

**BGGN 213**  
**Genome Informatics I**  
Lecture 13  
**Barry Grant**  
UC San Diego  
<http://thegrantlab.org/bggn213>

## TODAYS MENU:

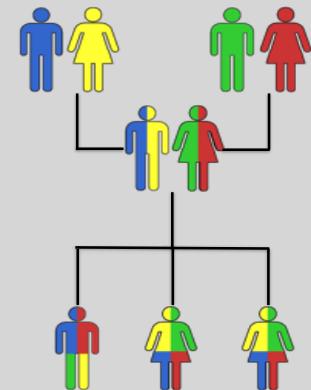
- **What is a Genome?**
  - Genome sequencing and the Human genome project
- **What can we do with a Genome?**
  - Compare, model, mine and edit
- **Modern Genome Sequencing**
  - 1st, 2nd and 3rd generation sequencing
- **Workflow for NGS**
  - RNA-Sequencing and Discovering variation

## Genetics and Genomics

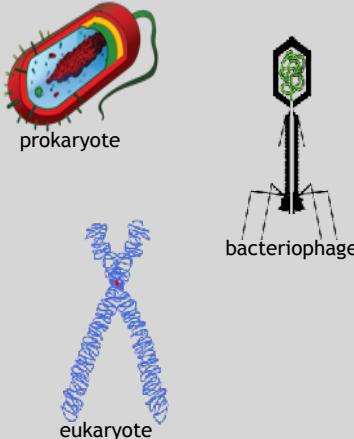
- **Genetics** is primarily the study of individual genes, mutations within those genes, and their inheritance patterns in order to understand specific traits.
- **Genomics** expands upon classical genetics and considers aspects of the entire genome, typically using computer aided approaches.

## 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



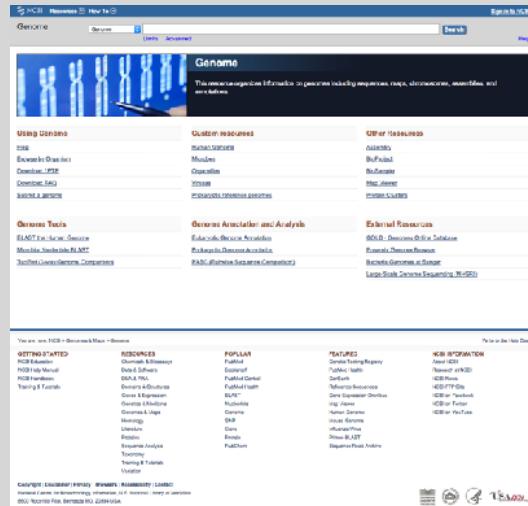
- Primarily DNA, but can be RNA in the case of some viruses
  - Some genomes are circular, others linear
  - Can be organized into discrete units (chromosomes) or freestanding molecules (plasmids)

Prokaryote by Mariana Ruiz Villarreal | Bacteriophage image by Solerete / CC BY-SA | Eukaryote image by Maanous Manske / CC BY-SA

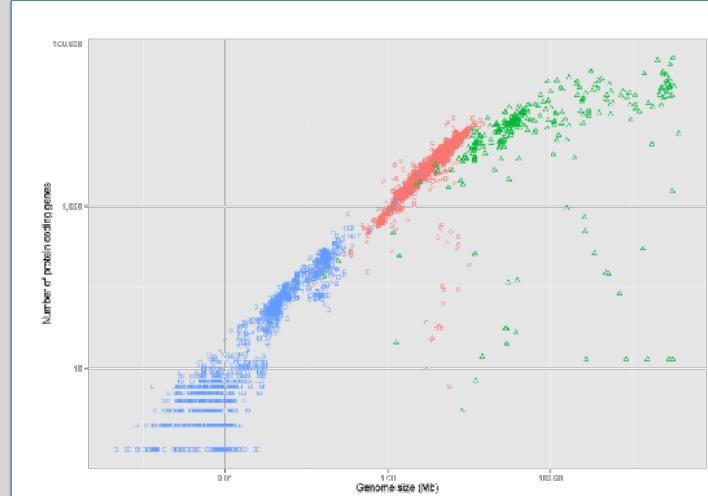
# Genome Databases

## NCBI Genome:

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

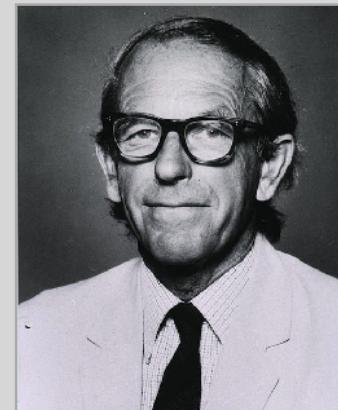


## Genomes come in many sizes



Modified from image by Estevani / CC BY-SA

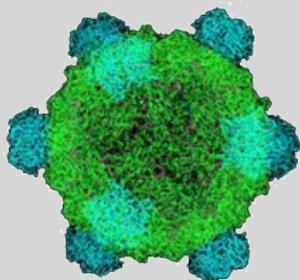
# Early Genome Sequencing



[http://en.wikipedia.org/wiki/Frederick\\_Sanger](http://en.wikipedia.org/wiki/Frederick_Sanger)

- 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

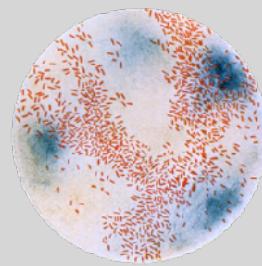
## The First Sequenced Genomes



Bacteriophage φ-X174

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

[http://en.wikipedia.org/wiki/Phi\\_X\\_174](http://en.wikipedia.org/wiki/Phi_X_174)



