

**1. Introduction.** This CWEB program simulates how the M<sup>M</sup>I<sup>X</sup> computer might be implemented with a high-performance pipeline in many different configurations. All of the complexities of M<sup>M</sup>I<sup>X</sup>'s architecture are treated, except for multiprocessing and low-level details of memory mapped input/output.

The present program module, which contains the main routine for the M<sup>M</sup>I<sup>X</sup> meta-simulator, is primarily devoted to administrative tasks. Other modules do the actual work after this module has told them what to do.

**2.** A user typically invokes the meta-simulator with a UNIX-like command line of the general form ‘`mmmix options configfile progfile`’ where the `configfile` describes the characteristics of an M<sup>M</sup>I<sup>X</sup> implementation and the `progfile` contains a program to be downloaded and run. Rules for configuration files appear in the module called `mmix-config`. The program file is either an “M<sup>M</sup>I<sup>X</sup> binary file” dumped by M<sup>M</sup>I<sup>X</sup>-SIM, or an ASCII text file that describes hexadecimal data in a rudimentary format. It is assumed to be binary if its name ends with the extension ‘.mmb’.

The only command-line option currently supported is `-s`, which will run the simulator silently until a `TRAP 0,Halt,0` instruction is executed.

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "mmix-pipe.h"

char *config_file_name, *prog_file_name;
⟨Global variables 5⟩
⟨Subroutines 10⟩
int main(argc, argv)
    int argc;
    char *argv[];
{
    ⟨Parse the command line 3⟩;
    MMIX_config(config_file_name);
    MMIX_init();
    mmix_io_init();
    ⟨Input the program 4⟩;
    if (silent) return MMIX_silent();
    else {
        ⟨Run the simulation interactively 13⟩;
        printf("Simulation ended at time %d.\n", ticks.l);
        print_stats();
        return 0;
    }
}
```

3. The command line might also contain additional options, some day. For now I'm forgetting them and simplifying everything until I gain further experience.

```

⟨ Parse the command line 3 ⟩ ≡
  for (n = 1; argv[n] ≠ Λ ∧ argv[n][0] ≡ '-'; n++) {
    if (argv[n][1] ≡ 's') silent = true;
    else argc = 0; /* unknown option */
  }
  if (argc ≠ n + 2) {
    fprintf(stderr, "Usage: %s [-s] configfile progfile\n", argv[0]);
    exit(-3);
  }
  config_file_name = argv[argc - 2];
  prog_file_name = argv[argc - 1];

```

This code is used in section 2.

```

4. ⟨ Input the program 4 ⟩ ≡
  if (strlen(prog_file_name) > 4 ∧ strcmp(prog_file_name + strlen(prog_file_name) - 4, ".mmb") ≡ 0)
    ⟨ Input an MMIX binary file 9 ⟩
  else ⟨ Input a rudimentary hexadecimal file 6 ⟩;
  fclose(prog_file);

```

This code is used in section 2.

**5. Hexadecimal input to memory.** A rudimentary hexadecimal input format is implemented here so that the simulator can be run with essentially arbitrary data in the simulated memory. The rules of this format are extremely simple: Each line of the file either begins with (i) 12 hexadecimal digits followed by a colon; or (ii) a space followed by 16 hexadecimal digits. In case (i), the 12 hex digits specify a 48-bit physical address, called the current location. In case (ii), the 16 hex digits specify an octabyte to be stored in the current location; the current location is then increased by 8. The current location should be a multiple of 8, but its three least significant bits are actually ignored. Arbitrary comments can follow the specification of a new current location or a new octabyte, as long as each line is less than 99 characters long. For example, the file

```
0123456789ab: SILLY EXAMPLE
0123456789abcdef first octabyte
fedcba9876543210 second
```

places the octabyte #0123456789abcdef into memory location #0123456789a8 and #fedcba9876543210 into location #0123456789b0.

