

Manipulation of categorical data edits and error localization with the **editrules** package

package version 1.7.0

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Abstract

*This vignette is nearly finished. Version 2.0 of the package will have the full vignette. At the moment, **functionality for treating categorical data has beta status** so bugs are likely.*

This paper is the second paper describing functionalities of the R **editrules** package. The first paper (De Jonge and Van der Loo, 2011) describes methods and implementation for handling numerical data while this paper is concerned with handling purely categorical data. The **editrules** package is designed to offer a user-friendly interface for edit definition, manipulation, and error localization based on the generalized paradigm of Fellegi and Holt for users of the R language. By providing basic manipulations, such as error checking, feasibility tests, variable elimination, value substitution, and redundancy checks, this package offers a tool set which may be used to investigate and maintain large sets of categorical or numerical edit sets. Finally, we note that the variable elimination method described in this paper appears to be new in the field of data editing.

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Reading guide. This paper contains a fair amount of background on the algorithms and methods behind the `editrules` package. Readers who want to get started without going through the theory can read subsections $1 \rightarrow 2.2 \rightarrow 2.3 \rightarrow 3.1 \rightarrow 3.4 \rightarrow 4.2 \rightarrow 4.3$

1 Introduction

The value domain of categorical data records is usually limited by rules interrelating these variables. The simplest examples are cases where the value of one variable excludes values of another variable. For example: if the age class of a person is “child”, then (by law) the marital status cannot be “married”. In survey or administrative data, violations of such rules are frequently encountered. Resolving such violations is an important step prior to data analysis and estimation.

A categorical data record v with n variables may be defined as an element of the Cartesian product space D (for domain):

$$D = D_1 \times D_2 \times \cdots \times D_n, \quad (1)$$

where each D_k is a finite set of d_k possible categories for variable k . We label the categories as follows:

$$D_k = \{v_k \in D_k \mid v_k = 1, 2, \dots, d_k\}. \quad (2)$$

Each restriction e is a subset of D and we say that that *if $v \in e$ then v violates e* . . Conversely, when $r \notin e$ we say that *v satisfies e* . In data editing literature, such rules are referred to as *edit rules* or *edits*, in short. In the context of contingency tables they are referred to as *structural zeros* since each rule implies that one or more cells in the $d_1 \times d_2 \times \cdots \times d_n$ contingency table must be zero. A record is *valid* if it satisfies every edit imposed on D .

Large, complex surveys may consist of hundreds of interrelated rules and variables, which impedes resolution of edit violations and renders manual manipulation infeasible. Winkler (1999) mentions practical cases where statistical offices handle 250, 300 or 750 categorical edit rules for surveys.

The R package `editrules` offers functionality to define, manipulate and maintain sets of edit rules with relative ease. It also implements error localization functionality based on the generalized principle of Fellegi and Holt (1976), which states that one should find the smallest (weighted) number of variables whose values can be adapted such that all edits can be satisfied. Fellegi and Holt’s principle should be considered as the last resort of data editing. It is useful in situations where a record violates one or more edits and there is no information about the cause of the error. In certain cases, the cause of error can be estimated with near certainty, for example in the case of typing errors in numerical data. We refer the reader to Scholtus (2008, 2009) and Van der Loo et al. (2011) for such cases.

The purpose of this paper is to give a technical overview of the representation and manipulation of edits in the `editrules` package, as well as some coded examples to get new users started.

2 Defining and checking categorical constraints

In this section we describe the representation of edits and records as implemented in the `editrules` package. Subsection 2.1 describes the background while subsection 2.2 describes implementation and gives coded examples.

2.1 Boolean representation of records and edits

Categorical records may be represented as a vector of boolean values. A boolean vector of dimension d is an element of the boolean algebra

$$\mathbb{B}^d = (\{0, 1\}^d, \wedge, \vee, \neg), \quad (3)$$

where 0 and 1 have the usual interpretations FALSE and TRUE and the logical operators work element-wise on their operands. To facilitate the discussion we will also allow the standard arithmetic operations addition and subtraction on boolean vectors (this is also consistent with the way R handles vectors of class `logical`).

To represent a record $v = (v_1, v_2, \dots, v_n)$, we assign to every category v_k in D_k a unique standard basis vector $\vec{\delta}_k(v_k)$ of \mathbb{B}^{d_k} . The boolean representation $\rho(v)$ of the full record is the direct sum

$$v \xrightarrow{\rho} \vec{\delta}_1(v_1) \oplus \vec{\delta}_2(v_2) \oplus \dots \oplus \vec{\delta}_n(v_n), \quad (4)$$

which we will write as the direct vector sum

$$\rho(v) = \mathbf{v}_1 \oplus \mathbf{v}_2 \oplus \dots \oplus \mathbf{v}_n \equiv \mathbf{v}. \quad (5)$$

The dimension d of $\rho(v)$ is given by the total number of categories of all variables

$$d = \sum_{k=1}^n d_k. \quad (6)$$

When each record in a dataset is represented this way, summing the vectors yields the d -dimensional vectorized representation of the $d_1 \times d_2 \times \dots \times d_n$ contingency table of the dataset. This is sometimes called the complete disjunctive table.

Example 2.1. *Consider the variables marital status, age, and position in household from the domain $D = D_1 \times D_2 \times D_3$. We define*

$$D_1 = \{\text{married, unmarried, widowed, divorced}\} \quad (7)$$

$$D_2 = \{\text{under-aged, adult}\} \quad (8)$$

$$D_3 = \{\text{partner, child, other}\}. \quad (9)$$

The record $r = (\text{married, adult, partner})$ has boolean representation

$$\rho(r) = (1, 0, 0, 0)_1 \oplus (0, 1)_2 \oplus (1, 0, 0)_3 = (1, 0, 0, 0, 0, 1, 1, 0, 0). \quad (10)$$

An edit e is a subset of D which can be written as the Cartesian product

$$e = A_1 \times A_2 \cdots \times A_n, \text{ where } A_k \subseteq D_k, k = 1, 2, \dots, n. \quad (11)$$

The interpretation of an edit is that if a record $v \in e$, then v is considered invalid. The following properties follow immediately.

