

# HGM functions for two way contingency tables.

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HGM functions for two way contingency tables on Risa/Asir

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by Y.Goto, Y.Tachibana, N.Takayama

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# 1 About this document

This document explains Risa/Asir functions for two way contingency tables by HGM(holonomic gradient method). Loading the package:

```
import("gtt_ekn3.rr");
```

The package gtt\_ekn3.rr is a major version up of gtt\_ekn.rr. In order to download the latest asir-contrib package, please use the asir\_contrib\_update() as follows.

```
import("names.rr");
asir_contrib_update(|update=1);
```

References cited in this document.

- [GM2016] Y.Goto, K.Matsumoto, Pfaffian equations and contiguity relations of the hypergeometric function of type  $(k+1, k+n+2)$  and their applications, arxiv:1602.01637 (version 1) (<http://arxiv.org/abs/1602.01637>)
- [T2016] Y.Tachibana, difference holonomic gradient method by the modular method. 2016, master thesis of Kobe University (in Japanese).
- [GTT2016] Y.Goto, Y.Tachibana, N.Takayama, implementation of difference holonomic gradient method for two way contingency tables. RIMS kokyuroku (in Japanese).
- [TGKT] Y.Tachibana, Y.Goto, T.Koyama, N.Takayama, Holonomic Gradient Method for Two Way Contingency Tables, arxiv:1803.04170 (the 3rd version) (<https://arxiv.org/abs/1803.04170>)
- [TKT2015] N.Takayama, S.Kuriki, A.Takemura, A-hypergeometric distributions and Newton polytopes. arxiv:1510.02269 (<http://arxiv.org/abs/1510.02269>)

The changelogs are described only in the Japanese version of this document.

## 2 Functions of HGM for two way contingency tables

### 2.1 Hypergeometric function $E(k,n)$

#### 2.1.1 `gtt_ekn3.gmvector`

`gtt_ekn3.gmvector(beta,p)`

:: It returns the value of the hypergeometric function  $E(k,n)$  and its derivatives associated to the two way contingency table with the marginal sum *beta*, parameter *p* (cell probability).

It is an alias of `gtt_ekn3.ekn_cBasis_2(beta,p)`

*return* vector, see below.

*beta* a list of the row sum and the column sum.

*p* the parameter.

- The name `gmvector` is an abbreviation of the Gauss-Manin vector defined in [GM2016].
- The return value is the vector  $S$  in the page 23 (the section 6) of [GM2016]. This is a constant multiple of the vector  $F$  in the section 4 of [GM2016] and the constant is determined so that the first element of the vector is equal to the value of the series  $S$  in the section 6 of [GM2016].
- Consider an  $r_1 \times r_2$  contingency table. Put  $m+1=r_1$ ,  $n+1=r_2$ . The normalizing constant  $Z$  is the sum of  $p^u/u!$  where  $u$  is an  $(m+1) \times (n+1)$  matrix (contingency table) with non-negative integer entries. The sum is taken over  $u$  such that the row sum and the column sum of  $u$  are equal to *beta*, see [TKT2015], [GM2016], [TGKT]. The first element of  $S$  (polynomial in this case) is equal to this polynomial  $Z$  with a normalized  $p =$

$$\begin{aligned} & [[1, y_{11}, \dots, y_{1n}], \\ & [1, y_{21}, \dots, y_{2n}], \dots, \\ & [1, y_{m1}, \dots, y_{mn}], \\ & [1, 1, \dots, 1]] \end{aligned}$$

- The following options are also accepted by several functions, e.g., `gmvector`, `expectation`, `nc`.
- A distributed computation is turned on by the option `crt=1` (`crt` = Chinese remainder theorem) [T2016]. The default is `crt=0`. Parameters for the distributed computation are set by `gtt_ekn3.setup`.
- Option `bs=1`. The matrix factorial, which is a product of contiguity relation matrices with different parameters, is evaluated by the binary splitting method. Examples: `gtt_ekn3.assert2(15|bs=1)` (3x3 matrix), `gtt_ekn3.test5x5(20|bs=1)` (5x5 matrix). The default is `bs=0`.
- Option `path`. A choice of algorithms to apply contiguity relations. `path=2` (the algorithm given in [GM2016]). `path=3` (the algorithm given in [TGKT] (revised version)). The default is `path=3`.
- Option `interval`. The period of the intermediate reduction of numerators and denominators. A relevant value of “interval” will lead to an efficient evaluation, but no

optimal value of it is known. See [TGKT] as to details. The default is no intermediate reduction.

