

# DiVM: Model Checking with LLVM and Graph Memory<sup>☆</sup>

Petr Ročkai, Vladimír Štill, Ivana Černá, Jiří Barnat

*Faculty of Informatics, Masaryk University  
Brno, Czech Republic*

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## Abstract

In this paper, we introduce the concept of a virtual machine with graph-organised memory as a versatile backend for both explicit-state and abstraction-driven verification of software. Our virtual machine uses the LLVM IR as its instruction set, enriched with a small set of *hypercalls*. We show that the provided hypercalls are sufficient to implement a small operating system, which can then be linked with applications to provide a POSIX-compatible verification environment. Finally, we demonstrate the viability of the approach through a comparison with a more traditionally-designed LLVM model checker.

*Keywords:*

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## 1. Introduction

Applying verification to real-world programs is undoubtedly desirable – it can increase code quality while cutting costs at the same time. Model checking is one of the approaches that can provide robust correctness guarantees without introducing false positives. This precision, however, does not come for free – model checking, especially in the context of software, is computationally very expensive. Nonetheless, as our previous work shows [1], a combination of state space reduction techniques, compression and of a tailored approach to test case construction makes model checking a genuinely useful programming aid. For example, we have successfully applied this approach in development of scalable concurrent data structures [2] in C++.

### 1.1. Application Area

The main area we are aiming at in this paper is verification of C and C++ programs that do not explicitly interact with their environment and in particular, do not read data from uncontrolled outside sources. As an example, it is

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*Email addresses:* xrockai@fi.muni.cz (Petr Ročkai), xstill@fi.muni.cz (Vladimír Štill), cerna@fi.muni.cz (Ivana Černá), barnat@fi.muni.cz (Jiří Barnat)

permissible for the program to read from a fixed file, in the understanding that the content of the file is treated as part of the program, not as variable (arbitrary) input. Implicit interactions are, however, allowed: thread scheduling is taken to be arbitrary, as are various failure scenarios like an “out of memory” condition during a `malloc` call.

Typically, computer programs are made from components of various size, ranging from individual functions and classes, through units and libraries to frameworks and complete applications. At the highest levels, static analysis can process large amounts of code in bulk, pointing out possible problems, with varying levels of precision. At the lowest level, a small number of well-isolated, well-defined and highly critical functions can be subjected to rigorous treatment via automated theorem proving or exhaustive symbolic model checking. In this paper, we are primarily concerned with the mid-low part of the component spectrum: the unit level. Units are collections of coupled functionality and data structures. It is common practice that individual units of a program are tested separately, often by writing *unit tests*: those are small, self-contained programs that exercise the functionality provided by a single unit (and indirectly also the functionality of its dependencies).

These *unit tests* very often exactly reflect the constraints outlined above: their interaction with the outside world is, by design, very limited. However, implicit interactions – thread scheduling, memory pressure and similar effects – are usually very hard to control in a testing environment. This makes an explicit-state model checker, which can defeat these remaining sources of non-determinism, an extremely valuable tool.

Explicit-state model checking is, however, not the only application area of the research presented in this paper; it is merely the primary one, as it is the one that is best understood. Abstraction-driven and symbolic approaches to software verification are a hot research topic, and the contributions of this paper can be combined with advances in those areas. We fully expect that such a combination will also work at higher levels of abstractions: complete libraries and applications (see also Section 6.3).

## 1.2. Goals

Our main goal is to design an abstract machine (DiVM), that is, a low-level programming language, with these two properties:

- i. The machine should be a suitable target for compiling C and C++ programs, including *system-level* software (an operating system kernel and system libraries like `libc`).
- ii. An efficient implementation of the semantics of this abstract machine should be possible. It should be easy to store and compare states of the machine and to quickly compute the transition function.

It is typical of contemporary software verification tools to include *ad-hoc* extensions of the C language. The reason for this is that system-level software (per our first criterion) needs additional facilities, not available in the C language.

In other words, C as a language is *incomplete*: system-level software cannot be expressed in the C language *alone* (same is true of C++ and many other languages). We would like to take, instead, a principled approach: provide an abstract machine with sufficient expressive power.

### 1.3. Contribution

We present an abstract machine (called DiVM), based on the widely-used LLVM IR<sup>1</sup> with a small number of extensions. Both criteria outlined in Section 1.2 are fulfilled by the proposed machine: it is possible to express all the usual constructs – such as threads, processes, memory management and (simulated) input and output – as routines running on the machine. Moreover, since the machine is based on LLVM IR, standards-compliant C and C++ compilers are readily available targeting the machine. Additionally, we provide ports of crucial system libraries: the C and C++ standard libraries, and a meaningful subset of the POSIX interface. In particular, POSIX threads and POSIX file system APIs are available.

Moreover, there are established methods for efficient implementation of languages built around the concept of instructions which act on the state of a machine. This is, after all, how computers operate on the hardware level. Likewise, compilation of high-level, expression-based languages with structured control flow (like C and C++) into low-level, instruction-based languages (such as LLVM) is a well researched topic, and high-quality implementations are available as off-the-shelf components.

What we show in this paper is that addition of graph memory has no detrimental effect on those established properties, and that, in fact, it makes operations on the state of the machine more efficient. Likewise, while the semantics are not, strictly speaking, simplified by the addition of graph memory, it does make certain properties of the program much easier to express. It is, therefore, our opinion, that the addition of graph memory makes the machine and its semantics more expressive in a meaningful way. The details of the graph structure of the machine’s memory are covered in Section 3.

Finally, a reference implementation is available under a permissive, open-source licence. All the source code relevant to this paper, along with additional data and other supplementary material is available online.<sup>2</sup>

### 1.4. Analysis and LLVM

LLVM is, primarily, a toolbox for writing compilers. Among other things, this means that it is not a complete virtual machine, merely an intermediate representation suitable for static analysis, optimisation and native code generation. In particular, it may not always be possible to encode an entire program in LLVM

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<sup>1</sup>Intermediate Representation. The LLVM IR is used across the majority of the LLVM toolchain and is an abstract counterpart of the machine-level assembly language. Unlike machine-level languages, the LLVM IR is easy to transform and optimise automatically.

<sup>2</sup><https://divine.fi.muni.cz/2017/divm/>

alone: compilers often work with individual units, where undefined references are common and expected. When the program is linked (whether statically or at runtime), these unresolved references are bound to machine code, which may or may not be derived from LLVM bitcode. A common example of such non-LLVM-derived code would be the syscall interface of an operating system, which is usually implemented directly in platform-specific assembly. At this level, cooperation of code from various sources is facilitated by machine-level calling conventions that live below the level of LLVM bitcode.

An important consequence is that analyses that require complete knowledge of the entire system cannot rely entirely on LLVM bitcode alone. Different LLVM-based tools approach this problem differently. The most common solution is to hard-wire knowledge about particular external functions (i.e. functions that usually come from system-specific libraries that are not available in pure LLVM form, like `pthread_create` or `read`) into the tool. This *ad hoc* approach is suitable for experiments and prototypes, but is far from scalable – covering functionality commonly required by simple programs entails hundreds of functions. To combat this problem, we propose a small extension to the LLVM language, based on a small set of *hypercalls* (a list is provided in Table 1). Unlike pure LLVM, the DiVM language is capable of encoding an operating system, along with a syscall interface and all the usual functionality included in system libraries.

