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Chapter 1

ACTOR-ORIENTED MODELS FOR CODESIGN

Balancing Re-Use and Performance

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Abstract: Most current hardware engineering practice is deeply rooted in discrete-event modeling and synchronous design. Most current software engineering is deeply rooted in procedural abstractions. The latter says little about concurrency and temporal properties, whereas the former lacks many of modularity capabilities of modern programming languages. Actor-oriented design emphasizes concurrency and communication between components while maintaining modularity. Components called actors execute and communicate with other actors. In contrast to the interfaces in object-oriented design (methods, principally, which mediate transfer of the locus of control), interfaces in actor-oriented design (which we call ports) mediate communication. But the communication is not assumed to involve a transfer of control. This paper discusses the structure of actor-oriented models and shows how data and behavioral type systems enhance modularity and re-use potential while enabling designs that embrace concurrency and time. This paper shows how components can be designed for re-use through parameterization and behavioral polymorphism, and how component specialization can offset the performance costs of doing so.

Keywords: Actor-oriented design, behavioral types, behavioral polymorphism, component specialization, code generation, parameterization, Ptolemy.

1 INTRODUCTION

Objects in object-oriented design present interfaces consisting principally of methods with type signatures. A method represents a transfer of the locus of control. Much of the talk of “models” in software engineering is about the static structure of object-oriented designs. However, essential properties of

hardware design, real-time software, and distributed systems-of-systems are poorly defined by such interfaces and by method structure. In contrast, modules in hardware design languages present interfaces based on signals. Signals represent pure dataflow between modules, allowing modules to operate concurrently. Unfortunately, hardware design languages also focus primarily on statically structured systems. This focus improves synthesizability, but stands in the way of common software idioms and presents a barrier for uniform representation of hardware and software systems. In this chapter we focus on a set of system modeling techniques that are capable of expressing concurrent, dynamic structures and techniques for statically analyzing those structures.

1.1 Actor-Oriented Design

A significantly different direction for embedded systems has been to develop domain-specific languages and synthesis tools for those languages. For example, Simulink, from The MathWorks, was originally created for control system modeling and design, and has recently come into significant use in embedded software development (using Real-Time Workshop and related products). Simulink is one of the most successful instances of *model-based design* [22]. It provides an appropriate and useful abstraction of control systems for control engineers.

Simulink also represents an instance of what we call *actor-oriented design*. Actors are concurrent components that communicate through *ports* and interact according to a common pattern of interaction. Primarily, actor-oriented design allows designers to consider the interaction between components distinctly from the specification of component behavior. This contrasts with software component technologies such as CORBA, where interaction between objects is expressed through method invocation. Higher-level patterns are codified only through the APIs of services, and usage patterns for these APIs are expressed only informally in documentation. As a consequence, the communication mechanism becomes an integral part of a component design.

By focusing on the actor-oriented architecture of systems, we can leverage structure that is poorly described and expressed in procedural abstractions. Managing concurrency, for instance, is notoriously difficult using threads, mutexes and semaphores, and yet even these primitive mechanisms are extensions of procedural abstractions. Conventions that ensure deadlock avoidance, such as acquisition of locks in a fixed order (see for example [9]), are not supported by the languages (nothing about a method signature declares what locks it will acquire, for instance). As a consequence, these conventions are difficult to apply in practice, and seemingly innocent changes to code can create disastrous failures such as deadlock.

In actor-oriented abstractions, these low-level mechanisms do not even rise to consciousness, forming instead the “assembly-level” mechanisms used to deliver much more sophisticated models of computation. Moreover, actor-oriented abstractions can embrace time and concurrency, and therefore match much better the modeling of hardware systems, which are intrinsically concurrent.

Our notion of actor-oriented modeling is related to the work of Gul Agha and others. The term “actor” was introduced in the 1970’s by Carl Hewitt of MIT to describe the concept of autonomous reasoning agents [7]. The term evolved through the work of Agha and others to describe a formalized model of concurrency [1]. Agha’s actors each have an independent thread of control and communicate via asynchronous message passing. We are further developing the term to embrace a larger family of models of concurrency that are often more constrained than general message passing. Our actors are still conceptually concurrent, but unlike Agha’s actors, they need not have their own thread of control. Moreover, although communication is still through some form of message passing, it need not be strictly asynchronous.

1.2 Platforms

Sangiovanni-Vincentelli has articulated clearly the benefits of *platform-based design* [19]. We have defined platforms to be a set of designs [11]. Examples of such sets are:

- The set of all boolean functions.
- The set of all x86 binaries.
- The set of syntactically correct Java programs.
- The set of all Java byte-code programs.
- The set of all Wintel PCs.
- The set of all ANSI C programs.

Fig.1 illustrates some platforms and their interrelationships. Each box is a platform. For example, the set of all Java programs has a downward arrow labeled “javac” which represents a function whose domain is the set of all syntactically correct Java programs, and whose range is the set of Java byte code programs. Similarly, the set of x86 programs contains a program, an implementation the Java virtual machine, that is related to the set of all Java byte code programs by its ability to execute members of the set. For more details about this view of platforms, see [11].