- Option `x=1`. It opens a window for each process.

Example: A 2 x 2 contingency table. The row sum is [5,1] and column sum is [3,3]. The parameter (cell probability) is `[[1/2,1/3],[1/7,1/5]]`.

```
[3000] import("gtt_ekn3.rr");
[3001] gtt_ekn3.gmvector([[5,1],[3,3]],[[1/2,1/3],[1/7,1/5]])
[775/27783]
[200/9261]
```

Example: Interval option.

```
[4009] P=gtt_ekn3.prob1(5,5,100);
[[[100,200,300,400,500],[100,200,300,400,500]],
[[[1,1/2,1/3,1/5,1/7],[1,1/11,1/13,1/17,1/19],
[1,1/23,1/29,1/31,1/37],[1,1/41,1/43,1/47,1/53],[1,1,1,1,1]]]]
[4010] util_timing(quote(gtt_ekn3.gmvector(P[0],P[1])[1];
[cpu,72.852,gc,0,memory,4462742364,real,72.856]
[4011] util_timing(quote(gtt_ekn3.gmvector(P[0],P[1]|interval=100)))[1];
[cpu,67.484,gc,0,memory,3535280544,real,67.4844]
```

Refer to Section 2.1.5 [gtt\_ekn3.setup], page 5, `<undefined>` [gtt\_ekn3.paffian\_basis], page `<undefined>`,

## 2.1.2 gtt\_ekn3.nc

`gtt_ekn3.nc(beta,p)`

:: It returns the normalizing constant  $Z$  and its derivatives for the two way contingency tables with the marginal sum  $beta$  and the parameter (cell probability)  $p$ . See, e.g., [TKT2015], [TGKT] as to the definition of  $Z$ .

*return* A list `[Z,[[d_11 Z, d_12 Z, ...], ..., [d_m1 Z, d_m2 Z, ..., d_mn Z]]]` where  $d_{ij}$   $Z$  denotes the partial derivative of  $Z$  with respect to the parameter  $p_{ij}$ .

*beta* The row sum and the column sum.

*p* The parameter (cell probability).

- The function `nc` obtains  $Z$  from the value of `gmvector` by Prop 7.1 of [GM2016].
- See options for `gmvector`.

Example: A 2x3 contingency table.

```
[2237] gtt_ekn3.nc([[4,5],[2,4,3]],[[1,1/2,1/3],[1,1,1]]);
[4483/124416,[ 353/7776 1961/15552 185/1728 ]
[ 553/20736 1261/15552 1001/13824 ]]
```

Refer to Section 2.1.5 [gtt\_ekn3.setup], page 5, Section 2.1.3 [gtt\_ekn3.lognc], page 4,

### 2.1.3 `gtt_ekn3.lognc`

`gtt_ekn3.lognc(beta,p)`

:: It returns the logarithm of Z.

*return* A list [ $\log(Z)$ , [ $d_{-11} \log(Z)$ ,  $d_{-12} \log(Z)$ , ...], [ $d_{-21} \log(Z)$ ,...], ... ]

- This function is used to solve the conditional maximal likelihood estimation [TKT2015].
- See options of `gmvector`.

Example: A 2x3 contingency table. The first element is an approximate value of  $\log(Z)$ . The rests are exact values when the arguments of `lognc` are rational numbers.

```
[2238] gtt_ekn3.lognc([[4,5],[2,4,3]], [[1,1/2,1/3],[1,1,1]]);
[-3.32333832422461674630, [ 5648/4483 15688/4483 13320/4483 ]
 [ 3318/4483 10088/4483 9009/4483 ]]
```

Refer to Section 2.1.5 [`gtt_ekn3.setup`], page 5, Section 2.1.2 [`gtt_ekn3.nc`], page 3,

### 2.1.4 `gtt_ekn3.expectation`

`gtt_ekn3.expectation(beta,p)`

:: It returns the expectation of the hypergeometric distribution with the marginal sum *beta* and the parameter *p*.

*return* The expectation of each cell.

