Demultiplexing Illumina® sequencing data with UMIs
# REVISION HISTORY

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<tr>
<th>Version</th>
<th>Release date</th>
<th>Description of changes</th>
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<tr>
<td>3</td>
<td>March 2022</td>
<td>Adjustment to title and updated template</td>
</tr>
<tr>
<td>2.1</td>
<td>May 2019</td>
<td>Updated document template</td>
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<tr>
<td>2</td>
<td>June 2018</td>
<td>Clarified instructions for constructing a read structure that matches the library</td>
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<td>1</td>
<td>October 2017</td>
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This document outlines an example workflow for demultiplexing Illumina sequencing data when unique molecular identifiers (UMIs) are in the index reads, starting from Illumina basecall (BCL) files through generating FASTQ files. The high level workflow is:

A. Determine the sample barcode for every read in an Illumina sequencer lane

B. Demultiplex each lane of Illumina BCL files and include the UMI data in the per-sample BAM files

C. Convert BAM files to FASTQ files

D. Map FASTQ reads and merge alignment data from aligned BAM files with molecular index data from unaligned BAM files

Note: If you require molecular index data for downstream, post-mapping analysis, extract the molecular index data from the unaligned BAM files, then merge the data with the aligned BAM files after mapping the FASTQ reads.

Referenced software package

The following software package is used in the examples within this document:

<table>
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<tr>
<th>Package</th>
<th>License</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Picard</td>
<td>MIT</td>
<td><a href="https://github.com/broadinstitute/picard">https://github.com/broadinstitute/picard</a></td>
</tr>
</tbody>
</table>
GUIDELINES

A. Determine the sample barcode for every read in an Illumina sequencer lane

Before demultiplexing Illumina basecall data, you must determine the barcode for each read in an Illumina sequencer lane. Use ExtractIlluminaBarcodes (Picard) to determine the barcode for each read in a lane by parsing the files in the basecalls directory. The tool determines the numbers of reads containing barcode-matching sequences and provides statistics on the quality of these barcode matches.

The Read Structure refers to a String that describes the order, the number of cycles, and the type of those cycles (T = template, B = sample barcode, M = molecular barcode, and S = skip). Illumina sequences can contain at least two types of barcodes: sample and molecular. Sample barcodes (B) are used to demultiplex pooled samples, while molecular barcodes (M) are used to differentiate multiple reads of a template when performing paired-end sequencing. Note that ExtractIlluminaBarcodes only extracts sample barcodes (B) and not molecular barcodes (M). An example invocation:

```
java -Xmx4g -jar picard.jar ExtractIlluminaBarcodes \
    BASECALLS_DIR=InputBCLdir \
    BARCODE_FILE=barcodesFile \
    READ_STRUCTURE=100T889MB100T \
    LANE=1 \
    OUTPUT_DIR=barcodes_outputdir \
    METRICS_FILE=barcode_metrics.txt
```

INPUT

1. **Basecalls directory** (required):
   The following input file types from the basecalls directory are needed:
   - *.bcl
   - *.stats
   - *.filter
   - *.control
   - *.locs

2. **Barcodes** (required):
   Barcodes are provided in the form of a list (BARCODE_FILE) or a string representing the barcode (BARCODE). The BARCODE_FILE contains multiple fields including "barcode_sequence_1", "barcode_sequence_2" (optional), "barcode_name", and "library_name". In contrast, the BARCODE argument is used for runs with reads containing a single barcode (nonmultiplexed) and can be added directly as a string of text (e.g., BARCODE = CAATAGCG). An example invocation:

<table>
<thead>
<tr>
<th>barcode_name</th>
<th>library_name</th>
<th>barcode_sequence_1</th>
<th>barcode_sequence_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>20160808-AP1SG-S1</td>
<td>Mix1_Rep1</td>
<td>CTGACTGTYNNNNNNNNN</td>
<td>GGCATAT</td>
</tr>
<tr>
<td>20160808-AP1SG-S2</td>
<td>Mix1_Rep2</td>
<td>AGTCTEGNNNNNNNNNN</td>
<td>CTGTACCA</td>
</tr>
<tr>
<td>20160808-AP1SG-S3</td>
<td>Mix1_Rep3</td>
<td>TGACGTAGNNNNNNNN</td>
<td>GAACGTTT</td>
</tr>
</tbody>
</table>
3. **Read structure:**
   A read structure is a description of the logical structure of clusters in an Illumina sequencing run. It should consist of integer/character pairs describing the number and type of cycles (T = template, B = sample barcode, M = molecular barcode, and S = skip). For example, if the input data consists of 225-base clusters and we provide a read structure of “100T8B9M8B100T”, then the sequence may be split into four reads:
   a. Read 1, with 100 cycles (bases) of template
   b. Read 2, with 8 cycles (bases) of sample barcode followed by 9 cycles (bases) of molecular barcode (e.g., unique molecular barcode)
   c. Read 3, with 8 cycles (bases) of sample barcode
   d. Read 4, with 100 cycles (bases) of template

4. **Lane:**
   *ExtractIlluminaBarcodes* determines the barcode for each read in an Illumina sequencer lane. Therefore, a lane number must be provided as an input.

**OUTPUT**

1. **Extracted barcode files**
   For each tile on the sequencing flowcell, a barcode file is written to the basecalls directory with the following file naming convention: *s_<lane>_<tile>_barcode.txt*. Barcode files contain the following tab-separated columns:
   a. Read subsequence at barcode position
   b. Y or N indicating the presence of a barcode match
   c. Matched barcode sequence (empty if the read did not match one of the barcodes)
      - If there is no match, but it is close to the threshold of calling it a match, the barcode would be output as if a match was called, but indicated with lowercase letters. Threshold values can be adjusted to accommodate barcode sequence mismatches from the reads.
   d. Number of mismatches
   e. Number of mismatches in the second-best barcode

   Example output barcode file (partial file shown):

   ```
   ACGAATTC Y ACGAATTC 0 4
   ACGTTCTG Y ACGTTCTG 0 4
   TGCTTCTC N ggaatctc 3 5
   TAGATTA Y TAGATTA 0 5
   TTAGATT Y TTTAGATT 1 5
   TACAGATTA Y TACAGATTA 1 4
   CTCGCCTA N cttcgcct 5 5
   ```
2. **Extracted barcode metrics file**

The metrics file produced by the `ExtractIlluminaBarcodes` program indicates the number of matches (and mismatches) between the barcode reads and the actual barcodes. These metrics are provided both per barcode and per lane. For poorly matching barcodes, the order of specification of barcodes can cause arbitrary output differences.

Metrics files contain the following fields:

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BARCODE</td>
<td>The barcode (from the set of expected barcodes) for which the following metrics apply. Note that the “symbolic” barcode of NNNNNNN is used to report metrics for all reads that do not match a barcode.</td>
</tr>
<tr>
<td>BARCODE_NAME</td>
<td>Barcode name provided in the BARCODE_FILE.</td>
</tr>
<tr>
<td>LIBRARY_NAME</td>
<td>Library name provided in the BARCODE_FILE.</td>
</tr>
<tr>
<td>READS</td>
<td>The total number of reads matching the barcode.</td>
</tr>
<tr>
<td>PF_READS</td>
<td>The number of passing-filter (PF) reads matching this barcode (always less than, or equal to, READS).</td>
</tr>
<tr>
<td>PERFECT_MATCHES</td>
<td>The number of all reads matching this barcode that matched with 0 errors or no-calls.</td>
</tr>
<tr>
<td>PF_PERFECT_MATCHES</td>
<td>The number of PF reads matching this barcode that matched with 0 errors or no-calls.</td>
</tr>
<tr>
<td>ONE_MISMATCH_MATCHES</td>
<td>The number of all reads matching this barcode that matched with 1 error or no-call.</td>
</tr>
<tr>
<td>PF_ONE_MISMATCH_MATCHES</td>
<td>The number of PF reads matching this barcode that matched with 1 error or no-call.</td>
</tr>
<tr>
<td>PCT_MATCHES</td>
<td>The fraction of all reads in the lane that matched this barcode.</td>
</tr>
<tr>
<td>RATIO_THIS_BARCODE_TO_BEST_BARCODE_PCT</td>
<td>The rate of all reads matching this barcode to all reads matching the most prevalent barcode. For the most prevalent barcode, this will be 1; for all others it will be less than 1 (except for the possible exception of when there are more orphan reads than for any other barcode, in which case the value may be arbitrarily large). One divided by the lowest number in this column, is the fold-difference in representation between barcodes.</td>
</tr>
<tr>
<td>PF_PCT_MATCHES</td>
<td>The fraction of PF reads in the lane that matched this barcode.</td>
</tr>
<tr>
<td>PF_RATIO_THIS_BARCODE_TO_BEST_BARCODE_PCT</td>
<td>The rate of PF reads matching this barcode to PF reads matching the most prevalent barcode. For the most prevalent barcode this will be 1; for all others it will be less than 1 (except when there are more orphan reads than reads matching other barcodes, in which case the value may be arbitrarily large). One divided by the lowest number in this column is the fold-difference in representation of PF reads between barcodes.</td>
</tr>
<tr>
<td>PF_NORMALIZED_MATCHES</td>
<td>The “normalized” matches to each barcode. This is calculated as the number of PF reads matching this barcode divided by the average of all PF reads matching any barcode (excluding orphans). If all barcodes are represented equally, this will be 1.</td>
</tr>
</tbody>
</table>

