In this truly adaptable approach, designers begin by defining the application environment and then work inward until they reach a level that can be handled by available DBMSs.

An Adaptable Methodology for Database Design

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Database design has changed considerably since its inception. A large part of the design used to deal with physical data allocation, load factors, and access methods of secondary storage. These aspects are no longer part of the database design process because they are part of all commercial database management systems and cannot be modified. Most current database designs, and possibly all future ones, will stop at logical access path optimization and use existing database systems with fixed physical designs. Consequently, the emphasis will be on design at the information system level.

The design method presented here is based on this very philosophy—that database design must be done "from the outside in." We must analyze the proposed system's environment and proceed progressively inward toward the computer implementation of the application. In most cases the analyst is then directly exposed to the requirements, which is really the key to a successful system design, if the system is to operate effectively within a particular environment. Take, for example, a project that automates existing manual procedures; the computer system is a direct reflection of the current operations, that is, of the environment.

The parts of the database design of most concern to us here are analyzing information processing requirements, constructing a conceptual model that specifies these requirements, and developing and optimizing a logical access path schema. The underlying assumption in our approach to database design is that conceptual modeling can be based on how information flows between an enterprise and its environment and among its components. [One may argue that some kind of model (possibly not precise) has already been conceived, and therefore that conceptual modeling has already begun before the information flow is conceived. Regardless of how true this supposition may be, our purpose here is to model the database, not to deal with how the human brain handles "chicken-or-the-egg" problems!] We consider conceptual modeling as a technique for specifying, in a formal language, concepts and ideas that can be interpreted by other humans familiar with the context of the enterprise and its environment.

For this reason, we start with the environment of the enterprise rather than the environment of the data processing system. In many cases, the requirements of the data processing system may be distorted by established practices, existing hardware and/or software, or personnel resistance to system upgrading. Starting conceptual modeling at the information system level rather than the data processing level helps avoid these low-level distortions. Furthermore, the goals and requirements of this level are more understandable to management. Hence, managers are more apt to make correct decisions.*

In our methodology, we also analyze the operational behavior of the enterprise, which we call system analysis, the word "system" referring to operational behavior, not to the data processing system. Without a complete understanding of how the enterprise operates, no effective design can be developed either for current operations or for future improvements.

*Several other design methodologies start from the environment and proceed inward. Jefferson et al.'s[1] database design departs from the requirement analysis at the corporate level where many of the interactions are between the organization and its environment. Kahn[2] also proceeds from corporate level requirements to information analysis where again interactions include the information flow between the environment and the organization. BIAIT[3] has also incorporated these kinds of interactions into its questionnaires.

Another main objective of the outside-in methodology is to provide a framework for the use of well-understood and proven techniques for both the analysis and the specification of the enterprise's objectives, requirements, and design. We have incorporated established data flow techniques,[4,5] control flow specification techniques,[6-8] structured interviewing and questionnaire techniques,[9] well-understood data modeling techniques,[10-16] and logical optimization techniques.[17-20] Emphasis has been placed on the understandability and the completeness of the requirements specification. All referenced approaches deal with *either* database design or program design. This methodology integrates techniques from *both* approaches because a database system is neither just a schema (structural component) nor just a set of transactions (procedural component). It is a schema with transactions running against this schema; consequently, the schema and the transactions must be designed hand in hand.

A major advantage of this framework is that significant design decisions are made explicit at the appropriate design phase. For example, obtaining optimal physical parameters, makes no sense if the logical design is ineffective. Similarly, obtaining optimal logical organization and indexing makes no sense if the corresponding conceptual schema is incorrect and violates the integrity of the data. Again, a good conceptual schema is useful only if it corresponds to the right operational behavior of the enterprise within its environment. This framework and the design decisions along with their specification are the important concepts of this proposal. The individual models and techniques to obtain, specify, and document these decisions can be chosen from the wide variety found in literature.

Methodology overview

Our proposed modular methodology consists of four phases: (1) environment and requirements analysis, (2) system analysis and specification, (3) conceptual data modeling, and (4) derivation of a logical access path schema. A schematic diagram of the methodology is given in Figure 1.

The objectives of the first phase are to understand the actual state of the enterprise and to collect all the information needed by the subsequent steps, including information and data processing requirements. Information requirements will be used in the conceptual data modeling phase to generate the conceptual schema of the target system. The data processing requirements will be passed to the logical access path schema derivation phase in which the logical optimization and the application programs are designed.

The objective of the second phase is to identify the applications that will use the database. Using input from the environment analysis phase, we obtain a good understanding of the target system. The output is a set of "tasks" to be performed during the database operation.

The objective of the third phase—conceptual data modeling—is to translate the knowledge about the target system collected in phases 1 and 2 into a formal representation—a conceptual data model. In this phase, designers are concerned only with the characteristics of the "entities" in the application environment and the relationships among them. They should not be concerned with the way they are represented in the computer.

In the last phase, we have several objectives: (1) to map the conceptual schema into the organization's data model structure, (2) to generate logical access paths of the tasks, (3) to integrate all paths into another schema that models their relationships and their cumulative usage weights, (4) to optimize this access schema, and (5) to realize the tasks' logical access paths against the optimized schema.

Numerous related papers have influenced our work. Phases 1 and 2 have been influenced by the works of Burnstine,[3] Bubenko,[21] Chen,[22] Lum et al.,[23] Tsichritzis and Lochovsley,[24,25] Sheppard-Rund,[9] and Kahn.[2] Phase 3 is based mainly on our work on the semantic models of databases that started with the semantic network model of databases[12,26,27] and its continuation in providing a language to support the design of conceptual schemata.[13] Approaches by Mylopoulos et al.,[14] Weber,[28] Hammer and McLeod,[29] Chen,[10] Sowa,[30] Falkenberg,[31] Smith and Smith,[32] and Brodie[33] can also be used in phase 3 as can other semantic models. Phase 4 has been influenced by Chang and Cheng,[34] Chang and Ke,[35] and Schkolnick.[18]

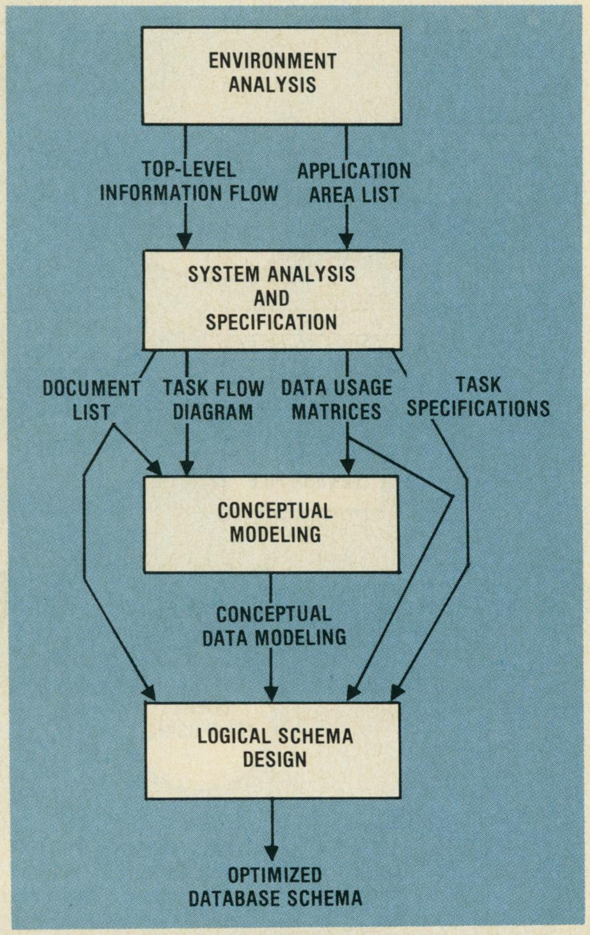


Figure 1. Schematic diagram of the phases of the database design methodology.

Phase 1: Environment and requirements analysis

In this phase, we investigate the information needs of and activities within the enterprise and determine the boundary of the design problem. Much of this phase involves information collection. An overall model of the enterprise as an information processing system is constructed. Since we are not attempting to model or discipline the way humans conceive "understanding," we provide only a list of information sources on which this understanding must be based and a list of things to be generated. In other words, we specify the input and the desired output of this phase, thus leaving the processing to human ingenuity.

Information sources: phase 1 input. The basic technique for collecting information consists of reviewing documents, interviewing people, and analyzing questionnaires to determine facts, policies, objectives, and constraints. These information sources describe the current status of the enterprise, possible inefficiencies, plans for the future, and constraints that have to be satisfied in conducting business.

Other sources of information include organization charts, reports, forms, files, and software documentation (if such documentation exists).

Functional specification: phase 1 output. In this step, we establish a functional model of the enterprise by identifying its major activities or functions and their relationships. This functional model will take the form of an information flow diagram.

Usually, the function associated with each operational activity is too complex to comprehend and model using a flat, single-level presentation. Therefore, we must usually divide the functions into smaller units called *tasks*.

