

miniAdapton

A Minimal Implementation of Incremental Computation in Scheme

Dakota Fisher Matthew A. Hammer

University of Colorado Boulder
first.last@colorado.edu

William Byrd Matthew Might

University of Utah
Will.Byrd@utah.edu might@cs.utah.edu

Abstract

We describe a complete Scheme implementation of *miniAdapton*, which implements the core functionality of the Adapton system for incremental computation (also known as *self-adjusting computation*). Like Adapton, miniAdapton allows programmers to safely combine mutation and memoization. miniAdapton is built on top of an even simpler system, *microAdapton*. Both miniAdapton and microAdapton are designed to be easy to understand, extend, and port to host languages other than Scheme. We also present *adapton variables*, a new interface in Adapton for variables intended to represent expressions.

Categories and Subject Descriptors D.1.1 [Programming Techniques]: Applicative (Functional) Programming

Keywords incremental computation, self-adjusting computation, Adapton, memoization, Scheme

1. Introduction

Memoization (Michie 1968) is a simple yet powerful optimization technique, avoiding redundancy in computation to save considerable amounts of time. When used properly, memoization can achieve asymptotic speedup of many algorithms. Amazingly, in some cases memoization can even transform an exponential-time program into a linear-time program (Cormen et al. 2006). Unfortunately, although memoization is an extremely powerful technique, it suffers from a serious limitation: memoization does not work in the presence of mutation.

Consider `max-tree` and `max-tree-path`, two memoized functions (see Appendix E for a complete definition of `define-memo`). Function `max-tree` finds the maximum number in a tree made of pairs and numbers and `max-tree-path` finds the path from the root of the tree to the maximum number.

```
(define-memo (max-tree t)
  (cond
    ((pair? t)
     (max (max-tree (car t))
          (max-tree (cdr t))))
    (else t)))
```

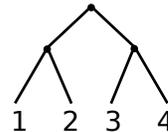
```
(define-memo (max-tree-path t)
  (cond
    ((pair? t)
     (if (> (max-tree (car t))
           (max-tree (cdr t)))
         (cons 'left (max-tree-path (car t)))
         (cons 'right (max-tree-path (cdr t)))))
    (else '())))
```

Observe that following the path returned by `max-tree-path` should yield the value returned by `max-tree`.

Suppose that we also have a tree, `some-tree`:

```
(define some-tree '((1 . 2) . (3 . 4)))
```

For clarity, here is `some-tree` explicitly represented as a tree:



Now let's consider a user session. First we ask for the maximum value of any leaf node in `some-tree`:

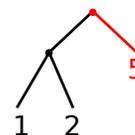
```
> (max-tree some-tree)
4
```

This is what we expect, since the maximum number in the tree is clearly 4.

Next we modify `some-tree`, replacing its entire right-hand branch with the number 5.

```
> (set-cdr! some-tree 5)
> some-tree
((1 . 2) . 5)
```

And here is the updated explicit tree representation of `some-tree`:



Once more we ask for the maximum number in the tree.

```
> (max-tree some-tree)
4
```

This answer is no longer correct, since now the maximum number in the tree is 5, not 4. In fact, 4 isn't even in the tree anymore! As soon as the user performs a single mutation in the tree, our statements about the supposed behavior of the program are promptly violated. *Memoization cannot handle mutation.*

We can use `max-tree-path`, which determines the path to the maximum value, to figure out what went wrong.

```
> (max-tree-path some-tree)
(right)
> (max-tree (cdr some-tree))
5
```

Following `max-tree-path` to the `cdr` of the tree yields a subtree containing a larger number than the entire tree!

In our implementation of memoization, shown in Appendix E, the problem is even worse, since the user has mutated the lookup key. Now *every* instance of `((1 . 2) . 5)` irreparably has the maximum number 4 somewhere in the tree according to the function, which is apparently in the path `(right)`, where a 5 resides.

In order to make memoization work in the presence of mutation, we must keep additional information about the computation while also keeping track of the mutations which have occurred. *Adapton* (Hammer et al. 2014) is a system that provides these capabilities, combining the flexibility of mutation with the potentially asymptotic speedup of memoization. Adapton is a form of *incremental computation* (sometimes called *self-adjusting computation*), an umbrella term for techniques which take changing inputs and save time by reusing previous results to compute new results for mutated inputs (Acar et al. 2006).

Although Adapton reconciles memoization and mutation, the complete code for an implementation of Adapton has not appeared in the literature. In addition, Adapton implementations have focused on performance rather than on understandability, portability, or hackability. Inspired by *microKanren* (Hemann and Friedman 2013), which presented a tiny, easily understandable implementation of the core of the *miniKanren* programming language (Byrd and Friedman 2006), we have created *microAdapton*, a tiny, easily understandable implementation of the core of Adapton. Also in the spirit of *microKanren* and *miniKanren*, we build a higher-level interface, *miniAdapton*, on top of the *microAdapton* core.

Our paper provides the first complete implementation of a version of Adapton in the literature. More specifically, our paper presents two small implementations of Adapton:

- *microAdapton* (section 3): a minimal substrate on which to build the *miniAdapton* system, providing only the barest interfaces to aid portability and readability. Separating *miniAdapton* into *microAdapton* and *miniAdapton*

allows us to provide a simple and portable core and layer user functionality on top of it. Inspired by *microKanren*, *microAdapton* contains zero macros and fits in under 50 lines of source code. It avoids building Adapton's Demanded Computation Graph, relegating it to be done by *miniAdapton*, or manually if used directly, making for a more flexible yet less immediately useful system.

