

Nanopore sequencing: from basecalling to structural variant detection

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Materials here:

https://github.com/yaozhong/mexico_workshop_nanopore_hands_on

https://github.com/yaozhong/mexico_workshop_nanopore_hands_on

Before we started, please do ...

1.Copy data and related folders

`cp -r /share/lect/nanopore/ ~/`

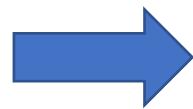
2.Prepare singularity environment

`singularity build --sandbox singularity_img/nanopore
docker://yaozhong/nanopore_analysis`

(*) If you want to use the same environment in your local computer

- {1}. Install docker in your local machine**
- {2}. https://hub.docker.com/r/yaozhong/nanopore_analysis**

2nd Generation



3rd Generation



Short-read sequencing

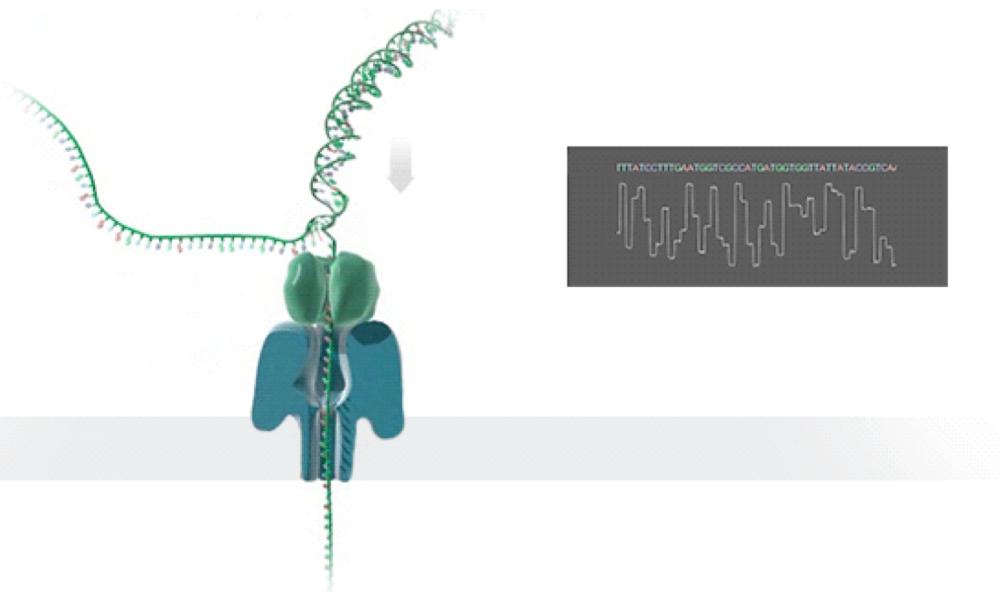
Long-read sequencing

Outline

1. *Nanopore sequencing basics*
2. *Basecalling*
3. *Assembly*
4. *Nanopore Structural variant detection*
5. *Hands-on section*

1.Nanopore sequencing basics

Nanopore sequencing (a third generation)



Advantage:

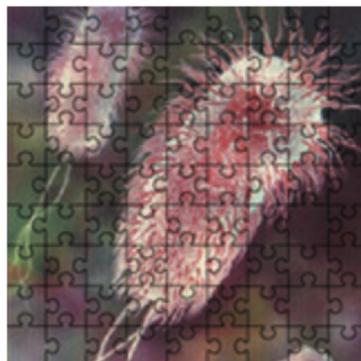
- ***Long reads*** (*up to 2Mb, avg. 10k)
- No PCR amplification
- Low-cost genotyping
- Mobility and real time

Disadvantage:

- High error rate of base-calling
(85% ~ 95%)

Advantage of long reads

- Easier assembly
- Ability to span repetitive genomic regions
- Identification of large structural variation

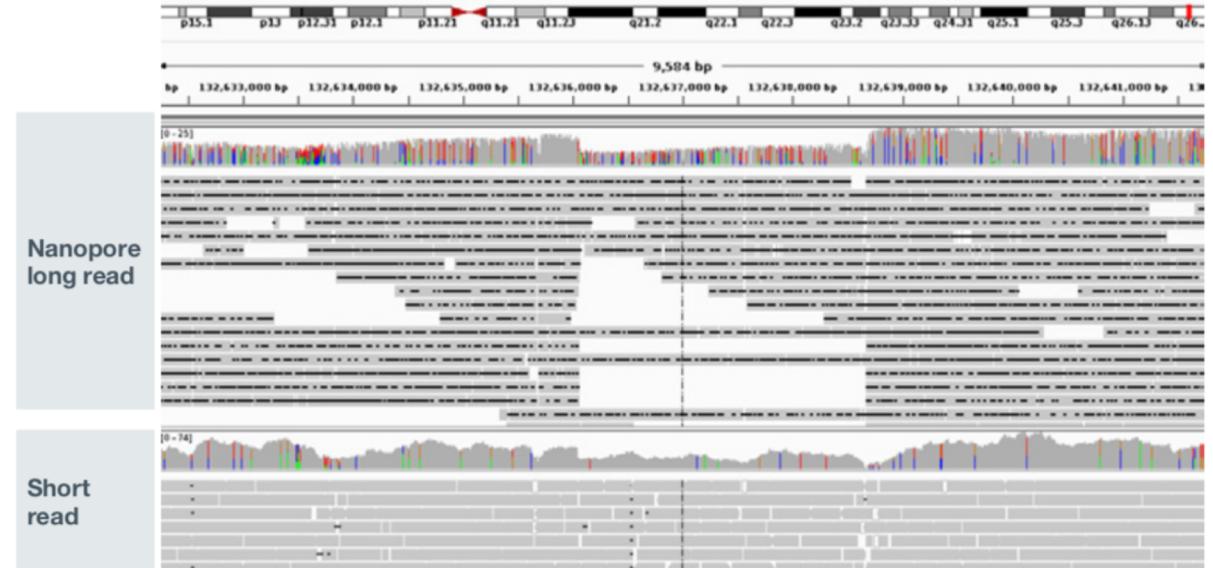


~ 50 base read
~ 92,000 "pieces"



~ 500,000 base read
~ 9 "pieces"

(ONT white papers)



Disadvantage

- Higher error rate
 - Read accuracy is in a range of 5% ~ 15%
 - Vs. Illumina 0.1% ~ 1%
- Current solutions:
 - Improving base-calling accuracy
 - Develop new error-tolerant aligner



For MinION / GridION
Flongle

Adapter to enable small, rapid nanopore sequencing tests, for mobile or desktop sequencers



MinION Mk1B

Your personal nanopore sequencer, putting you in control



MinION Mk1C

Your personal nanopore sequencer including compute and screen, putting you in control



GridION Mk1

Higher-throughput, on demand nanopore sequencing at the desktop, for you or as a service



PromethION 24/48

Ultra-high throughput, on-demand nanopore sequencing, for you or as a service

	Flongle	MinION Mk1B	MinION Mk1C	GridION Mk1	PromethION 24	PromethION 48
<u>Read length</u>	Nanopores read the length of DNA presented to them. Longest read so far: > 2Mb.					
Yield per flow cell, DNA/cDNA (Best Internal)	2 Gb	50 Gb	50 Gb	50 Gb	220 Gb	220 Gb
Number of flow cells per device	1	1	1	5	24	48
Yield per device		50 Gb	50 Gb	250 Gb	5.2 Tb	10.5 Tb
System access	From \$1,760	From \$1,000	From \$4,900	From \$49,995	From \$165,000	From \$285,000
Suitable applications include	Amplicons Panels/targeted sequencing Quality testing Small sequencing tests	Whole genomes/exomes Metagenomics Targeted sequencing Whole transcriptome (cDNA) Smaller transcriptomes (direct RNA) Multiplexing for smaller samples Particularly suitable for field use	Whole genomes/exomes Metagenomics Targeted sequencing Whole transcriptome (cDNA) Smaller transcriptomes (direct RNA) Multiplexing for smaller samples Particularly suitable for field use	Larger genomes or projects Whole transcriptomes (direct RNA or cDNA) Large numbers of samples	Very large genomes or projects Population-scale human Whole transcriptomes Very large numbers of samples	



<https://nanoporetech.com/products>

Oxford Nanopore in Mexico

The screenshot shows the Oxford Nanopore website's "Official Distributors & Partners" section. It features the Oxford Nanopore logo at the top left and a navigation bar with links for PRODUCTS, SERVICES, APPLICATIONS, GET STARTED, and RESOURCES. Below the navigation, there are two circular icons: one for "Logistics Partner" and one for "Distributor", both featuring the Nanopore logo.

Official Distributors & Partners

Oxford Nanopore sells its products directly in more than 70 countries. In some countries we benefit from local support. If you are interested in using nanopore products, and you are from one of the following countries, please contact the distributors below.

Brazil

Logistics partner
Enterprise Instrumentos Analiticos LTDA.

Tel: +55-19-3833-6822

[Website](#) [Email](#)

Seems not official available right now.

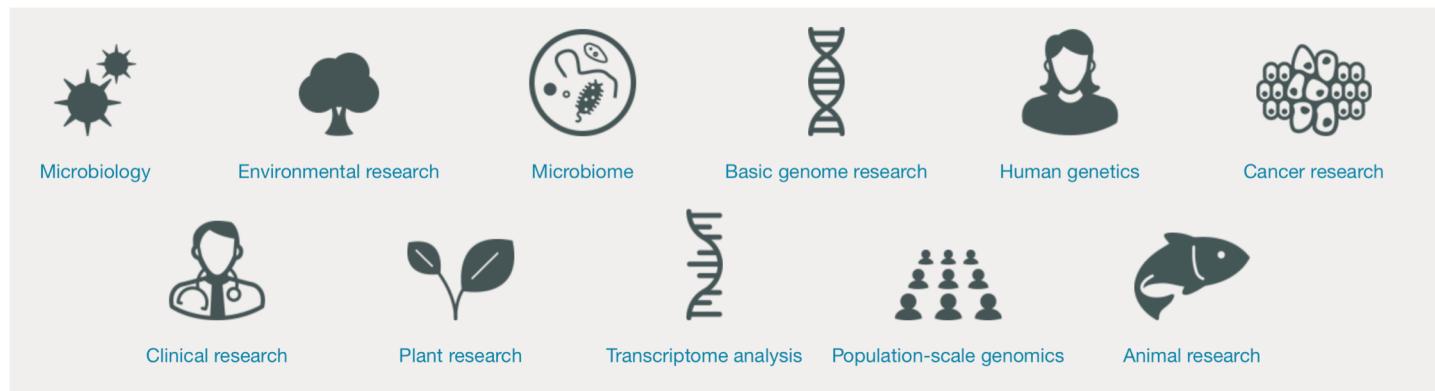
The geographical closest country in sale is Brazil.