Identification of activities and tasks is important in the design of the database system. If the system under design is to support the activities of an established enterprise, an organization chart can be used for identifying functions and tasks. However, this process becomes more difficult if (1) a new organization is to be established and its components have not yet been identified or (2) a system is designed to change part or certain aspects of an

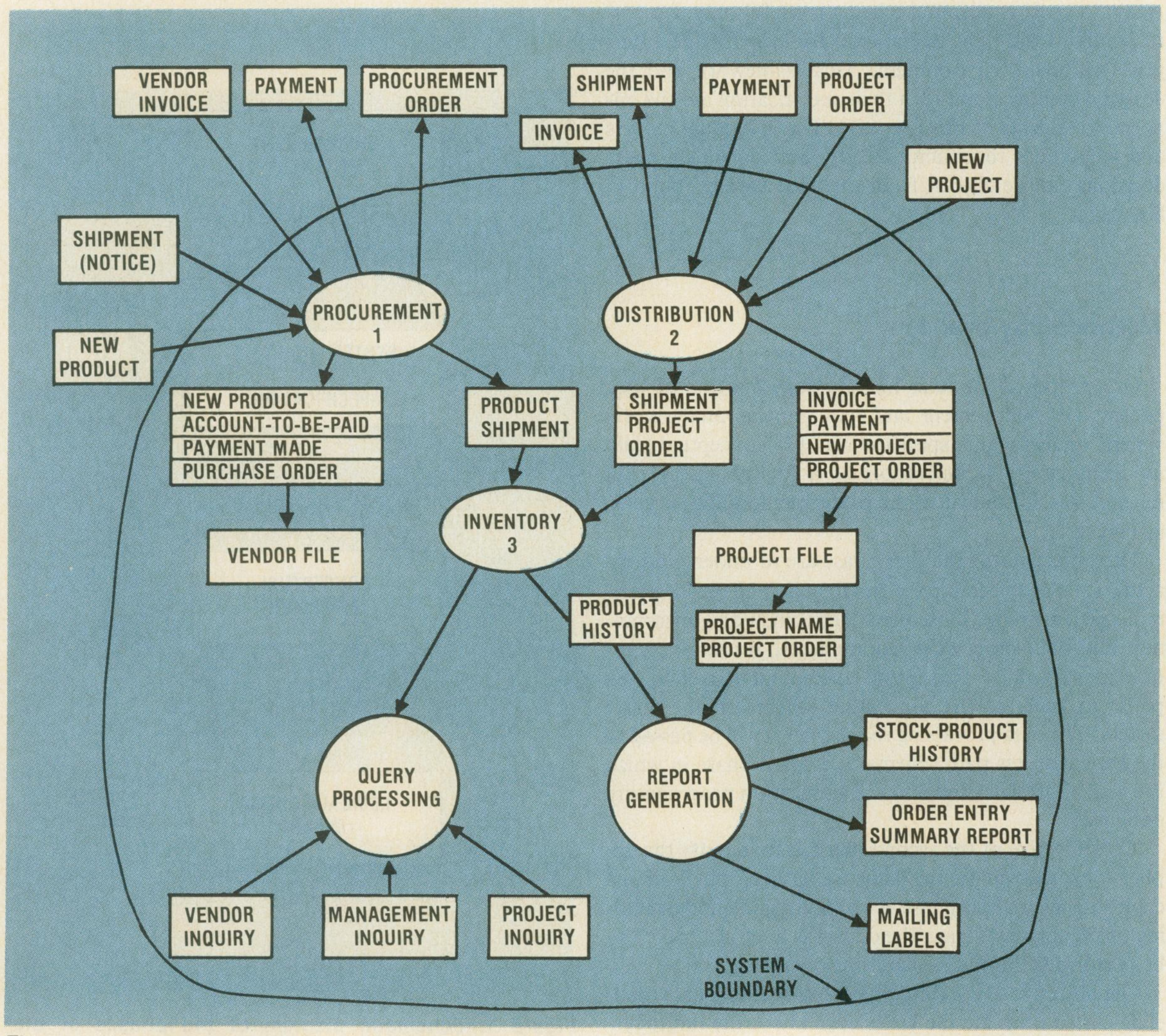


Figure 2. Top-level information flow diagram.

enterprise's activities. In these cases, we must use information collected from the previously described information sources to derive tasks.

The main activities of the enterprise, the interactions of the external entities and the enterprise, and the interactions of the main components can be described by a *system flow diagram* like the one shown in Figure 2.* This flow diagram, which is the goal of the first phase, contains (1) the main activities of the system (PROCUREMENT, INVENTORY, DISTRIBUTION), shown in the ellipses; (2) the data processing functions (QUERY-PROCESSING, REPORT-GENERATION), shown in circles; and (3) the documents that carry the data between components of the organization, shown in rectangles. (A document here is merely a general information-recording medium for information transfer. All messages, forms, files, inquiries, and reports will be referred to as documents.) The boundary of the system shows the interactions of the environment and the enterprise. Clearly, Figure 2 describes not only data flow but also control flow because many of these documents could be simple control messages that trigger tasks in the organization.

Phase 2: System analysis and specification

In this phase, we start with the overall information-flow diagram like that in Figure 2. Each activity is divided hierarchically into more and more detailed tasks and subtasks. The tasks should be reasonably independent so that we will have a small number of task-task interfaces. During the division process, the (data) documents used by each activity are also broken down into their component data elements or subsets of data elements. The tasks are further divided into subtasks until they become small enough to be clearly understood, and the I/O data documents can be conveniently expressed in terms of data elements that cannot be further divided. A new data- and control-flow diagram is developed using the tasks established through this breakdown. The following tasks were obtained for the Distribution activity through this process.

```
ENTER-NEW-PROJECT
ENTER-GRANT-ORDER
ORDER-PICKING
SELECT-SHIP-ROUTE
MAINTAIN-PROJ-TRANSACTION-RECORD
PROJECT-BILLING
```

Specifying tasks. For each task, the following attributes need to be specified:

- the person in charge (task performer),
- documents used and/or generated (I/O documents),
- procedure for carrying out the task,
- frequency of the task,
- conditions that specify the prerequisites for the task's activation and the effects after its termination,
- events triggered during the task's performance, and
- error (anomaly) conditions of the task.

Among these attributes, the I/O specifications, task frequency, and the operations performed are the ingredients needed to emulate the task and construct the logical access path schema for its optimization. The pre- and post conditions, events triggered, and error conditions specify the control and each task's interactions with the rest of the system.

A standardized task form has been designed to assist the responsible designer in extracting the important characteristics, features, and attributes of each task. A sample of this standardized form, which task performers and designers can cooperate in filling out, is shown for the Distribution activity (Figure 3).

This task allows the designer to analyze both existing activities and those considered for implementation that have not been divided into tasks and subtasks. Thus, starting with the main activities of the enterprise, the designer can specify all functional requirements in terms of this task form.

The following rules of thumb can be used to decide when a given task should be divided into subtasks:

Task-number:	S-1	
Task-name:	DISTRIBUTION	
Performer:	Distribution Department	
Authorization:	Various authorizations to be specified in the subtasks	
Purpose:	Distributes products to the projects and handles accounts	
Enabling-conditions:	Permanently executing	
Description:	Order Forms (D3) are used to determine which products are to be shipped to which customers.	
Frequency:	N/A	
Duration:	N/A	
Importance:	Very important	
Maximum-delay:	N/A	
Input:	Documents:	D2 (NEW-PROJ-FORM)
		D3 (ORDER-FORM)
		D5 (DAILY-ORDER-BATCH)
		D6 (PROJECT-BALANCE)
		D11(PAYMENT)
		D12(ADJUSTMENT)
Output:	Documents:	D4 (WEEKLY-ORDER-HISTORY)
		D5 (DAILY-ORDER-BATCH)
		D6 (PROJECT-BALANCE)
		D7 (PROJECT-INVOICE)
		D8 (PRODUCT-QUANTITY-ON-HAND)
		D9 (PRODUCT-TO-BE-SHIPPED)
		D10(SHIPPING-ROUTE)
		D13(MONTHLY-STATEMENT)
		D14(EXCEEDING-LIMIT-PROJ-LIST)
Use of documents:	All columns of D2, D3, D6, D11, D12	
Operations-performed:	The detailed operations are described in the subtasks.	
Subtasks:	ENTER-NEW-PROJECT (S-1-1)	
	ENTER-GRANT-ORDER (S-1-2)	
	ORDER-PICKING (S-1-3)	
	SELECT-SHIP-ROUTE (S-1-4)	
	MAINTAIN-PROJ-TRANSACTION-RECORD (S-1-5)	
	PROJECT-BILLING (S-1-6)	
Error-conditions:	N/A	

Figure 3. Task form filled for the Distribution activity.

*To facilitate an understanding of our methodology, we have chosen a model organization called the ABC Agency. The ABC Agency procures products from vendors and retails them to government projects. Each vendor can furnish several products, and products can exist in several versions or models. Similarly, each product model can be furnished by several vendors. A project may be located in several places. An order may be shipped to any location, but the invoice is always sent to the project's home office.
Naturally, the ABC Agency is only one type of a wide variety of organizations. The steps in our methodology, however, can be broadly applied.

- Many performers are required to carry out the task and each performer has different skills, or each can carry out a part independently.
- Different levels of authorization exist for carrying out different parts of the task.
- Different enabling conditions activate parts of the task.
- Different frequencies and durations apply to different parts of the task.
- Input documents are not used uniformly within the task.
- Different documents are used for different parts of the task.
- Many diversified operations are carried out within the task.
- Many subtasks are controlled by the task.

There are basically two ways of subdividing a task. In the first, the new task is a subtask of the original task. In this case, a "parent-child" relationship is established and part of the responsibilities are transferred to the subtask. However, control stays with the original task, which has to wait for the subtask to terminate before it can terminate. In the second type of subdivision, the new task is a "sibling" of the original task. In this situation, the "parent" of the original task assumes control, but the "sibling" tasks are carried out independently.

During the "parent-child" task division, the input documents of the original task are separated and split among the subtasks. If parts of one or more documents are needed for a subtask, then a new document is defined. The new document will include all the necessary data elements.

