Genomic Technologies

Michael Schatz

January 29, 2020

Lecture 2: Applied Comparative Genomics

Welcome!

The primary goal of the course is for students to be grounded in theory and leave the course empowered to conduct independent genomic analyses.

- We will study the leading computational and quantitative approaches for comparing and analyzing genomes starting from raw sequencing data.
- The course will focus on human genomics and human medical applications, but the techniques will be broadly applicable across the tree of life.
- The topics will include genome assembly & comparative genomics, variant identification & analysis, gene expression & regulation, personal genome analysis, and cancer genomics.

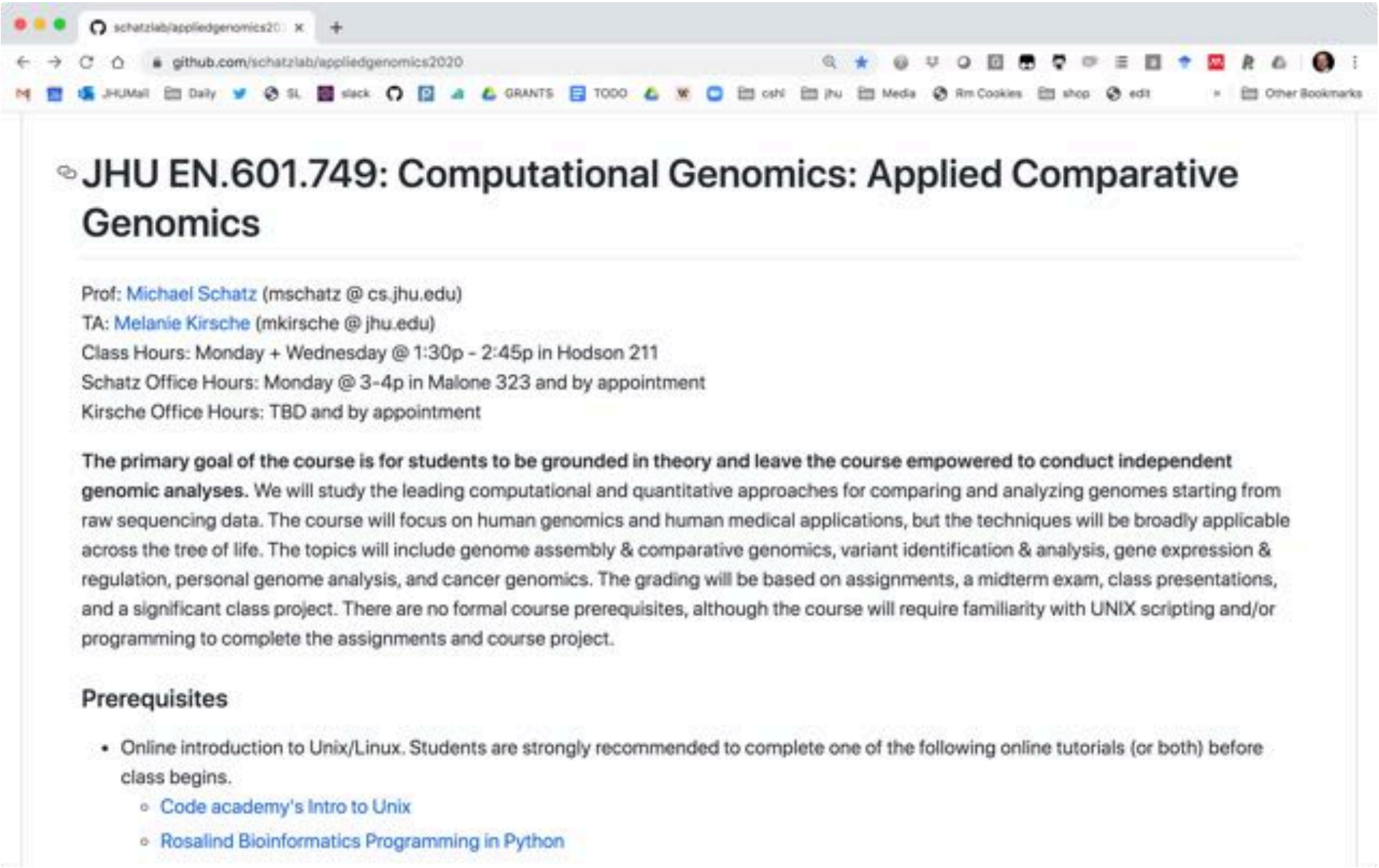
Course Webpage: https://github.com/schatzlab/appliedgenomics2020
Course Discussions: http://piazza.com

Class Hours: Mon + Wed @ 1:30p – 2:45p, Hodson 211

Schatz Office Hours: Mon @ 3-4p and by appointment
Kirsche Office Hours: TBD and by appointment

Please try Piazza first!

Course Webpage



JHU EN.601.749: Computational Genomics: Applied Comparative Genomics

Prof: Michael Schatz (mschatz @ cs.jhu.edu)
TA: Melanie Kirsche (mkirsche @ jhu.edu)
Class Hours: Monday + Wednesday @ 1:30p - 2:45p in Hodson 211
Schatz Office Hours: Monday @ 3-4p in Malone 323 and by appointment
Kirsche Office Hours: TBD and by appointment

The primary goal of the course is for students to be grounded in theory and leave the course empowered to conduct independent genomic analyses. We will study the leading computational and quantitative approaches for comparing and analyzing genomes starting from raw sequencing data. The course will focus on human genomics and human medical applications, but the techniques will be broadly applicable across the tree of life. The topics will include genome assembly & comparative genomics, variant identification & analysis, gene expression & regulation, personal genome analysis, and cancer genomics. The grading will be based on assignments, a midterm exam, class presentations, and a significant class project. There are no formal course prerequisites, although the course will require familiarity with UNIX scripting and/or programming to complete the assignments and course project.

Prerequisites

- Online introduction to Unix/Linux. Students are strongly recommended to complete one of the following online tutorials (or both) before class begins.
  - Code academy's Intro to Unix
  - Rosalind Bioinformatics Programming in Python

https://github.com/schatzlab/appliedgenomics2020

Assignment 1: Chromosome Structures
Due Feb 5 @ 11:59pm

appliedgenomics2020/assig

github.com/schatzlab/appliedgenomics2020/tree/master/assignments/assignment1

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Assignment 1: Chromosome Structures

Assignment Date: Wednesday, Jan 29, 2020
Due Date: Wednesday, Feb. 5, 2020 @ 11:59pm

Assignment Overview

In this assignment you will profile the overall structure of the genomes of several important species and then study the yeast genome in more detail. As a reminder, any questions about the assignment should be posted to Piazza

Question 1: Chromosome structures

Download the chomosome size files for the following genomes (Note these have been preprocessed to only include main chromosomes):

1. Arabidopsis thaliana (TAIR10) - An important plant model species [info]
2. Tomato (Solanum lycopersicum v4.00) - One of the most important food crops [info]
3. E. coli (Escherichia coli K12) - One of the most commonly studied bacteria [info]
4. Fruit Fly (Drosophila melanogaster, dm6) - One of the most important model species for genetics [info]
5. Human (hg38) - us :) [info]
6. Wheat (Triticum aestivum, IWGSC) - The food crop which takes up the largest land area [info]
7. Worm (Caenorhabditis elegans, ce10) - One of the most important animal model species [info]
8. Yeast (Saccharomyces cerevisiae, sacCer3) - an important eukaryotic model species, also good for bread and beer [info]

Using these files, make a table with the following information per species:

