SFyNCS User Manual

Version 0.15

I. Introduction

Somatic Fusions involving Non-Coding Sequences (SFyNCS) detects fusions involving both protein-coding genes and non-coding sequences from paired-end RNA-seq data. It uses discordant read pairs and split reads to detect the fusions and refine fusion breakpoints to the basepair resolution.

II. Prerequisites

1. Software environment

1.1. Unix/Linux system

1.2. Perl (v5.010 or above), can be downloaded at https://www.perl.org/get.html or installed with conda (https://anaconda.org/conda-forge/perl).

1.3. Bedtools (tested v2.25.0, v2.26.0, v2.27.1), can be downloaded at https://github.com/arq5x/bedtools2/releases or installed with conda (https://anaconda.org/bioconda/bedtools).

1.4. STAR (v2.6.1a or above, tested v2.6.1a, v2.6.1d, v2.7.0f), can be downloaded at https://github.com/alexdobin/STAR/releases or installed with conda (https://anaconda.org/bioconda/star).

1.5. Samtools (tested v0.1.19, v1.1, v1.3.1, v1.5), can be downloaded at https://github.com/samtools/samtools/releases or installed with conda (https://anaconda.org/bioconda/samtools).

1.6. It will take 4 minutes to install all above tools using conda:

```
conda create --no-default-packages -n SFyNCS
source activate SFyNCS
conda install -c conda-forge perl=5.26.2
conda install -c bioconda bedtools=2.27.1
```

```
conda install -c bioconda star=2.7.0f
conda install -c bioconda samtools=1.3.1
```

2. Reference, index and annotation files

2.1. Reference genome sequence in fasta format

2.2. STAR index of the reference genome (can be skipped if Chimeric.out.junction is available). The STAR index can be built with the following command. We suggest using chr1-chr22, chrX, chrY and chrM only. Please specify the number_of_thread in the command below.

```
mkdir -p /path_to/star_index_dir
STAR --runThreadN number_of_thread --runMode genomeGenerate --genomeDir /path_to/star_index_dir --genomeFastaFiles /path_to/genome.fasta
```

2.3. Fai index of the reference genome (automatically generated by samtools)

2.4. Gene annotation of the reference genome in Gene Predictions Extended (gpe) format (please refer to https://genome.ucsc.edu/FAQ/FAQformat.html#format9 for more detail). A header is needed (can be any artifact header). X chromosome should be chrX and Y chromosome should be chrY. Gencode_v29_hg38.gpe is provided with the package.

Example of gene annotation:

Column 1: Transcript ID (e.g., ENST00000485503.1)

Column 2: Chromosome (e.g., chr7)

Column 3: Strand (e.g., +)

Column 4: Transcript start position (e.g., 55192810)

Column 5: Transcript end position (e.g., 55200802)

Column 6: Coding region (CDS) start position (e.g., 55200802)

Column 7: Coding region end position (e.g., 55200802)

Column 8: Number of exons (e.g., 3)

Column 9: Exon start positions (e.g., 55192810,55198716,55200315)

Column 10: Exon end positions (e.g., 55192841,55198863,55200802)

Column 11: Score (e.g., 0)

Column 12: Gene symbol (e.g., EGFR)

Column 13: Status of CDS start annotation (none, unknown, incomplete, or complete. e.g., none)

Column 14: Status of CDS end annotation (none, unknown, incomplete, or complete. e.g., none)

Column 15: Exon frame offsets (e.g., -1,-1,-1)

3. Input files

3.1. Two paired-end fastq.gz files or fastq files. SFyNCS uses STAR to align reads and use Chimeric.out.junction generated by STAR to call fusion candidates. If users have Chimeric.out.junction prior to running SFyNCS, the STAR alignment step can be skipped, and it can speed up the process significantly.