- *miniAdapton* (section 4): a complete implementation of adapton, intended to provide a full Adapton system to the user, including:
 - an interface to adaptons which automatically maintains Adapton's Demanded Computation Graph (section 4.1);
 - functions and macros for function memoization (section 4.3);
 - a convenience macro for constructing elements of adapton thunks representing expressions similar to `delay` (section 4.2);
 - adapton variables: a new interface in Adapton for variables intended to represent expressions (section 4.4).

The code for these implementations is publicly available here: <https://github.com/fisherdj/miniAdapton>

2. Overview

Adapton, like memoization, stores the results of computation so that it can avoid redundant computation. Memoization, however, stores only the results, which means that even after mutation, the computation cannot be restarted, and even if it could, it might not be possible to figure out when it needs to be restarted. Instead of storing just the results of computations, Adapton stores their results, how it got those results and a graph of the dependencies between those computations. Then, whenever a value is mutated through the Adapton interface, the computations depending on that value are marked dirty to indicate that their computation must be restarted. This lets Adapton keep many of the benefits of memoization while still permitting mutation.

2.1 What is Adapton?

Adapton refers to a system for self-adjusting computation by keeping track of computation at runtime. An adapton thunk (or athunk) keeps track of any subcomputations it needs to determine its value and any supercomputations that need its value. The athunks maintain the property of *From-scratch Consistency*, meaning that after modifying referenced mutable elements through Adapton, the result of forcing these thunks is the same as if one had computed them from scratch. However, because athunks keep track of computation, they can avoid redundant re-computation, yielding the potential speedup of memoization while retaining the capability of mutation (see (Hammer et al. 2014) for performance discussion).

Here `athunks` are mutable promises: they store a computation which may reference mutable objects in memory (`adapton-refs`) and cache the result of the computation but when forced will always return the same value as if computed from scratch. Other behaviors may be possible, but this is the primary use case.

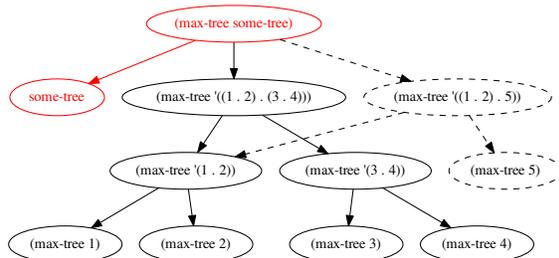
2.2 Supercomputation and Subcomputation

If a is some computation (an `athunk`), then a 's supercomputations are computations that depend on a , and a 's subcomputations are computations that a depends on. If b is a 's subcomputation, then a is b 's supercomputation.

2.3 Demanded Computation Graph

The demanded computation graph or DCG is a graph representing the dependencies between computations and their supercomputation/subcomputation relation. Each node of the graph is a computation and each edge is a supercomputation/subcomputation relation. This implementation provided uses inefficient implementations of sets and memoization, which may hinder its performance (see Sections D and E for discussion on speeding it up).

The figure below is a representation of the DCG for the computation `(max-tree some-tree)` when `some-tree` is modified from `((1 . 2) . (3 . 4))` to `((1 . 2) . 5)`. Nodes represent `athunks` and edges represent supercomputation/subcomputation relationships: An edge exists from node n to node m when n depends on m (i.e., this edge represents that n is the supercomputation and m is one of its subcomputations). Black nodes and edges represent portions of the original graph, red nodes and edges represent portions of the original graph which are dirtied or which propagate dirtiness, and gray nodes and edges will be created when the `adapton` is forced again later. Modifying `some-tree` dirties the root node; when forced again it will create new `thunks` for `(max-tree '((1 . 2) . 5))` and `(max-tree 5)` to complete the computation. Although the root node still points to `(max-tree '((1 . 2) . (3 . 4)))`, the edge between the two is removed before the `think` is recomputed, which regenerates the edge anew.



3. microAdapton Implementation

The implementation of `microAdapton` operates primarily on the `adapton` data structure, the datatype is defined as:

```
(define-record-type
  (adapton adapton-cons adapton?)
  (fields
    thunk
    (mutable result)
    (mutable sub)
    (mutable super)
    (mutable clean?)))
```

The fields are:

thunk the computation to cache

result cached result of the computation

sub set of subcomputations

super set of supercomputations

clean? whether or not the cached result is valid

Function `make-athunk` constructs an `athunk` representing a `think` yet to be computed.

```
(define (make-athunk thunk)
  (adapton-cons thunk
    'empty
    empty-set
    empty-set
    #f))
```

The first parameter of the constructor is the only parameter of the `make-athunk` function. The result is arbitrarily set to the symbol `empty`. The `sub` and `super` sets are both empty, since this `athunk` is not yet placed in the DCG. Finally, the `athunk` is not clean until after the `think` is computed, so cleanliness is false.

