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A bytecode set for adaptive optimizations

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Abstract

The Cog virtual machine features a bytecode interpreter and a baseline Just-in-time compiler. To reach the performance level of industrial quality virtual machines such as Java HotSpot, it needs to employ an adaptive inlining compiler, a tool that on the fly aggressively optimizes frequently executed portions of code. We decided to implement such a tool as a bytecode to bytecode optimizer, implemented above the virtual machine, where it can be written and developed in Smalltalk. The optimizer we plan needs to extend the operations encoded in the bytecode set and its quality heavily depends on the bytecode set quality.

The current bytecode set understood by the virtual machine is old and lacks any room to add new operations. We decided to implement a new bytecode set, which includes additional bytecodes that allow the Just-in-time compiler to generate less generic, and hence simpler and faster code sequences for frequently executed primitives. The new bytecode set includes traps for validating speculative inlining decisions and is extensible without compromising optimization opportunities. In addition, we took advantage of this work to solve limitations of the current bytecode set such as the maximum number of instance variable per class, or number of literals per method. In this paper we describe this new bytecode set. We plan to have it in production in the Cog virtual machine and its Pharo, Squeak and Newspeak clients in the coming year.

1. Introduction

The Cog virtual machine (VM) is quite efficient compared to popular language such as Python or Ruby, but is still far behind mainstream languages such as Java. This is because the VM does not have an adaptive Just-in-time (JIT) compiler, a tool that recompiles on the fly portion of code frequently executed to portion of code faster to run.

As we implement the adaptive optimizer as a bytecode to bytecode optimizer, we rely heavily on the bytecode set design. We need to adapt it to be suitable for optimizations and extend it with unsafe operations. The current bytecode set needs revising because of the lack of available bytecodes and the lack of unsafe operations (operations faster to run as they do not check any constraints) as well as the implementation of primitives, forbidding respectively to efficiently extend the bytecode and to inline primitive methods. In addition, the current bytecode set has well-known issues such as a maximum number of instructions a jump forward can encode and we took advantage of the bytecode set revamp to fix these problems, ending up with important simplification in the VM implementation.

We design a new bytecode set with the following improvements:

- It provides many available bytecodes to be easily and efficiently extendable.
- It features a set of unsafe operations for the runtime optimizer.
- It encodes the primitives in a way they can be inlined.
- It solves some well-known issues of the old bytecode set.

In this paper we describe the constraints we have to design a better bytecode set. We specify for each constraint if it applies for all the bytecode set designs or only in our case to design a bytecode set for adaptive optimizations.

After describing how the current bytecode is used in our virtual machine and Smalltalk clients, we discuss the current issues and missing features, then show how we solve the current issues. We also discuss some aspects of the new bytecode set and compare it to related work.

2. The Cog bytecode execution and memory model

Smalltalk has a runtime very similar to the Java Virtual Machine (JVM)[12], the Common Language Infrastructure (CLR)[6] and other common platform-independent object-oriented languages. To execute code, a high level compiler translates the Smalltalk source code into bytecode, a low level language. The bytecode is then executed by a virtual machine, being either interpreted or compiled down to na-

tive code through a just-in-time compiler. The virtual code is platform-independent and is encoded in bytes for compactness. Its byte encoding gives it the name bytecode.

A new memory manager, named Spur, has been recently introduced in the Cog VM[11]. All the figures and examples about memory representation we describe show the objects in the new Memory Manager format.

Two main bytecode sets are now supported in the Cog VM. One targets the Smalltalk clients, Squeak and Pharo, whereas the other one targets a research language named Newspeak. In this paper we focus on the bytecode set for Smalltalk clients, as the new bytecode set is for now exclusively for Smalltalk and would need to be adapted to be used with Newspeak.

2.1 Vocabulary

After looking at several bytecode sets and working on ours, we decided to describe bytecode operations by using three forms. Here is the definition of the three forms proposed, with examples from the new bytecode set:

- *single bytecode*: the instruction is encoded in a single byte. For example, the byte B0 means that the execution flow needs to jump forward by two instructions and the bytecode 4D means that the interpreter should push the boolean true on the stack.
- *extended bytecode*: the instruction is encoded in two bytes. The first byte defines the instruction and the second byte encodes an index relative to the execution of the instruction. For example, the byte E5 means that the interpreter should push a temporary variable on the stack, the index of the temporary variable being encoded in the next byte.
- *double extended bytecode*: the instruction is encoded in three bytes. The first byte defines the instruction and the second and third bytes encode an index relative to the execution of the instruction. For example, the byte FC means that the interpreter needs to push on the stack a variable in a remote array, the index of the remote array being encoded in the second byte and the index of the variable in the remote array is encoded in the third byte.

We call extended bytecode and double extended bytecode *argument bytecodes*, because they require extra byte(s) to encode the expected virtual machine behavior.

We always use the name bytecode to refer to the virtual code, i.e., the code understood by a virtual machine and not native code understood by a processor.

2.2 The Cog compiled method format

The bytecode, executable by the virtual machine, is saved in the heap - memory space reserved for object - in the form of compiled method[1]. A compiled method is an object encapsulating executable bytecode. In addition to the bytecode, a compiled method has, as shown in Figure 1:

- An object header (as every object in the system) to inform the virtual machine about basic properties such as its size, its class or its hash.
- A literal array that is used aside from the bytecode to fetch specific objects by the virtual machine to execute code.
- A compiled method header (specific to compiled method) to inform the virtual machine about basic properties such as its number of arguments or its number of temporaries.
- A source pointer to encode the way the IDE can get the method source code.

The format in memory of a compiled method is very specific. Common objects are word-aligned or byte-aligned on all their length. However, a compiled method is a mixed form of an array (its first fields in memory correspond to the compiled method header, encoded as a small integer, and its literals) and a byte array (its next fields correspond to its bytecode and its source pointer).

Memory representation of Compiled Method in 32 bits with the new Memory Manager Spur

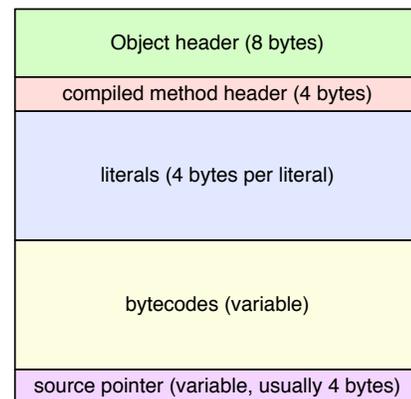


Figure 1. Memory representation of a Compiled method

Changes in the bytecode set design impacts both the memory zones for the compiled method header and for the bytecodes, but does not affect the compiled method object's header, its literal frame nor its source pointer encoding.

3. Challenges for a good bytecode set

3.1 Generic challenges

Any one who has to design a bytecode set faces some challenges. We enumerate the major ones we noticed in this subsection.

Platform-independent. Applications running on top of Cog are currently deployed on production on different operating systems: Linux, Mac OS X, Windows, iOS, Android and RISC OS and on different processors: ARM 32bits, Intel

x86 and Intel x86_64. Therefore, our bytecode set needs to be platform-independent, more specifically processor independent and operating system independent.

