has 500 years of exciting problems to work on.** It’s at that level.”*

Course Topic #1: Sequence Alignment

Question: How do we compare two genes/genomes?

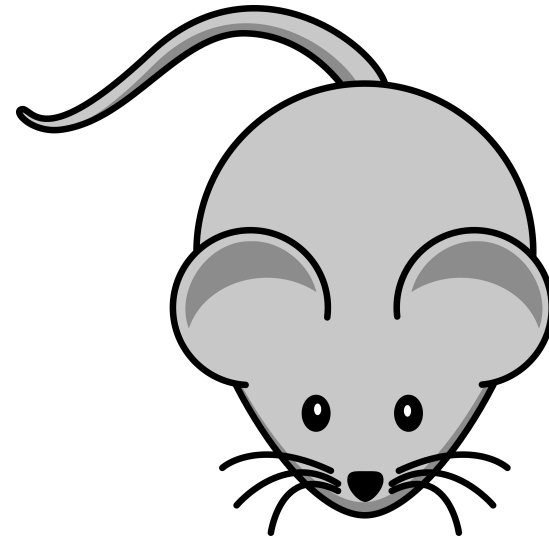


Human Genome:

...ACTCGACTGAGAGGATTTTCGAGCATGA...

$\approx 3.2 \times 10^9$ bp

vs.

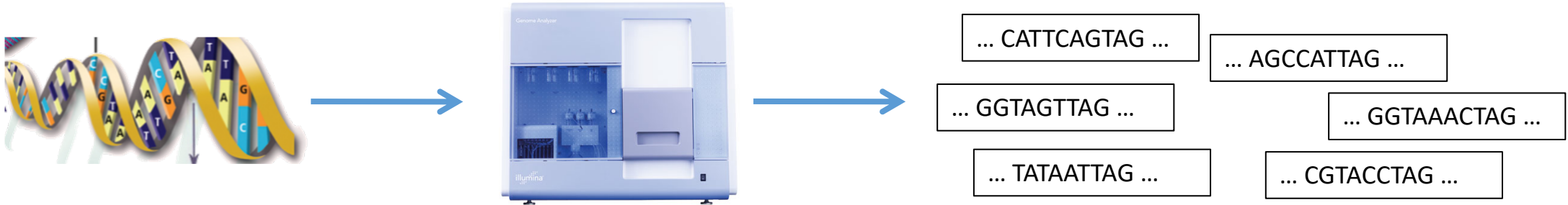


Mouse Genome:

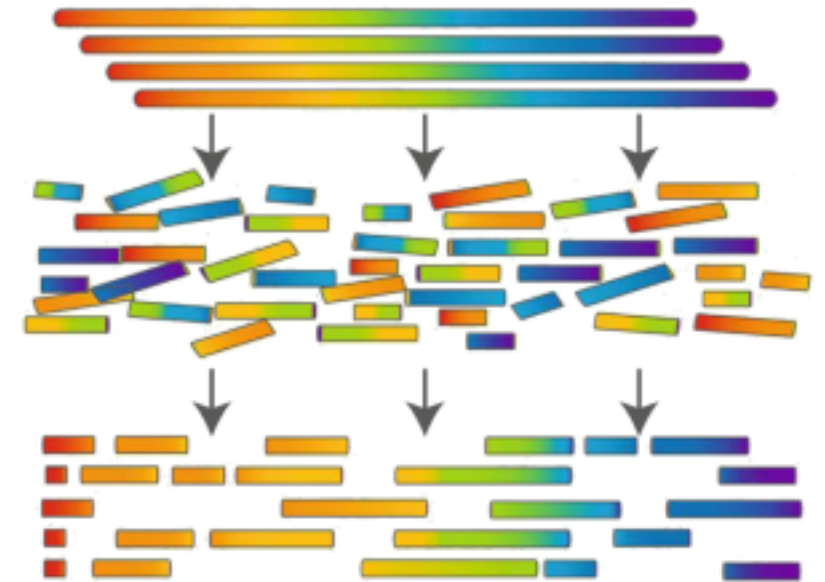
...ACTCAACTGAGATTCGAGCTTCAATGA...

$\approx 2.8 \times 10^9$ bp

Course Topic #2: Genome Assembly

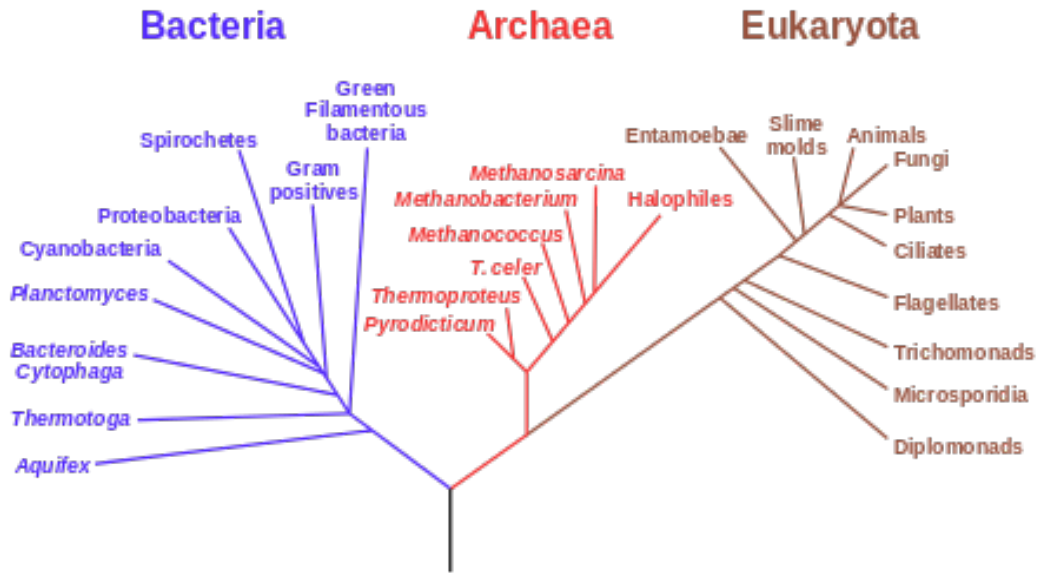


Question: How do we put all the pieces back together?



