Design and Test of Distributed Applications

by

Johan Fagerström

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Postaddress:
Institutionen för datavetenskap
Universitetet i Linköping och
Tekniska Högskolan
581 83 Linköping

Mailing address:
Department of Computer and
Information Science
Linköping University
S-581 83 Linköping, Sweden
The Department of Computer and Information Science
Linköping University

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Abstract: It is well known that programming and testing distributed systems can be extremely difficult. Reasons for this include non-deterministic behaviour, non-reproducability of events, complex timing of events, and complex states. This paper presents a paradigm and a system that will support a programmer when designing, programming, and testing a distributed application. Our main point is that the structure introduced by the paradigm must be kept and exploited during design, programming, and testing. One is not helped by a programming method which introduces a structure just to break it down again. We have developed a structural model based on common structures in distributed systems. This structural model is used to describe the logical relationships between components in a system. It is also integrated into the programming environment.

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Postadress: Institutionen för datavetenskap Universitetet i Linköping och Tekniska Högskolan 581 83 Linköping

Mailing address: Department of Computer and Information Science Linköping University S-581 83 Linköping, Sweden
Background
Designers of large programs traditionally start with high-level structural design. People introduced to programs also generally try to understand global structures before looking at sub-components. Structures and understanding of structural relationships is thus of vital importance for design and programming. Enforcing programs to conform to the designed structures not only guarantees up to date documentation but it also simplifies testing. This paper presents a structural model of distributed applications based on a few observations of common structures in such systems. The model is very general but specific enough to allow us to integrate it into a programming environment. The programmer can thus use structural relationships introduced by the designer when debugging. For instance, he can change viewpoints of the system consistent with abstraction levels in the design. This 'meta-level' debugging is a necessary methodology since debugging of distributed systems is complicated by non-deterministic behavior, complex causal relationships between events, complex timing of events, and complex states.

Introduction
The PEPSy project (Programming Environments for Parallel Systems) [Fagerström 86a & 86b] is an attempt to provide programmers with a suitable paradigm and appropriate tools for design and test of distributed applications. By "paradigm" we understand a conceptual framework for structuring ideas and concepts when solving problems. Our main point is that the structure introduced by the paradigm must be kept and exploited both during design and testing. One is not helped by a programming method that introduces a structure in the design phase just to break it down again later. An example on a small scale: it is common to implement complex knowledge structures in Lisp and still debug the program in terms of low-level primitives such as CARs and CDRs. Several formal models for describing parallel systems exist, for instance CCS [Milner 80] and CSP [Hoare 85]. Both can be used to describe communicating processes, concepts like encapsulation, observation and tracing, and even system design. However, they are primarily models to be used in the specification and formal analysis of systems. They do not support later phases, such as testing, especially well. We have developed a structural model that explain distributed systems in terms of processes, logical channels, interfaces and abstract objects. This structural model is used to describe the logical relationships between components in the system. We use communication for process composition and encapsulation to provide abstraction. At the same time the model is integrated into a programming environment. It supports distributed system construction in several ways:

- Documentation of system components and their relationships can be done in a consistent and intuitive way. It is focused around a graphical representation of the design.

- The paradigm can be used to enforce a limited and structured mechanism for incremental changes in the system. There are two reasons for this. First, the paradigm results in hierarchical designs. Secondly, this hierarchy is enforced. We have made 'change' a design issue.

- Programming environment tools can be improved since more knowledge of the system can be built into them. The main reason for this is the fact that knowledge introduced by the designer and the programmer is kept and exploited by the programming environment.

Our model strongly resembles the HPC - model [LeBlanc 85a & 85b]. Both models have the same purpose: to use process structures explicitly in the design of distributed systems.
A paradigm for design and test of distributed applications

Summary
We base our model on processes which are combined into so called software ICs. (We acknowledge [Cox 86] for this appropriate name, we have previously used various other names). The nature of processes is language dependent. For now, think of them as containing state and code. They have an interface and they communicate via logical channels. These channels are uni-directional. A software IC is a set of communicating processes encapsulated into a black box by means of a so called control unit. The control unit is responsible for linking and un-linking logical channels inside the software IC. It is also used to construct well-defined states locally inside the Software IC, so called clean points [Lyles 84]. A complete description of the model and its implementation and integration with the programming environment is given in [Fagerström 88].

Processes
The first architectural component in the paradigm is the process. Our processes corresponds to the usual concept of logical process. The paradigm is language independent. The only requirement is that processes must be able to "communicate" with the outside world. This can be done either explicitly, using for instance SEND and RECEIVE commands, or implicitly, dependent on the language used. A processes is created as an instantiation of a class. A class is a template that describes a generic process. On instantiation a few specializations on the process are always done. At least, the process is given a globally unique name. This name is known to its creator and the process itself. Names are used for resource management, testing, and monitoring the system, not for binding communication partners. It is also possible to initialize local state or instantiate types. For instance, a queue template can be used to generate a queue-process with buffer elements of a certain type (SIMULA-syntax [Dahl 70]):

```
  ref (queue) queueInstance1;
  queueInstance1 := new queue (numberOfElements,typeOfElements);
```

Processes can be written in almost any language. The only requirement is that it supports some means of communication with the outside world. However, for the purpose of this paper the reader can assume a language with explicit send and receive primitives.

