Achievements of Relational Database Schema Design Theory Revisited

Joachim Biskup

Fachbereich Informatik,
Universität Dortmund,
D-44221 Dortmund,
Germany,
biskup@ls6.informatik.uni-dortmund.de

Abstract. Database schema design is seen as to decide on formats for time-varying instances, on rules for supporting inferences and on semantic constraints. Schema design aims at both faithful formalization of the application and optimization at design time. It is guided by four heuristics: Separation of Aspects, Separation of Specializations, Inferential Completeness and Unique Flavor. A theory of schema design is to investigate these heuristics and to provide insight into how syntactic properties of schemas are related to worthwhile semantic properties, how desirable syntactic properties can be decided or achieved algorithmically, and how the syntactic properties determine costs of storage, queries and updates. Some well-known achievements of design theory for relational databases are reviewed: normal forms, view support, deciding implications of semantic constraints, acyclicity, design algorithms removing forbidden substructures.

1 Introduction

Due to its great importance for database applications, database schema design has attracted a lot of researchers, and, accordingly, a lot of insight into good schemas has been obtained. On the one side, practical experience suggests to follow some basic design heuristics, which have been ramified into considerable detail. On the other side, theoretical investigations have accumulated many formal notions and theorems on database schema design. Unfortunately, however, theory apparently does not have much impact on practice yet.

The purpose of this paper is to improve on this mismatch of theory and practice by presenting well-known theoretical results on schema design within a fresh and unifying framework. In a companion paper [Bis95a] we also discuss the present shortcomings of database schema design theory and suggest some directions for its future elaboration. This paper does not aim at providing a complete survey on well-established and current contributions but at highlighting important examples. Accordingly, all references to the literature are to be understood just as hints for further reading.

2 Problem of Schema Design

The purpose of a database system can be roughly summarized as follows: a database system aims at persistently and dependably storing a large amount of *structured* data, shared by *many and various* users, and at *efficiently* managing this data with respect to update execution and query evaluation. The database itself, i.e. the structured data, is organized in a self-describing way: it consists of a time independent part, its *schema*, and a time-varying part, its *instance*, where the schema describes the structure and the formal semantics of the possible instances. At design time, the database administrator (representing the group of people involved), basically, has to perform two steps: first abstracting and modeling the application, then formalizing and formatting the model.

In the first step, the administrator *models* the application at hand by employing some well-disciplined linguistic framework for descriptions of reality, let's say the framework of the widely accepted entity-relationship approach [Che76]. In the second step, the administrator *formalizes* the model and declares a database schema, using a data definition language, which is an implemented fragment of a first order logic, esssentially.

This two-step procedure is based on the fundamental paradigm of the semantic triade: reality – space of concepts (ideas) and laws of logic – language. Fig.1 sketches the basic assumptions of this paradigm, which is not at all obvious or indisputable, but rather a tried attempt helpful for restricted tasks.

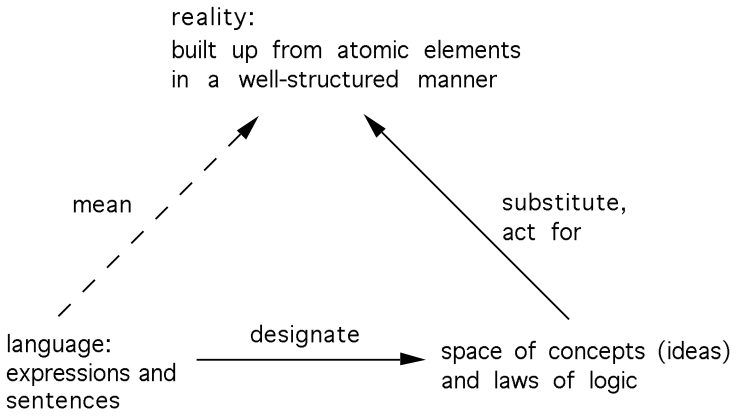


Fig.1. Fundamental paradigm of the semantic triade

Fig.2 indicates some correspondences between the framework of the entity-relationship approach, an approved heuristic tool for detecting and reconstructing the pertinent concepts, and the syntax of first order logic and its set theory based semantics, a well-studied formal language for declarative programming.

ER-approach	*logic and set theory*	
	syntax	*semantics*
entity { simple / composed	constant symbol / ground term (with function symbol)	element of a universe
relationship	ground fact	tuple of a relation
property (attribute)	{ (binary) ground fact / ground term	tuple of a (binary) relation / value of a function
role	place of a predicate symbol	component of a relation
abstraction		
universe of discourse	set of constant symbols	universe
separation/specialization	formula Φ	comprehension[1], power set
generalization	$\vee$	union
aggregation	$\wedge$, $=$	intersection, Cartesian product
constraint	(implicational) statement	model class
key constraint	with equality-conclusion	
isa constraint		
partition constraint		
many-one constraint	with equality-conclusion	
existence constraint		
referential constraint		
view rule	set of formulas	relation
action		
message	statement	
(positive) information	conjunctively added statement	reduction of model class

Fig.2. Some correspondences between the entity-relationship approach and first order logic with set theory based semantics

Both steps of the design require taking decisions. In the first step the administrator has to decide on the relevance of certain aspects of the "miniworld" under consideration. However, it is important to realize that a database system can be seen under three different though related viewpoints:

- the system constitutes a formal image of an outside miniworld;
- or it manages an autonomous formal miniworld (of documents, for example);
- or it mediates formal messages between communicating actors (one actor inserts a message, which is later on delivered to another actor as a query result, for example).