Remark 2.2. *If $e \subset D$ and $e' \subset D$ are edits, then $e \cup e' = \{e, e'\}$ and $e \cap e' = A_1 \cap A'_1 \times A_2 \cap A'_2 \times \cdots \times A_n \cap A'_n$ are also edits.* \square

An edit, expressed as in Eq. (11) is said to be in normal form. A variable k is *involved* in an edit if $A_k \subset D_k$. Conversely, we say that e *involves* k if k is involved in e . A variable k for which $A_k = D_k$ is not involved in e . Since every category v_k is mapped to a unique basis vector $\vec{\delta}_k(v_k)$, edits have a boolean representation $\rho(e)$, given by

$$e \xrightarrow{\rho} \bigvee_{v_1 \in A_1} \vec{\delta}_1(v_1) \oplus \bigvee_{v_2 \in A_2} \vec{\delta}_2(v_2) \oplus \cdots \oplus \bigvee_{v_n \in A_n} \vec{\delta}_n(v_n), \quad (12)$$

which may simply be written as

$$\rho(e) = \mathbf{a}_1 \oplus \mathbf{a}_2 \oplus \cdots \oplus \mathbf{a}_n \equiv \mathbf{a}. \quad (13)$$

Example 2.3. *Using the data model from Example 2.1, the edit that says that under-aged people cannot be married has set representation*

$$e = \{\text{married}\}_1 \times \{\text{under-aged}\}_2 \times \{\text{partner, child, other}\}_3 \quad (14)$$

which translates to the boolean representation

$$\rho(e) = (1, 0, 0, 0)_1 \oplus (0, 1)_2 \oplus (1, 1, 1)_3 = (1, 0, 0, 0, 0, 1, 1, 1, 1). \quad (15)$$

In the boolean representation some properties can be checked by simple calculations. For example, an edit involves variable k if and only if the inner product $\mathbf{1}_{d_k} \cdot \mathbf{a}_k < d_k$, where $\mathbf{1}_{d_k}$ is a d_k vector of ones.

A record v violates an edit if every $v_k \in A_k$. In the boolean representation this can be written as a condition on the standard inner product between the boolean representation of a record and an edit:

$$\sum_{k=1}^n \vec{\delta}_k(v_k) \cdot \mathbf{a}_k = \mathbf{v} \cdot \mathbf{a} = n. \quad (16)$$

Suppose that E is a set of edits of the form (11). It is not difficult to verify that an edit $e \in E$ is redundant if

$$A_k = \emptyset, \text{ for any } k \in 1, 2, \dots, n \quad (17)$$

or

$$e \subseteq e' \text{ with } e' \in E. \quad (18)$$

In (17), e is redundant since it cannot contain any records. It can be tested by checking if any $\mathbf{1}_{d_k} \cdot \mathbf{a}_k = 0$. In the case of (18), e is redundant because any edit violating e also violates e' . Using $\rho(e) = \mathbf{a}$ and $\rho(e') = \mathbf{a}'$, this can be tested by checking if $\mathbf{a} \wedge \mathbf{a}' = \mathbf{a}$ or equivalently if $\mathbf{a} \vee \mathbf{a}' = \mathbf{a}'$.

Remark 2.4. *The boolean representation of records and edits is invertible. For convenience we use the symbols \in , \subset and \subseteq for edits and record in set as well as in boolean representation. For example, in stead of writing $\mathbf{v} \cdot \mathbf{a} = n$ we write $\mathbf{v} \in \mathbf{a}$ (which is equivalent to $v \in e$) when convenient.* \square

In the `editrules` the boolean representation is mainly used to store edits and to manipulate them through variable substitution and elimination. Data records can be stored in `data.frame` objects, as usual.

2.2 The editarray object

In the `editrules` package, a set of categorical edits is represented as an `editarray` object. Formally, we denote an `editarray` E for n categorical variables and m edits as (brackets indicate a combination of objects)

$$E = \langle \mathbf{A}, \mathbf{ind} \rangle, \text{ with } \mathbf{A} \in \{0, 1\}^{m \times d} \text{ and } d = \sum_{k=1}^n d_k, \quad (19)$$

Each row \mathbf{a} of \mathbf{A} contains the boolean representation of one edit, and the d_k denote the number of categories of each variable. The object `ind` is a nested list which relates columns of \mathbf{A} to variable names and categories. Labeling variables with $k \in 1, 2, \dots, n$ and category values with $v_k \in 1, 2, \dots, d_k$, we use the following notations:

$$\mathbf{ind}(k, v_k) = \sum_{l < k} d_l + v_k \quad (20)$$

$$\mathbf{ind}(k) = \{\mathbf{ind}(k, v_k) \mid v_k \in D_k\}. \quad (21)$$

So $\mathbf{ind}(k, v_k)$ is the column index in \mathbf{A} for variable k and category v_k and $\mathbf{ind}(k)$ is the set of column indices corresponding to all categories of variable k . The `editarray` is the central object for computing with categorical edits, just like the `editmatrix` is the central object for computations with linear edits.

It is both tedious and error prone to define and maintain an `editarray` by hand. In practice, categorical edits are usually stated verbosely, such as: “a male subject cannot be pregnant”, or “an under-aged subject cannot be married”. To facilitate the definition of edit arrays, `editrules` is equipped with a parser, which takes R-statements in `character` format, and translates them to an `editarray`.

Figure 1 shows a simple example of defining an `editarray` with the `editrules` package. The first two edits in Figure 1 define the data model. The

```

> E <- editarray(c(
+   "gender %in% c('male','female')",
+   "pregnant %in% c('yes','no')",
+   "if (gender == 'male') pregnant == 'no'"
+ )
+ )
> E

Edit array:
  levels
edits gndr:feml gndr:male prgn:no prgn:yes
  e1      FALSE      TRUE  FALSE      TRUE

Edit rules:
d1 : gender %in% c('female', 'male')
d2 : pregnant %in% c('no', 'yes')
e1 : if( gender == 'male' ) pregnant != 'yes'

> datamodel(E)

  variable value
1  gender female
2  gender  male
3 pregnant   no
4 pregnant   yes

```

Figure 1: Defining a simple `editarray` with the `editarray` function. The array is printed with abbreviated column heads, which themselves consist of variable names and categories separated by a colon (by default). When printed to screen, a `character` version of the edits is shown as well, for readability.

`editarray` function derives the `datamodel` based on the variable names and categories it finds in the edits, whether they are univariate (defining domains) or multivariate. This means that if all possible variables and categories are mentioned in the multivariate edits, the correct `datamodel` will be derived as well.

When printed to the screen, the boolean array is shown with column heads of the form

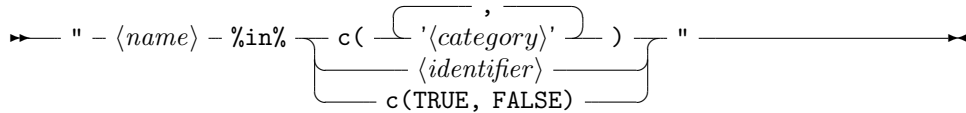
<abbreviated var. name><separator><abbreviated cat. label>

where both variable names and categories are abbreviated for readability, and the standard separator is a colon (:). The separator may not occur as a symbol in either variable or category name, and its value can be determined by passing a custom `sep` argument to `editarray`. For convenience, the function `datamodel` accepts an `editarray` as input and returns an overview of variables and their categories for easy inspection in the form of a `data.frame`.