Compaction. To have the minimum memory footprint, a bytecode set needs to be able to encode all the compiled methods of system in the minimum number of bytes.

Easy decoding. The bytecode is mainly used by the interpreter to be executed, the JIT compiler to generate native code and in-image to analyze the compiled methods. Therefore, a good bytecode set needs to be easy to decode, decoding being used for analysis, interpretation and compilation.

Conflicts. One cannot have a very compact and very easy to decode bytecode set. Related work[9] has shown that a bytecode set can be compressed by 40% to 60% by sharing the bytecode in a Huffman table, but the bytecode becomes then harder to decode, which complicates the virtual machine interpreter, the JIT compiler and bytecode analysis. This extra difficulty also impacts performance (9% performance loss in their work). Therefore, one has to choose between easier decoding or extreme compaction. Our targets, such as the latest iPhone or the Raspberry pie have at least 256Mb of RAM. The Pharo memory footprint is usually around 20 Mb on production application. Therefore, we prefer to ease the decoding over compacting the bytecode. We want the new bytecode encoding to be at worst the same size as the old bytecode encoding but easier to decode.

Backward compatibility. Some frameworks and libraries may rely on the bytecode format to work. It includes compilers and virtual machines implementations that the designer of the new bytecode set has obviously to consider, but it also includes other frameworks such as serializers. A serializer typically reuses the bytecode encoding to serialize a compiled method. Changing the code set implies either to be backward compatible to have these tools working or fix all the frameworks and libraries.

3.2 Challenges specific to our goals

The runtime bytecode to bytecode optimizer we plan will perform classical dynamic language adaptive optimizations such as inlining based on type feedback[7] and bounds check elimination[2]. Here is a typical example:

```
MyDisplayClass>>example: anArray
  anArray do: [ :elem | self displayOnScreen: elem ].
```

```
Array(SequenceableCollection)>>do: aBlock
  1 to: self size do:
    [:index | aBlock value: (self at: index)]
```

Firstly, based on type-feedback the runtime optimizer notices that the argument of `MyDisplayClass>>example:` is always an `Array`, and then inlines the message send to the array as well as the closure activation, adding a guard that triggers deoptimization if the assumption that `anArray` is an `Array`

is not valid any more. We represented the guard in pseudo Smalltalk code so the code is readable, but of course a guard is typically implemented in a very efficient way in native code.

```
MyDisplayClass>>OptimizedVersion1OfExample: anArray
  Guard: [ anArray class == Array
          ifFalse: [ DynamicDeoptimization ] ].
  1 to: anArray size do: [ :index |
    self displayOnScreen: (anArray at: index) ].
```

The optimizer wants then to inline additional messages sent to `anArray:` `size` and `at:`. After inlining these two messages, it notices that `index` is always within the bounds of `anArray` because the `to:do:` selector sent on an integer enforces that the block argument is an integer between 1 and `anArray size` (This is typically inlined statically by the compiler). Therefore the optimizer edit the `at:` instruction to fetch the field of the objects at the index without checking that the index is within the bounds of `anArray`. In pseudo code, it would mean:

```
MyDisplayClass>>OptimizedVersion1OfExample: anArray
  Guard: [ anArray class == Array
          ifFalse: [ DynamicDeoptimization ] ].
  1 to: anArray inlinedSize do: [ :index |
    self displayOnScreen: (anArray
      inlinedNoBoundsCheckAt: index) ].
```

To be able to do this kind of optimizations, the bytecode set needs specific requirements and instructions that we detail in this subsection.

All methods should be inlinable. All methods and closure activations should be able to be inlined by the optimizer, including primitives. Inlining non primitive methods removes the overhead of a CPU call and allows the optimizer to have bigger portions of code to optimize. Inlining performance critical primitives allows the optimizer to perform additional critical optimizations such as bound check elimination. Due to inlining, optimized methods are bigger than regular methods: they may have jumps of thousands of instructions or thousands of literals. In addition, inlining a method may allow an object to access directly the instance variable of another object. Therefore, the bytecode needs to be able to encode compiled methods with:

- Inlined primitives
- Very large jump
- Very large number of literals
- Access to non receiver instance variable

Unsafe operations. Smalltalk primitives are type safe, which means that calling a primitive with inappropriate arguments will trigger a primitive failure but will not crash the execution. Therefore, each primitive needs to guarantee that the receiver and arguments have one of the expected

type before being performed. Guaranteeing the type of an object means additional CPU instructions to run. The runtime optimizer may want to encode unsafe operations, such as unchecked array access, if it can guarantee that the given primitives will not fail to avoid this type check overhead. The bytecode set needs to be extended to support a set of unsafe operations, which corresponds to inlined primitives that are optimized.

Extendable. While implementing more and more optimization passes in our optimizer, we may need to add extra unsafe operations or to encode new bytecode operations. The bytecode set needs to be easily extendable without compromising optimization opportunities and complicating the logic of the optimizer.

3.3 Current Bytecode issues

The current bytecode set could be improved compared to the generic requirements and is definitely not good enough for our requirements (specification available in Appendix A). In this subsection we describe the issues we noticed.

Argument bytecodes limits. The current bytecode set has limitations regarding the size of arguments. There is no pattern to indefinitely expand an argument bytecode. One typical example is the jump bytecode. This bytecode supports jump forward up to 1024 instructions, but no more. This is already an issue because several Pharo users ended up having a compilation error due to this problem. They had to fix it by editing their code, whereas a user should not need to understand nor see these compiler details. These issues make it impossible for some methods or closures to be inlined due to the code creating a jump too big for the encoding.

Few available bytes. One of our main concerns was the lack of available bytecodes. Only three bytecodes were available (not associated with an operation). This clearly limits the extensibility of the current bytecode set, which is required by our optimizer to easily add new instructions. We estimate that 10 available bytecodes are needed to be extended and manipulated in the future.

Primitive index implementation forbid inlining. Another issue is with the primitive index: by being encoded in the compiled method header, inlining primitives is not possible. However, the runtime optimizer needs to optimize critical primitives such as array access.

DoubleExtendedDoAnything bytecode. The old bytecode set had a bytecode named "double extended do anything" bytecode. This bytecode is able, with the proper encoding, to do almost any operation in the virtual machine. However, This bytecode creates extra difficulties in the JIT compiler to properly map the native code program counter to the bytecode program counter because you always need extra checks to know if it is a message send or something else. This bytecode does not fit with our definition of easy decoding. To

be easy to decode, a bytecode set should not encode several operations in the same byte, or if this is the case then encodes very similar operation, such as push new Array and pop into array, but not operations such as a push, a store and a message send in one bytecode.

Primitive index is split. The compiled method header shown in Figure 2 has a strange primitive index field: this field is split in 2 fields, the main part of the primitive number and the high bit. This is here for backward compatibility with the 16bit Squeak version. However, as none of the Cog users has been using a Smalltalk dialects in 16bit for over multiple decades, and other recent changes have broken this compatibility. This split is now useless whereas it complicates the decoding.