During the "sibling-sibling" task division, the original task's input documents may need to be further divided, as in the "parent-child" case, to account for splitting responsibilities between the two. Some additional control documents may have to be introduced for communication among the tasks if they are required to pass data and/or synchronize some activities.

Figure 3 shows a list of subtasks obtained for the Distribution activity. By examining the input documents of the Distribution activity, new tasks such as ENTER-NEW PROJECT, ENTER-GRANT-ORDER, and ORDER-PICKING are identified. Further division may then be necessary as the forms for tasks ENTER-GRANT-ORDER and ORDER-PICKING show. (Figures 4 and 5).

Task-number:	S-1-2
Task-name:	ENTER-GRANT-ORDER
Performer:	Tom Keener, Distribution Coordinator
Authorization:	Scott Farley
Purpose:	Enters orders in the database and grants orders
Enabling-conditions:	Arrival of ORDER-FORM (D3)
Description:	ORDER-FORMS (D3) are distributed and recorded. Balance of ordering project is checked to determine whether order should be granted. Order history is generated every week.
Frequency:	300 per day
Duration:	N/A
Importance:	Very important
Maximum delay:	2 days
Input:	Documents: D3 (ORDER-FORM) D6 (PROJECT-BALANCE) D5 (DAILY-ORDER-BATCH)
Output:	Documents: D6 (PROJECT-BALANCE) D5 (DAILY-ORDER-BATCH) D4 (WEEKLY-ORDER-HISTORY)
Use of documents:	All columns of D3, D6, D5
Operations-performed:	Upon receipt of D3, it is numbered and distributed. Information on D3 is then entered into the database. The balance of the ordering project (D6) is updated and checked. If the project balance does not exceed its limit, the order is granted. Every morning all granted orders of the previous day are batched in (D5) together for a pickup. Every Friday D4 is generated.
Subtasks:	ORDER-FORMS-RECEIVE-DISTRIBUTE ENTER-ORDER-INFO UPDATE-PROF-BALANCE INSUFFICIENT-BUDGET-HANDLING ORDER-HISTORY-GENERATION
Error-conditions:	Operation of this task halts if the information of the projects and products does not match with the data in the database.

Figure 4. Task form filled for subtask ENTER-GRANT-ORDER.

Specification of documents. From the I/O specifications of the activities and tasks, we can obtain a list of the documents (reports, files, data elements, inquiries to files, forms, etc.). The list includes documents used within the enterprise or documents discovered by the requirements analysis. Messages received by the task performer during task execution are also considered data documents. Below is a partial document list for our sample enterprise:

```
D1 - PROJECT-RECORD
D2 - NEW-PROJ-RECORD
D3 - ORDER-FORM
D4 - WEEKLY-ORDER-HISTORY
D5 - DAILY-ORDER-HISTORY
D6 - PROJ-BALANCE
D7 - PROJ-INVOICE
D8 - PRODUCTION-QUANT-ON-HAND
D9 - PRODUCTS-TO-BE-SHIPPED
D10 - SHIPPING-ROUTE
D11 - PAYMENT
D12 - ADJUSTMENT
D13 - MONTHLY-STATEMENT
D14 - EXCEEDING-LIMIT-PROJECT-LIST
etc.
```

Each document is then expressed in terms of data elements. If a document is already being used, the data elements constituting it are readily available. The newly introduced documents must be divided into new or already established data elements. Documents D1 through D4 and their data elements are shown below

```
Document D1: PROJECT-RECORD
  PROJ-NO
  PROJ-NAME
  CRDT-CODE
  CRDT-LIMIT
  PROJ-MAIN-LOC-NO (zip code)
  PROJ-MAIN-LOC-ADDR
    PROJ-BRANCH-LOC-NO
    PROJ-BRANCH-LOC-ADDR
Document D2: NEW-PROJ-FORM
  PROJ-NAME
  PROJ-MAIN-LOC-NO
```

```
    PROJ-MAIN-LOC-ADDR
      PROJ-BRANCH-LOC-NO
      PROJ-BRANCH-LOC-ADDR
  Document D3: ORDER-FORM
    ORD-NO
    DATE-ENTERED
    DATE-POSTED
    PROJ-NO
    PROJ-MAIN-LOC-NO
    PROJ-BRANCH-LOC-NO
      ITEM-LINE-NO
      PROD-NO
      PROD-MOD-NO
      QUANT-ORDERED
  Document D4: WEEKLY-ORDER-HISTORY
    ORD-NO
    DATE-POSTED
    PROJ-NO
      ITEM-LINE-NO
      PROD-NO
      PROD-MOD-NO
      QUANT-ORDERED
      PRICE
```

Specification of data usage. From the I/O specification of tasks, and the document specifications, we can construct two usage matrices. The first is the task-document usage matrix, which specifies the task I/O in terms of documents (Figure 6). The second usage matrix is called the task-data element usage matrix and specifies task I/O in terms of data elements (Figure 7). Note that the task-data matrix is constructed from the task-document matrix and the document specifications.

Both data usage matrices can be easily obtained from the task forms and the document specifications. They can also be automatically generated as a report, as PSL/PSA does.[5]

Specification of task flow diagrams. The task-document usage matrix is now used to construct the task flow diagram, a chart that shows the control and data flow among the tasks in the system. Figure 8 shows the TFD of the Distribution function.

Phase 3: Conceptual modeling

The goal of this phase is to translate the knowledge about each activity, collected in the previous phases, into a formal representation called a *conceptual schema.* This data modeling refers only to the structural specification. (The general term of conceptual modeling used in phases 1 and 2 included the procedural specification as well.)

During the conceptual data modeling phase, we are concerned only with the conceptual entities used in each activity, their properties, and the conceptual relationships among them. The physical or computerized representation of the entities and their instances is irrelevant at this point.

To represent conceptual objects, then, we need a computer-independent semantic model that

- can capture the meaning of the conceptual objects;
- has well-defined interpretation rules so that people other than those in the design group (other designers or users of the system) understand the intended meaning; and
- has a friendly human interface with multiple representations (text and graphical) and high-level operators that manipulate the conceptual schema.

A modeling language like the conceptual schema definition language, or CSDL,[13] is best suited for expressing conceptual entities, their properties, and the relationships among them. The language has been slightly extended to offer two levels of syntax. The first is high-level syntax

Task-number:	S-1-3
Task-name:	ORDER-PICKING
Performer:	Bruce Smith, Inventory Controller
Authorization:	Howard Daniel
Purpose:	Pick up products of granted orders from the inventory.
Enabling-condition:	The arrival of the DAILY-ORDER-BATCH (D5)
Description:	The inventory is checked against the products specified in D5. Available products are then picked up for shipment.
Frequency:	5000 picked products per day
Duration:	One day
Importance:	Very important
Maximum delay:	4 hours
Input:	Documents: D5 (DAILY-ORDER-BATCH) D8 (PRODUCT-QUANT-ON-HAND)
Output:	Documents: D7 (PROJECT-INVOICE) D8 (PRODUCT-QUANT-ON-HAND) D9 (PRODUCT-TO-BE-SHIPPED) D17(STOCK-UP-REQUEST) D18(UNFULFILLED-ORDERS)
Use of documents:	Parts of D5 and D8, all columns of D7, D9 (as shown in Figure 7).
Operations-performed:	Upon arrival of D5 (DAILY-ORDER-BATCH), the inventory is checked to determine whether the quantity on hand for each ordered product in D8 is sufficient to satisfy all orders. If so, shipping tickets (D9) and invoices (D7) are issued.
Subtasks:	CHECK-INVENTORY ISSUING-SHIPPING-TICKETS PRODUCT-PICK-UP PROJECT-INVOICE-GENERATION
Error-conditions:	When the quantity on hand is not sufficient to satisfy all orders, a request for stocking up is issued (D17) and the order is queued (D18) for future fulfillment.

Figure 5. Task form filled for subtask ORDER-PICKING.

TASK / DOCUMENT	ENTER-NEW-PROJ	ENTER-GRANT-ORDER	ORDER-PICKING	. . .	. . .
D1 - PROJECT-RECORD	O				
D2 - NEW-PROJ-RECORD	I				
D3 - ORDER-FORM		I			
D4 - WEEKLY-ORDER-HISTORY		O			
D5 - DAILY-ORDER-BATCH		O	I		
D6 - PROJ-BALANCE		I			

Figure 6. Task-document usage matrix. *I* and *O* represent input and output, respectively.

very similar to Chen's entity-relationship (E-R) model.[10] The second level of syntax is more detailed and is needed for formal data definition. Both levels have a graphical representation that helps designers to visualize the underlying semantic connections among conceptual objects. In addition, the language's computer implementation provides a number of support facilities, such as data dictionary facilities, display facilities, and zoom-in/zoom-out facilities, which allow the designer to display the conceptual schema at different levels of detail. Such facilities are important in modeling large and complex systems, where unassisted manual modeling is tedious and error prone. A detailed description of CSDL is given elsewhere.[13]

Other modeling languages and/or modeling methodologies are suitable for this phase. The most notable are Taxis,[14] D-graphs,[28] semantic database model (SDM),[29] E-R model,[10] aggregation-generalization,[32] conceptual graphs,[29] and object-role model.[31] This list is by no means exhaustive; many other models can also be used.

Discovering entities, properties, and relationships. Conceptual data modeling consists of identifying the *entities,* the *properties,* and the *relationships* (called EPRs hereafter) in the application. In general, we have no algorithmic methods for identifying EPRs, but we can use some rules of thumb.