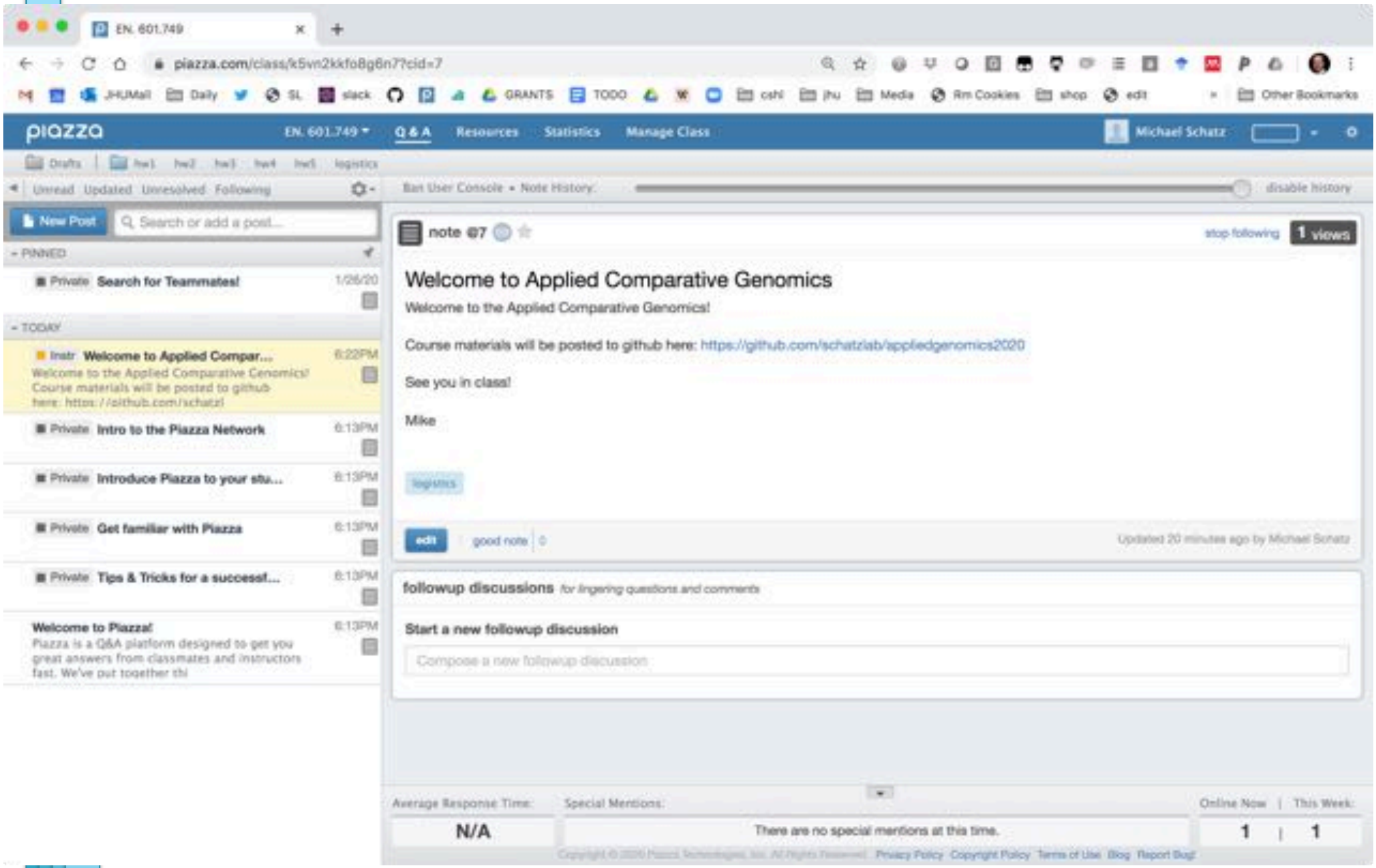
- Question 1.1. Total genome size
- Question 1.2. Number of chromosomes
- Question 1.3. Largest chromosome size and name
- Question 1.4. Smallest chromosome size and name
- Question 1.5. Mean chromosome length

Question 2: Sequence content

Download the yeast genome from here: http://schatz-lab.org/appliedgenomics2020/assignments/assignment1/yeast.fa.gz

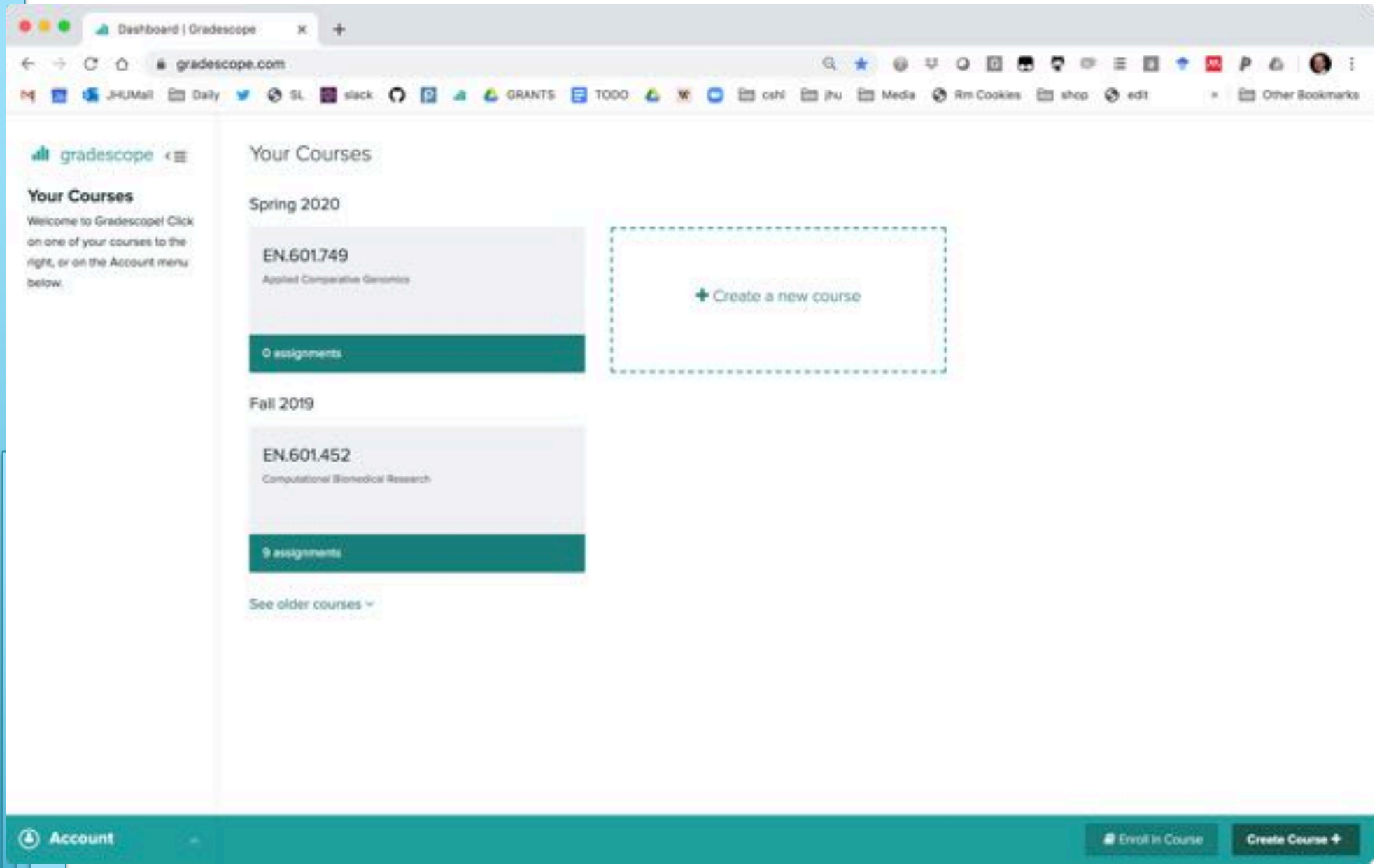
https://github.com/schatzlab/appliedgenomics2020

