

# Mit virtual machine specification

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## 1 Introduction

Mit is a simple virtual machine, designed to be easy both to implement efficiently on most widely-used hardware, and to compile for. It aims to be formally specified. This specification is intended for those who wish to implement or program Mit.

## 2 Parameters

The virtual machine has the following parameters:

Endianness	Memory can be either big- or little-endian.
word_bytes	The number of bytes in a word, 4 or 8.

## 3 Memory

The flat linear address space contains word\_bytes-byte words of 8-bit bytes. Addresses are unsigned words and identify a byte; the address of a quantity larger than a byte is that of the byte in it with the lowest address. Whether a given word may be read or written can change during execution.

## 4 Registers

The registers are word quantities:

Register	Function
pc	The program counter. Points to the next word of code.
ir	The instruction register. Contains instructions to be executed.

## 5 Stack

Computation is performed with series of nested last in, first out stacks. The **catch stack** is a stack of call stacks; a **call stack** is a stack of computation stacks; and a **computation stack** is a stack of words. To **push** an item on to a stack

means to add a new item to the top; to **pop** an item means to remove the top item.

The stack of each sort implicitly used by instructions at a given moment is called the **current** stack; the current stack is normally the top-most. Where it is not ambiguous, we refer simply to “the stack”.

Instructions implicitly pop their arguments from and push their results to the current computation stack. Subroutine call and return respectively push and pop a computation stack to and from the call stack; error handling call (catch) pushes a call stack to the catch stack, and raising an error (throw) pops a call stack from the catch stack.

The effect of an instruction on the catch stack is shown by its **stack effect**:

*before*  $\rightarrow$  *after*

where *before* and *after* are stack pictures showing the items on top of the stack *before* and *after* the instruction is executed. An instruction only affects the items shown in its stack effect.

A **stack picture** represents the catch stack. Ellipsis is used to elide parts of the stack. A computation stack picture looks like this:

$\dots i_n \dots i_1$

Each  $i_k$  is a stack item, and  $i_1$  is on top of the stack. A stack item  $[x]$  in square brackets is optional.

Computation stacks in a call stack are shown separated by a vertical bar  $|$ . A caller–callee pair of adjacent computation stacks is shown thus:

$\dots j_m \dots j_1 \mid \dots i_n \dots i_1$

where the  $j_k$  are on the caller’s computation stack and the  $i_k$  on the callee’s stack.

Call stacks in a catch stack are shown separated by a double vertical bar  $\parallel$ . A catcher–catchee pair of adjacent call stacks is shown thus:

$\dots j_m \dots j_1 \parallel \dots i_n \dots i_1$

where the  $j_k$  are on the catcher’s top-most computation stack and the  $i_k$  on the catchee’s top-most stack. Note that the ellipsis at the left-hand end of each computation stack may therefore elide whole call stacks.

## 6 Execution

Execution proceeds as follows:

Repeat:

Let **opcode** be the least significant byte of **ir**.  
Shift **ir** arithmetically one byte to the right.  
Execute the instruction given by **opcode**,  
or throw error  $-1$  if the opcode is invalid.

If an error condition is detected in the course of an instruction, the instruction has no effect other than throwing the error.

**Instruction fetch** is the action of setting **ir** to the word pointed to by **pc** and making **pc** point to the next word. This is done whenever extra instruction 0 (see section 7.9) or trap  $-1$  (see section 7.10) is executed.

## 6.1 Errors and termination

In exceptional situations, such as an invalid memory access or division by zero, an **error** may be **thrown**; see section 7.8. A **status code** is returned to the catcher.

Execution can be terminated explicitly by a **throw** instruction (see section 7.8), which throws an error.

Status codes are signed numbers. 0 to −127 are reserved for the specification. The defined status codes are given in table 1.

Code	Meaning
0	Normal termination.
−1	Invalid opcode (see section 7.11).
−2	Attempt to <b>throw</b> 0 (see section 7.8).
−3	Stack overflow.
−4	Invalid stack read.
−5	Invalid stack write.
−6	Invalid memory read.
−7	Invalid memory write.
−8	Address is insufficiently aligned.
−9	Division by zero attempted (see section 7.4).
−10	Division overflow (see section 7.4).

Table 1: Status codes

Errors with code −3 to −10 are optional: an implementation may choose not to detect these conditions.