Haemophilus influenzae

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

<http://phl.cdc.gov/>

## The Human Genome Project

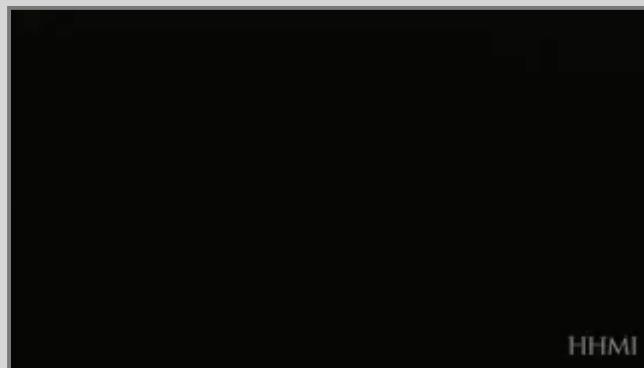
- The Human Genome Project (HGP) was an international, public consortium that began in 1990
  - Initiated by James Watson
  - Primarily led by Francis Collins
  - Eventual Cost: \$2.7 Billion
- Celera Genomics was a private corporation that started in 1998
  - Headed by Craig Venter
  - Eventual Cost: \$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



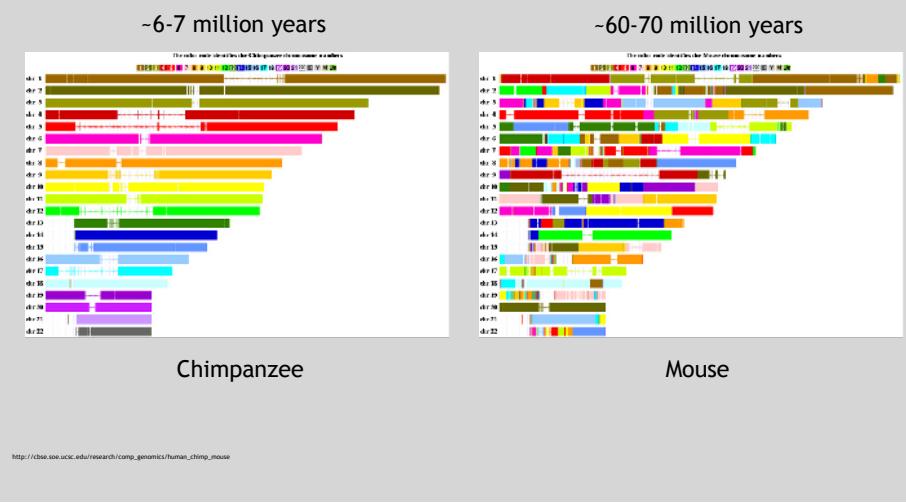
Jane Ades, Courtesy: [National Human Genome Research Institute](#)

## What can we do with a Genome?

- We can **compare** genomes, both within and between species, to identify regions of variation and of conservation
- We can **model** genomes, to find interesting patterns reflecting functional characteristics
- We can **mine** genomes, to find mutations and epigenetic correlations with disease, drug sensitivity, treatment efficacy and other phenotypic characteristics
- We can **edit** genomes, to add, remove, or modify genes and other regions for adjusting individual traits



## Comparative Genomics



## Conservation Suggests Function

- Functional regions of the genome tend to mutate slower than nonfunctional regions due to selective pressures
- Comparing genomes can therefore indicate segments of high similarity that have remained conserved across species as candidate genes or regulatory regions

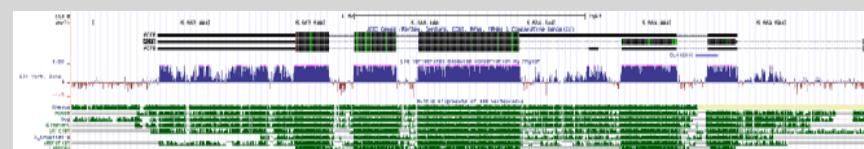


Figure generated from: <http://genome.ucsc.edu/>

## Conservation Indicates Loss

- Comparing genomes allows us to also see what we have lost over evolutionary time
- A model example of this is the loss of “penile spines” in the human lineage due to a human-specific deletion of an enhancer for the androgen receptor gene (McLean et al, Nature, 2011)



## 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

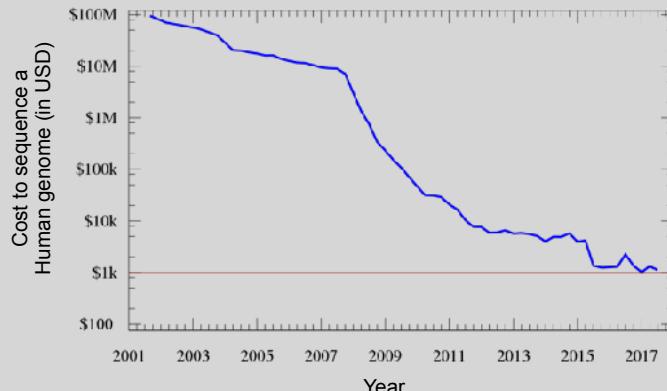


Image source: [https://en.wikipedia.org/wiki/Carlson\\_curve](https://en.wikipedia.org/wiki/Carlson_curve)

# Rapid progress of genome sequencing

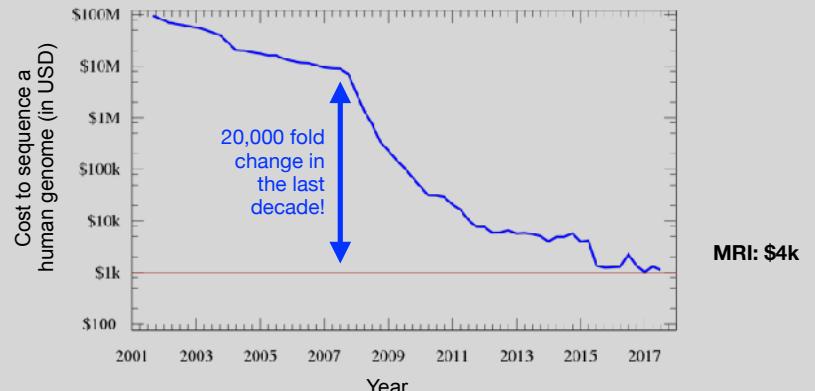
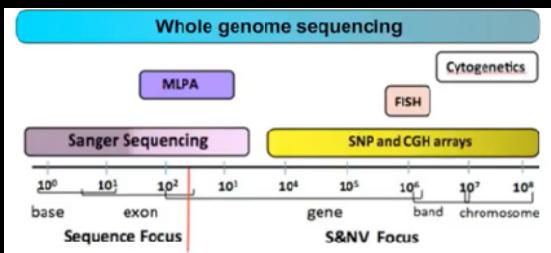


