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Expanding Event Systems to Support Signals by Enabling the Automation of Handler Bindings

YungYu Zhuang[1,a)] Shigeru Chiba[1,b)]

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Abstract: In event-driven programming we can react to an event by binding methods to it as handlers, but such a handler binding in current event systems is explicit and requires explicit reason about the graph of event propagation even for straightforward cases. On the other hand, the handler binding in reactive programming is implicit and constructed through signals. Recent approaches to support either event-driven programming or reactive programming show the need of using both the two styles in a program. We propose an extension to expand event systems to support reactive programming by enabling the *automation* of handler bindings. With such an extension programmers can use events to cover both the implicit style in reactive programming and the explicit style in event-driven programming. We first describe the essentials of reactive programming, signals and signal assignments, in terms of events, handlers, and bindings, then point out the lack of *automation* in existing event systems. Unlike most research activities we expand event systems to support signals rather than port signals to event systems. In this paper we also show a prototype implementation and translation examples to evaluate the concept of *automation*. Furthermore, the comparison with the predicate pointcuts in aspect-oriented programming and the details of the experimental compiler are discussed.

Keywords: event-driven programming, reactive programming, signal, behavior

1. Introduction

Recently reactive programming attracts a lot of interest since the need for reactive programs is steeply increasing, for example applications for mobile devices and web browsers. FRP (Functional-Reactive Programming) [7], [12], [25], [34], [35], [36] successfully introduces signals into functional programming. The concept of signals might come from data-flow languages [3], [4], [6], [16], [33], where variables are described as continuous data streams rather than states at a specific time. Such variables are signals, which can participate in the calculation to generate other signals or be given to functions for triggering the reactions; they are very declarative. This programming style is widely used in hardware design and spreadsheet programs, where the expressions are usually described without explicitly specifying the time. When FRP introduces signals into functional programming for reactive programs such as GUI programs, a time signal and event streams are also used in order to properly describe the temporal states in the program. An event denotes something happening, for example a mouse click occurs, and an event stream is a series of events on the timeline. Programmers can use event streams with the time signal to get a constant value (snapshot) of a signal at a specific time. They help to describe the states on the timeline more specifically while keeping the description declarative. This style is followed by several research activities and inspires the contributions towards writing GUI libraries for FRP [10], [27]. In these systems signals are given to describe the propagation of value change and then the compiler can translate them to some kind of events underneath.

The OO (Object-Oriented) community has been developing events, which look similar to signals but actually different. In OO languages that directly support event-driven programming, events are first-class objects, and an event handler bound to a specific event is implicitly invoked when that event happens. Although the OO community notices the convenience of using signals, OO languages have not been directly integrated with signals. Signals are brought into existing event systems, and existing GUI libraries are wrapped in FRP style [18], [22], [30]. Although events have been used with objects for a long time and well integrated into OO languages, propagating values by events is not implicit enough as propagating by signals. All handler bindings, in other words the statements for setting up the methods that react to specific events, must be explicitly specified according to the graph of event propagation. Even for a straightforward use case of events, programmers have to prepare all events and handlers, and bind them together one by one. For a complex event scenario programmers need to prepare too many events and handlers, and might lead to redundant event propagation. Thus, the research activities devoted to OO integration borrow signals from reactive programming and focus on how to integrate signals with events and objects. Most research results come up with a conclusion that the existence of events is still necessary, and signals are used to implicitly propagate parts of the change of values [31]. As a result, events and signals appear in both the FRP solution and the OO integration.

This research is targeted at allowing programmers to use both the implicit style and the explicit style in a program since the re-

1 The University of Tokyo, Bunkyo, Tokyo 113–8656, Japan
a) yungyu@acm.org
b) chiba@acm.org

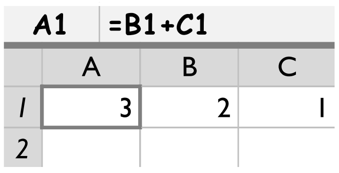
search activities mentioned above show the need of using both the two styles together. The contributions of this paper can be summarized as follows. First, we compare event-driven programming with reactive programming to point out the need of implicit binding in event systems. Second, we show how event systems can be expanded to cover the implicit style in reactive programming by enabling the *automation* of handler bindings. In order to show the feasibility of our idea, we give a prototype implementation of the *automation* on an event system, and discuss the advantages over ones without the *automation*. The issues that might happen when implementing this concept on OO languages are discussed as well. Moreover, the analysis on the essentials of reactive programming might give a better understanding of events and signals. Note that this paper is an extended journal version of the one we presented at COMPSAC2015 [*1]. The contents we added to this extended version include:

- A more complicated event example in Sections 4.4 and 4.5 to show how the *automation* works among different objects. We first introduce a kind of graph that makes it easier to check the dependencies among events and handlers on different objects. Then how our compiler infers through object references is explained.
- The details of our compiler implementation in Section 5.1. After briefly explaining the implementation of the event system we based this proposal on, how the idea of *automation* can be concretely implemented is demonstrated with sample code.
- Qualitative analysis of our reactive extension in comparison with others. In Section 5.4 we compare with the original event system and in Section 5.5 we compare with the predicate pointcuts in aspect-oriented programming. At the end of Section 6, we also compare the the meanings of reactive used in FRP and other event enhancements.

2. Motivating Example

Programs written in reactive programming can also be implemented by event-driven programming, though the code might look quite different. Here we take the example of spreadsheet programs to discuss the equivalence between what reactive programming can do and what event-driven programming can do. Although spreadsheet programs are developed for accounting, they can be regarded as an interactive programming environment. Cells are fields (or variables), and sheets are some sort of objects that hold a large number of fields. We can give a cell a constant value or an expression, where formulas can be used to perform complex calculations. **Figure 1** shows a sheet in a spreadsheet program, where B1 and C1 are given constant values: 2 and 1 respectively, and A1 is given an expression "B1 + C1". As a result, the value in the cell A1 will be always equal to the sum of the values in the cells B1 and C1 even if you arbitrarily change the value of B1 or C1.

Such a sheet defined in spreadsheet programs can be easily implemented by FRP [12] languages. For example, **Fig. 2** shows an


A1 =B1+C1

	A	B	C
1	3	2	1
2			

Fig. 1 A sheet in a spreadsheet program.

```
1  <body onload="loader()">
2    <table width=200>
3      <tr><th>A1</th>
4          <th>B1</th>
5          <th>C1</th>
6      </tr>
7      <tr><th><input id="A1" size=2 value="0" /></th>
8          <th><input id="B1" size=2 value="2" /></th>
9          <th><input id="C1" size=2 value="1" /></th>
10     </tr>
11   </table>
12 </body>
13
14 <script type="text/flapjax">
15 function loader() {
16   var b = extractValueB("B1");
17   var c = extractValueB("C1");
18   var a = b + c;
19   insertValueB(a, "A1", "value");
20 }
21 </script>
```

Fig. 2 Using Flapjax to implement the sheet example.

```
class Sheet {
  var a: Int = _
  var b: Int = _
  var c: Int = _
  def setB(nb: Int) { b = nb; }
  def setC(nc: Int) { c = nc; }

  evt eb[Unit] = afterExec(setB)
  evt ec[Unit] = afterExec(setC)
  def ha() { a = b + c; }
  eb += ha;
  ec += ha;
}
```

Fig. 3 Using EScala to implement the sheet example.

implementation in Flapjax [22], which is a JavaScript-based language supporting FRP. This program uses HTML elements to draw the sheet and cells, then gets and sets signals from/to the cells. Here we do not explain the syntax of Flapjax in detail but focus on the assignment in Line 18. We can consider the assignment without the declaration of a:

`a = b + c;`

Note that what the three variables hold are signals rather than constant values. The assignment looks not much different from the one in imperative programming languages such as Java, but the meaning is quite different. Whenever b or c is changed, a is updated automatically. The assignment is always effective and looks like an equation (although it is not bidirectional: only the change of the right-hand side can trigger the update of the left-hand side). Signals are very similar to the cells in spreadsheet programs, and thus can easily describe the expression in the sheet example. In reactive programming all updates are automatic and implicit.

