



BIMM 143

Genome Informatics I

Lecture 13

Barry Grant
UC San Diego

<http://thegrantlab.org/bimm143>

TODAYS MENU:

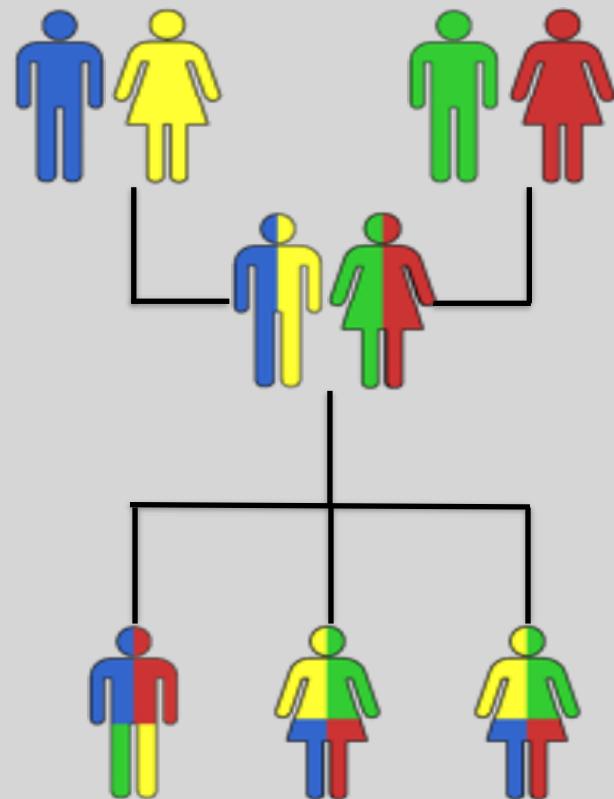
- ▶ **What is a Genome?**
 - Genome sequencing and the Human genome project
- ▶ **What can we do with a Genome?**
 - Compare, model, mine and edit
- ▶ **Modern Genome Sequencing**
 - 1st, 2nd and 3rd generation sequencing
- ▶ **Workflow for NGS**
 - RNA-Sequencing and Discovering variation

Genetics and Genomics

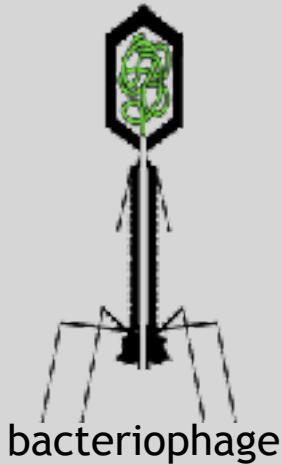
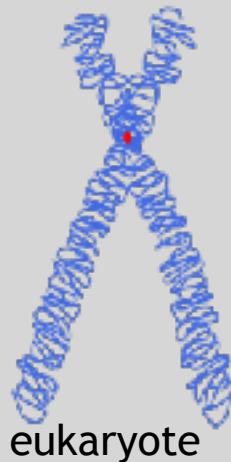
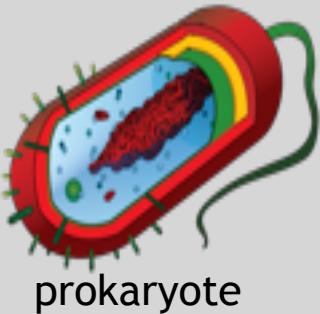
- **Genetics** is primarily the study of individual genes, mutations within those genes, and their inheritance patterns in order to understand specific traits.
- **Genomics** expands upon classical genetics and considers aspects of the entire genome, typically using computer aided approaches.

What is a Genome?

The total genetic material of an organism by which individual traits are encoded, controlled, and ultimately passed on to future generations

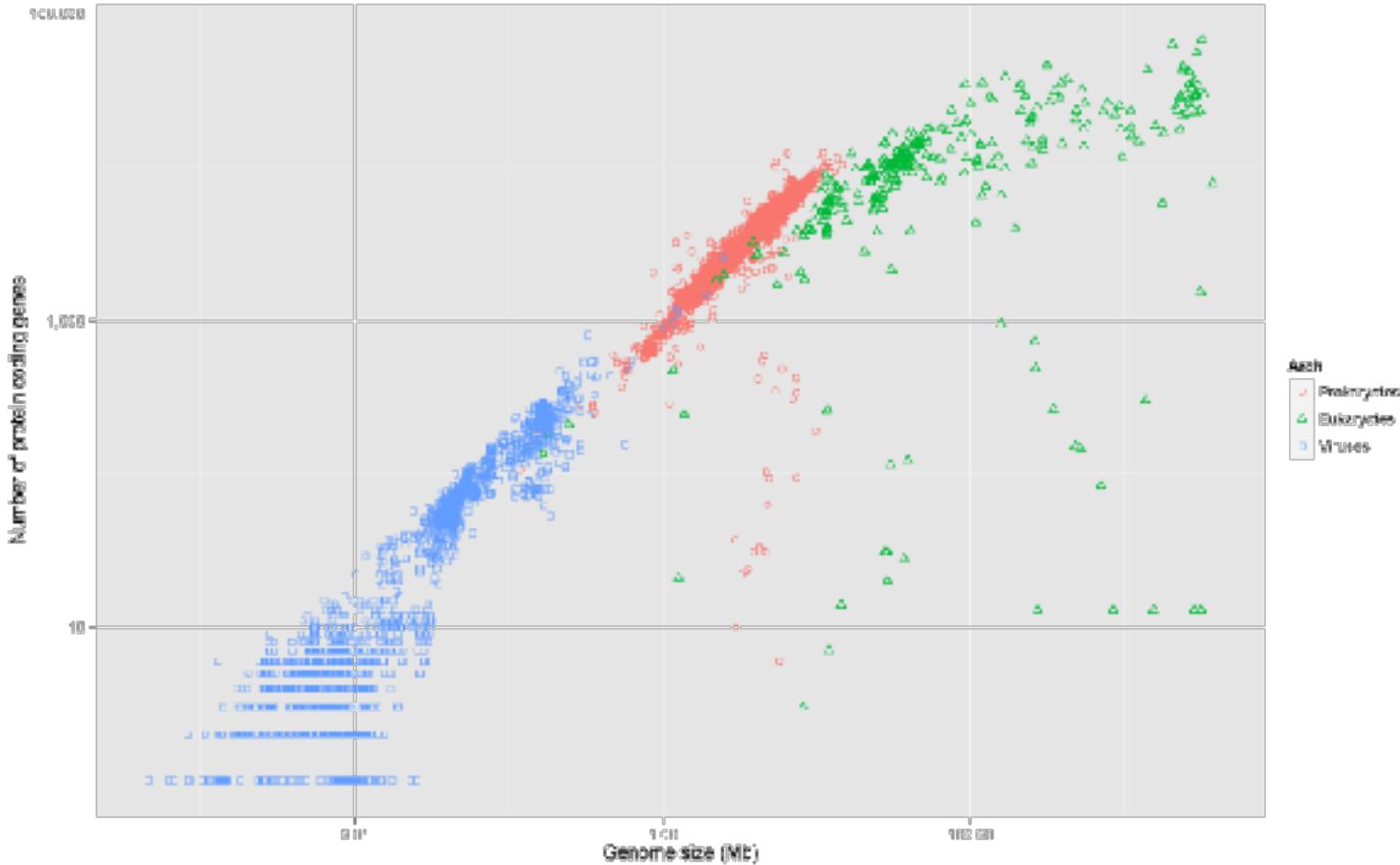


Genomes come in many shapes



- Primarily DNA, but can be RNA in the case of some viruses
- Some genomes are circular, others linear
- Can be organized into discrete units (chromosomes) or freestanding molecules (plasmids)

Genomes come in many sizes



Genome Databases

NCBI Genome:

<http://www.ncbi.nlm.nih.gov/genome>

NCBI Resources How To Sign in to NCBI

Genome

Search

Help

Using Genome

Help
Browse in Oracle
Download LTP
Download SGD
Upload a genome

Custom resources

Human Genome
Mouse
C. elegans
Yeast
PROKARYOTIC MICROBES DATABASES

Other Resources

ALBERT
BioProject
BioSample
BioAssay
MAGE Archive
MAGE Archives

Genome Tools

BLAST for Human Genome
Molecule Navigator
TaxDB (Query Genome Components)

Genome Annotation and Analysis

Eukaryotic Genome Annotation
Pathway Database
PASC (Pathway Sequence Comparison)

External Resources

SGD - Saccharomyces Genome Database
Escherichia Coli Resource
Bacteria Genome at Sanger
Large-Scale Genome Sequencing (N-50)

You are here: NCBI > Genome & Micro - Home

Get Started

NCBI Education
NCBI Help Manual
NCBI Handbook
Training & Tutorials

Resources

Chromosome Karyotype
Data & Objects
DNA & RNA
Diseases & Disorders
Gene Expression
Genes & Medicine
Genomes & Maps
Humanology
Microbes
Proteins
Sequence Analysis
Taxonomy
Training & Tutorials
Validator

Popular

PubMed
EcoCyc
PubMed Central
PubMed Health

BLAST™
Molecular

Contrace
GAP
Gene
Protein
PubChem

Featured

Gene Testing Registry
PubMed Health
GenBank
National Bioactive
Gene Expression Omnibus
Ingenuity
Human Genome
Avian Genome
Influenza Virus
Primate BLAST
Sequence Read Archive

NCBI Information

About NCBI
Research at NCBI
NCBI News
NCBI FTP Site
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NCBI on Twitter
NCBI on YouTube

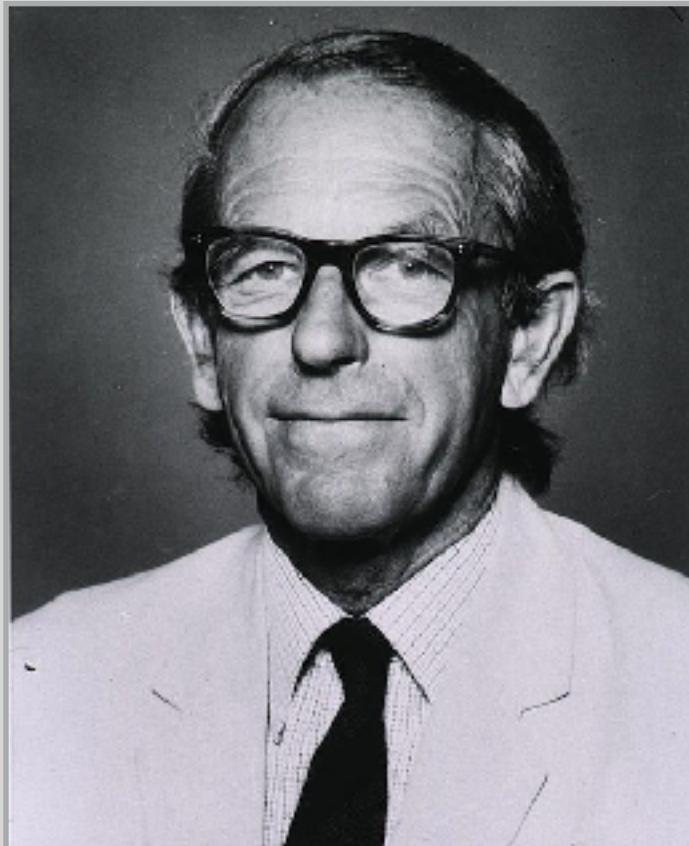
Footer

Copyright | Disclaimer | Privacy | Authors | Accessibility | Contact

National Center for Biotechnology Information, U.S. National Library of Medicine

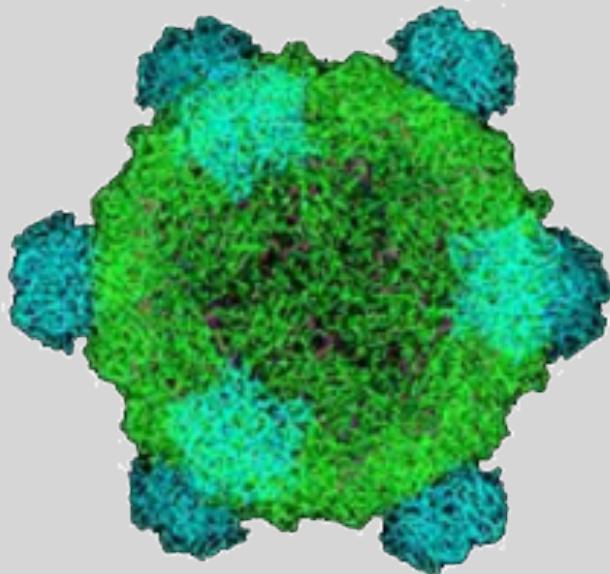
65 Bethesda North, Bethesda MD 20892 USA

Early Genome Sequencing



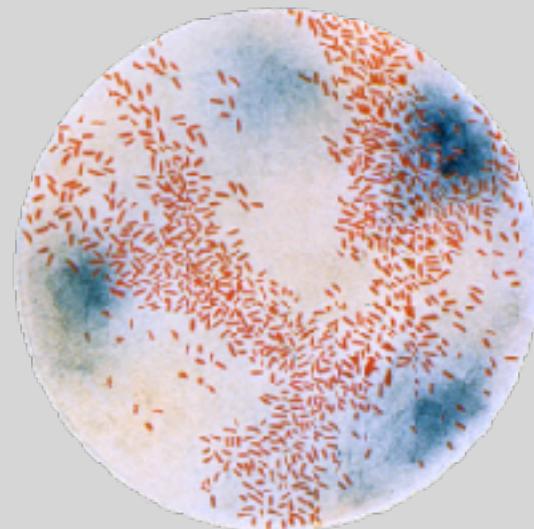
- Chain-termination “Sanger” sequencing was developed in 1977 by Frederick Sanger, colloquially referred to as the “Father of Genomics”
- Sequence reads were typically 750-1000 base pairs in length with an error rate of ~1 / 10000 bases

The First Sequenced Genomes



Bacteriophage φ-X174

- Completed in 1977
- 5,386 base pairs, ssDNA
- 11 genes



Haemophilus influenzae

- Completed in 1995
- 1,830,140 base pairs, dsDNA
- 1740 genes

The Human Genome Project

- The Human Genome Project (HGP) was an international, public consortium that began in 1990
 - Initiated by James Watson
 - Primarily led by Francis Collins
 - Eventual Cost: \$2.7 Billion
- Celera Genomics was a private corporation that started in 1998
 - Headed by Craig Venter
 - Eventual Cost: \$300 Million
- Both initiatives released initial drafts of the human genome in 2001
 - ~3.2 Billion base pairs, dsDNA
 - 22 autosomes, 2 sex chromosomes
 - ~20,000 genes