## 7 Instructions

The instructions are listed below, grouped according to function, in the following format:

NAME *...before → ...after*  
Description.

The first line consists of the instruction’s name on the left, and its stack effect on the right; underneath is its description.

Numbers are represented in two’s complement form. Where a stack item’s name (including any numerical suffix) appears more than once in a stack effect, it refers each time to the identical stack item. Ellipsis is used for indeterminate numbers of items. An item called *count* is interpreted as an unsigned number.

### 7.1 Stack manipulation

These instructions manage the computation stack.

pop *...x → ...*  
Pop *x* from the stack.

$\text{dup} \quad \dots x_{\text{count}} \dots x_0 \text{ count} \rightarrow \dots x_{\text{count}} \dots x_0 x_{\text{count}}$   
 Pop  $\text{count}$ . Copy  $x_{\text{count}}$  to the top of the stack.  
 $\text{set} \quad \dots x_{\text{count}+1} \dots x_0 \text{ count} \rightarrow \dots x_0 x_{\text{count}} \dots x_1$   
 Set the  $\text{count}+1$ th stack word to  $x_0$ , then pop  $x_0$ .  
 $\text{swap} \quad \dots x_{\text{count}+1} \dots x_0 \text{ count} \rightarrow \dots x_0 x_{\text{count}} \dots x_1 x_{\text{count}+1}$   
 Exchange the top stack word with the  $\text{count}+1$ th.

## 7.2 Memory

These instructions fetch and store quantities to and from memory.

$\text{load} \quad \dots \text{addr} \rightarrow \dots \text{val}$   
 Push the word  $\text{val}$  stored at  $\text{addr}$ , which must be word-aligned.  
 $\text{store} \quad \dots \text{val} \text{ addr} \rightarrow \dots$   
 Store  $\text{val}$  at  $\text{addr}$ , which must be word-aligned.  
 $\text{load1} \quad \dots \text{addr} \rightarrow \dots \text{val}$   
 Push the byte stored at  $\text{addr}$ , setting unused high-order bits to zero, giving  $\text{val}$ .  
 $\text{store1} \quad \dots \text{val} \text{ addr} \rightarrow \dots$   
 Store the least-significant byte of  $\text{val}$  at  $\text{addr}$ .  
 $\text{load2} \quad \dots \text{addr} \rightarrow \dots \text{val}$   
 Push the 2-byte quantity stored at  $\text{addr}$ , setting unused high-order bits to zero, giving  $\text{val}$ .  $\text{addr}$  must be a multiple of 2.  
 $\text{store2} \quad \dots \text{val} \text{ addr} \rightarrow \dots$   
 Store the 2 least-significant bytes of  $\text{val}$  at  $\text{addr}$ , which must be a multiple of 2.  
 $\text{load4} \quad \dots \text{addr} \rightarrow \dots \text{val}$   
 Push the 4-byte quantity stored at  $\text{addr}$ , setting any unused high-order bits to zero, giving  $\text{val}$ .  $\text{addr}$  must be a multiple of 4.  
 $\text{store4} \quad \dots \text{val} \text{ addr} \rightarrow \dots$   
 Store the 4 least-significant bytes of  $\text{val}$  at  $\text{addr}$ , which must be a multiple of 4.

## 7.3 Constants

$\text{push} \quad \dots \rightarrow \dots \text{val}$   
 Push the word  $\text{val}$  stored at  $\text{pc}$ , and add  $\text{word\_bytes}$  to  $\text{pc}$ .  
 $\text{pushrel} \quad \dots \rightarrow \dots \text{addr}$   
 Like  $\text{push}$  but add  $\text{pc}$  to the value pushed on to the stack.  
 $\text{pushi}_n \quad \dots \rightarrow \dots n$   
 Push  $n$  on to the stack.  $n$  ranges from  $-32$  to  $31$  inclusive.  
 $\text{pushreli}_n \quad \dots \rightarrow \dots \text{addr}$   
 Push  $\text{pc} + \text{word\_bytes} \times n$  on to the stack.  $n$  ranges from  $-64$  to  $63$  inclusive.

The operand of  $\text{pushi}$  and of  $\text{pushreli}$  is encoded in the instruction opcode; see section 7.11.