Internally, `editarray` uses the R internal `parse` function to transform the character expressions to a parse tree, which is subsequently traversed recursively to derive the entries of the `editmatrix`. The opposite is also possible. The R internal function `as.character` has been overloaded to derive a `char-`

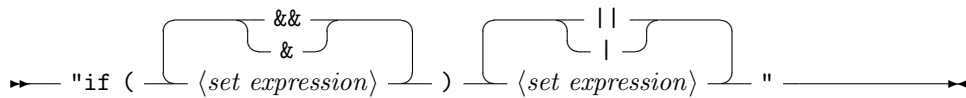
acter representation from a boolean representation. When printed to the screen, both the boolean and textual representation are shown.

Univariate edits define the domain of a variable. The domains form together a data model. A domain can be defined with common R syntax using the `%in%` operator. If a domain is defined explicitly, it must follow the following syntax diagram.

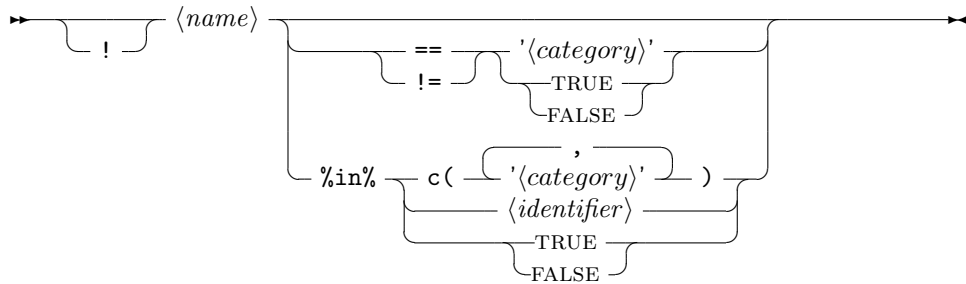


Here, $\langle name \rangle$ is the name of a categorical variable, and $\langle category \rangle$ is a literal category name. Note that the category name is enclosed by single quotes while the entire statement is between double quotes. That is, the entire statement has to be offered in string format to `editarray`. The $\langle identifier \rangle$ is the name of a predefined **character** variable storing the unique categories for a variable. In principle, $\langle identifier \rangle$ may be replaced by any valid R symbol evaluating to a **character** or **factor** vector. However, such constructions are not recommended, since multivariate edit rules depend on a fixed datamodel.

The multivariate rules can be defined in three ways. The most useful and common way to define edits follows the following syntax diagram.



Where each $\langle set\ expression \rangle$ is a logical statement, following



The reader can check that the examples given in Figure 1 follow this syntax. The example below illustrates the use of separately defined data models and boolean categories.

```
> xval <- letters[1:4]
> yval <- c(TRUE,FALSE)
> ( M <- editarray(c(
+   "x %in% xval",
+   "y %in% yval",
+   "if ( x %in% c('a','b') ) !y "
+   )) )
```



```

Edit array:
  levels
edits  x:a  x:b  x:c  x:d y:FALSE y:TRUE
      e1 TRUE TRUE FALSE FALSE  FALSE  TRUE

Edit rules:
d1  :  x %in% c('a', 'b', 'c', 'd')
d2  :  y %in% c(FALSE, TRUE)
e1  :  if( x %in% c('a', 'b') ) y == FALSE

```

The second way to define multivariate edits is based on rewriting on the basic classical logic law $P \Rightarrow Q = \neg P \vee Q$. It involves the following syntax diagram.



Where each $\langle setexpression \rangle$ is as in the syntax diagram above. In practice, a user will commonly not use this form since it is less readable. However, the `as.character` method for `editarray` can generate such statements by passing the argument `useIf=FALSE`, as shown below.

```

> as.character(M, useIf = FALSE)

              d1                      d2
      "x %in% c('a', 'b', 'c', 'd')"    "y %in% c(FALSE, TRUE)"
              e1
"! ( x %in% c('a', 'b') ) | y == FALSE"

```

The main advantage of this form is that contrary to the `if()` form, it allows for vectorized checking of edits, which is why it is used internally.

2.3 Coercion, checking, redundancy and feasibility

Table 1 lists basic functions of `editarray` objects. The `datamodel` function extracts the variables and categories from an `editarray`, and returns them as a two-column `data.frame`. With `as.data.frame` or `as.character` one can coerce an `editarray` so that it can be written to a file or database. Character coercion is used when edits are printed to the screen. Optionally, coercing the `datamodel` to character form can be switched off. The result of `as.data.frame` has columns with edit names, a character representation of the edits and a column for remarks.

The function `violatedEdits` takes an `editarray` and a `data.frame` as input and returns a logical matrix indicating which record (rows) violate which edits (columns). It works by parsing the `editarray` to R-expressions and evaluating them within the `data.frame` environment. By default, the records are checked against the data model. This can be turned off by providing the optional argument `datamodel=FALSE`.

When manipulating edit sets, redundant edits of the form of Eq. (17) may arise. Such redundancies can be detected in the boolean representation with

Table 1: Functions for objects of class `editarray`. Only mandatory arguments are shown, refer to the built-in documentation for optional arguments.

Function	description
<code>datamodel(E)</code>	get <code>datamodel</code>
<code>getVars(E)</code>	get a list of variables
<code>as.data.frame(E)</code>	coerce edits to <code>data.frame</code>
<code>contains(E)</code>	which edits contains which variable
<code>as.character(E)</code>	coerce edits to <code>character</code> vector
<code>blocks(E)</code>	Get list of independent blocks of edits
<code>reduce(E)</code>	Remove empty unnecessary variables and rows
<code>isObviouslyRedundant(E)</code>	find redundancies [Eq. (17)], duplicates
<code>duplicated(E)</code>	find duplicate edits
<code>isSubset(E)</code>	find edits, subset of another edit [Eq. (18)]
<code>isObviouslyInfeasible(E)</code>	detect simple contradictions
<code>isFeasible(E)</code>	detect if at least 1 valid record exists
<code>substValue(E,var,value)</code>	substitute a value
<code>eliminate(E,var)</code>	eliminate a variable (sect. 3.4)
<code>violatedEdits(E,det)</code>	check which edits are violated by x
<code>localizeErrors(E,det)</code>	localize errors (sect. 4.2)
<code>errorLocalizer(E,x)</code>	backtracker for error localization (sect. 4.3)

Algorithm 1 `ISSUBSET(E)`

Input: An `editarray` $E = \langle \mathbf{A}, \mathbf{ind} \rangle$.

```

1:  $\mathbf{s} \leftarrow (\text{FALSE})^m$ 
2: for  $(\mathbf{a}^{(i)}, \mathbf{a}^{(i')}) \in \text{rows}(\mathbf{A}) \times \text{rows}(\mathbf{A})$  do
3:   if  $\mathbf{a}^{(i)} \vee \mathbf{a}^{(i')} = \mathbf{a}^{(i')}$  then
4:      $s_i \leftarrow \text{TRUE}$ 

```

Output: Boolean vector \mathbf{s} indicating which edits represented by \mathbf{A} are a subset of another edit.