Piazza



https://piazza.com/class/k5vn2kkfo8g6n7

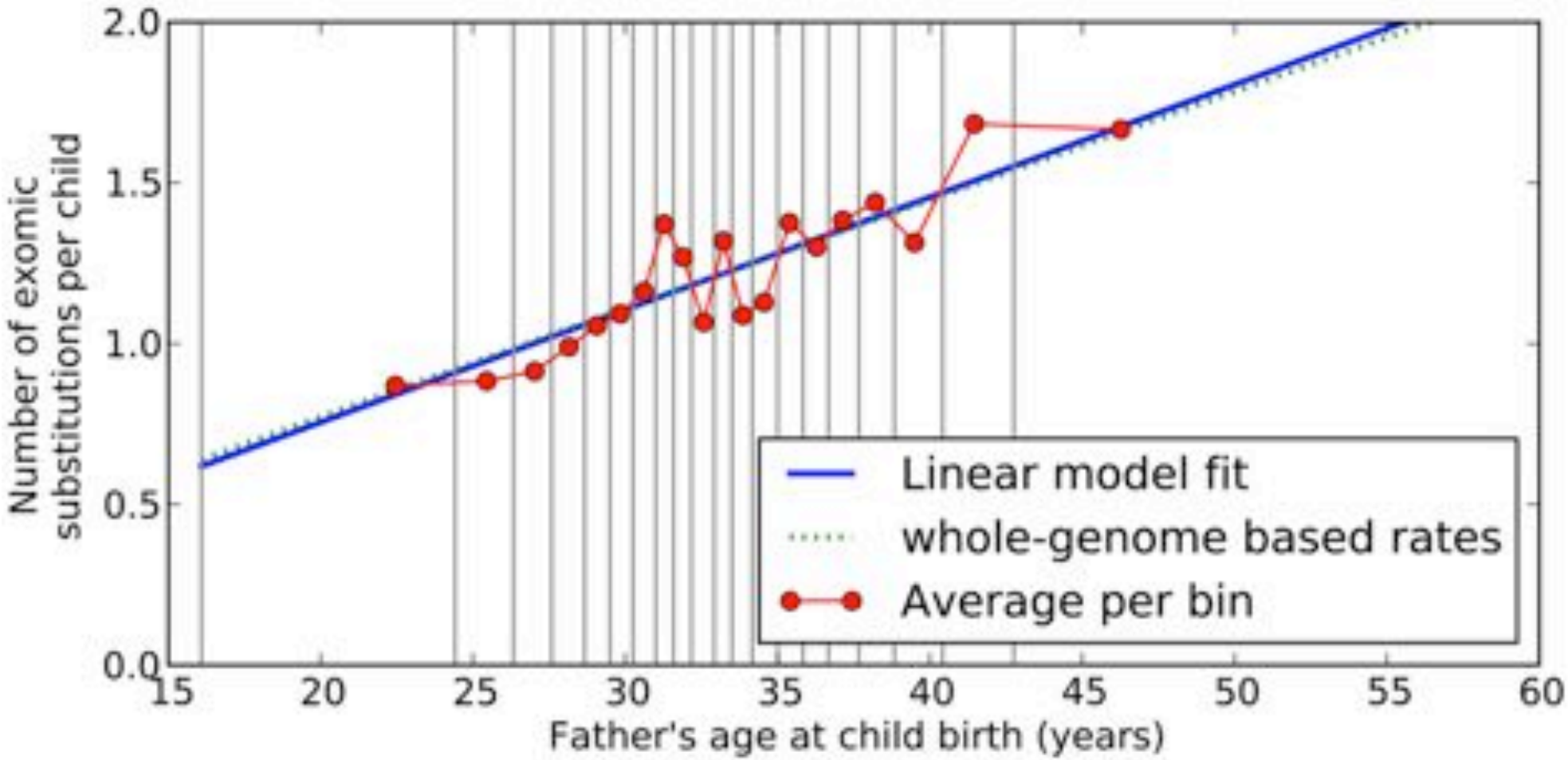
GradeScope



https://www.gradescope.com/

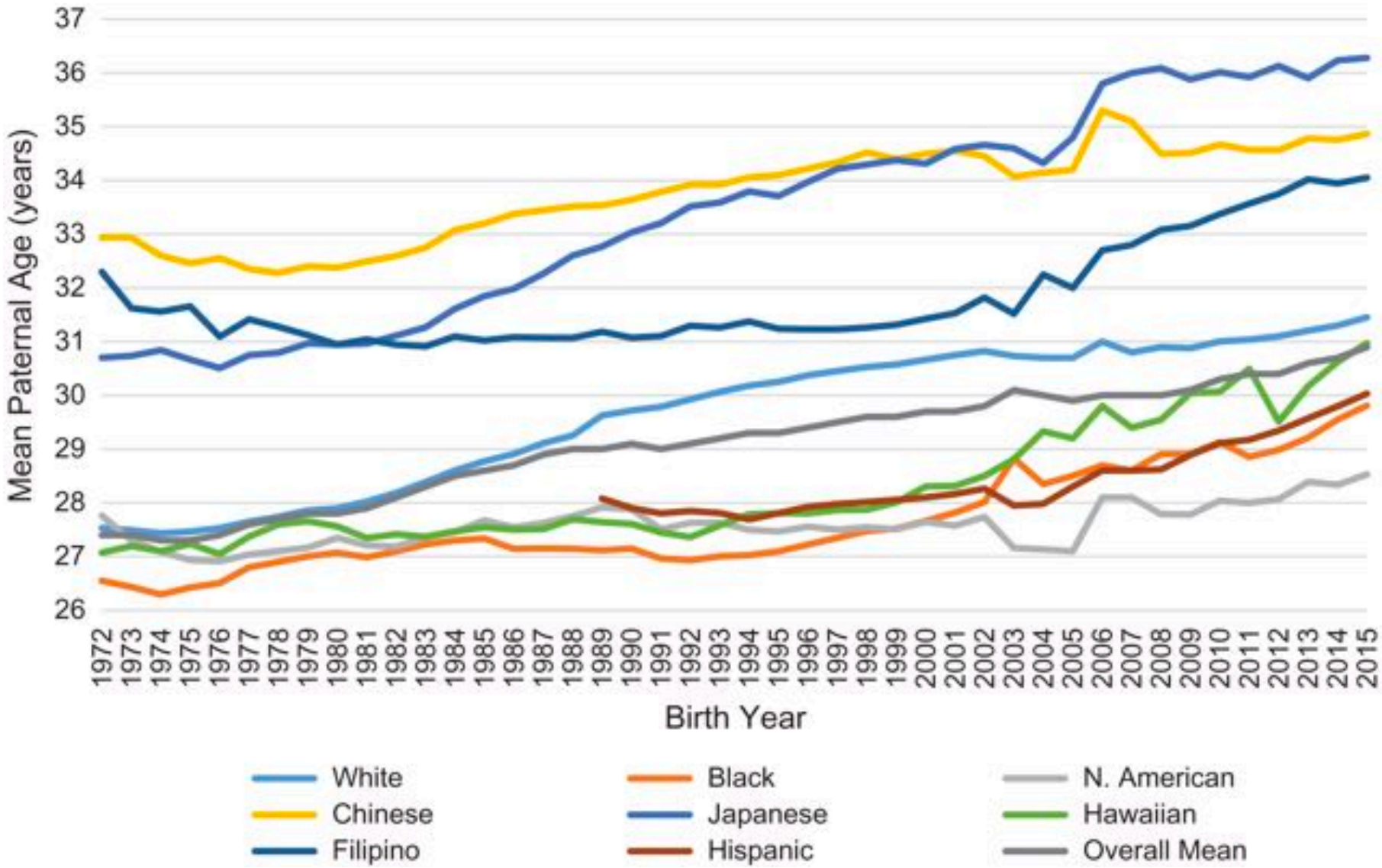
Entry Code: MR652Z

De novo Mutations in Men



The contribution of de novo coding mutations to autism spectrum disorder
Iossifov *et al* (2014) *Nature*. doi:10.1038/nature13908

Age of Fatherhood

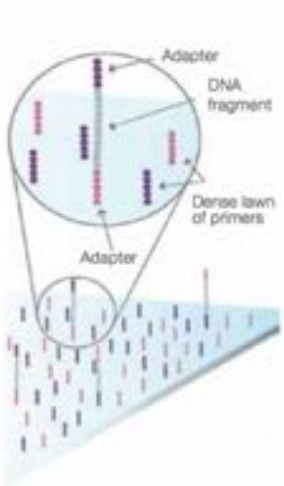


The age of fathers in the USA is rising: an analysis of 168 867 480 births from 1972 to 2015
Khandwala *et al* (2017) *Human Reproduction. https://doi.org/10.1093/humrep/dex267*

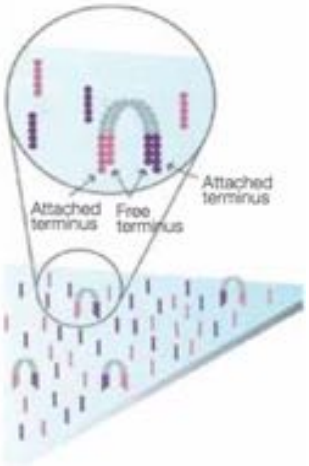
Second Generation Sequencing

Illumina NovaSeq 6000
Sequencing by Synthesis

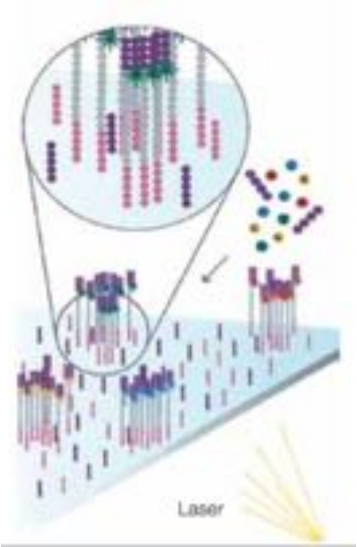
>3Tbp / day



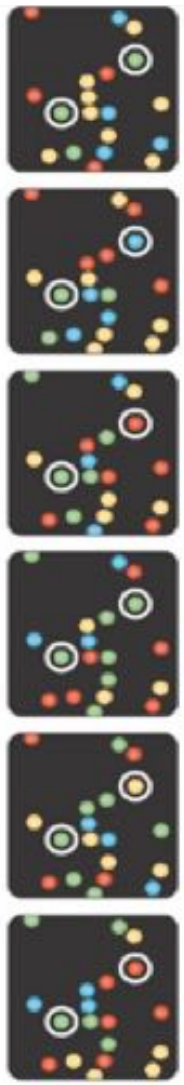
1. Attach



2. Amplify



3. Image

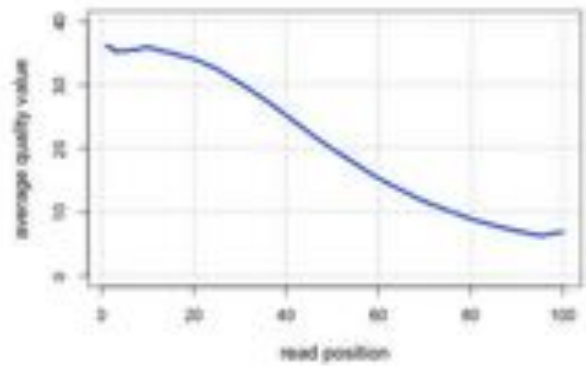


Metzker (2010) Nature Reviews Genetics 11:31-46
https://www.youtube.com/watch?v=fCd6B5HRaZ8