Course Topic #3: Phylogenetics

Phylogenetic Tree of Life

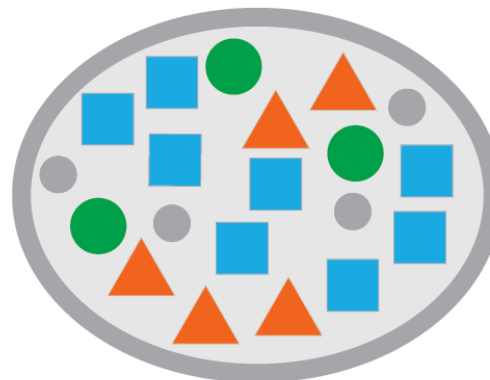


https://en.wikipedia.org/wiki/Phylogenetic_tree

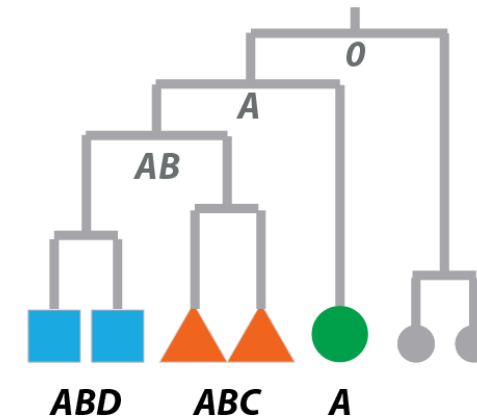
Question: Can we reconstruct the evolutionary history of different species?

Question: Can we recover how a tumor has evolved overtime?

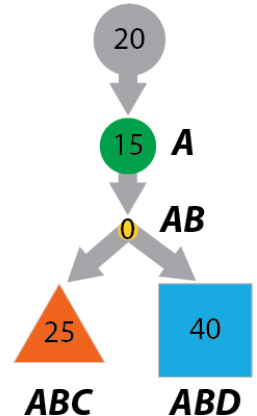
Poly-clonal tumor at sampling



Classical phylogenetic tree

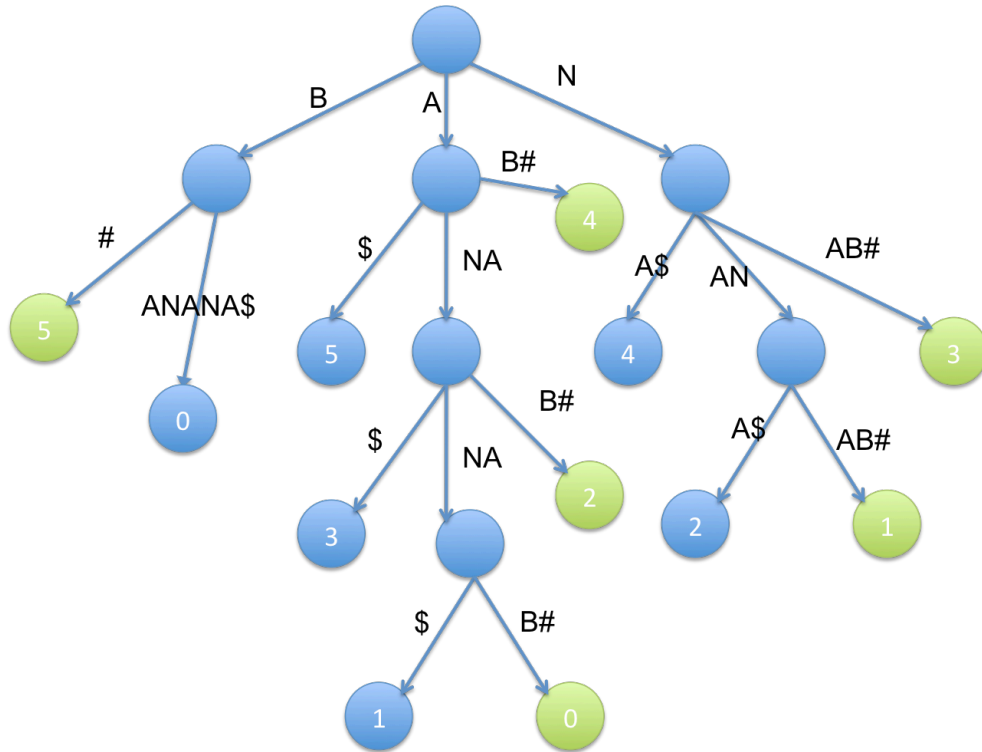


Clonal evolution tree

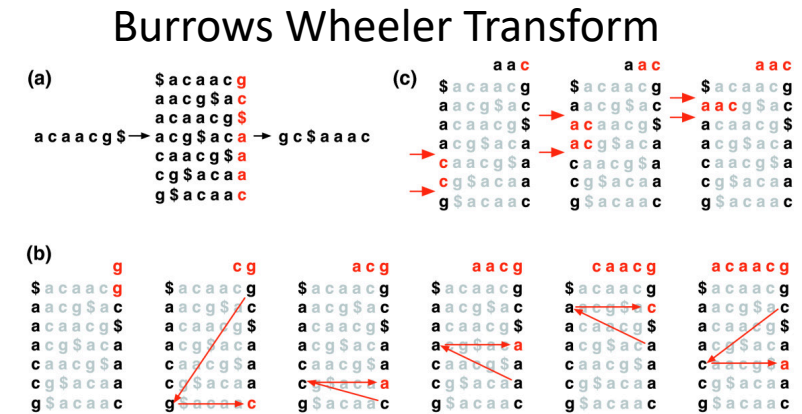


Course Topic #4: Pattern Matching

Question: How do we start to make sense of all these sequences?