Table 1: A list of hypercalls provided by DiVM.

Hypercall	Description
<code>obj_make</code>	Create a new object in the memory graph of the program
<code>obj_free</code>	Explicitly destroys a object in the memory graph
<code>obj_size</code>	Obtain the current size of an object
<code>obj_resize</code>	Efficiently resize an object (optional)
<code>obj_shared</code>	Mark an object as <i>shared</i> for $\tau$ reduction (optional)
<code>trace</code>	Attach a piece of data to an edge in the execution graph
<code>interrupt_mem</code>	Marks a memory-access-related interrupt point
<code>interrupt_cfl</code>	Marks a control-flow-related interrupt point
<code>choose</code>	Non-deterministic choice (a fork in the execution graph)
<code>control</code>	Read or manipulate machine control registers

### 1.5. Explicit-State Model Checking

Past experience has repeatedly shown that a successful explicit-state model checker needs to combine a fast evaluator (the component which computes successor states), partial order [3] and/or symmetry reductions [4] and efficient means to store the visited and open sets [5, 6]. The virtual machine (VM) we propose covers the evaluator, but it also crucially interacts with the remaining parts of the model checker.

Moreover, as outlined above, the verifier also interacts with the system under test (SUT). For our purposes, the SUT is not the user program alone, but it also

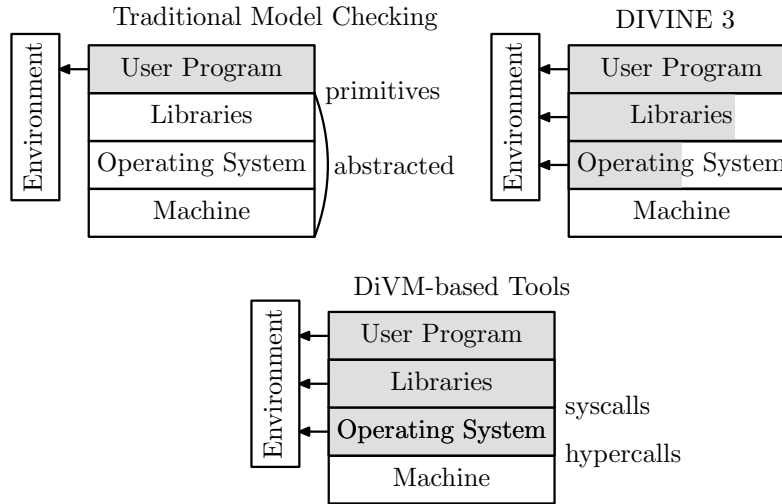


Figure 1: Evolution of model checking. White boxes are built into the model checker itself, shaded areas are part of the model (partially supplied by the user, partially by the tool).

includes all libraries it is linked to (including system libraries like `libc`) and an operating system (OS). This OS is, at least to some degree, bound to the VM it is executing in and relies on its particular capabilities. In the case of DiVM, this includes the interfaces related to verification, i.e. the hypercall interface. To a lesser degree, these may also be used by libraries which are part of the OS (typically `libc` and related low-level code, eg. a thread support library). Overall, while the OS itself is not very portable (running it on a typical hardware platform would require extensive changes), it can host programs which work on other systems, often without any modifications to the program.

From the semantic point of view, the VM comprises an abstract machine, and its semantics should be such that it is possible to (sufficiently faithfully) map C semantics<sup>3</sup> onto the semantics of the VM. The abstract machine executes a program, which is composed of functions (routines), which are composed of instructions – in our case, an instruction is either from the LLVM instruction set [7] or it is a hypercall invocation. Instructions manipulate the *state* of the abstract machine: under our proposed scheme, the state consists of two parts, a small, fixed set of *control registers* and of graph-structured memory (the *heap*).<sup>4</sup> The nodes of the memory graph – *heap objects* – are byte arrays. Whenever a numeric representation of a *pointer* is stored in a node (at an arbitrary offset), an edge is created in the graph, directed towards the heap object designated

<sup>3</sup>Or, to be more precise, the semantics of a C program executing in an operating system which provides additional facilities, like memory management.

<sup>4</sup>The state is made available to the verifier via an interface of the virtual machine. The verifier is free to modify the state as needed, in particular, it can easily store the state (say, in a hash table) and reset the VM to that particular state later.

by the numeric pointer. A set of *root pointers* is stored in the control registers: only objects reachable from this set are included in the state. The semantics are then, of course, given by a function which assigns, to a state and an instruction, a new state.

Our focus in this paper is twofold: first, design the hypercall interface of the VM – that is, describe the semantics of the abstract machine which is realised by the VM and how they relate to semantics of C programs; second, analyse the consequences of the chosen interface on the various components of the verifier and the SUT.

### 1.6. Design Motivation

There are three main advantages in the proposed approach to separation of components. First, components adhering to a small and well-defined interface can be much more easily re-used: for example, the OS part can be re-used with a different model checker, saving a substantial amount of work and thus reducing the barrier for achieving practicality for new tools. The `pthread` library alone comprises more than 100 functions which can be shared by multiple tools as long as they expose the same 10 basic hypercalls described in this paper. The same applies to hundreds of syscalls available in a modern Unix-like OS.

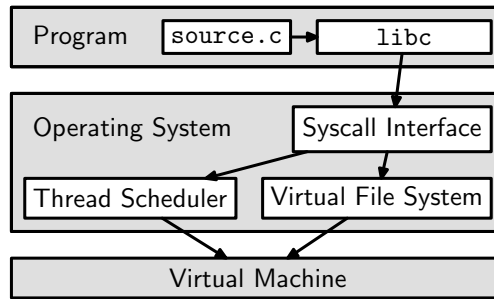


Figure 2: Scheme of the execution and/or verification environment.

Secondly, a small interface between the VM and the OS makes it quite easy to write special-purpose operating systems. The OS only needs to provide two fairly simple functions, `_boot` and a scheduler. This makes the model checker very flexible and easily adaptable to new needs, besides verification of C and C++ programs. Many modelling languages, including DVE, ProMeLa or Simulink, can be easily translated into C code, and with addition of a suitable miniature OS, can be verified by using our VM approach.

Finally, the virtual machine can remain comparatively simple, which is very important from reliability standpoint: bugs in the virtual machine will quietly cause incorrect verification results. However, the OS is executed by the virtual machine and subject to the same strict checking that is applied to the user program. Problems caused by the OS will therefore be detected by the virtual machine and reported to the user, reducing the risk of falsely positive verification result.

## 2. Related Work

The idea to use a virtual machine for model checking is not new – it is the natural middle ground between compiling the model all the way to a natively executable successor function (as in SPIN [8] and many later explicit-state model checkers) and a fully interpreted system (like UPPAAL [9] or earlier versions of DIVINE [10]).

One can obtain a suitable virtual machine for use with model checking in two basic ways: either choose (and possibly adapt) an existing VM with existing infrastructure (compilers, debuggers, etc.) or design a new one and re-target an existing compiler, or even create a new one. Of the newly-designed virtual machines (and their corresponding instruction sets), the most notable is NIPS VM [11]. Along with other similar designs that emerged from the model checking community, its focus is on fixed-layout, explicitly finite-state processes enriched with non-determinism and synchronisation/communication. VMs of this type are more suitable for specification-level verification and for verification of embedded software where use of dynamic memory and dynamic structures in general is limited.