Old compiled method header

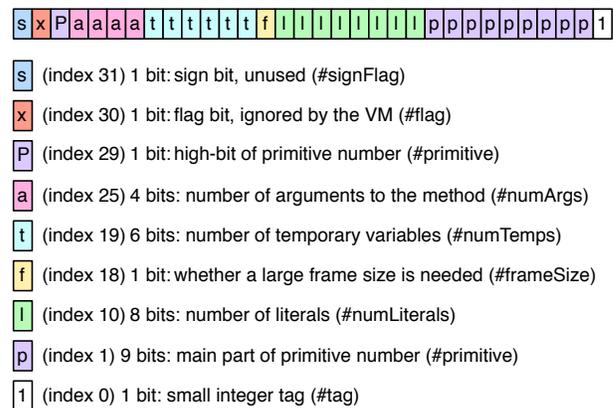


Figure 2. The old compiled method header

Immediate objects waste memory. The bytecode set misses some compact bytecode for immediate objects. For example, encoding the SmallInteger 5 requires at least 5 bytes, 4 bytes to store 5 in the literal array and 1 to 3 bytes for the push literal bytecode. It is very simple to encode and decode immediate objects in the bytecode, as their virtual machine representation is also encoded with bytes, and it greatly improves the compactness of the bytecode.

Late addition of closure bytecodes. Real closures were added in the supported Smalltalk dialects after the old bytecode set design. There was not a lot of free space in the bytecode set, so the bytecode for BlockClosure creation was added in a way that the same bytecode is used to push nil on the stack and to allocate temporary slots on stack for the BlockClosure. This makes the decoding of a BlockClosure complex for the JIT compiler and the in-image analysis due to the difficulty to fetch the number of temporaries.

Outdated constraints. The current bytecode set has a string property: most instructions are 16 bits aligned. For example, instructions 0 to 15 are mapped to push receiver

variable and instructions 16 to 31 are mapped to push temporary. We asked the old bytecode set designer, Dan Ingalls, who is also the implementor of the original Smalltalk-80. It happens that Smalltalk-80 used to run on the Xerox D, and that this 16 bits alignment was there to easily dispatch the instructions on microcoded machines. As we do not run Pharo any more on this kind of machines, we removed this constraint for the bytecode set design.

4. New bytecode set features

In this section we describe the features of the new bytecode set, starting by the ones we added for our runtime optimizer to the other one that improved the bytecode set in general. Then we explain how we convert a Smalltalk image from the old bytecode set to the new one to validate the approach.

4.1 Adaptive optimization features

Extendable instructions. One of the most notable feature of the bytecode set (specification available in Appendix B) is the addition of an extension bytecode. This bytecode, as a prefix, extends the following byte by an index encoded in a byte. In the new bytecode set, each bytecode correspond to a single instruction. It is not possible, as for the "double extended do anything" bytecode of the old bytecode set, to encode different operation in a single byte. By being a prefix, the extension bytecode does not complicate the JIT compilation, as each bytecode still represent a single instruction, and an extension bytecode just requires to fetch the appropriate instruction in a fixed distance (2 bytes further).

This feature allows for example the compiler to generate jump forward bytecode to an infinite number of instructions. The jump forward bytecode is a single extended bytecode, therefore it can jump up to 255 instructions (255 being encoded in the argument byte). By being prefixed by one extension, it can encode a jump up to 65535 instructions. If it is prefixed by two extensions, it can encode a jump up to 16777215 instructions. As one can add as many extensions as one wants, each instruction accepting extensions can be extended to the infinite.

Example: Extended conditional jump instruction
(Numbers in hexadecimal)

Byte number	EF + next byte
Name	jumpFalse:
Bit values	11101111 iiiiii
Explanation	Pop value on stack and jump if the value is false by a distance of distance := iiiiii+(ExtensionB*256)

Byte number	E1 + next byte
Name	ExtensionB (ExtB)
Bit values	11100001 bbbbbbbb
Explanation	ExtensionB ExtB := ExtB*256+bbbbbbbb

bytecode sequence	Explanation
EF 12	jumpFalse: 18
E1 05 EF 12	jumpFalse: 50D 50D = (5*FF)+12
E1 AF E1 05 EF 12	jumpFalse: ADA7BC ADA7BC = (AF*FF*FF)+(5*FF)+18

Inlined primitives and unsafe operations. The new bytecode set moved the primitive index of a method from the compiled method header to the beginning of the compiled method's bytecode (these two zones are shown in Figure 1). The primitive call is now a double extended bytecode, with the two argument bytes encoding the primitive number. The first bit of the first byte argument determines if the primitive is inlined or not. If the primitive is not marked as inlined, it automatically fails if it is not the first bytecode of the method. This change does not slow down the virtual machine due to the different method caches. Inlined primitives cannot fail, therefore one needs to be very careful while inlining a primitive to properly handle inlined primitive failure and its fall back code with control flow operations (for example, a flag on top of stack can force the execution flow to jump on a specific branch that handles the fall back code of the inlined primitive).

Byte number	F9 + next byte (> 127) + next byte
Name	callPrimitive
Bit values	11111001 0iiiiii jjjjjjj
Explanation	call primitive at iiiiii+(jjjjjj*FF) fails if not the first method's bytecode On success: triggers a hard return On failure: executes fallback code

Byte number	F9 + next byte (<= 127) + next byte
Name	callInlinedPrimitive
Bit values	11111001 1iiiiii jjjjjjj
Explanation	call inlined primitive at iiiiii+(jjjjjj*FF) Inlined primitives cannot fail, may be unsafe, never triggers a return, may or may not push a value on stack

To encode the primitives, we noticed that we needed to support at least 1000 primitives and 1000 inlined primitives to support all the operations we might want to implement in the next decade. We could have made CallPrimitive a single extended bytecode taking an extension according to the extendable instruction model introduced in the last paragraph, but that would complicate the VM's determination of the primitive number and the primitive error code store since the extension, being optional, would make the sequence variable length. So we decided to make it a double extended bytecode. Therefore the new representation of primitive allows 32768 primitives and 32768 inlined primitives which is more than enough.

Some of the inlined primitives are unsafe, which means that if you send them on incorrect objects you may corrupt the memory or crash the virtual machine. However, the optimizer can guarantee at compile-time that this cannot happen. The first unsafe operations we want to support are direct access to the field of an objects to optimize indexable objects access by removing bounds checks.

Access to non receiver instance variable. Instance variable access in Smalltalk does not require any specific checks, because an object cannot access any instance variable of any other objects than itself, and at compilation time the structure of the receiver is well-known. In 2008, for our efficient BlockClosure implementation, we added an extra bytecode to quickly allocate an Array on the heap and quickly access to its fields to be able to efficiently share some variables between a closure and its enclosing environment. These operations were also unchecked both for performance and because you know the size of the array at compilation time. We reused these accessing bytecodes to access the instance variables of non receiver objects.

Extendable. The new bytecode set has 15 available bytecodes. This allows us to extend it easily and efficiently.

Maximum number of literals increased. The maximum number of literal extension is quite specific. To overcome the previous limitation, we needed two changes. Firstly, we reused the free bits in the compiled method header from the primitive index to encode more literals. Secondly, we allowed the literal access bytecode to take an extension, allowing the bytecode to encode access to literals at a position over 255 in the literal frame of the compiled method.