Fig.1 shows a level labeled “actor-oriented models.” The platforms at this level are relatively immature, but play a central role in the future of codesign. In particular, actor-oriented models focus on the separation of concerns between communication and computation [8]. Without this level, the gap

between “applications” and “programs” is large enough to force very early decisions about hardware vs. software implementations.

Model-based design [22] concentrates on the specification of designs in platforms with useful modeling properties. For example, Simulink block diagrams represent control systems as visual representations of systems of ordinary differential equations. The set of Simulink designs, therefore, inherits the formal properties and analytical properties of systems of ODEs. These

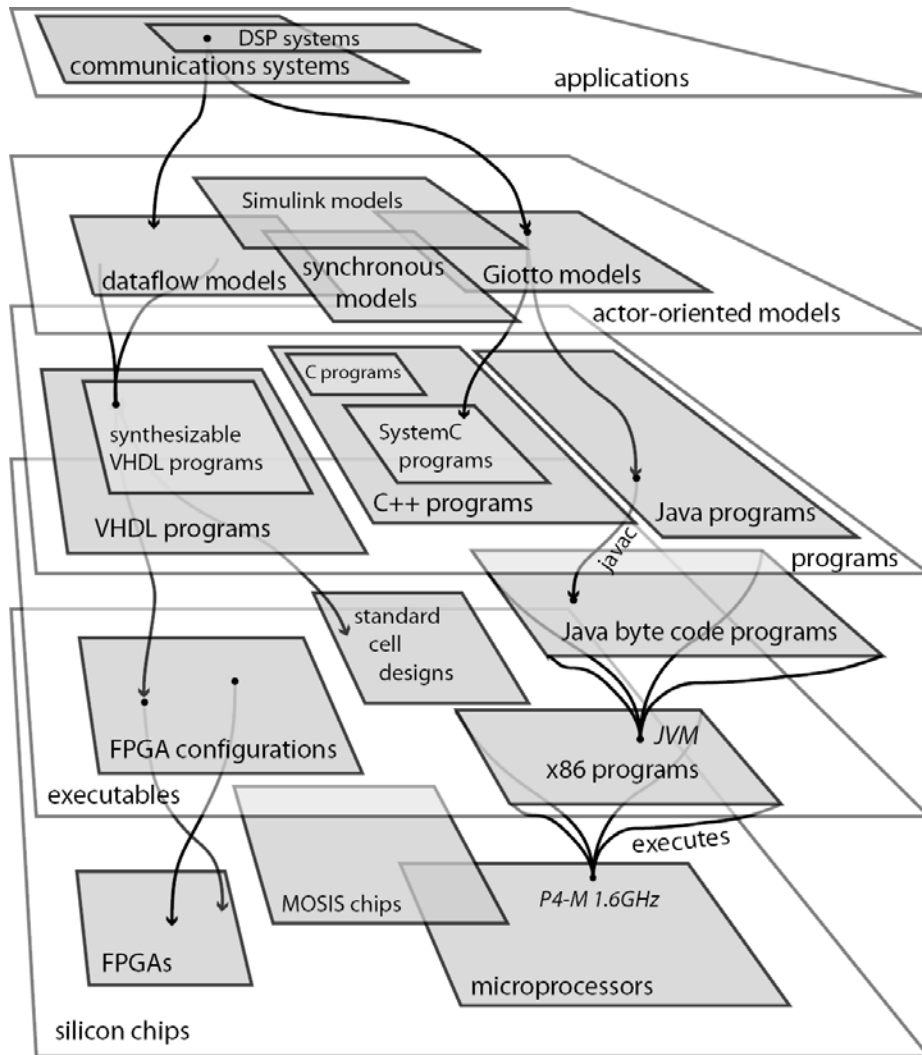


Figure 1: An illustration of some *platforms* (sets of designs) and their interrelationships.

properties are useful to control systems engineers for analyzing, for example, transient responses and stability.

1.3 Object-Oriented Programs

The level in Fig.1 labeled “programs” represents conventional object-oriented software design practice today. Much of the action here is about attempting to give useful modeling properties to designs at this level. For example, UML (the unified modeling language) and the MDA (model-driven architecture) from OMG (the object management group) are about giving modeling structure to designs at this level. Much of the work in design patterns that was kicked off by Gamma *et al.* [4] is about identifying modeling structure in programs at this level.

Actor-oriented design is illustrated in Fig.1 at a level above programs. It is a relatively immature area, with few well-structured programming languages and little software support. But early successes in this domain, such as Simulink, promise very effective modeling properties combined with effective implementation technologies. The implementation technologies will likely take the form of generators (such as Real-Time Workshop) that transform actor-oriented models into program-level models.

1.4 Properties of Actor-Oriented Models

Fig.2 illustrates the difference between object orientation and actor orientation. In current practice, as defined by languages such as C++ and Java, and as represented by abstractions such as UML, object-oriented components interact with one another principally by method calls, which represent a transfer of control. In actor-oriented models, components interact via some sort of messaging scheme that is typically concurrent. The messaging scheme and

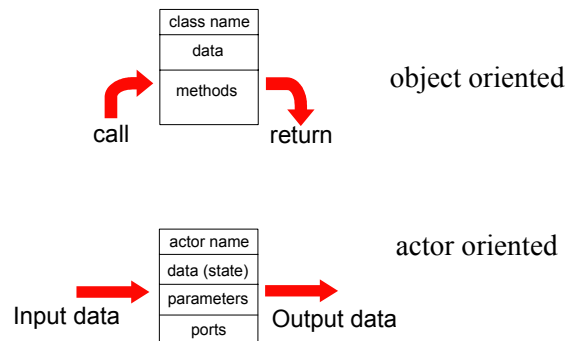


Figure 2: An illustration of the relationship between actor-oriented models and object-oriented components.

any constraints on flow of control together define a *model of computation* that governs the interaction of components.

