

Calico: An Ecosystem for Dynamic Languages

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Abstract

The Calico project was designed to be a dynamic languages ecosystem for learning, exploring, creating, and using dynamic languages, both individually, and in cooperation with each other. It defines a multi-language, multi-context programming framework and learning environment for computing education and research. The ecosystem is designed to support several interoperable programming languages (including Python, Scheme, and a drag-and-drop languages, called Jigsaw) running on a universal virtual computer. We plan that that Calico will provide a long-term, robust ecosystem that can be used to create and sustain a community of researchers, educators, and students working together in dynamic languages research.

Categories and Subject Descriptors D.3.4 [Programming Languages]: interpreters, runtime environments

General Terms Languages, Experimentation

Keywords Integrated Development Environment, dynamic languages, virtual machine, language implementation, language inter-operations

1. Overview

The Calico Project defines a collection of technologies designed to create an ecosystem for dynamic languages. The Calico ecosystem has a number of interesting properties: 1) allows multiple dynamic languages to interact and interoperate; 2) libraries written for the ecosystem are usable by all of the languages as if they were native to each language; 3) provides a smooth continuum of experience for the beginning computer programmer; 4) exposes a unified interface for exploring a variety of dynamic languages; and 5) is an open-source testbed for developing new concepts in dynamic languages. As such, Calico defines a useful ecosystem for students, educators, and developers wishing to explore computer science and pedagogy.

Calico is defined by three layers of technologies: a universal virtual computer, a dynamic language runtime, and support libraries and executables. In addition, an Integrated Development Environment (IDE) pulls all of these pieces together, for use by students and researchers. As implemented, Calico languages can all live and operate in the same space, share variables and code, and the code

can run competitively fast. The following sections go into the details of each of the pieces that comprise the Calico ecosystem.

1.1 Universal Virtual Computer

From the programmer's perspective, the foundation of Calico is a "universal virtual computer". The dynamic language programmer should be able to write code capable of modern functionality without having to worry about the details of the operating system or underlying hardware. For example, the programmer should be able to write programs capable of: turning text to speech; playing audio files; defining functions that can be used for tone generation; creating graphical user interfaces with unconstrained drawing abilities; reading and writing standard image formats; and providing access to modern input/output hardware devices, such as gamepads, joysticks, webcams, and robots. In addition, such a system should be easy to install and maintain, with limited need for platform-specific dependencies. Finally, we believe that a long term platform for research and education should be free, both in terms of price and ability to distribute and alter. Thus, the programmer should be able to program to a complete, easily-accessible, free, modern, universal virtual computer. This section examine the components of a universal virtual computer.

1.1.1 Virtual Machine

A large portion of the universal virtual computer is defined by a "process virtual machine." There are a number of process virtual machines (VMs) one could use for a dynamic language ecosystem. We wanted a VM with a large and active development community, and so excluded more narrowly-focused VMs such as the Squeak Virtual Machine [?]. Oracle's Java and Microsoft's .NET are two VMs that both define viable possibilities: both have object-oriented programming languages, compilers, and associated virtual machines and runtimes. The Java VM (JVM) has the Java language (among other possibilities), and .NET has the C# language (among other possibilities). Both systems compile to bytecode that is executed by their respective virtual machines' runtime.

Although both VMs have served as the foundation for dynamic languages, Java does not have a complete and robust open-source implementation. On the other hand, .NET's virtual machine components, called the Common Language Infrastructure (CLI), have been clearly defined in a pair of Ecma standards, specifically Ecma #334 and Ecma #335 [?], and is protected by a promise from Microsoft not to sue [?]. More importantly, these standards have been implemented independently by Mono as open source. We have put a high value on having a complete, independent, and open source "stack" of robust software layers. Although one could debate which system is more "open", we decided to select the CLI as implemented by Mono [?]. we will refer to Mono's implementation of the CLI as MVM (for Mono Virtual Machine).

However, we are not limited to only MVM-based technologies. Using IKVM (described below) we are able to utilize code compiled for the Java VM. In this manner, we have assembled components that bring together the best of both of these two virtual machine systems. In effect, we have a “universal virtual machine” that can use a wide variety of available open-source libraries on a varied set of operating systems. One such library is the Dynamic Language Runtime described in the next section.

