A Programmable Programming Language

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In addition to libraries and packages, programmers develop and use embedded problem-specific languages as building blocks of software systems. These languages help developers state solutions for the various aspects of the problem in appropriate terms. Complete software systems compose these partial solutions into a coherent whole. Sadly, this form of work is conducted without real support from the underlying programming language.

What this emerging development method calls for, then, are programming languages that make the creation and use of embedded languages as convenient as the creation of libraries. Implementing this kind of programming language has been the goal of our 20-year-old Racket project. This paper presents the state of the project and sketches how it will proceed.

1 PROBLEMS VS PROGRAMMING LANGUAGES

In the ideal world, software developers ought to analyze each problem in the language of its domain and then articulate solutions in matching terms. They could thus easily communicate with domain experts and separate problem-specific ideas from the details of general-purpose languages and specific program design decisions.

In reality, however, programmers use a mainstream programming language that someone else picked for them. To compensate for this conflict, they resort to—and on occasion build their own—domain-specific languages embedded within the chosen language (eDSLs).

For example, JavaScript programmers employ jQuery for interacting with the DOM and React for dealing with events and concurrency. As developers solve their problems in inappropriate eDSLs, they compose these solutions into one system. In short, developers effectively write multi-lingual software in a common host language.

Sadly, multi-lingual eDSL programming currently rests on an ad hoc basis and is rather cumbersome. To create and deploy a language, programmers must usually step outside the chosen language—a process which requires significant time and effort.

Finally, most available IDEs do not even understand eDSLs or perceive the presence of code written in eDSLs.

The goal of the Racket project is to explore this emerging idea of language-oriented programming (LOP) at two different levels. At the practical level, our goal is to build a programming language that enables language-oriented software design. This language must facilitate the easy creation of eDSLs, the immediate development of components in these newly created languages, and the integration of components in distinct eDSLs.

At the conceptual level, the case for LOP is analogous to the ones for object-oriented programming or for concurrency-oriented programming [3]. The former arose from making the creation and manipulation of objects syntactically simple and dynamically cheap, the latter from Erlang’s inexpensive process creation and message passing. Both of these innovations enabled new ways of developing software and triggered research projects. The question is how we will realize LOP and how this will affect the world of software.

The decision to develop a new language, Racket, is partly a historical artifact and partly due to our desire to free ourselves from any unnecessary constraints of industrial mainstream languages while we investigate LOP. The next section spells out how Racket got started, how we honed in on LOP, and what this idea implies.

2 THE PRINCIPLES OF RACKET

The Racket project dates back to January 1995, when we started it as a language for experimenting with pedagogic programming languages [15]. Working on these languages quickly taught us that a language itself is a problem-solving tool. We then soon found ourselves developing different languages for different parts of the project: one (meta-) language for expressing many pedagogic languages; another one for specializing the DrRacket IDE [15]; and a third for managing configurations. In the end, our software was a multi-lingual system—just as described in the introduction.

Racket’s guiding principle reflects the insight we gained:

Empower programmers to create new programming languages easily and to add them with a friction-free process to a code base.

With "language" we mean a new syntax, a static semantics, and a dynamic semantics, which usually maps the new syntax to elements of the host language and possibly external languages via an FFI.

For a concrete example, take a look at figure 1. It displays a diagram of the architecture of a recently developed pair of scripting languages for video editing [2]. Their purpose is to assist people who turn recordings of conference presentations into YouTube videos and channels. Most of their work is repetitive—adding preludes and postludes, concatenating playlists, and superimposing...
audio—and only a small number of steps demand manual intervention. The task calls for a domain-specific scripting language, and video is a declarative eDSL that meets this need.

The typed/video language adds a type system to video. Clearly, the domain of type systems comes with its own language of expertise: typed/video’s implementation therefore uses turnstile [6], an eDSL created for expressing type systems. Similarly, the implementation of video’s rendering facility calls for bindings to a multimedia framework. Ours separates the binding definitions and the repetitive details of FFI calls into two parts: an eDSL for multimedia FFIs, dubbed video/ffi, and a single program in it. Finally, in support of creating all these eDSLs, Racket comes with the syntax-parse eDSL [7], which targets the domain of eDSL creation.