On the other hand, such an assignment in imperative programming languages is only effective just after the assignment is executed, and the value at the left-hand side might not be the same as the one at the right-hand side later until the assignment is executed again. Nevertheless, it is still possible to implement such a program by imperative programming languages with events; we can use events to denote the value change and ask an event handler to execute the assignment again. Here we use EScala [15], an

[*1] Enabling the Automation of Handler Bindings in Event-Driven Programming. YungYu Zhuang and Shigeru Chiba. Year: 2015, Volume: 2, Pages: 137–146, DOI: 10.1109/COMPSAC.2015.48, Publisher: IEEE.

event system that provides events, handlers, and bindings based on Scala [26], to write the sheet example. EScala allows declaring a special kind of field named event to denote something happening. The event can be either implicitly triggered before/after a method call or imperatively triggered through a method-call syntax. As shown in **Fig. 3**, we have two methods setB and setC, which set the fields b and c respectively (Lines 5–6). Then we can declare two events e_b and e_c that denote the happening of value change of b and c through setB and setC using the primitive afterExec given by EScala, respectively. Line 8 says that e_b is the event occurring after the method setB is executed—here we assume that setB only changes the value of b and leave the discussion about join point model in Section 3. Line 9 is interpreted similarly for e_c. The next step is preparing a handler that reacts to the two events properly. As in most event systems, methods play the role of handler in EScala. As shown in Line 10, in this example we need a handler h_a that executes the assignment for updating the value of a according to the values of b and c. Finally we have to connect the events and the handler, or else the latter is unrelated to the two events (Lines 11–12). The two statements mean that h_a should be executed after e_b and e_c [*2]. Such statements are handler bindings, which bind the handler to events. The calculation in the event version is the same as the signal version, but it is manual and explicit. All events must be manually declared, and the handler bindings for them must be manually stated as well. These drawbacks not only make the code longer but also increase the risk of bugs. When the body of h_a (Line 10) is modified, we must carefully update the handler bindings in Lines 11–12 to ensure consistency between the bindings and the handler body.

The observation that both the paradigms can implement reactive programs motivates us to analyze the essentials of reactive programming from the viewpoint of event-driven programming. By comparing the essentials of reactive programming with event-driven programming we can know how to expand event systems to cover the implicit style in reactive programming.

3. An Expanded Event System Supporting Reactive Programming

In this section we propose an expanded event system that can cover both event-driven programming and reactive programming. To know what the extension should be, we clarify what the essentials of reactive programming are and point out what is necessary to support them in event-driven programming. We first describe how these essentials work in reactive programming, and then describe them in terms of events, handlers, and bindings. The comparison between the two descriptions reveals an insufficiency in existing event systems, and led us to propose the expanded event system.

[*2] Note that EScala supports event composition to improve the abstraction, but here we just enumerate events and bind the handler to them individually to simplify the explanation. For example, we can declare a composed event instead of e_b and e_c as shown below:
```
evt ebc[Unit] = afterExec(setB) || afterExec(setC)
```

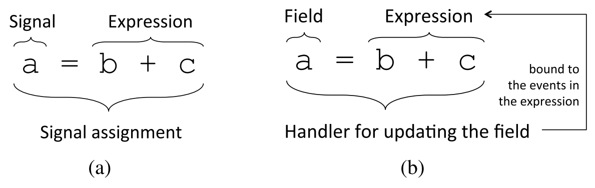


Fig. 4 The signal assignment in the sheet example.

3.1 The Essentials of Reactive Programming

The essentials of reactive programming are *signals* and *signal assignments*. **Figure 4** (a) shows the *signal assignment* in the sheet example mentioned in Section 2, where a is a *signal* and b + c is the expression assigned to the *signal*. We can give the description of *signals* and *signal assignments* as follows:

- A *signal* (i.e., behavior) is a time-varying field or variable, the value of which is implicitly reevaluated when any of the *signals* involved in its reevaluation varies. Then its value change also implicitly causes all the reevaluation that it is involved in.
- A *signal assignment* is composed of a *signal* and the expression assigned to the *signal*. The *signal* expression describes how to reevaluate the value of the *signal*. It also implies which *signals* are involved in this reevaluation and the expression has to be reevaluated for setting the value of this *signal* when any of the involved *signals* varies. Here the involved *signals* are the *signals* that are read in the expression.

In the sheet example a is the *signal*, the value of which will be implicitly reevaluated when any of b and c varies according to the expression in the *signal assignment* "a = b + c".

3.2 In Terms of Events, Handlers, and Bindings

Although event-driven programming and reactive programming are different paradigms, what they can do are very similar. They both can be used to implement reactive programs such as the sheet example we mentioned in Section 2. We can also translate the essentials of reactive programming, *signals* and *signal assignments*, into a description in terms of events, handlers, and bindings as listed below:

- A *signal* is translated to a field or variable whose value will be set when any of the events involved in its reevaluation occurs.
- A *signal assignment* is translated to a handler for setting the value of the field (or variable) at the left-hand side by reevaluating the expression at the right-hand side. Furthermore, this handler is bound to all events involved in the expression at the right-hand side. Here the involved events are the value change of the fields (or variables) read in the expression. Whenever such an involved event occurs, the handler is executed to reevaluate the expression and then set the value of this field (or variable).

Figure 4 (b) shows how the *signal assignment* in the sheet example is translated in an event system. This *signal assignment* is described as a handler for executing "a = b + c" to update the value of a. Note that we can simply say the handler is bound to all the involved fields (or variables) inside itself since the field (or variable) at the left-hand side is written rather than read.

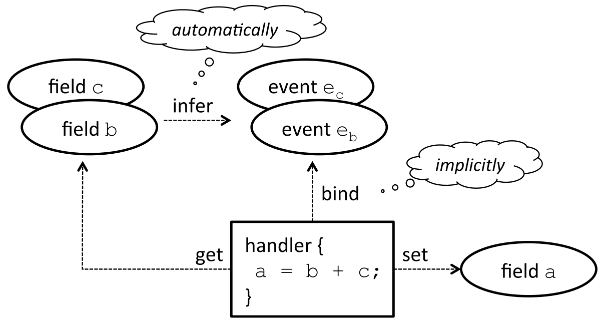


Fig. 5 The extension must be able to automatically infer the involved events and implicitly bind the handler to them.

3.3 The Expanded Event System

By comparing the two descriptions we can know that it is possible to translate a *signal assignment* to a handler. However, in existing event systems programmers have to manually check the body of the handler and infer the involved events by themselves. There is no mechanism to bind a handler to multiple events at once without event composition, either. Programmers have to enumerate the involved events or specify certain rules to filter the involved events manually. Once the body of the handler is modified, the bindings might be no longer consistent with the handler body. In other words, existing event systems lack a kind of *automation*, which means automatically inferring the involved events and implicitly binding the handler to them.

As shown in **Fig. 5**, an extension to event systems for supporting reactive programming must provide such *automation* in handlers, which means that a handler can be implicitly bound to all the involved events that are automatically found inside itself. If an extension can enable the *automation* in handlers, all existing reactive mechanisms can be simply translated to events and handlers.

3.3.1 Automatic Inference

The extension must be able to automatically infer all the involved events in a handler. As shown in Fig. 5, the involved events, e_b and e_c, are the events for the value change (or more broadly, the setting) of the fields (or variables) that are read in the handler, b and c. In the terminology of AOP (Aspect-Oriented Programming) these involved events are the join points matched by the set pointcuts for the fields that are read in the handler. Furthermore, we can consider the handler in a more generic way since the body of a handler in event systems might have method calls and conditional branches. In that case, the fields (or variables) that are read in the methods called by the handler must be recursively inferred since they might also be involved in the reevaluation. The fields (or variables) in all conditional branches should also be taken into account since any of them might be involved in the reevaluation at runtime.

3.3.2 Implicit Binding

The extension must also be able to implicitly bind a handler to all the involved events inside itself. When any involved event inside the handler occurs, the handler will be executed to update the values of fields (or variables). Such a binding must be implicit enough to bind a handler to multiple events without specifying the events individually. Event composition is not satisfying either since we still need to explicitly compose individual events into a higher-level event. A similar concept is the filter in event systems or the predicate in AOP, but they are usually used to filter events selected by other event detectors and compose the result into a higher-level one.

4. A Prototype Implementation

In order to show the feasibility of *automation*, we expand DominoJ [37] (DJ) to ReactiveDominoJ (RDJ) by enabling the *automation* in method slots as an example of such an expanded event system. DJ is a language that supports event-driven programming, which motivates us to propose RDJ. Note that RDJ is a prototype implementation and has several limitations, but the extension we proposed in Section 3 is more generic and can be implemented in any event system.

4.1 Method Slots and DominoJ

DJ is a Java-based language developed for introducing method slots, a generic construct supporting multiple paradigms. A method slot is an object's property, which can hold more than one closure at the same time. DJ replaces the methods in Java with method slots. All method-like declarations in DJ are method slot declarations. For example,

```
public void setX(int nx) { this.x = nx; }
```

the method-like declaration for setX is a method slot declaration. It is some sort of field that holds an array of closures. When the method slot is called, all closures in it are executed in order with the same given arguments and the value returned by the last one will be regarded as the return value of this method slot (if its return type is not void). The body of a method slot declaration is the default closure; it is optional. If the default closure is declared, it will be created and inserted into the array when the owner class is instantiated. At runtime the closures in a method slot can be added or removed using assignment operators, for example using += operator as shown below:

```
s.setX += o.update;
```

means that creating a closure calling the method slot o.update and appending it to the end of array in s.setX.