4.2 Generic features

Overall bytecode size. In the Pharo 3.0 release (version 30848), we installed the new compiler back-end for the new bytecode set support. The system reached then 75190 compiled methods (closures are included in compiled methods). As explained in Section 2.2, the new bytecode set impacts only the compiled method header and the bytecode zone of a compiled method. However, the compiled method header has a fixed size of a word (4 bytes in 32 bits, 8 bytes in 64bits). All the bytecode zones of the compiled methods in the image used to be encoded in 2,285,892 bytes with the old bytecode set, and are now encoded in 1,960,187 bytes. The new bytecode set is therefore more compact than the old one by 14.2%. However, the difference of around 325kb is hardly noticeable on typical Pharo application that are around 20Mb.

Immediate objects compaction. Immediate objects are now encoded in the bytecode instead of in the literal array. An object in the literal array always uses a word, which corresponds to 4 bytes in 32bits. Most immediate objects can be encoded in a single byte, such as integer from 0 to 255, or the 255 most common Characters. We use that property

to reduce the encoding size of most immediate objects. We added two single extended bytecode to support the encoding of SmallInteger and Character, the argument byte encoding the immediate object instead of a literal in the literal frame. These bytecodes support extension if they require extra bytes to be encoded. We have also reserved a double extended bytecode for SmallFloat, but we have not implemented it as our 64bits VM version is not stable enough. Depending on its memory manager and on its 64 bits or 32 bits form, Cog has from 1 to 3 immediate objects: SmallInteger, Character and SmallFloat. On the long term, all three will be always used, this variable number of immediate objects being due to the migration to the new Memory Manager Spur and to 64 bits.

Platform-independent. We have not introduced any platform dependent instruction, so the new bytecode set remains platform-independent.

Easy decoding. A massive improvement is related to the bytecode decoding. The bytecodes are now arranged with two simple rules:

- The bytecode are sorted by the number of bytes they need to encode their functionality: single byte bytecode are encoded between 0 and 223, extended bytecode are encoded between 224 and 248, double extended bytecode are encoded from 249 to 255.
- Within a number of byte categories, bytecodes are sorted by their functionalities: push bytecode are next to each other, send bytecodes are next to each others, ...

Easier closure decoding. A new bytecode was introduced to encode the number of temporaries in closures. We now do not need any more to walk over part of the closure bytecode to find out the number of temporaries.

About backward compatibility. Some mainstream language can hardly change their bytecode set. For example, when Java added the extra bytecode for invokeDynamic [15], the process to get it included in all virtual machines executing the Java bytecode was really tedious, and they didn't even have to edit all the bytecode compilers because this extra bytecode is provided for other languages on top of the JVM and not for Java itself. However, the Cog VM clients have two different production compilers. In addition, the most widely used serialization framework of our clients, Fuel[5], serialize the sources of a compiled method instead of its bytecode to support debugging and code edition of materialized methods in environments without decompilers. Therefore, by changing the virtual machine and the two compilers, we fixed most backward-compatibility issues.

4.3 Switching between bytecode sets to validate our approach

Difficulties with offline converters. One of the main concern, in a Smalltalk runtime, when implementing a new byte-

code set, is how to switch a snapshot from one bytecode set to another one. One solution is to implement an offline converter, that can translate the compiled method of an image from a bytecode set to another one. This solution has a big disadvantage: as long as the bytecode set implementation both image-side with the compiler back-end and VM-side with the interpreter and JIT front-end are not stable, the Smalltalk runtime crashes almost immediately at start-up and it is very hard to debug.

Multiple bytecode set support. When the Newspeak support was added to the Cog VM, the virtual machine was improved to support multiple bytecode set in the same runtime. In some Smalltalk virtual machines, such as the one of Smalltalk/X and Visual Age, the support of multiple bytecode set was implemented a while ago to be able to execute both the smalltalk bytecode and the Java bytecode. Claus Gittinger has worked on the Visual Age implementation and helped for this Cog VM improvement.

We decided to use the multiple bytecode set feature and we did not implement an offline converter. This approach has a big advantage, we can debug our bytecode compiler back end in Smalltalk on top of a VM that supports the old and the new bytecode set.

Encoding support for multiple bytecode sets. The support of multiple bytecode set is implemented part in the VM and part in the compiled method header format. The sign bit of the SmallInteger encoding the compiled method header is used to mark the method as using one or the other bytecode set, as shown in Figure 3. However, we discourage from using multiple bytecode set on top of the Cog VM for anything else than image conversion from a bytecode set to another or experiments. This is because different bytecode set have different limitations, and it may be that a method can be compiled in a bytecode set and not in another one. For example, the number of literals is limited to 255 in the old bytecode set and 65535 in the new one by assuming a CallPrimitive bytecode. This means that a method with 500 literals can be compiled in the new bytecode set but not in the old one.

Validation. Our bytecode set was validated by the implementation of a compiler back-end to generate the new bytecode out of the source code, the implementation of the interpreter front-end and the implementation of the JIT compile front-end. The whole infrastructure is running with the new bytecode set with similar performance, validating the design. This was easy as the compiler, the interpreter and the JIT compiler were designed with an abstraction layer over the bytecode set to easily change it. Moving an image from one bytecode set to another one was also not very difficult with the multi-bytecode set support feature of the VM.

New hybrid compiled method header

Depending on the first bit, the new compiled method header is encoded in one of the two format described below.



- 0 (index 31) 1 bit: sign bit, 0 selects the old bytecode set (#signFlag)
- x (index 30) 1 bit: flag bit, ignored by the VM (#flag)
- P (index 29) 1 bit: high-bit of primitive number (#primitive)
- a (index 25) 4 bits: number of arguments to the method (#numArgs)
- t (index 19) 6 bits: number of temporary variables (#numTemps)
- f (index 18) 1 bit: whether a large frame size is needed (#frameSize)
- l (index 10) 8 bits: number of literals (#numLiterals)
- p (index 1) 9 bits: main part of primitive number (#primitive)
- 1 (index 0) 1 bit: small integer tag (#tag)



- 1 (index 31) 1 bit: sign bit, 1 selects the new bytecode set(#signFlag)
- x (index 30) 1 bit: flag bit, ignored by the VM (#flag)
- (index 29) 1 bit: unused
- a (index 25) 4 bits: number of arguments to the method (#numArgs)
- t (index 19) 6 bits: number of temporary variables (#numTemps)
- f (index 18) 1 bit: whether a large frame size is needed (#frameSize)
- p (index 17) 1 bit: has primitive (#hasPrimitive)
- l (index 1) 16 bits: number of literals (#numLiterals)
- 1 (index 0) 1 bit: small integer tag (#tag)

Figure 3. The new hybrid compiled method header

5. Discussion

5.1 Compaction of message sends

To improve the compactness of the bytecode set, some Smalltalk dialects as Visual Works have a specific bytecode for common message send. This bytecode is a single extended bytecode, the argument byte being the index of the common selector in a common selector array. This way, sends with common selectors are most of the time encoded in 2 bytes instead of 5 bytes because the selector is not in the literal frame, at the cost of an indirection array.