Successful adaptations of pre-existing instruction sets for use in model checkers include the Java PathFinder [12] and the LLVM-based DIVINE 3 and later. The main difference between the two is that the JVM (the virtual machine underlying Java) is a memory-safe architecture, while the LLVM instruction set is designed primarily as a target for compilation of unsafe languages such as C and C++. Our current effort is an evolution of the design used in DIVINE 3, with emphasis on separation of concerns and a clean interface. We were able to move large amounts of code from the virtual machine proper into the (virtualised) OS, as a consequence of the improved set of primitives (hypercalls) provided by the virtual machine.

### 2.1. Language-Neutral Model Checking

Many model checkers provide some degree of interoperability with multiple specification languages. Those efforts are related to DiVM in the sense that DiVM can also be thought of as an interoperability framework. In explicit-state model checkers, the lowest common denominator is the functions for enumerating the state space: **initial** and **successors**. At this level, it is usually quite easy to connect existing unrelated model checking tools: for example, take the **successors** function of the Mur $\phi$  model checker and use DIVINE 3 to explore the state space. DIVINE 2 and DIVINE 3 both provided interfaces at this level. A more powerful (but also more complex) alternative is the PINS [13] interface provided by the LTSmin [14] model checker. The idea behind PINS is to partition the **successors** function based on transition groups (where some groups can be, for example, entirely independent of each other). This additional semantic information is exposed by the PINS interface, allowing state space reductions and more efficient search strategies to be implemented in the host model checker. Nonetheless, static analyses mostly remain specific to the particular specification language. An additional downside of the PINS method

is that it relies on the state representation being relatively static. This makes PINS inconvenient to use with extremely dynamic languages, like those typically used in software development.

In contrast, the DiVM language fully embraces the dynamic structure of program states. The model checker interface of DiVM is, however, nearly the simplest possible: obtain the initial and successor states. The only addition on top of the bare minimum is edge labelling, which can be used to record and present counterexamples. In the PINS approach, the additional structure is exposed to the model checker and the model checker makes use of the facilities provided by the model interpreter or compiler. With DiVM, the situation is reversed: the VM exposes its extended functionality to the SUT instead and maintains a trivial interface with the model checker. This way, static and semi-static analyses and transformations can work at the level of LLVM intermediate representation, which is already used by many tools.

## 2.2. LLVM-Based Model Checking

Besides DiVM, other approaches to LLVM-based verification exist. Our previous work on DIVINE 3 [10] is largely subsumed by the current VM-based approach as presented in this paper.

In [15], the author presents an extension for LTSmin based on LLVM and PINS, for model checking parallel algorithms under the *partial store order* memory model. Due to its focus on verification of algorithms and data structures, system-level software is not considered and LLVM is primarily used as convenient means of verifying algorithms given in the form of C code.

In addition to explicit-state approaches, symbolic, and in particular SMT-based, tools that build on the LLVM IR exist. A prime example in this category is LLBMC, which works, essentially, by translating LLVM bitcode into an SMT formula which describes the transition function of the original LLVM program. In this case, neither parallel programs nor system-level code<sup>5</sup> is considered. An additional restriction derives from the fact that the background SMT theory is decidable, and therefore loops with unknown bounds must be artificially bounded (i.e., LLBMC is a *bounded model checker*).

A different tool, VVT [16], extends the approach of LLBMC in two directions. First, it adds support for concurrency in the input program. Second, it takes a different approach to encoding the undecidable LLVM program into a decidable background theory, based on  $k$ -induction (and IC3 in particular). However, system-level interfaces are not considered in VVT either.

## 3. Graph-Organised Memory

In DiVM, the state of the program consists of memory (which is organised as a graph) and of control registers (described in Section 4.1). The semantics

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<sup>5</sup>To clarify, LLBMC can be used to verify C code that is part of system-level software: in fact, a typical use-case for symbolic model checkers is analysis of device drivers (where the actual device is modelled as a completely non-deterministic black box).



of an instruction of the DiVM language is, therefore, described by its effect on the machine’s memory and registers. In this section, we will first describe and justify the graph encoding, then we will describe the semantics of the memory-related hypercalls (as listed in Table 1) and finally, we will discuss the finer details and consequences of this approach.

A traditional computer treats memory as an array of bytes. Instructions exist to read data from and store data to a given memory location by using simple integer indices. Pointers (pieces of data that describe a location in memory) are, from the point of view of the CPU, really just integer values. That is, the machine language is untyped and a pointer can be added to, multiplied or divided just like any other number. Due to memory virtualisation in basically every modern CPU, which indices are valid is not determined by the size of the physical memory (as one would expect if the available memory locations were numbered from 1 to some  $n$ ), but are allocated to a given process by the OS.

Moreover, practically no programs (other than certain parts of operating system kernels) directly use a flat memory space. Instead, they usually take advantage of a higher-level interface for management of dynamic memory, based on the `malloc` C function. The `malloc` function takes care of obtaining unstructured memory from the OS and divides it into chunks which can be requested by the program on an as-needed basis.

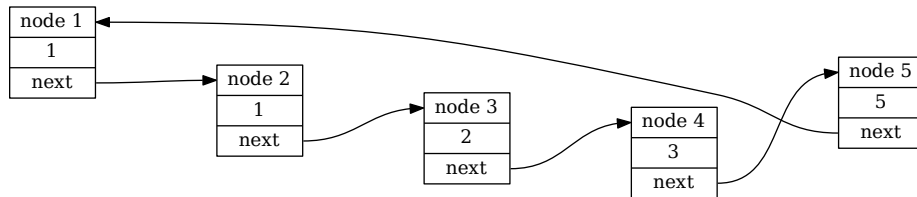


Figure 3: A circular linked list, an example of a common data structure which is often embedded in a heap, taking advantage of `malloc`-style memory management.

The use of `malloc`-style memory management is so pervasive in programs that it is sensible to abstract memory at the level of `malloc`-managed objects instead of the more universal, machine-level flat address space. This is especially true for programs where concurrency can cause the physical layout of the `malloc`-managed heap to vary substantially due to thread interleaving. However, when we treat the memory as a graph, heap configurations from different interleavings result in identical graphs. Hereafter, we will not make a distinction between *heap* as referring to the `malloc`-managed portion of memory and the graph memory structure which exists in the virtual machine (even though the latter is, in some sense, a superset of the former).

The only requirement of LLVM with regards to memory representation is that pointers need to be fixed-width arithmetic types. It is, however, neither memory safe nor are memory access instructions type safe. This poses challenges for model checkers in general and for graph-based memory organisation in particular. Due to this lack of a static type system, the virtual machine has

no choice but to impose a runtime (dynamic) type system of its own. The very least that the runtime type system must do is maintain the distinction between pointers and non-pointers: otherwise, the graph structure of memory cannot be recovered. Of course, when such a type system is already in place, it can be used for other purposes, like tracking uninitialised values. We will discuss this in more detail in Section 3.2.

