

# SEQLinkage Documentation [Version 1.0 alpha]

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# Contents

<b>1</b>	<b>SEQLinkage Reference Manual</b>	<b>2</b>
1.1	Introduction . . . . .	2
1.2	SEQLinkage Program Command Options . . . . .	2
1.2.1	Input files . . . . .	3
1.2.1.1	--vcf [required] . . . . .	3
1.2.1.2	--fam [required] . . . . .	4
1.2.1.3	--blueprint [default to RefSeq genes] . . . . .	4
1.2.2	Additional input options . . . . .	5
1.2.2.1	--freq [default to sample MAF calculated from founders in data] . . . . .	5
1.2.2.2	--maf-cutoff [default to 1.0] . . . . .	5
1.2.2.3	--chrom-prefix [default to empty] . . . . .	5
1.2.3	Collapsed haplotype pattern method coding options . . . . .	5
1.2.3.1	--bin [default to $R^2 > 0.8$ ] . . . . .	5
1.2.3.2	--single-markers [default to disabled] . . . . .	6
1.2.4	Linkage analysis options . . . . .	6
1.2.4.1	--prevalence [required] . . . . .	6
1.2.4.2	--moi [required] . . . . .	6
1.2.4.3	--wt-pen [required] / --mut-pen [required] . . . . .	6
1.2.4.4	--theta-max [default to 0.5] . . . . .	6
1.2.4.5	--theta-inc [default to 0.05] . . . . .	6
1.2.4.6	--run-linkage [default to disabled] . . . . .	6

1.2.4.7	--output-entries [default to 10]	7
1.2.5	Format conversion options	7
1.2.5.1	--format [default to LINKAGE]	7
1.2.5.2	--output [default to LINKAGE]	7
1.2.6	Runtime arguments	7
1.2.6.1	--jobs [default to 2]	7
1.2.6.2	--tempdir [default to system temporary folder]	7
1.2.6.3	--cache [default to disabled]	8
1.2.6.4	--quiet [default to disabled]	8
1.3	Linkage Analysis Results	8
1.3.1	Tables of LOD and HLOD scores	8
1.3.2	Heatmaps of LOD and HLOD scores	9
<b>2</b>	<b>Data Analysis Using SEQLinkage</b>	<b>10</b>
2.1	Introduction	10
2.2	Regional Markers from Sequence Data	11
2.2.1	Understanding terminal output and regional marker data	11
2.2.1.1	Terminal output	11
2.2.1.2	Regional marker data	12
2.2.2	Collapsing themes	12
2.2.2.1	LD based collapsing	12
2.2.2.2	Complete collapsing	13
2.2.2.3	No collapsing	13
2.2.2.4	Comparison between different themes	13
2.2.3	Population vs. founder allele frequencies	14
2.2.4	Recombination events	14
2.3	Two-point Linkage Analysis	14
2.3.1	Regional marker linkage analysis	15
2.3.2	Single variant marker linkage analysis	15
2.3.3	Accessing archived analysis results	16

2.4	SEQLinkage with Other Linkage Programs . . . . .	16
2.4.1	Output regional marker data to Mega2 format . . . . .	17
2.5	Prepare Customized “Blueprint” of Regional Markers . . . . .	17

# SEQLinkage Reference Manual

## 1.1 Introduction

This program implements a *collapsed haplotype pattern* (CHP) method to generate markers from sequence data for linkage analysis. The core concept is that instead of treating each variant as a separate marker, we create regional markers for variants in specified genetic regions (e.g. genes) based on haplotype patterns within families, and perform linkage analysis on markers thus generated. CHP method outperforms traditional single marker based approach for compound heterozygosity and allelic heterogeneity in genes. We recommend the use of CHP in conjunction with filtering based variant prioritization method in the analyses of sequence data of human pedigrees.

For details of the method and evaluation of performance using simulated data, please refer to our paper: ...

*Web resource:* please visit <http://bioinformatics.org/seqlink> for more information including download & installation instructions, software updates and supports from SEQLinkage user forum.

