Translating database mathematical schemes into relational database software applications with *MatBase*

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Abstract

We present a pseudocode algorithm for translating our (Elementary) Mathematical Data Model schemes into relational ones and associated sets of non-relational constraints, used by *MatBase*, our intelligent data and knowledge base management system prototype. We prove that this algorithm is very fast, solid, complete, and optimal. We apply it to a mathematical scheme modeling the genealogical trees subuniverse. We also provide examples of SQL and VBA code for enforcing some of its non-relational constraints, as well as guidelines to develop code for enforcing such constraints.

Keywords: (Elementary) Mathematical Data Model, Relational Data Model, database design, database constraints, software application architecture and development, *MatBase*.

1. INTRODUCTION

Every subuniverse of discourse is governed by business rules. For example, stocks may not be negative, people may not live more than 140 years, countries have only one capital city, dynasties only one founder, etc. Databases (dbs) and their managing software applications should enforce all of them to guarantee data plausibility – the highest possible syntactical data quality level.

Generally, this is done even today mostly informally, in rather ad-hoc manners, which is inevitably prone to errors. The process starts with establishing a set of Entity-Relationship diagrams (E-RDs) [1–3], then refining from them a relational db (rdb) model (RDM) scheme [3–5], which is implemented on a version of a Relational Database Management System (RDBMS). Too often, the corresponding software applications that manage these dbs are architectured and developed using UML, user diagrams, classes, agents, ontologies, etc., almost completely decoupled from the business rules. Generally, missed business rules are discovered only during db software application usage, reported as bugs, and fixed ad-hoc (sometimes even introducing new bugs).

This is why, after decades of IT developing, research, and Computer Science University teaching experience, we introduced a middle conceptual level between the E-R and relational ones, our (Elementary) Mathematical Data Model ((E)MDM) [6], as well as a db constraint-driven methodology for designing and developing db software applications [7].

In this framework, for any subuniverse of discourse, we start by algorithmically discovering and establishing the set of all business rules that govern it, along with the corresponding set of entity and relationship sets and their attributes (see Algorithm A0 from [3], Section 2.9).

Then, by using the E-R to (E)MDM translation algorithm [8], we refine the initial models, mainly by formalizing business rules as db constraints, i.e., closed Horn clauses of the first-order predicate calculus with equality (FOPC), but also formalizing E-R types as sets, and their attributes as functions. The first part of this paper presents the algorithm that we use in the next step: translating (E)MDM schemes into relational db ones and associated sets of non-relational constraints. Please recall that there are only 6 types of relational constraints (domain/range, not null, default value, unique key, foreign key, and tuple/check), whereas (E)MDM provides 75 [6].

Relational db schemes are then automatically translatable into corresponding ANSI SQL scripts by using Algorithm A8 from [3] (see Fig. 4.1, Section 4.1), which may then be similarly translated into rdbs managed by any desired version of a RDBMS, by the corresponding algorithm from the family AF8' from [3] (see exercise 4.3 from subsection 4.11.2).

All these algorithms may not only be manually run, but are also implemented in *MatBase*, our intelligent db and knowledge base management system prototype [9], currently developed with MS VBA in two versions – an Access-based one for small to medium dbs and a SQL Server-based one for large dbs. *MatBase* provides graphic user interfaces (GUIs) for both (E)MDM (which includes Datalog¬ [5]), RDM, and E-RDs, as well as algorithms to translate between them, be it directly or by reverse engineering [3, 8, 10].

For enforcing non-relational constraints, *MatBase* first automatically generates a Windows datasheet form for every table in any db it manages. Then, for most of the 75 (E)MDM constraint types, it automatically generates code into the classes of these forms [11–15]. For the rest of them, it invites its users to add their code.

The second part of this paper presents examples of enforcing non-relational constraints from the genealogical trees subuniverse, as well as our main guidelines for enforcing such constraints by using event-driven programming with embedded SQL.

2. RELATED WORK

Other related approaches to *MatBase* are based on business rules management (BRM) [16, 17] and their corresponding implemented systems (BRMS) and decision managers (e.g., [18–20]). From this perspective, (E)MDM is also a formal BRM, and *MatBase* is an automatically code generating BRMS.

(E)MDM is also a 5th generation programming language [21, 22] and *MatBase* is also a tool for transparent programming while modeling data at conceptual levels [23].

3. *MatBase* PSEUDOCODE ALGORITHM FOR TRANSLATING (E)MDM SCHEMES INTO RELATIONAL ONES AND ASSOCIATED SETS OF NON-RELATIONAL CONSTRAINTS

Figures 1 to 5 show the *MatBase M-R* pseudocode algorithm (referred to as *A*7 in [3]) for translating (E)MDM schemes into relational ones and associated sets of non-relational constraints.

```
Method addColumn(R, e)

add column e to table R, having domain constraint (i.e., data type
    and, if any, range [minValue, maxValue]) corresponding to e's
    codomain;
if e is computed then add corresponding computation trigger;
End Method addColumn;
```

Figure 1: Method *addColumn* of Algorithm *M-R*

```
Method addForeignKey(R, A, S)

add a numeric column A to table R;
if S is a table then
  declare A as foreign key having maximum value corresponding to S's
  cardinality restriction, and referencing primary key x of table S;
else code S' values numerically and add corresponding domain
  constraint to A;
end if;
End Method addForeignKey;
```

Figure 2: Method *addForeignKey* of Algorithm *M-R*

4. AN EXAMPLE

Applying the *M-R* algorithm to the (E)MDM scheme from [7, 10, 24], the relational scheme shown in Tables 1 to 7 and the associated sets of non-relational constraints shown in Figures 6 to 9 are obtained.

In fact, because of its unexpected limitation, for MS Access we had to change the type of the *Age* column from *Calculated* to NAT (and to subsequently add code for computing its values), as, although syntactically correct, it does not accept as expression IsNull(PassedAwayYear, Year(Date()), PassedAwayYear) – BirthYear for calculated fields.

To make table schemes fully understandable, we added to the relational schemes examples of plausible instances. We recall our convention for table schemes [3]:

```
                    Method completeScheme(R)

loop for all structural functions f from R to S, except for set
   inclusion-type ones (i.e., canonical injections)
   addForeignKey(R, f, S);
end loop;
loop for all attributes a of R, except for the object identifier x
   addColumn(R, a);
end loop;
loop for all totality constraints c associated to R
   add to R's scheme corresponding NOT NULL constraints;
end loop;
loop for all keys k associated to R
   add to R's scheme corresponding k key constraint;
end loop;
loop for all object constraints t associated to R involving only map-
       pings defined over R and one universally quantified variable
   add to R's scheme corresponding tuple constraint t;
end loop;
End Method completeScheme;
```

Figure 3: Method *completeScheme* of Algorithm *M-R*

- Table title contains its name, followed in parentheses by its (unique) keys (with the primary one underlined), and then by its tuple (check) constraints.
- First header line contains the column names.
- Second header line contains the column ranges (which, for foreign keys, are the images, i.e., the value sets, of the corresponding referenced columns) or, for computed ones, their computation formula.
- Third (and final) header line contains the corresponding NOT NULL constraints.