Interfaces & channels
Processes communicate with each other using message passing through well-defined interfaces. The message passing is between interfaces, the coupling between the interface and the associated process is where the language independent model meets a language. An interface is always created together with a process (or more generally, together with an object). An interface consists of a fixed number of ports. From the outside a port can be seen as an abstraction of a function implemented by the associated object. Logical channels can be set up between ports. Messages are sent on these channels asynchronously. Ports are named. The extra level of indirection introduced by using portnames instead of direct naming simplifies process migration and location transparency. This is not an implementation issue since entries can by simulated by direct naming and calculated GOTOs.
Figure 1: An interface

Figure 1 shows our view of an interface. This particular interface consists of three ports and an interface controller. The interface controller will intercept messages sent to the interface itself, e.g. a request to link a port to some other interface. (Interfaces are not implemented as processes, but it is conceptually simpler to think of interfaces as active objects containing an interface controller). We have also indicated that two ports are used for input and one for output. Keeping to the queue example, the three ports can be named controlPort, queuePut, and queueGet respectively. From the process point of view the following operations can be performed on an entry (defined inside the process and connected to the interface): send, receive, and a guarded command. Processes have thus no direct control over communication paths, this simplifies testing, process migration and fault-handling. An example of a physical realization of a port is shown in figure 2.

Figure 2: A port implementation

The port consists of three fields: a type, a name, and a register. The name is a constant. The register can either be used as an input register or as a placeholder for an output pointer. The output pointer either points to another port or it is nil. Incoming data will temporarily be stored in an input register. If it is not used it will contain nil. Values sent or received on nil-value ports are lost. If the output pointer is writeable it will be possible to dynamically change communication partners.

Encapsulations
Abstraction is an important tool often used in design and programming. The model introduces encapsulations as an abstraction mechanism. The user can specify a border around an arbitrary set of objects. This border together with a name defines a new object. Figure 3 is an example of an encapsulation with three component object, one of which is itself an encapsulation.
An encapsulation is not an object in the model, it is a tool used in the programming environment. This mechanism is very influential on the debugging of the system. We describe this idea here since it is reflected in the model by our next type of object. One can trace and examine an encapsulation as a single object. (Within reasonable limits.) This kind of multi-level abstraction is useful in many situations. For instance, the system architect can concentrate on high-level concepts, the programmer can build modules, encapsulate them and use them as new primitives, simulation of system behavior can be done with multi-level simulators and so on.

Software ICs
An encapsulation is transparent. One can observe and even change sub-components. It is also passive (as an object). In order to make it opaque we must transform it into an active object. Logically, an encapsulation can be turned into a black box by introducing a control unit. (In practice one does not start from an encapsulation, since they represent a user-defined categorization of instances, not a class). This new type of object is called a Software IC. A control unit is thus a part of a Software IC. It will set up and tear down logical channels between interfaces in the Software IC, so called internal interfaces. The control unit also controls the interface to the environment (the external interface). A software IC is opaque, its internal structure can not be observed or manipulated from the outside. It can not be distinguished from a single process. (Our implementation guarantees this by enforcing scope rules for process naming consistent with the design). In figure 4 an encapsulation (figure 3) has been turned into a software IC by introducing a control unit. We have also included a new logical channel from the environment, a channel directly to the control unit. It could represent a control channel used for sending interrupts, debug commands, etc.
The control unit has the following responsibilities:

- creating new instances of objects and their interfaces
- requesting termination or suspension of objects
- setting up and tearing down logical channels between objects
- setting up and tearing down logical channels between objects and the external interface.

The control unit is the only object in the system that can directly manipulate other objects. In this way we allow limited structured changes in the system. Unlimited creation, suspension and termination of objects in a distributed system very quickly leads to chaos.

Programming environment tools

Distributing systems introduce a number of new dimensions to the system design problem. For instance, designers must take time delays and limited bandwidth into account. Distributed systems also introduce a number of new types of possible bugs (in particular bugs introduced by failing nodes), and debugging is further complicated by non-reproducibility of events, non-determinism and complex timing of events. If robust, reliable, and correct programs are to be constructed, we must handle this extra complexity compared to sequential systems. We will examine a number of programming environment tools in light of our model in particular and distributed systems in general.

Editor, compiler, interpreter, linker, and loader

Traditional tools like these play an important role for program development. They must be re-evaluated in the distributed case. For example, the optimizing pass in compilers might try to add code to increase parallelism and thus performance [Hibbard 82]. "Objects" also provide an appropriate component for editing, compiling, and distributing. Incrementality can thus be provided at varying granularities. A related project has presented results on statement level incremental compilation in a host-target situation [Fritzson 84a & 84b]. Incrementality in our case must be on larger objects (processes) of varying sizes. We have two editors, one at a process level (language dependent) and one configuration editor which is used to create software ICs (language independent). The structure of the latter is shown in figure 6.