The LOP principle implies two subsidiary guidelines:

(1) **Enable creators of a language to enforce its invariants.**

A programming language is an abstraction, and abstractions are about integrity. Java, for example, comes with memory safety and type soundness. When a program consists of pieces in different languages, values flow from one context into another and need protection from operations that might violate that integrity. See section 4.

(2) **Turn extra-linguistic mechanisms into linguistic constructs.**

A LOP programmer who resorts to extra-linguistic mechanisms effectively acknowledges that the chosen language lacks expressive power [13]. The numerous external languages required to deal with Java projects—a configuration language, a project description language, a makefile language—represent symptoms of this problem. We treat such gaps as challenges. See section 5.

These principles have been developed in a feedback loop that includes DrRacket [15] plus typed [36], lazy [4], and pedagogical languages [15].

3 LIBRARIES AND LANGUAGES RECONCILED

Racket is an heir to Lisp and Scheme. Unlike its ancestors, Racket emphasizes functional over imperative programming without enforcing an ideology. Racket is agnostic when it comes to surface syntax, accommodating even conventional variants such as Algol 60.4 Like many languages, Racket comes with “batteries included.”

Most distinctively, Racket eliminates the hard boundary between library and language, overcoming a seemingly intractable conflict. In practice, this means new linguistic constructs are as seamlessly imported as functions and classes from libraries and packages. For example, Racket’s class system and for loops are imports from plain libraries, yet most programmers use these constructs without ever noticing their nature as user-defined concepts.

Racket’s key innovation is a modular syntax system [17, 26], an improvement of Scheme’s macro system [11, 24, 25], which in turn improves on Lisp’s tree-transformation system. A Racket module provides services such as functions, classes, and linguistic constructs. To implement these services, a module may require the services of other modules. In this world of modules, creating a new language simply means creating a module that provides the services for a language. Such a module may subtract linguistic constructs from a base language, re-interpret some others, and add a few new ones. A language is rarely built from scratch.

Like Unix shell scripts, which specify their dialect on the first line, every Racket module specifies its language on the first line, too. This language specification refers to a file that contains a language-defining module. Creating this file is all it takes to install a language. Practically speaking, a programmer may develop a language in one tab of the IDE, while another tab may be a module written in the language of the first. Without ever leaving the IDE to run compilers, linkers, or any other tools, the developer can modify the language implementation in the first tab and immediately experience this modification in the second. In short, language development is a friction-free process in Racket.

In the world of shell scripts, the first-line convention eventually opened the door to a slew of alternatives to shells: Perl, Python, Ruby, etc. The Racket world is experiencing a similar phenomenon, with language libraries proliferating within its eco-system: racket/base, the Racket core language; racket, the “batteries included” variant; and typed/racket, a typed variant. Some lesser-known examples are datalog and a web-server language [27, 30]. When precision is needed, we use the lower-case name of the language in typewriter font; otherwise we use just “Racket.”

```racket
#lang racket/base
(provide
  ;; type MaxPath = [Listof Edge]
  ;; Natural -> MaxPath
  walk-simplex)

(require "constraints" graph)

;; Natural -> MaxPath
(define (walk-simplex timing)
  (maximizer #:x 2 ...))
```

Fig. 2. A plain Racket module

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4Like many Programming Language researchers, we subscribe to a weak form of the Sapir-Whorf hypothesis.

5See docs.racket-lang.org/algol60/ [last visited May 24, 2017] as well as hashcollision.org/brainfudge [last visited Feb 6, 2017], which shows how Racket copes with obscure syntax.
Figure 2 is an illustrative module. Its first line—pronounced "hash lang racket base"—says that it is written in racket/base. The module provides a single function, walk-simplex. The accompanying line comments—introduced via semicolons—informally state a type definition and a function signature in terms of this type definition; figure 5 shows how developers can use typed/racket to replace such comments with statically checked types. To implement this function, the module imports functionality from the "constraints" module in figure 3. The last three lines of figure 2 sketch the definition of the walk-simplex function, which refers to the maximizer function imported from "constraints".