[1] If M is a structure with universe d and Φ is a formula with free occurances of the variables $x_1, \ldots, x_n$, then the *comprehension* is defined by

$d_{M,\Phi} := \{(\beta(x_1), \ldots, \beta(x_n)) \mid \beta$ is variable assignment into universe d, and Φ is true in structure M under assignment $\beta\} \subset \bigtimes_{i=1,\ldots,n} d.$

In fact, the last viewpoint appears to be most comprehensive:

- human individuals act communicatively within the (outside) miniworld (of the application),
- the basic facts and events of which are reflected by formal documents
- that in turn are mediated over time and space by the database system.

Thereby the database becomes part of the already overwhelming "formalism reality" [Bis94] surrounding its users.

Once the decisions about the relevant aspects are available from the first step of the design, in the second step the administrator has to decide on the structure of their formalization. More specifically, he has to decide on the following problems, essentially:

- Which aspects of the application should be *enumerated*, i.e. represented by a time-varying enumeration of ground facts the *formats* of which are statically declared in the schema?
- Which aspects of the application should be *inferrable*, i.e. derivable from the time-varying enumerations, possibly complemented by additional input, by *rules* which are declared in the schema?
- Which aspects should *constrain* the enumerations under updates, i.e. which format-conforming enumerations of ground facts should be considered meaningful in the sense that they satisfy *semantic constraints*, which are declared in the schema.

The decisions result in a *schema* that comprises

- the *formats* for enumerations (the time-varying extensional instances produced over the life time of the database),
- the *rules* (for intensional views supporting queries),
- and the *semantic constraints*.

Being fixed over the time, the schema statically determines the future dynamic behaviour of the database and, in particular, its usefulness for its end users. Fig.3 illustrates the design and the usage of a database, and it summarizes the terminology introduced so far.

The quality of a schema can be evaluated along two lines of reasoning:

- The schema should *formalize* the application as *faithful* as achievable.
- The schema should allow to execute queries and updates, as far as these operations can be foreseen, as efficiently as possible. From this point of view, schema design can be understood as *optimization at design time*.

Whether a *faithful formalization* has been achieved or not, cannot be evaluated solely based on formal mathematical reasoning. Rather we have to investigate whether the database will successfully provide technical support for communications among those persons that employ the database as end users. Presumably, successful support is based on a common agreement on the following questions:

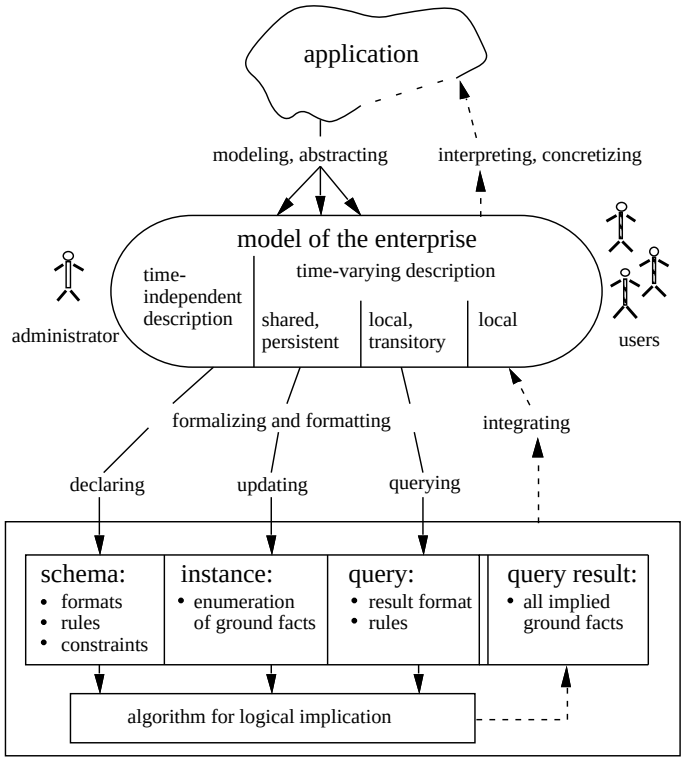


Fig.3. Design and usage of a database

- Which *entities* are to be considered basic?
- Which *relationships* are to be considered basic and
- how to select from the basic ones those for actual redundancy-free enumerations, such that all relationships can be completely inferred?
- Which actions are to be considered basic?

Optimization at design time, however, can be evaluated in formal mathematical terms by considering

- storage costs (basically determined by the size of the enumerated instances),
- query costs (basically the time complexity of anticipated queries, in particular those that are declared as rules in the schema),
- update costs (basically the time complexity of anticipated insertions and deletions, including maintenance of the semantic constraints that are declared in the schema).

3 Design Heuristics

Most guidelines for schema design can be summarized by the following four heuristics:

Separation of Aspects: A declared format should be appropriate to enumerate *exactly one aspect*.

Separation of Specializations: A declared format should be appropriate to conform to *exactly one specialization* of an aspect.

Inferential Completeness: All meaningful aspects that are not enumerated according to a declared format should be inferrable by using the query language.

Unique Flavor: Meaningful aspects should be identified and understood by expressing their basic attributes only (and omitting additional context information).

Clearly, an administrator will tentatively apply a separation heuristic by using an agreement that the entities or relationships of some class are considered basic. But afterwards he has to justify that property mathematically with respect to the formally declared schema and the inferential power of the formal query language. Similarly, an administrator will tentatively apply the Inferential Completeness heuristic by using an agreement on the selection of basic relationships for enumerations, and afterwards he has to justify the claimed completeness property mathematically with respect to the selected formalization. In the same spirit, an application of the Unique Flavor heuristic is, firstly, based on some intuitive agreements, which, afterwards, are subject to mathematical verification with respect to the selected formalization.