5. ENFORCING THE ASSOCIATED NON-RELATIONAL CONSTRAINT SETS

All non-relational constraints are enforced in the classes of the Windows forms generated over the corresponding relational db tables. For some of them, only SQL code is needed, but most of them need VBA/C# code with embedded SQL. For most types of such constraints, *MatBase* automatically generates code for their enforcement that calls its public methods from the *Constraint* library [9]; for the rest of them, especially the object-type ones, db software architects need to develop it.

Fortunately, thanks to clever null values logics, both MS Access and SQL Server may, however, enforce some non-relational constraints as well. For example, C_{17}: ($\forall x \in MARRIAGES$)(*MarriageYear*(x) $\notin$ NULLS $\Rightarrow$ *DivorceYear*(x) $\notin$ NULLS $\lor$ *DivorceYear*(x) $\geq$ *MarriageYear*(x)) (nobody may divorce somebody before marrying him/her) may be enforced by

the tuple (check) constraint $DivorceYear \geq MarriageYear$; similarly, C_{24}: $(\forall x \in REIGNS)(ToY(x) \in$ NULLS $\vee$ $ToY(x) \geq FromY(x))$ (no reign may end before starting) may be enforced by the tuple (check) constraint $ToY \geq FromY$.

```
Method createTable(R)

if there is no table R and R has attributes, or is referencing, or it
   is not referencing, but it is not static and with small cardinality
then create table R;
  if R is a subset of S then
     AddForeignKey(R, x, S);
     declare x as primary key;
     loop for all other sets T with R ⊆ T
       AddForeignKey(R, xT, T);
       add to R's scheme NOT NULL and UNIQUE constraints for xT;
     end loop;
  else add an autonumber primary key x, having maximum value
       corresponding to R's cardinality restriction;
  end if;
  completeScheme(R);
end if;
End Method createTable;
```

Figure 4: Method *createTable* of Algorithm *M-R*

Dually, we need to take into consideration the limitations of the underlying RDBMS, which sometimes force us to enforce relational-type constraints through code as well. For example, unfortunately, MS SQL Server accepts for the column *RULERS.Age* the computation definition AS isnull([PassedYear], year(getdate()))) – [BirthYear], but only as a virtual column, not a persisted one, as (due to getdate()) this expression is non-deterministic; consequently, constraint C_6: $(\forall x \in RULERS)(0 \leq Age(x) \leq 140)$ (anybody's age must be a natural at most equal to 140) must also be enforced through code, just like for MS Access, although it is of relational domain/range (check) type. Fig. 10 shows the corresponding VBA code. Please note that C_6 makes the tuple constraint *BirthYear* $\leq$ *PassedAwayYear* redundant.

Moreover, constraint "*Founder* key" of *DYNASTIES* (nobody founds more than one dynasty) may not be enforced by MS SQL Server, as *Founder* may take null values, and, unlike MS Access, it wrongly assumes that there is only one null value in the world (sic!), so it does not accept building and maintaining unique indexes containing columns that might store more than one null value! Consequently, code must be added to the *DYNASTIES* form class to enforce this constraint.

Unfortunately, this goes the same for the following 7 keys: *URL* key (no URL may be used to describe two persons), C_3: *Name* • *Dynasty* • *BirthYear* key (there may not be two persons of the same dynasty born in the same year and having the same name), C_{10}: *Mother* • *Name* key (no

mother gives the same name to 2 of her children), and C_{11}: *Father • Name* key (no father gives the same name to 2 of his children) of *RULERS*, C_{15}: *Husband • Wife • MarriageYear* key (nobody may marry the same person twice in a same year) and C_{16}: *Husband • Wife • DivorceYear* key (nobody may divorce the same person twice in a same year) of *MARRIAGES*, and C_{23}: *Ruler • Country • ToY* (it does not make sense to store twice that a ruler ended ruling a country during a year) of *REIGNS*.

```
Algorithm M-R (Translation of (E)MDM schemes into relational ones
           and associated sets of non-relational constraints)

Input: a(n) (E)MDM db scheme M.
Output: corresponding relational db scheme R and associated set of
   non-relational constraints C.
Strategy:

loop for all entity-type object sets E in M (in bottom-up order, from
    non-referencing object sets to non-referenced, only referencing
    ones)
    if E is not a computed set then createTable(E);
    else add a corresponding view E to the db scheme;
end loop;
loop for all relationship-type object sets R in D (in bottom-up order,
    from  only  referenced,  non-referencing  object  sets  to  non-
    referenced, only referencing ones)
    createTable(R);
    loop for all R's roles (canonical Cartesian projections) r
        addForeignKey(R, r, S);
        add to R's scheme a NOT NULL constraint for foreign key r;
    end loop;
end loop;
add all unused (non-relational) constraints to the non-relational
   constraint set C;
End Algorithm M-R;
```

Figure 5: Algorithm *M-R* (Translate (E)MDM schemes to RDM ones and associated sets of non- relational constraints)

Constraints C_7, C_8, C_{18}, and C_{19} may be very easily enforced only through adding a WHERE clause in four SELECT SQL statements as follows:

-       In the *RULERS* and *MARRIAGES* Windows forms, as *RULERS* has the unique key *Name • BirthYear • Dynasty*, *MatBase* generates for both foreign keys *Mother*, *Father*, *KilledBy*, *Wife*, and *Husband* combo-boxes whose row sources are computed by the following statement:

Table 1: *COUNTRIES*   Table 2: *CITIES*

COUNTRIES (x, *Country*, *Capital*)

x	Country	Capital
auto(3)	ASCII(255)	Im(CITIESx)
NOT NULL	NOT NULL	
1	U.K.	1
2	France	2
3	U.S.A.	

CITIES (x, *City • Country*)

x	City	Country
auto(6)	ASCII(255)	Im(COUNTRIESx)
NOT NULL	NOT NULL	NOT NULL
1	London	1
2	Paris	2
3	Sandringham	1
4	Reading	1
5	Los Angeles	3

C_2: *Country ° Capital* null-reflexive (The capital city of any country must belong to that country.)

