A Declarative Approach for Designing and Developing Adaptive Components

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Abstract

An adaptive component is a component that is able to adapt its behavior to different execution contexts. Building an adaptive application is difficult because of component dependencies and the lack of language support. As a result, code that implements adaptation is often tangled, hindering maintenance and evolution.

To overcome this problem, we propose a declarative approach to program adaptation. This approach makes the specific issues of adaptation explicit. The programmer can focus on the basic features of the application, and separately provide clear and concise adaptation information. Concretely, we propose *adaptation classes*, which enrich Java classes with adaptive behaviors. A dedicated compiler automatically generates Java code that implements the adaptive features. Moreover, these adaptation declarations can be checked for consistency to provide additional safety guarantees.

As a working example throughout this paper, we use an adaptive sound encoder in an audio-conferencing application. We show the problems associated with a traditional implementation using design patterns, and how these problems are elegantly solved using adaptation classes.

1 Introduction

A complex system is typically made up from separate components sharing common resources. The behavior of these components and the quality of service that they each provide is interdependent. So, the system must adapt when the available resources are limited. For this reason, adaptation technologies, such as feedback control mechanisms, are used to implement systems that dynamically react to resource variations. As an example, consider distributed multimedia applications that share network resources. These applications must adapt their behavior according to the network bandwidth to improve performance and to guarantee Quality of Service [3, 4, 6, 13].

Building adaptive software is difficult, code that implements adaptation is often tangled due to the resource and component dependencies. Furthermore, there is no convenient support in programming languages to easily associate given execution contexts with corresponding behaviors. Current adaptation mechanisms are ad hoc, which impedes maintenance and extensibility.

In this paper, we present a declarative approach for the design and development of adaptive components in an object-oriented language like Java. This approach makes explicit two specific issues: adaptation conditions and adaptation actions. Adaptation conditions express when adaptation should occur, depending on the program state and the execution context. Adaptation actions determine appropriate component behaviors. We declare both conditions

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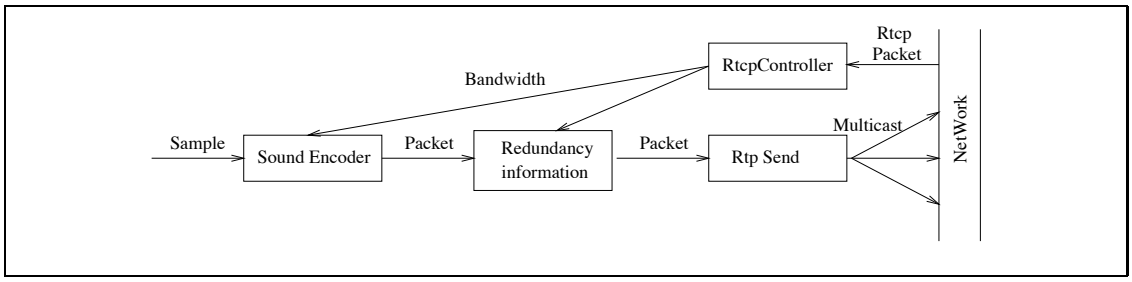

Figure 1: Audio-conference application, Send part

and corresponding actions in a concise and precise way using *adaptation classes*, which enrich existing Java classes with adaptive behavior.

These adaptation declarations are processed by a dedicated adaptation class compiler. This compiler generates Java code that implements the adaptive features declared in the adaptation classes. In particular, it automatically instruments the code with introspection mechanisms that capture state changes. These state changes trigger behavior switches according to the adaptation declarations, seamlessly integrating adaptation into programs.

Using the adaptation class approach, the programmer can focus on the basic features of the application, and separately provide adaptation information. The separation of concerns and the conciseness of adaptation classes improve development, maintenance and extensibility. Safety is also improved as the adaptation class compiler performs consistency checking. In addition, as opposed to manual, ad hoc approaches that are inevitably error-prone, the compiler systematically instruments the code whenever introspection is needed. Finally, there is no price performance price to pay compared to a manual approach, because the compiler generates efficient introspection and context switching mechanisms.

The rest of this paper is organized as follows. Section 2 presents a working example of an adaptive program in the multimedia domain. Section 3 introduces some terms and issues related to adaptation. Section 4 then describes two ways of designing an adaptive component: an ad hoc manner and using adaptation classes. In Section 5, we present the problems that arise when extending the adaptive component and how we handle them. Section 6 then gives an overview of adaptation classes and provides an informal semantics. Section 7 surveys related work, and Section 8 presents our concluding remarks and future work.

2 Working example: an adaptive sound encoder

Adaptation is crucial for multimedia [6]. Consider a live audio application for audio-conferencing. The quality of the audio depends primarily on the number of lost packets and the delay variations between successive packets. Furthermore, the average end-to-end delay must be small to allow interactions between participants. Therefore, the application must adapt to the available network bandwidth to respect the temporal constraints, and provide performance guarantees regarding loss rate or maximum delay [3, 13]. Bandwidth control mechanisms can adjust to network congestion by adapting the size of the packets to the load of the network [1, 18].

Figure 1 illustrates the general structure of the sending part of the adaptive audio-conference application *freephone* [2]. Before transmitting sound samples to the subscribers of the audio-conference, specific treatments reduce the amount of information sent over the network. First, the sound is compressed in the `SoundEncoder` component. To increase the tolerance to packet loss redundant information is added which is used to reconstruct lost packets (the `RedundancyInformation` component). The `RtpSend` component broadcasts the packet. The protocol used by audio-conferencing applications such as freephone is RTP (Real-time Transport Protocol) [3, 15], which provides feedback on the transmitted data as RTCP (Real-time Transport Control Protocol) control frames. The `RtcpController` component receives these frames and computes feedback information to approximate the network bandwidth available. This estimate is used by the `SoundEncoder` and `RedundancyInformation` components to adapt the compression rate and the amount of redundancy information.