* This table is based on Picard documentation. For the most up-to-date information, refer to the Picard website at [http://broadinstitute.github.io/picard/picard-metric-definitions.html#ExtractIlluminaBarcodes.BarcodeMetric](http://broadinstitute.github.io/picard/picard-metric-definitions.html#ExtractIlluminaBarcodes.BarcodeMetric).
**B. Demultiplex each lane of Illumina BCL files and include the UMI data in the per-sample BAM files**

Picard's *IlluminaBasecallsToSam* program collects, demultiplexes, and sorts reads across all of the tiles of a lane using barcodes generated by Picard's *ExtractIlluminaBarcodes* program, producing an unmapped BAM (uBAM) file. By default, *IlluminaBasecallsToSam* will check the presence of sequencing adapter sequences in the reads and mark them with the XT tag in the output BAM file. An example invocation:

```java
java -Xmx8g -jar picard.jar IlluminaBasecallsToSam \
   BASECALLS_DIR=inputBCLdir \
   BARCODES_DIR=extracted_Barcodes_Files \
   LANE=1 \
   READ_STRUCTURE=100T8B9M8B100T \
   RUN_BARCODE=160808_MO1253_API5G \
   LIBRARY_PARAMS=library.params.API5G.1.txt \
   TMP_DIR=/java_10_tmpdir \
   MOLECULAR_INDEX_TAG=RX \
   ADAPTERS_TO_CHECK=INDEXED \
   TAG_PER_MOLECULAR_INDEX=ZA \
   TAG_PER_MOLECULAR_INDEX=ZB
```

**INPUT**

1. **BASECALLS_DIR** (required)
   The following input files from the basecalls directory are needed:
   - *.bcl files
   - *.stats files
   - *.filter files
   - *.control files
   - *.locs files

2. **BARCODES_DIR**
   The directory contains the extracted barcodes files (_barcode.txt files) generated by *ExtractIlluminaBarcodes*.

3. **READ_STRUCTURE** (required)
   A read structure is a description of the logical structure of clusters in an Illumina sequencing run. It should consist of integer/character pairs describing the number and type of cycles (T = template, M = molecular barcode, B = sample barcode, and S = skip). For example, if the input data consists of 225-base clusters and we provide a read structure of “100T8B9M8B100T”, then the sequence may be split into four reads:
   a. Read 1, with 100 cycles (bases) of template
   b. Read 2, with 8 cycles (bases) of sample barcode followed by 9 cycles (bases) of molecular barcode (e.g., unique molecular barcode)
   c. Read 3, with 8 cycles (bases) of sample barcode
   d. Read 4, with 100 cycles (bases) of template

4. **LANE** (required)
   *IlluminaBaseCallsToSam* processes data one lane at a time; therefore, a lane number must be provided as an input.

