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Marianne Huchard

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Towards a catalog of design patterns for knowledge discovery with relational concept analysis

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Université du Québec à Montréal
16 novembre 2022

Introduction

Formal Concept Analysis

Relational Concept Analysis

Design patterns for RCA

Conclusion

Agenda

Introduction

Formal Concept Analysis

Relational Concept Analysis

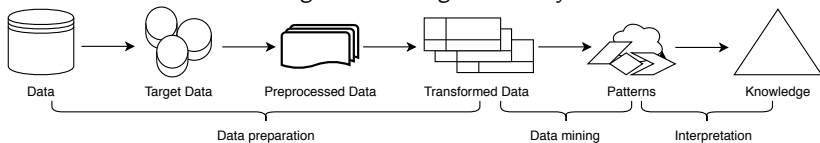
Design patterns for RCA

Conclusion

Knowledge Discovery (KD)

Fayyad, U., Piatetsky-Shapiro, G., Smyth, P. AI Magazine 1996

From Data Mining to Knowledge Discovery in Databases



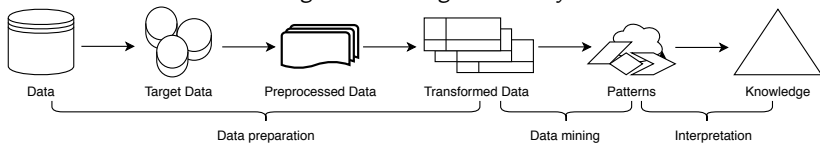
Directions

- Symbolic vs. subsymbolic
- White box vs. black box
- Supervised vs. unsupervised
- Structured vs. unstructured data

Knowledge Discovery (KD)

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Directions

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Roots



- **Concept lattices**
Rudolf Wille, 1982, Bernhard Ganter & Rudolf Wille, 1999
- **Lattice theory, Galois connections, Galois lattices**
Marc Barbut & Bernard Monjardet, 1970; Georges David Birkhoff, 1940; Øystein Ore, 1944
- **Galois connection, subgroups/subfields**
Evariste Galois, ~ 1830

Formal Concept Analysis

Formal concepts are “a natural feature of information representation which is as fundamental to hierarchies and object/attribute structures as set theory or relational algebra are for relational databases”.



Uta Priss. 40th anniv. vol. of Annual Review of Inf. Sc. and Tech., 2006

Simple but powerful **basics**

- Formal Context
- Galois connection
- Concept Lattice
- Implications and associations rules

Formal Context = Triple (O, A, R)

O is a finite set of objects, A is a finite set of attributes

$R \subseteq O \times A$ is a binary relation

$(o, a) \in R$ means that object o owns attribute a .

| Ingredient | <i>vege</i> | <i>vegan</i> | <i>spring</i> | <i>summer</i> | <i>autumn</i> |
|------------|-------------|--------------|---------------|---------------|---------------|
| goatcheese | × | | | × | |
| burrata | × | | × | | |
| scallop | | | × | | |
| tomato | × | × | | × | |
| shallot | × | × | | | × |
| mushroom | × | × | | | × |
| eggplant | × | × | | × | |

Formal Concept = Pair (Extent, Intent)

Extent = Maximal set of owner objects

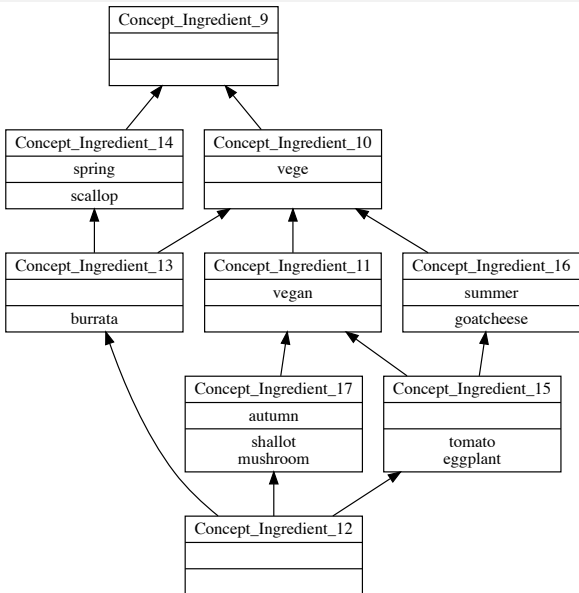
Intent = Maximal set of their shared attributes

| Ingredient | <i>vege</i> | <i>vegan</i> | <i>spring</i> | <i>summer</i> | <i>autumn</i> |
|------------|-------------|--------------|---------------|---------------|---------------|
| goatcheese | × | | | × | |
| burrata | × | | × | | |
| scallop | | | × | | |
| tomato | × | × | | × | |
| shallot | × | × | | | × |
| mushroom | × | × | | | × |
| eggplant | × | × | | × | |

Concept Lattice

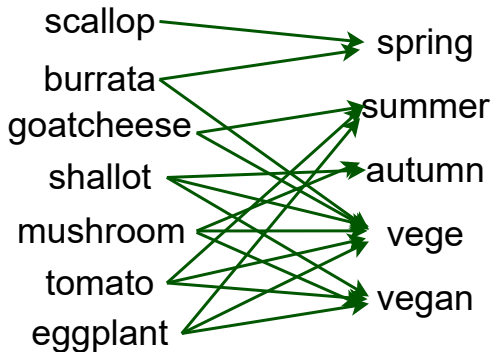
Set of all concepts provided with extent ↑ or intent ↓ inclusion

| |
|----------|
| C_I_11 |
| vege |
| vegan |
| shallot |
| mushroom |
| tomato |
| eggplant |



