

A novel approach to symbolic algebra

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Abstract

A prototype for an extensible interactive graphical term manipulation system is presented that combines pattern matching and nondeterministic evaluation to provide a convenient framework for doing tedious algebraic manipulations that so far had to be done manually in a semi-automatic fashion.

1 Introduction

Despite the availability of generic symbolic term manipulation packages – computer algebra systems like Mathematica, Maple, MuPAD, to name just a few well-known ones – and despite their wide application in calculation-intensive fields of study, such as (especially) theoretical physics, the necessity to do lengthy pen and paper calculations that take days or even weeks still persists – especially in string theory and related fields. The primary underlying reason for this seemingly paradoxical situation seems to be that the way how calculations are communicated to these automated systems does not mirror closely enough the way how one usually thinks about doing a calculation by hand. In particular, while these systems have their own ideas about implicit canonical reductions that should be applied to newly generated terms automatically, communicating a step to them as simple as ‘do quadratic completion on the second factor of the third summand’ that appears perfectly natural when mathematicians talk at the blackboard already requires comparatively sophisticated programming. While the presently available systems excel at doing lengthy symbol crunching along the lines of clearly stated procedures, it is especially their inherent weakness in doing user interaction that makes these systems virtually useless for the much more explorative calculation style one has to use frequently e.g. when trying to prove some algebraic property of a lengthy expression.

In this work, the `term-abacus` prototype is presented which targets specifically this problem. While this prototype is still in a too early stage to do any productive work with it, it both demonstrates the viability of the underlying approach and has reached a stage in its development where so many important design decisions have to be made that further scientific discussion is required first.

2 The Problem (and its solution)

To calculate means to apply transformation rules to a term. For operational purposes, one can regard these as substitutions having two parts: a *pattern* matching part of the structure of a term and a *template* that is parametrized by pieces of the pattern and dictates how the substitute has to be constructed. These rules can be quite complicated in some instances, and hence, due to human imperfection, lengthy pen and paper calculations are inherently prone to sloppiness errors. These are certainly not the only mistakes one can make, but the ones that can be avoided most easily by letting a machine take care of proper application of substitution rules. Furthermore, the less of one's time – and more importantly – mental energy one has to use for purely mechanical tasks, the more one can concentrate on the important aspects, and hence the deeper one can go.

Using pattern matching to express calculation rules is not a new idea – it plays a key role in many of the well known symbolic algebra systems, such as FORM or Mathematica, where it has proven its value. While many calculation rules can be formulated conveniently as pattern matching and substitution rules suitable for a computer (once an agreement on the underlying term representation has been made), one fundamental problem is that, quite in general, there often are different ways how to apply such a rule to a given term in a typical calculation. Whenever there is a purely mechanical way to decide which route to follow, the corresponding step in the calculation is not interesting, as it does not require human intelligence. But evidently, as every interesting calculation does require human intelligence for its solution, one is almost bound to encounter the difficulty to find a way to convey enough information to the machine to completely specify the particular transformation one has in mind. As this is a key issue in this work, we want to introduce special terminology here and from now on call this procedure *term clamping*.

It is essential that term clamping has to work in a most unobtrusive way, requiring as little thought from the end user as possible, or such a system would be perceived as clumsy and unusable when it comes to real-world applications.

First and foremost, this means that the amount of extra information that has to flow has to be minimized – typing a full command, or determining values for additional parameters, is already too much of a hassle. In addition, any information flowing back from the machine to the user during that process must be presented in such a way that it does not require any additional interpretation.

On the other side of the coin, it is strongly desirable to find a clean and concise way to express the logic behind term clamping in the program code of the implementation of a term manipulation system. The essence behind term clamping is basically a nondeterministic choice between different possible futures, introduced into the system by an intelligent (and hence unpredictable) human user. As humans usually do calculations on terms which they can easily capture visually as a whole, the truly minimal amount of information flows between human and machine if the machine offers a simple visual choice between all possibilities how to apply a given calculation rule to a term. For the program, however, this means that we have to produce multiple solutions to the problem of recognizing a given pattern inside some larger structure. This is most easily effected by making use of *ambiguous evaluation* [11, 1, 3].

