

# Package ‘matchingMarkets’

May 8, 2026

**Version** 1.0-5

**Depends** R (>= 3.0.2)

**Imports** Rcpp (>= 0.12.12), RcppProgress (>= 0.2), lpSolve, lattice,  
parallel, partitions, rJava, stats, utils

**SystemRequirements** Java

**LinkingTo** Rcpp, RcppProgress, RcppArmadillo

**Suggests** knitr, ggplot2, grDevices, graphics

**VignetteBuilder** knitr

**Title** Analysis of Stable Matchings

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**Description** Implements structural estimators to estimate preferences and correct for the sample selection bias of observed outcomes in matching markets. This includes one-sided matching of agents into groups (Klein, 2015) <[doi:10.17863/CAM.5812](https://doi.org/10.17863/CAM.5812)> as well as two-sided matching of students to schools (Klein et al., 2024) <[doi:10.1016/j.geb.2024.07.003](https://doi.org/10.1016/j.geb.2024.07.003)>. The package also contains algorithms to find stable matchings in the three most common matching problems: the stable roommates problem (Irving, 1985) <[doi:10.1016/0196-6774\(85\)90033-1](https://doi.org/10.1016/0196-6774(85)90033-1)>, the college admissions problem (Gale and Shapley, 1962) <[doi:10.2307/2312726](https://doi.org/10.2307/2312726)>, and the house allocation problem (Shapley and Scarf, 1974) <[doi:10.1016/0304-4068\(74\)90033-0](https://doi.org/10.1016/0304-4068(74)90033-0)>.

**URL** <https://matchingMarkets.org>, <https://klein.uk>

**BugReports** <https://github.com/thiloklein/matchingMarkets/issues>

**License** GPL (>= 2)

**RoxygenNote** 7.3.1

**Encoding** UTF-8

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**NeedsCompilation** yes

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**Repository** CRAN

**Date/Publication** 2025-12-22 10:40:02 UTC

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matchingMarkets-package

*An R package for the analysis of stable matchings.*

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## Description

The matchingMarkets package contains R, C++ and Java code for stable matching algorithms and the estimation of structural models that correct for the sample selection bias of observed outcomes in matching markets.

Matching is concerned with who transacts with whom, and how. For example, who works at which job, which students go to which school, who forms a workgroup with whom, and so on.

The empirical analysis of matching markets is naturally subject to sample selection problems. If agents match assortatively on characteristics unobserved to the analyst but correlated with both the exogenous variable and the outcome of interest, regression estimates will generally be biased.

The matchingMarkets package comprises

1. *Bayes estimators.* The estimators implemented in function `stabit` and `stabit2` correct for the selection bias from endogenous matching.  
The current package version provides solutions for two commonly observed matching processes: (i) the *group formation problem* with fixed group sizes and (ii) the *college admissions problem*. These processes determine which matches are observed – and which are not – and this is a sample selection problem.
2. *Post-estimation tools.* Setting `mfx=TRUE` in the summary function computes marginal effects from coefficients in binary outcome and selection equations and `khb` implements the Karlson-Holm-Breen test for confounding due to sample selection.
3. *Design matrix generation.* The estimators are based on independent variables for all feasible, i.e., observed and counterfactual, matches in the market. Generating the characteristics of all feasible matches from individual-level data is a combinatorial problem. The package returns design matrices based on pre-specified transformations to generate counterfactual matches.
4. *Algorithms.* The package also contains matching algorithms that can be used to simulated matching data: `hri`: A constraint model (Posser, 2014) for the **stable marriage** and **college admissions** problem, a.k.a. hospital/residents problem (see Gale and Shapley, 1962). `sri`: A constraint model for the **stable roommates problem** (see Gusfield and Irving, 1989). `ttc`: The top-trading-cycles algorithm for the **housing market problem**. These can be used to obtain stable matchings from simulated or real preference data (see Shapley and Scarf, 1974).
5. *Data.* In addition to the `baac00` dataset from borrowing groups in Thailand's largest agricultural lending program, the package provides functions `stabsim` and `stabsim2` to simulate one's own data from one-sided and two-sided matching markets.

## Frequently Asked Questions

- *Why can I not use the classic Heckman correction?*  
Estimators such as the Heckman (1979) correction (in package `sampleSelection`) or double selection models are inappropriate for this class of selection problems. To see this, note that a simple first stage discrete choice model assumes that an observed match reveals match partners' preferences over each other. In a matching market, however, agents can only choose from the set of partners who would be willing to form a match with them and we do not observe the players' relevant choice sets.
- *Do I need an instrumental variable to estimate the model?*  
Short answer: No. Long answer: The characteristics of other agents in the market serve as the source of exogenous variation necessary to identify the model. The identifying exclusion restriction is that characteristics of all agents in the market affect the matching, i.e., who matches with whom, but it is only the characteristics of the match partners that affect the outcome of a particular match once it is formed. No additional instruments are required for identification (Sorensen, 2007).

- *What are the main assumptions underlying the estimator?*

The approach has certain limitations rooted in its restrictive economic assumptions.

1. The matching models are *complete information* models. That is, agents are assumed to have a complete knowledge of the qualities of other market participants.
2. The models are *static equilibrium* models. This implies that (i) the observed matching must be an equilibrium, i.e., no two agents would prefer to leave their current partners in order to form a new match (definition of pairwise stability), and (ii) the equilibrium must be unique for the likelihood function of the model to be well defined (Bresnahan and Reiss, 1991).
3. Uniqueness results can be obtained in two ways. First, as is common in the industrial organization literature, by imposing suitable *preference restrictions*. A suitable restriction on agents' preferences that guarantees a unique equilibrium is alignment (Pycia, 2012). In a group formation model, (pairwise) preference alignment states that any two agents who belong to the same groups must prefer the same group over the other. Second, by choosing a *market assignment* based on matching algorithms that produce a unique stable matching, such as the well-studied Gale and Shapley (1962) deferred acceptance algorithm.
4. Finally, the models assume *bivariate normality* of the errors in selection and outcome equation. If that assumption fails, the estimator is generally inconsistent and can provide misleading inference in small samples.

### How to cite this package

Whenever using this package, please cite as

Klein, T. (2023). matchingMarkets: Structural Estimator and Algorithms for the Analysis of Stable Matchings. R package version 1.0-4.

### Author(s)

Thilo Klein

### References

- Bresnahan, T. and Reiss, P. (1991). Empirical models of discrete games. *Journal of Econometrics*, 48(1-2):57–81.
- Gale, D. and Shapley, L.S. (1962). College admissions and the stability of marriage. *The American Mathematical Monthly*, 69(1):9–15.
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- Heckman, J. (1979). Sample selection bias as a specification error. *Econometrica*, 47(1):153–161.
- Prosser, P. (2014). Stable Roommates and Constraint Programming. *Lecture Notes in Computer Science, CPAIOR 2014 Edition*. Springer International Publishing, 8451: 15–28.
- Pycia, M. (2012). Stability and preference alignment in matching and coalition formation. *Econometrica*, 80(1):323–362.
- Shapley, L. and H. Scarf (1974). On cores and indivisibility. *Journal of Mathematical Economics*, 1(1):23–37.

Sorensen, M. (2007). How smart is smart money? A two-sided matching model of venture capital. *The Journal of Finance*, 62(6):2725–2762.

### See Also

[sampleSelection](#)

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baac00

*Townsend Thai Project BAAC Annual Resurvey, 2000*

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### Description

The `baac00` data frame contains data of 292 borrowers from Thailand’s largest agricultural lending program. These data are collected as part of the Townsend Thai Project Bank for Agriculture and Agricultural Cooperatives (BAAC) Annual Resurvey (Townsend, 2000). The 292 borrowers are nested within 68 groups and 39 markets. This nestedness makes the dataset particularly relevant for matching applications. A more complete discussion of the data is found in Ahlin (2009), Section 3, and Klein (2015a).

### Usage

```
data(baac00)
```

### Format

This data frame contains the following columns:

**g.id** group identifier.

**m.id** market identifier.

**R** repayment outcome: BAAC never raised interest rate as a penalty for late repayment.

**pi** success probability: measure of group members’ project success probability.

**wst** worst year: indicator of economically worst year. 1:last year; 2:year before last year; 101-168:neither.

**loan\_size** loan size: average loan size borrowed by the group.

**loan\_size2** loan size squared.

**lngroup\_agei** log group age: log of number of years group has existed.

### Source

Townsend, R. (2000). Townsend Thai Project Bank for Agriculture and Agricultural Cooperatives (BAAC) Annual Resurvey, 2000. Available at [doi:10.7910/DVN/UD4QAV](https://doi.org/10.7910/DVN/UD4QAV), *Harvard Dataverse*.

### References

Ahlin, C. (2009). Matching for credit: Risk and diversification in Thai microcredit groups. Working Paper 251, *Bureau for Research and Economic Analysis of Development*.

Klein, T. (2015a). [Does Anti-Diversification Pay? A One-Sided Matching Model of Microcredit](#). *Cambridge Working Papers in Economics*, #1521.

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hri	<i>All stable matchings in the hospital/residents problem with incomplete lists</i>
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### Description

Finds *all* stable matchings in either the **hospital/residents** problem (a.k.a. college admissions problem) or the related **stable marriage** problem. Dependent on the problem, the results comprise the student and college-optimal or the men and women-optimal matchings. The implementation allows for *incomplete preference lists* (some agents find certain agents unacceptable) and *unbalanced instances* (unequal number of agents on both sides). The function uses the Prosser (2014) constraint encoding based on either given or randomly generated preferences.

