

Analyse Relationnelle de Concepts:  
Une approche pour fouiller  
des ensembles de données multi-relationnels  
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## Observation

- ▶ Relational datasets, multi-dimensional data
- ▶ A few approaches
  - ▶ Data warehouse (OLAP) cube (Gray et al. 2008)
  - ▶ Inductive Logic Programming (Dzeroski, 2003)
    - ▶ Propositionalization (Kuzelka, O., Zelezný, 2008)

## More specific objective

- ▶ extract patterns from data and relations
- ▶ interconnected classification of entities
- ▶ classification of extracted patterns

## Outline

- ▶ Formal Concept Analysis
- ▶ Relational Concept Analysis
- ▶ Applications
  - ▶ Class model refactoring

# Formal Concept Analysis

A methodology for:

- ▶ data analysis, data mining, clustering
- ▶ knowledge representation (ontology construction)
- ▶ classification, indexation (information retrieval)
- ▶ unsupervised learning (example description)
- ▶ supervised learning (adding classes in description)

Roots:

- ▶ lattice theory, Galois connections  
(Birkhoff, 1940; Barbut & Monjardet, 1970)
- ▶ concept lattices  
(Wille, 1982)

# Formal Concept Analysis

## Formal Context

- ▶ Simplest form: entities with characteristics

	Photo	PhysKeyboard	SquareScreen	FullHDScreen	4Gcapable	LowSAR	HighAutonomy	NFC
BlackberryPassport	x	x	x		x		x	x
BlackberryLeap	x				x		x	x
BlackberryQ5	x	x	x		x			x
iphone6plus	x			x	x		x	x
iphone6	x				x		x	x
NokiaLumia735	x				x		x	x
NokiaLumia930	x			x	x			x
SonyXperiaZ1	x			x	x		x	x
GoogleNexus5	x			x	x	x		x
AsusZE500CL	x				x			x
WikoHighway	x					x		
LGGFlex	x				x	x	x	x

# Formal context

## Formal Context $(O, A, R)$

- ▶ two finite sets  $O$  et  $A$
- ▶ binary relation  $R \subseteq O \times A$ .

## Mappings associated with $R$

- ▶ Attribute shared by an object set

$$f : \mathcal{P}(O) \rightarrow \mathcal{P}(A)$$

$$X \mapsto f(X) = \{y \in A \mid \forall x \in X, (x, y) \in R\} = X'$$

- ▶ Objects sharing an attribute set

$$g : \mathcal{P}(A) \rightarrow \mathcal{P}(O)$$

$$Y \mapsto g(Y) = \{x \in O \mid \forall y \in Y, (x, y) \in R\} = Y'$$

Alternative notation '

# Closure operators

$f \circ g$  (resp.  $g \circ f$ ) is a **closure operator** on attributes (resp. objects)

*op* closure operator on a poset  $(P, \leq_P)$

- ▶ isotone:  $X \leq_P Y \Rightarrow op(X) \leq_P op(Y)$
- ▶ extensive:  $X \leq_P op(X)$
- ▶ idempotent:  $op(op(X)) = op(X)$

$X$  is a **closed set** iff  $op(X) = X$

$f \circ g$  is a closure operator on  $(2^A, \subseteq)$

$g \circ f$  is a closure operator on  $(2^O, \subseteq)$

# Concept

A formal **concept**  $C$  is a pair  $(E, I)$  such that  
 $f(E) = I$  (or equivalently)  $E = g(I)$

$E = \{ e \in O \mid \forall i \in I, (e, i) \in R \}$   
is the **extent** (covered objects)

$I = \{ i \in A \mid \forall e \in E, (e, i) \in R \}$   
is the **intent** (shared attributes)

$E$  is a closed set for  $g \circ f$

$I$  is a closed set for  $f \circ g$



# Concept

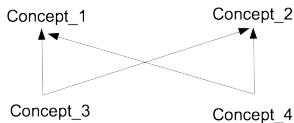
A maximal group of objects (object closed set, extent)  
sharing a maximal group of attributes (attribute closed set, intent)

	Photo	PhysKeyboard	SquareScreen	FullHDScreen	4Gcapable	LowSAR	HighAutonomy	NFC
BlackberryPassport	x	x	x		x		x	x
BlackberryLeap	x				x		x	x
BlackberryQ5	x	x	x		x			x
iphone6plus	x			x	x		x	x
iphone6	x				x		x	x
NokiaLumia735	x				x		x	x
NokiaLumia930	x			x	x			x
SonyXperiaZ1	x			x	x		x	x
GoogleNexus5	x			x	x	x		x
AsusZE500CL	x				x			x
WikoHighway	x					x		
LGGFlex	x				x	x	x	x

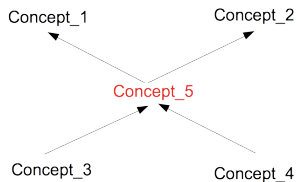
# Concept lattice

The concept set  $\mathcal{C}$  provided with:  
 $(E_1, I_1) \leq_{\mathcal{L}} (E_2, I_2) \Leftrightarrow E_1 \subseteq E_2$   
(or equivalently  $I_2 \subseteq I_1$ )  
has a lattice structure