1.1.2 Dynamic Language Runtime

Although the MVM and the JVM both define everything necessary to implement a dynamic language, neither has built-in support for allowing such dynamic languages to interoperate. That is, even though a variety of languages can be compiled to either VM, there is little common infrastructure in the VM itself. Without a dynamic language infrastructure, it is difficult for languages defined in the VM to define dynamic objects, and to share environments, data structures, objects, or functions. Two Java Specification Requests have been made to add such functionality to Java: JSR-223 would add language hosting and JSR-292 would add dynamic binding [?]. In fact, there are a number of projects underway to make the JVM more flexible for use with dynamic languages, including: the Da Vinci Machine [?] as the reference implementation of JSR-292; Project Lambda [?] adds lambda to the JVM; Project Jigsaw adds support for importing versioned modules [?]; and Nashorn [?] adds caches for dynamic invokes. When complete, these technologies will extend the Java technologies to make them much more suitable for dynamic languages.

On the other hand, the MVM has an existing, mature framework for implementing languages called the Dynamic Language Runtime (DLR) [?], and at least three dynamic languages have been written using the DLR: IronPython [?], IronRuby [?], and PowerShell [?]. The DLR contains many tools and technologies for language writers to create languages, and abilities for the languages to interoperate. Calico includes the DLR, and contains versions of IronPython and IronRuby. A language need not use the functionality of the DLR to be used in Calico, but this functionality is required for a language to be considered *first-class* (described below).

The DLR provides the following [?]:

- A dynamic, shared type system
- Dynamic method dispatch
- Dynamic code generation
- Hosting API

A new object type, `DynamicObject`, was created to implement this functionality. `DynamicObject` was initially defined in the DLR as an external library, but now has been incorporated into .NET 4.5, the C# language, and Mono. `DynamicObject` is a base class for creating objects that determine the behavior dynamically at runtime. The DLR contains all the support necessary for creating, parsing, and executing modern dynamic languages. However, even with the DLR and the virtual machine, there are still a large set of functions that a modern programmer would expect from a universal computer (including audio and graphics). We now explore these supporting libraries.

1.2 Supporting Libraries

To create a universal virtual computer, we need to have a set of capabilities on top of the virtual machine and dynamic language runtime that run the gamut from audio to graphics. Of course, operating systems and hardware vary wildly. Fortunately, there are open source libraries for the MVM that cover these requirements. For graphics, we selected Gtk# [?] which wraps low-level C-

based libraries. For accessing audio and hardware devices (such as gamepads), we selected the Simple DirectMedia Layer (SDL) [?]. SDL is quite popular in open source, providing additional capabilities for many projects, including pygame [?]. Finally, we also added espeak [?] to provide cross-platform text-to-speech functionality.

The MVM and the above mentioned libraries form the lowest level of the virtual computer. These libraries are machine-dependent, and, as such, must be compiled for each platform. We attempted to create the fewest number of machine-specific dependencies to make the virtual computer easy to maintain and port to new architectures. Finally, after this low-level set of dependencies are satisfied, additional libraries can be written in a machine-independent fashion using the MVM, or written with the JVM and converted with IKVM to the MVM.

IKVM is an interesting open source project that translates binary code between MVM/.NET and the JVM [?]. It has the ability to make code compiled for the JVM available to the MVM, and, likewise, to make code compiled for the MVM (or .NET in general) available to the JVM. We see an example of IKVM with Calico Java (discussed below).

Combined with the MVM and DLR, these libraries complete the functionality of a universal virtual computer so that one can write programs that utilize graphics user interfaces (including widgets, freestyle pixel manipulation, event handlers, and image formats), audio (including text-to-speech and tone generation), access to hardware devices, and other modern functionality. One can then write in dynamic languages with the full scope of abilities on most of the operating systems in use, including Windows, Linux, Mac OSX, and FreeBSD.

1.3 Integrated Development Environment

From the user’s perspective, an important part of using any programming language is the user interface implemented in the Integrated Development Environment (IDE). In fact, there are many subtle details that go into making a useful IDE. One could re-use an existing IDE to integrate the universal virtual computer. However, we choose to use the virtual computer to implement a new IDE. This serves as both a test of the system, but also makes it easy to make all of the IDE functionality accessible to the programmer.