Finally, with currently available data structures, large heaps (that is, heaps which store a large number of objects, regardless of their size) are appreciably more expensive to access and compare. For this reason, static data is kept in a small number of large objects. For example, all constant data is kept in a single object, and so is the program code (*text* in traditional UNIX terminology) and static data (global variables). Since all the relevant pieces (text, constants, static and dynamic memory) are part of the heap, they are accessed and represented uniformly by the virtual machine.

### 3.1. Memory Management Hypercalls

Since LLVM bitcode is not tied to a memory representation, its apparatus for memory management is quite limited. Just like in C, `malloc`, `free`, and related functions are provided by libraries, but ultimately based on some lower-level mechanism, like, for example, the `mmap` system call. This is often the case in POSIX systems targeting machines with a flat-addressed virtual memory system: `mmap` is tailored to allocate comparatively large, contiguous chunks of memory (the requested size must be an integer multiple of hardware page size) and management of individual objects is done entirely in user-level code. Lack of any per-object protections is also a source of many common programming errors, which are often hard to detect and debug.

It is therefore highly desirable that a single object obtained from `malloc` corresponds to a single VM-managed and properly isolated object. This way, object boundaries can easily be enforced by the model checker, and any violations reported back to the user. This means that, instead of subdividing memory obtained from `mmap`, the `libc` running in DiVM uses `obj_make` to create a separate object for each memory allocation. The `obj_make` hypercall obtains the object size as a parameter and writes the address of the newly created object into the corresponding LLVM register (LLVM registers are stored in memory, and therefore participate in the graph structure; this is described in more detail in Section 4.2). Therefore, the newly created object is immediately and atomically connected to the rest of the memory graph.

The standard counterpart to `malloc` is `free`, which returns memory, which is no longer needed by the program, into the pool used by `malloc`. Again, in DiVM, there is a hypercall – `obj_free` – with a role similar to that of standard `free`. In particular, `obj_free` takes a pointer as an argument, and marks the corresponding object as *invalid*. Any further access to this object is a *fault* (faults are described in more detail in Section 5.1). The remaining hypercalls in the `obj_` family exist to simplify bookkeeping and are not particularly important to the semantics of the language.

### 3.2. Runtime-Typed Memory

Even when the VM has a complete knowledge of the objects residing in program memory, which can be derived through the API described above, this alone is not enough to reconstruct the graph structure. The other necessary component is the knowledge of all pointers stored in the objects.

At first sight, it may seem that the static type system used by the SSA portion of LLVM (which is easily enforced) could be used to recover pointer information. The memory portion (that is, non-SSA), however, is completely untyped, and as such makes it trivial for a program to circumvent any protection afforded by the type system. The existence of type casting instructions therefore does not weaken the type system any further. Since recovering type information statically is very hard and often quite imprecise, a runtime type system is the only viable solution. Of course, this does not preclude the use of static analysis to improve evaluation efficiency.

Fortunately, in a virtual machine, it is easy enough to track type information through any and all operations performed by the program. The only limitation is that offsets within a single object should remain unaffected by the addition of type information. As described in [17], the solution to this problem is to store the type information in a shadow image of the entire address space. The model checker can keep, in addition to the byte array visible to the SUT, additional memory associated with each object, in such a way that this additional (shadow) memory can be easily looked up.

In our implementation of the abstract VM proposed in this paper, we also use the type system to track whether a particular byte of memory is *defined*, that is, whether a value has been stored at this address. The main motivation is that with this information, the model checker can report suspicious and probably unintended uses of such undefined values. Due to their low-level nature and focus on execution speed, both C and C++ elide initialisation code whenever possible. This elision is, however, not foolproof and can easily lead to unintended consequences: in some cases, compilers can spot this and emit a warning. In others, they cannot. The virtual machine can, however, detect inappropriate uses on all the paths that it explores.

### 3.3. Pointer Representation

The virtual machine mandates that pointers are represented as tuples, where the object identifier is separate from the offset within the object. In our implementation, this is achieved by splitting the 64 bit pointer into two 32 bit numbers, which are then treated separately. Moreover, while not strictly required, our implementation stores the offset part in the least significant bits of the pointer. This somewhat simplifies implementation of arithmetic instructions when one of the operands is a (converted) pointer. A strict requirement, however, is that when the pointer's offset overflows, the pointer becomes permanently invalid – the offset must *not* wrap to 0 independently of the object identifier, since the pointer would become accidentally valid.

Additionally, our implementation also guarantees that the object identifiers are stable along an execution path: that is, pointers to a particular object will

always use the same numeric object identifier. However, we acknowledge that in some circumstances, this limitation may be impractical (see also Section 6.2) and may be lifted at the expense of banning certain pointer-value-dependent operations in the program.

Besides regular *heap* pointers, there are 3 additional pointer types: *global*, *constant* and *code* pointers. While all data (as opposed to code) is stored on the heap, it is not the case that each global variable or each constant would reside in a separate heap object. The virtual machine instead uses *slot*-based allocation for these types of data, that is, there is a single heap object for global variables, another for constant data. A *global* or a *constant* pointer (distinguished from *heap* pointers by a 2-bit type tag) refer to slots within the designated *globals* heap object. Slot boundaries are enforced just like object boundaries.

The distinction between heap pointers and other pointer types is important when the OS wishes to implement `fork()`-like semantics: with slot-based global variables, different processes can share the same code (and constants). The OS can set a *control register* (see also Section 4.1) to tell the virtual machine which heap object currently holds global variables. The situation is illustrated in Figure 4.

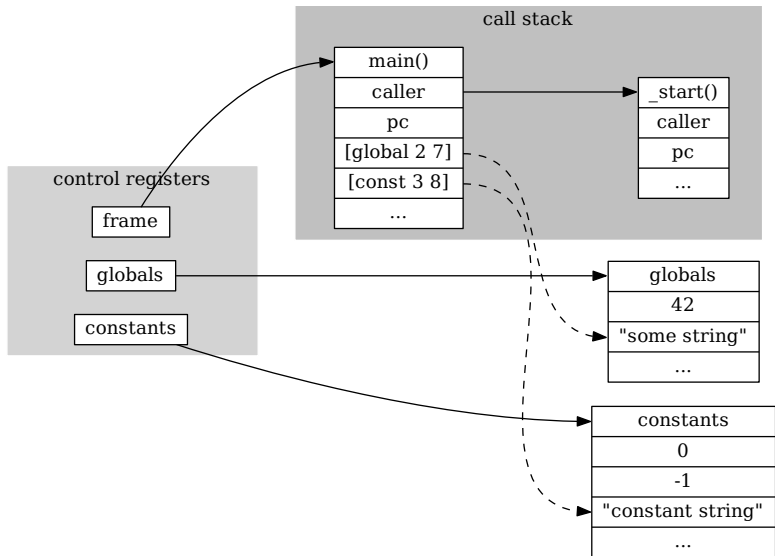


Figure 4: Different pointer types. Dashed lines represent indirect relationships: the value of the respective register is used when dereferencing such indirect pointers. The first number in an indirect pointer identifies the slot, the second the offset within the given slot.

