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An Integrative Approach for Software Architectures

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Abstract

This paper is on one hand a *survey* on /Na 90/ and newer results. On the other hand, it summarizes the *integrative nature* of the approach to architecture modeling presented there. Different views and aspects are brought together, which all are important, when building up or changing an architecture: the static part (how to compose components with connectors), the different paradigms and abstractions which can be used (locality, layers, object-orientation abbr. OO), bigger parts as subarchitectures and subsystems, and various patterns to be followed. Further and important aspects like semantics, concurrency, abstract connectors and the different mechanisms for their realization, distribution, and different styles, are regarded as well.

We follow the guideline, that if different artifacts are used, the relations between them must be clear and obvious. Furthermore, all fragments, artifacts, and documents - for architecture modeling as well as for other working areas of software development - must build up a product model for the system to be constructed or maintained. Both ideas come from the *architecture for buildings* (standard views and building information model).

Keywords: software architecture modeling, multiparadigmatic and integrative approach, clear relations between different artifacts, different views or aspects, overall and architectural configuration, analogy to the architecture for buildings

1 Introduction

The *term architecture* was first used for buildings. There, it denotes the overall result of the design process, which consists of surveys, floor plans, details to these plans, additions, and annotations, see section 2. The underlying views and notations are accepted worldwide. The architecture consists of many artifacts, aggregating different views, aspects, details, and corresponding data. However, it is always clear, how these aggregated items are related to each other, and how or why they form a description and plan for the whole building.

The *term software architecture* tries to introduce a similar understanding in the field of software system construction. We see that by looking at the covers of many books on software architectures, which mostly contain a building or a fragment thereof on the cover page (a bridge, a cathedral, a part of the outer shell). The software architecture is the essential description in the whole development process for software, it fixes the most important decisions, it determines the long-term properties of the software, and it predetermines the management, quality, and documentation of the process and the final product.

Nevertheless, there are quite *different* understandings of and *approaches for software architectures* in different domains /SEI 10/ or industrial sites /HK 07/. For example, there are *functional* or procedural approaches /Sc 13/, *process-oriented* approaches, (either (i) using processes as fundamental units, e.g. in telecom or automation software, or (ii) deriving the architecture from business processes /KM 04/, or (iii) detecting the architecture from the processes of a given program /PD 07/, or (iv) regarding the form of the design process), *object-oriented* approaches /JC 92, Me 97/, or *data flow* approaches, to name some of them. UML /BR 05/ collects different approaches with low effort to integrate them. This is better for specific and subset situations /Ru 11, Ru 12/. The concepts used for software architecture notations stem mostly from underlying programming paradigms and languages. In the 80ies, there were books on "structured analysis and design" which are no longer in the focus of software architectures. A variety of books on software architectures concentrate on the problem field of software architectures and looking at it from different views and perspectives. In this article, we concentrate on notations for architectures and methods to use these notations.

There were a lot of *papers* paving the way to a comprehensive understanding of software architectures as /DK 76, HP 80, Pa 72/. In the history of software architecture *books* we find /Na 90/, with predecessors /Al 78, Le 88/. We also see some books on programming languages, where the programming language has an architectural part, which can be regarded as a module interconnection language, as Eiffel /Me 91/ or Ada /Bu 84, Na 03/. Software architecture is still an actual topic, which we see from the vast amount of available books in the field /BK 03, Ja 00, SG 96/. The report /GS 94/ even claims that we live in the golden age of software architectures.

This paper is a *survey* of /Na 90/, also containing newer parts. The approach presented follows the ideas of architectures for buildings. Especially, it aims at building up artifacts where the mutual relations inside and between artifacts are evident. Furthermore, it should be clear what belongs to the architecture and how the parts of the architecture are built up and put together. We call the *approach integrative*. The message of this paper is that concepts, methods, and notations integrate along different dimensions, as they combine different paradigms, different views, and different hierarchies.

There is *neither a discussion* on architectural *tools* in this paper, nor on development tools in general, not for software construction, and not for application development, e.g., in the engineering domains. For all of that, the reader can find comprehensive collections of references in /Na 96, NM 08/.

The *contents of this paper* are as follows: In section 2, we discuss the situation of architectures for buildings. Section 3 introduces the different static parts of software architectures, namely components, connectors, but also syntax and method rules. Section 4 discusses further extensions, namely for semantics, concurrency, concrete forms of connectors, and for distribution. Section 5 transforms different notations of architectures (as pipelining, dataflow, etc.) back to the standard notation. Section 6 puts views, artifacts, relations, etc. together, which build up the architecture configuration. A summary and outlook in section 7 close the paper.

2 What we can learn from architectures for buildings

Let us first have a look on the *architecture* of a building, see fig. 1. The architecture describes the *essential structure* and, thereby, suppresses many details, like how to build a wall, a window, or the interiors. Also, important but more technical parts are left open in the first steps, e.g. how the foundation of the house or the roof is constructed. Specialists are doing this later. Analogously, the sanitary or the electrical installation are planned and constructed later, or, in larger buildings, the engineering design for air conditioning or any kind of automation. Thus, the architecture of a building starts with a sketch and ends with a series of determinations and details. However, they all are closely and also clearly related to each other.

The architect works with a computer-aided architectural design (CAAD) system, 3- or 2-dimensional. The result of this work bridges different levels. Let us have a look on the architecture of a one family house, see again fig. 1. On the topmost level, we see 3- or 2D drawings of the *whole house* from different perspectives. The result of this overview level might also be an animated walk through the house or an augmented flight over the house. One level down, we find the floor plans with more or fewer details, as dimensioning and possibly interior details. Further activities deliver additions, like technical details of the foundation or the roof, and installation plans for sanitary, or electricity. The architect also thinks about the later use of the house, in which room/ area to do what, or how to enter or leave the house, even in an emergency case.

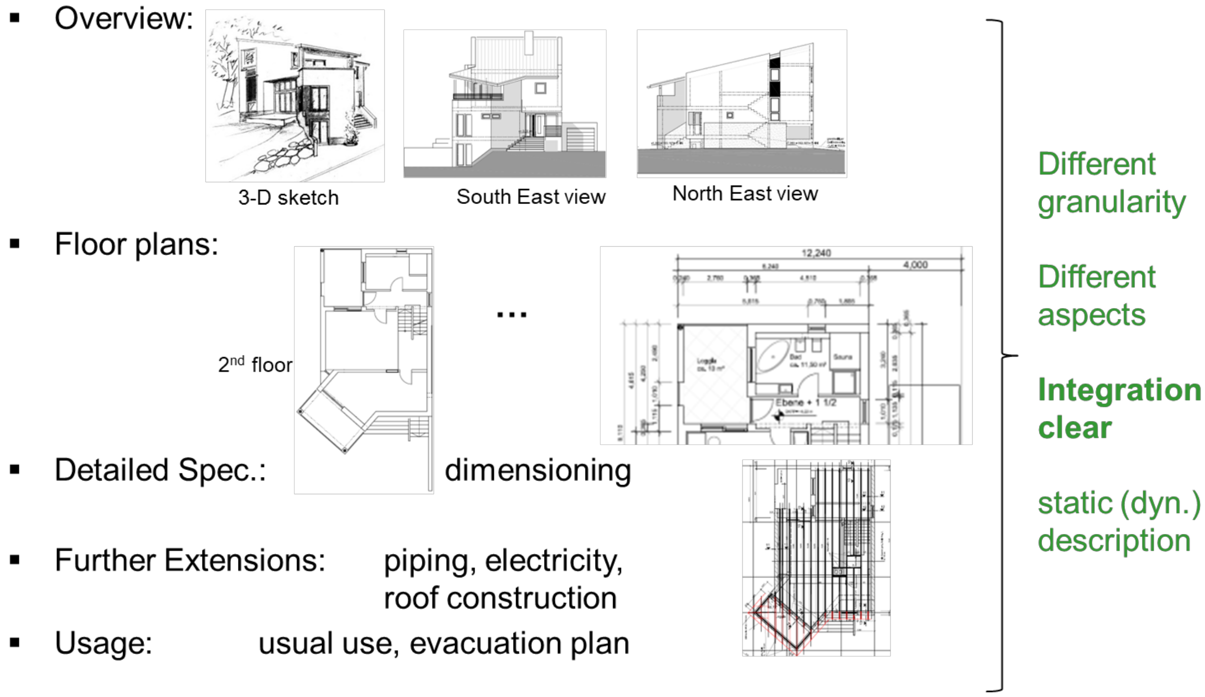


Fig. 1: The central role of the architecture for a family house: Overview, refinements, additions, different aspects, and their relations

Thus, we find different *artifacts* as parts of the house's architecture. Their *mutual relations*, however, are very *clear* and *accepted* worldwide: A building has floors, is looked at from different directions from north to west, shown in different perspectives, and we have different notations for the participating trades (mason, carpenter, plumber, electrician, etc.). Any specific artifact and also its parts can easily be located in the building. This is true for every stakeholder: architect, civil engineer, builder, craftsmen of the different trades, and, to a certain degree, also for the client.