## 1.2 SEQLinkage Program Command Options

To display the command interface

```
seqlink -h
```

SEQLinkage interface

```
usage: seqlink [--bin FLOAT] [-b FILE] [--single-markers] --fam FILE --vcf
FILE [--freq INFO] [-c P] [--chrom-prefix STRING] [-o Name]
[-f FORMAT [FORMAT ...]] [-K FLOAT] [--moi STRING] [-W FLOAT]
[-M FLOAT] [--theta-max FLOAT] [--theta-inc FLOAT]
[--run-linkage] [--output-entries N] [-h] [-j N]
[--tempdir PATH] [--cache]
SEQLinkage, linkage analysis using sequence data
```

```

[1.0.alpha]
Collapsed haplotype pattern method arguments:
--bin FLOAT          Defines theme to collapse variants. Set to 0 for
                    "complete collapsing", 1 for "no collapsing", r2 value
                    between 0 and 1 for "LD based collapsing" and other
                    integer values for customized collapsing bin sizes.
                    Default to 0.8 (variants having r2 >= 0.8 will be
                    collapsed).
-b FILE, --blueprint FILE
                    Blueprint file that defines regional marker (format:
                    "chr startpos endpos name avg.distance male.distance
                    female.distance").
--single-markers      Use single variant markers. This switch will overwrite
                    "--bin" and "--blueprint" arguments.

Input / output options:
--fam FILE            Input pedigree and phenotype information in FAM
                    format.
--vcf FILE            Input VCF file, bgzipped.
--freq INFO           Info field name for allele frequency in VCF file.
-c P, --maf-cutoff P  MAF cutoff to define "common" variants to be excluded
                    from analyses.
--chrom-prefix STRING
                    Prefix to chromosome name in VCF file if applicable,
                    e.g. "chr".
-o Name, --output Name
                    Output name prefix.
-f FORMAT [FORMAT ...], --format FORMAT [FORMAT ...]
                    Output format. Default to LINKAGE.

LINKAGE options:
-K FLOAT, --prevalence FLOAT
                    Disease prevalence.
--moi STRING          Mode of inheritance, AD/AR: autosomal
                    dominant/recessive.
-W FLOAT, --wt-pen FLOAT
                    Penetrance for wild type.
-M FLOAT, --mut-pen FLOAT
                    Penetrance for mutation.
--theta-max FLOAT     Theta upper bound. Default to 0.5.
--theta-inc FLOAT     Theta increment. Default to 0.05.
--run-linkage         Perform Linkage analysis using FASTLINK program.
--output-entries N    Write the highest N LOD/HLOD scores to output tables.
                    Default to 10.

Runtime arguments:
-h, --help            Show help message and exit.
-j N, --jobs N        Number of CPUs to use.
--tempdir PATH        Temporary directory to use.
--cache              Load cache data for analysis instead of starting
                    afresh.
-q, --quiet           Disable the display of runtime MESSAGE.

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Distributed under GNU General Public License
Home page: http://bioinformatics.org/seqlink

```

---

## 1.2.1 Input files

### ■ --vcf [required]

Input genotype data must be [bgzipped](http://samtools.sourceforge.net/tabix.shtml)<sup>1</sup> VCF file indexed by [tabix](http://samtools.sourceforge.net/tabix.shtml)<sup>2</sup>. To create such files from plain VCF file, e.g. data.vcf:

```

bgzip data.vcf
tabix -p vcf -f data.vcf.gz

```

You should end up with two files data.vcf.gz and data.vcf.gz.tbi. In SEQLinkage command

<sup>1</sup>bgzipped <http://samtools.sourceforge.net/tabix.shtml>

<sup>2</sup>tabix <http://samtools.sourceforge.net/tabix.shtml>

you can then use `--vcf data.vcf.gz` to load the genotype data.

#### ■ `--fam` [required]

This file contains information of pedigree structure, sample sex and disease status. It partially follows the [LINKAGE format](#)<sup>3</sup> convention: it has only 6 columns with each column being Family ID, Individual ID, Paternal ID, Maternal ID, Sex and Status.

#### ■ `--blueprint` [default to RefSeq genes]

A “blueprint” file can be supplied to define regional marker units. SEQLinkage has a default built-in blueprint which is suitable for WES studies when it is desired to group variants to create regional markers by genes. Customized blueprint file can be provided by users for specific studies. Even for WES studies one can provide alternative blueprint based on exome sequencing capture targets rather than genes. The file should contain 7 columns:

- Chromosome name, without leading chr character, e.g. “5” not “chr5”
- Start position of the genetic region
- End position of the genetic region
- Region name, e.g. gene names
- Average genetic map distance of the region on average
- Female genetic map distance of the region on average
- Male genetic map distance of the region on average

Genetic map distance will be useful for performing multi-point linkage analysis. Users can output regional markers from SEQLinkage to, for example, Merlin format and perform linkage analysis using Merlin. In the built-in blueprint file we use the map distance of the variant at the median position of a genetic region as a substitute for the map distance of the genetic region. Such information can be interpolated using [Rutgers Linkage-Physical Map](#)<sup>4</sup> database. If multi-point linkage analysis is not the aim of your study you can leave these columns with a placeholder symbol “.” (a dot) for missing data in the blueprint file you provide to SEQLinkage. Example lines of a blueprint file is shown below:

blueprint.txt						
...						
3	126111874	126113641	CCDC37-AS1	134.382	168.977	102.287
3	126113781	126155398	CCDC37	134.411	169.021	102.296
3	126156443	126194762	ZXDC	134.465	169.105	102.315
...						

<sup>3</sup>LINKAGE format <http://www.jurgott.org/linkage/LinkagePC.html>

<sup>4</sup>Rutgers Linkage-Physical Map <http://compgen.rutgers.edu/maps>

## 1.2.2 Additional input options

### ■ `--freq` [default to sample MAF calculated from founders in data]

Linkage analysis requires input of allele frequency for markers to control for type I error in the presence of missing genotypes. The INFO field name for population (minor) allele frequencies of variants in VCF file. For well defined populations we recommend using MAF for variants from publicly available data bases such as [Exome Variant Server](#) <sup>5</sup> or [1000 Genomes](#) <sup>6</sup>. For variants not presented in these data bases it is safe to assign a very small proportion, e.g. 0.00015 which is roughly the MAF for a singleton variant in 3000 samples ( $\frac{1}{3000 \times 2} = 0.000167$ ). You may use other bioinformatics tools such as [variant tools](#) <sup>7</sup> to obtain and update such information to your VCF file. If this option is left unset, MAF estimated from founders in the sample will be used for linkage analysis.