### Usage

```
hri(
  nStudents = ncol(s.prefs),
  nColleges = ncol(c.prefs),
  nSlots = rep(1, nColleges),
  s.prefs = NULL,
  c.prefs = NULL,
  s.range = NULL,
  c.range = NULL,
  randomization = NULL,
  seed = NULL,
  check_consistency = TRUE,
  verbose = FALSE,
  ...
)
```

### Arguments

nStudents	integer indicating the number of students (in the college admissions problem) or men (in the stable marriage problem) in the market. Defaults to <code>ncol(s.prefs)</code> .
nColleges	integer indicating the number of colleges (in the college admissions problem) or women (in the stable marriage problem) in the market. Defaults to <code>ncol(c.prefs)</code> .
nSlots	vector of length <code>nColleges</code> indicating the number of places (i.e. quota) of each college. Defaults to <code>rep(1, nColleges)</code> for the marriage problem.
s.prefs	matrix of dimension <code>nColleges x nStudents</code> with the <code>j</code> th column containing student <code>j</code> 's ranking over colleges in decreasing order of preference (i.e. most preferred first).
c.prefs	matrix of dimension <code>nStudents x nColleges</code> with the <code>i</code> th column containing college <code>i</code> 's ranking over students in decreasing order of preference (i.e. most preferred first).

<code>s.range</code>	range of two integers $s.range = c(s.min, s.max)$ , where $s.min < s.max$ . Produces incomplete preference lists with the length of each student's list randomly sampled from the range $[s.min, s.max]$ . Note: interval is only correct if either <code>c.range</code> or <code>s.range</code> is used.
<code>c.range</code>	range of two integers $c.range = c(c.min, c.max)$ , where $c.min < c.max$ . Produces incomplete preference lists with the length of each college's list randomly sampled from the range $[c.min, c.max]$ . Note: interval is only correct if either <code>c.range</code> or <code>s.range</code> is used.
<code>randomization</code>	determines at which level random lottery numbers for student priorities are drawn. The default is <code>randomization = "multiple"</code> , where a student's priority is determined by a separate lottery at each college (i.e. local tie-breaking). For the second variant, <code>randomization = "single"</code> , a single lottery number determines a student's priority at all colleges (i.e. global tie breaking).
<code>seed</code>	integer setting the state for random number generation.
<code>check_consistency</code>	Performs consistency checks (Checks if there are columns in the preference matrices that only contains zeros and drops them and checks the matrices for consistencies if they are given by characters). Defaults to TRUE but changing it to FALSE might reduce the running-time for large problems.
<code>verbose</code>	logical. When set to TRUE, writes information messages on the console (recommended). Defaults to FALSE, which suppresses such messages.
<code>...</code>	.

### Value

`hri` returns a list of the following elements.

<code>s.prefs.smi</code>	student-side preference matrix for the stable marriage problem with incomplete lists (SMI).
<code>c.prefs.smi</code>	college-side preference matrix for the stable marriage problem with incomplete lists (SMI).
<code>s.prefs.hri</code>	student-side preference matrix for the college admissions problem (a.k.a. hospital/residents problem) with incomplete lists (HRI).
<code>c.prefs.hri</code>	college-side preference matrix for the college admissions problem (a.k.a. hospital/residents problem) with incomplete lists (HRI).
<code>matchings</code>	edgelist of matched students and colleges, including the number of the match ( <code>matching</code> ) and two variables that indicate the student-optimal match ( <code>sOptimal</code> ) and college-optimal match ( <code>cOptimal</code> )
.	.

### Minimum required arguments

`hri` requires the following combination of arguments, subject to the matching problem.

`nStudents, nColleges` Marriage problem with random preferences.

`s.prefs, c.prefs` Marriage problem with given preferences.

nStudents, nSlots College admissions problem with random preferences.  
 s.prefs, c.prefs, nSlots College admissions problem with given preferences.

### Author(s)

Thilo Klein

### References

Gale, D. and L.S. Shapley (1962). College admissions and the stability of marriage. *The American Mathematical Monthly*, 69(1):9–15.

Morizumi, Y., T. Hayashi and Y. Ishida (2011). A network visualization of stable matching in the stable marriage problem. *Artificial Life Robotics*, 16:40–43.

Prosser, P. (2014). Stable Roommates and Constraint Programming. *Lecture Notes in Computer Science, CPAIOR 2014 Edition*. Springer International Publishing, 8451: 15–28.

### Examples

```
## -----
## --- Marriage problem

## 7 men, 6 women, random preferences:
hri(nStudents=7, nColleges=6, seed=4)

## 3 men, 2 women, given preferences:
s.prefs <- matrix(c(1,2, 1,2, 1,2), 2,3)
c.prefs <- matrix(c(1,2,3, 1,2,3), 3,2)
hri(s.prefs=s.prefs, c.prefs=c.prefs)

## 3 men, 2 women, given preferences:
s.prefs <- matrix(c("x","y", "x","y", "x","y"), 2,3)
colnames(s.prefs) <- c("A","B","C")
c.prefs <- matrix(c("A","B","C", "A","B","C"), 3,2)
colnames(c.prefs) <- c("x","y")
hri(s.prefs=s.prefs, c.prefs=c.prefs)

## -----
## --- College admission problem

## 7 students, 2 colleges with 3 slots each, random preferences:
hri(nStudents=7, nSlots=c(3,3), seed=21)

## 7 students, 2 colleges with 3 slots each, given preferences:
s.prefs <- matrix(c(1,2, 1,2, 1,NA, 1,2, 1,2, 1,2, 1,2), 2,7)
c.prefs <- matrix(c(1,2,3,4,5,6,7, 1,2,3,4,5,NA,NA), 7,2)
hri(s.prefs=s.prefs, c.prefs=c.prefs, nSlots=c(3,3))

## 7 students, 2 colleges with 3 slots each, given preferences:
s.prefs <- matrix(c("x","y", "x","y", "x",NA, "x","y",
                  "x","y", "x","y", "x","y"), 2,7)
colnames(s.prefs) <- c("A","B","C","D","E","F","G")
```

```

c.prefs <- matrix(c("A","B","C","D","E","F","G",
                  "A","B","C","D","E",NA,NA), 7,2)
colnames(c.prefs) <- c("x","y")
hri(s.prefs=s.prefs, c.prefs=c.prefs, nSlots=c(3,3))

## 7 students, 3 colleges with 3 slots each, incomplete preferences:
hri(nStudents=7, nSlots=c(3,3,3), seed=21, s.range=c(1,3))

s.prefs <- matrix(c('S1', 'S2', NA,
                  'S3', 'S1', NA,
                  'S1', NA, NA,
                  NA, NA,NA,
                  'S2', 'S1', 'S5'),
                  nrow = 3, ncol = 5)

# Note that we explicitly allow for the existence of entries referring to colleges
# that do not exist. A warning is generated and the entry is ignored.
colnames(s.prefs) <- c('A', 'B', 'C', 'D', 'E')
c.prefs <- matrix(c('B', 'C', 'D', 'A',
                  'C', 'D', NA, NA,
                  'D', 'B', 'A', 'E'),
                  nrow = 4, ncol = 3)
colnames(c.prefs) <- c('S1', 'S2', 'S3')

hri(s.prefs=s.prefs, c.prefs=c.prefs, nSlots=c(3,3,3), check_consistency = TRUE)

## -----
## --- Summary plots

## 200 students, 200 colleges with 1 slot each
res <- hri(nStudents=200, nColleges=200, seed=12)
plot(res)
plot(res, energy=TRUE)

```

---

hri2

*Resident-optimal matching in the hospital/residents problem with couples*


---

### Description

Implements the Roth Peranson matching algorithm for the **hospital/residents problem with couples** as described in Roth and Peranson (1999). The function is based on an adoption of Bacchus (2018) and the SAT-solver of Sorensen (2013).

### Usage

```
hri2(
```

```

nStudents = ncol(s.prefs),
nColleges = ncol(c.prefs),
nSlots = rep(1, nColleges),
nCouples = ncol(co.prefs),
s.prefs = NULL,
c.prefs = NULL,
co.prefs = NULL,
randomization = "multiple",
seed = NULL,
check_consistency = TRUE,
verbose = FALSE,
...
)

```

### Arguments

nStudents	integer indicating the number of students (in the college admissions problem) or men (in the stable marriage problem) in the market. Defaults to <code>ncol(s.prefs)</code> .
nColleges	integer indicating the number of colleges (in the college admissions problem) or women (in the stable marriage problem) in the market. Defaults to <code>ncol(c.prefs)</code> .
nSlots	vector of length <code>nColleges</code> indicating the number of places (i.e. quota) of each college. Defaults to <code>rep(1, nColleges)</code> for the marriage problem.
nCouples	integer indicating the number of couples (in the college admissions problem) or men (in the stable marriage problem) in the market. Defaults to <code>ncol(co.prefs)</code>
s.prefs	matrix of dimension <code>nColleges x nStudents</code> with the <i>j</i> th column containing student <i>j</i> 's ranking over colleges in decreasing order of preference (i.e. most preferred first).
c.prefs	matrix of dimension <code>nStudents x nColleges</code> with the <i>i</i> th column containing college <i>i</i> 's ranking over students in decreasing order of preference (i.e. most preferred first).
co.prefs	matrix of dimension <code>4 x nCouples</code> in long format with the 1th and 2th columns containing student couple id's; 3th and 4th is a 2-tuple ranking over college preference for the couple ( <code>coupleStudent1.pref</code> , <code>coupleStudent2.pref</code> ) in decreasing order of preference by rows (i.e. most preferred first).
randomization	determines at which level and in which order random lottery numbers for student priorities are drawn. The default is <code>randomization = "multiple"</code> , where a student's priority is determined by a separate lottery at each college (i.e. local tie-breaking). For the second variant, <code>randomization = "single"</code> , a single lottery number determines a student's priority at all colleges (i.e. global tie breaking). A third variant is common in the context of course allocation, where a "couple" represents a student who submits a preference ranking over single courses (first course) and combinations of courses (first and second course). Here, the option <code>randomization = "single-course-first"</code> gives applications for a student's single courses strictly higher priority than for course combinations. This ensures the fairness criterion that a student is only assigned a second course after single course applications of all students have been considered.

seed	integer setting the state for random number generation.
check_consistency	Performs additional consistency checks if the preference matrices are given by characters. Defaults to FALSE. Set to FALSE to reduce run-time.
verbose	logical. When set to TRUE, writes information messages on the console (recommended). Defaults to FALSE, which suppresses such messages.
...	.