The screenshot shows the Illumina website's "DOING BUSINESS WITH ILLUMINA" section. It includes a search bar, sign-in, view cart, and contact us links. Below the header, there is a navigation menu with links for Overview, Direct Commerce, Punchout, Electronic Data Interchange, Instrument Buying Options, Distributors & Partnerships, and More.

^ North America

Territory	Channel Partner	Address	Contact
Mexico	Abalat S.A. De C.V.	Abasolo # 78, Col. Pueblo Sta. Ursula Coyoacán, Mexico City 4650 Mexico	Phone Number (+52) 5580001500 Website www.abalat.com.mx
Mexico	Analitek SA DE C.V.	Lomas de los Pinos 5505-A Col. La Estanzuela Vieja Monterrey, Nuevo Leon 64984 Mexico	Phone Number (+52) 8181040267 Website www.analitek.com

Applications



Suitable for applied uses...



Infectious disease and microbiology



Water testing



Food safety & efficiency



Environmental monitoring



Supply chain monitoring & authentication



Biodefence / Outbreak surveillance



Forensics



Agriculture: Animal



Agriculture: Plant



Industrial diagnostics



Pharmaceuticals



Oncology



Reproductive medicine



Clinical genetics



Education



Consumer genetics

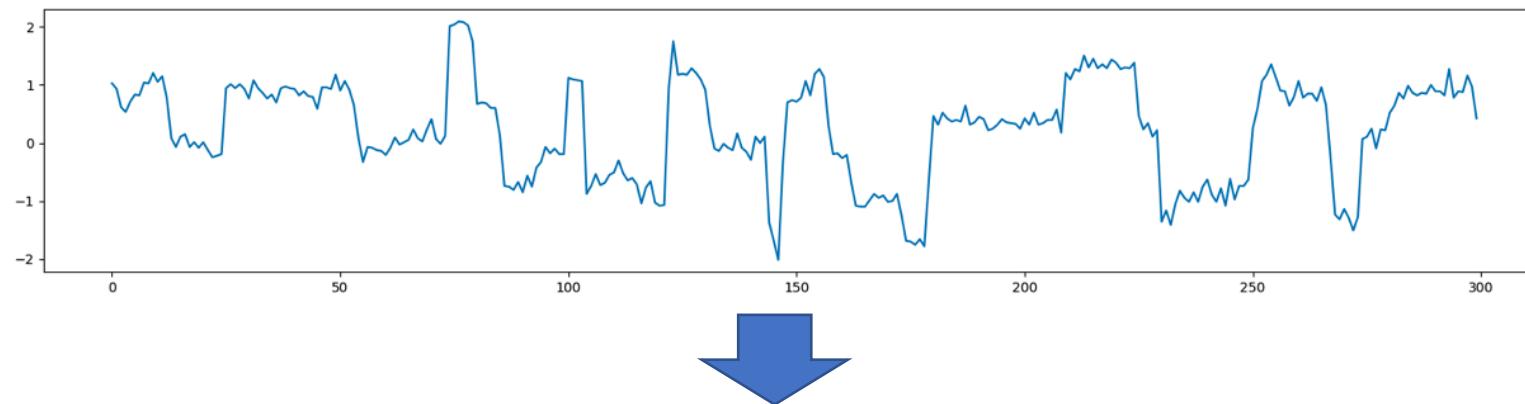
Data Analysis



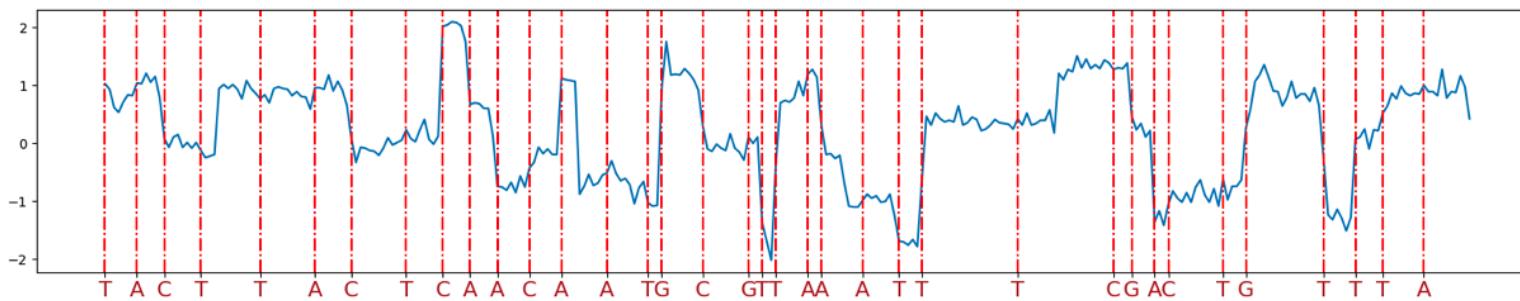
	EPI2ME	Protocol & analysis tutorials	Community developed tools	Custom analysis pipelines
Bioinformatic capability needed	● ● ● ●	● ● ● ●	● ● ● ●	● ● ● ●
How	Use the cloud-based EPI2ME platform for real-time analysis workflows.	Get analysis recommendations and clear tutorials on the use of open-source tools.	Run open-source tools written and developed by the Nanopore Community.	All the data, raw or basecalled, can be used in custom analysis pipelines written by the user for specific applications.

2. Basecalling methods

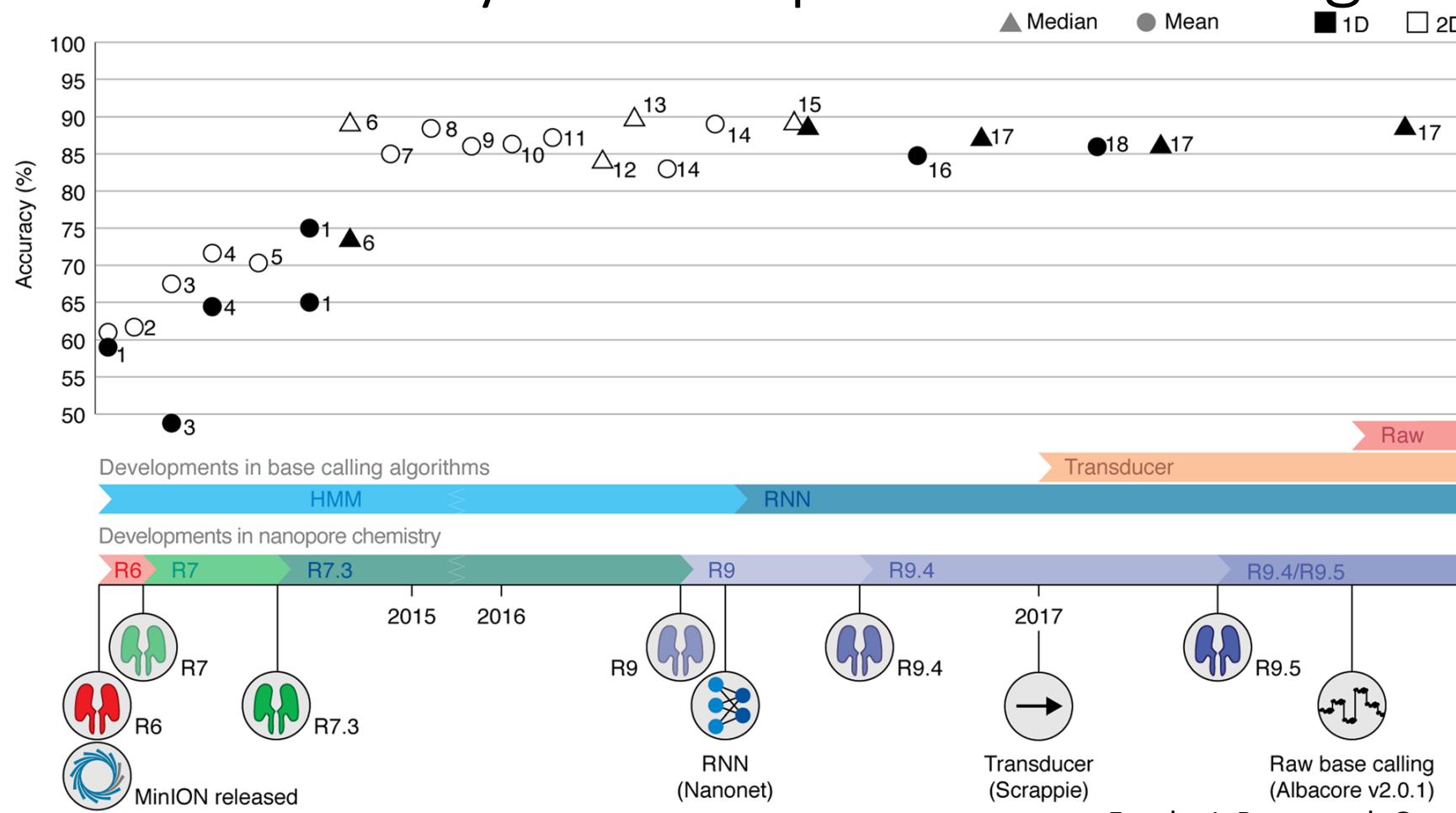
Basecalling



TACTTACTCAACAATGCGTTAAATTCTGACTGTTA



A brief history of nanopore base-calling:



Franka J. Rang et al. Genome biology 2018

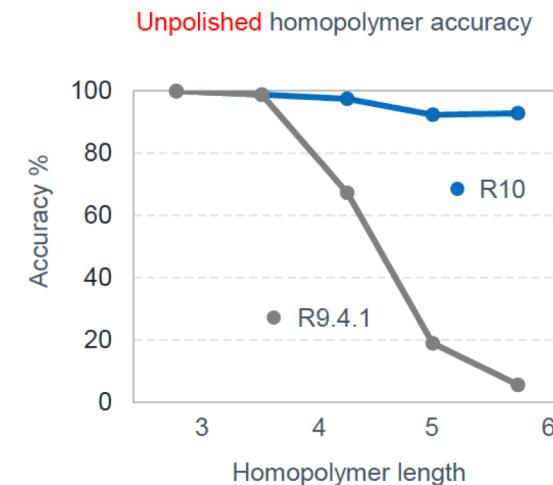
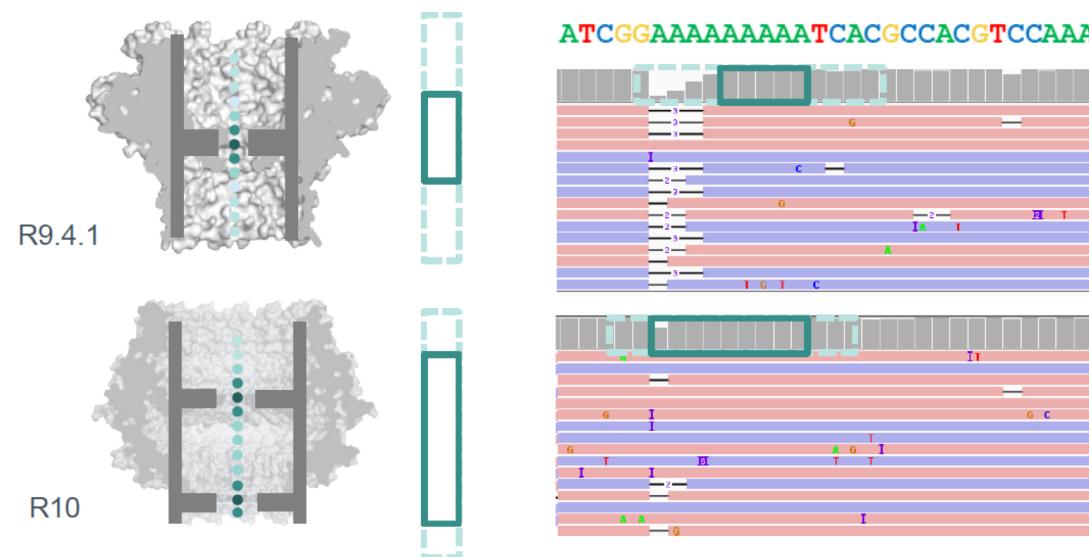
R10 chemistry

CONSENSUS SEQUENCING ACCURACY

New chemistry for improved accuracy – R10 **Just start shipping, July 8th**

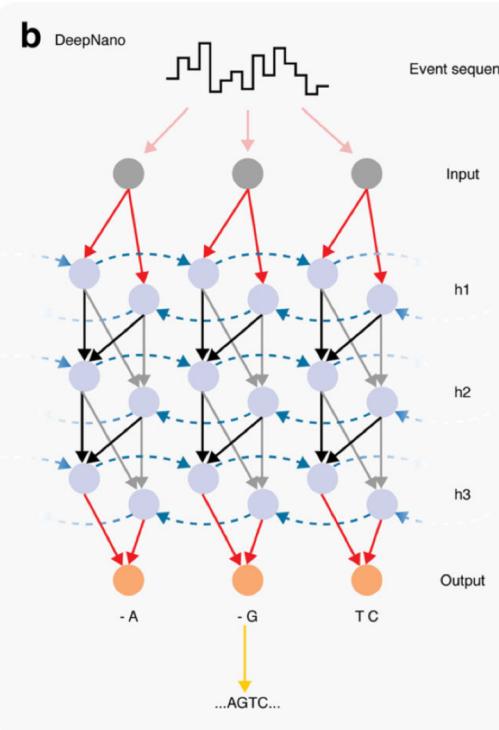
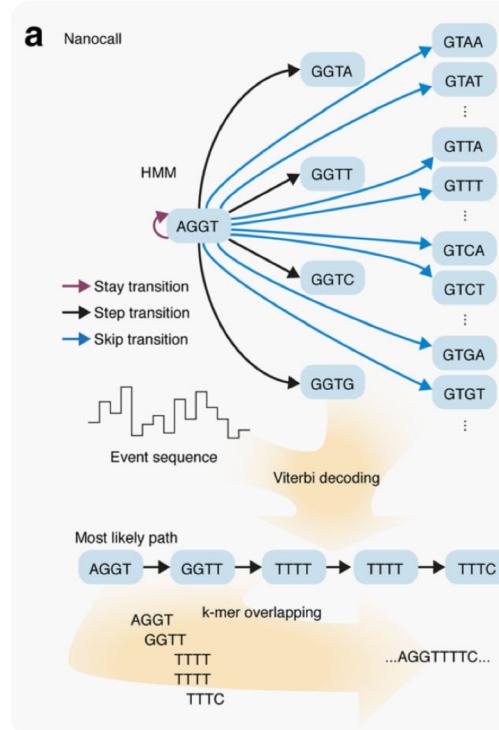
New pore accurately calls homopolymers

- A pore with a longer or multiple “readers” has more bases dominating the signal
- Longer homopolymers are “seen” by the pore and can be decoded with high accuracy

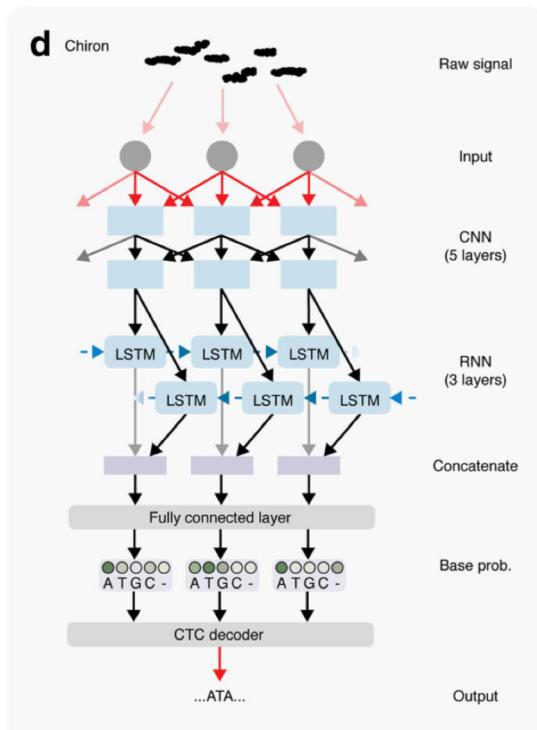
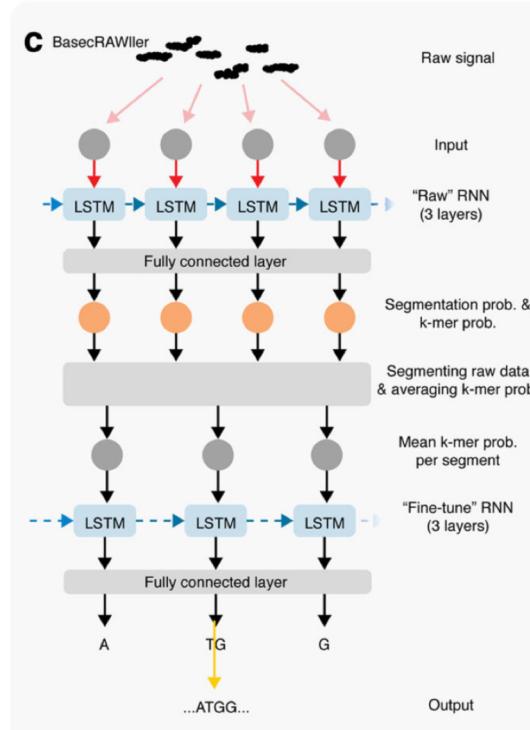


Existed methods of base-calling

Segmentation first



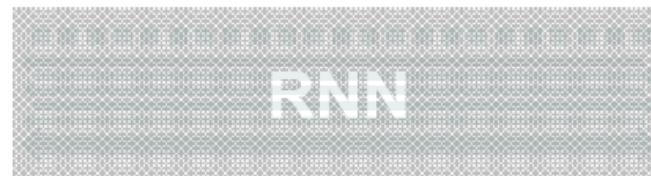
Segmentation later/ implicit segmentation



ONT Guppy (v3.2.2)



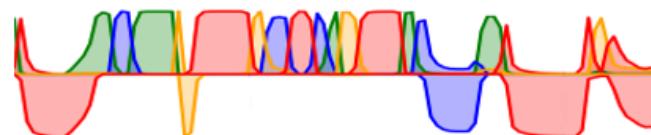
Raw signal



Recurrent Neural
Network
(over timesteps)



Base to base
transitions
(per time-step)



T+ A+C+A+G+ T+G+C+T+C+A+G+T+A+C+ A+T+
T- G- C- T- T+G+T+

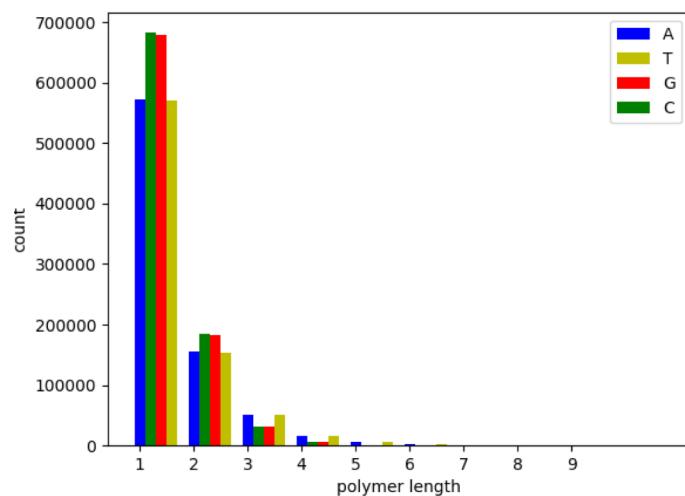
TTACAGGTGCTCAGTACCATTTGTT

Per-flip-flop
Base probabilities

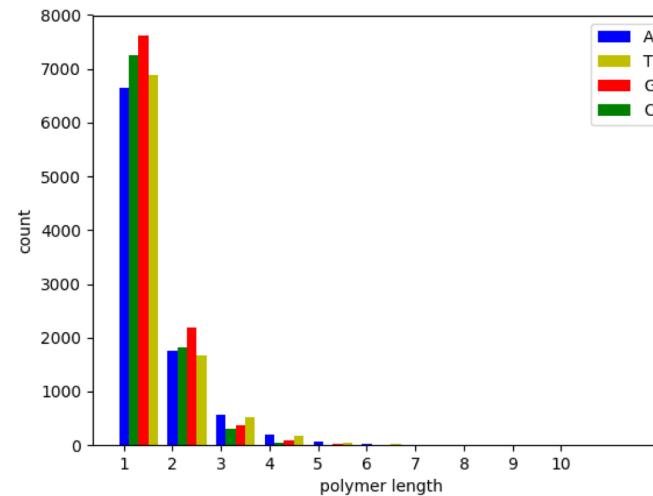
Basecall

Homo-polymer (Distributions from real genome)