A similar feature is present in the old and new bytecode set. A list of 16 arithmetic selectors and 16 common selector have a quick encoding form. Our representation could have been extended to have this single extended bytecode, so we would have many more selectors encoded in a compact way. However, this approach has issues. For instance, common selector are not always the same. Therefore, on a regular basis, the team maintaining the programming language needs to update this common selector array depend-

ing on the new common selectors. This is problematic for some tools, such as some serializer which needs to version the serialized methods to know what common selector array it needs to use for serialization and materialization. We kept the exact same compact selectors from the old bytecode set to the new one to avoid this kind of issue. In addition, we had already reached our compaction goals, so we didn't need to add extra complexity for more compaction.

5.2 Register-based bytecode set

Our bytecode set is stack based. This design date from the time where there were both register based and stack based CPU. However, modern common CPU are now all register-based, so one can wonder if a register-based bytecode set may not be better. At Google, the Dalvik VM team chose to rely on a register-based bytecode for their Android applications[4].

We didn't move to a register-based bytecode for different reasons. The main reason is that to generate register-based bytecodes, you need to give to the compiler the number of available registers. This generates extra complexity when running the application on different platforms which may have a different number of general purpose registers. For example, on our targets, intel x86 has 8 general purpose registers whereas intel x86_64 has 16 general purpose registers. Moving from one architecture to another one requires to loose performance by using less registers than available, to recompile all the code base with the new number of general purpose registers or to have a non trivial mapping from a limited number of register to an extended one in the JIT compiler.

5.3 Threaded FFI

The Cog VM now starts to support a threaded foreign function interface (FFI) to be able to call C function without blocking the virtual machine execution. The current process implementation requires the user to fetch a global variable and to execute a message send to access the current process. This implementation was good enough but does not scale for the new multithreaded FFI. Therefore, we are considering an extra bytecode to have a direct access on the active process.

We are not sure exactly if this bytecode will be used and how. The original idea was to extend the language with an extra reserved keyword, *thisProcess*, which will push on the stack the active process the same way the active context is pushed with the reserved keyword *thisContext*. But adding an extra reserved keyword adds extra constraints to the language, so we need to study other solutions.

6. Related Works

6.1 Bytecode and primitive operations

The main difference between most bytecode sets and a Smalltalk bytecode set is that we do not encode any primitive operations in the bytecode. For example, addition is

implemented as the message send named "+", and can be sent to any Object in the system. Integer addition will be performed only if the receiver is a SmallInteger. However, there are no integer addition encoded in the bytecode set that requires the operands to be SmallIntegers. Classic bytecode sets, such as the Java one[12], encodes primitive operations. For example the operation `iadd` in Java expects both operands to be Integers. All Smalltalk instructions expect objects of any type.

With the new bytecode set, we added encoding for inlined primitives at bytecode level, which includes typed operations. However, this encoding will only be used only by the runtime optimizer or very specific low-level tool such as an ABI compiler, and is not present by default in the Smalltalk semantics.

6.2 Bytecode set with superoperators

Several teams designed a bytecode set with superoperators to optimize the interpreter speed[3, 8, 13]. Superoperators are virtual machine operations automatically synthesized from smaller operations to avoid costly per-operation overheads. This is typically done statically at compile-time. The compiler detects common bytecode patterns and then extends the bytecode set with superoperators performing the common patterns. For an interpreter, this technique drastically improves the performance by reducing the overhead of bytecode fetching. However, in our case we would need to adapt many in-image tools, as well as the interpreter and the JIT to support it. In addition, this optimization speeds up only the interpreter, which is in most case not performance critical as our VM heavily relies on the JIT for performance. So we concluded that this optimization would cost too much time to implement compared to its benefits.

6.3 Bytecode extensions

To add infinite argument values to our argument bytecodes, we added the extension prefix bytecodes in the new bytecode set as explained in Section 4.1. We designed the extension this way to be able to encode one instruction per bytecode (only the argument is variable) and because we needed a limited number of different instructions.

Other systems have needed many more instructions, typically more than 255 which is the maximum number of different instructions you can encode in a byte. An example is the Z80 CPU bytecode[16] which needed many graphical instructions (the Z80 is the processor of the GameBoy and the SuperNintendo). In this case, they decided to use bytecode prefix to indicate to the processor to fetch the next bytecode in another bytecode table encoding other instructions. This is a convenient trick when you want an important number of instructions, but as we have much less different instructions that 255 in our virtual machine, we felt the extra complexity of this encoding didn't worth it.

6.4 Visual Works bytecode set

The Cog virtual machine is very different from the VisualWorks VM. However, they both run Smalltalk runtime, so the comparison is interesting.

BlockClosure bytecodes. One difference is that VisualWorks has another model to activate BlockClosure. When a BlockClosure is activated, it is present in the receiver slot of the context, because the BlockClosure received the block activation message. We instead have two fields in a context, one for the method activation's receiver and one for the closure. VisualWorks' model seems very pure and cleaner for the user. However, in term of the bytecode set, it means that accessing the receiver or the receiver fields in method has to be encoded differently between a method and a BlockClosure, because in one case it access the receiver of the active context whereas in the other case it access a variable from the lexically enclosed environment. In our implementation, the receiver slot of a BlockClosure context has the receiver of the homeContext, therefore accessing the receiver and the receiver's fields is the same whichever activation you are. Both implementation has pros and cons. We considered the other approach, but we preferred to simplify the virtual machine implementation at the cost of complicating a bit the model for the end user.

Loop encoding. Another difference is the support in the VisualWorks bytecode set to encode the beginning of a loop. This is convenient to be able in the JIT to generate native code in a single pass. However, loops are not very frequent in Smalltalk dialects: 5% of the compiled methods have a loop in the Pharo 3.0 release image and adding in our JIT implementation some code to handle loops didn't increase a lot the JIT complexity, therefore we preferred no to introduce this bytecode.

Common selector array. VisualWorks features a common selector array as it is described in Section 5.1. We didn't choose to add that in the Cog VM as explained in this subsection.

Non immediate entries in machine code. VisualWorks has support for non-immediate entries in machine code methods. This means that if you can guarantee that an object is not an immediate object, i.e., not a Character, a SmallInteger nor a SmallFloat, you can speed up monomorphic sends sites by targeting the method after the immediate entry. This is encoded in the bytecode with a specific send targeting the non-immediate entry in the machine code. This implementation leads to lots of complication, such as if the user change a temporary variable in the debugger leading to an immediate object being sent a message send with a non immediate entry, as well as VM-side complication as we needed to add an extra entry in the native methods, aside from the class check entry and unchecked entry.

7. Future work and Conclusion

The reason why we needed a new bytecode set was to be able to implement a runtime optimizer in the JIT compiler to optimize methods in a bytecode to bytecode fashion. This optimizer will therefore have some similarities with Soot[14], the Java bytecode to bytecode optimizer, but will be used at runtime and not statically. As the bytecode set is now ready, one needs to design and implement the runtime optimizer.

Reportedly, it is very difficult to produce correct marshaling code for FFI calls on some architectures, especially on x86_64bits[10], which is now very common. Generating marshaling code in the virtual machine is tedious, as debugging the virtual machine has always been much more complex than debugging high level languages, even with very good dedicated tools. One could implement the marshaling code of FFI calls by generating compiled methods encoding low level instructions with the unsafe operations of the new bytecode set in order to simplify this process.

In this paper, we showed how we designed a bytecode set suitable for runtime bytecode to bytecode optimizations for the Cog VM and its Smalltalk clients.