We can use DJ as an event system. A method slot declaration is equivalent to an event declaration. When the method slot is called, the event (i.e., the join point in the terminology of AOP) occurs and the handlers (closures) in it are executed. The default closure of a method slot can be regarded as the default handler for this event. Besides imperatively triggering by calls, a method slot can also be implicitly triggered after or before other method slot calls by using the assignment operators:

⟨*event*⟩ ⟨*assignment_operator*⟩ ⟨*handler*⟩;

The statement using += operator we showed above is used to let the event (method slot) update on an object o be triggered after s.setX is triggered. Note that in DJ a method slot can be not only an event but also a handler for other events. Thus, there is no difference between event-event binding and event-handler binding, and all the bindings are dynamically set at runtime by the assignment operators.

```java
public class Sheet {
  private int a, b, c;
  public void setB(int nb) { b = nb; }
  public void setC(int nc) { c = nc; }
  public void updateA() { a = b + c; }
}
```

Fig. 6 A simplified sheet example using fields.

```
1  procedure $braces\_operator(O_M, M)$ {
2    $S$ = new Set();
3    foreach $c$ in $getClosuresIn(M)$:
4      foreach $f$ in $findFieldsReadIn(c)$:
5        if $f$ isOwnedBy $O_M$:
6          foreach $m$ in $findMethodSlotsThatWrite(f)$:
7            if $m$ isOwnedBy $O_M$:
8              $S$.add($m$);
9      foreach ($O_N$, $N$) in $findMethodSlotsCalledIn(c)$:
10       if $O_N$ isOwnedBy $O_M$:
11         $S$.add($braces\_operator(O_N, N)$);
12   return $S$;
13 }
```

Fig. 7 The inference in the braces operator.

4.2 A New Syntax for Enabling the Automation

RDJ allows using the braces operator to enable the *automation* in method slots (i.e., handlers) in DJ. For example, if we have a method slot updateA in a class Sheet as shown in **Fig. 6**, we can use the following statement to enable the automation in updateA:

```
{this.updateA} += this.updateA();
```

When the value of b or c is set by setB/setC, this.updateA() will be executed to update the value of a. In other words, the statement means that binding the handler this.updateA() to all the involved events inside itself as we described in Section 3. The braces operator makes it possible to bind a handler to a set of events that are involved in its body without explicitly specifying them.

The braces operator selects the involved events inside a method slot by checking all closures in it at runtime. The semantics of the inference in the braces operator is described by a piece of pseudocode as shown in **Fig. 7**, where M is a method slot and O_M is the owner object of M, *getClosuresIn* returns all the closures in a specified method slot, *findFieldsReadIn* returns all the fields read in a specified closure, *findMethodSlotsThatWrite* returns all the method slots that write the specified field in the default closure, and *findMethodSlotsCalledIn* returns all method slots that are called in a specified closure. First, all the involved fields in the method slot, which are the fields read during executing the closures in this method slot, are inferred (Lines 3–4). Then all the method slots that write any of these involved fields are regarded as the involved events and selected (Lines 6–8). Take Fig. 6 as an example. {this.updateA} infers a set of method slots that write any of the involved fields, this.b and this.c, and thus the method slots that write this.b or this.c, this.setB and this.setC, are selected. Any method slot that is called in any closure of the method slot given to the braces operator are recursively inferred (Lines 9–11) since the fields read in the called method slots are also involved in the execution of this method slot. In this example no method slots are called in updateA, so that this step is skipped. If another method slot d.print is called in updateA, where d is a field added to Sheet to hold an object instance of another class Debug as shown in **Fig. 8**. Then the set of involved events inferred by {updateA} can be considered as shown below:

```java
public class Debug {
  private boolean e;
  private String f;
  private Object g;
  public void setE(boolean ne) { e = ne; }
  public void setF(String nf) { f = nf; }
  public void setG(Object ng) { g = ng; }
  public void resetG() { g = null; }
  public boolean getG() { return g; }
  public void print() {
    if(e)  System.out.println(f);
    else  System.out.println(g);
  }
}
```

Fig. 8 Another class Debug.

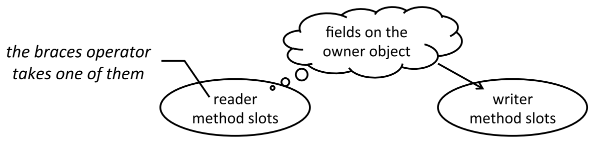


Fig. 9 The braces operator infers the writers.

{this.updateA}
→ (this.setB, this.setC) ∪ {d.print}
→ (this.setB, this.setC) ∪ (d.setE, d.setF, d.setG, d.resetG)
→ (this.setB, this.setC, d.setE, d.setF, d.setG, d.resetG)

Note that only the method slots that belong to the objects held in the fields in this owner object are recursively inferred (Line 10 of Fig. 7). To simplify the design, we simply ignore the method slots that belong to the objects held in local variables and parameters. The design decision and the limitation of RDJ will be discussed in a later subsection.

Some readers might notice that in Fig. 7 we only consider the fields and the method slots on the same object (Lines 5 and 7). It is a simplified inference in RDJ based on OO design rather than a limitation of the extension we proposed in Section 3. We observed the convention of OO design and made the assumption: usually fields are only directly used inside the owner object and other objects must access them through getters and setters. We can consider the relation between all the method slots reading a field and all the method slots writing the field as an extended getter-setter relation. We name it reader-writer relation since there might be more than one getter/setter and a getter/setter might get/set more than one field. The reader-writer relation extends getter-setter relation to N-to-N and is not limited to the naming scheme. The inference of the braces operator (Fig. 7) is a process of finding all the writers by a given reader through a set of fields on the owner object as shown in **Fig. 9**. For example, in Fig. 8 using {this.getG} will select both this.setG and this.resetG. Note that the events selected by the braces operator are the calls to the writers. In the terminology of AOP they are the join points matched by method pointcuts but not field pointcuts. As a result, in RDJ the execution of a closure is atomic and a handler cannot be bound for being executed just before/after the field is written inside a closure. The join point model is consistent with the one adopted by DJ, which is a region-in-time model [19]. Matching an arbitrary join point inside a closure is not supported.

To make our code clear the underscore symbol _ can be used within the braces operator to refer to the method slot at the right-hand side of the assignment operator. For example, enabling the automation in updateA can be simplified:

```
1 public class PlusSheet
2 extends Sheet {
3  private IntCell a1 = null;
4  private IntCell b1 = null;
5  private IntCell c1 = null;
6  public PlusSheet() {
7   super(2, 3);
8   setHeaders("A1", "B1", "C1");
9   a1 = new IntCell(0);
10  b1 = new IntCell(0);
11  c1 = new IntCell(0);
12  Behavior b = b1.extractValueB();
13  Behavior c = c1.extractValueB();
14  Behavior a = b + c;
15  a1.insertValueB(a);
16  add(a1);
17  add(b1);
18  add(c1);
19  pack();
20 }
21 public static
22  void main(String[] args) {
23  PlusSheet p = new PlusSheet();
24  p.show();
25 }
26 }
```

(a)

```
1 public class PlusSheet
2 extends Sheet {
3  private IntCell a = null;
4  private IntCell b = null;
5  private IntCell c = null;
6  public PlusSheet() {
7   super(2, 3);
8   setHeaders("A1", "B1", "C1");
9   a = new IntCell(0);
10  b = new IntCell(0);
11  c = new IntCell(0);
12  add(a);
13  add(b);
14  add(c);
15  pack();
16  b.setValue += this.changed;
17  c.setValue += this.changed;
18  this.changed += this.updateA;
19 }
20 public void changed(int v);
21 public void updateA(int v) {
22  a.setValue(b.getValue() + c.getValue());
23 }
24 public static
25  void main(String[] args) {
26  PlusSheet p = new PlusSheet();
27  p.show();
28 }
29 }
```

(b)

```
1 public class PlusSheet
2 extends Sheet {
3  private IntCell a = null;
4  private IntCell b = null;
5  private IntCell c = null;
6  public PlusSheet() {
7   super(2, 3);
8   setHeaders("A1", "B1", "C1");
9   a = new IntCell(0);
10  b = new IntCell(0);
11  c = new IntCell(0);
12  add(a);
13  add(b);
14  add(c);
15  pack();
16  {_} += this.updateA();
17 }
18 public void updateA() {
19  a.setValue(b.getValue() + c.getValue());
20 }
21 public static
22  void main(String[] args) {
23  PlusSheet p = new PlusSheet();
24  p.show();
25 }
26 }
```

(c)

Fig. 10 Using Flapjax-like pseudocode (a), DJ (b), and RDJ (c) to implement the sheet example.

```
public class IntCell {
  private int value = 0;
  public void setValue(int v) { this.value = v; }
  public int getValue() { return this.value; }
  public Behavior extractValueB() { ... }
  public void insertValueB(Behavior b) { ... }
    :
}
```

Fig. 11 The source code of IntCell.

```
{_} += this.updateA();
```

It is automatically translated by the RDJ compiler. In RDJ, the method slot that we want to infer the involved events (the method slot given to the braces operator) and the handler for reevaluation (the method slot call at the right-hand side) are not necessarily the same. The syntax of the braces operator allows observers to register a handler through a public method slot for getting a notification when private fields in the subject object are written.