`isObviouslyRedundant`. By default, this function also checks for duplicate edits, but this may be turned off. The function `duplicated` is overloaded from the standard R function and the function `isSubset` (pseudocode in Algorithm 1) detects which edits are a subset or duplicate of another one. In the actual R implementation, the only explicit loop is a call to R’s `vapply` function. The other loops are avoided using R’s indexing and vectorization properties.

Manipulations may also lead to edits of the form $e = D$, in which case every possible record is invalid, and the `editarray` has become impossible to satisfy. The function `isObviouslyInfeasible` detects whether any such edits are present. The function `isFeasible` checks if the set of edits in it’s argument allows at least one valid record. This may yield results which are counter-intuitive at first glance. For example, consider set of edits on the domain

$$D = \{(x, y) \in \{a, b\} \times \{c, d\}\}.$$

```
> M <- editarray(c(
+   "x %in% c('a', 'b')",
+   "y %in% c('c', 'd')",
+   "if ( x == 'a' ) y == 'c'",
+   "if ( x == 'a' ) y != 'c'"))
>
```

This set of edits is feasible, even though edits e_1 and e_2 seem contradictory:

```
> isFeasible(M)
```

```
[1] TRUE
```

The explanation is that e_1 and e_2 contradict each other only when $x = a$, so

```
> isFeasible(substValue(M, 'x', 'a'))
```

```
[1] FALSE
```

where the function `substValue` is discussed in the next section. One can check that the record $(x = b, y = d)$ indeed satisfies all edits in M .

The feasibility check works by eliminating all variables in an `editarray` one by one until either no edits are left or an obvious contradiction is found. Eliminating all variables amounts constructing the solution of an error localization problem in the branch-and-bound algorithm of De Waal (2003) where all variables have to be adapted. Variable elimination is discussed further in the next section while error localization is discussed in Section 4.

3 Manipulation of categorical restrictions

The basic operations on sets of categorical edits are value substitution and variable elimination. The former amounts to adapting the datamodel underlying the edit set while the latter amounts to deriving relations between variables not involving the eliminated variable.

In the next subsection we give an example of value substitution with the `editrules` package, as well as some background. In subsection 3.2 we describe an elimination method, which appears to be new to the field of data editing. In subsection 3.3 it is shown that the method yields results equivalent to Fellegi and Holt's elimination method. Finally, in subsection 3.4 we give an example of eliminating variables with the `editrules` package. The technical background described in Subsections 3.2 and 3.3 may be skipped on first reading.

Algorithm 2 SUBSTVALUE(E, k, v)

Input: an editarray $E = \langle \mathbf{A}, \mathbf{ind} \rangle$, a variable index k and a value v

1: $i \leftarrow \mathbf{ind}(k, v)$

2: $\mathbf{A} \leftarrow \mathbf{A} \setminus \{\mathbf{a} \in \text{rows}(\mathbf{A}) \mid a_i = \text{FALSE}\}$ \triangleright Remove rows not involving v

3: $\mathbf{A} \leftarrow \mathbf{A} \setminus \{\mathbf{a}_j^t \in \text{columns}(\mathbf{A}) \mid j \in \mathbf{ind}(k) \setminus i\}$ \triangleright Remove categories $\neq v$

4: Update \mathbf{ind}

Output: $\langle \mathbf{A}, \mathbf{ind} \rangle$ with v substituted for variable k .

3.1 Value substitution

If it is assumed that in a record, one of the variables takes a certain value, that value may be substituted in the edit rules. In the boolean representation this amounts to removing all edits which exclude that value, since the record cannot violate those edits. Secondly, the columns related to the substituted variable, but not to the substituted category are removed, thus adapting the datamodel to the new assumption. Algorithm 2 gives the pseudocode for reference purposes.

In the `editrules` package, value substitution is performed by the `substValue` function, which accepts an `editarray`, a variable name and a category name. In the following example the editmatrix defined in Figure 1 is used.

```
> substValue(E, "gender", "female")

Edit array:
  levels
edits  gndr:feml gndr:male prgn:no prgn:yes

Edit rules:
d1 : gender %in% c('female', 'male')
d2 : pregnant %in% c('no', 'yes')
```

In this case, the variable `gender` is substituted by the value `female`. The rules concerning `gender = male` may be deleted, so here only the datamodel is left with no multivariate rules left. In fact, the datamodel itself may be reduced, which can be achieved by setting the option `reduce=TRUE`.

```
> substValue(E, "gender", "female", reduce = TRUE)

Edit array:
  levels
edits  gndr:feml prgn:no prgn:yes

Edit rules:
d1 : gender %in% 'female'
d2 : pregnant %in% c('no', 'yes')
```

3.2 Variable elimination by category resolution

Given two edits e and e' , with boolean representations \mathbf{a} and \mathbf{a}' respectively. We define the *resolution operator* \mathfrak{R}_k as:

$$\begin{aligned} \mathbf{a} \mathfrak{R}_k \mathbf{a}' &= \mathbf{a}_1 \wedge \mathbf{a}'_1 \oplus \cdots \oplus \mathbf{a}_{k-1} \wedge \mathbf{a}'_{k-1} \\ &\oplus \mathbf{a}_k \vee \mathbf{a}'_k \oplus \mathbf{a}_{k+1} \wedge \mathbf{a}'_{k+1} \oplus \cdots \oplus \mathbf{a}_n \wedge \mathbf{a}'_n. \end{aligned} \quad (22)$$

For two edit sets \mathbf{A} and \mathbf{A}' , we also introduce the notation

$$\mathbf{A} \mathfrak{R}_k \mathbf{A}' = \{\mathbf{a} \mathfrak{R}_k \mathbf{a}' \mid (\mathbf{a}, \mathbf{a}') \in \text{rows}(\mathbf{A}) \times \text{rows}(\mathbf{A}')\}. \quad (23)$$

Observe that the resolution operator has the following properties, relevant for record checking.

$$\mathbf{v} \in \mathbf{a} \mathfrak{R}_k \mathbf{a}' \Rightarrow \mathbf{v} \in \mathbf{a} \vee \mathbf{v} \in \mathbf{a}' \quad (24)$$

$$\mathbf{v} \in \mathbf{a} \Rightarrow (\mathbf{v} \in \mathbf{a} \mathfrak{R}_k \mathbf{a}') \vee (\mathbf{a} \mathfrak{R}_k \mathbf{a}' = \emptyset), \quad (25)$$

where we used notation as defined in remark 2.4. That is, if a record violates $\mathbf{a} \mathfrak{R}_k \mathbf{a}'$, it does so because it violates \mathbf{a} and/or \mathbf{a}' . Therefore, $\mathbf{a} \mathfrak{R}_k \mathbf{a}'$ is also an edit in the sense that a record is invalid if it falls in the derived edit. When $\mathbf{a}_k = \mathbf{a}'_k$, the resulting edit is the intersection of the original edits, in which case the resulting edit is redundant.