![Figure 6: Editor for SIC](image-url)
When entered the configuration editor automatically creates a sub-class of the class control unit, an external interface and various control channels to the external world. The programmer can then use the editor to record the appropriate configuration code executed by the control unit when it is started (by pointing and using menus). Commands include creating and deleting sub-objects, and linking and un-linking channels between interfaces. The code for this (the configuration code) is generated and stored in the control unit. For sub-units, the editor will automatically create the appropriate interface and link it to the control unit via control ports (using symbolic names). The programmer can incrementally add, change and delete the configuration code. He/she can also inform the editor to generate a template (or a set of templates) for sending or receiving data on channels and insert data into the configuration code. Code for tracing (conditional or unconditional) and demons can be installed from the editor on ports, interfaces and channels. The appropriate code for this will then be generated. When the editing session is finished, the software IC and the control unit as sub-classes will be stored in the class hierarchy. (One can, of course, also start with an old sub-class of software IC and change it.) The programmer can create numerous instances of the configuration editor and the language editor so that various part of the design can be designed and accessed in parallel using the window system. Finally, he/she can load and start the system from the editor. This is implemented as an instantiation of the control unit which executes its configuration code. Space does not allow us to discuss resource allocation. However, the programmer has the freedom to specify (or not specify) resource requirements consistent with the model structure.

**Debugging tools**

The backbone of any debug system is a traditional debugger for sequential processes. It provides services such as conditional breakpoints, single-stepping and tracing. Sequential debuggers can be allocated on a one per object basis, together with a master debugger residing on the host from where the user interacts with the system. In our case we can provide more structure than this. The debug system will have knowledge about component relationships. The most important aspect of a debugger is that it presents the system in a way consistent with the users conceptual view. The debugger must thus know about encapsulations, control units, and interfaces. To support this we need a kernel which keeps track of logical structures and a name server which maps logical names into addresses. The model itself also simplifies debugging by introducing centralized control at various places: the control unit. For debugging purposes we have integrated the following tools with the configuration editor:

- **module interface testing**
  Protocols can be tested by monitoring, inserting, changing, or adding messages. This is done by dynamically "lifting" the object out of its environment from the debug tool.

- **tracing & monitoring**
  Information flowing on channels and interfaces can be stored on a file. The statically compiled code for tracing installed with the SIC tool can be lifted out or completely new code can be installed dynamically. (The starting time for this kind of tracing is of course dependent on the time it takes to send the command across the network). We also offer tools for browsing through the trace. For instance, information about ordering of events can be displayed (based on [Lamport 78]).

- **automatic surveillance**
  Traditionally the term 'demon' has been used for a process that observes a database. The demon consists of a trigger and an action. The action
associated with an instance of a demon is performed when the trigger condition is fulfilled. Demons recognize database changes that occur after their activation. Demons, in our case, is part of the debug tools watching and controlling objects. The user specifies the conditions which must be fulfilled for an action to occur, and the action itself. Typically, demons are used for testing relations between structures in the system (i.e., "protocols").

- control over the system
  Single-stepping, tracing, peek and poking on processes can be done via a traditional sequential debugger, allowing the user to introduce his own error handling.

These tools (except the last) can be used on processes, encapsulations and software ICs. For instance, by tracing the external interface of a software IC the programmer avoids generating the (possibly large) trace of all its sub-components. Debugging can thus be done in a bottom-up fashion where single components are tested before integrating them into a software IC. When all sub-components are believed to function correctly one can study their combined behavior. All control units have built-in methods for cooperating with the debug tool. Interfaces are also prepared for tracing and demon handling. We can thus manipulate objects within the system in several ways. It is also possible to manipulate logical channels in similar ways.

Conclusions

We have presented a unifying view of distributed computations based on a structural model and briefly discussed the consequences for programming environments. The model is based on communication for process composition, and encapsulation as an abstraction tool. The programming environment benefit since more knowledge is introduced and exploited. This provides a conceptual adequate view of the system to the user. Structures are enforced by the system and protocols can be tested in a hierarchical way. The model supports both structuring (interfaces, logical channels, and processes) and layering (encapsulations and software ICs). A prototype implementation has been constructed in Smalltalk-80 [Goldberg 83]. Present work includes refinement of the model and the tools, and porting the prototype onto a distributed system (using CONIC [Kramer 84] on a set of SUN workstations).

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Project: Design and Test of Distributed Applications

Author: Johan Fagerström

Abstract: It is well known that programming and testing distributed systems can be extremely difficult. Reasons for this include non-deterministic behaviour, non-reproducibility of events, complex timing of events, and complex states. This paper presents a paradigm and a system that will support a programmer when designing, programming, and testing a distributed application. Our main point is that the structure introduced by the paradigm must be kept and exploited during design, programming, and testing. One is not helped by a programming method which introduces a structure just to break it down again. We have developed a structural model based on common structures in distributed systems. This structural model is used to describe the logical relationships between components in a system. It is also integrated into the programming environment.

Keywords: Distributed systems, programming environments, debugging, structural models
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