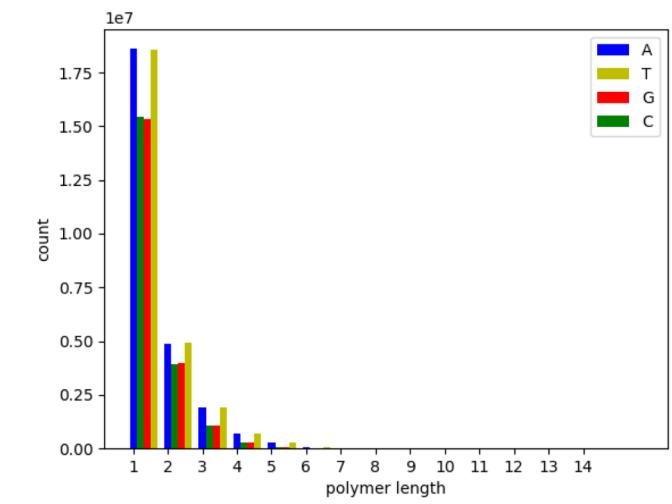
- Var different from species



E.coli

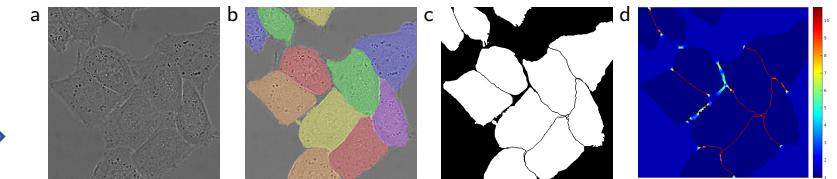
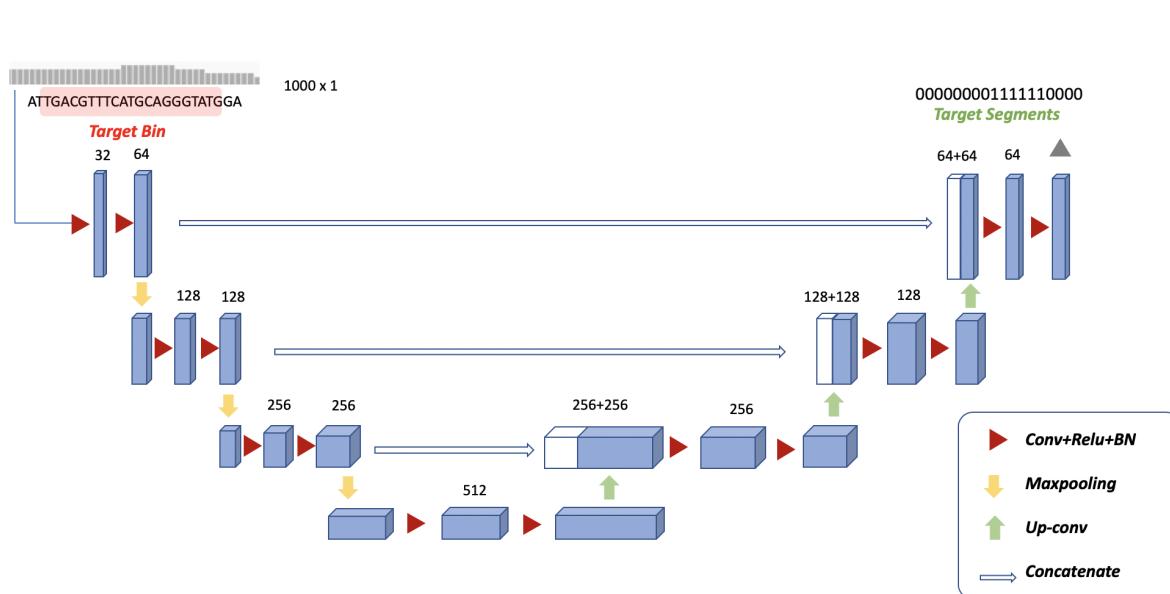


Phage

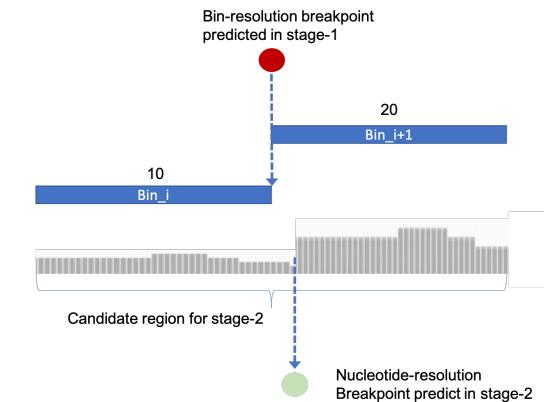


Human, Chr11

U-net model

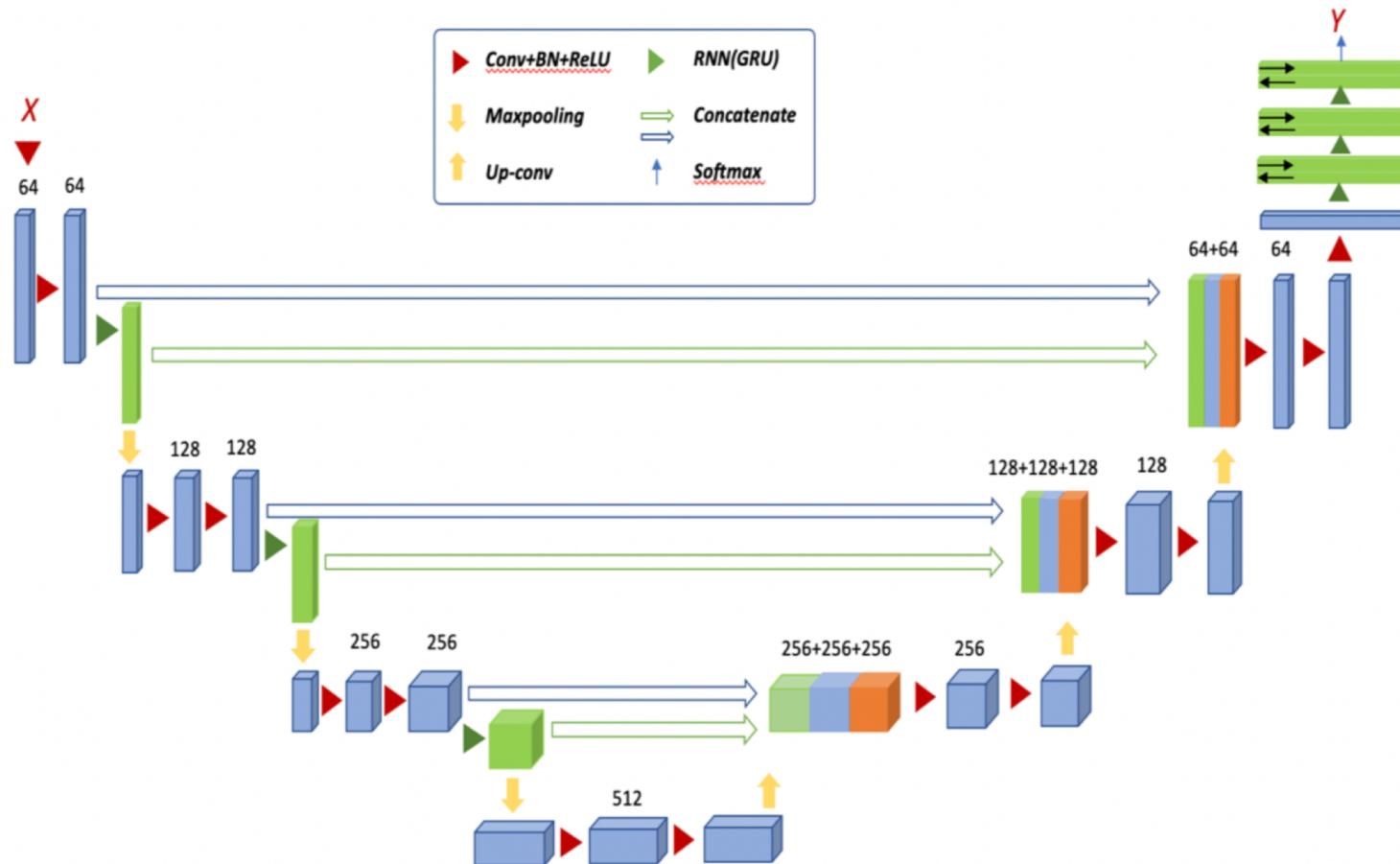


(Olaf Ronneberger et. al. arXiv 2015)