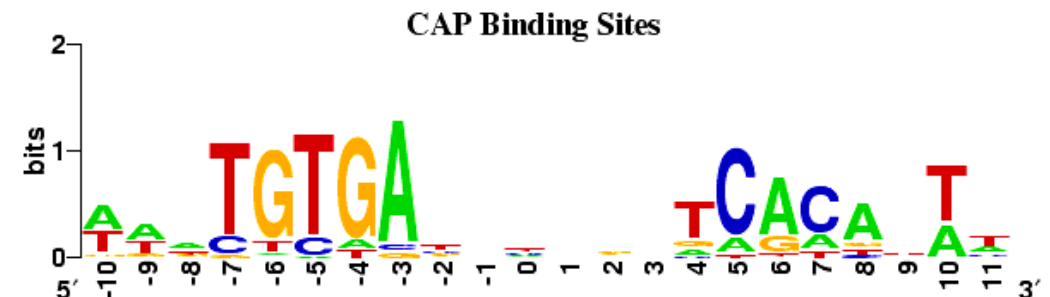


Suffix Trees



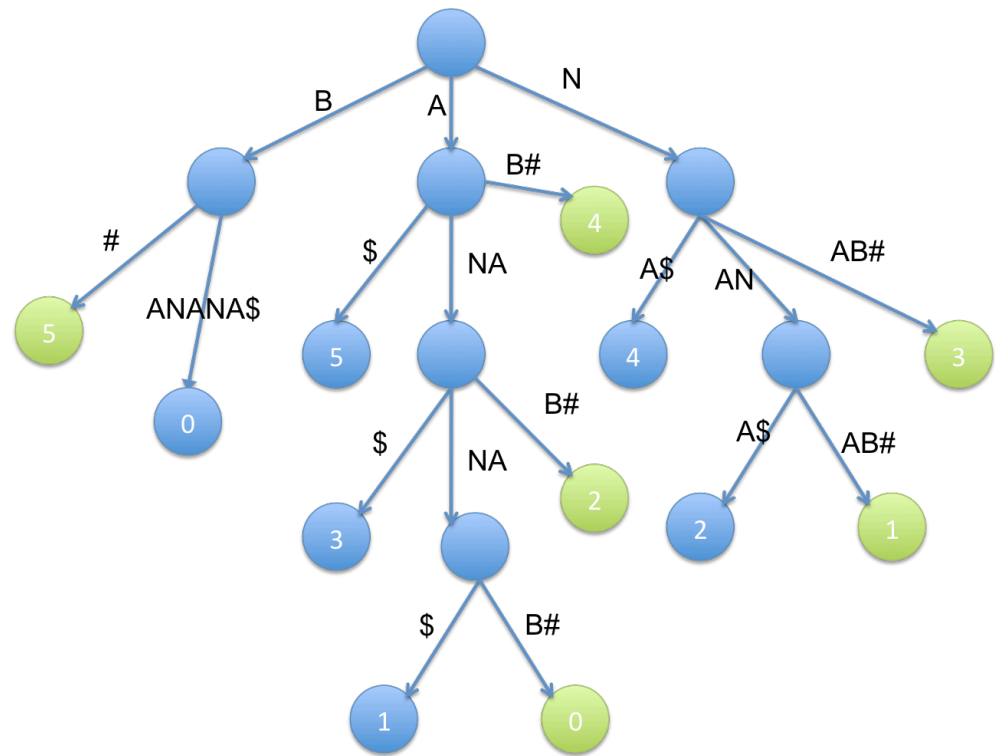
<http://www.genomebiology.com/2009/10/3/R25/figure/F1?highres=y>

Motif Finding



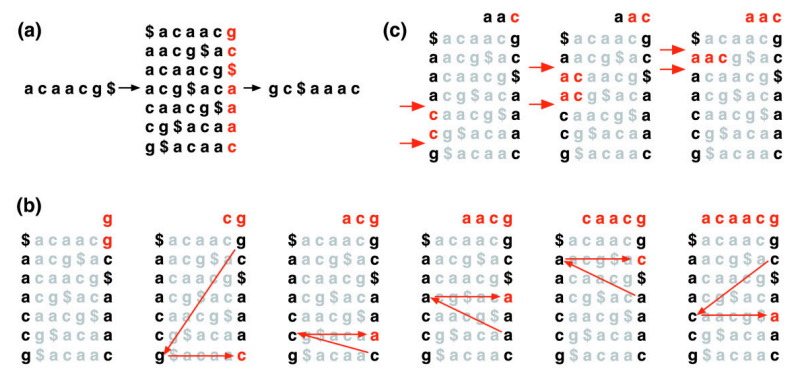
Course Topic #4: Pattern Matching

Question: How do we start to make sense of all these sequences?