Image source: [https://en.wikipedia.org/wiki/Carlson\\_curve](https://en.wikipedia.org/wiki/Carlson_curve)

## 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.

## Solving mystery diseases

- Diseases with a genetic origin effect 16 million people in the US and 23% of all pediatric admissions to hospital are for 'rare' genetic disorders.
- Most are "mystery diseases" in terms of their genetic origin
- Before the recent adoption of exome and genome sequencing these patients faced extensive periods of testing and inappropriate treatment (with cost estimates of \$5 million per person) before the basis of their disease was understood.
- Sequencing can thus help realize enormous savings in healthcare costs and spare patients and their families unnecessary, stressful, and time-consuming testing.

## How many Mendelian diseases are there?

- As of 01/10/18 ~7,800 Mendelian diseases have been described.
- For 3,963 of these, the likely disease gene is known.
- For many genes, different genetic variants can have distinct effects on the encoded protein, leading to distinct disease characteristics.
- Indeed, the 3,963 unique diseases that have been solved affect only 2,776 genes because different mutations in the same gene can cause different disease characteristics.

## How many Mendelian diseases are there?

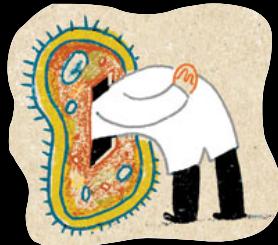
- It is probable that many more Mendelian diseases will be "solved" as genomic analysis becomes more integrated into clinical practice.
- There are ~20,000 protein coding genes and variants in many of these genes would be expected to cause human disease.
- Q: How are genes responsible for genetic diseases currently identified?
  - **Exome or whole genome sequencing**

## Currently disease causing mutations are found in only ~30% of cases

- For the majority of these cases finding disease causing mutations often does not lead to effective treatments.
- However, the information can still be helpful for guiding patient management, reproductive choices and future certainty. For example:
  - Can bring relief for patients and their families
  - Can be helpful for planning future pregnancies (e.g. IVF and genetic testing for embryo selection)
  - Predicting the possible disease course and long-term prognosis

## 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
Protein expression	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

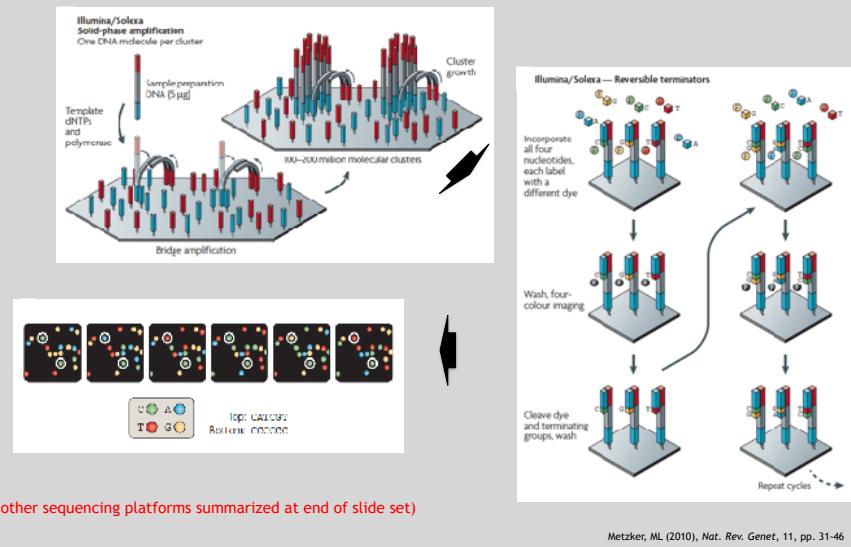
- **Sequencing by Synthesis:** Uses a polymerase to incorporate and assess nucleotides to a primer sequence
  - 1 nucleotide at a time
- **Sequencing by Ligation:** Uses a ligase to attach hybridized sequences to a primer sequence
  - 1 or more nucleotides at a time (e.g. dibase)

## 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+100 bp

Modified from Mardis, ER (2011), Nature, 470, pp. 198-203

## Illumina - Reversible terminators

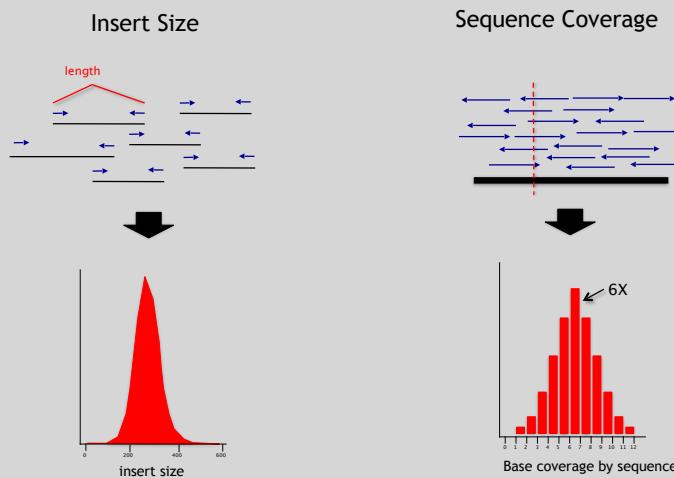


## Illumina Sequencing - Video



[https://www.youtube.com/watch?src\\_vid=womKfikWlxM&v=fCd6B5HRaZ8](https://www.youtube.com/watch?src_vid=womKfikWlxM&v=fCd6B5HRaZ8)

## NGS Sequencing Terminology



## Summary: “Generations” of DNA Sequencing

	First generation	Second generation <sup>b</sup>	Third generation <sup>a</sup>
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 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