To vary the compression rate, we can choose among different encoding algorithms [2], as

shown in Table 1. Choosing among these algorithms makes it possible to vary an 8 kHz sound speech sample from 5.6 kbits/s to 48 kbits/s. *ADPCM* [12, 17] is a differential encoder which can be parameterized from 16 kbits/s to 48 kbits/s with a precision parameter (between 2 and 6). *LPC* [8] and *GSM* [5, 16] are fixed low bit-rate encoders. Using these encoding algorithms, the application is able to adequately react to bandwidth variations.

Encoding	bit rates (kbits/s)
ADPCM(6)	48
ADPCM(2)	16
GSM	13.3
LPC	5.6

Table 1: Bit rates of the encoding algorithms

3 Adaptation basics

An adaptive component is a component that is able to adapt its behavior to different execution contexts. Adaptation can be *static* or *dynamic*. Static adaptation corresponds to configuration, i.e., performing adaptation before execution depending on fixed parameters. Dynamic adaptations are run-time changes depending on the execution context.

There are two ways to implement dynamic adaptation: *adaptation on change* and *adaptation on action*. Adaptation on change installs new behaviors each time that the execution context changes. When adaptive functionality is used, the execution context does not need to be checked; installed behaviors are blindly performed. On the contrary, adaptation on action inspects the execution context each time that an adaptive functionality is called, to determine which behavior should be performed.

The choice of which strategy is best (on change or on action) depends on both the frequency of change in the execution context and the number of calls of adaptive actions. In the following, we focus on adaptation on change. This strategy is usually the most appropriate for multimedia components because the same set of actions are often repeatedly called, whereas context changes require updating behaviors only when given thresholds are reached. Given that the rate change of the execution contexts is often lower than the frequency of action calls, adaptation on change requires less run-time management compared to adaptation on action.

Adaptation on change can be decomposed into three stages:

Introspection. Collecting information about the execution context. This introspection can be implemented by inserting guards that monitor given program states and notify the adaptation controller (the second stage) in case of changes. In our working example, the introspection stage is implemented by the `RtcpController` component which sends a notification to the `SoundEncoder` and `RedundancyInformation` components when the bandwidth changes.

Control. Adaptation conditions are expressed over the guarded program states. These predicates, often represented by threshold tests, determine which behavior is the most appropriate. In the example, the `SoundEncoder` component implements this control mechanism. Each time the `RtcpController` signals a bandwidth change, the `SoundEncoder` evaluates adaptation conditions based on the new bandwidth value, to choose the appropriate encoding algorithm.

Installation. Depending on the adaptation conditions, new behaviors are installed, replacing previous ones. In our example, the `SoundEncoder` installs one of the different encoding algorithms, balancing quality and packet sizes.

In this paper, we focus on the `RtcpController` and `SoundEncoder` components, and their relationship. We show that the traditional implementation of a simple adaptive system raises several problems in terms of construction and evolution.

4 Building an adaptive component

In this section, we study the implementation of the `SoundEncoder` component for a wireless network. Typically, a wireless network is characterized by low bandwidth, for which reason we use the two low bit-rate encoders, LPC and GSM.

The choice between these two algorithms depends on the available network bandwidth. For this reason, we need to create a relation between the `RtcpController` component, which estimates the network bandwidth, and the `SoundEncoder` component, which selects the appropriate encoding algorithm.

We build this adaptive component in two ways: first, we use an ad hoc technique based on design patterns and study its advantages and disadvantages. Then, we present the design of the same component using our declarative approach and examine its benefits.

4.1 Making an adaptive component "by hand"

Because adaptation is difficult to apprehend in a complex system, implementing an adaptive component requires a structured approach. A natural way to organize component implementation in an object-oriented language is to use design patterns [9]. Design patterns capture common structures that arise when designing and implementing programs, providing a good framework for conveying program design expertise. Over the last few years, they have become a standard tool in the design of object-oriented programs.

A selection of well-known design patterns can be used to express the three stages of our adaptive `SoundEncoder`. To build this adaptive component, we rely on:

- a subscription mechanism to the network observer (`RtcpController`) that can notify all the subscribers of guarded state changes (Introspection and Control stages)
- a mechanism to modify a behavior (Installation stage)

We use three design patterns to implement these features: *Observer*, *Strategy* and *Facade*. The Observer pattern allows the notification of a set of subscribers any of states change. The Strategy pattern describes the implementation of an object that can dynamically change its behavior. The Facade pattern provides an interface to encapsulate a set of objects. The composition of these design patterns is shown in Figure 2.

Introspection. The `RtcpController` must notify the `SoundEncoder` when the network bandwidth changes. To model this dependency, we use the Observer pattern. This pattern allows a set of objects, the *observers*, to be automatically notified when a state changes in an observed object, the *subject*. In our example, the Observer pattern describes how to establish the relation between the `RtcpController` (the subject) and the `EncoderStrategy` (an observer). Implementation details are presented in the appendix.

Control. When the bandwidth value changes, the appropriate conditions must be checked to determine which encoding algorithm is the most appropriate. To model this dependency, we could use a mediator pattern. In practice, this level of indirection is not needed here. It is easier to just extend the observer so that it notifies the subscribers only when an update is required, specifying explicitly which algorithm must be installed.

Installation. Update requests specify which encoding algorithm is to be used as the current behavior. To model this, we use the Strategy pattern, which allows dynamic changes in object behavior by letting complementary behaviors vary independently from the clients who use it. It is implemented by defining classes that encapsulate the different algorithms. These algorithms are implemented with `Gsm` and `Lpc` classes which provide an `encode` method that transforms sampled sound into compressed packets. The `EncoderStrategy` class defines the interface to the adaptive behavior (see the appendix for details).

Last, we have to provide an appropriate interface for the sound encoder component. To this end, we use the *Facade pattern*. A Facade defines a higher-level interface that makes the subsystem easier to use. We encapsulate the classes implementing the Observer and Strategy functionality to create the `SoundEncoder` component, using the Facade design pattern to provide a unified interface.