Function `adapton-add-dcg-edge!` adds edges of the DCG, and `adapton-del-dcg-edge!` removes edges of the DCG, from their parameters `a-super` and `a-sub`.

```
(define (adapton-add-dcg-edge! a-super a-sub)
  (adapton-sub-set!
    a-super
    (set-cons a-sub (adapton-sub a-super)))
  (adapton-super-set!
    a-sub
    (set-cons a-super (adapton-super a-sub))))
```

```
(define (adapton-del-dcg-edge! a-super a-sub)
  (adapton-sub-set!
    a-super
    (set-rem a-sub (adapton-sub a-super)))
  (adapton-super-set!
    a-sub
    (set-rem a-super (adapton-super a-sub))))
```

Adding the DCG edge means connecting the `athunks` together by adding to their respective `sub` and `super` sets, while removing the DCG edge means disconnecting the `athunks` by removing their `sub` and `super` sets.

Function `adapton-compute` computes an athunk and performs maintenance, returning the athunk's value, and keeping from-scratch consistency if the DCG is correctly maintained:

```
(define (adapton-compute a)
  (if (adapton-clean? a)
      (adapton-result a)
      (begin
        (set-for-each
         (lambda (x)
           (adapton-del-dcg-edge! a x))
         (adapton-sub a))
        (adapton-clean?-set! a #t)
        (adapton-result-set! a
          ((adapton-thunk a)))
        (adapton-compute a))))))
```

If the result is already available and valid, signified by the athunk being clean, then that value is returned. Otherwise, either because the result is not available or because the current result is invalid, additional maintenance must be performed. First, since computation is starting or restarting, all subcomputation relations are invalid and the subcomputation set must be removed. Second, the athunk must be marked as clean. Third, the result of the computation must be computed and stored in the athunk. After this maintenance, we restart computing the athunk, which may lead to restarting the computation if the athunk has been marked dirty during the computation. This maintains from-scratch consistency in certain edge cases where mutation occurs within computation. The order of maintenance operations is important: computing the result must be done after removing edges to subcomputations and after marking the athunk as dirty. Function `adapton-compute` is very sensitive to errors in the DCG. If an edge is added to a dirty athunk as a subcomputation, changes will not propagate until that athunk is clean. This is a direct consequence of Adapton's lazy change propagation strategy: changes are indicated in the DCG, but the changes themselves are not computed until forcing the corresponding athunks. Avoiding marking changes more than once prevents redundant repeated traversal of large DCGs.

Function `adapton-dirty!` implements this change propagation strategy. It marks an athunk dirty along with all supercomputations, under the assumption that the DCG is correctly maintained so that any dirty subcomputations are not subcomputations of clean nodes.

```
(define (adapton-dirty! a)
  (when (adapton-clean? a)
    (adapton-clean?-set! a #f)
    (set-for-each adapton-dirty!
      (adapton-super a))))
```

Calling `adapton-dirty!` on the immediate supercomputations of an athunk is sufficient for change propagation. Since `adapton-dirty!` only recurses for an athunk marked clean,

calling `adapton-dirty!` twice or more on any one athunk without computing it (and thus, cleaning it) between calls traverses the graph only once.

Finally, we need to be able to create mutable cells. Function `adapton-ref` takes a value creates a new ref cell with that value without needing to define an additional structure.

```
(define (adapton-ref val)
  (letrec ((a (adapton-cons
               (lambda () (adapton-result a))
               val
               empty-set
               empty-set
               #t)))
    a))
```

Because it references itself, the ref can be set just by modifying the value in its cell. Since this invalidates supercomputations, one must also call `adapton-dirty!` to guarantee from-scratch consistency. Function `adapton-ref-set!` sets the value of the ref cell in its first parameter to the second parameter.

```
(define (adapton-ref-set! a val)
  (adapton-result-set! a val)
  (adapton-dirty! a))
```

Function `adapton-ref-set!` is the sole method of mutation provided.

The `microAdapton` interface exposes these functions: `adapton-compute`, `adapton-ref`, `adapton-ref-set!`, `adapton?`, `make-athunk`, `adapton-add-dcg-edge!`, and `adapton-del-dcg-edge!`. All uses and users of `microAdapton`, including the higher-level `miniAdapton` interface, must use this interface; modifying the DCG directly, without using the interface functions, may result in unspecified or erroneous behavior.

```
(define r1 (adapton-ref 8))
(define r2 (adapton-ref 10))
(define a
  (make-athunk
   (lambda ()
     (adapton-add-dcg-edge! a r1)
     (adapton-add-dcg-edge! a r2)
     (- (adapton-compute r1)
        (adapton-compute r2))))))
```

```
> (adapton-compute a)
-2
> (adapton-ref-set! r1 2)
> (adapton-compute a)
-8
```

4. miniAdapton: A Higher-level Interface

A user of `microAdapton` has all the tools they need to get the benefits of from-scratch consistency and memoization. The

user must, however, build the DCG manually within computations. `microAdapton` provides only the low-level operations adding and removing edges for correct construction and use of DCGs. This process is tedious, mechanical, potentially error-prone and should be avoided where possible. Truly memoizing functions using `athunks` requires significant additional work: one has to use `letrec` to grab the thunk to add it, and must reference the thunk inside the other function. Thankfully, some extra interfaces can be made readily available to the user which avoids these difficulties.