Schadt, EE et al (2010), *Hum. Mol. Biol.*, 19(R12), pp. R227-R240

## Third Generation Sequencing

- Currently in active development
- Hard to define what “3<sup>rd</sup>” 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:

## SqAnswers Wiki

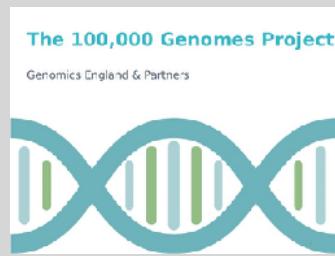
A good repository of analysis software can be found at  
<http://seqanswers.com/wiki/Software/list>

Software list							
Name		Summary	tags	tags	features	license	link
agpeptid	Identifying peptides from raw, event-based long sequencing reads using sequencing	bioinformatics, sequencing	bio discovery	Mapping	perl, perl5, perl6, perl6s	Perl, OS X	<a href="#">View source</a>
All Large Read Tool	Identifying reads in a BAM file. Use this tool to identify which reads are relevant to a reference genome.	bioinformatics, sequencing	bio discovery	Mapping	perl, perl5, perl6, perl6s	Perl, OS X	<a href="#">View source</a>
All Small Read Tool	This tool is a basic tool to process the raw sequencing data produced by the NGS. It's a "SeqAnswers Analysis Pipeline Tool" (Contra tool).	bioinformatics, sequencing	bio discovery	Mapping, Alignment	perl, perl5, perl6, perl6s	Perl, OS X	<a href="#">View source</a>
ABRA	Parallely aligned by paired-end sequences in a comparative gene assembler, which is able to handle large-scale genomic data sets and parallelize the assembly process.	bioinformatics, sequencing	bio discovery	Assembly, Searching	Amara, license	Perl	<a href="#">View source</a>
Autospacer	Map RNA-seq reads to target genome and compute the number of unique mappings, location and splice junctions.	bioinformatics, sequencing	bio discovery	Mapping, Alignment	c++, perl	GPLv3, Perl	<a href="#">View source</a>
AVES	PDFC is a bioinformatics assembler designed for short reads and large genomes.	bioinformatics, sequencing	bio discovery	Assembly, De Novo, Gaps	c++, license	Perl, Linux, Mac OS X	<a href="#">View source</a>

What can we do with all this sequence information?

## Population Scale Analysis

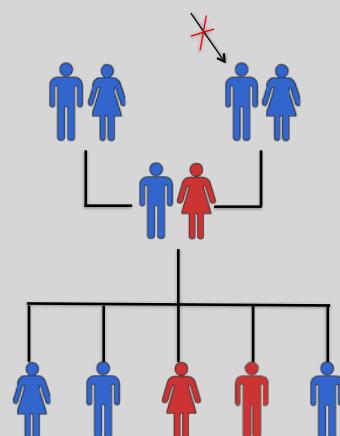
We can now begin to assess genetic differences on a very large scale, both as naturally occurring variation in human and non-human populations as well somatically within tumors



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

## 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



**"Variety's the very spice of life"**

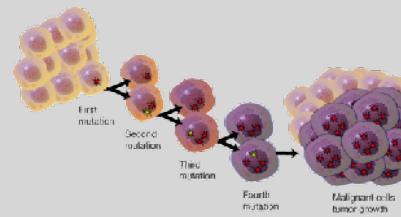
-William Cowper, 1785

**"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.

## Somatic Variation

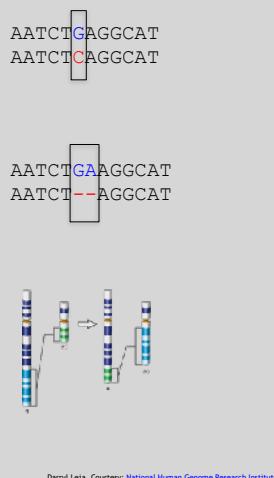


- Mutations in non-germline cells that are not passed along to offspring
- Can occur during mitosis or from the environment itself
- Are an integral part in tumor progression and evolution

Daryl Leja, Courtesy: National Human Genome Research Institute

## 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



## Discovering Variation: SNPs and INDELs

SNP

sequencing error or genetic variant?

reference genome

ATCCTGATTCCGTGAACGTTATCGACCATCCGATCGA  
ATCCTGATTCCGTGAACGTTATCGACCATCCGATCGA  
CCGTGAACGTTATCGACCATCCGATCGAAGCTGTCA  
GGTGAACTGTTATCGACCATCCGATCGAAGCTGTCA  
TGAACGTTATCGACCATCCGATCGAAGCTGTCA  
TGAACGTTATCGACCATCCGATCGAAGCTGTCA  
GTTATCGACCATCCGATCGAAGCTGTCA  
TTATCGACCATCCGATCGAAGCTGTCA

ATCCTGATTCCGTGAACGTTATCGACCATCCGATCGAACTGTCA  
GTCAGCGGCAAGCTGTCA  
ATCGATCGATGCTAGTG

sequencing error or genetic variant?

INDEL

## 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

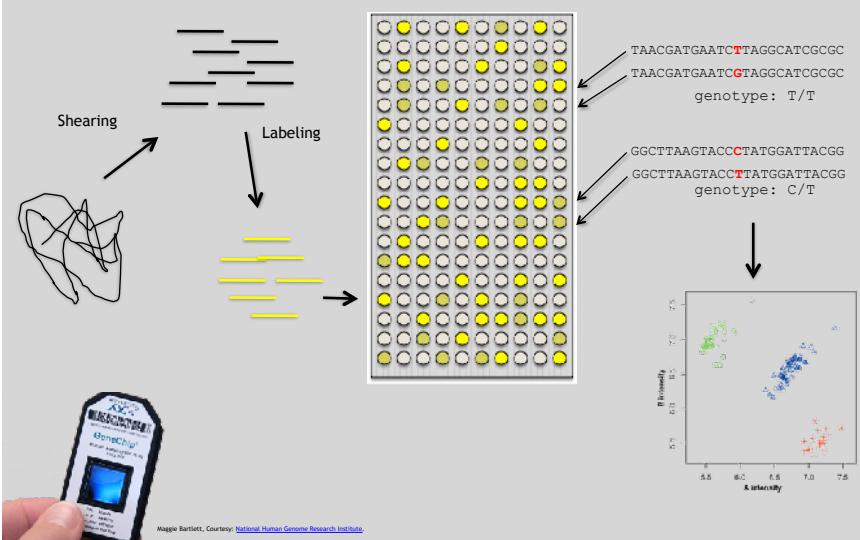
Numbers change depending on ancestry!