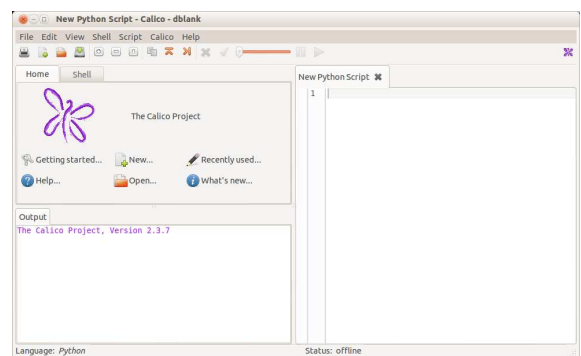


Figure 1. The Calico IDE. The IDE starts up ready to program in the default language. In this example, Calico Python is the default language.

The Calico IDE, as shown in Figure ??, is designed to be agnostic to any particular language, or particular use. That is not to say, however, that the IDE treats all languages identically. For example, a visual, block-based language does not have a separate “shell” as interactive functionality (such as evaluate an expression) is initiated through the visual interface. Text-based languages need the shell for the standard read-evaluate-print loop (REPL). Therefore,

the Calico IDE rearranges slightly depending on whether the languages is text-based or not.

2. Languages

A Calico language is composed of two abstract parts: a *document*, and an *engine*. The document is responsible for the visual representation and editing of scripts written in the language. The engine is responsible for executing the scripts. The document and engine make up a container *language* object which also identifies whether the language is text-based, the associated file extensions, and other language-specific details.

Not every use of Calico need be a complete language to take advantage of the Calico infrastructure. For example, we have two “languages” (Spreadsheet, and Image) that only have a document, but not an engine. This allows us to use the IDE for viewing and editing spreadsheets and images. We could have made spreadsheets and images just libraries (which they are as well). However, by raising them to the level of a language, they can be opened and manipulated directly by Calico.

Of course, the main purpose of Calico is to provide an environment for using dynamic languages. We divide up languages into two kinds: *first-class* and *second-class* languages. We define a first-class language to support the following features:

- has an interactive program stepper
- has a variable-speed tracer
- ability to set breakpoints
- ability to share variables with other languages
- ability to call functions, execute/evaluate code and expressions from other languages,
- ability to import Calico modules (e.g., libraries) as if they were native libraries

A second-class language is one that is missing one or more of these features. This includes naive language ports (i.e., languages that do not take advantage of the Calico ecosystem), possess minimal interoperability with other languages, or inability to import Calico modules. Most of the languages incorporated lie somewhere between first-class and second-class status. However, over time, we hope to move more languages to the first-class set.

Having an environment like Calico is a useful system unto itself for exploring dynamic language programming and interoperability. However, it can also be of great utility to the beginning programmer. We are currently exploring the use of Calico for computer science education [? ?]. Our goal in focusing on Jigsaw, Python, and the Scheme languages are for pedagogical purposes. Our educational goal for using Calico is to create a smooth learning experience, whereby students can transfer skills from one language to the next. In the next sections we will briefly explore a series of Calico languages.

2.1 Calico Jigsaw

Block-based programming languages have facilitated our ability to introduce computer programming to novice programmers. Perhaps the most notable example of this is Scratch [?]. Building executable programs by plugging together virtual blocks is a concept that is much less intimidating to a beginner, especially when compared with the precise syntactical rules demanded by many modern programming languages. For this reason we sought to include a block-based language as part of the Calico ecosystem. We named our block language Calico Jigsaw.

The Jigsaw editor provides a palette of blocks that are dragged onto a canvas using the mouse and connected to form an executable

program (Figure ??). Jigsaw blocks may have properties that can be assigned values by the programmer. For example, the Jigsaw “repeat” block has a Repetitions property that can be assigned a numeric value indicating the number of times an inner stack of blocks should be executed. But beyond the standard functionality expected in any block language, Jigsaw has several additional features that we feel make it unique.

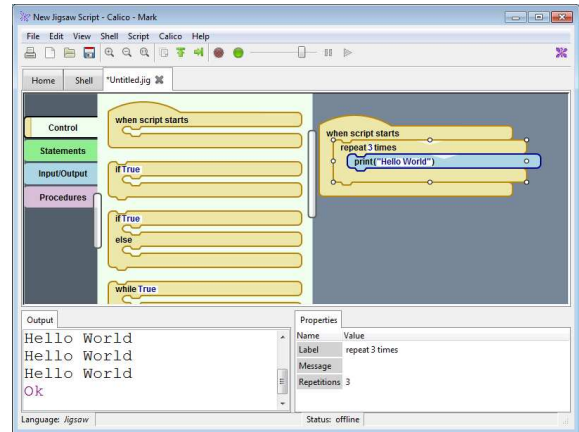


Figure 2. Jigsaw in action.