The "constraints" module in figure 3 expresses the implementation of its only service in a domain-specific language because it deals with simplexes, which are naturally expressed with a system of inequalities. The module's simplex language inherits the line-comment syntax from racket/base but uses infix syntax otherwise. As the comments state, the module exports a single function, maximizer, which consumes two optional keyword parameters. When called as (maximizer #:x n)—as in figure 2—it produces the maximal y value of the system of constraints. As the lower half of figure 3 shows, these constraints are specified with conventional syntax.

```scheme
#lang simplex

;; implicitly provides synthesized function maximizer:
;;  #:x Real -> Real
;;  #:y Real -> Real
#:variables x y
3 * x + 5 * y <= 10
3 * x - 5 * y <= 20
```

Fig. 3. A module for describing a simplex shape

In support of this kind of programming, Racket's modular syntax system benefits from several key innovations. A particularly illustrative one is the ability to incrementally re-define the meaning of existing language constructs via the module system. This ability allows eDSL creators to ease their users into a new language by reusing familiar syntax, re-interpreted.

Take lambda expressions, for example. Suppose a developer wishes to equip a scripting language such as video with functions that check whether their arguments satisfy specified predicates. Figure 4 shows the basic idea:

```scheme
(lof #lang racket

(provide (rename-out [new-lambda lambda]))

(require (for-syntax syntax/parse))

... 

;; Syntax -> Syntax
(define-syntax (new-lambda stx)
  (syntax-parse stx
    [(new-lambda (x:id (˜literal ::) predicate:id) body:expr)
      (syntax
        (lambda (x) (unless (predicate x)
          (define name (object-name predicate))
          (error 'lambda "a expected, given: " name x)
          (body)))])
    ...)

Fig. 4. lambda, re-defined
```

line 09 Like many functional languages, Racket comes with pattern-matching constructs. This one uses syntax-parse from the above-mentioned library. Its first piece specifies the to-be-matched tree (stx); the remainder specifies a series of pattern-responses clauses.

line 10 This pattern matches any syntax tree whose first token is new-lambda followed by a parameter specification and a body. The annotation :id demands that the pattern variables x and predicate match only identifiers in the respective positions. Similarly, :expr allows only expressions to match the body pattern variable.

line 11 A compile-time function synthesizes new trees with syntax.

line 12 The generated syntax tree is a lambda expression. Specifically, the function generates an expression that uses lambda. The underline marks its origin as the ambient language: here, racket.

others Wherever the syntax system encounters the pattern variables x, predicate, and body, it inserts the respective sub-trees that match x, predicate, and body.

When another module uses "new-lam" as its language, the compiler elaborates the surface syntax into the core language like this:

```scheme
(lambda (x :: integer?) (+ x 1))
```

The first elaboration step resolves lambda to its imported meaning [18], which is lambda. The second one reverses the "rename on export" instruction. Finally, the new-lambda compile-time function translates the given syntax tree into a racket function.

In essence, figure 4 implements a simplistic pre-condition system for one-argument functions. Next, the language developer might wish to introduce multi-argument lambda expressions, add a position for specifying the post-condition, or make the annotations...
optional. Naturally, the compile-time functions could then be modified to check some or all of these annotations statically, eventually resulting in a language that resembles typed/racket.

4 SOUND COOPERATION BETWEEN LANGUAGES

A LOP-based software system consists of multiple, cooperating components, each written in domain-specific languages. Cooperation means that the components exchange values, while “multiple languages” implies that these values are created in distinct languages. In this setting things can easily go wrong, as figure 5 demonstrates with a toy scenario. On the left, a module written in typed/racket exports a numeric differentiation function. On the right, a module written in racket imports this function and applies it in three different ways, all illegal. If such illegal uses of the function were to go undiscovered, developers would not be able to rely on type information for designing functions or for debugging, nor could compilers rely on them for optimizations. In general, cooperating multi-lingual components must respect the invariants that each participating language establishes.

```racket
#lang typed/racket
provide diff
define (diff f)
(lambda (x)
(define lo (f (- x eps)))
(define hi (f (+ x eps)))
(/ (- hi lo) (* 2 eps)))
```