5. **RUN_BARCODE** (required)
   The barcode of the run is prefixed to read names.
6. **LIBRARY_PARAMS** (required)
   
   All barcode, sample, and library data are provided in the library parameters file as input for running `IlluminaBaseCallsToSam`. The following is an example of a correctly formatted LIBRARY_PARAMS file:

<table>
<thead>
<tr>
<th>OUTPUT</th>
<th>SAMPLE_ALIAS</th>
<th>LIBRARY_NAME</th>
<th>BARCODE_1</th>
<th>BARCODE_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>/mnt/bam/L001/AT15G-S1_unmapped.bam</td>
<td>20160808-AT15G-S1</td>
<td>MixX_Rep1</td>
<td>CGATGNNN</td>
<td></td>
</tr>
<tr>
<td>/mnt/bam/L001/AT15G-S2_unmapped.bam</td>
<td>20160808-AT15G-S2</td>
<td>MixX_Rep2</td>
<td>CAGACCC</td>
<td></td>
</tr>
<tr>
<td>/mnt/bam/L001/AT15G-S3_unmapped.bam</td>
<td>20160808-AT15G-S3</td>
<td>MixX_Rep3</td>
<td>GATGNNN</td>
<td></td>
</tr>
</tbody>
</table>

7. **MOLECULAR_INDEX_TAG** and **TAG_PER_MOLECULAR_INDEX**
   
   If at least one molecular index is present, you can specify the `Molecular_Index_Tag` (default: `RX`). If more than one molecular index is present, you can specify a tag for each molecular index by setting the `TAG_PER_MOLECULAR_INDEX` tag. For example, if two molecular indexes are present, you can use `ZA` and `ZB` for each molecular index tag.

8. **ADAPTERS_TO_CHECK**
   
   This setting allows you to choose which adapters to look for in the read. The default value is `[INDEXED, DUAL_INDEXED, NEXTERA_V2, FLUIDIGM]`. This option can be set to “null” to clear the default value. Possible values: `{PAIRED_END, INDEXED, SINGLE_END, NEXTERA_V1, NEXTERA_V2, DUAL_INDEXED, FLUIDIGM, TRUSEQ_SMALLRNA, ALTERNATIVE_SINGLE_END}`. This option may be specified 0 or more times. The `XT` tag stores the position at which the SAM record contains sequencing adapter sequence.

**OUTPUT**

The output BAM files are in the location specified in the LIBRARY_PARAMS file. One unaligned BAM file is generated per lane per sample. These BAM files contain molecular index tags with molecular index sequences and `XT` tags for sequencing adapter sequences present in the reads.

**C. Convert BAM files to FASTQ files**

The `SamToFastq` tool (Picard) extracts read sequences and base quality scores from the input SAM/BAM file and writes them into the output file in FASTQ format. Sequencing adapter sequences present in the reads in the BAM file can be trimmed before writing to the FASTQ files. An example invocation:

```java
java -Xmx4g -jar picard.jar SamToFastq 
INPUT=input.bam \ 
FASTQ=S1_R1.fastq \ 
SECOND_END_FASTQ=S1_R2.fastq \ 
INCLUDE_NON_PF_READS=false \ 
CLIPPING_ATTRIBUTE=XT \ 
CLIPPING_ACTION=X \ 
CLIPPING_MIN_LENGTH=minFragSize
```

**INPUT**

1. **INPUT** (required)
   
   Input the unaligned BAM file generated by `IlluminaBasecallsToSam`.

2. **FASTQ** (required)
   
   The output FASTQ file is single-end FASTQ or, if paired, the first end of the pair FASTQ.

3. **SECOND_END_FASTQ**
   
   The output FASTQ file is, if paired, the second end of the pair FASTQ. The default value is null.
4. **INCLUDE_NON_PF_READS**
   Non-PF reads are reads whose “not passing quality controls” flag is set. Non-PF reads from the SAM file are included in the output FASTQ files. The default value is false. Possible values: {true,false}.

5. **CLIPPING_ATTRIBUTE**
   The clipping attribute stores the position at which the SAM record should be clipped. The default value is null.