4.3 Rewriting the Motivating Example

To show how the automation can be used we first use DJ to write the sheet example in Section 2 and then rewrite it by RDJ to compare with Flapjax. In order to make it easier to compare we assume that there were a Flapjax-like Java-based language, which could be used to rewrite Fig. 2 to **Fig. 10** (a). The class IntCell (**Fig. 11**) is used to emulate the HTML element and follows the getter-setter manner in OO design rather than accessing a field directly; it might be used to wrap a GUI component in existing libraries by extending a class such as the JTextField in Swing. Behavior is a class representing signals, the usage of which, such as extractValueB and insertValueB, is the same as in Fig. 2. Line 14 shows the merit of reactive programming: the propagation among signals can be simply described.

Figure 10 (b) is the DJ version, where only events are used. Note that no additional event declaration is needed since the getter/setter declarations in DJ can also be considered as the events declared for getting/setting the field. Line 14 of Fig. 10 (a) is now described in terms of getters and setters as shown in Line 22 of Fig. 10 (b). However, the handler h_a (updateA) will not be automatically executed to update the value of a. We need to check the body of h_a and find e_b and e_c by ourselves as mentioned in Section 2. Here the events e_b and e_c are b.setValue and c.setValue respectively since we know the relation between getter and setter. Then we can bind the handler this.updateA to them individually, or prepare a higher-level event this.changed as shown in Line 20 for event composition (Lines 16–17) and bind this.updateA to this.changed (Line 18). This program works well as the Flapjax version in Fig. 2, but the inference is not automatic and the binding is explicit. Once the body of updateA is modified, we have to carefully check the bindings in order to make them consistent with the events inside the body.

Figure 10 (c) shows the RDJ version. Most lines of code are the same as the DJ version, but the bindings and the higher-level event in Lines 16–18, 20 of Fig. 10 (b) are eliminated. Note that we still need a binding to enable the automation in the handler (Line 16 of Fig. 10 (c)), otherwise the compiler cannot know whether it is the implicit style used in reactive programming or the explicit style used in event-driven programming. We use the new syntax given by RDJ to automatically infer all the involved events in the handler this.updateA and implicitly bind the handler itself to them. By comparing Fig. 10 (a) with Fig. 10 (c), it is also easy to see how a signal can be translated to a field as we discussed in Section 3. The signal assignment for a in Line 14 of Fig. 10 (a) is moved to a method slot updateA (Lines 18–20 of Fig. 10 (c)), and an additional line for enabling its automation must be stated outside of it (Line 16 of Fig. 10 (c)). On the other hand, programmers do not have to explicitly specify which ones are signals, and transformations to/from constant values such as insertValueB/extractValueB are not necessary. RDJ expands the events in DJ to make a step towards reactive programming.

4.4 Dependency Graph

In order to compare the handler bindings in DJ with RDJ, here we use a graph to describe the dependencies among events and handlers: a node is an event or a handler, and an edge is a dependency relationship. As to the relationship, we use a solid line to note a handler binding and use a dashed line with words for

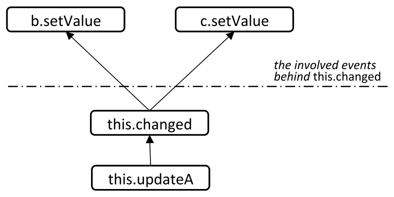


Fig. 12 Manually constructing the dependency of this.changed.

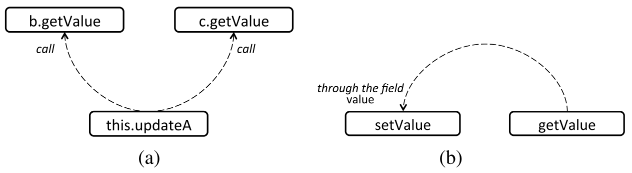


Fig. 13 The clues found inside this.updateA and IntCell.

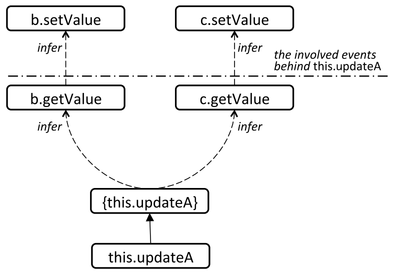


Fig. 14 Inferring the involved events based on the clues in Fig. 13.

other types of relationships. Note that here we do not distinguish events from handlers since a method slot can be regarded as both of them. The dependency graph of this.changed in Fig. 10 (b) is shown in **Fig. 12**, which means that a higher-level event changed depends on two events b.setValue and c.setValue, and the handler updateA is bound to changed. In the DJ version we know which events the higher-level event changed should depend on since we have the knowledge about the default closure of the handler updateA and the getter-setter relation between getValue and setValue. We have to check the implementation of the default closure of updateA, manually enumerate all the involved events, and then explicitly bind them to this.changed. It is not easy to ensure the correctness of the dependency since the dependency behind the default closure of a method slot might be changed later for further extension. On the other hand, in Fig. 10 (c) we simply enable the automation in updateA, in other words using the braces operator on it to select all the involved events, and let the RDJ compiler do the rest. The RDJ compiler recursively infers and selects all the involved events in the body of updateA based on the clues as shown in **Fig. 13** (a) and Fig. 13 (b), which can be found in the default closure of updateA and the declaration of IntCell, respectively. The inference performed by the RDJ compiler is shown in **Fig. 14**, where {this.updateA} is a kind of higher-level event as the this.changed in Fig. 12. Note that the dashed lines are completed by the RDJ compiler and only the one solid line needs to be constructed by programmers.

4.5 Inferring Involved Events through Object References

Figure 18 (a) is an example in DJ for demonstrating how the braces operator infers all the involved events through object references. This example implements a class Meter, which automatically calculates and prints out the distance between two given Shape objects in the Cartesian plane when either the name or the coordinates of the two objects are changed. Note that a Shape object can be placed on another Shape object by giving the parent object as the second argument to its constructor, and its coordinates will be relative to its parent object rather than the origin. In Shape class and Meter class we define several events and bind handlers to construct the dependency graphs as shown in **Fig. 15** and **Fig. 16**, respectively. Now we give two Shape objects s1 and s2, to the Meter object m, where the parent of s2 is s3. Whenever the name or the coordinates of s1, s2, and s3 are modified, m will recalculate the distance between s1 and s2 and print out a string. The RDJ version of this example is shown in Fig. 18 (b), where all events and explicit bindings for event composition are replaced with the line of enabling the automation in this.print (Line 39). In DJ version twelve bindings (with += operator) are used, while in RDJ version only one binding is needed. **Figure 17** shows how the RDJ compiler infers all the involved events through the references to these objects. This example shows that the braces operator can not only infer the involved events located on different objects, but can also greatly reduce the number of bindings for event composition.

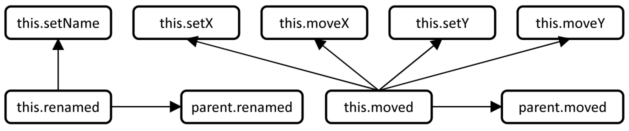


Fig. 15 The dependency graph of Shape constructed in Fig. 18 (a).

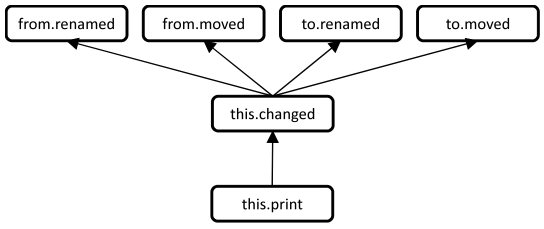


Fig. 16 The dependency graph of Meter constructed in Fig. 18 (a).

