Language Support for Connector Abstractions

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Abstract. Software connectors are increasingly recognized as an important consideration in the design and implementation of object-oriented software systems. Connectors can be used to communicate across a distributed system, coordinate the activities of several objects, or adapt one object's interface to the interface of another. Mainstream object-oriented languages, however, do not provide explicit support for connectors. As a result, connection code is intermingled with application code, making it difficult to understand, evolve, and reuse connection mechanisms.

In this paper, we add language support for user-defined connectors to the ArchJava language. Our design enables a wide range of connector abstractions, including caches, events, streams, and remote method calls. Developers can describe both the run-time semantics of connectors and the typechecking semantics. The connector abstraction supported by ArchJava cleanly separates reusable connection code from application logic, making the semantics of connections more explicit and allowing engineers to easily change the connection mechanisms used in a program. We evaluate the expressiveness and the engineering benefits of our design in a case study applying ArchJava to the PlantCare ubiquitous computing application.

1. Introduction

The high-level design of a software system is often expressed as a software architecture, consisting of a set of components and the connections through which the components interact [GS93,PW92]. Object-oriented languages provide a natural *object* abstraction for components, and encourage developers to compose systems out of interacting objects. However, mainstream object-oriented languages do not provide explicit support for connections. Instead, connections are implicit in the object references in the heap, or are expressed indirectly using design patterns such as Proxy and Adaptor [GHJ+94].

Despite this lack of language support, connections are increasingly recognized as a crucial element of software systems. The software architecture literature has proposed a *connector* abstraction for connections, complementing the class abstraction for components. In this context, a connector is a reusable design element that supports a particular style of component interactions. In a comprehensive taxonomy of connectors, Mehta et al. describe the wide variety of connectors used in software, including method calls, events, shared variables, adaptors, streams, semaphores, and many others [MMP00]. Connectors are particularly important in the context of distributed systems, where connector attributes such as bandwidth,

synchronicity, security, reliability, and the wire protocol used may be crucial to the functionality and performance of the application.

Implementation Approaches. Because of the lack of language abstractions for connectors, developers are forced to make engineering compromises when implementing them. One approach integrates connector code into the interacting components. Unfortunately, this tightly couples the component and connector, making each of them harder to evolve or reuse. Alternatively, connectors can be written as reusable libraries. However, these libraries must often be written to a generic interface (perhaps based on type `Object`), giving up many of the advantages of static typechecking. Furthermore, even if a connector library is reusable, dependencies on the connector often pervade a component's implementation, making it difficult to understand the component in isolation or reuse it with other connectors. Our discussion of the PlantCare application in sections 4.2-4.4 illustrates many of these issues.

Tool Support. Communication infrastructures such as RMI [Jav97], CORBA [OMG95], and COM [Mic95] address these challenges by using tools to automatically generate proxies for communication with remote objects. These proxies encapsulate the connector code in a distributed system, allowing application components to make remote method calls using the same syntax as local calls. Many CASE tools and code generation tools provide similar benefits. However, these infrastructures and tools fix a particular semantics for distributed communication—semantics based on synchronous method calls using particular encodings and wire protocols. While such tools may be ideal for applications that can leverage the built-in semantics, they are inappropriate for applications that need different connector semantics. For example, the PlantCare application discussed in our case study uses a custom message-passing library designed to support the very lightweight and adaptive communication style that is required in the ubiquitous computing domain. Although tools play an important role in implementing connectors, we believe that no single connection infrastructure will be sufficient for the diverse needs of all applications in the foreseeable future.

Our Approach. In this paper, we propose explicit language support for user-defined connectors. It is difficult to integrate user-defined connectors directly in a conventional object-oriented language such as Java, because connections between objects are not explicit in the source code, but are expressed implicitly through the run time structure of references. Instead, we present our design in the context of ArchJava, an extension to Java that allows developers to specify the software architecture of a system within the implementation [ACN02a]. Because ArchJava already supports explicit connections between component objects, it can be easily extended to enable user-defined connectors that override the built-in connection semantics.

Our design allows developers to implement connectors using arbitrary Java code, supporting a very wide range of connector types. We evaluate the expressiveness of our design by implementing a representative subset of the connectors from Mehta et al.'s catalogue [MMP00]. A novel feature of our approach is that connectors define not just the run-time semantics of the connector, but also the typechecking strategy that should be used. Thus, connectors can be used to link components with interfaces that would not match using the normal Java semantics. As long as connector developers implement typechecking correctly for the domain of their connectors, our system provides a static guarantee of type safety to connector clients.

Our approach provides a clean separation of concerns. Each connector is modularly defined in its own class. Components interact with connectors in a clean way using Java's existing method call syntax. In our approach, the connector used to bind two components together is specified in a higher-level component, so that the communicating components are not aware of and do not depend on the specific connector being used. Due to this design, it is easy to change

the connectors in a system. In contrast, changing connectors may be more difficult in languages without explicit support for connector abstractions.

Organization. The rest of this paper is organized as follows. In the next section, we review the ArchJava language design through a simple peer-to-peer system example. Section 3 extends ArchJava with explicit support for connector abstractions, describing by example how they can be defined and used. We evaluate the expressiveness and the engineering benefits of our system in section 4, both by implementing a wide range of connectors and by applying ArchJava to part of the PlantCare ubiquitous computing application. We discuss related work in section 5 before concluding in section 6.

2. The ArchJava Language

ArchJava is an extension to Java that allows programmers to express the architectural structure of an application within the source code [ACN02a]. ArchJava's type system verifies *communication integrity*, the property that implementation code communicates only along connections declared in the architecture [MQR95,LV95,ACN02b]. This paper extends ArchJava by supporting much more flexible kinds of interactions along connections.

We illustrate the ArchJava language through PoemSwap, a simple peer-to-peer program for sharing poetry online. To allow programmers to describe architectural structure, ArchJava adds new language constructs to support *components*, *connections*, and *ports*. The next subsection describes ArchJava's features for representing components and ports, while subsection 2.2 shows how developers can specify an architecture using components and connections. These sections review an earlier presentation of ArchJava [ACN02a].

2.1. Components and Ports

A *component* in ArchJava is a special kind of object that communicates with other components in a structured way. Components are instances of *component classes*, such as the `PoemPeer` component class in Figure 1. The `PoemPeer` component represents the network interface of the PoemSwap application.

Components in ArchJava communicate with each other through connected ports. A *port* represents a logical communication channel between a component and one or more components that it is connected to. For example, `PoemPeer` has a `search` port that provides search services to the PoemSwap user interface, and it has a `poems` port that it uses to access the local database of poems.

Ports declare two sets of methods, specified using the **`requires`** and **`provides`** keywords. A *provided* method is implemented by the component and is available to be called by other components connected to this port. For example, the `search` port provides searching and downloading methods that can be invoked from the user interface. Provided methods must be given definitions in the surrounding component class, as shown by the implementation of `downloadPoem` in Figure 1.