Figure 6: Non-relational constraint set associated with tables *COUNTRIES* and *CITIES*

Table 3: *DYNASTIES*   Table 4: *TITLES*

DYNASTIES (x, *Dynasty*, *Founder*)

x	Dynasty	Country	Founder
auto(8)	ASCII(255)	Im(COUNTRIESx)	Im(RULERSx)
NOT NULL	NOT NULL	NOT NULL	
1	Windsor	1	

TITLES (x, *Title*)

x	Title
auto(2)	ASCII(32)
NOT NULL	NOT NULL
1	King
2	Queen
3	Prince
4	Princess
5	Duchess

SELECT RULERS.x, [Name] & ", " & [BirthYear] & IIf(IsNull([RULERS].[Dynasty]),"",", " &
        [DYNASTIES].[Dynasty]) AS [Name, BirthYear, Dynasty]
FROM DYNASTIES RIGHT JOIN RULERS ON DYNASTIES.x = RULERS.Dynasty
ORDER BY [Name] & ", " & [BirthYear] & IIf(IsNull([RULERS].[Dynasty]),"",", " &
        [DYNASTIES].[Dynasty]);

-       For C_7 and C_{19}, injecting to it the clause WHERE Sex = 'F' for *Mother* and *Wife* will select
in them only female rulers (see, e.g., Fig. 11).

-       For C_8 and C_{18}, injecting to it the clause WHERE Sex = 'M' for *Father* and *Husband* will
select in them only male rulers (see, e.g., Fig. 12).

A partially similar approach may be used for enforcing constraint C_2: *Country ° Capital* null-
reflexive (the capital city of any country must belong to that country), which might be violated
either by choosing for a country a city from another one or/and by changing the country to which
a capital city belongs.

As *CITIES* has the unique key *City • Country*, *MatBase* generates for the row source of the *Capital*
combo-box from the *COUNTRIES* Windows form the following SQL statement:
SELECT CITIES.x, CITIES.City, COUNTRIES.Country
FROM COUNTRIES INNER JOIN CITIES ON COUNTRIES.x = CITIES.Country
ORDER BY COUNTRIES.Country, CITIES.City;

This allows users to choose capitals for any country from the whole set of known cities, as shown in Fig. 13.

Table 5: *RULERS*

$\textbf{\textit{RULERS}}\,(\underline{\textit{x}},\ \textit{URL},\ \textit{Name} \bullet \textit{Dynasty} \bullet \textit{BirthYear},\ \textit{Mother} \bullet \textit{Name},\ \textit{Father} \bullet \textit{Name})$

$BirthYear \leq PassedAwayYear$

x	Name	Sex	BirthYear	PassedAwayYear
auto(16)	ASCII(255)	{'M', 'F', 'N'}	[-6500, CurrentYear()]	[-6500, CurrentYear()]
NOT NULL	NOT NULL	NOT NULL		
1	CharlesIII	'M'	1948	
2	Diana Spencer	'F'	1961	1997
3	William	'M'	1982	
4	Harry	'M'	1984	
5	Catherine	'F'	1982	
6	Meghan	'F'	1981	
7	Camilla	'F'	1947	
8	Andrew Parker Bowles	'M'	1939	

Age	Mother	Father	KilledBy	Dynasty	Title
isNull(PassedAwayYear, CurrentYear()) − BirthYear	Im(x)	Im(x)	Im(x)	Im(DYNASTIES.x)	Im(TITLES.x)
78				1	1
36				1	4
44	2	1		1	3
42	2	1		1	3
44					4
45					5
79				1	2
87					

BirthPlace	Nationality	PassedAwayPlace	URL
Im(CITIES.x)	Im(COUNTRIES.x)	Im(CITIES.x)	ASCII(255)
1	1		en.wikipedia.org/wiki/Charles_III
3	1	2	en.wikipedia.org/wiki/Diana_Princess_of_Wales
1	1		en.wikipedia.org/wiki/William,_Prince_of_Wales
1	1		en.wikipedia.org/wiki/Prince_Harry,_Duke_of_Sussex
4	1		en.wikipedia.org/wiki/Catherine,_Princess_of_Wales
5	3		en.wikipedia.org/wiki/Meghan,_Duchess_of_Sussex
1	1		en.wikipedia.org/wiki/Queen_Camilla
	1		en.wikipedia.org/wiki/Andrew_Parker_Bowles

To prevent users from violating C_2 when choosing capital cities for countries, it is enough to replace this SQL statement with the following dynamic one, where x is the value of the primary key column of *COUNTRIES*, and run it every time when users enter a new line of this table:

"SELECT x, City FROM CITIES WHERE Country = " & x & " ORDER BY City".

The corresponding VBA code is shown in Fig. 14, and its effect is presented in Fig. 15, where it can be seen that, e.g., for U.K. only cities of U.K. are available to choose its capital from.

C_{27}: *Mother* : *RULERS* → *RULERS* acyclic (Nobody may be his/her maternal ancestor or descendant.)

C_{28}: *Father* : *RULERS* → *RULERS* acyclic (Nobody may be his/her paternal ancestor or descendant.)

C_{29}: *KilledBy* ⊢— *PassedAwayYear* (Death year must be known for any killing.)

C_4: *Dynasty* ° *Founder* null-reflexive (The founder of any dynasty must belong to that dynasty.)

C_5: $(\forall x \in RULERS)(Dynasty(x) \notin$ NULLS ∧ $Founder(Dynasty(x)) \notin$ NULLS ∧ $BirthYear(Founder($
$Dynasty(x))) \notin$ NULLS ⇒ $PassedAwayYear(x) \in$ NULLS ∨ $PassedAwayYear(x) > BirthYear($
$Founder(Dynasty(x))))$ (Nobody may belong to a dynasty that was founded after his/her death).

C_6: $(\forall x \in RULERS)(Sex(x) \neq$ 'N' ⇒ $0 \le Age(x) \le 140)$ (Age must be a natural at most equal to 140.)

C_7: $(\forall x \in RULERS)(Sex(Mother(x)) =$ 'F') (Mothers' sex must be 'F'.)

C_8: $(\forall x \in RULERS)(Sex(Father(x)) =$ 'M') (Fathers' sex must be 'M'.)

C_9: $(\forall x \in RULERS)(Sex(x) =$ 'N' ⇒ $Mother(x) \in$ NULLS ∧ $Father(x) \in$ NULLS ∧ $Dynasty(x) \in$ NULLS
∧ $KilledBy(x) \in$ NULLS) (Non-persons may not have parents or killers or belong to dynasties.)

C_{12}: $(\forall x \in RULERS)(BirthYear(x) \notin$ NULLS ∧ $Mother(x) \notin$ NULLS ∧ $BirthYear(Mother(x)) \notin$ NULLS
∧ $Sex(x) \neq$ 'N' ⇒ $5 \le BirthYear(x) - BirthYear(Mother(x)) \le 75$ ∧ $(PassedAwayYear(Mother(x))$
$\notin$ NULLS ⇒ $(BirthYear(x) \le PassedAwayYear(Mother(x)))$ (Women may give birth only between 5
and 75 years, but before passing away.)

C_{13}: $(\forall x \in RULERS)(BirthYear(x) \notin$ NULLS ∧ $Father(x) \notin$ NULLS ∧ $BirthYear(Father(x)) \notin$ NULLS
∧ $Sex(x) \neq$ 'N' ⇒ $9 \le BirthYear(x) - BirthYear(Father(x)) \le 100$ ∧ $(PassedAwayYear(Father(x))$
$\notin$ NULLS ⇒ $(BirthYear(x) \le PassedAwayYear(Father(x)) + 1))$ (Men may have children only
between 9 and 100 years, and at most one year after passing away.)

