GNU epsilon

an extensible programming language

Luca Saiu
<positron@gnu.org>

LIPN, Université Paris 13

PhD defense — Villetaneuse, 2012-11-19

Advisors: C. Fouqueré, J.-V. Loddo
Reviewers: E. Chailloux, M. Mauny
Jury: R. Di Cosmo, M. Serrano, B. Starynkevitch, P. Van Roy

We want more expressive languages

A crude chronology of programming language features:

- 1960s: structured programming, recursion, symbolic programming, higher order, garbage collection, meta-programming, object orientation, concatenative programming
- 1970s: relational programming, first-class continuations, quasiquoting, type inference
- 1980s:
- 1990s:
- 2000s:

We want more expressive languages

A crude chronology of programming language features:

- 1960s: structured programming, recursion, symbolic programming, higher order, garbage collection, meta-programming, object orientation, concatenative programming
- 1970s: relational programming, first-class continuations, quasiquoting, type inference
- 1980s: logic programming, constraint programming, purely functional programming
- 1990s: monads in programming; *err...* components?
- 2000s: *err...*

We should work harder to *improve expressivity*.

"Modern" languages aren't expressive enough

- Program requirements get more and more complex
- Programs grow, too: $\sim 10^6$ LoC is not unusual
- But languages don't evolve fast enough
  - Programs are hard to get right
  - Sometimes we *do* need to prove properties about programs (by machine, for realistic programs)...
    - ...so we need *formal specifications* for languages (necessary but not sufficient)

"Modern" languages are *way* too complex for proofs

- *The Definition of Standard ML, Revised Edition*, 1997, **128 pp.** (**very dense** formal specification)
- *Revised^6 Report on the Algorithmic Language Scheme*, 2007 **187 pp.**; R^{7}RS-WG1, 2013?, ∼**88 pp.** (**non-normative and partial** formal specification in an appendix)
- *Haskell 98 Language and Libraries – The Revised Report*, 2003, **270 pp.** (**no** formal specification)
- *ISO/IEC 9899:201x Programming languages – C*, March 2009 draft, **564 pp.** (**no** formal specification)
- *The Java Language Specification*, Third Edition, June 2009, **684 pp.** (**no** formal specification)
- *ANSI INCITS 226-1994 (R2004) Common Lisp*, **1153 pp.** (**no** formal specification)
- *ISO/IEC 14882:2011: Programming Language C++*, **1324 pp.** as per the N3337 draft (**no** formal specification)

The silver bullet in my opinion: **reductionism**

What killer features do we need?

- Of course I've got opinions, but in general **I don't know**
- So, *delay decisions* and let users build the language
  - Small core language
  - Syntactic abstraction
  - Formal specification
- We need radical experimentation again!
  - Many *personalities* on top of the same *core language*

Minimalistic, extensible languages: Scheme [and Forth]

Programming languages should be designed not by piling feature on top of feature, but by removing the weaknesses and restrictions that make additional features appear necessary. Scheme demonstrates that a very small number of rules for forming expressions, with no restrictions on how they are composed, suffice to form a practical and efficient programming language that is flexible enough to support most of the major programming paradigms in use today.

Revised^{i} Report on the Algorithmic Language Scheme
$i \in [3..6]$ — 1980s-2007

Sample extension: McCarthy's `amb` *backtracking operator*

Problems I see with Scheme

- High-level core
  - higher-order, closures, continuations
  - hard to compile efficiently and analyze...
  - ...you pay for the complexity of `call/cc` even when you don't use it
    - performance, in some implementations
    - intellectual complexity
- Still relatively complex
  - Latest official standard (R^{6}RS, 2007): 187 pages *in English*
    - R^{7}RS WG1 will be smaller: 88 pages as of November 2012
  - Too big to have a complete formal specification

The *reductionism* idea is not new.

"a language design of the old school is a pattern for programs. But now we need to 'go meta.' We should now think of a language design as a pattern for language designs, a tool for making more tools of the same kind. [...] My point is that a good programmer in these times does not just write programs. A good programmer builds a working vocabulary. In other words, a good programmer does language design, though not from scratch, but by building on the frame of a base language."
[my emphasis]

The *reductionism* idea is not new.