Illumina Quality

QV	p_{error}
40	1/10000
30	1/1000
20	1/100
10	1/10

$$Q_{\text{sanger}} = -10 \log_{10} p$$

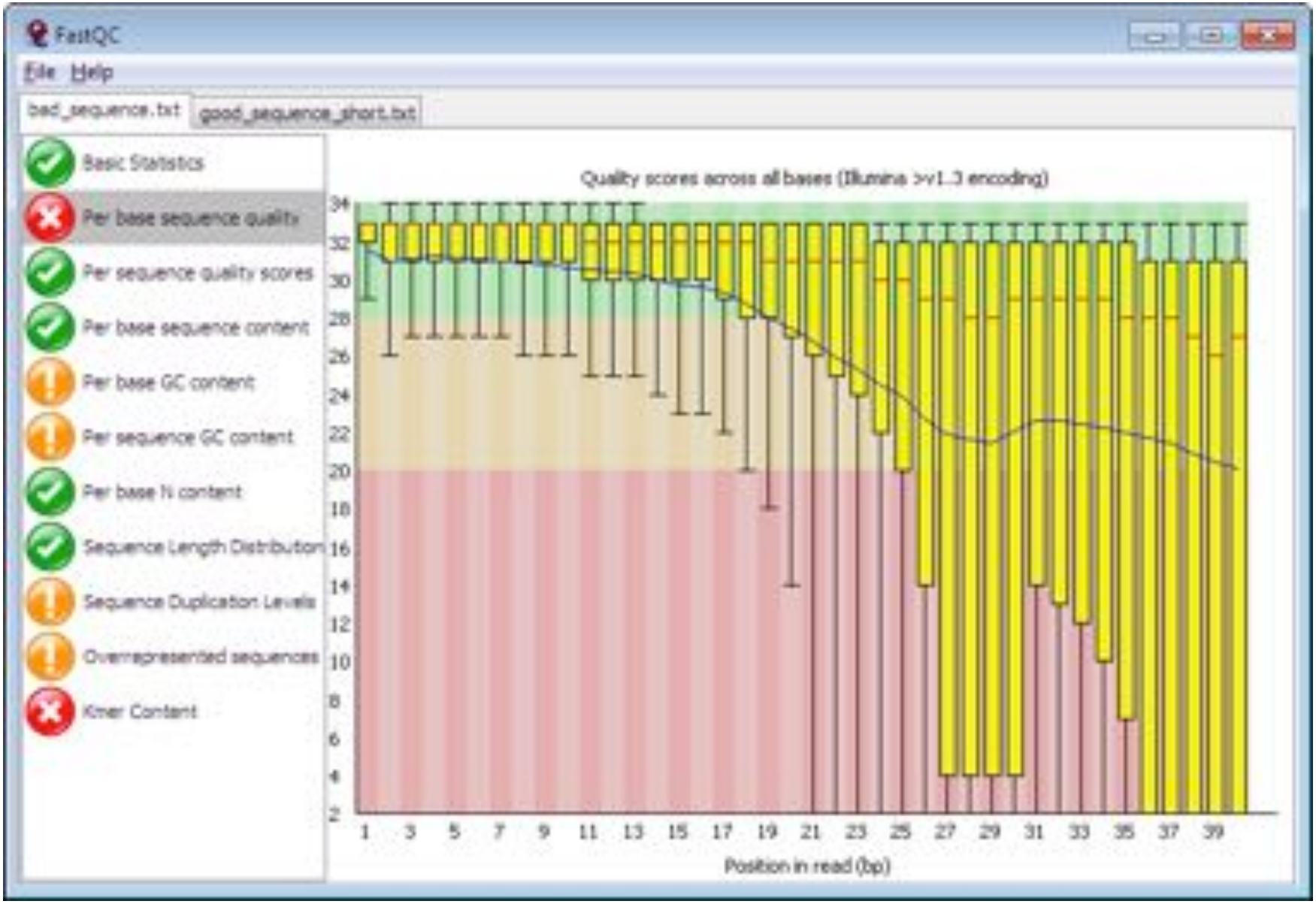



```
SSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSS.....................................................
.........................XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX.......................
...............................IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII.......................
................................JJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJJ.......................
LLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL.....................................................
!"#$%&'()*+,-./0123456789:;<=>?@ABCDEFGHIJKLMNOPQRSTUVWXYZ[\]^_`abcdefghijklmnopqrstuvwxyz{|}~
|                         |    |        |                              |                     |
33                        59   64       73                            104                   126

S - Sanger        Phred+33,  raw reads typically (0, 40)
X - Solexa        Solexa+64, raw reads typically (-5, 40)
I - Illumina 1.3+ Phred+64,  raw reads typically (0, 40)
J - Illumina 1.5+ Phred+64,  raw reads typically (3, 40)
   with 0=unused, 1=unused, 2=Read Segment Quality Control Indicator (bold)
   (Note: See discussion above).
L - Illumina 1.8+ Phred+33,  raw reads typically (0, 41)
```

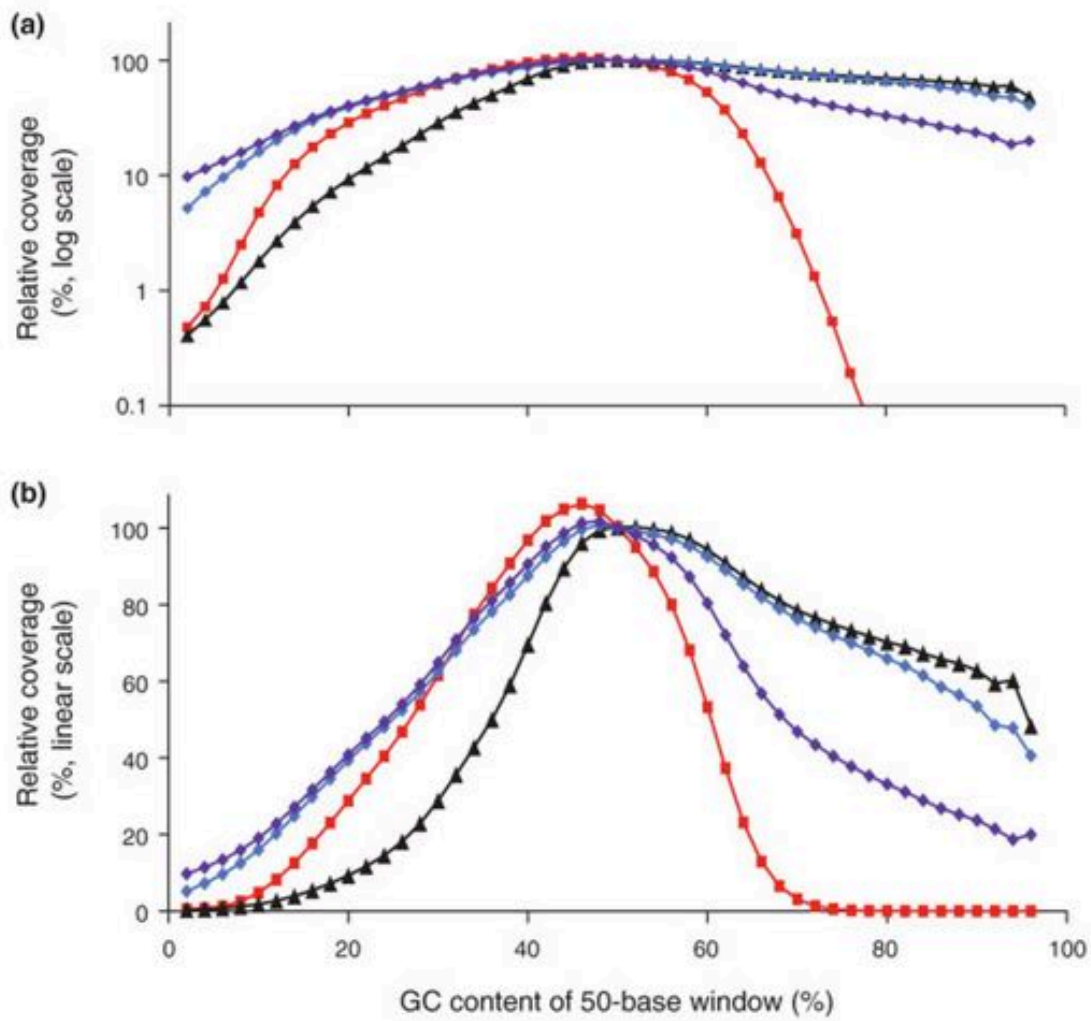
http://en.wikipedia.org/wiki/FASTQ_format