In the technique described here, we discover EPRs merely by examining nouns, adjectives, and verbs in the system's requirements. Nouns usually correspond to entities, verbs to relations, and adjectives to properties. The advantage of this technique is that the entities and relationships discovered in this way have meaning for the user because they draw on concepts from the application world. The disadvantage is that the naming process is very subjective, and different designers may come up with different names for the same entities or relationships. Other difficulties are the well-known dilemma of whether we should use a relationship "ship," the entity "shipment," or both to model the concept of shipping. The same difficulties are encountered in all similar techniques. A somewhat structured way for discovering EPRs is to use the document/data element specification as input (see Figures 6 and 7). The method can be used to discover the following:

DATA ELEMENT \ TASK	ENTER-NEW-PROJ	ENTER-GRANT-ORDER	ORDER-PICKING	. . .	. . .
PROJ-NO	O	IO	O		
PROJ-NAME	IO	I			
CRDT-CODE	O				
CRDT-LIMIT	O				
PROJ-MAIN-LOC-NO	IO	I			
PROJ-BRANCH-LOC-NO	IO	I			
PROJ-BRANCH-LOC-ADDR	IO				
⋮					

Figure 7. Task-data element usage matrix. *I* and *O* represent input and output, respectively.

- *Unique code identifiers* are usually introduced when organizations refer repeatedly to instances of entities (physical or abstract objects). In most cases, these identifiers uniquely identify the objects even though their names are not unique. For example, PROJ-NO and ORDER-NO denote entities PROJECT and ORDER.
- *Properties* can be discovered by asking the question: "Does element *A* characterize *B*?" If so, then *B* is usually an entity, and *A* is a property of *B*. For example, ADDRESS characterizes PROJECT; NAME characterizes PROJECT, etc.
- *Structural relationships* (*part-of relationships*) are discovered by asking the question: "Is element *D* a component of *C*?" If so, *C* is usually an entity, and an is-part-of relationship is identified. For example, LINE is-part-of ORDER. *D* can be either an entity by itself or a property of *C*. MODEL-NO, PRODUCT-NO, and QTY-ORD are all related to LINE by is-part-of relationships.
- *Is-a* (*-kind*) *relationships* are discovered by classifying data elements into generic types of entities; SHIP-LOCATION is-a LOCATION, DATE-ORDERED is-a DATE, etc. Both partners in these relationships are entities.
- *Events and actions* that involve data elements indicate general relationships among entities. For example, the event ORDER-PLACEMENT indicates a relationship between PROJECT and ORDER; similarly, the event FULFILLED-ORDERS indicates a relationship among the entities PROJECT, ORDER, SHIP-LOCATION, and DATE.
- *Numerical dependencies* of the entities in relationships are important; we must discover whether a relationship is one-one, one-many, or many-many. For example, an ORDER may have multiple LINES but each LINE has one PROD-NO and one QTY-ORD.

If we apply the preceding rules to our sample enterprise, we get the following EPRs.

entities		
PROJECT		
ORDER		
LOCATION		
SHIP-LOCATION		
PRODUCT		
DATE		
properties		
LOCATION	characterizes	PROJECT
ADDRESS	characterizes	PROJECT
PROJ-BALANCE	characterizes	PROJECT
SHIP-LOCATION	characterizes	ORDER
DATE-ENTERED	characterizes	ORDER
DATE-ORD	characterizes	ORDER
part-of-relationships		
LINE	is-part-of	ORDER
PROD-NO	is-part-of	LINE
QTY-ORD	is-part-of	LINE
is-a-kind relationships		
SHIP-LOCATION	is-a	LOCATION
DATE-ORD	is-a	DATE
general relationships		
ORDER-PLACEMENT	relates	ORDER, PROJECT, and SHIP-LOCATION

FULFILLED-ORDERS relates	PROJECT, ORDER, SHIP-LOCATION, and DATE

Note that after we discover the EPRs, we need to define the dependencies between the data values. These could be one-many or many-many. We especially need to define data dependencies of relationships requiring numerical quantification and arbitrary constraints, for example, "Every agency must procure every product from at least two suppliers."

Expressing EPRs in a multiple-level language. EPRs can be graphically represented as shown in Figure 9. The numerical quantifiers, can take the form[*m*} = at least *m*, [*m*] = exactly *m*, {m] = at most *m*, and [all] = all instances.

These quantifiers are used to express *m-n* relationships among entities and to define their constraints. For example, in Figure 9, the quantifiers on the line between ORDER-LINE and LINE show that each ORDER has at least one LINE. Further, each LINE is in one-one correspondence with PROD-NO and QTY-ORD through the LINE-PROD-NO-QTY-ORD relationship.

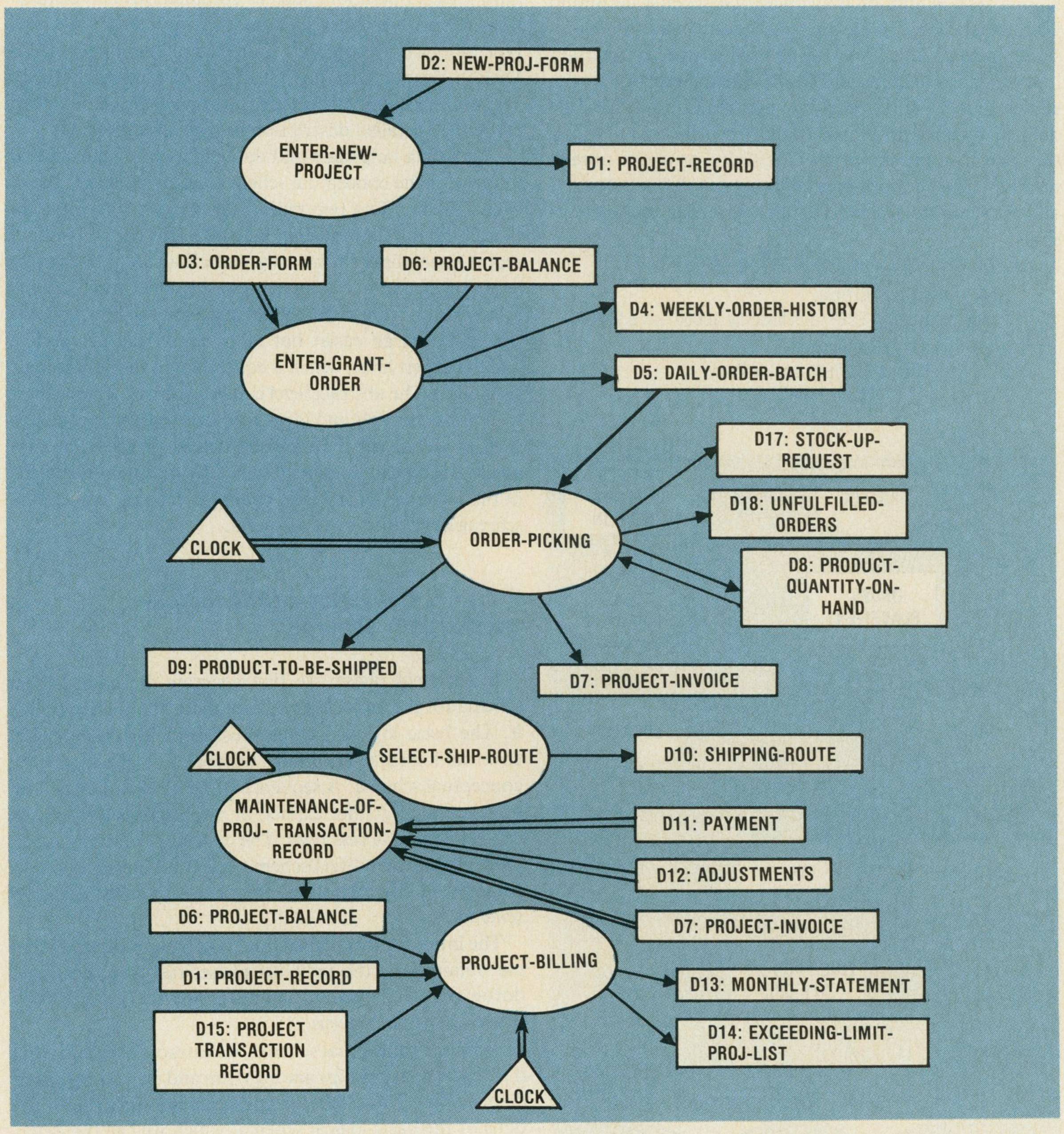


Figure 8. A task flow diagram for the Distribution activity. A triangle represents the clock, and any connected task is activated at a specific time and not by data passed to it by another task. Single-line arrows denote data flow, while double-line arrows denote control flow. For example, the single arrow between D5: DAILY-ORDER-BATCH and ORDER-PICKING means that D5 is used to carry information to the task, but does not activate it. The task, when activated by some other means, uses D5 to carry out its job. The task MAINTENANCE-OF-PROJ-TRANSACTION-RECORD, however, is activated whenever D7, D11, or D12 is passed to it.

This level of syntax is an extended version of Chen's E-R model,[10] the difference being the addition of numerical quantifiers. The implication of no numerical quantifier is that any m-n relationship $m \geq 1$ and $n \geq 1$, can be satisfied between the related values. However, the first level of syntax cannot express arbitrary quantified expressions because the scope of the quantifiers is not represented. For these types of relationships, we must use a language equivalent to first-order logic. Nevertheless, the preceding notation can express most common data relationships.