There are *further artifacts* belonging to a building, which are not shown in fig. 1. The statics of the building has to be calculated and approved, the construction has to be planned beforehand and the building has to be constructed. Later on, the building is changed and maintained. There are also economical aspects, which have to be noticed. The design, planning, and construction of the building have to follow legal restrictions, etc. (see /Kr 07/ for the various relations to bordering fields). The artifacts, their structure, and their mutual dependencies are put together in a database system, forming a complex overall configuration. This configuration is called the *Building Information Model* (in short BIM).

There is another topic, which we can learn. Architects in their *education* are trained by *learning from good examples*. Such an architecture example must be big enough. It can be smaller than a real-world example, as that worked out by an architectural bureau. However, it has to scale, i.e. all aspects of practice can be studied by looking on the simpler study example. This is often not the case for examples in the field of software architectures. They quite often are toy examples, which do not reflect the problems of practice. Whenever you see an example containing parts named like "foo", it is an example of this category.

Another aspect is that these *examples* must *reflect good practice*. The examples are carefully selected, as they should reflect a quality from which the student can learn. The examples follow a methodology, which he/ she should use, or they contain a clarity and simplicity from which the student can learn to argue. Corresponding to these goals there is often a lack in the field of software architectures. There is a wish for this kind of examples. If you look at the cover of software architecture books, you find quite often pictures of buildings, the architecture of which is regarded to be a shining example. In some cases, you find bridges, in some other cases gothic cathedrals. The underlying relations between these buildings and software architectures are not studied**.** In /Na 19/ the many relations between software engineering, architecture of buildings, and gothic cathedrals have been worked out for the first time.

What is the situation in software engineering/ software architectures, and how can this situation be compared to that of design and construction of buildings? The architecture of a software system is the center of the whole design, implementation, and maintenance process, the outcome of this process is a complex organization of artifacts with internal structures, built up by using different hierarchies and many mutual relationships within and between artifacts /Na 90/. But in software engineering, we do not have is the standardization of views and aspects, the worldwide standard of notations, and the vision to put everything together to form a building model of some standardized and predefined form as BIM /ET 08/. By the way, a somewhat similar standardization approach for all facets of a product named STEP took place some time ago in mechanical engineering, see e.g. /AT 00/.

3 Concepts for modeling structures

In this section, we give a brief *overview* of components, connections, consistency relations, patterns, and also of classes of systems, each within a subsection. These are the items occurring in the structural part of an architectural description according to /Na 90/.

Components

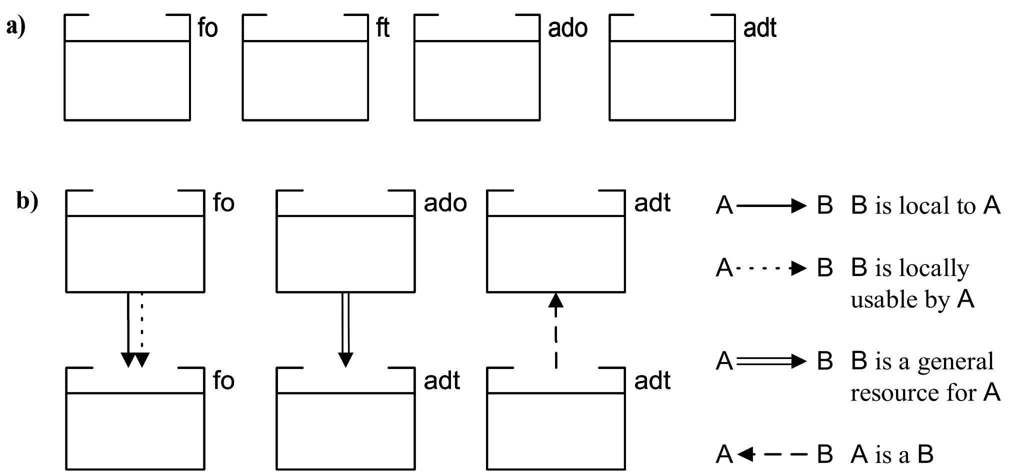
Components are smaller (or below also bigger) parts of architectures having the character of independence. We do not only introduce just units as components. Instead, we distinguish them for different *purposes* (cf. fig. 2.a): for functional or for data abstraction, for single examples or for characterizing types. So, we find function objects (abbr. `fo`, e.g. for a computation or coordination task), abstract data objects (`ado`, for complex data to forget their internal details), and abstract data types (`adt`, for complex data types abstracting from their details, the objects are created at runtime). Strict data abstraction means that data are always encapsulated within components. In the case of concurrent systems with processes, we also use function types `ft`, see below. *Atomic* design components, which are not further decomposed on design level, are called *modules*.

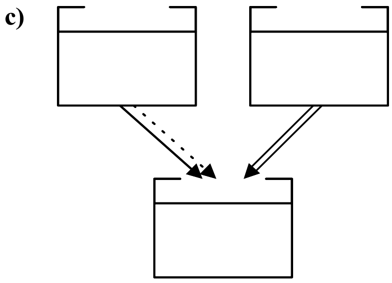
Relations between components

Analogously, we do not only have one *relation* between components (cf. fig. 2.b). Again, we distinguish for different *purposes*: (i) locality (thinking in decomposed and specific tasks), (ii) layers of a system and placing general components on different layers, (iii) object-orientation (thinking in commonalities and differences of types).
Underlying, we find different *structure relations*: (i) a component serves as a local resource of another component (which in Pascal-like textual languages is expressed by nesting), (ii) a component is put on a layer to make use of components of deeper levels, (iii) a type, adt or ft, is the specialization of another type. Therefore, we have three *different hierarchy relations*, where all of them come from programming language concepts.
In the same way, *different and corresponding usability* relations are introduced (i.e. a component is allowed to statically make use of another one): Local usability in locality structures, general usability of another component of a deeper level in layers, and usability within inheritance structures. Thus, we find different *import relations* depending on the situation (for locality, layers, and inheritance). Fig. 2.b gives some examples. In an architecture, we can find locality structures (specific part, only for that system), layers of general components, and also inheritance structures. All three have corresponding internal usabilities between corresponding components, and they can be connected to other structures by further usability relations.

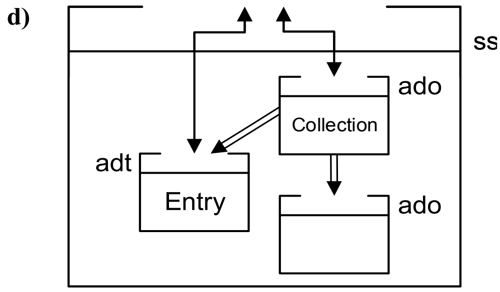
Consistency conditions

Consistency conditions forbid certain structures, which contain the above-mentioned components and relations. For example, it is not allowed that a component is made usable for other components both, by a local usability and at the same time by a general usability relation, see fig. 2.c. Thus, these two relations cannot end at the same component. Another example is that a component cannot import something from another component, which is not provided by this component. There are 28 consistency conditions of that kind. We do not discuss them here. They are the *context-sensitive syntax rules* of the graphical and textual architecture languages.





one of 28 consistency conditions



subsystem: collection ado of entries adt

Fig. 2: Components, relations, and consistency conditions (here only on graphical level)

Subarchitectures and subsystems

We find *subarchitectures* within architectures consisting of components and their connecting relations, and holding consistency conditions. A subarchitecture is a meaningful part of an architecture, which is not separated and closed from the rest.

Subsystems are *bigger components*. Usually, they have an aggregated interface of some of its components. In the body of the subsystem, we find a subarchitecture of inner components. This subarchitecture is separated, as it occurs within the body. In fig. 2.d we see a subsystem aggregating two interfaces. The corresponding components must occur in the body. The body may contain further components. The example is a collection ado of entries of a certain abstract entry type adt.

There are different *granularities* in architectural artifacts in growing *complexity*: from interfaces components of single modules, to their interface, to modules (interface and body, the latter not further decomposed on design level), to two modules with relations, to subarchitectures, to subsystems (bigger components aggregating interfaces and hiding subarchitectures), and to complete architectures. We also find different components in *size*, namely modules and subsystems.

Summing up: Modules are either single *objects* or *types,* they belong to different *abstractions* (functional abstraction or data abstraction). Relations also belong to different situations, local for specific components, layers of general components, inheritance for type components. Therefore, the approach for architecture modeling is *multi-paradigmatic*. By the way, the origin of all these ideas we find in programming language concepts (nesting of components, import relations of reusable components and separate compilation, modeling similarities and differences in OO languages). They have been changed and adapted for the use in architectural languages.