In actor-oriented design, components called actors execute and communicate with other actors in a model. Actors have a well-defined component interface. This interface abstracts the internal state and behavior of an actor, and restricts how an actor interacts with its environment. The interface includes ports that represent points of communication for an actor, and parameters that are used to configure the operation of an actor. Often, parameter values are part of the *a priori* configuration of an actor and do not change when a model is executed. The configuration of a model also contains explicit communication channels that pass data from one port to another. The use of channels to mediate communication implies that actors interact only with the channels that they are connected to and not directly with other actors.

Like actors, which have a well-defined external interface, *models* (which are compositions of interconnected actors) may also define an external interface. External interfaces allow for *hierarchical abstraction*, illustrated in Fig.3. This interface consists of external ports and external parameters, which are distinct from the ports and parameters of the individual actors in the model. The external ports of a model can be connected by channels to other external ports of the model or to the ports of actors that comprise the model. External parameters of a model can be used to determine the values of the parameters of actors inside the model.

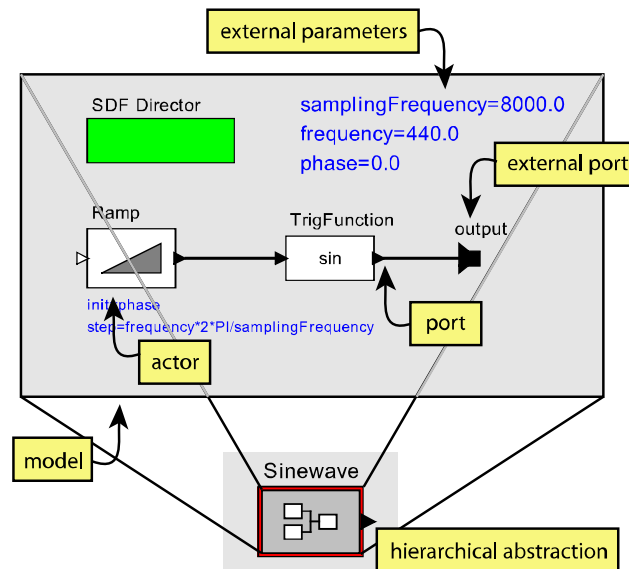


Figure 3: Hierarchical abstraction in actor-oriented design.

Taken together, the concepts of models, actors, ports, parameters and channels describe the abstract syntax of actor-oriented design. This syntax can be represented concretely in several ways, such as graphically, as in Fig.3, in XML, or in a program designed to a specific API. Ptolemy II [14] offers all three alternatives.

It is important to realize that the syntactic structure of an actor-oriented design says little about the semantics. The semantics is largely orthogonal to the syntax, and is determined by a *model of computation*. The model of computation defines the nature of communication between components, while the components themselves encapsulate computation. The model of computation consists of operational rules for executing a model. These rules determine when actors perform internal computation, update their internal state, and perform external communication.

There are many examples of actor-oriented languages, frameworks, and software techniques, including Simulink (The MathWorks), Labview (National Instruments), Modelica (Linkoping), GME: actor-oriented meta-modeling (Vanderbilt) [10], Easy5 (Boeing), SPW: signal processing work-system (Cadence), System studio (Synopsys), ROOM: real-time object-oriented modeling (Rational) [20], VHDL, Verilog, SystemC (Various), Polis & Metropolis (UC Berkeley) [5], and Ptolemy & Ptolemy II (UC Berkeley) [14].

Many of these, like Simulink, use a visual syntax to represent actor-oriented designs. Some are used for designing hardware, some for software, and some for both. An example of a model from Ptolemy II is shown in Fig.4. This model uses the actor defined in Fig.3. Of course, many different syntaxes

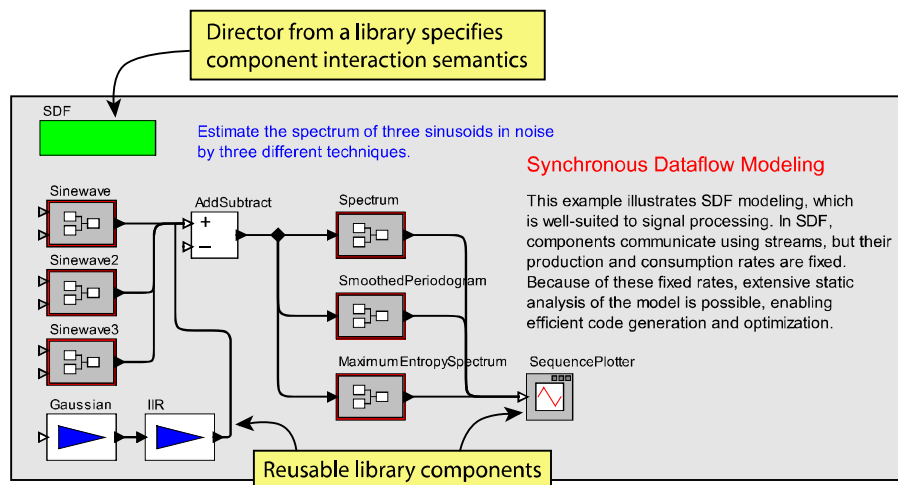


Figure 4: Ptolemy II model using the “synchronous dataflow” (SDF) model of computation.

are compatible with actor-oriented modeling, and for some applications, visual syntaxes like that in Fig.4 are entirely inappropriate.