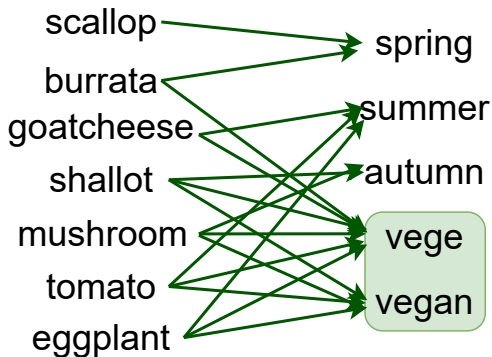
Another view of concept building

Links between objects and attributes



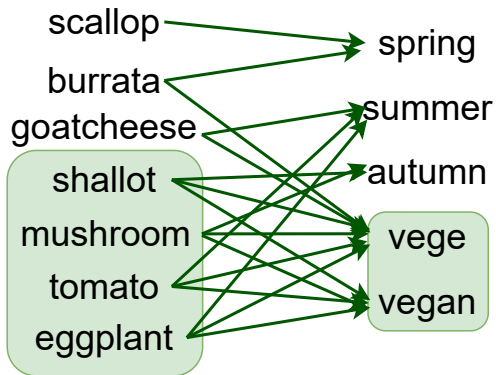
Another view of concept building

Links between objects and attributes *vege / vegan*



Another view of concept building

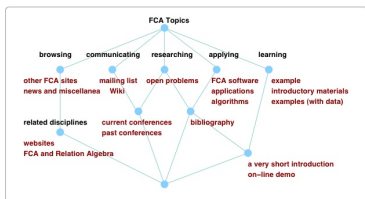
Concept of **vegan ingredients**



Dissemination 1982-2022

- Conceptualization, philosophical developments
- Data analysis, data mining, clustering
- Knowledge representation (ontology construction)
- Classification, indexation (information retrieval)
- Unsupervised learning
- Supervised learning (adding classes in description)
- Tools
- Applications

Dissemination 1982-2022



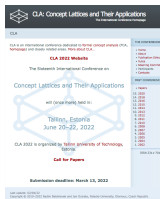
Credits Uta Priss <https://upriss.github.io/fca/fca.html>



ICCS



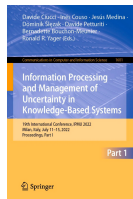
ICFCA



CLA



FCA4AI



IPMU

Complex data in FCA

- **Multi-valued attributes** : integers, double, terms, structures, symbolic objects, etc. (Ganter et Wille, Diday, Polaillon, ...)
- **Fuzzy** (Belohlavek et al., Cabrera, Cordero, Enciso, Mora, Lòpez-Ròd., Ojeda-Aciego et al., Cornejo, Medina et al., Yahia et al., Dubois Prade ...)
- **Value taxonomies** (Godin et al., Carpineto et Romano, ...)
- **Logical description** (Chaudron et al., Ferré et al., ...)
- **Graphs** (Ganter and Kuznetsov, Liquière, Prediger et Wille, Kötters et al., Graph-FCA Ferré et al....)
- **Multi-relational, RCA** (Priss, Rouane-Hacène et al., ...);
RCA+Fuzzy (Boffa et al.)
- **Polyadic** (Sacarea, Tronca et al.)
- **Sequences** (Boukhetta, Demko, Bertet et al., Buzmakov et al.)
- **Temporal** data (Wolff et al., Nica, Braud, Dolques, Le Ber et al., Boukhetta, Demko, Bertet et al.)
- **Pattern Structures** (Ganter et al., Kuznetsov et al., Napoli et al., Buzmakov et al.)

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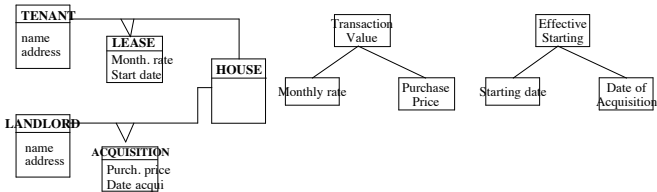
Conclusion

Roots: Class model refactorization [Godin&Mili 1993]

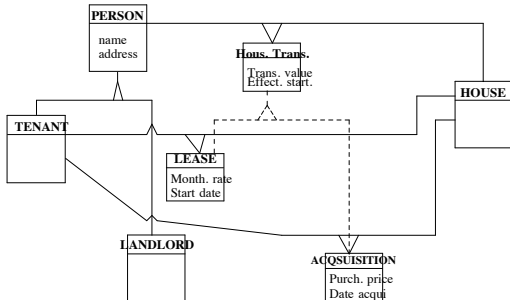
“ A formal method that organizes a set of class interfaces into a lattice structure ” - Associations in Sect. 3.2.3



From:



To:





Roots and follow up



- **Systematization of the idea** of Godin&Mili OOPSLA'93
- **Projects**
 - MACAO (LIRMM, Orange Labs) 2001-2003/2006-2009
 - PICS CNRS "CAAdOE" (LORIA, LIRMM, UQAM) 2011-2013
- **Premières thèses de doctorat**
 - Cyril Roume, Univ. Montpellier (2004)
 - Mohamed Amine Rouane-Hacène, UQAM (2007)
- **Foundational papers**
 - M. Huchard, C. Roume, P. Valtchev. When concepts point at other concepts: the case of UML diagram reconstruction. FCAKDD 2002@ECAI
 - M. Dao, M. Huchard, M. Rouane-Hacène, C. Roume, P. Valtchev. Improving generalization level in UML models iterative cross generalization in practice. In Conceptual Structures at Work. ICCS 2004.
 - M. Huchard, M. A. Rouane-Hacène, C. Roume, P. Valtchev: Relational concept discovery in structured datasets. AMAI 2007
 - M. A. Rouane-Hacene, M. Huchard, A. Napoli, P. Valtchev: Relational concept analysis: mining concept lattices from multi-relational data. AMAI 2013

Principles

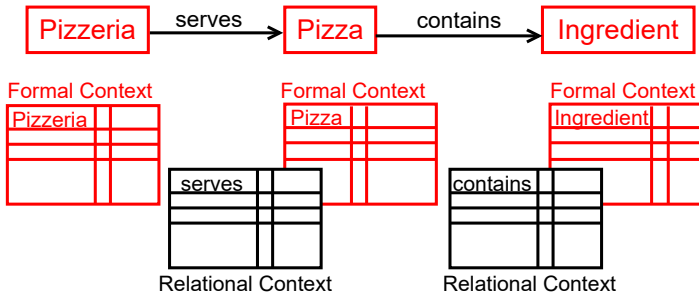
Relational Concept Analysis

- 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 (restricted to unidirectional binary relationships)
 - *relational attributes* integrate relations in formal contexts between objects
 - various operators (*quantifiers*) inspired by description logics
 - iterative and tunable process
- RCA provides a *set of interconnected lattices*
- Produced structures can be written in DLs

Principles: Input data

Relational Context Family (RCF)

- Set of Formal contexts (object-attribute)
 - Represent classes/instances
- Set of Relational contexts (object-object)
 - Represent Unidirectional binary associations/links



Relational Context Family Pizzerias

| Pizzeria | <i>IdHappizy</i> | <i>IdEataly</i> | <i>IdLafelicita</i> | <i>IdSmallitaly</i> |
|------------|------------------|-----------------|---------------------|---------------------|
| happizy | x | | | |
| eataly | | x | | |
| lafelicita | | | x | |
| smallitaly | | | x | |

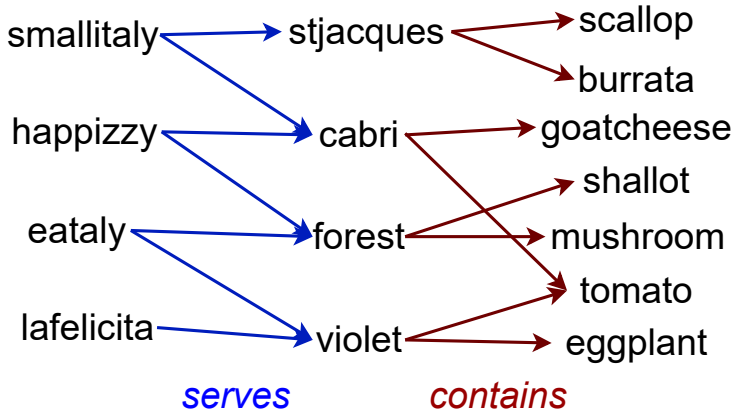
| Pizza | <i>IdCabri</i> | <i>IdForest</i> | <i>IdViolet</i> | <i>IdStjacques</i> |
|-----------|----------------|-----------------|-----------------|--------------------|
| cabri | x | | | |
| forest | | x | | |
| violet | | | x | |
| stjacques | | | x | |

| Ingredient | <i>vege</i> | <i>Vegan</i> | <i>Spring</i> | <i>Summer</i> | <i>autumn</i> |
|------------|-------------|--------------|---------------|---------------|---------------|
| goatcheese | x | | | x | |
| burrata | x | | x | | |
| scallop | | | x | | |
| tomato | x | x | | x | |
| shallot | x | x | | | x |
| mushroom | x | x | | | x |
| eggplant | x | x | | x | |

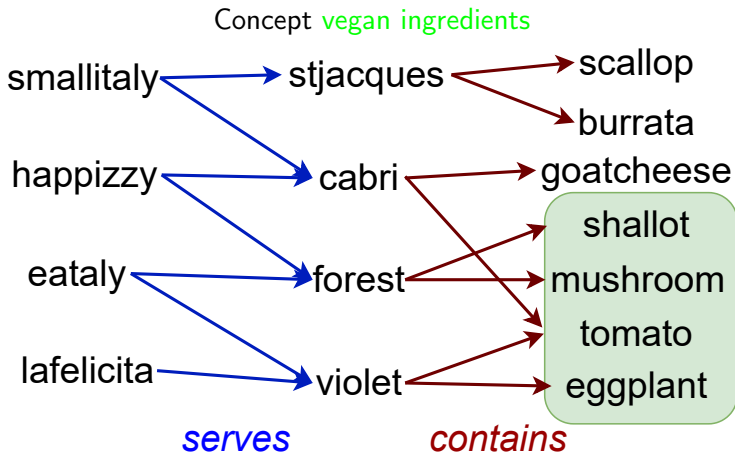
| contains | <i>goatcheese</i> | <i>burrata</i> | <i>scallop</i> | <i>tomato</i> | <i>shallot</i> | <i>mushroom</i> | <i>eggplant</i> |
|-----------|-------------------|----------------|----------------|---------------|----------------|-----------------|-----------------|
| cabri | x | | | x | | | |
| forest | | | | | x | x | |
| violet | | | | x | | | x |
| stjacques | | x | x | | | | |

| serves | <i>cabri</i> | <i>forest</i> | <i>violet</i> | <i>stjacques</i> |
|------------|--------------|---------------|---------------|------------------|
| happizy | x | x | | |
| eataly | | x | x | |
| lafelicita | | | x | |
| smallitaly | x | | | x |