C_{14}: $(\forall x \in RULERS)(KilledBy(x) \notin$ NULLS ∧ $BirthYear(KilledBy(x)) \notin$ NULLS ∧ $Sex(x) \neq$ 'N' ⇒
$BirthYear(KilledBy(x)) \le PassedAwayYear(x) \le isNull(PassedAwayYear(KilledBy(x)), BirthYear($
$KilledBy(x)) + 140))$ (Any killer of a person must have been alive when his/her victim was killed.)

Figure 7: Non-relational constraint set associated with table *RULERS*

For the second part of C_2, users must not be allowed to change the countries they belong to for capital cities. The corresponding VBA code is shown in Fig. 16. An example of the error message displayed by this method is shown in Fig. 17.

Please note that, when inserting data for a new city (i.e., *NewRecord = True*), C_2 needs not to be checked, as such cities may not be country capitals yet. Moreover and much more important, C_2 implies constraint *Capital* key, as no city might be selected for two countries in the corresponding combo-box: consequently, this unique key may be dropped from the relational db schema, making it more efficient.

Table 6: *MARRIAGES*

MARRIAGES (x, *Husband • Wife • MarriageYear, Husband • Wife • DivorceYear*)

MarriageYear ≤ DivorceYear

x	MarriageYear	DivorceYear	Husband	Wife
auto(16)	[-6500, CurrentYear()]	[-6500, CurrentYear()]	Im(RULERS.x)	Im(RULERS.x)
NOT NULL			NOT NULL	NOT NULL
1	1981	1996	1	2
2	2005		1	7
3	2011		3	5
4	2018		4	6
5	1973	1995	8	7

C_{18}: $(\forall x \in MARRIAGES)(Sex(Wife(x)) = \text{'F'})$ (Wives' sex must be 'F'.)

C_{19}: $(\forall x \in MARRIAGES)(Sex(Husband(x)) = \text{'M'})$ (Husbands' sex must be 'M'.)

C_{20}: $(\forall x \in MARRIAGES)(MarriageYear(x) \notin \text{NULLS} \Rightarrow ((BirthYear(Husband(x)) \in \text{NULLS} \vee BirthYear(Husband(x)) \leq MarriageYear(x)) \wedge (PassedAwayYear(Husband(x)) \in \text{NULLS} \vee PassedAwayYear(Husband(x)) \geq MarriageYear(x))) \wedge (BirthYear(Wife(x)) \in \text{NULLS} \vee BirthYear(Wife(x)) \leq MarriageYear(x)) \wedge (PassedAwayYear(Wife(x)) \in \text{NULLS} \vee PassedAway\text{-}Year(Wife(x)) \geq MarriageYear(x))))$ (Nobody may marry before being born or after death.)

C_{21}: $(\forall x \in MARRIAGES)(DivorceYear(x) \notin \text{NULLS} \Rightarrow ((BirthYear(Husband(x)) \in \text{NULLS} \vee BirthYear(Husband(x)) \leq DivorceYear(x)) \wedge (PassedAwayYear(Husband(x)) \in \text{NULLS} \vee PassedAwayYear(Husband(x)) \geq DivorceYear(x))) \wedge (BirthYear(Wife(x)) \in \text{NULLS} \vee BirthYear(Wife(x)) \leq DivorceYear(x)) \wedge (PassedAwayYear(Wife(x)) \in \text{NULLS} \vee PassedAway\text{-}Year(Wife(x)) \geq DivorceYear(x))))$ (Nobody may divorce before being born or after death.)

C_{30}: $(\forall x \in MARRIAGES)(PassedAwayYear(Husband(x)) \notin \text{NULLS} \wedge PassedAwayYear(Wife(x)) \notin \text{NULLS} \Rightarrow (BirthYear(Husband(x)) \in \text{NULLS} \wedge BirthYear(Wife(x)) \in \text{NULLS} \Rightarrow -140 \leq Passed\text{-}AwayYear(Husband(x)) - PassedAwayYear(Wife(x)) \leq 140) \vee BirthYear(Husband(x)) \leq BirthYear(Wife(x)) \leq PassedAwayYear(Husband(x)) \vee BirthYear(Wife(x)) \leq BirthYear(Husband(x)) \leq Passed\text{-}AwayYear(Wife(x))))$ (For any marriage, husband and wife must have been simultaneously alive at least one day.)

C_{31}: $(\forall x, y \in MARRIAGES)(x \neq y \wedge MarriageYear(y) \geq MarriageYear(x) \wedge MarriageYear(y) \leq isNull(Di\text{-}vorceYear(x), CurrentYear()) \vee MarriageYear(x) \geq MarriageYear(y) \wedge MarriageYear(x) \leq isNull(Di\text{-}vorceYear(y), CurrentYear()) \Rightarrow Husband(x) \neq Husband(y) \wedge Wife(x) \neq Wife(y))$ (No spouse may remarry while being married.)

C_{32}: $(\forall x \in MARRIAGES)(Father(Husband(x)) \neq Father(Wife(x)) \wedge Mother(Husband(x)) \neq Mother(Wife(x)) \wedge Father(Wife(x)) \neq Husband(x) \wedge Mother(Husband(x)) \neq Wife(x))$ (Incestuous marriages are forbidden.)

Figure 8: Non-relational constraint set associated with table *MARRIAGES*

Table 7: *REIGNS*

REIGNS ($\underline{x}$, *Ruler • Country • FromY, Ruler • Country • ToY*) *ToY ≥ FromY*

$\underline{x}$	*FromY*	*ToY*	*Ruler*	*Country*	*Title*
auto(16)	[-6500, *CurrentYear*()]	[-6500, *CurrentYear*()]	*Im(RULERS.x)*	*Im(COUNTRIES.x)*	*Im(TITLES.x)*
NOT NULL	NOT NULL		NOT NULL	NOT NULL	
1	2022		1	1	1
2	2022		7	1	2

C_{25}: $(\forall x \in REIGNS)((BirthYear(Ruler(x)) \notin \text{NULLS} \Rightarrow BirthYear(Ruler(x)) \leq FromY(x)) \land (Passed\text{-}$
$AwayYear(Ruler(x)) \notin \text{NULLS} \Rightarrow ToY(x) \notin \text{NULLS} \land PassedAwayYear(Ruler(x)) \geq ToY(x)))$

(Nobody may reign before being born or after death.)