In the real world, programming languages satisfy a spectrum of guarantees about invariants. For example, C++ is unsound. A running C++ program may apply any operation to any bit pattern and, as long as the hardware does not object, the program execution continues. The program may even terminate “normally,” printing all kinds of output after the misinterpretation of the bits. By contrast, Java does not allow the misrepresentation of bits; but it is only somewhat more sound than C++ [1]. ML improves on Java again and is completely sound; no value is ever manipulated by any inappropriate operation.

Racket aims to mirror this spectrum of soundness at two levels: the level of language implementation itself and the level of cooperation between two components written in different embedded languages. Consider the soundness of languages first. As the literature on domain-specific languages suggests [20], these languages normally evolve in a particular manner, and this is true for the Racket world, too. A first implementation is often a thin veneer over an efficient C-level API. Racket developers create this kind of veneer with a foreign interface that allows parenthesized C-level programming [5]. Programmers can refer to a C library, import functions and data structures, and wrap these imports in Racket values. Figure 6 illustrates the idea with the sketch of a module; video’s initial implementation consisted of just such a set of bindings to a video-rendering framework.

Of course, when a racket/base module imports the ffi/unsafe library, the language of the module is unsound.

A language developer that starts with the unsound eDSL is likely to make it sound as the second step. To this end, the language is equipped with run-time checks similar to those found in dynamically typed scripting languages to prevent the flow of bad values to unsound primitives. Unfortunately, this form of protection is ad hoc, and unless developers are hyper-sensitive, the error messages may originate from inside the library, blaming some racket/base primitive operation.

To address this form of problem, Racket comes with higher-order contracts [16]. With those, language developers may uniformly protect the API of a library from bad values. For example, the video/ffi language provides language constructs for making the bindings to the video-rendering framework safe. In addition to plain logical assertions, Racket’s developers are also experimenting with contracts for checking protocols, especially temporal ones [9]. The built-in blame mechanism of the contract library ensures sound blame assignment [10].

Finally, a language developer may wish to check some logical invariants before the programs run. Checking simple types is one particular example, but checking other forms of types is also possible. The typed/video language illustrates this point with a type system that checks the input and output types of functions and also numeric constraints on the integer arguments; as a result, no script can possibly render a video of negative length. Similarly, typed/racket is a typed variant of (most of) racket.

```racket
#lang racket/base
provide
(define (ffi-simplex set ... ...) ...)".
(define lib-simplex (ffi-lib "./coin-Clp/lib/libClp")
(define ffi-simplex-set (get-ffi-obj "simplex" lib-simplex (_fun _bytes -> _void)))
```

Now consider the soundness of cooperating languages. As before, it is up to the language developer to anticipate how programs in this language interact with others. For example, the creator of typed/video provides no protection for its programs. By contrast, the creators of typed/racket intended the language to be used

Fig. 5. Protecting invariants

Fig. 6. A Racket module using the foreign-function interface

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in a multi-lingual context. Therefore *typed/racket* compiles the
types of exported functions into the above-mentioned higher-order
contracts. When, for example, an exported function must always
be applied to integer values, the generated contract inserts a check
that ensures the “integerness” of the argument at every application
site for this function; there is no need to insert such a check for
the function’s return points, because the function is statically type
checked. For a function that consumes an integer-valued function,
the contract must ensure that the function argument always re-
turns an integer. In general, a contract wraps exported values with
a *proxy* [31] that controls access to the value. The idea is due to
Matthews and Findler [29], while Tobin-Hochstadt and Felleisen’s
Blame Theorem [35] shows that if something goes wrong with such
a mixed system, the run-time exception points to two faulty compo-
nents and their boundary as the provable source of the problem [10].
In general, *Racket* supplies a range of protection mechanisms, and
a language creator can use these mechanisms to implement a range
of soundness guarantees for cooperating eDSLs.