Concept building



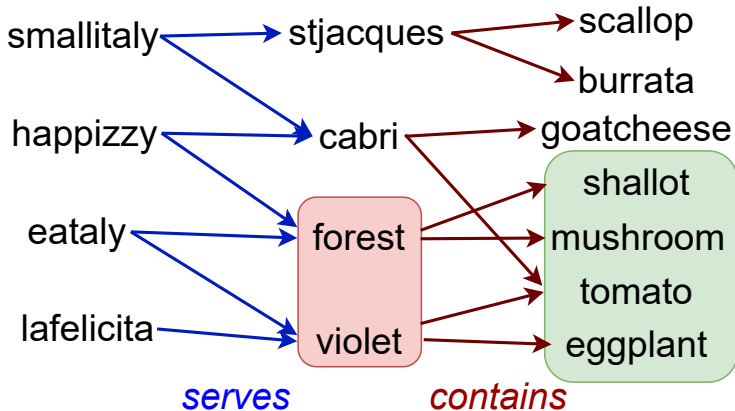
Concept building



Concept building

Concept pizzas that have all their ingredients in
concept vegan ingredients

forest and violet share: $\exists \forall$ contains (Vegan)

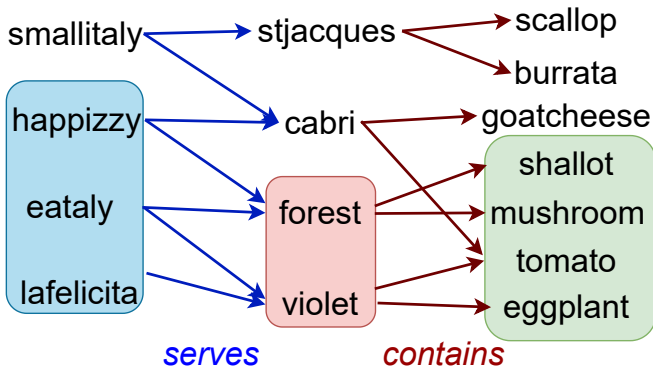


Concept building

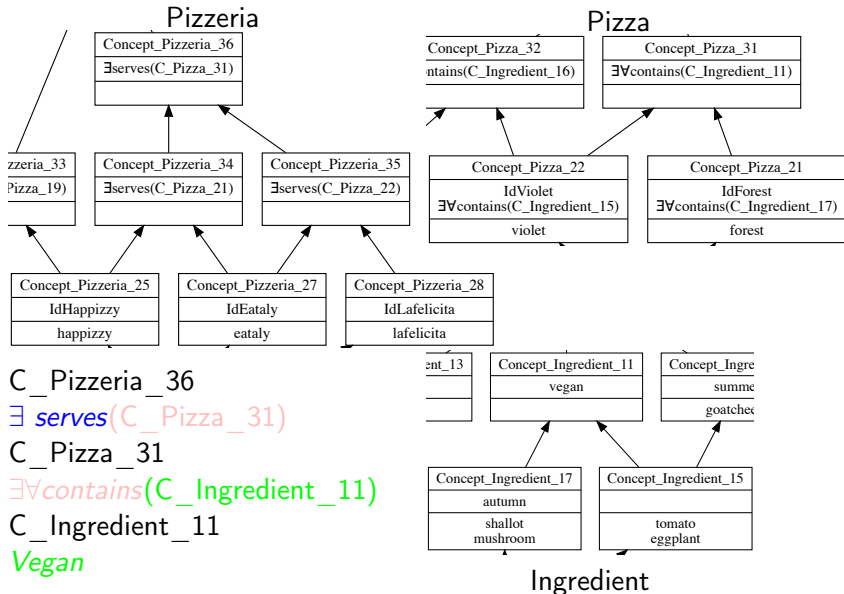
Concept **pizzerias** that have **at least one pizza** in concept **pizzas** that have all their ingredients in concept **vegan ingredients**

happizzy, eataly and lafelicitita share:

\exists *serves* ($\exists \forall$ *contains* (*Vegan*))



