

Directing JavaScript with Arrows

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Abstract

JavaScript programmers make extensive use of event-driven programming to help build responsive web applications. However, standard approaches to sequencing events are messy, and often lead to code that is difficult to understand and maintain. We have found that *arrows*, a generalization of *monads*, are an elegant solution to this problem. Arrows allow us to easily write asynchronous programs in small, modular units of code, and flexibly compose them in many different ways, while nicely abstracting the details of asynchronous program composition. In this paper, we present Arrowlets, a new JavaScript library that offers arrows to the everyday JavaScript programmer. We show how to use Arrowlets to construct a variety of state machines, including state machines that branch and loop. We also demonstrate how Arrowlets separate computation from composition with examples such as a drag-and-drop handler and a bubblesort animation.

Categories and Subject Descriptors D.2.2 [Software Engineering]: Design Tools and Techniques—Software libraries; D.1.1 [Programming Techniques]: Applicative (Functional) Programming

General Terms Design, Languages

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1. Introduction

JavaScript [Flanagan 2006, Crockford 2008] is the *lingua franca* of Web 2.0. With JavaScript code running in a client-side browser, applications can present a rich, responsive interface without unnecessary delays due to server communication. Most JavaScript programs are written in an event-driven style, in which programs register callback functions that are triggered on events such as timeouts or mouse clicks. A single-threaded event loop in the web browser dispatches the appropriate callback when an event occurs, and control returns to the loop when the callback completes.

To keep web applications responsive, it is crucial that callbacks execute quickly so that new events are handled soon after they occur. Thus to implement non-trivial features like long-running loops (e.g., for animations) or state machines (e.g., to implement drag-and-drop), programmers must chain callbacks together—each callback ends by registering one or more additional callbacks. For example, each iteration of a loop would end by registering the current

callback with a (short) timeout. Unfortunately, this style of event-driven programming is tedious, error-prone, and hampers reuse. The callback sequencing code is strewn throughout the program, and very often each callback must hard-code the names of the next events and callbacks in the chain.

To combat this problem, many researchers and practitioners have developed libraries to ease the construction of rich and highly interactive web applications. Examples include jQuery (jquery.com), Prototype (prototypejs.org), YUI (developer.yahoo.com/yui), MochiKit (mochikit.com), and Dojo (dojotoolkit.org). These libraries generally provide high-level APIs for common features, e.g., drag-and-drop, animation, and network resource loading, as well as to handle API differences between browsers. While these libraries do support a number of common scenarios, even slight customizations may be impossible to achieve without modifying the library internals.

In this paper, we describe *Arrowlets*, a new JavaScript library for *composable* event handling. Arrowlets is designed to be lightweight, and supports much easier reuse and customization than the approaches mentioned above. Arrowlets is based on *arrows*, a programming pattern closely related to monads [Hughes 2000], which are used extensively in Haskell. An arrow abstraction resembles a normal function, with the key feature that arrows can be composed in various ways to create new arrows. With Arrowlets, the code for handling events is clearly separated from the “plumbing” code required to chain event handlers together. This makes code easier to understand, change, and reuse: the flow of control is clearly evident in the composition of handlers, and the same handlers can be chained in different ways and set to respond to different events. Other approaches to enabling more modular and reusable JavaScript code have also been explored in the literature, e.g., Flapjax [Meyerovich et al. 2009], which is based around functional reactive programming [Wan and Hudak 2000]. Arrowlets offer a complementary approach that may be more similar to existing JavaScript programming style while still offering the benefits of separating computation from composition.

In the remainder of the paper, we begin by illustrating the standard approach for event-driven programming in JavaScript, along with its difficulties. Then we introduce our basic approach to allaying these difficulties using Arrowlets. We next scale up to include richer combinators and present several examples. We conclude by comparing our work to related approaches. We believe that Arrowlets provides JavaScript programmers a flexible, modular, and elegant way to structure their programs. The Arrowlets library, as well as several live examples, is freely available at <http://www.cs.umd.edu/projects/PL/arrowlets>.

2. Event Programming in JavaScript

In modern web browsers, JavaScript is implemented as a single-threaded programming language. This is a real problem for web developers, because the browser’s JavaScript interpreter typically

runs in the main UI thread. Thus a long-running script could stall a web page (and browser), making it appear unresponsive.

To solve this problem, JavaScript programmers make heavy use of *event-driven programming*, writing programs that register asynchronous callbacks to handle UI interactions and to break up long-running tasks. For example, the following program¹ registers the `clickTarget` callback on the HTML element named `target`, and will be called each time `target` is clicked:²

```
function clickTarget (evt) {
  evt.currentTarget.textContent = "You clicked me!";
}
document.getElementById("target")
  .addEventListener("click", clickTarget, false);
```

Events are also used to slice long-running loops into small tasks that quickly return control to the UI. For example, the following program scrolls a document one pixel at a time until the document can be scrolled no further. The call to `setTimeout` schedules a call to `scrollDown(el)` to occur *0ms* in the future:

```
function scrollDown(el) {
  var last = el.scrollTop++;
  if (last !== el.scrollTop)
    setTimeout(scrollDown, 0, el);
}
scrollDown(document.body);
```

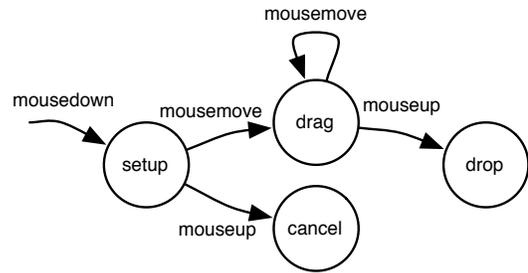
We can think of `scrollDown` as a state machine. In the initial state, it tries to scroll one pixel, and then either transitions to the same state (if the scroll succeeded) or to an accepting state (if scrolling is complete). The `scrollDown` function implements a very simple state machine with only one handler, and as such is easy to write. Chaining handlers together to implement more complicated state machines can be more difficult, as we show next using drag and drop.

2.1 Standard Drag-and-Drop

Consider the problem of supporting drag-and-drop in a web browser. Figure 1(a) gives a state machine showing the sequencing of event handlers we need for this feature. We begin with a `mousedown` event on an item of interest and transition to the `setup` state. From there, we cancel drag-and-drop if the user releases the mouse (`mouseup`), or start the drag for real on a `mousemove`. The user can keep dragging as much as they like, and we drop when the mouse button is released. In each of these states, we need to do various things, e.g., when we (re-)enter the `drag` state, we animate the motion of the selected object.