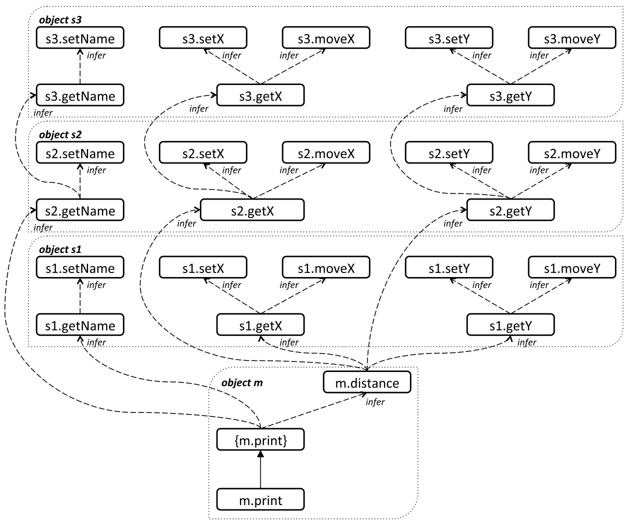


Fig. 17 The involved events located on different objects can be automatically inferred by the RDJ compiler.

```
public class Shape {
 private Shape parent; private String name;
 public String getName() {
  if(parent == null) return name;
  return parent.getName() + ":" + name;
 }
 public void setName(String n) { name = n; }
 public void renamed(String s);
 private int x = 0, y = 0;
 public void setX(int nx) { x = nx; }
 public void moveX(int dx) { x = x + dx; }
 public int getX() {
  if(parent == null) return x;
  return parent.getX() + x;
 }
 public void setY(int ny) { y = ny; }
 public void moveY(int dy) { y = y + dy; }
 public int getY() {
  if(parent == null) return y;
  return parent.getY() + y;
 }
 public void moved(int v);
 public Shape(String n, Shape p) {
  parent = p; name = n;
  setName += renamed;
  setX += moved; moveX += moved;
  setY += moved; moveY += moved;
  if(parent != null) {
   parent.moved += moved;
   parent.renamed += renamed;
  }
 }
}
public class Meter {
 private Shape from, to;
 public double distance() {
  double x2 = Math.pow(to.getX()-from.getX(), 2);
  double y2 = Math.pow(to.getY()-from.getY(), 2);
  return Math.sqrt(x2 + y2);
 }
 public void changed(Object[] args);
 public void print(Object[] args) {
  System.out.println("the distance between "
          + from.getName() + " and " + to.getName()
          + " is " + distance() + ".");
 }
 public Meter(Shape a, Shape b) {
  from = a; to = b;
  from.renamed += changed; from.moved += changed;
  to.renamed += changed; to.moved += changed;
  changed += print;
 }
}
```

(a)

```
public class Shape {
 private Shape parent; private String name;
 public String getName() {
  if(parent == null) return name;
  return parent.getName() + ":" + name;
 }
 public void setName(String n) { name = n; }
 private int x = 0, y = 0;
 public void setX(int nx) { x = nx; }
 public void moveX(int dx) { x = x + dx; }
 public int getX() {
  if(parent == null) return x;
  return parent.getX() + x;
 }
 public void setY(int ny) { y = ny; }
 public void moveY(int dy) { y = y + dy; }
 public int getY() {
  if(parent == null) return y;
  return parent.getY() + y;
 }
 public Shape(String n, Shape p) {
  parent = p; name = n;
 }
}
public class Meter {
 private Shape from, to;
 public double distance() {
  double x2 = Math.pow(to.getX()-from.getX(), 2);
  double y2 = Math.pow(to.getY()-from.getY(), 2);
  return Math.sqrt(x2 + y2);
 }
 public void print() {
  System.out.println("the distance between "
          + from.getName() + " and " + to.getName()
          + " is " + distance() + ".");
 }
 public Meter(Shape a, Shape b) {
  from = a; to = b;
  {_} += this.print();
 }
}
```

(b)

Fig. 18 The shape and meter example in DJ (a) and RDJ (b).

```
 1 public class Sheet {
 2  private int b, c, d;
 3  public void updateA() {
 4   int a;
 5   a = this.b + this.c;
 6   this.d = a;
 7  }
 8  public void count(int s) {
 9   ...
10  }
11   :
12 }
```

(a)

```
 1 public class Sheet {
 2  private int a, d, e;
 3  public void updateA(int b) {
 4   int c;
 5    :
 6   this.a = b + c;
 7  }
 8  public void notify() {
 9   updateA(this.d + this.e);
10  }
11   :
12 }
```

(b)

Fig. 19 Only fields are taken into account.

4.6 The Limitations of RDJ

In this subsection we discuss the limitations of RDJ, which are not the limitations of the extension we proposed in Section 3 but might occur when implementing it on an OO language such as DJ, especially when we are faced with making design decisions.

Only fields can be translated to signals. In Section 3, we described a signal as a field or a variable that is written in a handler with the automation, but in RDJ we ignore variables (i.e., local variables and parameters). There is a limitation that a local variable in RDJ cannot work as signals. As shown in **Fig. 19** (a), the assignment of the local variable a (Line 5) cannot be translated to a handler with the automation and passed to other method slots. The reason is that the braces operator is used for method slots, while a method slot in RDJ is an object's property and cannot be declared inside a method slot body like an inner method or closure. If the assignment in Line 5 of Fig. 19 (a) can be wrapped in a local method slot, the braces operator could enable the automation in the local method slot to let a be used as a signal later.

Only fields are used to infer involved events. In RDJ, local variables and parameters are not involved in the inference. For example, using the braces operator on the method slot updateA in Fig. 19 (b) cannot select involved events inside b and c. Since RDJ is a Java-based language, where the arguments are evaluated with pass-by-value strategy, a special class [18], [30] or a first-class method slot might be necessary to wrap the expressions passed to updateA.

The usage of the braces operator is not declarative. In RDJ, the automation of a handler is dynamically enabled by a statement in a method slot body rather than statically declared in its owner class. This means the concern of enabling the automation might be tangled with other concerns. This issue can be considered as a consequence of allowing dynamically inferring events at runtime. The braces operator can be regarded as a kind of event detector, but it is not separated from other code [5]. For example, if the automation of updateA in Fig. 6 must be enabled for all object instances of Sheet, programmers have to add the binding statement to the constructor of Sheet. However, this statement is used to enable the automation in updateA but not directly related to the construction of a Sheet object. A new modifier for method slots, for example reactive, could be introduced as syntax sugar to make it declarative. However, this design limits the way to give arguments and only the involved events in the default closure can be inferred.

Difficult to filter only the events for value change. As we mentioned in Section 3 an expanded system should be able to infer the events for value change or more broadly write access since the former is a subset of the latter. However, in RDJ there is no easy way to filter out the events occurring when writing fields with the same values; it is hard to get only the events for value change. A possible solution is to check the values in the fields at the beginning of the handler or insert another handler to check whether the handler should be called or not, but programmers have to manage the history of the values for fields. The history-based language features for AOP such as Ref. [2] or CEP (Complex Event Processing) [9], [13], [17] might be better solutions to resolve this issue in such an expanded event system.

Propagation loop cannot be totally avoided. When a field is not only read but also written in a handler, enabling the automation in this handler might cause a propagation loop. In current design of RDJ, the compiler can avoid such a case by excluding a handler from the involved events for itself. For example, even if the updateA in Fig. 6 is modified to:

```
public void updateA() { a += b + c; }
```

enabling the automation does not bind updateA to itself. In this case the intention is clear since an update is not expected to trigger itself again. However, if two handlers are set to trigger each other, it is hard to know the programmers' intention. For example, suppose that we have one more method slot named updateB in the class Sheet in Fig. 6:

```
public void updateB() { b = a + c; }
```

and the automation in updateA and updateB are both enabled. When updateA is called, an endless loop will happen. In modern spreadsheet programs such circular reference can be detected and a warning will be shown. However, in programming it is hard to detect such propagation loops until runtime. A static analysis of the dependencies between fields should help detect endless loops, but a loop might only appear depending on certain conditions at runtime. This issue also happens in FRP languages, and might remind readers of the advice loops in AspectJ. What RDJ currently supports is similar to applying the concept of !cflow(adviceexecution()) in AspectJ to handlers. A more generic solution to this issue might be introducing execution levels [32] to reactive programming.

5. Evaluation

Since in Section 4.3 the usability of such an expanded event system has been shown by rewriting the motivating example, in this section we further translate complex use cases of signals to evaluate its capability. A qualitative analysis of comparing it with the original event system and the predicate pointcuts in AOP is included as well. Before that, we go through the RDJ compiler implementation to explain how it works, and measure the impact of introducing the automation to DJ.

5.1 The Implementation of RDJ

The RDJ compiler [*3] transforms RDJ code into plain Java code and then compiles into Java bytecode as what the DJ compiler does. In the DJ compiler, a method slot is implemented by an array of closures with the methods for calling the closures in the array, adding a closure to the array, and removing closures from the array. For example, the following binding:

```
this.updateA += o.update;
```

is transformed into the following statement in Java:

```
this.updateA$after(c);
```

where c is a closure calling o.update. It means appending the closure c to the end of the array for the method slot this.update. The RDJ compiler implementation is based on the DJ compiler implementation and the semantics shown in Fig. 7, but the selection of method slots is split into compile-time and runtime in order to improve the runtime performance. At compile-time for every method slot the compiler collects the writer method slots according to its default closure and generates a helper method that binds a given closure to all the writer method slots. Furthermore, using the braces operator on a method slot is transformed to calling the helper method for that method slot. Then at runtime the corresponding helper method is called according to the actual type of the owner object to collect method slots and bind the given closure to them. Note that a method slot is owned by every instance. It is not shared among the instances of the same class.