Interconnected concept lattices

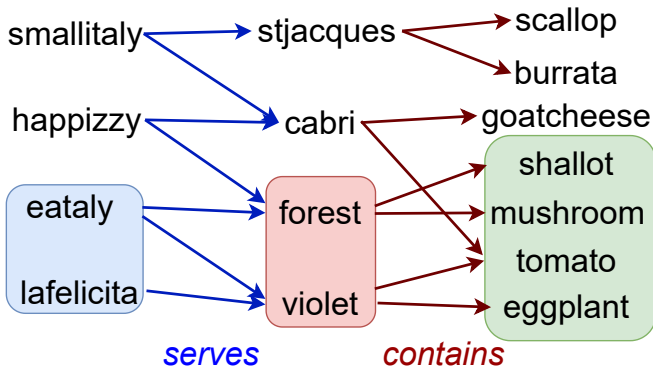


Concept building

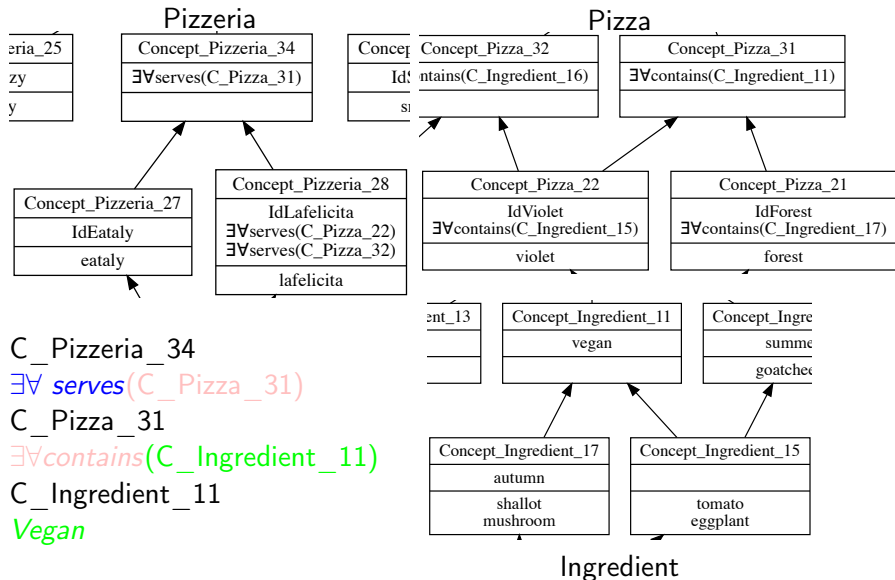
Concept **pizzerias** that have **all their pizzas in** concept **pizzas** that **have all their ingredients in** concept **vegan ingredients**

eataly and lafelicitita share:

$\exists \text{AE} \text{ serves } (\exists \text{AE} \text{ contains } (\text{Vegan}))$

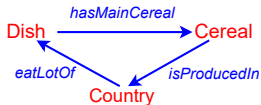


Interconnected concept lattices



Aspects of RCA

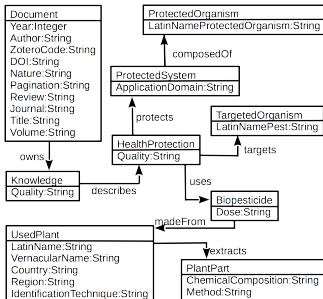
Cyclic-models



A variety of quantifiers

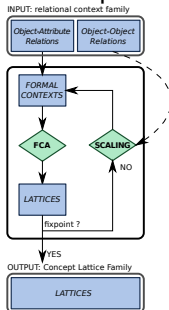
| Operator | Attribute form | Condition |
|---------------------------|--------------------------------|---|
| Universal (narrow) | $\forall r.c$ | $r(o) \subseteq Ext(c)$ |
| Universal strict | $\forall \exists r.c$ | $r(o) \subseteq Ext(c)$ and $r(o) \neq \emptyset$ |
| Universal-percent | $\forall \exists \geq n\% r.c$ | $ r(o) \cap Ext(c) \geq n(r(o) /100)$ |
| Covers | $\geq r.c$ | $r(o) \supseteq Ext(c)$ |
| Covers-percent | $\geq \geq n\% r.c$ | $ r(o) \cap Ext(c) \geq n Ext(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 | $\geq n r.T.c$ | $ r(o) \geq n$ |

Complex-models



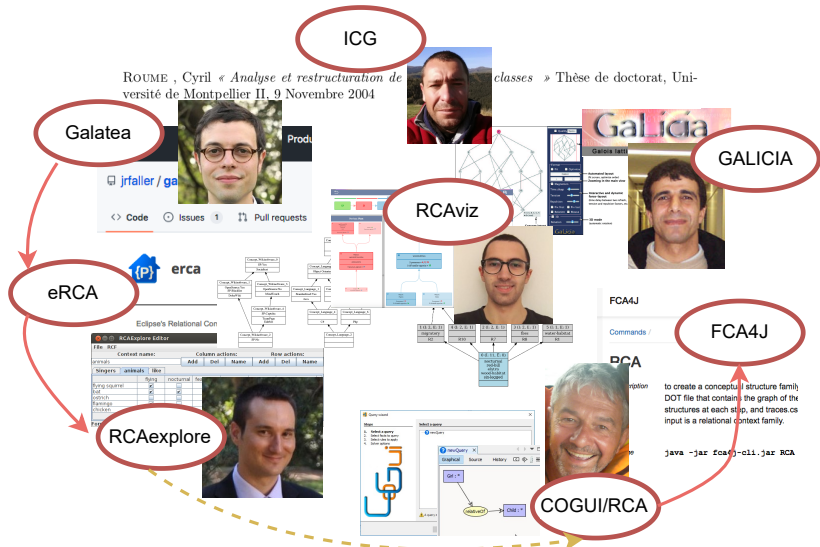
Credits P. Martin

Iterative-process



Credits X. Dolgues

RCA tools



Application domains

- **Environment** (Le Ber+, Martin+, Miralles+)
- **Health** (Wajnberg+)
- **Ontologies** (Rouane-Hacène+), **Link key extraction** (Atencia+)
- **Software engineering**
 - UML class model, use case model normalization (Huchard+, Dolques+)
 - Design defects refactoring (Moha+)
 - Model transformation pattern extraction (Dolques+)
 - Web service, component classification (Azmech+, Urtado/Vauttier+)
 - Multiple variability modelling (Galasso+, Waffo Kouhoué+), Feature mining or location (Al-Msie'deen, Eyal-Salman, Seriai+, Hlad+),
- **Industry** (Wajnberg+)
- **Legal documents** (Mimouni+)