1000 Genomes Project, Nature, 2012

## 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

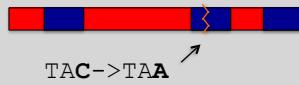


Maggie Bartlett, Courtesy: National Human Genome Research Institute.

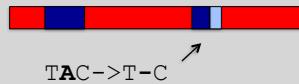
## Impact of Genetic Variation

There are numerous ways genetic variation can exhibit functional effects

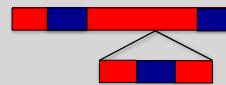
### Premature stop codons



### Frameshift mutation



### Gene or exon deletion



### Transcription factor binding disruption



## Hand-on time!

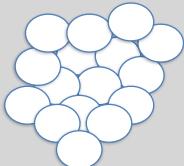
[https://bioboot.github.io/bggn213\\_S18/lectures/#13](https://bioboot.github.io/bggn213_S18/lectures/#13)

See IP address on website

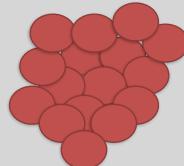
## RNA Sequencing

The absolute basics

Normal Cells

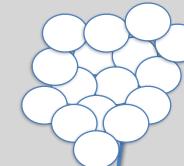


Mutated Cells

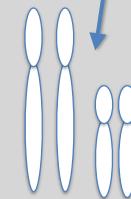


- The **mutated cells** behave differently than the **normal cells**
- We want to know what genetic mechanism is causing the difference
- One way to address this is to examine differences in gene expression via RNA sequencing...

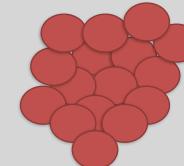
Normal Cells



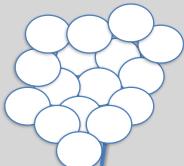
Each cell has a bunch of chromosomes



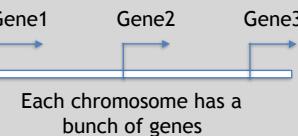
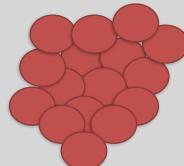
Mutated Cells