Chimeric.out.junction file can be produced by STAR with following command, please specify /path_to/star_index_dir, number_of_thread and /path_to/star_output_dir in the command:

```
STAR --genomeDir /path_to/star_index_dir \
     --readFilesIn 1.fastq.gz 2.fastq.gz \
     --readFilesCommand zcat \
     --runThreadN number_of_thread \
     --outFileNamePrefix /path_to/star_output_dir \
     --outReadsUnmapped None \
     --twopassMode Basic \
     --outSAMstrandField intronMotif \
     --outSAMunmapped Within \
     --chimSegmentMin 12 \
     --chimJunctionOverhangMin 12 \
     --chimOutJunctionFormat 1 \
     --alignSJDBoverhangMin 10 \
     --alignMatesGapMax 100000 \
     --alignIntronMax 100000 \
     --alignSJstitchMismatchNmax 5 -1 5 5 \
     --outSAMattrRGline ID:GRPundef  \
```

```
--chimMultimapScoreRange 10 \
--chimMultimapNmax 10 \
--chimNonchimScoreDropMin 10 \
--peOverlapNbasesMin 12 \
--peOverlapMMp 0.1 \
--outSAMtype BAM SortedByCoordinate \
--genomeLoad NoSharedMemory
```

3.2. Fusion breakpoints from normal samples. They are used to filter out germline events as well as artifacts. We provide fusion breakpoint files from TCGA normal samples (https://drive.google.com/drive/folders/1KatN9WevL_N9QGT9UVtSVRo5BKn47MGx?usp=sharing). Users can generate their own if RNAseq data from normal samples are available:

1) Generate Chimeric.out.junction for each normal sample (refer to 3.1/II).
2) Format split reads and discordant read pairs information in Chimeric.out.junction.

```
perl /path/to/format_STAR_chimeric_file.pl
    Chimeric.out.junction >format_chimeric.tsv
```

3) Remove duplicated reads and get the number of supporting reads for each breakpoint.

```
perl /path/to/get_juntions_in_normal_sample.pl
    format_chimeric.tsv
    >no_duplication_junction_read_count.tsv
```

Example of normal breakpoint file (no_duplication_normal_junctions.tsv):

Column 1: Chromosome of breakpoint 1 (e.g., chr1)

Column 2: Position of breakpoint 1 (e.g., 10005917)

Column 3: Strand of breakpoint 1 (e.g., +)

Column 4: Chromosome of breakpoint 2 (e.g., chr1)

Column 5: Position of breakpoint 2 (e.g., 10005936)

Column 6: Strand of breakpoint 2 (e.g., +)

Column 7: Breakpoint supported read count (e.g., 1)

4) Rename each sample's no_duplication_junction_read_count.tsv and put them under the same directory. Replace "sample_1" with each sample id.

```
mv no_duplication_junction_read_count.tsv sample_1.tsv
```

5) Optional: each normal junction file can be compressed.

```
gzip sample_1.tsv
```

III. Example

Note: all files under the example directory are for testing only.

1. Download SFyNCS:

```
git clone https://github.com/yanglab-
computationalgenomics/SFyNCS.git
```

2. Decompress example.tar.gz and enter example directory:

```
cd SFyNCS
tar -zxvf example.tar.gz
cd example
```

3. Build STAR index:

```
mkdir star_index
STAR --runThreadN 1 --runMode genomeGenerate --genomeDir
  star_index --genomeFastaFiles
  toy_reference_genome_sequence.fasta
```

4. Run SFyNCS:

4.1. Start from fastq.gz files:

```
bash ../run_SFyNCS.sh -p 1 -o demo_output -a
  toy_gene_annotation.gpe -g
  toy_reference_genome_sequence.fasta -s star_index -d
  toy_normal_directory  toy_pair_end_reads_1.fastq.gz
  toy_pair_end_reads_2.fastq.gz
```

4.2. Start from Chimeric.out.junction produced by STAR and fastq.gz files:

```
bash ../run_SFyNCS.sh -p 1 -c Chimeric.out.junction -o
  demo_output -a toy_gene_annotation.gpe -g
  toy_reference_genome_sequence.fasta -d toy_normal_directory
```

It will take 1 minute to run the example. Users should get fusions.tsv.gz and fusions_abridged.tsv.gz under demo_output, please make sure the content in these two output files is the same as the files under example.

IV. Workflow

1. Running SFyNCS

SFyNCS can be run by the following commands. Users can further provide "-p thread_numbers" to speed up the steps of STAR.