*Every concept pair has a lower bound and an upper bound*

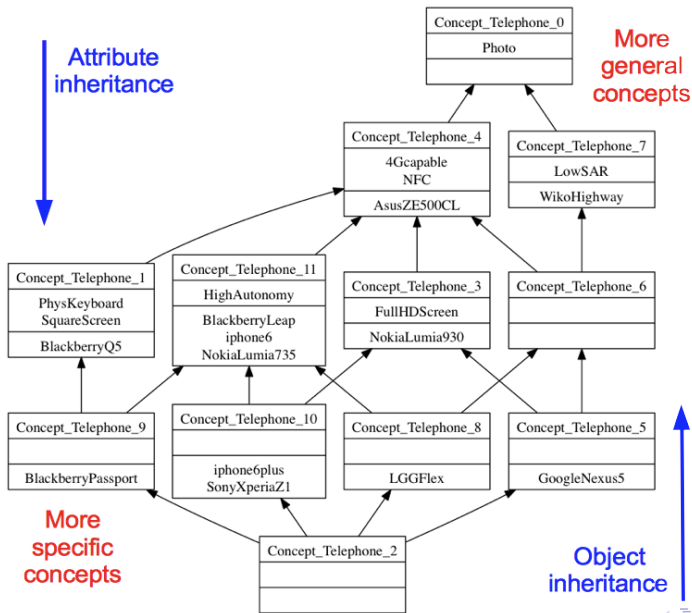


Partial order



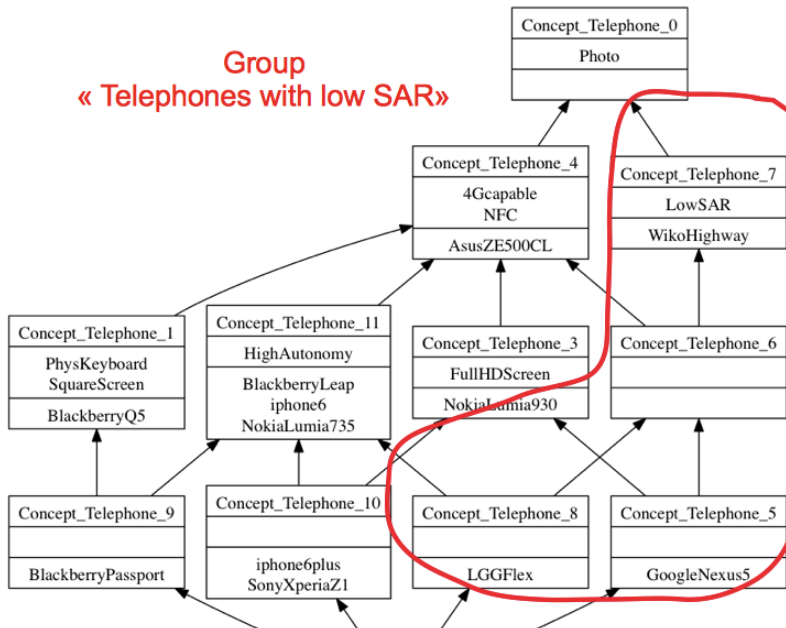
Partial order with **lattice structure**

# Formal Concept Analysis



# Formal Concept Analysis

Group  
« Telephones with low SAR »

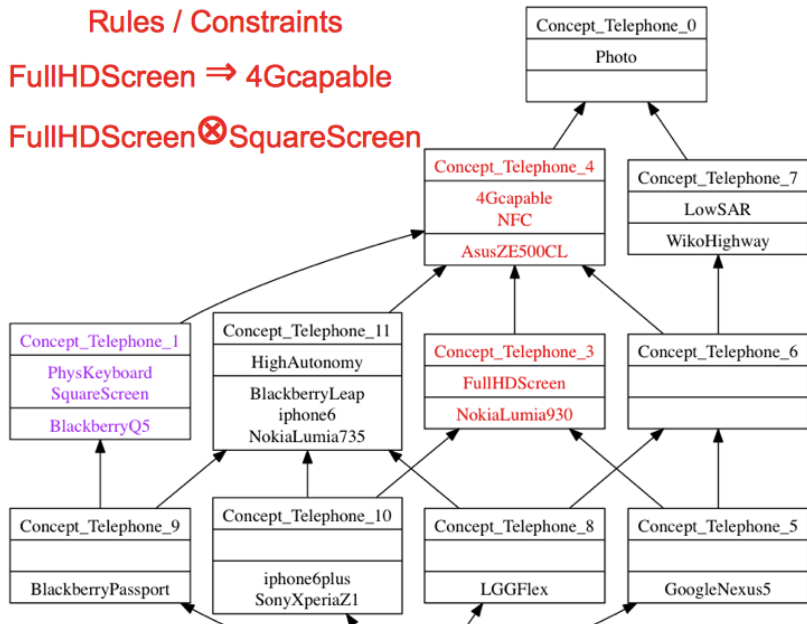


# Formal Concept Analysis

## Rules / Constraints

FullHDScreen  $\Rightarrow$  4Gcapable

FullHDScreen  $\otimes$  SquareScreen



# Implication rules

## Association rule - approximate rule

For  $A_1$  and  $A_2$  two attribute sets (itemsets)

$A_1 \Rightarrow A_2$  iff a (significant) part of objects that own  $A_1$  also own  $A_2$

Confidence =  $|f(A_1) \cap f(A_2)| / |f(A_1)|$

## Implication rule - exact rule

For  $A_1$  and  $A_2$  two attribute sets (itemsets)

