
RNA-Hi-C-tools Documentation

Release 0.3.2

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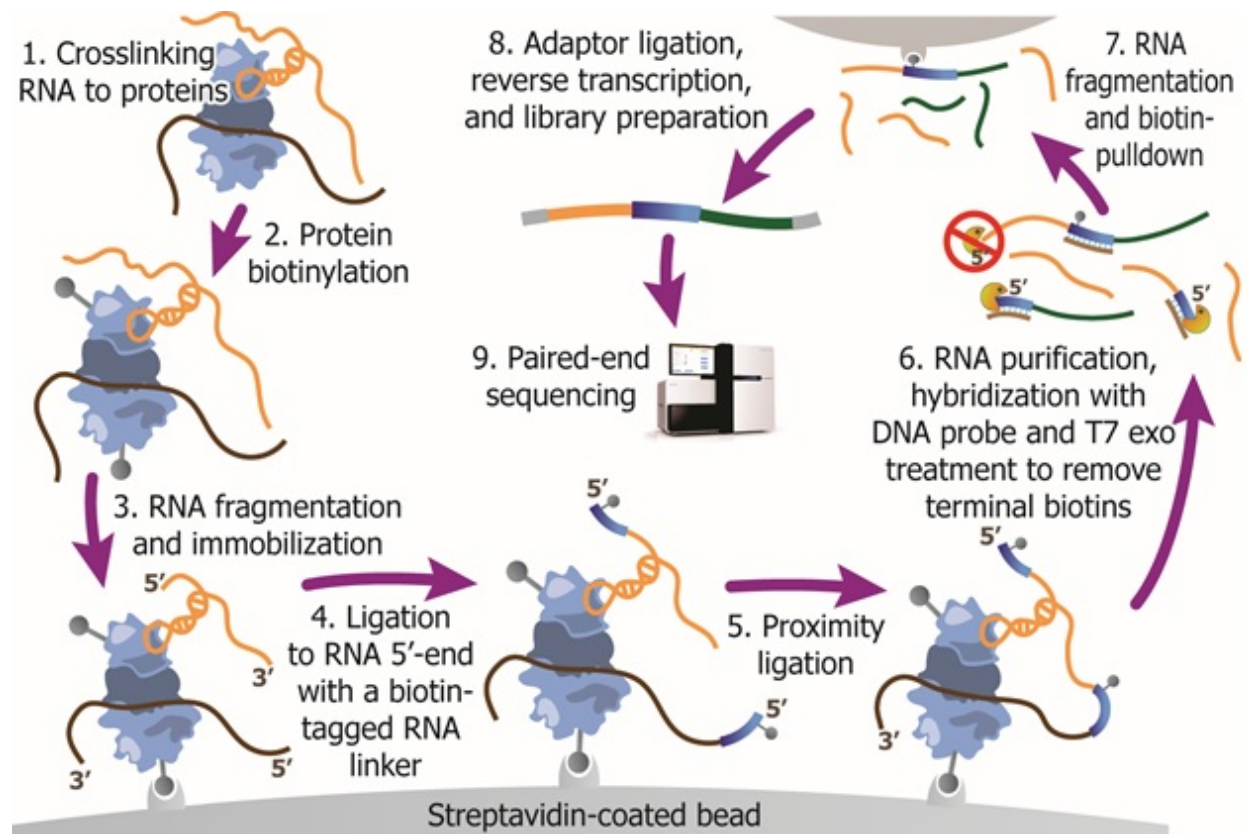
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RNA-HI-C-TOOLS 0.3 DOCUMENTATION

1.1 Overview

RNA-Hi-C-tools is a set of bioinformatic tools for analysis of a novel DNA sequencing based technology to detect RNA-RNA interactome and RNA-chromatin interactome (RNA-chromatin interactome is coming soon).

Below is a illustration for the experimental design of this new technology



See also:

Offline documentation.

Download a copy of RNA-Hi-C-tools documentation:

- [PDF](#)
- [Epub](#)

1.2 Installation

1.2.1 step 1: Install the dependent prerequisites:

1. Python libraries [for python 2.x]:
 - Biopython
 - Pysam
 - BAM2X
 - Numpy, Scipy
 - Parallel python (Only for `Select_strongInteraction_pp.py`)
2. The Boost.Python C++ library
3. Other softwares needed:
 - Bowtie (not Bowtie 2)
 - samtools
 - NCBI blast+ (use blastn)

1.2.2 Step 2: Download the package

Clone the package from GitHub:

```
git clone http://github.com/yu68/RNA-Hi-C.git
```

1.2.3 Step 3: Add library source to your python path

Add these lines into your `~/.bash_profile` or `~/.profile`

```
Location="/path/of/RNA-Hi-C-tools" # change accordingly
export PYTHONPATH="$Location/src:$PYTHONPATH"
export PATH="$PATH:$Location/bin"
Loc_lib="/path/of/boost_1_xx_0/lib/" # change accordingly
export LD_LIBRARY_PATH="$Loc_lib:$LD_LIBRARY_PATH"
```

1.3 Support

For issues related to the use of RNA-Hi-C-tools, or if you want to **report a bug or request a feature**, please contact Pengfei Yu <p3yu at ucsd dot edu>

ANALYSIS PIPELINE

2.1 Overview

The next generation DNA sequencing based technology utilize RNA proximity ligation to transform RNA-RNA interactions into chimeric DNAs. Through sequencing and mapping these chimeric DNAs, it is able to achieve high-throughput mapping of nearly entire interaction networks. RNA linkers were introduced to mark the junction of the ligation and help to split the chimeric RNAs into two interacting RNAs. This bioinformatic pipeline is trying to obtain the strong interactions from raw fastq sequencing data. The major steps are:

- *Step 1: Remove PCR duplicates.*
- *Step 2: Split library based on barcode.txt.*
- *Step 3: Recover fragments for each library.*
- *Step 4: Split partners and classify different types of fragments.*
- *Step 5: Align both parts of “Paired” fragment to the genome.*
- *Step 6: Determine strong interactions.*
- *Step 7: Visualization of interactions and coverages.*

Other functions:

1. *Determine the RNA types of different parts within fragments.*
2. *Find linker sequences within the library.*
3. *Find intersections between two different interaction sets based on genomic locations*
4. *Find intersections between two different interaction sets based on annotation*
5. *RNA structure prediction by adding digestion site information*

2.2 Pipeline

2.2.1 Step 1: Remove PCR duplicates.

Starting from the raw pair-end sequencing data, PCR duplicates should be removed as the first step if both the 10nt random indexes and the remaining sequences are exactly the same for two pairs. It is achieved by `remove_dup_PE.py`

```
usage: remove_dup_PE.py [-h] reads1 reads2
```

Remove duplicated reads which have same sequences for both forward and reverse reads. Choose the one appears first.

positional arguments:

reads1 forward input fastq/fastq file
reads2 reverse input fastq/fastq file

optional arguments:

-h, --help show this help message and exit

Library dependency: Bio, itertools

The program will generate two fastq/fastq files after removing PCR duplicates and report how many read pairs have been removed. The output are prefixed with 'Rm_dupPE'

Note: One pair is considered as a PCR duplicate only when the sequences of both two ends (including the 10nt random index) are the exactly same as any of other pairs.

2.2.2 Step 2: Split library based on barcode.txt.

After removing PCR duplicates, the libraries from different samples are separated based on 4nt barcodes in the middle of random indexes ("RRRBBBBRRR"; R: random, B: barcode). It is implemented by `split_library_paired.py`

```
usage: split_library_paired.py [-h] [-f | -q] [-v] [-b BARCODE]
                               [-r RANGE [RANGE ...]] [-t] [-m MAX_SCORE]
                               input1 input2
```

```
Example: split_library_paired.py -q Rm_dupPE_example.F1.fastq
        Rm_dupPE_example.R1.fastq -b barcode.txt
```

positional arguments:

input1 input fastq/fastq file 1 for paired data (contain
 barcodes)
input2 input fastq/fastq file 2 for paired data

optional arguments:

-h, --help show this help message and exit
-f, --fasta add this option for fasta input file
-q, --fastq add this option for fastq input file
-v, --version show program's version number and exit
-b BARCODE, --barcode BARCODE
 barcode file
-r RANGE [RANGE ...], --range RANGE [RANGE ...]
 set range for barcode location within reads, default is
 full read
-t, --trim trim sequence of 10nt index
-m MAX_SCORE, --max_score MAX_SCORE
 max(mismatch+indel) allowed for barcode match,
 otherwise move reads into 'unassigned' file
 default: 2.

Library dependency: Bio

Here is an example for barcode.txt

```
ACCT
CCGG
GGCG
```

The output of this script are several pairs of fastq/fasta files prefixed with the 4nt barcode sequences, together with another pair of fastq/fasta files prefixed with 'unassigned'.