### Value

hri2 returns a list of the following elements:

matchings	List of matched students and colleges.
summary	Detailed report of the matching result, including further information on ranks.

### Minimum required arguments

hri2 requires the following combination of arguments, subject to the matching problem.

nStudents, nColleges Residence hospital problem without couples and random preferences

nStudents, nColleges, nCouples, nSlots Residence hospital problem with couples and random preferences.

s.prefs, c.prefs, co.prefs, nSlots Residence hospital problem with couples and given preferences.

### Author(s)

Fahiem Bacchus, Sven Giegerich, Thilo Klein, Niklas Sorensson

### References

Bacchus, F. (2018). Stable matching suite. GitHub repository.

Gale, D. and L.S. Shapley (1962). College admissions and the stability of marriage. *The American Mathematical Monthly*, 69(1):9–15.

Roth, A. E., & Peranson, E. (1999). The redesign of the matching market for American physicians: Some engineering aspects of economic design. *American economic review*, 89(4), 748-780.

Kojima, F., Pathak, P. A., & Roth, A. E. (2013). Matching with couples: Stability and incentives in large markets. *The Quarterly Journal of Economics*, 128(4), 1585-1632.

Sorensen, N. (2013). minisat. GitHub repository.

### Examples

```
## Example with given preferences
s.prefs <- matrix(c(4,2,3,5, 2,1,3,NA, 1,2,3,4), 4,3)
c.prefs <- matrix(rep(1:5,5), 5,5)
co.prefs <- matrix(c(rep(4,3), rep(5,3), 3,3,NA, 3,NA,3), 3,4)
res <- hri2(s.prefs=s.prefs, c.prefs=c.prefs, co.prefs=co.prefs, nSlots=rep(1,5))
res$matchings
```

```

# summary(res)

## Example with random preferences
nStudents <- 50
nColleges <- 30
nCouples <- 4
nSlots <- sample(1:nStudents, nColleges)
res <- hri2(nStudents=nStudents, nColleges=nColleges, nCouples=nCouples, nSlots=nSlots)
res$matchings
# summary(res)

## Example with characters in the preferences matrices
s.prefs <- matrix(c("Micro1", NA, NA,
                  "Micro2", "Micro1", "Macro",
                  "Macro", NA, NA),
                ncol = 3)
colnames(s.prefs) <- c('Lea', 'Mia', 'Kai')
c.prefs <- matrix(c("Niklas", "Kai", "Mia", "Anna",
                  "Lea", "Kai", "Anna", NA,
                  "Kai", "Mia", "Lea", NA),
                ncol = 3)
colnames(c.prefs) <- c('Micro1', 'Micro2', 'Macro')
col1 <- c(rep("Niklas",4),rep("Anna",5))
col2 <- c(rep("Jan",4),rep("Lisa",5))
col3 <- c("Micro1","Macro","Micro1",NA,"Macro",
          NA,"Micro2","Micro2","Macro")
col4 <- c("Micro2","Micro1",NA,"Macro","Macro",
          "Micro1","Micro2","Macro",NA)
co.prefs <- matrix(c(col1,col2,col3,col4), ncol = 4)
res <- hri2(s.prefs=s.prefs, c.prefs=c.prefs, co.prefs=co.prefs,
          nSlots=c(2,1,1))
res$matching

## Example if students are allowed to apply and be accepted by two courses
col12 <- c(rep(c(rep("Niklas",4),rep("Anna",2)),2))
col3 <- c("Micro1","Macro","Micro1","Macro","Macro","Macro")
col4 <- c("Micro2","Micro1",NA,NA,"Micro1","Micro2")
co.prefs <- matrix(c(col12,col3,col4), ncol = 4)
res <- hri2(s.prefs=s.prefs, c.prefs=c.prefs, co.prefs=co.prefs,
          nSlots=c(2,1,1))
res$matching

```

---

hri3

*Immediate Acceptance Algorithm (a.k.a. Boston mechanism) for two-sided matching markets*


---

## Description

Finds the optimal assignment of students to colleges in the **college admissions** problem based on the Boston mechanism. The algorithm is also applicable to the stable marriage problem. The option

acceptance="deferred" instead uses the Gale-Shapley (1962) Deferred Acceptance Algorithm with student offer. The function works with either given or randomly generated preferences.

### Usage

```
hri3(
  nStudents = ncol(s.prefs),
  nColleges = ncol(c.prefs),
  nSlots = rep(1, nColleges),
  s.prefs = NULL,
  c.prefs = NULL,
  acceptance = "immediate",
  consent = rep(FALSE, nStudents),
  eaItersMax = 1e+06,
  seed = NULL
)
```

### Arguments

nStudents	integer indicating the number of students (in the college admissions problem) or men (in the stable marriage problem) in the market. Defaults to ncol(s.prefs).
nColleges	integer indicating the number of colleges (in the college admissions problem) or women (in the stable marriage problem) in the market. Defaults to ncol(c.prefs).
nSlots	vector of length nColleges indicating the number of places (i.e. quota) of each college. Defaults to rep(1, nColleges) for the marriage problem.
s.prefs	matrix of dimension nColleges x nStudents with the jth column containing student j's ranking over colleges in decreasing order of preference (i.e. most preferred first).
c.prefs	matrix of dimension nStudents x nColleges with the ith column containing college i's ranking over students in decreasing order of preference (i.e. most preferred first).
acceptance	if acceptance="deferred" returns the solution found by the student-proposing Gale-Shapley deferred acceptance algorithm; if acceptance="immediate" (the default) returns the solution found by the Boston mechanism.
consent	logical vector (TRUE/FALSE) indicating consent for each of the students
eaItersMax	integer giving the maximum number of iterations for the EA heuristic step
seed	(Optional) integer setting the state for random number generation.

### Value

iaa returns a list with the following elements.

s.prefs	student-side preference matrix.
c.prefs	college-side preference matrix.
iterations	number of iterations required to find the stable matching.
matchings	edgelist of matches
singles	identifier of single (or unmatched) students/men.

**Minimum required arguments**

iaa requires the following combination of arguments, subject to the matching problem.

nStudents, nColleges Marriage problem with random preferences.

s.prefs, c.prefs Marriage problem with given preferences.

nStudents, nSlots College admissions problem with random preferences.

s.prefs, c.prefs, nSlots College admissions problem with given preferences.

**Author(s)**

Thilo Klein

**References**

Gale, D. and Shapley, L.S. (1962). College admissions and the stability of marriage. *The American Mathematical Monthly*, 69(1):9–15.

Kojima, F. and M.U. Unver (2014). The "Boston" school-choice mechanism. *Economic Theory*, 55(3): 515–544.

**Examples**

```
##\dontrun{
## -----
## --- College admission problem

s.prefs <- matrix(c(1,2,3,
                  1,2,3,
                  1,2,3,
                  2,1,3,
                  2,1,3),
                byrow = FALSE, ncol = 5, nrow = 3); s.prefs
c.prefs <- matrix(c(1,4,2,3,5,
                  5,2,3,4,1,
                  1,2,3,4,5),
                byrow = FALSE, ncol = 3, nrow = 5); c.prefs
nSlots <- c(2,2,1)

## Boston mechanism
iaa(s.prefs = s.prefs, c.prefs = c.prefs, nSlots = nSlots)$matchings

## Gale-Shapley algorithm
iaa(s.prefs = s.prefs, c.prefs = c.prefs, nSlots = nSlots, acceptance="deferred")$matchings

## Same results for the Gale-Shapley algorithm with hri2() function (but different format)
set.seed(123)
iaa(nStudents=7, nSlots=c(3,3), acceptance="deferred")$matchings
set.seed(123)
hri2(nStudents=7, nSlots=c(3,3))$matchings
##}
```

---

iaa	<i>Immediate Acceptance Algorithm (a.k.a. Boston mechanism) for two-sided matching markets</i>
-----	--

---

### Description

Finds the optimal assignment of students to colleges in the **college admissions** problem based on the Boston mechanism. The algorithm is also applicable to the stable marriage problem. The option `acceptance="deferred"` instead uses the Gale-Shapley (1962) Deferred Acceptance Algorithm with student offer. The function works with either given or randomly generated preferences.