Basically, this means that the system which we want to use to implement

such a term manipulation system should support a notion of making choices and forking a calculation into many different branches, each of which may produce its own result, or may turn out as futile and fail to return anything if the corresponding choice is incompatible with extra requirements we want to impose.

To give a specific example, suppose we wanted to extract all non-overlapping (unordered) pairs of triples of consecutive five-letter-words from a sentence such as:

The swift small brown horse might never ever allow being shoed

One would basically want to express an idea like that – which admittedly sounds a bit synthetic, but actually has a lot in common in structure with the calculation rule patterns we are interested in – in a Scheme [10]¹ program of roughly the following form²:

```
(define sentence
  '("The" "swift" "small" "brown" "horse"
    "might" "never" "ever" "allow" "being" "shoed"))

(define empty? null?)

(define (n-th n list)
  (if (empty? list)
      (fail)
      (if (= n 1)
          (first list)
          (n-th (- n 1) (rest list)))))

(define (n-th-rest n list)
  (if (= n 0)
      list
      (if (empty? list)
          (fail)
          (n-th-rest (- n 1) (rest list)))))

(define (find-three-consecutive-5-letter-words list-words)
  (let ((word1 (n-th 1 list-words))
        (word2 (n-th 2 list-words))
        (word3 (n-th 3 list-words)))
    (either
     (if (and (= (string-length word1) 5)
              (= (string-length word2) 5)
              (= (string-length word3) 5))
         list-words
         (fail))
     (find-three-consecutive-5-letter-words (rest list-words)))))

(define (find-pairs-3x5 list-words)
```

¹This work is based on the free MzScheme implementation, which belongs to the PLT Scheme family [13]

²Clearly, this has been written with readability for a broad public in mind; a seasoned programmer would e.g. most probably not let index counting start at 1. Hint to non-Scheme programmers: Scheme code is read mostly by indentation, ignoring most of the parentheses.

```

(let* ((first-occurrence
      (find-three-consecutive-5-letter-words list-words))
      (second-occurrence
      (find-three-consecutive-5-letter-words
       (n-th-rest 3 first-occurrence))))
  (list (list (n-th 1 first-occurrence)
             (n-th 2 first-occurrence)
             (n-th 3 first-occurrence))
        (list (n-th 1 second-occurrence)
             (n-th 2 second-occurrence)
             (n-th 3 second-occurrence))))

(all-values (find-pairs-3x5 sentence))

#| Result:

(((("swift" "small" "brown") ("horse" "might" "never"))
  (("swift" "small" "brown") ("allow" "being" "shoed"))
  (("small" "brown" "horse") ("allow" "being" "shoed"))
  (("brown" "horse" "might") ("allow" "being" "shoed"))
  (("horse" "might" "never") ("allow" "being" "shoed"))))

|#

```

Even if not the details, at least the general structure of this program should be understandable even for non-Scheme-programmers. What is especially interesting here is that failure of a calculation branch can happen at very different places, at different nesting levels in the calculation, that is, the calculation is highly non-uniform between different branches.

The Scheme programming language does not provide such highly unusual constructs like `either` or `fail` or `all-values`. But remarkably enough, it does provide an universal tool that allows one to catch the future of any given computation to store it away, or even call it multiple times (jettisoning the future of the current actual calculation itself), called `call-with-current-continuation`. With this, it is possible to seamlessly extend the language by virtually construct that involves highly nontrivial changes in execution flow – such as in particular nondeterministic features of exactly the form presented above – with little effort. Indeed, it can be done in less than fifty lines of extra code; this is explained in the appendix.