Conversely, each *required* method is provided by some other component connected to this port. In Figure 1, the `poems` port requires methods that get descriptions of all the poems in the database, retrieve a specific poem by its description, and add a poem to the database. A port may have both required and provided methods, but as shown in the example, it is common for a port to have only one or the other.

```
public component class PoemPeer {
  public port search {
    provides PoemDesc[] search(PoemDesc partialDesc) throws IOException;
    provides void downloadPoem(PoemDesc desc) throws IOException;
  }

  public port poems {
    requires PoemDesc[] getPoemDescs();
    requires Poem getPoem(PoemDesc desc);
    requires void addPoem(Poem poem);
  }

  public port interface client {
    requires client(InetAddress address) throws IOException;
    requires PoemDesc[] search(PoemDesc partialDesc, int hops, Nonce n);
    requires Poem download(PoemDesc desc);
  }

  public port interface server {
    provides PoemDesc[] search(PoemDesc partialDesc, int hops, Nonce n);
    provides Poem download(PoemDesc desc);
  }

  void downloadPoem(PoemDesc desc) throws IOException {
    client peer = new client(desc.getAddress());
    Poem newPoem = peer.download(desc);
    if (newPoem != null) {
      poems.addPoem(newPoem);
    }
  }
  // other method definitions...
}
```

Figure 1. The `PoemPeer` class represents the network interface of the PoemSwap application. `PoemPeer` communicates with other components through its ports. It provides a network search service to the rest of the application through the `search` port, and it accesses the poem database through the `poems` port. Finally, it communicates with other PoemSwap applications over a wide-area network using complimentary `client` and `server` ports.

A component can invoke a required method declared in one of its ports by sending a message to the port. For example, in Figure 1, after downloading a new poem from a peer, the `downloadPoem` method adds the new poem to the poem database with the call `poems.addPoem(newPoem)`. As this example shows, ports such as `poems` are concrete objects, and required methods can be invoked on ports using Java's standard method call syntax.

If a component communicates with multiple different components using the same interface, it can declare a *port interface* and then create a port of that interface type for each component it needs to communicate with. A port interface defines the type of a port, just as a class defines the type of an object. In fact, concrete port declarations such as **`public port`** `search { ... }` are a convenient shorthand for declaring a port interface together with a single instance of that interface type. In the example, `PoemPeer` must communicate with many other PoemSwap peers through its `client` port interface, and it may serve requests from many peers through its `server` port interface. The two interfaces are symmetric, as each peer may act as both a client and a server.

The `client` port interface contains a *required connection constructor*, named `client` after the surrounding port interface, which the `PoemPeer` can invoke in order to create a connection to a peer at the given `InetAddress`. The `downloadPoem` method instantiates a port of type `client` with the same **`new`** syntax used to create objects in Java. The method can then call the required method `download` on the newly created port instance.

The goal of ports is to specify both the services implemented by a component and the services a component needs to do its job. Required interfaces make dependencies explicit, reducing coupling between components and promoting understanding of components in isolation. For example, the `PoemPeer` component is implemented without any knowledge of what connection protocol will be used to connect it to its peers. `PoemPeer` expects a connector that has synchronous method call semantics, but any connector that conforms to this constraint can be used.

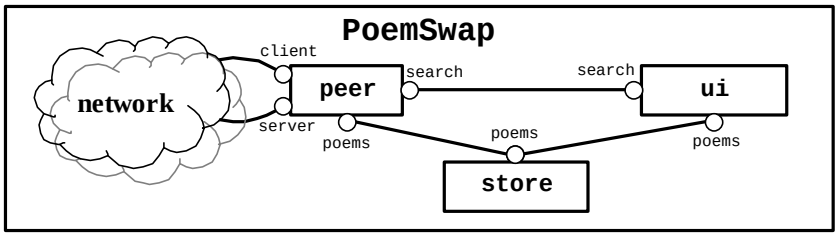
2.2. Software Architecture in ArchJava

In ArchJava, a hierarchical software architecture is expressed with a *composite component*, which is made up of a number of subcomponents connected together. A *subcomponent* is a component instance nested within another component. For example, Figure 2 shows how `PoemSwap`, the main component of the PoemSwap application, is composed of three subcomponents: a user interface, a poem database, and a `PoemPeer` instance. The subcomponents are declared as fields within `PoemSwap`.

In ArchJava, architects declare the set of permissible connections in the architecture using *connect patterns*. A connect pattern specifies two or more port interfaces that may be connected together at run time. For example, the first three connect patterns in Figure 2 specify that both the user interface and the network interface connect to the `poems` port interface of the `PoemStore`, and that the `search` port interface of the user interface connects to the corresponding port interface of the network peer. The default typechecking rule for connect patterns ensures that for every method required by one or more of the connected port interfaces, there is exactly one corresponding provided method with the same name and signature.

Actual connections are made using *connect expressions* that appear in the methods of a component. A connect expression specifies the concrete component instances to be connected in addition to the connected ports. In the example, the `PoemSwap` constructor makes three connections, one for each of the connect patterns declared in the architecture. A static check ensures that the types of the connected ports conform to the types declared in one of the connect patterns.

The built-in semantics of ArchJava connections binds required methods to provided methods, so that when a required method is called on one port, the corresponding provided method of the other port is invoked. For example, when the `PoemPeer` in Figure 1 invokes `addPoem` on its `poems` port, the invocation will be forwarded across the connection created in the `PoemSwap` constructor. The `addPoem` method implementation provided by the `poems` port of the `PoemStore` (not shown) will be invoked.




```
public component class PoemSwap {
  private final SwapUI ui = new SwapUI();
  private final PoemStore store = new PoemStore();
  private final PoemPeer peer = new PoemPeer();

  connect pattern SwapUI.poems, PoemStore.poems;
  connect pattern PoemPeer.poems, PoemStore.poems;
  connect pattern SwapUI.search, PoemPeer.search;

  public PoemSwap() {
    TCPConnector.registerObject(peer, POEM_PORT, “server”);

    connect(ui.poems, store.poems);
    connect(peer.poems, store.poems);
    connect(ui.search, peer.search);
  }

  connect pattern PoemPeer.client, PoemPeer.server with TCPConnector {

     client(PoemPeer sender, InetAddress address) throws IOException {
        connect(sender.client, PoemPeer.server)
           with new TCPConnector(address, POEM_PORT, “server”);
     }
  };
}
```

Figure 2. A graphical and textual description of the PoemSwap architecture. The `PoemSwap` component class contains three subcomponents—a user interface, a poem store, and the network peer. Connect patterns show statically how these components may be connected, and the connect expressions in the constructor link the components together following these patterns. A final connect pattern shows how peers on different machines communicate via a `TCPConnector`. The `client` connection constructor creates a connection when the `PoemPeer` requests one.