In Ptolemy II, the model of computation is indicated by a *director*, represented by the boxes at the upper left of each of Fig.3 and Fig.4. Ptolemy II is unique among the frameworks listed above in that it has no built-in preferred model of computation, but rather supports a variety of models of computation via components called directors. This capability enables hierarchically heterogeneous design [3], where the modeling properties engendered by different models of computation can be combined.

Fig.5 shows a hierarchically heterogeneous Ptolemy II model that uses a continuous time (CT) director at the top level of the hierarchy and a Giotto director at the next level down. The CT director includes an ODE solver and has semantics somewhat similar to Simulink. The Giotto director implements the semantics of the Giotto language [6], which supports periodic hard-real-time tasks and mode switching. The key here is that the Giotto modeling framework (the Giotto director) is not designed specifically to interact with a continuous-time director. Instead, it exports a well-defined behavioral interface for hierarchical composition.

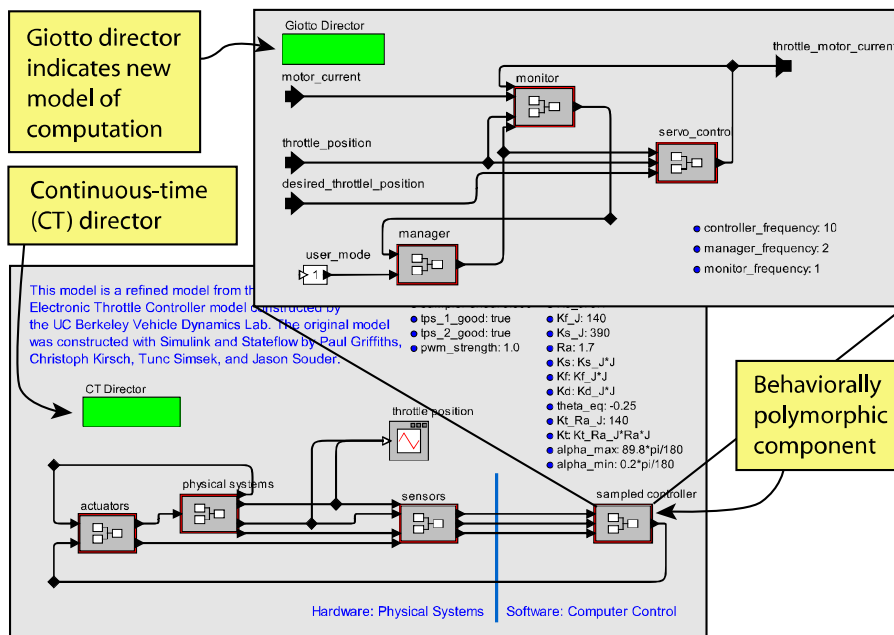


Figure 5: Hierarchical heterogeneity enables an actor refinement to use a different model of computation than that overall framework.

1.5 Actors are Components

We consider actors to be *abstract system components* in the following senses:

- They have a well-defined interface, given by ports and parameters, through which they can interact with the rest of the model. Other interactions are not allowed.
- They are generalizable across different uses of the same component. For instance, a component may be given new parameter values or may be connected to a different set of channels.
- They may have vastly different levels of granularity. For instance, an actor may represent algorithms ranging from the boolean OR of two bits to the boolean satisfiability solution of an arbitrary logic formula.
- Larger components may be assembled from smaller components. Component composition is the primary mechanism by which complex behavior is constructed.
- They are executable specifications of behavior. (i.e. Actor models have an operational semantics)

Of these, the generality of actors is something that often varies from one actor to the next. Many actors are designed specifically to fill a particular role in a single model, whereas other actors are designed to be more widely applicable. Although general actors are often more difficult to design, they can be reused in a wider variety of contexts. By maximizing the possibilities for *component reuse*, systems can be designed more quickly and design effort can be leveraged more easily.

Component generality also allows for the possibility of *dynamic reconfiguration* during execution. For example, an actor that is not specialized to a connection with another actor has the potential to be dynamically reconnected to a different actor with no modification. Similarly, an actor that is not specialized to particular parameter values has the potential to be dynamically reconfigured with new values. The use of generalized components increases the available design possibilities when using components.

Object-oriented languages primarily offer generality through variable function arguments. Any set of actual arguments that are compatible with the formal arguments of a function may be passed to that function. Furthermore, a function may be called from many places in a program using different arguments in each case. We call such generality *data polymorphism*. Many object-oriented languages add the notion of *type polymorphism*, where a program can operate uniformly on different types of objects, as long as those types expose similar operations. We identify several types of generality in actor-oriented models, all of which are exhibited in Ptolemy II:

- data polymorphism: An actor may be given data with different values.