Having in mind the achievements of design theory presented in the rest of this paper, we will somehow artificially distinguish desirable syntactic properties of schemas from worthwhile semantic requirements: the former properties only refer to the purely syntactically given schema, whereas the latter requirements are explicitly related to the semantics of the query language. Accordingly, the separation heuristics will primarily suggest desirable syntactic properties, and the completeness and uniqueness heuristics worthwhile semantic requirements. It should be understood, however, that, on the one side, syntax and semantics are always closely related, and, on the other side, in computing we aim at eventually finding appropriate syntactic expressions for any kind of notion.

4 Tasks of Design Theory

In order to be helpful in achieving faithful formalizations and in pursuing the design heuristics, the following tasks of design *theory* are due:

- **Task 1:** Formalize the worthwhile semantic requirements and the desirable syntactic properties of schemas!

- **Task 2:** State and prove relationships between the formalized versions of worthwhile semantic requirements and desirable syntactic properties!
- **Task 3:** Find algorithms for deciding on or even achieving syntactic properties of schemas, and prove their correctness and efficiency!

In order to be helpful for optimization at design time, additionally, design *theory* should tackle a fourth task:

- **Task 4:** Prove that desirable syntactic properties actually ensure low costs!

Being supplied with appropriate solutions for these tasks, an administrator can effectively benefit from design theory. For, at design time,

- the administrator, essentially, has to deal with syntactic material only (supported by Task 3)
- which must be evaluated with respect to its semantic properties (as stated by Task 1 and Task 2) on the one side
- and the future operational cost (as stated by Task 4) on the other side.

5 Achievements for Relational Databases

5.1 Notations

For the sake of readability and conciseness we will employ (more or less) standard notations in a somehow sloppy, and sometimes also imprecise, way. In order to study carefully elaborated versions of the notations and of the results, the reader should consult the references, in particular the textbooks [Mai83, Ull88, Ull89, PDGvG89, Vos91, MR92, AD93, AHV95, Bis95b].

(R_i, X_i, SC_i)[1]	denotes a relation scheme where
R_i	is a relation symbol,
X_i	is a set of attributes (possibly with a range for its values), i.e. a format, and
SC_i	are the local semantic constraints.

A (database) schema comprises relation schemes, rules, and global semantic constraints:

$\langle(R_1, X_1, SC_1), \ldots, (R_n, X_n, SC_n)\mid$	relation schemes for extensional enumerations,
$Q_1, \ldots, Q_m \mid$	rules (queries) for intensional views,
$SC_{global}\rangle$[1]	global semantic constraints.

Semantic constraints are denoted as follows where X, Y, Y_i, Z are sets of attributes and R_i, R_j are relation symbols:

[1] Later on we will sometimes omit those components which are not relevant for the current discussion. For instance, using the notation $(\ , U, SC)$, we indicate that only the set of attributes U and the semantic constraints SC are important, but not the omitted relation symbol.

$X \rightarrow Y$	functional dependency,
$X \twoheadrightarrow Y \mid Z$ or $\bowtie [X \cup Y, X \cup Z]$	multivalued dependency,
$\bowtie [Y_1, \ldots, Y_k]$	join dependency,
$\Pi_X(R_i) \subset \Pi_Y(R_j)$	inclusion dependency,
SC^+	implicational closure of a set of semantic constraints SC.

5.2 Normal Forms: Separation of Aspects Formalized as Desirable Syntactic Property

The first design heuristic, Separation of Aspects, can be rephrased by considering formats and semantic constraints as some kind of structure and by requiring that any nontrivial substructure should correspond to, refer to or identify exactly one aspect of the application. Depending on the class of semantic constraints involved, we can define different notations of "nontrivial substructure"; but in all cases the notion of "exactly one aspect" is related to the concept of identification of unit pieces of information. In order to formalize the heuristic as desirable syntactic property, normally referred to as "normal form", see Task 1, we favor expressing the separation requirement in a negative form: the structure should *not* contain any *forbidden substructures* that might be harmful with respect to the quality measures. Then most algorithms to achieve high quality schemas can be conveniently described as iterated *schema transformations* that stepwise detect and remove forbidden substructures.

The most popular normal forms are listed in Fig.4, giving their names and forbidden substructures [Cod70, Cod72, Fag77, Del78, Zan76, BBG78, Fag81, Ken83, MR86, BDLM91, DF92]:

name	forbidden substructures
3 NF, third normal form	$Z \rightarrow A \in SC^+$, $A \notin Z$, A nonkey-attribute, (but) $Z \rightarrow X_i \notin SC^+$.
BCNF, Boyce/Codd normal form	$Z \rightarrow A \in SC^+$, $A \notin Z$, (but) $Z \rightarrow X_i \notin SC^+$.
4 NF, fourth normal form	$X \twoheadrightarrow Y \in SC^+$, $Y \not\subset X$, $X \cup Y \subsetneqq X_i$, (but) $X \rightarrow X_i \notin SC^+$.
5 NF, fifth normal form	$\bowtie [Y_1 \ldots Y_k] \in SC^+$, $\bowtie [Y_1 \ldots Y_{i-1}, Y_{i+1}, \ldots, Y_k] \notin SC^+$ for $i = 1, \ldots, k$, (but) there exists j : $Y_j \rightarrow X_i \notin SC^+$.
referential normal form	$\Pi_X(R_i) \subset \Pi_Y(R_j) \in SC^+$, $i \neq j$, (but) $Y \rightarrow X_j \notin SC^+$.
unique key normal form	$X \rightarrow X_i \in SC^+$, X minimal, $Y \rightarrow X_i \in SC^+$, Y minimal, (but) $X \neq Y$.