1.1. Start from fastq.gz files:

```
/path/to/run_SFyNCS.sh -o /path_to/output_dir -a
  /path_to/gene_annotation.gpe -g /path_to/genome.fasta -s
  /path_to/star_index_dir -d
  /path/to/normal_junction_directory 1.fastq.gz 2.fastq.gz
```

1.2. Start from Chimeric.out.junction produced by STAR and fastq.gz files:

```
/path/to/run_SFyNCS.sh -c /path_to/Chimeric.out.junction -o
  /path_to/output_dir -a /path_to/gene_annotation.gpe -g
  /path_to/genome.fasta -d /path/to/normal_junction_directory
```

1.3. run_SFyNCS.sh options. Note that the default parameters are optimized for TCGA data.

-a --annotation_file STR Gene annotation gpe file (section 2.4/II)

-g --genome_fasta STR Reference genome fasta file

-o --output_directory STR Output directory [default: current directory]

-p --thread_number INT Number of threads [default: 1]. Multiple threads can speed up the steps of STAR and TopHat2

-s --star_index STR Path to STAR index. This option can be skipped if "-c" is provided

-c --chimeric_file STR Chimeric.out.junction file generated by STAR

-d --normal_junction_dir STR Directory contains normal samples' junctions (section 3.2/II)

--adjust_adjacent_distance INT Breakpoints within this distance will be adjusted [default: 5]

--cluster_distance INT Split reads and read pairs within this distance will be clustered together [default: 1000000]

--min_split_reads INT Minimal number of split reads for a fusion transcript to be identified [default: 1]

--min_read_pairs INT Minimal number of discordant read pairs for a fusion transcript to be identified [default: 1]

--min_total_reads INT Minimal number of total reads (split reads and discordant read pairs combined) for a fusion transcript to be identified [default: 3]

--read_pair_distance INT Maximal distance between the TopHat2 alignment of read pairs and breakpoint [default: 10000]

--motif_searching_length INT Splice site motifs (GT in the donor, AAG/CAG/TAG in the acceptor) are searched within this window size of breakpoints [default: 5]

--filter_by_canonical_splice_motif STR Filter by canonical splice site motif [default: Y]

--length_in_sd INT Breakpoint flanking size to calculate standard deviation [default: 100]

--sd_cutoff FLOAT Standard deviation cutoff to filter fusions [default: 0.1]

--filter_in_the_same_gene STR Filter fusions in the same gene [default: Y]

--normal_adjacent_distance INT Window size to search for breakpoints in normal samples [default: 10000]

--normal_read_count_cutoff INT Filter fusions if numbers of reads (discordant pairs or split reads) in normal samples are equal to or more than the specified value [default: 2]

--deletion_like_distance INT Minimal distance allowed between fusion breakpoints for deletion-like fusions [default: 500000]

--duplication_like_and_inversion_like_distance INT Minimal distance allowed between breakpoints for duplication-like and inversion-like fusions [default: 20000]

"adjust_adjacent_distance" controls how to adjust adjacent breakpoints. A read might be aligned to a locus in different ways, STAR will not always choose the same position for reads aligned to the locus (**Figure 1**), resulting in multiple nearby breakpoints. Since they are likely from the same breakpoint, SFyNCS will adjust them to use the same breakpoint if their breakpoints are within the defined distance. That is, split reads with same orientations and within the range defined by this parameter were considered to support the same fusion. Users can use the default parameter.

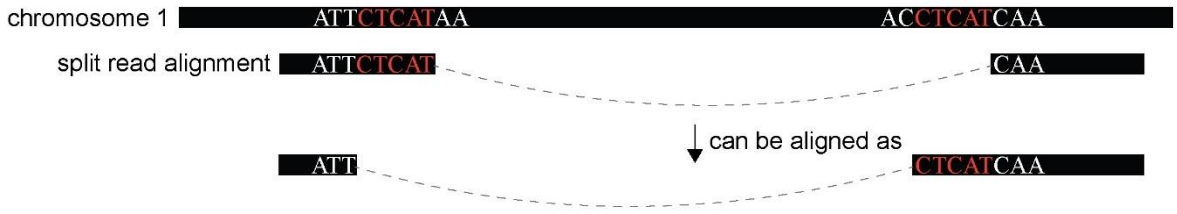

Figure 1. Alternative alignments of split read.