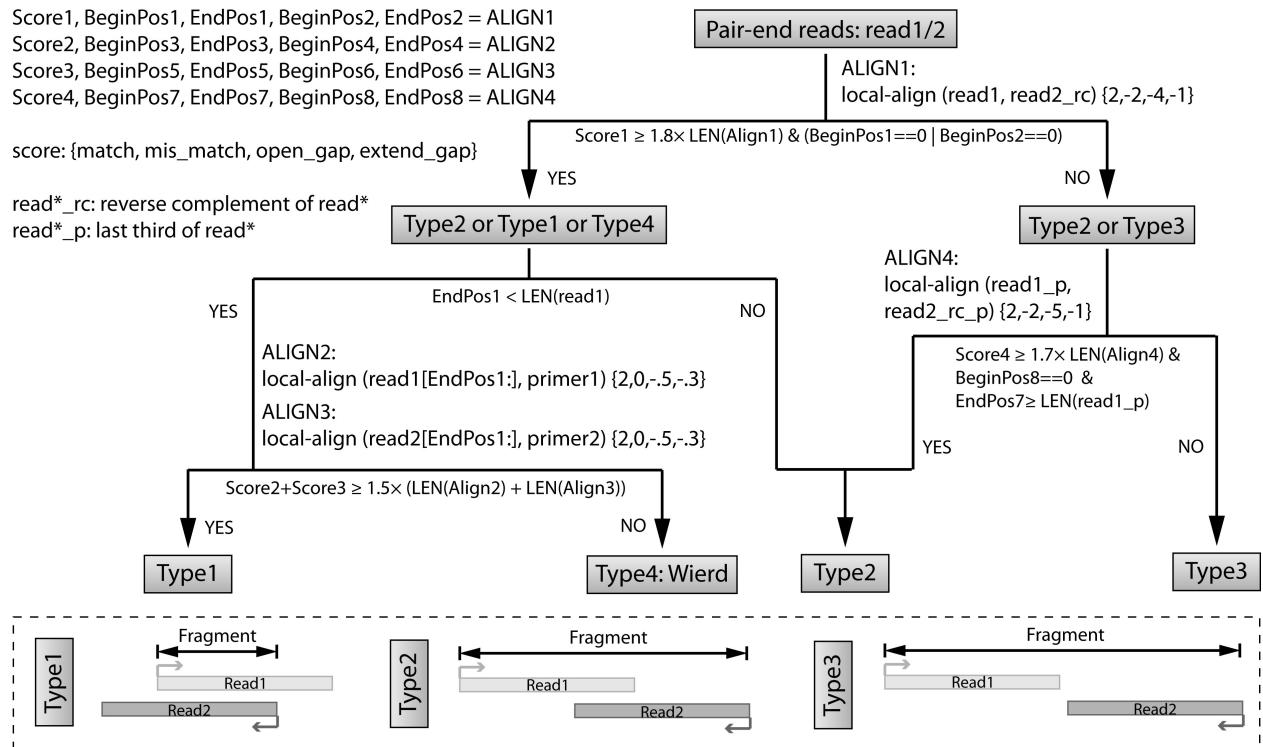
For example, if the input fastq/fasta files are `Rm_dupPE_example.F1.fastq` and `Rm_dupPE_example.R1.fastq`, and the barcode file is the same as above, then the output files are:

- `ACCT_Rm_dupPE_example.F1.fastq`
- `ACCT_Rm_dupPE_example.R1.fastq`
- `CCGG_Rm_dupPE_example.F1.fastq`
- `CCGG_Rm_dupPE_example.R1.fastq`
- `GGCG_Rm_dupPE_example.F1.fastq`
- `GGCG_Rm_dupPE_example.R1.fastq`
- `unassigned_Rm_dupPE_example.F1.fastq`
- `unassigned_Rm_dupPE_example.R1.fastq`

2.2.3 Step 3: Recover fragments for each library.

After splitting the libraries, the later steps from here (Step 3-7) need to be executed parallelly for each sample.

In this step, we are trying to recover the fragments based on local alignment. The fragments are classified as several different types as shown in the figure below. The flow chart is also clarified at the top.



We will use a compiled program `recoverFragment` to do that

```
recoverFragment - recover fragment into 4 different categories from pair-end seq data
=====
```

SYNOPSIS

DESCRIPTION

```

-h, --help
    Displays this help message.
--version
    Display version information
-I, --inputs STR
    input of forward and reverse fastq file, path of two files separated by SPACE
-p, --primer STR
    fasta file containing two primer sequences
-v, --verbose
    print alignment information for each alignment

```

EXAMPLES

```

recoverFragment -I read_1.fastq read_2.fastq -p primer.fasta
    store fragment using fasta/fastq into 4 output files
    'short_*', 'long_*', 'evenlong_*', 'wierd_*'

```

VERSION

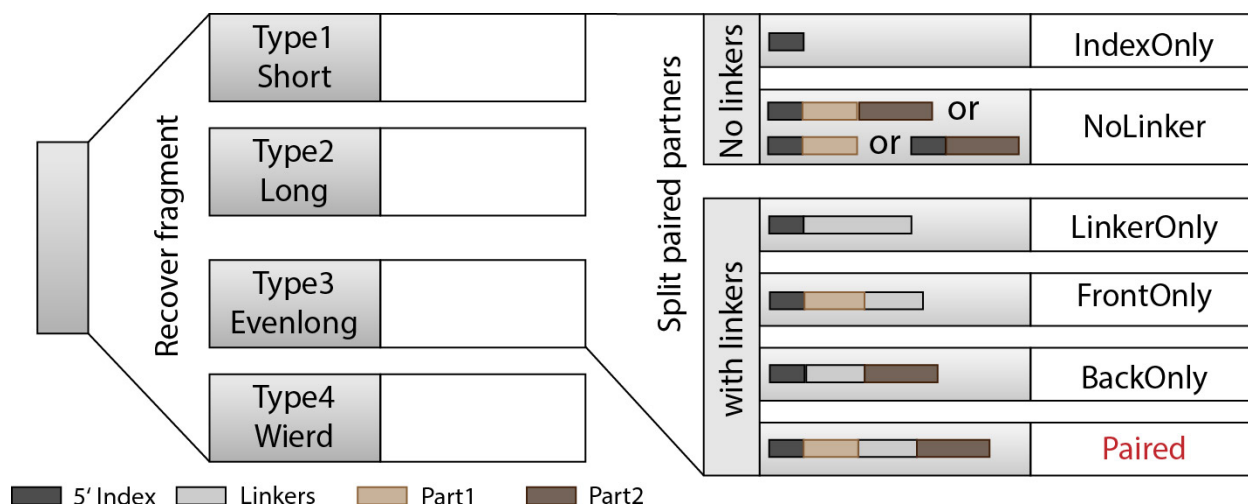
```

recoverFragment version: 0.1
Last update August 2013

```

2.2.4 Step 4: Split partners and classify different types of fragments.

When we recovered the fragments, the next we are going to do is to find parts that are separated by the linkers, and from here, we will be able to classify the fragments into different types: “IndexOnly”, “NoLinker”, “LinkerOnly”, “BackOnly”, “FrontOnly”, “Paired”. (see the figure below).



This will be done by `split_partner.py`

```

usage: split_partner.py [-h] [-e EVALUE] [--linker_db LINKER_DB]
    [--blast_path BLAST_PATH] [-o OUTPUT] [-t TRIM]
    [-b BATCH] [-l LENGTH]
    input type3_1 type3_2

```

DESCRIPTION: Run BLAST, find linker sequences and split two parts connected by linkers

positional arguments:

input the input fasta file containing fragment sequences of

```
type3_1          type1 and type2
read_1 for evenlong (type3) fastq file
type3_2          read_2 for evenlong (type3) fastq file
```

optional arguments:

```
-h, --help          show this help message and exit
-e EVALUE, --evaluate EVALUE
                    cutoff evalues, only choose alignment with evalue less
                    than this cutoffs (default: 1e-5).
--linker_db LINKER_DB
                    BLAST database of linker sequences
--blast_path BLAST_PATH
                    path for the local blast program
-o OUTPUT, --output OUTPUT
                    output file containing sequences of two sepatated
                    parts
-t TRIM, --trim TRIM trim off the first this number of nt as index,
                    default:10
-b BATCH, --batch BATCH
                    batch this number of fragments for BLAST at a time.
                    default: 200000
-r, --release        set to allow released criterion for Paired fragment in
                    Type 3, include those ones with no linker in two reads
-l LENGTH, --length LENGTH
                    shortest length to be considered for each part of the
                    pair, default: 15
```

Library dependency: Bio, itertools

Note: New option added in version 0.3.1, which could allow two different strategies for selection of “Paired” fragments from the Type3 fragments. The `--release` option will allow a read pair to be called as “Paired” fragment even when the linker are not detected in both reads.

The linker fasta file contain sequences of all linkers

```
>L1
CTAGTAGCCCATGCAATGCGAGGA
>L2
AGGAGCGTAACGTACCCGATGATC
```

The output fasta files will be the input file name with different prefix (“NoLinker”, “LinkerOnly”, “BackOnly”, “FrontOnly”, “Paired”) for different types. The other output file specified by `-o` contains information of aligned linker sequences for each Type1/2 fragment.