### Usage

```
iaa(
  nStudents = ncol(s.prefs),
  nColleges = ncol(c.prefs),
  nSlots = rep(1, nColleges),
  s.prefs = NULL,
  c.prefs = NULL,
  acceptance = "immediate",
  short_match = TRUE,
  seed = NULL
)
```

### Arguments

<code>nStudents</code>	integer indicating the number of students (in the college admissions problem) or men (in the stable marriage problem) in the market. Defaults to <code>ncol(s.prefs)</code> .
<code>nColleges</code>	integer indicating the number of colleges (in the college admissions problem) or women (in the stable marriage problem) in the market. Defaults to <code>ncol(c.prefs)</code> .
<code>nSlots</code>	vector of length <code>nColleges</code> indicating the number of places (i.e. quota) of each college. Defaults to <code>rep(1, nColleges)</code> for the marriage problem.
<code>s.prefs</code>	matrix of dimension <code>nColleges x nStudents</code> with the <code>j</code> th column containing student <code>j</code> 's ranking over colleges in decreasing order of preference (i.e. most preferred first).
<code>c.prefs</code>	matrix of dimension <code>nStudents x nColleges</code> with the <code>i</code> th column containing college <code>i</code> 's ranking over students in decreasing order of preference (i.e. most preferred first).
<code>acceptance</code>	if <code>acceptance="deferred"</code> returns the solution found by the student-proposing Gale-Shapley deferred acceptance algorithm; if <code>acceptance="immediate"</code> (the default) returns the solution found by the Boston mechanism.
<code>short_match</code>	(Optional) If <code>FALSE</code> then in the returned matching, free capacities will be indicated with 0 entries. If <code>TRUE</code> , free capacities will not be reported in the returned matching but an additional data.frame is returned that contains free capacities. Defaults to <code>TRUE</code> .
<code>seed</code>	(Optional) integer setting the state for random number generation.

**Value**

iaa returns a list with the following elements.

s.prefs	student-side preference matrix.
c.prefs	college-side preference matrix.
iterations	number of iterations required to find the stable matching.
matchings	edgelist of matches
singles	identifier of single (or unmatched) students/men.

**Minimum required arguments**

iaa requires the following combination of arguments, subject to the matching problem.

nStudents, nColleges Marriage problem with random preferences.

s.prefs, c.prefs Marriage problem with given preferences.

nStudents, nSlots College admissions problem with random preferences.

s.prefs, c.prefs, nSlots College admissions problem with given preferences.

**Author(s)**

Thilo Klein

**References**

Gale, D. and Shapley, L.S. (1962). College admissions and the stability of marriage. *The American Mathematical Monthly*, 69(1):9–15.

Kojima, F. and M.U. Unver (2014). The "Boston" school-choice mechanism. *Economic Theory*, 55(3): 515–544.

**Examples**

```
## -----
## --- College admission problem

s.prefs <- matrix(c(1,2,3,
                  1,2,3,
                  1,2,3,
                  2,1,3,
                  2,1,3),
                byrow = FALSE, ncol = 5, nrow = 3)
c.prefs <- matrix(c(1,4,2,3,5,
                  5,2,3,4,1,
                  1,2,3,4,5),
                byrow = FALSE, ncol = 3, nrow = 5)
nSlots <- c(2,2,1)

## Boston mechanism
iaa(s.prefs = s.prefs, c.prefs = c.prefs, nSlots = nSlots)$matchings
```

```
## Gale-Shapley algorithm
iaa(s.prefs = s.prefs, c.prefs = c.prefs, nSlots = nSlots, acceptance="deferred")$matchings

## Same results for the Gale-Shapley algorithm with hri2() function (but different format)
set.seed(123)
iaa(nStudents=7, nSlots=c(3,3), acceptance="deferred")$matchings
set.seed(123)
hri2(nStudents=7, nSlots=c(3,3))$matchings
```

---

khh

*Karlson-Holm-Breen method for comparing probit coefficients*

---

### Description

Significance test for confounding; that is, the difference between regression coefficients from same-sample nested logit and probit models. The test procedure follows Karlson et al (2012), Section 3.4.

### Usage

```
khh(X, y, z)
```

### Arguments

X	data frame comprising independent variables including confounding variable.
y	vector of dependent variable.
z	character string giving the name of the confounding variable in X.

### Value

khh returns for all model coefficients the p-value for the null hypothesis that the change in coefficients is not attributable to confounding by z.

### Author(s)

Thilo Klein

### References

Karlson, K.B., A. Holm and R. Breen (2012). Comparing regression coefficients between same-sample nested models using logit and probit: A new method. *Sociological Methodology*, 42(1):286–313.

**Examples**

```
## 1. load results from Klein (2015a)
data(klein15a)

## 2. apply KHB method
with(klein15a$variables, khb(X=X, y=Y, z="eta"))
```

---

klein15a	<i>MCMC results in Klein (2015a)</i>
----------	--------------------------------------

---

**Description**

MCMC results in Klein (2015a).

**Usage**

```
data(klein15a)
```

**Format**

A list containing the following elements:

**model.list** .

**coefs** .

**References**

Klein, T. (2015a). [Does Anti-Diversification Pay? A One-Sided Matching Model of Microcredit.](#) *Cambridge Working Papers in Economics*, #1521.

---

klein15b	<i>Results of Monte Carlo Simulations in Klein (2015b)</i>
----------	--

---

**Description**

Results of Monte Carlo Simulations in Klein (2015b) for 40 two-group markets.

**Usage**

```
data(klein15b)
```

## Format

A list containing the following elements:

**exp.5.5.ols** Benchmark study, OLS: coefficient estimates for 40 markets with groups of 5. Data for all 5 group members is observed.

**exp.5.5.ntu** Benchmark study, structural model.

**exp.6.5.ols** Experiment 1, OLS: coefficient estimates for 40 markets with groups of 6. Only Data for 5 group members is observed.

**exp.6.5.ntu** Experiment 1, structural model.

**exp.6.6.ols** Experiment 2, OLS: coefficient estimates for 40 markets with groups of 6. Data for all 6 group members is observed but only a random sample of 250 of the 922 counterfactual groups is used in the analysis.

**exp.6.6.ntu** Experiment 2, structural model.

## References

Klein, T. (2015a). [Does Anti-Diversification Pay? A One-Sided Matching Model of Microcredit](#). *Cambridge Working Papers in Economics*, #1521.

Klein, T. (2015b). [Analysis of stable matchings in R: Package matchingMarkets](#). *Vignette to R package matchingMarkets*, The Comprehensive R Archive Network.

## Examples

```
## Plot of posterior distributions

data(klein15b)

tpe <- c(rep("Benchmark",2), rep("Experiment 1",2), rep("Experiment 2",2))

for(i in seq(1,length(klein15b)-1,2)){
  ntu <- klein15b[[i]]
  ols <- klein15b[[i+1]]

  ntu <- ntu[,colnames(ntu) == "beta.wst.ieq"]
  ols <- ols[,colnames(ols) == "beta.wst.ieq"]

  if(i == 1){
    draws <- data.frame(Structural=ntu, OLS=ols, type=tpe[i]) #, stringsAsFactors=FALSE
  } else{
    draws <- rbind(draws, data.frame(Structural=ntu, OLS=ols, type=tpe[i]))
  }
}

library(lattice)
lattice.options(default.theme = standard.theme(color = FALSE))
keys <- list(text=c("Structural model","OLS"), space="top", columns=2, lines=TRUE)
densityplot( ~ Structural + OLS | type, plot.points=FALSE, auto.key=keys,
  data = draws, xlab = "coefficient draws", ylab = "density", type = "l",
  panel = function(x,...) {
```

```

    panel.densityplot(x,...)
    panel.abline(v=-1, lty=3)
  })

## Modes of posterior distributions

## load data
data(klein15b)

## define function to obtain the mode
mode <- function(x){
  d <- density(x,bw="SJ")
  formatC(round(d$x[which.max(d$y)], 3), format='f', digits=3)
}

## Benchmark study
apply(klein15b$exp.5.5.ntu, 2, mode)
apply(klein15b$exp.5.5.ols, 2, mode)

## Experiment 1
apply(klein15b$exp.6.5.ntu, 2, mode)
apply(klein15b$exp.6.5.ols, 2, mode)

## Experiment 2
apply(klein15b$exp.6.6.ntu, 2, mode)
apply(klein15b$exp.6.6.ols, 2, mode)

```

---

plp

*Partitioning Linear Programme for the stable roommates problem*

---

### Description

Finds the stable matching in the **stable roommates problem** with transferable utility. Uses the Partitioning Linear Programme formulated in Quint (1991).

### Usage

```
plp(V = NULL, N = NULL)
```

### Arguments

V	valuation matrix of dimension NxN that gives row-players valuation over column players (or vice versa).
N	integer (divisible by 2) that gives the number of players in the market.

**Value**

plp returns a list with the following items.

Valuation.matrix

input values of V.

Assignment.matrix

upper triangular matrix of dimension  $N \times N$  with entries of 1 for equilibrium pairs and 0 otherwise.

Equilibrium.groups

matrix that gives the  $N/2$  equilibrium pairs and equilibrium partners' mutual valuations.

**Author(s)**

Thilo Klein

**References**

Quint, T. (1991). Necessary and sufficient conditions for balancedness in partitioning games. *Mathematical Social Sciences*, 22(1):87–91.

**Examples**

```
## Roommate problem with 10 players, transferable utility and random preferences:
plp(N=10)
```

```
## Roommate problem with 10 players, transferable utility and given preferences:
V <- matrix(rep(1:10, 10), 10, 10)
plp(V=V)
```

---

predict.stabit2	<i>Predict method for fitted matching models</i>
-----------------	--

---

**Description**

Calculate predicted values for matching models fitted with functions `stabit` and `stabit2`.

**Usage**

```
## S3 method for class 'stabit2'
predict(object, newdata = NULL, ...)
```

**Arguments**

object	a fitted object of class <code>stabit</code>
newdata	optionally, a data frame in which to look for variables with which to predict. If omitted, the fitted linear predictors or the fitted response values are returned.
...	.