- type polymorphism: An actor may be given data of different types.
- parameter generality: An actor may be given a different set of parameter values.
- connection generality: An actor may be connected to a different set of actors.
- behavioral polymorphism: An actor may interact with other actors according to different models of computation.

In the following sections, we deal more specifically with type, parameter and domain generality.

1.6 Leveraging Static Structure

As mentioned previously, many object-oriented modeling techniques are concerned with expressing the static object-oriented structures. Actor-oriented models also emphasize static structure in a model. We often build models whose structure does not change during the execution of a model, and when we do, we can exploit the fact that the structure is static. Such models have a fixed set of actors, interacting according to a specific model of computation. The ports of an actor form the declared interface of the actor, and this interface does not change. The connections between actors in a model are specified during the construction of the model and do not change during execution of a system. In fact, the Ptolemy II system is specifically designed to allow the construction of models that dynamically evolve during their execution, and yet this capability has been rarely leveraged.

From a software architect's point of view, an emphasis on static structure is a convenient design abstraction. A UML entity-relationship diagram can be considered as the permanent structure of the system, and the fact that this structure is dynamically created in an object-oriented system can often be ignored. Hardware architects, on the other hand, must carefully choose the static computational structure that will be placed in an ASIC since this structure cannot, in most cases, be modified after synthesis. Traditionally, hardware design languages have forced designers to manually provide for circuit reconfiguration.

We have leveraged the static structure of actor-oriented models in two key ways. Firstly, static model structure combined with appropriate type analysis enables detection of unsafe actor compositions. Analysis of both traditional data types and modern behavioral types support generic, reusable components. It is well known how to make such a component polymorphic in a data type sense (*type polymorphism*). It can be designed to be able to add numbers (int, float, double, Complex), add strings (concatenation), add composite types (arrays, records, matrices), and add user-defined types. The formal structure of such type systems is much better known than the formal structure

of parameterization and behavioral polymorphism, both of which have re-use benefits at least as great. For this reason, the following sections describe type systems for static analysis of reconfiguration and heterogeneous compositions.

Secondly, we have developed the notion of *actor-oriented specialization* which makes use of the static context of an actor to improve performance in software. Specialization enables practical application of type polymorphism, parameterization, and behavioral polymorphism, since providing these abstractions at run-time incurs significant performance cost. Specialization leverages the static structure in models, as determined through static model analysis, to enable component-based design at all levels of hierarchy. Specialization also enables ASIC and FPGA implementation synthesis without explicit management of reconfiguration.

2 PARAMETERIZATION

Actor parameters are a simple way to configure the behavior of a hierarchical model. At design time, parameters help keep the size of actor libraries manageable and allow models to be quickly modified or tuned for performance. At run time, actor parameters allow for dynamic reconfiguration of actors (and models) while a model is running. Dependencies between parameter values allow simple reconfiguration options to be exposed while hiding the reconfiguration of individual parameters from a designer. However, unconstrained reconfiguration can be problematic during design, since semantic modeling constraints can be violated.

2.1 Representing Reconfiguration

There are many common modeling syntaxes for generically representing reconfiguration in actor-oriented models. For instance, reconfiguration can be represented using a *modal model* controlled by a finite state machine. Each state of the finite state machine corresponds to a hierarchical model that gives the behavior of the modal model in that state. Finite state machine transitions represent switching to a new configuration of a model. Transitions can also set the value of actor parameters. In a hierarchical model, modal models appear as just another level of abstraction. An example of a modal model is shown in Fig. 6.

Reconfiguration can also be tied directly to dataflow in a model, using *reconfiguration ports*. A reconfiguration port is associated with an actor parameter and data received by the port reconfigures the value of that parameter. Reconfiguration ports exist in many commercial dataflow environments,

such as AVS/Express (Advanced Visual Systems, Inc.). An example of a reconfiguration port is shown in Fig.7.

Reconfiguration can also be represented using a special actor with a single input port. This `SetParameter` actor is bound to a parameter of parameter of a model in a similar fashion to the reconfiguration port. However, since the `SetParameter` actor does not require the presence of hierarchy in the model, it is often more convenient. It can also be more difficult to use, since

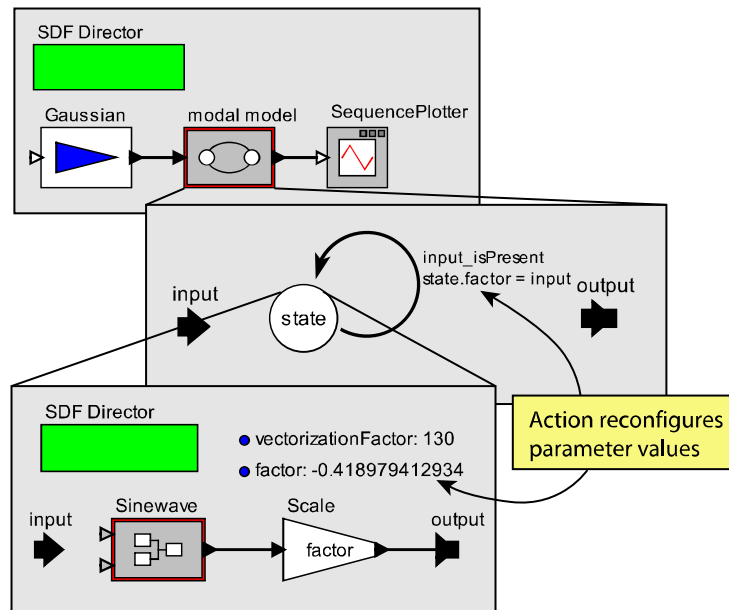


Figure 6: Ptolemy II model using a modal model for reconfiguration.