The second level of syntax specifies the details of the rectangles (relationships) and ellipses (entities). The second-level syntax of the conceptual schema definition language for some of the previously described EPRs is presented below. This level can be used to specify arbitrary quantified expressions and to provide data dictionary facilities. Every entity, property, and relationship must be defined by a "definitional frame," which fully specifies the system's understanding of the entity, property, or relationship. The keyword *concept* is used to define an entity, and the keyword *frame* to define properties and relationships.

```
Concept PROJECT (x) primary denoted-by PROJ-NO
  frame   PROJ-DEFINITION
        [x  of-type INTEGER is-defined-by 10000 ≤x≤99999]
  frame   PROJECT-PROPERTIES
          [x of-type PROJECT has-property:
            [1] y of-type NAME
            [1] z of-type LOCATION-NO
            [1] w of-type ADDRESS
            [1] u of-type PROJ-BUDGET-CODE
            [1] v of-type PROJ-BUDGET-LIM
            [1] r of-type PROJ-BALANCE
            [1} s of-type SHIP-LOCATION-NO
            [1} t of-type SHIP-ADDRESS]
  frame  ORDER-PLACEMENT
            [all] x of-type PROJ-NO
            [all] y of-type ORDER-NO
            [1]  z of-type SHIP-LOCATION;
          order (agent:x, object:y, destination:z)]
```

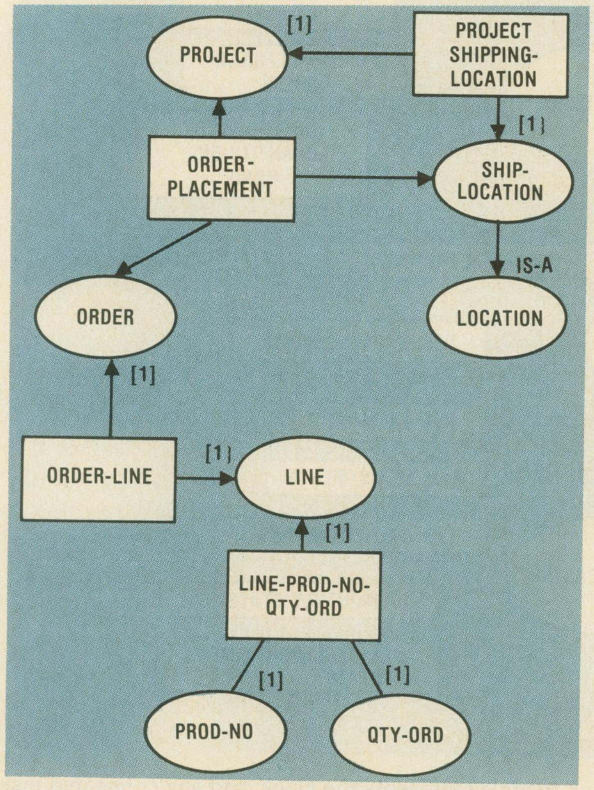


Figure 9. Graphical representation of entities, properties, and relationships, or EPRs, where circles represent entities and rectangles represent relationships and where [1} means at least one and and [1] means exactly one EPR.

A *simple frame* provides scoping rules for the qualified expressions. *Composite frames* are built by applying standard logical operations such as conjunctions and disjunctions. Typed variables such as *x,y,z,* are variables whose type is explicitly specified. For example, *y* of-type ADDRESS denotes that *y* is a variable of type ADDRESS. The numerical quantifiers are the same as those described earlier. (A detailed description is given elsewhere.[13])

Other data languages and data dictionaries can be used in place of the conceptual schema design language. However, CSDL offers two major advantages. First, it combines both a data modeling language and data dictionary report capabilities in the same notation. Second, the two levels of syntax allow us to view the conceptual schema specification from different perspectives: the abstract level that provides an easier but more superficial perspective and the expert level, which is equivalent to first-order logic languages. The abstract level can be used by the nonexpert to express concepts and ideas, while the expert level can be used to define all the required details precisely. A new abstract level can then be obtained by masking the details of the second level and used again to verify the conceptual schema developed by the experts.

Phase 4: Derivation of the logical access path schema

In the final phase, we first generate the basic logical schema for the target system's database and then optimize it. The basic logical schema must explicitly or implicitly cover all logical relationships expressed or implied by the conceptual schema. A sequence of database accesses used to generate all (either explicit or implicit) relationships is called a *logical access path.* The collection of many LAPs integrated into a unified schema that combines shared subpaths by adding their usage frequencies is called the *LAP schema.*[20]

The input for this phase consists of the conceptual schema obtained by the previous phase, task specifications, document specifications, and usage matrices generated by phase 2, system analysis.

From the conceptual schema, we extract the records and the logical relationships among them and express them in a data model. These relationships correspond to the relations of the basic logical schema, which we call the *enterprise logical base schema.* Next, we generate the I/O data requirements of each task by writing queries against the ELBS. The data input requirements of a task are the queries; the data output requirements are either reports or updates to the database. The LAPs of these queries are collected and integrated into a schema, which is then optimized for maximum efficiency on both retrieval and updates.[19]

The output of this phase consists of the LAP schema to be maintained; the task emulations, which are at this point the application programs of the database; and the constraints that must be considered to maintain data integrity.

Mapping to the enterprise logical base schema. Our objective here is to map the conceptual model onto other data models, such as the relational or Codasyl models supported by commercial database management systems. We can then use the resultant ELBS to define the logical access paths of each task by emulating the tasks against the ELBS.

The input to this step is the conceptual schema, expressed in the graphical notation described previously or in equivalent notation. The mapping to the relational data model is given below. A similar one has been done for the Codasyl data model.[36] During this mapping, we need not be concerned with issues of efficiency or redundancy. The efficiency and the amount of redundancy allowed in the obtained logical schema will be taken into account later during optimization.

Entities. For every entity, a one-column table (unary relation) is constructed. The name given to the relation is the same as the name of the entity. The attribute name is either the same as the entity name or the same as its database denotation (such as PROJ-NO and SUPPLIER-NO, if such denotation is available). In Figure 10, for example, the entity PROJECT (10a), is mapped onto the unary relation PROJECT (10b). INTEGER is the domain over which attribute PROJ-NO of relation PROJECT ranges. Thus, we have an explicit representation of the domain.

Properties and relationships. Most relationships expressed in the conceptual schema are mapped onto other relations. Property relationships are mapped onto two-column (binary) relations. The name of such a relation is the concatenation of the concept and property names. The attribute names used are PROPERTY-OF and VALUE. Take for example, the mapping of PROJECT-PROPERTIES in the CDSL second-level syntax.

Two things should be noted here. First is that the dependencies (one-one, one-many, or many-many) are constraints, so they are explicitly written in the attribute box of the relations. The quantifier [1] denotes that there is exactly one value of attribute VALUE for every value of attribute PROPERTY-OF. PROPERTY-OF and VALUE range over the domains PROJ-NO and NAME (or LOCATION-NO, ADDRESS), respectively. Second, whenever a concept is used to define a property and this concept has some denotation, this system denotation is used in the domain box of the relations; in Figure 11, LOCATION-NO is used in the domains of PROJECT-LOCATION rather than LOCATION.

For some property relationships, we are interested only in the *intension* and not the *extension*. The intension of a relationship is expressed using symbols and/or properties that define the elements of the relationship. The extension, on the other hand, is given in terms of the actual values satisfying it. A relationship defined by intension can be found in the frame PROJECT-DEFINITION

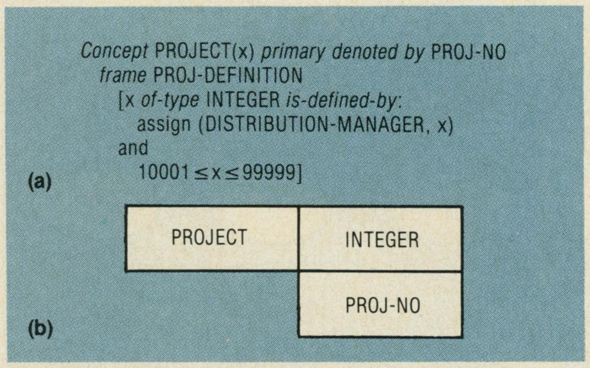
$$10001 \le \text{PROJ-NO}$$
$$\text{PROJ-NO} \le 99999.$$

One of its extensions is

$$10001 \le \text{PROJ-NO} = 10001 \le 99999$$
$$10001 \le \text{PROJ-NO} = 10002 \le 99999$$
$$10001 \le \text{PROJ-NO} = 10003 \le 99999.$$

Clearly, for most applications we would not be interested in storing such extensions. Instead we would like to include the intensions only and use them as the logical schema integrity constraints, which are activated to validate every new instance of PROJ-NO that enters the system.

Another type of relationship in the conceptual schema is expressed in the form of *procedural attachments* of frames. For example, the "assign" procedural attachment in the PROJECT-DEFINITION frame represents a procedure followed by the DISTRIBUTION-MANAGER in assigning a PROJ-NO to a new project. In this case, the manager examines the characteristics of the new project so



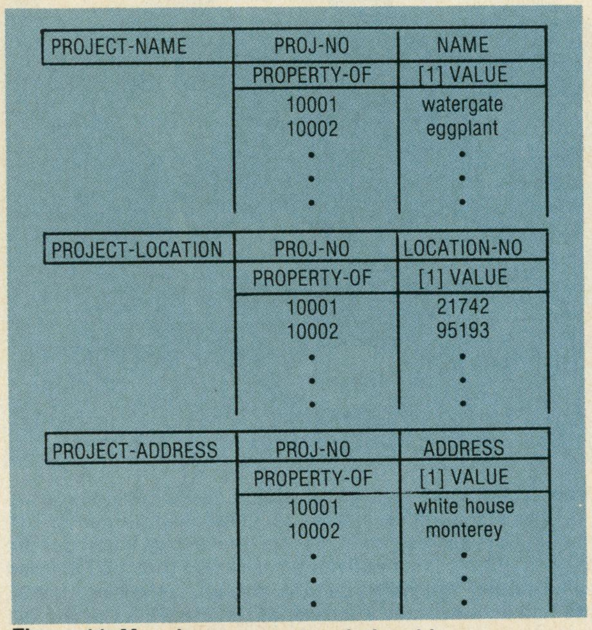
(a)

```
Concept PROJECT(x) primary denoted by PROJ-NO
  frame PROJ-DEFINITION
    [x of-type INTEGER is-defined-by:
      assign (DISTRIBUTION-MANAGER, x)
    and
      10001≤x≤99999]
```

(b)

PROJECT	INTEGER
	PROJ-NO

Figure 10. Mapping an entity.