"cluster_distance" controls how to cluster split reads and discordant read pairs. Based on GENCODE V29 gene annotation, 99% of genes are longer than 400Kbp (99% of protein-coding genes are longer than 617Kbp), so the parameter should be greater than 400000. A bigger value is acceptable, but it will impact the run time, and the standard deviation cutoff. Default value should be fine for most cases.

"length_in_sd" and "sd_cutoff" filter false fusion transcripts based on read alignment around the fusion breakpoints. Artifacts can arise from repetitive regions of the genome. In these cases, there are many candidate fusion clusters supporting different fusions. True fusions often have large SD and artifacts usually have small SD. "length_in_sd" controls the window size to search for candidate fusion clusters. See 2.5/IV below for how SD is calculated.

1.4. Output. There are two output files named fusions.tsv.gz and fusions_abridged.tsv.gz. The second one contains subset columns of the first file and is much smaller. The columns of fusions.tsv.gz are:

Column 1: Chromosome of breakpoint 1 (e.g., chr1)

Column 2: Position of breakpoint 1 (e.g., 46389)

Column 3: Strand of breakpoint 1 (e.g., +)

Column 4: Chromosome of breakpoint 2 (e.g., chr2)

Column 5: Position of breakpoint 2 (e.g., 16337)

Column 6: Strand of breakpoint 2 (e.g., -)

Column 7: Split read count (e.g., 1)

Column 8: Read pair count (e.g., 4)

Column 9: Minimal distance between read pair and breakpoint 1 (e.g., 13)

Column 10: Minimal distance between read pair and breakpoint 2 (e.g., 22)

Column 11: Standard deviation for candidate fusion clusters around breakpoint 1 (e.g., NA, NA for only one cluster)

Column 12: Standard deviation for candidate fusion clusters around breakpoint 2 (e.g., NA, NA for only one cluster)

Column 13: Presence of canonical splice site (Y or N)

Column 14: Whether fusion transcript locates in the same gene (Y or N)

Column 15: Fusion type (non-coding or protein-coding)

Column 16: Overlapped gene in breakpoint 1 (e.g., C9/DAB2, genes were separated by "/")

Column 17: Gene type in breakpoint 1 (non-coding_gene, protein-coding_gene or unknown, different genes' type were separated by "/")

Column 18: Gene strand in breakpoint 1 (e.g., +)

Column 19: Breakpoint 1's location (intron, exon, splice_site or unknown)

Column 20: Breakpoint 1's region type (5'UTR, 3'UTR, CDS, non-coding or unknown)

Column 21: Exon frame after breakpoint 1 (0, 1, 2 or N, N means unknown)

Column 22: Overlapped gene in breakpoint 2 (e.g., EML4)

Column 23: Gene type in breakpoint 2 (non-coding_gene, protein-coding_gene or unknown, different genes' type were separated by "/")

Column 24: Gene strand in breakpoint 2 (e.g., -)

Column 25: Breakpoint 2's location (intron, exon, splice_site or unknown)

Column 26: Breakpoint 2's region type (5'UTR, 3'UTR, CDS, non-coding or unknown)

Column 27: Exon frame before breakpoint 2 (0, 1, 2 or N, N means unknown)

Column 28: Fusion frame (in-frame, out-frame, or unknown)

Column 29: Split reads

Column 30: Read pairs

Column 31: Distance between each read pair and breakpoint 1 (e.g., 740,23,13)

Column 32: Distance between each read pair and breakpoint 2 (e.g., 292,2592,22)

Column 33: Discordant read pair cluster IDs around breakpoint 1 (e.g., 1)

Column 34: Discordant read pair cluster IDs around breakpoint 2 (e.g., 1)

Column 35: Supporting reads count in each cluster around breakpoint 1 (e.g., 4)

Column 36: Supporting reads count in each cluster around breakpoint 2 (e.g., 3)

2. Details of run_SFyNCS.sh

run_SFyNCS.sh is a bash script that integrates several scripts to identify split reads and read pairs and filter false fusion transcripts. Advanced users can customize it to optimize the pipeline. Below are the detailed steps in run_SFyNCS.sh.