The first feature worth noting is that Jigsaw is built as a wrapper around Python. Python thus serves as the engine for evaluating Jigsaw expressions. We could really use any Calico language for this purpose; however, because of our pedagogical goals, we decided to use Python as we suggest educators use Python as the next step in a student’s computer science educational journey.

Even though Jigsaw is written in C#, most Jigsaw statement blocks are implemented as Python statements. This integration between C# and Python is possible with help from the DLR. Block statements are compiled and held as compiled code objects that are ready to be evaluated when the Jigsaw program runs. A consequence of this design decision is that Python syntax often can be used directly in Jigsaw. For example, instead of entering primitive values for block properties, Python expressions can be substituted directly. The IfTest conditional statement in a Jigsaw “if” block can be a boolean expression written using Python syntax (Figure ??). We believe that this approach better prepares the student for a smooth transition to higher level languages.

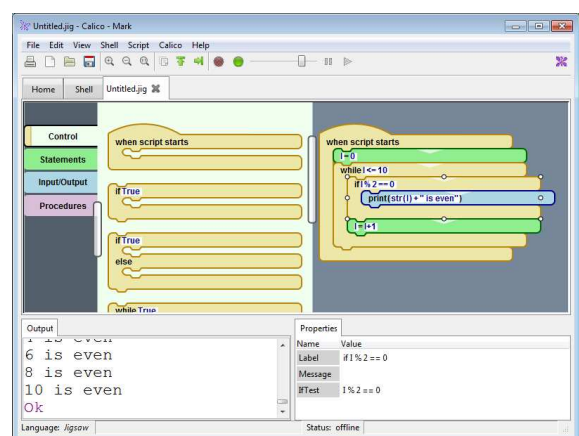


Figure 3. Jigsaw blocks leverage Python expressions.

Although Jigsaw statements and expressions are borrowed from Python, Jigsaw implements its own program control structures.

Blocks that provide looping, conditionals and procedures are all implemented entirely in C#. Program execution is managed using Jigsaw's own implementation of call stacks and stack frames along with local and global namespaces, an idea that is borrowed from Python.

Another unique feature of Jigsaw is that it has a form of multitasking baked in to its execution engine. A Jigsaw program begins execution at a "when script starts" block, and proceeds down the attached stack of blocks, executing each in sequence. But a Jigsaw program can contain any number of "when script starts" blocks, which all begin execution at the same time. As a result, a Jigsaw program can execute multiple block stacks in parallel. See Figure ?? for an example. Blocks colored white indicate that it is currently being executed.

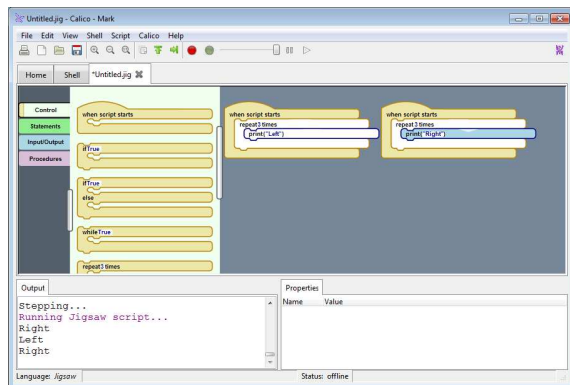


Figure 4. A Jigsaw program running multiple block stacks in parallel.

The parallelism implemented in Jigsaw is a form of cooperative multitasking, not the more common preemptive style. Jigsaw executes multiple block stacks in a round-robin fashion. It is important to note that the execution of one block does not necessarily complete before the Jigsaw engine switches to a block in another stack. Indeed, multiple blocks in different stacks can execute at the same time. This is possible because block execution is implemented as a C# Enumerator, which is carefully designed for each block type to yield at safe places throughout its execution. With this approach a novice programmer can assemble a program that multitasks while avoiding the subtle bugs that often crop up with a true preemptive model. For example, a "background" task that continuously monitors a sensor and updates a global variable can safely coexist with a second loop that uses the value of the global variable to draw a graphic on the screen.