For example, if the commend is

```
split_partner.py fragment_ACCT.fasta evenlong_ACCTrm_dupPE_stitch_seq_1.fastq
evenlong_ACCTrm_dupPE_stitch_seq_2.fastq
-o fragment_ACCT_detail.txt --linker_db linker.fa
```

Then, the output files will be:

- backOnly_fragment_ACCT.fasta
- NoLinker_fragment_ACCT.fasta
- frontOnly_fragment_ACCT.fasta
- Paired1_fragment_ACCT.fasta

- Paired2_fragment_ACCT.fasta
- fragment_ACCT_detail.txt

The format of the last output file `fragment_ACCT_detail.txt` will be “Name | linker_num | linker_loc | Type | linker_order”. Here are two examples:

```
HWI-ST1001:238:H0N9EADXX:1:1101:10221:1918      L1:2;L2:1  19,41;42,67;68,97      None      L2;L1;L1
HWI-ST1001:238:H0N9EADXX:1:1101:4620:2609      L1:2  28,46;47,79      Paired  L1;L1
```

In the **first** fragment, there are three regions can be aligned to linkers, 2 for L1 and 1 for L2, the order is L2, L1, L1. And they are aligned in region [19,41], [42,67], [68,97] of the fragment. “None” means this fragment is either ‘LinkerOnly’ or ‘IndexOnly’ (in this case it is ‘LinkerOnly’). This fragment won’t be written to any of the output fasta files.

In the **second** fragment, two regions can be aligned to linkers, and they are both aligned to L1. The two regions are in [28,46], [47,79] of the fragment. the fragment is “Paired” because on both two sides flanking the linker aligned regions, the length is larger than 15nt. The left part will be written in `Paired1_fragment_ACCT.fasta` and the right part in `Paired2_fragment_ACCT.fasta`

2.2.5 Step 5: Align both parts of “Paired” fragment to the genome.

In this step, we will use the Paired1* and Paired2* fasta files output from the previous step. The sequences of part1 and part2 are aligned to the mouse genome mm9 with Bowtie and the pairs with both part1 and part2 mappable are selected as output. We also annotate the RNA types of each part in this step. All of these are implemented using script `Stitch-seq_Aligner.py`.

```
usage: Stitch-seq_Aligner.py [-h] [-s samtool_path] [-a ANNOTATION]
                             [-A DB_DETAIL]
                             miRNA_reads mRNA_reads bowtie_path miRNA_ref
                             mRNA_ref
```

Align miRNA-mRNA pairs for Stitch-seq. print the alignable miRNA-mRNA pairs with coordinates

positional arguments:

part1_reads	paired part1 fasta file
part2_reads	paired part2 fasta file
bowtie_path	path for the bowtie program
part1_ref	reference genomic seq for part1
part2_ref	reference genomic seq for part2

optional arguments:

-h, --help	show this help message and exit
-b, --bowtie2	set to use bowtie2 (--sensitive-local) for alignment, need to change reference index and bowtie_path
-u, --unique	set to only allow unique alignment
-s samtool_path, --samtool_path samtool_path	path for the samtool program
-a ANNOTATION, --annotation ANNOTATION	If specified, include the RNA type annotation for each aligned pair, need to give bed annotation RNA file
-A DB_DETAIL, --annotationGenebed DB_DETAIL	annotation bed12 file for lincRNA and mRNA with intron and exon

Library dependency: Bio, pysam, itertools

An annotation file for different types of RNAs in mm9 genome (bed format, 'all_RNAs-rRNA_repeat.txt.gz') was included in Data folder. The annotation bed12 file for lincRNA and mRNA ('Ensembl_mm9.genebed.gz') was also included in Data folder. One can use the option `-a ../Data/all_RNAs-rRNA_repeat.txt.gz -A ../Data/Ensembl_mm9.genebed.gz` for annotation.

Here is a example:

```
Stitch-seq_Aligner.py Paired1_fragment_ACCT.fasta Paired2_fragment_ACCT.fasta
~/Software/bowtie-0.12.7/bowtie mm9 mm9 -s samtools
-a ../Data/all_RNAs-rRNA_repeat.txt.gz -A ../Data/Ensembl_mm9.genebed.gz
> ACCT_fragment_paired_align.txt
```

The format for the output file `ACCT_fragment_paired_align.txt` will be:

Column ¹	Description
1	chromosome name of part1
2,3	start/end position of part1
4	strand information of part1
5	sequence of part1
6	RNA type for part1
7	RNA name for part1
8	RNA subtype ² for part1
9	name of the pair

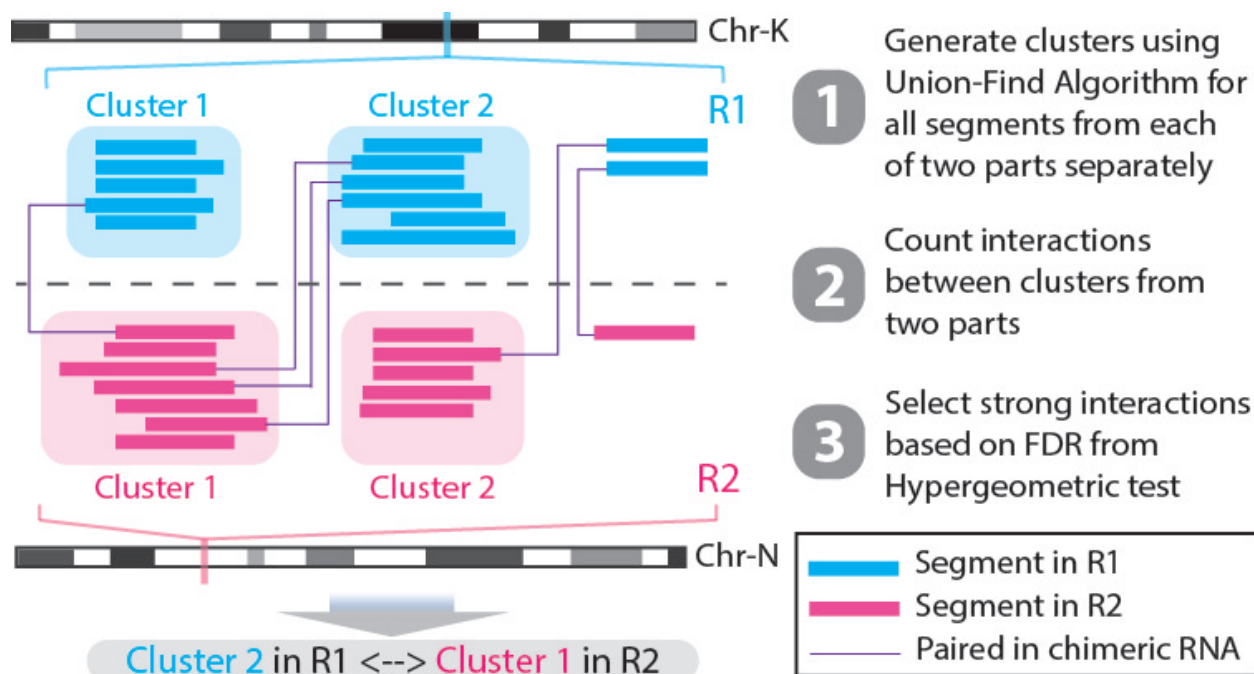
Note: Bowtie2 (“-sensitive-local” mode) option is added in version 0.3.1 for the user to choose, the `reference_index` and `bowtie_path` need to be changed accordingly if you use bowtie2 instead of bowtie. User can also choose unique aligned reads or not by setting `--unique` option.

2.2.6 Step 6: Determine strong interactions.

In this step, we will generate clusters with high coverage separately for all part1 (R1) and part2 (R2) segments. Then based on the pairing information, we count the interactions between clusters from part1 and part2. The strong interactions can be selected by applying a p-value cutoff from hypergeometric test. (See figure below)

¹column 10-17 are the same as column 1-8 except they are for part2 instead of part1.

²subtype can be intron/exon/utr5/utr3 for lincRNA and mRNA (protein-coding), ‘.’ for others



We will use the script `Select_strongInteraction_pp.py`, parallel computing are implemented for clustering parallelly on different chromosomes:

```
usage: Select_strongInteraction_pp.py [-h] -i INPUT [-M MIN_CLUSTERS]
                                     [-m MIN_INTERACTION] [-p P_VALUE]
                                     [-o OUTPUT] [-P PARALLEL] [-F]
```

find strong interactions from paired genomic location data

optional arguments:

```
-h, --help                show this help message and exit
-i INPUT, --input INPUT    input file which is the output file of Stitch-seq-
                           Aligner.py
-M MIN_CLUSTERS, --min_clusterS MIN_CLUSTERS
                           minimum number of segments allowed in each cluster,
                           default:5
-m MIN_INTERACTION, --min_interaction MIN_INTERACTION
                           minimum number of interactions to support a strong
                           interaction, default:3
-p P_VALUE, --p_value P_VALUE
                           the p-value based on hypergeometric distribution to
                           call strong interactions, default: 0.05
-o OUTPUT, --output OUTPUT
                           specify output file
-P PARALLEL, --parallel PARALLEL
                           number of workers for parallel computing, default: 5
-F, --FDR                  Compute FDR if specified
```

need Scipy for hypergeometric distribution

The input of the script is the output of Step 5 (`ACCT_fragment_paired_align.txt` in the example). “`annotated_bed`” class is utilized in this script.