```
#define BUF_SIZE 100
```

⟨Global variables 5⟩ ≡

```
octa cur_loc;
octa cur_dat;
bool new_chunk;
char buffer[BUF_SIZE];
FILE *prog_file;
```

See also sections 16 and 25.

This code is used in section 2.

**6.** ⟨Input a rudimentary hexadecimal file 6⟩ ≡

```
{
    prog_file = fopen(prog_file_name, "r");
    if (!prog_file) {
        fprintf(stderr, "Panic: Can't open MMIX hexadecimal file %s!\n", prog_file_name);
        exit(-3);
    }
    new_chunk = true;
    while (1) {
        if (!fgets(buffer, BUF_SIZE, prog_file)) break;
        if (buffer[strlen(buffer) - 1] != '\n') {
            fprintf(stderr, "Panic: Hexadecimal file line too long: '%s...'\n", buffer);
            exit(-3);
        }
        if (buffer[12] == ':') ⟨Change the current location 7⟩
        else if (buffer[0] == ' ') ⟨Read an octabyte and advance cur_loc 8⟩
        else {
            fprintf(stderr, "Panic: Improper hexadecimal file line: '%s'\n", buffer);
            exit(-3);
        }
    }
}
```

This code is used in section 4.

7.     $\langle$  Change the current location 7  $\rangle \equiv$

```
{
  if (sscanf(buffer, "%4x%8x", &cur_loc.h, &cur_loc.l)  $\neq$  2) {
    fprintf(stderr, "Panic: Improper_hexadecimal_file_location: '%s'!\n", buffer);
    exit(-3);
  }
  new_chunk = true;
}
```

This code is used in section 6.

8.     $\langle$  Read an octabyte and advance *cur\_loc* 8  $\rangle \equiv$

```
{
  if (sscanf(buffer + 1, "%8x%8x", &cur_dat.h, &cur_dat.l)  $\neq$  2) {
    fprintf(stderr, "Panic: Improper_hexadecimal_file_data: '%s'!\n", buffer);
    exit(-3);
  }
  if (new_chunk) mem_write(cur_loc, cur_dat);
  else mem_hash[last_h].chunk[(cur_loc.l & #ffff)  $\gg$  3] = cur_dat;
  cur_loc.l += 8;
  if ((cur_loc.l & #fff8)  $\neq$  0) new_chunk = false;
  else {
    new_chunk = true;
    if ((cur_loc.l & #fff0000)  $\equiv$  0) cur_loc.h++;
  }
}
```

This code is used in section 6.

**9. Binary input to memory.** When the program file was dumped by MMIX-SIM, it has the simple format discussed in exercise 1.4.3'–20 of the MMIX fascicle [*The Art of Computer Programming*, Volume 1, Fascicle 1]. We assume that such a program has text, data, pool, and stack segments, as in the conventions of that book. We load it into four  $2^{32}$ -byte pages of physical memory, one for each segment; page zero of segment  $i$  is mapped to physical location  $2^{32}i$ . Page tables are kept in physical locations starting at  $2^{32} \times 4$ ; static traps begin at  $2^{32} \times 5$  and dynamic traps at  $2^{32} \times 6$ . (These conventions agree with the special register settings  $rT = \#8000000500000000$ ,  $rTT = \#8000000600000000$ ,  $rV = \#369c200400000000$  assumed by the stripped-down simulator.)

```

⟨Input an MMIX binary file 9⟩ ≡
{
    prog_file = fopen(prog_file_name, "rb");
    if (¬prog_file) {
        fprintf(stderr, "Panic: Can't open MMIX binary file %s!\n", prog_file_name);
        exit(-3);
    }
    while (1) {
        if (¬undump_octa()) break;
        new_chunk = true;
        cur_loc = cur_dat;
        if (cur_loc.h & #9fffffff) bad_address = true;
        else bad_address = false, cur_loc.h >>= 29;
        /* apply trivial mapping function for each segment */
        ⟨Input consecutive octabytes beginning at cur_loc 11⟩;
    }
    ⟨Set up the canned environment 12⟩;
}

```

This code is used in section 4.

**10.** The *undump\_octa* routine reads eight bytes from the binary file *prog\_file* into the global octabyte *cur\_dat*, taking care as usual to be big-endian regardless of the host computer's bias.