$A_1 \Rightarrow A_2$  iff  $f(A_1) \subseteq f(A_2)$

Confidence = 1

# Implication rules

## Duquenne-Guigues implication basis

A minimal (in the number of implications) implication set

<12> {}  $\Rightarrow$  Photo

<11> Photo NFC  $\Rightarrow$  4Gcapable

<2> Photo PhysKeyboard  $\Rightarrow$  SquareScreen 4Gcapable NFC

<2> Photo SquareScreen  $\Rightarrow$  PhysKeyboard 4Gcapable NFC

<4> Photo FullHDScreen  $\Rightarrow$  4Gcapable NFC

<11> Photo 4Gcapable  $\Rightarrow$  NFC

<7> Photo HighAutonomy  $\Rightarrow$  4Gcapable NFC

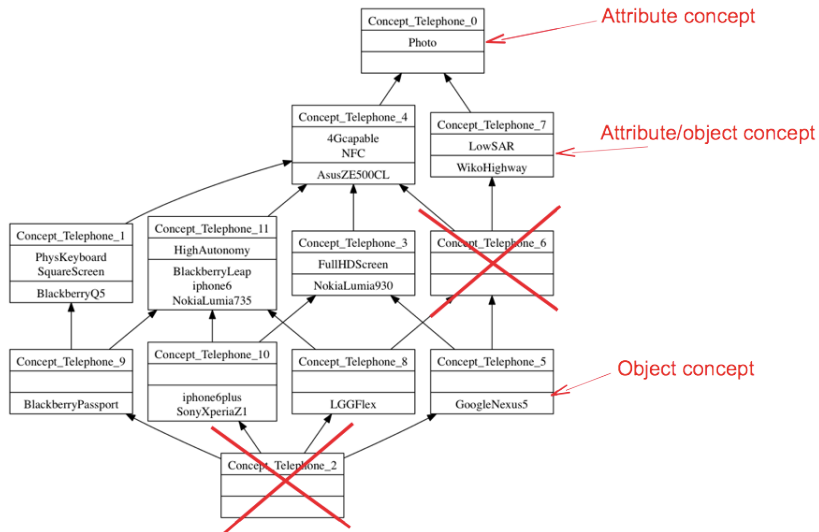
<0> *Photo PhysKeyboard SquareScreen FullHDScreen 4Gcapable NFC  $\Rightarrow$   
LowSAR HighAutonomy*

<0> *Photo PhysKeyboard SquareScreen LowSAR 4Gcapable NFC  $\Rightarrow$   
FullHDScreen HighAutonomy*

<0> *Photo FullHDScreen HighAutonomy LowSAR 4Gcapable NFC  $\Rightarrow$   
PhysKeyboard SquareScreen*

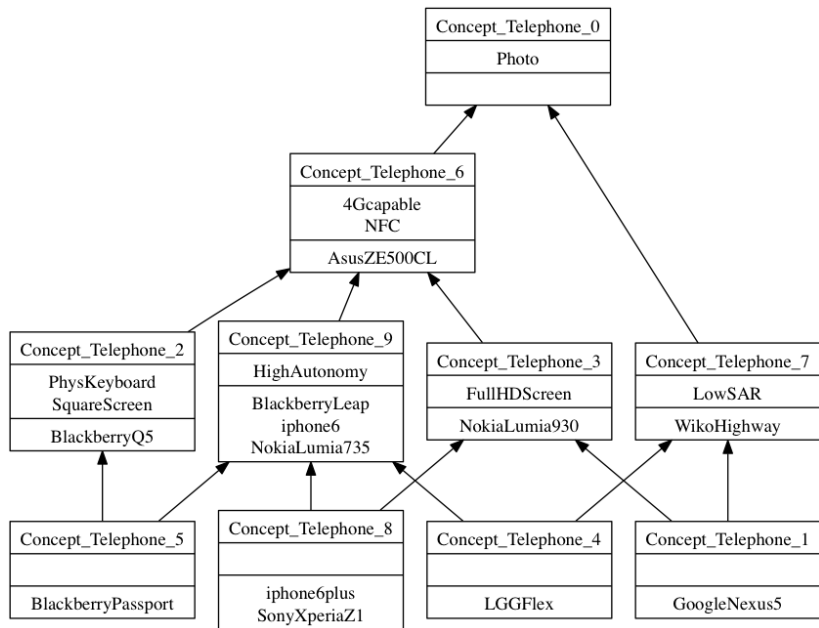
Conexp (<http://conexp.sourceforge.net/>)

# AOC-poset





# AOC-poset



# Complexity of conceptual structures

## Formal context $(O, A, R)$

- ▶ two finite sets  $O$  et  $A$
- ▶ binary relation  $R \subseteq O \times A$

## Concept lattice

$$\# \text{concepts} < 2^{\min(|A|, |O|)}$$

Reached with the lattice of all subsets of  $E$ , where  $E$  is  $O$  if  $|O| = \min(|A|, |O|)$  (otherwise,  $E$  is  $A$ )

## AOC-poset

$$\# \text{concepts} < |A| + |O|$$

Reached if  $|A| = |O|$  and every attribute is shared by several distinct objects (a bipartite crown graph for ex.)

## Generalization: Galois connection

The mapping pair  $(f, g)$  associated with a  $R \subseteq A \times B$  binary relation is a (monotone) Galois connection between  $(2^A, \subseteq)$  and  $(2^O, \subseteq)$

This is a particular case of a more general theory

### Galois connection

For two posets  $(A, \leq_A)$  and  $(B, \leq_B)$ ,  
and two mappings  $f : A \rightarrow B$  et  $g : B \rightarrow A$

The pair  $(f, g)$  is a Galois connection if:

$$\forall a \in A \text{ and } \forall b \in B, a \leq_A g(b) \Leftrightarrow b \leq_B f(a).$$

### Property

If  $(f, g)$  is a Galois connection between  $(A, \leq_A)$  and  $(B, \leq_B)$   
 $h_A = g \circ f$  et  $h_B = f \circ g$  are closure operators

The corresponding closed sets can be provided with a lattice structure

They can be associated by  $f$  and  $g$

# Generalization: Galois connection

## Pattern structures, Ganter and Kuznetsov 2001

In the following framework:

- ▶ a set of objects  $G$
- ▶ a set of descriptions  $(D, \sqcap)$  which is a semilattice
- ▶ a partial order on  $D$ :  $a \sqsubseteq b$  iff  $a \sqcap b = a$  ( $a$  is subsumed by  $b$ )
- ▶ a map  $\delta : G \rightarrow D$

A Galois connection  $(f, g)$  can be defined:

- ▶  $\forall X \subseteq G, f(X) = \sqcap_{g \in X} \delta(g)$
- ▶  $\forall d \in D, g(d) = \{g \in G \mid d \sqsubseteq \delta(g)\}$

# FCA and complex data

By transforming multi-valued contexts into binary contexts (scaling) or by using a general Galois connection,

- ▶ many-valued contexts (integers, floats, terms, structures, symbolic objects, etc.) (Ganter et Wille, Polaillon, ...)
  - ▶ fuzzy descriptions (Yahia et al., Belohlavek, ...)
  - ▶ hierarchies on values (Godin et al., Carpineto et Romano, ...)
  - ▶ logical description (Chaudron et al., Ferré et al., ...)
  - ▶ graphs (Liquière, Prediger and Wille, Ganter and Kuznetsov, ...)
  - ▶ etc.
- ▷ A unique classification centered on a unique object set

# Relational Concept Analysis (RCA)

- ▶ Extends the purpose of FCA for taking into account object categories and links between objects
- ▶ Main principles:
  - ▶ a relational model based on the entity-relationship model
  - ▶ integrate relations between objects as *relational* attributes
  - ▶ iterative process
- ▶ RCA provides a set of interconnected lattices
- ▶ Produced structures can be represented as ontology concepts within a knowledge representation formalism such as description logics (DLs).