The operator is called resolution operator since in certain cases its action is equivalent to a resolution operation from formal and automated logic derivation (Robinson, 1965). If $\mathbf{a}_k \vee \mathbf{a}'_k = (\text{TRUE})^{d_k}$, the operator “resolves” or eliminates the k^{th} variable and we are left with a relation between the other variables, regardless of the value of variable k . The edit resulting from a resolution operation on two explicitly defined edits is called an *implied edit*. If the resolution operation happens to eliminate one of the variables, it is called an *essentially new implied edit*. These terms were introduced by Fellegi and Holt (1976) who first solved the problem of error localization for categorical data.

The resolution operator can be used to eliminate a variable k from a set of edits (represented by \mathbf{A}) category by category as follows (Algorithm 3). Suppose that j is the column index of the first category of k . Collect all pairs of $(\mathbf{a}^+, \mathbf{a}^-)$ obeying $a_j^+ = \text{TRUE}$ and $a_j^- = \text{FALSE}$. If there are no edits of type \mathbf{a}^+ , the variable cannot be eliminated and the empty set is returned. Otherwise, copy all \mathbf{a}^+ to a new set of edits and add every $\mathbf{a}^+ \mathfrak{R}_k \mathbf{a}^-$. By construction, these new edits all have $a_j = \text{TRUE}$. Possibly, redundant edits have been produced, and these may be removed. The procedure is iterated for every category of k , adding a category for which each $a_j = \text{TRUE}$ at each iteration.

Algorithm 3 ELIMINATE(E, k)

Input: an editarray $E = \langle \mathbf{A}, \mathbf{ind} \rangle$, a variable index k

```
1: for  $j \in \mathbf{ind}(k)$  do
2:    $\mathbf{A}^+ = \{\mathbf{a} \in \text{rows}(\mathbf{A}) : a_j = \text{TRUE}\}$ 
3:    $\mathbf{A}^- = \{\mathbf{a} \in \text{rows}(\mathbf{A}) : a_j = \text{FALSE}\}$ 
4:   if  $\mathbf{A}^+ = \emptyset$  then
5:      $\mathbf{A} \leftarrow \emptyset$ 
6:     break
7:    $\mathbf{A} \leftarrow \mathbf{A}^+ \cup \mathbf{A}^+ \Re_k \mathbf{A}^-$ 
8:   Delete rows which have  $\text{ISUBSET}(\langle \mathbf{A}, \mathbf{ind} \rangle) = \text{TRUE}$ .
```

Output: editarray $\langle \mathbf{A}, \mathbf{ind} \rangle$ with variable k eliminated

3.3 Some properties of the elimination method

In this subsection we prove that the function ELIMINATE of Algorithm 3 generates all edits necessary to solve the error localization problem. A short comparison with the elimination method of Fellegi and Holt (1976) is given as well.

Given a set of m edits:

$$E = \{e^{(i)} \in \mathcal{P}(D) \mid e^{(i)} \text{ as in Eq. (11), } i \in 1, 2, \dots, m\}, \quad (26)$$

where $\mathcal{P}(D)$ is the powerset of D . Fellegi and Holt (1976), but also De Waal et al. (2011) define a way to derive new edits, which may be written as a function F_k ,

$$\begin{aligned} F_k(E) = & \cap_{i=1}^m A_1^{(i)} \times \cap_{i=1}^m A_2^{(i)} \times \dots \times \cap_{i=1}^m A_{k-1}^{(i)} \times \\ & \times \cup_{i=1}^m A_k^{(i)} \times \cap_{i=1}^m A_{k+1}^{(i)} \times \dots \times \cap_{i=1}^m A_m^{(i)}, \end{aligned} \quad (27)$$

where k is called the *generating variable*. In the boolean representation, we have $\mathbf{A} = \rho(E)$. Using the relations $\rho(e \cap e') = \rho(\mathbf{e}) \wedge \rho(\mathbf{e}')$ and $\rho(e \cup e') = \rho(\mathbf{e}) \vee \rho(\mathbf{e}')$ we may write

$$F_k(\mathbf{A}) = \mathbf{a}^{(1)} \Re_k \mathbf{a}^{(2)} \Re_k \dots \Re_k \mathbf{a}^{(m)}, \quad \mathbf{a}^{(i)} = \rho(e^{(i)}), \quad (28)$$

where we used some obvious properties (symmetry, associativity) of the \wedge and \vee operators as well. The following lemma and corollary show that we can do all the work, necessary for implied edit derivation with the resolution operator.

Lemma 3.1 (Fellegi and Holt (1976)). *If E is a set of edits, every edit, logically implied by E can be derived by repeated application of Eq. (27) on subsets of E .*

Proof. The proof is given in the reference and will not be repeated here. \square

Corollary 3.2. *If E is a set of edits, all implied edits can be derived by repeated application of the resolution operator on elements of the boolean representation of E .*

Proof. This follows from the equivalence between Eqs. (27) and (28). \square

Having established the use of the resolution operator, it becomes interesting to study its algebraic properties. By substitution in the definition, it is easily shown that the resolution operator is symmetric, associative and idempotent. As a reminder, these properties are defined as follows.

$$\begin{aligned} \text{symmetry:} \quad & \mathbf{a} \mathfrak{R}_k \mathbf{b} = \mathbf{b} \mathfrak{R}_k \mathbf{a} \\ \text{associativity:} \quad & (\mathbf{a} \mathfrak{R}_k \mathbf{b}) \mathfrak{R}_k \mathbf{c} = \mathbf{a} \mathfrak{R}_k (\mathbf{b} \mathfrak{R}_k \mathbf{c}) \\ \text{idempotency:} \quad & \mathbf{a} \mathfrak{R}_k \mathbf{a} = \mathbf{a}. \end{aligned} \tag{29}$$

The resolution operator (although not called as such) was found earlier and independently of the current authors by Willenborg (1988), who also discovered these properties. The following property shows that the resolution operator leaves redundancy relations untouched.

Lemma 3.3. *If $\mathbf{b} \subseteq \mathbf{c}$, then $\mathbf{a} \mathfrak{R}_k \mathbf{b} \subseteq \mathbf{a} \mathfrak{R}_k \mathbf{c}$.*

Proof. We may write $\mathbf{a} = \mathbf{a}_k \oplus \mathbf{a}'$ and similarly for \mathbf{b} and \mathbf{c} . This gives

$$\begin{aligned} \mathbf{a} \mathfrak{R}_k \mathbf{b} &= \mathbf{a} \mathfrak{R}_k (\mathbf{b} \wedge \mathbf{c}) \\ &= \mathbf{a}_k \vee (\mathbf{b}_k \wedge \mathbf{c}_k) \oplus \mathbf{a}' \wedge (\mathbf{b}' \wedge \mathbf{c}') \\ &= (\mathbf{a}_k \vee \mathbf{b}_k) \wedge (\mathbf{a}_k \vee \mathbf{c}_k) \oplus (\mathbf{a}' \wedge \mathbf{b}') \wedge (\mathbf{a}' \wedge \mathbf{c}') \\ &= \mathbf{a} \mathfrak{R}_k \mathbf{b}_k \wedge \mathbf{a} \mathfrak{R}_k \mathbf{c} \subseteq \mathbf{a} \mathfrak{R}_k \mathbf{c}, \end{aligned}$$

and we are done. \square

This lemma is important because it shows that removing redundant edits (as shown in Algorithm 3) does not affect the outcome of ELIMINATE in the sense that the resulting edit set covers the same subset of D with or without the redundancy removal step.