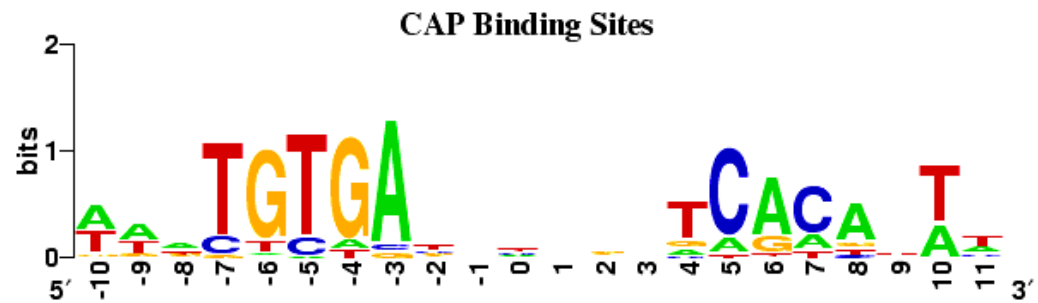
Suffix Trees

Burrows Wheeler Transform

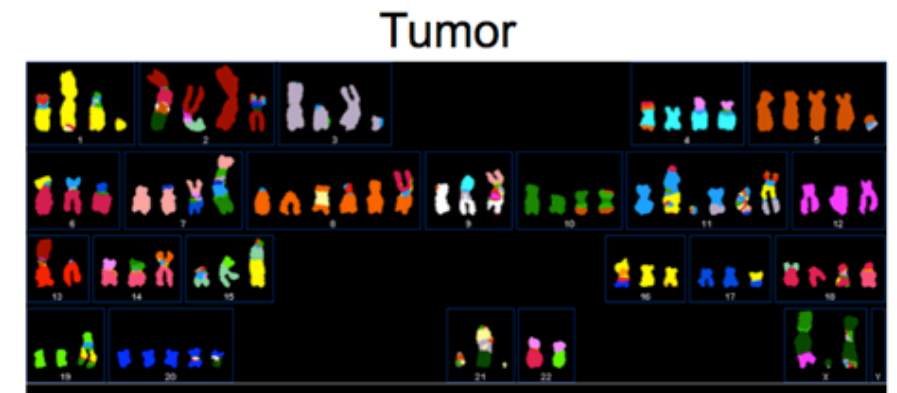
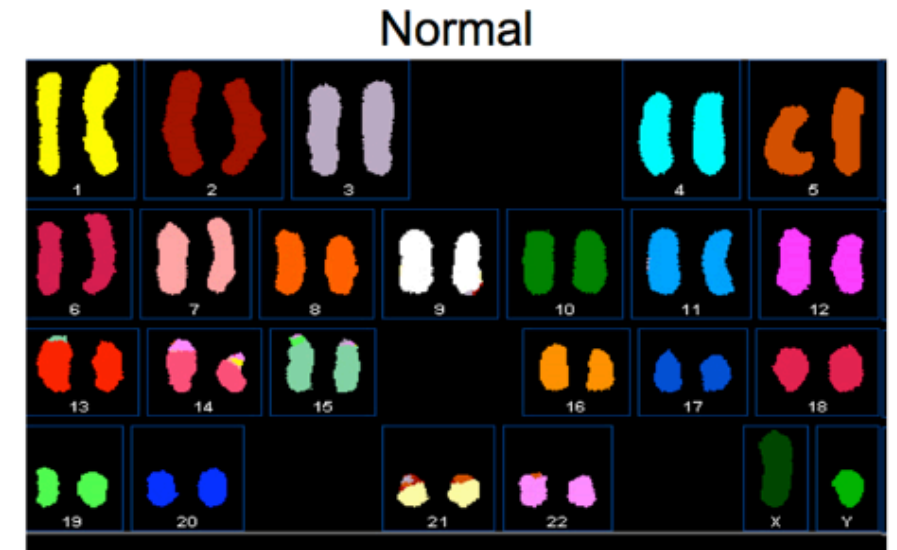
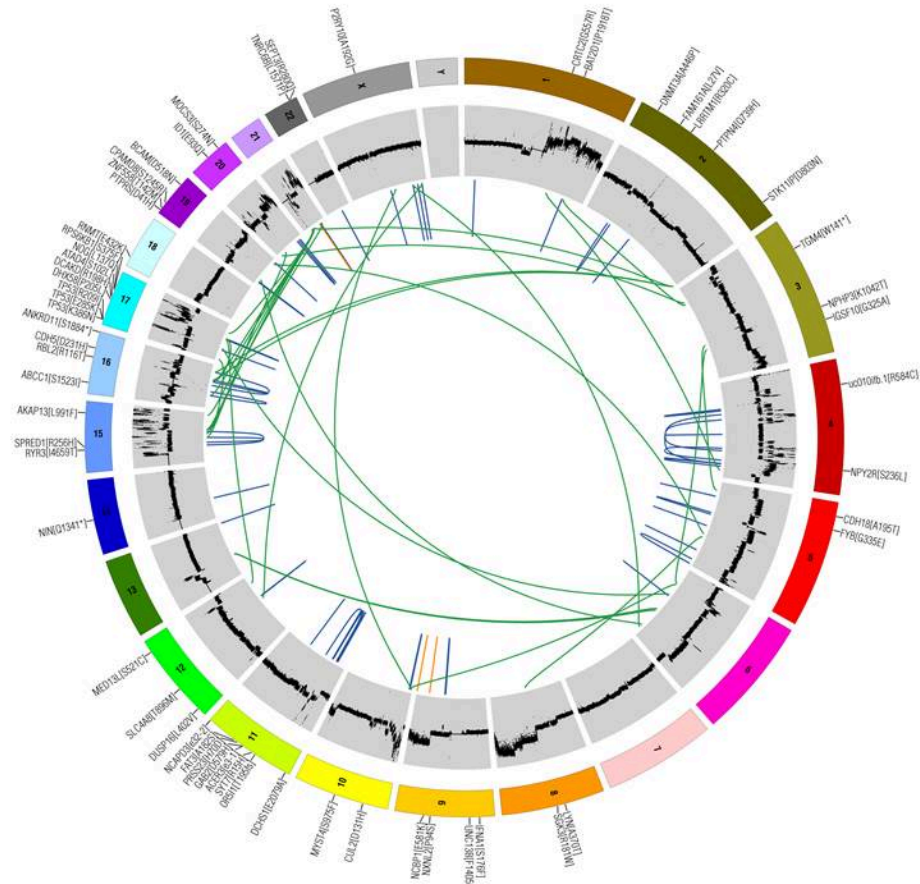


<http://www.genomebiology.com/2009/10/3/R25/figure/F1?highres=y>

Motif Finding



Course Topic #5: Cancer Genomics



Question: How can we analyze available data to determine what drives tumor growth and how to treat or prevent it?

Course Topics

1. Sequence alignment
'How do we compare two genes/genomes?'
2. Genome assembly
'How do we put all the pieces back together?'
3. Phylogenetics
'What is the evolutionary history of different sequences?'
4. Pattern matching
'How do we start to make sense out of all these sequences?'
5. Cancer genomics
'How do we identify what drives tumor growth and how to treat/prevent it?'