C_{26}: $(\forall x,y \in REIGNS)(x \neq y \land Country(x) = Country(y) \land Ruler(x) \neq Ruler(y) \land (FromY(y) \geq FromY(x)$
$\land FromY(y) \leq isNull(ToY(x), CurrentYear()) \lor FromY(x) \geq FromY(y) \land FromY(x) \leq isNull(ToY(y),$
$CurrentYear()) \Rightarrow Sex(x) = \text{'N'} \lor Sex(y) = \text{'N'} \lor (Father(Ruler(y)) = Ruler(x) \lor Father(Ruler(x))$
$= Ruler(y) \lor Mother(Ruler(y)) = Ruler(x) \lor Mother(Ruler(x)) = Ruler(y)) \lor (\exists z \in MARRIAGES)$
$(Husband(z) = Ruler(x) \land Wife(z) = Ruler(y) \lor Husband(z) = Ruler(y) \land Wife(z) = Ruler(x)))$ (No
country may be simultaneously ruled by 2 persons, except for cases where at least one of them has
sex 'N', or the two were married, or parent and child.)

C_{33}: $(\forall x,y \in REIGNS)(x \neq y \land Country(x) = Country(y) \land (FromY(y) \geq FromY(x) \land FromY(y) \leq$
$isNull(ToY(x), CurrentYear()) \lor FromY(x) \geq FromY(y) \land FromY(x) \leq isNull(ToY(y), CurrentYear()) \Rightarrow$
$Ruler(x) \neq Ruler(y))$ (Nobody may reign twice in the same country in the same period.)

Figure 9: Non-relational constraint set associated with table *REIGNS*

```vba
'RULERS class
Option Compare Database
Option Explicit

Private Sub Form_BeforeUpdate(Cancel As Integer)
'C6
If Sex <> "N" And Not IsNull(BirthYear) Then
  Dim RAge As Integer
  RAge = IIf(IsNull(PassedAwayYear), Year(Date), PassedAwayYear) _
        - BirthYear
  If RAge < 0 Or RAge > 140 Then
    Cancel = True
    MsgBox "Please change BirthYear or/and PassedAwayYear, " & _
        "such that age is between 0 and 140!", _
        vbCritical, "Age for " & Me![Name] & " is " & RAge & "!"
  End If
End If
End Sub
```

Figure 10: VBA code for enforcing constraint C_6
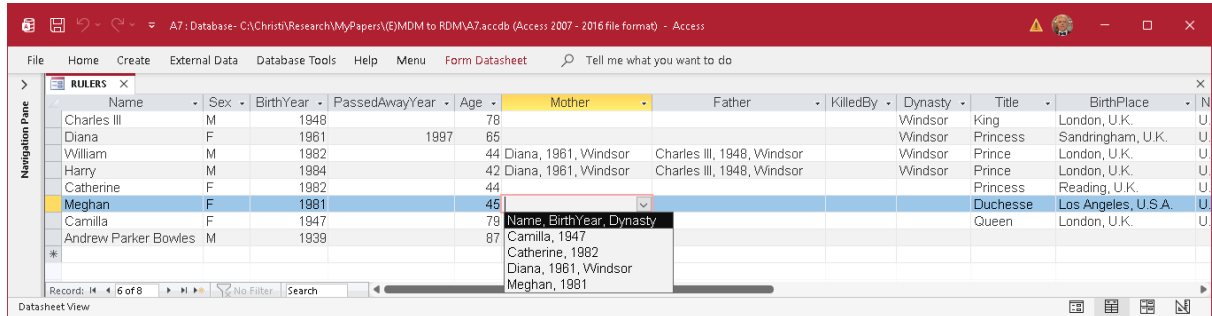
Figure 11: Selecting only females in the *Mother* combo-box of form *RULERS*
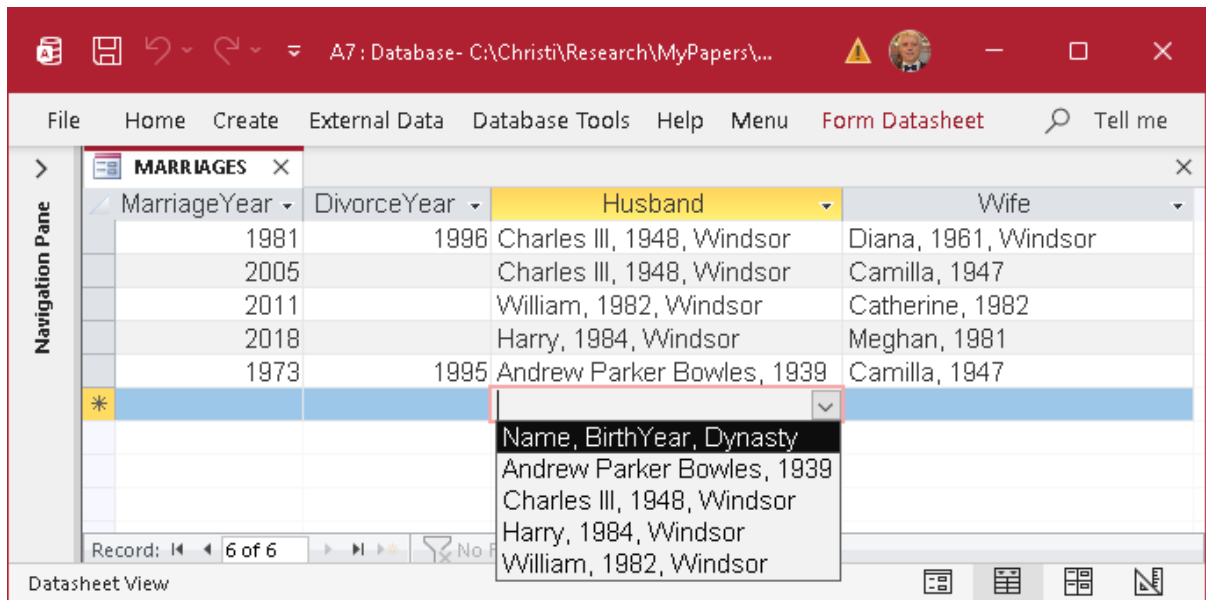
Figure 12: Selecting only males in the *Husband* combo-box of form *MARRIAGES*
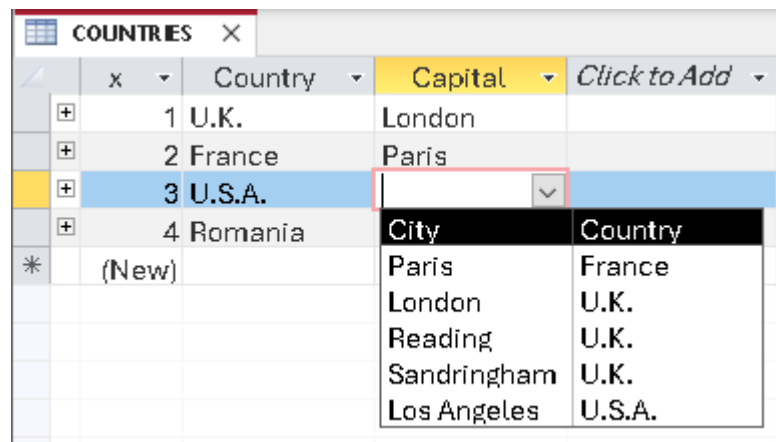
Figure 13: Selecting cities in the *Capital* combo-box of form *COUNTRIES*

Constraint C_4: *Dynasty ° Founder* null-reflexive (the founder of any dynasty must belong to that dynasty) is of the same type as C_2, so it may be enforced similarly, with a *Form_Current* method in the *DYNASTIES* class and a *Dynasty_BeforeUpdate* one in the *RULERS* class; the only difference should be that, in the *Form_Current* method, the dynamic SQL query must select not only the persons belonging to the current dynasty, but also those not belonging to any dynasty.