Here is a example:


```
Select_strongInteraction.py -i ACCT_fragment_paired_align.txt -o ACCT_interaction_clusters.txt
```

The column description for output file `ACCT_interaction_clusters.txt` is:

Column	Description
1	chromosome name of cluster in part1
2,3	start/end position of cluster in part1
4	RNA type for cluster in part1
5	RNA name for cluster in part1
6	RNA subtype for cluster in part1
7	# of counts for cluster in part1
8-14	Same as 1-7, but for cluster in part2
15	# of interactions between these two clusters
16	log(p-value) of the hypergeometric testing

2.2.7 Step 7: Visualization of interactions and coverages.

There are two ways of visulization provided (LOCAL and GLOBAL):

- *Visualization of local interactions.*
- *Visualization of global interactome.*

2.3 Other functions

2.3.1 Determine the RNA types of different parts within fragments.

2.3.2 Find linker sequences within the library.

2.3.3 Find intersections between two different interaction sets based on genomic locations

The script tool `intersectInteraction.py` could be used to identify overlap of interactions between two interaction set from independent experiments based on genomic locations (two replicates or two different samples)

```
usage: intersectInteraction.py [-h] -a FILEA -b FILEB [-s START] [-n NBASE]
                             [-o OUTPUT] [-c]
```

find intersections (overlaps) between two interaction sets

optional arguments:

```
-h, --help                show this help message and exit
-a FILEA, --filea FILEA   file for interaction set a
-b FILEB, --fileb FILEB   file for interaction set b
-s START, --start START   start column number of the second part in each
                           interaction (0-based), default:7
-n NBASE, --nbase NBASE   number of overlapped nucleotides for each part of
                           interactions to call intersections, default: 1
-o OUTPUT, --output OUTPUT
```

```

                                specify output file
-p, --pvalue                    calculate p-values based on 100times permutations

```

require 'random' & 'numpy' & 'scipy' module if set '-p'

if “-p” option is set, then the program will do permutation for 100 times by shuffling the two partners of interactions in set a. A p-value will be calculate based on permutation distribution.

2.3.4 Find intersections between two different interaction sets based on annotation

The script tool `intersectInteraction_genePair.R` could be used to identify overlap of interactions between two interaction set from independent experiments based on the RNA annotations (two replicates or two different samples)

```

usage: intersectInteraction_genePair.R [-h] [-n NUM [NUM ...]] [-p] [-r]
                                      [-o OUTPUT]
                                      interactionA interactionB

```

Call intersections based on gene pairs

positional arguments:

```

interactionA                    the interaction file a, [required]
interactionB                    the interaction file b, [required]

```

optional arguments:

```

-h, --help                      show this help message and exit
-n NUM [NUM ...], --num NUM [NUM ...]
                                Column numbers for the gene name in two part, [default:
                                [5, 12]]
-p, --pvalue                    set to do 100 permutations for p-value of overlap
-r, --release                   set to only require match of chromosome and RNA name,
                                but not subtype
-o OUTPUT, --output OUTPUT      output intersection file name, pairs in A that overlap
                                with B, [default: intersect.txt]

```

if “-p” option is set, then the program will do permutation for 100 times by shuffling the two partners of interactions in both set a and set b. A p-value will be calculate based on permutation distribution.

2.3.5 RNA structure prediction by adding digestion site information

The script will take selfligated chimeric fragments from given snoRNA (ID) and predict secondary structures with and without constraints of digested single strand sites. It is also able to compare the known structure in dot format if the known structure is available and specified by “-a”. The script needs RNAstructure software for structure prediction (“-R”) and and VARNA command line tool for visualization (“-v”).

```

usage: RNA_structure_prediction.py [-h] [-g GENOMEFA] [-R RNASTRUCTUREEXE]
                                   [-a ACCEPTDOT] [-o OUTPUT]
                                   [-s samtool_path] [-v VARNA]
                                   [-c COLORMAPSTYLE]
                                   ID linkedPair

```

plot RNA structure with distribution of digested end, refine structure with loc of digested end

positional arguments:

ID	Ensembl gene ID of RNA
linkedPair	file for information of linked pairs, which is output of 'Stitch-seq_Aligner.py'

optional arguments:

```
-h, --help                show this help message and exit
-g GENOMEFA, --genomeFa GENOMEFA
                           genomic sequence, need to be fadix-ed
-R RNASTRUCTUREEXE, --RNAstructureExe RNASTRUCTUREEXE
                           folder of RNAstrucutre suite excutable
-a ACCEPTDOT, --acceptDot ACCEPTDOT
                           accepted structure in dot format, for comparing of
                           accuracy, no comparison if not set
-o OUTPUT, --output OUTPUT
                           output distribution of digested sites with dot
                           structures, can be format of eps, pdf, png,...
-s samtool_path, --samtool_path samtool_path
                           path for the samtool program
-v VARNA, --varna VARNA
                           path for the VARNA visualization for RNA
-c COLORMAPSTYLE, --colorMapStyle COLORMAPSTYLE
                           style of color map, choose from: "red", "blue",
                           "green", "heat", "energy", and "bw", default: "heat"
```

Here is a example:

```
python RNA_structure_prediction.py \
  ENSMUSG00000064380 \
  /data2/sysbio/UCSD-sequencing/2013-11-27-Bharat_Tri_Shu/Undetermined_indices/Sample_lane8/ACCT_GGC
-a Snora73_real_dot.txt \
-o Snora73_distribution.pdf
```

Here “Snora73_real_dot.txt” is dot format of known Snora73 structure This will generate three eps files with secondary structures (“Predict”, “Refine”, “Accepted (known)”. Also the output pdf file contains the distribution of digested sites in whole RNA molecule.

VISUALIZATION OF LOCAL RNA-RNA INTERACTIONS

3.1 Prerequisite

This program require python modules: xplib, matplotlib, numpy, bx-python

3.2 Run the program to generate visualization

The script “Plot_interaction.py” will be used for this purpose,

```
usage: Plot_interaction.py [-h] [-n N] [-s START [START ...]] [-d DISTANCE]
                        [-g GENEDED] [-w PHYLOP_WIG] [-p PAIR_DIST] [-S]
                        [-o OUTPUT]
                        interaction linkedPair
```

plot linked pairs around a given interaction. information of linked pairs are stored in file ‘*_fragment_paired_align.txt’

positional arguments:

interaction	Interaction file from output of ‘Select_strongInteraction_pp.py’
linkedPair	file for information of linked pairs, which is output of ‘Stitch-seq_Aligner.py’

optional arguments:

-h, --help	show this help message and exit
-n N	Choose region to plot, it can be a number (around n-th interaction in the interaction file). This is mutually exclusive with ‘-r’ option
-r R [R ...]	Choose region to plot, give two interaction regions with format ‘chr:start-end’, this is mutually exclusive with ‘-n’ option
-s START [START ...], --start START [START ...]	start column number of the second region in interaction file and linkedPair file, default=(7,8)
-d DISTANCE, --distance DISTANCE	the plus-minus distance (unit: kbp) flanking the interaction regions to be plotted, default=10
-g GENEDED, --genebed GENEDED	the genebed file from Ensembl, default: ../Data/Ensembl_mm9.genebed
-w PHYLOP_WIG, --phyloP_wig PHYLOP_WIG	the bigWig file for phyloP scores, default:

```

                                mouse.phyloP30way.bw
-p PAIR_DIST, --pair_dist PAIR_DIST
                                two interacted parts within this distance are
                                considered as self-ligated and they are marked or
                                eliminated (see option -s for slim mode), default:
                                200bp
-S, --Slim                      set slim mode to eliminate self ligated interactions
-o OUTPUT, --output OUTPUT
                                output plot file, can be format of emf, eps, pdf, png,
                                ps, raw, rgba, svg, svgz

```

Note: linkedPair file is the output *_fragment_paired_align.txt from *Step5:Stitch-seq_Aligner.py* of the pipeline; Interaction txt file is the output of *Step6:Select_strongInteraction_pp.py*.