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Modeling for RCA

- Naive view: A model is provided with data which can be used
 - Practice is more complex, e.g.
 - Associations: bidirectional or N-ary
 - Particular relations: E.g. *is-a*, *instance-of*, *contains*
 - The analyst may want to focus on specific parts of the data
 - Data may be provided without a model (e.g. textual data)
- ⇒ The RCF has to be built by considering a transformation of the initial model, or even created from scratch

The spirit is similar to *scaling* of FCA that transforms non-Boolean attributes into Boolean ones.

Here the needed modeling addresses **models**, **instances (objects)** and **values**.

Rationalizing RCF design

- Recurring situations
- Capitalizing them would accelerate future applications
- Design Pattern approach (C. Alexander, GOF: E. Gamma, J. Vlissides, R. Johnson, R. Helm)
 - Problem
 - Recurring solution
 - Typical example
 - Variants and discussion

Design Pattern Separate/Gather Viewpoints

Problem

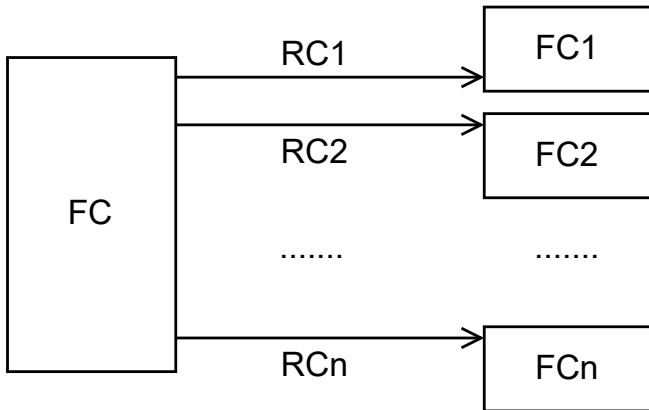
- Objects are described by Boolean attributes that can be put into different categories; or initial multi-valued attributes have been transformed into Boolean attributes
- Each attribute category is a view or a concern
- It is relevant to analyze objects through the perspective of:
 - a single view
 - several views (including all)

Focus on Separate/Gather Viewpoints

Solution

- Formal contexts (FC)
 - One FC for the initial objects
 - FC objects are the initial objects, FC attributes are initial object identifiers, or other description, or none
 - One FC_i for each view $i, 1 \leq i \leq n$, one per attribute category
 - FC_i objects are views on the initial objects, FC_i attributes are initial Boolean attributes of one view
- Relational contexts (RC)
 - For each $i, 1 \leq i \leq n$, one RC_i connecting an object of FC to its corresponding view object in an FC_i

RCF multi-views model



Focus on Separate Viewpoints: an application

Assist Feature location in Software Products Lines
(Hlad, Lemoine, Huchard, Seriai, GPCE 2021)

- Migrate a similar software family into a software product line
- Feature location: find the software artefacts (E.g. code) corresponding to a feature
- Principle: if a group of artefacts and a group of features are shared by products, this suggests that these features may be coded through these artefacts
- Challenges:
 1. have a sufficient product number to discriminate and associate a single feature to a group of artefacts
 2. some pieces of code do not correspond to a feature but suggest an interaction between features, or missing features in the product description

Focus on Separate Viewpoints: Vehicles

Input

Features and code
of similar products

```
[MOVE, SECU,PROGCONT,WATER]
public class Vehicle{
  public void move_(){..}
  public void passControl_(){..}
  public void float_(){..}
} //Oceanis30
```

```
[MOVE, SECU,PROGCONT,AIR]
public class Vehicle{
  public void move_(){..}
  public void passControl_(){..}
  public void fly_(){..}
} //A380
```

Output

Annotated SPL code

```
public class Vehicle{
  // #if MOVE & SECU & PROGCONT
  public void move_(){...}
  public void passControl_(){...}
  // #endif
  // #if WATER
  public void float_(){...}
  // #endif
  // #if AIR
  public void fly_(){...}
  // #endif
}
```

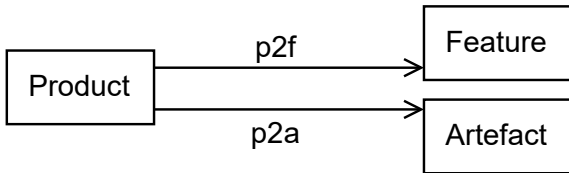
Products derived according
selected features

Focus on Separate Viewpoints: an application

Assist Feature location in Software Products Lines
(Hlad, Lemoine, Huchard, Seriai, GPCE 2021)

- Separately group features and artefacts to extract:
 - **Feature variability** (variability model)
 - **Artefact variability** (potentially reusable code pieces)
 - **Traceability** between propositional logic formula on features vs. code artefacts
 - Identification of apparition context of artefacts in terms of positive vs. negative features followed by formula reduction
 - Generation of code annotations `#if FORMULA-ON-FEATURES`
- RCF
 - Objects: similar products
 - **View 1**: products described by features
 - **View 2**: products described by software artefacts