Fig.4. Normal forms and their forbidden substructures

5.3 View Support: Inferential Completeness Formalized as Worthwhile Semantic Requirements

The third design heuristic, Inferential Completeness, can be rephrased by considering those aspects of the application that are not explicitly represented by enumerations and by requiring that these aspects are completely supported as intensional views by appropriate rules. There are, essentially, three versions of support: *view instance support*, *view query support*, *view update support*.

Restricting our discussion to one-relation views or even so-called universal relation views, we suppose that a database schema of the form
$DS = \langle$schemes for extensional enumerations$|$ $|$global semantic constraints$\rangle$
is given, and that some candidate view (or external schema)
$ES = (\ , U, SC)$
with set of attributes U and semantic constraints SC should be supported.
Then we state the following formal versions of the heuristic as worthwhile semantic property, see Task 1.

- Schema DS provides *view instance support* for ES
  :iff there exists a query Q on DS such that
  $\{instances\ of\ ES\} \subset Q[\{instances\ of\ DS\}]$.

If we have even equality, the view instance support is called *faithful*. In that case, if, additionally, the supporting query Q is injective on $\{instances\ of\ DS\}$, the view instance support is called *unique*.

- Schema DS provides *view query support* for ES
  :iff for each query P on ES there exists a query P' on DS such that:
  for all instances u of ES there exists an instance $(r_i)_{i=1,\ldots,n}$ of DS such that
  $P(u) = P'((r_i)_{i=1,\ldots,n})$.

Under some rather weak assumptions on the query language we have a fundamental equivalence [AABM82, Hul86, BR88]:

Theorem 1. *DS provides view instance support for ES*
iff DS provides view query support for ES.

If DS provides view query support for ES, then the query P' corresponding to the identity query on ES supports the instances of ES. On the other hand, if DS provides view instance support for ES by some query Q, then Q can be composed with queries on ES. Such compositions yield a query translation from queries on the view to queries on the full schema.

For the support of *updates* on views, however, we essentially need that the view instance support is *unique*. For otherwise, well-known as the *view update problem* [BS81, DB82, FC85, Kel86, GHLM93], there is no information available to resolve the ambiguity caused by non-injectivity.

5.4 Syntactic Characterization of View Support

According to Task 2, the worthwhile semantic requirements of view support should be related to desirable syntactic properties of a schema. The main results available concern universal relation views, the supporting query of which is the natural join. For instance we have the following theorems [Ris77, Ris82, BBG78].

Theorem 2. *A schema DS with formats $X_1, \ldots, X_n$ for the extensional enumerations (ignoring local and global semantic constaints of DS)* supports *a universal relation view $(\ , U, SC)$ by* the natural join
iff $\bowtie [X_1, \ldots X_n] \in SC^+$.

Theorem 3. *A schema DS with formats $X_1, \ldots, X_n$ for the extensional enumerations and functional dependencies $F_1, \ldots, F_n$ as local semantic constraints* faithfully supports *a universal relation view $(\ , U, F)$, where F is a set of functional dependencies,* by the natural join
if $\bowtie [X_1, \ldots X_n] \in F^+$ *and* $(\bigcup_{i=1,\ldots,n} F_i)^+ \supset F$.

The proof of Theorem 2 is straightforward just by confirming that the formal semantics of join dependencies is appropriately defined. The faithfulness of the natural join results from the inclusion $r_j \supset \pi_{X_j}(\bowtie_{i=1,\ldots,n} r_i)$, showing that functional dependencies that are valid in some component r_j are also valid in the join $\bowtie_{i=1,\ldots,n} r_i$. More refined results appear for example in [Var82, CM87].

In [Heg94] a rather general theory of schema decomposition is presented. This theory explores an algebraic framework, in which the class of instances of a database schema is partially ordered and possesses a least element and the inverses of supporting queries (which are the projections in case of a natural join) are isotonic and preserve least elements. It turns out that, within this framework, the components of a schema DS faithfully supporting a universal relation view uniquely "complement" each other. Besides treating many further topics, the theory also deals with the union as supporting query (with the selection as inverse) and thus with the so-called horizontal decomposition [DP84, PDGvG89], and it clarifies the role of null values in schema decomposition.

5.5 Deciding Desirable Syntactic Properties for Normal Forms and View Support

Both heuristics treated so far finally lead to syntactic properties that are basically expressed in terms of implications of semantic constraints. In Section 5.2 normal forms, formalizing the Separation of Aspects heuristic, are just defined in these terms, and in Section 5.4 view support, formalizing the Inferential Completeness heuristic, has been reduced to these terms. According to Task 3, then, we have to design algorithms to decide implications among semantic constraints and, additionally, to explore all relevant implications systematically .

Here are some prominent examples for results [Arm74, Men79, Bis80, BV84a,

BV84b, Var84, Mit83, KCV83, CFP84, CV85, FV84, Var88a, Tha91, BC91, Her95]:

Theorem 4. *The implication problem of "$\Phi \in SC^+$" is decidable for "many important classes" of semantic constraints.*

Theorem 5. *The implication problem "$\Phi \in SC^+$" is undecidable for the class of "functional and inclusion dependencies".*

The important semantic constraints can be expressed as implicational first order logic formulae. Then the various proof procedures, called chase procedures, are based on specialized versions of the more general proof techniques of (hyper-) resolution and paramodulation. Roughly described, hyperresolution, applied to an implicational formula with a nonequality-conclusion and its previously generated premises, yields the conclusion as additional statement, and paramodulation, applied to an implicational formula with an equality-conclusion and its previously generated premises, equates the terms in the equality-conclusion, i.e. one side is substituted by the other side. Chase procedures are designed to apply such rules, starting with the premises of the constraint to be decided, until no further change can be produced. If the procedure terminates, the constraint is implied iff its conclusion is among the finally produced statements.