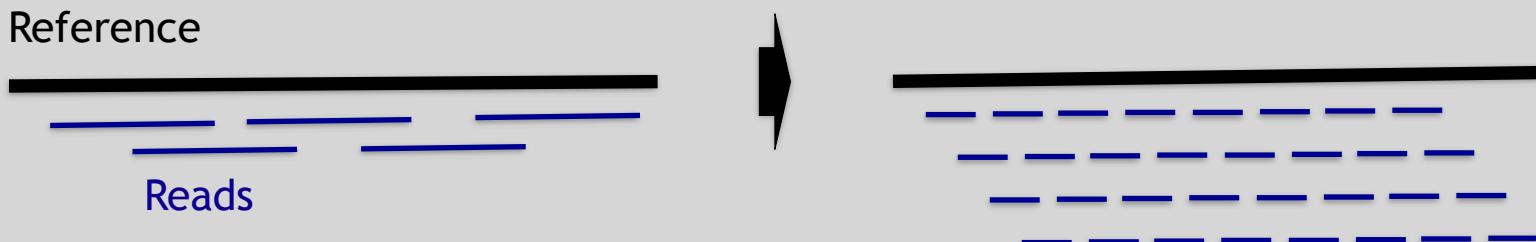




HHMI

Modern Genome Sequencing

- Next Generation Sequencing (NGS) technologies have resulted in a paradigm shift from long reads at low coverage to short reads at high coverage
- This provides numerous opportunities for new and expanded genomic applications



Rapid progress of genome sequencing

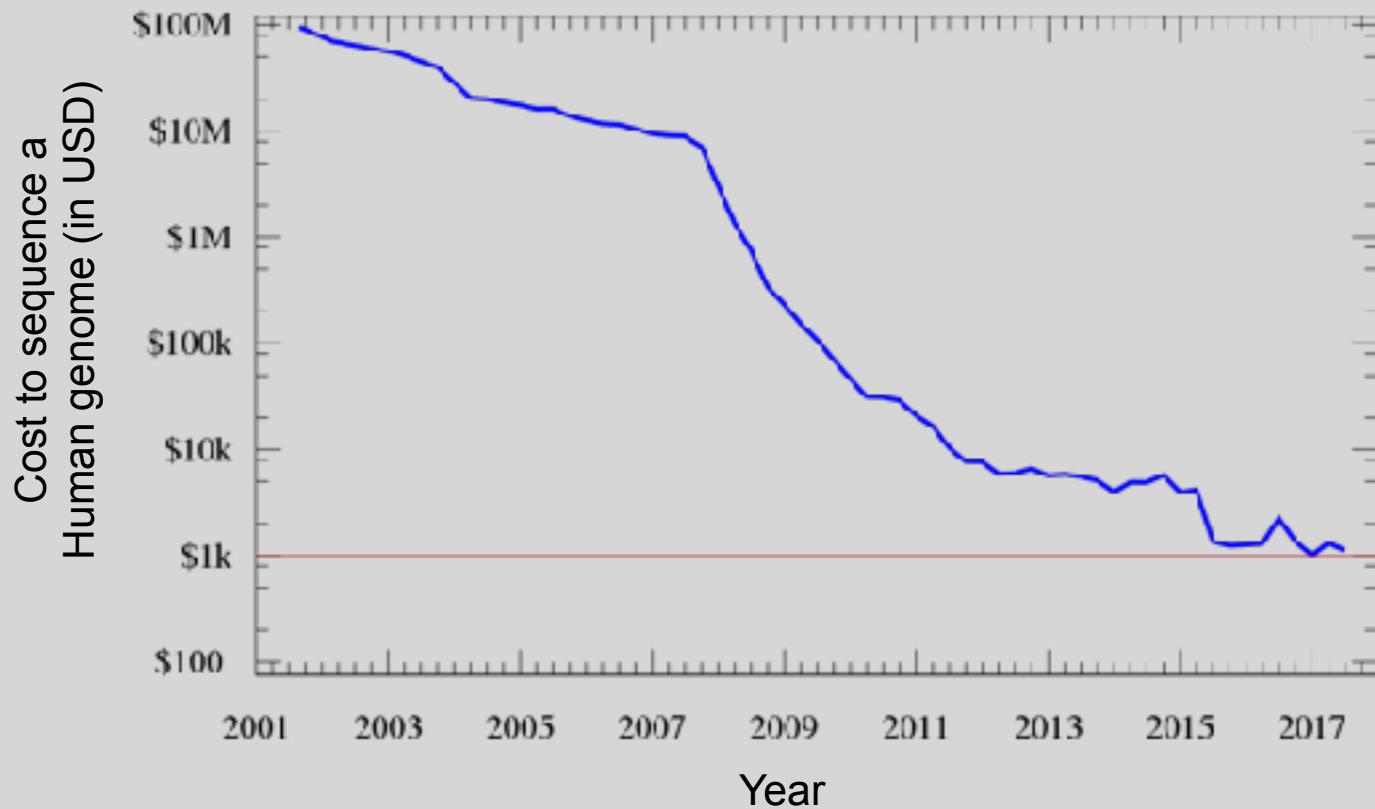


Image source: https://en.wikipedia.org/wiki/Carlson_curve

Rapid progress of genome sequencing

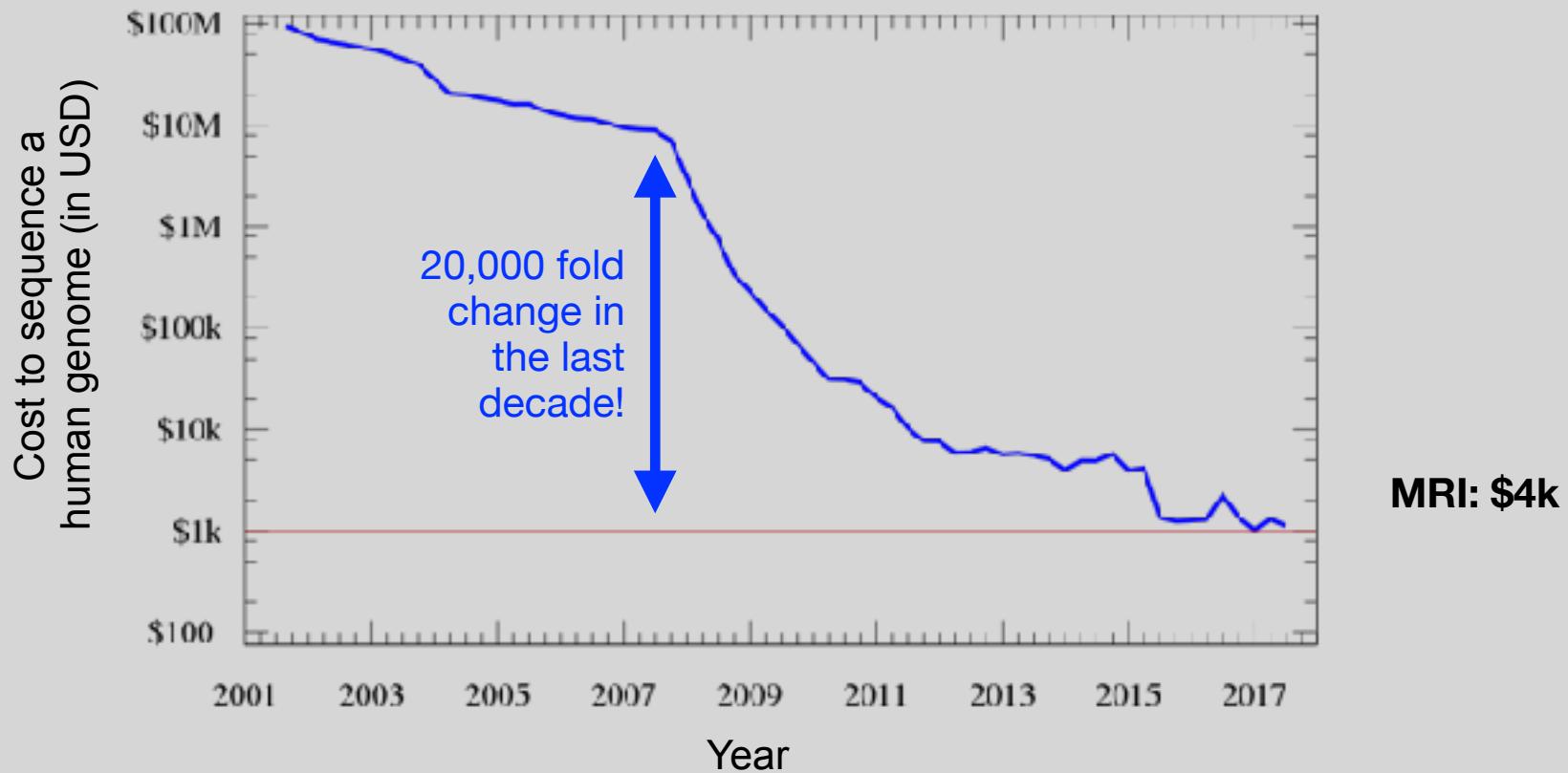
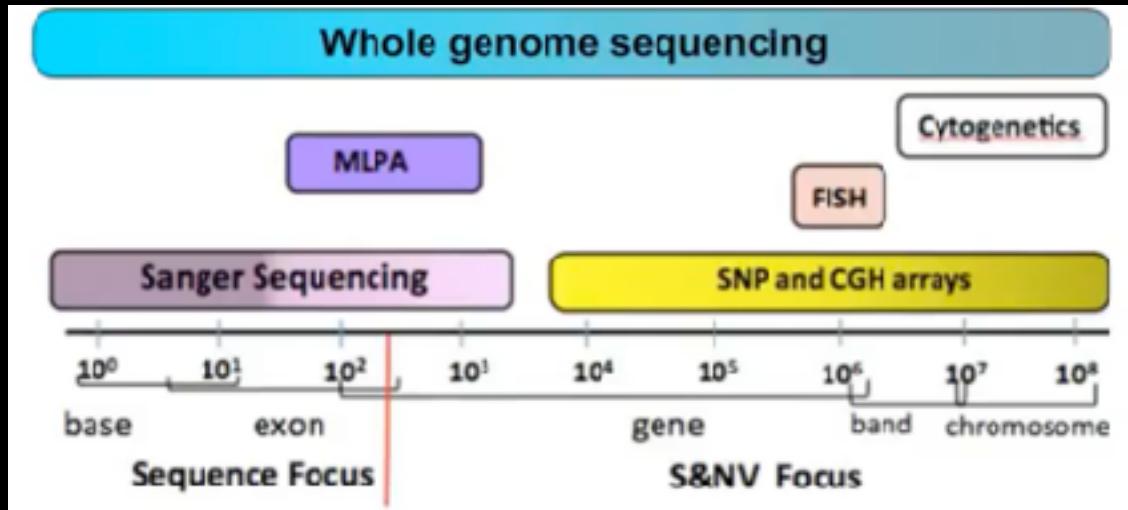


Image source: https://en.wikipedia.org/wiki/Carlson_curve

Whole genome sequencing transforms genetic testing



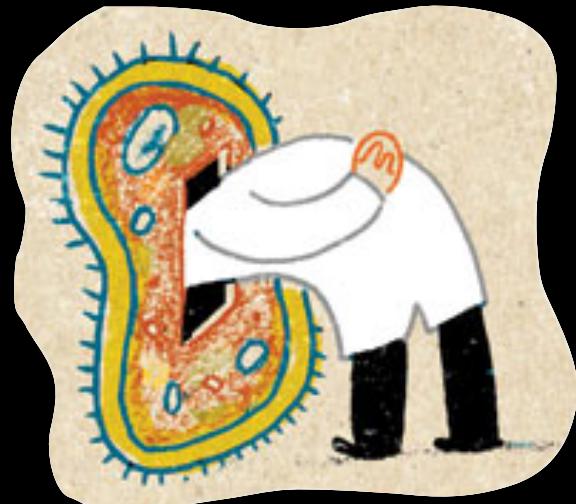
- 1000s of single gene tests
- Structural and copy number variation tests
- Permits hypothesis free diagnosis

Major impact areas for genomic medicine

- **Cancer:** Identification of driver mutations and drugable variants, Molecular stratification to guide and monitor treatment, Identification of tumor specific variants for personalized immunotherapy approaches (precision medicine).
- **Genetic disease diagnose:** Rare, inherited and so-called ‘mystery’ disease diagnose.
- **Health management:** Predisposition testing for complex diseases (e.g. cardiac disease, diabetes and others), optimization and avoidance of adverse drug reactions.
- **Health data analytics:** Incorporating genomic data with additional health data for improved healthcare delivery.

Goals of Cancer Genome Research

- Identify changes in the genomes of tumors that drive cancer progression
- Identify new targets for therapy
- Select drugs based on the genomics of the tumor
- Provide early cancer detection and treatment response monitoring
- Utilize cancer specific mutations to derive neoantigen immunotherapy approaches



What can go wrong in cancer genomes?

Type of change	Some common technology to study changes
DNA mutations	WGS, WXS
DNA structural variations	WGS
Copy number variation (CNV)	CGH array, SNP array, WGS
DNA methylation	Methylation array, RRBS, WGBS
mRNA expression changes	mRNA expression array, RNA-seq
miRNA expression changes	miRNA expression array, miRNA-seq
<i>Protein expression</i>	Protein arrays, mass spectrometry

WGS = whole genome sequencing, WXS = whole exome sequencing

RRBS = reduced representation bisulfite sequencing, WGBS = whole genome bisulfite sequencing

DNA Sequencing Concepts

- **Sequencing by Synthesis:** Uses a polymerase to incorporate and assess nucleotides to a primer sequence
 - 1 nucleotide at a time
- **Sequencing by Ligation:** Uses a ligase to attach hybridized sequences to a primer sequence
 - 1 or more nucleotides at a time (e.g. dibase)

Modern NGS Sequencing Platforms

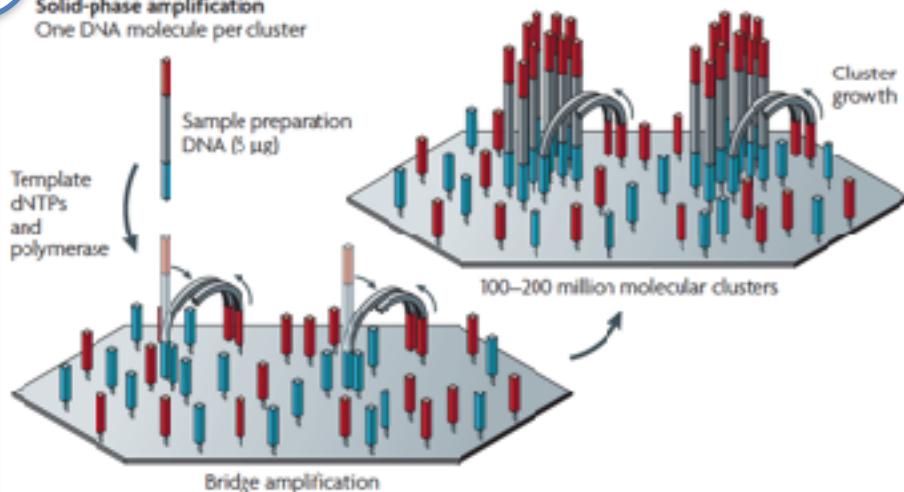
	Roche/454	Life Technologies SOLiD	Illumina Hi-Seq 2000
Library amplification method	emPCR* on bead surface	emPCR* on bead surface	Enzymatic amplification on glass surface
Sequencing method	Polymerase mediated incorporation of unlabelled nucleotides	Ligase mediated addition of 2-base encoded fluorescent oligonucleotides	Polymerase mediated incorporation of end-blocked fluorescent nucleotides
Detection method	Light emitted from secondary reactions initiated by release of PPI	Fluorescent emission from ligated dye-labelled oligonucleotides	Fluorescent emission from incorporated dye-labelled nucleotides
Post incorporation method	NA (unlabelled nucleotides are added in base-specific fashion, followed by detection)	Chemical cleavage removes fluorescent dye and 3' end of oligonucleotide	Chemical cleavage of fluorescent dye and 3' blocking group
Error model	Substitution errors rare, insertion/deletion errors at homopolymers	End of read substitution errors	End of read substitution errors
Read length (fragment/paired end)	400 bp/variable length mate pairs	75 bp/50+25 bp	150 bp/100+100bp