Calico Jigsaw allows the export of any Jigsaw script to Calico Python (described below). However, to export it must convert Jigsaw's controls to those of the Python language, the semantics must also be converted. Figure ?? shows the above Jigsaw program as it appears after it has been exported to Python. Python does not have the built-in ability to run functions simultaneously as does Jigsaw. But, the Calico Myro module (described below) includes a friendly interface for using threads through the "doTogether" function, and so the export translates the Jigsaw program to the proper form. Notice, however, that the Output tab indicates that Python's threads do not guarantee even multitasking inside the for-block as the 'Left' and 'Right' outputs are not perfectly interleaved.

2.2 Calico Python and Ruby

Calico Python is based on IronPython, with compiler options set to be as much like Python 3 as possible. This includes treating print as a function, and making the division operator produce a floating-

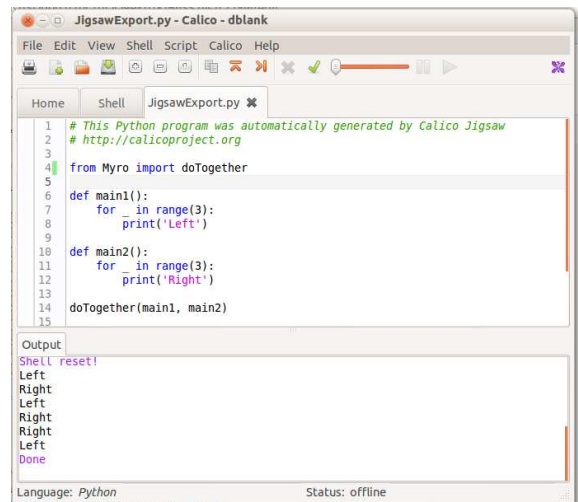


Figure 5. The Jigsaw program from Figure ?? exported as Python. Note that the blocks have been converted to functions (main1, and main2) but the output is not guaranteed to run in lockstep as it does with Jigsaw's multitasking.

point number instead of the standard truncated integer, when a integer is divided by another.

IronPython is the most developed and tested language using the DLR. By default, a DLR-based language has the ability to use DLLs directly. However, to make a language a first-class Calico language, it must also provide debugger and interoperation functionality. Because of the DLR, this additional functionality was fairly easy to implement.

Likewise, Calico Ruby is based on IronRuby. Although not as well developed, IronRuby is a very complete implementation of the language. Calico Ruby is currently a second-class language, as we have not implemented the stepping support needed.

2.3 Calico Scheme

We wrote a properly tail-recursive implementation of Scheme from scratch and integrated it into Calico. Tail-recursion is an idiom that students often discover on their own as a way of implementing iteration [?]. Unfortunately, most of the languages commonly used in introductory courses (for example, Java, Python, and C++) do not handle tail-recursion correctly, which may lead to crashes if a student's program exceeds the language's recursion depth limit. This is seen by students as a bug in their code, whereas it is really a limitation of the underlying language implementation. Unlike other Scheme implementations for the MVM, Calico Scheme does not rely on the underlying call stack of the implementation language to manage function calls, nor does it require functions to be compiled to Common Language Runtime (CLR) bytecode. Consequently, tail calls are handled properly in Calico Scheme, as required by the Scheme language specification [?], imposing no limit on the depth of the call stack (aside from system memory limitations).

Our Scheme implementation is itself written in Scheme, utilizing full continuation-passing style (CPS). Because the interpreter is in CPS, adding support for new types of control structures or other language constructs to Calico Scheme is easy. We wrote a transformation program to automatically transform the high-level CPS code into a low-level trampolined register machine [?]. Although the resulting register machine code is still in Scheme, it does not rely on Scheme's call stack, higher-order procedures, or parameter-passing mechanisms. Thus it can be translated directly into low-level C# code and then compiled for the MVM.

Calico Scheme supports all of the main language features of standard Scheme, such as first-class procedures and continuations, but also adds several new features of its own. For example, we included support for exception handling in the form of `try`, `catch`, `finally`, and `raise` expressions. Of course, the equivalent functionality can also be easily achieved with `call/cc`, but since many students may already be familiar with exception handling constructs in Java or Python, we decided to include similar types of constructs in Calico Scheme as well. To aid in debugging when an exception is thrown, we implemented a user-configurable stack-trace reporting mechanism that mimics the appearance of stack traces generated in Python. We also included support for McCarthy’s nondeterministic choice operator `amb [?]`, called `choose` in Calico Scheme. This allows students to easily explore the very different—and very powerful—paradigm of nondeterministic computing, to which most of them have probably not been exposed before.