4.1 Essential Interface

The essential interface to `miniAdapton` is `adapton-force`, a function that marks `athunks` as subcomputations if their computation occurs during the computation of a different `athunk`. Although using `adapton-compute` directly cannot provide this, we can instead define `adapton-force` and use it exclusively in place of `adapton-compute`, as shown in this user session:

```
(define r (adapton-ref 5))
(define a
  (make-athunk
   (lambda ()
     (+ (adapton-force r) 3))))

> (adapton-force a)
8
> (adapton-ref-set! r 2)
> (adapton-force a)
5
```

Here is the definition of `adapton-force`:

```
(define adapton-force
  (let ((currently-adapting #f))
    (lambda (a)
      (let ((prev-adapting
             currently-adapting))
        (set! currently-adapting a)
        (let ((result (adapton-compute a)))
          (set! currently-adapting
                 prev-adapting)
          (when currently-adapting
                (adapton-add-dcg-edge!
                 currently-adapting
                 a))
          result))))))
```

Function `adapton-force` keeps track of any `Adapton` computation that we are immediately in and, when called with a single `athunk` argument, computes the result of its argument and places the `athunk` in the DCG.

4.2 The adapt Form

A useful macro styled after `delay` takes expressions and turns them into `athunks`. Translating our example for `adapton-force` to use `adapt`:

```
(define r (adapton-ref 5))
(define a (adapt (+ (adapton-force r) 3))))
```

The `adapt` macro is straightforward, it takes an expression, wraps it in a thunk and then packages it with `make-athunk`:

```
(define-syntax adapt
  (syntax-rules ()
    ((_ expr)
     (make-athunk (lambda () expr)))))
```

4.3 Memoization

Function `adapton-force`, paired with a memoization implementation (Appendix E), allows us to define two memoization procedures for `Adapton`. Here are `max-tree` (find maximum number in tree) and `max-tree-path` from the introduction (find path to maximum number in tree) translated into a variant utilizing `Adapton`:

```
(define-amemo (max-tree t)
  (cond
   ((adapton? t)
    (max-tree (adapton-force t)))
   ((pair? t)
    (max (max-tree (car t))
         (max-tree (cdr t))))
   (else t)))

(define-amemo (max-tree-path t)
  (cond
   ((adapton? t)
    (max-tree-path (adapton-force t)))
   ((pair? t)
    (if (> (max-tree (car t))
          (max-tree (cdr t)))
        (cons 'left
              (max-tree-path (car t)))
        (cons 'right
              (max-tree-path (cdr t)))))
   (else '())))
```

The following functions are conveniences for defining memoized functions:

```
(define (adapton-memoize-1 f)
  (memoize (lambda x (adapt (apply f x)))))

(define (adapton-memoize f)
  (let ((f* (adapton-memoize-1 f)))
    (lambda x (adapton-force (apply f* x)))))
```

The first function produces memoized functions returning `athunks`, where the “l” suffix means “lazy.” The second produces functions which are both memoized and from-scratch consistent within the `adapton` system. Function `adapton-memoize-l` operates by memoizing a version of its function argument returning `athunks`. A standard implementation of memoization in conjunction with the `adapt` form is sufficient to perform this task. Function `adapton-memoize` operates by taking the result of `adapton-memoize-l` and making a new function equivalent except that it returns the result of forcing the `athunk` instead of the `athunk` itself.

A small battery of convenience macros for memoization are also useful to have. We have two macros for constructing procedures with the syntax of `lambda`:

```
(define-syntax lambda-amemo-l
  (syntax-rules ()
    ((_ (args ...) body ...)
     (let ((f* (adapton-memoize-l
                (lambda (args ...)
                  body ...))))
       (lambda (args ...) (f* args ...))))))
```

```
(define-syntax lambda-amemo
  (syntax-rules ()
    ((_ (args ...) body ...)
     (let ((f* (adapton-memoize
                (lambda (args ...)
                  body ...))))
       (lambda (args ...) (f* args ...))))))
```

and two for defining procedures with the syntax of `define`:

```
(define-syntax define-amemo-l
  (syntax-rules ()
    ((_ (f args ...) body ...)
     (define f (lambda-amemo-l (args ...)
                             body ...))))
```

```
(define-syntax define-amemo
  (syntax-rules ()
    ((_ (f args ...) body ...)
     (define f (lambda-amemo (args ...)
                             body ...))))
```

4.4 Adapton Variables

Function `adapton-ref-set!` can be a somewhat unwieldy interface, one can only set references equal to values, when we might want to set those references to expressions instead. Consider these definitions:

```
(define r1 (adapton-ref 2))
(define r2
  (adapton-ref (+ (adapton-force r1) 4)))
(define a
  (adapt (+ (adapton-force r1)
```

```
(adapton-force r2))))
```

Notice that we force `r1` to get the value of `r2`. Upfront, we expect that `r1` has 2 stored in it and `r2` has 6 stored in it. Now consider this user session:

```
> (adapton-force a)
8
> (adapton-ref-set! r1 10)
> (adapton-force a)
16
```

The first answer is not surprising, it corresponds to adding 2, 2 and 4 (8). After we set and force `a`, one might desire to get the result of adding 10, 10 and 4 (24), but instead we get the result of adding 10, 2 and 4 (16). This happens because `r2` is a `ref` and retains its value instead of updating to match the value of its expression. The final useful interfaces provided are the “`avar`” macros and functions, short for “`adapton variable`.” `Adapton` variables provide the behavior of acting as expressions rather than values:

```
(define-syntax define-avar
  (syntax-rules ()
    ((_ name expr)
     (define name
       (adapton-ref (adapt expr)))))
```

```
(define (avar-get v)
  (adapton-force (adapton-force v)))
```

```
(define-syntax avar-set!
  (syntax-rules ()
    ((_ v expr)
     (adapton-ref-set! v (adapt expr)))))
```

An `avar` is a variable representing an expression which can be changed and will remain from-scratch consistent with other changes. It is made of an `adapton-ref` that itself contains an `athunk` for the desired expression. Macro `define-avar` defines an `avar` and assigns it an expression. Function `avar-get` gets the value resulting from evaluating the `avar`’s expression, forcing the `adapton ref` to get the `thunk` and then forcing that to actually obtain the value from the `thunk`. Macro `avar-set!` sets the expression of an `avar`.