The example presented here indeed can be regarded as a specific instance of a matching problem of just the type that covers a large set of calculation rules. Under the premise of doing algebraic calculations, our terms generally will be sums of individual summands that consist of a coefficient plus a series of further factors that should be treated as noncommuting by default, as we want to be able to convey extra information in the order of factors. A typical ‘local’ calculation transformation will then have a form like

$$a_\mu a_\nu^\dagger \rightarrow a_\nu^\dagger a_\mu + \eta_{\mu\nu} \tag{2.1}$$

where it is understood that $a_\mu a_\nu^\dagger$ is a pattern that matches against a subsequence of two operators of types aa^\dagger that carry small Greek indices that have to be substituted into the expression on the right hand side wherever the corresponding actual indices mentioned in the rule appear.

Besides this, we also want to be able to apply rules where the location of individual pieces in the sequence of factors does not matter, and hence matching should succeed regardless of their position, and especially without first having to move pieces around. One simple example of such a rule would be:

$$\begin{aligned} \dots \epsilon_{ijk} \dots \epsilon_{imn} \dots &\rightarrow \dots \delta_{jm} \dots \delta_{kn} \dots \\ &- \dots \delta_{jn} \dots \delta_{km} \dots \end{aligned} \quad (2.2)$$

One will typically prefer to place the deltas in other places than in this specific example, but this is not essential here. What is important is this particular form of a pattern.

There furthermore are rules where one that have both properties at the same time, that is: one wants to match a number of specific fixed-length sequences of factors which may appear at various positions in a term. An example of a rule that is usually expressed in such a way is the Fierz-Pauli identity, which rather should be regarded as a collection of various calculation rules that allow to re-arrange certain expressions that carry four fermions (denoted by small Greek letters), such as³

$$\begin{aligned} \dots \psi \Gamma^\alpha \phi \dots \lambda \Gamma_\alpha \eta \dots &\rightarrow \dots \psi \eta \dots \lambda \phi \dots \\ &- \frac{1}{2} \dots \psi \Gamma^\alpha \eta \dots \lambda \Gamma_\alpha \phi \dots \\ &- \frac{1}{2} \dots \psi \Gamma^{\alpha\beta\gamma} \eta \dots \lambda \Gamma_{\alpha\beta\gamma} \phi \dots \\ &- \dots \psi \Gamma^5 \eta \dots \lambda \Gamma^5 \phi \dots \end{aligned} \quad (2.3)$$

This is – up to the issue of ordering pieces – precisely the structure of our text matching example: we want to be able to match a collection of non-overlapping fixed-length subexpressions with additional constraints in a sequence in all possible ways and let the user choose. This type of pattern is also so common that we should coin a special term for it – let us call this a sequences-of-factors-pattern, in short *sofpa*. At the core of the **term-abacus** prototype lies a nondeterministic sofpa-matching engine.

Internally, this matching engine produces a list of sub-sequences which carry annotations which part of the pattern they matched, or if they lie between patterns, plus information about identifications of jokers within these patterns.

While this general structure covers many calculation rules, there are as well examples of term transformations that cannot be expressed in such a way. Among those, however, one also finds many re-occurring structures. One major central concept which re-occurs in many guises but can not be captured in a sofpa rule is forming a variation of an entire term (not only a specific summand) along the lines of the Leibniz rule:

$$\delta(ab) = a(\delta b) + (\delta a)b \quad (2.4)$$

Within the present framework, the approach taken is to first implement them in a more ad-hoc way, and look for re-occurring structure that should be abstracted out while the prototype evolves.

In the present form of the prototype, a sofpa rule is represented internally as an associative list containing a pattern (which is a list of chains of factors), a substitution part, and additional information about highlighting telling which

³See any textbook on quantum field theory like [7] or [9]

matched parts of a pattern to display in a visually distinct way. In particular, a rule like quantum mechanical normal ordering

$$aa^+ \rightarrow a^+a + 1$$

is denoted internally as follows:

```
(define *rule-normal-ordering-a*
  '((pattern . ((, (as-pattern '?a '((a))
                  , (as-pattern '?a+ '((a "+"))))))
    (subs .
      #(; summands
        (1 .
          #(; one subs for every factor-block pattern
            ((a "+") ((a))))
          (1 .
            #((
              )))
          )))
    (highlighting .
      ((?a . green)
       (?a+ . green))))))
```