"a language design of the old school is a pattern for programs. But now we need to 'go meta.' We should now think of a language design as a pattern for language designs, a tool for making more tools of the same kind. [...] My point is that a good programmer in these times does not just write programs. A good programmer builds a working vocabulary. In other words, a good programmer does language design, though not from scratch, but by building on the frame of a base language."
[my emphasis]

—**Guy L. Steele Jr.**, ***Growing a Language***, **1998**

The *reductionism* idea is not new.

"a language design of the old school is a pattern for programs. But now we need to 'go meta.' We should now think of a language design as a pattern for language designs, a tool for making more tools of the same kind. [...] My point is that a good programmer in these times does not just write programs. A good programmer builds a working vocabulary. In other words, a good programmer does language design, though not from scratch, but by building on the frame of a base language."
[my emphasis]

—Guy L. Steele Jr., ***Growing a Language***, 1998

He planned to build on Java (!)
To Steele's credit, his later proposals based on Fortress are more realistic.

Reflection (1/2: self-analysis)

The program has to be able to **(1)** *access its own dynamic state*:

- *Analyses* on the program state:
  - **self-analysis**: in the style of static analyses (for example type inference);
  - **"*unexec*" operation**: dump the current dynamic state (to files, sockets...) — *definable as an ordinary procedure*;
  - **compilation** — *definable as an ordinary procedure*

Reflection (2/2: self-modification)

The program has to be able to **(2)** *update* its own state, including procedures, «*à chaud*»:

- Transformations à-la-CPS
- **Code optimizations** [my idea: nondeterministic rewrite system, hill-climbing]
- «Compile-time» garbage collection

Point **(2)** is more delicate

- Use syntax abstraction to rewrite into non-self-modifying programs *where possible*...
  - ...otherwise inefficient and unanalyzable (but *not* an "error")

Our core language ε_0

We call our core language ε_0.

ε_0 is a first-order imperative language of global recursive procedures, with threads. Here's its *complete* grammar:

$$
\begin{array}{l}
e ::= \\
\quad\quad x_h \\
\quad\mid c_h \\
\quad\mid [\texttt{let}\ x^*\ \texttt{be}\ e\ \texttt{in}\ e]_h \\
\quad\mid [\texttt{call}\ x\ e^*]_h \\
\quad\mid [\texttt{primitive}\ x\ e^*]_h \\
\quad\mid [\texttt{if}\ e \in \{c^*\}\ \texttt{then}\ e\ \texttt{else}\ e]_h \\
\quad\mid [\texttt{fork}\ x\ e^*]_h \\
\quad\mid [\texttt{join}\ e]_h \\
\quad\mid [\texttt{bundle}\ e^*]_h
\end{array}
$$

Our core language ε_0 **[This is the *core language* grammar!]**

We call our core language ε_0.

ε_0 is a first-order imperative language of global recursive procedures, with threads. Here's its *complete* grammar:

$$
\begin{aligned}
e ::= \; & x_h \\
\mid \; & c_h \\
\mid \; & [\texttt{let}\ x^*\ \texttt{be}\ e\ \texttt{in}\ e]_h \\
\mid \; & [\texttt{call}\ x\ e^*]_h \\
\mid \; & [\texttt{primitive}\ x\ e^*]_h \\
\mid \; & [\texttt{if}\ e \in \{c^*\}\ \texttt{then}\ e\ \texttt{else}\ e]_h \\
\mid \; & [\texttt{fork}\ x\ e^*]_h \\
\mid \; & [\texttt{join}\ e]_h \\
\mid \; & [\texttt{bundle}\ e^*]_h
\end{aligned}
$$

Why ε_0 has no side effects or definitions

The ε_0 grammar lacks explicit *side effect* and *definition* operators. Our "initial state" (globals, primitives, procedures, memory, ...) will allow:

- memory side effects *by primitives*
  - *store* is a primitive among *load*, *allocate*, ...
- global and procedure definitions by *procedures*
  - Global tables for globals and procedures, in memory

So, programs can *self-modify*:

- if a program doesn't, it can be compiled more efficiently

A feel of ε_0 dynamic semantics: sample rules

$$\frac{}{([\texttt{call}\ f\ e_{h_1}...e_{h_n}]_{h_0},\ \rho).S\ \ \wr V\ \ \ \Gamma \longrightarrow_{\mathbb{E}} (e_{h_1},\ \rho)...(e_{h_n},\ \rho).([\texttt{call}\ f\ \Box]_{h_0},\ \varnothing).S\ \ \wr\ddagger V\ \ \ \Gamma}$$

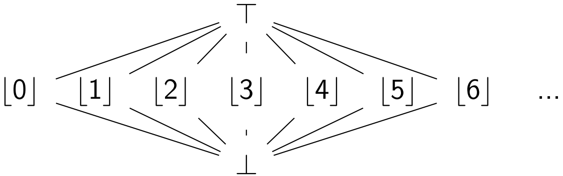
$$\frac{}{([\texttt{bundle}\ \Box]_{h_0},\ \rho).S\ \ \wr c_n \wr c_{n-1} \wr ... \wr c_2 \wr c_1 \wr \ddagger V\ \ \ \Gamma \longrightarrow_{\mathbb{E}} S\ \ \wr c_n c_{n-1} ... c_2 c_1 \wr V\ \ \ \Gamma}$$

$$\frac{}{([\texttt{join}\ \Box]_{h_0},\ \rho).S\ \ \wr \mathcal{T}(t) \wr V\ \ \ \Gamma \longrightarrow_{\mathbb{E}} S\ \ \wr c_t \wr V\ \ \ \Gamma}\ \Gamma_{\texttt{futures}} : t \mapsto (\langle\rangle,\ \wr c_t \wr)$$

The full dynamic semantics of ε_0 fits in *two* pages; *three* if we also include failure semantics.

My ε_0 semantics is actually usable

- Formally developed "dimension analysis", as a sample static analysis on ε_0 programs — a form of type inference



- Dimension analysis *proved sound* with respect to dynamic semantics:

"well-dimensioned programs do not go wrong"

User syntax: by s-expressions

Lisp-style s-expressions are a data structure convenient for encoding syntax.

- A "list" structure:

```
(average x 10)
```

User syntax: by s-expressions

Lisp-style s-expressions are a data structure convenient for encoding syntax.

- A "list" structure:

```
(average x 10)
```

- The same structure, making conses explicit:

```
(average . (x . (10 . ())))
```

User syntax: by s-expressions

Lisp-style s-expressions are a data structure convenient for encoding syntax.

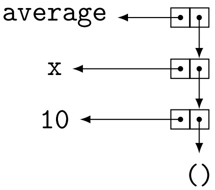
- A "list" structure:

```
(average x 10)
```

- The same structure, making conses explicit:

```
(average . (x . (10 . ())))
```

- The same structure, graphically:



Expansion of s-expressions into ε_0 expressions (1/2)

A trivial encoding for ε_0 syntax into s-expressions.

We use the s-expression

$$(\overbrace{\texttt{e0:if-in}}^{\text{form name}}\ \underbrace{\texttt{x (1 4 6) 10 50}}_{\text{sub-forms}})$$

to represent the ε_0 conditional expression

$$[\texttt{if}\ x_{h_2} \in \{1, 4, 6\}\ \texttt{then}\ 10_{h_3}\ \texttt{else}\ 50_{h_4}]_{h_1}$$

for some fresh handles h_1, h_2, h_3, h_4.

Expansion of s-expressions into ε_0 expressions (2/2)

Default case, if the first element is not a form name:

We use the s-expression

$$(\,\overbrace{\texttt{average}}^{\text{operator}}\ \underbrace{\texttt{x 10}}_{\text{operands}}\,)$$

to represent the ε_0 procedure call

$$[\texttt{call average x}_{h_2}\ \texttt{10}_{h_3}]_{h_1}$$

for some fresh handles h_1, h_2, h_3.