Connection Constructors. Each connect pattern must provide a *connection constructor* for each of the required connection constructors declared in the connected ports. A connection constructor is named after the port that required the constructor, and the first argument is the component that requested the connection. The other arguments match the ones declared in the corresponding required connection constructor. For example, the `client` port interface in `PoemPeer` declares a required connection constructor that accepts an `InetAddress`. Therefore, the last connect pattern in Figure 2 declares a connection constructor with two arguments—the `PoemPeer` that requested the connection and an `InetAddress`. The body of a connection constructor must contain exactly one connect expression that matches the surrounding connect pattern. The connect expression must include the port interface through

which the `sender` component requested the connection (`sender.client` in the example). We explain the **`with`** keyword in the next section.

3. Connector Abstractions in ArchJava

In this section, we describe the new language features and libraries that support connector abstractions in ArchJava. We extend the syntax of connect patterns and connect expressions to describe which connector abstractions should be used to typecheck and implement the connections. Subsection 3.1 demonstrates these language features by examples, showing how a user-defined TCP/IP connector can be used to connect different `PoemSwap` peers across a wide-area network. New connectors can be written using the `archjava.reflect` library, described in Subsection 3.2, which reifies connections and required method invocations. Subsection 3.3 shows how the TCP/IP connector can be implemented using this library. Finally, subsection 3.4 discusses the use of connector abstractions, identifying when connector abstractions are beneficial and when a more conventional connector implementation may be appropriate.

3.1. Using Connector Abstractions

Connector Typechecking. Instead of using ArchJava's default typechecking rules, connect patterns can specify that a user-defined connector class should be used for typechecking instead. For example, the connect pattern at the end of Figure 2 specifies a user-defined connector class to be used for typechecking using the syntax **`with`** <*connector class*>. Every connector class has a static `typecheck` method that defines the typechecking semantics of that connector (see Figure 3 below). In the example, when the `PoemSwap` component class is compiled, the compiler loads the `TCPConnector` class and invokes the `typecheck` method to check the validity of the connect pattern (see Figure 5 and the discussion in subsection 3.3). This typechecking replaces the default ArchJava typechecking semantics, allowing the connector abstraction to define arbitrary typechecking rules.

In the case of `TCPConnector`, the `typecheck` method first invokes the standard ArchJava typechecker, and then additionally checks that all arguments and results of all methods in the connection are subtypes of the `Serializable` interface. Because the `TCPConnector` uses Java's serialization mechanism to send method arguments and results across a network, a run-time error will result if the method arguments and results are not serializable. By defining its own typechecking semantics to extend those of ArchJava, the `TCPConnector` can detect this error at compile time[1].

Instantiating Connectors. Connectors are instantiated whenever a connect expression that specifies a user-defined connector object is executed at run time. A connect expression uses the syntax **`with`** <*expression*> to specify the connector instance that should be used for the connection it is creating. For example, the connection constructor in Figure 2 executes a connect expression when it is called, and the connect expression creates a user-defined `TCPConnector` object, passing the address, TCP/IP port, and the name of the remote peer to the constructor of the connector. The expression in the **`with`** clause must be have a type that is

[1] This check would have been handy when testing the PoemSwap application. Before customized typechecking was implemented, we got run time errors because we forgot to make class `Poem` serializable.

```
public class Connector {
  public static Error[] typecheck(Connection c);
  public Object invoke(Call c) throws Throwable;

  public Connector();
  protected Connector(Object components[], String portNames[]);

  public final Connection getConnection();
}

public final class Connection {
  public Port[] getPorts()
  public Connector getConnector()
}

public final class Port {
  public String getName();
  public Method[] getRequiredMethods();
  public Method[] getProvidedMethods();
  public Object getEnclosingObject();
}

public final class Method {
  public String getName();
  public Type[] getParameterTypes();
  public Object invoke(Object args[]) throws Throwable;
}

public final class Type {
  public String getName();
  public boolean isAssignableFrom(Type other);
  public static Type forName(String qualifiedName);
}

public final class Call {
  public Method getMethod();
  public Object[] getArguments();
}
```

Figure 3. The `archjava.reflect` library includes classes reifying connectors, connections, ports, methods, types, and calls. User-defined connector classes extend the `Connector` class, overriding the `invoke` method to define customized dynamic semantics and providing a `typecheck` method that implements typechecking.

a subclass of the connector type declared in the corresponding connect pattern, to ensure that the connector implementation used at run time matches the connector that was used to typecheck the connection statically.

In the case of `PoemSwap`, the component to be connected to the `PoemPeer` is a peer on a remote machine, and so we cannot use a direct reference to it in the connect expression. ArchJava allows developers to specify connections to remote components (to which they cannot have a direct reference) by specifying the type of the connected component rather than an actual concrete instance. This type allows the compiler to check the connect expression against the surrounding connect pattern. The `TCPConnector` is responsible for identifying and communicating with the remote component, and it does this using the `InetAddress` passed to the constructor.

3.2. The `archjava.reflect` Library

Connector abstractions are defined using the `archjava.reflect` library, whose most important classes and methods are shown in Figure 3. This library defines a `Connector` class that user-defined connector classes extend, as well as classes that reify connections, ports, and methods.

Class `Connector` provides a hook for defining customized connectors. Connector abstractions can define custom typechecking semantics by defining a static `typecheck` method, which is called at compile time to typecheck a connect pattern, returning a possibly empty array of errors. For example, the default implementation of `typecheck` returns an error for each required method that has no matching provided method, or has more than one matching provided method. If a connector defines no `typecheck` method, the compiler looks in that connector's superclass for a `typecheck` method, and so on until the compiler gets to the default `typecheck` method in class `Connector`.

Run-time connection behavior can be defined by overriding the `invoke` method, which accepts a `Call` object reifying an invocation on a required method. The default implementation finds the corresponding provided method and invokes it, passing the resulting return value or exception back to the caller.

`Connector` provides a default public constructor that is used by all direct clients and most subclasses. A second constructor creates a connection programmatically (i.e., without a connect expression) from the specified arrays of components and corresponding port names. This constructor is provided since some connectors (including `TCPConnector`) must be able to create a connector object that represents the "local end" of a connection that was originally made on a remote machine. Since this constructor allows connections to be created dynamically without being typechecked statically, it is accessible only to `Connector` subclasses, not to clients.

Classes `Connection`, `Port`, `Method`, and `Type` reify the connection that is associated with the connector, along with its ports and method signatures. Figure 3 shows only a fraction of the interface of these classes. User-defined connectors do not extend these classes, but instead may use them as a library for getting information about the current connection. This information, accessible through the `getConnection` method of `Connector`, can be used statically when typechecking or dynamically when dispatching a required method invocation. For example, the connector can invoke provided methods at run time by calling `invoke` on the relevant `Method` object.