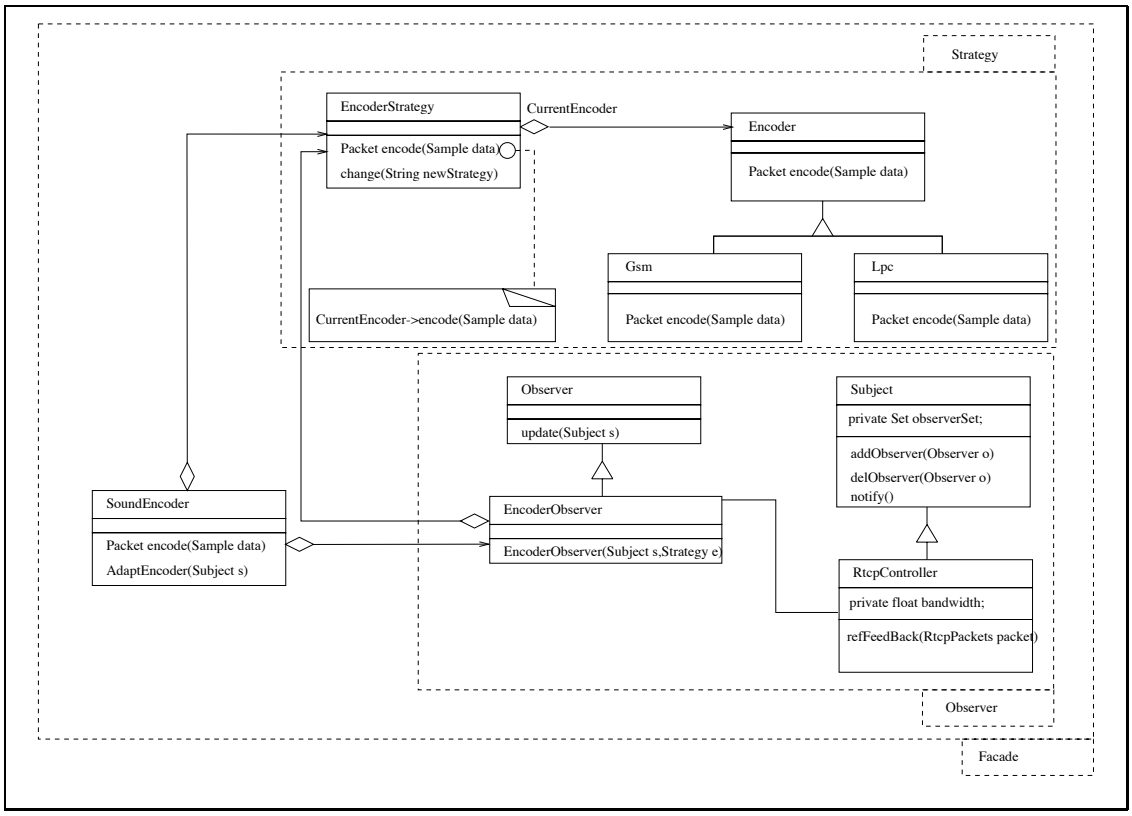

Figure 2: UML diagram of the cooperation between Encoder and RtcpController

Usage. At instantiation time, the `SoundEncoder` component is connected to the `RtcpController` component in order to be informed of network bandwidth changes. When the bandwidth changes, the `update` method of the `EncoderObserver` object is invoked by the `RtcpController`. The `EncoderObserver` object queries the transmitter for its new state with the `get_bandwidth` method. Given the bandwidth, the `EncoderObserver` object then determines the best encoding strategy given this bandwidth. It invokes the `change` method of the `EncoderStrategy` object to switch the encoding algorithm.

The `SoundEncoder` must create an instance of each behavior, which can be done either *lazily* (when needed) or *strictly* (at instantiation time). Strict creation initially consumes more resources than lazy creation, but ensures responsiveness after initialization has completed, which makes it preferable for our component. Thus, the system first creates all adaptive behaviors, after which the `SoundEncoder` component is synchronized with the `RtcpController` component by invoking the `update` method, in order to acquire the actual bandwidth.

Assessment. Design patterns describe solutions to specific problems in object-oriented software design. For example, the structure of the Strategy pattern provides different implementations of the same behavior offering a way to support a variety of algorithms and facilitating future extensions. The use of design patterns isolates different functionality (creational, structural and behavioral) and splits up behaviors (Strategy, Mediator, Observer...). However, in the case of adaptation, using design patterns has some drawbacks.

The design of the adaptive `SoundEncoder` component is complex (see Figure 2 and the code in the appendix). The use of the Strategy and Observer design patterns for the `SoundEncoder` component introduces communication overhead and increases the number of classes. In our example, it is necessary to declare 9 classes bound together by 5 references. In addition, the object interaction protocol is computationally expensive. It requires 2 indirections for each call of the `encode` method and 3 calls for each modification of the `bandwidth` field (4 if the current encoder has to be changed). Furthermore, the decomposition into different subcomponents makes code modification difficult. The dependencies between objects requires propagation of all modifications to all the classes in order to keep the code coherent, as will

```
adaptclass SoundEncoder adapts Encoder {
   RtcpController rtpControl;
   SoundEncoder (RtcpController _rtpControl) { rtpControl=_rtpControl; }
   when (rtpControl.bandwidth <  13.3) Lpc();
   when (rtpControl.bandwidth >= 13.3) Gsm();
}
```

Figure 3: Declaration of adaptive behaviors on Encoder class

be apparent in Section 5.

4.2 Declaration of an adaptive encoder

To simplify the design and development of adaptive components, we propose to declare adaptive behaviors and automatically generate code from these declarations. The principle of our approach is to separate the adaptation declaration from the basic implementation of the main program. We use adaption classes to declare which encoding algorithm to use depending on the bandwidth computed by the `RtcpController` component. The adaptation class compiler evaluates the declarations, creates the `SoundEncoder` component, and modifies the `RtcpController` to plug in the introspection mechanism.