Joint work with:

A. Napoli, C. Roume, M. Rouane-Hacène, P. Valtchev

# Relational Context Family (RCF)

A simple entity-relationship model to introduce RCA

## Relational Context Family

- ▶ **object-attribute contexts**
  - ▶ Pizza
  - ▶ Ingredient
- ▶ **object-object context**
  - ▶ has-topping  $\subseteq$  Pizza  $\times$  Ingredient

# Relational Context Family (RCF)

A RCF  $\mathcal{F}$  is a pair  $(K, R)$  with:

- ▶  $K$  is a set of object-attribute contexts  $K_i = (O_i, A_i, I_i)$
- ▶  $R$  is a set of object-object contexts  $R_j = (O_k, O_l, I_j)$ ,
  - ▶  $(O_k, O_l)$  are the object sets of formal contexts  $(K_k, K_l) \in K^2$
  - ▶  $I_j \subseteq O_k \times O_l$
  - ▶  $K_k$  is the *source/domain context*
  - ▶  $K_l$  is the *target/range context*.
  - ▶ we may have  $K_k = K_l$ .



# RCF / object-attributes contexts

	thin	thick	calzone
Pizza			
okonomi			×
alberginia		×	
margherita	×		
languedoc	×		
four-cheeses	×		
three-cheeses	×		
frutti-di-mare	×		
quebec		×	
regina	×		
hawai		×	
lorraine	×		
kebab			×

Ingredient	fruit-vegetable	meat	fish	dairy	cereal-leguminous	veg-oil
tomato-sauce	×					
cream				×		
tomato	×					
basilic	×					
olive	×					
olive oil						×
soy	×					
mushroom	×					
eggplant	×					
onion	×					
pepper	×					
ananas	×					
mozza				×		
goat-cheese				×		
emmental				×		
fourme-ambert				×		
squid			×			
shrimp			×			
mussels			×			
ham		×				
bacon		×				
chicken		×				
maple-sirup	×					
corn					×	

# RCF / object-object context / part 1

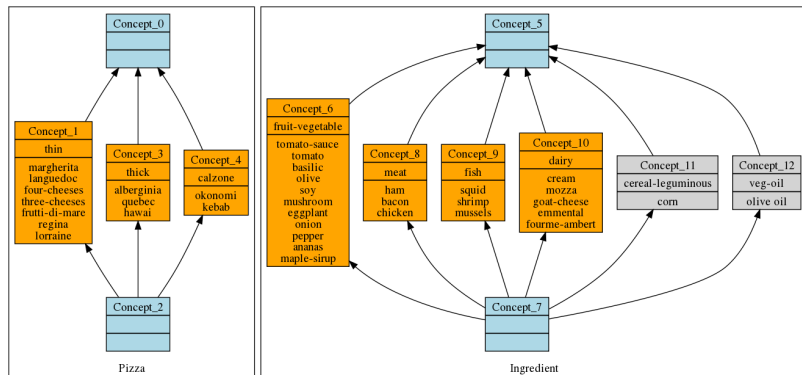
	tomato-sauce	cream	tomato	basilic	olive	olive oil	soy	mushroom	eggplant	onion	pepper	ananas
has-topping												
okonomi	x					x	x	x				
alberginia	x					x	x		x	x		
margherita	x		x	x	x	x						
languedoc	x		x	x	x	x				x	x	
four-cheeses		x										
three-cheeses		x										
frutti-di-mare	x				x	x						
quebec	x											
regina	x							x				
hawai	x											x
lorraine		x								x		
kebab	x		x		x					x		

## RCF / object-object context / part 2

	mozza	goat-cheese	emmental	fourme-ambert	squid	shrimp	mussels	ham	bacon	chicken	maple-sirup	corn
has-topping												
okonomi												
alberginia												
margherita	x											
languedoc	x											
four-cheeses	x	x	x	x								
three-cheeses	x	x	x									
frutti-di-mare	x				x	x	x					
quebec	x							x			x	x
regina	x								x			
hawai	x							x				
lorraine			x						x			
kebab			x							x		

# RCA - Initial Lattice building

At the beginning, only the object-attribute contexts are used to build the foundation of the concept lattice family



## RCA - Introducing relations as relational attributes

Given an object-object context  $R_j = (O_k, O_l, I_j)$ ,

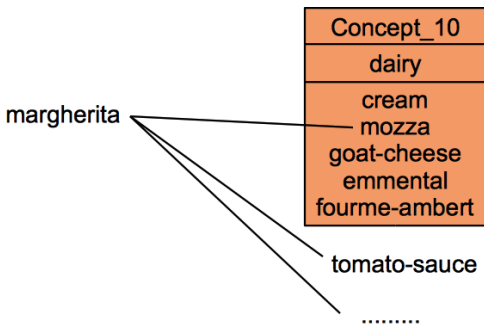
There are different notable schemas between an object of domain  $O_k$  and concepts formed on  $O_l$ .