The standard approach to implementing this state machine is shown in Figure 1(b). Each function corresponds to one state, and mixes together “plumbing”, i.e., the state transition code, to install and uninstall the appropriate event handlers and “action” code to implement the state’s behavior. For example, we install the `setup` function to handle the `mousedown` event on line 27. When called, `setup` uninstalls itself and adds handlers to transition to the `drag` and `cancel` states (lines 3–5), and then carries out appropriate actions (line 6).

Even though this code has been distilled down to only the control flow, it is not that easy to understand. The flow of control is particularly convoluted: each event handler ends by returning, but the actual control “continues” indirectly to one of several subsequent



(a) State machine

```

1 function setup(event) {
2   var target = event.currentTarget;
3   target.removeEventListener("mousedown", setup, false);
4   target.addEventListener("mousemove", drag, false);
5   target.addEventListener("mouseup", cancel, false);
6   /* setup drag-and-drop */
7 }
8 function drag(event) {
9   var target = event.currentTarget;
10  target.removeEventListener("mouseup", cancel, false);
11  target.addEventListener("mouseup", drop, false);
12  /* perform dragging */
13 }
14 function drop(event) {
15   var target = event.currentTarget;
16   target.removeEventListener("mousemove", drag, false);
17   target.removeEventListener("mouseup", drop, false);
18   /* perform dropping */
19 }
20 function cancel(event) {
21   var target = event.currentTarget;
22   target.removeEventListener("mousemove", drag, false);
23   target.removeEventListener("mouseup", cancel, false);
24   /* cancel drag-and-drop */
25 }
26 document.getElementById("dragtarget")
27   .addEventListener("mousedown", setup, false);
```

(b) Standard JavaScript implementation

Figure 1: Drag-and-drop in JavaScript

event handlers. Code reuse is also hard, because each event handler hard-codes its subsequent event handlers, and the side-effects of drag-and-drop are interspersed with the state transition code. For example, if we wanted to initiate drag-and-drop with a `mouseover` event, we would need to make a new copy of `setup` and modify only the state transition code.

2.2 Drag-and-Drop with Arrowlets

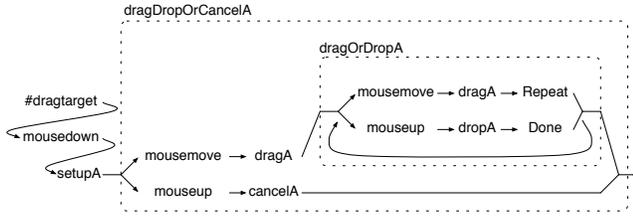
Event-driven programming in JavaScript does not have to be convoluted and monolithic: with Arrowlets, we can easily write event-driven code that is clean, understandable and reusable.

Figure 2(a) gives an *arrow composition diagram* outlining drag-and-drop with Arrowlets. It corresponds almost directly to the state machine in Figure 1(a), except we have indicated the target (`#dragtarget`) and written events as nodes. The two dashed boxes indicate portions of the composition we intend to reuse.

Figure 2(b) shows the complete implementation of drag-and-drop with Arrowlets. As before, we introduce four functions, `setupA`, `dragA`, `dropA`, and `cancelA`, to handle the respective drag-and-drop states. Each handler takes as input a *drag proxy* and the triggering event. The *drag proxy* wraps the actual target, and additionally implements four methods—`setupDrag`, `moveDrag`,

¹For brevity, the code as shown in this paper does not run in Internet Explorer due to minor API differences. The examples have been verified to work in Safari and Firefox.

²The last parameter to `addEventListener`, required by Firefox, selects the order of event handling, and can be ignored for this and all other examples in the paper.



(a) Arrow diagram

```

1  function setupA(proxy, event) {
2    proxy.setupDrag(event);
3    return proxy;
4  }
5  function dragA(proxy, event) {
6    proxy.moveDrag(event);
7    return proxy;
8  }
9  function dropA(proxy, event) {
10   proxy.dropDrag(event);
11   return proxy;
12  }
13 function cancelA(proxy, event) {
14   proxy.cancelDrag(event);
15   return proxy;
16  }
17
18 var dragOrDropA =
19   ((EventA("mousemove").bind(dragA)).next(Repeat))
20   .or((EventA("mouseup").bind(dropA)).next(Done))
21   ).repeat();
22
23 var dragDropOrCancelA =
24   ((EventA("mousemove").bind(dragA)).next(dragOrDropA))
25   .or((EventA("mouseup").bind(cancelA)));
26
27 var dragAndDropA = /* drag-and-drop */
28   (EventA("mousedown").bind(setupA))
29   .next(dragDropOrCancelA);
30
31 DragElementA("dragtarget").next(dragAndDropA).run();

```

(b) JavaScript implementation

```

32 DragElementA("dragtarget")
33   .next(EventA("mouseover").bind(setupA))
34   .next(dragDropOrCancelA)
35   .run()

```

(c) Alternative—setup on mouseover

```

36 (nextPieceA
37   .next(EventA("click").bind(setupA))
38   .next((dragOrDropA
39     .next(repeatIfWrongPlaceA)).repeat()
40   )
41   ).repeat()
42   .run()

```

(d) Jigsaw game re-using drag-and-drop elementary arrows

Figure 2: Drag-and-drop with arrows

dropDrag, cancelDrag. The bodies of these four methods correspond exactly to the code represented by lines 6, 12, 18, and 24 in Figure 1(b). Using proxy objects affords greater flexibility in customizing the side-effect of drag-and-drop, and is a standard trick found in many JavaScript libraries. For example, one drag-and-drop application could use a proxy that moves the target when

Combinator	Use
<code>f.AsyncA()</code>	lift function <code>f</code> into an arrow (called automatically by combinators below)
<code>h = f.next(g)</code>	<code>h(x)</code> is <code>g(f(x))</code>
<code>h = f.product(g)</code>	<code>h</code> takes a pair <code>(a,b)</code> as input, passes <code>a</code> to <code>f</code> and <code>b</code> to <code>g</code> , and returns a pair <code>(f(a), g(b))</code> as output
<code>h = f.bind(g)</code>	<code>h</code> calls <code>f</code> with its input <code>x</code> , and then calls <code>g</code> with a pair <code>(x, f(x))</code> .
<code>h = f.repeat()</code>	<code>h</code> calls <code>f</code> with its input; if the output of <code>f</code> is: <code>Repeat(x)</code> , then <code>f</code> is called again with <code>x</code> ; <code>Done(x)</code> , then <code>x</code> is returned
<code>h = f.or(g)</code>	<code>h</code> executes whichever of <code>f</code> and <code>g</code> is triggered first, and cancels the other
<code>h.run()</code>	begins execution of <code>h</code>

Table 1: Arrow combinators used by drag-and-drop.

dragged, while another could use a proxy that draws a trail behind the dragged target.

