UMONS
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Mémoire

Data Repairing

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Chapter 1

Introduction

Many institutions and companies collect, store and use a lot of data. These data could be dirty which means they contain erroneous information. An Erroneous information may mislead anyone who want to use the database. To prevent this problem, data should respect integrity constraints which are rules in database. Any information who doesn't fit these constraints is considered as a dirty data. But these constraints may be imprecise as well, failing to identify good data and dirty data. For this reason, some data aren't identify as violation as they should be and others data are identify as violent and they shouldn't be. Both mistakes on data and integrity constraints are a problem for anyone using the database.

During my training, i had to work on a project related to a database with such problems. It has a huge impact for a part of my project. The repair of these data is a project for 2018 and i feel it would be interesting to study the data repairing concept.

Data repairing means recover erroneous data but also repair bad integrity constraints. It would be naive to think we can delete dirty data as we wish. The number of loss would be huge because sometimes there is only one error in a row. Furthermore, integrity constraint can also be dirty which means row deletion could erase some clean data. For this reason we need techniques to repair a data without loosing too much information and without failling to identifie dirty data.

In this thesis we are going to analyse the *θ-tolerant repair model* as explained in a scientifique article[4]. First of all, we have to re-explain some notions and definition to understand the θ-tolerant model and we also need to present some database we used to illustrate data repairing models. Next we'll present some data repairing models with among them the θ-model. We'll theorically compare them and identify pros and cons for all them.
TO CONTINUE.

Chapter 2

Integrity constraints

In this chapter we'll remind some important notions that we are going to use to explain some data repairing models. We use database following the relational model which was introduced by E.F. Codd [2]. We'll also present some database we're going to use to illustrate different notions.

2.1 Database

In this section we'll present databasse we used as example in this thesis. These databases are used to ulistrate data repairing models and others notions we'll define.

The first database comes from the main article used as bibliography in this thesis[4].

	Name	BirthDay	Cellphone Number	Year	Income	Tax
t1	Ayres	8-8-1984	322-573	2007	21k	0
t2	Ayres	5-1-1960	***-389	2007	22k	0
t3	Ayres	5-1-1960	564-389	2007	22k	0
t4	Stanley	13-8-1987	868-701	2007	23k	3k
t5	Stanley	31-7-1983	***-198	2007	24k	0
t6	Stanley	31-7-1983	930-198	2008	24k	0
t7	Dustin	2-12-1985	179-924	2008	25k	0
t8	Dustin	5-9-1980	***-870	2008	100k	21k
t9	Dustin	5-9-1980	824-870	2009	100k	21k
t10	Dustin	9-4-1984	387-215	2009	150k	40k

Table 2.1: Table of the main article[4]

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The second database we are going to use comes from a personal experience. In a training, i had to work on a project related to a database with some dirty data. These data can't

be used outside the company but we'll try to get the main idea. It's a table named person, who got several basic information on people from Belgium [1].

- **NISS:** The national number of the person. A national number is unique. Usually, a NISS is formated like this[1]
  - It start with the birthdate of the person in a YY-MM-DD format. Exception are made for stranger(People without Belgian nationality), but for ease we won't consider these cases.
  - Number 7 to 9 is even for men and odd for female.
  - Remaining number are the modulo 97 of the 9 first number.
- **LN:** Person's lastname.
- **FN:** Person's firstname.
- **Birth_Date:** birthDate in DD-MM-YYYY format.
- **Decease_Date:** Person's date decease.
- **Civil_State:** Person's current civil state(example: single, married, divorced, decease, widow,...)
- **City** : The city where the person lives.
- **Post_code** : The postal code of the city.
- **Salary** : The salary of the person for one year
- **Tax** : The tax amount the person have to pay every year
- **Child** : the number of children the person have.

	Niss	LM	FN	Birth_date	Decease_date	Civil_state	City	Post_code	Salary	Tax	Child
t1	14050250845	Dupont	Jean	14-05-1902	18-05-1962	decease	Ath	7822	25k	4k	2
t2	08042910402	Brel	Jacques	08-04-1929	09-10-1978	decease	Schaerbeek	1030	100k	8k	1
t3	45060710204	Merckx	Eddy	07-06-1945	null	decease	Schaerbeek	1030	125k	9k	2

Table 2.2: Table Person

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[1] Every data in our database are fictional person.

2.2 Constraint on database

When you want to add rows in a database, you can't put what you want. It would be a problem if it was possible to add non-logical value on some columns of a table. To avoid this kind of problems, we can add rules on a database. Basically a rule works on this way: if the entry row t_α respects some conditions, we can accept the value. Otherwise t_α is not correct and something is wrong with the value of this entry row.

On the relational database model which is used in most of the database, the notion of *functional dependency(FD)* is used.

Definition 1. *Given a relation R and a set of attributes $X \in R$, a **functional dependency** determine another set $Y \in R$ (written X → Y) if and only if each X value is associated with one Y value.*

In other words, for a dependency $X \rightarrow Y$ means that for a specific value X there's only one possible value for Y. If the DF is respected on a relation R, we say that R satisfy the DF. Let's take some examples on the table 2.2.

1. A NISS identify a person. This constraint can be describe by a key constraint $KeyNiss$
2. Two persons with the same post code lived in the same district. The functional dependency for this constraint is $post\_code \rightarrow district$
3. If some got a decease date, his civil status should be equal to decease. In this case we need a conditional functional dependency(CFD) which is typically a functional dependency with equality operator on some columns. A functional dependency should work for all records on the table, CFD can hold some conditions on collumns. $[Decease\_date =$'18-05-1962'$] \rightarrow [civil\_status = decease]$

Definition 2. *A set Σ of DF on the relation schema A. The relation R satisfy Σ noted $R \models \Sigma$ if for each DF in Σ, R satisfy the DF.*

However we can't express everything as functional dependencies. Sometimes it fails. For example, if we want to express "Nobody can die before his own birth", in this case we need to compare the birth date and the decease date. Functional dependencies can't work in this case. We can use the first-order logic.

$$\forall t_\alpha \in R,\ \neg(t_\alpha.decease\_date \leq t_\alpha.birth\_date)$$

We can express the others examples in first-order logic.