2.1. Step 1. Generate a file named Chimeric.out.junction that contains split reads and read pairs by running STAR (refer to section 3 in II for STAR parameters, and refer to https://github.com/alexdobin/STAR/blob/master/doc/STARmanual.pdf for more detail). Each file line contains the alignment information of a split read or a read pair. Following 14 columns of Chimeric.out.junction is needed:

Column 1: Chromosome of the donor

Column 2: First base of the intron of the donor (1-based)

Column 3: Strand of the donor

Column 4: Chromosome of the acceptor

Column 5: First base of the intron of the acceptor (1-based)

Column 6: Strand of the acceptor

Column 7: Breakpoint type: -1=encompassing breakpoint (between the mates), 1=GT/AG, 2=CT/AC, 0=any other motif

Column 8: Repeat length to the left of the breakpoint

Column 9: Repeat length to the right of the breakpoint

Column 10: Read name

Column 11: First base of the first segment (on the + strand)

Column 12: CIGAR of the first segment

Column 13: First base of the second segment

Column 14: CIGAR of the second segment

2.2. Step 2. Process STAR alignment information. This step includes formatting split reads and read pairs alignment, removing split reads and read pairs with multiple alignments, removing duplicates, and adjusting alignment for adjacent split reads. The scripts include:

1) format_STAR_chimeric_file.pl

```
perl format_STAR_chimeric_file.pl Chimeric.out.junction
    >format_chimeric.tsv
```

2) remove_multiple_mapped_reads.pl

```
perl remove_multiple_mapped_reads.pl format_chimeric.tsv
   >no_multiple_mapped.tsv
```

3) remove_duplicate_reads.pl

```
perl remove_duplicate_reads.pl no_multiple_mapped.tsv
     >temp_no_duplicate.tsv
```

Note: there would be two breakpoint lines if both read 1 and read 2 are spilt read and have the same breakpoint. Use following command to remove duplicates:

```
head -n 1 temp_no_duplicate.tsv >no_duplicate.tsv
sort temp_no_duplicate.tsv | uniq | grep -v
   "Chr_breakpoint_1" >>no_duplicate.tsv
```

4) adjust_ajacent_breakpoints.pl

```
perl adjust_ajacent_breakpoints.pl [options] no_duplicate.tsv
   >adjust_ajacent.tsv
```

-a --adjacent_distance INT Breakpoints within this distance will be adjusted [default: 5]

2.3. Step 3 cluster_discordant_reads.pl. Cluster split reads and read pairs if breakpoints are aligned to the same chromosomes, the same strands and the distance of breakpoints are less than or equal to the defined distance (-w parameter).

```
Perl cluster_discordant_reads.pl [options] merge_ajacent.tsv
   >cluster.tsv
```

-w --window_size INT Split reads and read pairs within this distance will be clustered together [default: 1000000]

2.4. Step 4. Generate fusion transcript candidates.

```
perl identify_fusion_candidates_from_cluster_reads.pl
   cluster.tsv >preliminary_candidates.tsv
```

Note: fusion candidates are further filtered by the number of split reads, read pairs, total reads, fusion transcript related to mitochondria, and fusion distance:

```
awk -v min_split_reads=$min_split_reads -v
   min_read_pairs=$min_read_pairs -v
   min_total_reads=$min_total_reads 'NR==1 ||
   ($9>=min_split_reads && $10>=min_read_pairs &&
```

```
    ($9+$10)>=min_total_reads)' preliminary_candidates.tsv
    | grep -v chrM >temp.tsv
  mv temp.tsv preliminary_candidates.tsv
  awk -v deletion_like_distance =$ deletion_like_distance -v
    duplication_like_and_inversion_like_distance=$duplicat
    ion_like_and_inversion_like_distance 'NR==1{print $0;}
    $1!=$4{print $0;} $1==$4{if($3=="+" && $6=="-
    "){if(($5-$2)>= deletion_like_distance) print $0;}
    else{if(($5-
    $2)>=duplication_like_and_inversion_like_distance )
    print $0;}}' preliminary_candidates.tsv >temp.tsv
  mv temp.tsv preliminary_candidates.tsv
```