Taking the example of Fig. 10 (c), the following helper method is generated for using the braces operator with the += operator on the method slot updateA:

```
public void updateA$helper$after(Closure closure) {
  if(a != null)  a.setValue$helper$after(closure);
  if(b != null)  b.getValue$helper$after(closure);
  if(c != null)  c.getValue$helper$after(closure);
}
```

No method slots are directly selected in this helper method since the fields a, b, and c, which are read by updateA, are not written by any method slot in the owner object. However, the method slots a.setValue, b.getValue, and c.getValue are called in updateA, so that the given closure is passed to the helper methods for them recursively. The body of the helper method setValue$helper$after is empty since no fields are read in setValue of IntCell as shown in Fig. 11. On the other hand, the helper method getValue$helper$after looks like this:

```
public void getValue$helper$after(Closure c) {
  setValue$after(c);
}
```

The method setValue$after is a method for appending a closure to the array of the method slot setValue, which has been generated in the DJ compiler. Note that the helper methods setValue$helper$after and getValue$helper$after are declared in IntCell. After generating the helper methods the compiler transforms the following binding:

```
{_} += this.updateA();
```

into the call to the helper method:

```
this.updateA$helper$after(c);
```

[*3] The prototype compiler of RDJ is built on top of DJ and JastAddJ [11], and available from https://github.com/csg-tokyo/rdominoj

```
procedure transform($O$, $M$, $C$) {
  $A$ = the apparent type of class of $O$;
  procedure $generate\_helper$($A$, $M$, $C$) {
    $\overline{S_A}$ = All the super classes of $A$ including $A$;
    $D$ = the default closure of $M$ declared in $A$;
    $\overline{f}$ = the fields which are read in $D$
            AND declared in any of $\overline{S_A}$;
    $\overline{m}$ = the method slots which write any of $\overline{f}$
            AND are declared in any of $\overline{S_A}$;
    $\overline{M'}$ = the method slots called in $D$
            AND belong to the objects held in the fields of $O$;
    $H$ = method($C$) {
              add $C$ to the array of $\overline{m}$;
              execute $\overline{H_{M'}(C)}$;
          };
    declare $H$ in $A$;
  }
  ∀ subclasses $\overline{A'}$ of $A$ do $generate\_helper$($A'$, $M$, $C$);
  replace "{$O$.$M$} += $C$" with "$O$.$H$($C$)";
}
```

Fig. 20 How the compiler transforms a binding with the braces operator.

where c is an anonymous class which extends the Closure interface of DJ and calls this.updateA(). Therefore, at runtime the helper method updateA$helper$after is called for collecting all method slots and binding the closure c to them. Note that for all subclasses of PlusSheet that override updateA and all subclasses of IntCell that override getValue and setValue, the compiler generates helper methods for them individually, so that the corresponding helper method can be called on the object according to the actual type of the object; the dynamic method dispatch in Java is preserved. Note that in order to simplify the implementation the RDJ compiler generates helper methods for every method slot in every class. Furthermore, the calls to a method slot that is not compiled by RDJ are not recursively inferred.

How the RDJ compiler generates helper methods is described in **Fig. 20**. What the procedure generate_helper does is basically the same as the semantics shown in Fig. 7, but the compiler generates helper methods for all subclasses of the apparent type of the given object. The procedure generate_helper adds (suppose that += operator is used) the given closure to collected method slots immediately rather than returns the set of collected method slots. The proper helper method can be selected by the dynamic method dispatch in OOP. As a consequence, if a method slot is selected in both different helper methods, it is difficult to avoid binding to the same method slot twice.

A limitation of this implementation is the changes of objects. The object referred to by a field might be changed after the binding is performed. In that case, the handler is still bound to the previous object rather than the new one. Such usage is not recommended since it is hard to trace. For example, suppose that there is a setter method slot setB for b in Fig. 10 (c) and at first the object held by the field b is O_b. Then the method slots selected by the braces operator in Line 16 of Fig. 10 (c) include the setB on p and the setValue on O_b. When the object held by b is changed to another object $O_{b'}$ by calling the setB on p, the handler updateA() will be executed and thus has a chance to check if the object held by b is the same. However, the handler is still bound to the setValue on O_b rather than the one on $O_{b'}$. A possible work-around is to prepare two additional handlers: one for unbinding the handler updateA() from O_b before setB is called, and one for rebinding the handler updateA() to $O_{b'}$ after setB is called, either by the compiler or by programmers themselves.

A more powerful implementation is possible. As we explained above the braces operator in the current version of the RDJ compiler only takes the default closure into account due to the performance concern. In this implementation, only the default closure is inferred for a method slot given to the braces operator. It is possible to infer all the closures added to the given method slot at runtime if we implement reflection API for method slots. However, in such an implementation all the selection must be done at runtime and the performance will not be good. Another solution is to generate helper methods for all the method slots that might be added to the given method slot. For example, if we use the braces operator on the method slot this.updateA as follows:

```
{this.updateA} += this.refresh();
```

and then append a closure calling another method slot logger.debug to this.updateA somewhere in the program:

```
this.updateA += logger.debug;
```

It might be possible to find out all the method slots like logger.debug, generate helper methods for them, and prepare a switch for calling every helper method in the event selection for {this.updateA}. If the statement for adding logger.debug is executed, switching on the call to the helper method for logger.debug. Then the events selected by logger.debug can also be selected when selecting the events for this.updateA. In other words, not only the default closure but also the closures calling other method slots in the given method slot are inferred for selecting the events. As a trade-off the whole program must be compiled together to find out all the method slots that might be added to the method slot given to the braces operator; separate compilation is not available. Such an implementation is more powerful since after using the assignment to add the closure calling a method slot, we do not have to use the braces operator for that method slot again as follows:

```
this.updateA += logger.debug;
  :
{this.updateA} += this.refresh();
{logger.debug} += this.refresh();
```

Instead, we can:

```
this.updateA += logger.debug;
  :
{this.updateA} += this.refresh();
```

In the latter one we do not have to apply the braces operator again for this.refresh. Some readers might notice that investigating all closures in a method slot can further improve the modularity when using the braces operators along with event-driven programming or AOP, though it might be a little slower and disable the separate compilation. In this paper we only implement the simple one that infers the default closure for showing such an extension to method slots is possible. Implementing such a powerful one that infers all the closures in the method slot is included in our future work.

5.2 Preliminary Microbenchmarks

To measure the impact of enabling the automation in method slots we can consider only the inference overheads since a binding using the braces operator is eventually boiled down to the bindings that are manually enumerated in DJ. For example, the binding in Line 16 of Fig. 10 (c) is boiled down to the following

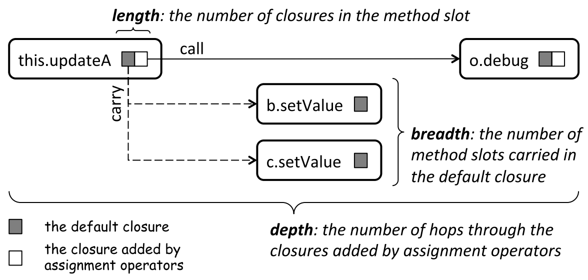

length: the number of closures in the method slot
this.updateA
call
o.debug
carry
b.setValue
c.setValue
breadth: the number of method slots carried in the default closure
the default closure
the closure added by assignment operators
depth: the number of hops through the closures added by assignment operators

Fig. 21 The metrics for measuring the impact.