3.3. Implementing Connector Abstractions

Figure 4 shows how the run-time semantics of `TCPConnector` can be defined in Java code. The example shows primarily the interface of the connector and how it uses the `archjava.reflect` library. We omit the code in two helper classes: `TCPDaemon`, which listens for incoming network connections on a TCP/IP port, and `TCPEndpoint`, which serializes and deserializes data going through a connection endpoint.

When the `downloadPoem` method in Figure 1 creates a new instance of the `client` port interface, the corresponding connection constructor links the `client` port instance to a remote server by creating a `TCPConnector` object, passing the Internet address of the remote machine together with a port and string identifying the server. The `TCPConnector` constructor shown in Figure 4 creates a `TCPEndpoint` object that opens a network connection to the remote host.

```
public class TCPConnector extends Connector {
  // data members
  protected TCPEndpoint endpoint;

  // public interface
  public TCPConnector(InetAddress host, int prt, String objName)
                                                        throws IOException {
    endpoint = new TCPEndpoint(this, host, prt, objName);
  }

  public Object invoke(Call call) throws Throwable {
    Method meth = call.getMethod();
    return endpoint.sendMethod(meth.getName(), meth.getParameterTypes(),
                               call.getArguments());
  }

  public static void registerObject(Object o, int prt, String objName)
                                                        throws IOException {
    TCPDaemon.createDaemon(prt).register(objName, o);
  }

  // interface used by TCPDaemon
  TCPConnector(TCPEndpoint endpoint, Object receiver, String portName) {
    super(new Object[] { receiver }, new String[] { portName });
    this.endpoint = endpoint;
    endpoint.setConnector(this);
  }

  Object invokeLocalMethod(String name, Type parameterTypes[],
                           Object arguments[]) throws Throwable {
    // find method with parameters that match parameterTypes
    Method meth = findMethod(name, parameterTypes);
    return meth.invoke(arguments);
  }

  // typechecking semantics defined in Figure 5
}
```

Figure 4. The `TCPConnector` class extends the `archjava.reflect.Connector` class to define the dynamic semantics of a connector based on a TCP/IP network connection. The `invoke` method passes the method name, parameter types, and arguments to a daemon that uses Java's serialization facilities to send them over a TCP/IP network connection. The daemon at the other end of the connection, created when the other peer called `registerObject`, calls `invokeLocalMethod` on a `TCPConnector` object, which identifies the right method to call and invokes it.

When a required method is called on the `client` port instance, the runtime system reifies the call and redirects it to the `invoke` method on the `TCPConnector`. `TCPConnector`'s `invoke` method determines which required method was called, and then passes the name of the method, its parameter types, and the actual call arguments to the `TCPEndpoint`. The `TCPEndpoint` sends this data over the TCP/IP network connection.

At the other side of the network, the `PoemSwap` application uses `registerObject` to register a `PoemPeer` component under the name "server" (see Figure 2). The `registerObject` method starts a `TCPDaemon` listening at the assigned TCP/IP port. When the daemon receives an incoming connection, it creates a `TCPEndpoint` object representing that TCP/IP connection and creates a `TCPConnector` object to represent the

```
public class TCPConnector extends Connector {
  public static Error[] typecheck(Connection c) {
    // First invoke the default Java typechecker
    Error [] errors = Connector.typecheck(c);
    if (errors.length > 0)
      return errors;

    // ensure all arguments and results are Serializable
    Type serializable = Type.forName("java.lang.Serializable");
    for (int pI = 0; pI < c.getPorts().length; ++pI) {
      for (int mI = 0; mI < c.getPorts()[pI].getMethods().length; ++mI){
        Method method = c.getPorts()[pI].getMethods()[mI];
        Type returnType = method.getReturnType();
        if (!serializable.isAssignableFrom(returnType))
          return new Error[] { new Error("type not serializable", c) };
        // similar check for method arguments
      }
    }
  }

  // dynamic semantics defined in Figure 4
}
```

Figure 5. The `typecheck` method in the `TCPConnector` class ensures that method arguments and results are serializable.

connector locally. The daemon uses the non-public `TCPConnector` constructor, passing the local `TCPEndpoint` object as well as the object to be connected and the name of its connected port to the constructor. Since the originating connection was created on the other machine, there is no information about this connection in the runtime system, and so it is necessary to specify the components and ports to be connected when calling the protected constructor of the `Connector` superclass.

When the `TCPEndpoint` receives an incoming method, it calls `invokeLocalMethod` on the `TCPConnector` associated with the receiver object. `invokeLocalMethod` uses the `findMethod` helper function (not shown) to identify the matching provided method, and then invokes the method through a reflective call. The result, or any exception that is thrown, will be packaged back up by the `TCPEndpoint`, sent back over the network, returned to the implementation of `invoke` in the source `TCPConnector`, and returned to the caller.

User-Defined Typechecking. For each connect pattern in the system, the compiler loads the appropriate connector class and calls its `typecheck` method at compile time. The compiler passes `typecheck` a `Connection` object that reifies the port interfaces in the connect pattern, so that the typechecker can examine the methods and types in the connected port interfaces.

The `typecheck` method returns a possibly empty array of `Error` objects describing any semantic errors in the connect pattern. The `Error` class encapsulates a `String` describing the problem as well as a syntax element (a `Connection`, `Port`, or `Method`) that describes where the error occurred, allowing the compiler to determine an accurate line number for the reported error.

Figure 5 shows the definition of the `typecheck` method of `TCPConnector`. The code begins by running the standard `typecheck` method defined in class `Connector`, which ensures that for each required method there is exactly one provided method with an identical name and signature. It returns any errors found by this method. If standard typechecking succeeds, the `TCPConnector` visits every required and provided method in the connection,

making sure that all method arguments and results are `Serializable`, so that the `TCPEndpoint` will be able to serialize them successfully at run time.

3.4. Connector Implementation.

Connectors can be implemented in a wide variety of ways, each with its own benefits and drawbacks. For example, in addition to our connector abstractions, connectors could be built into the language, expressed idiomatically through a design pattern, or described using ArchJava's component construct.

The key benefit of using connector abstractions is that the same connector can be reused to support the same interaction semantics across many different interfaces, while still providing a strong, static guarantee of type safety to clients. For example, the `TCPConnector` can connect any two ports with matching signatures, as long as the arguments to methods in those ports are `Serializable`. Other solutions that guarantee type safety require separate stub and skeleton code to be written for each interface, causing considerable code duplication and hindering reuse and evolution. Alternatively, a standard library for sending objects across a TCP/IP connection could be used, but this solution does not guarantee that the messages sent and received across the connection have compatible types, so run time errors are possible.

The main drawback of using connector abstractions is that they are defined using a reflective mechanism. Although connectors can define typechecking rules for their clients, there is no way to statically check that a connector's implementation performs the communication in a type-safe way. Also, there is some run-time overhead associated with reifying a method call so that a connector can process it dynamically. Thus, in situations where a connector is not reused across different interfaces, it may be better to use objects or components to implement the connector.