### 3.4. Memory Protection

The VM we propose does not have a traditional, page-based MMU (Memory Management Unit). Nonetheless, since the execution is strictly controlled, there is a different mechanism which can be employed to enforce address space

separation: if a particular process does not possess a pointer to a given object, this object cannot be accessed. This is because the virtual machine enforces object boundaries, therefore, it is impossible to construct a valid pointer by overflowing a pointer to a different object (when the offset part of the pointer overflows, the pointer becomes invalid; likewise, if any operation changes the numeric value of the object identifier, the value ceases to be a valid pointer). The only way to access a particular object is, therefore, by obtaining a pointer to this object, which can be easily prevented by the OS.

The only pitfall of this approach is in the implementation of inter-process communication (IPC). That is, the enforcement of memory protection depends on the ability of the OS to invalidate pointers which are sent to other processes via IPC. If the OS wishes to preserve pointers that are sent through IPC to another process and then returned the same way while also enforcing process isolation, it must provide a translation mechanism. Similar caveats apply to shared memory segments which may contain pointers to themselves, or to other such segments. This scenario is illustrated in Figure 5.

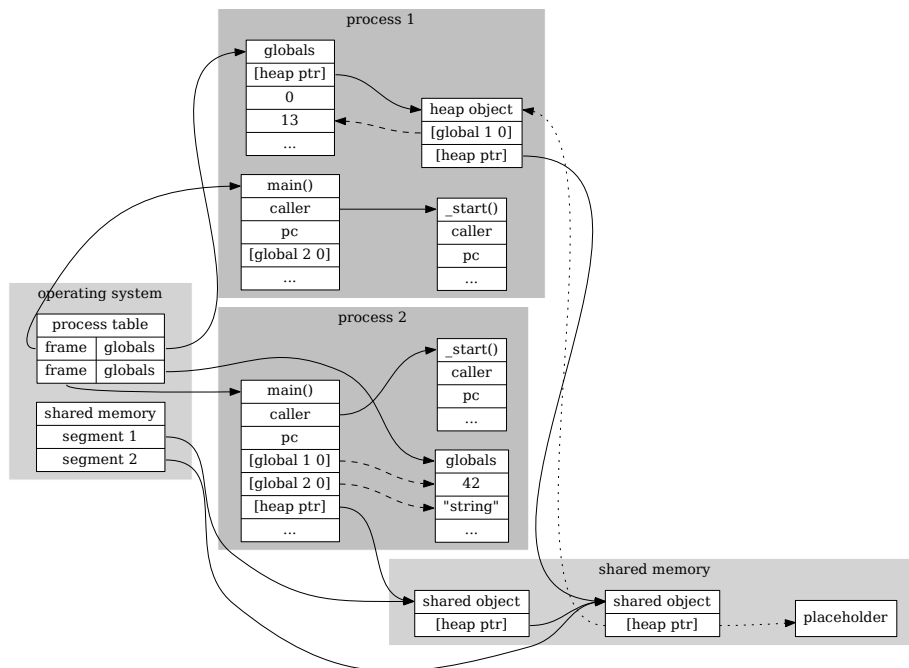


Figure 5: Example heap with OS memory, 2 processes and 2 shared memory segments. Dashed arrows represent *indirect* pointers (see also Figure 4). The dotted arrow represents a hazardous pointer (violating memory protection constraints) – this pointer must be flipped between the two possible values when processes are switched. When process 1 executes, it should point into the memory of process 1, otherwise it should point to the (shared) placeholder object.

## 4. Control Flow

In addition to the standard array of features related to control flow (which are directly inherited from LLVM), our virtual machine also needs to provide features that are more-or-less specific to verification environments. These include a tightly-controlled scheduling policy, non-deterministic choices and explicit atomic sections. Additionally, when compared to a standard, execution-focused VM, there are differences in how activation frames (that is, the call stack) are represented, and there are specifics pertaining to control registers.

### 4.1. Machine Control Registers

In addition to the (structured) memory, the virtual machine maintains a set of *control registers*. Together, these form the entirety of the execution state of the machine (in other words, the effect of any given instruction is entirely determined by these two components). The registers can be read and manipulated through a single hypercall, `control`, the interface of which is documented in more detail in our technical documentation [18].

The important distinction between the heap and the registers is that registers are not part of the *persistent* state of the program: their values are not taken into account when comparing or storing program states. They do, however, influence the execution within a single state space transition (and after evaluation of a given transition is finished, the values in those registers are cleared).

### 4.2. Activation Frames

Unlike traditional hardware-based implementations of C, our VM does not use a continuous stack. The present virtual machine takes the approach of DIVINE3 one step further: the execution stack is no longer a special structure maintained by the model checker itself, but instead is entirely allocated in the graph-based memory, as a linked list of activation frames. These frames are fixed in size, as is common when interpreting LLVM bytecode, since they only contain statically-allocated registers, not variable-sized objects. The latter are always allocated through the `alloca` LLVM instruction, which in our virtual machine obtains an appropriately-sized memory object from `obj_make`. Besides LLVM registers, the frame contains a pointer to the caller frame (forming the linked-list structure of the stack) and a slot for storing the value of the program counter across calls.

Frames are automatically allocated by `call` and `invoke` instructions, but can also be constructed and populated “manually” by the OS when needed. Likewise, the `ret` instruction deallocates the current frame, along with all its `alloca`-obtained memory.

There are 2 main advantages in this stack representation. First, it means that all the required bookkeeping is done by the graph memory subsystem (frames are not special in this regard). Second, this interface naturally allows a high degree of introspection in the SUT. The OS can, for example, construct an activation frame for the `main()` function by using the existing `make_obj` hypercall, instead of requiring additional functionality from the VM.

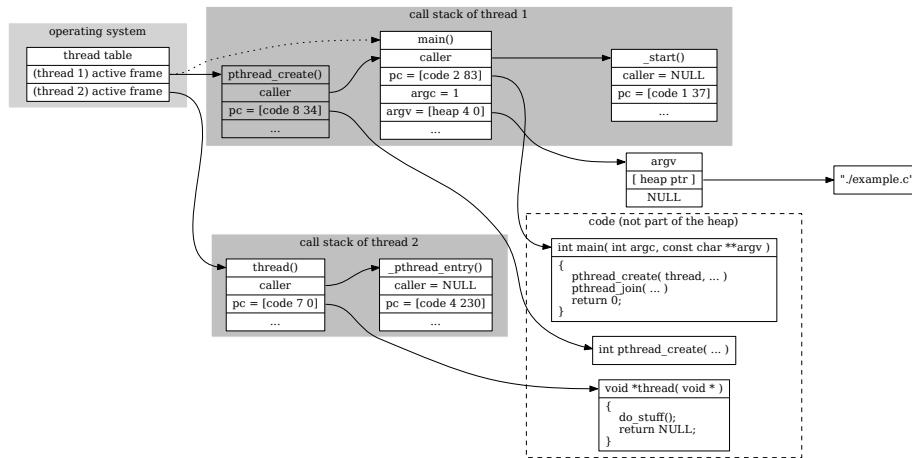


Figure 6: Interaction of activation frames and the operating system scheduler. In this snapshot, `pthread_create` is about to return; as soon as an interrupt happens, the OS will update the active frame of thread 1 to point to `main`, as shown by the dotted arrow. The now-orphaned frame is destroyed by the virtual machine.