Extension mechanisms

Even with side effects and definitions, ε_0 is inconvenient to use directly.

We introduce two syntactic extension mechanisms:

- a *macro* rewrites an s-expression into an expression
  - [in case you're wondering: *not homoiconic*, unlike Lisp]
  - "local": it cannot access its surrounding s-expression
- a *transform* rewrites an expression into another expression
  - "global" syntactic abstraction (example: Closure Conversion)

Sample macroexpansion (s-expression to ε_0)

User-defined forms can also be encoded as s-expressions.

An example with the *sequential composition macro* $\overbrace{\texttt{e1:begin}}^{\text{a single name}}$:

```
(e1:begin
  (string:write "The result is ")
  (fixnum:write n)
  (string:write "\n"))
```

$$\Rightarrow$$

$[\texttt{let}\ \langle\rangle\ \texttt{be}\ [\texttt{call string:write "The result is "}_{h_3}]_{h_2}\ \texttt{in}$
$[\texttt{let}\ \langle\rangle\ \texttt{be}\ [\texttt{call string:write n}_{h_6}]_{h_5}\ \texttt{in}\ [\texttt{call string:write "\textbackslash n"}_{h_8}]_{h_7}]_{h_4}]_{h_1}$

for some fresh handles $h_1, h_2, h_3, h_4, h_5, h_6, h_7, h_8$.

A sample macro definition

A *definition* of `e1:begin`, as a quite simple (recursive) macro:

```
(e1:define-macro (e1:begin first-form . more-forms)
  (e0:if-in (sexpression:null? more-forms) (#t)
    first-form
    `(e0:let () ,first-form
       (e1:begin ,(sexpression:car more-forms)
                 ,@(sexpression:cdr more-forms)))))
```

In case you're wondering:

- quasiquote is itself a macro; quasiquoting (like quoting) yields an *expression*
- `e1:define-macro` is itself a macro, built on `e1:destructuring-bind`, yet another macro

Transforms (à-la-CPS)

Expression-to-expression rewriting, to be applied to *all toplevel forms* from a certain point on, or *to the whole program*.

- define an ordinary procedure turning an expression into another expression
- "install" it so that it is automatically applied from now on (possibly even retroactively, as for CPS)

Ask me later if you want more details [presentation part 4]

The ε_1 personality

Also including the syntax we've just shown, the ε_1 personality is a set of extensions to conveniently write other personalities.

- S-expression syntax à-la-Lisp
- *macroexpansion* and *transforms*
- many general-purpose syntactic forms to make the user's life easier

ε_1 as a programming language:

- Lispy feel; low-level, potentially efficient
- *untyped (not even dynamically-typed)*

I implemented ε_1 on top of ε_0

I implemented ε_1 in ε_0 :

- I defined the *macroexpansion* and *transformation* machinery in ε_0
- then ε_1 syntactic forms, by macros and transforms
  - expressivity grows fast: I can use an extension to build the next one

Main ε_1 forms (defined over ε_0) (1/2)

Just showing syntactic construct *names*:

`e1:begin`, `e1:if`, `e1:when`, `e1:unless`, `e1:and`, `e1:or`, `e1:cond`, `sexpression:quote`, `sexpression:quasiquote`, `e1:quote`, `e1:quasiquote`, `e1:destructuring-bind`, `e1:define-macro`, `e1:define`, `list:list`, `sexpression:list`, `e1:case`, `e1:let*`, `variadic:call-left-deep`, `variadic:call-right-deep`, `variadic:call-associative`, `variadic:define-left-deep`, `variadic:define-right-deep`, `variadic:define-associative`, `fixnum:+`, `fixnum:-`, `fixnum:*` [variadic versions], `e1:begin1`, `e1:begin2` ... `e1:begin-2`, `e1:value-list`, `tuple:make`, `tuple:explode`, `tuple:with`, ...