Illumina - Reversible terminators

1

Enzymatic amplification on glass surface

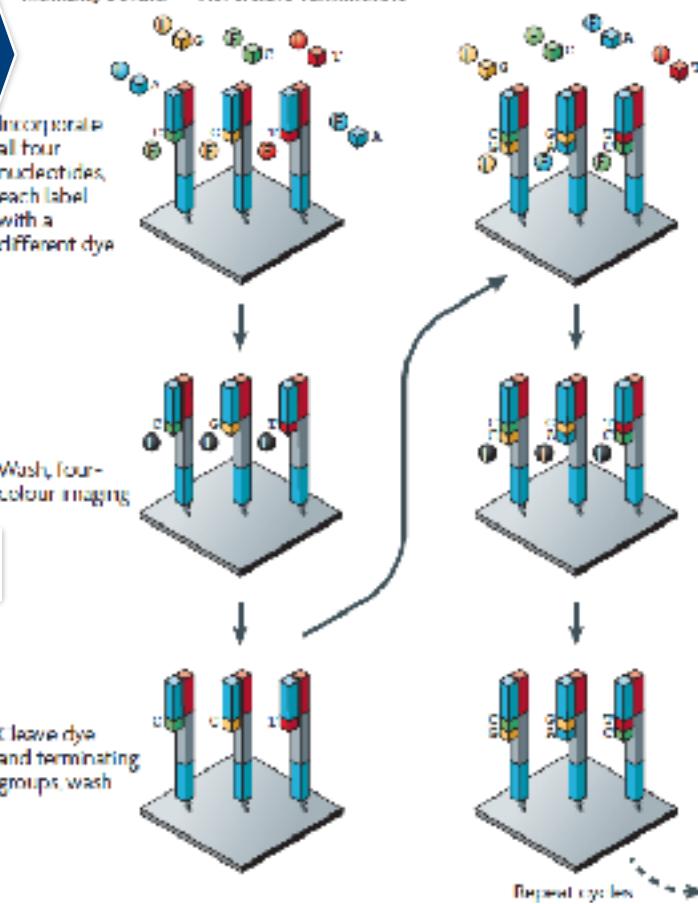
Illumina/Solexa
Solid-phase amplification
One DNA molecule per cluster



2

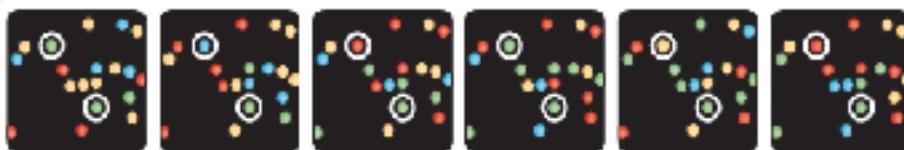
Polymerase-mediated incorporation of end blocked fluorescent nucleotides

Illumina/Solexa — Reversible terminators



3

Fluorescent emission from incorporated dye-labeled nucleotides



Top: CATCGT
Bottom: CGCCCG

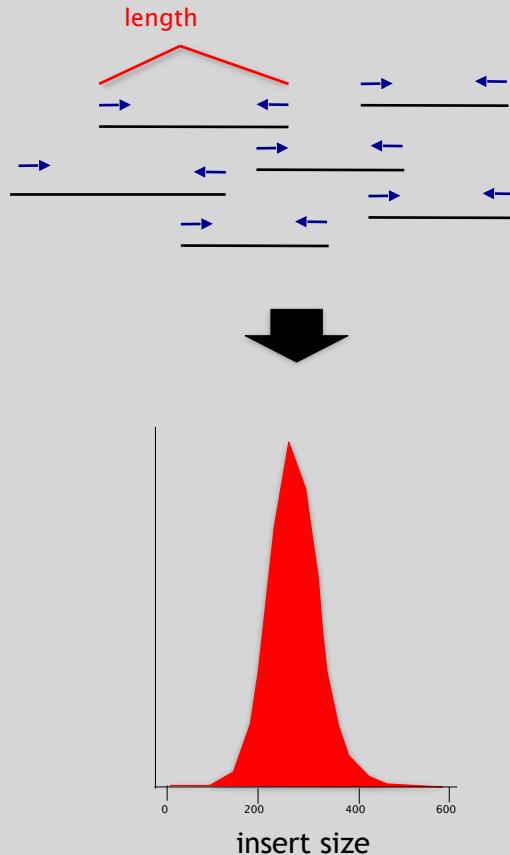
Illumina Sequencing - Video



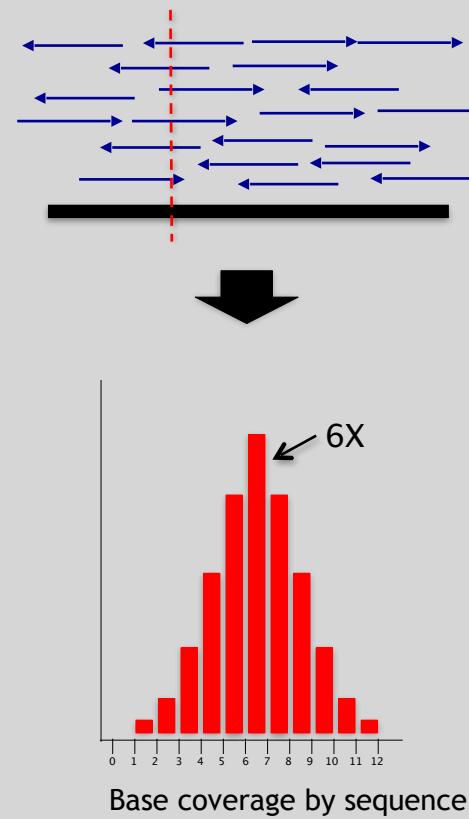
https://www.youtube.com/watch?src_vid=womKfikWlxM&v=fCd6B5HRaZ8

NGS Sequencing Terminology

Insert Size



Sequence Coverage



Summary: “Generations” of DNA Sequencing

	First generation	Second generation ^b	Third generation ^b
Fundamental technology	Size separation of specifically end-labeled DNA fragments, produced by SBS or degradation	Wash-and-scan SBS	SBS, by degradation, or direct physical inspection of the DNA molecule
Resolution	Averaged across many copies of the DNA molecule being sequenced	Averaged across many copies of the DNA molecule being sequenced	Single-molecule resolution
Current raw read accuracy	High	High	Moderate
Current read length	Moderate (800–1000 bp)	Short, generally much shorter than Sanger sequencing	Long, 1000 bp and longer in commercial systems
Current throughput	Low	High	Moderate
Current cost	High cost per base	Low cost per base	Low-to-moderate cost per base
	Low cost per run	High cost per run	Low cost per run
RNA-sequencing method	cDNA sequencing	cDNA sequencing	Direct RNA sequencing and cDNA sequencing
Time from start of sequencing reaction to result	Hours	Days	Hours
Sample preparation	Moderately complex, PCR amplification not required	Complex, PCR amplification required	Ranges from complex to very simple depending on technology
Data analysis	Routine	Complex because of large data volumes and because short reads complicate assembly and alignment algorithms	Complex because of large data volumes and because technologies yield new types of information and new signal processing challenges
Primary results	Base calls with quality values	Base calls with quality values	Base calls with quality values, potentially other base information such as kinetics

Third Generation Sequencing

- Currently in active development
- Hard to define what “3rd” generation means
- Typical characteristics:
 - Long (1,000bp+) sequence reads
 - Single molecule (no amplification step)
 - Often associated with nanopore technology
 - But not necessarily!

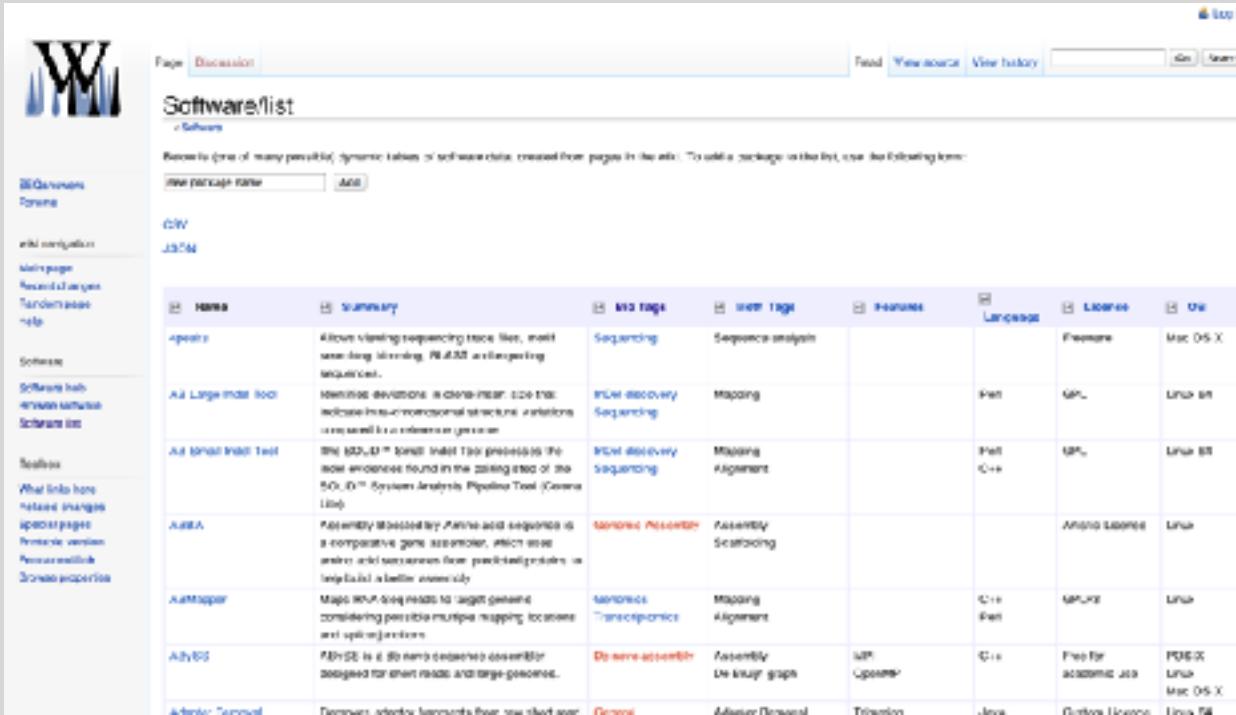
The first direct RNA sequencing by nanopore

- For example this new nanopore sequencing method was just published!
<https://www.nature.com/articles/nmeth.4577>
- "Sequencing the RNA in a biological sample can unlock a wealth of information, including the identity of bacteria and viruses, the nuances of alternative splicing or the transcriptional state of organisms. However, current methods have limitations due to short read lengths and reverse transcription or amplification biases. Here we demonstrate nanopore direct RNA-seq, a highly parallel, real-time, single-molecule method that circumvents reverse transcription or amplification steps."

Side-Note:

SeqAnswers Wiki

A good repository of analysis software can be found at
<http://seqanswers.com/wiki/Software/list>



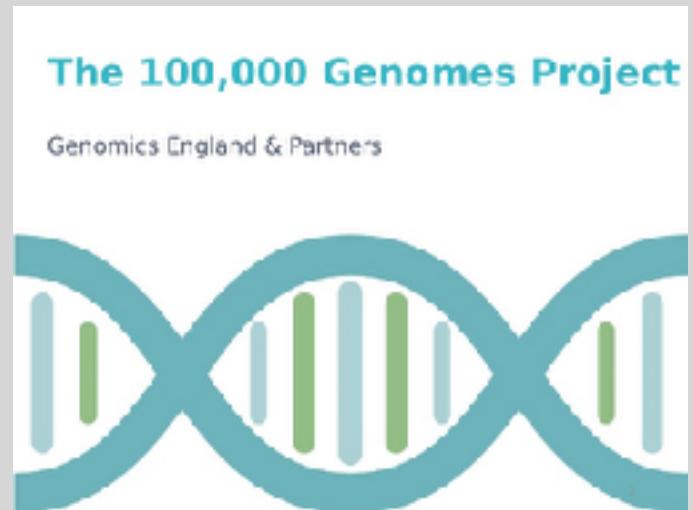
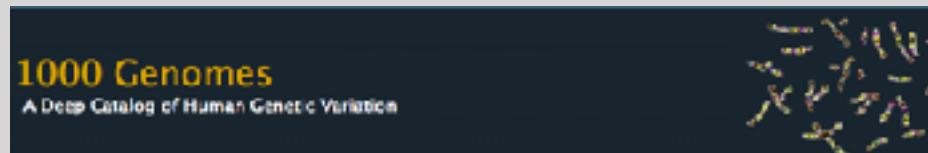
The screenshot shows a table titled "Software/list" on the SeqAnswers Wiki. The table lists various bioinformatics tools, each with a brief description, categories, and technical details like language and license.

Name	Summary	Tags	User tags	Features	Language	Licence	OS
fastQC	Allows viewing sequencing trace files, most commonly illumina, PE/ILL and long sequencing.	Sequencing	Sequence analysis			Freeware	Mac, OS-X
All Large Read Tool	Identifies deviations in short-read size that indicate trans-structural structural variations compared to a reference genome.	INDEL discovery Sequencing	Mapping		Perl	GPL	Linux, OS
All Small Read Tool	The SGD-3D Small Read tool provides the most evidence found in the catalog tool of the SGD3D™ System Analysis Pipeline Tool (Cavaria Life)	INDEL discovery Sequencing	Mapping Alignment		Perl C++	GPL	Linux, OS
ABBA	Polymerase Directed by Amino-acid sequence is a comparative gene assembler, which uses amino acid sequences from predicted proteins to help build a better assembly.	bioinformatics bioassembly	Assembly Scaffolding			Apache License	Linux
AutMapper	Maps RNA-seq reads to target genome considering possible multiple mapping locations and splice junctions.	bioinformatics bioinformatics	Mapping Alignment		C/C++	GPL	Linux
ABES	ABES is a BioPerl-based assembler designed for short reads and large genomes.	bioinformatics bioassembly	Assembly De-bruijn graphs	API Casper	C/C++	Free for academic use	PGSSR Linux Mac, OS-X
Automer	Automer identifies isoforms from raw short reads.	bioinformatics bioassembly	Automer	Trilateration	C/C++	Apache License	Linux, OS

What can we do with all
this sequence information?