In general, the implication problem for semantic constraints is fairly well understood in the relational case:

- As long as the constraints are "full", i.e., basically, in their implicational formulae no existentially quantified variable occurs positively, we have decidability.
- Otherwise, for "embedded" constraints, we have undecidability due to positively occuring existentially quantified variables. Such variables can cause the generation of an unlimited number of terms in executing proof procedures that do not terminate in this case.

Actually, even for the restricted case of embedded multivalued dependencies the implication problem has been proved to be undecidable [Her95]. The sophisticated proof employs a reduction of the word problem for finite semigroups, known to be undecidable, to the implication problem for embedded multivalued dependencies.

As already mentioned above, null values are important for the theory of schema decompositions [CM87, Heg94] and also for so-called "representative instances" of fragmented database schemas [Hon82, Sag83, GMV86]. Accordingly, the meaning of semantic constraints in the presence of relations with null values and the corresponding variant of the implication problem have been studied [Lie79, Vos79, Gra84, AM86, Tha91, LL94].

Theorem 6. *For the class of relation schemes $(\ , U, F)$, where F is a set of functional dependencies, the problem "$(\ , U, F)$ is in third normal form" is NP-complete.*

The deep reason for the negative result is that, in this situation, the problem "attribute A appears in a key of relation scheme $(\ , U, F)$" is already NP-complete; this result in turn is related to the fact that a relation scheme $(\ , U, F)$ can possibly have exponentially many keys [LO78, JF82, MR83, Kat92, VS93a, DKMST95].

Theorem 7. *For the class of relation schemes $(\ , U, F)$, where F is a set of functional dependencies, the problem "$(\ , U, F)$ is in Boyce/Codd normal form" is decidable in polynomial time.*

Indeed, a decision procedure can be based on the following equivalence [Osb78]: Boyce/Codd normal form iff for all $X \to Y \in F$ with $Y \not\subseteq X$: $X \to U \in F^+$. It should be noted, however, that also for Boyce/Codd normal form some important decision problems are of high computational complexity. In particular, deciding Boyce/Codd normal form for a *projection* of a scheme is coNP–complete [BB79]. This result on intractability as well as Theorem 6 contrast to the fact that the corresponding decision problems for relations, rather than schemes, are decidable in polynomial time (in the number of attributes and tuples of the relation under consideration) [DLM92].

Theorem 8. *For the class of relation schemes $(\ , U, F)$, where F is a set of functional dependencies, the problem "$(\ , U, F)$ is in unique key normal form" is decidable in polynomial time.*

Again, a decision procedure can be based on an equivalence statement [BDLM91]: unique key normal form iff $\{A \mid A \in U \text{ and } U \backslash A \to A \notin F^+ \} \to U \in F^+$.

5.6 Achieving Normal Forms and View Support Simultaneously

So far, the Separation of Aspects and the Inferential Completeness heuristics have been treated separately, although, as we have seen in Section 5.5, both heuristics lead to related implication problems. According to Task 2, we have to explore the relationship between their formalizations in more detail, in particular, whether their formal versions are compatible. As far as we can actually achieve the desirable syntactic properties simultaneously, according to Task 3, we have to design algorithms to obtain them.

The following two theorems are the most well-known examples of results on compatibility.

Theorem 9. *For every (universal relation) scheme $ES = (\ , U, F)$, where F is a set of functional dependencies, there exists a database schema DS with relation schemes $(\ , X_1, F_1), \ldots, (\ , X_n, F_n)$ for extensional enumerations such that:*
i) Schema DS supports *ES* by the natural join.
ii) Each scheme $(\ , X_i, F_i)$ of DS is in Boyce/Codd normal form.

Theorem 10. *For every (universal relation) scheme $ES = (\ , U, F)$, where F is a set of functional dependencies, there exists a database schema DS with relation schemes $(\ , X_1, F_1), \ldots, (\ , X_n, F_n)$ for extensional enumerations such that:*

i) Schema DS faithfully supports ES by the natural join.
ii) Each scheme $(, X_i, F_i)$ *of* DS *is in third normal form.*

The proofs of these and related theorems are constructive, yielding outlines of design methods of decomposition and synthesis, respectively [Cod72, Fag77, Fag81, Ber76, BB79, BDB79, KM80, LTK81, BK86, SR88, BM87, TLJ90, YÖ92a, YÖ92b]. Such methods will be discussed in a more general framework in Section 5.11.

5.7 Normal Forms Ensure Low Storage and Update Costs

We have introduced normal forms as desirable syntactic properties, formalizing the Separation of Aspects heuristics. According to Task 4, we now justify these normal forms in terms of cost, thus providing formal counterparts to informal motivations of the Separation of Aspects heuristic to avoid so-called "update anomalies".