6. **CLIPPING_ACTION**
   The clipping action indicates what action should be taken with clipped reads:
   - “X” means the reads and qualities should be trimmed at the clipped position.
   - “N” means the bases should be changed to Ns in the clipped region.
   - An integer means that the base qualities should be set to that value in the clipped region.
   - The default value is null.

7. **CLIPPING_MIN_LENGTH**
   CLIPPING_MIN_LENGTH is the minimum read length after clipping with the CLIPPING_ATTRIBUTE and CLIPPING_ACTION parameters. If the original read is shorter than minimum read length, then the original read length will be maintained. The default value is 0. This option can be set to “null” to clear the default value.

**OUTPUT**

A single-end FASTQ file or two paired-end FASTQ files will be generated from each unaligned BAM file for each sample per lane. These FASTQ files do not contain any molecular index information.

**D. Map FASTQ reads and merge alignment data from aligned BAM files with molecular index data from unaligned BAM files**

After aligning the FASTQ files using a short-read aligner, such as Burrow-Wheeler Aligner (bwa) you will need to run the **MergeBamAlignment** tool (Picard) to merge the alignment data in the aligned BAM file with the Molecular Index Tag data in the unaligned BAM file (generated by IlluminaBasecallsToSam in step B above).

The **MergeBamAlignment** tool produces a new BAM file that includes all aligned and unaligned reads, plus has additional read attributes from the uBAM that may otherwise be lost during the alignment process. Note that **MergeBamAlignment** expects to find a sequence dictionary in the same directory as REFERENCE_SEQUENCE and expects it to have the same base name as the reference FASTA, but with the extension “.dict”. The sequence dictionary can easily be generated using **CreateSequenceDictionary** (Picard). An example invocation:

```java
java -Xmx4g -jar picard.jar MergeBamAlignment \
    ALIGNED=aligned.bam \n    UNMAPPED=unaligned.bam \n    OUTPUT=merged.bam \n    REFERENCE_SEQUENCE=hg38.fa \n    EXPECTED_ORIENTATIONS=FR \n    MAX_GAPS=1 \n    SORT_ORDER=coordinate \n    CREATE_INDEX=true \n    ALIGNER_PROPER_PAIR_FLAGS=false
```
INPUT

1. **ALIGNED** (required)
   These SAM or BAM file(s) contain alignment data.

2. **UNMAPPED** (required)
   The original SAM or BAM file contains unmapped reads, which must be in queryname order.

3. **OUTPUT** (required)
   This is the merged SAM or BAM file that will contain the final data from this alignment process.

4. **REFERENCE_SEQUENCE** (required)
   You must provide the path to the FASTA file for the reference sequence.

5. **EXPECTED_ORIENTATION**
   This is the expected orientation of proper read pairs. Possible values: {FR, RF, TANDEM}. This option may be specified 0 or more times.

6. **MAX_GAPS**
   This is the maximum number of allowable insertions or deletions for an alignment to be included. Alignments with more than this many insertions or deletions will be ignored. You may set the MAX_GAPS to –1 to allow any number of insertions or deletions. The default value is 1.

7. **SORT_ORDER**
   This specifies the order in which the merged reads will be output. The default value is coordinate. Possible values: {unsorted, queryname, coordinate, duplicate}.

8. **CREATE_INDEX**
   This specifies whether or not to create a BAM index when writing a coordinate-sorted BAM file. The default value is false. Possible values: {true, false}.

9. **ALIGNER_PROPER_PAIR_FLAGS**
   You may use the aligner software definition of a proper pair rather than compute proper pairs in this program. The default value is false. Possible values: {true, false}.

OUTPUT:

You will receive a new BAM file that includes all aligned and unaligned reads and also contains additional read attribute from the BAM that may otherwise be lost during the alignment process.
Demultiplexing Illumina sequencing data with UMIs

For more than 30 years, IDT's innovative tools and solutions for genomics applications have been driving advances that inspire scientists to dream big and achieve their next breakthroughs. IDT develops, manufactures, and markets nucleic acid products that support the life sciences industry in the areas of academic and commercial research, agriculture, medical diagnostics, and pharmaceutical development. We have a global reach with personalized customer service.

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