We reuse the `Encoder` class hierarchy and the `RtcpController` class as presented in Section 4.1. The `Encoder` class defines an abstraction of a sound encoder and an interface to the encoding method. This abstract class is refined by concrete sub-classes (`Gsm` and `Lpc`) which each implement an encoding algorithm. The `RtcpController` class is the network interface for receiving control packets. These are our starting point for designing the adaptive component.

We define an adaptation class `SoundEncoder` (shown in Figure 3) to adapt the abstract class `Encoder`. The fields and the interface of the `Encoder` class are used as information to define when and how to substitute behaviors. The adaptation class introduces a reference `rtpControl` to an `RtcpController` object to access the value of the current bandwidth. It defines a constructor to initialize this reference, linking the adaptive component with the `RtcpController` object. Two adaptation conditions (`when` statements) are introduced, which express condtions over the value of the `bandwidth` field of the `rtpControl` object. If this value is less than 13.3 kbits/s, then the current behavior is defined by the class `Lpc`, otherwise it is defined by the class `Gsm`. To access the value of the private `bandwidth` field, the adaptation class compiler introduces an accessor method into the `RtcpController` class.

The adaptation class compiler can use the information defined in adaptation classes to generate the implementation of the adaptation mechanisms. We know at compile time which observers are needed and we have a precise description of the information required to switch behaviors. Thus, we can generate an implementation specific to the adaptation needs:

- We can simplify the connection mechanism by replacing the management of the set of observers by a reference to each observer.
- It is possible to make observer-specific update protocols, since we know exactly what information is needed about each change. The subject can send observers detailed information as an argument to the `update` method. This optimization reduces the cost of each state change.
- One of the indirections otherwise needed for calling the `encode` method can be eliminated. The compiler automatically produces a complete component with all necessary mechanisms. It is not necessary to use a design pattern like Facade to provide a concise interface.

The compilation of this adaptation class modifies the `RtcpController` class creates the `SoundEncoder` class as shown in the appendix. The `RtcpController` class is modified by adding a subscription mechanism and analyzing the code to insert guards to detect modifications of the `bandwidth` field. These modifications do not affect the behavior of the `RtcpController`; they are transparent for any other objects that may use `RtcpController`. The resulting `SoundEncoder` class is composed of references to adaptive behaviors and methods for implementing adaptive mechanisms.

Usage. We insert the generated `SoundEncoder` component into the program. The use of this class is similar to the use of the `SoundEncoder` component defined by hand in the Section 4.1. First, we create an `rtcpSession` object to receive and handle RTCP control frames. Second, we create an instance of the `SoundEncoder` and pass it a reference to the `rtcpSession` object. Then, the `soundEncoder` object connects to the `rtcpSession` object in order to be notified of each modification to its state, and it initializes all possible behaviors defined in the adaptation class (strict creation). To synchronize with the initial `rtcpSession` bandwidth, the `soundEncoder` object calls the `acUpdate` method and determines an initial behavior.

When the value of the `bandwidth` field is modified, the `rtcpSession` object notifies the `soundEncoder` object by calling the `update` method with the bandwidth value. The `soundEncoder` object re-computes its adaptation state and applies the appropriate encoding algorithm, as specified in the adaptation class (cf. Figure 3).

Assessment. Our approach separates adaptation aspects from the code. First, it reduces the complexity of the adaptive `SoundEncoder` component design. The implementation only needs the `Encoder` and `RtcpController` classes and one adaptation class; our approach separates adaptation mechanisms from the code. Second, performance is improved. The generated code requires one indirection for each call of the `encode` method, and one call for each modification of the `bandwidth` field (or two if it is necessary to change the current behavior). Last, evolution is easier. The evolution of an adaptive component is done by redefining the adaptation classes. The compiler automatically propagates all modifications into the code (such evolution is explored in the next section).

5 Evolution of an adaptive component

In the previous section, we defined an adaptive component with the ability to change behavior depending on network bandwidth variations. Suppose that this component needs to be used in another environment, namely for audio-conferencing on the web. The available bandwidth is higher than for a wireless network, so we can raise the audio quality by increasing the bandwidth adaptation domain of our audio-conferencing application. This section presents the repercussions of this extension of the `SoundEncoder` component, namely adding a new encoding algorithm, Adpcm, which extends the adaptive encoder up to 48 kbits/s (cf. Figure 1).

The addition of a new encoding algorithm in the `Encoder` hierarchy must be propagated to all components that are using these classes. Conceptually, the modifications are minor. We just have to extend the adaptation domain of the `Gsm` behavior and add new adaptation conditions to the object `Adpcm`:

- when the bandwidth is between 16 and 48 kbits/s, use `Adpcm(2)`,
- when bandwidth is greater than 48 kbits/s, use `Adpcm(6)`.

In the rest of this section, we show how this extension can be implemented, first using the ad hoc method, and then our declarative approach.

Ad hoc extension. To add these behaviors into the adaptive component defined in Section 4.1, we need to modify the `EncoderStrategy` and `EncoderObserver` classes in order to propagate state modifications to all the components as illustrated in Figure 4. First, we must add references to the new behaviors (1) and modify the `EncoderStrategy` constructor to create and initialize them (2). Second, we have to add the assignments to the `CurrentEncoder` variable in the `change` method (3). Last, we extend the control mechanism in the `update` method (4). This example illustrates that a simple change like the addition of new behaviors in an adaptive component is a non-trivial task. It implies modifications throughout the entire program.

Extension by declaration. With adaptation classes, the generation of an adaptive component is automatic. The addition of a new algorithm in the `SoundEncoder` components requires only the modification of the `SoundEncoder` adaptation class as shown in Figure 5 and a re-compilation.