PROJECT-NAME	PROJ-NO	NAME
	PROPERTY-OF	[1] VALUE
	10001	watergate
	10002	eggplant
	•	•
	•	•
	•	•

PROJECT-LOCATION	PROJ-NO	LOCATION-NO
	PROPERTY-OF	[1] VALUE
	10001	21742
	10002	95193
	•	•
	•	•
	•	•

PROJECT-ADDRESS	PROJ-NO	ADDRESS
	PROPERTY-OF	[1] VALUE
	10001	white house
	10002	monterey
	•	•
	•	•
	•	•

Figure 11. Mapping a property relationship.

```
frame ORDER-PLACEMENT (x,y,z)
      [[all] x of-type PROJ-NO
       [all] y of-type ORDER-NO
       [1]   z of-type SHIP-LOCATION :
        order(agent:x, object:y, destination:z) ]
```

ORDER-PLACEMENT	PROJ-NO	ORDER-NO	SHIP-LOCATION-NO
	{all} AGENT	{all} OBJECT	[1] DESTINATION
	10001	OM-336	21742
	10001	OS-112	21742
	10002	OM-348	95193
	•	•	•
	•	•	•
	•	•	•

Figure 12. Mapping an event relationship.

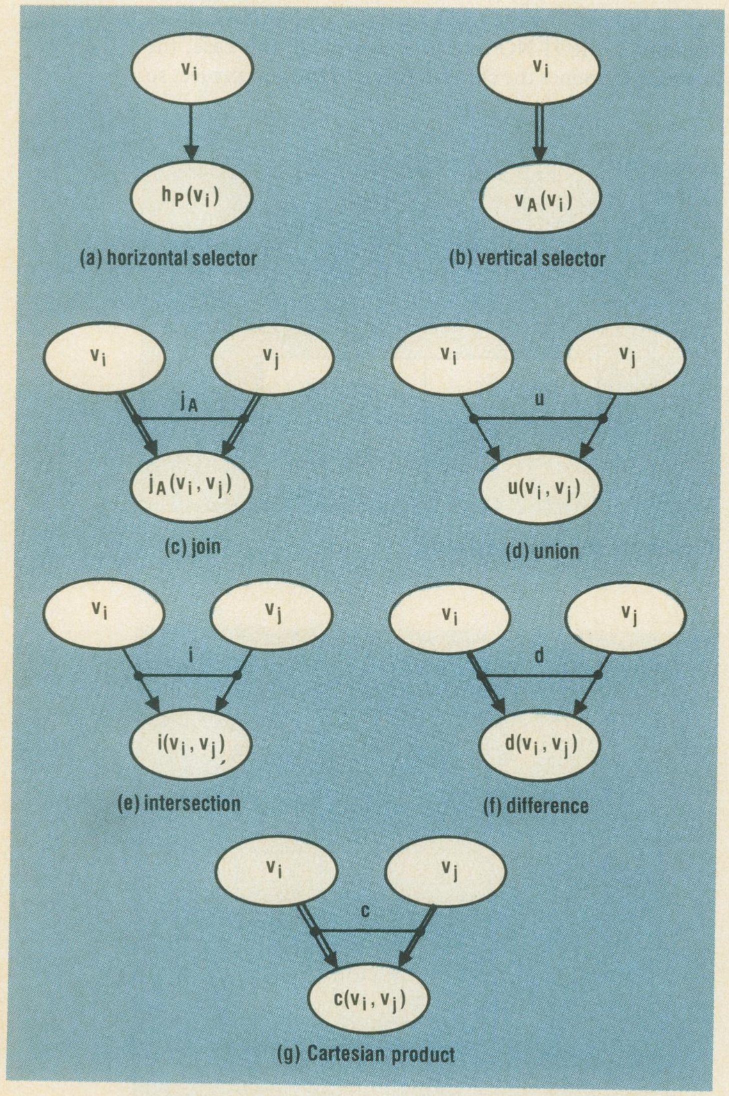


Figure 13. Graphical notation for the relational operators: (a) horizontal selector, (b) vertical selector, (c) join, (d) union, (e) intersection, (f) difference, and (g) Cartesian product. Single-line arrows (arcs) denote "subset" relations; that is, the head node has tuples that are included in the tail node. Double-line arrows denote "project" relations; that is, the head node has as attributes a subset of the attributes of the tail node. Links between arrows represent the derivations of views (dots).

that he can assign the PROJ-NO. Because these characteristics are of no interest to the system or to the system's users, they are hidden. Such assignments may be done, for example, on the basis of the information about project location, priority, and budget limits—notions that will not be needed again by system users.

The preceding discussion has focused on property relationships. Another kind of relationship expressed in the conceptual schema is the *event relationship*. These relations are mapped onto *n*-column relations. The name of the event is used as the relation name. The domains of the relation are the entities that participate in the relationship. Attribute names are chosen from a relatively small set of "roles" such as agent, recipient, object, source, destination, and time, which define the part each entity plays in the relationship. Figure 12a is an example of the event relationship ORDER-PLACEMENT which is mapped onto a synonymous relation (12b).

Emulating tasks. In this step, we obtain a query and an update model, which respectively reflect the data input and output requirements of each task. The result of the task emulation step is a collection of logical local subschemata, each of which is tailored to the data I/O requirements of a task.

Each task is emulated using the ELBS generated by the previous step. In this emulation, the data input required by each task (see the "input" line in the task form in Figure 3) is expressed by queries against the ELBS. For example, if information is needed about a project's location, a query is made against the PROJECT-LOCATION relation.

The term "query" implies a well-formed expression in a relational query language. However, since every query in a relational query language can be expressed by a relational algebraic expression, we assume that a query is a valid relational expression. Some queries are *generic;* that is, they produce a set of values, each of which may be the answer to a simple query. For example, a query that specifies the retrieval of projects located in New York generates as an answer a set of projects (possibly empty). This result may, in turn, be accessed by another application program to process each of the New York projects individually.

The answers to generic queries, called *views,* are, in general, virtual relations that have a form similar to a base relation except that they may be stored differently. The collection of these virtual relations, which corresponds to the data input of a task, is nothing but a local logical subschema tailored to the needs of this task.

Updates are generated from the output specifications of the task and are expressed in a data manipulation language. Only updates to the *base relations* of the enterprise logical base schema are allowed. Base relations are those that cannot be derived by queries made against other relations. Updates to views are in general problematic because some of these updates may not reflect valid updates to the base relations.[37-39] Since the only view updates that can be handled correctly are those that can be translated into sets of updates to base relations, we consider only base relation updates. The queries and the updates obtained during each task's emulation and their usage frequencies are used to construct the query and update model, which is then used to optimize the collection of logical access paths. In other words, the query and the update models are the composition of the data input and output requirements of all the tasks. The task emulation step is divided into the following substeps: (1) generate the data input requirements of each task, (2) compute the probabilities of all queries, and (3) compute the update probabilities for the base relations.

Generate the data input requirements of each task. Each query made to generate data input requirements of a task is represented by a *query graph* composed of view nodes. A view node (or simply a view) is a representation of the answer that corresponds to a relation derived by a query. For example, the virtual relation EXCEEDING-BUDGET-PROJECT is a view node that corresponds to the answer of the query "Give me the projects whose balance exceeds their budget limit."

A graphical representation for query graphs is introduced (Figure 13) in which each relational operator is represented by one or two linked arcs (depending on whether the operator is unary or binary). Any relational query can be represented by such a query graph because this set includes all relational operators. Figure 14 is a query graph for local projects. Here, LOCAL-PROJECT is a view obtained from PROJECT of ELBS by selecting projects that are local (LOCAL ≡ LOCATION ≡ Washington, DC).

Compute the probabilities of query graphs. The global probability of a query graph is the probability of executing the corresponding query against the database from within any task. These computed probabilities are then used during optimization, a step required by any optimization algorithm.[18,19,40]

The technique for computing global capabilities uses the frequency of each task found in the task forms and the number of times each query graph is executed from within each task. Weights indicating the importance of each task or application can also be used as an alternative or in addition.

Assume that there is a total of n tasks and m query graphs. We use a simple computation matrix for obtaining the global probabilities of all queries. Figure 15 is the task-query frequency matrix, where the upper $m \times n$ portion contains the frequencies of the query graphs within the tasks. For example, a_{ji} (where $1 \le j \le m$ and $1 \le i \le n$) is the number of times the query graph q_j is executed from within task t_i. If q_j is never made from within t_i, then the corresponding entry is zero. The $(m+1)$ row, shown in the matrix as

$$\sum_{j=1}^{m} a_{ji}$$

is used to store the total number of query graphs made by task t_i. The $(m+2)$ row (labeled F_{t_i}) contains the frequencies of the task's activations. The $(n+1)$ column with label p_j stores the computed global probabilities of each query graph. The following algorithm[20] computes the query graph probabilities by filling out the matrix in Figure 15.

```
BEGIN
  FOR i=1 UNTIL n DO
      BEGIN
        qnum=0
        FOR j=1 UNTIL m DO qnum=qnum+$a_{ji}$
        $a_{m+1,i}$=qnum
      END
  ftot=0
  FOR j=1 UNTIL n DO ftot=ftot+$a_{m+2,i}$
  FOR j=1 UNTIL m DO
      BEGIN
       psum=0
         BEGIN
           FOR i=1 UNTIL n DO
                 psum=psum+($a_{ji}$ ÷ $a_{m+1,i}$)*($a_{m+2.i,}$ ÷ ftot)
         END
       $a_{j,n+1}$=psum
    END
END
```

The first double loop in the algorithm fills out the $(m+1)$ row. The second simple loop computes the total number of tasks f_{tot}. The last double loop computes the global probability p_{sum} of each query q_j.