3.3 Example of result graph

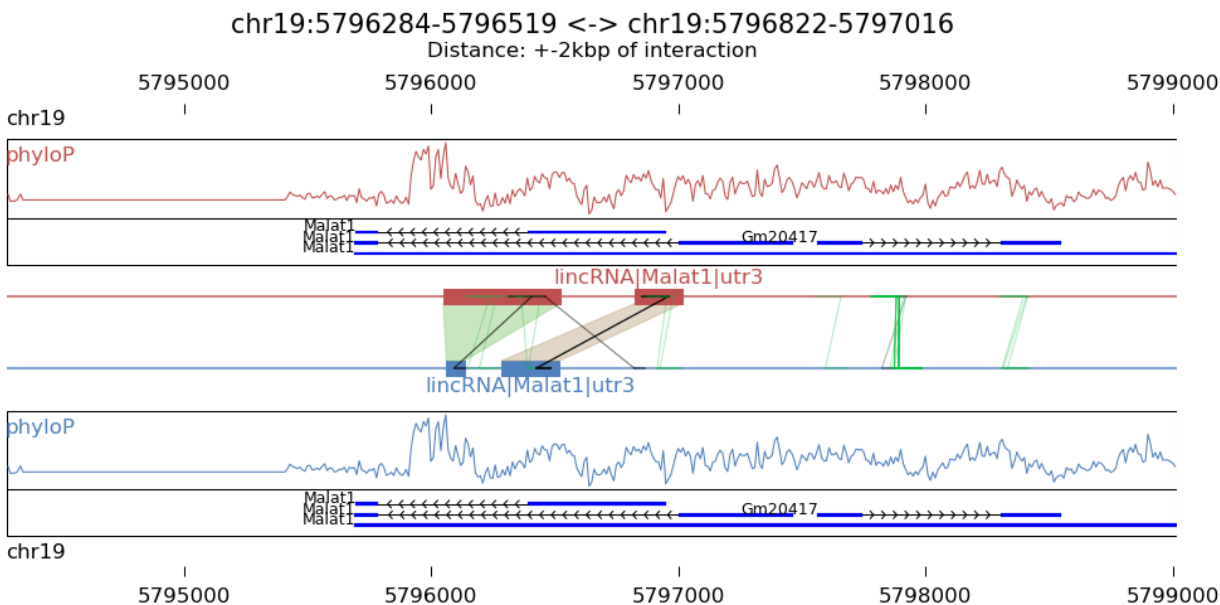
Example code:

```

python Plot_interaction.py
    ACCT_interaction_clusters_rmrRNA.txt \
    ACCT_fragment_paired_align_rmRNA_sort.txt.gz \
    -n 2412 \
    -d 5 \
    -o local_interaction.pdf

```

Result figure:



Explanation:

VISUALIZATION OF INTRA-RNA INTERACTIONS BY HEATMAP

4.1 Prerequisite

This program require python modules: xplib, matplotlib, numpy

4.2 Run the program to generate heatmap for interactions within RNA molecule

This program could generate an heatmap to show interactions between different regions within an RNA molecule which are spatially proximate to each other. We use the script “Plot_interaction_heatmap.py”

```
usage: Plot_interaction_heatmap.py [-h] [-n NAME] [-r R]
                                  [-s START [START ...]] [-g GENEDED]
                                  [-p PAIR_DIST] [-S] [-t STEP] [-I]
                                  [-o OUTPUT]
                                  interaction linkedPair
```

plot interactions using a heatmap. information of linked pairs are stored in file ‘*_fragment_paired_align.txt’

positional arguments:

interaction	Interaction file from output of ‘Select_strongInteraction_pp.py’
linkedPair	file for information of linked pairs, which is output of ‘Stitch-seq_Aligner.py’

optional arguments:

-h, --help	show this help message and exit
-n NAME, --name NAME	give a gene name and plot the interaction heatmap new the gene region, exclusive with ‘-r’ option
-r R	Choose region to plot, give region with format ‘chr:start-end’, exclusive with ‘-n’ option
-s START [START ...], --start START [START ...]	start column number of the second region in interaction file and linkedPair file, default=(7,9)
-g GENEDED, --genebed GENEDED	the genebed file from Ensembl, default: Ensembl_mm9.genebed
-p PAIR_DIST, --pair_dist PAIR_DIST	two interacted parts within this distance are considered as self-ligated and they are marked or eliminated (see option -s for slim mode), default:

```

                                1000bp
-S, --Slim                     set slim mode to eliminate self ligated interactions
-t STEP, --step STEP          step or resolution or unit size of the heatmap,
                                default=10bp
-I, --SI                       Specify to add strong interaction in the
                                figure,default: False
-o OUTPUT, --output OUTPUT    output plot file, can be format of emf, eps, pdf, png,
                                ps, raw, rgba, svg, svgz

```

Require: xplib, matplotlib, numpy

Note: linkedPair file is the output *_fragment_paired_align.txt from *Step5:Stitch-seq_Aligner.py* of the pipeline; Interaction txt file is the output of *Step6:Select_strongInteraction_pp.py*. Users can use two different ways to give the region to be plotted. One is directly use the '-r' option to specify the region, another is to give a gene name and the script can find a larger region covering the gene region.

4.3 Example of result graph

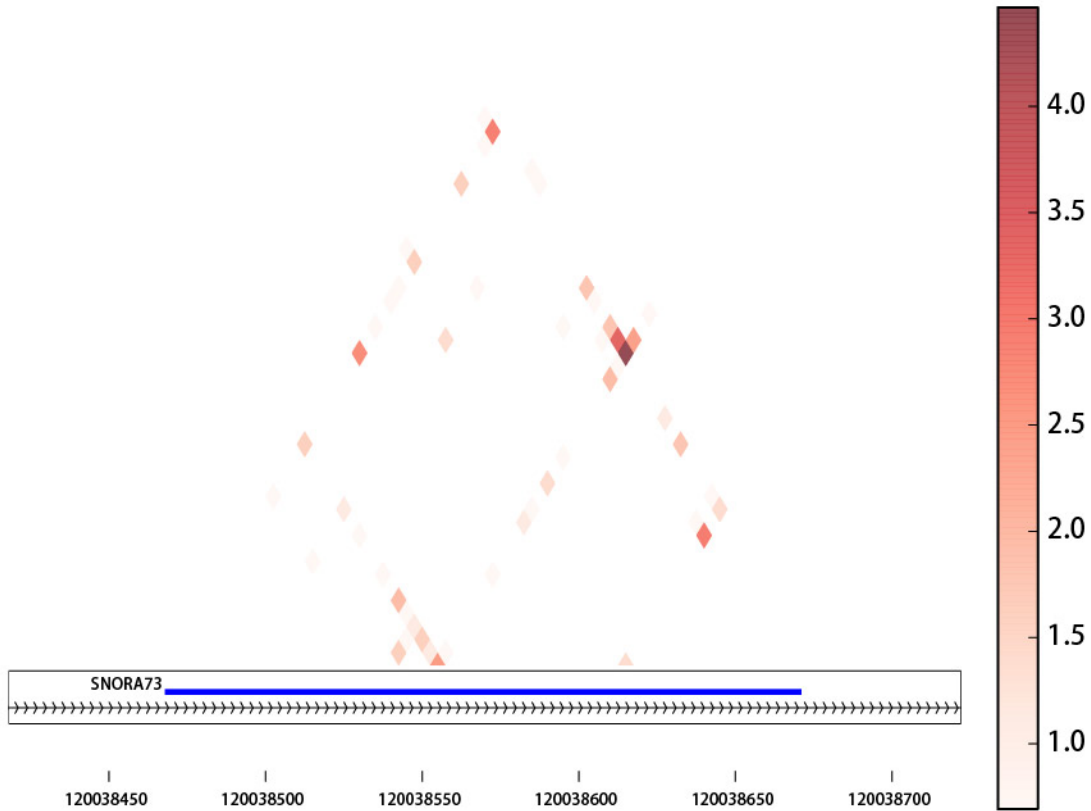
Example code:

```

python Plot_interaction_heatmap.py
    ACCT_GGCG_interaction_clusters.txt \
    ACCT_GGCG_fragment_paired_align_rmRNA_sort.txt.gz \
    -r chr9:120038418-120038722 \
    -t 5 \
    -s 7 9 \
    -g ../Data/Ensembl_mm9.genebed.gz \
    -o Snora73_intra_interaction.pdf

```

Result figure:



Explanation:

The heatmap is based on the $\log(\text{count}+1)$ of mapped linkage pairs across two windows with size [step]bp

VISUALIZATION OF GLOBAL RNA-RNA INTERACTOME

5.1 Prerequisite

This program is powered by [RCircos](#).