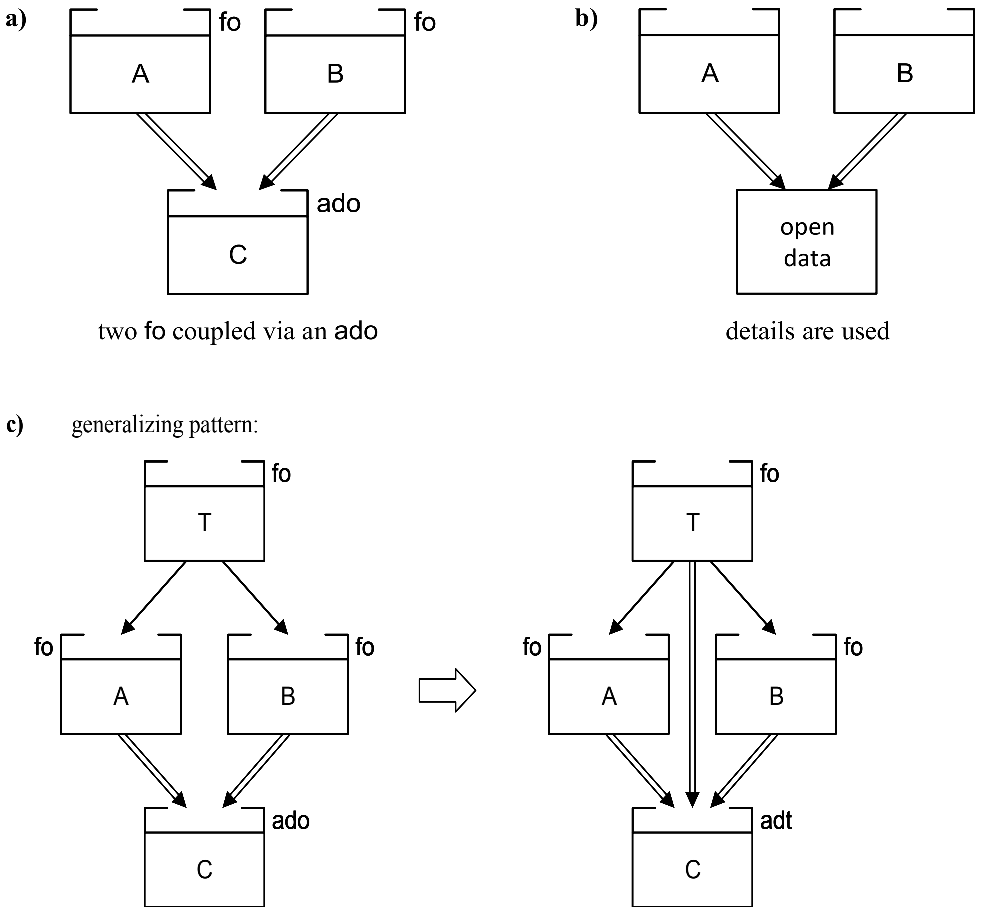
Consistency conditions belong to the *syntax* of architectural languages. Another topic is the recommendations for how to use the language. These are *method rules*, usually named patterns, which we explain next.

Patterns

There are *different kinds of patterns*:
(a) A situation *as it should be*. That is the *usual meaning* of patterns, as coined by books like /BM 96, GH 95, SS 00/. In fig. 3.a, we see two fo modules A and B coupled via an ado module C, which prevents that data details of C are known in A or B.

(b) But also a bad situation (negative pattern or *antipattern*) is useful to show a situation, which should be avoided. In fig. 3.b two components are coupled via an open data structure, which means that A and B know details of C, they should not know.
(c) There are also patterns saying, how to correct a bad to a good situation (*correction pattern*). A rule having fig. 3.b on the left and fig. 3.a on the right side, is such a correction pattern.
(d) There are also patterns transforming an object situation to a more general type situation (*generalizing pattern*). Fig. 3.c gives an example of two function modules coupled by an ado module. If we need more than one coupling, we switch to an adt at the bottom. This enforces a new usability from T to C, as now in the body of T objects are created, which are passed as parameters to A for writing and B for reading.
(e) Furthermore, there are patterns transforming from a fuzzy situation (e.g. many different components from different logical layers use another component of a deeper level) to a clear situation (changed by introducing intermediate abstractions to avoid these many and different uses, see fig. 3.d). We call them *clarifying patterns*.
(f) There are *experience patterns*, e.g. showing in which situations data abstraction should be used (from hiding data details, to different user interface details, or schema details in database systems, etc., thereby listing all applications of data abstraction). Another example is showing that data abstraction comes in multiple layers, e.g. the ISO/ OSI layers /Ta 12/).

All above-mentioned descriptions are *subarchitecture patterns*, how it should be, not be, how it should be corrected, or how to transform for different goals (generalization, gaining clarification, showing experience, or where to use data abstraction and layers of data abstraction).



d) clarifying pattern:

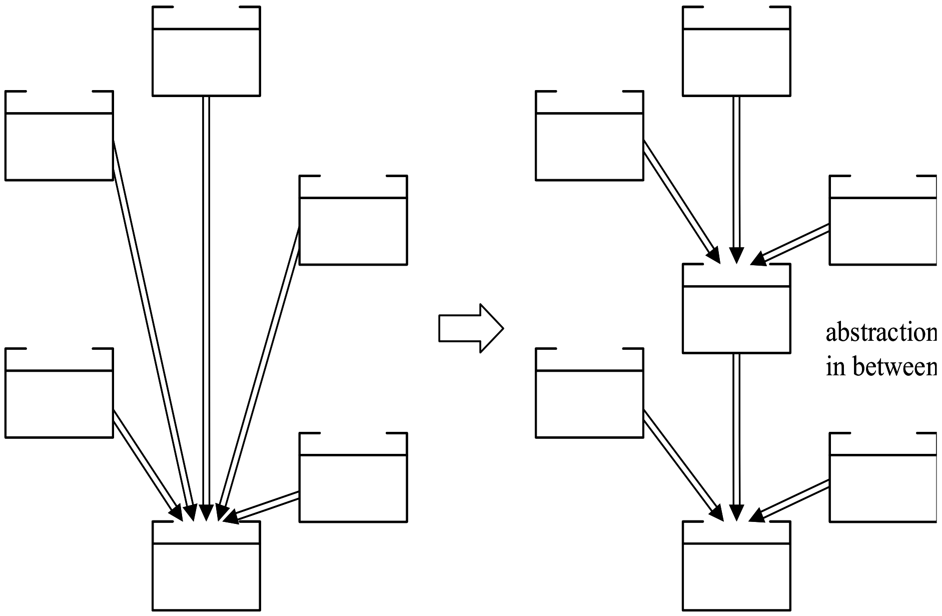


Fig. 3: Patterns of different kinds: usual pattern, antipattern, correction, generalization, and clarifying pattern

(g) *Global patterns* in the sense of complete and recommended build plans for the whole system are even much more important. They are patterns you can trust and follow for the design and development of a whole system.

We now explain such a global plan for a well-studied problem, namely to build a *compiler* according to the *multiphase approach* /AL 06/, see fig. 4. We find a control component on top, starting each of the next level phase components and after its end switching to the next, namely scanning, parsing (context-free syntax check), static semantics (context-sensitive syntax check), intermediate code generation, optimization, addressing and code generation, and post-optimization. These are the phases of the compiler, each of which is finished before going to the execution of the next. The first steps build up the so-called frontend, the last ones the backend of the compiler. At the bottom we find the data structures which loosely couple the phase components; namely source text input, tokens (lexical units) list, abstract syntax tree, attributed tree, intermediate graph, machine code, and optimized machine code. Fig. 4 shows only a part of the compiler.

At the top, we have a functional object module, in the middle, we have functional subsystems, at the bottom, we find abstract data objects or subsystems. In the case of a language with separate compilation units (different source code units can be compiled in one compilation run), the bottom layer consists of abstract data type components, then with slightly different imports, see fig. 3.c.

Patterns (of whatever form) have *not* the purpose to *avoid thinking, arguing,* and *adapting*. They are just good examples for the architecture education as a basis for discussions, see arguments in section 2. In my opinion, it is a wrong perception that the complete design process can be organized in form of patterns in a way that the designer only has to find the right and available pattern to paste it into his/ her architectural design and to combine it with other patterns, which are also available and pasted.