The benefits of all purely decompositional normal forms in terms of *storage costs* are summarized as follows:

Theorem 11. *A relation scheme* $(, U, SC)$ *is in decompositional normal form (i.e. BCNF, 4 NF, 5 NF), relative to the class of semantic constraints considered in SC (i.e. functional dependencies, multivalued dependencies, join dependencies)*
iff for each decomposed database schema DS that supports $(, U, SC)$ *by the natural join, for each instance of* $(, U, SC)$*:*
size (instance of $(, U, SC)$*)* $\leq$ *size (decomposed instance).*

Here size means the number of occurences of constant symbols in the instances. This "folklore theorem" is closely related to a theorem of [VS93b] that characterizes normal forms in terms of data redundancy. The intuitive reasoning of the proof is the following. Assume that $(, U, SC)$ is already in decompositional normal form. Then any further decomposition would result in duplicating the key components of tuples (and thus would increase the size) without getting any compensating size benefit. If on the other hand $(, U, SC)$ is not in decompositional normal form, then the forbidden substructure can cause a redundant representation of facts, and the size benefit of removing this redundancy by decomposition can exceed the disadvantage of duplicating tuple components, necessary for support by the natural join.

Decompositional normal forms are also helpful to ensure low *update costs* [BG80, Vos88, Bis89, Cha89, HC91, BD93]. As an example, we present a theorem that takes care of functional and inclusion dependencies [BD93]. The theorem characterizes those database schemas that allow maintenance of all semantic constraints by simply checking whether a newly inserted tuple does not violate a key condition.

Theorem 12. *A database scheme DS with relation schemes $(R_1, X_1, F_1), \ldots, (R_n, X_n, F_n)$ with functional dependencies as local semantic constraints and inclusion dependencies I as global semantic constraints allows $X \subset X_i$, for some i, as* update object*, i.e.*

i) $X \to X_i \in (I \cup \bigcup_{i=1,\ldots,n} F_i)^+$ *and*

ii) *for each instance $(r_1, \ldots, r_i \ldots, r_n)$ of DS, for each tuple μ with $\mu\lceil X \notin \pi_X(r_i)$:*
$(r_1, \ldots, r_i \cup \{\mu\}, \ldots, r_n)$ *is instance of DS*

iff the following properties hold:

iii) R_i *is "not referencing" by inclusion dependencies of I.*

iv) R_i *is in unique key normal form.*

v) R_i *is in Boyce/Codd normal form.*

The proof is based on a careful analysis and equivalent reformulations of the fundamental notions, as well as, on separation conditions that restrict the interaction of functional dependencies and inclusion dependencies (which may be very complex in general, according to Theorem 5).

5.8 Unique Essences: Unique Flavor Formalized as Worthwhile "Semantic" Requirement

The fourth design heuristic, Unique Flavor, can be formalized in the framework of designing a so-called universal relation interface for a database schema [MUV84, KKFVU84, Var88b, BB83, BBSK86, BV88, Lev92]. Such an interface should translate queries, which are expressed in terms of attributes only (omitting the information about relation schemes), into join paths within the hypergraph structure of the schema. If there are several candidate join paths, then, according to the Unique Flavor heuristic, all these candidates should provide essentially the same query answer [BBSK86].

Given a database schema DS, a formalized version of this requirement is defined as follows:
$U := \bigcup_{i=1,\ldots,n} X_i$ and $H := \{X_1, \ldots, X_n\}$ describes the *hypergraph* of DS.
$jp : \wp U \to \wp\wp H$, $jp(Y) := \{E \mid E \subset H,\ E$ *connected*, $Y \subset \bigcup E,\ E$ *minimal*$\}$ defines the translation from a set of attributes into *join paths*.
$essence(E, Y) := \{X_i \cap (Y \cup \bigcup_{X_j \in E, X_j \neq X_i} X_j) \mid X_i \in E\}$ is the *essence* of a join path E over a set of attributes Y.

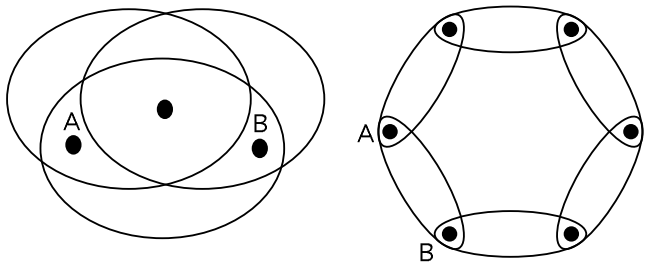
- Finally, Unique Flavor motivates that essences should be unique:
  For all $Y \subset U$, for all $E, F \in jp(Y) : essence(E, Y) = essence(F, Y)$.

Of course, here the property of unique essences is already defined in purely syntactic terms although it is "semantically" motivated.

5.9 Acyclicity: Unique Flavor Formalized as Desirable Syntactic Property

The fourth design heuristic, Unique Flavor, can also be rephrased by considering the hypergraph *structure* of a database schema, as defined by the formats, and by requiring that the hypergraph is to some degree acyclic [Fag83, BFMY83, BBSK86]. The two most important degrees are listed below by their names and their *forbidden substructures*:

– γ-*acyclic*:



– α-*acyclic*: a nontrivial hypergraph as produced by the GYO-reduction applied to the schema [Gra79, YÖ79].

As a contribution to Task 2, it turns out that γ-acyclicity syntactically characterizes the "semantic" property of Section 5.8 [BBSK86]:

Theorem 13. *DS is γ-acyclic iff DS has unique essences.*

We can easily construct join paths over some set of attributes Y with different essences from the cyclic substructures forbidden for γ-acyclic database schemas: in each case, $Y := \{A, B\}$ is contained in a single relation scheme, which constitutes a trivial covering join path, and Y is covered by an essentially different join path containing two or more relation schemes (namely those connecting A with B running the "long way"). The converse claim of the theorem is proved by a tedious and subtle examination of the so-called *intersection hypergraph* of DS, which is generated from the hypergraph by adding all nonempty intersections of its hyperedges.