Required R packages (our program will check for the presence of these packages and install/load them automatically if not present):

- `argparse`, `RCircos`, `biovizBase`, `rtracklayer`

The program also require a python script “bam2tab.py” (already in `/bin/` folder) to call coverage from [BAM2X](#)

5.2 Run the program to generate visualization

We will use the script “Plot_Circos.R” for this purpose.

```
usage: Plot_Circos.R [-h] [-g GENOME] [-b BIN] [-o OUTPUT]
                    interaction part1 part2
```

positional arguments:

interaction	the interaction file, [required]
part1	aligned BAM file for part1, [required]
part2	aligned BAM file for part2, [required]

optional arguments:

-h, --help	show this help message and exit
-g GENOME, --genome GENOME	genome information, choice: mm9/mm10/hg19 et.al., [default: mm9]
-b BIN, --bin BIN	window size for the bins for coverage calling, [default: 100000.0]
-o OUTPUT, --output OUTPUT	output pdf file name, [default: Interactome_view.pdf]

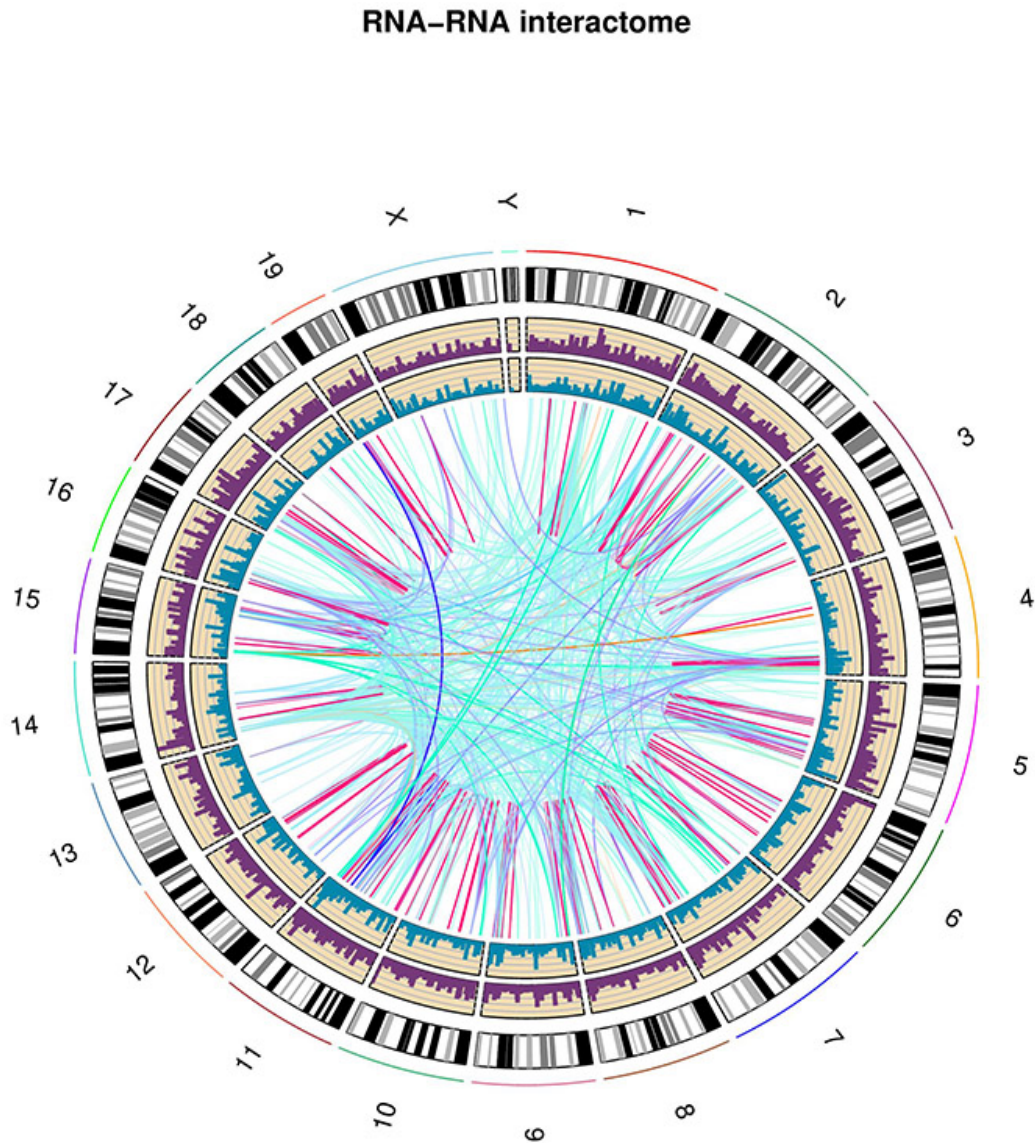
Note: part1, part2 BAM files are the ones generated from [Step5:Stitch-seq_Aligner.py](#) of the pipeline; Interaction txt file is the output of [Step6:Select_strongInteraction_pp.py](#).

5.3 Example of result graph

Example code:

```
Rscript Plot_Circos.R GGCG_interaction_clusters.txt  
sort_Paired1_fragment_GGCG.bam sort_Paired2_fragment_GGCG.bam  
-b 100000 -o Interactome_GGCG.pdf
```

Result figure:



Explanation:

VISUALIZATION OF INTERACTION TYPES ENRICHMENT

6.1 Prerequisite

Required R packages (our program will check for the presence of these packages and install/load them automatically if not present):

- “argparse”, “ggplot2”, “scales”

6.2 Run the program to generate visualization for enrichment of different types of interactions

We will use the script “Interaction_type_enrichment.R” for this purpose.

```
usage: ../../bin/Interaction_type_enrichment.R [-h] [-n NUM [NUM ...]]
                                              [-o OUTPUT]
                                              interaction

plot the statistical significance for enrichment of different interaction
types

positional arguments:
  interaction          the strong interaction file, [required]

optional arguments:
  -h, --help            show this help message and exit
  -n NUM [NUM ...], --num NUM [NUM ...]
                        Column numbers for the type name in two part, [default:
                        [4, 11]]
  -o OUTPUT, --output OUTPUT
                        output pdf figure file, [default:
                        interaction_type.pdf]
```

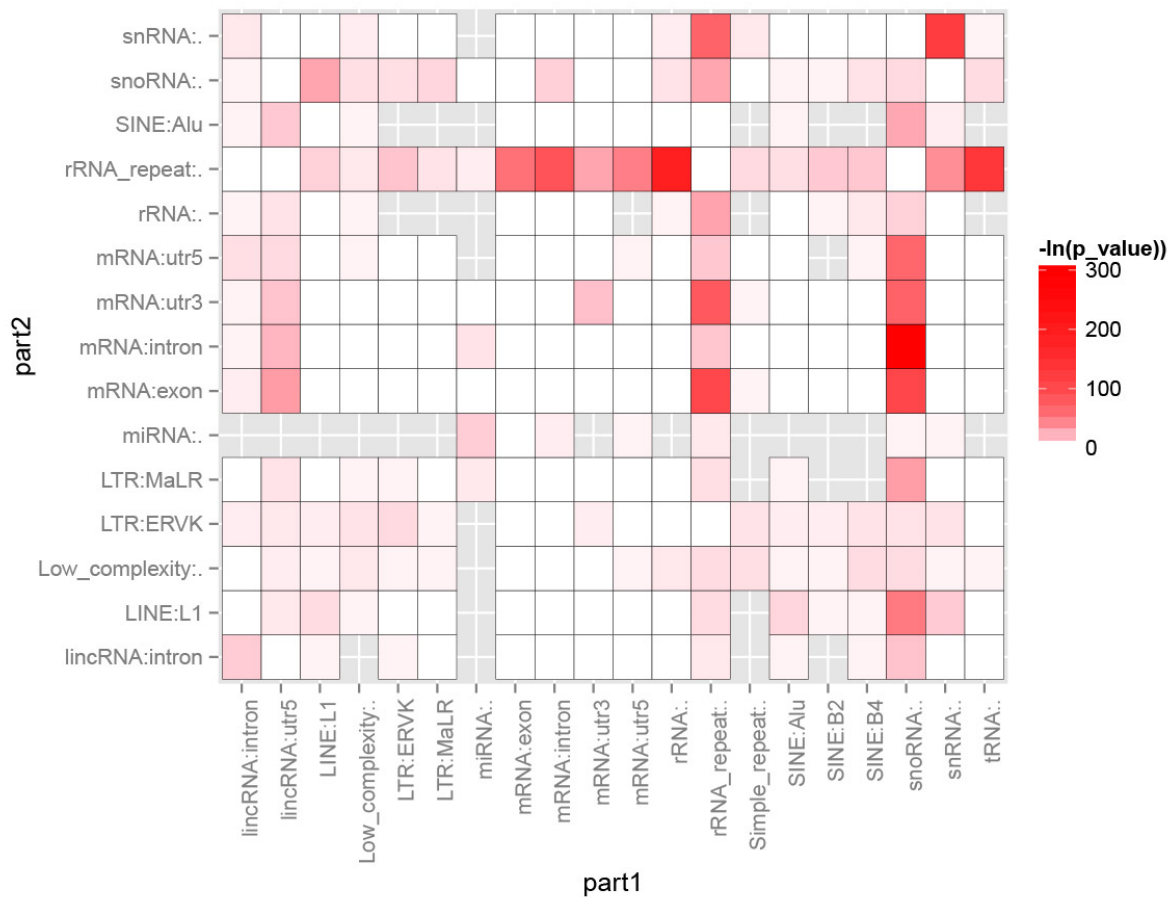
Note: Interaction txt file is the output of *Step6:Select_strongInteraction_pp.py*.