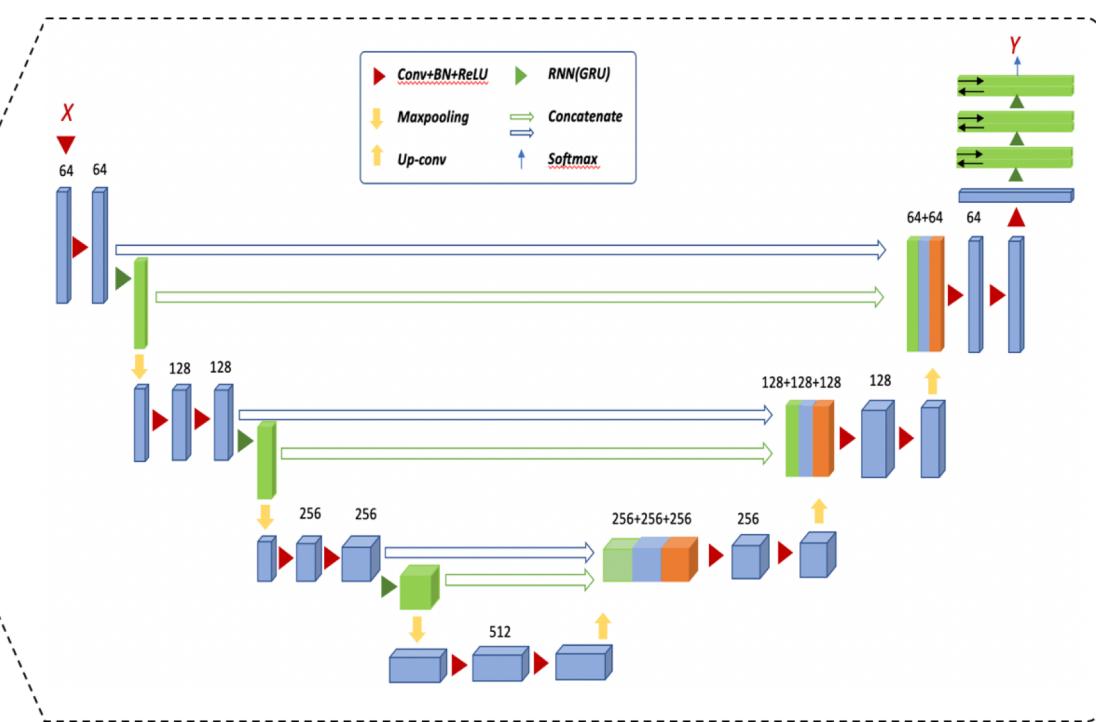
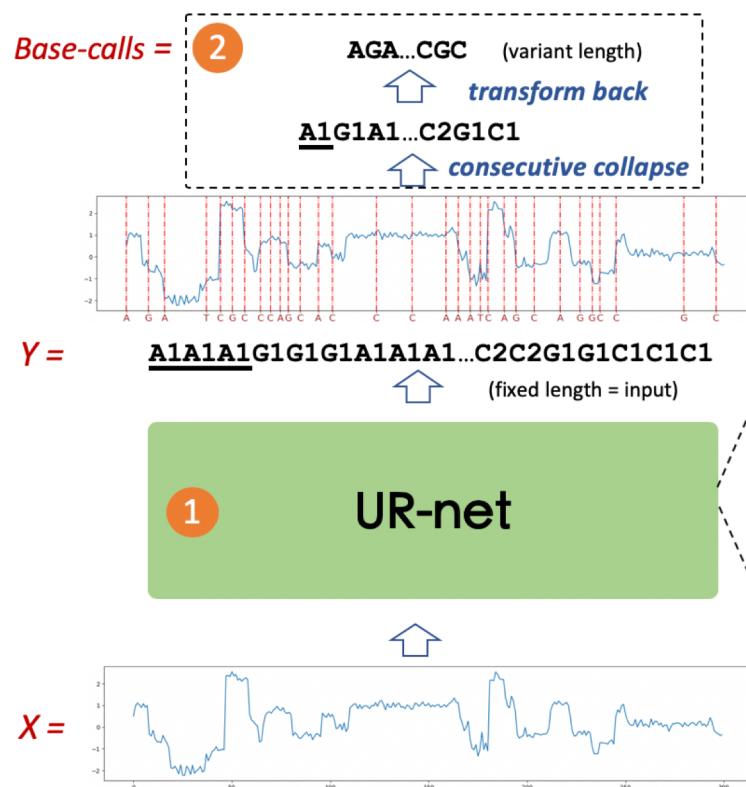


(Zhang et. al. BioArxiv 2019)

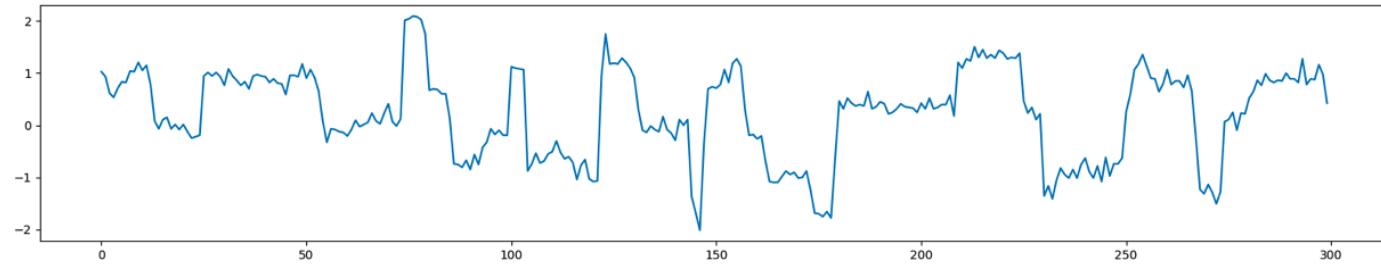
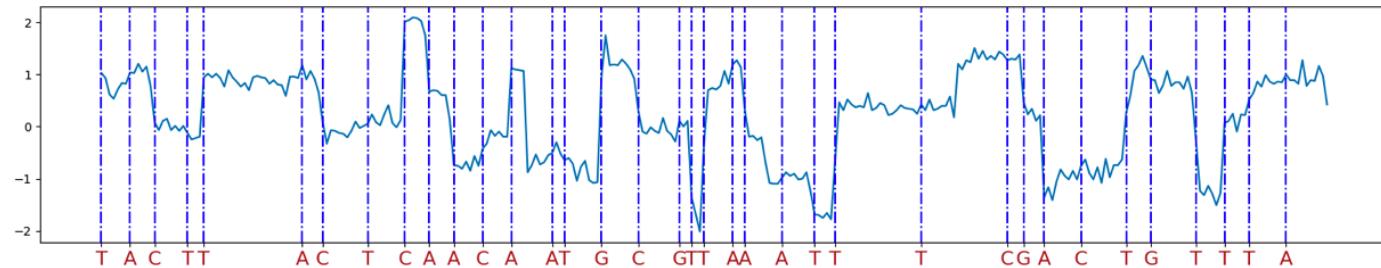
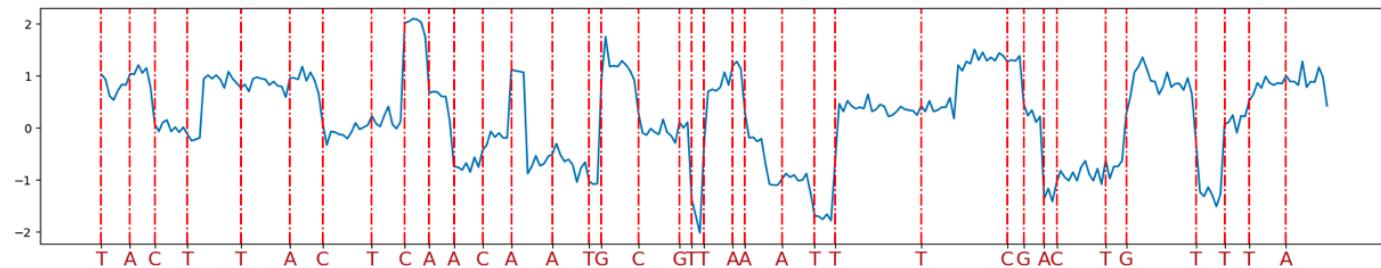
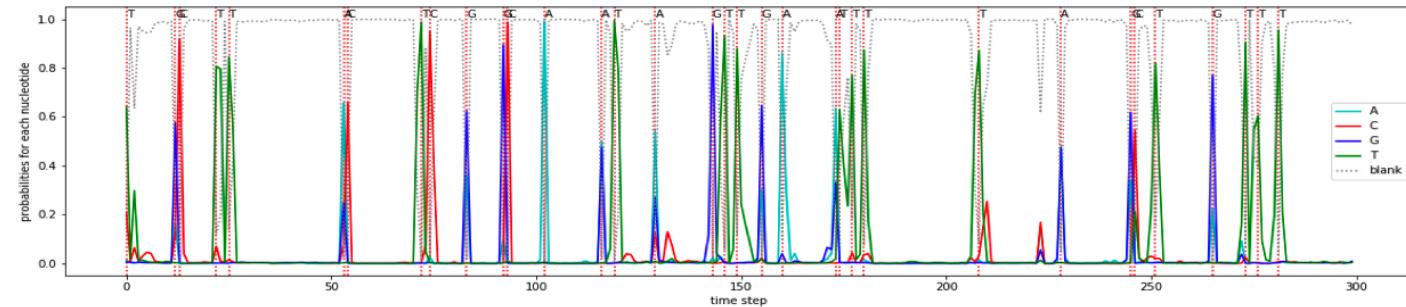
Enhancement with sequential context modeling: UR-net



URnano



Zhang et al., 2019 BMC Bioinformatics, accepted



Incremental evaluation of different network structures

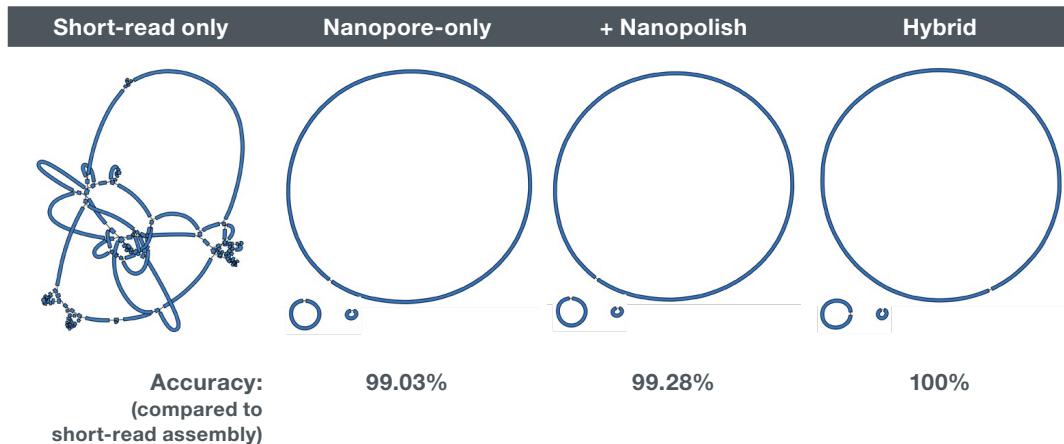
Network structure	Mean	Std
Unet	0.3528	0.2448
3GRU	0.2808	0.1631
Unet+3GRU	0.1800	0.1296
UR-net	0.1665	0.1329