This new bytecode set encodes an extendable set of unsafe operations to provide information to the JIT compiler for producing better machine code, encodes primitives in a way the optimizer can inline them, has many available bytecodes to be easily extended and fixes the old bytecode set issues we described.

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A. The old bytecode set

Old Bytecode set

0	Push Receiver Variable	1	Push Receiver Variable	2	Push Receiver Variable	3	Push Receiver Variable	4	Push Receiver Variable	5	Push Receiver Variable	6	Push Receiver Variable	7	Push Receiver Variable	8	Push Receiver Variable	9	Push Receiver Variable	10	Push Receiver Variable	11	Push Receiver Variable	12	Push Receiver Variable	13	Push Receiver Variable	14	Push Receiver Variable	15	Push Receiver Variable																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
16	Push Temp	17	Push Temp	18	Push Temp	19	Push Temp	20	Push Temp	21	Push Temp	22	Push Temp	23	Push Temp	24	Push Temp	25	Push Temp	26	Push Temp	27	Push Temp	28	Push Temp	29	Push Temp	30	Push Temp	31	Push Temp																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
32	Push Lateral Constant	33	Push Lateral Constant	34	Push Lateral Constant	35	Push Lateral Constant	36	Push Lateral Constant	37	Push Lateral Constant	38	Push Lateral Constant	39	Push Lateral Constant	40	Push Lateral Constant	41	Push Lateral Constant	42	Push Lateral Constant	43	Push Lateral Constant	44	Push Lateral Constant	45	Push Lateral Constant	46	Push Lateral Constant	47	Push Lateral Constant																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
48	Push Lateral Constant	49	Push Lateral Constant	50	Push Lateral Constant	51	Push Lateral Constant	52	Push Lateral Constant	53	Push Lateral Constant	54	Push Lateral Constant	55	Push Lateral Constant	56	Push Lateral Constant	57	Push Lateral Constant	58	Push Lateral Constant	59	Push Lateral Constant	60	Push Lateral Constant	61	Push Lateral Constant	62	Push Lateral Constant	63	Push Lateral Constant																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
64	Push Lateral Variable	65	Push Lateral Variable	66	Push Lateral Variable	67	Push Lateral Variable	68	Push Lateral Variable	69	Push Lateral Variable	70	Push Lateral Variable	71	Push Lateral Variable	72	Push Lateral Variable	73	Push Lateral Variable	74	Push Lateral Variable	75	Push Lateral Variable	76	Push Lateral Variable	77	Push Lateral Variable	78	Push Lateral Variable	79	Push Lateral Variable																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
80	Push Lateral Variable	81	Push Lateral Variable	82	Push Lateral Variable	83	Push Lateral Variable	84	Push Lateral Variable	85	Push Lateral Variable	86	Push Lateral Variable	87	Push Lateral Variable	88	Push Lateral Variable	89	Push Lateral Variable	90	Push Lateral Variable	91	Push Lateral Variable	92	Push Lateral Variable	93	Push Lateral Variable	94	Push Lateral Variable	95	Push Lateral Variable																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
96	PopInto Receiver Variable	97	PopInto Receiver Variable	98	PopInto Receiver Variable	99	PopInto Receiver Variable	100	PopInto Receiver Variable	101	PopInto Receiver Variable	102	PopInto Receiver Variable	103	PopInto Receiver Variable	104	PopInto Receiver Variable	105	PopInto Receiver Variable	106	PopInto Receiver Variable	107	PopInto Receiver Variable	108	PopInto Receiver Variable	109	PopInto Receiver Variable	110	PopInto Receiver Variable	111	PopInto Receiver Variable																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
112	Push Receiver	113	Push true	114	Push false	115	Push nil	116	Push -1	117	Push 0	118	Push 1	119	Push 2	120	Return receiver	121	Return true	122	Return false	123	Return nil	124	Return	125	Block Return	126	Block Return	127	Block Return																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
128	(0) Push LongForm	129	(0) Store LongForm	130	(0) PopInto LongForm	131	(1) Single Extended send	132	(3) Double extended	133	Super send	134	(2) Second extended	135	Pop Stack top	136	Duplicate	137	Push this Context	138	(4) Push or PopInto Array	139	Return nil	140	Return	141	Block Return	142	(5) Store Temp in temp Vector	143	(6) Push Closure																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
144	Jump 1	145	Jump 2	146	Jump 3	147	Jump 4	148	Jump 5	149	Jump 6	150	Jump 7	151	Jump 8	152	Jump 1	153	Jump 2	154	Jump 3	155	Jump 4	156	Jump 5	157	Jump 6	158	Jump 7	159	Jump 8																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
160	Long Jump	161	Long Jump	162	Long Jump	163	Long Jump	164	Long Jump	165	Long Jump	166	Long Jump	167	Long Jump	168	Long Jump	169	Long Jump	170	Long Jump	171	Long Jump	172	Long Jump	173	Long Jump	174	Long Jump	175	Long Jump																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
-1024 to -769	176	-768 to -513	-512 to -257	-256 to -1	0 to 255	256 to 512	513 to 768	768 to 1024	1024 to 1279	1280 to 1523	1524 to 1767	1768 to 2011	2012 to 2255	2256 to 2500	2501 to 2744	2745 to 2988	2989 to 3232	3233 to 3476	3477 to 3720	3721 to 3964	3965 to 4208	4209 to 4452	4453 to 4696	4697 to 4940	4941 to 5184	5185 to 5428	5429 to 5672	5673 to 5916	5917 to 6160	6161 to 6404	6405 to 6648	6649 to 6892	6893 to 7136	7137 to 7380	7381 to 7624	7625 to 7868	7869 to 8112	8113 to 8356	8357 to 8600	8601 to 8844	8845 to 9088	9089 to 9332	9333 to 9576	9577 to 9820	9821 to 10064	10065 to 10308	10309 to 10552	10553 to 10796	10797 to 11040	11041 to 11284	11285 to 11528	11529 to 11772	11773 to 12016	12017 to 12260	12261 to 12504	12505 to 12748	12749 to 12992	12993 to 13236	13237 to 13480	13481 to 13724	13725 to 13968	13969 to 14212	14213 to 14456	14457 to 14700	14701 to 14944	14945 to 15188	15189 to 15432	15433 to 15676	15677 to 15920	15921 to 16164	16165 to 16408	16409 to 16652	16653 to 16896	16897 to 17140	17141 to 17384	17385 to 17628	17629 to 17872	17873 to 18116	18117 to 18360	18361 to 18604	18605 to 18848	18849 to 19092	19093 to 19336	19337 to 19580	19581 to 19824	19825 to 20068	20069 to 20312	20313 to 20556	20557 to 20800	20801 to 21044	21045 to 21288	21289 to 21532	21533 to 21776	21777 to 22020	22021 to 22264	22265 to 22508	22509 to 22752	22753 to 22996	