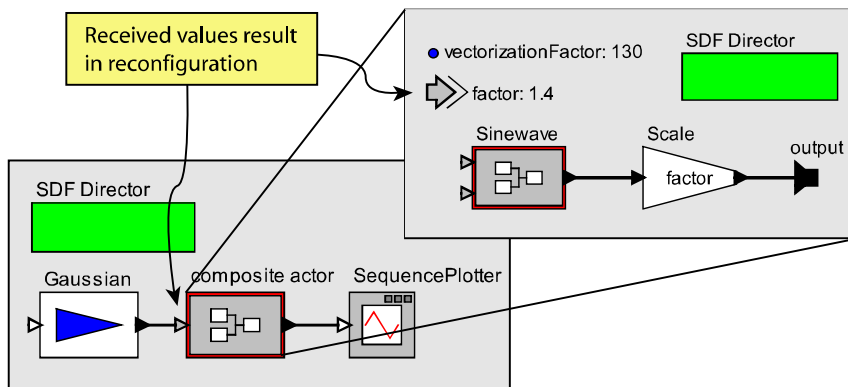


Figure 7: Ptolemy II model illustrating reconfiguration ports.

the point in execution of a model that the `SetParameter` actor is executed is more dependent on its interaction with other actors in the model. One approach to this difficulty is to treat the `SetParameter` actor as a *request* for reconfiguration at the next possible time, resulting in delayed reconfiguration at a well-defined point in the execution of the model.

2.2 Mobile Models

Although most reconfiguration replaces simple data values in a model, we note that reconfiguration in actor-oriented models can also replace portions of an actor-oriented model. The `MobileModel` actor, designed by Yang Zhao, acts as a placeholder for other components. This actor receives actor-oriented components and behaves as the received component. Fig.8 shows an example of the `MobileModel` actor operating in a model of a control system with a reconfigurable control algorithm [17]. Like more conventional representations of mobile code, as in Java, Ptolemy II allows actors to be transported over the network and safely executed elsewhere. Execution of mobile code relies heavily on strong type systems for ensuring safety. In Java, data type systems are sufficient, while Ptolemy II also relies on behavioral type systems for ensuring safety.

2.3 Constraining Reconfiguration

Generally speaking, reconfiguration modeling syntaxes can modify any parameter in a hierarchical model. However, unconstrained reconfiguration can possibly violate semantic constraints of a model of computation, resulting in unexpected behavior. Unconstrained reconfiguration can also result in

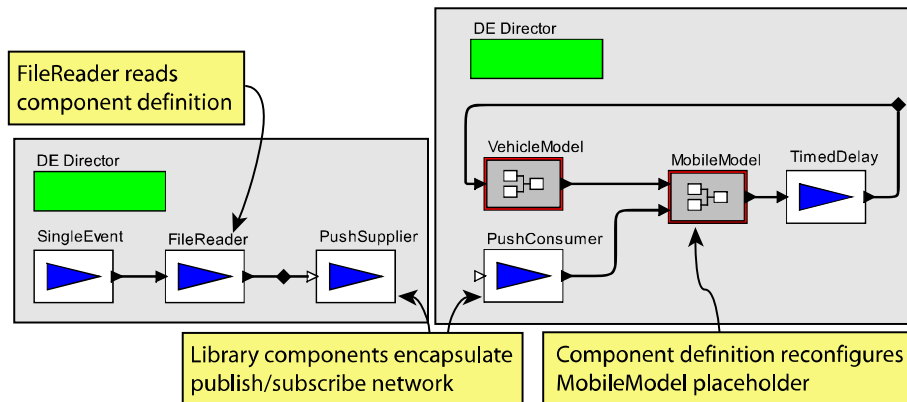


Figure 8: A mobile model is a model that, like mobile code, can be transported over the network and safely executed elsewhere.

unstructured communication outside of a model of computation. For both of these reasons, we would like constrain reconfiguration to ensure understandable models with predictable behavior.

We have focused on *hierarchical reconfiguration* as the key interesting modeling constraint. Informally, hierarchical reconfiguration implies that a parameter associated with a particular actor in a hierarchical model is not reconfigured while that actor is executing. Hierarchical reconfiguration solidifies our intuition that the behavior of an actor is a function of its parameters and the interesting fine-grained interaction of an actor with its environment is strictly expressed through ports.

In order to ensure that reconfiguration in a model is hierarchical, we have developed a *reconfiguration type system* that approximately analyzes how each parameter in a model is reconfigured [18]. This theory determines a *least change context* for each parameter that summarizes the effect of reconfiguration and parameter dependency on that parameter. Reconfiguration constraints, such as hierarchical reconfiguration, can be easily expressed as a constraint on the least change context and efficiently checked. This type system is built-in to Ptolemy II and used to guarantee safe uses of reconfiguration.