Normal Cells



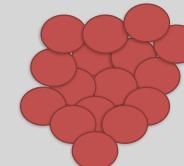
Mutated Cells



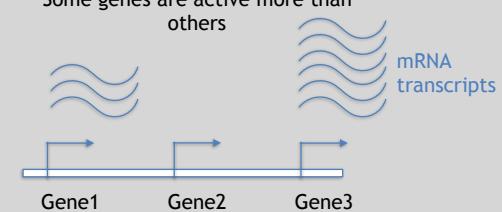
Normal Cells

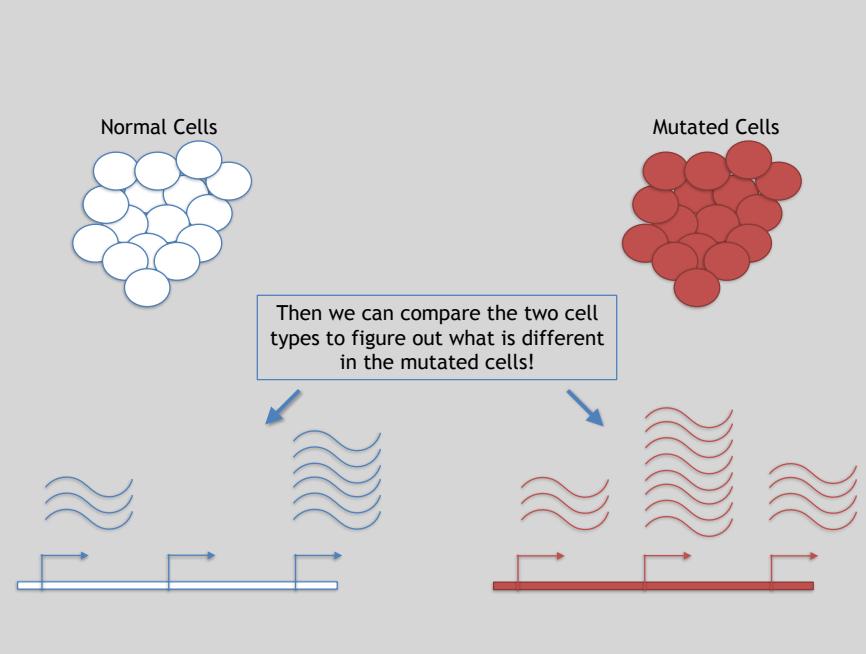
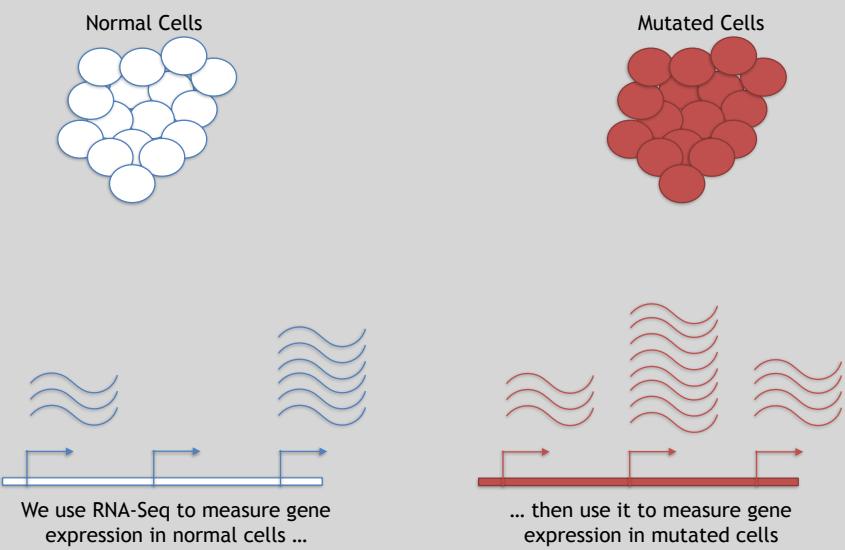
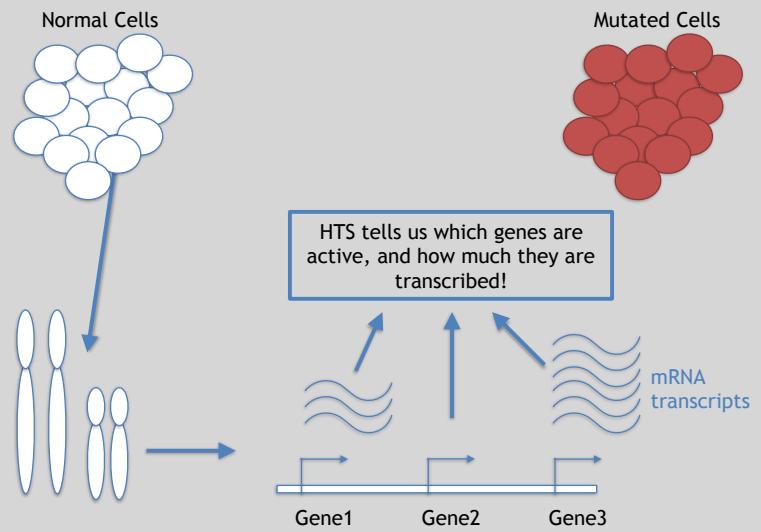
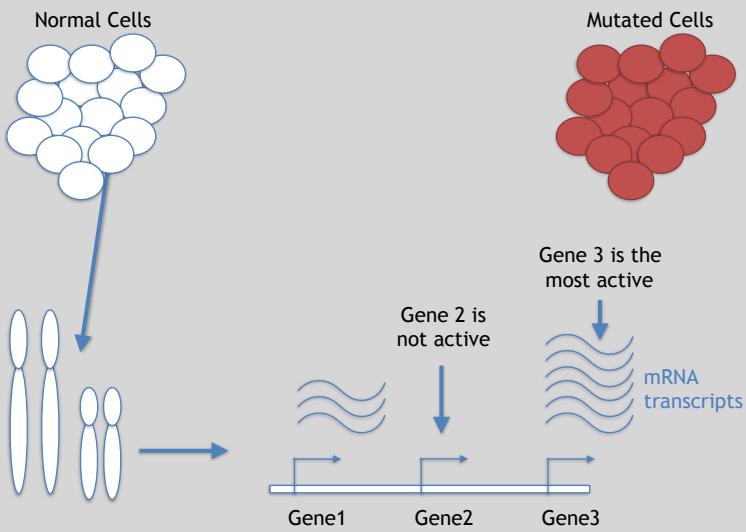


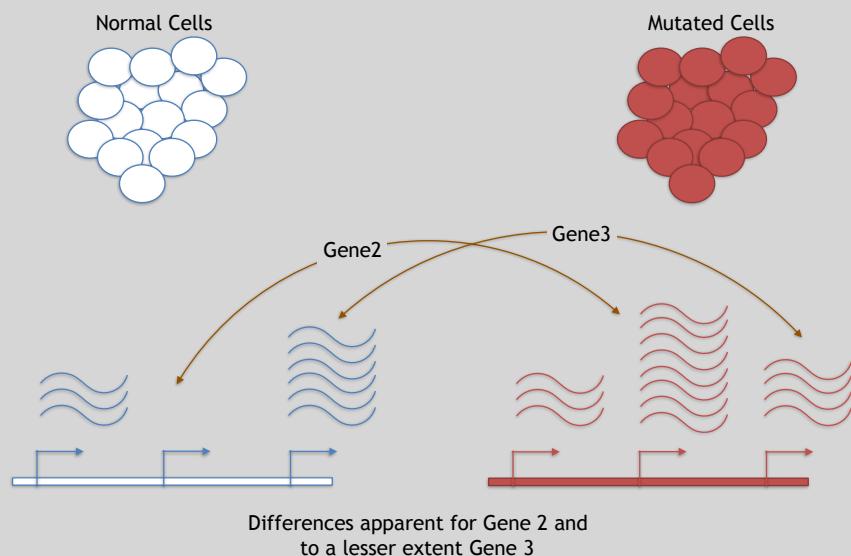
Mutated Cells



Some genes are active more than others







### 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

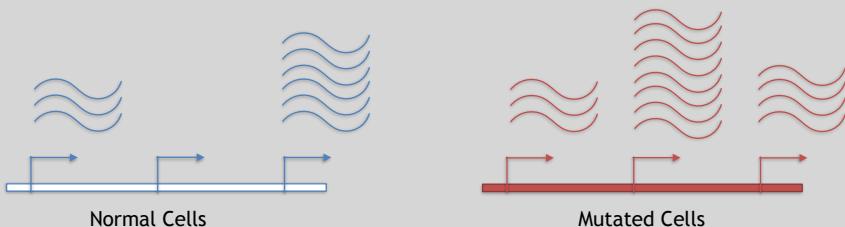
(Often the major bottleneck to overall success!)

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

Access a jetstream galaxy instance!