FASTQC: Is my data any good?



http://www.bioinformatics.babraham.ac.uk/projects/fastqc/

Beware of GC Biases

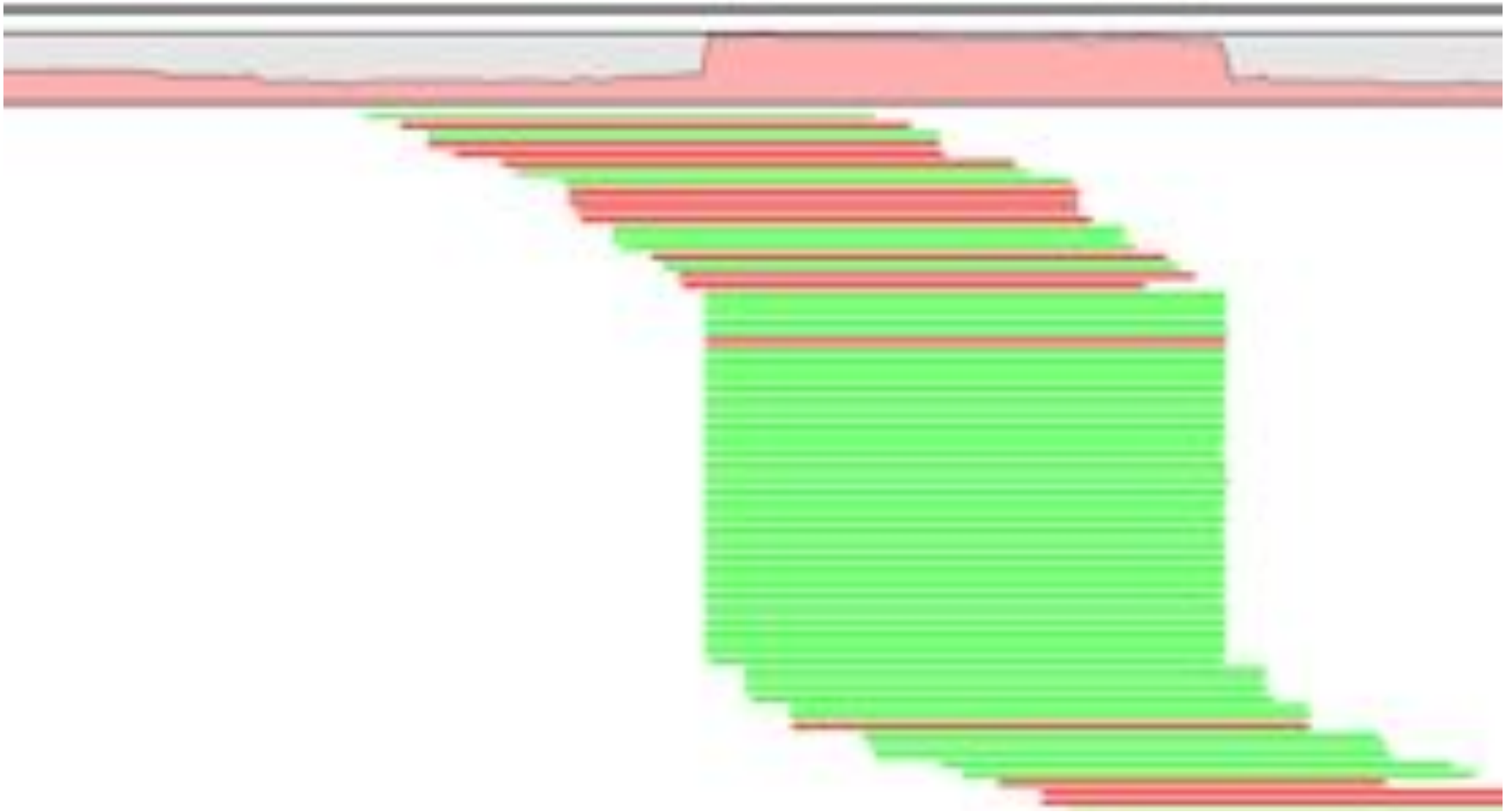


Illumina sequencing does not produce uniform coverage over the genome

- Coverage of extremely high or extremely low GC content will have reduced coverage in Illumina sequencing
- Biases primarily introduced during PCR; lower temperatures, slower heating, and fewer rounds minimize biases
- This makes it very difficult to identify variants (SNPs, CNVs, etc) in certain regions of the genome

Analyzing and minimizing PCR amplification bias in Illumina sequencing libraries.
Aird et al. (2011) *Genome Biology.* 12:R18.

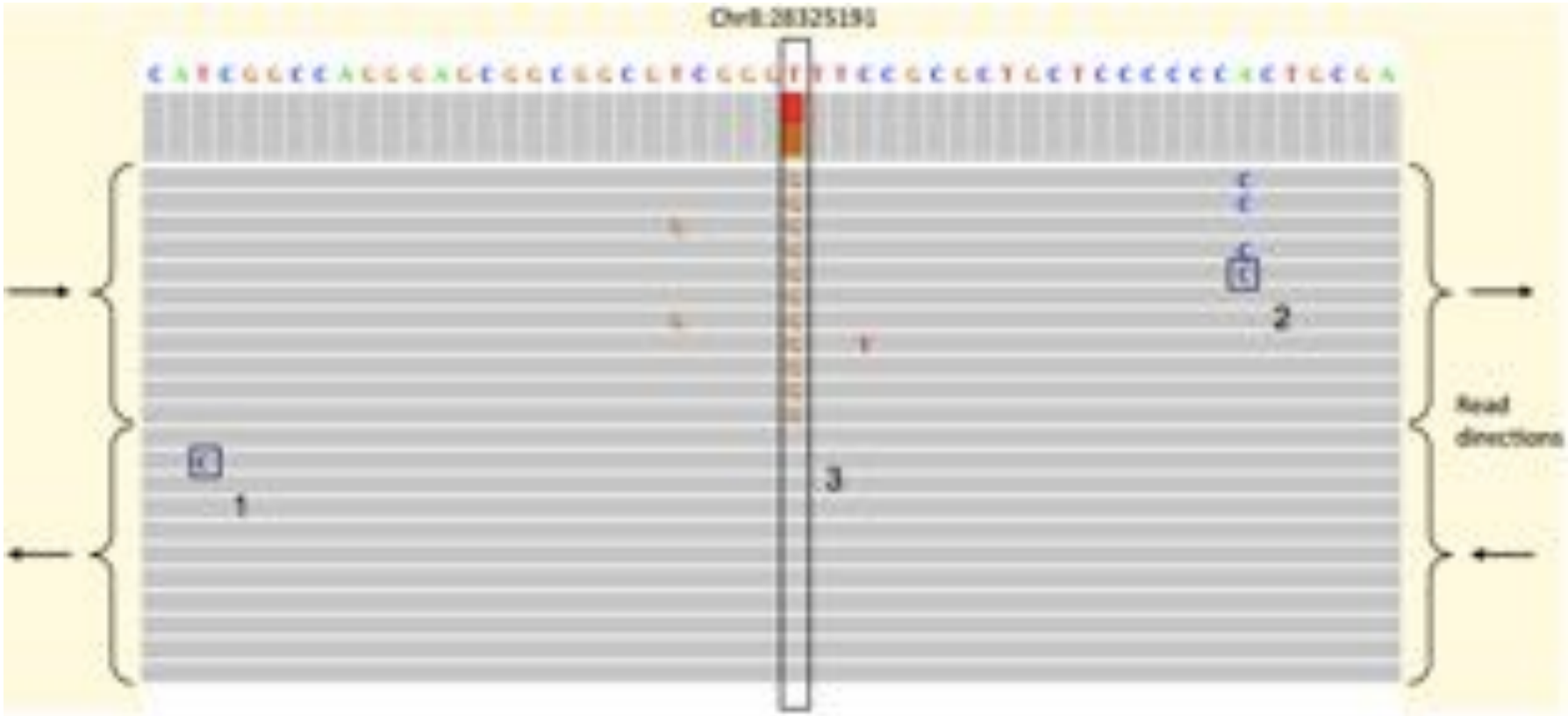
Beware of Duplicate Reads



The Sequence alignment/map (SAM) format and SAMtools.
Li et al. (2009) *Bioinformatics.* 25:2078-9

Picard: http://picard.sourceforge.net

Beware of (Systematic) Errors



Identification and correction of systematic error in high-throughput sequence data
Meacham et al. (2011) *BMC Bioinformatics.* 12:451

A closer look at RNA editing.
Lior Pachter (2012) *Nature Biotechnology.* 30:246-247

Question?