5 UNIVERSALITY VS EXPRESSIVENESS
Just because a general purpose language can compute all partial-
recursive functions, programmers cannot necessarily express all
their ideas about programs in this language [13]. This point is best
illustrated with an example. Imagine the problem of building an IDE
for a new programming language in the very same language. Like
any modern IDE, it is supposed to enable users to compile and run
their code. If the code goes into an infinite loop, the user must be
able to terminate it with a mouse click. To implement this capability
in a natural\(^5\) manner, the language must internalize the idea of a
controllable process, a thread. If it does not, the implementor of the
IDE must step outside the language and somehow re-use processes
from the underlying operating system.

For a programming language researcher, “stepping outside the
language” signals a failure. Or, as Dan Ingalls [21] phrases it, “[an
operating system is a collection of things that don’t fit into a lan-
guage[; there] shouldn’t be one.” Hence, we have worked to identify
services that *Racket* borrows from the surrounding operating sys-
tem and to assimilate such extra-linguistic mechanisms into the
language itself [19]. Here are three sample constructs for which
programmers used to step outside of Racket but no longer need to:

- **sandboxes**: which restrict access to resources;
- **inspectors**: which control reflective capabilities;
- **custodians**: which manage resources (e.g., threads, sockets).

To understand how the inclusion of such services helps language
designers, let us turn to a recent example, the *shill* language [32].
Roughly speaking, *shill* is a secure scripting language in *Racket’s*
eco-system. With *shill*, a developer articulates fine-grained secu-
rity and resource policies—say, which files a function may access
or which binaries the script may run—and the language ensures
that these constraints are satisfied. To make this concrete, consider
a homework server to which students can submit programs. The
instructor might wish to run an auto-grade process for all the sub-
misions. Using a *shill* script, the homework server can execute

5An alternative is to rewrite the entire program before handing it to the given compiler,
which is exactly what distinguishes “expressiveness” from “universality”

student programs that cannot successfully attack the server, poke
around in the file system for solutions, access external connections
to steal other students’ solutions, and so on. Naturally, *shill*’s
implementation makes extensive use of Racket’s means for running
code in sandboxes and harvesting resources via custodians.

6 THE STATE OF AFFAIRS
The preceding sections explain how *Racket* enables programmers

- (1) to create languages via linguistic reuse for specific tasks
  and aspects of a problem;
- (2) to equip a language with almost any conventional level
  of soundness (as found in ordinary language implementa-
tions); and
- (3) to exploit a variety of internalized operating-system ser-
  vices for the construction of run-time libraries for these
  embedded languages.

What makes this form of language-oriented programming work is
incrementality. If conventional syntax is not a concern, developers
can create new languages from old ones, one construct at a time.
Similarly, they do not have to deliver a sound and secure product
all at once. They can create a new language as a wrapper around an
existing C-level library, gradually tease out more of the language
from the interface, and make the language as sound or secure as
time permits or a growing user based demands.

Furthermore, the entire process takes place within the *Racket*
eco-system. A developer creates a language as a Racket module
and installs it by “importing” it into another module. This tight
coupling has two implications. First, the development tools of the
eco-system can be used for the creation of language modules and
their clients. Second, the language becomes available for creating
more languages. Large projects often employ a tower involving a
few dozen languages—all of which helps manage the huge degree
of complexity in modern software systems.

![Fig. 7. A sketch of an industrial example](image)

Sony’s *Naughty Dog* game studio has created such a large project—
actually, a framework for creating projects. Roughly speaking, their
Racket-based architecture provides languages for describing scenes,
transitions between scenes, the scores for scenes, and so on. Domain
specialists use these languages to describe pieces of a game. The
Racket implementation composes these domain-specific programs and then compiles them into dynamically linked libraries for a C-based game engine. Figure 7 sketches the arrangement graphically.

Racket’s approach to language-oriented programming is by no means perfect. To start with, recognizing when a library should become a language requires a tasteful judgment call. The next steps require good choices in terms of linguistic constructs, syntax, and run-time primitives.