Use assigned IP address

The screenshot shows the Galaxy web interface with a workflow step titled "Bowtie2 - map reads against reference genome (Galaxy Version 2.2.6.2)". The step details the following parameters:

- Is this single or paired library? Single-end
- FASTQ file: HC00109\_2.fastq
- Must be of datatype "FastqSequence"
- Write unaligned reads (in fastq format) to separate file(s): Yes
- Unaligned reads trigger --un parameter for single reads and --un-conc for paired reads
- Will you select a reference genome from your history or use a built-in index?: No
- Use a built-in genome index: Built-ins were indexed using default options. See "Indexes" section of help below.
- Select reference genome: Human (hg19)
- If your genome of interest is not listed, contact the Galaxy team
- Set read groups information: Do not set
- Specifying read group information can greatly simplify your downstream analyses by allowing combining multiple datasets.
- Select analysis mode: Default setting only
- Do you want to use presets?: No, just use defaults
- Presets:
  - Very fast end-to-end (-very-fast)
  - Fast end-to-end (-fast)
  - Medium end-to-end (-medium)
  - Very sensitive end-to-end (-very-sensitive)
  - Very fast local (-very-fast-local)
  - Fast local (-fast-local)
  - Sensitive local (-sensitive-local)
  - Very sensitive local (-very-sensitive-local)
- Allowing switching among several preset parameter settings. Choosing between these will result in dramatic changes in runtime. See help below to understand effects of these presets.

The History panel on the right shows several completed steps, including:

- HC00109\_2.fastq
- 23: fastq-count on data 18 and data 17 (one feature)
- 24: fastq-count on data 18 and data 17
- 25: Cufflinks on data 18 and data 16. Skipped TRA records
- 26: Cufflinks on data 18 and data 16 assembled transcriptome
- 27: Cufflinks on data 18 and data 16 transcript expression
- 19: Cufflinks on data 18 and data 16 gene expression
- 28: tabulate database hg19

Do it Yourself!

## 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](https://bioboot.github.io/bimm143_W18/lectures/#13)

## Feedback: [Muddy Point Assessment]

## Raw data usually in FASTQ format

```
@NS500177:196:HFTTAFXX:1:11101:10916:1458 2:N:0:CGGGCTG  
ACACGACATGAGGTACAGTCACGGAGATAAGATCAATGCCCTCATTAAGCAGCCGGTAA  
+  
AAAAAAEEEEEEEEE//AAAAAEEEEEEEEE/EE/<<EE/AEEFAEE//EEEAEAAA<
```

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:HFTTAFXX:1:11101:10916:1458 2:N:0:CGGGCTG  
ACACGACGATGAGGTGACAGTCACGGAGGATAAGATCAATGCCCTCATTAAGCAGCCGGTAA  
+  
AAAAAEEEEEEEEE//AEEEAEeeeeeee/EE/<<EE/AEEEAEE//EEEAEAAE< 4
```

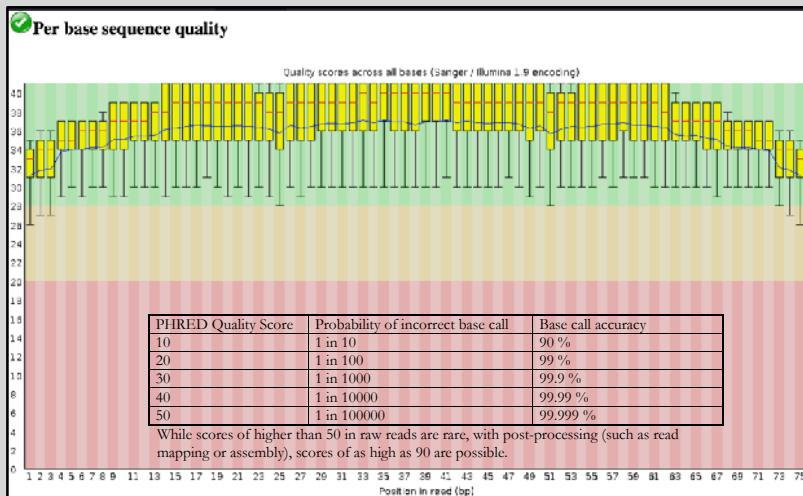
- Each sequence base has a corresponding numeric quality score encoded by a single ASCII character typically on the 4th line (see ④ above)
- ASCII characters represent integers between 0 and 127
- Printable ASCII characters range from 33 to 126
- Unfortunately there are 3 quality score formats that you 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("DDDCDEDCCDDDBBDDCC@") ) - 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 35 33 33 35 35 35 34 34 31
> prob <- 10**(-phred/10)
```

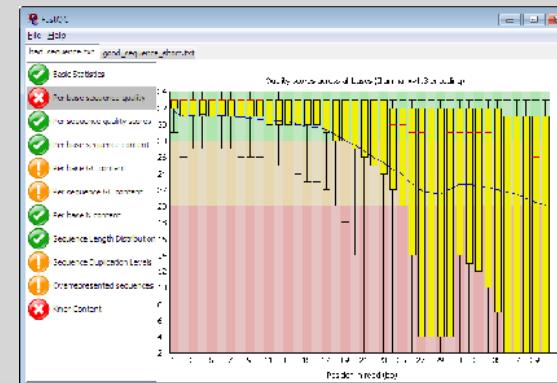
## FastQC Report



## 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	SqMap	
Bfast	SLIDER	

## Example SAM File

## Header section

### Alignment section

<http://genome.sph.umich.edu/wiki/SAM>

# 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>

## 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/bggm213\\_f17/class-material/sam\\_format/](https://bioboot.github.io/bggm213_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 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)

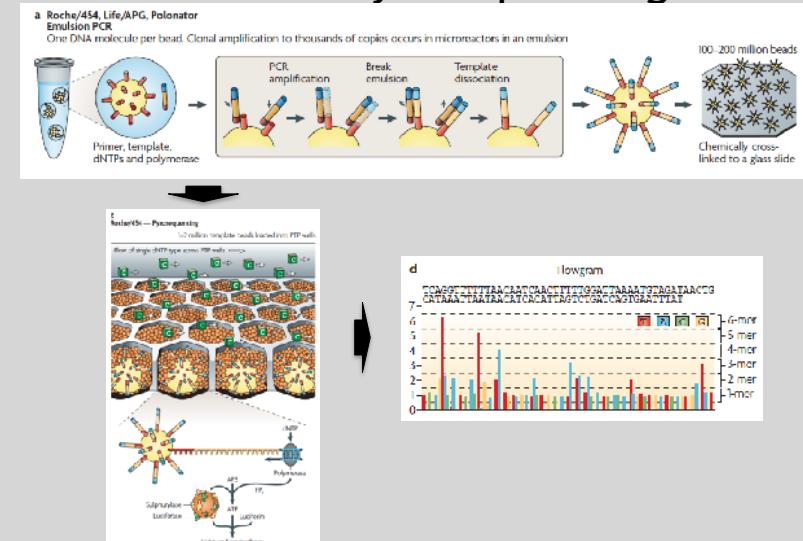
Additional Reference Slides  
on Sequencing Methods

Do it Yourself!