### ■ `--maf-cutoff` [default to 1.0]

When specified, variants having MAF (defined by `--freq` option) greater than this value will be excluded from analyses.

### ■ `--chrom-prefix` [default to empty]

This option specifies the prefix to chromosome names in VCF file. For example for VCF files having chromosome names such as “1”, “5” and “X” there is no need to specify this option. For files having names such as “chr1”, “chr5” and “chrX” you need to use `--chrom-prefix chr` in SEQLinkage command.

## 1.2.3 Collapsed haplotype pattern method coding options

The CHP method has been described in the SEQLinkage paper (see “Introduction” section of this chapter). This section introduces the usage of parameters involved in implementing the CHP method.

### ■ `--bin` [default to $R^2 > 0.8$ ]

This option defines the collapsing theme of variants in a genetic region, before computing haplotype patterns. Several collapsing themes are available via this option:

- “Linkage disequilibrium (LD) based collapsing”. The bin value takes a fraction number (between 0 and 1) as the  $R^2$  cutoff to define LD blocks. Variant sites having LD greater than  $R^2$  will be collapsed to binary codes.

---

<sup>5</sup>Exome Variant Server <http://evs.gs.washington.edu/EVS/>

<sup>6</sup>1000 Genomes <http://www.1000genomes.org/>

<sup>7</sup>variant tools <http://varianttools.sourceforge.net>



- “No collapsing”. Set `--bin 1` which literally means collapsing variants by units of 1 variant site, i.e., no collapsing is applied to variants before computing haplotype patterns.
- “Complete collapsing”. Set `--bin 0` to collapse variant in the entire region to a single binary code.
- “Arbitrary collapsing”. Set `--bin` to any arbitrary positive integer value  $N$  to collapse  $N$  variants to a single binary code.

#### ■ `--single-markers` [default to disabled]

When this switch is turned on, single variant markers will be generated from data instead of regional markers, and both `--bin` and `--blueprint` options will be ignored.

### 1.2.4 Linkage analysis options

SEQLinkage has a built-in two-point linkage analysis routine to analyze data generated via the CHP method. Below are options for configuring linkage model parameters and producing graphic / HTML format analysis reports.

#### ■ `--prevalence` [required]

Disease prevalence.

#### ■ `--moi` [required]

Mode of inheritance, choose from “AD” (autosomal dominant) and “AR” (autosomal recessive).

#### ■ `--wt-pen` [required] / `--mut-pen` [required]

Penetrance of wild type / mutation.

#### ■ `--theta-max` [default to 0.5]

Recombination rate value upper bound ( $\theta_{max}$ ) up to which the linkage analysis will evaluate.

#### ■ `--theta-inc` [default to 0.05]

Increment steps from 0 to  $\theta_{max}$ . At each step the  $\theta$  value will be used to calculate a LOD score.

#### ■ `--run-linkage` [default to disabled]

When this switch is on, two-point linkage analysis will be performed.

- `--output-entries` [default to 10]

Output to HTML file the best  $N$  markers in terms of LOD and HLOD scores respectively. When  $N = 0$ , no heatmap graph or HTML file will be generated.

### 1.2.5 Format conversion options

SEQLinkage supports output in some population linkage software format including LINKAGE, Merlin and MEGA2. Many more linkage software format can be converted from MEGA2 format using the MEGA2 software. With the format conversion feature, CHP coding of sequence data can be written to these file formats for use in various linkage analysis software.

- `--format` [default to LINKAGE]

Output format for CHP coded data.

- `--output` [default to LINKAGE]

Output file / folder name prefix.

### 1.2.6 Runtime arguments

- `--jobs` [default to 2]

Number of CPUs to use for SEQLinkage. SEQLinkage supports analyzing many markers in parallel and the more CPUs it is assigned the shorter the computational time will be.

- `--tempdir` [default to system temporary folder]

The linkage analysis routine in SEQLinkage performs analysis per marker per family, thus involving frequent file I/O operations which can be a computational bottleneck. By default such I/O operations take place in one of the system temporary folders, e.g. `/tmp`, `/var/tmp` in Linux system. To speed things up one can set the SEQLinkage temporary directory to some high speed hard drives, e.g. a solid state drive (SSD), or, if possible, a “RAM drive”. Below is an example to create a 5GB RAM drive in Linux:

```
sudo mkdir /tmp/ramdisk; sudo chmod 777 /tmp/ramdisk
sudo mount -t tmpfs -o size=5120M ramfs /tmp/ramdisk
```

With `--tempdir /tmp/ramdisk` option the newly created RAM drive will be used for the intensive file I/O in the analysis.

- **--cache [default to disabled]**

To speed up repeated runs of SEQLinkage on the same data set under similar parameter settings, data are archived to the cache folder under the work directory the first time SEQLinkage executes. With this switch on, SEQLinkage will use the archived data whenever appropriate to skip as many steps previously performed. For example in a repeated analysis under the same setting but only change `--output-entries` from 10 to 50, SEQLinkage will skip the CHP coding and linkage analysis step, only updating the result HTML table using archived analysis results.