We would love to generate
longer and longer reads with this technology

What can we do?

Illumina Hacking

BIOINFORMATICS ORIGINAL PAPER
Vol. 29 no. 12 2013, pages 1492–1497
doi:10.1093/bioinformatics/bt178

Genome analysis
Advance Access publication May 22, 2013

Assembling the 20 Gb white spruce (*Picea glauca*) genome from whole-genome shotgun sequencing data

Inanc Birol[1,2,3,*], Anthony Raymond[1], Shaun D. Jackman[1], Stephen Pleasance[1], Robin Coope[1], Greg A. Taylor[1], Macaire Man Saint Yuen[4], Christopher I. Keeling[4], Dana Brand[1], Benjamin P. Vandervalk[1], Heather Kirk[1], Pawan Pandoh[1], Richard A. Moore[1], Yongjun Zhao[1], Andrew J. Mungall[1], Barry Jaquish[5], Alvin Yanchuk[5], Ca
Brian Boyle[7], Jean Bousquet[7,8], Kermit Ritland[6], John MacKay[7,8], Jörg B
Steven J.M. Jones[1,2,9]

[1]Genome Sciences Centre, British Columbia Cancer Agency, Vancouver, BC V5Z 4S6, Canada,
Genetics, University of British Columbia, Vancouver, BC V6H 3N1, Canada, [3]School of Comp
Fraser University, Burnaby, BC V5A 1S6, Canada, [4]Michael Smith Laboratories, University of B
Vancouver, BC V6T 1Z4, Canada, [5]British Columbia Ministry of Forests, Lands and Natural Re
Victoria, BC V8W 9C2, Canada, [6]Department of Forest Sciences, University of British Columbi
1Z4, Canada, [7]Institute for Systems and Integrative Biology, Université Laval, Québec, QC G1
[8]Department of Wood and Forest Sciences, Université Laval, Québec, QC G1V 0A6, Canada
Molecular Biology and Biochemistry, Simon Fraser University, Burnaby, BC V5A 1S6, Canada

Associate Editor: Michael Brudno

ABSTRACT
White spruce (Picea glauca) is a dominant conifer of the boreal forests of North America, and providing genomics resources for this commercially valuable tree will help improve forest management and conservation efforts. Sequencing and assembling the large and highly repetitive spruce genome though pushes the boundaries of the current technology. Here, we describe a whole-genome shotgun sequencing strategy using two Illumina sequencing platforms and an assembly approach using the ABySS software. We report a 20.8 giga base pairs draft genome in 4.9 million scaffolds, with a scaffold N50 of 20 356 bp. We demonstrate how recent improvements in the sequencing technology, especially increasing read lengths and paired end reads from longer fragments have a major impact on the assembly contiguity. We also note that scalable bioinformatics tools are instrumental in providing rapid draft assembles.

Availability: The Picea glauca genome sequencing and assembly data are available through NCBI (Accession#: ALWZ01000000000 PID: PRJNA83435). http://www.ncbi.nlm.nih.gov/bioproject/83435.
Contact: birol@bcgsc.ca
Supplementary information: Supplementary data are available at Bioinformatics online.

Received on March 20, 2013; revised on April 10, 2013; accepted on April 11, 2013

1 INTRODUCTION

The assembly of short reads to develop genomic resources for non-model species remains an active area of development (Schatz *et al.*, 2012). The feasibility of the approach and its scalability to large genomes was demonstrated b
(Simpson *et al.*, 2009) using human
and was later used to assemble the
SOAPdenovo tool (Li *et al.*, 2010).
high quality results, as demonstrate
et al., 2012; Ladner *et al.*, 2013; Rib
been successfully applied numerous ti
omes (Chan *et al.*, 2011; Chu *et al.*, 2
2011; Godel *et al.*, 2012; Swart *et al.*,
Estimated at 20 giga base pairs (Gi
cing and assembly of the genome of t
the pine (*Pinaceae*) family present uni
generation end, those challenges inclu
whole-genome shotgun sequencing da
ing reduced representation resources
tude of the problem. On the bioin
massive sequencing datasets is extrem
ing cycles, memory usage, storage req
programming implementations on co
We addressed the data representati
and sequencing multiple whole-genom
HiSeq 2000 and MiSeq sequencers
CA, USA). Compared with localized
as building and sequencing fosmi
approach of isolating ~10 kb DNA
sequencing fragments in high through
CA, USA), a shotgun only sequencing
sequence data effectively covering th
that can be an order of magnitude le
especially substantial when sequencin
In this work, we demonstrate that
at this scale remains viable and pro

*To whom correspondence should be addressed.

assemble the spruce genome, we used the ABySS algorithm (Simpson *et al.*, 2009), which captures a representation of read-to-read overlaps by a distributed de Bruijn graph and uses parallel computations to build the target genome. The modular nature of the tool allowed us to execute a large number of tests to tune the message passing interface for a successful execution, train the assembly parameters for an optimal assembly and quantify the utility of long reads for large genome assemblies. To the best of our knowledge, the ABySS algorithm is unique in its ability to enable genome assemblies of this scale using whole-genome shotgun sequencing data.

2 METHODS

2.1 Sample collection

Apical shoot tissues were collected in April 2006 from a single white spruce (*Picea glauca*, genotype PG29) tree at the Kalamalka Research Station of the British Columbia Ministry of Forests and Ranges, Vernon, British Columbia, Canada. Genomic DNA was extracted from 60 gm tissue by BioS&T (http://www.biost.com/, Montreal, QC, Canada) using an organelle exclusion method yielding 300 μg of high quality purified nuclear DNA.

2.2 Library preparation and sequencing

DNA quality was assessed by spectrophotometry and gel electrophoresis before library construction. DNA was sheared for 45 s using an E210 sonicator (Covaris) and then analysed on 8% PAGE gels. The 200–300 bp (for libraries with 250 bp insert size) or 450–550 bp (for libraries with 500 bp insert size) DNA size fractions were excised and eluted from the gel slices overnight at 4°C in 300 μl of elution buffer [5:1 (vol/vol) LoTE buffer [3 mM Tris–HCl (pH 7.5), 0.2 mM EDTA]/7.5 M ammonium acetate] and was purified using a Spin-X Filter Tube (Fisher Scientific) and ethanol precipitation. Genome libraries were prepared using a modified paired-end tag (PET) protocol supplied by Illumina Inc. This involved DNA end repair and formation of 3′ adenosine overhangs using the Klenow fragment of DNA polymerase I (3′–5′ exonuclease minus) and ligation to Illumina PE adapters (with 5′ overhangs). Adapter-ligated products were purified on QIAquick spin columns (Qiagen) and amplified using Phusion DNA polymerase (NEB) and 10 PCR cycles with the PE primer 1.0 and 2.0 (Illumina). PCR products of the desired size range were purified from adapter ligation artifacts using 8% PAGE gels. DNA quality was assessed and quantified using an Agilent DNA 1000 series II assay (Agilent) and Nanodrop 7500 spectrophotometer (Nanodrop). DNA was subsequently diluted to 8 nM. The final concentration was confirmed using a Quant-iT dsDNA HS assay kit and Qubit fluorometer (Invitrogen).

The mate pair (MPET, a.k.a. jumping) libraries were constructed using 4 μg of genomic DNA with the Illumina Nextera Mate-Pair library construction protocol and reagent (FC-132-1001). The genomic DNA sample was simultaneously fragmented and tagged with a biotin containing mate pair junction adapter, which left a short sequence gap in the tagmented DNA. The gap was filled by a strand displacement reaction using a polymerase to ensure that all fragments were flush and ready for circularization. After an AMPure Bead cleanup, size selection was done on a 0.6% agarose gel to excise 6–9 kb and 9–13 kb fractions, which were purified using a Zymoclean Large Fragment DNA Recovery Kit. The fragments were circularized by ligation, followed by a digestion to remove any linear molecules and left circularized DNA for shearing. The sheared DNA fragments that contain the biotinylated junction adapter (mate pair fragments) were purified by means of binding to streptavidin magnetic beads, and the unwanted unbiotinylated molecules were washed away. The DNA fragments were then end repaired and A-tailed following the protocol and ligated to indexed TruSeq adapters. The final library was enriched by a 10-cycle PCR and purified by AMPure bead clean-up. Library quality and size were assessed by Agilent DNA 1000 series II assay and KAPA Library Quantification protocol. The two fractions were pooled for sequencing paired end 100 bp using Illumina HiSeq2000.