We now define more formally the notion of variable elimination.

Definition 3.4. *Given a function $f : \mathcal{P}(D) \rightarrow \mathcal{P}(D)$, and a set of edits $E \subset \mathcal{P}(D)$. If none of the edits in $f(E)$ contain variable k , we say that f eliminates that variable from E .*

Remember that in the boolean representation, this means that $\mathbf{a}_k = (\text{TRUE})^{d_k}$. The following theorem shows that every essentially new implied edit, generated by k is found by Algorithm 3.

Theorem 3.5. *If E is a set of edits. The function $\text{ELIMINATE}(E, k)$ generates every edit derived from E from which variable k has been eliminated. Moreover, these edits are mutually non-redundant.*

Proof. The rows are mutually non-redundant since redundant rows are removed explicitly in line 8 of the algorithm. The fact that the removing these rows does not alter the result (in the sense that the resulting edits will cover the same subdomain of D) is a consequence of Lemma 3.3.

Denote by $\mathbf{A}(j)$ the state of \mathbf{A} after j iterations. We have

$$\mathbf{A}(1) = \mathbf{A}^+ \cup \mathbf{A}^+ \mathfrak{R}_k \mathbf{A}^-. \quad (30)$$

Here $\mathbf{A}(1)$ contains every nonredundant derived edit with column $\mathbf{ind}(k, 1)$ equal to TRUE. For, if there is another derived edit, by corollary 3.2 it must be in $\mathbf{A}^+ \mathfrak{R}_k \mathbf{A}^+$, since $\mathbf{A}^- \mathfrak{R}_k \mathbf{A}^-$ only generates edits where $a_{\mathbf{ind}(k, 1)} = \text{FALSE}$. Now, consider two edits \mathbf{a}^+ and $\mathbf{a}'^+ \in \mathbf{A}^+$. We have $\mathbf{a}^+ \mathfrak{R}_l \mathbf{a}'^+ \subseteq \mathbf{a}^+ \cup \mathbf{a}'^+ \subseteq \mathbf{A}^+ \subseteq \mathbf{A}(1)$ so each element of $\mathbf{A}^+ \mathfrak{R}_k \mathbf{A}^+$ is redundant (remember Remark 2.2). It follows from the definition of \mathfrak{R}_k that if $\mathbf{A}(j-1)$ contains every nonredundant edit with columns $\mathbf{ind}(k, 1), \dots, \mathbf{ind}(k, j-1)$ equal to TRUE then $\mathbf{A}(j)$ contains all nonredundant edits with columns $\mathbf{ind}(k, 1), \dots, \mathbf{ind}(k, j)$ equal to TRUE. Since the algorithm iterates over all $j \in \mathbf{ind}(k)$ the result follows. \square

It is interesting to compare the procedure in Algorithm 3 with Fellegi and Holt's procedure for generating implicit edits. This procedure, which is also described by De Waal et al. (2011) may be summarized as follows.

- 1: **function** FH(E, k)
- 2: Find every $E_j \subseteq E$, with $j \in 1, 2, \dots, s$ such that
 - $F_k(E_j)$ eliminates k .
 - E_j has a minimal number of elements $|E_j|$.
 - The E_j are mutually non-redundant in the sense $F_k(E_j) \not\subseteq F_k(E_l)$.
- 3: $E \leftarrow \cup_{j=1}^s F_k(E_j)$
- 4: **return** E

Here, E is a set of categorical edits in some form, and k the variable to eliminate. Most of the computational complexity is contained in line 2, where the search space is determined by the power set of E , yielding exponential complexity in the number of edits.

The complexity of the ELIMINATE algorithm is determined by the 7th line in Algorithm 3, which is quadratic in the current number of edits in the for-loop. This recurrence relation also yields exponential complexity in the number of edits. However, by removing the redundant edits at every iteration (a quadratic operation in itself), the actual number of edits can be kept to a minimum which reduces the complexity encountered in practice.

3.4 An example with eliminate

The purpose of the `eliminate` function is to derive all possible non-redundant edits from an edit set that do not contain a certain variable. For categorical

data edits, this amounts to logical resolution. For example, consider the syllogism

P_1	An under-aged subject cannot be married
P_2	A marriage partner has to be married
<hr/>	
C	An under-aged subject cannot be a marriage partner.

Here, the conclusion C is derived from premises P_1 and P_2 by eliminating *marital status*. In `editrules` the above operation can be performed as follows. We first define a data model and edit rules:

```
> E <- editarray(c(
+   "age %in% c('under-aged','adult')",
+   "maritalStatus %in% c('married','not married')",
+   "positionInHousehold %in% c('partner','child','other')",
+   "if (age == 'under-aged') maritalStatus != 'married'",
+   "if (positionInHousehold == 'partner') maritalStatus == 'married'"
+ ))
```

We may derive the conclusion by eliminating the *marital status* variable:

```
> eliminate(E, "maritalStatus")

Edit array:
  levels
edits age:adlt age:und- mrtS:mrrd mrtS:ntmr psIH:chld psIH:othr psIH:prtn
e1    FALSE      TRUE      TRUE      TRUE      FALSE      FALSE      TRUE

Edit rules:
d1 : age %in% c('adult', 'under-aged')
d2 : maritalStatus %in% c('married', 'not married')
d3 : positionInHousehold %in% c('child', 'other', 'partner')
e1 : if( age == 'under-aged' ) positionInHousehold != 'partner'
```

This indeed yields the right conclusion. Alternatively, we may eliminate *age*:

```
> eliminate(E, "age")

Edit array:
  levels
edits age:adlt age:und- mrtS:mrrd mrtS:ntmr psIH:chld psIH:othr psIH:prtn
e1    TRUE      TRUE      FALSE      TRUE      FALSE      FALSE      TRUE

Edit rules:
d1 : age %in% c('adult', 'under-aged')
d2 : maritalStatus %in% c('married', 'not married')
d3 : positionInHousehold %in% c('child', 'other', 'partner')
e1 : if( maritalStatus == 'not married' ) positionInHousehold != 'partner'
```

This deletes the only rule actually involving *age*. That is, no new rules not involving *age* can be derived.

4 Error localization in categorical data

4.1 A Branch and bound algorithm

The editrules package implements an error localization algorithm, based on the branch-and-bound algorithm of De Waal and Quere (2003). The algorithm has been extensively described in De Waal (2003) and De Waal et al. (2011). The algorithm is similar to the branch-and-bound algorithm used for error localization in numerical data in the editrules package as described in De Jonge and Van der Loo (2011), except that the elimination and substitution subroutines are implemented for categorical data.