Course Topics

1. Sequence alignment
Dynamic programming: edit distance
2. Genome assembly
Graphs: de Bruijn graph, Eulerian and Hamiltonian paths
3. Phylogenetics
Trees and distances: distance matrices, neighbor joining, hierarchical clustering.
Phylogenies: Sankoff/Fitch algorithms, perfect phylogeny and compatibility
4. Pattern matching
Suffix trees/arrays. Burrows-Wheeler transform, Hidden Markov Models (HMMs)
5. Cancer genomics
Cancer phylogenies: Integer linear optimization and graph algorithms

Problem \neq Algorithm

Problem Π with instance X and solution set $\Pi(X)$:

- Decision problem:
 - Is $\Pi(X) = \emptyset$?
- Optimization problem:
 - Find $y^* \in \Pi(X)$ s.t. $f(y^*)$ is optimum.
- Counting problem:
 - Compute $|\Pi(X)|$.
- Sampling problem:
 - Sample uniformly from $\Pi(X)$.
- Enumeration problem:
 - Enumerate all solutions in $\Pi(X)$

Algorithms:

Set of instructions for solving problem.

- Exact
- Heuristic

The Change Problem

- Suppose we have three coins:



- What is the minimum number of coins needed to make change for ***M*** cents?

The Change Problem

- Suppose we have three coins:

$$\mathbf{c} = (\text{5 cent}, \text{3 cent}, \text{1 cent})$$

- What is the minimum number of coins needed to make change for **M** cents?

Change Problem: Given amount $M \in \mathbb{N} \setminus \{0\}$ and coins $\mathbf{c} = (c_1, \dots, c_n) \in \mathbb{N}^n$
s.t. $c_n = 1$ and $c_i \geq c_{i+1}$ for all $i \in [n-1] = \{1, \dots, n-1\}$,
find $\mathbf{d} = (d_1, \dots, d_n) \in \mathbb{N}^n$ s.t. (i) $M = \sum_{i=1}^n c_i d_i$ and (ii) $\sum_{i=1}^n d_i$ is minimum

Idea #1: Choose largest coin possible

GreedyChange(M, c_1, \dots, c_n)

1. **for** $i \leftarrow 1$ **to** n
2. $d_i \leftarrow \lfloor M/c_i \rfloor$
3. $M \leftarrow M - d_i c_i$

Idea #1: Choose largest coin possible

GreedyChange(M, c_1, \dots, c_n)

1. **for** $i \leftarrow 1$ **to** n
2. $d_i \leftarrow \lfloor M/c_i \rfloor$
3. $M \leftarrow M - d_i c_i$

Is this a good algorithm? Two properties of a good algorithm:

Idea #1: Choose largest coin possible

GreedyChange(M, c_1, \dots, c_n)

1. **for** $i \leftarrow 1$ **to** n
2. $d_i \leftarrow \lfloor M/c_i \rfloor$
3. $M \leftarrow M - d_i c_i$

Is this a good algorithm? Two properties of a good algorithm:

Correctness: gives the correct output for any input.

- Works for $\mathbf{c} = (5, 3, 1)$ and $M = 8$.
- But what about $\mathbf{c} = (5, 4, 1)$ and $M = 8$?

Efficient: *running time* of the algorithm does not increase too rapidly with input size.

Idea #2: When in doubt, apply brute force...

Change Problem: Given amount $M \in \mathbb{N} \setminus \{0\}$ and coins $\mathbf{c} = (c_1, \dots, c_n) \in \mathbb{N}^n$
s.t. $c_n = 1$ and $c_i \geq c_{i+1}$ for all $i \in [n-1] = \{1, \dots, n-1\}$,
find $\mathbf{d} = (d_1, \dots, d_n) \in \mathbb{N}^n$ s.t. (i) $M = \sum_{i=1}^n c_i d_i$ and (ii) $\sum_{i=1}^n d_i$ is minimum

$\mathbf{c} = ($  $,$  $,$  $)$

Correct? yes
Efficient? no

- Check all possible solutions:

- $11 = 5 + 5 + 1$
- $11 = 5 + 4 + 1 + 1$
- $11 = 5 + 1 + 1 + 1 + 1 + 1 + 1$
- $11 = 4 + 4 + 1 + 1 + 1$
- ...

ExhaustiveChange(M, c_1, \dots, c_n)

1. **for** $(d_1, \dots, d_n) \in \{0, \dots, \lfloor M/c_1 \rfloor\} \times \dots \times \{0, \dots, \lfloor M/c_n \rfloor\}$
2. **if** $\sum_{i=1}^n c_i d_i = M$
3. **return** (d_1, \dots, d_n)

Idea #3: Recursion

$c = (\text{5 cent}, \text{3 cent}, \text{1 cent})$

Value	1	2	3	4	5	6	7	8	9	10	11
Min # coins	?	?	?	?	?	?	?	?	?	?	?

Diagram illustrating the recursive relationship for the minimum number of coins required to make a given value. The table shows values from 1 to 11, and the minimum number of coins required for each value is unknown (indicated by '?'). The arrows show that the optimal solution for a value i depends on the optimal solutions for subproblems $i-1$, $i-3$, and $i-5$.

Optimal substructure:

Optimal solution is obtained from optimal solutions of subproblems

Idea #3: Recursion

$c = (5, 3, 1)$

Value	1	2	3	4	5	6	7	8	9	10	11
Min # coins	?	?	?	?	?	?	?	?	?	?	?

- This example can be expressed using a recurrence relation
- Let $\text{minNumCoins}(M)$ be the minimum number of coins to make change for M cents

$$\text{minNumCoins}(M) = \min \begin{cases} \text{minNumCoins}(M - 1) + 1, \\ \text{minNumCoins}(M - 3) + 1, \\ \text{minNumCoins}(M - 5) + 1. \end{cases}$$

Idea #3: Recursion

Change Problem: Given amount $M \in \mathbb{N} \setminus \{0\}$ and coins $\mathbf{c} = (c_1, \dots, c_n) \in \mathbb{N}^n$
s.t. $c_n = 1$ and $c_i \geq c_{i+1}$ for all $i \in [n-1] = \{1, \dots, n-1\}$,
find $\mathbf{d} = (d_1, \dots, d_n) \in \mathbb{N}^n$ s.t. (i) $M = \sum_{i=1}^n c_i d_i$ and (ii) $\sum_{i=1}^n d_i$ is minimum

$$\text{minNumCoins}(M) = \min \begin{cases} \text{minNumCoins}(M - c_1) + 1, \\ \text{minNumCoins}(M - c_2) + 1, \\ \dots \\ \text{minNumCoins}(M - c_n) + 1. \end{cases}$$