To the system, every term is a vector of pairs of a coefficient and a list of factors, and every factor within a summand is a pair of a stem and either an exponent or a list of tensor (upper and lower, which denote contravariant and covariant) indices. The stem itself consists of a symbol and additional ornaments which are symbol specific, that is, the system contains a set of hooks where one can provide arbitrary code that defines the meaning and visual representation of that particular symbol. Via those means, it is e.g. possible to extend the system by a definition of a `del` symbol which carries as ornament some other field plus an index and renders e.g. `((del ((F) (down . mu) (down . nu))) (down . rho))` visually as $\partial_\rho F_{\mu\nu}$. While one would wish to retain the highest possible flexibility for extending the system with new interpretations for term ornaments, there are a few slightly subtle issues including (but not limited to) behaviour under renaming of silent indices one has to be aware of. (Upon a closer look, category theory appears to be a language especially well suited to talk about these subtleties.)

At a more elementary level, the matcher tries to perform a one-to-one recursive structural match between pattern and value similar to the `equal?` Scheme function, but with the additional features that a special ‘joker symbol’ in the pattern (the default convention – which can be changed – is that all symbols whose name starts with a ‘?’ are joker symbols) matches either an arbitrary value, or if it occurs more than one time in the pattern, a set of `equal?` values. Furthermore, there are other special classes of jokers that e.g. match a sublist of arbitrary length of a given list (an inherently nondeterministic specification). One may also place jokers into the right-hand side substitution template, where they are either instantiated to the corresponding pieces matched by the template, or to letters from various alphabets with the additional guarantee that no such joker is instantiated to a letter that occurs somewhere else in the summand (this is to conveniently implement the generation of silent indices). If the pattern contains a function, this function is called with the corresponding

part of the value and information about previous matches as arguments and may nondeterministically fail, or provide multiple choices of further successful match information. One observes that this scheme is flexible enough to easily transfer the spirit of any complex pattern matching notion to this system, such as those of guards or as-patterns in Haskell, by using pattern-matching-function-generating-functions, like `as-pattern`, which maps a joker name and a sub-pattern to a function matching against the sub-pattern and, if successful, binding the matched value against the provided joker name.

The design decisions about the internal structure of terms are in part motivated by the goal to use it for tensor algebra as required for quantum field theory. While it may seem strange at first to provide direct support e.g. for such a special detail as tensor indices, which one might rather like to think of an issue to be resolved at the level of specifying factor ornaments, this actually turns out to be necessary. One may catch a glimpse of the underlying issues by observing that it certainly makes sense to allow factors to carry powers and provide direct support for this, while powers and indices are a non-orthogonal concept in the sense that one cannot make sense of an expression like $(C_{abc})^3$.

Clearly, the language in which calculation rules are expressed is still way too low-level to be of use to end users of the system, but as implementing application-specific languages (in the broadest sense) is what systems such as Scheme from the LISP family truly excel at [1], this is merely a question of experimenting with different notations until one is discovered that turns out to be simple, powerful, and well-suited for use by non-schemers.

A further comment has to be made concerning the possibility to use the flexibility of the system to transfer ‘sloppy’ calculations one-to-one to the machine – in the sense that one may choose representations of factors that are ignorant of certain aspects that are conceptually vital from the mathematical point of view (such as the dependency of fields on the particular point in space-time) but do not matter for some particular calculation one wants to do. While it is nice to specify all the mathematical structure in full detail, as this helps to come to a deep understanding of the subject and discover many interesting conceptual subtleties⁴, it is perhaps nevertheless a good idea not to impose too great restrictions on the level of rigor to the user, as the ability to leave even conceptually important details that turn out not to have any influence on the calculation out of the description does have its advantages.