22997 to 23240	23241 to 23484	23485 to 23728	23729 to 23972	23973 to 24216	24217 to 24460	24461 to 24704	24705 to 24948	24949 to 25192	25193 to 25436	25437 to 25680	25681 to 25924	25925 to 26168	26169 to 26412	26413 to 26656	26657 to 26900	26901 to 27144	27145 to 27388	27389 to 27632	27633 to 27876	27877 to 28120	28121 to 28364	28365 to 28608	28609 to 28852	28853 to 29096	29097 to 29340	29341 to 29584	29585 to 29828	29829 to 30072	30073 to 30316	30317 to 30560	30561 to 30804	30805 to 31048	31049 to 31292	31293 to 31536	31537 to 31780	31781 to 32024	32025 to 32268	32269 to 32512	32513 to 32756	32757 to 33000	33001 to 33244	33245 to 33488	33489 to 33732	33733 to 33976	33977 to 34220	34221 to 34464	34465 to 34708	34709 to 34952	34953 to 35196	35197 to 35440	35441 to 35684	35685 to 35928	35929 to 36172	36173 to 36416	36417 to 36660	36661 to 36904	36905 to 37148	37149 to 37392	37393 to 37636	37637 to 37880	37881 to 38124	38125 to 38368	38369 to 38612	38613 to 38856	38857 to 39100	39101 to 39344	39345 to 39588	39589 to 39832	39833 to 40076	40077 to 40320	40321 to 40564	40565 to 40808	40809 to 41052	41053 to 41296	41297 to 41540	41541 to 41784	41785 to 42028	42029 to 42272	42273 to 42516	42517 to 42760	42761 to 43004	43005 to 43248	43249 to 43492	43493 to 43736	43737 to 43980	43981 to 44224	44225 to 44468	44469 to 44712	44713 to 44956	44957 to 45200	45201 to 45444	45445 to 45688	45689 to 45932	45933 to 46176	46177 to 46420	46421 to 46664	46665 to 46908	46909 to 47152	47153 to 47396	47397 to 47640	47641 to 47884	47885 to 48128	48129 to 48372	48373 to 48616	48617 to 48860	48861 to 49104	49105 to 49348	49349 to 49592	49593 to 49836	49837 to 50080	50081 to 50324	50325 to 50568	50569 to 50812	50813 to 51056	51057 to 51300	51301 to 51544	51545 to 51788	51789 to 52032	52033 to 52276	52277 to 52520	52521 to 52764	52765 to 53008	53009 to 53252	53253 to 53496	53497 to 53740	53741 to 53984	53985 to 54228	54229 to 54472	54473 to 54716	54717 to 54960	54961 to 55204	55205 to 55448	55449 to 55692	55693 to 55936	55937 to 56180	56181 to 56424	56425 to 56668	56669 to 56912	56913 to 57156	57157 to 57400	57401 to 57644	57645 to 57888	57889 to 58132	58133 to 58376	58377 to 58620	58621 to 58864	58865 to 59108	59109 to 59352	59353 to 59596	59597 to 59840	59841 to 60084	60085 to 60328	60329 to 60572	60573 to 60816	60817 to 61060	61061 to 61304	61305 to 61548	61549 to 61792	61793 to 62036	62037 to 62280	62281 to 62524	62525 to 62768	62769 to 63012	63013 to 63256	63257 to 63500	63501 to 63744	63745 to 63988	63989 to 64232	64233 to 64476	64477 to 64720	64721 to 64964	64965 to 65208	65209 to 65452	65453 to 65696	65697 to 65940	65941 to 66184	66185 to 66428	66429 to 66672	66673 to 66916	66917 to 67160	67161 to 67404	67405 to 67648	67649 to 67892	67893 to 68136	68137 to 68380	68381 to 68624	68625 to 68868	68869 to 69112	69113 to 69356	69357 to 69600	69601 to 69844	69845 to 70088	70089 to 70332	70333 to 70576	70577 to 70820	70821 to 71064	71065 to 71308	71309 to 71552	71553 to 71796	71797 to 72040	72041 to 72284	72285 to 72528	72529 to 72772	72773 to 73016	73017 to 73260	73261 to 73504	73505 to 73748	73749 to 73992	73993 to 74236	74237 to 74480	74481 to 74724	74725 to 74968	74969 to 75212	75213 to 75456	75457 to 75700	75701 to 75944	75945 to 76188	76189 to 76432	76433 to 76676	76677 to 76920	76921 to 77164	77165 to 77408	77409 to 77652	77653 to 77896	77897 to 78140	78141 to 78384	78385 to 78628	78629 to 78872	78873 to 79116	79117 to 79360	79361 to 79604	79605 to 79848	79849 to 80092	80093 to 80336	80337 to 80580	80581 to 80824	80825 to 81068	81069 to 81312	81313 to 81556	81557 to 81800	81801 to 82044	82045 to 82288	82289 to 82532	82533 to 82776	82777 to 83020	83021 to 83264	83265 to 83508	83509 to 83752	83753 to 84000	84001 to 84244	84245 to 84488	84489 to 84732	84733 to 84976	84977 to 85220	85221 to 85464	85465 to 85708	85709 to 85952	85953 to 86196	86197 to 86440	86441 to 86684	86685 to 86928	86929 to 87172	87173 to 87416	87417 to 87660	87661 to 87904	87905 to 88148	88149 to 88392	88393 to 88636	88637 to 88880	88881 to 89124	89125 to 89368	89369 to 89612	89613 to 89856	89857 to 90100	90101 to 90344	90345 to 90588	90589 to 90832	90833 to 91076	91077 to 91320	91321 to 91564	91565 to 91808	91809 to 92052	92053 to 92296	92297 to 92540	92541 to 92784	92785 to 93028	93029 to 93272	93273 to 93516	93517 to 93760	93761 to 94004	94005 to 94248	94249 to 94492	94493 to 94736	94737 to 94980	94981 to 95224	95225 to 95468	95469 to 95712	95713 to 95956	95957 to 96200	96201 to 96444	96445 to 96688	96689 to 96932	96933 to 97176	97177 to 97420	97421 to 97664	97665 to 97908	97909 to 98152	98153 to 98396	98397 to 98640	98641 to 98884	98885 to 99128	99129 to 99372	99373 to 99616	99617 to 99860	99861 to 100104	100105 to 100348	100349 to 100592	100593 to 100836	100837 to 101080	101081 to 101324	101325 to 101568	101569 to 101812	101813 to 102056	102057 to 102300	102301 to 102544	102545 to 102788	102789 to 103032	103033 to 103276	103277 to 103520	103521 to 103764	103765 to 104008	104009 to 104252	104253 to 104496	104497 to 104740	104741 to 104984	104985 to 105228	105229 to 105472	105473 to 105716	105717 to 105960	105961 to 106204	106205 to 106448	106449 to 106692	106693 to 106936	106937 to 107180	107181 to 107424	107425 to 107668	107669 to 107912	107913 to 108156	108157 to 108400	108401 to 108644	108645 to 108888	108889 to 109132	109133 to 109376	109377 to 109620	109621 to 109864	109865 to 110108	110109 to 110352	110353 to 110596	110597 to 110840	110841 to 111084	111085 to 111328	111329 to 111572	111573 to 111816	111817 to 112060	112061 to 112304	112305 to 112548	112549 to 112792	112793 to 113036	113037 to 113280	113281 to 113524	113525 to 113768	113769 to 114012	114013 to 114256	114257 to 114500	114501 to 114744	114745 to 114988	114989 to 115232	115233 to 115476	115477 to 115720	115721 to 115964	115965 to 116208	116209 to 116452	116453 to 116696	116697 to 116940	116941 to 117184	117185 to 117428	117429 to 117672	117673 to 117916	117917 to 118160	118161 to 118404	118405 to 118648	118649 to 118892	118893 to 119136	119137 to 119380	119381 to 119624	119625 to 119868	119869 to 120112	120113 to 120356	120357 to 120600	120601 to 120844	120845 to 121088