In short, a binary tree is created with the full set of edits and an erroneous record at the root node. Two child nodes are created. In the first child node the first variable of the record is assumed correct, and it's values is substituted in the edits. In the second child node the variable is assumed incorrect and it is eliminated from the set of edits. The tree is continued recursively until choices are made for each variable. Branches are pruned when they cannot lead to a solution, leaving a partial binary tree where each path from root to leaf represents a solution to the error localization problem. Computational complexity is reduced further by pruning branches leading to higher-weight solutions then solutions found earlier.

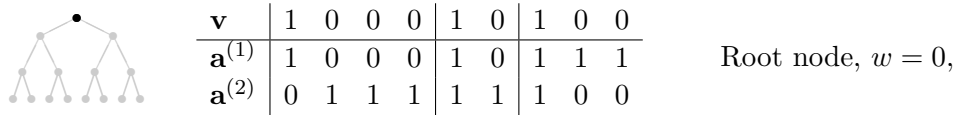
Recall the datamodel of Example 2.1, with variables *marital status*, *age* and *position in household*. We define the following two edits:

- $e^{(1)}$ An under-aged subject cannot be married
- $e^{(2)}$ A (marriage) partner has to be married

As an example we treat the following record with the branch-and-bound algorithm to localize the errors:

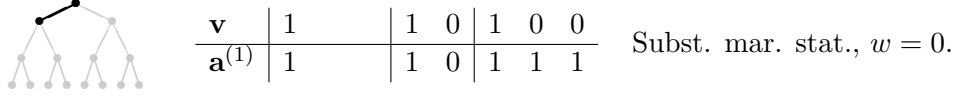
$$v = (\text{married}, \text{under-aged}, \text{partner}). \quad (31)$$

At the beginning of the algorithm, only the root node is filled. The situation may be represented as follows:

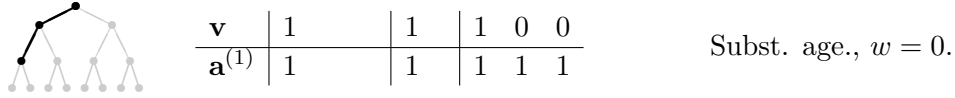


where $\mathbf{v} = \rho(v)$, and \mathbf{a}_1 and \mathbf{a}_2 are the boolean representations of e_1 and e_2 respectively. The record and edits are denoted in boolean representation as shown in Example 2.1. The weight w counts the number of variables that are assumed to be incorrect, which at the root node is zero.

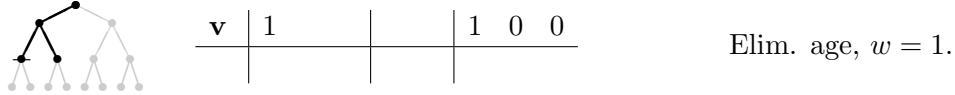
The tree is traversed in depth-first fashion. In the first step, we substitute *married* in *marital status*, yielding



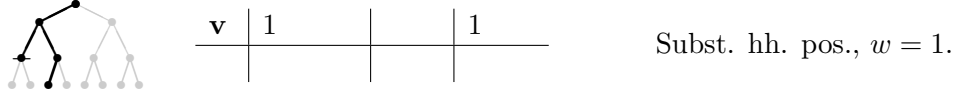
Here, $\mathbf{a}^{(2)}$ is removed, since it has no meaning for \mathbf{v} anymore. The positions for the categories unmarried, widowed and divorced are left empty here to signify that the datamodel has a fixed marital status now. The dark part of the tree on the left shows which nodes have been treated. Continuing we find



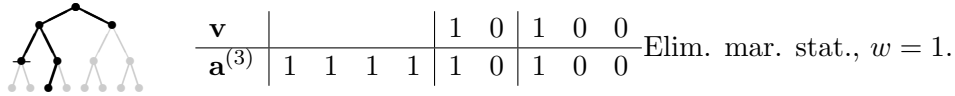
At this point we have fixed the value for *marital status* and *age*. It can be seen from the value of $\mathbf{a}^{(1)}$ for *position in household* that no matter what value is chosen for that field, the value $\mathbf{v} \cdot \mathbf{a}^{(1)} = 3$. This shows that this path will never lead to a valid solution. We therefore prune the tree here, go up one node and turn right.



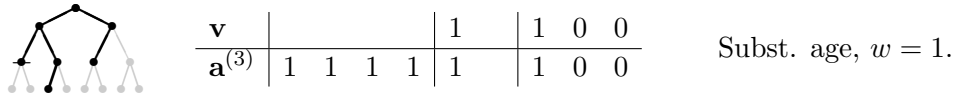
Eliminating the *age* variable yields an empty edit set. We may continue down and substitute the value *partner* for *position in household*.



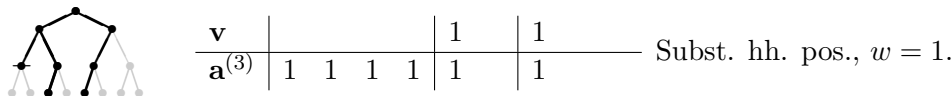
This yields the first solution: only the age variable needs to be changed. In search for more solutions, we move up the tree and try to eliminate *age*. However, since eliminating age would increase the weight to 2 we will prune the tree at this point. Moving up to the root node and eliminating *marital status* gives



Here $\mathbf{a}^{(3)} = \mathbf{a}^{(1)} \mathfrak{R}_1 \mathbf{a}^{(2)}$. It is interpreted as the rule that under-aged people cannot be a partner in the household (no matter what the value of *marital status* is). Creating the next child node by substituting *age*, we get



Going down the tree and substituting *position in household* yields



However, whatever value we would choose for *marital status*, it would always result in an erroneous record since $\mathbf{a}^{(3)}$ has TRUE on all categories of that variable. Therefore, we go up one step in the tree. Eliminating *age* would increase the weight to 2, but since we already found a solution with weight equal to 1, this path need not be followed. We go up another node and bound on the fact that eliminating *position in household* would yield the same problem. The final tree may be represented as follows:



Here, every evaluated node is colored black, and a node is crossed when a bound condition was encountered. The only (minimal) solution created is represented by the path substitute *marital status* \rightarrow eliminate *age* \rightarrow substitute *position in household*. This corresponds to the solution where *age* has to be altered to fix the record, and indeed changing *age* from under-aged to adult will make the record fully valid. Note that the branch-and-bound algorithm reduced the number of nodes to be evaluated from 15 to 8 in this case.

4.2 Error localization with localizeErrors

The function `localizeErrors` applies the branch-and-bound algorithm to determine the minimal weight error location for every record in a `data.frame`. The columns may be in `character` or `factor` format. The function has an identical interface for numerical data under linear edits and categorical data under categorical edits. It is implemented as an `S3` generic function, accepting either an `editmatrix` or an `editarray` as the first argument and a `data.frame` as the second argument. Further arguments are a vector of variable weights, a maximum search time (in seconds) to spend on a single record, a maximum weight and the maximum number of variables which may be changed. The latter two arguments introduce extra bound conditions in the branch-and-bound algorithm.