## 7.4 Arithmetic

All calculations are made modulo  $2^{(8 \times \text{word\_bytes})}$ , except as detailed below.

neg  $\dots a \rightarrow \dots b$

Negate  $a$ , giving  $b$ .

add  $\dots a \ b \rightarrow \dots c$

Add  $a$  to  $b$ , giving the sum  $c$ .

mul  $\dots a \ b \rightarrow \dots c$

Multiply  $a$  by  $b$ , giving the product  $c$ .

divmod  $\dots a \ b \rightarrow \dots q \ r$

Divide  $a$  by  $b$ , giving the quotient  $q$  and remainder  $r$ . The quotient is rounded towards zero. If  $b$  is zero, throw error  $-9$ . If  $a$  is  $-2^{(8 \times \text{word\_bytes} - 1)}$  and  $b$  is  $-1$ , throw error  $-10$ .

udivmod  $\dots a \ b \rightarrow \dots q \ r$

Divide  $a$  by  $b$ , giving the quotient  $q$  and remainder  $r$ . If  $b$  is zero, throw error  $-9$ .

## 7.5 Logic

Logic functions:

not  $\dots a \rightarrow \dots b$

$b$  is the bitwise complement of  $a$ .

and  $\dots a \ b \rightarrow \dots c$

$c$  is the bitwise “and” of  $a$  with  $b$ .

or  $\dots a \ b \rightarrow \dots c$

$c$  is the bitwise inclusive-or of  $a$  with  $b$ .

xor  $\dots a \ b \rightarrow \dots c$

$c$  is the bitwise exclusive-or of  $a$  with  $b$ .

## 7.6 Shifts

lshift  $\dots a \ count \rightarrow \dots b$

Shift  $a$  left by  $count$  bits, filling vacated bits with zero, giving  $b$ .

rshift  $\dots a \ count \rightarrow \dots b$

Shift  $a$  right by  $count$  bits, filling vacated bits with zero, giving  $b$ .

arshift  $\dots a \ count \rightarrow \dots b$

Shift  $a$  right by  $count$  bits, filling vacated bits with the most significant bit of  $a$ , giving  $b$ .

## 7.7 Comparison

These instructions compare two numbers on the stack:

**eq**  $\dots a \ b \rightarrow \dots flag$   
*flag* is 1 if *a* is equal to *b*, otherwise 0.

**lt**  $\dots a \ b \rightarrow \dots flag$   
*flag* is 1 if *a* is less than *b* when considered as signed numbers, otherwise 0.

**ult**  $\dots a \ b \rightarrow \dots flag$   
*flag* is 1 if *a* is less than *b* when considered as unsigned numbers, otherwise 0.

## 7.8 Control

Unconditional and conditional branches:

**jump**  $\dots [addr] \rightarrow \dots$   
 If *ir* is zero, set *pc* to *addr*, which must be aligned, otherwise to *pc* + *ir* × *word\_bytes*. Set *ir* to 0.

**jumpz**  $\dots flag \ [addr] \rightarrow \dots$   
 If *flag* is 0 then perform the action of **jump**; otherwise, set *ir* to 0.

Subroutine call and return; the quantities called *args* and *rets* are treated as unsigned numbers:

**call**  $\dots x_{args} \dots x_1 \ args \ rets \ [addr] \rightarrow$   
 $\dots rets \ ret-addr \ | \ \dots x_{args} \dots x_1$

Let *ret-addr* be the value of *pc*. Perform the action of **jump**. Move  $x_{args} \dots x_1$  from the caller's stack to the callee's.

**ret**  $\dots rets \ ret-addr \ | \ \dots x_{rets} \dots x_1 \rightarrow$   
 $\dots x_{rets} \dots x_1$   
 or  $\dots rets \ ret-addr \ || \ \dots x_{rets} \dots x_1 \rightarrow$   
 $\dots x_{rets} \dots x_1 \ 0$

Pop the current computation stack from the call stack; if the call stack is now empty, pop the current call stack. Set *pc* to *ret-addr*, and move  $x_{rets} \dots x_1$  to the new computation stack. Set *ir* to 0. If a call stack was popped, push 0 on to the computation stack.