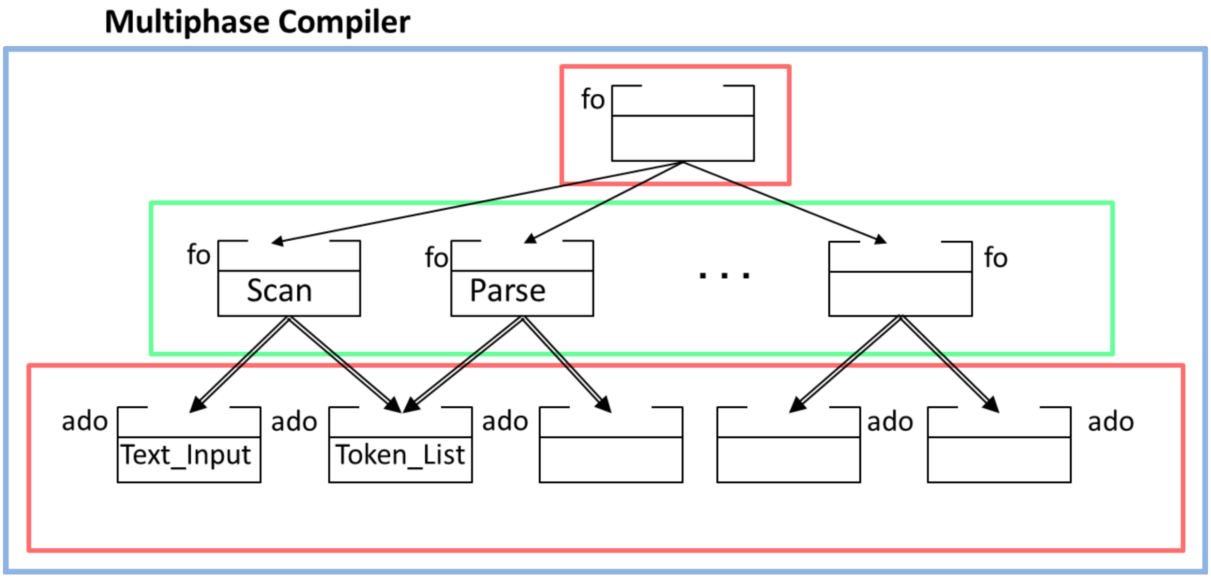


Fig. 4: The architectural structure of a multiphase compiler: a sketch

Classes of Structures

There are three basic *structure classes* of software systems (batch systems, interactive systems, and concurrent systems, the latter mostly also embedded). The above example of a multiphase compiler is a batch system. A big part of industrial systems is of one of these three forms. They define standard structures, i.e. global patterns, which are a good foundation, if a system of one of these three kinds has to be designed.

There can also be *mixtures* of these basic structure classes, like a batch system for making complex computations, which, for example, also has an interactive part to change parameters in an online mode. Then, the main part is batch, that specific part is interactive.

Application domains are business administration (BA), like calculating insurance contracts, technical computations (TC), as a crash simulation, embedded systems (ES), as automation and control of a chemical plant, systems programming (SP), like building an operating system, etc. The corresponding systems build up *application classes*. We find batch systems in BA (monthly salary computation), in SP (compiler), and in TC (crash simulation). All have a similar global structure, although they belong to different application domains. We find interactive systems in BA (change of customers' data) or SP (design tool). A concurrent system can exist in ES, but also in SP, e.g. an operating system. Therefore, from the pattern relevance point of view, structure classes are more interesting than application classes.

A further *extension* of the above classifications (structure classes, application classes, etc.) can be made according to the following *dimensions*: (a) underlying *interaction mechanisms* in systems (e.g. call vs. events), (b) *target system* platforms (mainframe, personal computer, network of machines, fine-grained sensor networks), (c) *distribution* (from bound on one computer to distributed cloud computing, or even computed on the fly /OTF 20/), and (d) how *computation is done and gained* (fixed in program code, interpretation of specifications, selection of rules to be applied, code generated, tables for interpretation, machine learning from examples).

Most important of the above classification are *structure classes* in the sense of formative experiences and examples in education. In fig. 4 we see an example from the systems software domain which shows the characteristics of batch systems (different computations on the second layer put together by a control component on top, which are loosely coupled via data abstraction components). This global pattern we also find in different other application domains. In the same way, we can argue about interactive systems or concurrent systems. Taking also the application classes and further differentiations into account, may refine the arguments and deliver further variations of structure classes.

4 Various Further Aspects are Necessary

In section 3, we have discussed syntactical and static properties of architectures, how they are denoted, and which methodological hints we can find. Now, we discuss *further aspects*, like semantics, concurrency, or distribution.

We follow the approach, which we discussed in the architectural design for buildings, see section 2. We define further refinements, views, and detail levels. However, we do not define new artifacts, where it is not clear or obvious, where they appear, and how these artifacts are related to other ones. We rather annotate already existing artifacts. Thereby, we define further aspects as *enrichment of the architecture* notation as explained in section 3. Therefore, it is always clear, where and in which sense the annotations deliver further information and to which part of the architecture the extended information belongs, see arguments in connection to fig. 1.

Semantic annotations

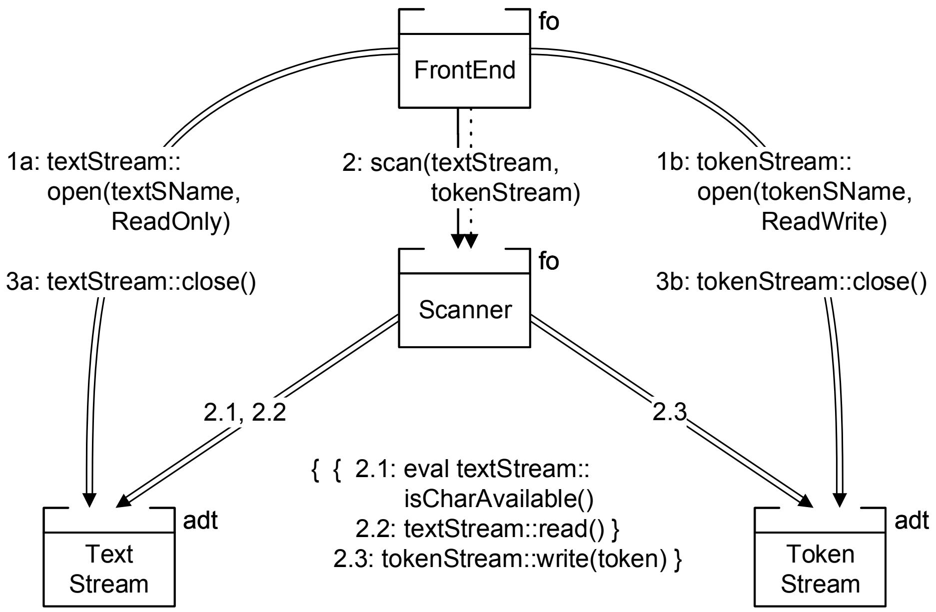
Let us go back to the multiphase *compiler* example (see fig. 4) and let us concentrate on the *scanner part* (see fig. 5.a). We assume that the underlying data structures are `adt` modules, which enforces a modification of the usability edges, see arguments of fig. 3.c.

We can specify the *semantics* of component *interfaces* by *pre-* and *postconditions*. For example, the scanner transforms a sequence of characters (precondition) into the corresponding lexical unit (or token, post condition), e.g. an identifier, a word symbol, a delimiter, a literal, etc. of the underlying programming language.

For the interface of the underlying data types (first part of fig. 5.b) we here use a *notation* of *functional* languages. In our example both are queues, e.g. the scanner writes the tokens at one side, the parser reads them from the other side. Our example in 5.b shows a stack, more relevant for the parser than the scanner. Usually, we use an Ada-like notation for interfaces in the textual part of the architecture language.

For this interface, we can give a semantical description in form of *algebraic equations* (see /Gu 76, LZ 74/). In the lower part of fig. 5.b we find an algebraic description of the interface under the assumption that the middle part of the fig. 5.b holds.

In this way, either by pre and postconditions or by algebraic equations we can specify the *semantics of single components*. The specifications belong to the interfaces of the components of fig. 5.a.



a)

```
spec ITEM_STACK_TYPE
    –– imports of other specs are necessary, e.g. of ITEM
    sorts ITEM_STACK_TYPE
    operations
                        –– export interface:
                        NEW: ⟶ ITEM_STACK_TYPE
                        PUSH: ITEM x ITEM_STACK_TYPE ↦ ITEM_STACK_TYPE
signature: sort / ops part    POP: ITEM_STACK_TYPE ↦ ITEM_STACK_TYPE
partial / total functions     READ_TOP: ITEM_STACK_TYPE ↦ ITEM
                        IS_EMPTY: ITEM_STACK_TYPE ⟶ BOOLEAN
                        IS_FULL: ITEM_STACK_TYPE ⟶ BOOLEAN

    preconditions
                        –– preconditions of ops such that algebraic spec. holds
                        pre POP(ST: ITEM_STACK_TYPE) = not IS_EMPTY(ST)
                        pre READ_TOP(ST: ITEM_STACK_TYPE) = not IS_EMPTY(ST)
                        pre PUSH(EL: ITEM; ST: ITEM_STACK_TYPE) = not IS_FULL(ST)
    equations
                        for all EL: ITEM, ST: ITEM_STACK_TYPE:
                        IS_EMPTY(NEW())
semantics of ops by           not IS_EMPTY(PUSH(EL, ST))
determining mutual relations, not IS_FULL(NEW())
assuming preconditions        not IS_FULL(POP(ST))
                        READ_TOP(PUSH(EL,ST)) = EL
                        POP(PUSH(EL, ST) = ST
end spec ITEM_STACK_TYPE
```

b)

Fig. 5: Semantic annotations: Interface specifications and runtime traces

An even more important part of the semantical description is the *runtime semantics*. Not in all cases, this part can formally be defined, or it is useful to do it. However, we can define the runtime semantics at least in a coarse form by *traces* /Kl 00/, see again fig. 5.a. The trace specification of fig. 5.a says that Scan has two loops. The inner loop reads characters from

Text_Input belonging to a token (2.1 and 2.2), and writes the corresponding token to Token_List (2.3). In the outer, loop this is repeated until Text_Input is completely read (2.1). Before, at the beginning of the scanning process, Text_Input and Token_List are opened (1.a, 1,b). Then, Scan is called from Control. The files are closed at the end (3.a, 3.b).