Note that change of some input parameters will overwrite the effect of `--cache`. For example changing `--moi` will result in re-run of linkage analysis; changing `--vcf` or `--fam` input will result in re-run of CHP coding step.

- `--quiet` [default to disabled]

When this switch is on, the program will not display any log message during runtime. It will, however, display error message if an error occurs.

### 1.3 Linkage Analysis Results

SEQLinkage summarizes two-point linkage analysis results to heatmap plots and tables in HTML format, which can be viewed with a web browser program. Note that on the HTML document each section can be temporarily folded such that you can focus only on the section of interest (see the hand gesture on the heatmap screenshot below).

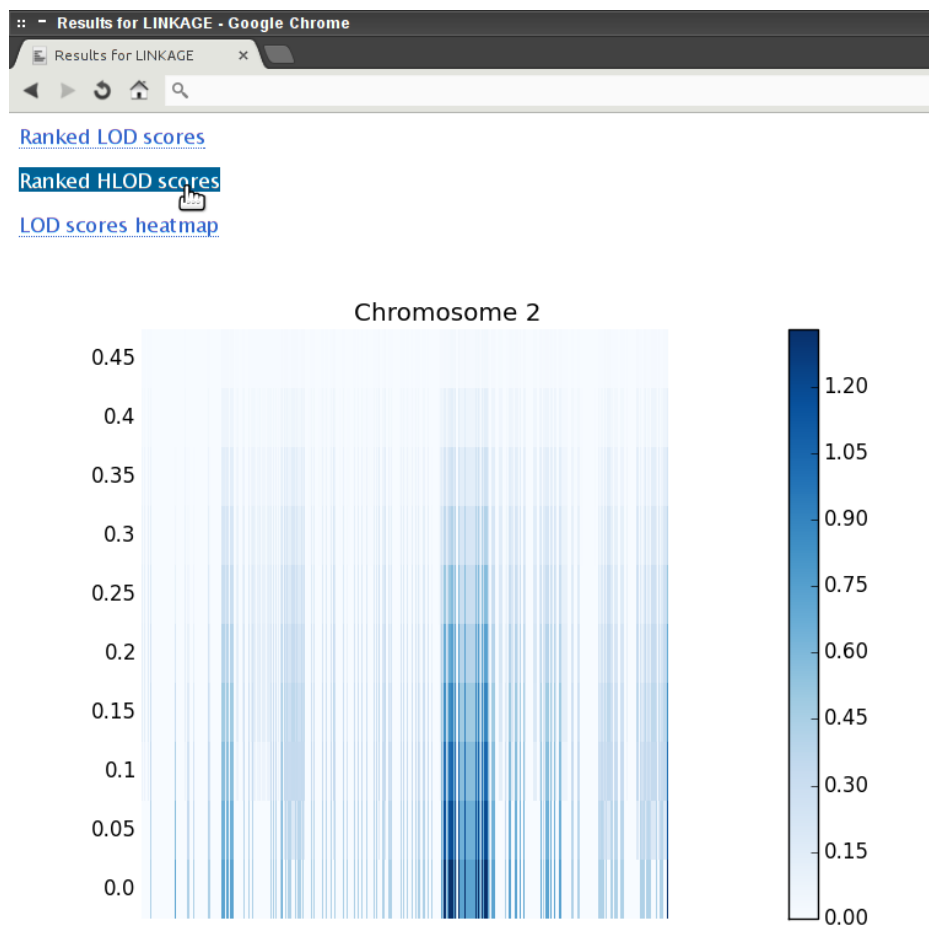
### 1.3.1 Tables of LOD and HLOD scores

[illegible]

The top ranked  $N$  LOD and HLOD scores for each  $\theta$  value evaluated are summarized in HTML table as displayed on the screenshot above (left: LOD, right: HLOD). Results are annotated

with the names and the genomic coordinates of the regional markers. For HLOD scores the corresponding  $\alpha$  values are also displayed. The length of the table  $N$  is controlled by the `--output-entries` option.

### 1.3.2 Heatmaps of LOD and HLOD scores

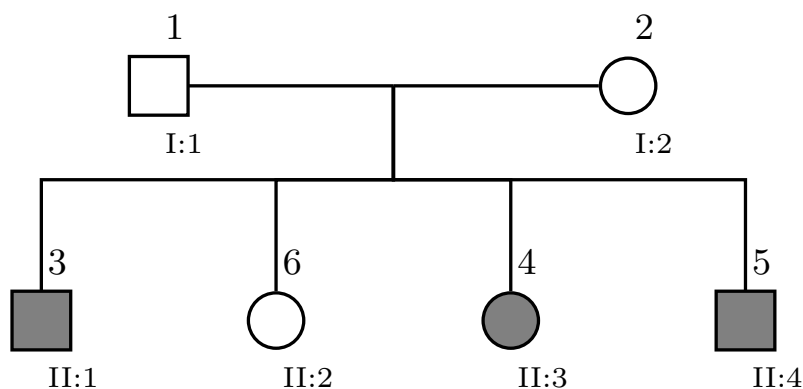


LOD and HLOD scores for all markers analyzed are displayed per chromosome as heatmaps, using a sequence of blue colors from light to dark for the score values; the darker the color the higher the score. Linkage regions of potential interest across the entire genome can be easily identified on the heatmaps. Notice that scales for per-chromosome heatmaps might differ from each other, as labeled on the right side of each heatmap.