1. A NISS identify a person. $\forall t_\alpha, t_\beta \in R\ \neg(t_\alpha.NISS = t_\beta.NISS)$ (We suppose in this notation, we can't take $t_\alpha = t_\beta$)

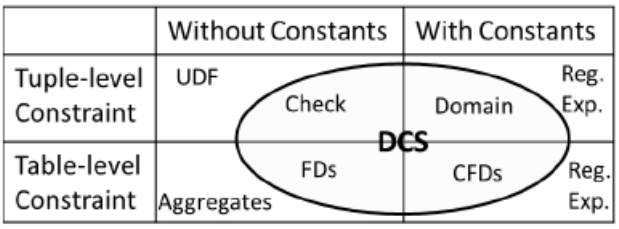

Figure 2.1: A denial constraint(DC) can express many type of others constraints

2. Two persons with the same post code lived in the same district. $\forall t_\alpha, t_\beta \in R \neg(t_\alpha.post\_code = t_\beta.post\_code \wedge t_\alpha.district \neq t_\beta.district)$

3. If some got a decease date, his civil status should be equal to decease. $forallt_\alpha, t_\beta \in R$ $\neg(decease\_date = null \wedge civil\_state = decease)$

On the main paper which this thesis is based, they define a denial constraint as [4]:

Definition 3. *Consider a relation scheme R with attributes $attr(R)$. Let predicate space $\mathbb{P}$ be a set of predicate P in the form $v_1 \phi V_2$ or $v1\phi c$ with $v_1, v_2 \in t_x.A$, $x \in \{\alpha, \beta\}$, $t_\alpha, t_\beta \in R$, $A \in attr(R)$, c is a constant and $\phi \in \{=, <, >, \leq, \geq, \neq\}$ is a build-in operator. A **Denial Constraint(DC)**:*

$$\varphi : t_\alpha, t_\beta, ... \in R, \neg(P_1 \wedge ... \wedge P_m)$$

states that for any tuples $t_\alpha, t_\beta, ...$ from R, all the predicates $P_i \in pred(\varphi)$,i = 1,...,m should not be true at the same time.

In other words, a denial constraint is a first-order logic conjunction of predicates that shouldn't be true all in the same time. So if one of the predicates is false, the data is consider to be clean.

A DC can be oversimplified which means a correct data could consider as a violation. Let's take an example on the table 2.1. If we take the following constraint:

$$\varphi : t_\alpha, t_\beta \in R, \neg(t_\alpha.Name = t_\beta.Name \wedge t_\alpha.CP \neq t_\beta.CP)$$

This constraint means that any person with the same *Name* should get the same cellphone number (*CP*), which is incorrect because two person different person can get the same name and of course different cellphone number. For example t_1 and t_2 don't respect this denial constraint. So it's considered as a violation, but we can see it's two different person because they don't have the same age. If we want a correct DC we need to check their age, i.e their *Birthdate*:

$$\varphi : t_\alpha, t_\beta \in R \neg(t_\alpha.Name = t_\beta.Name \wedge t_\alpha.CP \neq t_\beta.CP \wedge t_\alpha.Birthday = t_\beta.Birthday)$$

In the opposite of oversimplified, a DC can be overrefined which means a dirty data could be consider as a clean data. An example could be :

$$\varphi : t_\alpha, t_\beta \in R \neg(t_\alpha.Name = t_\beta.Name \wedge t_\alpha.CP \neq t_\beta.CP \wedge t_\alpha.Birthday = t_\beta.Birthday \wedge t_\alpha.Year = t_\beta.Year)$$

In this case the Year information is not usefull. We don't recognize t_5 and t_8 as a violation with this constraint.

2.2.1 Some definitions and properties

In this section we'll present some definitions and properties on the denial constraint. They are going to help us in following chapters.

2.2.1.1 Trivial DC

A DC can be useless and always true. Such DCs shouldn't be present because they never identify any violations. In that case we say that the denial constraint is*trivial*. We'll definie a trivial DC as:

Definition 4. *We say a denial constraint φ is **trivial** if for any instance I of R we have $\varphi \models I$*

It's quite easy to discover trivial denial constraint with the following property [3]:

Property 1. *$\forall P_i, P_j$ if $P_i \in Imp(P_j)$, then $\neq (P_i \wedge P_j)$ is a trivial DC.*

In [4], they said for $Imp(\phi)$:

Definition 5. *For any two values a and b, if $a\phi_2 b$ always implies $a\phi_1 b$, it means $\phi_2 \in Imp(\phi_1)$.*

With this definition, we see that if P_i is true, P_j is false and vice versa.

For example if we have $x = y$ as predicate and we add $x < y$, both the predicates can't be true at the same time. Table 2.3 show for each ϕ the correspondent $Imp(\phi)$.

ϕ	=	$\neq$	>	<	$\leq$	$\geq$
$\overline{\phi}$	$\neq$	=	$\leq$	$\geq$	<	>
$Imp(\phi)$	= $\geq$,$\leq$	$\neq$	>,$\geq$,$\neq$	<,$\leq$,$\neq$	$\geq$	$\leq$

Table 2.3:

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If we say for the table 2.1:

$$\varphi : t_\alpha, t_\beta \in R \neg(t_\alpha.Tax = t_\beta.Tax \wedge t_\alpha.Tax < t_\beta.Tax)$$

It's quite obvious it's impossible that two persons have the same tax rate and one's tax rate is greater than the other. For the rest of this study we won't consider trivial DCs

2.2.1.2 Augmentation

Further in this report, we'll see addition and deletion operations in order to perform data repairing on these constraint. But adding predicates to valid DCs is useless because of the augmentation property [3]:

Property 2. *If $\varphi = \neg(P_1 \wedge P_2 \wedge ... \wedge P_n)$ is a valide DC, then $\varphi' = \neg(P_1 \wedge P_2 \wedge ... \wedge P_n \wedge Q)$ is also a valide DC*

It's quite easy to prove this property. If φ is valid it means every $t_\alpha \in R$ is accepted by the constraint. If it's accepted, $\forall t_\alpha$ one of the $P_i \in \varphi$ is false. So whatever Q is, t_α will still be accepted.

2.2.1.3 Transitivity

In [3] they defined the transitivity of DCs as:

Property 3. *If $\varphi = \neg(P_1 \wedge P_2 \wedge ... \wedge P_n \wedge Q_1)$ and $\varphi' = \neg(R_1 \wedge Q_2 \wedge ... \wedge Q_n \wedge Q_2)$ are both valid DCs and $Q_2 \in Imp(\overline{Q_1})$,*
then $\varphi'' = \neg(P_1 \wedge ... \wedge P_n \wedge R_1 \wedge ... \wedge R_n)$ is also a valid DC.

In other words if two **valid** DCs, each with predicates that can't be false in the same time, then merging those DCs and removing the two predicates will produce a **valid** DC.