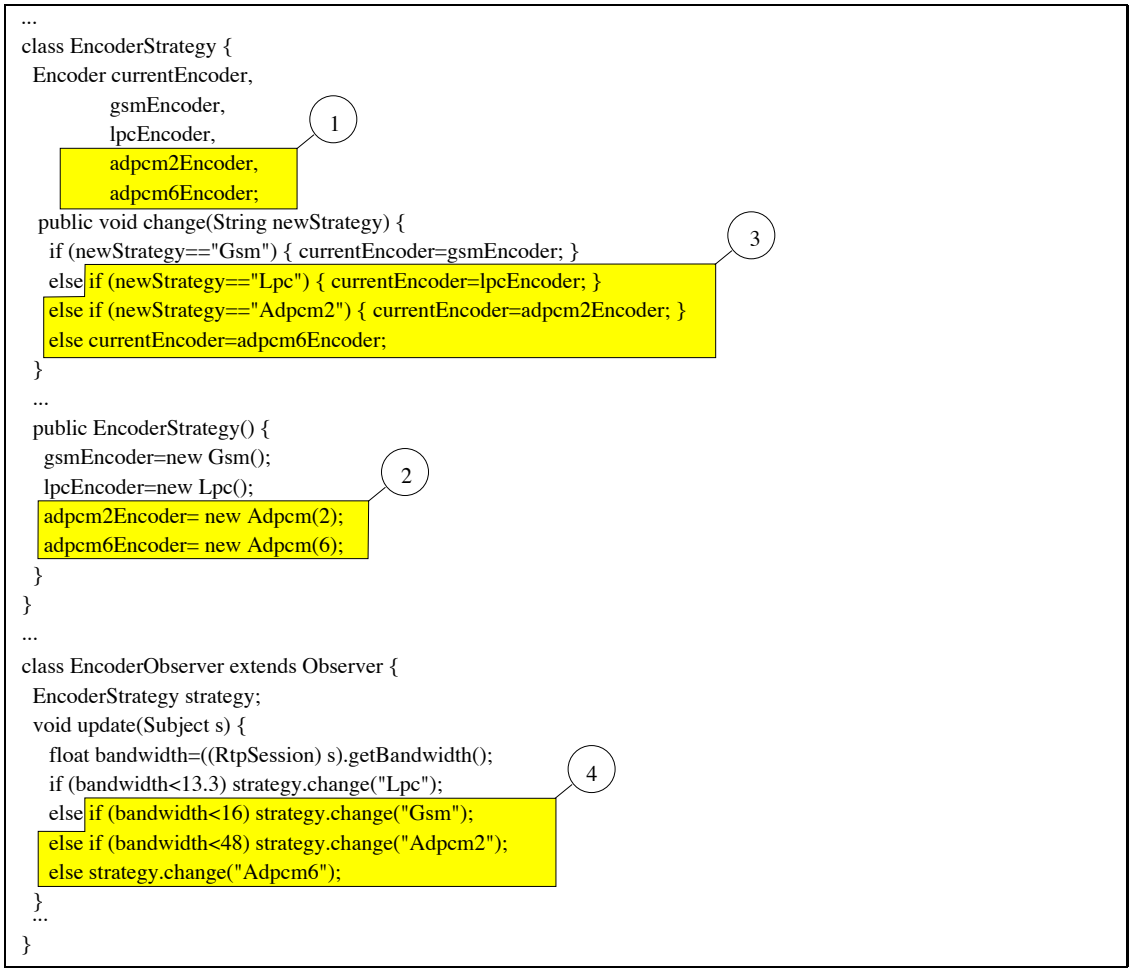

Figure 4: Evolution of SoundEncoder component

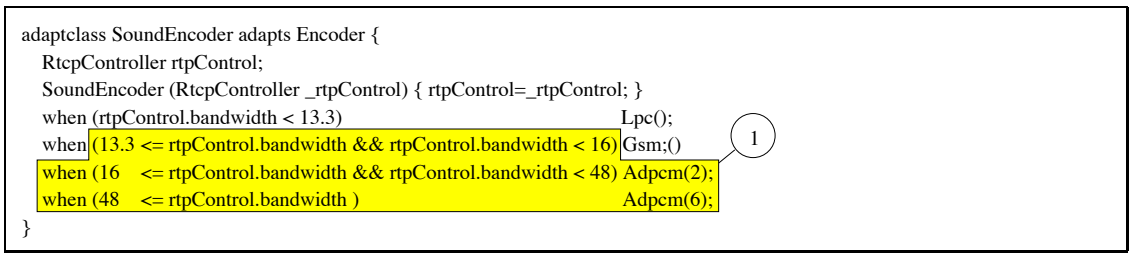

Figure 5: Adding a new adaptive behavior

```
adaptclass ExtendedSoundEncoder extends SoundEncoder {
   when (16  <= rtpControl.bandwidth && rtpControl.bandwidth < 48) Adpcm(2);
   when (48  <= rtpControl.bandwidth) Adpcm(6);
}
```

Figure 6: Inheritance extension of the adaptation class SoundEncoder

AcDecl	::=	`adaptclass` *Identifier* `(adapts | extends)` *Identifier AcBody*
AcBody	::=	`{` $(FieldDeclaration)^*$ $(ConstructorDeclaration)^*$ $(AcCond)^*$ `}`
AcCond	::=	$(\texttt{when}\ AcPred)^+$ *AcBehavior*`;`
AcBehavior	::=	*Identifier* $(($*ArgumentList*$)^?)$
AcPred	::=	*LinearExpression*

Figure 7: Adaptation classes syntax

Alternatively, adaptation class inheritance (explained in detail in the next section) could be used. Figure 6 shows the `ExtendedSoundEncoder` adaptation class which is a sub-class of `SoundEncoder`, that inherits all of the `SoundEncoder` definitions. It defines two levels of predicate evaluation:

- if the `bandwidth` is greater than 16, then the `ExtendedSoundEncoder` behaviors are applied,
- otherwise, it relies on the conditions defined in `SoundEncoder` to find an appropriate behavior.

This use of adaptation class inheritance necessitates the modification of the program using the encoder: the newly generated `ExtendedSoundEncoder` class must be substituted for the `SoundEncoder` class.