**Value**

`predict.stabit2` returns a vector of predicted values for the latent outcome variable of an object of class `stabit`.

**Author(s)**

Thilo Klein

**References**

Klein, T. (2015a). [Does Anti-Diversification Pay? A One-Sided Matching Model of Microcredit](#). *Cambridge Working Papers in Economics*, #1521.

**Examples**

```
## load the results from Klein (2015) paper
data(klein15a)

## predict the latent outcome variable
predict(klein15a)
```

---

rsd

*Random serial dictatorship mechanism*

---

**Description**

Implements the **random serial dictatorship** algorithm for a fair division of indivisible objects among individuals. The mechanism takes individuals' priority order as an input or alternatively draws a random permutation of the agents from the uniform distribution. Individuals are then successively assigned an object in that order (so the first agent in the ordering gets the first pick and so on).

**Usage**

```
rsd(
  nIndividuals = ncol(prefs),
  nObjects = nrow(prefs),
  prefs,
  priority,
  seed = NULL,
  nSlots = rep(1, nObjects)
)
```

**Arguments**

nIndividuals	integer indicating the number of individuals in the matching problem. Defaults to ncol(prefs).
nObjects	integer indication the number of objects in the matching problem. Defaults to nrow(prefs).
prefs	matrix of dimension nObjects x nIndividuals with the jth column containing students j's ranking over the objects in decreasing order of preference (i.e. most preferred first).
priority	(Optional) vector of length nIndividuals indicating the priority of the individuals in decreasing order (i.e. highest individuals first). If none is given, a random order is chosen.
seed	(Optional) integer setting the state for random number generation. Defaults to seed = 123.
nSlots	(Optional) vector of length nObjects indicating the owners/slots possible/available for each object. (If nSlots only consists of ones this means that every object can only have one owner, if the numbers are higher interpreting objects for example as schools might be more intuitive). Defaults to a vector of length nObjects filled with ones.

**Value**

rsd returns a data frame containing the final matching of individuals (ind) to objects (obj).

**Author(s)**

Thilo Klein, Alexander Sauer

**Examples**

```
## Generate preference-matrix
prefs <- matrix(c(1,2,3,
                 3,1,2,
                 1,3,2),
               byrow = FALSE, ncol = 3)

priority <- c(1,2,3)
nSlots <- c(1,1,1)

rsd(prefs = prefs, priority = priority, nSlots = nSlots)
```

**Description**

Finds all stable matchings (if one exists) in the **stable roommates problem** with incomplete lists using the Prosser (2014) constraint encoding based on either given or randomly generated preferences.

**Usage**

```
sri(prefs = NULL, nAgents = NULL, seed = NULL, p.range = NULL)
```

**Arguments**

prefs	valuation matrix of dimension $nAgents \times nAgents$ that gives column-players' ranking over other players in decreasing order of preference (i.e. most preferred first).
nAgents	integer that gives the number of players in the market.
seed	integer setting the state for random number generation.
p.range	range of two integers $p.range = c(p.min, p.max)$ , where $p.min < p.max$ . Produces incomplete preference lists with the length of each player's list randomly sampled from the range $[p.min, p.max]$ . Note: interval is always too small because non-permissible matches are automatically deleted.

**Value**

sri returns a list with the following items.

prefs	agents' preference list.
matching	edgelist of matched pairs, including the number of the match (matching).

**Author(s)**

Thilo Klein

**References**

- Gusfield, D.M. and R.W. Irving (1989). *The Stable Marriage Problem: Structure and Algorithms*, MIT Press.
- Prosser, P. (2014). *Stable Roommates and Constraint Programming*. *Lecture Notes in Computer Science, CPAIOR 2014 Edition*. Springer International Publishing, 8451: 15–28.
- Irving, R.W. (1985). An efficient algorithm for the "stable roommates" problem. *Journal of Algorithms*, 6(4): 577–595.
- Irving, R.W. and S. Scott (2007). The stable fixtures problem: A many-to-many extension of stable roommates. *Discrete Applied Mathematics*, 155: 2118–2129.

**Examples**

```
## Roommate problem with 10 players, given preferences:
prefs <- matrix(rep(1:10, 10), 10, 10)
sri(prefs=prefs)

## Roommate problem with 10 players, random preferences:
sri(nAgents=10, seed=1)

## Roommate problem with no equilibrium matching:
sri(nAgents=10, seed=2)

## Roommate problem with 3 equilibria:
sri(nAgents=10, seed=3)
```

---

stabchk

*Stability-Check*


---

**Description**

Checks a given two sided matching for blocking pairs.

**Usage**

```
stabchk(
  matching,
  c.prefs,
  s.prefs,
  nColleges = ncol(c.prefs),
  nStudents = ncol(s.prefs)
)
```

**Arguments**

matching	data frame or matrix of dimension $(\min[n\text{Colleges}, n\text{Students}]) \times 2$ containing in column 1 the colleges and in column 2 the students with each row forming a couple.
c.prefs	matrix of dimension $n\text{Students} \times n\text{Colleges}$ with column $j$ containing college $j$ 'th ranking over students in decreasing order of preferences.
s.prefs	matrix of dimension $n\text{Colleges} \times n\text{Students}$ with column $j$ containing student $j$ 'th ranking over colleges in decreasing order of preferences.
nColleges	integer indicating the number of colleges
nStudents	integer indicating the number of students

**Value**

stabchk returns a data frame with as many rows as blocking pairs were found. Column 1 indicates the college and column 2 indicate the student of the blocking pairs. Returns NULL if no blocking pair is found.

**Author(s)**

Thilo Klein, Alexander Sauer

**Examples**

```
## 1-a. Generate preferences for colleges
c.prefs = matrix(c(1,2,3,
                  3,2,1,
                  3,2,1),
                byrow = FALSE, ncol = 3)

## 1-b. Generate preferences for students
s.prefs = matrix(c(1,2,3,
                  3,2,1,
                  2,1,3),
                byrow = FALSE, ncol = 3)

## 1-c. Generate matching
matching = matrix(c(1,2,
                  2,1,
                  3,3),
                byrow = TRUE, ncol = 2)

## 1-d. Check stability
stabchk(matching = matching, c.prefs = c.prefs, s.prefs = s.prefs)

## 2-a. Generate new matching without blocking pairs as a data frame
matching = data.frame('colleges' = c(1,2,3), 'student' = c(1,3,2))
stabchk(matching = matching, c.prefs = c.prefs, s.prefs = s.prefs)

## 3-a. Example with missing values:
matching <- matrix(c(1,1,2,2,3,3), byrow = FALSE, ncol = 2)
c.prefs <- matrix(c(1,1,3,rep(NA, 6)), byrow = TRUE, ncol = 3)
s.prefs <- matrix(c(2,2,3,rep(NA, 6)), byrow = TRUE, ncol = 3)
stabchk(matching = matching, c.prefs = c.prefs, s.prefs = s.prefs)
```

## Description

The function provides a Gibbs sampler for a structural matching model that estimates preferences and corrects for sample selection bias when the selection process is a one-sided matching game; that is, group/coalition formation.

The input is individual-level data of all group members from one-sided matching markets; that is, from group/coalition formation games.

In a first step, the function generates a model matrix with characteristics of *all feasible* groups of the same size as the observed groups in the market.

For example, in the stable roommates problem with  $n = 4$  students  $\{1, 2, 3, 4\}$  sorting into groups of 2, we have  $\binom{4}{2} = 6$  feasible groups: (1,2)(3,4) (1,3)(2,4) (1,4)(2,3).

In the group formation problem with  $n = 6$  students  $\{1, 2, 3, 4, 5, 6\}$  sorting into groups of 3, we have  $\binom{6}{3} = 20$  feasible groups. For the same students sorting into groups of sizes 2 and 4, we have  $\binom{6}{2} + \binom{6}{4} = 30$  feasible groups.

The structural model consists of a selection and an outcome equation. The *Selection Equation* determines which matches are observed ( $D = 1$ ) and which are not ( $D = 0$ ).

$$\begin{aligned} D &= 1[V \in \Gamma] \\ V &= W\alpha + \eta \end{aligned}$$

Here,  $V$  is a vector of latent valuations of *all feasible* matches, ie observed and unobserved, and  $1[\cdot]$  is the Iverson bracket. A match is observed if its match valuation is in the set of valuations  $\Gamma$  that satisfy the equilibrium condition (see Klein, 2015a). This condition differs for matching games with transferable and non-transferable utility and can be specified using the method argument. The match valuation  $V$  is a linear function of  $W$ , a matrix of characteristics for *all feasible* groups, and  $\eta$ , a vector of random errors.  $\alpha$  is a parameter vector to be estimated.

The *Outcome Equation* determines the outcome for *observed* matches. The dependent variable can either be continuous or binary, dependent on the value of the binary argument. In the binary case, the dependent variable  $R$  is determined by a threshold rule for the latent variable  $Y$ .

$$\begin{aligned} R &= 1[Y > c] \\ Y &= X\beta + \epsilon \end{aligned}$$

Here,  $Y$  is a linear function of  $X$ , a matrix of characteristics for *observed* matches, and  $\epsilon$ , a vector of random errors.  $\beta$  is a parameter vector to be estimated.

The structural model imposes a linear relationship between the error terms of both equations as  $\epsilon = \delta\eta + \xi$ , where  $\xi$  is a vector of random errors and  $\delta$  is the covariance parameter to be estimated. If  $\delta$  were zero, the marginal distributions of  $\epsilon$  and  $\eta$  would be independent and the selection problem would vanish. That is, the observed outcomes would be a random sample from the population of interest.