Population Scale Analysis

We can now begin to assess genetic differences on a very large scale, both as naturally occurring variation in human and non-human populations as well somatically within tumors



<https://www.genomicsengland.co.uk/the-100000-genomes-project/>

“Variety’s the very spice of life”

-William Cowper, 1785

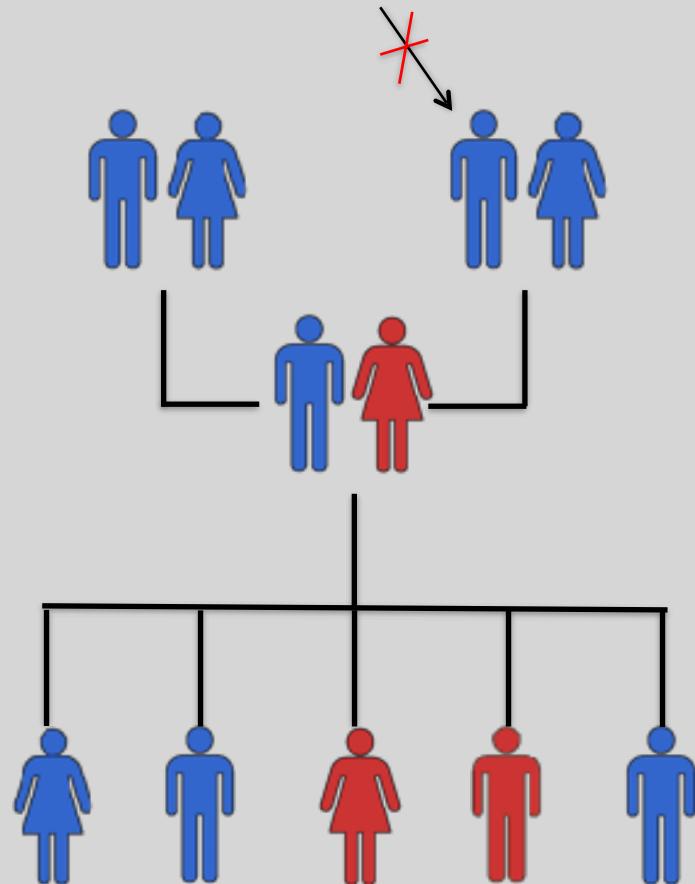
“Variation is the spice of life”

-Kruglyak & Nickerson, 2001

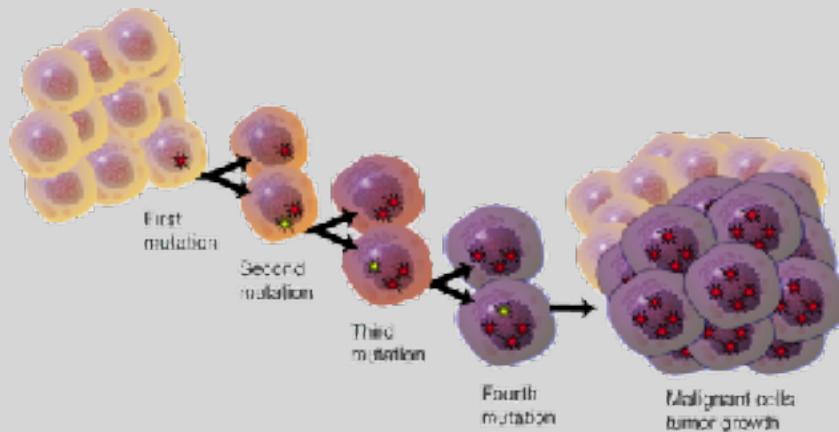
- While the sequencing of the human genome was a great milestone, the DNA from a single person is not representative of the millions of potential differences that can occur between individuals
- These unknown genetic variants could be the cause of many phenotypes such as differing morphology, susceptibility to disease, or be completely benign.

Germline Variation

- Mutations in the germline are passed along to offspring and are present in the DNA over every cell
- In animals, these typically occur in meiosis during gamete differentiation



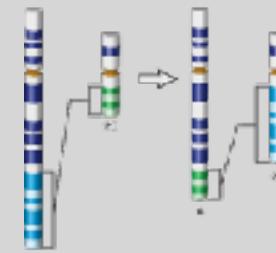
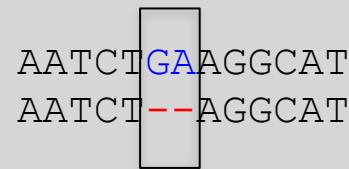
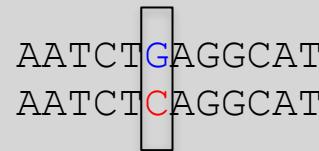
Somatic Variation



- Mutations in non-germline cells that are not passed along to offspring
- Can occur during mitosis or from the environment itself
- Are an integral part in tumor progression and evolution

Types of Genomic Variation

- **Single Nucleotide Polymorphisms (SNPs)** - mutations of one nucleotide to another
- **Insertion/Deletion Polymorphisms (INDELs)** - small mutations removing or adding one or more nucleotides at a particular locus
- **Structural Variation (SVs)** - medium to large sized rearrangements of chromosomal DNA



Differences Between Individuals

The average number of genetic differences in the germline between two random humans can be broken down as follows:

- 3,600,000 single nucleotide differences
- 344,000 small insertion and deletions
- 1,000 larger deletion and duplications

Numbers change depending on ancestry!

Discovering Variation: SNPs and INDELS

SNP

sequencing error or genetic variant?

ATCCTGATTCGGTGAACGTTATCGACGATCCGATCGA
ATCCTGATTCGGTGAACGTTATCGACGATCCGATCGA
CGGTGAACGTTATCGACGATCCGATCGAACTGTCAGC
GGTGAACGTTATCGACGTTCCGATCGAACTGTCAGCG
TGAACGTTATCGACGTTCCGATCGAACTGTCATCGGC
TGAACGTTATCGACGTTCCGATCGAACTGTCAGCGGC
TGAACGTTATCGACGTTCCGATCGAACTGTCAGCGGC
GTATCGACGATCCGATCGAACTGTCAGCGGAAGCT
TTATCGACGATCCGATCGAACTGTCAGCGGAAGCT

ATCCTGATTCGGTGAACGTTATCGACGATCCGATCGAACTGTCAGCGGAAGCTGATCGATCGATGCTAGTG

reference genome

sequencing error or genetic variant?

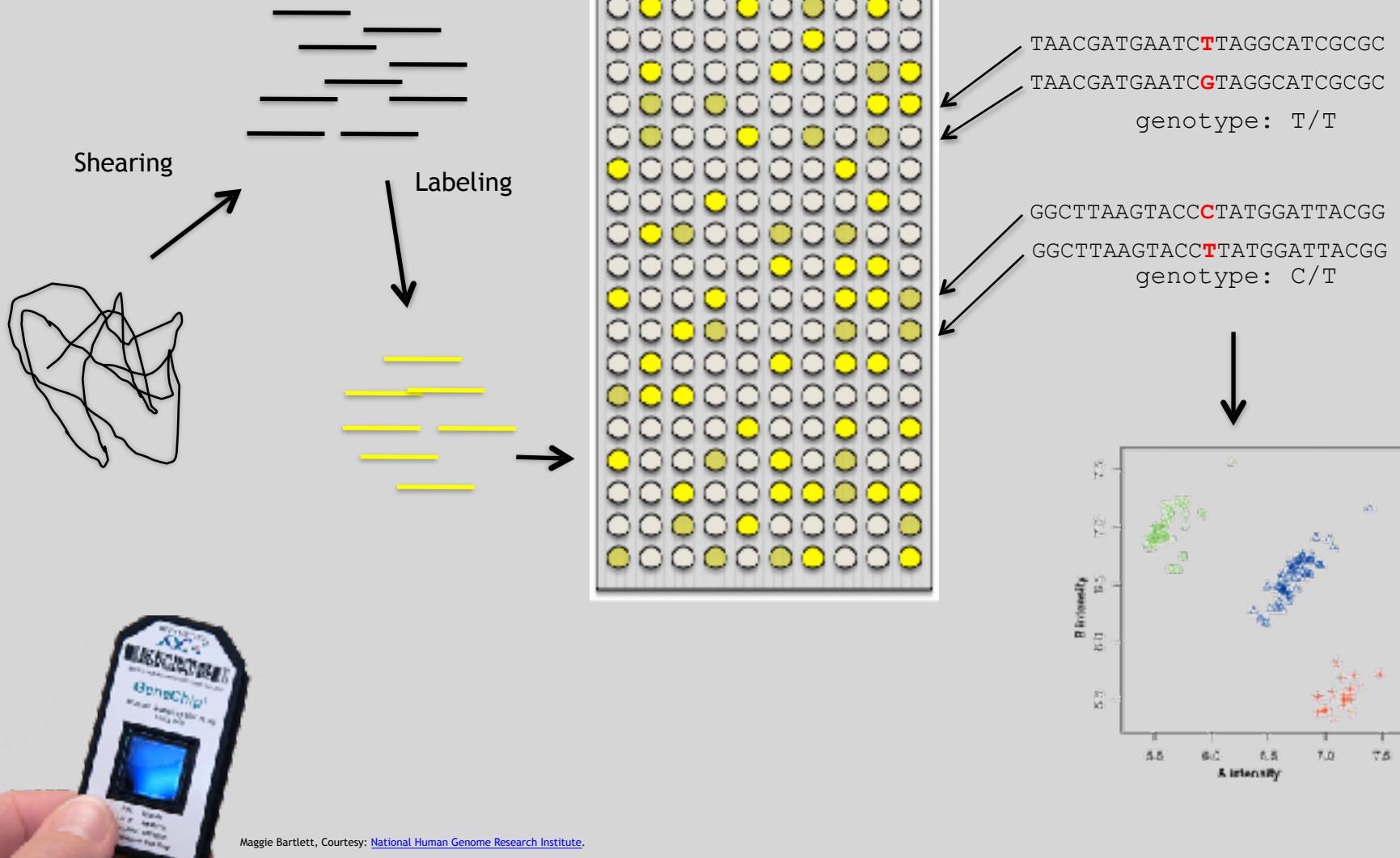
TTATCGACGATCCGATCGAACTGTCAGCGGAAGCT
TCGACGATCCGATCGAACTGTCAGCGGAAGCTGATCG
ATCCGATCGAACTGTCAGCGGAAGCTGATCGCGATCG
TCCGAGCGAACTGTCAGCGGAAGCTGATCGCGATCG
TCCGATCGAACTGTCAGCGGAAGCTGATCGATCGA
GATCGAACTGTCAGCGGAAGCTGATCGCGATCGA
AACTGTCAGCGGAAGCTGATCGCGATCGATGCTA
TGTCAAGCGGAAGCTGATCGATCGATCGATGCTAG
TCAGCGGAAGCTGATCGATCGATCGATGCTAGTG

INDEL

Genotyping Small Variants

- Once discovered, oligonucleotide probes can be generated with each individual allele of a variant of interest
- A large number can then be assessed simultaneously on microarrays to detect which combination of alleles is present in a sample

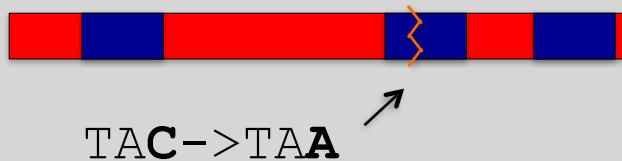
SNP Microarrays



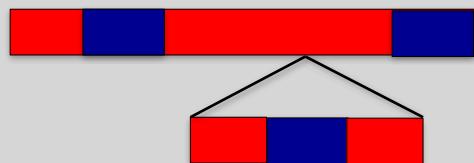
Impact of Genetic Variation

There are numerous ways genetic variation can exhibit functional effects

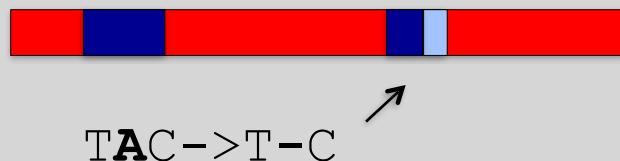
Premature stop codons



Gene or exon deletion

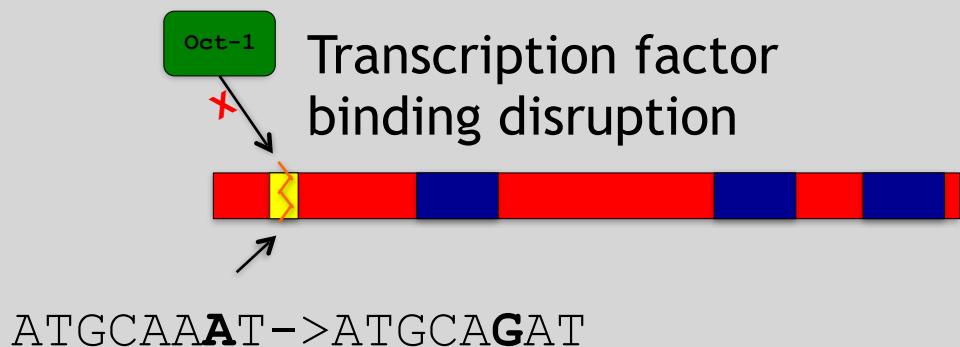


Frameshift mutation



Oct-1

Transcription factor binding disruption



Hand-on time!

https://bioboot.github.io/bimm143_S18/lectures/#13

Sections **1** to **3** please (up to running Read Alignment)

See IP address on website for **your** Galaxy server

<http://uswest.ensembl.org/Help/View?id=140>

The screenshot displays the Ensembl genome browser interface for Human (GRCh38.p0) at location 12:25,204,789-25,290,914. The interface is organized into three main sections:

- Chromosome image:** The top panel shows a chromosome 12 banding pattern with a red vertical bar indicating the "Region of interest". To the right, a box labeled "Haplotypes and patches" contains a small diagram of colored rectangles. A callout points to this area.
- Overview image:** The middle panel, titled "Region in detail", provides a detailed view of the genomic region. It includes a table of genes and their coordinates, a "Gene" track, and a "Genome" track. A callout points to the "Gene or region of interest" section. On the left, there are "Change or add data tracks" buttons and a "Configure this page" link, both circled in red.
- Zoomable Region Image:** The bottom panel shows a zoomed-in view of the genomic region. It features a "Genome" track and a "Transcripts (splice variants)" track. A callout points to the "Genome" track. On the left, there is another "Change or add data tracks" button and a "Configure this page" link, also circled in red.