The current transformation of Calico Scheme into C# does not use the AST from the DLR. Therefore, our current version runs quite a bit slower than it could. However, to move to the DLR’s AST, we will need to define our own elements for handling continuations (see a simple performance comparison, below).

2.4 Experimental Languages

To add a language to Calico, one need only define a single function that returns a `Language` class instance. In fact, Calico comes with a fill-in-the-blank wizard for creating new text-based languages. For text-based languages, one need only provide the language’s name, a string for beginning line comments, and the language’s source code file extension (such as “.py” for the Python language). Further details can help make the language more useful for programmers. Such details include providing language keyword details for the IDE’s color syntax highlighting, and, of course, the language’s parser and interpreter. Because Calico supports calling other language, new languages can be written in existing Calico languages. For example, Calico’s Basic and Logo languages are themselves written in Calico Python. As another example, Calico Java’s language definition is written in Python, but the Java interpreter is written in Java (described in more detail below).

One might want to use the Calico infrastructure for testing out a new language. For example, if you had an interpreter (written in any Calico language, or converted to use the MVM or JVM) then you could put a light wrapper around it, and simply use the Calico IDE to make it available. If you provide the keywords, and a few other items, you could also have color syntax highlighting. If you add hooks to your language to import Calico modules, then your experimental language would have access to all of the included libraries (described below). Finally, if you add a method to provide line numbers, and intercept breakpoints, then your language would also be a first-class Calico language.

Because it is so easy to add a new language to Calico (given that such a language might initially be a second-class language with little connection to the rest of Calico) there are a few languages that have been initiated, but which have limited integration in Calico.

2.4.1 Calico Java

Calico Java is an example of a second-class language in the ecosystem. However, the technology to bring it into the Calico fold is quite interesting. We use the Java interpreter from DrJava [?]. Unfortunately that code is written in Java. Using IKVM, we convert the Java bytecode directly to MVM bytecode. Thus, Calico can parse and interpret Java in the MVM.

Even more interesting, to allow Calico Java to use the Calico DLL modules, they needed to be able to be consumed from the Java side. So, the DLL modules were converted to jar files via IKVM.

Therefore, the Calico modules can be used in the Java, both the real JVM and also our Java interpreted.

The complete effect is that Calico Java can load jar files that were once DLLs, but interpret the language in the MVM rather than the JVM. Unfortunately, the DrJava interpreter needs additional support for stepping, access to line number when errors are encountered, and access to other languages to be able to make Java a first-class Calico language.

2.4.2 Calico Basic, Logo

Because all of the languages live in the same environment, it is easy to develop a new Calico language in one of the existing Calico languages. For example, Calico Basic and Calico Logo are both interpreters written in Python. We have added the ability of both of those languages to use Calico libraries; however, neither has debugging support. Thus, both Logo and Basic are now languages with access to all of the Calico libraries. For example, one can write programs in these languages with access to the modern libraries, such as Processing, Arduino, and robots (described below).

2.5 Performance

Compared to other dynamic languages, the performances of Calico languages ranges from competitive to slow [?]. Likewise, between Calico languages, there is also large performance variability. Some of these differences can be mitigated over time with refinements at various levels of implementations. For example, Calico Scheme has yet to be converted to use the DLR AST. Once that transformation is in place, we expect a 10 to 100-fold increase in performance. Other differences are likely to remain, however. For example, Calico Basic is written in Calico Python, so speed improvements will probably be minimal.

Language	Time (in Seconds), Factorial of 1000
Calico Scheme (non-recursive)	0.002
CPython (recursive)	0.003
Calico Python (recursive)	0.020
Calico Ruby (recursive)	0.024
Calico Basic (using goto)	0.053
Calico Jigsaw (recursive)	0.072
Calico Scheme (recursive)	0.368

Table 1. Performance comparison between languages on a simple function: computing the factorial of 1000.

2.6 Interoperations

As mentioned, first-class languages can call functions and use values directly from other languages. There are two methods for running code in one language from another: *Evaluate* and *Execute*. Both of these methods are contained in the `calico` global environment variable. Like their names suggest, `calico.Evaluate` will evaluate an expression in the given language, and return the result, while `calico.Execute` will execute a series of statements in the given language for their side-effects.