- It is an implementation of Algorithm 7.8 of [GM2016]. A faster algorithm in [TGKT] is chosen with the default option `path=3`.
- By the option “`index`”, it returns only the expectations standing for the “`index`”. For example, `index=[[0,0],[1,1]]` in the case of a 2 x 2 contingency table, it returns the expectations for the (2,1) and (2,2) elements (0 stands for no evaluation and 1 stands for doing the evaluation).
- See also options of `gmvector`.

Examples of the evaluation of expectations for 2 x 2 and 3 x 3 contingency tables.

```
[2235] gtt_ekn3.expectation([[1,4],[2,3]], [[1,1/3],[1,1]]);
[ 2/3 1/3 ]
[ 4/3 8/3 ]
```

```
[2236] gtt_ekn3.expectation([[4,5],[2,4,3]], [[1,1/2,1/3],[1,1,1]]);
[ 5648/4483 7844/4483 4440/4483 ]
[ 3318/4483 10088/4483 9009/4483 ]
```

```
[2442] gtt_ekn3.expectation([[4,14,9],[11,6,10]], [[1,1/2,1/3],[1,1/5,1/7],[1,1,1]]);
[ 207017568232262040/147000422096729819 163140751505489940/147000422096729819
 217843368649167296/147000422096729819 ]
[ 1185482401011137878/147000422096729819 358095302885438604/147000422096729819
 514428205457640984/147000422096729819 ]
[ 224504673820628091/147000422096729819 360766478189450370/147000422096729819
 737732646860489910/147000422096729819 ]
```

Refer to Section 2.1.5 [`gtt_ekn3.setup`], page 5, Section 2.1.2 [`gtt_ekn3.nc`], page 3,

### 2.1.5 gtt\_ekn3.setup

`gtt_ekn3.setup()`

:: It sets parameters for a distributed computation or report the current values of the parameters.

*return* 0

- It shows the number of processes, the number of primes, the minimal prime which is used.
- Option `nps` : the number of processes.
- Option `nprm` : the number of the primes used. When the argument of this option is a string, a list of primes are supposed to be given in the file by the name given by the string.
- Option `minp` : the minimal prime. It is used with the option `nprm`. It generates `nprm` primes more than or equal to `minp`. When the option `fgp` is given, the generated primes are stored in the file of the name `fgp`.
- The default values of `nps`, `nprm`, and `fgp` are `nps=1`. `nprm=10`. `fgp=0` (no saving).
- The option `report=1` shows the current parameters.
- Option `subprogs=[file1,file2,...]`. These files are loaded to the child processes. The default value is `subprogs=["gtt_ekn3/childprocess.rr"]`.
- The function `gtt_ekn3.set_debug_level(Mode)` is used to set a debug message level (`Ekn_debug`)

Example: Generating a list of primes and outputting them to the file `p.txt`.

```
gtt_ekn3.setup(|nps=2,nprm=20,minp=10^10,fgp="p.txt")$
```

Example: Evaluating the gmvector by the Chinese remainder theorem (`crt`).

```
[2867] gtt_ekn3.setup(|nprm=20,minp=10^20);
[2868] N=2; T2=gtt_ekn3.gmvector([[36*N,13*N-1],[38*N-1,11*N]],
                                [[1,(1-1/N)/56],[1,1]] | crt=1)$
```

Refer to Section 2.1.2 [`gtt_ekn3.nc`], page 3, Section 2.1.1 [`gtt_ekn3.gmvector`], page 2,

### 2.1.6 gtt\_ekn3.upAlpha, gtt\_ekn3.downAlpha

`gtt_ekn3.upAlpha(i,k,n)`

`gtt_ekn3.downAlpha(i,k,n)`

::

*i* It indicates the direction of the contiguity relation to get. In other words, the contiguity relation from  $a_i$  to  $a_{i+1}$  (from  $a_i$  to  $a_{i-1}$ , the `downAlpha` case) is obtained.

*k, n* The contiguity relation for the hypergeometric function  $E(k+1, n+k+2)$  standing for the  $(k+1)(n+1)$  contingency table is obtained.

*return* The matrix representation of the contiguity relation with respect to the pfaffian\_basis (see `gtt_ekn3.pfaffian_basis`). See also Cor 6.3 of [GM2016].

- The function `upAlpha` returns the matrix  $U_i$  of Cor 6.3 in [GM2016].