The remainder of Figure 2(b) assembles the drag-and-drop state machine from the handlers we have written. To do so, we use *combinators* to compose the handlers with the appropriate event triggers. These combinators compose *arrows*, which include regular functions or specialized event listeners that we provide, and describe serial and parallel combinations of arrows. Table 1 describes the arrow combinators we use to implement drag-and-drop; full details appear in Sections 3 and 4.

In Figure 2(b), we have split the composition into three pieces: `dragOrDropA`, `dragDropOrCancelA`, `dragAndDropA`. Each handler is connected to its triggering event using `bind`, and then connected to each other with other combinators. For example, the arrow `dragOrDropA` on lines 18–21 (shown in a dashed box in the part (a)) connects the drag state to itself (upon a `mousemove`) or to the drop state (upon `mouseup`).

Finally, the entire drag-and-drop composition is installed on the `DragElementA("dragtarget")` drag proxy on line 31. The arrow `DragElementA`, which we have elided, locates and returns the named HTML element wrapped in the proxy object that implements the animation of drag-and-drop.

Notice that the composition on lines 18–31 is simply a transliteration of the arrow diagram. We think this is a much more direct way to construct this event handling code than the standard approach we saw earlier, while retaining its basic computational structure. In particular, with Arrowlets the code implementing the effect of each handler is essentially unchanged; the difference is that hard-coded, indirect state transitions have been traded for more flexible, direct arrow compositions. Moving to a system like Flapjax, which uses an entirely different computational model, would require more pervasive changes [Meyerovich et al. 2009]. (See Section 5 for more discussion.)

Once we have used Arrowlets to separate `setupA`, `dragA`, `dropA`, and `cancelA` from each other and their event triggers, we can reuse them in different compositions of arrows. For example, Figure 2(c) shows an alternative drag-and-drop implementation that is initiated by a mouseover event, rather than a mousedown event.

We can even reuse the elementary arrows of drag-and-drop in a different application. Figure 2(d) shows the basic control-flow of a jigsaw puzzle game. One piece of the jigsaw puzzle is first displayed (line 36), picked up with a `click` event (line 37), and then moved with the cursor until being dropped by the mouseup event inside `dragOrDropA` (line 38). However, the piece may be automatically picked up again if it was dropped in the wrong place (line 39). And the whole composition repeats with the next

```

class Arrow a where
  arr :: (b → c) → a b c
  (>>>) :: a b c → a c d → a b d

instance Arrow (→) where
  arr f = f
  (f >>> g) x = g (f x)

```

(a) Arrows in Haskell

```

Function.prototype.A = function() { /* arr */
  return this;
}
Function.prototype.next = function(g) { /* >>> */
  var f = this; g = g.A(); /* ensure g is a function */
  return function(x) { return g(f(x)); }
}

```

(b) Function arrows in JavaScript

Figure 3: Two definitions of arrows

jigsaw piece. Re-using the code in Figure 1(b) to build this new structure would be non-trivial, while with Arrowlets, building such compositions is straightforward.

3. Implementation of Arrowlets

The design of Arrowlets is based on the concept of arrows from Haskell [Hughes 2000]. Arrows are generalizations of monads [Wadler 1992], and like them, they help improve *modularity*, by separating composition strategies from the actual computations; they are *flexible*, because operations can be composed in many different ways; and they help *isolate* different program concerns from one another.

We will first explain the concept of arrows with the simplest possible arrows, namely regular functions, and then build on it to describe how various components of the Arrowlets library are implemented in JavaScript.

3.1 Function Arrows

Figure 3(a) gives a (very) simplified definition of the *Arrow* type class in Haskell. A type *a* is an instance of *Arrow* (written *Arrow a*) if it supports at least two operations: *arr f*, which lifts function *f* into *a*, and *f >>> g*, which produces a new arrow in which *g* is applied to the output of *f*.

The simplest arrow instance, *Arrow (→)*, represent standard functions where *arr* is the identity function, and *>>>* is function composition. With these operations, we can compose functions using arrow operations:

```

add1 x = x + 1
add2 = add1 >>> add1

result = add2 1    {- returns 3 -}

```

Figure 3(b) shows function arrows in JavaScript. In JavaScript, every object has a *prototype* object (analogous to a class). Properties (e.g., methods) of an object are first looked up in the object itself, and if not found, are looked up in the object's prototype. JavaScript functions are themselves objects, and hence they have a prototype, named *Function.prototype*.

In Figure 3(b), we add two methods to every function object. The *A* method, corresponding to *arr*, lifts a function into an arrow. As in Haskell, the *A* method is just the identity. The *next* combinator, corresponding to *>>>*, composes two arrows by returning a

```

1 function CpsA(cps) {
2   this.cps = cps; /* cps :: (x, k) → () */
3 }
4 CpsA.prototype.CpsA = function() { /* identity */
5   return this;
6 }
7 CpsA.prototype.next = function(g) {
8   var f = this; g = g.CpsA();
9   /* CPS function composition */
10  return new CpsA(function(x, k) {
11    f.cps(x, function(y) {
12      g.cps(y, k);
13    });
14  });
15 }
16 CpsA.prototype.run = function(x) {
17   this.cps(x, function(y) { });
18 }
19 Function.prototype.CpsA = function() { /* lifting */
20   var f = this;
21   /* wrap f in CPS function */
22   return new CpsA(function(x, k) {
23     k(f(x));
24   });
25 }

```

Figure 4: CPS function arrows in JavaScript

new (anonymous) function invoking the composition. In this code, binding *f* to *this* sets *f* to refer to the object (i.e., function) whose *next* combinator is invoked. We also lift argument *g* to an arrow with the call *g.A()*. This check helps ensure that *g* is a function (all of which have the *A* method).