The construction of the 12 kb mate pair libraries was achieved by a hybrid 454/Illumina procedure. Briefly, 50 μg of genomic DN
mented for 20 cycles at speed code 12 using a Hydrosh
Marlborough, MA) equipped with a large assembly modu
mented DNA was loaded on a 1% agarose gel, and fragmen
18 kb were extracted. Biotinylated circularization adapters
Titanium Paired-end Adaptor set (454 Life Sciences/Roch
CT) were added to ends of the gel-extracted fragments.
recombination of the ends was performed with Cre recom
England Biolabs, Ipswich, MA), and linear molecules rema
tion were removed with Plasmid Safe (Epicentre, Madison,
molecules were fragmented using GS Rapid Library Nebul
Sciences/Roche, Branford, CT), and fragment end-repair fo
tailing was performed with the GS Rapid Library preparation
Sciences/Roche, Branford, CT). TruSeq Adapters (Illumina
CA) were ligated to the repaired/A-tailed ends. Biotinylat
were enriched using Streptavidin-coupled Dynabeads (Life
Grand Island, NY) and amplified by PCR using Illu
primers.

Random bacterial artificial chromosome (BAC) seq
performed using DNA from the same genotype on 4
Titanium with 6 kb paired-end libraries at the PlateForm
Génomiques of the Institute for Systems and Integra
(Université Laval, Québec City, QC). A single paired-end
prepared on a pool of 15 BACs (equimolar concentrations)
earlier in the text with the following modifications: 15 μg
fragmented using a Hydroshear with a standard assembly
at speed code 18, 6–10 kb fragments were extracted from
GS-FLX library adaptors were ligated to the repaired/A
ments. GS-FLX sequencing using the titanium chemistry w
according to manufacturer's instructions (454 Life Sc
Branford, CT). Sanger sequencing method was used to ob
BAC sequencing data as previously described (Hamberger
Keeling *et al.*, 2010).

2.3 MiSeq modification

In sequencing the spruce genome, we generated longer rea
modifying the MiSeq platform. The MiSeq uses a clamshell
(Supplementary Fig. S1A) to hold reagent tubes in an arr
cessed by the MiSeq's sippers. Most of the reagents are
length independent steps such as denaturation and cluster ge
three reagents, the Scan, Cleavage and Incorporation mi
sumed at each cycle. Although the MiSeq allows any read
specified in the control software, the reagent cartridge cann
during the run without stopping it. Increasing the read leng
requires increasing the quantity of the length-dependent
cartridge. This led to the solution of combining the leng
reagents of two kits into one.

A tool was designed that opens the snap-hook latches
cartridge together (Supplementary Figs S1B and S2), giv
the reagent tubes, yet allowing the cartridge to be put b
without damage to its components (Supplementary Fig
40 ml, the stock length-dependent reagent containers allo
imum of ~650 cycles in total. To maximize the potential of
kit approach, a new reagent tray with 70 ml wells was
placed in a modified clamshell base.

Assembling the 20 Gb white spruce (*Picea glauca*) genome from whole-genome shotgun sequencing data

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[7] Université Laval, Institute for Systems and Integrative Biology, Québec, QC G1V 0A6
[8] Université Laval, Department of Wood and Forest Sciences, Québec, QC G1V 0A6
[9] Simon Fraser University, Department of Molecular Biology and Biochemistry, Burnaby, BC V5A 1S6

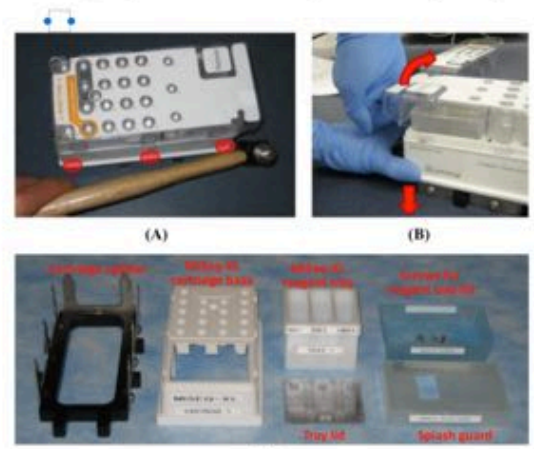


Figure S1. Modification of the MiSeq cartridge. MiSeq reagent cartridge was modified to allow for longer read lengths. **(A, B)** Opening of the clamshell style cartridge. **(C)** Contents of the modified cartridge. This was initially used to combine two PE150 kits for PE300 runs. When Illumina introduced the P250 kit, the same apparatus was used to enable PE500 runs.