# Data Analysis Using SEQLinkage

## 2.1 Introduction

Here we demonstrate the use of SEQLinkage to generate regional markers from sequence data and perform linkage analysis. For demonstration purpose we will use a [simulated example data set](#)<sup>1</sup> of two nuclear families of the same structure and phenotypic pattern (see pedigree illustration below) containing sequence data of 18 variants. From the phenotypic pattern it is reasonable to assume the disease follows a recessive mode of inheritance. We will first generate regional markers using CHP method with various collapsing themes, then perform two-point linkage analysis using regional markers generated. We further demonstrate the usage of SEQLinkage in conjunction with other linkage programs by formatting the regional markers into MEGA2 and Merlin input, and perform additional analysis using those software. Finally we demonstrate how to create blueprint file for customized regional marker definition.



<sup>1</sup>simulated example data set <http://bioinformatics.org/seqlink/download/seqlinkage-example.zip>

## 2.2 Regional Markers from Sequence Data

### 2.2.1 Understanding terminal output and regional marker data

Here we perform a test run of SEQLinkage to generate regional marker data without running linkage analysis. For now we (mostly) stick to default settings and focus on interpretation of terminal output and marker data generated by the program.

```
seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz -f MERLIN
```

#### ■ Terminal output

Command above generates the following output:

---

terminal info

---

```
MESSAGE: Binary trait detected in [/ramcache/seqlinkage-example.fam]
MESSAGE: Checking local resources 5/5 ...
MESSAGE: 12 samples found in [/ramcache/seqlinkage-example.vcf.gz]
MESSAGE: 2 families with a total of 12 samples will be scanned for 25,305 pre-defined units
MESSAGE: 2 units (from 18 variants) processed; 3 Mendelian inconsistencies and 2 recombination events handled
MESSAGE: 25,302 units ignored due to absence in VCF file
MESSAGE: 1 units ignored due to absence of variation in samples
MESSAGE: Archiving regional marker data to directory [/ramcache/cache]
MESSAGE: 2 units will be converted to MERLIN format
MESSAGE: 2 units successfully converted to MERLIN format
MESSAGE: Archiving MERLIN format to directory [/ramcache/cache]
MESSAGE: Saving data to [/ramcache/LINKAGE]
```

---

**Line 2** of MESSAGE checks for some resource programs & files required for the execution of SEQLinkage. These files are stored in a hidden folder `~/.SEQLinkage` on your computer. SEQLinkage will automatically download these files the first time it is executed on your computer so please make sure your computer is **connected to Internet when running SEQLinkage for the first time!** Out of the 5 resource files only one of them is relevant to the generation of regional markers: the *blueprint* file that defines genetic regions to be considered as one *marker*. This *blueprint* is based on UCSC RefSeq database. We use genomic coordinates of RefSeq genes to determine start and end positions for regional markers. The genomic coordinates are based on UCSC hg19 (or NCBI build 37) reference genome. To convert to previous builds for your data we recommend running the [UCSC liftOver tool](http://genome.ucsc.edu/cgi-bin/hgLiftOver) <sup>2</sup> to get updated *blueprint* and use the `--blueprint` option to load the file.

**Line 3** checks samples from VCF file against FAM file. For our test data samples in VCF file matches those in FAM file. SEQLinkage allows for samples in VCF file but not in FAM file, or otherwise. For such cases only samples in both files will be analyzed and a warning message will be given if samples are found in FAM but not VCF file.

---

<sup>2</sup>UCSC liftOver tool <http://genome.ucsc.edu/cgi-bin/hgLiftOver>

**Line 4** summarizes data information, mostly from FAM file, VCF header and the blueprint file. In the example one family with six members are found in both VCF and FAM input; also there are 25,305 pre-defined genetic regions in the blueprint file.

**Line 5** is dynamic: it was a progress meter during runtime, and becomes a summary of run-time statistics after the CHP algorithm is complete for all regional marker units. “2 units (from 18 variants) were processed” is based on those variants in both VCF file and covered by the blueprint definition. **You should comparing the number of variants processed with the total number of variants in the VCF file to evaluate how much data was covered by the pre-defined regional marker positions in blueprint file**, and decide whether or not a customized blueprint should be provided. SEQLinkage performs Mendelian error check on the fly, ignoring genotype calls due to Mendelian inconsistency when there is not enough information to infer them correctly. It also deals with recombination events during haplotype construction and CHP coding process, and for those regions with recombination events the regional markers are divided into sub-units. This will be discussed in details later.

**Lines 6-7** provide additional information on variants and units ignored in the analysis. Note that values on lines 6 and 7 plus the number of units processed on line 5 equals the total number of pre-defined units in the blueprint (line 4).