Figure 16 is the result of applying the algorithm to the matrix in Figure 15. Note that the probabilities were computed as if there were no updates against the database. In real life, of course, queries and updates are intermixed activities of each database system. Thus, the global probabilities should be computed so that the updates are also taken into account. To account for the influence of the updates onto the probabilities of the queries, we can add to the $(m+1)$ row the number of updates done from

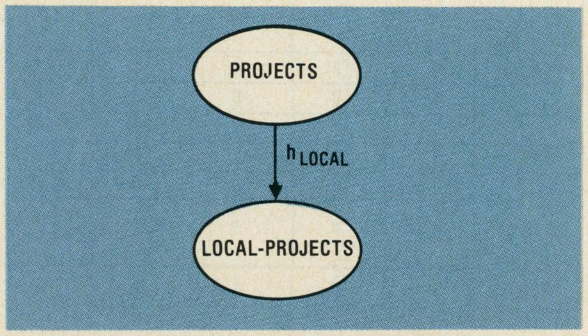


Figure 14. A query graph for local projects.

q_i \ t_i	t_1	t_2	t_3	t_4	p_j
q_1	0	2	1	1	
q_2	1	0	0	0	
q_3	0	1	0	0	
q_4	1	1	1	0	
q_5	2	0	0	0	
$\sum_{j-1}^{m} a_{ji}$					▨
F_{t_i}	1	2	1	3	7.

Figure 15. A task-query frequency matrix in which $(q_1 \ldots q_5) \times (t_1 \ldots t_5)$ contains the frequencies of query graphs within the tasks. The remainder of the matrix is used to store the total number of graphs made by task t_i and how often the task is activated.

within each task, assuming that the cost of retrievals and updates is about the same. Or, before we add anything to the $(m+1)$ row, we may want to multiply the number of updates by a weight, depending on the cost of the updates when they are compared with the retrieval queries.

Generate update probabilities. We can get the probabilities of updates on base relations from task output. We are not considering updates against views because studies show that only a few view updates can be reflected into valid sequences of valid updates on the base relations used to derive the updated views.[37-39] We assume here that all updates considered correspond to valid updates on base relations and that they have been translated onto base relation updates. The update probabilities u_j (where $j = 1,2,\ldots, k$) of base relations are computed in a manner similar to that for queries. Figure 17 is an example of a probability computation matrix for updates. It differs from the query matrix in that the first column of this matrix corresponds to base relations r_j rather than to views. For example, in Figure 17, task t_1 makes two updates: one on the base relation r_1 and one on r_3. Task t_3 makes two updates on r_2. Note that the task frequencies for this example are the same as the ones on the query computation matrix. The same algorithm described previously is used to fill out the rest of the computation matrix as shown in Figure 18.

q_i \ t_i	t_1	t_2	t_3	t_4	p_j
q_1	0	2	1	1	0.641
q_2	1	0	0	0	0.035
q_3	0	1	0	0	0.071
q_4	1	1	1	0	0.177
q_5	2	0	0	0	0.071
$\sum_{j-1}^{m} a_{ji}$	4	4	2	1	
F_{t_i}	1	2	1	3	7

Figure 16. Figure 15 matrix after applying an algorithm to compute query graph probability.

BASE REL. \ TASKS	t_1	t_2	t_3	t_4	q_j
r_1	1	0	0	1	0.21
r_2	0	0	2	0	0.14
r_3	1	0	0	1	0.21
r_4	0	0	0	0	0
r_5	0	1	0	1	0.42
$\sum_{j-1}^{m} a_{ij}$	2	1	2	3	
F_{t_i}	1	2	1	3	7

Figure 17. Probability computation matrix for updates in which the base relations are the first column rather than views (Figures 15 and 16).

Integrating query graphs into a LAP schema. In this integration step, we use the query graphs generated by the task emulation, the global probabilities, and the update probabilities to generate a logical access path schema that models the use of LAPs in the database. This schema is based on database activities, (retrievals and updates) found in the tasks, and integrates their logical access paths by recognizing common subpaths and increasing the weight of the shared subpaths. The schema provides a comprehensive picture of LAPs and the cumulative use of the shared subpaths and/or intermediate results. It is both a model of the access requirements during database design and a model for optimization during database operation.

Integration is achieved when two query graphs are merged to form a single one. During this merging, a simple algebra is defined that adds the probabilities of the common views on the obtained LAP schema. When the first two graphs have been merged, a third one is merged with the first two, and so on until eventually all query graphs have been merged into the final LAP schema. (More rigorous descriptions of merging algorithms are given elsewhere.[20,41]) Figure 18 shows query graphs for (a) EXCEEDING-BUDGET-PROJECTS, (b) SHIPPED-ORDERS, and (c) ORDERS-IN-PROCESS. Since 18a and 18b have no common views, they remain disconnected after merging. Figure 19 shows the merging of Figures 18a, b, and c. Note that the query probabilities of the common view ORDERS have been added. In Figure 20, the query graph for "Orders in process for projects exceeding their budgets" is shown.[1] The graph is obtained by making (1) two horizontal selections on PROJECTS and ORDERS to obtain EXCEEDING-BUDGET-PROJECTS and ORDERS-IN-PROCESS and (2) a join on the last two views on the attribute PROJ-NO. When we merge this query graph with Figure 19, we get the graph in Figure 21. As the figure shows, the probabilities of accessing PROJECTS and EXCEEDING-BUDGET-PROJECTS have been increased because they appear in a number of query graphs. The more each view appears in query graphs, the higher its probability of being supported in the optimal schema becomes.

A view (which does not correspond to a base relation) may be affected by an update to any of the base relations used in the derivation of the view. Since we assume that the updates on base relations are independent, the update probability u that a view may be affected by any update is the sum of the update probabilities of all base relations used in the derivation of the view. In Figure 21 we show the update probabilities u_n as they propagate from the base relations to the views. The view ORDERS-IN-PROCESS-FOR-PROJECTS-EXCEEDING-BUDGET is affected by both updates in PROJECT and ORDERS and thus its u probability is $u_1 + u_2$. The graph obtained by this step along with the retrieval and update probabilities is the LAP schema of the database.

Optimizing the LAP schema. The goal of this step is to enhance the execution efficiency of the frequently used (or important) tasks by explicitly indexing the subschemata they operate on. Clearly, not all of the subschemata should be indexed because a great deal of redundancy is generated, costing both storage and update time.

A view in the LAP schema can either be supported by an index to the base relation tuples that make up the view's tuples or constructed on demand from the base relations it is derived from. The construction is associated with I/O and CPU cost—to be called the "cons" cost. On the other hand, if an index is kept for the view, the cons cost is avoided. In this case, however, storage is required for the index, and updates become more time consuming because the index needs maintenance.

A useful indexing policy is to retain all indexes until an update is required. Consequently, an index is updated if it corresponds to a frequently accessed view but dropped if the view is infrequently accessed. In this manner, existing indexes are used as cache memory aids. These aids do not cost much overhead because they are created to answer queries. The only overhead is for the recognition of such cache indexes. The payoff can be significant because we trade CPU time (required for the recognition/matching algorithm) with extra I/O (required by the construction cost of a view). Given that (1) certain logical access paths among data expressed in some subschemata are used more often than others, and (2) in general not all paths should be indexed, we clearly need an optimization process that decides which paths must be supported.

The optimization is based on the following elements:

- the set of the derived views;
- the sizes of the indexes for those views, when the views are explicitly supported (cardinality times the size of the pointer);
- the construction cost of the derived views assuming that their index is not available;
- the probabilities of making queries against those derived views;
- the update cost of the indexes; and
- the probabilities of the updates.

Estimates of these elements could be easily obtained during the design in terms of upper bounds and complexity order of the algorithms. They are even more easily obtained when the database is operational. In the latter case, the index size and the construction cost of the index can be measured by monitoring the execution of the views. The same is true for the update cost, which can be measured by executing the updates. Optimization would then be based on actual costs of the index mechanism's implementation, the operating system, the database system, the buffering facilities, and all the other influencing parameters of the execution environment.

A cost model is needed to give us the cost of querying views and updating indexes. First we define index allocation and the construction cost based on this allocation. An index allocation A over a set of views V is a mapping

$$A : V \rightarrow \{0, 1\}$$

where $A(v) = 1$ means that view v has been indexed, whereas $A_v = 0$ means the opposite. For simplicity, we treat base relations as views (even though they are explicitly stored) and assume that $A(r) = 1$ for all base relations r. A construction cost function *cons* over a set of views V is a mapping

$$cons: (f, v) \rightarrow \{0, \infty\}$$

where $v \in V$ is a derived view and f is the set of views or base relations from which v can be constructed. Clearly, more than one set f can be used to construct a given view. Note also that a base relation has no f set because by definition base relations cannot be constructed from others.