Constraint C_9: $(\forall x \in RULERS)(Sex(x) = $ 'N' $\Rightarrow Mother(x) \in$ NULLS $\wedge$ $Father(x) \in$ NULLS $\wedge$ $Dynasty(x) \in$ NULLS $\wedge$ $KilledBy(x) \in$ NULLS) (non-persons may not have parents or killers or belong to dynasties) may be elegantly enforced by the code shown in Fig. 18: method *Form_Current* blocks updating these 4 columns for lines having *Sex* = 'N' and allows it for 'M' and 'F', while the *Sex_AfterUpdate* one nullifies their values whenever *Sex* is changed to 'N', also displaying the warning message shown in Fig. 19.

```
'COUNTRIES class
Option Compare Database
Option Explicit

Private Sub Form_Current()
Capital.RowSource = "SELECT x, City " _
      & "FROM CITIES WHERE Country = " & x _
      & " ORDER BY City"
Capital.Requery
End Sub
```

Figure 14: VBA code for enforcing the first half of constraint C_2

Figure 15: Selecting cities in the *Capital* combo-box of form *COUNTRIES* after enforcing C_2

```
'CITIES class
Option Compare Database
Option Explicit

Private Sub Country_BeforeUpdate(Cancel As Integer)
'C2: The capital city of any country must belong to that country.
If Not NewRecord Then
  Dim cntry As Variant
  cntry = DLookup("Country", "COUNTRIES", "Capital = " & x)
  If Not IsNull(cntry) And (IsNull(Country) Or Country <> Country.OldValue) Then
    Cancel = True
    MsgBox "Request denied: you cannot change Country for this city...", _
      vbCritical, City & " is the capital of " & cntry & "!"
    Country.Undo
  End If
End If
End Sub
```

Figure 16: VBA code for enforcing the second half of constraint C_2
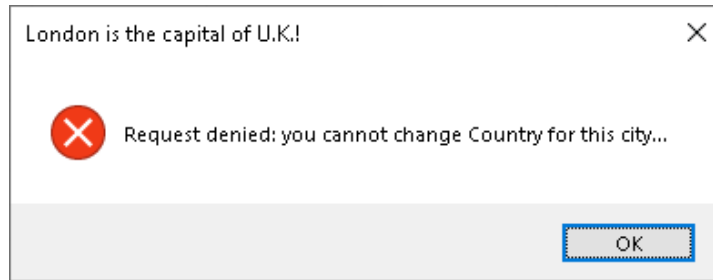
Figure 17: Error message displayed when users attempt to violate constraint C_2

```
'RULERS class
Option Compare Database
Option Explicit

Private Sub Form_Current()
If Sex = "N" Then
  Mother.Locked = True
  Father.Locked = True
  KilledBy.Locked = True
  Dynasty.Locked = True
Else
  Mother.Locked = False
  Father.Locked = False
  KilledBy.Locked = False
  Dynasty.Locked = False
End If
End Sub

Private Sub Sex_AfterUpdate()
If Sex = "N" Then
  Mother = Null
  Father = Null
  KilledBy = Null
  Dynasty = Null
  MsgBox "As not physical persons may not have parents, " _
    & "killers, or belong to dynasties, any such not null " _
    & "data for this person has been automatically deleted!", _
    vbExclamation, "Warning!"
End If
End Sub
```

Figure 18: VBA code for enforcing non-relational constraint C_9
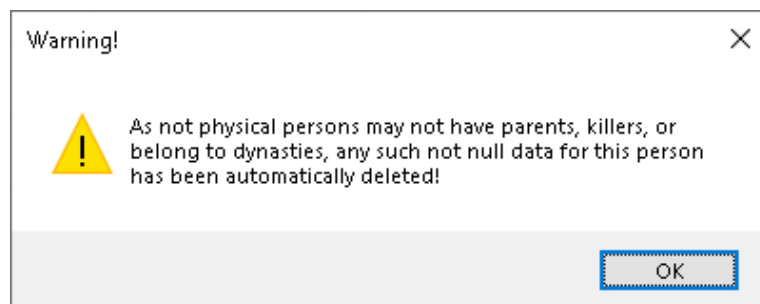
Figure 19: Warning message displayed when users attempt to violate constraint C_9

Object constraints C_{12} to C_{15}, as well as C_{20}, C_{21}, C_{25}, C_{26}, and C_{29} to C_{33} may also be enforced through VBA *Form_BeforeUpdate* and *column_BeforeUpdate* (.Net *Validating*) methods, like C_6 (see Fig. 10) and C_2 (see Fig. 16).

MatBase automatically generates corresponding code in the *RULERS* class for enforcing both the acyclicity constraints C_{27} and C_{28} (see [13]) and the existence C_{29} one (see [14]).

6. DISCUSSION

Proposition (Characterization of Algorithm *M–R*)

Algorithm *M-R* (Figures 1 to 5) is:

(i)   linear (i.e., has complexity $O(n)$, *n* natural).
(ii)   sound
(iii)   complete
(iv)   optimal.

Proof:

(i) (*complexity*) Let *e* be the number of entity-type sets of scheme M, *r* the one of relationship-type ones, *a* the number of all their attributes, $f = ccp + nccp$ the one of their structural functions (with *ccp* canonical Cartesian projections and *nccp* non-canonical Cartesian projections), and $c = rc + nrc$ the one of associated constraints (with *rc* relational and *nrc* non-relational); the first loop of *M-R* is executed *e* times, calling method *createTable* at most *e* times in total; the second loop is executed *r* times, calling method *createTable r* times and generating *ccp* foreign keys and corresponding not null constraints; finally, its third loop is executing *nrc* times; consequently, method *createTable* is called at most $e + r$ times and, in total, creates the tables of the output relational scheme *R* (at most $e + r$), their primary key constraints, their *nccp* foreign key columns not corresponding to canonical Cartesian projections (including those corresponding to canonical inclusions), as well as calling in the end the method *completeScheme*; this method adds in its first loop the *nccp* foreign key constraints, through calls to method *addColumn* all *a* attributes, all their domain (range), not null, unique key, and tuple (check) constraints, i.e., all rc relational constraints of *R*; as methods *addColumn* and *addForeignKey* do not have loops, it follows that, in total, *M-R* performs exactly $n = e + r + f + c$ steps, hence it never loops infinitely and is linear in the sum of the total numbers of sets, functions, and constraints of the input (E)MDM scheme *M*.
(ii)(*soundness*) As *M-R* outputs only relational tables, views, constraints, and sets of associated non-relational constraints, it is sound.
(iii)   (*completeness*) As *M-R* accepts as inputs any (E)MDM scheme, it is also complete.
(iv)   (*optimality*) As *M-R* treats any input set, function, and constraint only once and generates any table, view, column, and constraint only once, it is also optimal.   *Q.E.D.*