## Usage

```
stabit(
  x,
  m.id = "m.id",
  g.id = "g.id",
  R = "R",
```

```

selection = NULL,
outcome = NULL,
simulation = "none",
seed = 123,
max.combs = Inf,
method = "NTU",
binary = FALSE,
offsetOut = 0,
offsetSel = 0,
marketFE = FALSE,
censored = 0,
gPrior = FALSE,
dropOnes = FALSE,
interOut = 0,
interSel = 0,
standardize = 0,
niter = 10,
verbose = FALSE
)

```

### Arguments

x	data frame with individual-level characteristics of all group members including market- and group-identifiers.
m.id	character string giving the name of the market identifier variable. Defaults to "m.id".
g.id	character string giving the name of the group identifier variable. Defaults to "g.id".
R	dependent variable in outcome equation. Defaults to "R".
selection	list containing variables and pertaining operators in the selection equation. The format is <code>operation = "variable"</code> . See the Details and Examples sections.
outcome	list containing variables and pertaining operators in the outcome equation. The format is <code>operation = "variable"</code> . See the Details and Examples sections.
simulation	should the values of dependent variables in selection and outcome equations be simulated? Options are "none" for no simulation, "NTU" for non-transferable utility matching, "TU" for transferable utility or "random" for random matching of individuals to groups. Simulation settings are (i) all model coefficients set to $\alpha=\beta=1$ ; (ii) covariance between error terms $\delta=0.5$ ; (iii) error terms $\eta$ and $\xi$ are draws from a standard normal distribution.
seed	integer setting the state for random number generation if <code>simulation=TRUE</code> .
max.combs	integer (divisible by two) giving the maximum number of feasible groups to be used for generating group-level characteristics.
method	estimation method to be used. Either "NTU" or "TU" for selection correction using non-transferable or transferable utility matching as selection rule; "outcome" for estimation of the outcome equation only; or "model.frame" for no estimation.

binary	logical: if TRUE outcome variable is taken to be binary; if FALSE outcome variable is taken to be continuous.
offsetOut	vector of integers indicating the indices of columns in X for which coefficients should be forced to 1. Use 0 for none.
offsetSel	vector of integers indicating the indices of columns in W for which coefficients should be forced to 1. Use 0 for none.
marketFE	logical: if TRUE market-level fixed effects are used in outcome equation; if FALSE no market fixed effects are used.
censored	draws of the delta parameter that estimates the covariation between the error terms in selection and outcome equation are 0:not censored, 1:censored from below, 2:censored from above.
gPrior	logical: if TRUE the g-prior (Zellner, 1986) is used for the variance-covariance matrix.
dropOnes	logical: if TRUE one-group-markets are excluded from estimation.
interOut	two-colum matrix indicating the indices of columns in X that should be interacted in estimation. Use 0 for none.
interSel	two-colum matrix indicating the indices of columns in W that should be interacted in estimation. Use 0 for none.
standardize	numeric: if <code>standardize&gt;0</code> the independent variables will be standardized by dividing by <code>standardize</code> times their standard deviation. Defaults to no standardization <code>standardize=0</code> .
niter	number of iterations to use for the Gibbs sampler.
verbose	logical. When set to TRUE, writes information messages on the console (recommended). Defaults to FALSE, which suppresses such messages.

## Details

Operators for variable transformations in selection and outcome arguments.

`add` sum over all group members and divide by group size.

`int` sum over all possible two-way interactions  $x * y$  of group members and divide by the number of those, given by `choose(n, 2)`.

`ieq` sum over all possible two-way equality assertions  $1[x = y]$  and divide by the number of those.

`ive` sum over all possible two-way interactions of vectors of variables of group members and divide by number of those.

`inv` ...

`dst` sum over all possible two-way distances between players and divide by number of those, where distance is defined as  $e^{-|x-y|}$ .

## Value

`stabit` returns for `method = "model.frame"`, a list of data from a NTU or TU matching market with the following elements.

OUT	Model matrix of the outcome data, where <code>m.id</code> and <code>g.id</code> are categorical variables for market and group identifier.
SEL	Model matrix of the selection data, again with categorical variables <code>m.id</code> and <code>g.id</code> for market and group identifier.
combs	List of length of the number of markets with each element containing a matrix of all counterfactual group constellations in a market.

For any other setting of `method`, a list of the estimation results is returned.

### Author(s)

Thilo Klein

### References

Klein, T. (2015a). *Does Anti-Diversification Pay? A One-Sided Matching Model of Microcredit*. *Cambridge Working Papers in Economics*, #1521.

Zellner, A. (1986). *On assessing prior distributions and Bayesian regression analysis with g-prior distributions*, volume 6, pages 233–243. North-Holland, Amsterdam.

### Examples

```
## --- SIMULATED EXAMPLE ---

## 1. Simulate one-sided matching data for 200 markets (m=200) with 2 groups
##   per market (gpm=2) and 5 individuals per group (ind=5). True parameters
##   in selection equation is wst=1, in outcome equation wst=0.

## 1-a. Simulate individual-level, independent variables
idata <- stabsim(m=200, ind=5, seed=123, gpm=2)
head(idata)

## 1-b. Simulate group-level variables
mdata <- stabit(x=idata, simulation="NTU", method="model.frame",
  selection = list(add="wst"), outcome = list(add="wst"), verbose=FALSE)
head(mdata$OUT)
head(mdata$SEL)

## 2. Bias from sorting

## 2-a. Naive OLS estimation
lm(R ~ wst.add, data=mdata$OUT)$coefficients

## 2-b. epsilon is correlated with independent variables
with(mdata$OUT, cor(epsilon, wst.add))

## 2-c. but xi is uncorrelated with independent variables
with(mdata$OUT, cor(xi, wst.add))
```

```

## 3. Correction of sorting bias when valuations V are observed

## 3-a. 1st stage: obtain fitted value for eta
lm.sel <- lm(V ~ -1 + wst.add, data=mdata$SEL)
lm.sel$coefficients

eta <- lm.sel$resid[mdata$SEL$D==1]

## 3-b. 2nd stage: control for eta
lm(R ~ wst.add + eta, data=mdata$OUT)$coefficients

## 4. Run Gibbs sampler
fit1 <- stabit(x=idata, method="NTU", simulation="NTU", censored=1,
              selection = list(add="wst"), outcome = list(add="wst"),
              niter=2000, verbose=FALSE)

## 5. Coefficient table
summary(fit1)

## 6. Plot MCMC draws for coefficients
plot(fit1)

## Not run:
## --- REPLICATION, Klein (2015a) ---
## see vignette/script for the full replication

## 1. Load data
data(baac00)

## 2. Run Gibbs sampler
klein15a <- stabit(x=baac00, selection = list(inv="pi",ieq="wst"),
                  outcome = list(add="pi",inv="pi",ieq="wst",
                                add=c("loan_size","loan_size2","lgroup_agei")), offsetOut=1,
                  method="NTU", binary=TRUE, gPrior=TRUE, marketFE=TRUE, niter=800000)

## 3. Marginal effects
summary(klein15a, mfx=TRUE)

## 4. Plot MCMC draws for coefficients
plot(klein15a)

## End(Not run)

```

## Description

The function provides a Gibbs sampler for a structural matching model that estimates preferences and corrects for sample selection bias when the selection process is a two-sided matching game; i.e., a matching of students to colleges.

The structural model consists of a selection and an outcome equation. The *Selection Equation* determines which matches are observed ( $D = 1$ ) and which are not ( $D = 0$ ).

$$\begin{aligned} D &= 1[V \in \Gamma] \\ V &= W\beta + \eta \end{aligned}$$

Here,  $V$  is a vector of latent valuations of *all feasible* matches, ie observed and unobserved, and  $1[\cdot]$  is the Iverson bracket. A match is observed if its match valuation is in the set of valuations  $\Gamma$  that satisfy the equilibrium condition (see Sorensen, 2007). The match valuation  $V$  is a linear function of  $W$ , a matrix of characteristics for *all feasible* matches, and  $\eta$ , a vector of random errors.  $\beta$  is a parameter vector to be estimated.

The *Outcome Equation* determines the outcome for *observed* matches. The dependent variable can either be continuous or binary, dependent on the value of the binary argument. In the binary case, the dependent variable  $R$  is determined by a threshold rule for the latent variable  $Y$ .

$$\begin{aligned} R &= 1[Y > c] \\ Y &= X\alpha + \epsilon \end{aligned}$$

Here,  $Y$  is a linear function of  $X$ , a matrix of characteristics for *observed* matches, and  $\epsilon$ , a vector of random errors.  $\alpha$  is a parameter vector to be estimated.

The structural model imposes a linear relationship between the error terms of both equations as  $\epsilon = \kappa\eta + \nu$ , where  $\nu$  is a vector of random errors and  $\kappa$  is the covariance parameter to be estimated. If  $\kappa$  were zero, the marginal distributions of  $\epsilon$  and  $\eta$  would be independent and the selection problem would vanish. That is, the observed outcomes would be a random sample from the population of interest.