It's possible to prove that:

Proof. $\forall t_\alpha \in R$, we have φ and φ' verified.
We have $Q_2 \in Imp(\overline{Q_1})$ so Q_2 and Q_1 can not be true or false at the same time.

1. if Q_1 is false, then Q_2 is true . Therefore $\exists R_i suchas R_i$ is false (because φ should be verified). φ'' is verified too because $R_i \in \varphi''$
2. if Q_1 is true, then Q_2 is false . Therefore $\exists P_i suchas P_i$ is false (because φ should be verified). φ'' is verified too because $P_i \in \varphi''$

□

2.2.1.4 Refinement

In [4] they define the refinement of a DC as :

Definition 6. *φ_2 is a **refinement** of φ_1, denoted by $\varphi_1 \preceq \varphi_2$, if for each $P : x\phi_1 y \in pred(\varphi_1)$, there exists a $Q : x\phi_2 y \in pred(\varphi_2)$ such that $\phi_1 \in Imp(\phi_2)$*

Definition 7. *Σ_2 is a **refinement** of Σ_1, denoted by $\Sigma_1 \preceq \Sigma_2$, if for each $\varphi_2 \in \Sigma_2$, there exists a $\varphi_2 \in \Sigma_1$ such that $\varphi_1 \preceq \varphi_2$*

As we can see, if you want to change less data, you should refine your DCs with insertion or substitution. For example if our DC is $t_\alpha.Tax \leq t_\beta$ and we change it to $t_\alpha.Tax < t_\beta$ you'll change less data.

Chapter 3

Data Repairing

Errors are frequent in database. Because these anomalies can make applications unreliable, some methods detect them but don't repair the detected anomalies. But if you simple filter the dirty data you've detected, applications could still be unreliable. [5] Instead of only detecting errors and delete them, it's better to repair the dirty data.

The goal of data repairing is to find a modification I' for I,an instance of R, in which all of violation in the constraints Σ are eliminated. In other words, we want $I' \models Sigma$ (I' satisfy Σ). Data repairing process follows the minimum change principle: the data repair I' have to minimize the data repair cost define as [4]:

Definition 8. *If I' is a repair for I instance of R by modifying attribute values without any deletion or assertion tuples, the data repair cost is:*

$$\Delta(I, I') = \sum_{t \in I, A \in attr(R)} w(t.A).dist(I(t.A), I'(t.A)$$

where :

- $dist(I(t.A), I'(t.A))$ *is the distance between two values on cell $t.A$ in I and I'.*
- $w(t.A)$ *is the weight of cell $t.A$.*

We can see that the cost can be the number of cell we changed if we put:

$$dist(I(t.A), I'(t.A)) = \begin{cases} 1 \; if I(t.A) \neq I'(t.A) \; (the \; value \; changed) \\ 0 \; otherwhise \; (no \; changes \; were \; made) \end{cases}$$

We can put the distance for numerical values on the difference of the two values. For string values we can use the edit distance.

The weight $w(t.A)$ can show the trust of the original value in cell which is subjective or simply be a constant if we don't have a lot of knowledge about the data.

/	t_β									
t_α	/	1	2	3	4	5	6	7	8	9	10
	1	/	V	V	V	V	V	V	V	V	V
	2	F	/	V	V	V	V	V	V	V	V
	3	F	V	/	V	V	V	V	V	V	V
	4	V	V	V	/	V	V	V	V	V	V
	5	F	F	F	F	/	V	V	V	V	V
	6	F	F	F	F	V	/	V	V	V	V
	7	F	F	F	F	F	F	/	V	V	V
	8	V	V	V	V	V	V	V	/	V	V
	9	V	V	V	V	V	V	V	V	/	V
	10	V	V	V	V	V	V	V	V	V	V

Figure 3.1: All the violation for φ

It's important to notice it's not impossible to don't find any repair I' that can eliminates all the violations. It's possible any values in $dom(A)$ can fit the constraint. In that case, we can use a *fresh variable (fv)* out of the current domain $dom(A)$ in order to extend the domain. This fresh variable is a value that does not satisfy any predicate, we are sure that we can satisfy the DC. (it's satisfy if at least one of the predicates is false).

Let's take an example on the table 2.1. Let's say our Denial Constraint is the following one:

$$\varphi : t_\alpha, t_\beta \in R, \neg(t_\alpha.Income > t_\beta.Income \wedge t_\alpha.Tax \leq t_\beta.Tax)$$

In other words, we supposed that if someone get a higher income than another person then he should paid an higher tax every year. We have $\langle t_1, t_2\rangle \not\models \varphi$ because t_1.Income < $t2$.Income and $t2$.Tax $\leq$ $t1$.Tax. Same problem with $\langle t_1, t_3\rangle$, $\langle t_1, t_5\rangle$, ect... you can find all the violation in the figure 3.1 A repair I' could be the following one:

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_18	t_9	t_10
Tax	0	fv_1	fv_2	3k	fv_3	fv_4	fv_5	21k	21k	40k

Table 3.1: Example of repair with Tax

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The reason we put fv_1 as Tax value for t_2 is because we knew the following things:

1. $I(t_1.Tax) = 0$ so $I(t_2.Tax) > 0$ because $I(t_1.Income) < I(t_2.Income)$
2. $I(t_3.Tax) = 3$ so $I(t_2.Tax) < 3$ because $I(t_2.Income) < I(t_3.Income)$

3. $dom(Tax) = \{0, 3k, 21k, 40k\}$

Because we had no value in the $dom(Tax)$ that would respect 1 and 2, we need to use a fresh variable fv_1 out of the $dom(Tax)$. The same logic can be used to understand why we had to use fv_2 to fv_5. We could put random value instead but it could be a problem if we insert correct value in the future (These correct values could be see as dirty one). We only know that 0< fv_1,fv_2 <3k in order to respect 1 and 2. In the same idea, we have 3k < fv_3,fv_4,fv_5 < 21k.

We can compute the repair cost for Tax in this table. Let's say that:

$$\forall a, b \in dom(A) \; with \; a \neq b. \begin{cases} dist(a, a) = 0 \\ dist(a, b) = 1 \\ dist(a, fv) = 1.5 \end{cases}$$

When we don't change anything, the distance is obviously equal to zero. $dist(a, fv)$ have to be higher than $dist(a, b)$ otherwise the cost for a non-domain value will be lower than a domain value and we want to avoid fresh variable as much as possible. If we had $dist(a, fv)$ lower than $dist(a, b)$, any repair that uses fresh variable outside the domain would be better and of course it's not a good behavior. In our example, with the value said just before, we can compute a $\Delta(I, I')$ = 7.5

3.1 Integrity constraints variations

We saw earlier that a constraint can be overrefined failing to detect some error or in the opposite a constraint can be oversimplified leading to consider some good data as an error. Because constraints can be inaccurate we need to modify them. We'll consider two types of constraint variance: predicate deletion and in the opposite predicate insertion.