To summarize this section, the problem of allowing the user to communicate choices about where to apply a given calculation rule if there are multiple possibilities is most directly expressed in terms of nondeterministic evaluation and continuations. This is a suitable language to formulate rule patterns in a concise fashion, but there are many details one has to be aware of that require additional discussion.

3 Anatomy of the term-abacus prototype

As mentioned previously, the `term-abacus` prototype is implemented in `MzScheme`, as this provides a lot of highly useful infrastructure such as lisp-style `defmacro` macros, a lexer and parser as well as (most important!) continuations and even

⁴One may consider especially the treatise on classical mechanics [15] as a prophetic exemplification of the power of this philosophy

a framework to implement continuation-based web services following the ideas presented in [4].

The first and foremost problem that has to be overcome is to find means to visually display terms in a convenient way and also allow user input. The requirement to support user input as well as the generic problem that solutions built by coercing various independent components to cooperate which were never intended to do so by making massive use of interprocess communication typically leads to brittle systems that may react very badly to version updates of individual components basically excludes any solution based on employing \TeX to do the rendering. While the idea may be tempting to try to implement this system as a special Emacs mode, as Emacs at least in spirit intends to be a substrate for such kinds of application, this does not work as the text rendering features of Emacs are not sophisticated enough to do term typesetting at the level required for this application with it. Furthermore, Emacs Lisp does not support continuations, not even closures. At first sight, \TeX macs [16] appears as a much more attractive alternative, being an Emacs-inspired WYSIWYG-style text editor with advanced \TeX rendering capabilities and a proper scheme (FSF's guile [5]) as scripting language. Unfortunately, \TeX macs is still quite power-hungry, and the amount of rendering functionality exported to Scheme was too small to build such a system on top of it for a long time (this may have changed by now).

An earlier LISP-based version of the `term-abacus` prototype used Screamer [14] to implement nondeterminism (which turned out too weak as it could not handle nondeterministic anonymous functions well and led to overly clumsy code) and Zebu [17] as parser generator, and employed an own simple renderer that was very loosely inspired by the way how monadic I/O works in Haskell to implement abstract rendering functionality which was then used by specialized renderers to generate \TeX , ASCII, as well as graphical output. \TeX output capability is evidently important to be able to directly use results obtained in `term-abacus`. ASCII output is important as we obviously need functionality to use a simple syntax for ASCII term input, and even with the most powerful system, one might want to do ad-hoc modifications not covered by any known calculation rule on terms that are best done by editing an ASCII representation. Graphical output was implemented by building a tree of typographic glyphs with additional relative positioning information which were then drawn by help of the `clg` [6] LISP-GTK interface, extended with some own functions. Eventually – mostly due to difficulties based on missing continuation support in LISP – MzScheme turned out to be a system much better suited to build this prototype on.

The switch to MzScheme made a very different and quite exciting approach to the rendering problem possible: as this Scheme implementation contains a full-fledged webserver and special infrastructure to build highly interactive continuation-based web services, the possibility to abuse a web browser with MathML support as a graphical front-end becomes feasible. (Incidentally, the idea behind employing continuations for web services is to use them to implement specialized control flow structures to hide all the underlying control transfer complexity – which comes from the web request-response model in this case. This is quite similar in spirit to the central idea behind `term-abacus`.) This is attractive for two reasons: first, MathML is gradually emerging as a standard for typesetting formulae that can be used with a variety of different

applications, second, this immediately allows one to provide all the functionality of this system as a web service. The drawback of such an approach is that it brings along certain restrictions concerning the user interface. Basically, experience tells us that in order to use such a system in a fast and efficient way, one wants to be able to use it via keystroke commands, which means that JavaScript has to be used to a certain extent to implement the user side of the system, and furthermore, there are limitations on the keystroke commands one may use as some interfere badly with web browser internal keystroke commands. Another issue is that MathML support is still poor with many graphical web browsers. At present, the prototype is intended to be a system which specifically abuses the mozilla firefox browser[8] as graphical interface which accidentally also can be used over the internet and not yet a generic browser independent web application. Firefox users which have appropriate fonts for MathML installed⁵ can have a peek at an early stage of the system, which is under active development, at <http://term-abacus.aei.mpg.de:8000> (the source is also available there).