One reason one might do this is to convert from a type in one language to a type in another. As a simple example, if you were writing Scheme code, but wanted to create a Python tuple, then you could define, and call, a Scheme function to take any number of arguments and return a Python tuple (see Figure ??).

```

1  scheme> (define pytuple
2            (calico.Evaluate
3              "lambda *args: args"
4              "python"))
5  Ok
6  scheme> (pytuple 1 2 3)
7  (1, 2, 3)

```

Listing 1. Defining a function `pytuple` in Calico Scheme that directly uses Calico Python’s `lambda` to construct a Python tuple. Notice that in line 7 that the tuple’s displayed representation reflects the style from Python rather than Scheme’s.

A more interesting example is calling a Scheme function from Python. One might wish to do this, for example, because of Scheme’s lack of limitations on a recursive stack size. To call a Scheme function requires that we connect Scheme’s function-calling machinery to the standard MVM function-calling system. This is a three step process:

1. Write a regular (perhaps recursive) Scheme function
2. Place the Scheme function in a MVM-compatible function wrapper
3. Make the wrapper available in the shared global environment

For example, consider defining a recursive function to compute if a number is even. In Python, there is a limited function-calling stack size (set differently depending on the version of Python), whereas Scheme has no such limitation as mentioned. In Listing ?? we first define the `iseven?` function (lines 1 – 7). Line 9 does two things: it wraps the `iseven?` function in a MVM function-calling wrapper using the Scheme primitive `func`, and also places the new function in the global environment, using the Scheme primitive `define!`. At this point, any Calico language with access to the global environment can now call the `iseven` function without worrying about recursion depth.

```

1 scheme> (define iseven?
2           (lambda (n)
3             (cond
4               ((= n 0) #t)
5               ((= n 1) #f)
6               ((< n 0) (iseven? (- n)))
7               (else (iseven? (- n 2)))))
8 Ok
9 scheme> (define! iseven (func iseven?))
10 Ok

```

Listing 2. Calling Scheme from Python.

If one of the languages is not a first class Calico language, they can still interoperate. For example, as mentioned, Java is not currently a first-class Calico language, but you can still execute statements, and evaluate expressions from any language that has access to the calico object. In the example in Listing ??, Calico Python calls Java to create a variable with a particular value.

```

1 python> calico.Execute("int x = 1;", "java")
2 Ok
3 python> pyx = calico.Evaluate("x", "java")
4 Ok
5 python> print(pyx)
6 <java.lang.Integer object at 0x002B [1]>
7 Ok
8 python> print(pyx.intValue())
9 1
10 Ok

```

Listing 3. Calling Java from Python.

The value of `pyx` is actually a value directly from the Java world: a `java.lang.Integer` object. To convert it to a MVM value depends on the specifics of the foreign system. In this case, calling `pyx.intValue()` is required.

2.7 Current Limitations and Future Work

As Calico is a work-in-progress, there are many directions to explore. For example, Calico cannot currently directly use C-based libraries. However, this limitation could be overcome (see the Iron-Clad project for IronPython [?]). Currently, there are a limited number of exports from one language to another. We believe that having additional exports between languages would facilitate learning transfer and transitions from one language to another. Finally, we are working to move more languages from their second-class status to be full first-class languages.

3. Calico Modules

A Calico “module” is a library written in such a manner that it is available to all of the Calico first-class languages. However, not only is the functionality in the module available to these languages, but the modules appear as if they are a native library to each language. For example, in Calico Python one would write “import Processing” to make the Calico Processing module (discussed below) available to Python. One could then write “Processing.window(400, 300)” in Python to create a 400x300 pixel window. In Scheme, one would write “(using ”Processing”)” to make the Calico Processing module available to Scheme. One could then write “(Processing.window 400 300)” in Scheme to do the same thing. Finally, in Calico Jigsaw, selecting “Use a Module; Processing” from the menu would allow the window-block to be dragged onto the Jigsaw workspace. Thus, the Processing module is written and compiled once, becomes available to all of the first-class Calico languages, and used as if it were written as a native language. Likewise, if a new first-class language is introduced into the Calico ecosystem, all of these modules can be used by the new language.