*E. g.*

- ▶ **Existential:** an object is linked (by  $R_j$ ) to at least one object of the extent of a concept
- ▶ **Universal:** an object is linked (by  $R_j$ ) only to objects of the extent of a concept

## RCA - Existential relational attributes

**margherita** has one topping in **Concept\_10** extent: **mozza**.  
It has other links to other concept extents.



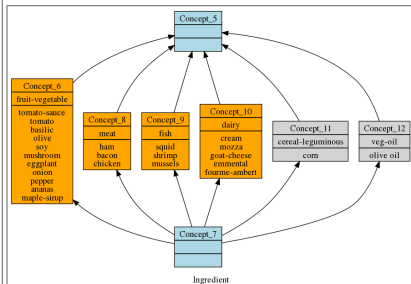
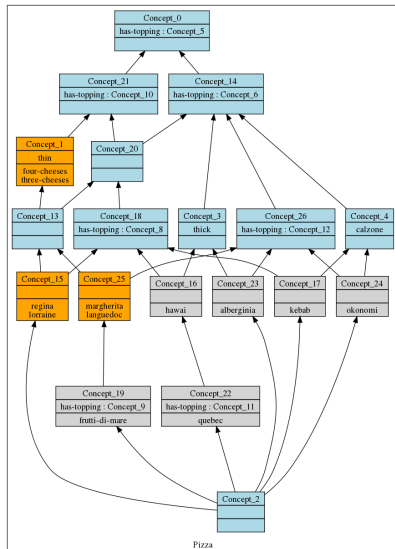
$\exists$ has-topping.Concept\_10 is assigned to **margherita**

# RCA - Existential relational attributes

Scaled relations with domain  $O_i$  are concatenated to  $K_i$ , the object-attribute context on  $O_i$

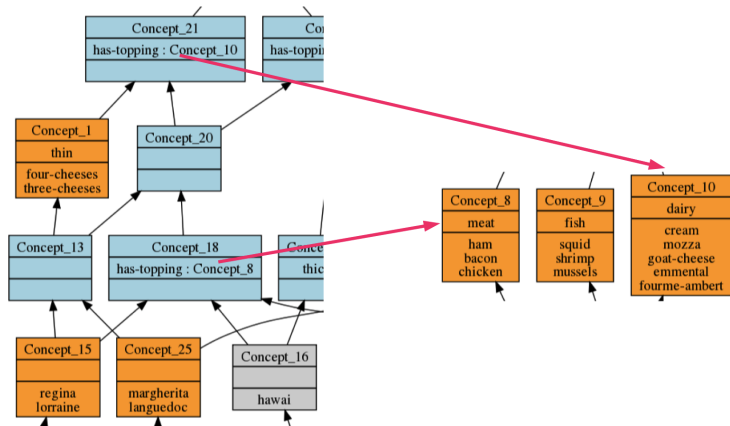
Pizza	thin	thick	calzone		has-topping. Concept_7	has-topping. Concept_5	has-topping. Concept_6	has-topping. Concept_8	has-topping. Concept_9	has-topping. Concept_10	has-topping. Concept_11	has-topping. Concept_12
okonomi			x									
alberginia		x										
margherita	x											
languedoc	x			has-topping	$\exists$ has-topping. Concept_7	$\exists$ has-topping. Concept_5	$\exists$ has-topping. Concept_6	$\exists$ has-topping. Concept_8	$\exists$ has-topping. Concept_9	$\exists$ has-topping. Concept_10	$\exists$ has-topping. Concept_11	$\exists$ has-topping. Concept_12
four-cheeses	x			okonomi		x	x					x
three-cheeses	x			alberginia		x	x					x
frutti-di-mare	x			margherita		x	x			x		x
quebec		x		languedoc		x	x			x		x
regina	x			four-cheeses		x				x		
hawai		x		three-cheeses		x				x		
lorraine	x			frutti-di-mare		x	x		x	x		x
kebab			x	quebec		x	x	x		x	x	
				regina		x	x	x		x		
				hawai		x	x	x		x		
				lorraine		x	x	x		x		
				kebab		x	x	x		x		

# Relational Concept Family / exists





# Relational Concept Family / exists



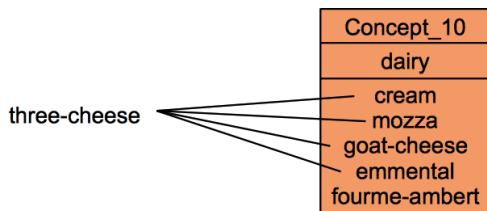
Concept\_21: pizzas with at least one topping in dairy

Concept\_18: pizzas with at least one topping in meat

have at least one meat topping  $\Rightarrow$  have at least one dairy topping

## RCA - Universal relational attributes

**three-cheese** has topping in and only in **Concept\_10** extent.



$\forall e \text{ has-topping. Concept\_10}$  is assigned to **three-cheese**

# RCA - Universal relational attributes

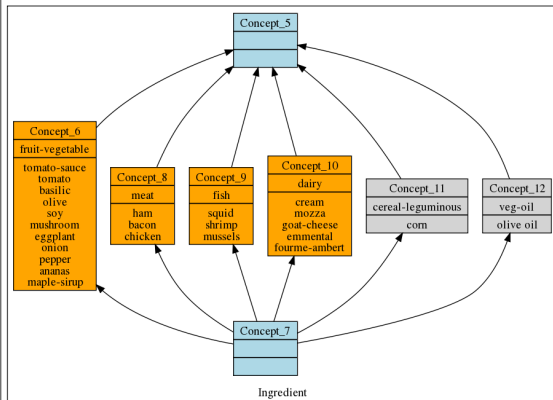
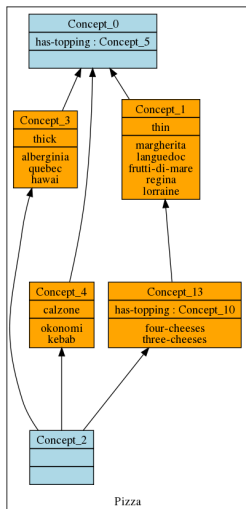
Scaled relations with domain  $O_i$  are concatenated to  $K_i$ , the object-attribute context on  $O_i$

Pizza	thin	thick	calzone
okonomi			x
alberginia		x	
margherita	x		
languedoc	x		
four-cheeses	x		
three-cheeses	x		
frutti-di-mare	x		
quebec		x	
regina	x		
hawai		x	
lorraine	x		
kebab			x