When we perform a predicate insertion, some tuples no longer violate the DC. With this variation we can repair a oversimplified constraint but we need to be careful otherwise the DC can be useless. We need to avoid insertion which can lead to a trivial DC or insertion of predicates with obvious constants(like $t_\alpha.Salary$<0 in the table 2.2).

An example of trivial DC is a DC φ with a predicate $P_i : x\phi_i y$ and we had another predicate $P_j : x\phi_j y$ in the DC with $\overline{\phi_j} \in Imp(\phi_i)$.

For overrefined DCs, we need to remove some predicates but we need to be careful. If too many predicates are withdraw, we can get an new oversimplified DCs. The more the predicates are deleted, the higher the data repair cost will be as stated in the Lemma1 in [4]. In the other hand the more the predicates are added, the lower the data repair will be. So if you add more predicates than you remove, the changed data will be smaller than removing more predicates and deleting more. The *data repair cost function* take this effect into consideration. It count positively predicate insertion and negatively predicate

addition. For Σ' a variant of Σ in which all $\varphi' \in \Sigma'$ are obtained by insertion or deletion of predicates for corresponding $\varphi \in \Sigma$, in [4] they define the constraint variation cost:

Definition 9. *For a variant Σ' of Σ, the contraint variation cost is defined as*

$$\Theta(\Sigma, \Sigma') = \sum_{\varphi in \Sigma} edit(\varphi, \varphi')$$

where φ' is a variant of ϕ and $edit(\varphi, \varphi')$ is the corresponding cost.

the $edit(\varphi, \varphi')$ indicating the cost of changing φ to φ' is defined as:

Definition 10.

$$edit(\varphi, \varphi') = \sum_{P \in \varphi \varphi'} c(P) + \lambda \sum_{P \in \varphi' \varphi} c(P)$$

where $c(P)$ denote the weighted cost of predicate P and λ is the weight of a deletion compare to an addition and -1<λ<0.

We don't have to use λ =-1 otherwise a deletion followed by an addition would have a cost equal to 0(and it's a bad idea for predicate substitution). For example if we have:

$$\varphi : t_\alpha, t_\beta \in R, \neg(t_\alpha.Income > t_\beta.Income \wedge t_\alpha.Tax \leq t_\beta.Tax)$$

This DC express the fact that if I get a higher income than someone else, i should pay a higher tax rate. We'll change this DC by deleting $\alpha.Tax \leq t_\beta.Tax$ by $\alpha.Tax < t_\beta.Tax$. It can express the fact that someone with a very low Income could get a Tax equals to 0.

$$\varphi' : t_\alpha, t_\beta \in R, \neg(t_\alpha.Income > t_\beta.Income \wedge t_\alpha.Tax < t_\beta.Tax)$$

The constraint variation with $\lambda = \frac{1}{2}$ and $c(P) = 0$ is : $edit(\varphi, \varphi') = c(t_\alpha.Tax < t_\beta.Tax) + \frac{1}{2}c(\alpha.Tax \leq t_\beta.Tax) = \frac{1}{2}$

With this new constraint, we got less violations. All the violations can be found the figure 3.2. The modifications we made in table 3.2 changed to:

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_18	t_9	t_10
Tax	0	0	0	0	0	0	0	21k	21k	40k

Table 3.2: Example of repair with Tax

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Indeed, a column with only one mistakes is more likely correct than a column with five dirty data. On our new DC, only the ($t_4.Tax$)=3k have to be changed with the value 0.

When we do constraint modification, we should not consider the case where we delete an entire constraint. We should not remove all the predicates because a DC like $\neg()$ doesn't mean anything. We can't even say if it's always true or always false.

/	t_β									
t_α	/	1	2	3	4	5	6	7	8	9	10
	1	/	V	V	V	V	V	V	V	V	V
	2	V	/	V	V	V	V	V	V	V	V
	3	V	V	/	V	V	V	V	V	V	V
	4	V	V	V	/	V	V	V	V	V	V
	5	V	V	V	F	/	V	V	V	V	V
	6	V	V	V	F	V	/	V	V	V	V
	7	V	V	V	F	V	V	/	V	V	V
	8	V	V	V	V	V	V	V	/	V	V
	9	V	V	V	V	V	V	V	V	/	V
	10	V	V	V	V	V	V	V	V	V	V

Figure 3.2: All the violation for φ'

3.1.1 Maximal Constraint Variants

Every constraint variant Σ' with cost $\Theta(\Sigma, \Sigma')$ shouldn't be considered. They're some variation that we're sure they are not better. To perform a prunning of constraints variant that doesn't generate minimum data repair, we'll use the definition of refinement we explained in the previous chapter at the section 2.2.1.4.

Definition 11. *[4] We say that a variant φ' of a constraint φ with $\varphi \preceq \varphi'$ is **maximal**, if there does not exist another φ'' such that $\varphi' \preceq \varphi''$ and $edit(\varphi, \varphi'') = edit(\varphi, \varphi')$*

Property 4. *[4]*
For any inserted predicate $P : x\phi y \in pred(\varphi') \setminus pred(\varphi)$, if $\phi \in \{\leq, \geq, \neq\}$, then φ' is not maximal.

With this property we see that it's useless to insert every predicate that you're able to construct. We only have to insert predicates with operators >,<,= when considering variants of φ Let's illustrate that with an example. We'll take two denial constraint on table 2.1 for this.

$$\varphi_1 : \forall t_\alpha, t_\beta \in R, \neg(t_\alpha.Name = t_\beta.Name \wedge t_\alpha.Income = t_\beta.Income \wedge t_\alpha.CP \neq t_\beta.CP)$$

$$\varphi_2 : \forall t_\alpha, t_\beta \in R, \neg(t_\alpha.Name = t_\beta.Name \wedge t_\alpha.Income \leq t_\beta.Income \wedge t_\alpha.CP \neq t_\beta.CP)$$

We know that $\leq \in Imp(=)$ (see table 2.3) for Income so we have $\varphi_2 \preceq \varphi_1$. By the last property we know that φ_2 is not maximal because it contains $\leq$ operator. In this scenario the data repair cost is 7 for φ_2 and φ will get a data repair cost equal to 3.