Error catchers and raising errors:

**catch**  $\dots x_{args} \dots x_1 \ args \ rets \ addr \rightarrow$   
 $\dots rets \ ret-addr \ || \ \dots x_{args} \dots x_1$

Set *ir* to 0. Perform the action of **call**, then push a new call stack on to the catch stack and move the top-most computation stack from the old call stack to the new one.

**throw**  $\dots rets \ ret-addr \ || \ \dots n \rightarrow \dots n$

If *n* is 0, throw error −2. Pop the current call stack from the catch stack. Set *pc* to *ret-addr*, and *ir* to 0. Pop *rets*. Move *n* from the old computation stack to the new one.

## 7.9 Extra instructions

Extra instructions, using the `extra` instruction, offer necessary functionality too rare or slow to deserve a core instruction.

`extra` ... → ...

Perform extra instruction `ir`; if `ir` is not the code of a valid extra instruction, throw error `-1`. The stack effect depends on the extra instruction. Extra instruction `0` performs instruction fetch (see section 6).

## 7.10 Traps

Traps, using the `trap` instruction, are similar to extra instructions, but are intended to be implementable as add-ons to an implementation, rather than as an integrated part of it. Traps may modify the memory and stack, but may not directly change the values of registers.

`trap` ... → ...

Perform trap `ir`; if `ir` is not the code of a valid trap, throw error `-1`. The stack effect depends on the trap. Trap code `-1` performs instruction fetch (see section 6).

## 7.11 Instruction encoding

Instructions are encoded as bytes, packed into words, which are executed as described in section 6. The bytes have the following internal structure:

7	6	5	4	3	2	1	0	
opcode				0	0	0		instruction
$n$				1	0	0		<code>pushi <math>n &lt; 0</math></code>
$n$					1	0		<code>pushreli <math>n &lt; 0</math></code>
$n$					0	1		<code>pushreli <math>n \geq 0</math></code>
$n$				0	1	1		<code>pushi <math>n \geq 0</math></code>
opcode				1	1	1		instruction

Table 2 lists the opcodes for instructions whose least-significant 3 bits are 000, and table 3 for 111. Other instruction opcodes with those endings are invalid. Table 4 lists the valid extra instruction opcodes.

## 8 External interface

- Implementations can add extra instructions to provide extra computational primitives and other deeply-integrated facilities, and traps to offer access to system facilities, native libraries and so on; see section 7.9.
- Implementations should provide an API to create and run virtual machine code, and to add more traps.

Opcode	Instruction	Opcode	Instruction
0x00	extra	0x10	load
0x01	not	0x11	store
0x02	and	0x12	load1
0x03	or	0x13	store1
0x04	xor	0x14	load2
0x05	lshift	0x15	store2
0x06	rshift	0x16	load4
0x07	arshift	0x17	store4
0x08	pop	0x18	push
0x09	dup	0x19	pushrel
0x0a	set	0x1a	negate
0x0b	swap	0x1b	add
0x0c	jump	0x1c	mul
0x0d	jumpz	0x1d	eq
0x0e	call	0x1e	lt
0x0f	ret	0x1f	ult

Table 2: Instruction opcodes for “000” instructions

Opcode	Instruction
0x1f	trap

Table 3: Instruction opcodes for “111” instructions

## Acknowledgements

Martin Richards introduced me to Cintcode [2], which kindled my interest in virtual machines, and led to Beetle [3] and Mite [4], of which Mit is a sort of synthesis. GNU *lightning* [1] helped inspire me to greater simplicity, while still aiming for speed. Alistair Turnbull has for many years been a fount of ideas and criticism for all my work in computation, and lately a staunch collaborator on Mit.

Opcode	Instruction
0x1	divmod
0x2	udivmod
0x3	catch
0x4	throw

Table 4: Extra instruction opcodes



## References

- [1] Paulo Bonzini. Using and porting GNU *lightning*, 2000. <https://www.gnu.org/software/lightning/>.
- [2] Martin Richards. Cintcode distribution, 2000. <https://www.cl.cam.ac.uk/~mr/BCPL.html>.
- [3] Reuben Thomas. Beetle and pForth: a Forth virtual machine and compiler. BA dissertation, University of Cambridge, 1995. <https://rrt.sc3d.org/>.
- [4] Reuben Thomas. *Mite: a basis for ubiquitous virtual machines*. PhD thesis, University of Cambridge Computer Laboratory, November 2000. <https://rrt.sc3d.org/>.