Idea #3: Recursion

Given coins $\mathbf{c} = (1, 3, 7)$ and amount $M = 77$, find $\mathbf{d} = (d_1, \dots, d_n) \in \mathbb{N}^n$ such that: (i) $M = \sum_{i=1}^n c_i d_i$ and (ii) $\sum_{i=1}^n d_i$ is minimum.

$$\text{minNumCoins}(77) = \min \begin{cases} \text{minNumCoins}(77 - 1) + 1, \\ \text{minNumCoins}(77 - 3) + 1, \\ \text{minNumCoins}(77 - 7) + 1, \end{cases}$$

$$\text{minNumCoins}(76) = \min \begin{cases} \text{minNumCoins}(76 - 1) + 1, \\ \text{minNumCoins}(76 - 3) + 1, \\ \text{minNumCoins}(76 - 7) + 1, \end{cases}$$

\vdots

$$\text{minNumCoins}(7) = 1$$

$$\text{minNumCoins}(3) = 1$$

$$\text{minNumCoins}(1) = 1$$

Idea #3: Recursion

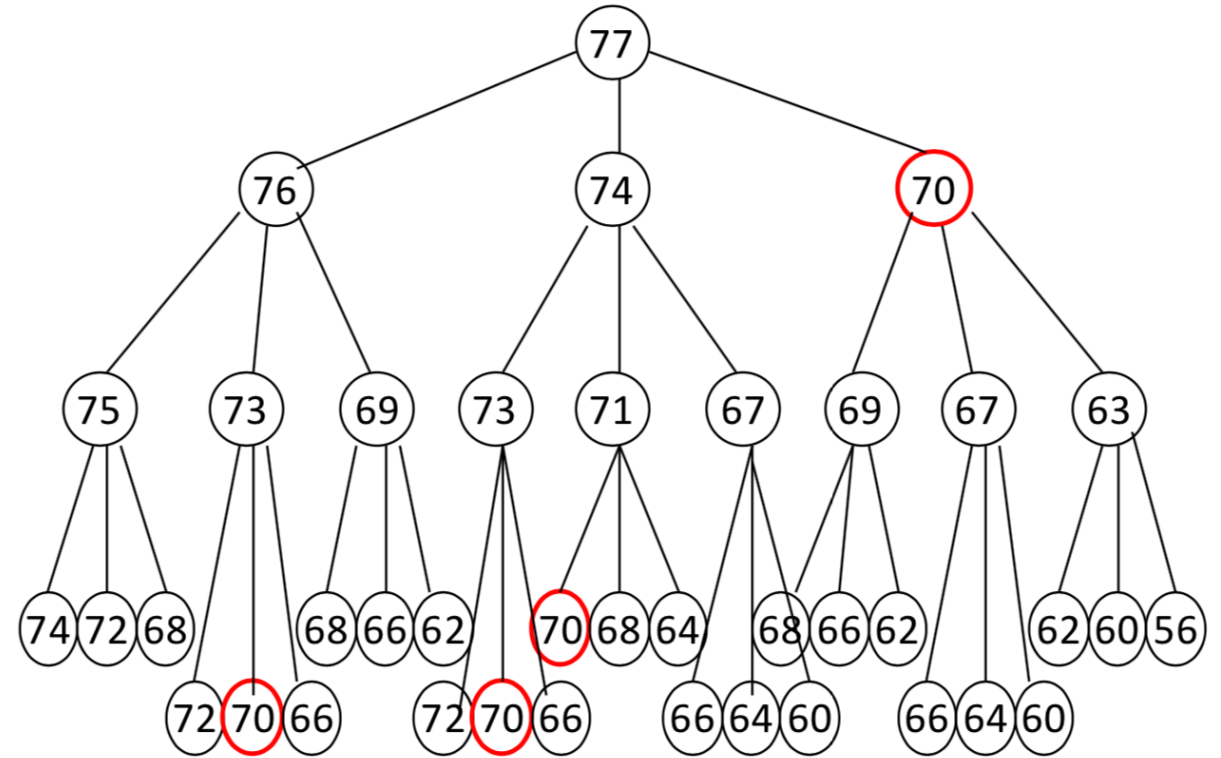
RecursiveChange(M, c_1, \dots, c_n)

- ```

1. if $M = 0$
2. return 0
3. $\text{bestNumCoins} \leftarrow \infty$
4. for $i \leftarrow 1$ to n
5. if $M \geq c_i$
6. $\text{numCoins} \leftarrow$

 $\text{RecursiveChange}(M - c_i, c_1, \dots, c_n)$
7. if $\text{numCoins} + 1 < \text{bestNumCoins}$
8. $\text{bestNumCoins} \leftarrow \text{numCoins} + 1$
9. return bestNumCoins

```



## Correct but inefficient:

Same subproblem is solved many times!