	Name	Cellphone Number	Income
t1	Ayres	564-389	22k
t2	Ayres	564-389	22k
t3	Ayres	564-389	22k
t4	Stanley	930-198	24k
t5	Stanley	930-198	24k
t6	Stanley	930-198	24k
t7	Dustin	824-870	100k
t8	Dustin	824-870	100k
t9	Dustin	824-870	100k
t10	Dustin	824-870	100k

Table 3.3: Correction with φ_2: 7 changes needed only for the collumn CP.

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	Name	Cellphone Number	Income
t1	Ayres	322-573	21k
t2	Ayres	564-389	22k
t3	Ayres	564-389	22k
t4	Stanley	868-701	23k
t5	Stanley	930-198	24k
t6	Stanley	930-198	24k
t7	Dustin	179-924	25k
t8	Dustin	824-870	100k
t9	Dustin	824-870	100k
t10	Dustin	387-215	150k

Table 3.4: Correction with φ_1 : only 3 changes are needed.

.

We see that the refinement got a better data repair cost. It's not a coincidence because the following lemma exist: [4]

Lemma 1. *Given two constraitn variants Σ_1, Σ_2 of Σ such that Σ_2 is also a refinement of Σ_1, have $\Sigma \preceq \Sigma_1 \preceq \Sigma_2$, is always has $\Delta(I, I_1) \geq \Delta(I, I_2)$, where I_1 and I_2 are the minimum data repairs with regards to Σ_1 and Σ_2, respectively.*

As a consequence of this Lemma, any non-maximal set of denial constraint Σ can be removed from the possibilities of good repair

3.1.2 Pruning our candidates

In this subsection we'll focus on removing the constraint variant Σ' that can't generate the minimum data repair. We are going to consider two bounds of possible minimum data repairs cost for the instance I : the lower bound noted as $\delta_l(\Sigma', I)$ and the upper bound noted $\delta_u(\Sigma, I)$. We consider the following property:

Property 5. *For two constraints variants Σ and Σ' for the instance I of R, if $\delta_u(\Sigma, I) < \delta_l(\Sigma', I)$ then Σ' can be discarded.*

Which means the worst bound(upper) of repair for Σ is still better than the best bound(lower) of repair for Σ'.

3.1.2.1 Conflict Graph

Now, we'll introduce the conflict graph which can represent the violations in an instance I of R. In the first place, we need to find all the violations and we could get the data repair cost bound from them. We define the violation set as: [4]

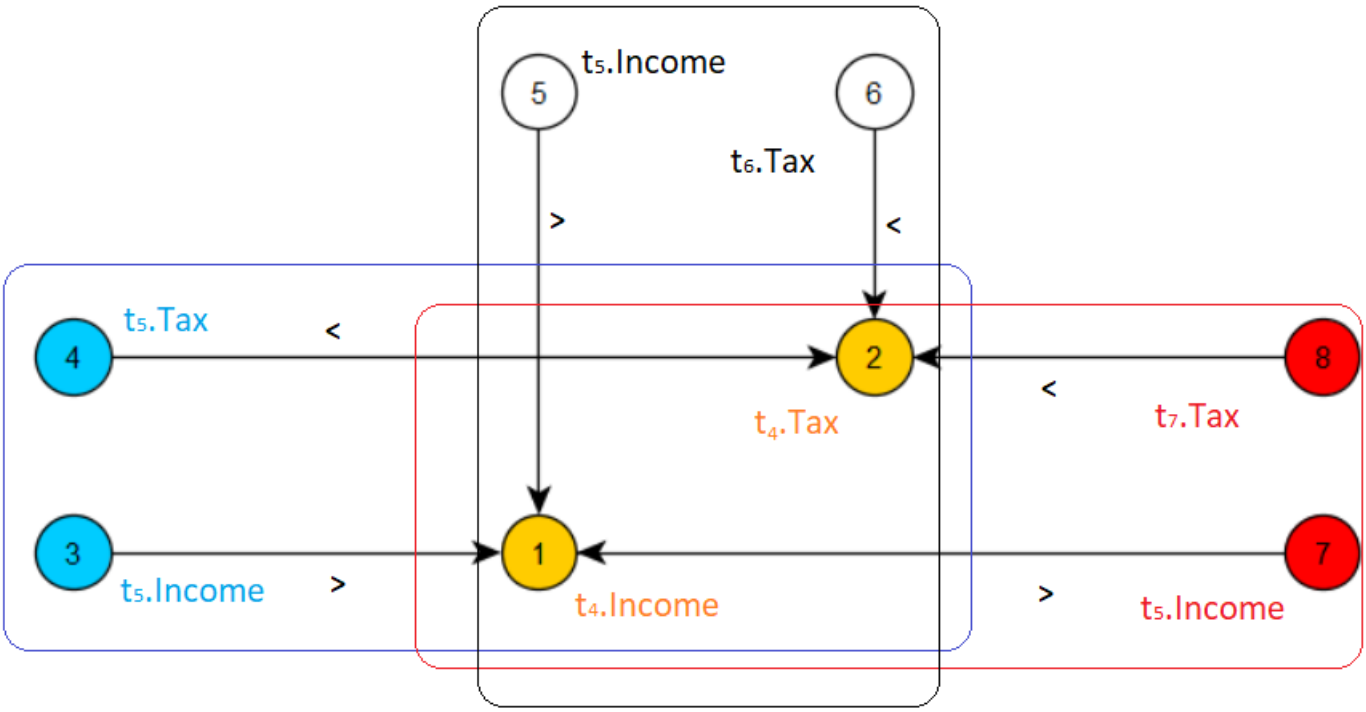

Figure 3.3: Conflict hypergraph for φ

Definition 12. *The violation set noted as* $viol(I, \varphi) = \langle t_i, t_j \rangle | \langle t_i, t_j \rangle \not\models$ *is a set of tuple lists that violate* φ*. The violation set of* Σ *is* $viol(I, \Sigma) = \cup_{\varphi \in \Sigma} viol(I, \varphi)$.

With the conflict hypergraph G we can represent the violations in I. For each violation tuples $\langle t_i, t_j, ... \rangle \in viol(I, \varphi)$ there are an edge for $cell(t_i, t_j, ..., \varphi)$ in G. A good repairing I' consist in correcting the data base to be able to remove all the edge on the graph. The hypergraph of I' should be empty.