6.3 Example of result graph

Example code:

```
Rscript Plot_Circos.R ACCT_interaction_clusters.txt
-n 4 11 -o ACCT_interaction_type.pdf
```

Result figure:



Explanation:

For each interaction types (Type1_in_Part1<->Type2_in_Part2), we calculated the number of Type1 in Part1 from all interactions $n1$ and number of Type2 in Part2 from all interactions $n2$. Then we calculate the number of interactions with this type: Type1_in_Part1<->Type2_in_Part2 $n12$. The p-value for each interaction type is calculated based on the hypergeometric distribution with R command: `phyper(n12, n1, total_n - n1, n2, lower.tail=F)`. Here `total_n` is the total number of strong interactions. The color for each cell (each interaction type) are coded based on the value of “ $-\ln(p\text{-value})$ ”.

PYTHON APIS CREATED FOR THIS PROJECT

7.1 Annotation module

For the purpose of annotating RNA types for genomic regions.

`Annotation.overlap (bed1, bed2)`

This function compares overlap of two Bed object from same chromosome

Parameters

- **bed1** – A Bed object from `xplib.Annotation.Bed` (BAM2X)
- **bed2** – A Bed object from `xplib.Annotation.Bed` (BAM2X)

Returns boolean – True or False

Example:

```
>>> from xplib.Annotation import Bed
>>> from Annotation import overlap
>>> bed1=Bed(["chr1", 10000, 12000])
>>> bed2=Bed(["chr1", 9000, 13000])
>>> print overlap (bed1, bed2)
True
```

`Annotation.Subtype (bed1, genebed)`

This function determines intron or exon or utr from a BED12 file.

Parameters

- **bed1** – A Bed object defined by `xplib.Annotation.Bed` (BAM2X)
- **genebed** – A Bed12 object representing a transcript defined by `xplib Annotation.Bed` with information of exon/intron/utr from an BED12 file

Returns str – RNA subtype. “intron”/”exon”/”utr3”/”utr5”/”.”

Example:

```
>>> from xplib.Annotation import Bed
>>> from xplib import DBI
>>> from Annotation import Subtype
>>> bed1=Bed(["chr13", 40975747, 40975770])
>>> a=DBI.init("../Data/Ensembl_mm9.genebed.gz", "bed")
>>> genebed=a.query (bed1).next ()
>>> print Subtype (bed1, genebed)
"intron"
```

`Annotation.annotation (bed, ref_allRNA, ref_detail, ref_repeat)`

This function is based on `overlap()` and `Subtype()` functions to annotate RNA type/name/subtype for any genomic region.

Parameters

- **bed** – A Bed object defined by `xplib.Annotation.Bed` (in BAM2X).
- **ref_allRNA** – the `DBI.init` object (from BAM2X) for bed6 file of all kinds of RNA
- **ref_detail** – the `DBI.init` object for bed12 file of lincRNA and mRNA with intron, exon, UTR
- **ref_repeat** – the `DBI.init` object for bed6 file of mouse repeat

Returns list of str – [type,name,subtype]

Example:

```
>>> from xplib.Annotation import Bed
>>> from xplib import DBI
>>> from Annotation import annotation
>>> bed=Bed(["chr13",40975747,40975770])
>>> ref_allRNA=DBI.init("../Data/all_RNAs-rRNA_repeat.txt.gz","bed")
>>> ref_detail=DBI.init("../Data/Ensembl_mm9.genebed.gz","bed")
>>> ref_repeat=DBI.init("../Data/mouse.repeat.txt.gz","bed")
>>> print annotation(bed,ref_allRNA,ref_detail,ref_repeat)
["protein_coding","gcnt2","intron"]
```

7.2 “annotated_bed” data class

class `data_structure.annotated_bed (x=None, **kwargs)`

To store, compare, cluster for the genomic regions with RNA annotation information. Utilized in the program *Select_stronginteraction_pp.py*

Cluster (c)

Store cluster information of self object

Parameters c – cluster index

Example:

```
>>> a=annotated_bed(chr="chr13",start=40975747,end=40975770)
>>> a.Cluster(3)
>>> print a.cluster
3
```

Note: `a.cluster` will be the count information when `a` become a cluster object in *Select_stronginteraction_pp.py*

Update (S, E)

Update the upper and lower bound of the cluster after adding segments using Union-Find.

Parameters

- **S** – start loc of the newly added genomic segment
- **E** – end loc of the newly added genomic segment

Example:


```
>>> a=annotated_bed(chr="chr13", start=40975747, end=40975770)
>>> a.Update(40975700, 40975800)
>>> print a.start, a.end
40975700 40975800
```

__init__ (*x=None, **kwargs*)

Initiation example:

```
>>> str="chr13 40975747 40975770 + ATTAAG...TGA protein_coding gcnt2"
>>> a=annotated_bed(str)
or
>>> a=annotated_bed(chr="chr13", start=40975747, end=40975770, strand='+', type="protein_coding")
```

__lt__ (*other*)

Compare two objects self and other when they are not overlapped

Parameters *other* – another annotated_bed object

Returns boolean – “None” if overlapped.

Example:

```
>>> a=annotated_bed(chr="chr13", start=40975747, end=40975770)
>>> b=annotated_bed(chr="chr13", start=10003212, end=10005400)
>>> print a>b
False
```

__str__ ()

Use print function to output the cluster information (chr, start, end, type, name, subtype, cluster)

Example:

```
>>> str="chr13 40975747 40975770 + ATTAAG...TGA protein_coding gcnt2"
>>> a=annotated_bed(str)
>>> a.Cluster(3)
>>> a.Update(40975700, 40975800)
>>> print a
"chr13 40975700 40975800 protein_coding gcnt2 intron 3"
```

overlap (*other*)

Find overlap between regions

Parameters *other* – another annotated_bed object

Returns boolean

7.3 “RNAstructure” class

class RNAstructure.**RNAstructure** (*exe_path=None*)

Interface class for RNAstructure executable programs.

DuplexFold (*seq1=None, seq2=None, dna=False*)

Use “DuplexFold” program to calculate the minimum folding between two input sequences

Parameters

- **seq1, seq2** – two DNA/RNA sequences as string, or existing fasta file name
- **dna** – boolean input. Specify then DNA parameters are to be used

Returns minimum binding energy, (unit: kCal/Mol)

Example:

```
>>> from RNAstructure import RNAstructure
>>> RNA_prog = RNAstructure(exe_path="/home/yu68/Software/RNAstructure/exe/")
>>> seq1 = "TAGACTGATCAGTAAGTCGGTA"
>>> seq2 = "GACTAGCTTAGGTAGGATAGTCAGTA"
>>> energy=RNA_prog.DuplexFold(seq1,seq2)
>>> print energy
```

Fold (seq=None, ct_name=None, sso_file=None, Num=1)

Use “Fold” program to predict the secondary structure and output dot format.

Parameters

- **seq** – one DNA/RNA sequence as string, or existing fasta file name
- **ct_name** – specify to output a ct file with this name, otherwise store in temp, default: None
- **sso_file** – give a single strand offset file, format see http://rna.urmc.rochester.edu/Text/File_Formats.html#Offset
- **Num** – choose Num th predicted structure

Returns dot format of RNA secondary structure and RNA sequence.

Example:

```
>>> from RNAstructure import RNAstructure
>>> RNA_prog = RNAstructure(exe_path="/home/yu68/Software/RNAstructure/exe/")
>>> seq = "AUAUAAUUAAAAAUGCAACUACAAGUCCGUGUUUCUGACUGUUAGUUAUUGAGUUUUU"
>>> sequence,dot=RNA_prog.Fold(seq)
>>> assert (seq==sequence)
```

__init__ (exe_path=None)

Initiation of object

Parameters **exe_path** – the folder path of the RNAstructure executables

Example:

```
>>> from RNAstructure import RNAstructure
>>> RNA_prog = RNAstructure(exe_path="/home/yu68/Software/RNAstructure/exe/")
```

scorer (ct_name1, ct_name2)

Use ‘scorer’ pogram to compare a predicted secondary structure to an accepted structure. It calculates two quality metrics, sensitivity and PPV

Parameters

- **ct_name1** – The name of a CT file containing predicted structure data.
- **ct_name2** – The name of a CT file containing accepted structure data, can only store one structure.

Returns sensitivity, PPV, number of the best predicted structure.