Traces only show in which order the components are visited. However, they do not show, what is done during the visit of a component. However, traces are better than nothing. They correspond to sequence diagrams of UML /BR 05/. Introducing traces within architectural diagrams avoids defining another artifact, as the sequence diagram, where its contents have to be related to the diagrams artifact. Following the argumentation of section 2, traces are annotations of the diagram and not a new artifact.

For the scanner of fig. 5.a. we can even give a nearly complete semantical description, not only the algebraic interface specifications and the coarse trace specification. The behavior of the scanner component Scan can be described by a finite automaton (or alternatively by a regular grammar) both defining the lexical syntax of the programming language to be scanned /AL 06/. This corresponds to the body of the scanner in fig. 5.a. This, together with the interface semantics and the traces, gives a nearly *complete and formal semantical description* of the situation described in fig. 5.a. We could also have chosen the parser part or the context-sensitive analysis (static semantics) part, to argue in the same way.

We should mention that examples of such a *formal* degree (scanner, parser, context-sensitive analysis, etc.) are rather *seldom*. Software systems can depend on taste (like the user interface of an interactive system), on nonfunctional efficiency parameters (like the runtime parameters of an embedded system), on restrictions of the underlying hardware (the system is to run on a special hardware system, a part of the system representing a specific component must be used, which is programmed in a specific way and only runs on certain remote hardware), and so forth. In general, formal *semantic definitions* are in most cases *only partially available*: some interfaces, typical traces, formal descriptions only for some components' behavior.

Concurrency annotations

For inherently *concurrent problems* we need different *processes running concurrently,* the competition and collaboration of these processes, and an agreement on how to synchronize in the case of concurrency and competition for resources and of collaboration. Any sequential schedule would make the solution harder to understand. It would also avoid that a certain part can continue, if another part is blocked for some time.

In fig. 6, we see the well-known *producer-consumer* example as a subarchitechture in graphical form. Producer and Consumer are function objects (two separate single components in the architecture having the character of a function). In between, there is a Buffer component as an abstract data object, as only one buffer is needed.

Producer and Consumer have to work independently. Thus, we make both to a *process*, expressed by *annotations* p for the components Producer and Consumer. As both are processes, we have to define a synchronization for the case of parallel access. It is not necessary to make the buffer to a process. This *synchronization* is expressed by the *annotation* Monitor (mutual exclusion of all operations of the buffer /BF 95/) as a synchronization specification (in short sp). The synchronization protocol could also be a protected object of Ada (mutual exclusion of writers, but parallel readers, if no writer is active /Na 03/), or anything else suitable.

Again, we see that we can *annotate* an architecture diagram to express *concurrency aspects*. This avoids further and separate artifacts.

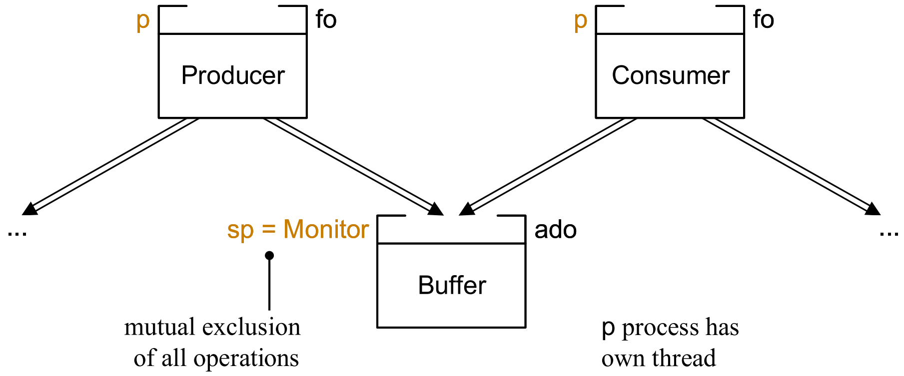


Fig. 6: Annotations for concurrency: processes and synchronization

In the context of concurrency, we might have many producers or many consumers. It is not reasonable to paste as many - function object and process - components as needed. In some cases, the number of such processes cannot even be determined at program development time. For such situations, we introduce *function type components*, from which we can create as many function objects as wanted at runtime in the bodies of using components. These processes, however, cannot be directly seen on architecture level.

For *embedded systems,* also the explicit *start* and *stop* have to be modeled. Embedded systems run "forever" until they are not explicitly stopped in a controlled way. Analogously, they are explicitly started in a controlled way. In the same way, *emergency handling* has to be modeled. Both start/ stop as well as emergency handling can be modeled by the above and further annotations, which is not discussed here. This altogether explains that the productivity of developers programming embedded systems is much lower (about one third of the productivity of sequential systems, as further additional tasks have to be solved (processes and synchronization, controlled start and stop, and emergency handling).

Component use connections: abstract and concrete

Up to now, a *usability edge* between a service user component A and a service provider component B, offering one or different services, is denoted in an *abstract form*, see fig. 7.a: There is a usability relation between both. It can be a local, a general, or an inheritance usability relation. It says that a service of B will be needed for A. The service use is written down in the code of the body of A. At runtime, if the corresponding part of the body of A is executed, the service is provided.

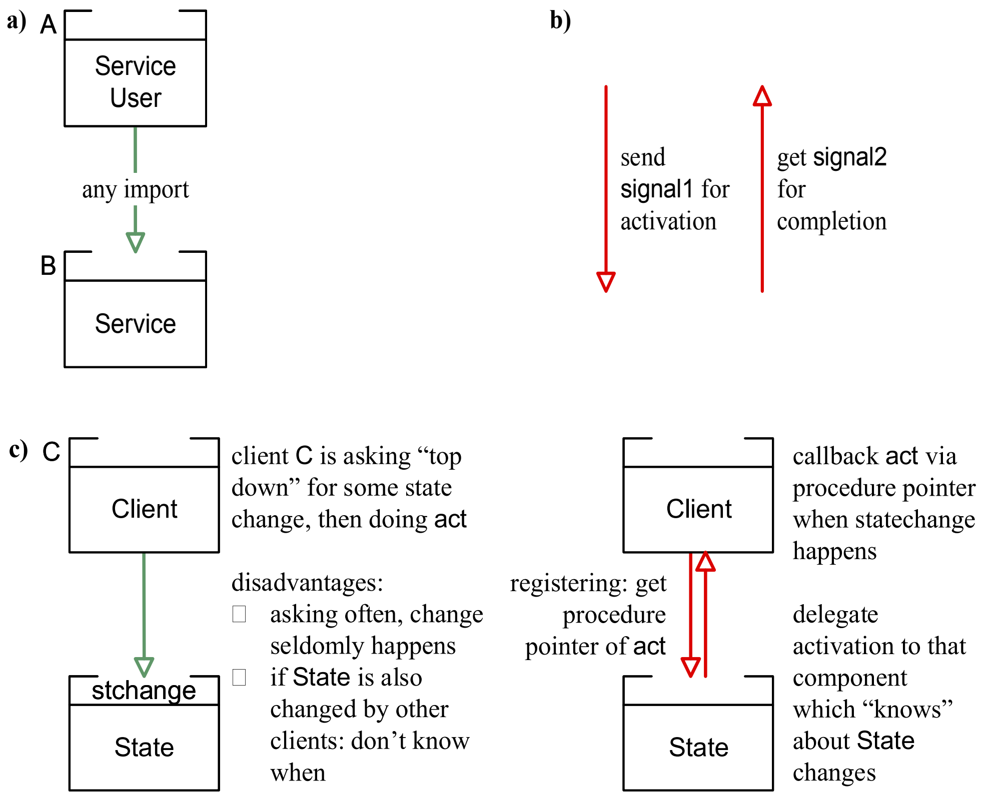
Up to now, we had in mind that the service is realized by a *procedure* or *function* of the interface of B and a corresponding *call*. The service provider may be a fo, ft, ado, or adt component. The caller invokes the call, the caller is stopped, and the service is called at the callee side. If the callee has finished, it stops, and control goes back to the caller.

This *abstract situation* 'service of B is used from A' can be realized by *different mechanisms*. The service might be provided by a coroutine, an entry call, or a task activation. In all these cases A and B may run in parallel. A and B are synchronized later again, either by programming language mechanisms or by means delivered by the programmer.