Do it Yourself!

Access a jetstream galaxy instance!

Use assigned IP address

The screenshot shows the Galaxy web interface running on port 149.165.169.186. The main page displays the configuration for the "Bowtie2 - map reads against reference genome" tool (Galaxy Version 2.2.6.2). The configuration includes:

- Is this single or paired library?**: Single-end.
- FASTQ file**: A dropdown menu showing "4: HC00109_2.fastq" selected, with a note: "Must be of datatype 'Fastqsanger'".
- Write unaligned reads (in fastq format) to separate file(s)?**: Yes.
- Write aligned reads (in fastq format) to separate file(s)?**: Yes.
- Will you select a reference genome from your history or use a built-in index?**: Use a built-in genome index.
- Select reference genome**: Baboon (Papio anubis); papfam1.
- Set read groups information?**: Do not set.
- Select analysis mode**: 1. Default setting only.
- Do you want to use presets?**: No, just use defaults.

The right side of the interface shows the History panel, which contains a list of recent analyses:

- 12.12 MB
- 25: rseq-count on data_18 and data_17 (no feature)
- 24: rseq-count on data_18 and data_17
- 23: Cufflinks on data_18 and data_16; Skipped Transcripts
- 21: Cufflinks on data_18 and data_16; assembled transcripts
- 20: Cufflinks on data_18 and data_16; transcript expression
- 19: Cufflinks on data_18 and data_16; gene expression
- 575 lines

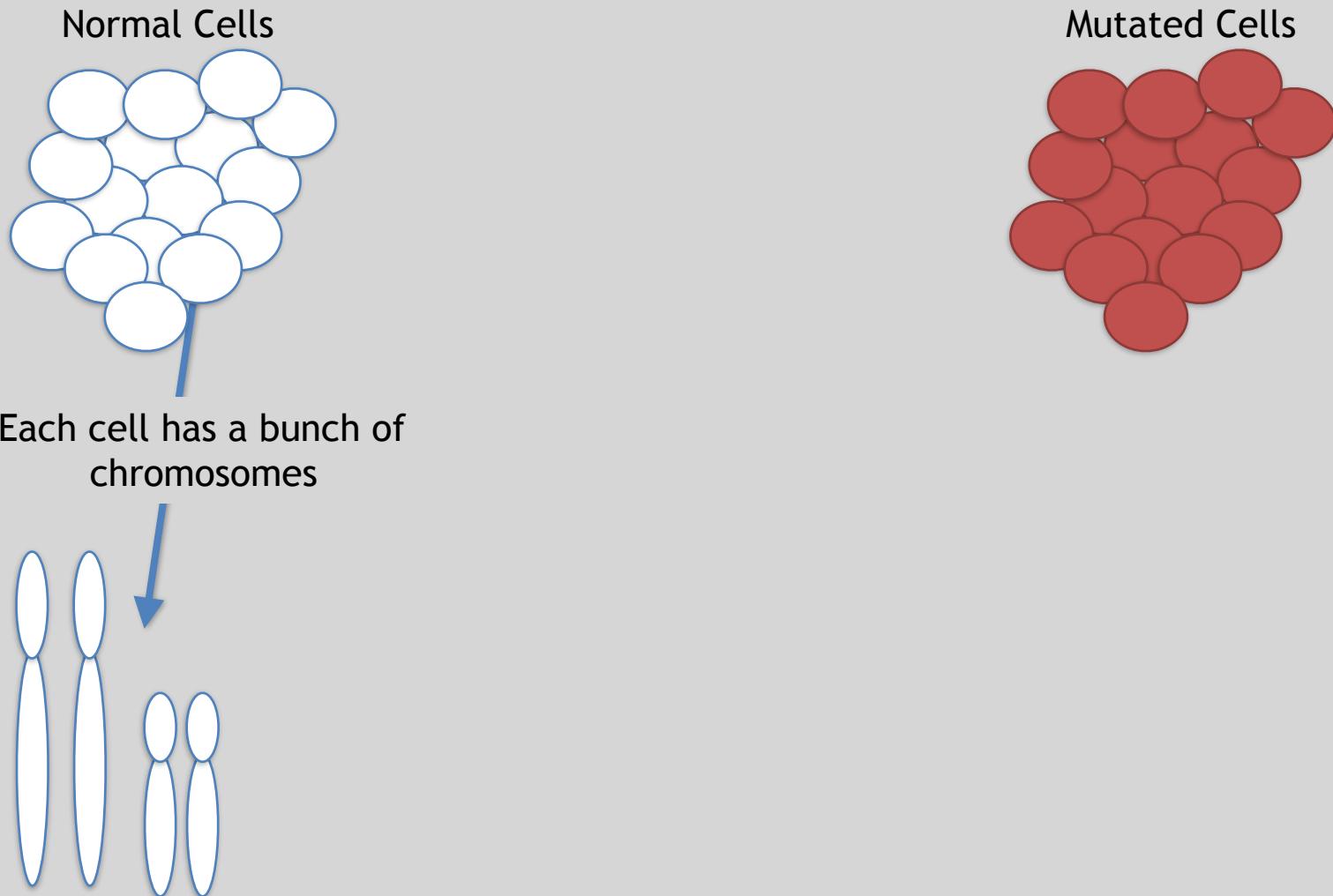
At the bottom, there is a footer note: "From the bowtie2 mapping statistics to the history."