The current MathML renderer is a modified variant of the \TeX renderer that was transliterated directly from the LISP predecessor and still uses string blocks and templates internally. This is bound to change, as XML (of which MathML is an application) can be embedded directly into Scheme S-expressions, which is considered a much cleaner and more powerful approach.

Besides the matching engine, the renderer and the web interface code, another important component of the system is the term input parser. At present, the intention behind this parser is to provide the most basic means to input terms as strings like

```
-7/2 e**4 X_a_b Q^a^b_alpha + 5 Z_alpha
```

only in order to keep things simple, but also be extensible by allowing users to register (almost) arbitrary extra parsers for special symbols that process symbol ornaments. The only restriction on such special user-definable parsers is that symbol ornaments will be delimited by matching pairs of brackets []; hence, it is easily possible to introduce e.g. a user-defined parser for things like lepton spinor factors using a syntax like `u[bar,mu;p_1]` or `v[tau;p_2]` if the application wants this, but it is not possible to introduce parsers for ornaments with non-well-formed bracket structure. At the implementation level, a two-stage LALR(1) parser is constructed employing MzScheme's parser generator functionality as it is not possible to let matching brackets delimit tokens by employing a regular lexer only.

4 Conclusions and Outlook

While the idea to build a term manipulation system that is suited for a much more interactive style of working than all other existing symbolic algebra packages by using nondeterministic language to concisely model user interaction non-determinism at the level of the implementation is very attractive, and has been shown to be feasible with very moderate programming effort, this approach still has to prove its value, as the prototype implemented here is still a bare-bones system that provides all the abstract functionality to implement specific term

⁵Debian GNU/Linux users should install the `latex-xft-fonts` package

manipulation systems on top of it, but no such system that uses `term-abacus` has been constructed yet. At least, preliminary experiments with an implementation of a thermodynamics-oriented term algebra of partial derivatives on top of the LISP-based predecessor of that system seemed quite promising. One interesting smoke test that should be within reach with justifiable effort would be to implement a set of transformation rules which allow one to do calculations such as the derivation of the Lagrangian of eleven-dimensional supergravity [2] as easily as possible. This should also show where the `term-abacus` system still requires to be refined and extended.

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Appendix: On nondeterministic evaluation and Scheme

While continuation-based techniques are well established in the functional programming community, they gained surprisingly little attention (especially when considering their power) in the mainstream so far. Considering especially their perceived usefulness for building highly interactive web services – an approach that was popularized especially by Paul Graham [4] – they may well be on the verge of becoming the next hot issue that makes its way into the mainstream via convoluted paths which has been known to lisp hackers for decades – just as it was the case with standardized support for hash tables, print-read-consistency for textual representations of recursively structured data [12], proper garbage collection, and many others.

The basic idea behind continuations is that there is a symmetry between calling a function and returning a value from a function, the latter one being just a ‘call to the function representing the entire future of the present calculation’. If we forget about technicalities such as when to free which type of memory object, then on the conceptual level, even the return address from a C function on the stack may just as well be regarded as an extra function pointer parameter denoting ‘the entire rest of the program as a callable function to which we pass on our return value’. With this philosophy in mind, it is possible to mechanically transform every program to so-called ‘continuation passing style’ (CPS) where all functions take as an extra parameter. For a very simple function like a naive implementation of the factorial, this would look as follows:

```
(define (factorial n)
  (if (= n 0) 1 (* n (factorial (- n 1)))))

;; === the same after a full CPS transform ===

(define (return x)
  (lambda (c) (c x)))

(define (cps= cont-a cont-b cont)
  (cont-a
```

```

(lambda (a)
  (cont-b
    (lambda (b)
      (cont (= a b)))))))

(define (cps* cont-a cont-b cont)
  (cont-a
    (lambda (a)
      (cont-b
        (lambda (b)
          (cont (* a b)))))))

(define (cps- cont-a cont-b cont)
  (cont-a
    (lambda (a)
      (cont-b
        (lambda (b)
          (cont (- a b)))))))

(define (cps-if cont-test cont-then cont-else cont)
  (cont-test
    (lambda (bool)
      (if bool
          (cont-then cont)
          (cont-else cont)))))

(define (cps-factorial cont-n cont)
  (cps-if
    (lambda (c) (cps= cont-n (return 0) c))
    (return 1)
    (lambda (c)
      (cps* cont-n
        (lambda (c)
          (cps-factorial
            (lambda (c) (cps- cont-n (return 1) c)) c))
        c))
    cont))

;; (cps-factorial (return 5) display) ==> 120