### 4.3. Scheduling

In a traditional software model checker, threads are first-class, verifier-managed objects. In our virtual machine design, this does not need to be the case: it is possible for threads to be implemented within the virtualised OS in terms of the hypercall interface. Like other design choices in our approach, this simplifies the VM by moving responsibility into the OS layer, where functionality is easier to implement and its correctness is less critical.

In particular, the OS running in the virtual machine is responsible for providing a *scheduler routine* which decides what to execute in what order, and the virtual machine uses *interrupts* to return control to the scheduler whenever the user code executes a possibly *visible action*. Visible actions must be explicitly marked in the bytecode. Since visible actions are explicit, the exact semantics of what is or is not visible is not part of the VM interface: for the VM, an explicit hypercall, either `interrupt_cfl` or `interrupt_mem` is the definition of a visible action.<sup>6</sup> The difference between those two interrupt types is described in Section 6.1.

The variables local to the *scheduler routine* or any functions it calls are not retained across multiple entries into the scheduler. Moreover, the scheduler cannot access global variables either. Besides the transient local variables, all

<sup>6</sup>In a realistic implementation, these explicit *interrupt points* are inserted automatically by the bytecode loader in suitable locations. For a formalism with shared memory, accesses to memory locations that may be shared would constitute visible *memory* actions. Likewise, a formalism where invariant loops are possible, all loops that may be invariant need to contain a visible *control flow* action.

its state must be stored in explicitly allocated heap objects. One such object is called the *scheduler state* and a pointer to this object is stored in one of the control registers. The scheduler can therefore read the value of this register to access and modify its internal data structures. Other than the limitations mentioned above, the OS is entirely free to organise the state information any way it likes.

From the point of view of the state space that is being constructed, the scheduler decides what the successors of a given state are. When the verifier needs to obtain successors to a particular state, it executes the scheduler in that state; the scheduler decides which thread to run (usually with the help of the non-deterministic choice operator, see Section 4.5) and transfers control to that thread, by instructing the virtual machine to execute a particular activation frame (a pointer to which is stored for this purpose in the scheduler state).

#### 4.4. Atomic Sections

In the present design, support for explicit atomic sections in the virtual machine is not strictly necessary. Since the virtual machine supports standard atomic memory access instructions, it is possible to implement mutual exclusion on top of these. However, this is inefficient: it is, in general, impossible to recover the relationship between atomic operations or explicit locks and the memory accesses they guard (this is one of the reasons we need a model checker in the first place). This would make a system that does not make use of atomic sections substantially less efficient when running in the virtual machine, due to a large number of extra interrupts.

Additionally, when static analysis can prove that a particular section of code is protected by a mutual exclusion device (that is, all relevant memory locations it accesses), it can insert an explicit atomic section, making subsequent verification more efficient. Likewise, this ability of the virtual machine can be used to implement adaptive-precision model checking, where certain operations are assumed to be thread-safe, again making the verification process less demanding.

#### 4.5. Non-deterministic Choice and Counterexamples

It is often the case that the behaviour of a program depends on outside influences, which cannot be reasonably described in a deterministic fashion and wired into the SUT. Such influences are collectively known as the *environment*, and the effects of the environment translate into non-deterministic behaviour. A major source of this non-determinism is thread interleaving – or, equivalently, the choice of which thread should run next after an interrupt.

In our design, all non-determinism in the program (and the operating system) is derived from uses of the `choose` hypercall (which non-deterministically returns an integer between 0 and a given number). Since everything else in the SUT is completely deterministic, the succession of values produced by calls to `choose` specifies an execution trace unambiguously. This trait makes it quite



simple to store counterexamples and other traces in a tool-neutral, machine-readable fashion. Additionally, hints about which interrupts fired can be included in case the counterexample consumer does not wish to reproduce the exact interrupt semantics of the given VM implementation.

Finally, the `trace` hypercall serves to attach additional information to transitions in the execution graph. In particular, this information then becomes part of the counterexample when it is presented to the user. For example, the `libc` provided by DIVINE uses the `trace` hypercall in the implementation of standard IO functions. This way, if a program prints something to its standard output during the violating run, this output becomes visible in the counterexample.

## 5. Property Specification

An important aspect of a verifier is the specification of desirable properties of the program. In our design, this task is largely delegated to the OS. However, there are 2 aspects of property specification that require support from the VM. First, there are many circumstances in which the VM can detect problematic behaviour in the program that would be impractical to detect by other means. This includes out-of-bounds memory accesses, use of undefined values, mismatches between formal and actual arguments in `call` instructions and so on. For maximal flexibility, these conditions are not directly exposed as program properties, but are instead signalled to the OS by invoking a *fault handler*. This fault handler is then free to decide how to respond to this particular fault and whether to signal a property violation or not.

The other area where the virtual machine must be involved is the communication of the operating system with the verification algorithm. That is, the OS must be able to signal the fact that a particular transition is an error transition (or an accepting transition, in case of  $\omega$ -regular properties). For this purpose, a pair of bits is reserved in one of the machine state registers, corresponding to either an error or an accepting transition. In turn, the verifier obtains this information from the VM to inform its decisions.

### 5.1. Faults

When the program attempts to execute an illegal instruction, the virtual machine will enter a designated *fault handler* instead of continuing execution. The reasons why the instruction is deemed illegal are various, but they roughly correspond to conditions checked by standard CPUs, which on POSIX systems translate to signals. The checks done by the VM are, however, stricter than the corresponding checks in normal execution environments. This includes more granular information about objects, impossibility to overflow a pointer from one object into another, tracking of undefined values, checks on correct use of variadic function arguments, immutability of constant data, validity of target addresses in branch instructions and strict checking of validity of heap operations. Additionally, all uses of the hypercall interface are strictly checked for conformance with the specification.

Faults are, in principle, not fatal: the fault handler may choose to continue execution despite the raised error. For this reason, the VM passes a *continuation*<sup>7</sup> to the fault handler, which it may choose to invoke; alternatively, the fault handler may abort execution and report the error to the verifier, and through that, to the user. This mechanism is especially important when a fault arises due to a control flow instruction – typically, the target of a conditional branch instruction could depend on an undefined value. In this case, the continuation is chosen *as if* the value was defined and had the specific value observed at the point of the fault.<sup>8</sup>

### 5.2. Monitors and LTL

Thanks to the flexible scheduler design, it is very easy to implement properties as *monitors*, that is, additional finite-state automata which synchronise with the executing program to observe its behaviour. These automata can then either flag error transitions (for safety verification) or mark accepting transitions (for liveness verification). Classical algorithms for automata-based LTL model checking can then be used to verify LTL properties translated into monitors.

## 6. Reduction and Abstraction

In our earlier work [17], we described a number of reduction techniques tailored toward verification of LLVM bitcode. Many of these can be recovered in the new VM-based approach without significant semantic changes. However, some of the technical solutions are rather different. In the case of  $\tau$ -reduction, we have opted to insert interruption points (instructions) explicitly into the program, instead of co-opting memory access instructions for this purpose. The advantages are two-fold: it substantially simplifies tools which work with counterexamples, since they do not need to know anything at all about  $\tau$  reduction – the trace from the verifier can, without significant expense, include the information whether a given interrupt fired or did not fire. This way, replaying the counterexample involves simplified implementations of both `choose` and of the `interrupt_*` family of hypercalls, where they simply read the next entry in the counterexample trace to either obtain the return value or to decide whether an interrupt should fire.