## Usage

```
stabit2(
  OUT = NULL,
  SEL = NULL,
  colleges = NULL,
  students = NULL,
  outcome = NULL,
  selection,
  binary = FALSE,
  niter,
  gPrior = FALSE,
  censored = 1,
  thin = 1,
  nCores = max(1, detectCores() - 1),
  verbose = FALSE,
  ...
)
```

**Arguments**

OUT	data frame with characteristics of all observed matches, including market identifier <code>m.id</code> , college identifier <code>c.id</code> and student identifier <code>s.id</code> .
SEL	optional: data frame with characteristics of all observed and unobserved matches, including market identifier <code>m.id</code> , college identifier <code>c.id</code> and student identifier <code>s.id</code> .
colleges	character vector of variable names for college characteristics. These variables carry the same value for any college.
students	character vector of variable names for student characteristics. These variables carry the same value for any student.
outcome	formula for match outcomes.
selection	formula for match valuations.
binary	logical: if TRUE outcome variable is taken to be binary; if FALSE outcome variable is taken to be continuous.
niter	number of iterations to use for the Gibbs sampler.
gPrior	logical: if TRUE the g-prior (Zellner, 1986) is used for the variance-covariance matrix. (Not yet implemented)
censored	draws of the kappa parameter that estimates the covariation between the error terms in selection and outcome equation are 0:not censored, 1:censored from below, 2:censored from above.
thin	integer indicating the level of thinning in the MCMC draws. The default <code>thin=1</code> saves every draw, <code>thin=2</code> every second, etc.
nCores	number of cores to be used in parallel Gibbs sampling.
verbose	logical. When set to TRUE, writes information messages on the console (recommended). Defaults to FALSE, which suppresses such messages.
...	.

**Value**

`stabit2` returns a list of the estimation results with the following elements.

<code>sigma</code>	numeric scalar: standard deviation fixed to 1.
<code>eta</code>	numeric vector: residuals of the selection equation.
<code>vcov</code>	List of variance covariance matrices for coefficients alpha and beta of selection and outcome equations.
<code>coefficients</code>	numeric vector: coefficients of selection and outcome equations.
<code>fitted.values</code>	numeric vector: fitted values for outcome data.
<code>residuals</code>	numeric vector: residuals of the outcome equation.
<code>df</code>	integer: degrees of freedom.
<code>binary</code>	logical: if TRUE outcome variable was taken to be binary; if FALSE outcome variable was taken to be continuous.
<code>formula</code>	estimated formula.

call	function call.
method	One of "Sorensen", "Klein" or "Klein-selection". Method "Sorensen" is used when a single selection equation is passed. It assumes an equal sharing rule for student and college utility. Method "Klein" is used when two selection equations (one for students, one for schools) and one outcome equations are passed. Method "Klein-selection" only models selection and therefore does not require an outcome equations.
draws	List of Gibbs sampling draws for alpha and beta coefficients.
coefs	Posterior means of the Gibbs sampling draws.
variables	List of data used in the estimation.

### Author(s)

Thilo Klein

### References

Sorensen, M. (2007). How Smart is Smart Money? A Two-Sided Matching Model of Venture Capital. *Journal of Finance*, 62 (6): 2725-2762.

### Examples

```
## --- SIMULATED EXAMPLE ---

## 1. Simulate two-sided matching data for 20 markets (m=20) with 100 students
##   (nStudents=100) per market and 20 colleges with quotas of 5 students, each
##   (nSlots=rep(5,20)). True parameters in selection and outcome equations are
##   all equal to 1.

xdata <- stabsim2(m=20, nStudents=100, nSlots=rep(5,20), verbose=FALSE,
  colleges = "c1", students = "s1",
  outcome = ~ c1:s1 + eta + nu,
  selection = ~ -1 + c1:s1 + eta
)
head(xdata$OUT)

## 2. Correction for sorting bias when match valuations V are observed

## 2-a. Bias from sorting
lm1 <- lm(y ~ c1:s1, data=xdata$OUT)
summary(lm1)

## 2-b. Cause of the bias
with(xdata$OUT, cor(c1*s1, eta))

## 2-c. Correction for sorting bias
lm2a <- lm(V ~ -1 + c1:s1, data=xdata$SEL); summary(lm2a)
etahat <- lm2a$residuals[xdata$SEL$D==1]
```

```

lm2b <- lm(y ~ c1:s1 + etahat, data=xdata$OUT)
summary(lm2b)

## 3. Correction for sorting bias when match valuations V are unobserved

## 3-a. Run Gibbs sampler (when SEL is given)
fit2 <- stabit2(OUT = xdata$OUT,
               SEL = xdata$SEL,
               outcome = y ~ c1:s1,
               selection = ~ -1 + c1:s1,
               niter=1000
              )

## 3-b. Alternatively: Run Gibbs sampler (when SEL is not given)
fit2 <- stabit2(OUT = xdata$OUT,
               colleges = "c1",
               students = "s1",
               outcome = y ~ c1:s1,
               selection = ~ -1 + c1:s1,
               niter=1000
              )

## 4. Implemented methods

## 4-a. Get coefficients
fit2

## 4-b. Coefficient table
summary(fit2)

## 4-c. Get marginal effects
summary(fit2, mfx=TRUE)

## 4-d. Also try the following functions
#coef(fit2)
#fitted(fit2)
#residuals(fit2)
#predict(fit2, newdata=NULL)

## 5. Plot MCMC draws for coefficients
plot(fit2)

```

---

stabsim

*Simulated data for group formation problem*


---

## Description

Simulate individual-level data for one-sided matching markets.

**Usage**

```
stabsim(m, ind, seed = 123, singles = NULL, gpm = 2)
```

**Arguments**

<code>m</code>	integer indicating the number of markets to be simulated.
<code>ind</code>	integer (or vector) indicating the number of individuals per group.
<code>seed</code>	integer setting the state for random number generation. Defaults to <code>set.seed(123)</code> .
<code>singles</code>	integer giving the number of one-group markets.
<code>gpm</code>	integer giving the number of groups per market.

**Value**

`stabsim` returns a data frame with the randomly generated variables mimicking those in dataset [baac00](#).

<code>m.id</code>	categorical: market identifier.
<code>g.id</code>	categorical: group identifier.
<code>wst</code>	binary: indicator taking the value 1 if last year was worse than the year before; 0 otherwise.
<code>R</code>	NA: group outcome is not simulated. It can be obtained using the simulation argument in function <code>stabit</code> .

**Author(s)**

Thilo Klein

**Examples**

```
## Coalitions [gpm := 2 !]
## Simulate one-sided matching data for 4 markets (m=4) with 2 groups
## per market (gpm=2) and 2 to 4 individuals per group (ind=2:4)
idata <- stabsim(m=4, ind=2:4, seed=124, singles=2, gpm=2)

## Rommmates [ind := 2 !]
## Simulate one-sided matching data for 3 markets (m=3) with 3 groups
## per market (gpm=3) and 2 individuals per group (ind=2)
idata <- stabsim(m=3, ind=2, seed=124, gpm=3)
```

---

stabsim2

*Simulated data for college admissions problem*


---

### Description

Simulate data for two-sided matching markets. In the simulation for the Sorensen (2007) model with one selection equation, an equal sharing rule of  $\lambda = 0.5$  is used.

### Usage

```
stabsim2(
  m,
  nStudents,
  nColleges = length(nSlots),
  nSlots,
  colleges,
  students,
  outcome,
  selection,
  binary = FALSE,
  seed = 123,
  verbose = TRUE
)
```

### Arguments

<code>m</code>	integer indicating the number of markets to be simulated.
<code>nStudents</code>	integer indicating the number of students per market.
<code>nColleges</code>	integer indicating the number of colleges per market.
<code>nSlots</code>	vector of length <code>nColleges</code> indicating the number of places at each college, i.e. the college's quota.
<code>colleges</code>	character vector of variable names for college characteristics. These variables carry the same value for any college.
<code>students</code>	character vector of variable names for student characteristics. These variables carry the same value for any student.
<code>outcome</code>	formula for match outcomes.
<code>selection</code>	formula for match valuations.
<code>binary</code>	logical: if TRUE outcome variable is binary; if FALSE outcome variable is continuous.
<code>seed</code>	integer setting the state for random number generation. Defaults to <code>set.seed(123)</code> .
<code>verbose</code>	.

**Value**

stabsim2 returns a list with the following items.

```
OUT
SEL
SElc
SEls
```

**Author(s)**

Thilo Klein

**Examples**

```
## Simulate two-sided matching data for 2 markets (m=2) with 10 students
## (nStudents=10) per market and 3 colleges (nColleges=3) with quotas of
## 2, 3, and 5 students, respectively.

xdata <- stabsim2(m=2, nStudents=10, nSlots=c(2,3,5), verbose=FALSE,
  colleges = "c1", students = "s1",
  outcome = ~ c1:s1 + eta + nu,
  selection = ~ -1 + c1:s1 + eta
)
head(xdata$OUT)
head(xdata$SEL)
```

---

ttc

*Top-Trading-Cycles Algorithm with existing tenants*

---

**Description**

Implements an algorithm for the **house allocation problem** proposed by Abdulkadiroglu and Sonmez (1999) for a matching problem in which there are both vacant houses and existing tenants.

**Usage**

```
ttc(
  nStudents = ncol(s.prefs),
  nHouses = length(houses),
  s.prefs,
  houses,
  priority = NULL,
  seed = NULL
)
```

**Arguments**

nStudents	integer indicating the number of students. Defaults to ncol(s.prefs).
nHouses	integer indicating the number of houses. Defaults to length(houses).
s.prefs	matrix of dimension nHouses x nStudents with column j containing student jth ranking over houses in decreasing order of preferences (i.e. most preferred first).
houses	vector of length nHouses which represents the occupation of the houses. Entry in k contains j if student j is living in house k and NA if house k is vacant.
priority	(Optional) vector of length nStudents. Gives the priority ordering of the students in the search for cycles (Do not confuse it with the preferences!), if nothing is specified a random ordering is chosen.
seed	(Optional) integer setting the state for random number generation. Defaults to seed = NULL

**Value**

ttc returns a data frame of the matching of students (int) to houses (obj) for the house allocation problem based on the Top-Trading-Cycles algorithm.