With these simple definitions, we can now compose functions as arrows in JavaScript in the same way as Haskell.³

```

function add1(x) { return x + 1; }
var add2 = add1.next(add1);

var result = add2(1);    /* returns 3 */

```

JavaScript lacks Haskell's sophisticated type system, so we unfortunately cannot statically ensure arrows are used correctly. For example, the definition in Figure 3(b) only works for single argument functions. Moreover, we may have different kinds of arrows that cannot be simply mixed together. Thus in practice (and in the examples below), we will introduce new prototypes to distinguish different kinds of arrows from each other.

3.2 CPS Function Arrows

Regular function composition will not work as a basis for event handling arrows because event handlers are invoked asynchronously, e.g., they are registered as callbacks with functions such as *addEventListener*. Instead, in Arrowlets we use *continuation passing style* (CPS) [Appel 1992], a well-known programming technique. We convert all functions to take a continuation parameter, which is akin to an event handler callback, and use CPS composition to compose regular functions and asynchronous functions.

Figure 4 shows how we use CPS in Arrowlets. A CPS function takes two arguments: the "normal" argument *x* and a continuation *k*, called with the function's final result. In the figure, *CpsA* (lines 1–3) constructs a CPS arrow from a *cps* function. In JavaScript, constructors are simply regular functions, and when we invoke

³Notice that we did not need to apply the *A* method to *add1*, because we have added the *next* combinator to all functions, thus implicitly making them arrows.

```

1 function SimpleEventA(eventname) {
2   if (!(this instanceof SimpleEventA))
3     return new SimpleEventA(eventname);
4   this.eventname = eventname;
5 }
6 SimpleEventA.prototype = new CpsA(function(target, k) {
7   var f = this;
8   function handler(event) {
9     target.removeEventListener(
10      f.eventname, handler, false );
11     k(event);
12   }
13   target.addEventListener(f.eventname, handler, false );
14 });

```

Figure 5: SimpleEventA for handling JavaScript listeners

`new CpsA(cps)`, JavaScript creates a new object and then initializes it by calling `CpsA(cps)` with `this` bound to the new object.

On line 4 we introduce our convention of giving `CpsA` objects an identity `CpsA` method, which we use like the `A` method from Figure 3(b): if we successfully invoke $x = x.CpsA()$, we know x is a CPS arrow. The `next` combinator is implemented using the CPS equivalent of function composition,⁴ invoking `f`, and passing in a continuation that invokes `g`, which itself continues with `k` (lines 7–15). We call a CPS arrow by invoking its `run` method (lines 16–18), which simply calls the function in the `cps` field with the actual argument and a do-nothing function that acts as the final continuation. Finally, we extend `Function`'s prototype with a `CpsA` method to lift a normal one-argument function into a CPS arrow. With this method, programmers using Arrowlets can write regular functions, and the details of CPS are effectively hidden.

With these definitions, we can convert our `add1` and `add2` functions to CPS and compose them:

```

function add1(x) { return x + 1; }
var add2 = add1.CpsA().next(add1.CpsA());

var result = add2.run(1);    /* returns 3 */

/* where: add1.CpsA().cps = function(x,k) { k(add1(x)); }
          add1.CpsA().next(add1.CpsA()).cps
          = function(x,k) { k(add1(add1(x))); } */

```

3.3 Simple Asynchronous Event Arrows

Building on CPS arrows we can now define simple event arrows, which are CPS functions that register their continuations to handle particular events. Ultimately we will want several forms of composition, but for now, we define an event arrow `SimpleEventA` that supports linear sequencing, shown in Figure 5.

In this code, the function `SimpleEventA` acts as a constructor, where line 3 implements a convenient JavaScript idiom. If the constructor is called as a regular function (i.e., without `new`), it calls itself again as a constructor to create a new `SimpleEventA` object. This allows us to omit `new` when using `SimpleEventA`. Line 4 stores the name of the event this arrow handles.

Lines 6–14 define the `SimpleEventA` prototype object to be a `CpsA` arrow constructed from an anonymous function. By making the prototype a `CpsA` object, `SimpleEventA` inherits all the properties of `CpsA`. The anonymous function installs the local function handler to be triggered on `eventname` (line 13). When this event fires, handler deregisters itself from handling that event, and then

⁴ JavaScript lacks tail-call optimization, so this simple definition of `next` can cause the call stack to overflow. Our actual implementation uses trampolines to avoid this issue.

invokes the continuation `k` with the received event. We chose to immediately deregister event handlers that have fired since this corresponds to transitions in a state machine, according to our motivating use case.

Examples Let us rewrite the very first example in Section 2 to use our simple event arrows. First we write a handler arrow for the event:

```

var count = 0;
function clickTargetA(event) {
  var target = event.currentTarget;
  target.textContent = "You clicked me! " + ++count;
  return target;
}

```

This function extracts the target of the event, updates its text, and then returns it (for the next event handler). To register this code to handle a single click, we write the following plumbing code:

```

SimpleEventA("click").next(clickTargetA)
  .run(document.getElementById("target"));

```

This code creates an event arrow for a `click` event (on the target element) and composes it with our handler arrow. When the event fires, `clickTargetA` is called with the event's target, and the event handler is removed. Also, in this code, the structure of event handling is quite apparent. And, because we have separated the plumbing from the actions, we can reuse the latter easily. For example, to count button clicks on another target, we just create another `SimpleEventA`, reusing the code for `clickTargetA` (the effect on `count` is shared by the two handlers):

```

SimpleEventA("click").next(clickTargetA)
  .run(document.getElementById("anotherTarget"));

```

If we want to track a sequence of events on the same target, we simply compose the handlers:

```

SimpleEventA("click").next(clickTargetA)
  .next( SimpleEventA("click").next(clickTargetA) )
  .run(document.getElementById("target"));

```

This code waits for one click, increments the count, and then waits again for a click, and increments the count once more. Sequential composition of asynchronous event arrows using `next` is associative, as expected, so we could equivalently write the above as

```

SimpleEventA("click").next(clickTargetA)
  .next(SimpleEventA("click"))
  .next(clickTargetA)
  .run(document.getElementById("target"));

```

Event arrows have another useful property in addition to easy composition: The details of different browser event handling libraries can be hidden inside of the arrow library, rather than being exposed to the programmer. For example, Internet Explorer uses `attachEvent` instead of `addEventListener`, and we could modify the code in Figure 5 to call the appropriate function depending on the browser.