- The function `downAlpha` is for the contiguity relation from  $a_i$  to  $a_{i-1}$ .
- The function `marginaltoAlpha`([row sum,column sum]) translates the marginal sum to values of  $a_i$ 's.
- The function `pfaffian_basis` returns  $F$  in section 4 of [GM2016]. See the example below.
- The variables  $a_i$  and  $x_{i,j}$  can be specialized to numbers by the optional arguments `arule` and `xrule`. See the example below.

Example: 2x2 contingency table (E(2,4)), 2x3 contingency table (E(2,5)). Outputs of [2221] — [2225] are left out.

```
[2221] gtt_ekn3.marginaltoAlpha([[1,4],[2,3]]);
[[a_0,-4],[a_1,-1],[a_2,3],[a_3,2]]
[2222] gtt_ekn3.upAlpha(1,1,1); // contiguity relation of E(2,4)
// for the a_1 direction
[2223] gtt_ekn3.upAlpha(2,1,1); // E(2,4), a_2 direction
[2224] gtt_ekn3.upAlpha(3,1,1); // E(2,4), a_3 direction
[2225] function f(x_1_1);
[2232] gtt_ekn3.pfaffian_basis(f(x_1_1),1,1);
[ f(x_1_1) ]
[ (f1(x_1_1)*x_1_1)/(a_2) ]
[2233] function f(x_1_1,x_1_2);
f() redefined.
[2234] gtt_ekn3.pfaffian_basis(f(x_1_1,x_1_2),1,2); // E(2,5), 2*3 contingency table
[ f(x_1_1,x_1_2) ]
[ (f1,0(x_1_1,x_1_2)*x_1_1)/(a_2) ]
[ (f0,1(x_1_1,x_1_2)*x_1_2)/(a_3) ]

[2235] RuleA=[[a_2,1/3],[a_3,1/2]]$ RuleX=[[x_1_1,1/5]]$
base_replace(gtt_ekn3.upAlpha(1,1,1),append(RuleA,RuleX))
-gtt_ekn3.upAlpha(1,1,1 | arule=RuleA, xrule=RuleX);

[ 0 0 ]
[ 0 0 ]
```

Refer to Section 2.1.2 [gtt\_ekn3.nc], page 3, Section 2.1.1 [gtt\_ekn3.gmvector], page 2,

### 2.1.7 gtt\_ekn3.cmle

`gtt_ekn3.cmle(u)`

:: It finds a parameter  $p$  (cell probability) which maximizes  $P(U=u \mid \text{row sum, column sum} = \text{these of } U)$  for given observed data  $u$ . The value of  $p$  is an approximate value.

$u$  The observed data.

*return* An estimated parameter  $p$

- `Todo`, optional parameter to set the step size of the gradient descent.

Example: 2x4 contingency table.

```
U=[[1,1,2,3],[1,3,1,1]];
```



```

gtt_ekn3.cmle(U);
[[ 1 1 2 3 ]
 [ 1 3 1 1 ],[[7,6],[2,4,3,4]], // Data, row sum, column sum
 [ 1 67147/183792 120403/64148 48801/17869 ] // p obtained.
 [ 1 1 1 1 ]]

```

Refer to Section 2.1.4 [gtt\_ekn3.expectation], page 4,

### 2.1.8 gtt\_ekn3.set\_debug\_level, gtt\_ekn3.show\_path, gtt\_ekn3.get\_svalue, gtt\_ekn3.assert1, gtt\_ekn3.assert2, gtt\_ekn3.assert3, gtt\_ekn3.probl