As for concrete syntax, Racket currently has strong support for the typical, incremental Lisp-style syntax development. It comes with merely traditional support for conventional syntax, i.e., generating lexers and parsers. While traditional parsing introduces the above-mentioned natural separation between surface syntax and meaning, it also means that the development process is no longer incremental. The proper solution would be to inject Racket ideas into a context where conventional syntax is the default.6

As for static checking, Racket currently forces language designers to develop such checkers wholesale, not on an incremental basis. The type checker for typed/racket, for example, looks like the type checker for any conventionally typed language; it is a complete recursive-descent algorithm that traverses the module’s representation and algebraically checks types. What Racket developers really want is a way to attach type checking rules to linguistic constructs, so that such algorithms can be synthesized as needed.

Chang et al.’s recent work is probably a first step toward a solution of this problem [6]. Thus far, they have demonstrated how their approach can equip a DSL with any structural type system in an incremental and modular manner. A fully general solution will also have to cope with sub-structural type systems, such as Rust’s, and static program analyses, such as those found in most compilers.

As for dynamic checking, Racket suffers from two problems. On one hand, it provides the building blocks for making language cooperation sound, but developers must create the necessary soundness harnesses on an ad hoc basis. To facilitate the composition of components in different languages, we need both a theoretical framework and abstractions for the partial automation of this task.

On the other hand, the available spectrum of soundness mechanisms lacks power at both ends, and how to integrate these powers seamlessly is unclear. To achieve full control over its context, Racket probably needs access to assembly languages on all possible platforms—from hardware to browsers. To realize the full power of types, typed/racket will have to be equipped with dependent types. For example, when a Racket program uses vectors, its corresponding typed variant type-checks what goes into these vectors and what comes out, but like ML or Haskell, indexing is left to a (contractual) check in the run-time system. Tobin-Hochstadt and his Typed Racket group are currently working on first steps in this direction, focusing on numeric constraints [23], similar to Xi and Planning’s work [37].

As for security, the Racket project calls for a significant breakthrough. While the sh11 team was able to construct the language inside the Racket eco-system, their work exposed serious gaps between Racket’s principle of language-oriented programming and its approach to enforcing security policies. The team had to alter many of Racket’s security mechanisms and invent new ones. Clearly, Racket must make this step much easier, meaning more research is needed to turn security into an integral part of language creation.

Finally, LOP poses brand new challenges for tool builders. An IDE typically provides tools for a single programming language or a family of related languages, among them debuggers, tracers, and profilers. Good tools communicate with developers on the terms of the source language. By its very nature, LOP calls for customization of such tools to many languages, their abstractions, and their invariants. We have partially succeeded in building a tool for debugging programs in the syntax language [8]; we have the foundations of a debugging framework[28]; and we have started to explore how to infer scoping rule and high-level semantics for newly introduced, language-level abstractions [33, 34]. Customizing such tools automatically to newly created (combinations of) languages remains a wide-open challenge.

In sum, programming language research has stopped short of the ultimate goal, namely, to provide software developers with tools to formulate solutions in the languages of problem domains. Racket is one attempt to continue the search for proper linguistic abstractions. While the project has achieved remarkable success in this direction, it also shows that programming language research has many problems to solve before the vision of language-oriented programming becomes reality.

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Over 20 years, this work has been generously supported by our host institutions (Rice University, University of Utah, Brown University, University of Chicago, Northeastern University, Northwestern University, Brigham Young University, University of Massachusetts Lowell, Indiana University) as well as several funding agencies, foundations, and companies: AFSOR, CISCO, CORD, Darpa, the Department of Education's FIPSE program, the ExxonMobil Foundation, Microsoft, the Mozilla Foundation, NSF, and the Texas Advanced Technology Program.

Software. Racket is available at racket-lang.org.

6Language workbenches, such as Spoofax [22], deal with conventional syntax for DSLs but do not support the incremental modification of existing languages. A recent report [12] suggests, however, that these tool chains are also converging toward the idea of language creation as language modification. We conjecture that, given sufficient time, the development of Racket and language workbenches will arrive at similar designs and the latter will then support DSL integration, too.

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