Let's take an example on the table 2.1 with a denial constraint we already used:

$$\varphi' : \forall t_\alpha, t_\beta \in R, \neg(t_\alpha.Income > t_\beta.Income \wedge t_\alpha.Tax < t_\beta.Tax)$$

For this relation the violation set is:

$$viol(I, \varphi') = \{\langle t_5, t_4 \rangle, \langle t_6, t_4 \rangle, \langle t_7, t_4 \rangle\}$$

On our hypergraph, $\langle t_5, t_4 \rangle \in viol(I, \varphi')$ consist of $cell(t_5, t_4; \varphi')$ which is equal to $\{t_5.income, t_4.Income, t_5.Tax, t_4.Tax\}$. We want to remove a vertex, i.e eliminate a conflict. Let's first introduce some definition and a Lemma: [4]

Definition 13. *We denote* $\min_{a \in dom(A)} dist(I(t.A), a)$ *the weight of a vertex t.A, i.e, the minimum cost should be paid to repair t.A.*

Definition 14. $\mathbb{V}(G)$ *is the* ***minimum weighted vertex cover*** *of the hypergraph G corresponding to* Σ *with weight*

$$||\mathbb{V} * (\mathbb{G})|| = \sum_{t.A \in \mathbb{V}(G)} min_{a \in dom(A)} dist(I(t.A), a)$$

Lemma 2. *For any valid repair* I' *of* I*, i.e,* $I' \models \Sigma$*, we have* $\Delta(I, I') \leq ||V * (G)||$.

In [4] they define the upper and lower bound in this way :

$$\delta_l(\Sigma, I) = \frac{||\mathbb{V}(G)||}{Deg((\Sigma)}$$

$$\delta_u(\Sigma, I) = \sum_{t.A \in \mathbb{V}(G)} dist(I(t.A), fv)$$

If we come back to our example and suppose that we have :

$$\forall a, b \in dom(A) \; with \; a \neq b. \begin{cases} dist(a, a) = 0 \\ dist(a, b) = 1 \\ dist(a, fv) = 1.1 \end{cases}$$

So if each vertex has a weight of 1 (=$dist(a, b)$) and if we put $\mathbb{V}(G)$ = $\{t_4.Tax\}$ we get $||\mathbb{V}(G)||$ = 1. We also have $Deg(\varpi')$ = 4, so with formula we have we know upper and lower bound : $\delta_l(\Sigma, I)$=$\frac{||\mathbb{V}(G)||}{Deg((\Sigma)}$ = $\frac{1}{4}$ = 0.25 and $\delta_u(\Sigma, I) = \sum_{t.A \in \mathbb{V}(G)} dist(I(t.A), fv)$ = $dist(a, fv)$=1.1 .

3.2 θ-tolerant model

In this section we'll talk about the θ-tolerant repair model which is the main models we want to study. θ is a threshold on the variation on the set of constraint Σ, so we don't want a constraint variation cost greater than θ : $\Theta(\Sigma, \Sigma') \leq \theta$. It helps to avoid any kind of over-refinement and so don't detect some dirty data. To avoid the over-simplification and identify correct data as dirty data, the repairing should pursue the minimum change principle. We need to find a repair I' of the original instance I and minimize $\Delta(I, I')$.

Finding the best (minimum) θ-tolerant repair is difficult, it's a NP-hard problem. An NP-hard problem is a class of decision problems which are at least as hard as the hardest problems in NP. What we have to remind of it, it's not possible to resolve it in a polynomial time. Even is the first approach we could made is to get all the constraints variant Σ' and then compute $\Theta(\Sigma, \Sigma')$, look if it's lower than θ and then find the minimum data

repair I'.

We saw that we could replace some value by a fresh variable fv. It's better to not turn all of them in a fresh variable mainly because fv is not $dom(A)$ and also a repair like this will never return the optimal repair because we want to minimize the repair cost.

Now, consider $\mathbb{D} = \Sigma'_1 x \Sigma'_2 x ... \Sigma'_{|\Sigma|}$ where each $\Sigma'_i \in \mathbb{D}$ is a variant of Σ obtained by previous variations. Consider those variations bounded by θ so we have $\Theta(\Sigma, \Sigma') \leq \theta$. The algorithm 1 return the best instance I_min for our set of constraint variation Σ. The algorithm is simple. For each Σ_i , if the lower bound is lower than the previous upper bound (remember the property 5). we update the value of δ_{min} if a better repaired instance comes from I_i.

Algorithm 1: θ-TolerantRepair$(\mathbb{D}, \Sigma, I)$

Input : Instance I, a constraint set Σ, a set $\mathbb{D}$of constraint variants with variation bound by θ

Output: A minimum data repair I_{min}

```
δ_min = δ_u(Σ, I)
for each constraint variant Σ_i ∈ 𝔻 do
    if δ_l(Σ_i, I) ≤ δ_min then
        I_i = DATAREPAIR(Σ_i, I, 𝕍(G_i), δ_min
        if Δ(I, I_i) ≤ δ_min then
            δ_min = Δ(I, I_i)
            I_min = I_i
return I_min
```

To get an example , imagine we have for a $\theta = \frac{1}{2}$, a set of constraint variation $\mathbb{D} = \{\Sigma_1, \Sigma_2\}$ with the first set of constraints $\Sigma_1 = \{\varphi'\}$ and the second set of constraints $\Sigma_2 = \{\varphi''\}$ with:

$$\varphi' : \forall t_\alpha, t_\beta \in R, \neg(t_\alpha.Income > t_\beta.Income \wedge t_\alpha.Tax < t_\beta.Tax)$$

$$\varphi'' : \forall t_\alpha, t_\beta \in R, \neg(t_\alpha.Income > t_\beta.Income \wedge t_\alpha.Tax = t_\beta.Tax)$$

We already have done the conflict hypergraph for φ in figure 3.3 we also know that $\delta(\Sigma_1, I) = 1.1$

For $\Sigma 2$ we obtain the hypergraph in figure 3.4 (and the violations in figure 3.5) with $\mathbb{V}(G_2) = \{t_2.Tax, t_3.Tax, t_5.Tax, t_6.Tax, t_7.Tax\}$. We have $Deg(\Sigma_2) = Deg(\varphi')$ [1], so we have $\delta_l(\Sigma_2, I) = \frac{6}{2}$ = 1,5. Remember that $\delta_u(\Sigma_1, I)$ =1.1, so we have $\delta_u(\Sigma_1, I) < \delta_l(\Sigma_2, I)$ which means we can ignore $\Sigma 2$ and don't call the DATAREPAIR function on it.