- `gtt_ekn3.set_debug_level(m)`  
 :: It sets the level of debug messages.
- `gtt_ekn3.contiguity_mat_list_2`  
 :: It returns a list of contiguity directions to be used.
- `gtt_ekn3.show_path()`  
 :: It returns the path to apply contiguity relations. See [TGKT].
- `gtt_ekn3.get_svalue()`  
 :: It returns the values of the static variables.
- `gtt_ekn3.assert1(N)`  
 :: It checks the system by 2x2 contingency tables. *N* is proportional to the marginal sum.
- `gtt_ekn3.assert2(N)`  
 :: It checks the system by 3x3 contingency tables.
- `gtt_ekn3.assert3(R1, R2, Size)`  
 :: It checks the distributed computation system by *R1* x *R2* contingency tables.
- `gtt_ekn3.probl(R1,R2,Size)`  
 :: It returns a test data for *R1* x *R2* contingency tables in the format [marginal sum, parameter *p*]. The marginal sum is proportional to *Size*. See benchmark tests in [TGKT].
- Let *m* be the debug level. When  $(m \& 0x1) == 0x1$ , the values by `g_mat_fac_test_plain` and `g_mat_fac_itor` (distributed method is used) are computed. Note that `gtt_ekn3.setup()` is properly executed before doing these evaluations.
  - When  $(m \& 0x2) == 0x2$ , the arguments of `g_mat_fac_test` are stored in the file `tmp-input-[number].ab`.
  - When  $(m \& 0x4) == 0x4$ , the arguments for the matrix factorial computation are printed.
  - The function `get_svalue` returns the list of the values of [`Ekn_plist`,`Ekn_IDL`,`Ekn_debug`,`Ekn_mesg`,`XRule`,`ARule`,`Verbose`,`Ekn_Rq`].
  - Options of `assert3`: “`x=1`” shows the window attached to every subprocess. With “`nps=m`”, *m* processes are used to obtain contiguity relations. The options `crt`, `interval`, ... of `gmvector` are also accepted. In order to display the timing data, do `load("gtt_ekn3/ekn_eval-timing.rr")`; before starting this function.

Example:

```
[2846] gtt_ekn3.set_debug_level(0x4);
[2847] N=2; T2=gtt_ekn3.gmvector([[36*N,13*N-1],[38*N-1,11*N]],
                                [[1,(1-1/N)/56],[1,1]])$
[2848]
level&0x4: g_mat_fac_test([ 113/112 ]
[ 1/112 ],[ (t+225/112)/(t^2+4*t+4) (111/112*t+111/112)/(t^2+4*t+4) ]
[ (1/112)/(t^2+4*t+4) (111/112*t+111/112)/(t^2+4*t+4) ],0,20,1,t)
Note: we do not use g_mat_fac_itor. Call gtt_ekn3.setup(); to use the crt option.
level&0x4: g_mat_fac_test([ 67/62944040755546030080000 ]
[ 1/125888081511092060160000 ],[ (t+24)/(t^2+25*t+46) (2442)/(t^2+25*t+46) ]
[ (1)/(t^2+25*t+46) (-111*t-111)/(t^2+25*t+46) ],0,73,1,t)
level&0x4: g_mat_fac_test ----- snip
```

Example:

```
[2659] gtt_ekn3.nc([[4,5,6],[2,4,9]],[[1,1/2,1/3],[1,1/5,1/7],[1,1,1]])$
[2660] L=matrix_transpose(gtt_ekn3.show_path())$
[2661] L[2];
[2 1]
```

This means that the contiguity relations for the directions [2 1] ( $a_{-2}$ ,  $a_{-1}$ ) are used to evaluate the normalizing constant  $Z$ .  $L[0]$  is the contiguity matrix,  $L[1]$  is a list of the steps to apply for corresponding relations.

Example: Finding a path without evaluations of gmectors.

```
A=gtt_ekn3.marginaltoAlpha_list([[400,410,1011],[910,411,500]])$
[2666] gtt_ekn3.contiguity_mat_list_2(A,2,2)$
[2667] L=matrix_transpose(gtt_ekn3.show_path())$
[2668] L[2];
[ 2 1 5 4 3 ]
[2669] gtt_ekn3.contiguity_mat_list_3(A,2,2)$ // new alg in [TGKT]
[2670] L=matrix_transpose(gtt_ekn3.show_path())$
[2671] L[2];
[2 1] // shorter
```