Main ε_1 forms (defined over ε_0) (2/2)

…, `set-as-list:make`, `set-as-list:union`, `set-as-list:intersection`, `set-as-list:subtraction`, `record:define`, `sum:define`, `sum:define-open`, `sum:extend-open`, `e1:lambda`, `closure:ml-lambda`, `e1:call-closure`, `e1:named-let`, `e1:do`, `e1:while`, `e1:dolist`, `e1:dotimes`, `e1:for`, `e1:let` [including *named let*], `e1:future`, `e1:join`, `unexec:unexec`, `e1:match` [ML-style pattern matching].

- Notice that we included **closures** (`e1:lambda`).

Some ε_1 forms are defined with transforms

Some code-to-code transformations depend on the context.

- *Closure-conversion*
  - expression non-locals depend on context
- *First-class continuations* with `e1:call/cc` (experimental)
  - inherently *global*: CPS-transformed expressions are incompatible with untransformed ones

Bootstrap: implementing $\varepsilon_1/\varepsilon_0$

ε_0 syntax encoded by s-expressions: using Guile Scheme, plus C for primitives.

- Data structures as untyped memory buffers, with pointers
  - primitives to allocate, load, store
- s-expression as a data structure: "open" sum type;
  - *expressions* (themselves an open sum!) as one case;
- Reliance on the *s-expression parser* from Guile's frontend

Bootstrapping final step:

- Unexec
- exec into a different runtime implementation

  (final data representation more efficient than Guile's)

Back to soundness proofs: ε_1 properties

The static semantics we proved sound was on ε_0.

How to do soundness proofs on ε_1 (or higher-level personalities):

- provide *informal* "abstract syntax" for ε_1 forms and mappings to ε_0. Example:
  - $[\![[\texttt{begin}\ e_{h_1}]_h]\!] =$ $[\![e_{h_1}]\!]$
  - $[\![[\texttt{begin}\ e_{h_1}\ e_{h_2}\ \ldots\ e_{h_n}]_h]\!] =$ $[\texttt{let}\ \langle\rangle\ \texttt{be}\ [\![e_{h_1}]\!]\ \texttt{in}\ [\![[\texttt{begin}\ e_{h_2}\ \ldots\ e_{h_n}]_{h'}]\!]]_{h''}$
- Use properties on ε_0 forms as lemmas for properties on ε_1 forms

Just an idea for future work.

Parallel garbage collector

Memory management may be a bottleneck in high-level parallel programs

- parallel mark-sweep, conservative pointer finding, no safe points
- BiBOP, efficient for programs where most heap-allocated objects have one of a few shapes
- scales well on multi-cores, on micro-benchmarks (8 cores)
- nontrivial — 5000 lines of (heavily commented) C
- currently not generational
    - promising *as the old generation* of a generation system

GNU epsilon project: current status

- bootstrapped from Guile Scheme
  - now I only use Guile for its s-expression parser/printer
- three different runtimes: *untagged*, *tagged*, based on Guile
- ε_0 interpreter in itself (slow), in C (fast)
- unexec
- closure-conversion as a transform
  - unexpected uses: imperative loops, friendly syntax with nonlocals for futures and unexec
- experimental CPS transform

GNU epsilon project: short-term developments

Developed but not integrated yet:

- parallel BiBOP collector
  - another garbage collector, sequential semispace [suitable as the young generation when joined];
- prototype compiler;
- extensible scanner (in OCaml; partial translator to maintainable ε_1);
- custom virtual machine written in low-level C (threaded code), native backends easy to add;

About ε

http://www.gnu.org/software/epsilon

GNU epsilon is free software, released under the GNU GPL version 3 or later.

You're welcome to share and change it under certain conditions; please see the license text for details.