For the above example, of course, $e = 7$ (as there are 7 entity-type sets, *COUNTRIES, CITIES, DYNASTIES, TITLES, RULERS, MARRIAGES*, and *REIGNS*, all of them translated into corresponding rdb tables), $r = ccp = 0$ (there is no relationship-type set), $a = 21$ (with the 7 object identifiers translated into surrogate primary keys *x*, *Country* from *COUNTRIES*, *City* from *CITIES*, *Dynasty* from *DYNASTIES*, *Title* from *TITLES*, *Name, Sex, BirthYear, PassedAwayYear, Age*, and *URL* from *RULERS, MarriageYear* and *DivorceYear* from *MARRIAGES*, *FromY* and *ToY* from *REIGNS*), $f = nccp = 17$ (*Capital* : *COUNTRIES* $\leftrightarrow$ *CITIES, City* : *CITIES* $\rightarrow$ *COUNTRIES*,

Country : *DYNASTIES* → *COUNTRIES*, *Founder* : *DYNASTIES* ↔ *RULERS*, *Mother* : *RULERS* → *RULERS*, *Father* : *RULERS* → *RULERS*, *KilledBy* : *RULERS* → *RULERS*, *Dynasty* : *RULERS* → *DYNASTIES*, *Title* : *RULERS* → *TITLES*, *BirthPlace* : *RULERS* → *CITIES*, *PassedAwayPlace* : *RULERS* → *CITIES*, *Nationality* : *RULERS* → *COUNTRIES*, *Husband* : *MARRIAGES* → *RULERS*, *Wife* : *MARRIAGES* → *RULERS*, *Ruler* : *REIGNS* → *RULERS*, *Country* : *REIGNS* → *COUNTRIES*, and *Title* : *REIGNS* → *TITLES*, all of them translated into corresponding foreign keys), $rc = 21 + 13 + 14 + 17 + 14 + 3 = 82$ (with 7 primary keys and their 7 domain and 7 not null associated constraints, other 13 not null ones, one for *COUNTRIES* and *TITLES*, 2 for *CITIES*, *DYNASTIES*, *RULERS*, and *MARRIAGES*, and 3 for *REIGNS*, 14 domain ones for the rest of the attributes, 17 foreign keys, the 14 unique keys *Country* and *Capital* of *COUNTRIES*, *City* • *Country* of *CITIES, Dynasty* and *Founder* of *DYNASTIES*, *Title* of *TITLES*, *URL*, *Name* • *Dynasty* •*BirthYear*, *Name* • *Mother*, and *Name* • *Father* of *RULERS*, *Husband* • *Wife* • *MarriageYear* and *Husband* • *Wife* • *DivorceYear* of *MARRIAGES*, *Ruler* • *Country* • *FromY* and *Ruler* • *Country* • *ToY* from *REIGNS*, as well as the 3 tuple ones, *BirthYear* ≤ *PassedAwayYear*, *MarriageYear* ≤ *DivorceYear* and *FromY* ≤ *ToY*), and $nrc = 23$ (the one from Figure 6, the 12 from Figure 7, 7 from Figure 8, and 3 from Figure 9). In total, algorithm *M-R* performs $n = 7 + 21 + 17 + 82 + 23 = 150$ steps to translate this (E)MDM scheme.

Fortunately, as C_2 implies the key *Capital*, C_4 implies the key *Founder*, and C_{33} implies the keys *Ruler* • *Country* • *FromY* and *Ruler* • *Country* • *ToY*, there are only 78 relational constraints to be enforced. Unfortunately, although C_6 implies the tuple constraint *BirthYear* ≤ *PassedAwayYear* for physical persons (i.e., having *Sex* 'F' or 'M'), but MS check constraints do not accept either *Sex* = 'N' ⇒ *BirthYear* ≤ *PassedAwayYear* or *if Sex* = 'N' then *BirthYear* ≤ *PassedAwayYear*, this tuple constraint must be enforced in the rdb scheme.

Moreover, in [24] we have shown that both *Mother* • *Father* and *Husband* • *Wife* are irreflexive, asymmetric, transitive, intransitive, inEuclidean, and acyclic, but all these other 12 non-relational constraints are implied by $C_7 \wedge C_8$ and $C_{18} \wedge C_{19}$, respectively, so that we did not consider them here.

Please note that, as the *A*9 and *AF*9' algorithms from [3] are also linear, sound, complete, and optimal, the whole process of translating (E)MDM schemes to actual rdbs using *MatBase* is very fast and secure.

Of course, the *M-R* algorithm presented here is used by *MatBase* when importing (E)MDM schemes (from text files). Besides it, *MatBase* also has a corresponding incremental one, embedded in its (E)MDM GUI classes: immediately as users add a new db, it creates the corresponding rdb one; immediately after they add a new set to a db, it creates its corresponding table/view and standard Windows form; as soon as they add a new function defined on a set, it adds the corresponding column to the corresponding table/view and correspondingly updates its Windows form; and, finally, immediately after they add a new constraint to a db, *MatBase* first checks whether it is both syntactically (i.e., from the coherence point of view) and semantically (i.e., from the current db instance point of view) valid [25]; if it is not, *MatBase* rejects it (with a context-dependent error message); otherwise, not only it accepts it, but for relational ones it correspondingly alters the underlying rdb scheme, while for the non-relational ones it either automatically generates code in the corresponding Windows form classes to enforce them or, for the general object-type ones, it invites users to do it.