```

⟨Subroutines 10⟩ ≡
static bool undump_octa ARGS((void));
static bool undump_octa()
{
    register int t0, t1, t2, t3;
    t0 = fgetc(prog_file); if (t0 == EOF) return false;
    t1 = fgetc(prog_file); if (t1 == EOF) goto oops;
    t2 = fgetc(prog_file); if (t2 == EOF) goto oops;
    t3 = fgetc(prog_file); if (t3 == EOF) goto oops;
    cur_dat.h = (t0 << 24) + (t1 << 16) + (t2 << 8) + t3;
    t0 = fgetc(prog_file); if (t0 == EOF) goto oops;
    t1 = fgetc(prog_file); if (t1 == EOF) goto oops;
    t2 = fgetc(prog_file); if (t2 == EOF) goto oops;
    t3 = fgetc(prog_file); if (t3 == EOF) goto oops;
    cur_dat.l = (t0 << 24) + (t1 << 16) + (t2 << 8) + t3;
    return true;
oops: fprintf(stderr, "Premature end of file on %s!\n", prog_file_name);
    return false;
}

```

See also sections 17 and 20.

This code is used in section 2.

11.  $\langle \text{Input consecutive octabytes beginning at } cur\_loc \text{ 11} \rangle \equiv$

```

while (1) {
  if ( $\neg undump\_octa()$ ) {
    fprintf(stderr, "Unexpected_end_of_file_on_%s!\n", prog_file_name);
    break;
  }
  if ( $\neg (cur\_dat.h \vee cur\_dat.l)$ ) break;
  if (bad_address) {
    fprintf(stderr, "Panic: Unsupported_virtual_address_%08x%08x!\n", cur_loc.h, cur_loc.l);
    exit(-5);
  }
  if (new_chunk) mem_write(cur_loc, cur_dat);
  else mem_hash[last_h].chunk[(cur_loc.l & #ffff) >> 3] = cur_dat;
  cur_loc.l += 8;
  if ((cur_loc.l & #fff8)  $\neq$  0) new_chunk = false;
  else {
    new_chunk = true;
    if ((cur_loc.l & #ffff0000)  $\equiv$  0) {
      bad_address = true;
      cur_loc.h = (cur_loc.h << 29) + 1;
    }
  }
}

```

This code is used in section 9.

**12.** The primitive operating system assumed in simple programs of *The Art of Computer Programming* will set up text segment, data segment, pool segment, and stack segment as in MMIX-SIM. The runtime stack will be initialized if we UNSAVE from the last location loaded in the .mmb file.