We discuss only three of the many possible forms. In fig. 7.b, we see that the service of B is activated by an *activation signal*, naming the service and providing the parameters. After service completion a *completion signal* is sent back, containing eventual result parameters. In the meantime, A and B may run independently. Also, signals, events, triggers, or interrupts may be used to handle this service request and service provide situation.

In fig. 7.c, a *callback situation* is discussed. In the left part, the situation is described: Client A would like to answer to a state change of B by doing an activity act. This happens, for example, if a user is doing something, which has to be answered by the activity act. Instead of polling (A is always asking B whether the state change has already happened), the operation act is delegated to the State component. State registers for act and gets a procedure pointer for act. Situations like this are often interpreted in a wrong way. People say 'my architecture has completely inverted'. This is not the case: The abstract situation (cf. fig. 7.a) remains the same, the mechanism for realizing it, however, has changed.

An even more complicated situation we find in *event handling systems using broadcasting*, see fig. 7.d (and /Kl 00/). There are components Producer1 and Producer2 producing events e and e' which are sent to the Broadcasting Service. The components Comp1 and Comp2, for example, have registered to get the event e to react by act1 and act2. This corresponds to the abstract situation that Producer1 and Producer2 may use service act1 of Comp1 and act2 of Comp2. Corresponding to who has registered at runtime, dynamic use switches are possible, which can produce a system behavior, which is hard to understand and more confusing than goto-programming. It should be denoted at development time, who is using whom at runtime.



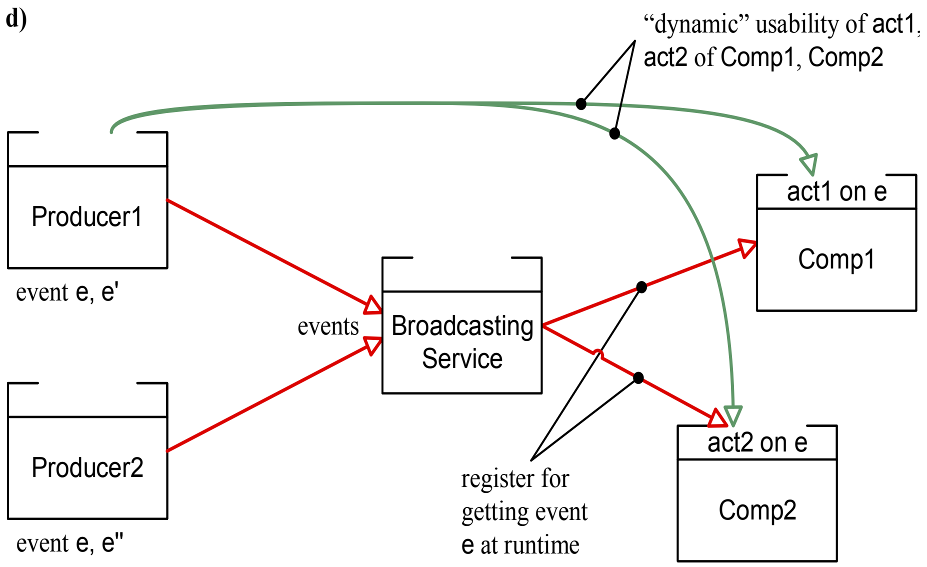


Fig. 7: Abstract use and three different concrete mechanisms

Looking on all these situations, we see that the underlying *abstract situation* of fig. 7.a is realized by using quite different concrete mechanisms for service use. Therefore, we would rather use the abstract situation of fig. 7.a and provide *different annotations*, as pc for procedure call, cc for coroutine call, ec for entry call, cb for a callback, and via bc for via broadcasting. That has the advantage of abstraction (the underlying abstract situation is to be seen directly) and flexibility (the used mechanism can easily be changed).

Distribution

A further aspect to be studied now is *distribution* and *deployment*. A software system is divided and deployed on different computers. This is done in the later stages of development, which starts with virtual and abstract notations.

Fig. 8.a shows the sketch of the architecture of an *interactive business administration system*, which was *reengineered* from a monolithic mainframe system /Cr 00/, by introducing subarchitectures (inner details not shown in fig. 8.a), which are clear areas of concern: The control part for managing the dialog, the UI part to keep all UI details away from the inner system, the main application parts determining the functionality of the interactive system, and the underlying database subsystem, which hides data and schema details. Reengineering via subarchitectures of clear concern has made the system to consist of loosely coupled parts as shown in fig. 8.a.

We now decide to put these parts on different machines: the UI part on intelligent workstations, the control, the main business functions and the data handling on function and data servers, by reasons of security or redundancy. The lines of separation are given as an annotation in fig. 8.a, the used distribution infrastructure, here Corba /COR 20/ for remote procedure calls, is also annotated.

Fig. 8.b shows the technical solution for Corba /Kl 00/: On both sides of a cutting line and distribution, technical components are introduced, which are either provided (RPC Basic Services, Marshalling, Unmarshalling) by Corba or are generated by Corba from a specification (client stub and server stub). They provide that the procedure call is transformed into a data stream, sent over a connection, put together on the server side, and is executed on the server

side. Similarly, it finds the way back. There are various distribution infrastructures, working similarly as Corba, which can also be used, e.g. Remote Method Invocation for Java /WR 96/.

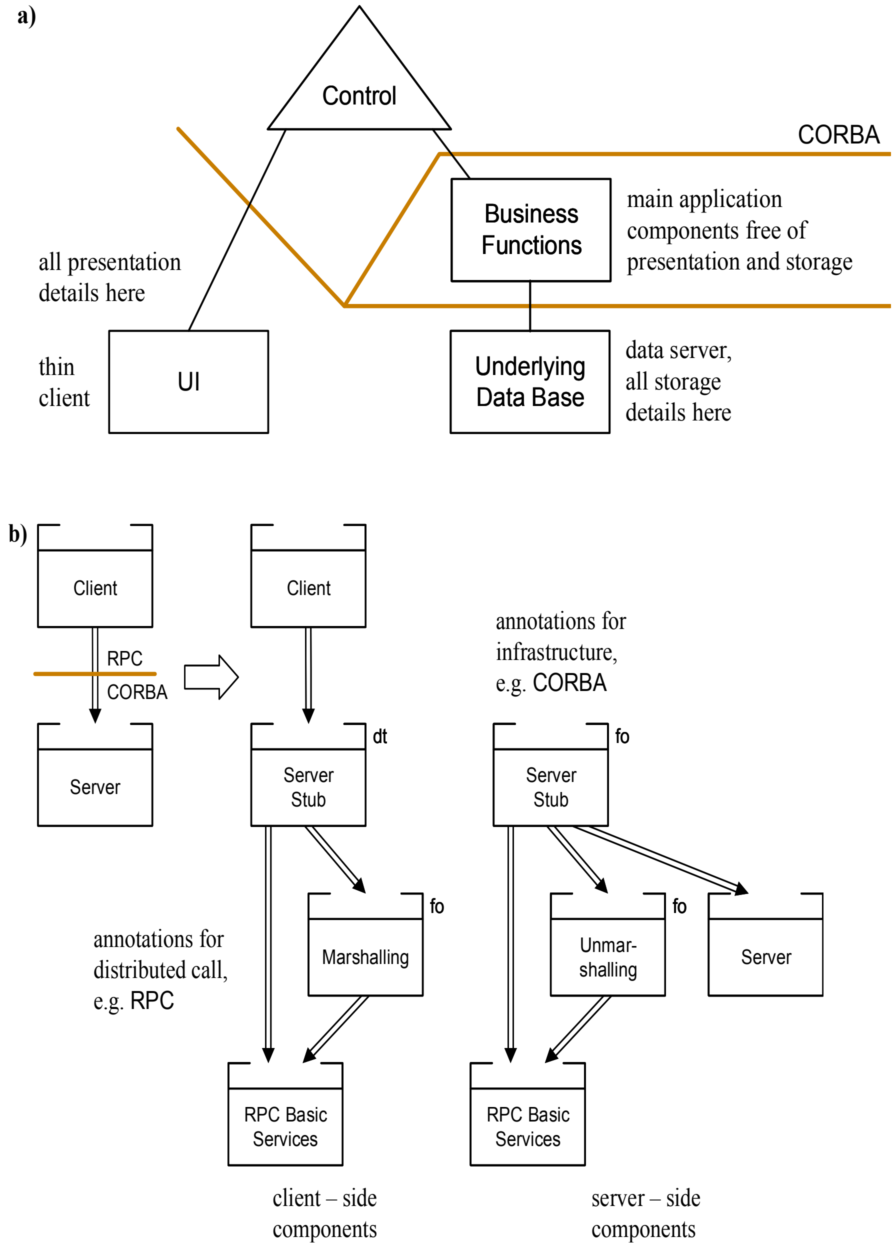


Fig. 8: Distribution characterization and its realization by making use of a distribution infrastructure

Two remarks at the end of this short discussion: (a) Again, it should be noted that the more *abstract solution* with *annotations* says more than the detailed technical solution. It also allows to easily change the annotations and to use another distribution infrastructure. (b) Distributing software over different machines might introduce some technical concurrency. For example, if different main application functions run in parallel and have access to a data server. Then, these accesses have to be synchronized.