4. Evaluation

We have implemented language support for connector abstractions in the ArchJava compiler, which is available for download at the ArchJava web site [Arc02]. Thus, all examples in this paper, including PoemSwap and PlantCare, are simplified versions of working code.

We evaluate our design in two ways. In the next subsection, we evaluate the expressiveness of our connector abstraction mechanism by describing how a wide range of connectors can be implemented. In the following subsection, we evaluate the engineering benefits of connector abstractions with a small case study on the PlantCare ubiquitous computing application. Subsection 4.3 discusses the case study and reports feedback from the developers of PlantCare. Finally, subsection 4.4 compares our connector abstraction approach to an alternative approach using design patterns in the PlantCare system.

4.1. Expressiveness

In order to evaluate the expressiveness of our connector abstraction mechanisms, we use Mehta et al.'s taxonomy of connectors as a benchmark for our design [MMP00]. The taxonomy describes eight major types of connectors: procedure call, event, data access, linkage, stream, arbitrator, adaptor, and distributor connectors. We discuss each connector type in turn, describing which species of that connector can benefit from using connector abstractions. All

of the connector abstraction examples described here are available for download as part of the ArchJava distribution [Arc02].

Procedure Call. Procedure call connectors enable the transfer of control and data through various forms of invocation. Although most programming languages provide explicit support for procedure calls, there are a number of semantic issues that justify user-defined procedure call connectors. For example, parameters could be passed by reference, by value, by (deep) copy, etc.; calls could be synchronous or asynchronous; calls could use one-to-many broadcast semantics, many-to-one collecting semantics, or conceivably even a many-to-many semantics.

ArchJava's connector abstractions are well suited to implementing procedure call connectors because the interface for defining connectors reifies method calls on ports. As an example, we have implemented an `AsynchronousConnector` that accepts incoming required method calls, returns to the sender immediately, and then invokes the corresponding provided method asynchronously in another thread.

We have also implemented a `SummingBroadcastConnector` that accepts an incoming method call, broadcasts it to all connected components, and sums the results of all the invocations before returning the sum to the original caller. This second connector relies on ArchJava's multi-way connections, which can connect more than two ports. Both connectors implement appropriate typechecking; for example, the `AsynchronousConnector` ensures that all methods in connected ports return **`void`**, while the `SummingBroadcastConnector` ensures that all of the methods return an integer. The `TCPConnector` shown in Figure 4 above is a procedure call connector that connects components running on different virtual machines.

Event. Event connectors support the transfer of data and control using an implicit mechanism, where the producer and consumer of an event are not aware of each other's identity. Semantic issues with event connectors include the cardinality of producers and consumers, event priority, synchronicity, and the event notification mechanism.

Events are often implemented as inner-class callback objects in languages such as Java, but this technique can make programs very difficult to reason about and evolve, as it is hard to see which components might be communicating through an event channel. In contrast, using a custom ArchJava event connector may aid in program understanding, because the connection between components is explicit in the software architecture of the system. Connector abstractions provide additional benefit by allowing components to communicate using different event semantics. For example, we have implemented an `EventDispatchConnector` that enqueues event notifications and dispatches them asynchronously to consumers.

The PlantCare application, described below in subsection 4.2, uses a user-defined connector to support asynchronous event-based communication across a loosely coupled ad-hoc network.

Data Access. Data access connectors are used to access a data store, such as a SQL database, the file system, or a repository such as the Windows registry. Issues in data access components include initialization and cleanup of connections to data sources, and the conversion and presentation of data. Conventional library-based techniques are appropriate for implementing many kinds of data access connectors. However, connector abstractions can be used to provide a convenient view of the data source, or adding semantic value to a data source in a reusable way. For example, one could imagine a connector that provides an object-oriented view of a relational database, translating each row of each table into an object and providing a collection-like access to clients. As a more concrete example, Figure 6 shows a `CachingConnector` that caches the results of method calls to a data store and returns the same result if the method is called again with identical arguments.

```
public class CachingConnector extends Connector {
  protected Map cache = new Hashtable();

  public Object invoke(Call call) throws Throwable {
    List arguments = Arrays.asList(call.getArguments());
    Object result = cache.get(arguments);
    if (result != null)
      return result;

    result = super.invoke(call);

    if (result != null)
      cache.put(arguments, result);
    return result;
  }
}
```

Figure 6. A `CachingConnector` that caches method invocations to avoid recomputation.

Linkage. Linkage connectors bind a name in one module to the implementation provided by another module. Examples of linkage connectors include imported names and references to names defined in other source files. ArchJava's connector abstractions are intended to connect object instances at run time, not link names at compile time. Therefore, Linkage connectors are outside of the scope of ArchJava's connector abstraction design.

Stream. Stream connectors support the exchange of a sequence of data between loosely coupled producer and consumer components. Semantic issues with streams include buffering, bounding, synchronicity, data types, data conversion, and the cardinality of the producers and consumers. Many of these issues can be encapsulated within a reusable connector abstraction. For example, we have developed a `BufferedStreamConnector` that implements a stream with a bounded buffer size, supporting one producer but an arbitrary number of consumers. The `BufferedStreamConnector` is reusable for streams of many different data types, but checks that the types of data produced and consumed match. A plain Java implementation would either sacrifice reusability or use `Object` as the data type, giving up the checking benefits of a typed stream. Here connector abstractions provide an advantage similar to generics proposals for Java such as GJ [BOS+98].

Arbitrator. Arbitrator connectors provide services that coordinate and facilitate interactions among components. Examples of arbitrators include semaphores, locks, transactions, fault handling connectors with failover, and load balancing connectors. Semaphores and locks typically have the same interface no matter which components they connect, and so they are probably best implemented using ordinary objects or as ArchJava components. However, more sophisticated arbitrators can benefit from ArchJava's connector abstraction mechanism. For example, we have built a `LoadBalancingConnector` that accepts incoming method calls from a client and distributes them to a bank of server components based on the current server loads. The `LoadBalancingConnector` is reusable across any client interface, while still providing typechecking between clients and services.

We have also implemented a `BarrierSynchronizationConnector`. Components invoke a different method on the barrier after each stage of work, and the barrier ensures that all its clients have called a given barrier method before it allows any of the method calls to return.

Adaptor. Adaptor components retrofit components with different interfaces so that they can interact. Adaptors may convert data formats, adapt to different invocation mechanisms,

transform protocols, or even make presentation changes like internationalization conversions. Well-known design patterns such as Adaptor, Wrapper, and Façade are often used to implement adaptors [GHJ+94]. However, connector abstractions can be useful for performing similar adaptations to different interfaces. For example, the `RainConnector` in section 4.2 below adapts data types using structural subtyping, so that two components can communicate with different datatypes as long as the data sent in a message has a superset of the information expected by the receiver.

Distributor. Distributor connectors identify paths between components and route communication along those paths. Distributors are not first-class connectors, but provide routing services to other connectors. Both the `EventDispatchConnector` described above and the `RainConnector` described below include distributor functionality.