The last line of MESSAGE displays the path of output data, which in our case is in Merlin format. We will examine next the content of the output.

## ■ Regional marker data

[FIXME: write this part after the Merlin format is ready ... marker name is gene name. allele numbering based on per family per unit]

### 2.2.2 Collapsing themes

## ■ LD based collapsing

The default collapsing theme is LD based with the  $R^2 > 0.8$  rule; variants within LD blocks thus defined will be collapsed to binary codes before haplotype patterns are computed. You may set `--bin` to other values  $R^2 \in (0, 1)$  for different LD block definitions. The output result will be written to MERLIN format (via the `--format MERLIN` argument) for use later.

```
seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz --format MERLIN --output RMBPt8 --jobs 8
```

terminal info

```
MESSAGE: Binary trait detected in [/ramcache/seqlinkage-example.fam]
MESSAGE: Checking local resources 5/5 ...
MESSAGE: 12 samples found in [/ramcache/seqlinkage-example.vcf.gz]
MESSAGE: 2 families with a total of 12 samples will be scanned for 25,305 pre-defined units
MESSAGE: 2 units (from 18 variants) processed; 3 Mendelian inconsistencies and 2 recombination events handled
MESSAGE: 25,302 units ignored due to absence in VCF file
MESSAGE: 1 units ignored due to absence of variation in samples
```

```
MESSAGE: Archiving regional marker data to directory [/ramcache/cache]
MESSAGE: 2 units will be converted to MERLIN format
MESSAGE: 2 units successfully converted to MERLIN format
MESSAGE: Archiving MERLIN format to directory [/ramcache/cache]
MESSAGE: Saving data to [/ramcache/RMBPt8]
```

---

## ■ Complete collapsing

Setting `--bin 0` will collapse all variants in the region to generate one marker per region. Haplotype patterns are thus simply either “1” for all wild type or “2” for any mutation in the region.

```
seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz --format MERLIN --output RMB0 --jobs 8 --bin 0
```

---

terminal info

---

```
MESSAGE: Binary trait detected in [/ramcache/seqlinkage-example.fam]
MESSAGE: Checking local resources 5/5 ...
MESSAGE: 12 samples found in [/ramcache/seqlinkage-example.vcf.gz]
MESSAGE: 2 families with a total of 12 samples will be scanned for 25,305 pre-defined units
MESSAGE: 2 units (from 18 variants) processed; 3 Mendelian inconsistencies and 2 recombination events handled
MESSAGE: 25,302 units ignored due to absence in VCF file
MESSAGE: 1 units ignored due to absence of variation in samples
MESSAGE: Archiving regional marker data to directory [/ramcache/cache]
MESSAGE: 2 units will be converted to MERLIN format
MESSAGE: 2 units successfully converted to MERLIN format
MESSAGE: Archiving MERLIN format to directory [/ramcache/cache]
MESSAGE: Saving data to [/ramcache/RMB0]
```

---

## ■ No collapsing

Setting `--bin 1` will compute the haplotype pattern for the region as is, without collapsing.

```
seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz --format MERLIN --output RMB1 --jobs 8 --bin 1
```

---

terminal info

---

```
MESSAGE: Binary trait detected in [/ramcache/seqlinkage-example.fam]
MESSAGE: Checking local resources 5/5 ...
MESSAGE: 12 samples found in [/ramcache/seqlinkage-example.vcf.gz]
MESSAGE: 2 families with a total of 12 samples will be scanned for 25,305 pre-defined units
MESSAGE: 2 units (from 18 variants) processed; 3 Mendelian inconsistencies and 2 recombination events handled
MESSAGE: 25,302 units ignored due to absence in VCF file
MESSAGE: 1 units ignored due to absence of variation in samples
MESSAGE: Archiving regional marker data to directory [/ramcache/cache]
MESSAGE: 2 units will be converted to MERLIN format
MESSAGE: 2 units successfully converted to MERLIN format
MESSAGE: Archiving MERLIN format to directory [/ramcache/cache]
MESSAGE: Saving data to [/ramcache/RMB1]
```

---

## ■ Comparison between different themes

[FIXME: visualize the output after MERLIN format is done]



### 2.2.3 Population vs. founder allele frequencies

In the examples above we left `--freq` option unspecified, thus MAF from founders in samples are used to compute the regional marker frequencies. To demonstrate the use of external MAF reference we annotated the example VCF file with allele frequency for European Americans in Exome Variant Server (EVS), assuming the simulated variant data is from European American samples. We incorporated the information to the VCF file INFO field EVSEAAF as long as the variant is found in EVS; for variants not found in EVS we set EVSEAAF=0.00015. Command below show the use of the EVSEAAF frequency INFO field:

```
seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz --freq EVSEAAF --format MERLIN --jobs 8
```

Result comparison:

---

OUTPUT

---

FIXME: write this after Merlin format is done

---

### 2.2.4 Recombination events

For regional markers sub-divided into smaller units by recombination events, we use [1], [2], ..., [i] convention to label different units (see below). They can be treated different regional markers. In the linkage analysis pipeline incorporated in SEQLinkage, we choose the one sub-unit that gives strongest evidence of linkage to represent the entire region under consideration when computing combined LOD scores and HLOD scores for all samples.