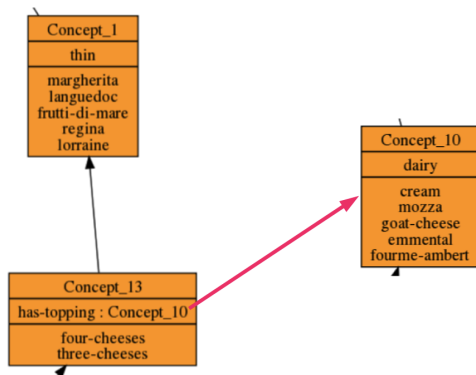
  

has-topping	$\forall \exists \text{has-topping. Concept\_7}$	$\forall \exists \text{has-topping. Concept\_5}$	$\forall \exists \text{has-topping. Concept\_6}$	$\forall \exists \text{has-topping. Concept\_8}$	$\forall \exists \text{has-topping. Concept\_9}$	$\forall \exists \text{has-topping. Concept\_10}$	$\forall \exists \text{has-topping. Concept\_11}$	$\forall \exists \text{has-topping. Concept\_12}$
okonomi		x						
alberginia		x						
margherita		x						
languedoc		x						
four-cheeses		x				x		
three-cheeses		x				x		
frutti-di-mare		x						
quebec		x						
regina		x						
hawai		x						
lorraine		x						
kebab		x						

# Relational Concept Family / forall



# Relational Concept Family / forall



Concept\_13: pizzas with only dairy topping

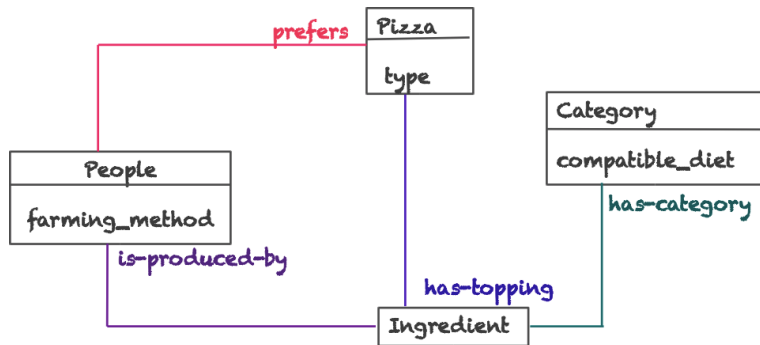
Concept\_1: thin pizzas

have only dairy topping  $\Rightarrow$  thin

# Scaling operators

Operator	Attribute form	Condition
Universal (narrow)	$\forall r.c$	$r(o) \subseteq Ext(c)$
Universal strict	$\forall \exists r.c$	$r(o) \subseteq Ext(c)$ and $r(o) \neq \emptyset$
Universal-percent	$\forall \exists \_ \geq n\% r.c$	$ r(o) \cap Extent(C)  \geq n r(o) /100$
Covers	$\supseteq r.c$	$r(o) \supseteq Ext(c)$
Covers-percent	$\supseteq \_ \geq n\% r.c$	$ r(o) \cap Extent(C)  \geq n Extent(C) /100$
Existential (wide)	$\exists r.c$	$r(o) \cap Ext(c) \neq \emptyset$
Universal strict	$\forall \exists r.c$	$r(o) \subseteq Ext(c)$ and $r(o) \neq \emptyset$
Qualif. card. restriction	$\geq n r.c$	$r(o) \subseteq Ext(c)$ and $ r(o)  \geq n$
Card. restriction	$\geq n r.T_{\mathcal{L}}$	$ r(o)  \geq n$

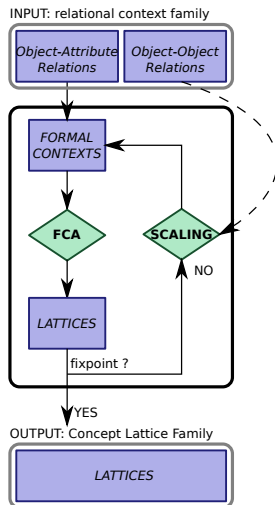
# General Entity-Relationship diagram



General ER diagram may present cycle/circuits between classes/objects

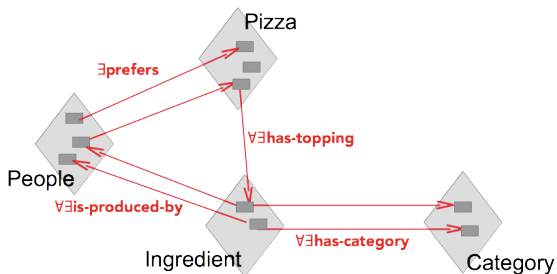
$\exists$  prefers  $\forall \exists$  has-topping  $\forall \exists$  has-category  $\forall \exists$  is-produced-by

# RCA schema





# Interconnected lattices



# Applications to Knowledge Representation and Data Mining

- ▶ Ontology construction (R. Bendaoud, M. Rouane Hacene, Y. Toussaint, B. Delecroix, A. Napoli)
- ▶ Ontology restructuring (M. Rouane-Hacene, R. Nkambou and P. Valtchev)
- ▶ Discovering hidden user profiles in a semantic actors-activities network (Z. Azmeh, I. Mirbel)
- ▶ Information retrieval in legal document collections (queries) (N. Mimouni, A. Nazarenko, S. Salotti)

# FRESQUEAU project (ANR11\_MONU14)

Joint work with: A. Braud, X. Dolques, C. Grac, F. Le Ber, C. Nica  
<http://engees-fresqueau.unistra.fr>

- ▶ Develop new methods to study, compare and exploit the whole set of available parameters describing the state of watercourses
- ▶ Extraction of implication rules (with premise of size 1)  
*Presence of taxons of size from 0 to 2 cm and with a lifetime of 1 month implies presence of SO4*
- ▶ 4 OA-contexts (49 sites, 197 macro-invertebrates, 27 Physico-Chemical parameters, 18 life traits (116 modalities)), 5+6+3 OO-contexts
- ▶ variants on scaling operators
- ▶ Lattices: > 10 000 concepts
- ▶ AOC-posets: from ~600 to ~1500 concepts, ~130 to ~300 rules