4. Full Asynchronous Arrows

Now that we have developed simple event arrows, we can extend them with features for implementing more sophisticated examples, like drag-and-drop. To do this we need to introduce a number of arrows and combinators. We introduce these by example `next`, and defer a detailed description of their implementation to Section 4.2.

4.1 Arrows and Combinators

Asynchronous Event Arrows with Progress Previously, we introduced an arrow `SimpleEventA` for handling particular events. In practice, we want to support multiple arrows “in flight” at a time, e.g., in the setup state of drag-and-drop, we wait for multiple events at once. Thus we must be able to cancel an event handling arrow while it is active so that we can switch to another state.

Our solution is to create a new arrow `AsyncA`, which extends `CpsA` with support for tracking progress and cancellation. When an `AsyncA` is run, it returns a *progress arrow*, which can be used to observe or cancel execution of the arrow. We use `AsyncA` to build `EventA`, which similarly extends `SimpleEventA` with support for progress and cancellation. Using `EventA`, we can augment the two-click example from the prior section so that it returns a progress arrow `p`. We can then use `p` to affect the arrow in flight, e.g., to stop waiting for clicks after 10 seconds, as shown below.

```
var target = document.getElementById("target");
var p = EventA("click").next(clickTargetA)
    .next(EventA("click").next(clickTargetA))
    .run(target);
/* p can be used to abort the event arrow */

setTimeout(function() {
  p.cancel(); /* cancels event arrow */
  target.textContent = "Can't click this";
}, 10000);
```

We can also use `p` to track when an event begins:

```
var status = document.getElementById("status");
p.next(function() {
  /* called when event arrow finishes */
  status.textContent = "I've been clicked!";
}).run();
```

We can use progress arrows in combination with looping, described next, to build widgets like progress bars for long operations.

Looping with repeat() To support loops in state machines, such as the drag state in our drag-and-drop example, we provide a `repeat` combinator. The expression `f.repeat(t)` creates an arrow that puts `f` in a loop. If `f` returns `Repeat(x)`, then `f` is called again with `x` after `t` milliseconds have elapsed; otherwise if `f` returns `Done(x)`, then the loop completes and returns `x`.

As an example, we can use `repeat` to implement an animation of bubble sort:

```
var bubblesortA = function(x) {
  var list = x.list, i = x.i, j = x.j;
  if (j + 1 < i) {
    if (list.get(j) > list.get(j + 1)) {
      list.swap(j, j + 1);
    }
    return Repeat({ list: list, i: i, j: j + 1 });
  } else if (i > 0) {
    return Repeat({ list: list, i: i - 1, j: 0 });
  } else {
    return Done();
  }
}.AsyncA().repeat(100);

/* list is an object with methods get and swap */
bubblesortA.run({ list: list, i: list.length, j: 0 });
```

The arrow `bubblesortA` takes as input an object that contains three properties: the `list` to be sorted, and indices `i` and `j` representing the iteration state. Here, `list` is a proxy object with methods for looking up an element (`get`) and for swapping two elements (`swap`); these methods could be implemented to visualize the progress of sorting in the display.

The body of `bubblesortA` is a standard bubble sort, except instead of a `do-while` loop, we continue iteration by returning a `Repeat` object with updated values for `list`, `i`, and `j`, or we return `Done` when the loop is complete. We create the arrow by using the `repeat` combinator with an interval of `100ms` so that the bubble sort can be visualized slowly. We could also use a shorter interval for improved performance.

Parallel arrows with product() In addition to sequencing, the standard definition of arrows in Haskell includes combinators for parallel compositions. The `product` combinator (`***` in Haskell) takes two arrows and produces a new arrow that takes as input a pair, applies the constituent arrows to each component of the pair, and outputs the result in a pair. For `Arrowlets`, we additionally define the `product` combinator to execute concurrently and synchronize at the completion of both arrows.

Using the `product` combinator, we can extend the example at the end of Section 3.3 to respond only after the user clicks on two targets in any order. First, we modify `clickTargetA` to update two targets:

```
function clickTargetsA(target1, target2) {
  target1.textContent = "You clicked me!";
  target2.textContent = "And me too!";
}
```

Note that `Arrowlets` automatically unpacks a pair of targets into the argument list of `clickTargetsA`. We can then register this handler on two targets with the following plumbing:

```
(EventA("click").product(EventA("click")))
  .next(clickTargetsA)
  .run(Pair(document.getElementById("target1"),
            document.getElementById("target2")));
```

Now only after both targets are clicked on, which may be in any order, will the `clickTargetsA` handler be called to display the message.

Branching with Either-or() Our next addition to `AsyncA` is an “or” combinator that combines two asynchronous arrows and allows only one, whichever is triggered first, to execute. For example, this allows us to wait for a keystroke or a mouse movement, and respond to only one. An “or” combinator is necessary for supporting any branching state machine, as with drag-and-drop.

As an example, we demonstrate a simple coin-toss game implemented with `or` below. We first define `WriteA` to create an arrow that writes into an event’s target element. Then, we compose two arrows that respond to clicks in `heads` and `tails`. Finally, we combine the arrows with `or`, ensuring that the player can only click once, on either `heads` or `tails`.

```
function WriteA(str) {
  return function(event) {
    var target = event.currentTarget;
    target.textContent = str;
    return target;
  };
}
```

```
var heads = ConstA(document.getElementById("heads"));
var tails = ConstA(document.getElementById("tails"));

(heads.next(EventA("click")).next(WriteA("I win!")))
.or(tails.next(EventA("click")).next(WriteA("You lose!")))
.run();
```

Forwarding Arrow Inputs Finally, most arrows take an input, perform some computation on it, and output the result of the computation to the next arrow in sequence. However, there are many

```

1  function AsyncA(cps) { this.cps = cps; }
2  AsyncA.prototype.AsyncA = function() { return this; }
3  AsyncA.prototype.next = function(g) {
4    var f = this; g = g.AsyncA();
5    return new AsyncA(function(x, p, k) {
6      f.cps(x, p, function(y, q) {
7        g.cps(y, q, k);
8      });
9    });
10 }
11 AsyncA.prototype.run = function(x, p) {
12   p = p || new ProgressA();
13   this.cps(x, p, function(y) {});
14   return p;
15 }
16 Function.prototype.AsyncA = function() {
17   var f = this;
18   return new AsyncA(function(x, p, k) { k(f(x), p); });
19 }
20
21 function ConstA(x) {
22   return (function() { return x; }).AsyncA();
23 }