Summary. As the discussion above makes clear, ArchJava's connector abstractions are very flexible, supporting a wide range of different connector types. Some kinds of connectors are most clearly expressed using conventional mechanisms such as objects and components. However, connector abstractions provide a unique level of reusability across port interfaces while still providing clients with a strong static guarantee of type safety.

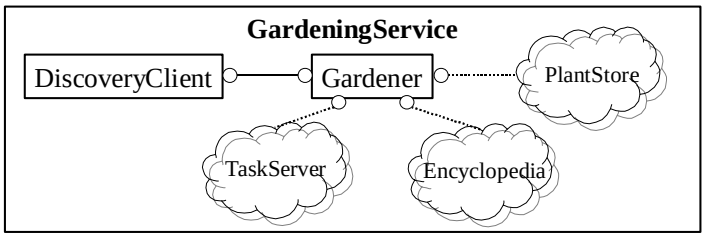
4.2. PlantCare Case Study

In order to evaluate the engineering benefits of user-defined connector abstractions, we performed a small case study with the PlantCare ubiquitous computing application [LBK+02]. PlantCare is a project at Intel Research Seattle that uses a collection of sensors and a robot to care for houseplants autonomously in a home or office environment. This application illustrates many of the challenges of ubiquitous computing systems: it must be able to configure itself and react robustly to failures and changes in its environment.

The Gardening Service. Figure 7 shows the architecture of the gardening service, one of several services in the PlantCare system. The gardening service consists of a central gardener component that uses three external services as well as a client for a well-known discovery service. The gardener periodically executes a cycle of code that cares for plants as follows. First, the gardener requests from the `PlantStore` a list of all the plants in the system and the sensor readings from each plant. For each plant, it queries the `Encyclopedia` to determine how that plant should be cared for. After comparing the recommended and actual plant humidity levels, it adds or removes watering tasks from the `TaskServer` so that each plant remains in good health.

We have chosen to include the interfaces of relevant external services as part of the gardening service architecture, because then we can use the connectors in the architecture to reason about the protocols used to communicate with these services. A more conventional architectural depiction would represent these protocols as connectors in an enclosing architecture. However, in ubiquitous computing systems, there is no way to statically specify the entire enclosing architecture, because the services available in a system may change frequently as devices move and connections fail. Instead, the gardening service architecture includes a partial view of the surrounding architecture, including the external components with which the gardener communicates.

Below the visual architectural diagram in Figure 7 is the ArchJava code describing the architecture (the complete gardener service code is about 500 lines long). The concrete `Gardener` and `DiscoveryClient` component instances are declared with final fields. The




```
public component class GardeningService {
  private final Gardener gardener = new Gardener(getServiceID());
  private final DiscoveryClient client = new DiscoveryClient();

  connect client.discovery, gardener.discovery;

  connect pattern Gardener.PlantInfo, PlantStore.PlantInfo
    with RainConnector {
      PlantInfo(Gardener sender, ServiceID id) {
        connect(sender.PlantInfo, PlantStore.PlantInfo)
                with new RainConnector(id);
      }
    }
  // other architectural connections not shown
}

public component class Gardener extends StateMachineNode {
  public port discovery {
    requires ServiceID find(String serviceType);
  }
  public port interface PlantInfo {
    requires PlantInfo(ServiceID id);
    requires void statusQuery();
    provides void statusReply(PlantStatus data);
  }
  private PlantInfo plantInfoPort;

  public startStateCycle() {
    ServiceID ID = discovery.find("Plant Store");
    plantInfoPort = new PlantInfo(ID);
    plantInfoPort.statusQuery();
    ...
  // remaining Gardener implementation not shown
}
```

Figure 7. The architecture of the PlantCare gardening service

connect declaration linking the `discovery` ports of the `client` and the `gardener` is syntactic sugar for a connect pattern and a corresponding connect expression.

The connect pattern links the `PlantInfo` port interfaces of the gardener and the plant store. When the gardener requests a new connection, the provided connection constructor specifies that it should be connected with a `RainConnector`, using a `ServiceID` to identify the location of the remote `PlantStore` component. The other connect patterns, although omitted from this diagram, are similar.

The `RainConnector` class implements the Rain communication protocol used in the PlantCare system. When methods are invoked through connections of type `RainConnector`, the user-defined connector code will package the method name and

arguments as an XML message, send them over a HTTP connection, and call the appropriate provided method on the other side. Since Rain messages are asynchronous and do not return a response, `RainConnector` also defines a custom typechecker that verifies that methods in the connected ports have a **`void`** return type. Although `RainConnector` is similar to `TCPConnector` in that both connect components that may be located on different hosts, it provides very different semantics (asynchronous messages vs. synchronous method calls), demonstrating the versatility of ArchJava's connector abstractions.

The `RainConnector` implementation is similar to the `TCPConnector` defined earlier. The connector uses the name of the method called as the name of the XML message to be sent. The method arguments are serialized and sent over the network using the same Rain library that is currently used by the PlantCare application. Because Rain messages are asynchronous, the `RainConnector` returns immediately after sending a message, without waiting for an acknowledgement or response.

The `Gardener` class has a concrete port for discovery, but port interfaces for communicating with other components. This is a natural choice, because discovery is a fundamental service that must be in place in order for the `Gardener` to dynamically discover other available services. The discovery interface allows the `Gardener` to look up a service by its type. It returns a `ServiceID` data structure that can then be used in a connection constructor to connect to other components.

The code in `startStateCycle` shows the beginning of the cycle of code that the `Gardener` executes when caring for plants. The code uses the discovery service to find the `ServiceID` of an available `PlantStore` service. It then allocates a new `PlantInfo` port instance and stores it in a variable. The final line of code shown sends an asynchronous message through the newly allocated port, querying the status of the plants in the system. The `PlantStore` will reply with another asynchronous message, which will be translated by the `RainConnector` into a call to the `statusReply` method, which carries out the next stage in the cycle. If an internal timer (not shown) expires before the `statusReply` message is received, the gardener assumes that the `PlantStore` component (or an intervening network link) has failed, and restarts the state cycle, using the discovery service once again to connect to a functioning `PlantStore`.

4.3. Discussion

In this section, we analyze the results of our case study according to three criteria: program understanding, program correctness, and software evolution. Finally, we report feedback from the developers of the PlantCare application.

Program Understanding. The ArchJava version of the gardening service code has a number of characteristics that make it easier to understand the service's implementation. In the Java version, the information about which messages are sent and received is spread throughout the source code. Figure 7 shows how the ArchJava architecture documents the sent and received messages explicitly as required and provided methods in the ports of `Gardener`, making it easier to understand the interactions between the gardener and other services.