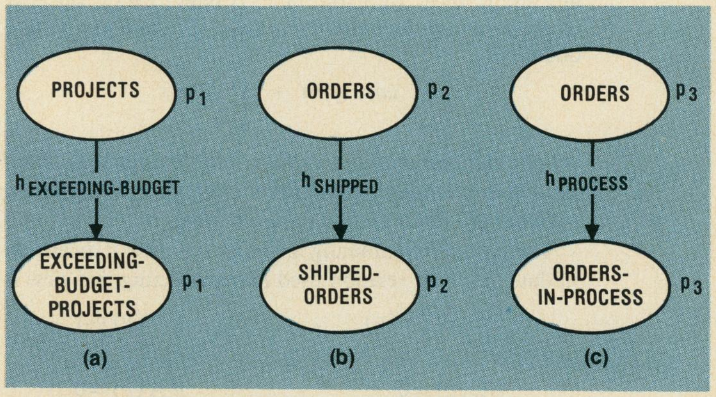


Figure 18. Query graphs for (a) EXCEEDING-BUDGET-PROJECTS, (b) SHIPPED ORDERS, and (c) ORDERS-IN-PROCESS.

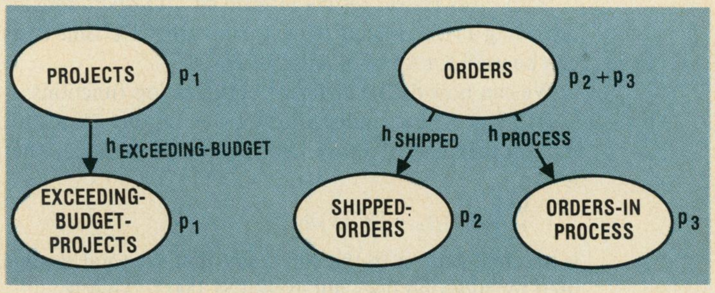


Figure 19. Merging of the three graphs in Figure 18. Note that 18a remains disconnected from the others because it has no views in common with 18b and c.

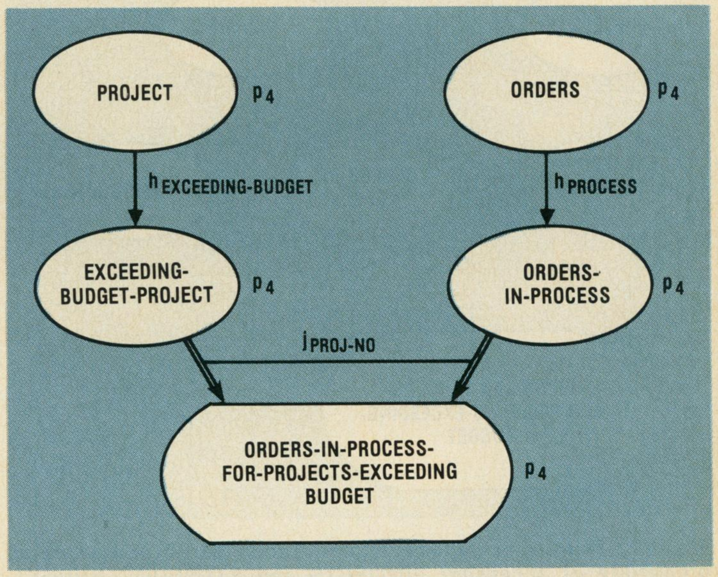


Figure 20. Query graph for "orders in process for projects exceeding their budgets."

The cost of answering a query that uses view v, given index allocation A, is

$$C(v) = c_r(v) \qquad \text{if } A(v) = 1$$

or

$$C(v) = \min_f [cons(f,v) + \sum_{x \in f} C(x)] \qquad \text{if } A(v) = 0$$

where $C_r(v)$ is the cost of retrieving the view from its index and is linear with size $|v|$. If $cons(f,v)$ is the cost of constructing the index for v from its ancestors f, then quantity

$$cons(f,v) + \sum_{x \in f} C(x)$$

reflects the cost required to first obtain all elements x in f needed to construct v plus the construction cost of putting together the elements of f to construct v.

The cost of maintaining an index for view v during an update of a base relation used in constructing this view is

$$UC(v) = c(v) \qquad \text{if } A(v) = 1$$

or

$$UC(v) = 0 \qquad \text{if } A(v) = 0$$

This cost reflects the cost c_r of retrieving and updating the view's index, if one is maintained for it; otherwise, it is zero.

Both costs reflect results in term of I/O operations of retrieving a view or modifying it. Similarly CPU time costs can be used for CPU-bound systems.

We can now define different optimization functions:

(1) Find the best index allocation A on the views such that the total cost of answering all queries is minimal. That is

$$\sum \{C(v)p_v + UC(v)u_v\}$$

is minimal subject to the constraint that the total storage used for indexing does not exceed SLIMIT. That is

$$\sum |v| A(v) \leq \text{SLIMIT}$$

In the previous formula, p_v is the probability of accessing v, and u_v the probability that v needs to be maintained because of an update for a base relation.

(2) Find the best index allocation A such that for weights w_1 and w_2

$$\sum \{w_1 C(v)p_v + w_2 UC(v)u_v\}$$

is minimal

(3) Find the best index allocation A such that

$$\sum A(v) \; |v|$$

is minimal subject to the constraint that no query takes more than TLIMIT time to answer; that is

$$\sum C(v) \leq \text{TLIMIT}$$

If I/O operation cost is used, TLIMIT can be estimated by multiplying the cost by the time in milliseconds to do one I/O operation.

(4) Find the best allocation A such that

$$\sum C(v)p_v$$

is minimal,

$$\sum UC(v)u_v$$

is minimal, and

$$\sum A(v) \; |v| \leq \text{SLIMIT}$$

Algorithms for obtaining the best index allocation for any of these optimization functions are computationally very difficult (NP-complete[42]). However, heuristics and knowledge on the accessing provided by the logical access path schema can help optimization. A heuristically directed algorithm, which guarantees that whenever a solution is reached, it is the optimal allocation for the LAP schema, is described elsewhere.[19]

We have now completed the last phase of the database design methodology. At this point, we have obtained the optimized logical access path schema and the application programs (task emulations). Now the operational phase of the database can begin.

We have presented a comprehensive step-by-step methodology for an adaptable database design—adaptable because each phase can be facilitated by a number of models and representation primitives.

Many of the tools and analysis techniques in the methodology can be and have been automated. Others, such as tools that help us to analyze objectives, constraints, policies, etc., or formal verifiers for consistency, are more difficult to automate. To help solve these problems, we must rely on user-directed instead of system-directed walkthroughs and/or specialized presentation techniques and reports.

The design specification techniques used in this methodology are valuable for system maintenance, as well. Changes in the environment and/or requirements can be traced back to the specification (output) of each phase to see the effects of these changes. Efficiency improvement from statistical observations and/or changes in access usage can be handled when deriving and optimizing a logical access path schema.

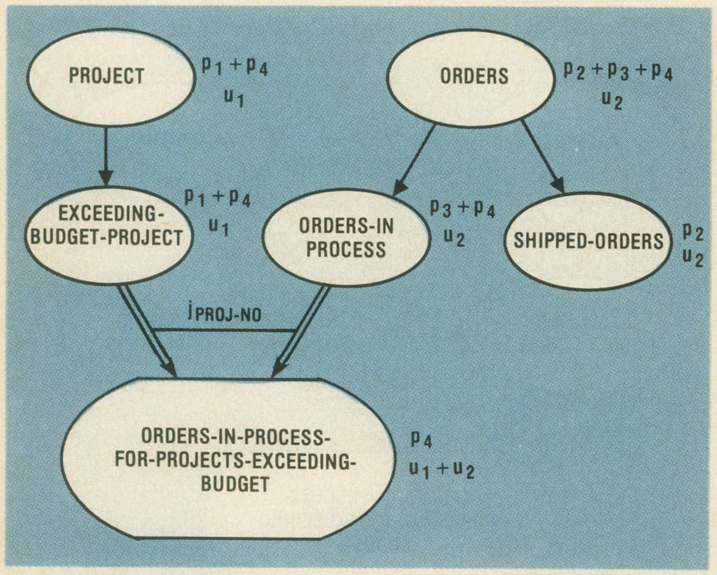


Figure 21. Merging of graphs in Figure 19 and Figure 20. Note that the probability of accessing PROJECTS and EXCEEDING-BUDGET-PROJECTS has increased because each appears in a number of query graphs.

We have successfully used our methodology in a number of applications including the ABC Agency inventory database, Naval Printing Office database, a Telephone Answering Service Processing System, a Happy-Boozer Bar database and a database to support an IFIP conference. We found that the method is easy to teach to people because the designer has the freedom to use familiar models.

We have also been using the methodology in a class of approximately 50 students taking their first undergraduate database course. The students receive one to two lectures for each phase (squeezed between regular lectures.) For the course term project, the students teamed up in groups of two to find the information requirements of an organization, designed the database system, and implemented it on an available database management system. The only step of the methodology not required in completing this project was the optimization of the LAP schema. From the approximately 20 designs and implementations on each application, about five were excellent. Ten were good designs with complete requirements and design specifications.

One of our initial hypotheses was that task emulation would speed up implementation. The experiment with the students verified this assumption. Task emulation helps to ensure that the logical schema is complete, because if some parts of the schema are not covered, some tasks cannot be emulated. Also, each emulated task forms the skeleton of the application program (transaction) that is to carry out the task—the part that deals with the necessary I/O interactions with the database. Therefore, very little work is left to complete the implementation of the application program. ✻

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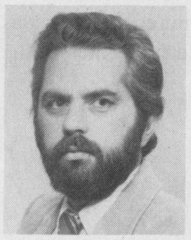

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