As a contribution to Task 3, the desirable syntactic property of acyclicity can be efficiently decided [YÖ79, Gra79, Fag83, TY84, DM86]:

Theorem 14. *The problems "DS is γ-acyclic" and "DS is α-acyclic" are decidable in polynomial time.*

For each degree of acyclicity a recursive decision procedure can be based on a "pruning" predicate on hyperedges. At each stage the procedure can delete a hyperedge that satisfies the predicate. The initial schema is acyclic iff the procedure succeeds in reducing the schema to nothing. The pruning predicate for

γ-acyclicity can be paraphrased by "either there exists another hyperedge that has the same set of intersections with the remaining hyperedges or all nonempty intersections with the remaining hyperedges are identical". The pruning predicate for α-acyclicity can be paraphrased as "there exists a remaining hyperedge that contains all the intersections with the remaining hyperedges". These decision procedures are elaborated variants of the well-known acyclicity test for ordinary graphs: the test recursively deletes a leaf and its corresponding edge and recognizes acyclic graphs, i.e. trees, as those graphs that can be reduced to nothing.

5.10 Acyclicity Ensures Low Query Costs

According to Task 4, the impact of acyclicity as desirable syntactic property on costs should be examined. As suggested by the corresponding worthwhile semantic requirement, the evaluation of view queries that are join paths should be efficient. Indeed, we have the following assertions which have subtle and tedious proofs [Fag83, BFMY83]:

Theorem 15. *DS is γ-acyclic*
iff all *noncartesian join trees are* monotone
(i.e. for pairwise consistent relations $r_1, \ldots r_n$ all partial results are consistent)
iff projections $\pi_Y(u)$ with $u := \bowtie_{i=1,\ldots,n} r_i,\ r_i := \pi_{X_i}(u)$,
can be computed by determining a covering join path and evaluating it (i.e. $\pi_Y(u) = \pi_Y(\bowtie_{X_i \in E} r_i)$ for some $E \in jp(Y)$).

Theorem 16. *DS is α-acyclic*
iff there exists a monotone join tree
(which, essentially, is determined by the GYO-reduction).

5.11 Design Algorithms Remove Forbidden Substructures

Fig.5 summarizes the presented achievements with respect to Tasks 1, 2 and 4. Finally, according to Task 3, a lot of design methods for *achieving* desirable syntactic properties have been proposed. Apparently, any concrete refinement of such a method will, necessarily, result into a highly interactive design procedure. The general skeleton of such procedures and the division of labour between the insightful administrator and the automatic algorithm [Bis95, BC86, BC89, Bis95b] can be outlined as shown in Fig.6.

formalize heuristics

separation

Task 1. syntactic properties
no forbidden substructure:

- 3 NF
- BCNF
- 4 NF
- 5 NF
- referential NF
- unique key NF

unique flavour

Task 1. "semantic" requirements

- join paths are essentially unique

Task 1. syntactic properties
no forbidden substructure:

- γ-acyclic
- α-acyclic

inference

Task 1. semantic requirements

- (faithful) view instance support
- view query support

Task 2. syntactic characterization
for FDs, join support:

- $\bowtie [X_1, \ldots, X_n] \in SC^+$
- $(\bigcup_i F_i)^+ \supset F$

Task 2. relationships between syntactic properties and semantic requirements

- BCNF and join support are compatible (decomposition)
- 3 NF and faithful join support are compatible (synthesis)
- γ-acyclic iff join paths are essentially unique

optimize at design time

Task 4. syntactic properties ensure low costs

storage

- normal forms

query

- γ-acyclic:
  - join trees are monotone
  - projection by covering joins
- α-acyclic: existence of monotone join trees

update

- $\begin{cases} \text{not referencing} \\ \text{one key} \\ \text{BCNF} \end{cases}$

Fig.5. A short summary of presented achievements with respect to Tasks 1, 2 and 4.