### 6.1. $\tau$ -Based Reductions

Within the verifier, the implementation of `interrupt_mem` and `interrupt_cfl` are where most of the  $\tau$  reduction logic is implemented. The `interrupt_mem` hypercall signals to the VM that a memory operation is

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<sup>7</sup>This consists of the code pointer and the frame where execution would continue if the instruction succeeded.

<sup>8</sup>All undefined values come into existence with 0 as their *as if defined* value, but may be combined with other (defined) values to obtain *undefined* but non-zero values. For example, for `int a, b = a + 7` the value of `b` would be *undefined 7*.

about to be executed, along with the affected address and type of memory access. On the other hand, `interrupt_cfl` signals that a loop in the program state space may have formed. In a simple implementation, both these hypercalls could simply cause an unconditional interrupt, without compromising correctness in any way. The additional information (the type of interrupt – `cfl` vs `mem` – and the memory location and access type in the latter) is provided in order to improve efficiency. Clearly, if an interrupt can be safely suppressed, fewer distinct program states need to be stored, saving both time and space.

In our current version, the control flow interrupts are treated as described in [17], that is, the VM keeps track of program counter values that execution passed through, and only causes an interrupt if the particular instruction was already evaluated once within the given state space transition. In addition to [17], the new implementation only stores program counter values that correspond to `interrupt_cfl` calls, reducing evaluation overhead for other instructions.

Likewise, memory interrupts can often be suppressed: first, multiple independent loads can be all coalesced until a store instruction is encountered, or until a load from an address that was already used is repeated [19]. That is, an interrupt is only performed for `store`-type instructions, or for repeated `load` instructions.

Second, some stores and some repeated loads are also invisible; in particular, when a memory location is only reachable from a single thread, all interrupts related to that location can be suppressed [17]. We say that a memory object is *thread private* when no other thread is in possession of a pointer to this object. Since only one thread can access the memory, changes in this memory cannot be observed by any other thread. Since the VM maintains the entire memory as an oriented graph, a simple heuristic can be used to suppress interrupts related to such non-observable memory operations. In particular, the VM can maintain a set of *shared* objects – those that are not *thread private*. The invariant property of the set of *shared* objects is that it is closed under reachability along pointers (edges of the memory graph). When the program starts, global variables (which are accessible from any thread) are initially included in this set. Likewise, when a new thread is created and is given access to some objects, those objects are included in the set. All other operations simply maintain the invariant: when a pointer to object *A* is written to *B* and *B* is shared, all objects reachable from *A* (including *A* itself) are added to the *shared* set.

Since the VM has no concept of threads, it is the responsibility of the OS to inform the VM when new objects become shared via thread creation. That is, when a pointer to a previously private object is written directly to another private object, owned by a different thread, the operating system must call the `obj_shared` hypercall on this pointer. Outside of the operating system, the only way to share new objects is by writing their addresses into an already shared memory location.

## 6.2. Symmetry-Based Reductions

Like equivalent thread interleavings in  $\tau$  reductions, heap symmetry is an important source of redundancy in the state space. Since the virtual machine

has access to the graph structure of memory, it can easily compute a canonic form for comparison purposes. One simple approach is to execute DFS from the root object (that is, the object corresponding to the *state* of the scheduler) and sequentially assign numbers to objects in pre-order, adjusting pointers along the way. Another is to use a mark-and-copy garbage collector to compact the entire memory into a contiguous chunk and store this chunk in a hash table – this is basically the approach DIVINE 3 uses. Both these approaches have an important problem though: the meaning of values derived from pointer-to-number conversions and the pointer ordering are not preserved during execution. In some cases, like hash tables with pointer-based keys, this can cause incorrect results. Therefore, the recommended way to implement heap symmetry reduction is to only use the canonic form for comparison purposes, but for successor generation, store a particular non-canonic form. This way, continuity of pointer-derived values can be guaranteed along any given execution. Of course, more sophisticated – and more efficient – approaches based on partial hashes are possible.

Additionally, since all persistent data in the program are now stored uniformly in the graph structure, the benefits of symmetry reduction also extend to stacks, global variables and other auxiliary data structures. This effect therefore also makes it possible to avoid exploring states where multiple instances of the same thread only differ in order of execution among themselves.

### 6.3. Abstractions and Symbolic Data

In addition to compatibility with important state space reductions, the proposed virtual machine works seamlessly with transformation-based abstractions [20]. While in theory, all the environment-induced non-determinism is the same, reading a number from the environment causes non-deterministic branching of a very high degree (corresponding to the number of distinct values that can be represented by a given data type, say  $2^{32}$  for a typical `int` value). This is clearly impractical. For this reason, it is important that our virtual machine can be co-opted for abstraction-based model checking. Since the method described in [20] works by transforming code ahead of time, there are only two requirements on the virtual machine: first, it needs to support non-deterministic choice, since abstracted operations could have indeterminate results; second, it must be able to provide machine-readable counterexamples (ideally in a form that is easy to process). Both these requirements are easily fulfilled in the proposed design (see also Section 4.5).

Finally, formula- or decision-diagram-based symbolic data can be represented as a type of abstract domain, and as such is subsumed by the above. The difference is that when symbolic data is used, this must be reflected in the decision procedure – at minimum, state comparison must be altered to use semantic formula equivalence on the symbolic portion of the state, instead of structural comparison used for explicitly-represented portions of memory. This translates to an additional requirement for the virtual machine, that is, the interface with the verification core needs to support a sufficiently simple method to read and interpret the heap. However, this is a purely technical problem:

nothing in the semantics of the VM prevents such interface, and our reference implementation in DIVINE 4 does provide this access.

## 7. Implementation & Evaluation

Besides providing the specification of the interface and (informal) semantics of the virtual machine, we also make available the source code of a reference implementation.<sup>9</sup> While the DiVM language is, in principle, based on the LLVM instruction set and therefore our implementation relies on LLVM for C and C++ compiler frontends and for code transformation, in principle, the hypercall interface could be adapted to other instruction sets. This is because it is fully possible to realize the hypercall interface as C functions, and as such, it could be combined with a different instruction set and used from any C-compatible programming language. In addition to the VM itself, we provide a C++ implementation of a small, verification-focused operating system, DiOS.<sup>10</sup> The main focus of DiOS is to support verification of C and C++ programs written using POSIX APIs.

There is an additional implementation-related benefit of DiVM. Namely, the virtual machine itself does not depend on LLVM libraries. Since LLVM does not provide a stable interface and constitutes a substantial dependency, not linking to LLVM makes the resulting code more portable and easier to build. The compiler and transformation passes of course still require the LLVM infrastructure, but these can be kept separate from the model checking tool itself.