Figure 7 also shows how the ArchJava source code documents the architecture of the service, showing which other services the gardener depends on. This information is obscured in the original gardener source code; it would have to be deduced from the types of messages exchanged. Another benefit is that the connector specification explicitly documents that the Rain communication protocol is used between components. This would be especially valuable

Java Version:

```
protected void handleMessageIn(Message m) {
  if ... { ... // cases for plant status messages above...
  } else if (msg instanceof PlantInfoReply) {
    // case for plant info message
    PlantInfoReply p = (PlantInfoReply) msg;
    careMap.put(p.name,p);
    state = AWAITING_TASKS;
    sendTasksRequest();
    return;
  } else if (msg instanceof TaskListReply) {
    // case for task reply message below...
}

protected void sendTasksRequest() {
  try {
    TaskListQuery q = new TaskListQuery();
    q.list = "Water Plants";
    sendMessage(taskServer,q,newClosure());
  } catch (Exception ex) {
    // an error occurred, restart the cycle
    ex.printStackTrace();
    resetState();
  }
}
```

ArchJava Version:

```
void infoReply(PlantInfoReply data) {
  careMap.put(data.name, data);
  state = AWAITING_TASKS;
  try {
    taskPort.taskQuery("Water Plants");
  } catch (Exception ex) {
    // an error occurred, restart the cycle
    ex.printStackTrace();
    resetState();
  }
}
```

Figure 8. A comparison of the old and new versions of the `Gardener` code that responds to the `PlantInfoReply` message.

if the gardener used different protocols to communicate with different external services, as may often be the case in heterogeneous ubiquitous computing systems.

Figure 8 compares the Java and ArchJava versions of the code that responds to a `PlantInfoReply` message from the encyclopedia. Here, ArchJava's abstraction mechanisms for inter-component communication make the application logic of the gardener clearer. In the original Java code, a single `handleMessageIn` method responds to all incoming messages. The `PlantInfoReply` message is one case in a long list of messages; the code stores the plant care information in an internal data structure and then calls a separate `sendTasksRequest` function to send out the next batch of messages. In the ArchJava version, this response code is more cleanly encapsulated in a single method, which responds to the original message and then sends the next set of messages through the task port. The process of sending a message is also simpler and cleaner in ArchJava. The programmer simply calls a

method in the `taskPort`, rather than constructing a custom message and sending it using the Rain library.

Correctness. The ArchJava language performs a number of checks that help to ensure the correctness of the `GardeningService` implementation. For example, the `RainConnector` typechecker verifies interface compatibility between the ports of `Gardener` and the connected ports of the external services at compile time. In the original Java code, this problem would show up as a run time error when a component does not recognize a message that was sent to it.

ArchJava also verifies communication integrity [MQR95,LV95,ACN02b], a property which guarantees that the `Gardener` only communicates with the services declared in the `GardeningService` architecture (We assume that the gardener does not directly use Java's networking library, a property that could also be checked in a straightforward way). This property guarantees that the architecture can be relied on as an accurate representation of the communication in the system, increasing the program understanding benefits of architecture.

Software Evolution. Because of ArchJava's explicit abstractions for ports and connectors, some evolutionary steps are easier to perform. For example, if a service needs to interact with a device that cannot generate XML messages, we can replace `RainConnector` with a new connector type that can communicate with the more restricted device. Also, we can reuse an existing service in a new environment by simply inserting adaptor components or connectors that retrofit the old service to the message protocol expected by the new environment. In both cases, ArchJava's explicit descriptions of component interfaces and connections make architectural evolution easier.

An important criterion to consider in the evolvability of a system is the degree to which the system's modularization hides information within a single module. One benefit of the ArchJava version of the gardening service is that the gardener's functionality is encapsulated in `Gardener` while the communication protocol used is encapsulated in `GardeningService`. The ports of `Gardener` serve as the interfaces used to hide this information. Thus, in the ArchJava code, the gardening functionality can be changed independently of the communication protocol, facilitating evolution of this service.

Developer Feedback. Perhaps the most important evaluation criterion is feedback from the developers of PlantCare. We found that the developers were able to understand the ArchJava notation fairly quickly. They said that the `GardeningService` architecture captured their informal architectural view of the system well. Finally, they agreed that ArchJava was able to provide the benefits describe in the analysis above. We are currently working with them to put ArchJava to production use in a future ubiquitous computing system.

4.4. Design Pattern Alternatives to Connector Abstractions

In this section, we compare the connector abstraction technique we used in the PlantCare application to an alternative solution using conventional object-oriented design techniques. Many design patterns are intended to provide benefits like separation of concerns and ease of change, similar to the benefits provided by connectors [GHJ+94]. In order to be concrete, our comparison focuses on the PlantCare application.

For example, Figure 9 shows the PlantCare code for responding to the `PlantInfoReply` message, rewritten using the Proxy design pattern. In this example, the application-defined response code is contained in an `infoReply` method that is similar to the `infoReply` message in the ArchJava example. Instead of invoking the `taskQuery` method on the

Design Patterns Version:

```
protected void handleMessageIn(Message m) {
  if ... { ... // cases for plant status messages above...
  } else if (msg instanceof PlantInfoReply) {
    // case for plant info message
    infoReply(msg);
  } else if (msg instanceof TaskListReply) {
    // case for task reply message below...
}

void infoReply(PlantInfoReply data) {
  careMap.put(data.name, data);
  state = AWAITING_TASKS;
  try {
    taskProxy.taskQuery("Water Plants");
  } catch (Exception ex) {
    // an error occurred, restart the cycle
    ex.printStackTrace();
    resetState();
  }
}

protected class TaskProxy {
  public void taskQuery(String task) {
    TaskListQuery q = new TaskListQuery();
    q.list = task;
    sendMessage(taskServer,q,newClosure());
  }
  // methods for other TaskServer messages...
}
```

Figure 9. The response code for the `PlantInfoReply` message, written using design patterns to separate communication code from application logic.

`taskPort`, as in ArchJava, it invokes the method on a proxy that sends the message on to the task server. Like the ArchJava version, this solution cleanly separates communication code from application logic.

The main difference between the design pattern code and the ArchJava code is that in the design pattern solution, custom code must be written to dispatch each message to the handler function (`infoReply` in this example) and to send each message using the Rain library (`taskQuery` in this example). By comparison, in ArchJava the dispatch code and the message sending code are written once in the connector, and can then be reused for each connection in the system.

Analysis. The primary disadvantages of our approach, relative to design patterns, are twofold. First, our approach involves a new language construct. Although it is a very tiny addition to the ArchJava language, it does increase the complexity of the language, and this comes on top of the (more substantial) ArchJava additions to Java. Second, our approach uses reflection, thereby losing some understandability and efficiency relative to custom-written object-oriented code.

On the other hand, our approach offers key advantages over conventional object-oriented solutions. Perhaps the most significant advantage is that connector abstractions can define typechecking rules that verify different properties than the default Java rules. Thus, connectors can statically verify that certain classes of connector-specific errors will not occur at run time.