Styles: Integrating different notations

In /GS 94/ different notations for architectures have been introduced for specific integration situations occurring in software construction. They were called *architectural styles*. Reading about these styles creates the impression that any of these styles introduces a separate notation and that these different notations have nothing to do with each other. They all lead to *separate architecture worlds*.

/GS 94, SG96/ introduce different *architectural notations*, namely (a) pipeline, (b) data flow architectures, (c) loosely coupled systems, and others. We only discuss pipeline architectures here and leave the other style discussions to a separate and forthcoming paper.

We express *pipeline architectures* by the concepts we have introduced so far. Fig. 9.a gives an *example* of such a pipeline architecture. There are three components f1 to f3, executed one after the other, i.e. the output of f1 is the input of f2 and so forth. They make up one bigger component F, where the input of which is directed to f1, and the output of f3 is the output of F.

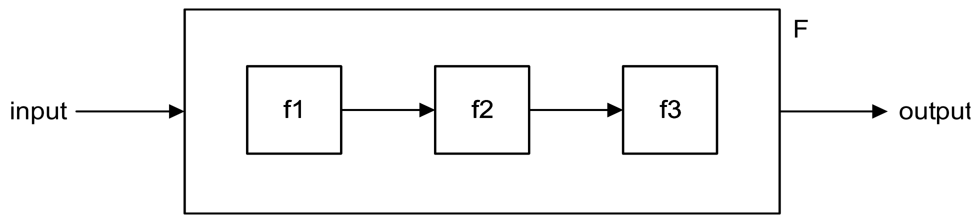
There are mainly *two* possibilities for the *semantics*. The first, here called *discrete case*, works in the way that F takes the input, then executes the pipeline - functions f1, f2, and f3 - and outputs the result. Then, F takes the new input. In the second possibility, called *continuous case*, the input of F is passed to f1. After f1 has produced its result, the next input of F can be taken by f1. Thus, in this case, three inputs of F can be taken and passed to f1, before the first output of f3 gives the first output of F.

Fig. 9.b gives the *simulation* for the *discrete case*. The control component takes the input from input, then controls the sequence of executions f1 to f3 , where for every fi an output is passed back to Control. At the end of this sequence, the output of f3 is passed by Control as output of F.

Fig. 9.c simulates the *continuous case*. Now f1, f2, and f3 work in parallel, so they are made to processes, see annotations p. The input is taken from f1, passed by an entry call to f2, and f1 takes the next input. It should be noted that further semantics are possible, which can also be simulated.

What we have demonstrated for pipeline architectures, can also be shown for the other style notations, as data flow architectures, loosely coupled architectures, and others. Thus, all these different notations are traced back to the modular notation introduced above in section 3. Therefore, the style notations - like pipelining - are not really new and completely different. We can use them for architecture modeling, just as abbreviations for situations we can express otherwise in the standard notation.

a)



the result of f1 is input to f2; the result of f2 ist input to f3; ...

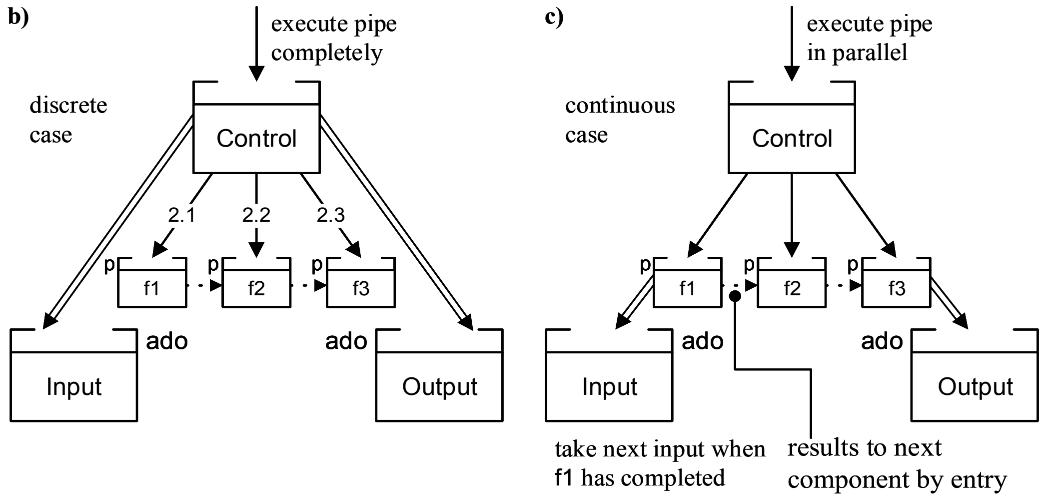


Fig. 9: Pipeline architecture style is traced back to the standard notation

Thereby, we found another *integration dimension*: We have integrated different notations by tracing them back to a 'standard' notation. Furthermore, as the *semantics* of the style architectures can vary from paper/ book to the next, we can *define* the semantical differences *appropriately*.

5 Relations between artifacts and putting together

Hierarchies and other relations

The *architectural configuration* of a software development process *consists* of the following *artifacts*, in the sense "all is part of": overview diagram, architectural diagrams of parts of the overview diagram, architecture diagrams of subsystem bodies, text artifacts for component interfaces and also for detailed usability relations. The examples of this paper were mostly on diagram level and there on the level of overviews. The architectural configuration is an organization relation for "collecting everything that is needed" for architecture modeling.

Within artifacts, we find *internal diagram hierarchy relations* for expressing locality, layering, and inheritance within a diagram. Structure relations as "is local to", "located on a certain abstraction layer", or "is a" establish underlying relationships, from which we select corresponding usability relations (import relations) between components, as "locally usable", "usable between layers", or "usable within an inheritance structure".

There are *hierarchy relations for delivering details*: For example, from a shorthand notation of a subsystem to its details (the aggregated interfaces, the architecture diagram for the body), from a module to its textual description of the interface, and also to the structure and usability relations as text clauses. The relations are from a diagram to a more detailed diagram, or from a diagram to its corresponding detailed text. We also find details from an annotated diagram to the details of the annotation in another diagram, so here from diagram to diagram.

Some of the relations come from/ go to the *outside of the architectural configuration*: (a) From a requirement to the parts of the architecture realizing this requirement, or vice versa from architectural items to the requirement items they belong to. We also find them (b) from architectural items to the realization/ programming/ coding items or vice versa, (c) from architectural items to the management items organizing the work or vice versa, (d) from architectural items to quality assurance items or vice versa, (e) from architectural items to documentation items explaining the decisions or vice versa. All these relations facilitate to understand, realize, or manage the architectural configuration. They were not regarded in this paper, see /Na 96/.

The architectural configuration is the *center* or the most important part of the *overall configuration*, which also contains parts for requirements, realizations, management, quality, and documentation. The architectural configuration contains the main decisions, the long-term quality properties, and the organization of the whole development process. To a big part the overall configuration is determined by the decisions in the architectural configuration. The overall configuration contains all documents/ artifacts of the development process, together with corresponding relations inside and between the documents/ artifacts.

These relations split into different *fine-grained relations* inside and outside of the architectural configuration and within the overall configuration. Examples are: (i) For an interface item of a module which is a procedure header to the procedure definition in the programming part, (ii) for a module to its explanation in the documentation, (iii) for a module inside the body of a subsystem to the specific quality assurance measures taken for this module, (iv) from an annotation in a diagram to the corresponding detail information, etc. These fine-grained links /Na 96, NM 08/ are very important and have to be obeyed in a program systems' development. In a usual tool suite, there is no proper support for them.

Different languages are used

- *Diagrammatical* languages for overviews, *textual* languages for details. In this article, we concentrated on the graphical languages.
- *Formal* languages, for the specification of an interface are used, or *informal* ones to sketch the purpose of a component in the documentation.
- Architectural *style notations* stand for abbreviations of architectural situations as sketched in section 4.
- Various forms of *consistency relations* (context-sensitive syntax) appear inside the architectural configuration.
- Different forms of *method rules* and *patterns* say what and how to design.
- The architectural languages consist of different parts along with a historical development /Al 78, Le 88, Na 90, Bö 94/ and this paper.

Usable for different architectural approaches, applications, and problems

The approach can be used in different ways:

- *Functional decomposition* with data abstraction, see the compiler example. It can also be used for *layers*, e.g. for different layers of data abstraction. We can model *inheritance* hierarchies.
- It can be used in *OO* approaches by some form of *"backward" simulation*: fo and ado components as abstract classes, inheritance inside, and layering between components outside of inheritance.
- *Style notations* can be introduced as abbreviations of modular situations, for pipeline, data flow, or loosely coupled systems.
- *Structure classes* (batch systems, interactive systems, and embedded systems) are characterized by global patterns. Further differentiation, e.g. for application domains, etc. (see discussion in section 3) can be expressed.