## Genome Analysis Toolkit (GATK)

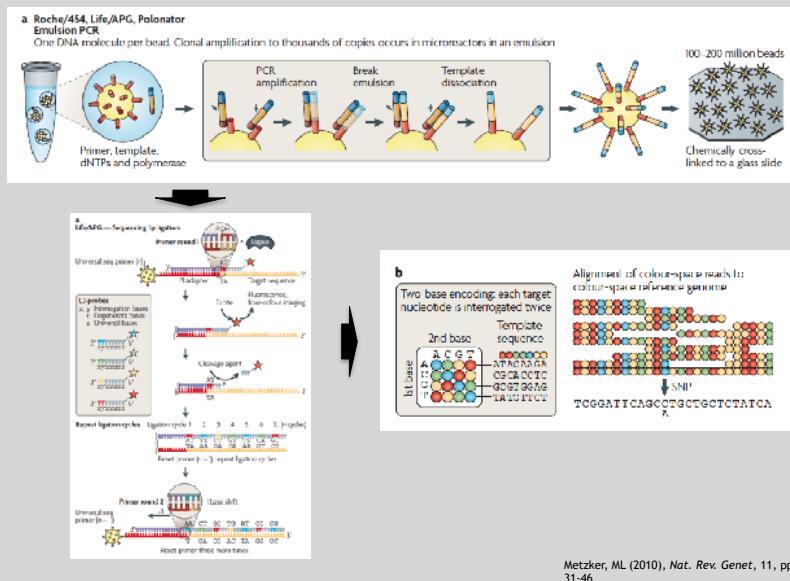
- Developed in part to aid in the analysis of 1000 Genomes Project data
- Includes many tools for manipulating, filtering, and utilizing next generation sequence data
- <http://www.broadinstitute.org/gatk/>

## Roche 454 - Pyrosequencing

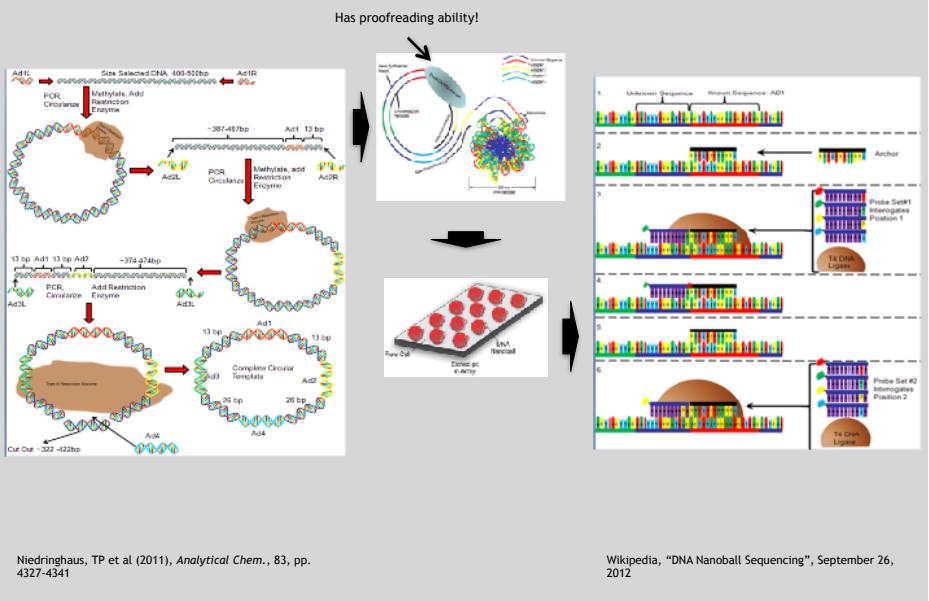


Metzker, ML (2010). *Nat. Rev. Genet.*, 11, pp. 31-46.

Life Technologies SOLiD - Sequence by Ligation



Complete Genomics - Nanoball Sequencing



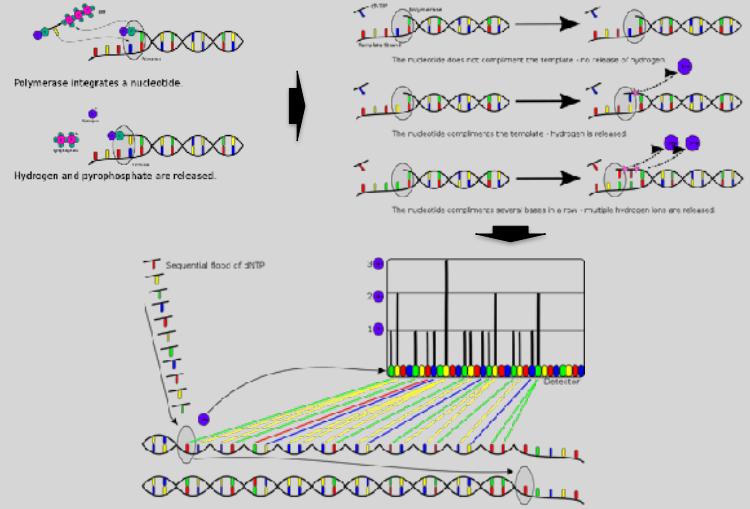
# “Benchtop” Sequencers

- 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 <sup>a,b</sup>	\$225 <sup>c</sup>	10 Mb (100 bases)	3 h	\$22.5	3.3
(316 chip)		\$425	100 Mb <sup>d</sup> (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 x 150 bases)	27 h	\$0.5	55.5

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

# PGM - Ion Semiconductor Sequencing



Wikipedia, "Ion Semiconductor Sequencing", September 26, 2012