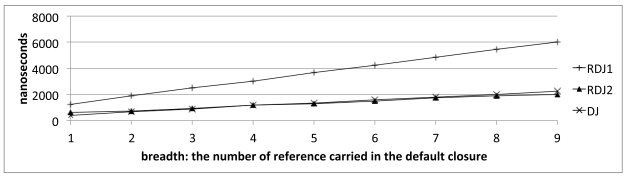
bindings by inference:

```
b.setValue += this.updateA();
c.setValue += this.updateA();
```

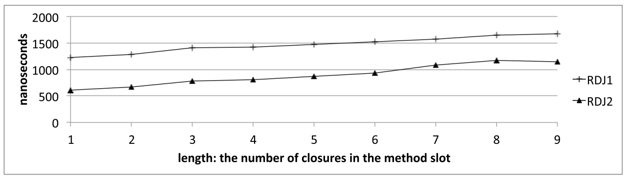
The cost of these bindings in RDJ is the same as in DJ except that a closure must be dynamically created to hold the arguments passed to the handler. Since the arguments passed to the handler might be non-literal and thus need to be dynamically evaluated, it is not able to create the closure in advance. A way to avoid the additional overheads is to prohibit programmers from giving non-literal arguments to the handler. In the following preliminary microbenchmarks we compare the two implementations to separate the overheads of creating the handler closure from the inference overheads: RDJ1 always creates the handler closure while RDJ2 does not, though in both cases no arguments are given. The three metrics we use to measure the impact of the inference are shown in **Fig. 21**. We bind and then unbind a method slot to the involved events of another method slot one million times to get the average. The results of running the microbenchmarks on OpenJDK 1.7.0_65 with Intel Core i7 2.67GHz 4 cores and 8GB memory are shown in **Fig. 22**. Note that the DJ compiler was version 0.2 taken from DominoJ project web site, and the result shown in each graph includes the time of performing a binding and an unbinding. Figure 22 (a) shows that binding and then unbinding the same number of method slots in RDJ1 always takes three times as long as in DJ. On the other hand, the performance of RDJ2 is very close to DJ; the inference overheads are negligible and do not grow with the breadth. The difference can be considered as the overheads of creating the handler closure. In Fig. 22 (b) we inserted a number of closures that call a method slot whose default closure carries no reference to measure the overheads of iterating a closure. The result is linear and shows that the average of iterating a closure carrying nothing is about 30ns in both RDJ1 and RDJ2. In Fig. 22 (c) the only method slot is selected through a number of method slot calls. Similarly, the result is also linear in both implementations, and shows the overheads of traversing an object are about 217ns. To benefit from both the implementations the current version of RDJ compiler allows arbitrarily giving arguments, but automatically optimizes when no arguments need to be evaluated; the impact is not significant. Furthermore, the inference overheads only appear in binding or unbinding a handler.

5.3 Translation Examples

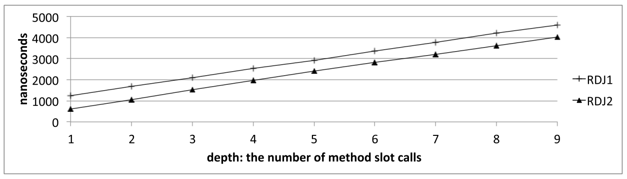
We have shown typical translation examples of signals, but it might be interesting to check if it is possible to translate complex use cases such as the examples given in the REScala paper [30]. REScala is a hybrid event system that supports both events and



(a) breadth



(b) length



(c) depth

Fig. 22 The three microbenchmarks.

```
val age = new Var(0)
val size = new Var(1)
val canLive: Signal[Boolean] = Signal {
  (age()<=maxAge) && (size()<=3000) && (size()>=1)
}
evt shouldDie = canLive.changed && !canLive() || killed
```

(a)

```
int age = 0;
int size = 1;
boolean canLive = true;
boolean updateCanLive() {
  canLive = (age<=maxAge) && (size<=3000) && (size>=1);
  return !canLive;
}
boolean shouldDie() { return $retval; };
// then within the body of a method slot
{_} += this.updateCanLive();
this.updateCanLive += this.shouldDie;
this.killed += this.shouldDie;
```

(b)

Fig. 23 Rewriting the changed example (a) to (b).

signals, and provides conversion API as primitives for complex usage of signals. Translating such complex use cases in REScala to RDJ not only evaluates the feasibility of the extension we proposed in Section 3 but also gives a good understanding of such kinds of primitives for signals.

The signals and primitives given in REScala can be lowered to fields, method slots, and bindings in RDJ according to the following translation rules. A Var is translated to a field with the same type. A Signal is translated to a field and a method slot (handler), and the automation for that method slot should be enabled if any Var or Signal is used in the signal assignment. An evt (event) is translated to a method slot that is bound to all the events given in the event declaration by using operator +=. In general, one line for declaring a Signal in REScala will be translated to three lines in RDJ, and one line for declaring an evt in REScala will be translated to at least two lines in DJ and RDJ. For a Signal, RDJ needs one line for declaring a field, one line for declaring a method slot for updating the value in the field, and one line for enabling the automation in the method slot. For an evt DJ and RDJ need one line for declaring a method slot and at least one line for

```
1 evt click: Event[(Int, Int)] = mouse.click
2 val circle: Var[(Int, Int),Int] = Var((1,1),10)
3 val lastClickOnCircle: Signal[Boolean] = Signal{
4   over(click.hold(), circle())
5 }
```

(a)

```
1  void click(Point p);
2  Circle circle = new Circle(new Point(1,1), 10);
3  Point holdClick = new Point(0,0);
4  void updateHoldClick() { holdClick = p; }
5  boolean lastClickOnCircle = false;
6  void updateLastClickOnCircle() {
7    lastClickOnCircle = over(holdClick, circle);
8  }
9  // then within the body of a method slot
10 mouse.click += this.click;
11 this.click += this.updateHoldClick;
12 {_} += this.updateLastClickOnCircle();
```

(b)

Fig. 24 Rewriting the hold example (a) to (b).

```
1 evt click: Event[(Int, Int)] = mouse.click
2 var nClick: Signal[Int] = click.fold(0)( (x, ) => x+1 )
```

(a)

```
1 void click(Point p);
2 int nClick = 0;
3 void updateNClick(Point p) { nClick++; }
4 // then within the body of a method slot
5 mouse.click += this.click;
6 this.click += this.updateNClick;
```

(b)

Fig. 25 Rewriting the fold example (a) to (b).

binding; if there are more than one event given at the right-hand side of the event declaration, more bindings are needed for event composition.

The first example we are going to check is the direct conversion from a signal to an event as shown in **Fig. 23** (a). Note that the signal canLive in Lines 3–5 of (a) is translated to the field canLive, the method slot updateCanLive, and the binding for enabling the automation in updateCanLive as shown in Lines 3–7,10 of (b); the event shouldDie in Line 6 of (a) is translated to the method slot shouldDie [*4] and the bindings for it as shown in Lines 8,11–12 of (b). The function changed used in Line 6 of (a) is a primitive used to convert the signal canLive to an event, which is exactly the call to the handler updateCanLive in (b) since changed means the event when the given signal is updated. Such a REScala code can be translated to RDJ code step by step, though the lexical representation tends to be a little longer. The next example is shown in **Fig. 24** (a), where the function hold is a primitive for converting an event to a signal. Here how to translate click, circle, and lastClickOnCircle (Lines 1–3) is the same as the steps in the previous example. However, click.hold() in Line 4 is an anonymous signal converted from the event click, so that we need an extra field holdClick and an extra method slot updateHoldClick for updating holdClick as shown in Lines 3–4 of Fig. 24 (b). Furthermore, we need an extra statement that binds updateHoldClick to the event click (Line 11) since function hold means updating the value of the anonymous signal when the given event occurs. The third example is function fold as shown in **Fig. 25** (a), which is a primitive used to perform stateful conversion of events to signals. The function fold in Line 2 takes an initial value 0 and a function that is used to evaluate the value of the signal nClick when the event click occurs. In this case, the function taken by fold is exactly the handler for updating the field nClick—the method slot updateNClick in Line 3 of Fig. 25 (b). Furthermore, the event at the left-hand side of fold, click, is the event that updateNClick must be bound to as shown in Line 6 of (b). The last example we want to discuss here is function snapshot, which is a primitive introduced to integrate signals into event-driven computations. In Line 3 of **Fig. 26** (a) function snapshot returns a signal to lastClick whose value is updated according to the value of another signal position when the given event clicked occurs. In RDJ, it means assigning the value of position to lastClick when the event clicked occurs. Thus, what we need to do is to set the value of position to lastClick in the body of updateLastClick as shown in Line 5 of (b) and bind updateLastClick to the event clicked (Line 9 of (b)).

[*4] The keyword $retval in DJ is used to get the value returned by the previous closure in the same method slot.

```
1 evt clicked: Event[Unit] = mouse.clicked
2 val position: Signal[(Int,Int)] = mouse.position
3 val lastClick: Signal[(Int,Int)] = position snapshot clicked
```

(a)

```
1 void clicked();
2 Point position = new Point(0,0);
3 void updatePosition() { position = mouse.position; }
4 Point lastClick = new Point(0,0);
5 void updateLastClick() { lastClick = position; }
6 // then within the body of a method slot
7 mouse.clicked += this.clicked;
8 {_} += this.updatePosition();
9 this.clicked += this.updateLastClick();
```

(b)

Fig. 26 Rewriting the snapshot example (a) to (b).

To conclude, these complex use cases of signals in REScala can be translated to RDJ code step by step according to the translation rules we explained above. It might give a clear understanding of such primitives for signals since the RDJ code shows how to describe them in an event system where the signal notation is not given. It also shows the automation we proposed is sufficient even in these complex use cases and then the primitives for signals can be simply translated to handler bindings. Although the number of lines of code in RDJ is increased, it can be expected and does not explode; it is generally two or three times as long as in REScala. Note that the drawback that the binding in RDJ is not declarative is not a limitation of the extension proposed in Section 3 but the limitation of DJ. As a consequence of allowing the addition or removal of closures in a method slot at runtime, the binding must be a statement within the body of a method slot rather than a declaration.