Example: When `assert2()` returns 0 matrices, then the results of `g_mat_fac_plain` and `g_mat_fac_int` agree. In other words, the system is OK.

```
[8859] gtt_ekn3.assert2(1);
Marginal=[[130,170,353],[90,119,444]]
P=[[17/100,1,10],[7/50,1,33/10],[1,1,1]]
Try g_mat_fac_test_int: Note: we do not use g_mat_fac_itor. Call gtt_ekn3.setup(); to
Timing (int) =0.413916 (CPU) + 0.590723 (GC) = 1.00464 (total), real time=0.990672

Try g_mat_fac_test_plain: Note: we do not use g_mat_fac_itor. Call gtt_ekn3.setup(); to
Timing (rational) =4.51349 (CPU) + 6.32174 (GC) = 10.8352 (total)
diff of both method =
[ 0 0 0 ]
[ 0 0 0 ]
[ 0 0 0 ]
```

```
[8860]

[8863] gtt_ekn3.setup(|nprm=100,minp=10^50);
Number of processes = 1.
Number of primes = 100.
Min of plist = 1000000000000000000000000000000000000000000000000151.
0
[8864] gtt_ekn3.assert2(1 | crt=1);
Marginal=[[130,170,353],[90,119,444]]
P=[[17/100,1,10],[7/50,1,33/10],[1,1,1]]
Try [[crt,1]]
---- snip
```

Example: 3x5 contingency table. The parameter p (cell probability) is a list of 1/(prime number) 's.

```
[9054] L=gtt_ekn3.prob1(3,5,10 | factor=1, factor_row=3);
[[[10,20,420],[30,60,90,120,150]], [[1,1/2,1/3,1/5,1/7],[1,1/11,1/13,1/17,1/19],[1,1,1,1,1],
[9055] number_eval(gtt_ekn3.expectation(L[0],L[1]));
[ 1.65224223218613 ... snip ]
```

Example:

```
[5779] import("gtt_ekn3.rr"); load("gtt_ekn3/ekn_eval-timing.rr");
[5780] gtt_ekn3.assert3(5,5,100 | nps=32, interval=100);
-- snip
Parallel method: Number of process=32, File name tmp-gtt_ekn3/p300.txt is written.
Number of processes = 32.
-- snip
initialPoly of path=3: [ 2.184 0 124341044 2.1831 ] [CPU(s),0*,real(s)]
contiguity_mat_list_3 of path=3: [ 0.04 0 630644 9.6774 ] [CPU(s),0*,real(s)]
Note: interval option will lead faster evaluation. We do not use g_mat_fac_itor (crt).
g_mat_fac of path=3: [ 21.644 0 1863290168 21.6457 ] [CPU(s),0*,real(s)]
Done. Saved in 2.ab
Diff (should be 0)=[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,..., 0,0,0]
```

Refer to Section 2.1.2 [gtt\_ekn3.nc], page 3,

## 3 Modular method

### 3.1 Chinese remainder theorem and itor

#### 3.1.1 gtt\_ekn3.chinese\_itor

`gtt_ekn3.chinese_itor(data, idlist)`

:: It performs a rational reconstruction by the Chinese remainder theorem (itor = integer to rational).

*return* [val, n], the vector val is the value by the rational reconstruction.  $n = n_1 * n_2 * \dots$

*data* [[val1, n1], [val2, n2], ...], val1, val2 are values evaluated in mod n1, mod n2, ... respectively. The relations  $\text{val mod } n_1 = \text{val}_1$ ,  $\text{val mod } n_2 = \text{val}_2, \dots$  are satisfied.

*idlist* The list of server id's for itor.

- When it cannot find val, it returns failure.

Example:  $[3!, 5^3 * 3!] = [6, 750]$  is the return value. The relations  $6 \bmod 109 = 6$ ,  $750 \bmod 109 = 96$  stand for  $[[6, 96], 109]$ , ...

```
gtt_ekn3.setup(|nps=2, nprm=3, minp=101, fgp="p_small.txt");
SS=gtt_ekn3.get_svalue();
SS[0];
[103, 107, 109] // list of primes
SS[1];
[0, 2] // list of server ID's
gtt_ekn3.chinese_itor([[ [6, 96 ], 109 ], [ [6, 29 ], 103 ], [ [6, 1 ], 107 ] ], SS[1]);
[[ 6 750 ], 1201289]

// The argument may be a scalar.
gtt_ekn3.chinese_itor([[96, 109], [29, 103]], SS[1]);
[[ 750 ], 11227]
```

Refer to Section 2.1.5 [gtt\_ekn3.setup], page 5,

## 4 Binary splitting

### 4.1 Matrix factorial

#### 4.1.1 `gtt_ekn3.init_bsplrit`, `gtt_ekn3.init_dm_bsplrit`, `gtt_ekn3.setup_dm_bsplrit`

`gtt_ekn3.init_bsplrit(|minsize=16,levelmax=1);`  
 :: It sets parameters for the binary splitting to evaluate the matrix factorial  $M(1) M(2) \dots M(n)$  where  $M(k)$  is a matrix with a parameter  $k$ .