Here is our example again, translated to use `avars`:

```
(define-avar v1 2)
(define-avar v2 (+ (avar-get v1) 4))
(define-avar b
  (+ (avar-get v1) (avar-get v2)))
```

```
> (avar-get b)
8
> (avar-set! v1 10)
> (avar-get b)
24
```

This code is much easier to reason about, since we can get the correct value by only looking at the expressions.

4.5 Putting it All Together: Extended Example

Now that we have all of miniAdapton available to us, we can translate and extend the example of our introduction. Before we do so, let's define a new function to help us inspect trees containing our new data structures:

```
(define (remove-adapton v)
  (cond
    ((pair? v)
     (cons (remove-adapton (car v))
           (remove-adapton (cdr v))))
    ((adapton? v)
     (remove-adapton (adapton-force v)))
    (else v)))
```

This recursively takes any athunks in our structures and replaces them with their values. Here are some avar definitions in addition to our original some-tree:

```
(define-avar lucky 7)
(define-avar t1 (cons 1 2))
(define-avar t2 (cons 3 4))
(define-avar some-tree
  (cons (avar-get t1) (avar-get t2)))
```

Now our user session from the start:

```
> (avar-get some-tree)
((1 . 2) 3 . 4)
> (max-tree some-tree)
4
> (max-tree-path some-tree)
(right right)
```

So far, so good, but this is where the original broke last time. We do the same thing, setting the cdr of some-tree to 5:

```
> (avar-set! t2 5)
> (avar-get some-tree)
((1 . 2) . 5)
> (max-tree some-tree)
5
> (max-tree-path some-tree)
(right)
> (max-tree (cdr (avar-get some-tree)))
5
> (max-tree-path (cdr (avar-get some-tree)))
()
```

The memoized functions are now reporting the correct results in spite of the mutation. In fact, we have even more flexibility than our introduction example might suggest. We can set our subtrees to expressions instead of values:

```
> (avar-set! t2
  (cons 20 (* 3 (avar-get lucky))))
> (avar-get some-tree)
```

```
((1 . 2) 20 . 21)
> (max-tree some-tree)
21
> (max-tree-path some-tree)
(right right)
```

This is all as usual, t2 has the value (20 . 21).

```
> (avar-set! lucky 3)
> (avar-get some-tree)
((1 . 2) 20 . 9)
> (max-tree some-tree)
20
> (max-tree-path some-tree)
(right left)
```

Even in the presence of more complicated dependencies of computation, from-scratch consistency is maintained. In addition, the code is made easier to reason about, all the properties that were lacking in our introductory example are once again present.

5. Related Work

Researchers have provided many language-based approaches to incremental computation (Acar et al. 2006; Hammer and Acar 2008; Acar and Ley-Wild 2009; Hammer et al. 2015). In particular, researchers have shown that for certain algorithms, inputs, and classes of input changes, IC delivers large, even *asymptotic* speed-ups over full reevaluation (Acar et al. 2007, 2008). IC has been developed in many different language settings (Shankar and Bodik 2007; Hammer et al. 2007, 2009; Chen et al. 2014b), and has addressed open problems in computational geometry (Acar et al. 2010).

Some PL approaches to IC are *static*, transforming programs to derive a second program that can process input changes. Static approaches perform these transformations a priori, before any dynamic changes. As such, static approaches are often lack the ability to transform general recursion or to fully cache and exploit dynamic dependencies (Liu and Teitelbaum 1995; Liu et al. 1998; Cai et al. 2014).

In contrast to static approaches, dynamic approaches attempt to trade space for time savings. A variety of dynamic approaches to IC have been proposed. Most early approaches fall into one of two camps: they either perform function caching of pure programs (Bellman 1957; McCarthy 1963; Michie 1968; Pugh 1988), or they support input mutation and employ some form of dynamic dependency graphs, along with a mechanism for performing *change propagation* (Acar et al. 2004, 2006; Hammer and Acar 2008; Acar and Ley-Wild 2009; Hammer et al. 2015). Earlier work restricted programs to those expressible as *attribute grammars* (Demers et al. 1981; Reps 1982a,b; Vogt et al. 1991). Various threads of research propose general schemes for practical memoization, either making it applicable in more settings, or more efficient. Researchers have ex-

tended memoization to parallel C and C++ programs (Bhatotia et al. 2015) and to distributed, cloud-based settings (Bhatotia et al. 2011), and have reduced the (often large) space overhead (Chen et al. 2014a).

6. Conclusion

We have presented the complete implementation of microAdapton, a minimal system for incremental computation, and the higher-level miniAdapton interface built on top of it. Like full Adapton, microAdapton and miniAdapton allow programmers to safely combine memoization and mutation.