**Author(s)**

Thilo Klein, Alexander Sauer

**References**

Abdulkadiroglu, A. and T. Sonmez (1999). House Allocation with Existing Tenants. *Journal of Economic Theory*, 88 (2): 233-260.

Shapley, L. and H. Scarf (1974). On Cores and Indivisibility. *Journal of Mathematical Economics*, 1(1): 23-37.

**Examples**

```
## 1-a. Generate matrix of individuals' preference rankings over objects,
## a.k.a. Rank Order Lists (ROL).
s.prefs <- matrix(c(3,2,4,1,      # ROL of student 1
                  3,5,6, NA,
                  3,1, NA,NA,
                  2,5,6,4,
                  1,3,2,NA,
                  2,4,5,6), nrow = 4, ncol = 6, byrow = FALSE)

## 1-b. Generate vector of house occupation objects ('obj') and their owners ('ind')
houses <- 1:6

## 1-c. Find assignment based on TTC algorithm
ttc(s.prefs = s.prefs, houses = houses, nHouses = 6, priority = 1:6)

## 2-a. Compare the example in the paper Abdulkadiroglu et al. (1999)
```

```

## on page 246-248 (section 5.1 An Example):
## generate matrix of students' preference rankings over houses, a.k.a. Rank Order Lists (ROL)
s.prefs <- matrix(c(2,6,5,1,4,3,7,NA,
                  7,1,6,5,4,3,2,NA,
                  2,1,4,7,3,6,5,NA,
                  2,4,3,6,1,7,5,NA,
                  4,3,7,1,2,5,6,NA), byrow = FALSE, ncol= 5)

## 2-b. Generate house occupation, so student 1 lives in house 1, ..., student 4 lives in house 4
## and the other houses are vacant.
houses <- c(1,2,3,4,NA,NA,NA,NA)

## 2-c. Generate priority ordering
priority <- 1:5

## 2-d. Find assignment
ttc(s.prefs = s.prefs, houses = houses, priority = priority)

```

---

ttc2

---

*Top-Trading-Cycles Algorithm for a two sided matching problem*


---

## Description

Implements the school matching algorithm proposed in Abdulkadiroglu and Sonmez (2003) for a matching problem in which both sides have preferences. Missing preferences are handled in the following ways: Suppose that a student only ranked colleges that are already matched to other students. This student is removed from the matching process and a list with all unmatchable students is printed. If `full_return` is set to `TRUE`, a vector with this students is returned as well. Now suppose during the matching process a student points to a college that still has capacities but does not rank any more students. We assume now that the college is indifferent over all other students (so we do not allow for free capacities) and we match the student who wants to go there to the college.

## Usage

```

ttc2(
  nStudents = ncol(s.prefs),
  nColleges = ncol(c.prefs),
  s.prefs = NULL,
  c.prefs = NULL,
  nSlots = NULL,
  priority = NULL,
  seed = NULL,
  full_return = FALSE,
  verbose = FALSE
)

```

**Arguments**

nStudents	integer indicating the number of students in the matching problem. Defaults to ncol(s.prefs).
nColleges	integer indicating the number of colleges in the matching problem. Defaults to ncol(c.prefs).
s.prefs	matrix of dimension nColleges x nStudents with the jth column containing student j's ranking over colleges in decreasing order of preference (i.e. most preferred first).
c.prefs	matrix of dimension nStudents x nColleges with the ith column containing college i's ranking over students in decreasing order of preference (i.e. most preferred first).
nSlots	vector of length nColleges indicating the number of places (i.e. quota) of each college.
priority	(Optional) vector of length nStudents. Gives the priority ordering of the students in the search for cycles (Do not confuse it with the preferences!), if nothing is specified a random ordering is chosen.
seed	(Optional) integer setting the state for random number generation. Defaults to seed = NULL
full_return	(Optinal) If TRUE the return value is a list with the matching, the remaining seats and the unmatchable students is returned. Defaults to FALSE and only the matching is returned.
verbose	logical. When set to TRUE, writes information messages on the console (recommended). Defaults to FALSE, which suppresses such messages.

**Value**

ttc2 returns a data frame of the matching of students (ind) to colleges (obj) for the school market problem based on the Top-Trading-Cycles algorithm.

**Author(s)**

Thilo Klein, Alexander Sauer

**References**

Abdulkadiroglu, A. and T. Sonmez (2003). School Choice: A Mechanism Design Approach. *American Economic Review*, 93 (3): 729-747.

**Examples**

```
## 1-a. Compare example from the Abdulkadiroglu et al. (2003) (in the Appendix, page 742-744)
## 1-b. Generate matrix of students' preference rankings over schools, a.k.a. Rank Order Lists (ROL)
s.prefs <- matrix(c(
  2,1,3,4,
  1,2,3,4,
  3,2,1,4,
  3,4,1,2,
```

```

1,3,4,2,
4,1,2,3,
1,2,3,4,
1,2,4,3),
byrow = FALSE, ncol = 8)

## 1-c. Generate matrix of schools' preference rankings over students, a.k.a. Rank Order Lists (ROL)
c.prefs <- matrix(c(
  1,2,3,4,5,6,7,8,
  3,5,4,8,7,2,1,6,
  5,3,1,7,2,8,6,4,
  6,8,7,4,2,3,5,1),
  byrow = FALSE, ncol = 4)

## 1-d. Generate capacities
nSlots <- c(2,2,3,3)

## 1-e. Find assignment based on TTC algorithm
ttc2(s.prefs = s.prefs, c.prefs = c.prefs, nSlots = nSlots)

## 2-a. Generate college preferences with college 1 only ranking student 1
c.prefs <- matrix(c(
  1,rep(NA,7),
  3,5,4,8,7,2,1,6,
  5,3,1,7,2,8,6,4,
  6,8,7,4,2,3,5,1),
  byrow = FALSE, ncol = 4)

## 2-b. Find assignment based on TTC algorithm
ttc2(s.prefs = s.prefs, c.prefs = c.prefs, nSlots = nSlots, priority = 1:8)

## If all schools have the same preferences the two sided ttc and the serial dictator yield
## the same outcome if the preferences are taken to be the priority order for the serial dictator

# Preferences are the same for all schools:
c.prefs <- matrix(c(
  5,3,1,7,2,8,6,4,
  5,3,1,7,2,8,6,4,
  5,3,1,7,2,8,6,4,
  5,3,1,7,2,8,6,4),
  byrow = FALSE, ncol = 4)
priority <- c.prefs[,1]

match_ttc <- ttc2(s.prefs = s.prefs, c.prefs = c.prefs, nSlots = nSlots)
match_sd <- rsd(prefs = s.prefs, priority = priority, nSlots = nSlots)
all(match_ttc == match_sd)

```

**Description**

Implements the Top Trading Cycle and Chains algorithm proposed by Roth et al. (2004) for the kidney exchange problem. The algorithm requires a rule to determine which chain will be used if there is more than one possibility. The chosen rule is to search for the longest chain and remove it from the problem (even the first kidney which was unassigned).

**Usage**

```
ttcc(nPatients = ncol(prefs), prefs, priority = NULL, seed = NULL)
```

**Arguments**

nPatients	integer indicating the number of patient/donor-pairs in the matching problem. Defaults to ncol(prefs).
prefs	matrix of dimension (nPatients + 1) x nPatients with column j containing patient j's ranking over kidneys in decreasing order of preferences (i.e. most preferred first). An entry with value (nPatients + 1) indicates that the patient prefers the waiting list to all kidney below in his ranking (therefore they do not matter and can be neglected/NA).
priority	(Optional) vector of length nPatients. Gives the priority ordering of the students in the search for cycles (Do not confuse it with the preferences!), if nothing is specified a random ordering is chosen.
seed	(Optional) integer setting the state for random number generation. Defaults to seed = NULL

**Value**

ttcc returns a list with the matching and a vector containing the patients who are assigned to the waiting list. The matching comprises a data frame of the operations to be performed between patient-donor pairs (ind-obj).

**Author(s)**

Thilo Klein, Alexander Sauer

**References**

Roth, A.; T. Sonmez; U. Unver (2004). Kidney Exchange. *Quarterly Journal of Economics*, 119 (2): 457-488.

**Examples**

```
## Compare Example 1 from Roth et al. (2004) on page 469 - 475
## generate matrix of patients' preference rankings over kidneys, a.k.a. Rank Order Lists (ROL)

prefs <- matrix(c( 9,10, 1,NA,NA,NA,NA,
                  11, 3, 5, 6, 2,NA,NA,
                  2, 4, 5, 6, 7, 8,13,
                  5, 9, 1, 8,10, 3,13,
```

```
      3, 7,11, 4, 5,NA,NA,
      3, 5, 8, 6,NA,NA,NA,
      6, 1, 3, 9,10, 1,13,
      6, 4,11, 2, 3, 8,NA,
      3,11,13,NA,NA,NA,NA,
      11, 1, 4, 5, 6, 7,13,
      3, 6, 5,11,NA,NA,NA,
      11, 3, 9, 8,10,12,NA),
  byrow = FALSE, ncol = 12)
priority <- 1:12
ttcc(prefs = prefs, priority = priority)
## The final matching differs slightly because in Round 3 another chain is chosen due to a different
## decision rule (compare Figure 3, p472. Here W1 instead of W2 is chosen)
```

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