---

OUTPUT

---

FIXME: write this after Merlin format is done

---

## 2.3 Two-point Linkage Analysis

SEQLinkage incorporates [FASTLINK](http://www.ncbi.nlm.nih.gov/CBBresearch/Schaffer/fastlink.html)<sup>3</sup> routine to perform two-point linkage analysis. It is difficult to handle the original FASTLINK routine to analyze data for our purpose, due to the nature of both the FASTLINK software and the way SEQLinkage generates markers. The FASTLINK routine involves running 4 standalone programs sequentially, some of which are “interactive mode” only (i.e. users will have to follow a series of “questions” from the program, entering input parameters only when prompted). The coding and allele frequencies of regional markers are unique to each family; as a result only one marker from one family can be processed with each FASTLINK analysis, which means numerous input files are required. To ease such efforts, SEQLinkage automatically generates markers from VCF file input, executes the FASTLINK analysis workflow hiding under the hook issues discussed above, and generates user friendly

<sup>3</sup>FASTLINK <http://www.ncbi.nlm.nih.gov/CBBresearch/Schaffer/fastlink.html>

table and graphical summaries to present analysis results. This document only focus on the SEQLinkage command interface and output results. The FASTLINK website offers a number of documentations explaining details involved in linkage analysis, to which users should resort for questions regarding choice of parameters, analysis algorithms and interpretation of LOD scores from linkage analysis.

In addition to reporting LOD scores computed by FASTLINK, for analysis involving multiple families SEQLinkage computes HLOD scores based on methods described in [Terwilliger and Ott \(1994\)](#) <sup>4</sup>, but instead of using grid search method we applied numerical optimizations to find the  $\alpha$  value that maximize the HLOD score.

### 2.3.1 Regional marker linkage analysis

We use default CHP parameters to generate regional markers and perform linkage analysis with command below:

```
seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz --freq EVSEAAF -o LinkageAnalysis \
-K 0.001 --moi AR -W 0 -M 1 --theta-max 0.5 --theta-inc 0.05 -j 8 --run-linkage
```

Parameters `-K/--moi/-W/-M` are important user input that defines the parametric model for linkage analysis. Here we assume a prevalence of  $\frac{1}{1000}$ , autosomal recessive disease with complete penetrance. In practice users should carefully set these parameters for specific studies. The terminal output is as follows:

---

regional marker linkage

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```
MESSAGE: Binary trait detected in [/ramcache/seqlinkage-example.fam]
MESSAGE: Checking local resources 5/5 ...
MESSAGE: 12 samples found in [/ramcache/seqlinkage-example.vcf.gz]
MESSAGE: 2 families with a total of 12 samples will be scanned for 25,305 pre-defined units
MESSAGE: 2 units (from 18 variants) processed; 3 Mendelian inconsistencies and 2 recombination events handled
MESSAGE: 25,302 units ignored due to absence in VCF file
MESSAGE: 1 units ignored due to absence of variation in samples
MESSAGE: Archiving regional marker data to directory [/ramcache/cache]
MESSAGE: 2 units will be converted to LINKAGE format
MESSAGE: 2 units successfully converted to LINKAGE format
MESSAGE: Archiving LINKAGE format to directory [/ramcache/cache]
MESSAGE: Linkage analysis succesfully performed for 2 units
MESSAGE: Reports in html format generated
```

---

Results are written to file `LinkageAnalysis/LinkageAnalysis.Report.html`.

### 2.3.2 Single variant marker linkage analysis

It is also possible to apply linkage analysis directly on the original sequence data, taking advantage of the user friendly linkage analysis feature in SEQLinkage. Simply add `--single-markers` switch to the command above:

```
seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz --freq EVSEAAF --single-markers \
-o LinkageAnalysisSNV -K 0.001 --moi AR -W 0 -M 1 --theta-max 0.5 --theta-inc 0.05 -j 8 --run-linkage
```

<sup>4</sup>Terwilliger and Ott (1994) Joseph Douglas Terwilliger and Jurg Ott, Handbook of Human Genetic Linkage, Johns Hopkins Univ Pr, 1994 (ISBN: 9780801848032)

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```

MESSAGE: Binary trait detected in [/ramcache/seqlinkage-example.fam]
MESSAGE: Checking local resources 5/5 ...
MESSAGE: 12 samples found in [/ramcache/seqlinkage-example.vcf.gz]
MESSAGE: 2 families with a total of 12 samples will be scanned for 18 pre-defined units
MESSAGE: 17 units (from 18 variants) processed; 3 Mendelian inconsistencies and 0 recombination events handled
MESSAGE: 1 units ignored due to absence of variation in samples
MESSAGE: Archiving regional marker data to directory [/ramcache/cache]
MESSAGE: 17 units will be converted to LINKAGE format
MESSAGE: 17 units successfully converted to LINKAGE format
MESSAGE: Archiving LINKAGE format to directory [/ramcache/cache]
MESSAGE: Linkage analysis successfully performed for 17 units
MESSAGE: Reports in html format generated

```

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Note that the total number of units analyzed is now 17, which is the number of polymorphic sites in sample. Results are written to `LinkageAnalysisSNV/LinkageAnalysisSNV_Report.html`