```

Note that in the definition of `cps-factorial`, there is not a single place left where a value is returned; furthermore, execution order is totally specified now. While transformation to CPS plays an important role ‘under the hood’ of a scheme system, complex code written in full CPS style is evidently almost unreadable to human beings. It needn’t be, however, as all continuation-related issues are hidden from the user, the only exception being just the `call-with-current-continuation` function (and the values it generates), which allows the user to get a handle at the future of the entire program at an arbitrary point to store it away and *jump* back to this place in the program at any point in time, even multiple times, with all the surrounding context properly set up.

This construct gives us a bewildering flexibility to extend the language with new control flow constructs. For example, nondeterministic evaluation as used

in the term-abacus prototype may be implemented along the following lines (the idea being to let all-values jump down deeply into a calculation which contains many choice points over and over again until all choices have been seen and the list of all values is passed on to its own continuation):

```
(require (lib "defmacro.ss"))

(define call/cc call-with-current-continuation)
(define __cont-other '())

(define (__all-values lambda-expr)
  (let ((results '()))
    (fluid-let ((__cont-other '()))
      (call/cc
        (lambda (ret) ; catch the continuation of all-values
          (set! __cont-other '(,(lambda () (ret (reverse results))))))
          (set! results (cons (lambda-expr) results))
          ((car __cont-other))))))

(define-macro (all-values . body)
  '(__all-values (lambda () . ,body)))

(define (choose choices)
  (let ((rest-choices choices))
    (call/cc (lambda (c) (set! __cont-other (cons c __cont-other))))
    (if (null? rest-choices)
      (begin
        (set! __cont-other (cdr __cont-other))
        ((car __cont-other)))
      (let ((next (car rest-choices)))
        (set! rest-choices (cdr rest-choices))
        next))))

;; This must be a macro, since we do not want to eval this and that!
;; primitive method, just along the lines of CHOOSE.

(define-macro (either this that)
  (let ((sym-c (gensym "c-"))
        (sym-todo (gensym "todo-"))
        (sym-next (gensym "next-")))
    '(let ((,sym-todo (list (lambda () ,this) (lambda () ,that))))
      (call/cc
        (lambda (,sym-c) (set! __cont-other (cons ,sym-c __cont-other))))
      (if (null? ,sym-todo)
        (begin
          (set! __cont-other (cdr __cont-other))
          ((car __cont-other)))
        (let ((,sym-next (car ,sym-todo)))
          (set! ,sym-todo (cdr ,sym-todo))
          (,sym-next))))))

(define (fail) (choose '()))

;; (all-values (cons (choose (list 1 (choose (list 2 3))))))
```

```
;;          (+ 100 (choose (list 10 20 30))))
;; => ((1 . 110) (1 . 120) (1 . 130))
;;      (2 . 110) (2 . 120) (2 . 130))
;;      (1 . 110) (1 . 120) (1 . 130))
;;      (3 . 110) (3 . 120) (3 . 130))
```

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Calculation - Mozilla Firefox

File Edit View Go Bookmarks Tools Help

http://localhost:8000/serve

Firefox Help Firefox Support Plug-in FAQ

Apply normal-order here?

$$7 a a + a - 3 a a a + + 2 a a + a a +$$

Gives:

$$-3 a a + a - 3 a$$

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