5.4 Comparing with the Original Event System

Using the braces operator to select events can avoid binding to all involved events explicitly. The merits include writing the dependency among events only once, improving the encapsulation, and simplifying the event propagation. On the other hand, if only parts of events need to be selected, it is not proper to use the braces operator. In such a case, binding a handler to the events selected by the braces operator will cause unnecessary event propagation. In this subsection we compare with DJ since it is the original event system that RDJ is based on. Comparing RDJ with other event systems such as EScala might be possible, but it is not easy to see the consequence of using the brace operator due to the difference between them and DJ.

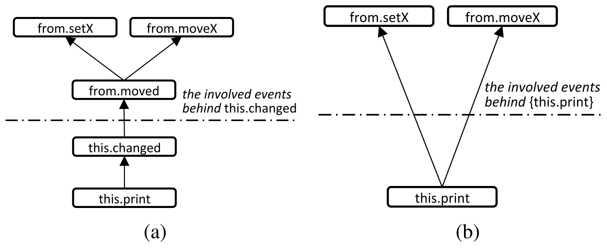


Fig. 27 The difference on the event propagation constructed by DJ and RDJ.

Write the dependency once. The dependency among events in a typical event mechanism is usually described twice. As shown in Fig. 10 (b), once for calculating values (Line 22) and once for making it automatic (Line 16–17). In other words, for each dependency programmers have to maintain it in two places. In RDJ the bindings for all dependencies in a method slot are reduced to a binding to the higher-level event, so that the number of lines of source code can be smaller. The maintainability can also be improved since we do not have to ensure the consistency between the binding and the calculation. The binding to a method slot with the braces operator is always the same no matter how the source code for the calculation is modified.

Improve the encapsulation. The inference mechanism in RDJ improves the encapsulation of a class. Some readers might notice that in Fig. 10 (c) it is also possible to write the following statement in the body of main rather than the binding in Line 16:

```
{_} += p.updateA();
```

The braces operator improves the encapsulation of a class since using the braces operator can bind a handler to the events inside the object without directly touching the fields in that object. The fields in the class can be observed through getter methods and the observers can be unaware of the implementation of the class. In this example the fields of PlusSheet, i.e. a, b and c, and the field in IntCell, i.e. value, do not have to be exposed by declaring as public while they still can be observed outside. In other words, the fields do not have to be public and the clients can be oblivious to the implementation details of PlusSheet.

Simplify the event propagation. It is also possible to simplify the event propagation since the handler is directly bound to the selected method slots through the fields behind the higher-level event. **Figure 27** (a) shows parts of the dependency graph of Fig. 18 (a). When from.setX or from.moveX is executed, from.moved and this.changed will be triggered in order and then cause the execution of this.print. However, with the automation the propagation is simpler. Figure 27 (b) shows the bindings eventually performed by the RDJ compiler. In other words, the event propagation in a typical event mechanism is reduced to one step.

Unnecessary event propagation. In some special cases, using the braces operator to select events for binding might cause unnecessary event propagation. For example, suppose that in the sheet example we only want to update a when b is changed:

```
a = b + c;
```

However, using the braces operator on updateA in Line 18–20 of Fig. 1 (c) will select the events for both b and c. On the other hand, in the DJ version it is obvious that programmers can configure them since the bindings are manually enumerated (Line 16–18 of Fig. 1 (b)). Similarly, in the shape and meter example

```
public aspect Update {
    :
  pointcut moved(Point p):
    (set(int Point.x) || set(int Point.y))
    && target(p);
  after(Point p): moved(p) {
    System.out.println("x=" + p.getX() + ", y=" + p.getY());
  }
}
```

Fig. 28 Selecting events for printing two fields in AspectJ.

```
public class Update {
  Point p;
    :
  public Update() {
      :
    {_} += this.print();
  }
  public void print() {
    System.out.println("x=" + p.getX() + ", y=" + p.getY());
  }
}
```

Fig. 29 Selecting events for printing two fields in RDJ.

(Fig. 16), it is not able to select only events for x but not y, or to select event moveX but not event setX. This consequence is the same in FRP languages since all variables are signals. As we discussed in the previous subsection, REScala can satisfy this need by providing both Var and Signal: Var is for normal variables and Signal is for signals. In RDJ, using the braces operator can be considered as converting all fields read in a method slot to signals. Therefore, if this is not desirable, programmers have to properly separate those field accesses from the method slot taken by the braces operator or manually enumerating the bindings as in DJ. That is why we propose expanding the original event system rather than a new system; both the implicit style in FRP and the explicit style in the original event system are supported.

5.5 Comparing with the Predicate Pointcuts in AOP

The inference of the braces operator in RDJ can be regarded as some sort of predicate. However, it is differnt from the predicate pointcuts in AOP since the braces operator takes a handler body as a hint rather than describing which events should be selected. We can regard event composition as merging multiple sources to a sink; the sources are lower-level events and the sink is the higher-level event. In that sense, the predicate pointcuts in AOP is used to describe the sources while the braces operator in RDJ takes a sink as the hint to infer the sources. For example, a statement in reactive programming that prints the values of two signals x and y (we simply assume that they are variables in a Point object due to the difference between functional-reactive languages and OO languages) can be rewritten using AspectJ as shown in **Fig. 28**. The write access to the fields x and y are selected by set pointcut. Then predicate pointcuts such as target and within can be used to further select the join points. The RDJ version is shown in **Fig. 29**. We can move advice body to a method slot and enable its automation by using the braces operator. The RDJ version is very implicit while needs a method slot body for inferring which events to select.

As an extension to AspectJ, there are also research activities devoted to pointcuts for doing similar things as the braces operator. Dataflow pointcuts [20] are proposed to trap join points according to dataflow. It can be used with other kinds of pointcuts to address the origins of values between join points. However, the implementation for Java-like languages is not trivial. A successive work [1] showed a formal and practical framework that statically propagates dataflow tags to trace data dependencies. On the other hand, RDJ traces method call chains rather than low-level dataflows, so the implementation is simpler and feasible in Java.

6. Related Work

In the world of events, more and more techniques are introduced to make events more powerful and expressive. For example, Ptolemy [28] supports quantification and type for events, EventJava [14] considers event correlation, and EScala [15] discusses implicit events found in AOP. However, such advanced event systems still lack the implicit style in reactive programming. Other research activities such as Frappé [8] and SuperGlue [21] can be regarded as examples of using events and signals together since they use signals in specific components. The signals are considered as objects' properties. This approach allows using signals in a limited scope at language level for a specific usage.

Other examples of using events along with signals include the library approach such as Flapjax [22]. This approach makes it easy to use signals in existing languages since signals are represented by existing elements in the languages. There are also several libraries developed for the reactive support in collections. The incremental list in Scala.React [18] is a functional-reactive data structure for Scala [26], which can automatically propagate incremental change. Although in such libraries signals might be implemented through events underneath, the involved events cannot be automatically inferred. Programmers need to manually specify which fields or variables are signals in order to ask the underneath to create handler bindings properly.

Unlike the research activities mentioned above that introduce the signals in FRP to make event propagation implicit, ReactiveX [29] enhances the Observer pattern with regard to concurrency and error handling by proposing an API for asynchronous programming and is implemented as a library in several platforms and languages: Rx.NET [23] is a library on .NET for writing asynchronous and event-based programs with LINQ, and RxJava [24] is the implementation for Java VM. Although those extensions to event systems are named with the term reactive, what they provide is asynchronous handling rather than implicit propagation. ReactiveX helps programmers to react to the events for data items in a collection without blocking, and prevent from writing tangled callbacks. On the other hand, with our proposal programmers can avoid manually enumerating events and bindings, and thus make event propagation as implicit as using signals in FRP languages. In a certain sence, ReactiveX is a broad enhancement on event handling, while our proposal is a deep enhancement with regard to event propagation.

7. Conclusion

We analyzed the essentials of reactive programming from the viewpoint of event-driven programming, and pointed out the need of implicit binding in existing event systems. To satisfy this need we proposed an extension that enables the *automation* of handler bindings to support the implicit style in reactive programming. Then we gave an implementation to show the feasibility of such an extension. Although the implementation is a prototype that has several limitations, it showed the advantages over the event system without the *automation*. The design decisions and limitations happening when implementing the extension on OO languages are discussed as well.

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YungYu Zhuang received his Ph.D. degree in information science and technology from the University of Tokyo in 2014. Currently he serves as Project Research Associate in the University of Tokyo, and will be Assistant Professor at National Central University from August 2016. His research interests include programming language design and software engineering.

Shigeru Chiba is Professor at the University of Tokyo. Before starting his current position, he worked at Tokyo Institute of Technology and University of Tsukuba. He received his Ph.D. in science in 1996 from the University of Tokyo. His research interests are in programming language design and implementation.