Even when variables are weighted, the solution to the error localization problem may not be unique. In those cases `localizeErrors` will draw uniformly from the set of lowest-weight solutions. The degeneracy (number of equivalent solutions found) is reported in the output.

The result of a call to `localizeErrors` is an object of class `errorLocation`. It contains a boolean matrix with error locations for each record as well as a status report containing degeneracies, solution weights run times and whether the maximum runtime was exceeded. It also contains a timestamp

```

> E <- editarray(c(
+   "age %in% c('under-aged','adult')",
+   "maritalStatus %in% c('unmarried','married','widowed','divorced')",
+   "positionInHousehold %in% c('marriage partner', 'child', 'other')",
+   "if( age == 'under-aged' ) maritalStatus == 'unmarried'",
+   "if(positionInHousehold == 'marriage partner') maritalStatus == 'married'"
+ )
+ )
> (dat <- data.frame(
+   maritalStatus=c('married','unmarried','widowed' ),
+   age = c('under-aged','adult','adult' ),
+   positionInHousehold=c('child','other','marriage partner')
+ ))

  maritalStatus      age positionInHousehold
1    married under-aged             child
2   unmarried      adult             other
3    widowed      adult marriage partner

> set.seed(1)
> localizeErrors(E,dat)

Object of class 'errorLocation' generated at Wed Oct 12 15:58:30 2011
call : localizeErrors(E, dat)
slots: $adapt $status $call $user $timestamp

Values to adapt:
  adapt
record maritalStatus      age positionInHousehold
  1         FALSE TRUE             FALSE
  2         FALSE FALSE             FALSE
  3         FALSE FALSE             TRUE

Status:
  weight degeneracy user system elapsed maxDurationExceeded
1      1          2    0      0    0.007              FALSE
2      0          1    0      0    0.002              FALSE
3      1          2    0      0    0.008              FALSE

```

Figure 2: Localizing errors in a data.frame of records. The data model is as defined in Example 2.1. The randseed is set before calling `localizeErrors` to make results reproducible. The third record has degeneracy 2, which means that the chosen solution was drawn uniformly from two equivalent solutions with weight 1.

(in the form of a Date object) and the name of the user running R. Table 2 gives an overview of the slots involved.

In Figure 2 an example of the use of `localizeErrors` is given. The data model and rules are as in subsection 4.1. The records are given by

```

  maritalStatus      age positionInHousehold
1    married under-aged             child
2   unmarried      adult             other
3    widowed      adult marriage partner

```

The edits state that under-aged cannot be married and that you cannot be a marriage partner if you're not married. Clearly, the first and third

Table 2: Slots in the `errorLocation` object

Slot	description.
<code>\$adapt</code>	boolean array, stating which variables must be adapted for each record.
<code>\$status</code>	A <code>data.frame</code> , giving solution weights, number of equivalent solutions, timings and whether the maximum search time was exceeded.
<code>\$user</code>	Name of user running R during the error localization
<code>\$timestamp</code>	<code>date()</code> at the end of the run.
<code>\$call</code>	The call to <code>localizeErrors</code>

record disobey some of these rules while the second record is valid. The first record can be repaired by adapting age and the second record can be made consistent by changing either *position in household* or *marital status*. In the latter case, both solutions have equal weight and `localizeErrors` has drawn one solution.

4.3 Error localization with `errorLocalizer`

Just like for linear edits, the function `errorLocalizer` gives more control over the error localization process since it allows to parameterize the search separately for each record. This can be useful, for example when reliability weights are calculated for each record.

The `errorLocalizer` function is described extensively in De Jonge and Van der Loo (2011), so here we will discuss the example shown Figure 3.

The data model and edits are the same as in Figure 2. The difference here is that a record must be offered as a named `character` vector. A call to `errorLocalizer` generates a `backtracker` object which contains all information necessary to start searching the binary tree. After calling `$searchNext()` the weight and first found solution are returned, while the `backtracker` object stores some meta-information about the process, most significantly the duration of the search. A second call yields a better solution and the third call returns `NULL`, indicating that all minimal weight solutions have been found.

5 Conclusions

This paper describes the theory and implementation of categorical edit manipulation of the `editrules` package. Categorical restrictions may be defined textually in standard R syntax. New edits may be derived with the resolution method. A new formulation of the elimination method in terms of the resolution operator was developed which facilitated the development of a fast elimination algorithm which seems to be new in the field of data editing.

```

> # Define a record
> r <- c(age = 'under-aged', maritalStatus='married', positionInHousehold='child')
> el <- errorLocalizer(E,r)
> el$searchNext()

$w
[1] 1

$adapt
      age      maritalStatus positionInHousehold
      FALSE              TRUE              FALSE

> el$duration

  user  system elapsed
0.000   0.000   0.004

> el$maxdurationExceeded

[1] FALSE

> el$searchNext()

$w
[1] 1

$adapt
      age      maritalStatus positionInHousehold
      TRUE              FALSE              FALSE

> el$searchNext()

NULL

```

Figure 3: Finding errors with `errorLocalizer`. The data model and edits in E are as in Figure 2.

The package offers functionality to check records against rules and can determine the location of errors based on the generalized principle of Fellegi and Holt.

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A Notation

Symbol	Explanation and reference
\oplus	Direct vector sum.
\mathbf{a}	An edit, in boolean representation: $\mathbf{a} = \rho(e)$, Eq. (13).
\mathbf{a}_k	Boolean representation of one variable in \mathbf{a} . $\mathbf{a} = \oplus_{k=1}^n \mathbf{a}_k$.
\mathbf{A}	Set of edits, in $m \times d$ boolean representation.
D	Set (domain) of all possible categorical records, Eq. (1).
D_k	Set of possible categories for variable k . Eq. (2).
d	Number of categories (in total), Eq. (6).
d_k	Number of categories in D_k .
e	An edit, in set representation: $e \subseteq D$, [Eq. (11)].
E	An editarray, Eq. (19), or a set of edits in set representation.
\mathbf{ind}	Function relating categories c of variable k to columns in \mathbf{A} , Eqs.(20) and (21).
i	row index in \mathbf{A} (labeling edits).
j	column index in \mathbf{A} (labeling categories).
k	Labels a categorical variable.
m	Number of edits.
n	Number of variables.
\mathfrak{R}_k	Resolution operator Eq. (22).
ρ	Map, sending set representation to boolean representation.
v	Categorical record, in set representation: $v = (v_1, \dots, v_n) \in D$.
v_k	Label for a single category of D_k .
\mathbf{v}	Categorical record, in boolean representation: $\mathbf{v} = \rho(v)$.
\mathbf{v}_k	Boolean representation of a single variable $\mathbf{v} = \oplus_{k=1}^n \mathbf{v}_k$.

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