To create a Calico module, a single file is written and compiled once to a Dynamic Link Library (DLL). There are DLL files that are Windows-specific; however, these DLLs are platform-neutral and can be created on any operating system for use on any other operating system. To remain platform-neutral these DLL’s must be written such that they do not take advantage of Windows-specific functionality, do not rely on lower-level platform-specific C libraries (e.g., are completely “managed”), and use a subset of all possible functionality. Currently, to be accessible to all Calico languages, we currently restrict the module to only use static class methods in a toplevel-defined class. However, this limit could be relaxed in a future Calico to allow more flexibility (constructors, nested classes, etc). In general, any managed DLL could be fully utilized by a properly flexible, dynamic, first-class languages, but might require specific knowledge about the layout of the internal classes, methods, and namespaces. Thus, we have specified a subset of all that is possible for our own modules so that no additional knowledge or discovery is needed.

```

1 // C# ModuleName.cs compiles to ModuleName.dll
2 public class ModuleName {
3     public static int Plus(int a, int b) {
4         return (a + b);
5     }
6 }

```

Listing 4. Example module template.

If the code in Figure was compiled and placed into the Calico/modules folder, then it could be used in Python (as in the form `import ModuleName`, Scheme (as in the form `(use "ModuleName")`) and in Jigsaw and all of the other Calico languages, in their respective forms. We now explore three modules that provided a variety of functionality for Calico first-class languages.

3.1 Processing

Calico Processing is a module for developing digital works of art, data visualizations, interactive applications and animations. It offers Calico programmers the option to work with the familiar and popular *Processing* command set (see [?]). The Calico Processing module attempts to be faithful to the Processing command set, including function names, arguments, and usage. The majority of the command set has been implemented, although some differences exist.

The original Processing language is a subset of Java with a wide variety of commands included for creating visualization and animations. The Calico Processing module brings the Processing command set to all of the Calico programming languages that can access Calico modules. This module does not make use of the Java language syntax. Instead, native data types and control structures of your chosen Calico language will determine how your application is constructed.

We rely upon each of the native Calico languages for the following capabilities:

- Data structures
- Program control (conditionals, iterations, etc.)
- Files and file access
- String functions
- Objects and inheritance

Mouse and keyboard events are not handled by implementing predefined functions. The Calico Processing module raises events, which are handled by the native language event handling syntax. Events raised by the module include `onMousePressed`, `onMouseReleased`, `onMouseClicked`, `onKeyPressed`, and `onKeyReleased`. Loops are implemented by handling a timer tick event named `onLoop`.

Certain predefined fields in Processing are implemented as functions.

- `"mouseX"` and `"mouseY"` are implemented in Calico Processing as the functions `"mouseX()"` and `"mouseY()"`.
- `"pmouseX"` and `"pmouseY"` are implemented as `"pmouseX()"` and `"pmouseY()"`.
- `"width"` and `"height"` are implemented as `"width()"` and `"height()"`.
- `"focused"` and `"frameCount"` are implemented as `"focused()"` and `"frameCount()"`.
- `"key"` and `"keyCode"` are implemented as `"key()"` and `"keyCode()"`.

The result is a pixel-by-pixel faithful representation of the original Processing primitives' output. However, combined with the Calico dynamic languages, the Processing module provides functionality not available within the original Processing environment. For example, Calico allows the drag-and-drop creation of Processing art via Jigsaw, line-by-line stepping through programs, and breakpoints by using any of the Calico first-class languages.

The Calico Processing module is similar in some respects to the port of the original Processing commands to the Python library *pyprocessing* [?], and perhaps other ports to specific languages. However, our module has been written, and compiled, just once and is then available to all of the Calico languages. In addition, the *pyprocessing* has additional dependencies that must be maintained and installed.

3.2 Myro and Graphics

Calico comes with a rich library for exploring robots, called Myro. The Myro module allows students to control a real or simulated robot, take pictures, do image processing, make the robot speak, go through a maze, draw a picture, etc. The Myro library is described in detail in [?].

The Calico Graphics module is a 2D graphics library for creating art, games, and animations in any of the Calico languages. The Calico Graphics module forms the basis for the Physics-based simulations and animations (for use in creating games such as Angry Birds) and contains GIS functionality. A full reference of the Calico Graphics module can be found at [?].

4. Conclusion

The Calico project was designed to be a dynamic languages ecosystem for learning, exploring, creating, and using dynamic languages, both individually, and in cooperation with each other. It defines a multi-language, multi-context programming framework and learning environment for computing education and research. The ecosystem is designed to support several interoperable programming languages (including Python, Scheme, and Jigsaw) running on a universal virtual computer, a variety of pedagogical modules (including robotics, and art), and an assortment of physical devices (including different educational robotics platforms and a variety of physical sensors). In summary, we hope that Calico will provide a long-term, robust ecosystem that can be used to create and sustain a community of researchers, educators, and students working together.

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