### 2.3.3 Accessing archived analysis results

The HTML output only displays top  $N$  signals of LOD and HLOD but the result for all markers can be found at the output directory. For example for regional marker analysis above the text files of LOD and HLOD are stored to `LinkageAnalysis/heatmap/*.lods` and `LinkageAnalysis/heatmap/*.hlods` respectively. Similar is the case for single variant marker analysis. The default  $N = 10$  signals are displayed on the HTML file for single marker analysis but you may want to set  $N = 20$  so that all 17 units can be displayed. To do this without re-running the entire analysis (which may be very time consuming for real world WES or WGS data), you can add the `--cache` switch to the command, for example:

```

seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz --freq EVSEAAF --single-markers \
-o LinkageAnalysisSNV -K 0.001 --moi AR -W 0 -M 1 --theta-max 0.5 --theta-inc 0.05 -j 8 --run-linkage \
--cache --output-entries 20

```

---

```

MESSAGE: Binary trait detected in [/ramcache/seqlinkage-example.fam]
MESSAGE: Checking local resources 5/5 ...
MESSAGE: Loading regional marker data from archive ...
MESSAGE: Loading LINKAGE data from archive ...
MESSAGE: Loading linkage analysis result from archive ...
MESSAGE: Reports in html format generated

```

---

The terminal output suggests that archived results are used, but the HTML table now contains complete entries for all markers in data analyzed.

## 2.4 SEQLinkage with Other Linkage Programs

We have previously shown the use of SEQLinkage to write regional markers generated to LINKAGE and MERLIN formats. Here we demonstrate one more supported program format, the Mega2 format.

### 2.4.1 Output regional marker data to Mega2 format

Mega2<sup>5</sup> is a versatile data-handling program for facilitating genetic linkage analysis. It can be used to convert data formats between various linkage software. SEQLinkage supports output of regional markers to Mega2 format which can then be converted to input for a number of other linkage analysis programs via Mega2. For example,

```
seqlink --fam seqlinkage-example.fam --vcf seqlinkage-example.vcf.gz --freq EVSEAAF -o example --bin 0 --format MEG\
A2
```

Mega2 format

```
MESSAGE: Binary trait detected in [/ramcache/seqlinkage-example.fam]
MESSAGE: Checking local resources 5/5 ...
MESSAGE: 12 samples found in [/ramcache/seqlinkage-example.vcf.gz]
MESSAGE: 2 families with a total of 12 samples will be scanned for 25,305 pre-defined units
MESSAGE: 2 units (from 18 variants) processed; 3 Mendelian inconsistencies and 2 recombination events handled
MESSAGE: 25,302 units ignored due to absence in VCF file
MESSAGE: 1 units ignored due to absence of variation in samples
MESSAGE: Archiving regional marker data to directory [/ramcache/cache]
MESSAGE: 2 units will be converted to MEGA2 format
MESSAGE: 2 units successfully converted to MEGA2 format
MESSAGE: Archiving MEGA2 format to directory [/ramcache/cache]
MESSAGE: Saving data to [/ramcache/example]
```



#### Note

The collapsing theme --bin 0 is used for Mega2 format, because unlike with the LINKAGE program it can only handle bi-allelic variants.

## 2.5 Prepare Customized “Blueprint” of Regional Markers

A utility program<sup>6</sup> can be used to find, for male, female and also on average, the genetic positions (in cM) for genes provided by users. To use the program, you must have Python and tabix programs installed to your system, and the human linkage-physical map<sup>7</sup> downloaded to your hard drive. The first 4 columns of input file should be chromosome, start position (hg19 coordinate), end position (hg19 coordinate), gene name delimited by white space (tab or multiple spaces). The columns of output file are chromosome, start position, end position, gene name, genetic position of the gene on average, in female and in male, delimited by tab. The command is:

```
./genetic_pos_searcher /path/to/input/file
```

The RutgersMap provides the physical and genetic positions of large amount of SNPs, allowing determination of cM-scale linkage-based map positions for any marker, given its physical position.

<sup>5</sup>Mega2 [http://watson.hgen.pitt.edu/docs/mega2\\_html/mega2.html](http://watson.hgen.pitt.edu/docs/mega2_html/mega2.html)

<sup>6</sup>utility program downloadable via command `wget http://www.bioinformatics.org/seqlink/uploads/genetic_pos_searcher`

<sup>7</sup>the human linkage-physical map <http://compugen.rutgers.edu/maps>

The utility program works as follows. For a given gene, it will take the middle position of a gene as the position of the gene. Two closest SNP markers to this position will be searched in RutgersMap. Then the genetic position of the gene will be interpolated using the relative distance from the position to the two markers. Under the circumstances that the position of the gene is outside of the boundary of the smallest or largest positions provided by RutgersMap, the genetic position of the gene will be interpolated in scale with respect to the smallest or largest positions.

For chromosome X, if the position falls in [175751,2800677] or [155045646,155150393], i.e. pseudo-autosomal regions (hg19 coordinate), genetic position in both male and female will be interpolated; otherwise only genetic position in female are available. No genetic position on average can be obtained for chromosome X.