3 BEHAVIORAL POLYMORPHISM

The ability to construct hierarchical models using multiple models of computation is a key capability of Ptolemy II, but it creates an interesting challenge. Primarily, a hierarchical component like that in Fig.3 must be able to operate within a foreign model of computation. That is, the semantics of component interaction inside a hierarchical component must be able to differ from the semantics of component interaction outside the hierarchical component. To achieve this, Ptolemy II has pioneered the use of *behavioral polymorphism*. A component is behaviorally polymorphic in that its behavior will depend on the external context in which it is placed. Behavioral polymorphism enables hierarchical heterogeneity.

3.1 Motivating Example

Consider the AddSubtract actor in the center of Fig.4, which adds or subtracts signals that are provided at the input ports. We notice that the function performed by this actor is entirely independent of how data is transported to the actor. For example, the actor can be used in a dataflow framework, where it will add when all connected inputs have data. Or it can be used in a time-triggered framework, where it will add when the clock ticks. Or it can be used

in a discrete-event framework, where it will add when any connected input has data, and add in zero time. Or it can be used in a process network framework, where it will execute an infinite loop in a thread that blocks when reading empty inputs and adds when it has read data from all connected inputs. Or it can be used in a CSP-based framework, where it will execute an infinite loop that performs rendezvous on input or output. Etc.

By not choosing among these when defining the component, we get a huge increment in component reusability. Essentially, the interaction pattern between actors is an aspect that is independent from the actors' functionality. Behaviorally polymorphism is essential to managing the complexity of hierarchically heterogeneous models. Without behavioral polymorphism, each hierarchical component would have to be designed for a specific combination of the inside and outside models.

A key problem when describing behavioral polymorphism is defining exactly how polymorphic a component actually is. How do we describe the behavioral requirements of a component, in order to ensure that a component will work in a particular circumstance? In a data type system, a type checker ensures that the data type requirements of a component are satisfied in a given context. A corresponding *behavioral type system* is needed to robustly support behavioral polymorphism.

3.2 Object-Oriented Approach to Achieving Behavioral Polymorphism

In Ptolemy II, the director in a model defines the model of computation, which includes the communication mechanism between components. As

illustrated in Fig.9, the director instantiates an object that implements a Java interface called Receiver, shown in UML form at the upper right of Fig.9.

The six methods of Receiver shown in Fig.9 have different implementations depending on the model of computation. These implementations can, for example, queue messages, or implement rendezvous, or post events to an event queue, for example. Since the receiver instance used in communication is supplied by the director, not by the component, the component becomes behaviorally polymorphic. Whether a call to the `get()` method (which reads an input) reads from a queue, blocks, or waits for a rendezvous is not up to the component designer. It is up to the director designer.

3.3 Behavioral Types

The object-oriented approach of the previous section has its limitations. What if:

- The component requires data at all connected input ports?
- The component can only perform meaningful operations on two successive inputs?
- The component can produce meaningful output before the input is known (enabling it to break potential deadlocks)?
- The component has a mutex monitor with another component (e.g. to access a common hardware resource)?

None of these is expressed in the object-oriented interface definition, yet each can interfere with behavioral polymorphism.

The problem is that the Receiver interface only describes object-oriented structure between method calls. It defines abstract data types, but not the dynamic behavior that is central to these communication protocols. Instead of

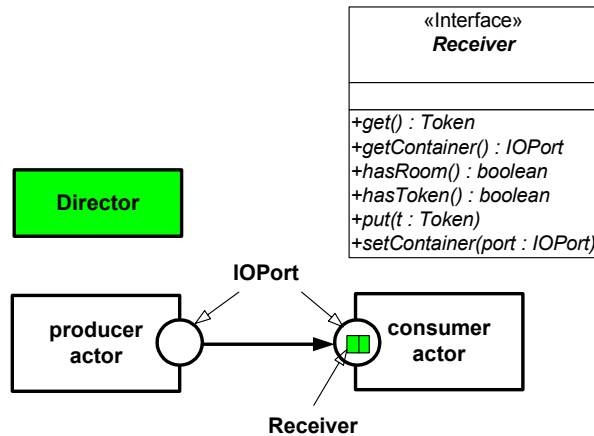


Figure 9: The Ptolemy II Receiver interface.

relying on inadequate object-oriented data types, we use a *behavioral type system* (which we previously called a “system-level type system” [12]) to obtain benefits analogous to data typing.

An example of a behavioral type signature for communication protocols is shown in Fig.10. This signature describes a component’s interaction with its environment using an extension of *interface automata* [2][13]. Type checking is done through automata composition, which will detect component incompatibilities. Subtyping order is given by the alternating simulation relation [2], supporting behavioral polymorphism. An alternative representation of behavioral types would be pre/post conditions [15], which may be essentially equivalent, but lacks the intuitive visualization of Fig.10. For details on how to specify behavioral types, see [12][13].

The use of a behavioral type system enables key quality control techniques.

Checking behavioral compatibility of components that are composed. Composition of components that cannot effectively work together because of conflicts in their dynamics (e.g. differing assumptions about communication protocols) is identified as an error. This is analogous to type conflicts in conventional type systems.