## Reengineering of existing software, by building new software artefacts

- ▶ UML class diagram refactoring (M. Dao, M. Huchard, M. Rouane Hacene, C. Roume, P. Valtchev, G. ArÃvalo, J.-R. Falleri, C. Nebut)
- ▶ UML Use case diagram refactoring (X. Dolques, M. Huchard, C. Nebut, P. Reitz)
- ▶ Blob design defect correction (N. Moha, M. Rouane Hacene, P. Valtchev, Y.-G. GuÃhÃneuc)
- ▶ Extracting architectures in object-oriented software (A.-E. El Hamdouni, A. Seriai, M. Huchard)

# Applications to Software engineering

## Learning from model transformation examples, and inferring transformation rules

- ▶ Learning model Transformation patterns in MDE (H. Saada, X. Dolques, M. Huchard, C. Nebut, H. A. Sahraoui)

## Classification of software artefacts

- ▶ Classification of web services (Z. Azmeh, M. Driss, F. Hamoui, M. Huchard, N. Moha, C. Tibermacine)

## Software analysis

- ▶ Analysis of the evolution of class diagrams (A. Osman-Guédi, A. Miralles, B. Amar, M. Huchard, T. Libourel and C. Nebut)

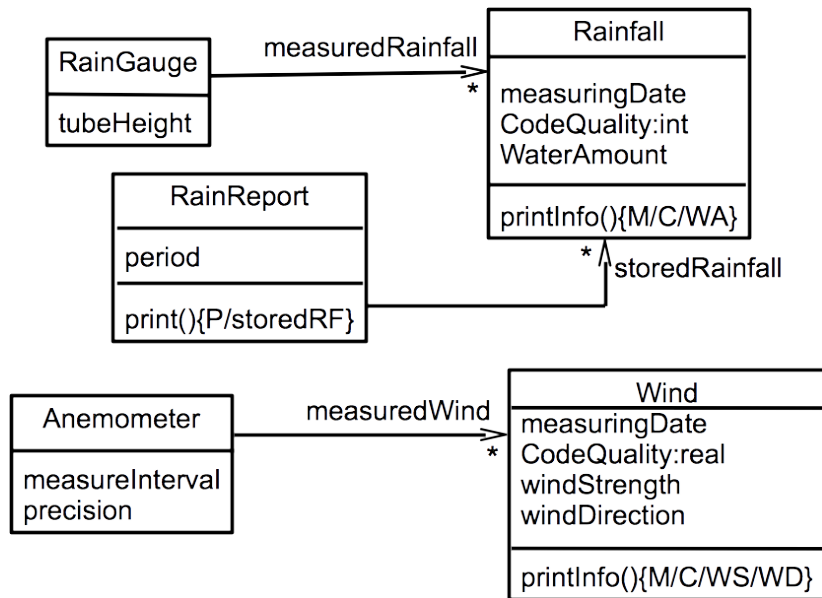
# Class model normalization: Context and Problematic

## Environment and Territory domains

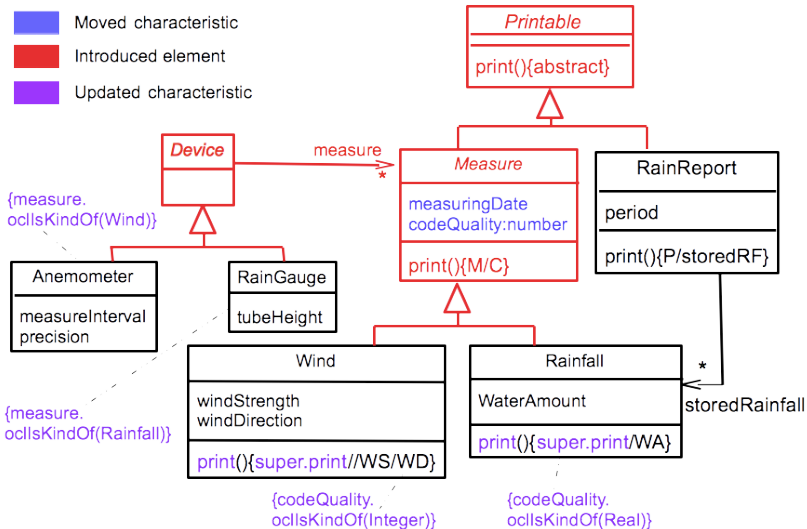
- ▶ Development of Information System involves many actors and scientists: *EIS-Pesticides*
- ▶ Meeting after meeting, the designer has to merge various viewpoints in a global UML that evolves progressively
- ▶ During the analysis phase, models are archived after each major change

*Joint work with B. Amar, X. Dolques, F. Le Ber, T. Libourel, A. Miralles, C. Nebut, A. Osman-Guédi*

## RCA for class model normalization

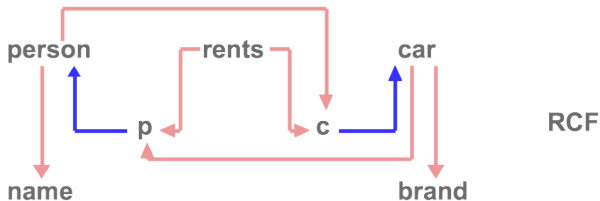
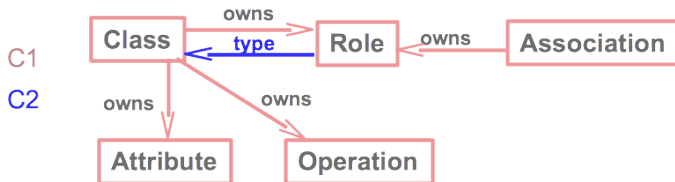