7. GUIDELINES FOR ENFORCING NON-RELATIONAL CONSTRAINTS

For developing elegant and optimal code to enforce general object-type non-relational constraints we would strongly recommend obeying the following 17 guidelines:

a) Always use our db constraint-driven approach for designing and developing db software applications [7].

b) Always use client software application's event-driven programming languages embedding SQL: not only extended SQL (i.e., T-SQL, PL/SQL, SQL PL, etc.) triggers are slower, but it does not make sense to pass invalid data to SQL engines when you can reject it from the client side.

c) You must use at least one method in any Windows form class for which the corresponding constraint has a quantifier or a function defined on a corresponding set. For example, as C_{26} contains two quantifiers, namely ($\forall x,y \in REIGNS$) and ($\exists z \in MARRIAGES$), you need for it at least one method in *REIGNS*' class and one in *MARRIAGES*' class; moreover, as it also contains functions defined on *RULERS* (i.e., *Sex*, *Father*, and *Mother*), you also need at least one method in the *RULERS*' class.

d) You must track value changes for any column corresponding to the functions occurring in the corresponding constraint formula. Keep in mind that almost any value update in any of these columns might violate the corresponding constraint. Dually, however, except valid changes from checking (e.g., when users delete one or both parents of a person corresponding constraints might not be affected, whereas replacing null with non-null values generally is potentially harmful). For example, to enforce C_{26}, you need to track changes in columns *Country*, *FromY*, *ToY*, and *Ruler* from table *REIGNS*, *Sex*, *Father*, and *Mother* from *RULERS*, as well as *Husband* and *Wife* from *MARRIAGES*. In this case, for example, if the current *RULERS* line contains 'N' in the *Sex* column, you can stop checking values in all other columns.

e) If only one column of a table is involved in a constraint, you should always use the corresponding VBA *column_BeforeUpdate* (.Net *Validating*) method-type, like in Fig. 16 for C_2: this way, users are immediately told if their new value is invalid and must fix it on the spot.

f) If more than one column of a table is involved in a constraint, you should always use the corresponding VBA *Form_BeforeUpdate* (.Net *Validating*) method-type, like in Fig. 10 for C_6: otherwise, you implicitly impose users an order in which to make the updates and sometimes prevent them from entering valid data.

g) Do not track the keys typed by users: let them finish typing and start enforcing constraints only after they (implicitly or explicitly) ask to save the data they just entered. Consequently, for example, never use VBA methods of the type *KeyPress*, *KeyUp*, *KeyDown*, *Change*, etc. for enforcing constraints. Tracking key-typing must be used only when db software applications need to provide hot keys of their own.

h) Do not ever present users in combo-boxes with invalid data, but only with valid one. Use the VBA *Form_Current* method-type for filtering valid data, like in Fig. 14.

i) Do not hesitate to use even VBA *column/Form_AfterUpdate* (.Net *Validated*) methods for enforcing constraints. For example, as mentioned above, when enforcing constraint C_4 (the founder of any dynasty must belong to that dynasty), we should select in the *Founder* combo-box of form *DYNASTIES* all persons from *RULERS* belonging to the current dynasty or not belonging to any one; whenever users choose a person not belonging to a dynasty, we must use the *Form_AfterUpdate* of this class to run a SQL UPDATE query to set his/her dynasty to the current one.

j) Similarly, also use the VBA *Form_Delete* event method to enforce constraints containing a variable quantified existentially. For example, constraint C_{26} might be also violated by

deleting data of a marriage between two persons not related as parent – child, whenever they both simultaneously reigned over a same country; consequently, such deletion must be rejected.

k) Whenever possible, use (static or/and dynamic) blocking update/write access to columns or/and entire forms instead of writing complex code to achieve it (e.g., see Fig. 18).

l) For optimality reasons, do not ever check constraints for lines that, by definition, may not violate them. For example, when adding a new line of data in table *RULERS*, that person may not yet be the mother, father, or killer (not even for suicides!), or husband, or wife, or ruler, or dynasty founder; similarly, when adding a new line of data in table *CITIES*, that city may not yet be a country capital, etc.

m) Do not ever forget that, except for one-to-one (injective) ones, functions may take same values for several argument ones (i.e., are "many-to-one"/"one-to-many" relationships): consequently, you should check for only one value in codomain classes, but for several ones in the corresponding domain ones. For example, when enforcing C_5 (nobody may belong to a dynasty that was founded after his/her death), in the *RULERS* class you have at most to compare only the passed away year of the current person with the birth year of the founder of the corresponding dynasty (if any); dually, in the *DYNASTIES* class, you have to compare the birth year of the founder (if any) with the passed away year of all the persons from *RULERS* who belong to the current dynasty.

n) Generally, there is no need to duplicate enforcing the relational constraints with Windows class methods: all commercial RDBMSes are correctly enforcing them. However, sometimes you must do it, because, generally, interpreters first run your event-driven associated methods and only then, if they did not reject the corresponding updates, are checking the relational ones. For example, although both MS Access and SQL Server correctly enforce NOT NULL constraints, because C_{20} needs to be enforced in the *MarriageYear_BeforeUpdate*, C_{21} in the *DivorceYear_BeforeUpdate*, and C_{30} in the *Form_BeforeUpdate* methods of class *MARRIAGES*, although both *Husband* and *Wife* are declared as NOT NULL in the table's scheme, if users enter data on a new line only in *MarriageYear* and/or *DivorceYear* and then move the cursor to the next new line, as both these methods need the corresponding *Husband* and *Wife* values, the application crashes if they do not first enforce their totality.

o) Always help users correct their mistakes as much as possible, not only by displaying context-dependent error messages indicating exactly the violated constraint and how to satisfy it (e.g., Fig. 17) but also restoring previous valid values (generally mistakenly modified).

p) Always replace context-independent system error messages with context-dependent ones: for example, even the least inconvenient ones of type "Are you sure you want to delete this line?" become much more user-friendly if rephrased as, e.g., "Are you sure you want to delete data for the Mar-a-Lago city from the Florida state of the U.S.A.?"; moreover, even if you do not have time or you are not paid for such "sweeties", replace at least the awful RDBMS error messages issued when users try to duplicate values in unique (sets of) columns: for example, a message of the type "A dynasty named Windsor is already stored in this table! Please give a unique name to the dynasty you want to add or cancel your request." will always make our customers happier.

q) Pay maximum attention to the treatment of null values, as this is the most complicated and tricky part of computer programming. First, as they may have several meanings: for example, the ones in *MarriageYear*, *BirthYear*, etc. means (temporarily) unknown values, while those in *PassedAwayYear*, *DivorceYear*, and *ToY*, may mean "unknown", but also still alive, married, ruling, respectively. Moreover, beware that treatment of null values is not standardized across interpreters and programming libraries.

8. CONCLUSIONS

We introduced and discussed the *M-R* (*A*7) *MatBase* pseudocode algorithm for translating our (E)MDM db schemes into relational ones and associated sets of non-relational constraints. We proved that this algorithm is very fast, sound, complete, and optimal. Of course, *M_R* may be also manually used by any db and software architect who does not have access to *MatBase*.

We applied this algorithm to a beautiful example from the genealogical trees subuniverse, made of 7 entity-type sets, 38 functions, and 117 constraints (82 relational and 35 non-relational).

We identified the implications between some of the 117 db constraints governing this subuniverse and eliminated 12 non-relational and 4 relational redundant ones.

We provided examples of both SQL and VBA code for enforcing non-relational constraints of all major types.

We also offered main 17 guidelines for designing and developing elegant and efficient code for enforcing non-relational constraints in user-friendly db software applications within our db constraint-driven framework.

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