Conclusion

- Reductionism is a viable style of designing and implementing practical programming languages, leading to solutions which are easier to extend, experiment with and formally analyze.
- Strong syntactic abstraction makes easy what is *impossible* in other languages
- Thanks to reflection we can build language tools as part of the program
- Performance doesn't need to be bad

Conclusion

- Reductionism is a viable style of designing and implementing practical programming languages, leading to solutions which are easier to extend, experiment with and formally analyze.
- Strong syntactic abstraction makes easy what is *impossible* in other languages
- Thanks to reflection we can build language tools as part of the program
- Performance doesn't need to be bad

Thank you

— thanks to LIPN and Université Paris 13 as well, for having supported me in this endeavor

Backup slides

4. A transform definition in (some) detail
   - Add new expression cases, and their syntax
   - Define ordinary procedures
   - Install transform procedures
5. Approximated tombstone diagrams
   - Interpreters
   - Runtimes
   - Unexec

Sample transform (1/5: add new expression cases)

```
(sum:extend-open e0:expression
  (lambda handle formals body)
  (call-closure handle closure-expression actuals))

;; Define "builder" procedures like for ε0 expression cases:
(e1:define (e1:lambda* formals body)
  (e0:expression-lambda (e0:fresh-handle) formals body))
(e1:define (e1:call-closure* closure-expression actuals)
  (e0:expression-call-closure (e0:fresh-handle)
                              closure-expression
                              actuals))
```

In case you're wondering:

- expressions are a sum type à-la-ML, open to new cases (like exn in OCaml)
  - sum types definition and extension operators are macros...
  - ultimately just untyped memory structures: integers, pointers to buffers

Sample transform (2/5: add new expression case syntax)

The macro for our new forms will call the builder procedures at macroexpansion time:

```
(e1:define-macro (e1:lambda formals . body-forms)
  (sexpression:inject-expression
    (e1:lambda* (sexpression:eject-symbols formals)
                (e1:macroexpand `(e1:begin ,@body-forms)))))

(e1:define-macro (e1:call-closure closure-expression . actuals)
  (sexpression:inject-expression
    (e1:call-closure* (e1:macroexpand closure-expression)
                      (e1:macroexpand-sexpressions actuals))))
```

In case you're wondering:

- *injection* and *ejection* convert to and from s-expressions.

Sample transform (3/5: ordinary recursive procedure)

```
(e1:define (closure-convert expression bound-variables)
  (e1:match expression
    ((e0:variable x)
     (e0:variable* x))
    ((e0:let let-variables bound-expression body)
     (e0:let* let-variables
              (closure-convert bound-expression
                               bound-variables)
              (closure-convert body
                               (set:union bound-variables
                                          let-variables))))
    ;; ... the actually interesting cases ...
   ))
```

In case you're wondering:

- `e1:match` is a macro (quite long, but no transforms are needed)
- expressions are an ordinary sum type à-la-ML
    - sum types à-la-ML are defined with macros...

Sample transform (4/5: transform procedures)

Again ordinary procedure definitions, with the good “types”.

```
(e1:define (closure-convert-expression expression)
  (closure-convert expression set:empty))

(e1:define (closure-convert-procedure name formals body)
  (e0:bundle name
             formals
             (closure-convert body
                              formals)))
```

Sample transform (5/5: install)

```
(transform:prepend-expression-transform!
    (e0:value closure-convert-expression))

(transform:prepend-procedure-transform!
    (e0:value closure-convert-procedure))
```

From now on we can execute `e1:lambda` and `e1:call-closure`.

In case you're wondering:

- Some transforms have to be applied retroactively (ex.: CPS)
  - `transform:transform-retroactively!`

Tombstone diagrams: interpreters

Bootstrap ε_0 interpreter, ε_0 interpreter in C:

ε_0
Guile

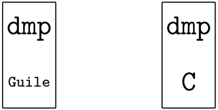
ε_0
C

ε_1 implementation:

ε_1
ε_0

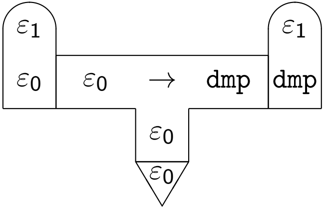
Tombstone diagrams: runtimes

Guile runtime, efficient runtime:



Tombstone diagrams: unexec

Unexec:



ε_1 is built on top of ε_0 by side effects, as a program. An interactive REPL is also effectively a program.