```

Figure 6: Full asynchronous arrows (part 1)

cases where we want pass the input “around” the next arrow, i.e., to keep the original input in addition to the output. For example, in our drag-and-drop example from Section 2.2, an event handler receives not just the event it was triggered on, but also the proxy object on which the event listeners were installed on. The bind combinator provides this feature. In the short example below, we show how an image manipulator can display before-and-after shots of a brightened image.

```
var showBeforeAndAfterA = brightenA.bind(displayA);
```

4.2 Implementation Details

Progress and Asynchronous Arrows The first step of our implementation is to extend CpsA so that continuations take both the normal function argument x and a progress arrow argument p . Progress arrows are created with the ProgressA constructor, described below. Our CpsA definition extended with progress arrows is called AsyncA, for *asynchronous arrow*, and is shown in lines 1–10 of Figure 6. The constructor (line 1) and identity function (line 2) work analogously to those of CpsA; next (lines 3–10) simply passes the extra parameter through the CPS composition. The run method now optionally takes a progress arrow argument p , or sets p to an empty progress arrow on line 12 if no argument is passed.⁵ Then run passes the arguments to **this.cps**, as before, and finally returns p back to the caller. This last step allows the caller of run to make use of the progress arrow later, in the case that it was created on line 12 rather than passed in. Finally, the code to lift functions to AsyncA (lines 16–19) is the same as before. For convenience, we also introduce a function ConstA(x), which produces an arrow that ignores its input and returns x (lines 21–23).

Next, we use AsyncA to implement an arrow constructor EventA in Figure 7(a), just as we used CpsA to implement SimpleEventA. The arrow constructor (lines 1–5) is as before. EventA inherits from AsyncA (line 6), also as before. When an event arrow is run, it registers (line 17) the cancel function (lines 8–11) with the progress arrow, and installs an event handler (line 18). This allows us to later abort the arrow (i.e., remove the event handler) if we wish. When an event is triggered, we inform the progress arrow by invoking

⁵ If the argument p is not given, then it is set to **undefined**, in which case $p || e$ evaluates to e .

```

1  function EventA(eventname) {
2    if (!(this instanceof EventA))
3      return new EventA(eventname);
4    this.eventname = eventname;
5  }
6  EventA.prototype = new AsyncA(function(target, p, k) {
7    var f = this;
8    function cancel() {
9      target.removeEventListener(f.eventname,
10     handler, false);
11    }
12    function handler(event) {
13      p.advance(cancel);
14      cancel();
15      k(event, p);
16    }
17    p.addCanceller(cancel);
18    target.addEventListener(f.eventname, handler, false);
19 });

```

(a) Event arrows

```

1  function ProgressA() {
2    if (!(this instanceof ProgressA))
3      return new ProgressA();
4    this.cancellers = []; /* empty arrays */
5    this.observers = [];
6  }
7  ProgressA.prototype = new AsyncA(function(x, p, k) {
8    this.observers.push(function(y) { k(y, p); });
9  })
10 ProgressA.prototype.addCanceller = function(canceller) {
11   /* add canceller function */
12   this.cancellers.push(canceller);
13 }
14 ProgressA.prototype.advance = function(canceller) {
15   /* remove canceller function */
16   var index = this.cancellers.indexOf(canceller);
17   if (index >= 0) this.cancellers.splice(index, 1);
18   /* signal observers */
19   while (this.observers.length > 0)
20     this.observers.pop()();
21 }
22 ProgressA.prototype.cancel = function() {
23   while (this.cancellers.length > 0)
24     this.cancellers.pop()();
25 }

```

(b) Progress arrows

Figure 7: Full asynchronous arrows (part 2)

its advance method (line 13). Upon receiving this method call, a progress arrow p will in turn alert any other objects that are listening for progress messages from p . For example, a progress bar object might ask to be informed each time an arrow composition advances, to update the image of the bar. The remainder of the code is as with SimpleEventA: we cancel the event handler (line 14) and call the continuation k , this time with both the event to process and the progress arrow (line 15).

To actually implement progress arrows, we could most likely extend regular function arrows (from Figure 3(b)), but since AsyncA is somewhat more flexible, we choose that as our starting place. Figure 7(b) defines ProgressA, our progress arrow type. Each progress arrow has two sets of listeners: cancellers (line 4), which are invoked when the arrow’s cancel method is called, and observers (line 5), invoked via the arrow’s advance method.

Users can add to the set of observers by invoking the next combinator inherited from AsyncA. On lines 7–9, we set the underlying

```

1 AsyncA.prototype.repeat = function() {
2   var f = this;
3   return new AsyncA(function rep(x, p, k) {
4     f.cps(x, p, function(y, q) {
5       if (y.Repeat) {
6         function cancel() { clearTimeout(tid); }
7         q.addCanceller(cancel);
8         var tid = setTimeout(function() {
9           q.advance(cancel);
10          rep(y.value, q, k);
11        }, 0);
12       } else if (y.Done)
13         k(y.value, q);
14       else
15         throw new TypeError("Repeat or Done?");
16     });
17   });
18 }
19
20 function Repeat(x) { return { Repeat:true, value:x }; }
21 function Done(x) { return { Done:true, value:x }; }
22
23 Function.prototype.repeat = function(interval) {
24   return this.AsyncA().repeat(interval);
25 }

```

Figure 8: Looping with AsyncA

CPS function of the arrow to push its argument onto the observer list. Thus, invoking `p.next(f).run()` for progress arrow `p` adds `f` to observers. Making `ProgressA` an asynchronous arrow gives it all the flexible compositional properties of arrows, e.g., it allows adding multiple, complex observers. For example, we could write `p.next(f).next(g)` for a progress arrow that invokes `g(f())` when progress occurs, or call `p.next(f).run()`; `p.next(g).run()` to add both observers `f` and `g`.