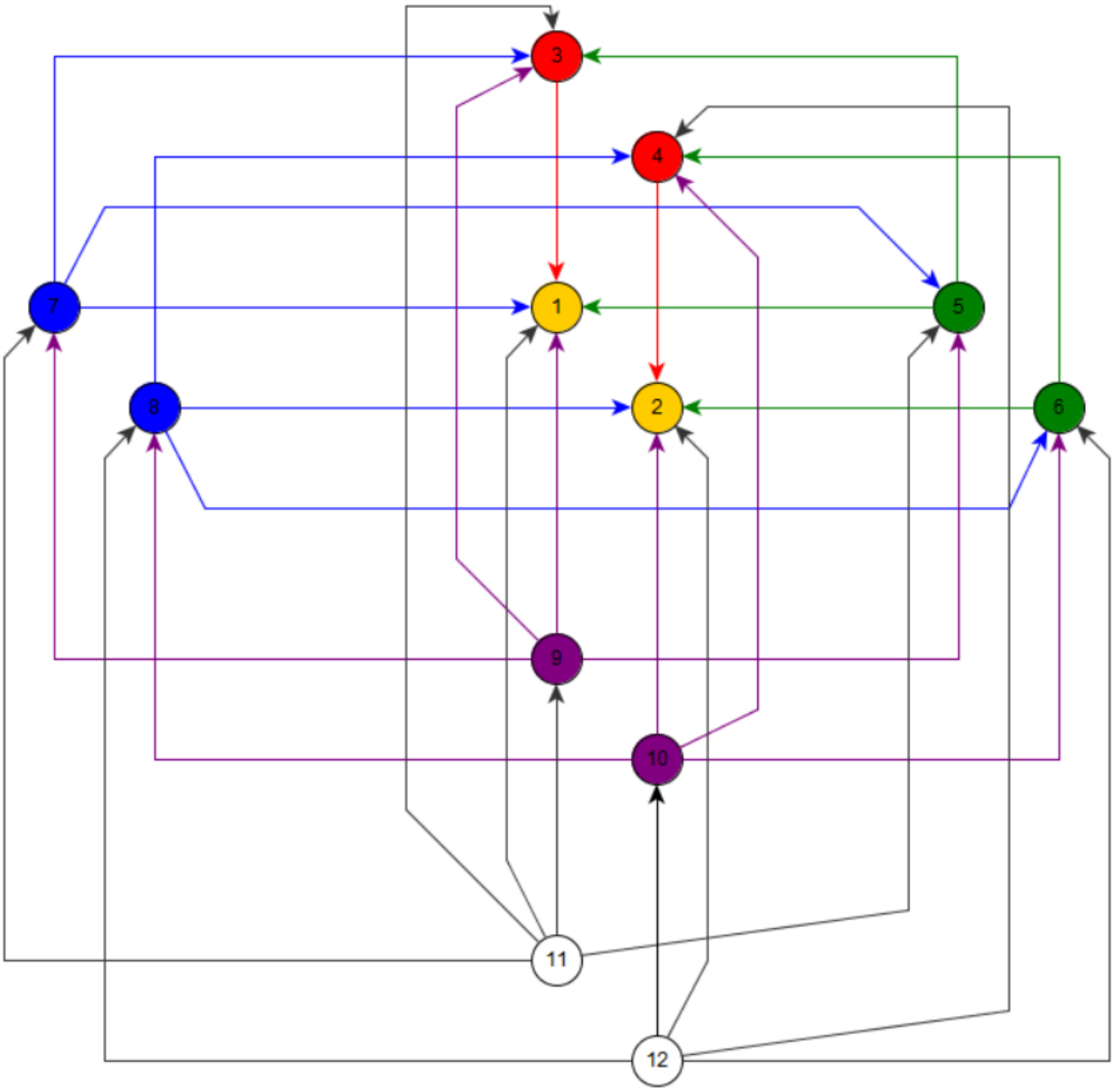

Figure 3.4: Conflict hypergraph for Σ_2 with :
odd number for Tax, even number for Income.
t_1 in yellow, t_2 in red, t_3 in green,
t_4 in blue, t_5 in purple and t_6 in white.

/	t_β									
t_α	/	1	2	3	4	5	6	7	8	9	10
	1	/	V	V	V	V	V	V	V	V	V
	2	F	/	V	V	V	V	V	V	V	V
	3	F	V	/	V	V	V	V	V	V	V
	4	V	V	V	/	V	V	V	V	V	V
	5	F	F	F	V	/	V	V	V	V	V
	6	F	F	F	V	V	/	V	V	V	V
	7	F	F	F	V	F	F	/	V	V	V
	8	V	V	V	V	V	V	V	/	V	V
	9	V	V	V	V	V	V	V	V	/	V
	10	V	V	V	V	V	V	V	V	V	V

Figure 3.5: All the violations for φ''

Let's talk about the complexity. If we say that l is the maximum number involved in a constraint of Σ then we can say that the construction of G_i for each $\Sigma_i \in \mathbb{D}$ cost $O(|I|^l)$. The data repairing algorithm get a complexity in time of $O(|I|^l)$ and the algorithm 1 runs in $O(|I|^l|\mathbb{D}|)$ time. Usualy a denial constraint get 2 tuples [4].

3.3 Minimum Data Repair and Violation Free

After using the θ-tolerant model, we know which constraint set Σ' derived from Σ we have to use to perform a repairing. But we haven't see how to repair yet. In this section we'll focus on the minimum data repair I' based on the Σ'. To make this we'll use the violation free to be sure we don't create any violation after correcting one data. For example, if we put $t5.Tax$ to 22, we solved the violation $\langle t_5, t_4\rangle$ we had with φ' [2]but we introduce a new violation $\langle t_8, t_5\rangle$.

Remember we already said that finding a minimum repairing is NP-hard problem. For this reason we need to make some approximation in order to repair. For the following explanation and definition we'll note $\mathbb{C}$ the selected cells $\mathbb{V}(G)$

3.3.1 Suspect identification

Definition 15. *[4] The suspect set $susp(\mathbb{C}, \varphi)$ of a φ is a set of tuple lists $\langle t_i, t_j, ... : \varphi\rangle$ satisfying all the predicates in φ which do not involve cells in$\mathbb{C}$.*

[1]same reasoning: 4 cells involved.