RCF product model



Focus on Separate Viewpoints: Vehicles

The two views: by **feature** and by **artefacts**

| Feature | MOVE | AIR | WATER | GROUND | SECU_ | PROG_CONT_ | UNAN_INSP_ |
|----------------|------|-----|-------|--------|-------|------------|------------|
| A380Feat | x | x | | | x | x | x |
| Oceanis30Feat | x | | x | | x | x | |
| AkoyaFeat | x | x | x | | x | x | |
| SqubaFeat | x | | x | x | x | x | |
| TringaT650Feat | x | | x | x | x | x | |
| TwingoFeat | x | | | x | x | x | |

| Artefact | move | ride | honk | float | fly | takeoff | land | ditch | dive | raisewheel ⁻ | reportinsp ⁻ | passcontrol |
|---------------|------|------|------|-------|-----|---------|------|-------|------|-------------------------|-------------------------|-------------|
| A380Art | x | x | | | x | x | x | | | | x | x |
| Oceanis30Art | x | | | x | | | | | | | | x |
| AkoyaArt | x | | | x | x | x | x | x | | | | x |
| SqubaArt | x | x | x | x | | | | | x | | | x |
| TringaT650Art | x | x | x | x | | | | | | x | | x |
| TwingoArt | x | x | x | | | | | | | | | x |

Focus on Separate Viewpoints: Vehicles

Formal Context **Product** →

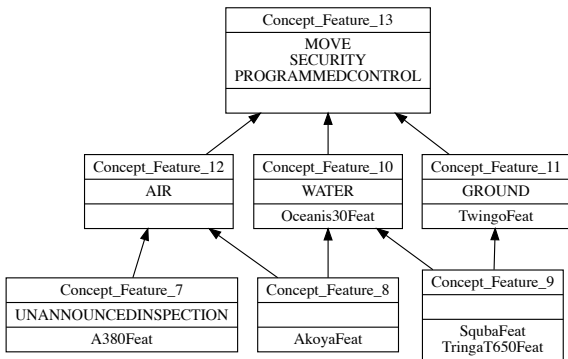
Relational contexts connecting products
to the **feature view** or to the **artefact view** ↓

| Product |
|------------|
| A380 |
| Oceanis30 |
| Akoya |
| Squba |
| TringaT650 |
| Twingo |

| p2f | A380Feat | Oceanis30Feat | AkoyaFeat | SqubaFeat | TringaT650Feat | TwingoFeat |
|------------|----------|---------------|-----------|-----------|----------------|------------|
| A380 | x | | | | | |
| Oceanis30 | | x | | | | |
| Akoya | | | x | | | |
| Squba | | | | x | | |
| TringaT650 | | | | | x | |
| Twingo | | | | | | x |

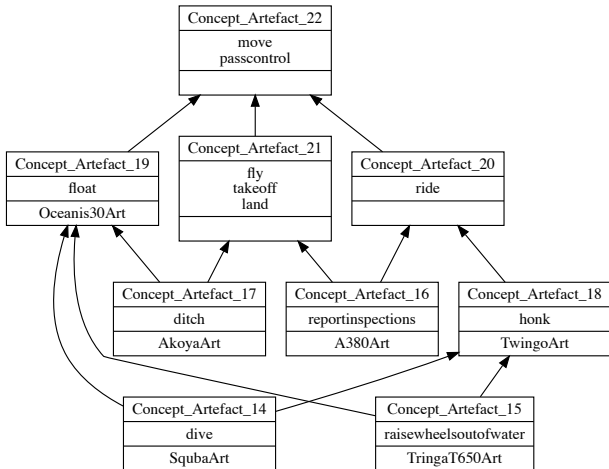
| p2a | A380Art | Oceanis30Art | AkoyaArt | SqubaArt | TringaT650Art | TwingoArt |
|------------|---------|--------------|----------|----------|---------------|-----------|
| A380 | x | | | | | |
| Oceanis30 | | x | | | | |
| Akoya | | | x | | | |
| Squba | | | | x | | |
| TringaT650 | | | | | x | |
| Twingo | | | | | | x |

Feature view



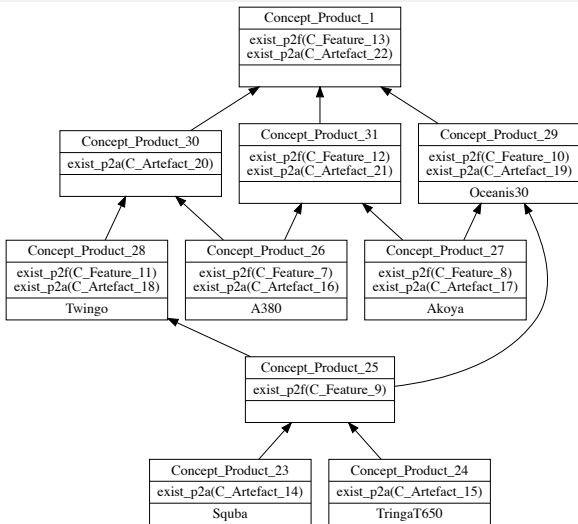
May be used to derive a feature model: *J. Galasso-Carbonnel et al. Modelling equivalence classes of feature models with concept lattices to assist their extraction from product descriptions. J. Syst. Softw. 152: 1-23 (2019)*