Read accuracy

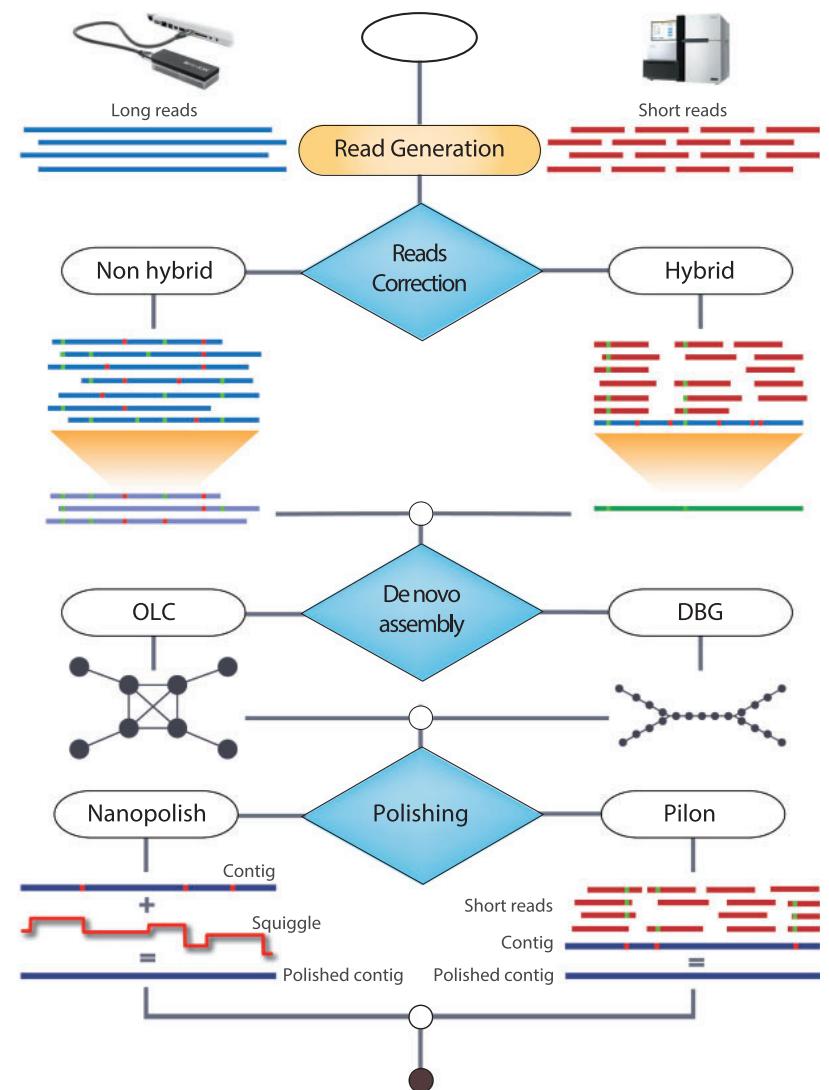
Species	basecaller	Deletion	Insertion	Mismatch	Read Identity	unaligned	Read Accuracy
E. coli	Chiron	0.0692	0.0465	0.0600	0.8709	7/2000	0.8243
	URnano	0.0584	0.0533	0.0407	0.9010	8/2000	0.8476
	Guppy_taiyaki	0.0585	0.0343	0.0436	0.8978	7/2000	0.8636
λ -phage	Chiron	0.0799	0.0467	0.0641	0.8559	9/2000	0.8093
	URnano	0.0662	0.0455	0.0363	0.8975	10/2000	0.852
	Guppy_taiyaki	0.0655	0.0397	0.0481	0.8864	6/2000	0.8467
Species	basecaller	Deletion	Insertion	Mismatch	Read Identity	unaligned	Read Accuracy
Human	Chiron	0.0983	0.0687	0.0866	0.8151	385/1000	0.7464
	URnano	0.0957	0.0788	0.0727	0.8316	375/1000	0.7528
	Guppy_taiyaki	0.0822	0.0748	0.0756	0.8422	352/1000	0.7674

3.Assembly

De novo assembly



Nanopore white paper



Magi et al. *Briefings in Bioinformatics* 2017

Overall Process of de-novel Assembling

1. Read-Read Mapping

- Mapping reads to each other to find overlaps between them

2. Contig generation

- Using consensus of multiple overlaps to generate contigs

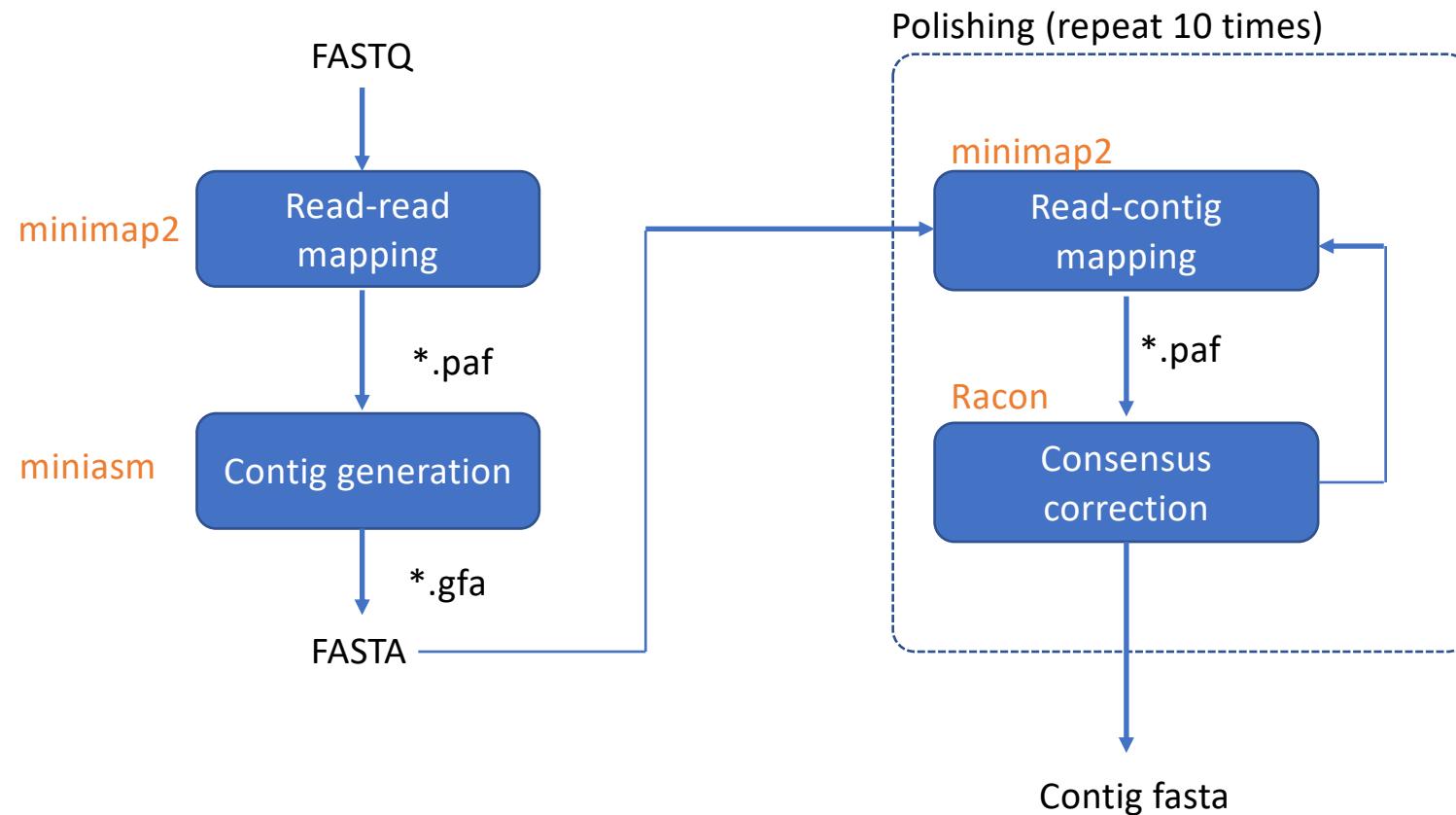
3. Read-Contig Mapping

- Mapping the initial reads back to contigs

4. Consensus correction (Polishing)

- taking the consensus of all mapped reads to a specific contig region to remove possible errors in contigs

Workflow of read assembly



1. Read - Read Mapping

- Main drawback of ONT sequencing : High error rates (5-15%)
- Read-read mapping before assembly is necessary to have meaningful overlaps
- **Minimap2** offers read-read mapping for finding overlaps between long reads
 - Uses k-mer minimizers (e.g. k=12)



```
Minimap2 -x ava-ont -k12 -w5 reads.fastq reads.fastq > read-overlaps.paf
```