`gtt_ekn3.init_dm_bsplrit(|bsplrit_x=0, bsplrit_reduce=0)`  
 :: It sets parameters for the binary splitting by a distributed computation.

`gtt_ekn3.setup_dm_bsplrit(C)`  
 :: It starts  $C$  processes for the binary splitting.

*Option minsize.*

When the size of the matrix factorial is less than the minsize, the binary splitting is not used and sequential multiplication is used instead.

*Option levelmax.*

The maximum of recursions of the recursive binary splitting in the distributed computation. See `gtt_ekn3/dm_bsplrit.rr`  $C$  should be set to `levelmax-1`. When `levelmax=1`, the distributed computation is not performed.

*Option bsplrit\_x.*

When `bsplrit_x=1`, a window attached to every process is opened.

Example: A comparison of `bs=1` and no `bs`.

```
[4618] cputime(1)$
[4619] gtt_ekn3.expectation(Marginal=[[1950,2550,5295],[1350,1785,6660]],
                             P=[[17/100,1,10],[7/50,1,33/10],[1,1,1]]|bs=1)$
4.912sec(4.914sec)
[4621] V2=gtt_ekn3.expectation(Marginal,P)$
6.752sec(6.756sec)
```

Example: Note that distributed computations are often slower than computations on a single process in our implementation of the binary splitting. The option `bsplrit_x=1` opens a debug windows, it makes things slower. The function `gtt_ekn3.test_bs_dist()` is a test function of the binary splitting by a distributed computation.

```
[3669] C=4$ gtt_ekn3.init_bsplrit(|minsize=16,levelmax=C+1)$
gtt_ekn3.init_dm_bsplrit(|bsplrit_x=1)$
[3670] [3671] [3672] gtt_ekn3.setup_dm_bsplrit(C);
[0,0]
[3673] gtt_ekn3.assert2(10|bs=1)$
```

Refer to Section 2.1.1 [`gtt_ekn3.gmvector`], page 2, Section 2.1.4 [`gtt_ekn3.expectation`], page 4, `<undefined>` [`gtt_ekn3.assert1`], page `<undefined>`, `<undefined>` [`gtt_ekn3.assert2`], page `<undefined>`,

# Index

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(Index is nonexistent)

## Short Contents

1	About this document .....	1
2	Functions of HGM for two way contingency tables .....	2
3	Modular method .....	10
4	Binary splitting .....	11
	Index .....	12

# Table of Contents

<b>1</b>	<b>About this document .....</b>	<b>1</b>
<b>2</b>	<b>Functions of HGM for two way contingency tables .....</b>	<b>2</b>
2.1	Hypergeometric function $E(k,n)$ .....	2
2.1.1	<code>gtt_ekn3.gmvector</code> .....	2
2.1.2	<code>gtt_ekn3.nc</code> .....	3
2.1.3	<code>gtt_ekn3.lognc</code> .....	4
2.1.4	<code>gtt_ekn3.expectation</code> .....	4
2.1.5	<code>gtt_ekn3.setup</code> .....	5
2.1.6	<code>gtt_ekn3.upAlpha, gtt_ekn3.downAlpha</code> .....	5
2.1.7	<code>gtt_ekn3.cmle</code> .....	6
2.1.8	<code>gtt_ekn3.set_debug_level, gtt_ekn3.show_path, gtt_ekn3.get_svalue, gtt_ekn3.assert1, gtt_ekn3.assert2, gtt_ekn3.assert3, gtt_ekn3.prob1..</code>	7
<b>3</b>	<b>Modular method .....</b>	<b>10</b>
3.1	Chinese remainder theorem and itor .....	10
3.1.1	<code>gtt_ekn3.chinese_itor</code> .....	10
<b>4</b>	<b>Binary splitting .....</b>	<b>11</b>
4.1	Matrix factorial .....	11
4.1.1	<code>gtt_ekn3.init_bsplrit, gtt_ekn3.init_dm_bsplrit, gtt_ekn3.setup_dm_bsplrit</code> .....	11
	<b>Index.....</b>	<b>12</b>