Cancellers are registered explicitly via the `addCanceller` method (lines 10–13). If `cancel` is invoked, the progress arrow calls all cancellers (lines 23–24). If `advance(c)` is invoked, the progress arrow first removes `c` from cancellers (lines 16–17) and then calls any observers (lines 19–20). A call to `advance` implies that a unit of progress was made (e.g., an event triggered), and so the corresponding cancellation handler `c` for the unit of progress is removed as it is no longer needed. The corresponding observers are also removed and invoked (line 20). This behavior is analogous to the removal of event listeners after an event triggers.

repeat() Figure 8(a) shows the implementation of `repeat` that creates an arrow that executes repeatedly while yielding to the UI thread via `setTimeout` recursion. We return a new asynchronous arrow containing the function `rep` (line 3). When invoked, `rep` calls `f` (the arrow from which the repeating arrow was created) and passes it a new, nested continuation with argument `y` and progress arrow `q`.

The argument `y` is an object created with either `Repeat` or `Done` (lines 20–21). These methods store their argument `x` in a JavaScript approximation of a tagged union—an object with the `value` field set to `x` and either the `Repeat` or `Done` field set to `true`.

Given argument `y`, there are two cases. If `y` is tagged with `Done` (lines 12–13), then we extract the value from `y` and pass it to the continuation `k` for the entire arrow. If `y` is tagged with `Repeat` (lines 5–11), we use the looping idiom from Section 2 to execute `rep` again after `interval` has elapsed. To allow the loop to be cancelled during this timeout period, we extend the list of can-

```

1 function Pair(x, y) { return { fst:x, snd:y }; }
2 AsyncA.prototype.product = function(g) {
3   var f = this; g = g.AsyncA();
4   return new AsyncA(function(x, p, k) {
5     var out1, out2, c = 2;
6     function barrier() {
7       if (--c == 0) k(Pair(out1, out2), p);
8     }
9     f.next(function(y1) { out1 = y1; barrier(); })
10    .run(x.fst, p);
11    g.next(function(y2) { out2 = y2; barrier(); })
12    .run(x.snd, p);
13  });
14 }

```

Figure 9: Combining arrows in parallel

```

1 AsyncA.prototype.or = function(g) {
2   var f = this; g = g.AsyncA();
3   return new AsyncA(function(x, p, k) {
4     /* one progress for each branch */
5     var p1 = new ProgressA();
6     var p2 = new ProgressA();
7     /* if one advances, cancel the other */
8     p1.next(function() { p2.cancel();
9       p2 = null; }).run();
10    p2.next(function() { p1.cancel();
11      p1 = null; }).run();
12
13    function cancel() {
14      if (p1) p1.cancel();
15      if (p2) p2.cancel();
16    }
17    /* prepare callback */
18    function join(y, q) {
19      p.advance(cancel);
20      k(y, q);
21    }
22    /* and run both */
23    p.addCanceller(cancel);
24    f.cps(x, p1, join);
25    g.cps(x, p2, join);
26  });

```

Figure 10: Branching with AsyncA

cellers to kill the timeout (lines 6 and 7), and since we progressed by one iteration, we advance the progress arrow (line 9).

product() Figure 9 shows the `product` combinator for the `AsyncA` arrow. We use the `Pair` function to create pairs as objects with two properties, `fst` and `snd`. To implement `product`, we first define the function `barrier` on lines 6–8, which serves to synchronize the arrow at the completion of its constituent arrows. Then, we run the arrows `f` on lines 9–10 and `g` on lines 11–12, giving as input the first and second components of `x`, respectively. Upon completion of each arrow, we store the result into `out1` or `out2` and call `barrier`. When `c` reaches 0, i.e., when both `f` and `g` have completed, the `barrier` function will in turn call the continuation `k` with the results. Although not shown above, Arrowlets also unpacks pairs automatically into the argument list of regular (non-CPS) functions for convenience.

Either-or() Figure 10 gives the code for the `or` method, which combines the current arrow `f` with the argument `g` (line 2). Calling `f.or(g).run()` executes whichever of `f` or `g` is triggered first, and cancels the other. To keep the presentation simpler, we assume both `f` and `g` are asynchronous event arrows. When invoked, the new arrow first creates progress arrows `p1` and `p2`, which when advanced

```

1 var idA = function(x) { return x; }.AsyncA();
2 var dupA = function(x) { return Pair(x, x); }.AsyncA();
3
4 AsyncA.prototype.bind = function(g) {
5   var f = this; g = g.AsyncA();
6   return dupA.next(idA.product(f))
7     .next(g);
8 }

```

Figure 11: Passing state around arrows

calls `cancel` on the other arrow (lines 8–11). We also register (line 22) the `cancel` function (lines 12–15), which will remove any handlers that are still installed. Then, we invoke the component arrows, `f` with `p1` (line 23) and `g` with `p2` (line 24). When either arrow completes, they call `join` (lines 17–20), which first advances the progress arrow `p` for the composition itself (line 18) and then invokes the regular continuation.

bind() `bind` can be implemented with `next` and `product` along with two helper arrows, as shown in Figure 11. `bind` creates a new arrow that first duplicates its input into a pair with `dupA`, passes through the first component untouched via `idA` and applies `f` to the second component, and finally applies `g` to the resulting pair.

Many combinators in Arrowlets such as `bind` are implemented with just `next` and `product`. In general, we find it quite simple in practice to compose additional convenience combinators as needed.

4.3 Discussion

We believe our asynchronous arrow library to be potentially useful for a variety of applications beyond those presented. In essence, Arrowlets can be used to construct arrows corresponding to arbitrary state machines, where transitions between states occur via synchronous or asynchronous calls. The combinators `next` and `or` can construct machines that are DAGs (where each machine state corresponds to a single handler), and with `repeat` we can create arbitrary graphs. It is easy to imagine other applications that could be built from such state machines, such as games (where related actions in the game, e.g., matching two cards, could be composed into a state machine) or productivity applications (where various elements of the UI have state).

In addition to timeouts and UI events, Arrowlets can also support other kinds of events, e.g., completion of a network or file I/O call. Indeed, our original motivation for developing Arrowlets was to make it easier to write a web-based code visualization tool⁶ that starts by loading XML files over the network. To do this we create a composite asynchronous arrow that first loads an index file, and then iteratively loads each file present in the index, where one load commences when the previous one completes. Our limited experience with this application suggests that it is quite easy to adopt Arrowlets for creating new widgets in existing applications, or to retrofit existing code to be more modular and easier to maintain. We intend to explore the use of Arrowlets to compose entire applications in future work.