6 Adaptation classes

The evolution of an adaptive component is problematic since its dependencies are scattered throughout the program code. Our declarative approach exposes all adaptation capabilities, and new code can easily be generated by recompiling the modified declarations. This section defines the syntax of adaptation classes and explains the semantics of the language.

The syntax of the adaptation class language is given in Figure 7. The definition of non-terminals *Identifier*, *FieldDeclaration*, *ArgumentList* and *ConstructorDeclaration* are given in the Java syntax [10]. The definition of non-terminal *LinearExpression* is similar to a Java expression, but slightly is constrained as explained later. Adaptation classes are similar to Java classes in their use and syntax. An adaptation class declares adaptation over an abstract Java class. It has a name (both used to build the resulting Java class and to define the inheritance relation), the name of the adapted abstract Java class, and a set of members. These members include fields, constructor declarations, and adaptation conditions which describe the conditions under which adaptive behaviors are applied.

6.1 Adaptation class members

All adaptation declarations are described by the *AcCond* rule. This rule can be divided into two parts: the condition part <`when` *AcPred*>, and the action part, *AcBehavior*.

Introspection and condition stages. Adaptation conditions express when adaptation should occur, by expressing a condition over the state of the adapted object or its execution context. Conditions are declared with the statement `when` *AcPred*, where the predicate *AcPred* may reference class fields. An adaptation is applicable when the predicate evaluates to true. In our example (cf. Figure 3), the adaptation condition consists of testing the bandwidth value of an `RtcpController` object. For this object to be known by `SoundEncoder`, we declared the reference `rtpControl` in the adaptation class.

The compiler gathers the variables used in the predicates and systematically inserts guards to watch these variables and to notify the adapted component in case of changes (introspection stage). To ensure that all changes to these variables are captured, it is necessary to protect them from being directly written by external objects. The variables must be written through an accessor method which is automatically inserted by the compiler. Consequently, the adaptation context may only contain private fields, such as the `bandwidth` field in the `RtcpController` class.

An incorrect declaration of predicates can cause errors or inconsistencies: if two predicates overlap, the choice of a behavior becomes nondeterministic. An adaptation class must respect *completeness* and *uniqueness*. Completeness guarantees that for every possible situation, there exists an adaptation action. Uniqueness guarantees that for each situation, there is only one adaptation action which is applicable. To enforce these two properties we use the logic language $CLP(\Re)$ [11]. With this language, we can solve linear arithmetic constraints and perform computations over real numbers (non linear constraints are not allowed). As a consequence, when a condition is expressed as a set of linear constraints, it is possible to verify completeness and uniqueness.

Declaration of actions. An action is the substitution of one behavior (*i.e., object*) by another one. Each adaptive behavior is represented by an object. To enable substitution of objects, they must have a similar interface and must inherit from the same abstract Java class. In our example, all encoding algorithms inherit from the `Encoder` class, and they all implement a version of the `encode` method.

For the program to run, it is necessary to instantiate all classes which represent an adaptive behavior. The creation and the initialization of these objects are declared by their constructors. For example, in Figure 5, the instantiation of the Adpcm encoder was declared with a prediction value of 6 (for an available bandwidth superior to 48 kbits).

6.2 Adaptation Classes

Adaptation actions are encapsulated in an adaptation class, which represents the unity of adaptation of our approach. An adaptation class is applied to a Java class or extends some other adaptation class by inheritance.

Class structure changes. An adaptation class declares adaptive aspects of an existing Java class. The adaptation class compiler takes as input a Java program and a set of adaptation classes which controls how adaptation features are added to the program code. An adaptation class is applied to an abstract Java class; this abstract class corresponds to a set of behaviors in the form of sub-classes, each sub-class implements a concrete behavior. The adaptation class compiler creates a sub-class of the abstract super class which can switch between concrete behaviors depending on an execution context. Furthermore, the compiler inserts guards throughout the program code to notify the adaptive object of any context modification.

Figure 6.2a shows a diagram of the classes used in Section 4.2 to build the adaptive `SoundEncoder` component. The `Encoder` class is the abstract class to be adapted; the `Gsm` and `Lpc` classes define concrete encoding algorithms; and, the `RtcpController` class contains the execution context to be monitored. Figure 6.2b shows the result of compilation. The compiler creates the `SoundEncoder` class as a sub-class of the `Encoder` class, and references are created to access the concrete behaviors and to notify of any state changes in the `RtcpController`.

Method mapping. Each abstract method defined in the abstract super class (`Encoder`) is implemented in the adaptive class (`SoundEncoder`) as a wrapper to a concrete method. This mapping is trivial since the methods have the same parameters.

State mapping. It may be necessary to share a variable between all adaptive behaviors. In our framework, we share a variable when it is defined in the abstract Java class or any of its super classes. The sharing of these variables is implemented by copying shared state when a behavior is switched, using the `acCopyEnv` method which is added by the adaptation class compiler (see the appendix for details). As an example of shared variable, assume that

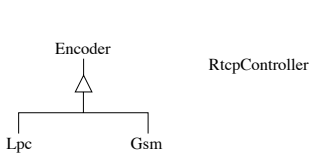

Figure 8: (a) before compilation

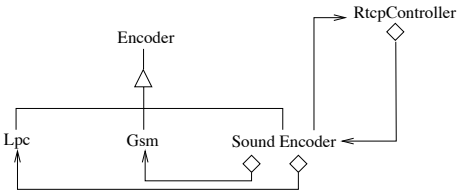

Figure 9: (b) after compilation

one wants to count each call of the `encode` method of each encoder instance, one could add a variable `counter` to the class `Encoder`. This variable would be incremented each time an `encode` method is called. But when the encoding algorithm changes to adapt to the network bandwidth, if the compiler did not handle shared variables, one would have to copy the value of the variable from the current behavior to the new one.

Inheritance relation. Rather than directly adapting an existing Java class, an adaptation class can extend another adaptation class by inheritance. The inheritance relation is similar to that of an object-oriented language, enabling the definition of a hierarchy of increasingly refined adaptation classes. The use of inheritance in adaptation classes allows us to define a partial order between adaptive behaviors, which again makes it possible to define a decision tree on the adaptation conditions for selecting which behavior to use. Thus, we can add new behaviors in an incremental way, as was illustrated in Figure 6.