PAF format

- Each line contains the start - end indexes for overlaps between 2 reads

```
|Singularity nanopore:~/output/assembly> cat lambda.paf | head -10
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 53 6644 + fe559c88-7255-4173-8f6f-9e578071601c 17884 10400 17011 3392 6741 0
A:S cm:i:608 s1:i:3362 dv:f:0.0823 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 53 6644 - f96b452f-119c-4a59-b321-5ee4ee87c201 10446 882 7517 3099 6748 0
A:S cm:i:543 s1:i:3068 dv:f:0.0899 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 53 6644 + fe2dab60-20e0-4b98-9954-dc287e810453 8444 941 7572 3070 6751 0
A:S cm:i:544 s1:i:3035 dv:f:0.0897 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 28 6644 + fc2be91e-073e-4d60-a920-5202f87e4c7e 10399 2875 9518 3030 6767 0
A:S cm:i:537 s1:i:3002 dv:f:0.0909 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 28 6644 + fc804f36-5a3f-43e2-9cf8-d4ee2e940818 12718 5208 11837 2998 6771 0
A:S cm:i:504 s1:i:2964 dv:f:0.0951 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 53 6644 + ff05b1b9-7aaa-4512-b05f-c568c9dc9dd2 9791 2343 8925 2958 6720 0
A:S cm:i:493 s1:i:2927 dv:f:0.0963 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 53 6644 - fcf9d1b4-882b-4adc-ba6b-f388f77a76b8 7608 867 7470 2949 6744 0
A:S cm:i:490 s1:i:2915 dv:f:0.0967 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 28 6644 + f7bed5f4-87c0-46cd-8504-7444ec5e09c7 9826 2375 8985 2923 6743 0
A:S cm:i:518 s1:i:2893 dv:f:0.0933 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 28 6623 - faa0e2f3-1dba-4846-b910-500566e3480e 8958 926 7589 2861 6785 0
A:S cm:i:471 s1:i:2820 dv:f:0.0996 r1:i:1184
f79f7821-2a95-4368-9ef7-4e813b1f41d2 6739 28 6644 + fc3c44f0-4de1-4b0e-ae24-d1755db7c2f8 10519 2988 9635 2843 6777 0
A:S cm:i:479 s1:i:2807 dv:f:0.0985 r1:i:1184
```

2. Contig generation

- Contig : A contiguous sequence of nucleotides formed by taking the consensus of overlapping reads
- Contain more errors and does not overlap nicely



```
miniasm -f reads reads_overlap.pfa > contig.gfa  
  
# extract contig fastq file  
awk '$1 ~/S/ {print ">"$2"\n"$3}' contig.gfa > contigs.fasta
```

Read-Contig Mapping

- Similar to read-read mapping, but change the target to the contigs

```
minimap2 contigs.fasta reads.fastq > read_contigs.paf
```

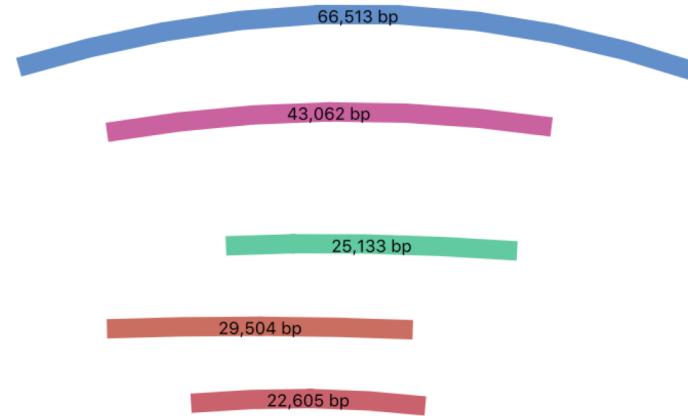
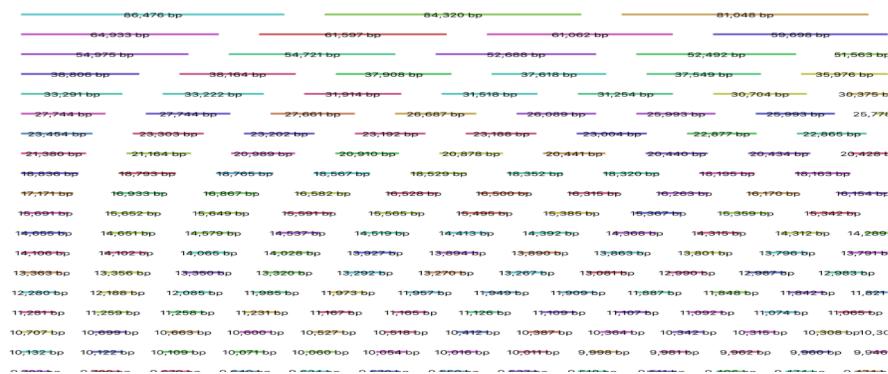
Polishing

- Repeat read-contig alignment and consensus correction for contigs
- Each round returns better contigs which in turn results in better overlap with initial reads

Visualization Using Bandage

Only high-quality contigs are taken

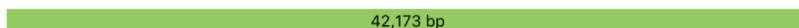
Contigs formed



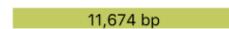
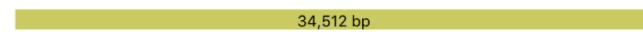
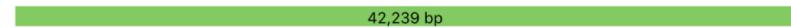
Visualization Bandage 2

Polishing reduces error rate and generates longer contigs

5th round



10th round



Assembly evaluation metrics

- Assembly identity and relative length

Assembly identity (AI) and relative length (RL). We assembled genomes using the results of each basecaller. Assembly identity and relative length are calculated by taking the mean of individual accuracy rates and relative lengths for each shredded contig, respectively.

$$AI = \frac{1}{N} \sum_{i=1}^N RA_i \quad RL = \frac{1}{N} \sum_{i=1}^N \frac{L_{pred_i}}{L_{ref_i}}$$

where N is the total number of aligned parts, L_{pred_i} is the length of the assembled i^{th} basecall and L_{ref} is the length of the reference genome.

Assembly evaluation with different basecallers

Dataset	basecaller	Assembly Identity (%)	Relative Length (%)
E. coli	Chiron	97.1995	99.0589
	URnano	97.4994	99.8868
	Guppy_taiyaki	98.272	99.3644
λ -phage	Chiron	90.8901	99.8352
	URnano	99.6525	99.9211
	Guppy_taiyaki	99.1734	99.3223
Human	Chiron	92.0374	99.9770
	URnano	91.2176	101.553
	Guppy_taiyaki	93.2813	99.7087

4. Structural variant detection

Genomic variation

- Single-nucleotide variants (SNP)
- Small indels (< 50bp)
- Structural variant (> =50 bp)
 - Insertion
 - Deletions
 - Duplications
 - Inversions
 - ...
- Copy number variant
 - Deletion
 - Amplification

Advantages and challenge of Long reads

- Advantage:

- Repetitive regions
- Nested SVs

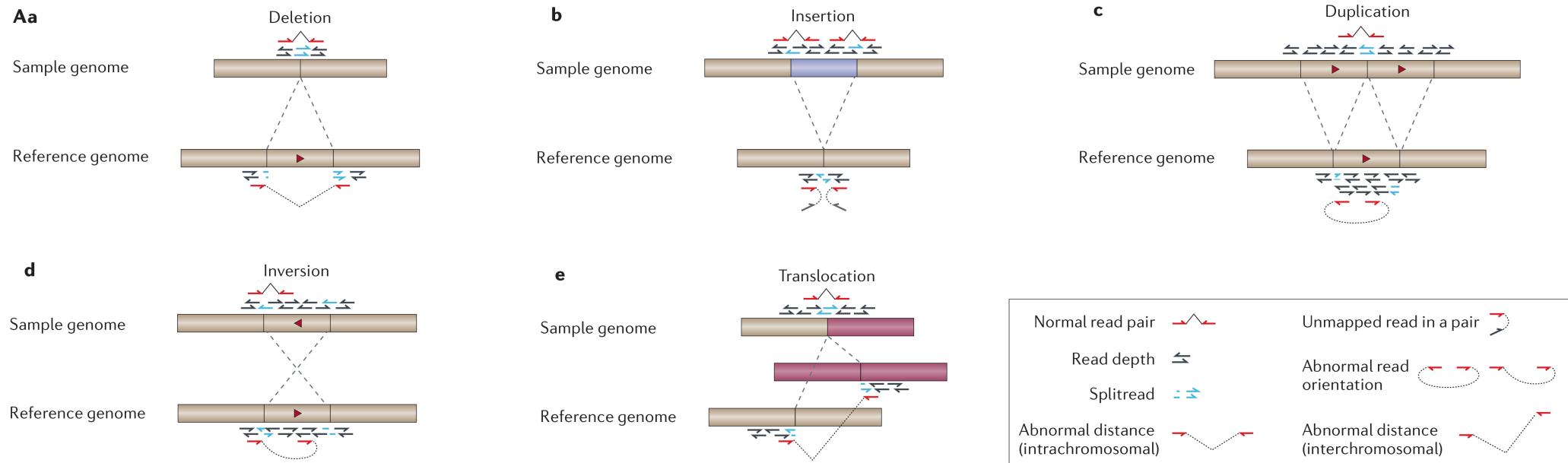


- Challenge

- Higher error rate => alignment



Different types of Structural Variations



(J Weischenfeldt et. al. Nature Review 2013)