Checking behavioral compatibility of components and frameworks. Use of a component in a framework that cannot effectively meet the assumptions of the component is identified as an error.

Behavioral subclassing enables interface/implementation separation. Behavioral type signatures define interfaces that can be implemented by a number of components. For example, components that are simple memoryless

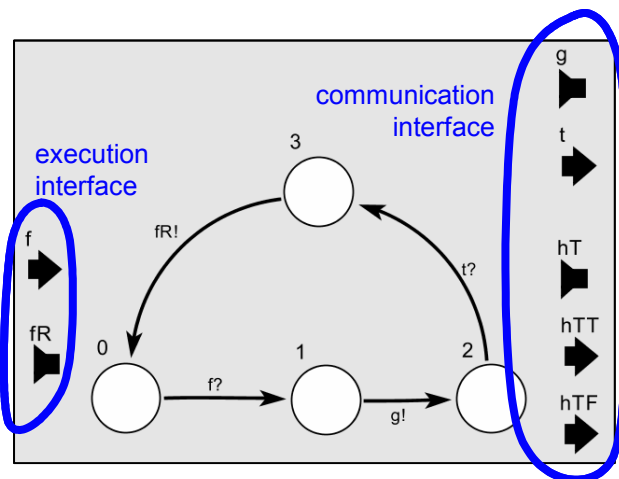


Figure 10: Behavioral type signature using interface automata.

stream transformers (which react to input data, transform it in some way, and produce output results) all share the same behavioral interface definition.

Helps with the definition of behaviorally-polymorphic components. Behavioral type signatures declare the minimal assumptions that are required for the component to work. This maximizes the number of contexts in which the component can be used.

4 ACTOR-ORIENTED SPECIALIZATION

Although high-level models can be useful simply for behavioral design and conceptualization, these models become truly powerful when they become a designer's primary programming paradigm. Design tools are more than capable of compiling designs from a modeling platform into an executable platform. Object-oriented modeling tools emphasize round-trip engineering for maintaining consistency between models and code. Many actor-oriented design tools provide code generation capability for automatically translating a model into executable software and hardware. In particular, Simulink's real-time workshop has become commonly used in the control-systems community.

Specialization of object-oriented programs has grown out of the long history of partial evaluation for functional languages and method inlining optimization in procedural languages. Object-oriented specialization relies on program analysis and extra program annotations to indicate opportunities for specialization [21], and 'optimal' specialization is known to be an undecidable problem. Whereas object-oriented specialization concentrates on transforming the method calls between objects, actor-oriented specialization concentrates on transforming interaction patterns between actors. Because the interaction patterns between actors are explicitly described, actor-oriented specialization is straightforward to apply and relatively simple to understand.

In the context of actor-oriented design, we claim that specialization of a model to a particular context is the primary operation in transforming actor-oriented models into program-level models. Executability alone is not sufficient for resource constrained systems. If it were, then we would simply embed a complete simulation environment in every system and declare success. In reality, optimization to reduce resource usage is crucial for reducing system cost and satisfying timing requirements. Actor-oriented specialization results in optimized behavior while still allowing generic design-time constructs [16]. Specialization implements a transformation from a modeling platform to an efficient implementation platform.

We consider several forms of actor-oriented specialization according to the various generic aspects of Ptolemy II components:

- Parameter specialization
- Type specialization
- Connection specialization
- Domain specialization

Parameter specialization replaces actor parameters that are not reconfigured with a constant value. This specialization relies on analysis of an actor-oriented model to determine constraints on reconfiguration, as described in Section 2. Efficient computation of the values of parameters is possible through partial evaluation of parameter expressions dependent on constant parameters. Additionally, reconfiguration constraints allow for further optimization, since parameter reconfiguration occurs only at well determined points in the execution of a model.

Type specialization replaces generic data types with specific types inferred from the model context. For software implementation, specific types allow the removal of abstract data type indirection through *token unboxing*. In Java implementations synthesized from Ptolemy II, token unboxing greatly reduces load on the garbage collector, resulting in faster and more predictable execution. For hardware implementations, specific types are crucial to selecting efficient representation of data values and operations.

Connection and domain specialization deal directly with the implementation of a model of computation on a particular implementation platform. These specializations are possible when the structure of models and the modeling semantics are fixed at design time. We expect that a provider of a synthesis system will be largely concerned with the efficient implementation of component interaction in a particular system. Given that a designer wishes to target a particular implementation platform, he will select a model of computation that has been provided for that platform and begin designing. Retargeting the model to another implementation platform that provides the same high-level semantics is easy, while targeting an implementation platform without direct support of a model of computation, or migrating a model from one semantics to another is likely to be much more difficult.

5 CONCLUSION

We have outlined a class of design techniques that we call actor-oriented design, and have related it to model-based design, platform-based design, and object-oriented design. We have described mechanisms for generalizing

actors, promoting re-use in various contexts. We have focused on parameterization and behavioral polymorphism, and presented described type systems for statically determining valid modeling compositions. These type systems bring to actor-oriented design benefits similar to what abstract data types and their corresponding type systems have brought to object-oriented design. Lastly, we have argued that component specialization can offset the performance costs associated with component-based design.

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