When an adaptation class is extended, our compiler generates a sub-class which extends the adaptive Java class. This new sub-class overloads the condition adaptation. As an example, recall how the `SoundEncoder` adaptation class was extended with the declaration of an adaptation sub-class `ExtendedSoundEncoder` in Section 5. This declaration caused the compiler to create a sub-class `ExtendedSoundEncoder` of the class `SoundEncoder`.

7 Related work

Predicate classes. Predicate classes [7] are a syntactic and semantic extension of the Cecil language. They allow the applicability of a method to be declared via a *predicate expression*, which is a logical formula over class tests (i.e., test that an object is a particular class or one of its subclasses) and boolean-valued expressions. Compared with our approach, predicate classes are intrusive. Declaration must be included directly in the code, and each method call requires the evaluation of its associate predicate, which is an on change adaptation and thus not appropriate in all cases (multimedia for example).

Specialization classes. Specialization classes [19] are an extension of the Java language. They declare adaptation program by specialization on the methods of a class. The conditions of adaptation depend on predicates parameterized by object fields. Using these declarations, a program specializer produces specialized methods, and the specialization class compiler modifies the existing classes to integrate a customized execution support the specialized methods. Our approach treats a more general form of adaptation since behavior can be substituted as opposed to only adding more specific behavior. Adaptation classes do not automatically produce a specialized behavior, but adaptation classes could be used with specialization classes to provide adaptive components with specialized actions.

Aspect-Oriented Programming. Kiczales et al [14] describe many programming problems for which neither procedural nor object-oriented programming techniques are sufficient to clearly capture some important features in program implementation. This forces the implementation of these features to be scattered throughout the code, resulting in "tangled" code that is excessively difficult to develop and maintain. These features are refered to as *Aspects*. Kiczales et al present a new programming technique called Aspect-Oriented Programming, which makes it possible to clearly express programs involving such aspects, including appropriate isolation, composition and re-use of the aspect code. A specific compiler, a weaver,

injects the declared aspect in the program code. Our approach is a special case of Aspect-Oriented Programming which expresses adaptation concerns. Using adaptation classes, we enrich the capacity of an object to dynamically change its behavior depending on an execution context.

8 Conclusion

In this paper, we have shown that for designing adaptive components, ad hoc techniques can be complex and introduce communication overhead. Decomposition into different subcomponents makes code modification difficult because implementation of the adaptation is tangled due to resource and component dependencies.

To overcome this software engineering challenge, we have developed a declarative approach for the design and implementation of adaptive components. This approach separates adaptation declarations from the program code. A compiler generates Java code that fully implements adaptation in the program and automatically instruments the code with an introspection mechanism that captures state changes. With adaptive declaration, the compiler generates optimized mechanisms for introspection and context switching mechanisms. Adaptation classes are integrated with the object oriented paradigm in the sense that they extend existing classes with adaptive behavior, and declare adaptation without disturbing the source program.

We are currently studying how to extend the expressiveness of adaptation classes to use them for static adaptation, i.e., adaptation before execution. By providing constraints on the values guarded by an adaptation class, the compiler can evaluate adaptation conditions and generate specific code which only includes the needed behavior. As a result, static and dynamic adaptation classes offer an abstraction to define the adaptation time with respect to the context usage of adaptive components. For example, if we wanted to use the SoundEncoder component with a network protocol which can guarantee a specific bandwidth (for example ATM), we would not need dynamic adaptation. The adaptation class compiler could generate a specific SoundEncoder component without any dynamic adaptation mechanisms. Static adaptation can eliminate dead code and further simplify the adaptation mechanisms, improving overall performance. Taking this idea even further, adaptation classes can be mixed with specialization classes, allowing each behavior to be specialized to given static constraints.

As for applications, we are studying the Java SWING library [20] to re-design the pluggable look-and-feel mechanism to allow the user to choose between a dynamically pluggable look-and-feel or a statically fixed look-and-feel. We believe that statically configuring this feature can improve the performance of applications written using this library.

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A Implementation details

This appendix provides implementation details about the ad hoc `SoundEncoder` component and the automatically generated `SoundEncoder` component.

A.1 Ad hoc SoundEncoder implementation

The ad hoc `SoundEncoder` implementation source code is shown in Figure 10.

Implementation of the Observer design pattern

The Observer pattern describes how to establish the relationships between the Observer `EncoderStrategy` and the subject `RtcpController` (cf. Figure 2). The set of observers (`ObserverSet`) is modified by a subscription mechanism (methods `addObserver` and `delObserver`). When the subject state changes, it invokes the `notify` method. This method propagates the notification to all observers and invokes the `update` method. This method is invoked for each observer with the reference to the subject as an argument. Thus, observers can know the identity of the subject, and obtain information about the observed object.

Implementation of the Strategy design pattern

We have implemented the Strategy pattern in the definitions of the classes `Encoder`, `Gsm`, `Lpc` and `EncoderStrategy` (cf. Figure 2). The abstract class `Encoder` unifies the concept of encoder and encapsulates the behavior associated with each strategy of encoding. This class provides a method `Packet encode(Sample data)`. This method transforms sampled sound into a package of bytes of compressed sound. Each sub-class `Gsm` and `Lpc` implements a specific encoding strategy. The class `EncoderStrategy` defines the interface of the adaptive object and manages a reference `CurrentEncoder` to an object `Encoder`. Each request is redirected towards an object sub-class of the `Encoder` class: when the `encode` method is invoked, the call is redirected towards the encoding method of the current algorithm.

A.2 Automatic generation of the adaptive component SoundEncoder

The compilation of the adaptation class modifies the class `RtcpController` as shown in Figure 11, and creates the class `SoundEncoder` which is shown in Figure 12.