- The approach can be used for *new development,* for *reverse* and *reengineering,* for *maintenance,* and for *extensions* of systems. It can even be used for systems written in old programming languages.

Remarkable experience in architecture modeling

The software architecture *approach*, presented in this paper, has been used for research, design, and development *tasks* of *remarkable size*. We mention only some of them here.

The main activities were tightly *integrated tools for software development* in the IPSEN project /Na 96/, tools in *chemical engineering* in the IMPROVE project /NM 08/, and design tools for *mechanical engineering* /NW 99/. In all these cases not only tools for architectural design were regarded. Also, documentation, management, and requirements engineering have been studied. Furthermore, specialized integration tools to keep fine-grained relations between artifacts consistent to each other have been studied and implemented.

But there are also other and *specific applications*, as technical applications containing *expert systems* /Ba 95/, *reverse and reengineering* in *business administration* /Cr 00/, reengineering of *telecom systems* /Ma 05, Mo 09/, tools for *authoring* /Ga 05/, and for *automotive* /Me 12/, and smart homes /Ar 10, Re 10/. Furthermore, in a project aiming at new concepts for a non-standard database system in the *systems programming domain*, there are many architectural descriptions /Ba 00/.

Finally, in /KN 07, Kr 07/ we came back to the architectural design of *buildings*. We extended CAAD systems to give specific support for the *conceptual design* of buildings and to *specialize* this support for *specific classes of buildings*, like e.g. medium size office buildings. A knowledge engineer architect develops this knowledge, which is then taken up by a traditional architect. Buildings (bridges, cathedrals) or parts of it are used as role models for good software design. In /Na 19/ the design of gothic cathedrals and its relation to software architectures was worked out for the first time.

6 Summary and Open Problems

Integration w.r.t. different dimensions

Summary of the *static part's integration aspects* with the following *dimensions*: We have introduced different kinds of *components*, for functional and for data abstraction, as objects (fo, ado) or as types (ft, adt). Also different kinds of *relations* were introduced, namely structure and usability relations. Therefore, different kinds of *construction principles* can be applied: locality, layers, and object orientation, different kinds of *consistency relations* from the context-sensitive syntax of the underlying design languages on one hand, and from the viewpoint of good and clear use of the languages on the other. These *method rules* (*patterns*) are of different kinds: patterns, as it should be, from wrong to right, from specific to more general (as object to type), from abstract and clear to detailed or efficient, etc. We have also introduced *components* of different *size*, modules or subsystems, or *units* of the design *languages*: from interface specs of modules, to complete modules, to pairs of modules with relations, to subarchitectures, to subsystems containing subarchitectures, to complete architectures. Finally, the approach unites design and *parametric* design (genericity). This all was presented in this paper (section 3) using *different languages*, graphical and textual (as discussed in section 5).

Summary of *further aspects*: Further aspects have been introduced which result in *annotations* of the design artifacts, mostly together with further refinements of the artifacts in form of additional details in the same or in other artifacts. We introduced *semantical notations* for interface specifications, runtime traces, or behavioral specifications, e.g. in form of finite automata. *Concurrency* annotations denote the information for processes and synchronization protocols: Further parts for start/ stop of the system and emergency *handling* can be added for *embedded systems*. For *abstract connectors* (request and supply of services) different *mechanisms* can be introduced, from coroutine, signal, trigger, interrupt to event handling by broadcast. The *distribution* of a system can be annotated by *distribution lines* and *annotations*, or in detail by additional *components* and *connectors* of an underlying distribution *platform*. All these aspects introduce detailed views to more abstract ones. Thus, abstract and detailed views can be regarded to be integrated. In many cases, the detailed views will be developed and studied only by specialists or/ and afterwards.

Different notations from *architectural styles*, as pipeline, data flow, loosely coupled systems, etc, are *abbreviations* of our architectural notation. Therefore, they can be used together with the standard notations without leaving the conceptual framework of architecture modeling, as introduced in this paper. Thus, we have integrated different architectural notations.

As already discussed, the architecture is the essential structure of the development process, used for decision making, arguing about structures, realization, extensions, and maintenance, explaining the structure and concepts, and also methodologies to build the system, therefore integrating essential activities. The architecture is composed of different views regarding different aspects, with more or fewer details. The relations between different artifacts and units of artifacts should be clear. All the stakeholders of a system development have to do with the architecture in different degrees of detail, for writing or verifying an artifact, in other cases to roughly explain and coarsely understand it.

The *architecture* is a *configuration* of diagrams, detailing texts, annotations within a description, references to corresponding more and detailed elaborations. A part of this configuration is directly devoted to architectural views and aspects. Other parts and outside of the architectural configuration belong to quality, documentation, and management of the development process or are derived from the architecture, as the program code. In total, the architecture integrates different aspects and corresponding artifacts or is the center for integration for other aspects.

This architecture configuration is a part of the *overall configuration* of the system to be built, extended, or maintained. The overall configuration contains further artifacts for requirements engineering (outside views, the system to be developed has to follow), as well as artifacts for the realization (programming, implementation). The architectural configuration is the essential part of the overall configuration. By the way, this kind of overall configuration we find in all engineering domains: outside view for requirements, essential internal view, from an abstract logical level (conceptual modeling) down to the level of describing the essence of the system as it is delivered to the customer /Na 90, Na 96, NM 08, NW 99/, and adding all details of realization (detail engineering). In this paper, we concentrated on architecture modeling, forgetting upwards about requirements and also downwards about detail engineering. We only regarded the links from and to architectural units. The overall configuration corresponds to the BIM model for buildings, cf. section 2. We could also say, the overall configuration is our product information model for system development.

Different ideas in one notation

Summaries like /SAD, SEI 10, WSA/ show *different ideas*, which came up in the context of software architectures. They present these ideas, one aside of each other. Also, in most books on software architectures usually only fragments of these ideas are presented, namely the parts favored by the author. These fragments vary from book to book or even from a version of the book of an author to the next. We hope to have shown an approach in this article, which overcame both problems and puts these fragments *together* to a whole in one *notatio*n: The notations (i) contain all fragments/ or all fragments can be expressed in the approach and (ii) the approach integrates the corresponding ideas.

We supported the *integration of artifacts* in two ways: (a) We understand how they relate to each other in the architectural configuration and also beyond, and how they relate to artifacts outside the architectural configuration. This is (b) facilitated by the two-level approach using annotations: annotations are used in a more abstract form which is denoted within usual architectural diagrams, and their detailed form is mostly presented separately. In this way, the integration is easy to understand and the details are simply exchanged. In these above ways, we hope to contribute in some form to *integration* within the research *field* of *software architectures*.

Outlook

Further aspects and corresponding annotations are possible. (i) For example, we could have discussed *efficiency transformations* in section 4. There is an abstract and possible inefficient form for an architectural situation and there are possible ways to make it more efficient, but also less clear and understandable. Thus, we introduce different annotations in the abstract form and corresponding realizations by corresponding supplements.

Section 4 introduced several forms of further aspects and additions, as semantics, concurrency, concrete use connectors, and distribution. However, (ii) we did not discuss, how to *organize* such *additions* and in *which order*. This is, of course, dependent on the structure class, the application domain, but also the history of development in a certain company. A forthcoming paper will argue that there is not only one architecture but a series of architectures. Putting these architectures in some order has to be well-thought-out and carefully discussed.

Section 2 has introduced Building Information Models as the collection and composition of all artifacts belonging to the design and construction of buildings. A similar approach (iii) should be used for the collection and composition of all artifacts corresponding to design and realization of software systems and further documents around, as e.g. technical acceptance and validation, the contract, the protocols of sessions, etc. All this information is called the *product and process model*. There is no accepted standard available for this model. Such a standard cannot totally be fixed. It has to be flexible to allow differences of domains, of cultures of companies, of methodologies, and so on. But, there could be at least a standard, what this process and product model should address, e.g. in a checklist, or specific forms of this list for different structure classes, application domain, etc.

More research is necessary to (iv) study the *similarities* and *differences* of *design* and *development* in *different engineering domains* and to compare it with the experiences we can contribute from the software engineering side. We did some steps in this direction /Na 96, NM 08, NW 99, NW 03/. Activities are necessary to collect the advantages of different approaches and to learn from each other. There are merits in the areas of production engineering, chemical process engineering, automation and control, and communication systems, which can push software engineering forward. Conversely, the methods in direction of intelligent software construction can influence the engineering fields. There was some time at Carnegie Mellon University (CMU) where this idea to synthesize patterns and cooperations, applicable in different engineering disciplines, was very visible.

Integration of different *methods*, *models*, and *tools* are still big topics for software development in any domain, as for tools /Na 96/ and embedded systems /BF 10/. The process has to be improved to better understand it, to make it precise, and to support novel techniques, as model-driven development /PB 16/ and generation of code. Even more ambitious is the process if we do not regard a single system but a *family of systems* /CN 07, Ja 00, PB 05/.

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