2.5. Step 5. Filter fusion by standard deviation of fusion-supporting read clusters in fusion breakpoint flanking region. For each breakpoint's upstream and downstream 100bp region, the number of clusters that are assigned in step 3 and the number of reads supporting each cluster is calculated, the standard deviation is then calculated as the formula below.

Standard deviation = $\sqrt{\frac{\sum_{i=1}^{N}(n_i-\mu)^2}{N}}$, where $n_i = \frac{m_i}{\sum_{i=1}^{N} m_i}$ and $\mu = \frac{\sum_{i=1}^{N} n_i}{N}$

N is the number of clusters, m_i is the number of reads in cluster i, n_i is the proportion of reads in cluster i.

```
perl filter_fusion_by_standard_deviation.pl [options]
   preliminary_candidates.tsv >
   fusions_filtered_by_standard_deviation.tsv
```

-f --flanking_length INT Breakpoint flanking size to calculate standard deviation [default: 100]

-s --sd_cutoff FLOAT Standard deviation cutoff to filter fusions [default: 0.1]

Note: A file named temp_cluster.bed including cluster information must exist, and it is generated by the following command. To speed up the process and reduce memory requirement, preliminary_candidates.tsv is split into 50 small pieces in run_SFyNCS.sh.

The command used to generate temp_cluster.bed:

```
awk 'BEGIN{FS=OFS="\t"} NR>1{print $1,$2-1,$2,$3,$7,$8,$9;
   print $4,$5-1,$5,$6,$7,$8,$9;}' cluster.tsv | sort -k1,1 -
   k2,2n | uniq >temp_cluster.bed
```

2.6. Step 6. Filter fusion by canonical splice site motif, sequence identity.

```
perl filter_fusion_by_splicing_motif.pl [options] -f
   $genome_fasta fusions_filtered_by_standard_deviation.tsv >
   fusions_filtered_by_splicing_motif.tsv
```

-m --motif_searching_length INT Splice site motifs (GT in the donor, AAG/CAG/TAG in the acceptor) are searched within this window size of breakpoints [default: 5]

-f --fasta STR Reference genome fasta file (must be given)

-c --filter_by_canonical_splice_motif STR Filter by canonical splice site motif [default: "Y"]

2.7. Step 7. Filter fusion which locates in the same gene and annotate each fusion.

```
perl annotate_fusions.pl [options] -a $genome_fasta
   $annotation_file fusions_filtered_by_splicing_motif.tsv >
   fusions_unfiltered_by_normal.tsv
```

-a --fasta STR Reference genome fasta file, must be given.

-f --filter_in_the_same_gene STR Whether filter fusions in the same gene [default: Y]

Note: user must provide $annotation_file in section 2.4 in II. To speed up the process and reduce memory requirement, fusions_filtered_by_splicing_motif.tsv is split into 50 small pieces in run_SFyNCS.sh.

2.8. Step 8. Filter by breakpoints from normal samples filter_fusion_by_normal_junctions.pl. Fusion transcript will be filtered if there are at least two fusion supporting reads (either discordant read pairs or split reads) within 10kb of both breakpoints in any normal samples.

```
perl filter_fusion_by_normal_junctions.pl [options]
   normal_junctions.tsv fusions_unfiltered_by_normal.tsv >
   fusions_filtered_by_normal.tsv
```

-a --adjacent_distance INT Window size to search for breakpoints in normal samples [default: 10000]

-t --threshould_normal_read_count INT Filter fusions if numbers of reads (discordant pairs or split reads) in normal samples are equal to or more than the specified value [default: 2]

V. Reference

TBD

VI. Contact

If users have questions, please contact Xiaoming Zhong (xiaomingzhong@uchicago.edu) and Lixing Yang (lixingyang@uchicago.edu).