[2]remember the $\varphi : \forall t_\alpha, t_\beta \in R, \neg(t_\alpha.Income > t_\beta.Income \wedge t_\alpha.Tax < t_\beta.Tax)$ we used many times

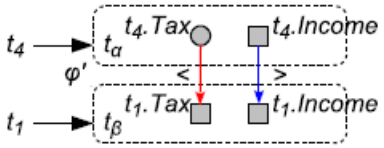

Figure 3.6: Suspect condition represented by blue arrows and repair context represented by red arrow (with inverse operator)

and they satisfy the suspect condition:

$$sc(t_\alpha, t_\beta, ... : \varphi) = \{I(v_1)\phi c | P : v_1\phi c \in pred(\varphi), v_1 \in \{C\}\} \cup \{I(v_1)\phi v_2 | P : v_1\phi v_2 \in pred(\varphi), v_1, v_2 \in \{C\}\}$$

Any violation is of course in the suspect list, which lead to the trivial lemma:

Lemma 3. *For any $\mathbb{C}$, it always has $viol(I, \varphi) \subseteq susp(\mathbb{C}, \varphi$*

And by this way, if we catch all the suspect, we also get all the violation.

To explain it, let's return on the example φ' related with the hypergraph at figure 3.3. We will change only $t_4.Tax$ as we made in the figure 3.2. So we have $\mathbb{C}$ = $\{t_4.Tax\}$ and $susp(\mathbb{C}, \varphi') = \{\langle t_4, t_1\rangle, \langle t_4, t_2\rangle, \langle t_4, t_3\rangle, \langle t_5, t_4\rangle, \langle t_6, t_4\rangle, \langle t_7, t_4\rangle, \langle t_8, t_4\rangle, \langle t_9, t_4\rangle, \langle t_{10}, t_4\rangle\}$ If we get $\langle t_4, t_1\rangle$, we have $t_4.Income > t_1.Income$ but there is a chance that any change on $t_4.Tax$ leads to a new violation($I'(t_4.Tax) < I(t_1.Tax)$. This is the reason why it's on the suspect list. In the figure 3.6 we have a graph with cells not in $\mathbb{C}$ are circle and cell in $\mathbb{C}$ are squares. Red arrow are predicates that are not respected and blue arrows are respected predicates.

3.3.2 Repair context over suspects

We can now define a repair context. The repair contest of a suspect tuple is something that makes sure the suspect will not satisfy the predicates declared on $\mathbb{C}$. The reason why we need it is because a denial constraint needs at least one false predicate for every rows of the database. The repair context takes the inverse operator of predicates in $\mathbb{C}$. In [4], the repair context $rc(t_i, t_j, ... : \varphi)$ of a suspect $\langle t_i, t_j, ...\rangle$is defined as:

Definition 16.

$$\begin{aligned} rc(t_\alpha, t_\beta, ... : \varphi) = &\{I'(v_1)\overline{\phi}c | P : v_i\phi c \in pred(\varphi), v_1 \in \mathbb{C}\} \cup \\ &\{I'(v_1)\overline{\phi}I'(v_2) | P : v_i\phi v_2 \in pred(\varphi), v_1, v_2 \in \mathbb{C}\} \cup \\ &\{I'(v_1)\overline{\phi}'(v_2) | P : v_i\phi v_2 \in pred(\varphi), v_1, \in \mathbb{C}, v2 \notin \mathbb{C}\} \cup \\ &\{I(v_1)\overline{\phi}I'(v_2) | P : v_i\phi v_2 \in pred(\varphi), v_2 \in \mathbb{C}, v_1 \notin \mathbb{C}\}. \end{aligned}$$

Property 6. *Any assignment that satisfies all the repair contexts forms a valid repair I' without introducing any new violations, i.e, $I' \preceq \Sigma$*

If we continue with our previous example with φ', we have $rc(t_4, t_1 : \varphi')$ = $\{I'(t_4.Tax \geq I(t_1.Tax)\}$, $\geq$ is the inverse operator of $<$, and we only consider predicates of φ' with cells from $\mathbb{C}$ which are red arrows on the figure 3.6. We also have $rc(t_5, t_4 : \varphi')$ = $\{I'(t_5.Tax \geq I(t_4.Tax)\}$. With both of these repair constraint we have $0 = t_1.Tax \leq t_4.Tax \leq t_5.Tax = 0$ which lead to only one possible value : $t_4.Tax = 0$. Remember that previously we put a fresh variable fv instead of 0 (see the table 3.2 in the previous chapter).

We want a repair cost as small as possible, which leads to to minimize the repair cost under repair cost constraint:

$$\min \sum_{t_i.A \in \mathbb{C}} dst(I(t_i.A), I'(t_i.A))$$
$$under\ the\ constraint : rc(t_i, t_j, ... : \varphi)\ with\ \langle t_i, t_j, ... \rangle \in susp(\mathbb{C}, \varphi), \varphi \in \Sigma$$

But it could be possible that we can't assign any value (in our domain) that can fit all the repair context. In these case can't put any value except a fresh variable. If a cell is assigned by a fresh variable fv we can remove every repair context with this cell. The reason is that fv are defined as a way they don't satisfy any kind of predicates which include predicates in repair context. If we can solved our problems i.e we can't found value in dom(A) for a repaired instance I', we'll assign a fresh variable until the problems is solvable. It's better to start by cells with the largest number of appearance in predicates in the repair context. We can say $I'(t.A)$ = fv if $rc(t.A, \Sigma)$ which represent all the repair context declared between a constant or between $t.A$ and $v_i \notin \mathbb{C}$.

If we come back to one of our first example : $\varphi : t_\alpha, t_\beta \in R, \neg(t_\alpha.Income > t_\beta.Income \wedge t_\alpha.Tax \leq t_\beta.Tax)$ For t_2 we have $rc(t_2.Tax, \{\varphi\}) = \{I'(t_2.Tax) > I(t_1.Tax), I(t_4.Tax) > I'(t_2.Tax), I(t_8.Tax) > I'(t_2.Tax), I(t_9.Tax) > I'(t_2.Tax), I(t_10.Tax) > I'(t_2.Tax)\{$ In the same we we did for φ', here we have $0 = I(t_1.Tax) < I'(t_2.Tax) < I(t_4.Tax) = 3k$ and there is no value who respect it in dom(A) = $\{0, 3k, 21k, 40\}$

3.4 Other repairing

3.4.1 Holistic data repair

3.4.2 ...

Chapter 4

Implementation and comparison with others models

Chapter 5

Conclusion

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