5. Related Work

An earlier version of this work appeared as a poster at ICFP 2008, which included a much shorter, 2-page writeup. There are several threads of related work.

JavaScript libraries JavaScript libraries, such as jQuery, Prototype, YUI, MochiKit, and Dojo, provide high-level APIs for common GUI features, such as drag-and-drop and animation. For example, in jQuery, one can make a document widget box “draggable”

⁶<http://www.cs.umd.edu/projects/PL/PP/>

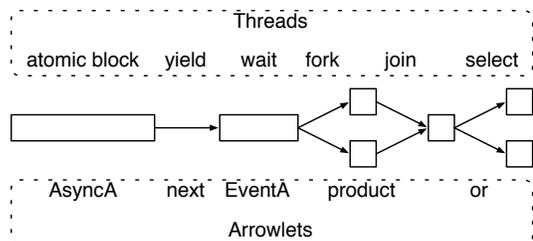


Figure 12: Analogies between threads and Arrowlets

within its parent container with the syntax `$(box).draggable()`. These high-level APIs are easy to use, but they are often not modular and have limited options for customization, as we have found with drag-and-drop.

One form of customizability that is offered by library interfaces is an animation queue. The queue contains one or more animation steps (called *effects*). Programmers can sequence animation steps dynamically by adding to the queue. Such queues and other more complex compositions are easily implemented with Arrowlets.

Some libraries also make use of an idiom called *method chaining*. In this idiom, all methods of an object return the object itself, such that further methods can be invoked on it. Combinators in Arrowlets can be seen as a variation of this idiom that returns newly composed arrows while leaving the original arrows unmodified. Avoiding mutation makes it easier to reuse arrows in several distinct compositions.

Flapjax Flapjax [Meyerovich et al. 2009] is another JavaScript library that solves the problems we have mentioned, but takes a *data-flow oriented* approach, in the style of *functional reactive programming* [Wan and Hudak 2000]. In Flapjax, programmers use combinators to construct, compose, and filter first-class *event streams*, and these streams drive the processing that will ultimately update the display, write files, send messages, etc. Arrowlets is more *control-flow oriented*. In particular, handler arrows are naturally chained together to form state machines: each handler corresponds to a node in the machine, and how handlers are composed determines the transitions in the machine. We can customize the machine by composing handlers differently; in Flapjax we might instead customize the makeup of the event stream. Since Arrowlets do not manipulate first-class event streams, they are lower-level than Flapjax’s abstractions, and arguably closer to Javascript programming practice. Indeed, in Section 2.2 we showed it was fairly straightforward to move from existing code to Arrowlets, and thus to gain Arrowlets’ benefits of improved composability and reuse.

Threads and event-driven programming Perhaps surprisingly, programming with Arrowlets bears a striking resemblance to programming with threads, despite the fact that JavaScript is single-threaded. Indeed, it is well-known that threads and events are computationally equivalent [Lauer and Needham 1978]. The basic observation is that single-threaded event-driven programming is analogous to multi-threading with cooperative scheduling, in which one thread runs at a time and yields the CPU either voluntarily or when it would block on an I/O operation [Adya et al. 2002, von Behren et al. 2003].

Li and Zdancewic [2007] have built a thread monad for Haskell that follows this observation. We can translate their observation to arrows by viewing a thread as a sequence of event handlers, where each handler’s final action is to register an event that triggers the next handler in the sequence (e.g., after a timeout or I/O event completion). By this view, a thread is analogous to an arrow composition using Arrowlets; Figure 12 suggests the relationship between threads and Arrowlets.

Haskell's Arrow libraries Our inspiration to develop an arrow-based library comes from a number of related libraries in Haskell such as Fudgets [Carlsson and Hallgren 1993] and Yampa [Hudak et al. 2003]. Fudgets is a library for building graphical user interfaces (GUI), and uses arrows to implement GUI elements such as buttons, menus, and scroll bars, as well as event handlers. A complete GUI application is composed of Fudgets using various combinators. Yampa is arrow-based library for functional reactive programming, as with Flapjax. In Yampa, arrow combinators compose *signals* with *signal functions*. Yampa has been used to implement a robotics simulator as well as a GUI library named Fruit [Courtney and Elliott 2001].

Unlike standard GUI applications such as those written in Fudgets or Fruit, web applications are typically developed in a combination of HTML and CSS to define the graphical layout of interface elements, and JavaScript for the interface behavior (i.e., event handling). Arrowlets is designed with this distinction in mind and focuses on composing event handlers in JavaScript.

Twisted's Deferred Twisted (twistedmatrix.com) is an event-driven networking library for Python, which, like Arrowlets, provides an abstraction to manage event callbacks. In Twisted, asynchronous functions such as network file access do not take a callback parameter, but instead return Deferred objects that represent values that may have yet to arrive. The value in Deferred can be accessed by adding a callback function via its `addCallback` method. This approach resembles *monads*, a concept that is closely related to arrows.

Unlike `addCallback`, the next combinator in Arrowlets provides a consistent interface to compose asynchronous or synchronous functions with each other. To have a similarly consistent interface using Deferred, programmers have to be careful to wrap the return value of every function in a Deferred object, which is an error-prone endeavor in dynamically-typed languages such as Python or JavaScript. Also, `addCallback` composes Deferred objects with functions, whereas `next` composes arrows with arrows. This asymmetry makes it more verbose to write reusable compositions. Furthermore, Arrowlets provides a richer library of combinators for synchronization and asynchronous looping.

6. Conclusion

We presented the Arrowlets library for using arrows in JavaScript. The key feature of Arrowlets is support for asynchronous event arrows, which are triggered by events in a web browser such as mouse or key clicks. By providing sequencing, parallel, looping, and branching combinators, programmers can easily express how their event handlers are composed and also separate event handling from event composition. Arrowlets supports sophisticated interface idioms, such as drag-and-drop. Arrowlets also includes progress arrows, which can be used to monitor the execution of an asynchronous arrow or abort it. In translating arrows into JavaScript, Arrowlets provides programmers the means to elegantly structure event-driven web components that are easy to understand, modify, and reuse.

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