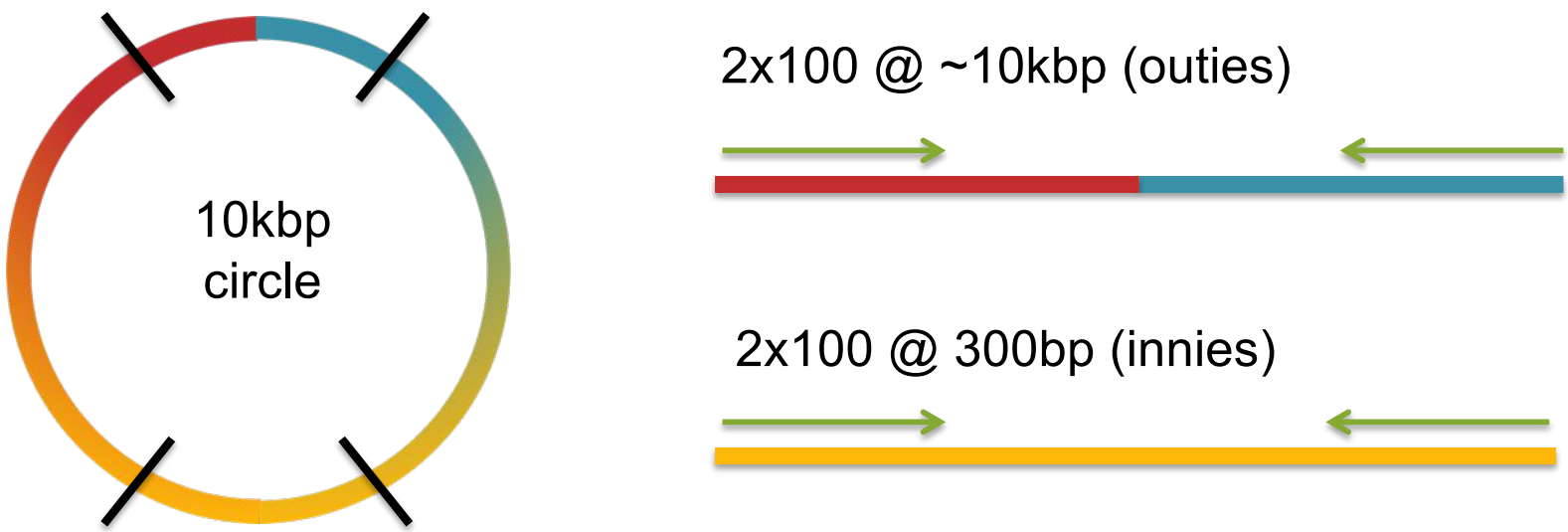
Paired-end and Mate-pairs

Paired-end sequencing

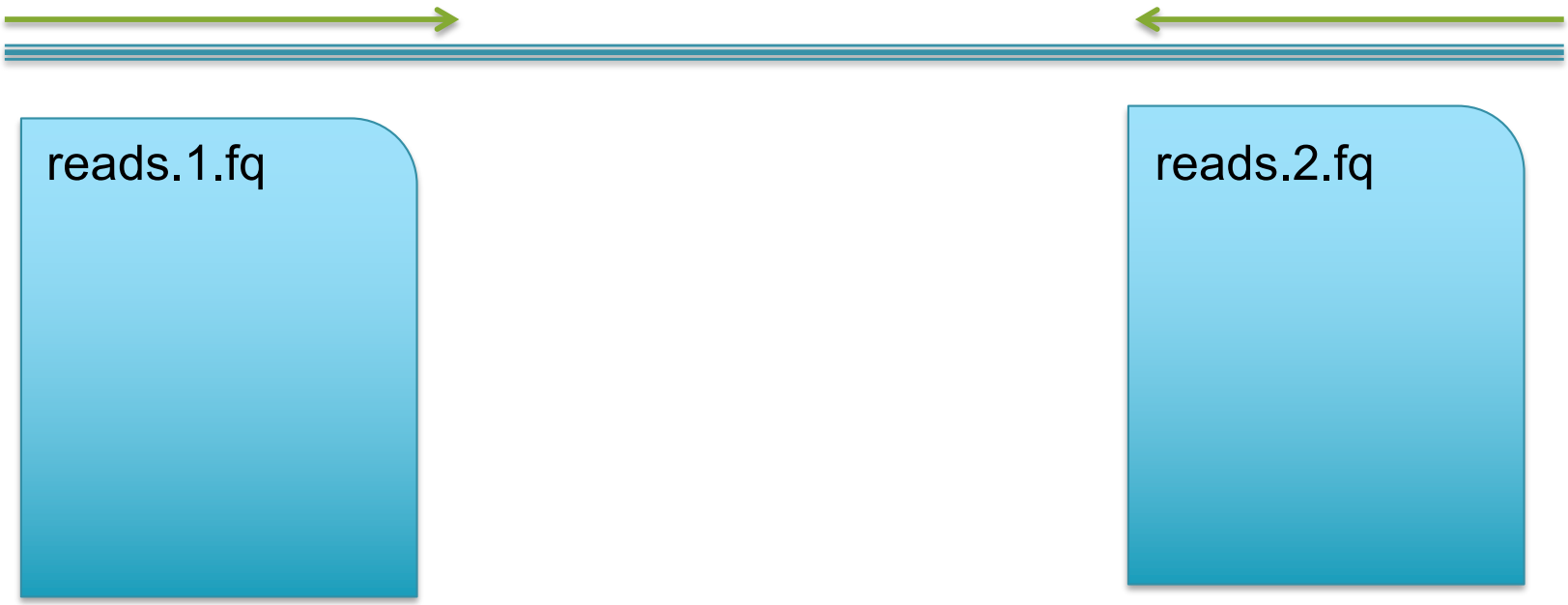
- Read one end of the molecule, flip, and read the other end
- Generate pair of reads separated by up to 500bp with inward orientation

Mate-pair sequencing

- Circularize long molecules (1-10kbp), shear into fragments, & sequence
- Mate failures create short paired-end reads



FASTQ Files




```
@SEQ_ID
GATTTGGGGTTCAAAGCAGTATCGATCAAATAGTAAATCCATTTGTTCAACTCACAGTTT
+
!''*((((***+))%%%++)(%%%%).1***-+*''))**55CCF>>>>>>CCCCCCC65
```

@Identifier
Sequence
+Separator
Quality Values
…

http://en.wikipedia.org/wiki/FASTQ_format

Illumina Sequencing Summary

Advantages:

- Best throughput, accuracy and read length for any 2nd gen. sequencer
- Fast & robust library preparation

Disadvantages:

- Inherent limits to read length (practically, 150bp)
- Some runs are error prone
- Requires amplification, sequences a population of molecules

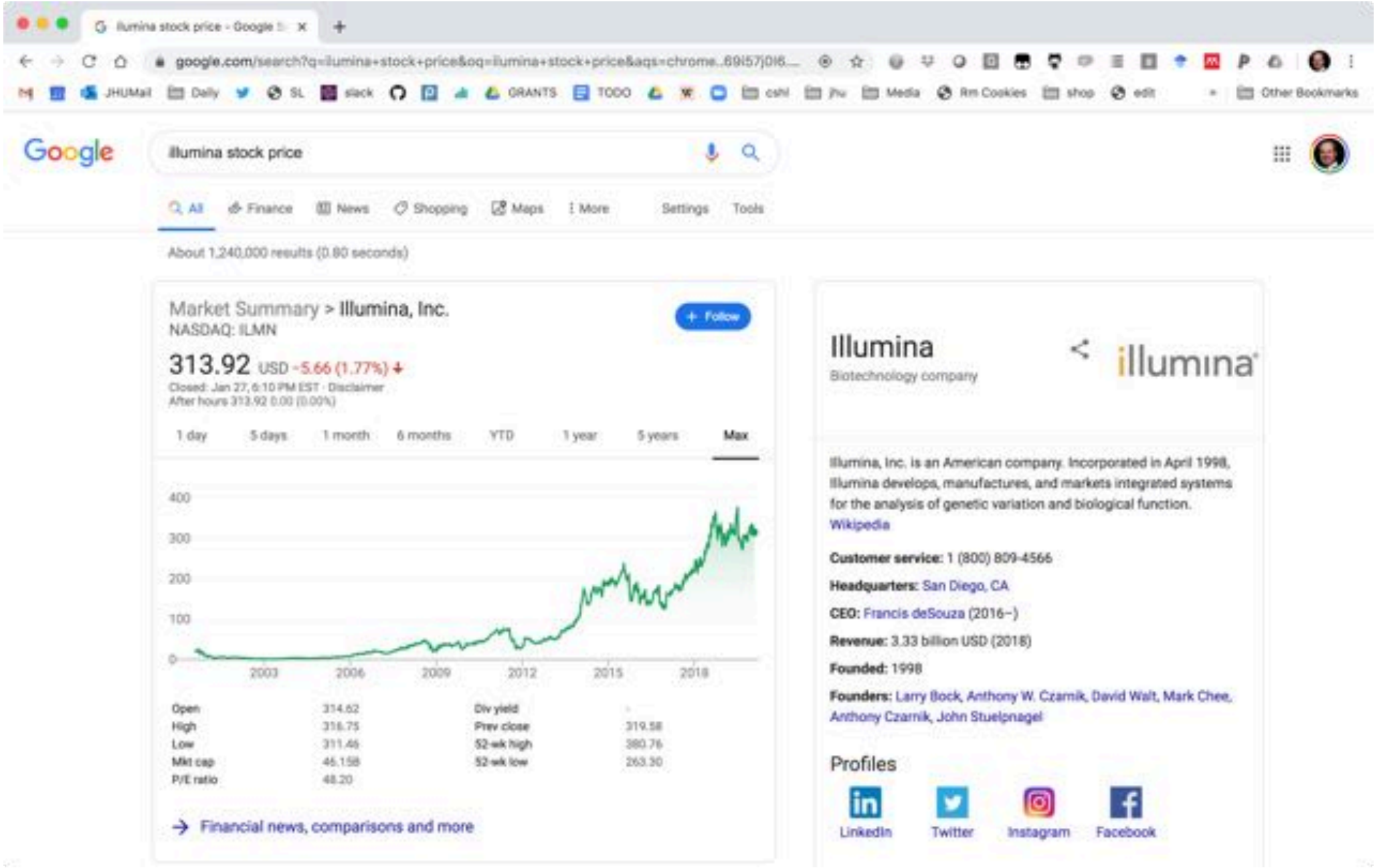
Illumina HiSeq
~3 billion paired 100bp reads
~600Gb, $10K, 8 days
(or "rapid run" ~90Gb in 1-2 days)

Illumina X Ten
~6 billion paired 150bp reads
1.8Tb, <3 days, ~1000 / genome($$)
(or "rapid run" ~90Gb in 1-2 days)

Illumina NextSeq
One human genome in **<30 hours**

Ira Hall

ILMN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About 1,240,000 results (0.80 seconds)
Market Summary > Illumina, Inc.
NASDAQ: ILMN
Follow
313.92 USD -5.66 (1.77%)
Closed: Jan 27, 6:10 PM EST · Disclaimer
After hours 313.92 0.00 (0.00%)
1 day
5 days
1 month
6 months
YTD
1 year
5 years
Max
400
300
200
100
0
2003
2006
2009
2012
2015
2018
Open 314.62
High 316.75
Low 311.46
Mkt cap 46.158
P/E ratio 48.20
Div yield
Prev close 319.58
52-wk high 380.76
52-wk low 263.30
Financial news, comparisons and more
Illumina
Biotechnology company
illumina
Illumina, Inc. is an American company. Incorporated in April 1998, Illumina develops, manufactures, and markets integrated systems for the analysis of genetic variation and biological function.
Wikipedia
Customer service: 1 (800) 809-4566
Headquarters: San Diego, CA
CEO: Francis deSouza (2016–)
Revenue: 3.33 billion USD (2018)
Founded: 1998
Founders: Larry Bock, Anthony W. Czarnik, David Walt, Mark Chee, Anthony Czarnik, John Stuelpnagel
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Next Steps

1. Reflect on the magic and power of DNA ☺
2. Check out the course webpage
3. Register on Piazza
4. Work on Assignment 1
    1. Set up Linux, set up Virtual Machine, set up Ubuntu
    2. Set up Dropbox for yourself!
    3. Get comfortable on the command line