## Idea #3: Recursion

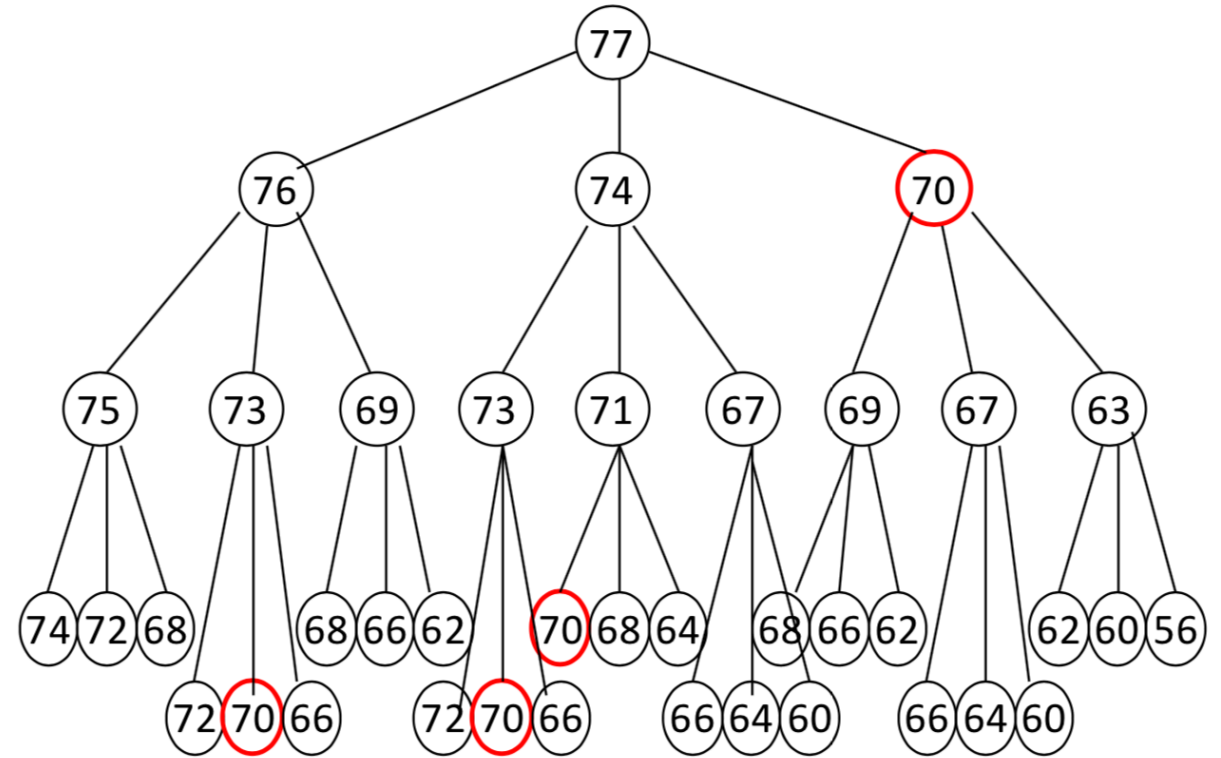
RecursiveChange( $M, c_1, \dots, c_n$ )

- ```

1. if  $M = 0$ 
2.   return 0
3.  $\text{bestNumCoins} \leftarrow \infty$ 
4. for  $i \leftarrow 1$  to  $n$ 
5.   if  $M \geq c_i$ 
6.      $\text{numCoins} \leftarrow$   

        $\text{RecursiveChange}(M - c_i, c_1, \dots, c_n)$ 
7.     if  $\text{numCoins} + 1 < \text{bestNumCoins}$ 
8.        $\text{bestNumCoins} \leftarrow \text{numCoins} + 1$ 
9. return  $\text{bestNumCoins}$ 

```



Correct but inefficient:

Same subproblem is solved many times!

Solutions:

- Remember previously computed values: memoization
- Bottom up computation: dynamic programming

Idea #4: Solve recurrence with dynamic programming

Fill in table “bottom up”: from smallest to largest.

$c = (\text{5} , \text{3} , \text{1})$

Value	1	2	3	4	5	6	7	8	9	10	11
Min # coins	1		1		1						

$$\text{minNumCoins}(M) = \min \begin{cases} \text{minNumCoins}(M - 1) + 1, \\ \text{minNumCoins}(M - 3) + 1, \\ \text{minNumCoins}(M - 5) + 1. \end{cases}$$

Only one coin is needed to make change for the values 1, 3 and 5

Idea #4: Solve recurrence with dynamic programming

Fill in table “bottom up”: from smallest to largest.

$c = (\text{5} , \text{3} , \text{1})$

Value	1	2	3	4	5	6	7	8	9	10	11
Min # coins	1	2	1	2	1	2					

$$\text{minNumCoins}(M) = \min \begin{cases} \text{minNumCoins}(M - 1) + 1, \\ \text{minNumCoins}(M - 3) + 1, \\ \text{minNumCoins}(M - 5) + 1. \end{cases}$$

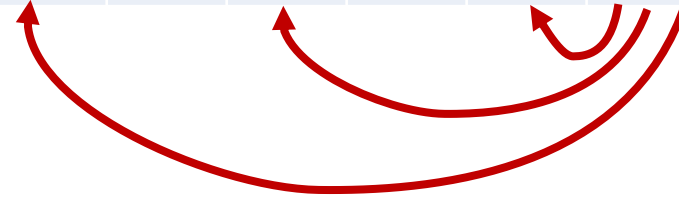
Two coins are needed to make change for the values 2, 4 and 6

Idea #4: Solve recurrence with dynamic programming

Fill in table “bottom up”: from smallest to largest.

$c = (\text{5} , \text{3} , \text{1})$

Value	1	2	3	4	5	6	7	8	9	10	11
Min # coins	1	2	1	2	1	2	3				



$$\text{minNumCoins}(M) = \min \begin{cases} \text{minNumCoins}(M - 1) + 1, \\ \text{minNumCoins}(M - 3) + 1, \\ \text{minNumCoins}(M - 5) + 1. \end{cases}$$

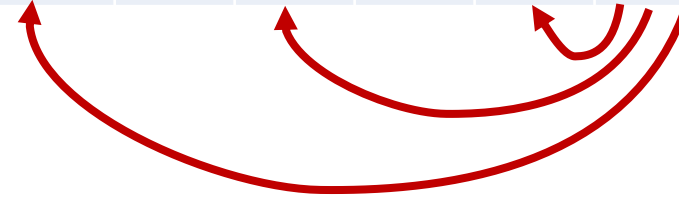
Three coins are needed to make change for the value 7

Idea #4: Solve recurrence with dynamic programming

Fill in table “bottom up”: from smallest to largest.