B. The new bytecode set

New Bytecode set

0	Push Receiver Variable	1	Push Receiver Variable	2	Push Receiver Variable	3	Push Receiver Variable	4	Push Receiver Variable	5	Push Receiver Variable	6	Push Receiver Variable	7	Push Receiver Variable	8	Push Receiver Variable	9	Push Receiver Variable	10	Push Receiver Variable	11	Push Receiver Variable	12	Push Receiver Variable	13	Push Receiver Variable	14	Push Receiver Variable	15	Push Receiver Variable
16	Push Literal Variable	17	Push Literal Variable	18	Push Literal Variable	19	Push Literal Variable	20	Push Literal Variable	21	Push Literal Variable	22	Push Literal Variable	23	Push Literal Variable	24	Push Literal Variable	25	Push Literal Variable	26	Push Literal Variable	27	Push Literal Variable	28	Push Literal Variable	29	Push Literal Variable	30	Push Literal Variable	31	Push Literal Variable
32	Push Literal Constant	33	Push Literal Constant	34	Push Literal Constant	35	Push Literal Constant	36	Push Literal Constant	37	Push Literal Constant	38	Push Literal Constant	39	Push Literal Constant	40	Push Literal Constant	41	Push Literal Constant	42	Push Literal Constant	43	Push Literal Constant	44	Push Literal Constant	45	Push Literal Constant	46	Push Literal Constant	47	Push Literal Constant
48	Push Literal Constant	49	Push Literal Constant	50	Push Literal Constant	51	Push Literal Constant	52	Push Literal Constant	53	Push Literal Constant	54	Push Literal Constant	55	Push Literal Constant	56	Push Literal Constant	57	Push Literal Constant	58	Push Literal Constant	59	Push Literal Constant	60	Push Literal Constant	61	Push Literal Constant	62	Push Literal Constant	63	Push Literal Constant
64	Push Temp	65	Push Temp	66	Push Temp	67	Push Temp	68	Push Temp	69	Push Temp	70	Push Temp	71	Push Temp	72	Push Temp	73	Push Temp	74	Push Temp	75	Push Temp	76	Push Temp	77	Push Temp	78	Push Temp	79	Push Temp
80	Push 0	81	Push context Push process	82	Push context Push process	83	Duplicate Stack Top	84	Return Receiver	85	Return Receiver	86	Return Receiver	87	Return Receiver	88	Return Receiver	89	Return Receiver	90	Return Receiver	91	Return Receiver	92	Return Receiver	93	Return Receiver	94	Return Receiver	95	Return Receiver
96	at: <	97	at: <	98	at: <	99	at: <	100	at: <	101	at: <	102	at: <	103	at: <	104	at: <	105	at: <	106	at: <	107	at: <	108	at: <	109	at: <	110	at: <	111	at: <
112	at: next	113	at: next	114	at: next	115	at: next	116	at: next	117	at: next	118	at: next	119	at: next	120	at: next	121	at: next	122	at: next	123	at: next	124	at: next	125	at: next	126	at: next	127	at: next
128	Send 0 args selector at	129	Send 0 args selector at	130	Send 0 args selector at	131	Send 0 args selector at	132	Send 0 args selector at	133	Send 0 args selector at	134	Send 0 args selector at	135	Send 0 args selector at	136	Send 0 args selector at	137	Send 0 args selector at	138	Send 0 args selector at	139	Send 0 args selector at	140	Send 0 args selector at	141	Send 0 args selector at	142	Send 0 args selector at	143	Send 0 args selector at
144	Send 1 args selector at	145	Send 1 args selector at	146	Send 1 args selector at	147	Send 1 args selector at	148	Send 1 args selector at	149	Send 1 args selector at	150	Send 1 args selector at	151	Send 1 args selector at	152	Send 1 args selector at	153	Send 1 args selector at	154	Send 1 args selector at	155	Send 1 args selector at	156	Send 1 args selector at	157	Send 1 args selector at	158	Send 1 args selector at	159	Send 1 args selector at
160	Send 2 args selector at	161	Send 2 args selector at	162	Send 2 args selector at	163	Send 2 args selector at	164	Send 2 args selector at	165	Send 2 args selector at	166	Send 2 args selector at	167	Send 2 args selector at	168	Send 2 args selector at	169	Send 2 args selector at	170	Send 2 args selector at	171	Send 2 args selector at	172	Send 2 args selector at	173	Send 2 args selector at	174	Send 2 args selector at	175	Send 2 args selector at
176	Jump	177	Jump	178	Jump	179	Jump	180	Jump	181	Jump	182	Jump	183	Jump	184	Jump	185	Jump	186	Jump	187	Jump	188	Jump	189	Jump	190	Jump	191	Jump
192	Jump False	193	Jump False	194	Jump False	195	Jump False	196	Jump False	197	Jump False	198	Jump False	199	Jump False	200	Jump False	201	Jump False	202	Jump False	203	Jump False	204	Jump False	205	Jump False	206	Jump False	207	Jump False
1	Popinto Temp	2	Popinto Temp	3	Popinto Temp	4	Popinto Temp	5	Popinto Temp	6	Popinto Temp	7	Popinto Temp	8	Popinto Temp	9	Popinto Temp	10	Popinto Temp	11	Popinto Temp	12	Popinto Temp	13	Popinto Temp	14	Popinto Temp	15	Popinto Temp	16	Popinto Temp
208	Popinto Temp	209	Popinto Temp	210	Popinto Temp	211	Popinto Temp	212	Popinto Temp	213	Popinto Temp	214	Popinto Temp	215	Popinto Temp	216	Popinto Temp	217	Popinto Temp	218	Popinto Temp	219	Popinto Temp	220	Popinto Temp	221	Popinto Temp	222	Popinto Temp	223	Popinto Temp
224	Extension A	225	Extension B	226	Extension B	227	Extension B	228	Extension B	229	Extension B	230	Extension B	231	Extension B	232	Extension B	233	Extension B	234	Extension B	235	Extension B	236	Extension B	237	Extension B	238	Extension B	239	Extension B
240	Extended Popinto Receiver Variable	241	Extended Popinto Receiver Variable	242	Extended Popinto Receiver Variable	243	Extended Popinto Receiver Variable	244	Extended Popinto Receiver Variable	245	Extended Popinto Receiver Variable	246	Extended Popinto Receiver Variable	247	Extended Popinto Receiver Variable	248	Extended Popinto Receiver Variable	249	Extended Popinto Receiver Variable	250	Reserved for Push Float Primitive	251	Push Closure Copy	252	Push Temp in temp Vector	253	Store Temp in temp Vector	254	Popinto Temp in temp Vector	255	Extended Pop And Jump False

Figure 5. The new bytecode set