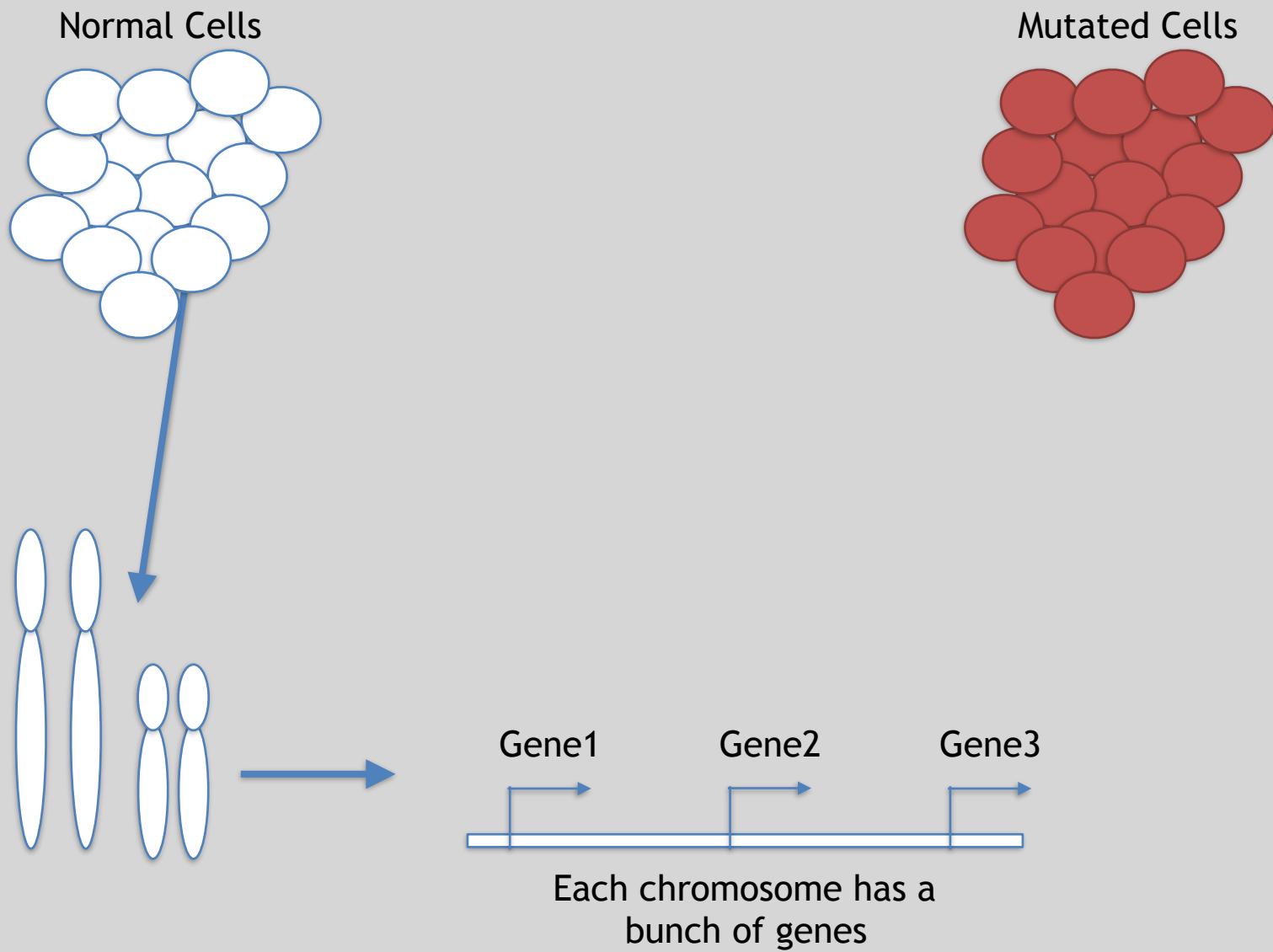
RNA Sequencing

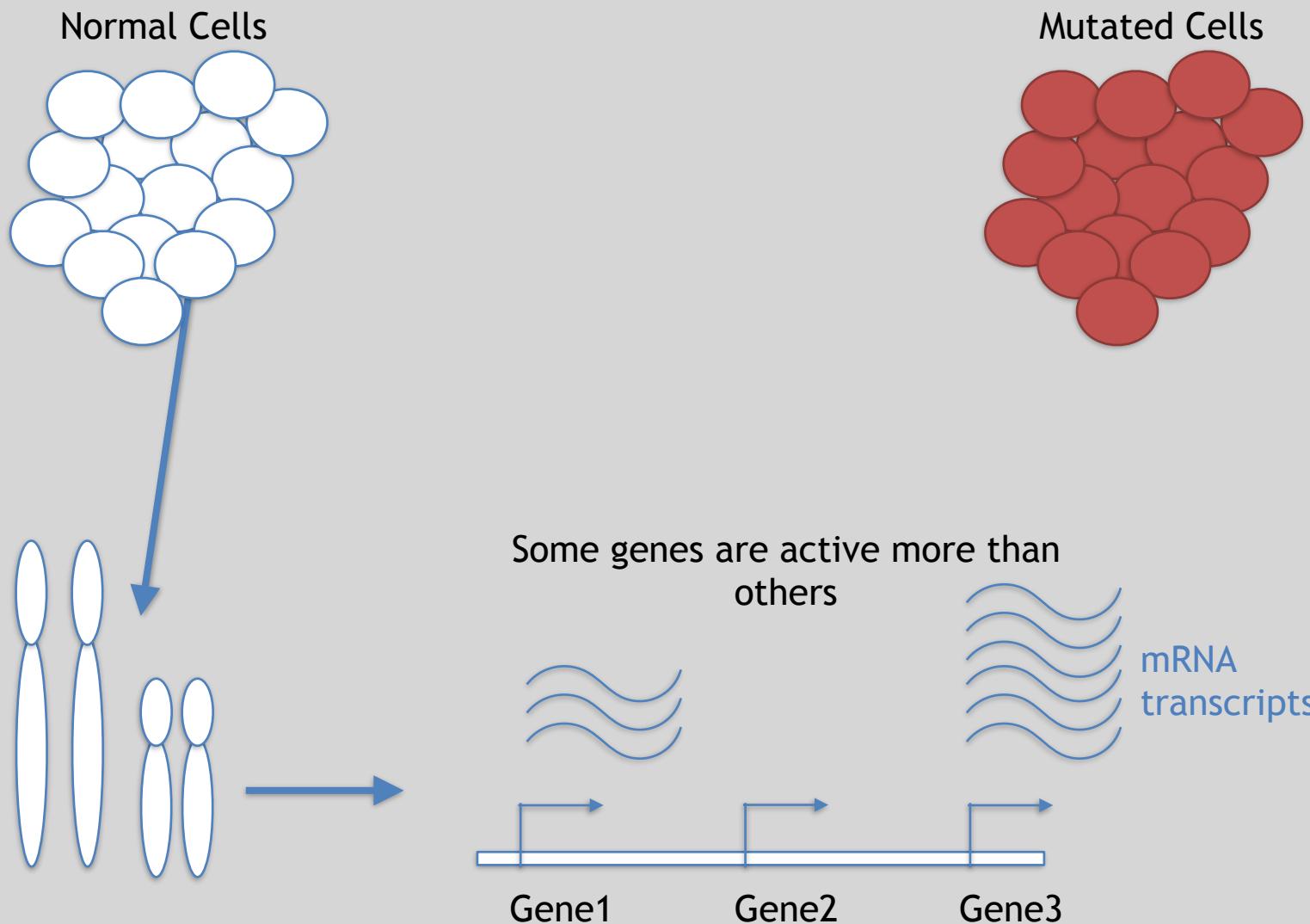
The absolute basics

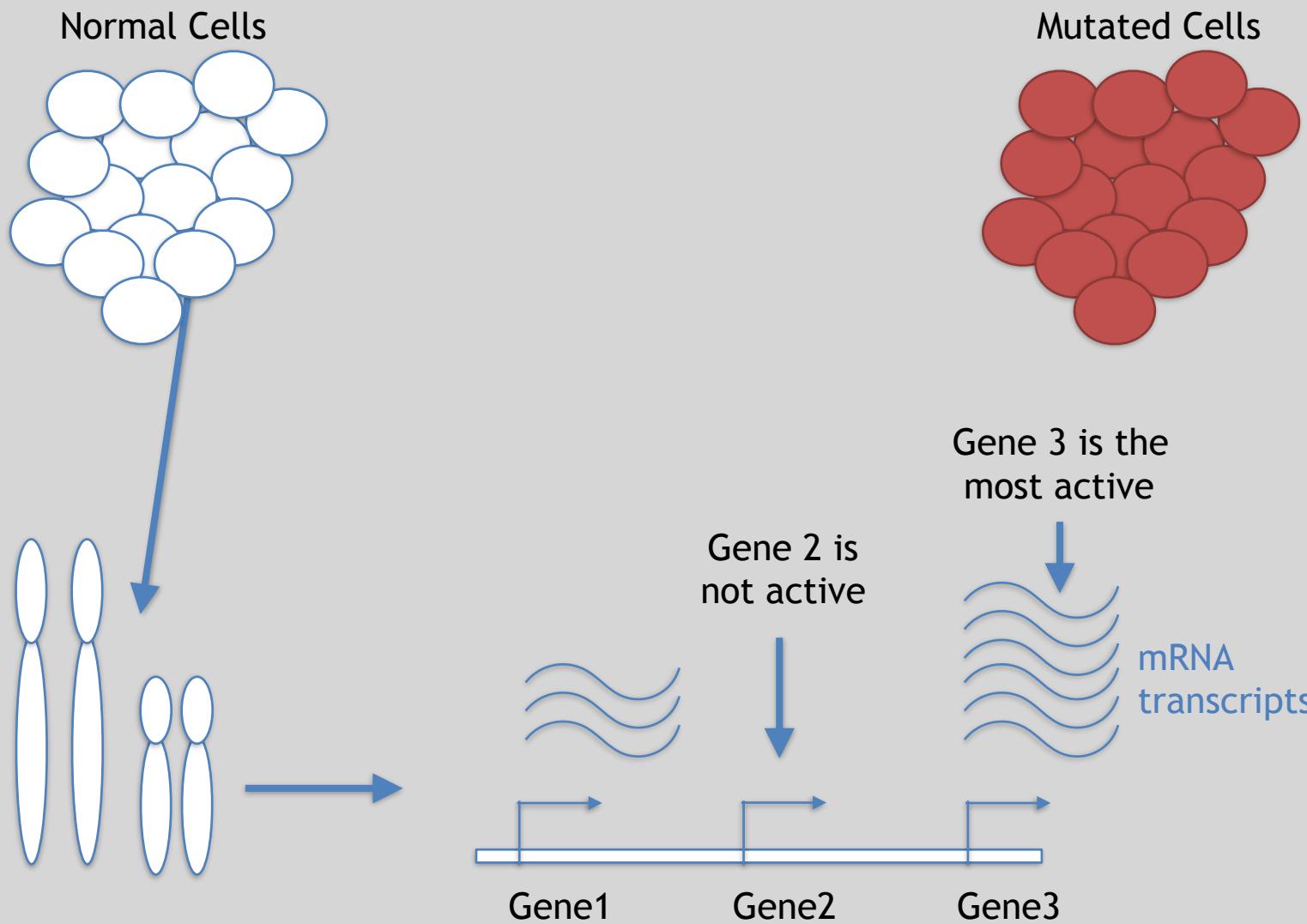


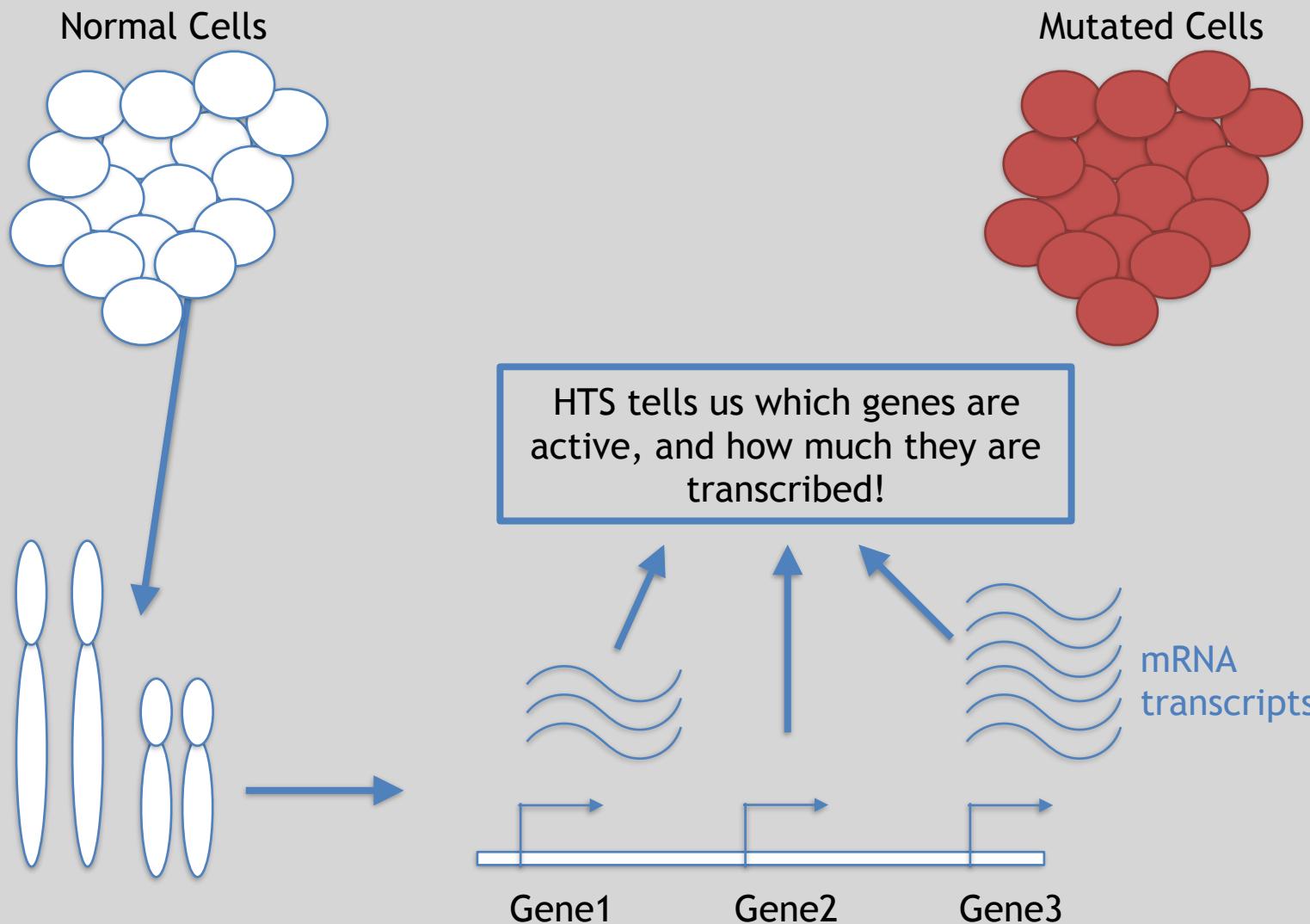
- The **mutated cells** behave differently than the **normal cells**
- We want to know what genetic mechanism is causing the difference
- One way to address this is to examine differences in gene expression via RNA sequencing...

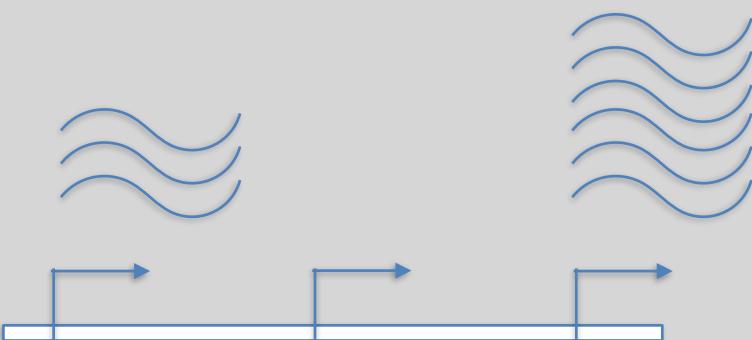
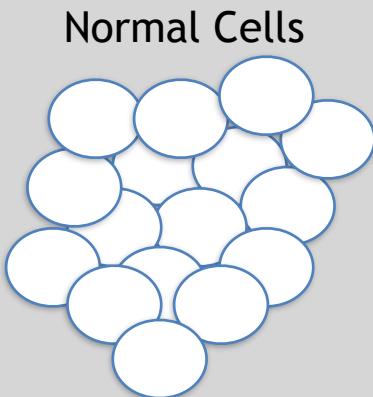




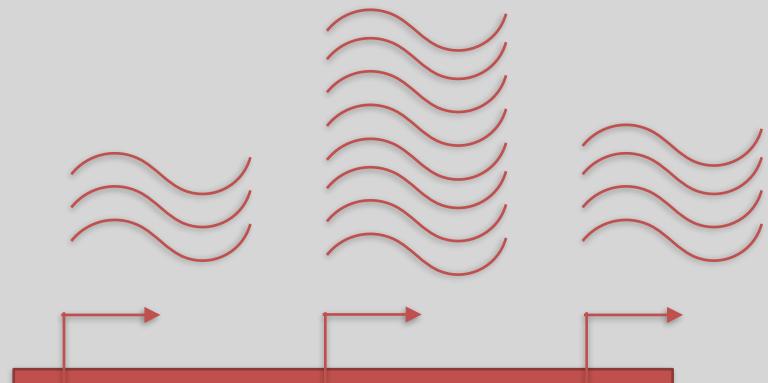
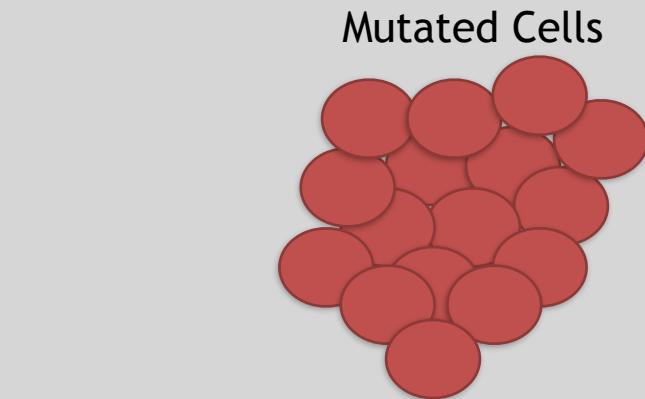




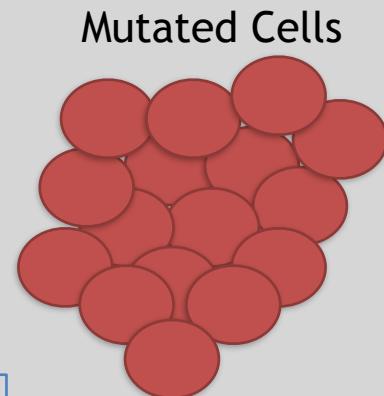
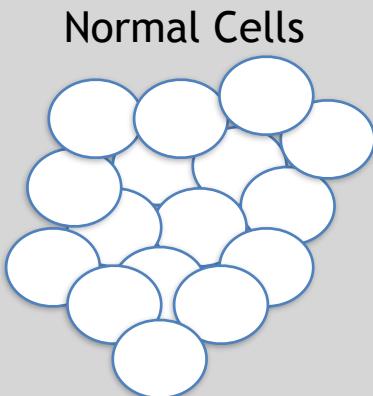




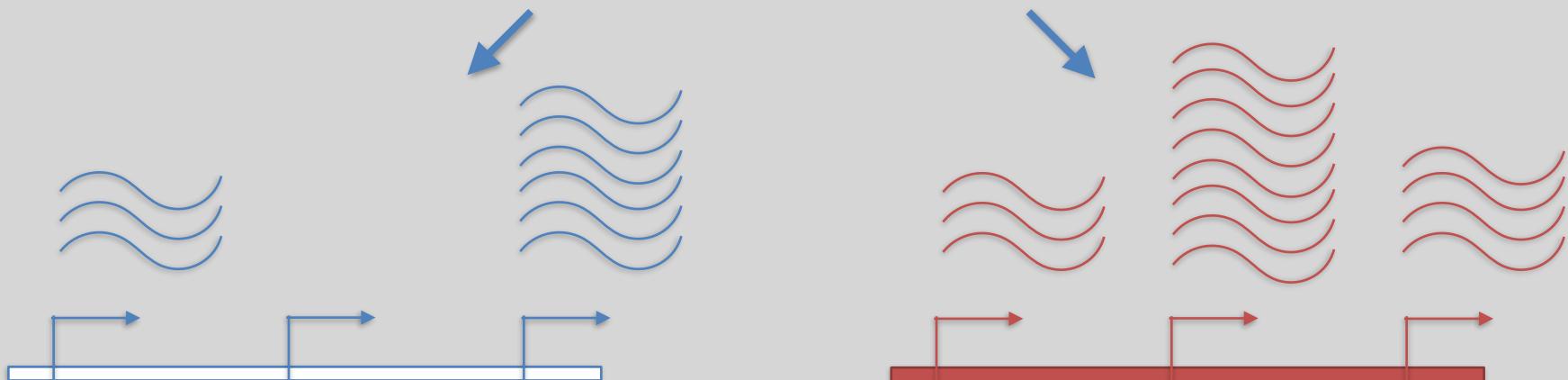
We use RNA-Seq to measure gene expression in normal cells ...

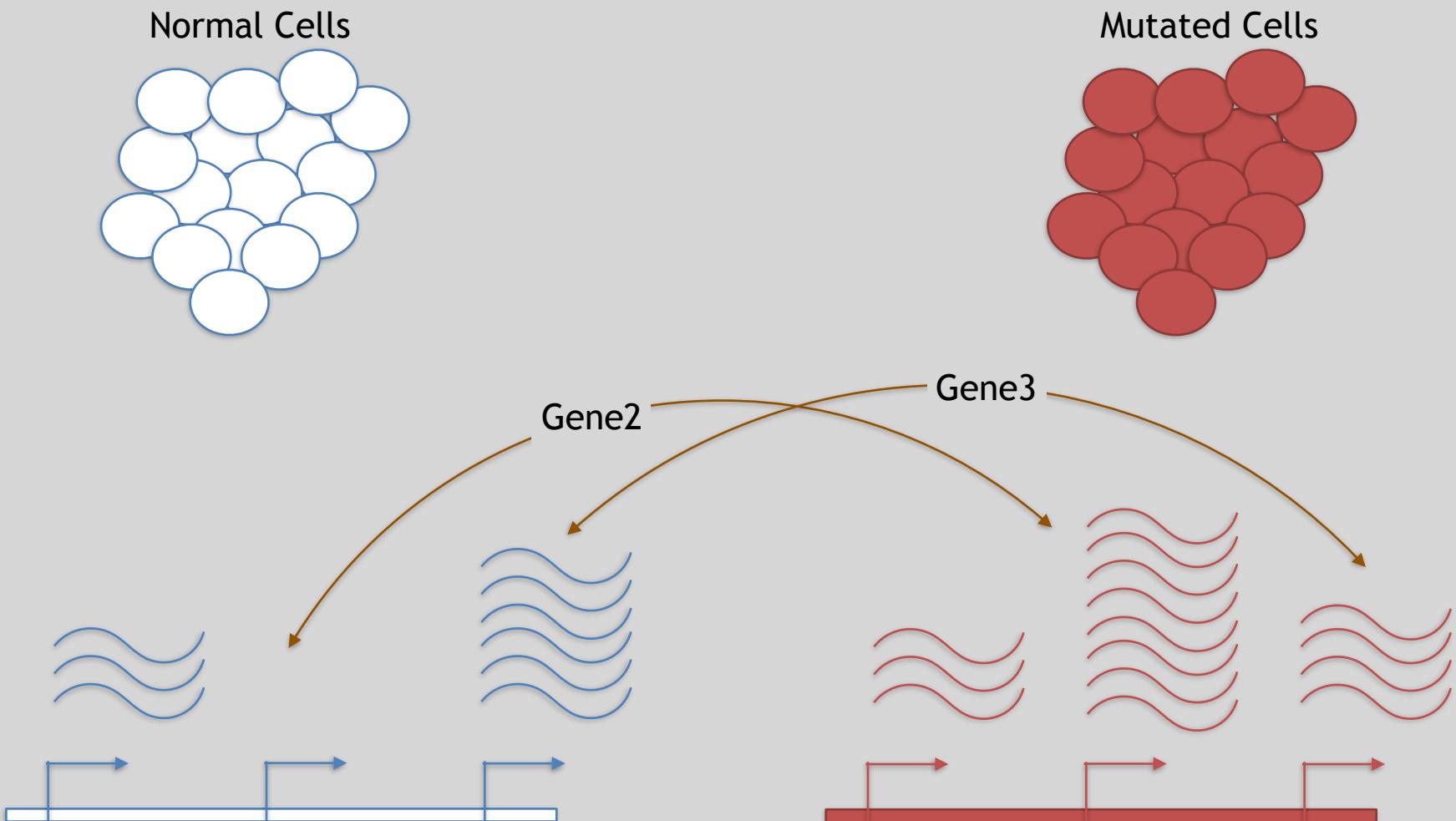


... then use it to measure gene expression in mutated cells



Then we can compare the two cell types to figure out what is different in the mutated cells!