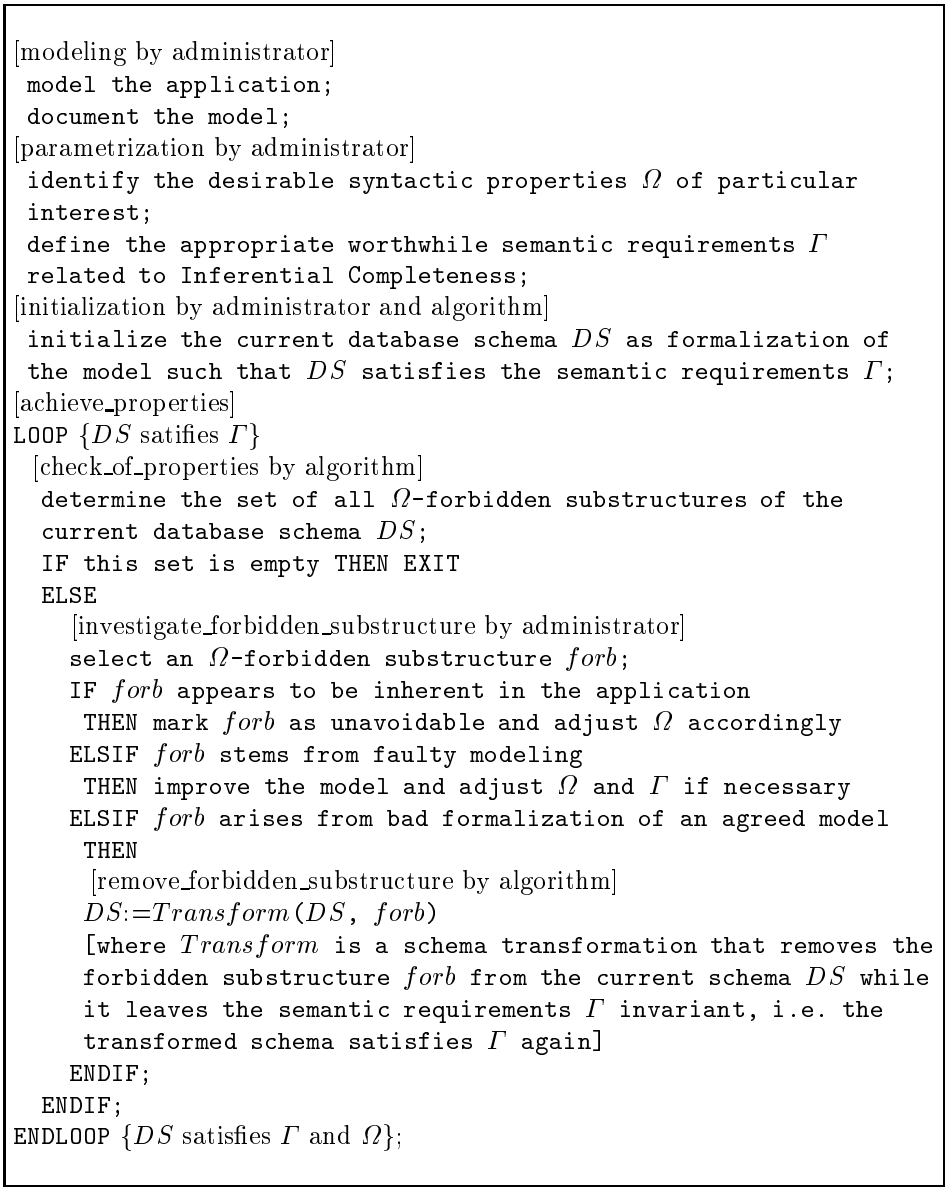


Fig.6. Outline of interactive design procedures.
[ ] embraces comments indicating a module together with its active entity or semantics, respectively;
{ } embraces state conditions, i.e. the invariant and the post condition of the main loop.

We shortly discuss some examples that fit the skeleton of Fig.6 by indicating Ω, Γ and $Transform$:

- Classical *decomposition*, based on Theorem 9 and related statements, identifies Ω as Boyce/Codd or higher normal form and selects Γ as view support of an initial universal relation scheme by the natural join. $Transform$ splits a current relation scheme with attribute set X_i into fragments that are determined by the components of the forbidden join dependency; $Transform$ is Γ-invariant by the semantics of join dependencies (and because any functional dependency implies a corresponding multivalued dependency).
- Classical *synthesis*, based on Theorem 10 and related statements, has two phases. The first phase achieves faithfulness, and the second phase adds view support of an initial universal relation scheme by the natural join. In the first phase Ω is identified as third normal form, and Γ is selected as faithfulness (syntactically characterized as the preservation of the given set of functional dependencies). $Transform$ removes all kinds of redundancy (which can lead to Ω-forbidden substructures) from the functional dependencies. An early version of synthesis [Ber76] achieves this goal by computing a minimal cover of the functional dependencies, leaving Γ invariant. A later version [BM87] achieves this goal by removing so-called "abnormal nonprime" attributes from relation schemes following some sophisticated strategy, whereby a somewhat stronger invariant Γ (namely faithfulness and "object-faithfulness" and "strong normativity") is preserved. In the second phase view support of an initial universal relation scheme by the natural join is guaranteed by ensuring the existence of a relation scheme that contains a global key [BDB79]. If necessary, such a key component is added (in this case as a previously "missing substructure").
- In *view integration*, as formalized in [BC86], Ω is identified as absence of so-called "integration constraints", which indicate a redundant overlap of views and, thus, are interpreted as forbidden substructures in the wanted integrated schema, and Γ is selected as view support of all given view database schemas. $Transform$ removes an integration constraint by appropriately merging the relation schemes involved, leaving Γ invariant.

Examining the general skeleton of design procedures, we can further comment on the tasks of design theory. The parametrization step is based on Task 1 and Task 2. The check_of_properties step and the remove_forbidden_substructure step are based on Task 3. Finally, after getting the final output schema, the administrator can evaluate the quality of the design based on results of Task 4, and, if necessary, he can iteratively process the design procedure using a different parametrization.

The skeleton also shows the impact of the administrator's interaction: he is responsible for modeling, parametrization, selection and investigation of forbidden substructure. While modeling and investigation of forbidden substructures is principally outside the scope of automatic algorithms, parametrization and selection of forbidden substructures could possibly be better supported by algorithms as known today.

6 Final Remarks

Since the first pioneering work of E.F. Codd [Cod70, 72] and W.W. Armstrong [Arm74], a substantial body of results on database schema design theory has been published. This paper summarizes only a small part of the highly detailed work. It emphasizes the tasks of design theory in producing and using interactive design tools. In a companion paper [Bis95a] three main topics for further enhancement of the design theory are outlined: all current achievements still have to be carried out within one unifying framework; the current achievements have to be embedded in the full design process and to be extended to deal more deeply with advanced database features like incomplete information, recursive query languages, complex objects or object identifiers; all achievements have to be reconsidered from the viewpoint of distributed computing, abandoning the classical centralized approach to databases.

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