$c = (\text{5} , \text{3} , \text{1})$

Value	1	2	3	4	5	6	7	8	9	10	11
Min # coins	1	2	1	2	1	2	3	2			



$$\text{minNumCoins}(M) = \min \begin{cases} \text{minNumCoins}(M - 1) + 1, \\ \text{minNumCoins}(M - 3) + 1, \\ \text{minNumCoins}(M - 5) + 1. \end{cases}$$

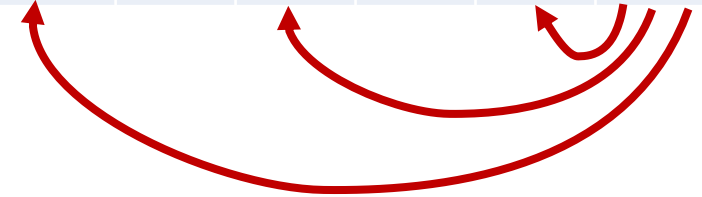
Optimal substructure: Optimal solution obtained from optimal subsolutions

Idea #4: Solve recurrence with dynamic programming

Fill in table “bottom up”: from smallest to largest.

$c = (\text{5} , \text{3} , \text{1})$

Value	1	2	3	4	5	6	7	8	9	10	11
Min # coins	1	2	1	2	1	2	3	2	3	2	3



$$\text{minNumCoins}(M) = \min \begin{cases} \text{minNumCoins}(M - 1) + 1, \\ \text{minNumCoins}(M - 3) + 1, \\ \text{minNumCoins}(M - 5) + 1. \end{cases}$$

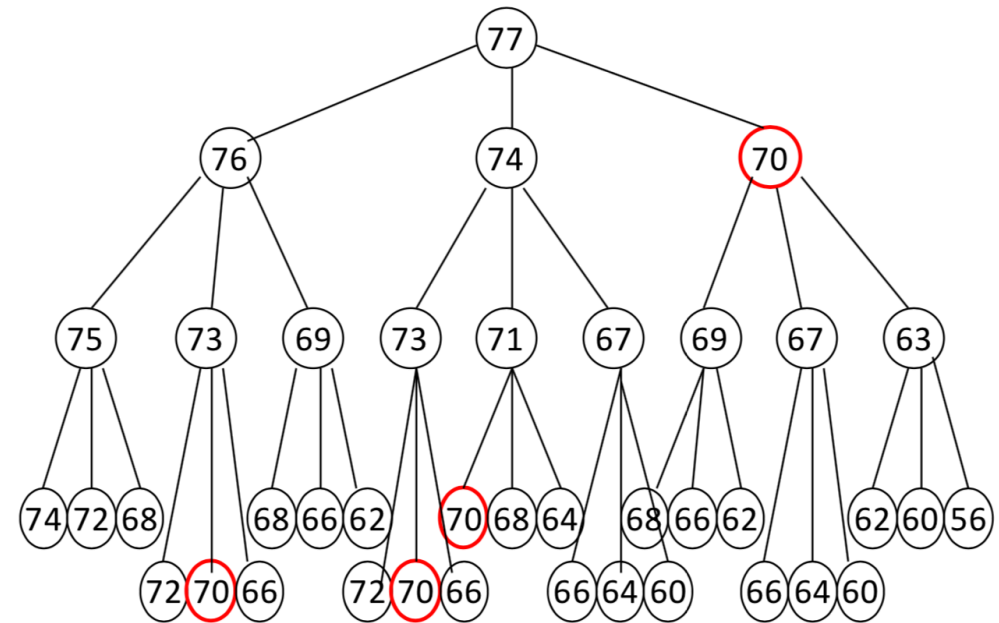
Optimal substructure: Optimal solution obtained from optimal subsolutions

Idea #4: Solve recurrence with dynamic programming

Change Problem: Given amount $M \in \mathbb{N} \setminus \{0\}$ and coins $\mathbf{c} = (c_1, \dots, c_n) \in \mathbb{N}^n$
s.t. $c_n = 1$ and $c_i \geq c_{i+1}$ for all $i \in [n - 1] = \{1, \dots, n - 1\}$,
find $\mathbf{d} = (d_1, \dots, d_n) \in \mathbb{N}^n$ s.t. (i) $M = \sum_{i=1}^n c_i d_i$ and (ii) $\sum_{i=1}^n d_i$ is minimum

$$\text{DPChange}(M, c_1, \dots, c_n)$$

1. **for** $m \leftarrow 1$ **to** M
2. $\text{minNumCoins}[m] \leftarrow \infty$
3. **for** $i \leftarrow 1$ **to** n
4. $\text{minNumCoins}[c_i] \leftarrow 1$
5. **for** $m \leftarrow 1$ **to** M
6. **for** $i \leftarrow 1$ **to** n
7. **if** $m > c_i$
8. $\text{minNumCoins}[m] \leftarrow \min(1 + \text{minNumCoins}[m - c_i], \text{minNumCoins}[m])$
9. **return** $\text{minNumCoins}[M]$



Correct? yes
Efficient? yes

Different algorithm techniques

Change Problem: Given amount $M \in \mathbb{N} \setminus \{0\}$ and coins $\mathbf{c} = (c_1, \dots, c_n) \in \mathbb{N}^n$
s.t. $c_n = 1$ and $c_i \geq c_{i+1}$ for all $i \in [n - 1] = \{1, \dots, n - 1\}$,
find $\mathbf{d} = (d_1, \dots, d_n) \in \mathbb{N}^n$ s.t. (i) $M = \sum_{i=1}^n c_i d_i$ and (ii) $\sum_{i=1}^n d_i$ is minimum

Technique	Correct?	Efficient?
Greedy algorithm [GreedyChange]	no	yes
Exhaustive enumeration [ExhaustiveChange]	yes	no
Recursive algorithm [RecursiveChange]	yes	no
Dynamic programming [DPChange]	yes	yes

Summary

- DNA, RNA and proteins are sequences
 - Central dogma of molecular biology: DNA → RNA → protein
- Problem != algorithm
- Different algorithm techniques
 - Greedy
 - Exhaustive search/brute force
 - Recursive algorithm
 - Dynamic programming algorithm
- Reading:
 - “Biology for Computer Scientists” by Lawrence Hunter (http://www.el-kebir.net/teaching/CS466/Hunter_BIO_CS.pdf)
 - Jones and Pevzner: Chapters 2.1, 2.3, 2.4, 6.2

Sources

- CS 362 by Layla Oesper (Carleton College)
- CS 1810 by Ben Raphael (Brown/Princeton University)
- An Introduction to Bioinformatics Algorithms book (Jones and Pevzner)