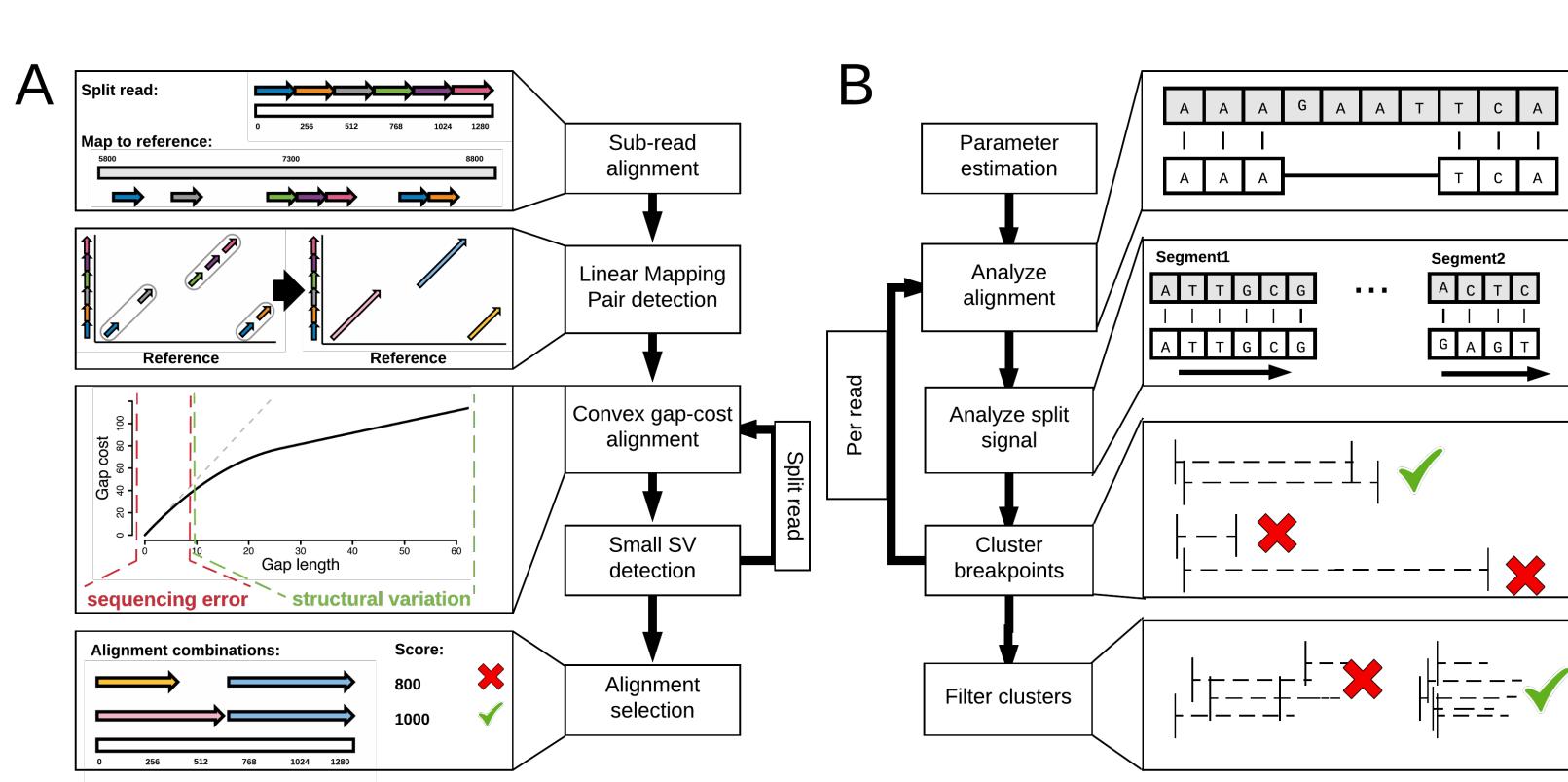


Figure 1: Overview of the main steps implemented in NGMLR (A) and Sniffles (B). For details see Supplementary Sections 1 and 2 for NGMLR and Sniffles, respectively.

Sedlazeck et al. 2018

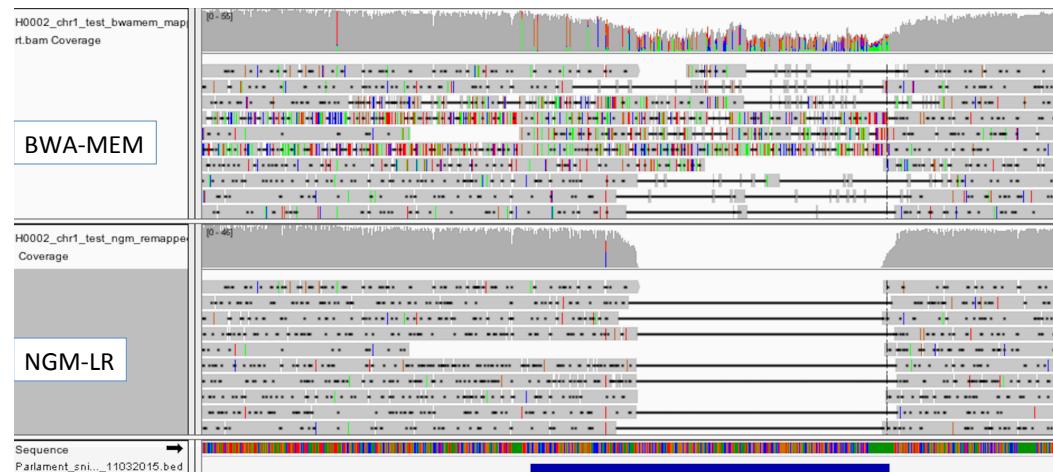
Convex Pairwise Alignment

AAAGAATTCA
A-A-A-T-CA

vs.

AAAGAATTCA
AAA----TCA

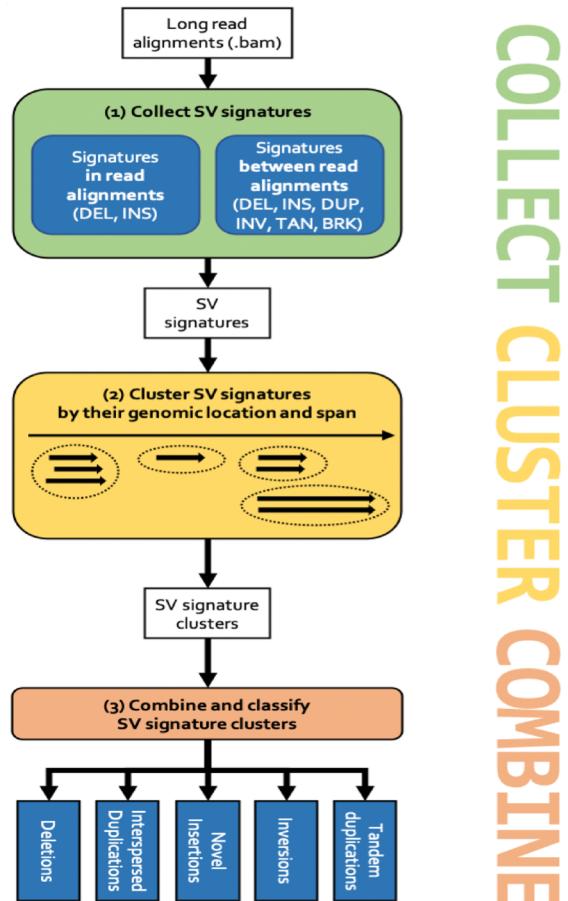
- Gap cost is the same, but not good for downstream SV analysis.
- Considering the SV in the early alignment stage for long reads.



Sniffles for detecting SV

1. Estimate parameters for the underlying data set.
E.g. distribution and distance between indels and mismatches on the read
2. Search for putative read alignment and segments.
3. Clustering putative SVs
4. Genotyping SV for homozygous or heterozygous SVs
5. Provide clustering SV based on the overlap with the same reads

The SVIM workflow. (1) Signatures for SVs are collected from the input read alignments. SVIM collects them



COLLECT CLUSTER COMBINE

SVIM does not filter its output but writes out all SV calls and their respective scores

5. Hands-on section

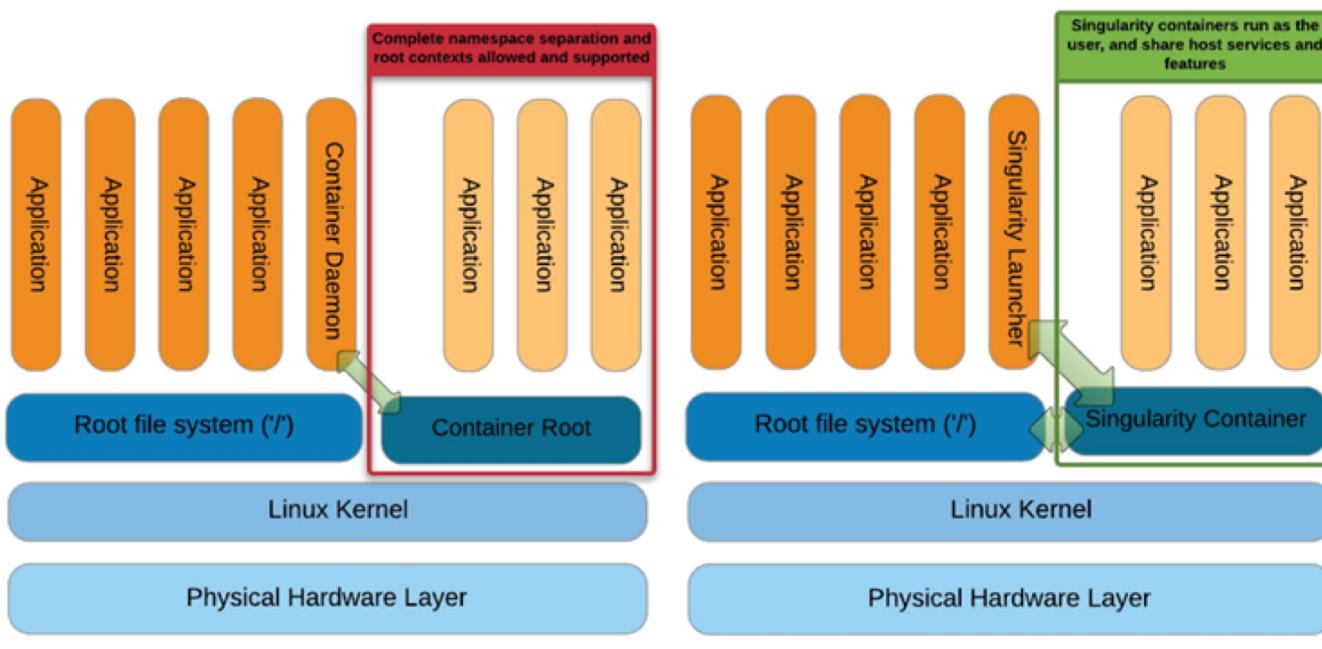
Materials are available on Github.

[https://github.com/yaozhong/mexico workshop nanopore hands on
/commits/master](https://github.com/yaozhong/mexico_workshop_nanopore_hands_on/commits/master)

Things to do in general:

1. Set up computing environment with docker/singularity
2. Get input data ready
3. Get output and analysis

Containers (Docker and Singularity)



General Container
eg Docker

HPC Container
Singularity

Optional GPUs available in Shirokane-5

- 80 V100 GPU cards
- Commonly used for:
 - Training deep learning models
 - Acceleration of genome analysis pipeline



Nanopore Data resources

- <https://www.plabipd.de/portal/solanum-pennellii>
- <https://www.ebi.ac.uk/ena/data/view/PRJEB26791>
- <https://github.com/nanopore-wgs-consortium/CHM13>
- <https://www.nature.com/articles/nmeth.3444>
- <https://github.com/nanopore-wgs-consortium/NA12878>