The modifications to the `RtcpController` class consists in the addition of a subscription mechanism (insertion of a reference to `SoundEncoder` (1) and of a method `acAttachSoundEncoder` (3)), and of analyzing the code to insert guards that detect modifications to the `bandwidth` field (2). It should be noted that these modifications do not affect the behavior of `RtcpController`. It is transparent for other objects that may use `RtcpController`.

The `SoundEncoder` class is composed of a field `rtpControl` (which has a reference to the `RtcpController` object), a number of `Encoder` variables required for adaptive behavior (`acEncoder`, `acLpc` and `acGsm`), and a number of methods implementing adaptive behavior (`acCopyEnv`, `acUpdate`, `SoundEncoder` and `encode`). The `acCopyEnv` method is used to copy shared variables between two behaviors (see Section 6.1 for details). The goal of the `acUpdate` method is to notify `SoundEncoder` when the network bandwidth changes and to pass the bandwidth as an argument.

The `SoundEncoder` constructor has the same interface as defined in the adaptation class. The adaptation class compiler inserts in it some code to initialize the adaptive component (creation of all required adaptive behaviors, connection with the subject `RtpController`, and setting a current behavior).

```
class SoundEncoder {
  EncoderStrategy strategy;
  EncoderObserver observer;
  public void encode(int[] sample) {
    strategy.encode(sample);
  }
  public SoundEncoder (Subject subject) {
    strategy=new EncoderStrategy();
    observer=new EncoderObserver(subject,strategy);
    observer.update(subject);
  }
}
abstract class Encoder {
  public abstract void encode(int[] sample);
}
class Gsm extends Encoder {
  public void encode(int [] sample) { ... }
}
class Lpc extends Encoder {
  public void encode(int[] sample) { ... }
}
class EncoderStrategy {
  Encoder currentEncoder,
          gsmEncoder,
          lpcEncoder;
  public void change(String newStrategy) {
    if (newStrategy=="Gsm")
       currentEncoder=gsmEncoder;
    else if (newStrategy=="Lpc")
            currentEncoder=lpcEncoder;
  }
  public void encode(int[] sample) {
    currentEncoder.encode(sample);
  }
  public EncoderStrategy() {
    gsmEncoder=new Gsm();
    lpcEncoder=new Lpc();
  }
}
```

```
class Subject {
  private Set observerSet;
  public void addObserver(Observer o) { ... }
  public void deleteObserver(Observer o) { ... }
  public void onotify() { ... }
  Subject() { ... }
}

class RtpSession extends Subject {
  private float bandwidth;
  public float getBandwidth() { return bandwidth; }
  public void recFeedBack(float value) {
    bandwidth=value;
    notify();
  }
}
abstract class Observer {
  abstract void update(Subject s);
}
class EncoderObserver extends Observer {
  EncoderStrategy strategy;
  void update(Subject s) {
    float bandwidth=((RtpSession) s).getBandwidth();
    if (bandwidth<13.3) strategy.change("Lpc");
    else strategy.change("Gsm");
  }
  EncoderObserver(Subject subject,
                  EncoderStrategy _strategy) {
    subject.addObserver(this);
    strategy=_strategy;
  }
}
```

Figure 10: Design patterns implementation

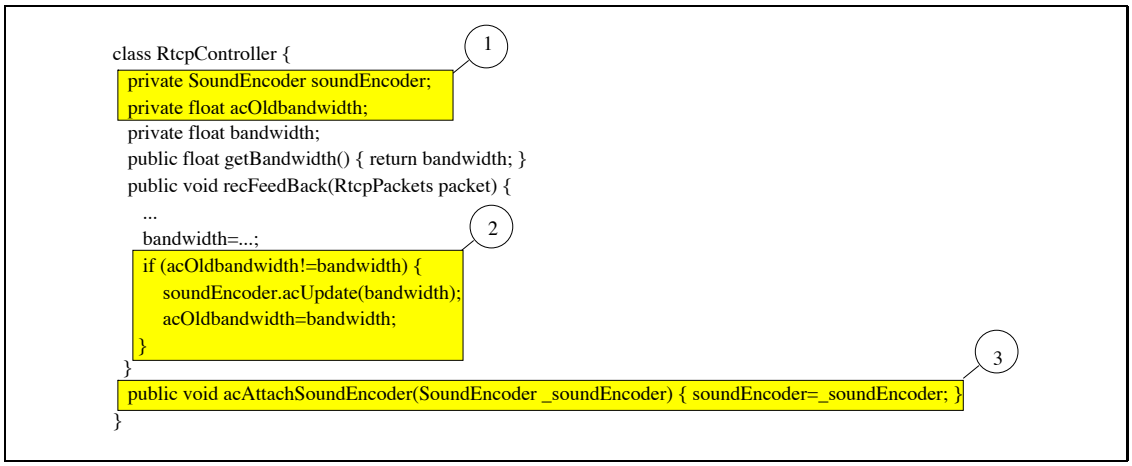

Figure 11: Modifications of the RtcpController class

```
class SoundEncoder  extends Encoder {
    private RtcpController rtpControl;
    private Encoder acEncoder,        /* Current Encoder */
                    acLpc,
                    acGsm;
    private void acCopyEnv(Encoder src, Encoder dest) {...}
    public  void acUpdate (float bandwidth) {
        if (bandwidth<13.3) { acCopyEnv(acEncoder,acLpc);
                              acEncoder=acLpc; }
        else if (bandwidth>=13.3) { acCopyEnv(acEncoder,acLpc);
                                    acEncoder=acGsm; }
        else throw AdaptiveError;
    }
    public SoundEncoder(RtcpController _rtpControl) {
        rtpControl=_rtpControl;
        /* strict creation of adaptation behaviors */
        acGsm=new Gsm();
        acLpc=new Lpc();
        rtpControl.acAttachSoundEncoder(this);
        /* compute the adaptation state */
        acUpdate(rtpControl.getBandwidth());
    }
    public void encode(int[] sample) {  acEncoder.encode(sample);  }
}
```

Figure 12: Result of compiling of adaptation classes