Our approach of dividing our implementation into a “mini”-level built on top a core “micro”-level is inspired by microKanren and miniKanren. As with microKanren, we take care to separate the hygienic macros in miniAdapton from the “micro” core. This separation, and the careful exposition of the microKanren code in Hemann and Friedman (2013), has resulted in readers of that paper porting microKanren to several dozen languages in addition to Scheme (Byrd). We hope that microAdapton and miniAdapton will make the ideas and implementation of incremental computation similarly accessible, and will also result in readers porting the system to other languages and extending the system. One such extension would be to add cycle detection for the DCG.

Acknowledgements

This material is partially based on research sponsored by DARPA under agreement number AFRL FA8750-15-2-0092 and by NSF under CAREER grant 1350344. The views expressed are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon.

We would also like to thank Jason Hemann and Dan Friedman for their work on the original microKanren system, which was a significant inspiration for this paper.

We also thank the Scheme workshop reviewers for their helpful comments.

References

- Umut A. Acar and Ruy Ley-Wild. Self-adjusting computation with Delta ML. In *Proceedings of the 6th International Conference on Advanced Functional Programming*, AFP’08. 2009.
- Umut A. Acar, Guy E. Blelloch, and Robert Harper. Adaptive memoization. Technical Report CMU-CS-03-208, Carnegie Mellon University, November 2004.
- Umut A. Acar, Guy E. Blelloch, Matthias Blume, Robert Harper, and Kanat Tangwongsan. A library for self-adjusting computation. *Electr. Notes Theor. Comput. Sci.*, 148(2):127–154, 2006.
- Umut A. Acar, Alexander Ihler, Ramgopal Mettu, and Özgür Sümer. Adaptive Bayesian inference. In *Neural Information Processing Systems (NIPS)*, 2007.
- Umut A. Acar, Guy E. Blelloch, Kanat Tangwongsan, and Duru Türkoğlu. Robust kinetic convex hulls in 3D. In *Proceedings of the 16th Annual European Symposium on Algorithms*, September 2008.
- Umut A. Acar, Andrew Cotter, Benoît Hudson, and Duru Türkoğlu. Dynamic well-spaced point sets. In *Symposium on Computational Geometry*, 2010.
- Richard Bellman. *Dynamic Programming*. Princeton Univ. Press, 1957.
- Pramod Bhatotia, Alexander Wieder, Rodrigo Rodrigues, Umut A. Acar, and Rafael Pasquin. Incoop: MapReduce for incremental computations. In *SOCC*, 2011.
- Pramod Bhatotia, Pedro Fonseca, Umut A. Acar, Björn B. Brandenburg, and Rodrigo Rodrigues. iThreads: A threading library for parallel incremental computation. In *ASPLOS*, 2015.
- William E. Byrd. minikanren.org (official miniKanren website). <http://minikanren.org/>. Accessed: 2016-06-25.
- William E. Byrd and Daniel P. Friedman. From variadic functions to variadic relations: A miniKanren perspective. In Robby Findler, editor, *Proceedings of the 2006 Scheme and Functional Programming Workshop*, University of Chicago Technical Report TR-2006-06, pages 105–117, 2006.
- Yufei Cai, Paolo G. Giarrusso, Tillmann Rendel, and Klaus Ostermann. A theory of changes for higher-order languages: Incrementalizing λ -calculi by static differentiation. In *PLDI*, 2014.
- Yan Chen, Umut A. Acar, and Kanat Tangwongsan. Functional programming for dynamic and large data with self-adjusting computation. In *ICFP*, 2014a.
- Yan Chen, Joshua Dunfield, Matthew A. Hammer, and Umut A. Acar. Implicit self-adjusting computation for purely functional programs. *J. Functional Programming*, 24(1):56–112, 2014b.
- Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest, and Clifford Stein. *Introduction to Algorithms*. MIT Press, 2006.
- Alan Demers, Thomas Reps, and Tim Teitelbaum. Incremental evaluation of attribute grammars with application to syntax-directed editors. In *POPL*, 1981.
- Matthew Hammer and Umut A. Acar. Memory management for self-adjusting computation. In *ISMM*, 2008.
- Matthew Hammer, Umut A. Acar, Mohan Rajagopalan, and Anwar Ghuloum. A proposal for parallel self-adjusting computation. In *Declarative Aspects of Multicore Programming*, 2007.
- Matthew A. Hammer, Umut A. Acar, and Yan Chen. CEAL: a C-based language for self-adjusting computation. In *ACM SIGPLAN Conference on Programming Language Design and Implementation*, 2009.
- Matthew A. Hammer, Khoo Yit Phang, Michael Hicks, and Jeffrey S. Foster. Adapton: Composable, demand-driven incremental computation. In *PLDI*, 2014.
- Matthew A. Hammer, Joshua Dunfield, Kyle Headley, Nicholas Labich, Jeffrey S. Foster, Michael Hicks, and David Van Horn. Incremental computation with names. In *OOPSLA*, 2015.
- Jason Hemann and Dan Friedman. μ kanren: A minimal functional core for relational programming, November 2013. URL <http://www.schemeworkshop.org/2013/papers/HemannMuKanren2013.pdf>.

Yanhong A. Liu and Tim Teitelbaum. Systematic derivation of incremental programs. *Science of Computer Programming*, 24 (1):1–39, 1995.