# RCA for class model normalization





# RCA for class model normalization



# RCA for class model normalization

Strong properties of the resulting class model

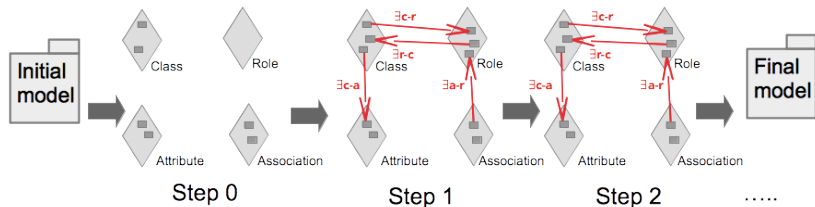
- ▶ No redundancy
- ▶ All abstractions are created
- ▶ All specialization links are present

## Approach

Develop methods using the class model normal form obtained with RCA for class model construction and evolution:

- ▶ monitoring
- ▶ assisting

# Classical RCA approach

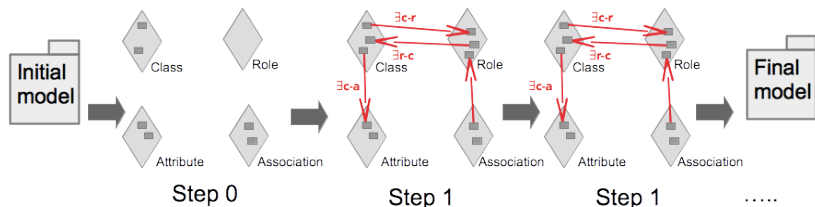


## Issue

The final model contains many merged or new elements, this is difficult to analyze to keep the relevant part

# Exploration path

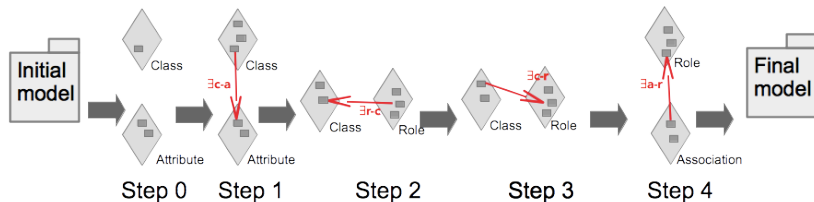
Fighting against possible high number of concepts to be analyzed  
by choosing good configurations  
by bringing concepts step by step



**Auto path:** all contexts are considered, but the process stops at each step and presents the concepts to the designer

# Exploration path

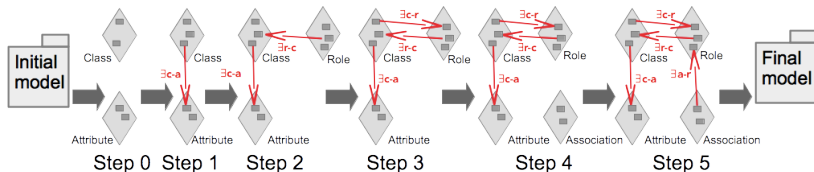
Fighting against possible high number of concepts to be analyzed  
by using parts of the RCF



**Path 1:** each step considers a specific part of the RCF

# Exploration path

Fighting against possible high number of concepts to be analyzed  
by using parts of the RCF - cumulative



**Path 2:** Begin by class/attributes, add roles, add associations

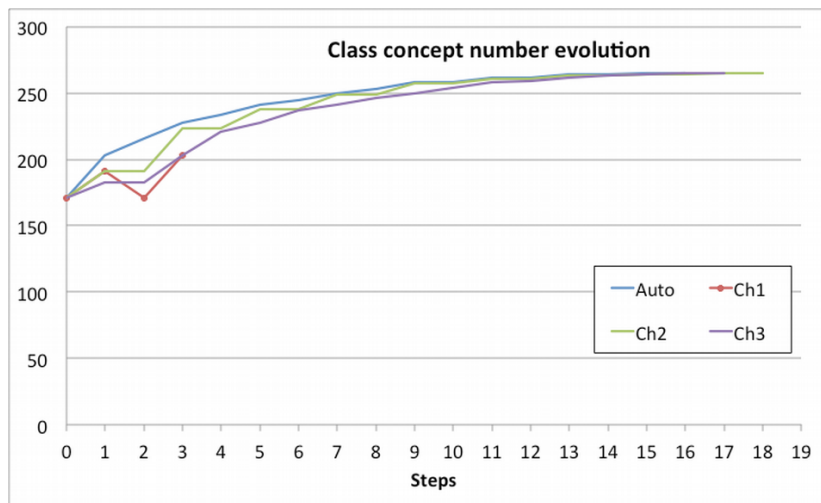
**Path 3:** A variant that begins by class/roles

## Quantitative analysis: ex. with class concepts to be analyzed at each step

RCA application on Pesticides: 171 classes, 265 class concepts

step tr.	Auto	Path 1	Path 2	Path 3	step tr.	Auto	Path 1	Path 2	Path 3
0 → 1	32	20	20	12	10 → 11	4		4	4
1 → 2	13	-20	0	0	11 → 11	0		0	1
2 → 3	12	32	32	20	12 → 13	2		2	3
3 → 4	6		0	18	13 → 14	0		0	1
4 → 5	7		15	7	14 → 15	1		1	1
5 → 6	4		0	9	15 → 16	0		0	1
6 → 7	5		11	4	16 → 17	Auto		1	0
7 → 8	3		0	5	17 → 18	Auto		0	
8 → 9	5		8	4					
9 → 10	0		0	4					

# Class concept number evolution





# Discussion

- ▶ Exploration divides the burden of the analysis
- ▶ The process is controlled by the expert
- ▶ Paths cannot be chosen by chance, cumulative paths ensure completeness
- ▶ Perspectives: define a complete methodology and tools

# General Conclusion

- ▶ RCA: an opportunity for analyzing more deeply datasets composed of objects and relations
- ▶ Can be mixed with other FCA extension (to numerical data for example)
- ▶ Exploratory RCA allows us step-by-step analysis, considering a subset of the dataset and changing structures (lattices, AOC-posets, iceberg)
- ▶ , Queries, metrics to guide exploration

## Tools

- ▶ Galicia: <http://galicia.sourceforge.net/>
- ▶ eRCA: <http://code.google.com/p/erca/>
- ▶ RCAexplore: <http://dolques.free.fr/rcaexplore/>

Questions?