Example:

```
>>> ct_name1 = "temp_prediction.ct"
>>> ct_name2 = "temp_accept.ct"
>>> from RNAstructure import RNAstructure
>>> RNA_prog = RNAstructure(exe_path="/home/yu68/Software/RNAstructure/exe/")
>>> sensitivity, PPV, Number = RNA_prog.scorer(ct_name1,ct_name2)
```

RESOURCES OF STRONG INTERACTIONS FROM TWO MOUSE CELL TYPES

8.1 Description of different samples

8.1.1 E14_WP_1

Cell line ESC E14

Barcode ACCT

Experimental Details Actively growing E14 cells were UV irradiated (254 nm) at 200mJ/cm to crosslink proteins to interacting RNAs. After cell lysis, we trim down RNAs into 1000-2000 nt using RNase I and remove DNA by TURBO DNase. To recover RNAs bound to RNA-binding proteins, we biotin-labeled them with EZ-Link Iodoacetyl-PEG2-Biotin from Pierce. RNA-protein complexes were next immobilized on Streptavidin-coated beads. The beads are then saturated with free biotin, preventing it from interfering with following ligation with biotin-tagged linker. A biotin-tagged RNA linker was ligated to the 5'-end of immobilized RNAs. Proximity ligation was then carried out under diluted conditions while the RNA-protein complexes are still bound on bead. After RNA purification by Proteinase K and phenol-chloroform extraction, we specifically removed the unligated biotin by first anneal a complementary DNA oligo to the biotin-tagged linker by using the annealing protocol: 70oC for 5 min, 25oC for 20 min, T7 Exo for 30 min. Exonuclease T7 was added to remove terminal unligated biotin at the double-stranded RNAlinker-DNAoligo hybrid. T7 Exonuclease acts in the 5' to 3' direction, catalyzing the removal of 5' mononucleotides from duplex DNA and RNA/DNA hybrids in the 5' to 3' direction. The resulted RNAs were fragmented again into ~200 nt using RNase III RNA Fragmentation Module from NEB (1ul of RNase III in 6 min at 37C). The RNAs were purified by column and ligated with sequencing adapter, then reverse-transcribed and PCR for library construction. We applied an rRNA removal step after constructing cDNA by using an rRNA removal protocol based on the Duplex-Specific thermostable nuclease (DSN) enzyme using the protocol recommended by [Illumina](#). The constructed cDNAs were quality-checked by Bioanalyzer. The cDNAs were next subjected paired-end sequencing on HiSeq-2500 platform.

Linker *mL5*: 5' - rCrUrA rG/iBiodT/rA rGrCrC rCrArU rGrCrA rArUrG rCrGrA rGrGrA - 3'

8.1.2 E14_WP_2

Cell line ESC E14

Barcode GGCG

Experimental Details Same as E14_WP_1 but this time rRNA removal was performed right after Proteinase K and phenol-chloroform treatment using the GeneRead rRNA Depletion Kit by Qiagen.

Furthermore, the annealing of RNA linker and complementary DNA oligo was changed into: denature for 90 s at 90°C, and then anneal at -0.1°C/s to 25 °C and then incubate for 25 min at 25 °C. Since after rRNA depletion the amount of RNA remained was less than that obtained from E14 #1, we reduced the duration of RNA fragmentation by RNase III from 6 min to 3 min. However, this reduction in RNase III treatment led to large fragments than desirable.

Linker *mL5*: 5' - rCrUrA rG/iBiodT/rA rGrCrC rCrArU rGrCrA rArUrG rCrGrA rGrGrA - 3'

8.1.3 E14_WP_3

Cell line ESC E14

Barcode AATG

Experimental Details To detect interactions between RNAs that are not bound to the same protein but to interacting proteins, we used formaldehyde in conjunction with a second crosslinker, EGS. The combination of formaldehyde and EGS crosslinks both RNA-protein and protein-protein interactions thereby maximize the detection of RNA-RNA interactions that are facilitated by interacting proteins. Actively grown E14 cells was crosslinked with 1.5 mM of freshly prepared EthylGlycol bis(SuccinimidylSuccinate) (EGS)) for 45 minutes at room temperature and then 1% of formaldehyde for 10 minutes also at room temperature. Since crosslinking by formaldehyde makes the cells very rigid and less amenable to be broken down lysis buffer. Therefore, we utilized sonication to fragment the protein-bound RNA into ~1000 nt size range. The remaining steps were performed similarly to E14_WP_2.

Another main difference between this sample and other samples is that we didn't remove the nuclei, thus effectively including RNA-RNA interactions inside the nucleus into the sample. In other samples, only the cytoplasm was enriched.

Linker *mL5*: 5' - rCrUrA rG/iBiodT/rA rGrCrC rCrArU rGrCrA rArUrG rCrGrA rGrGrA - 3'

8.1.4 MEF_WP_1

Cell line MEF

Barcode GGCG

Experimental Details We irradiated actively grown 1E8 MEF cells (254 nm). This time, the RNAs were fragmented into 300nt size range. RNase III fragmentation was also modified accordingly to adjust for smaller amount of RNAs: instead of adding 1ul of RNase III, we added only 0.5uL of RNase III and then incubated at 37C for 5 min. The subsequent steps were performed using the same procedure as E14_WP_2.

Linker *mL5*: 5' - rCrUrA rG/iBiodT/rA rGrCrC rCrArU rGrCrA rArUrG rCrGrA rGrGrA - 3'

8.2 Resources of Strong Interactions

8.2.1 From merged data of E14_WP_1 and E14_WP_2:

Genome mm9

Explanation

- First seven column is for information of cluster in Part1 of interaction (5'side of linker); second seven column is for information of cluster in Part2 of interaction (3'side of linker)

- *Type*: RNA types or repeat types; *Name*: RNA or repeat names; *Subtype*: intron/utr3/utr5/exon for mRNA, intron/utr for lincRNA or repeat family; *Count*: number of supported reads in that cluster
- Second last column is the number of mapped pairs that support this interaction.
- Last column is the “ln(p_value)” for the significance of interaction. P_value is based on a hypergeometric test

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8.2.2 From E14_WP_3 dual crosslinking:

Genome mm9

Explanation

- First seven column is for information of cluster in Part1 of interaction (5’ side of linker); second seven column is for information of cluster in Part2 of interaction (3’ side of linker)
- *Type*: RNA types or repeat types; *Name*: RNA or repeat names; *Subtype*: intron/utr3/utr5/exon for mRNA, intron/utr for lincRNA or repeat family; *Count*: number of supported reads in that cluster
- Second last column is the number of mapped pairs that support this interaction.
- Last column is the “ln(p_value)” for the significance of interaction. P_value is based on a hypergeometric test

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8.2.3 From MEF_WP_1 sample:

Genome mm9

Explanation

- First seven column is for information of cluster in Part1 of interaction (5’ side of linker); second seven column is for information of cluster in Part2 of interaction (3’ side of linker)
- *Type*: RNA types or repeat types; *Name*: RNA or repeat names; *Subtype*: intron/utr3/utr5/exon for mRNA, intron/utr for lincRNA or repeat family; *Count*: number of supported reads in that cluster
- Second last column is the number of mapped pairs that support this interaction.
- Last column is the “ln(p_value)” for the significance of interaction. P_value is based on a hypergeometric test

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8.2.4 Number of different types of interactions:

Link to file

- For each cell type, there are two columns,
- The first column gives the number of strong interactions with this interaction type,
- the second column gives the number of mapped pairs that support this interaction type.

Note: RNA Hi-C tools benefits a lot from BAM2X, a convenient python interface for most common NGS datatypes. Try [BAM2X](#) now!

UPDATES

2014-5-15:

- Add result *resources* for identified strong interactions in mouse E14 cells and MEF cells.
- New function to generate heatmap for intra-RNA interactions: *Plot_interaction_heatmap.py*.

2014-05-14:

- Add new function to find overlap between two interaction sets based on their RNA annotations, see: *intersectInteraction_genePair.R*.
- Allow input of two genomic regions to visualize local interactions using `-r` option in “*Plot_interaction.py*” function

2014-05-11:

- Add new function to show enrichment of different types of interactions: *Interaction_type_enrichment.R*.

Version 0.3.2 (2014-05-07):

- change the name into RNA-Hi-C

2014-05-06:

- In “*Select_strongInteraction_pp.py*” function, now annotations are updated after doing clustering and for strong interaction. The indexing of annotation files may take some time.
- New “*RNA_structure_prediction.py*” function to refine RNA structure prediction based on empirical offset of free energies for single strand nucleotide.

New features in 0.3.1 (2014-05-02):

- Add “`-release`” option in “*split_partner.py*” function. Allow a Type3 read-pair considered to be a “Paired” chimeric fragment even linker does not show up.
- Fix bugs in “*Select_strongInteraction_pp.py*” function when the number of mapped pairs is low and some chromosomes don’t have any mapped read in part1 or part2.
- Add bowtie 2 option and Unique-align option in “*Stitch-seq_Aligner.py*” function.
- Different colors for different types of interactions in the *visualization of interactome*.
- New API for folding energies of two RNA molecules, see “*RNAstructure*”.
- Allow permutation-based strategies to calculate the p-value for the overlap between two independent interaction sets in “*intersectInteraction.py*” function

New features in 0.2.2:

- “*Plot_interaction.py*” function to plot local RNA-RNA interactions.
- “*intersectInteraction.py*” function to call overlap between two independent interaction sets.

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