Yanhong A. Liu, Scott Stoller, and Tim Teitelbaum. Static caching for incremental computation. *ACM Transactions on Programming Languages and Systems*, 20(3):546–585, 1998.

John McCarthy. A basis for a mathematical theory of computation. In *Computer Programming and Formal Systems*, 1963.

Donald Michie. "Memo" Functions and Machine Learning. *Nature*, 218(5136):19–22, April 1968.

William Pugh. *Incremental Computation via Function Caching*. PhD thesis, Cornell University, 1988.

Thomas Reps. *Generating Language-Based Environments*. PhD thesis, Cornell University, August 1982a.

Thomas Reps. Optimal-time incremental semantic analysis for syntax-directed editors. In *POPL*, 1982b.

Ajeet Shankar and Rastislav Bodik. DITTO: Automatic incrementalization of data structure invariant checks (in Java). In *Programming Language Design and Implementation*, 2007.

Harald Vogt, Doaitse Swierstra, and Matthijs Kuiper. Efficient incremental evaluation of higher order attribute grammars. In *PLILP*, 1991.

A. Complete microAdapton Implementation

This appendix presents the full code for microAdapton. microAdapton requires an appropriate implementation of sets—see Appendix D for a compatible set implementation using lists, and a brief performance discussion.

```
(define-record-type
  (adapton adapton-cons adapton?)
  (fields
   thunk
   (mutable result)
   (mutable sub)
   (mutable super)
   (mutable clean?)))

(define (make-athunk thunk)
  (adapton-cons thunk
    'empty
    empty-set
    empty-set
    #f))

(define (adapton-add-dcg-edge! a-super a-sub)
  (adapton-sub-set! a-super
    (set-cons a-sub (adapton-sub a-super)))
  (adapton-super-set! a-sub
    (set-cons a-super (adapton-super a-sub))))

(define (adapton-del-dcg-edge! a-super a-sub)
  (adapton-sub-set! a-super
    (set-rem a-sub (adapton-sub a-super)))
```

```
(adapton-super-set! a-sub
  (set-rem a-super (adapton-super a-sub))))

(define (adapton-compute a)
  (if (adapton-clean? a)
      (adapton-result a)
      (begin
        (set-for-each
         (lambda (x)
           (adapton-del-dcg-edge! a x))
         (adapton-sub a))
        (adapton-clean?-set! a #t)
        (adapton-result-set! a
          ((adapton-thunk a)))
        (adapton-compute a))))

(define (adapton-dirty! a)
  (when (adapton-clean? a)
    (adapton-clean?-set! a #f)
    (set-for-each adapton-dirty!
      (adapton-super a))))

(define (adapton-ref val)
  (letrec ((a (adapton-cons
    (lambda () (adapton-result a))
    val
    empty-set
    empty-set
    #t)))
    a))

(define (adapton-ref-set! a val)
  (adapton-result-set! a val)
  (adapton-dirty! a))
```

B. Complete miniAdapton Implementation

This appendix presents the full code for miniAdapton. miniAdapton requires a memoization implementation—see Appendix E for a compatible memoization implementation using association lists, and a brief performance discussion.

```
(define adapton-force
  (let ((currently-adapting #f))
    (lambda (a)
      (let ((prev-adapting
        currently-adapting))
        (set! currently-adapting a)
        (let ((result (adapton-compute a)))
          (set! currently-adapting
            prev-adapting)
          (when currently-adapting
            (adapton-add-dcg-edge!
              currently-adapting
              a))
          result))))))
```

```

(define-syntax adapt
  (syntax-rules ()
    ((_ expr)
     (make-athunk (lambda () expr)))))

(define (adapton-memoize-l f)
  (memoize (lambda x (adapt (apply f x)))))

(define (adapton-memoize f)
  (let ((f* (adapton-memoize-l f)))
    (lambda x (adapton-force (apply f* x)))))

(define-syntax lambda-amemo-l
  (syntax-rules ()
    ((_ (args ...) body ...)
     (let ((f* (adapton-memoize-l
                (lambda (args ...)
                  body ...))))
       (lambda (args ...) (f* args ...)))))

(define-syntax lambda-amemo
  (syntax-rules ()
    ((_ (args ...) body ...)
     (let ((f* (adapton-memoize
                (lambda (args ...)
                  body ...))))
       (lambda (args ...) (f* args ...)))))

(define-syntax define-amemo-l
  (syntax-rules ()
    ((_ (f args ...) body ...)
     (define f (lambda-amemo-l (args ...)
                              body ...))))

(define-syntax define-amemo
  (syntax-rules ()
    ((_ (f args ...) body ...)
     (define f (lambda-amemo (args ...)
                              body ...))))

(define-syntax define-avar
  (syntax-rules ()
    ((_ name expr)
     (define name
      (adapton-ref (adapt expr)))))

(define (avar-get v)
  (adapton-force (adapton-force v)))

(define-syntax avar-set!
  (syntax-rules ()
    ((_ v expr)
     (adapton-ref-set! v (adapt expr)))))

```

C. Spreadsheet Example Redux

The motivating example for the original Adapton work (Hammer et al. 2014) consists of an incremental “spreadsheet” evaluator, given as a simple interpreter, made incremental via use of the Adapton primitives. In this section, we show that miniAdapton can also express this example.