### 7.1. Benchmarks

To evaluate the work presented in this paper, we have used a set of 1045 benchmarks – each of is a C or a C++ program. Out of those programs, the majority (926) is correct, while 119 contain an error. Most of the programs are C++, with the exception of the “svc-pthread”, “pt-w32” and “libc-std” categories, which are written in standard C (and they make use of POSIX threads, outside of the “libc-std” category). The “alg” category includes sequential algorithmic and data structure benchmarks, the “courses” category contains unit tests for student assignments in various C++ courses, including concurrent data structures and other parallel programs, “libcxx” contains a selection of the `libc++` test suite, “bricks” contains unit tests for various C++ helper classes, including concurrent data structures, “llvm-bench” category contains programs from the LLVM test-suite and the “svc-pthread” category includes pthread-based C programs from the SV-COMP benchmark set. The “libc-std” category contains tests of `libc` functionality, while `pt-w32` test the POSIX threading API. The “other” category is a selection of programs which did not fit any other category.

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<sup>9</sup>Instructions for downloading the source code can be found at <http://divine.fi.muni.cz/download.html>. The code is covered by the ISC (simplified BSD) open-source licence.

<sup>10</sup>Available from the same source repository.

In most of the programs, it was assumed that `malloc` and `new` never fail, with the notable exception of part of the “bricks” category unit tests.

### 7.2. Results

We have executed all the benchmarks described in Section 7.1 with 4 tools. The approach of the present paper is represented by DIVINE 4, an explicit-state model checker based on DiVM. Our primary comparison was with DIVINE 3, which is an earlier version of this tool, in some sense a predecessor to our current approach based on DiVM. Two variants of DIVINE 3 were used, because in the course of evaluation, it was discovered that DIVINE 3 in its original version suppresses certain valid thread interleavings. Since this omission did not lead to any false negatives on the benchmark set, we include both the original results (with the interleaving incorrectly suppressed) and a fixed version (marked as “D3+p” in the comparison tables).

The results are very promising: we did not see any substantial regression caused by the higher abstraction level and increased isolation of components in DIVINE 4. Quite to the contrary, in many cases, the new approach is substantially more efficient, which we ascribe to better isolation of components: smaller and simpler components are usually easier to optimise than large, complex ones.

The verification time and state count for DIVINE 4 for all models are summarised in Table 2. This is the baseline to which all other tools are compared.

Table 2: Benchmark results for DIVINE 4, an explicit-state model checker based on DiVM.

tag	models	D4 search	D4 states
bricks	295	3:07:18	7233 k
courses	28	33:30	5399 k
libcxx	461	42:37	2182 k
libc-std	81	26:53	3787 k
pt-w32	10	22:30	1680 k
llvm-bench	22	2:42:44	10.7 M
svc-pthread	17	15:40	1685 k
other	12	4:29	298.8 k
<b>total</b>	<b>926</b>	<b>8:15:44</b>	<b>33.0 M</b>

### 7.3. Comparison to DIVINE 3

The previous version of DIVINE is based on a custom LLVM bitcode interpreter, with an ad-hoc set of extensions. Unlike DiVM, it has a built-in notion of threads based on asynchronous execution and special operations for thread creation and management, on which a pthread-compatible API is built. Like DIVINE 4, it is an explicit-state model checker and also contains a large subset of standard C and C++ libraries. However, its libraries are less complete, which is part of the reason more than a half of the models could not be verified with DIVINE 3.

Comparison of verification time and the number of states explored is shown in Table 3. In this case, we can see that DIVINE 4 is much faster in all benchmark categories with the exception of “svc-pthread” and “pt-w32” which both focus on threaded programs and are written in plain C. Additionally, DIVINE 4 reduced the state spaces more successfully, with the sole exception of “pt-w32”.

As outlined above, the difference in performance with thread-heavy models was tracked down to an omission of a particular set of interleavings in DIVINE 3. When this problem is corrected, the time and state space size difference in “pt-w32” is reversed (with 2 models now running out of memory in DIVINE 3). The results of this comparison are shown in Table 4.

Table 3: Comparison of DIVINE 4 and DIVINE 3. Out of the 926 error-free models, it was only 457 possible to verify 457 with DIVINE 3, typically due to incomplete standard libraries.

tag	models	D4 search	D3 search	D4 states	D3 states
courses	1	0:00	0:02	57	287
libcxx	344	20:15	5:48:12	787.4 k	4190 k
libc-std	76	0:51	1:27	33.7 k	54.1 k
llvm-bench	3	2:11	27:17	306.6 k	2351 k
pt-w32	10	22:30	6:53	1680 k	542.7 k
svc-pthread	16	15:24	27:15	1658 k	4123 k
other	7	4:03	9:22	263.4 k	302.6 k
<b>total</b>	457	1:05:17	7:00:33	4729 k	11.6 M

Table 4: Comparison of DIVINE 4 and modified DIVINE 3, where additional interleavings were taken into account (original DIVINE 3 did not allow newly starting threads to be delayed).

tag	models	D4 search	D3+p search	D4 states	D3+p states
courses	1	0:00	0:02	57	287
libcxx	342	17:08	4:20:52	687.8 k	3605 k
libc-std	76	0:51	1:29	33.7 k	54.1 k
llvm-bench	2	1:31	17:18	306.5 k	808.4 k
pt-w32	8	4:54	11:44	414.9 k	849.3 k
svc-pthread	12	0:56	0:50	113.9 k	183.2 k
other	7	4:03	9:23	263.4 k	302.6 k
<b>total</b>	448	29:27	5:01:40	1820 k	5803 k

#### 7.4. Comparison to ESBMC 4.1

The other tool we have chosen for comparison is ESBMC, an SMT-based symbolic model checker with support for C++. Part of the reason for this choice was that many of our benchmarks are C++, and most tools, even those

based on LLVM, can only handle C. Unfortunately, the C++ support in ESBMC is incomplete, and only supports older C++ revisions (C++98, but C++11 is already in widespread use). Likewise, the support for standard C++ library is quite limited in ESBMC, since it was only able to verify 42 out of over 400 tests in the “libcxx” category. Another major problem we encountered in ESBMC is inefficient support for threads, which can be seen in the very large time difference in the “svc-pthread” category. Overall, it was possible to verify only a small number of models and the models that could be verified often took much longer in ESBMC than they did DIVINE 4.

Table 5: Comparison of DIVINE 4 and ESBMC 4.1.

tag	models	D4 search	ESBMC search	D4 states
libcxx	42	0:23	0:07	217
libc-std	6	0:03	0:03	322
llvm-bench	5	8:18	1:56:37	1819 k
pt-w32	1	0:00	0:00	7
svc-pthread	4	1:35	46:43	280.8 k
other	2	0:01	0:08	390
<b>total</b>	60	10:22	2:43:39	2101 k

## 8. Conclusion

We have shown that many features expected in an explicit-state model checker are readily recovered in the proposed virtual-machine-based approach. In many cases, the solutions are simpler and cleaner and without a substantial performance penalty, as demonstrated in experiments. Additionally, both the greater overall simplicity and the fact that a large portion of verification-related code can be executed in the strict, error-checking virtual machine, contribute to appreciable improvements in robustness.

Rather importantly, the proposed virtual machine interface is compatible with all the important techniques that improve efficiency of explicit-state model checking – including reductions based on partial orders and path compression ( $\tau$ -reductions) and reductions based on heap configuration symmetries. Likewise, it can be easily combined with abstraction techniques based on program transformation.

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