Differences apparent for Gene 2 and
to a lesser extent Gene 3

3 Main Steps for RNA-Seq:

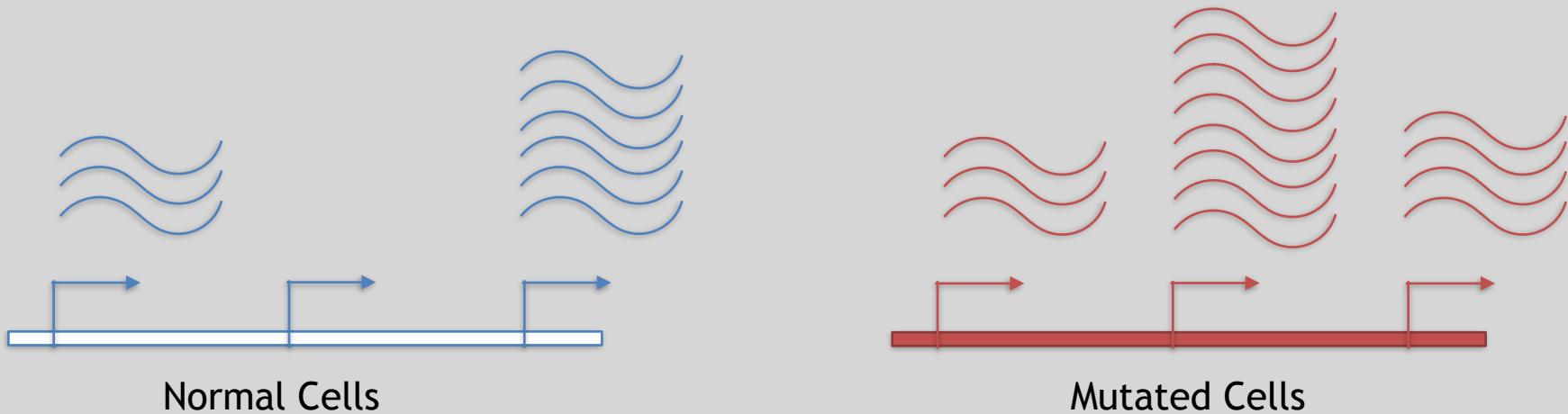
- 1) Prepare a sequencing library**
(RNA to cDNA conversion via reverse transcription)
- 2) Sequence**
(Using the same technologies as DNA sequencing)
- 3) Data analysis**
(Often the major bottleneck to overall success!)

We will discuss each of these steps in detail
(particularly the 3rd) next day!

Today we will get to the start of step 3!

Gene	WT-1	WT-2	WT-3	...
A1BG	30	5	13	...
AS1	24	10	18	...
...

We sequenced, aligned, counted the reads per gene in each sample to arrive at our data matrix



TODAYS MENU:

- ▶ **What is a Genome?**
 - Genome sequencing and the Human genome project
- ▶ **What can we do with a Genome?**
 - Comparative genomics
- ▶ **Modern Genome Sequencing**
 - 1st, 2nd and 3rd generation sequencing
- ▶ **Workflow for NGS**
 - RNA-Sequencing and discovering variation

Additional Reference Slides

(On FASTQ format, ASCII Encoded Base Qualities,
FastQC, Alignment and SAM/BAM formats)

Hands-on worksheet:

https://bioboot.github.io/bimm143_W18/lectures/#13

Raw data usually in FASTQ format

```
@NS500177:196:HFTTTAFXX:1:11101:10916:1458 2:N:0:CGCGGCTG  
ACACGACGATGAGGTGACAGTCACGGAGGATAAGATCAATGCCCTCATTAAAGCAGCCGGTGTAA  
+  
AAAAAAEEEEEEEEEEE//AEEEAEeeeeeee/EE/<<EE/AEAAEE//EEEAEAAEA<
```

1

2

3

4

Each sequencing “read” consists of 4 lines of data :

- 1 The first line (which always starts with ‘@’) is a unique ID for the sequence that follows
- 2 The second line contains the bases called for the sequenced fragment
- 3 The third line is always a “+” character
- 4 The forth line contains the quality scores for each base in the sequenced fragment (these are ASCII encoded...)

ASCII Encoded Base Qualities

```
@NS500177:196:HFTTTAFXX:1:11101:10916:1458 2:N:0:CGCGGCTG  
ACACGACGATGAGGTGACAGTCACGGAGGATAAGATCAATGCCCTCATTAAAGCAGCCGGTGTAA  
+  
AAAAAAEEEEEEEEEEE//AEEEAEeeeeeee/EE/<<EE/AEAAEE//EEEAEAAEA< 4
```

- Each sequence base has a corresponding numeric quality score encoded by a single ASCII character typically on the 4th line (see ④ above)
- ASCII characters represent integers between 0 and 127
- Printable ASCII characters range from 33 to 126
- Unfortunately there are 3 quality score formats that you may come across...

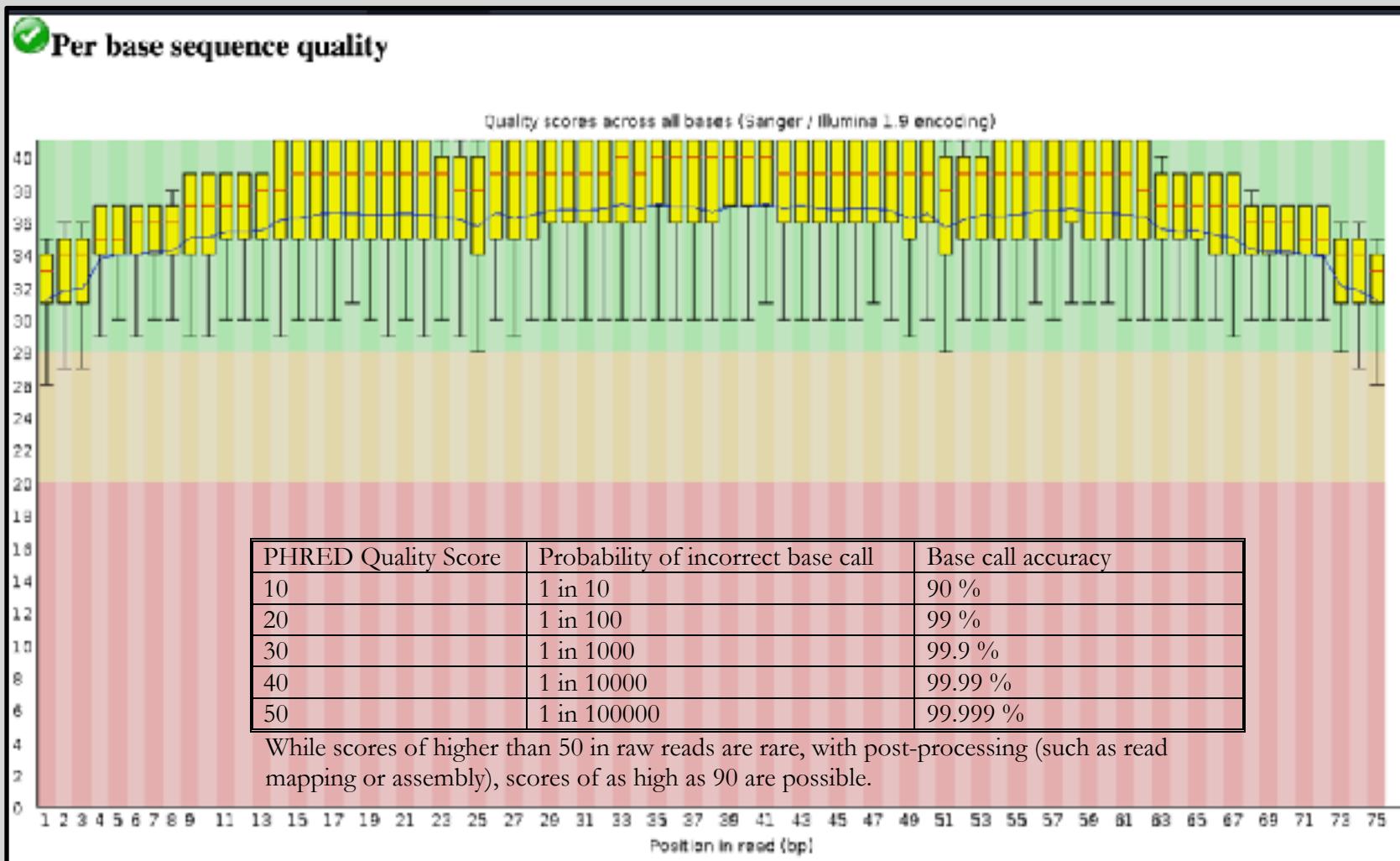
Interpreting Base Qualities in R

		ASCII Range	Offset	Score Range
Sanger, Illumina (Ver > 1.8)	fastqsanger	33-126	33	0-93
Solexa, Illumina (Ver < 1.3)	fastqsolexa	59-126	64	5-62
Illumina (Ver 1.3 -1.7)	fastqillumina	64-126	64	0-62

```
> library(seqinr)
> library(gtools)
> phred <- asc( s2c("DDDDCDEDCCDDDBBDDCC@") ) - 33
> phred
## D D D D C D E D C D D D D B B D D D C C @
## 35 35 35 35 34 35 36 35 34 35 35 35 35 33 33 35 35 35 34 34 31

> prob <- 10**(-phred/10)
```

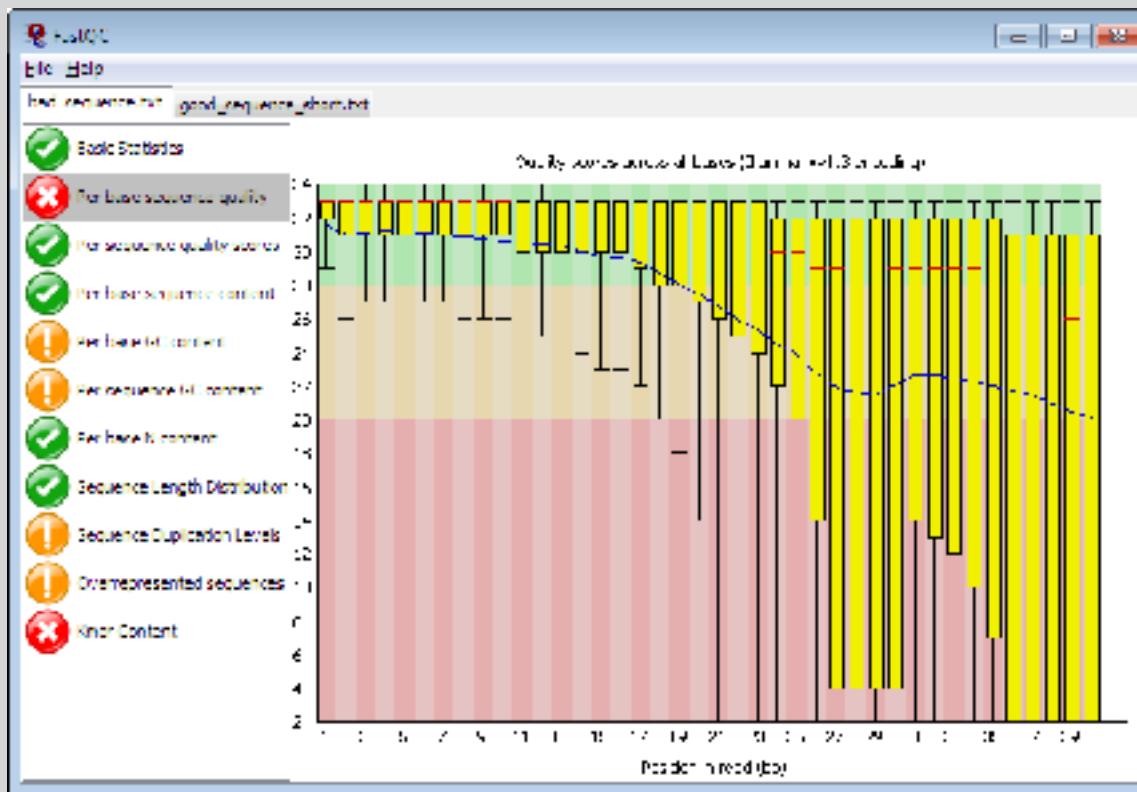
FastQC Report



FASTQC

FASTQC is one approach which provides a visual interpretation of the raw sequence reads

- <http://www.bioinformatics.babraham.ac.uk/projects/fastqc/>



Sequence Alignment

- Once sequence quality has been assessed, the next step is to align the sequence to a reference genome
- There are *many* distinct tools for doing this; which one you choose is often a reflection of your specific experiment and personal preference

BWA	BarraCUDA	RMAP
Bowtie	CASHx	SSAHA
SOAP2	GSNAP	etc
Novoalign	Mosiak	
mr/mrsFast	Stampy	
Eland	SHRiMP	
Blat	SeqMap	
Bfast	SLIDER	

SAM Format

- Sequence Alignment/Map (**SAM**) format is the almost-universal sequence alignment format for NGS
 - binary version is BAM
- It consists of a header section (lines start with '@') and an alignment section
- The official specification can be found here:
 - <http://samtools.sourceforge.net/SAM1.pdf>

Example SAM File

Header section

```
@HD     VN:1.0          SO:coordinate
@SQ     SN:1             LN:249250621   AS:NCBI37      UR:file:/data/local/ref/GATK/human_glk_v37.fasta  M5:1b22b98cdeb4a9304cb5d48026a85128
@SQ     SN:2             LN:243199373   AS:NCBI37      UR:file:/data/local/ref/GATK/human_glk_v37.fasta  M5:a0d9851da00400dec1098a9255ac712e
@SQ     SN:3             LN:198022430   AS:NCBI37      UR:file:/data/local/ref/GATK/human_glk_v37.fasta  M5:fd1d811849cc2fadebc929bb925902e5
@RG     ID:UM0098:1      PL:ILLUMINA    PU:HWUSI-EAS1707-615LHAAXX-L001 LB:80        DT:2010-05-05T20:00:00-0400  SM:SD37743   CN:UMCORE
@RG     ID:UM0098:2      PL:ILLUMINA    PU:HWUSI-EAS1707-615LHAAXX-L002 LB:80        DT:2010-05-05T20:00:00-0400  SM:SD37743   CN:UMCORE
@PG     ID:bwa           VN:0.5.4
```