In many cases, connector abstractions allow programmers to reuse connector code that would be duplicated in a conventional solution using adaptors or proxies. Since code does not have to be duplicated or customized for each communication interface, the resulting system is easier to evolve when connector abstractions are used. For example, changing the connector used takes only one line of code in ArchJava, but in the design pattern solution, a new Proxy class must be written that adapts the communication interface to the new connection protocol. Our design also expresses the intent of a connector directly through the abstraction, rather than indirectly through a design pattern. Finally, ArchJava explicitly documents the software architecture of the system, providing benefits for reasoning about and evolving code.

Our design shares many benefits with the design-pattern solution described above. Connector code is isolated from application code, and the interfaces used to communicate between objects are documented and checked. However, in the design-pattern case, these benefits only accrue if the developer anticipates the need to evolve the connectors in a system, and chooses to use the appropriate design pattern in the system. An important advantage of language support for connector abstractions is that it encourages developers to think and program in terms of connectors, gaining all of the benefits described above. In contrast, developers may balk at implementing design patterns that may result in duplicated code if they seem unnecessary at the time, discovering only later that the system would have been easier to understand or evolve had design patterns been used.

5. Related Work

Software Architecture. Most architecture description languages (ADLs) support the specification or implementation of software connectors [MT00]. For example, Wright specifies the temporal relationship of events on a connector and provides tools for checking properties such as freedom from deadlock [AG97]. SADL formalizes connectors in terms of theories and describes how abstract connectors in a design can be iteratively refined into concrete connectors in an implementation [MQR95]. Rapide specifies connectors within a reactive system using event traces [LV95].

Several ADLs provide tools that can generate executable code from an architectural description. UniCon's tools use an architectural specification to generate connector code that links components together [SDK+95]. C2 provides runtime libraries in C++ and Java that implement C2 connectors [MOR+96]. Darwin provides infrastructure support for implementing distributed systems specified in the Darwin ADL [MK96]. These code generation tools, however, support a limited number of built-in connector types, and developers cannot easily define connectors with custom semantics.

User-Defined Connectors. The work most similar to our own is a specification of how user-defined connector types can be added as plugins to the UniCon compiler [SDZ96]. UniCon connector plugins are fairly heavyweight, as connector developers must understand the details of several phases of the compiler. However, this design allows new connectors to be tightly integrated into the compiler system, permitting new kinds of architectural analysis to be defined over these connectors. In contrast, ArchJava's connector abstractions are lightweight, and a wide range of connectors can be implemented with knowledge of a small library interface.

Dashofy et al. describe how off-the-shelf middleware can be used to implement C2 connectors [DMT99]. Their work differs from ours in that the semantics of the connectors is fixed by the C2 architectural style, while our connector abstractions are intended to support a wide range of architectural styles.

Mezini and Ostermann describe language support for adaptor connections that allow components with different data models to work together [MO02]. Their language makes wrapper code less tedious to write, and provides support for the difficult problem of

maintaining consistent wrapper identity. ArchJava's connector abstractions provide weaker support for adaptors, but facilitate a range of connector types beyond adaptors.

Object-Oriented Languages. A number of proposals have added connection support to object-oriented languages such as Java. For example, ComponentJ [SC00] and ACOEL [Sre02] as well as the original design of ArchJava [ACN02a] all provide primitives for linking components together with connections. However, these languages all fix the semantics of connections to the same synchronous method call semantics used by Java.

Aspect-Oriented Programming. Aspect-oriented programming (AOP) languages allow programmers to more effectively separate code that implements different application concerns. For example, Soares et al. showed how the AspectJ language can be used to implement distribution and persistence in a health complaint system [SLB02]. Aspect-oriented programming developed out of meta-object protocols, which allow programmers to define how an object should react to events like method calls [KRB91]. Relative to languages such as AspectJ and the more powerful meta-object protocol technique, ArchJava's connector abstractions provide a more limited kind of separation of concerns, restricted to the semantics of connectors. However, because connectors are bound in the surrounding architecture of a component, they support more local reasoning about connector aspect code.

Composition filters is the aspect-oriented approach most similar to ArchJava's connector abstractions. In this technique, developers interpose filter objects that can inspect incoming method calls and perform operations like translation, adaptation, and forwarding on the messages [BA01]. ArchJava's connector abstractions are similar to composition filters, but instead of processing all messages called on a single object, they process messages exchanged between two component objects in an architecture.

Distributed System Infrastructures. A number of libraries and tools have been defined to support distributed programming. Commercial examples include RPC [BCL+87] as well as COM [Mic95], CORBA [OMG95], and RMI [Jav97]. These systems offer a convenient method-call interface for remote communication, much like the interface provided by ArchJava's connector abstractions. Furthermore, these systems check statically that communication through their connections is well typed. Infrastructures support some flexibility—for example, RMI allows the developer to specify the wire protocol to be used, and CORBA provides an event service that can be used in place of remote method calls. However, each of these commercially available systems defines a particular semantics (usually synchronous method call) for the connections it supports, rather than providing a general interface that programmers can implement in various ways to support their application-specific needs.

Recently, researchers have been developing extensible middleware such as the OpenORB [BCA+01] and the Universally Interoperable Core [Ubi02]. These systems allow developers to customize middleware aspects such as the network transport protocol, object marshalling, and method invocation semantics. DADO provides features of aspect-oriented programming in the context of a reflective middleware system, supporting connector functionality like caching and performance monitoring [WJD03]. Compared to ArchJava's connector abstractions, these middleware systems provide a great deal of built-in services, but are not tightly integrated into programming languages and do not provide customized connection typechecking.

CASE Tools. Several computer-aided software engineering tools, including Consystant and Rational Rose RealTime, generate code to connect components together. This connection code can range from stubs and skeletons for an infrastructure like CORBA or RMI to wires that connect different processors in an embedded system. Like many of the technologies discussed above, these tools typically support a fixed set of connectors.

6. Conclusion

This paper described a technique for adding explicit support for connector abstractions to the ArchJava programming language. In our system, connector abstractions can be defined using a very flexible reflective library-based mechanism. We have evaluated the expressiveness of our technique by implementing representative connectors from a wide range of connector types, and we have evaluated the engineering tradeoffs in a small case study on the PlantCare ubiquitous computing application. The benefits of connector abstractions include separating communication code from application logic, documenting and checking connector interfaces, and reusing connector abstractions more effectively compared with alternative techniques.

In future work, we intend to implement more connectors and evaluate their expressiveness on a wider variety of systems. We also hope to develop a library-based framework for composing connectors together so that complex connectors can be easily created from simple building blocks. Another important area of future work is more effective support for adaptor-style connections, extending recently developed adaptation techniques such as on-demand remodularization [MO02]. Finally, we would like to provide specification and checking of connector properties that go beyond simple typechecking. We believe that enhanced language and system support for connectors is crucial to the effective development and evolution of many classes of software systems.

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