In the original example, given in a variant of ML, the programmer specifies a data structure to represent expressions that change over time, and a recursive function that evaluates these expressions to their valuation. In this version, we do not employ an explicit data structure representation for expressions; rather, we use the host Scheme evaluator in place of this programmer-defined interpreter. This approach employs `avars` to hold (Scheme) expressions that can change over time; in particular, `avars` hold suspended computations that represent the formulae of the spreadsheet cells. In this way, each `avar` is like a cell in a (very) simple spreadsheet. Under this representation, we can encode the example from the prior work as follows:

```

(define-avar n1 1)
(define-avar n2 2)
(define-avar n3 3)
(define-avar p1 (+ (avar-get n1) (avar-get n2)))
(define-avar p2 (+ (avar-get p1) (avar-get n3)))

```

This code creates five cells in the spreadsheet, which hold three constants (1, 2 and 3) and two sums over these (`p1` and `p2`).

With these bindings in place, we can encode the example session as follows:

```

> (avar-get p1)
3
> (avar-get p2)
6

```

Because Adapton (and miniAdapton) are demand-driven, the evaluation of `p1` and `p2` are suspended until they are forced to execute, by the uses of `avar-get` above; these operations compute their valuations, 3 and 6, respectively.

```

> (avar-set! n1 5)
> (avar-get p1)
7

```

Next, the user mutates an `avar` using `avar-set!`, and re-observes the valuation of `avar-get`. Meanwhile, the valuation of `n2` is unaffected, and need not be recomputed. In this case, `n2` is merely a constant value, but if it were more complex, this entire computation would still be reusable. This demonstrates how miniAdapton allows memoization and mutation to safely coexist.

As with Adapton, if the user decides to mutate the input by *swapping* expression trees, miniAdapton responds by swapping their corresponding memoized sub-computations behind the scenes:

```
> (avar-set! p2 (+ (avar-get n3) (avar-get p1)))
> (avar-get p2)
10
```

Finally, the following user interactions demonstrate how miniAdapton permits memoization to benefit from *switching*, where the user updates `avar p1`, but then changes their mind and reverts its expression:

```
> (avar-set! p1 4)
> (avar-get p2)
7
> (avar-set! p1 (+ (avar-get n1) (avar-get n2)))
> (avar-get p2)
10
```

In this case, the original computation (with `p1` holding `(+ (avar-get n1) (avar-get n2))`) is recovered from the memoized cache.

By using Scheme's evaluator, rather than a special language that we define (as in the original Adapton work), our spreadsheet language can use primitives from Scheme, rather than having to encode them. In effect, we acquire the spreadsheet formulae language from Scheme, merely by using `avars`. As a simple example, we can immediately use other primitives (like multiplication) without having to re-define their meaning for this spreadsheet language:

```
> (avar-set! p1 (* (avar-get n1) (avar-get n2)))
10
> (avar-get p2)
13
```

Doing the equivalent in the original paper would have required modifying the interpreter, but here, Scheme's standard multiplication function suffices.

D. Set Implementation

The microAdapton implementation in Appendix A requires an implementation of sets. This appendix presents a minimal but sufficient list-based set implementation which yields the desired semantics. Most operations take linear time on average, which can cause microAdapton to run slowly when adding or deleting edges in an athunk that has large numbers of ingoing or outgoing nodes. More efficient set representations include self-balancing trees and hashtables. Mutable set implementations are also compatible with the microAdapton implementation in Appendix A, provided the microAdapton code is modified for the mutable interface.

```
(define empty-set '())
(define (set-mem e s)
  (memv e s))
(define (set-cons e s)
  (if (set-mem e s) s (cons e s)))
(define (set-rem e s)
  (filter (lambda (x) (not (eqv? e x))) s))
```

```
(define (set-union s1 s2)
  (fold-left set-cons s2 s1))
(define (set-intersect s1 s2)
  (fold-left set-rem s2 s1))
(define set-for-each for-each)
(define set->list (lambda (x) x))
```

E. Memoization

This appendix presents an implementation of memoization, compatible with the miniAdapton implementation in Appendix B.

```
(define (memoize f)
  (let ((s (make-kv-store)))
    (lambda x ; variadic memoization
      (let ((k/v (lookup-kv-store s x)))
        (if k/v
            (cdr k/v)
            (let ((result (apply f x)))
              (add-kv-store! s x result)
              result)))))))

(define simple-memoization-test
  (memoize (lambda x (read))))

(define-syntax lambda-memo
  (syntax-rules ()
    ((_ (args ...) body ...)
     (let ((f* (memoize
                (lambda (args ...)
                  body ...))))
       (lambda (args ...) (f* args ...))))))

(define-syntax define-memo
  (syntax-rules ()
    ((_ (f args ...) body ...)
     (define f (lambda-memo (args ...)
                          body ...))))))
```

The memoization code requires a key-value store implementation, such as this one, which uses association lists:

```
(define (make-kv-store) (list '()))
(define (add-kv-store! s k v)
  (set-car! s '((k . ,v) . ,(car s))))
(define (lookup-kv-store s k)
  (assoc k (car s)))
```

This key-value store implementation is inefficient, taking linear time looking up any item not currently in the store. For reasonable performance a more efficient key-value store implementation should be used. Most memoization implementations use hash tables, which typically take constant time for most operations. In addition, our implementation uses `equal?` (through `assoc`) where the more efficient pointer equality tests `eq?` or `eqv?` might be preferred.