Artefact view



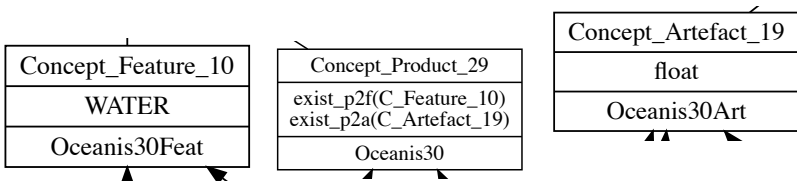
May be used to suggest reusable code pieces: E.g. methods fly, takeoff, land can be grouped in a component AirVehicle

Gathered product views



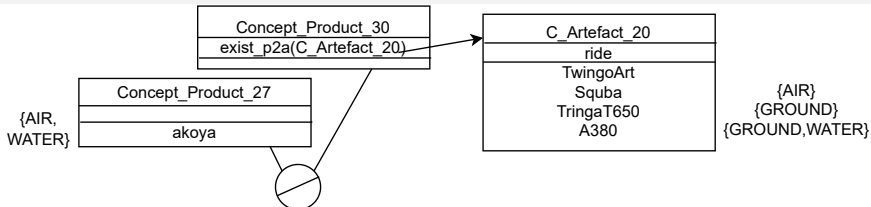
Used to find annotations and create the annotated code of the SPL

Gathered product views: annotation extraction



```
public class Vehicle{  
    ...  
    // #if WATER  
    public void float_(){...}  
    // #endif  
    ...  
}
```

Gathered product views: annotation extraction



```
public class Vehicle{
  // #if (AIR || GROUND) && ! ( AIR && WATER )
  public void ride_(){...}
  // #endif
  ...
}
```

Extent(C_Prod._30) = {Twingo, Squba, TringaT650, A380}

Positive part from C_Art._20: (AIR || GROUND)

Extent(C_Prod._30) \cap Extent(C_Prod._27) = \emptyset

Extent(C_Prod._27) = {Akoya}

Negative part from C_Prod._27 = ! (AIR && WATER)

Focus on Separate Viewpoints: an application

For more details

- **Identification** of artefacts at the instruction-level
- **Reduction** of annotation formulas (e.g. by factorization, using implications from the AOC-poset, etc.)
- **Tools:** CLEF (J. Galasso), IsiSPL (N. Hlad, B. Lemoine)
- Experimentations
 - FakePrinterSPL, DrawSPL, ArgoUML, NotePad, GameOfLife, Elevator
 - évaluation de la régénération correcte des produits et réduction des formules en nombre ($\sim 30\%$) et taille des formules ($\sim 60\%$ de features)

Focus on Separate Viewpoints: an application

For more details

- Readings
 - N. Hlad, thèse de doctorat, *IsiSPL : un processus automatisé pour faciliter l'ingénierie des lignes de produits logiciels selon une stratégie d'adoption industrielle réactive ou extractive*, Univ. Montpellier 2022, ISIA
 - B. Lemoine, thèse de Master, *Localisation de caractéristiques dans le cadre des lignes de produits logiciels*, Univ. Montpellier 2021, prix IESF-CODIGE
 - N. Hlad et al. *Leveraging relational concept analysis for automated feature location in software product lines*. GPCE 2021: 170-183

Focus on Separate Viewpoints

Another developed application

- Analyzing Visual Accessibility Options in Operating Systems
 - Objects are operating systems (OS); Views are three visual accessibility options categories (contrast, text, zoom)
 - Allows to analyze constraints on these options e.g.: implications, mutual exclusion
 - Objectives: recommendations for a new system version (OS developer), or user assistance in changing versions
 - A. Waffo Kouhoué et al. *Exploring Variability of Visual Accessibility Options in Operating Systems*. Future Internet 13(9): 230 (2021)

Towards a catalog of DPs

Opportunities for other design patterns

- **Collapse Specialization** Godin/Mili (classes), Huchard/Miralles+ (Java interfaces, UML), Martin+ (plants)
- **N-ary relation reification /split** Martin+ (plants)
- **Separate topics** Martin+ (plants), Miralles+ (UML)
- **Instances2Model** Dolques+ (Model transformation pattern extraction), B.Seriai+ (RDF)
- **Workflow** Azmeh+ (web services workflow classification)
- **Query** Azmeh+ (web service replacement in a workflow)
- **Temporal** Le Ber+ (hydrological data)
- **Correspondence/matching** Dolques+ (Model transformation pattern extraction)

Agenda

Introduction

Formal Concept Analysis

Relational Concept Analysis

Design patterns for RCA

Conclusion

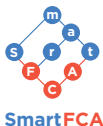
Conclusion

- FCA as a **symbolic/white-box/structured-data** KD method
- RCA, a variant for **multi-relational datasets**
- Practicing RCA demands a quite complex **data preparation**
- Recurring situations to be capitalized in **Design Patterns**

Perspectives

- Pursue the **formalization of DPs**
- Develop the corresponding **interpretation tools**
- Analyze **effects on extracted knowledge**:
 - conceptual structures
 - logical constraints: implication and association rules, mutual exclusion, OR groups, XOR groups
- Develop a **methodology** integrating DPs usage
- Build **bridges** with Graph-FCA and Polyadic Concept Analysis

Thank you!



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This reflexion could not have happened without ...