Alignment section

1:497:R:-272+13M17D24M	113	1	497	37	37M	15	100338662	0
CGGGTCTGACCTGAGGAGAACGTGCTCCGCCCTTCAG	0;====9;>>>>=>>>>>>=>>>>>>	XG:i:0	MD:Z:37	XT:A:U	NM:i:0	SM:i:37	X0:i:1	X1:i:0
19:20389:F:275+18M2D19M	99	1	17644	0	37M	=	17919	314
TATGACTGCTAATAATACCTACACATGTTAGAACCAT	>>>>>>>>>>>>><<>><<>>4:>>:<9	XO:i:0	XG:i:0	RG:Z:UM0098:1	XT:A:R	NM:i:0	AM:i:0	X0:i:4
XI:i:0	XM:i:0	XO:i:0	MD:Z:37					
19:20389:F:275+18M2D19M	147	1	17919	0	18M2D19M	=	17644	-314
GTAGTACCAACTGTAAGTCCTATCTTCATACTTTGT	;44999;499<8<<8<<><<<><7<;<<>><<	XG:i:2	MD:Z:18^CA19	XT:A:R	NM:i:2	SM:i:0	AM:i:0	X0:i:4
XM:i:0	XO:i:1	XG:i:2						
9:21597+10M2I25M:R:-209	83	1	21678	0	8M2I27M	=	21469	-244
CACCACATCACATATACCAAGCCTGGCTGTCTTCT	<;9<<5><<<><<>><<>><9>><>>>><>	XO:i:2	MD:Z:35	XT:A:R	NM:i:2	SM:i:0	AM:i:0	X0:i:5
XM:i:0	XO:i:1	XG:i:2						

SAM header section

- Header lines contain vital metadata about the reference sequences, read and sample information, and (optionally) processing steps and comments. Each header line begins with an @, followed by a two-letter code that distinguishes the different type of metadata records in the header. Following this two-letter code are tab-delimited key-value pairs in the format **KEY:VALUE** (the SAM format specification names these tags and values).
- Because SAM files are plain text (unlike their binary counterpart, BAM), we can take a peek at a few lines of the header with head, See:

https://bioboot.github.io/bggn213_f17/class-material/sam_format/

SAM Utilities

- **Samtools** is a common toolkit for analyzing and manipulating files in SAM/BAM format
 - <http://samtools.sourceforge.net/>
- **Picard** is another set of utilities that can be used to manipulate and modify SAM files
 - <http://picard.sourceforge.net/>
- These can be used for viewing, parsing, sorting, and filtering SAM files as well as adding new information (e.g. Read Groups)

Genome Analysis Toolkit (GATK)

- Developed in part to aid in the analysis of 1000 Genomes Project data
- Includes many tools for manipulating, filtering, and utilizing next generation sequence data
- <http://www.broadinstitute.org/gatk/>

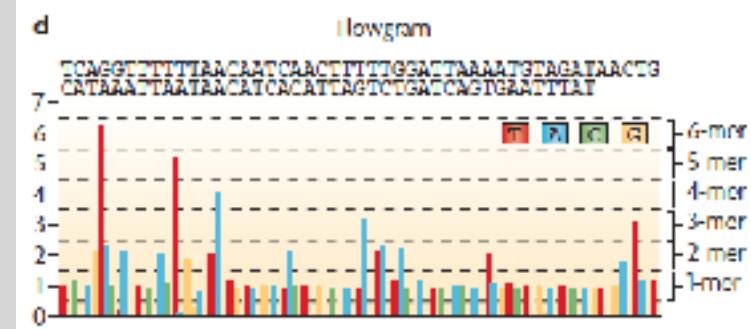
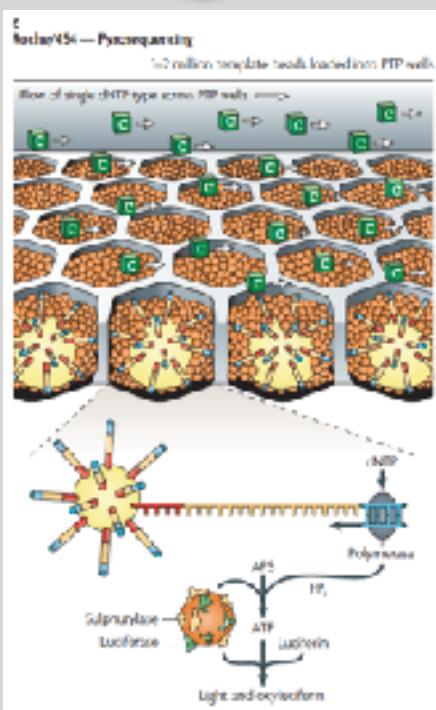
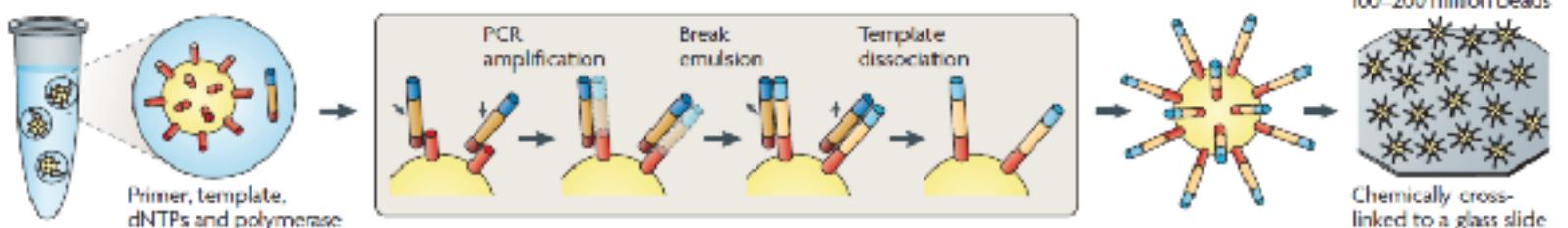
Do it Yourself!

Additional Reference Slides on Sequencing Methods

Roche 454 - Pyrosequencing

a. Roche/454, Life/APG, Palonator Emulsion PCR

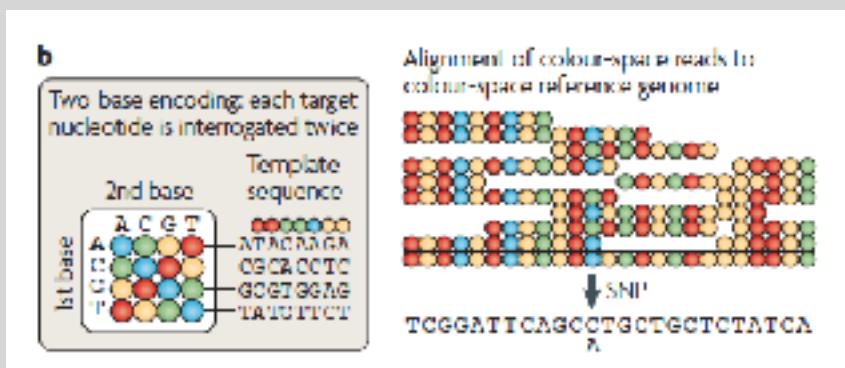
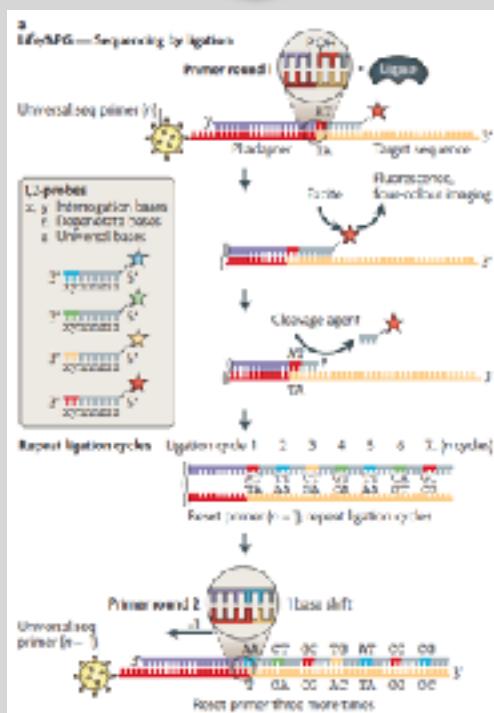
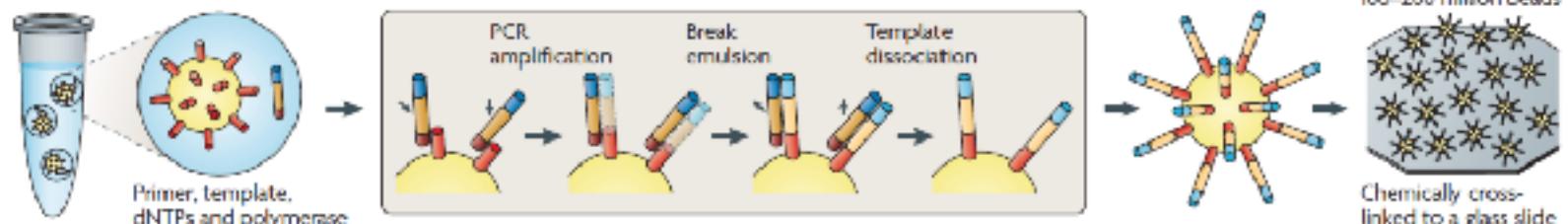
One DNA molecule per bead. Clonal amplification to thousands of copies occurs in microreactors in an emulsion



Life Technologies SOLiD - Sequence by Ligation

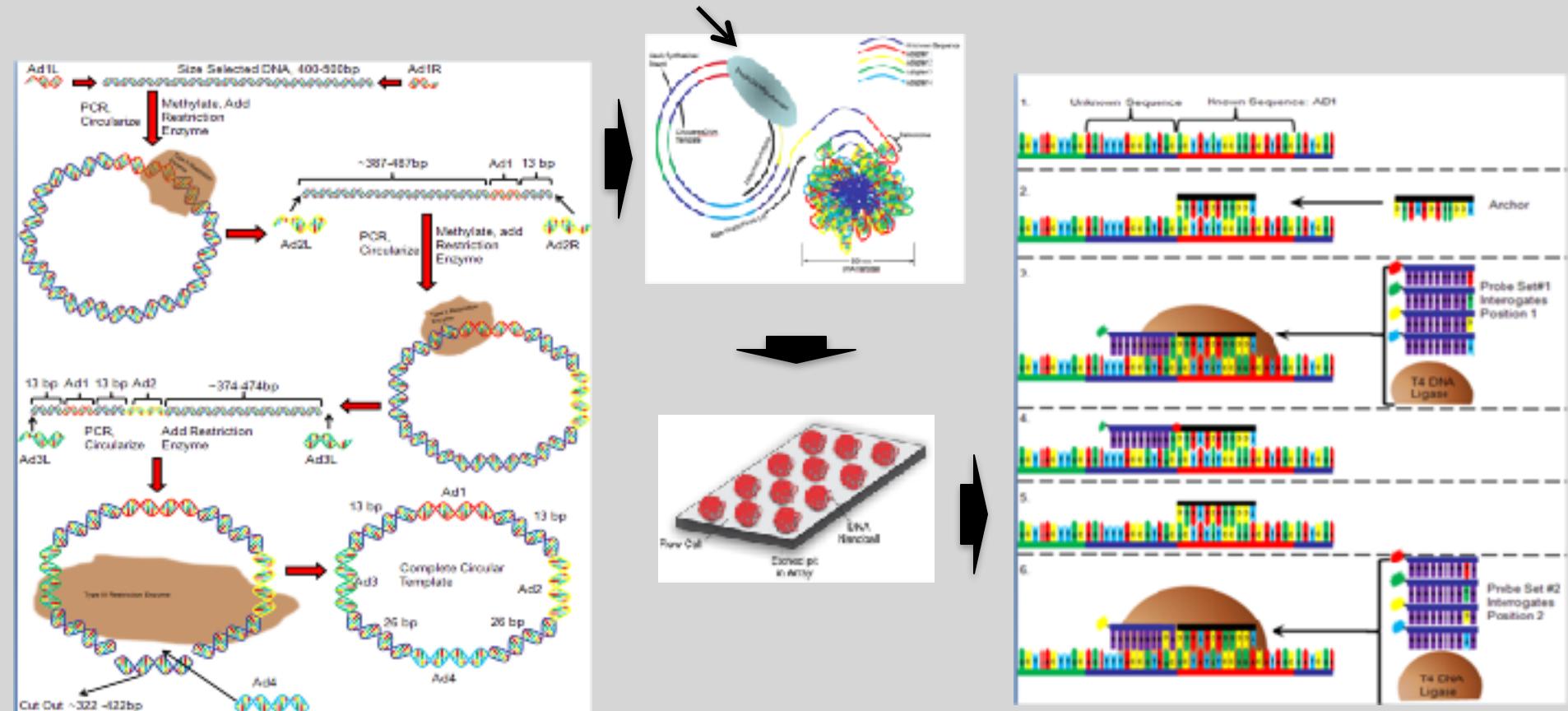
a. Roche/454, Life/APG, Palonator Emulsion PCR

One DNA molecule per bead. Clonal amplification to thousands of copies occurs in microreactors in an emulsion



Complete Genomics - Nanoball Sequencing

Has proofreading ability!



“Benchtop” Sequencers

- Lower cost, lower throughput alternative for smaller scale projects
- Currently three significant platforms
 - Roche 454 GS Junior
 - Life Technology Ion Torrent
 - Personal Genome Machine (PGM)
 - Proton
 - Illumina MiSeq

Platform	List price	Approximate cost per run	Minimum throughput (read length)	Run time	Cost/Mb	Mb/h
454 GS Junior	\$108,000	\$1,100	35 Mb (400 bases)	8 h	\$31	4.4
Ion Torrent PGM (314 chip)	\$80,490 ^{a,b}	\$225 ^c	10 Mb (100 bases)	3 h	\$22.5	3.3
(316 chip)		\$425	100 Mb ^d (100 bases)	3 h	\$4.25	33.3
(318 chip)		\$625	1,000 Mb (100 bases)	3 h	\$0.63	333.3
MiSeq	\$125,000	\$750	1,500 Mb (2 × 150 bases)	27 h	\$0.5	55.5

Loman, NJ (2012), *Nat. Biotech.*, 5, pp. 434-439

PGM - Ion Semiconductor Sequencing