```
#define rQ 16
⟨Set up the canned environment 12⟩ ≡
  if (cur_loc.h ≠ 3) {
    fprintf(stderr, "Panic: MMIX_binary_file_didn't_set_up_the_stack!\n");
    exit(-6);
  }
  inst_ptr.o = mem_read(incr(cur_loc, -8 * 14)); /* Main */
  inst_ptr.p = Λ;
  cur_loc.h = #60000000;
  g[255].o = incr(cur_loc, -8); /* place to UNSAVE */
  cur_dat.l = #f0;
  if (mem_read(cur_dat).h) inst_ptr.o = cur_dat; /* start at #f0 if nonzero */
  head-inst = (UNSAVE ≪ 24) + 255, tail--; /* prefetch a fabricated command */
  head-loc = incr(inst_ptr.o, -4); /* in case the UNSAVE is interrupted */
  g[rT].o.h = #80000005, g[rTT].o.h = #80000006;
  cur_dat.h = (RESUME ≪ 24) + 1, cur_dat.l = 0, cur_loc.h = 5, cur_loc.l = 0;
  mem_write(cur_loc, cur_dat); /* the primitive trap handler */
  cur_dat.l = cur_dat.h, cur_dat.h = (NEGI ≪ 24) + (255 ≪ 16) + 1;
  cur_loc.h = 6, cur_loc.l = 8;
  mem_write(cur_loc, cur_dat); /* the primitive dynamic trap handler */
  cur_dat.h = (GET ≪ 24) + rQ, cur_dat.l = (PUTI ≪ 24) + (rQ ≪ 16), cur_loc.l = 0;
  mem_write(cur_loc, cur_dat); /* more of the primitive dynamic trap handler */
  cur_dat.h = 0, cur_dat.l = 7; /* generate a PTE with rwx permission */
  cur_loc.h = 4; /* beginning of skeleton page table */
  mem_write(cur_loc, cur_dat); /* PTE for the text segment */
  ITcache-set[0][0].tag = zero_octa;
  ITcache-set[0][0].data[0] = cur_dat; /* prime the IT cache */
  cur_dat.l = 6; /* PTE with read and write permission only */
  cur_dat.h = 1, cur_loc.l = 3 ≪ 13;
  mem_write(cur_loc, cur_dat); /* PTE for the data segment */
  cur_dat.h = 2, cur_loc.l = 6 ≪ 13;
  mem_write(cur_loc, cur_dat); /* PTE for the pool segment */
  cur_dat.h = 3, cur_loc.l = 9 ≪ 13;
  mem_write(cur_loc, cur_dat); /* PTE for the stack segment */
  g[rK].o = neg_one; /* enable all interrupts */
  g[rV].o.h = #369c2004;
  page_bad = false, page_r = 4 ≪ (32 - 13), page_s = 32, page_mask.l = #ffffffff;
  page_b[1] = 3, page_b[2] = 6, page_b[3] = 9, page_b[4] = 12;
```

This code is used in section 9.

**13. Interaction.** When prompted for instructions, this simulator understands the following terse commands:

- $\langle \text{positive integer} \rangle$ : Run for this many clock cycles.
- $\mathcal{O} \langle \text{hexadecimal integer} \rangle$ : Set the instruction pointer to this virtual address; successive instructions will be fetched from here.
- $k$ : Toggle the sign bit of the instruction pointer.
- $b \langle \text{hexadecimal integer} \rangle$ : Set the breakpoint to this virtual address; simulation will pause when an instruction from the breakpoint address enters the fetch buffer.
- $v \langle \text{hexadecimal integer} \rangle$ : Set the desired level of diagnostic output; each bit in the hexadecimal integer enables certain printouts when the simulator is running. Bit #1 shows instructions when issued, deissued, or committed; #2 shows the pipeline and locks after each cycle; #4 shows each coroutine activation; #8 each coroutine scheduling; #10 reports when reading from an uninitialized chunk of memory; #20 asks for online input when reading from addresses  $\geq 2^{48}$ ; #40 reports all I/O to memory address  $\geq 2^{48}$ ; #80 shows details of branch prediction; #100 displays full cache contents including blocks with invalid tags.
- $-\langle \text{integer} \rangle$ : Deissue this many instructions.
- $l \langle \text{integer} \rangle$  or  $g \langle \text{integer} \rangle$ : Show current “hot” contents of a local or global register.
- $m \langle \text{hexadecimal integer} \rangle$ : Show current contents of a physical memory address. (This value may not be up to date; newer values might appear in the write buffer and/or in the caches.)
- $f \langle \text{hexadecimal integer} \rangle$ : Insert a tetrabyte into the fetch buffer. (Use with care!)
- $i \langle \text{integer} \rangle$ : Set the interval counter  $rI$  to the given value; this will trigger an interrupt after the specified number of cycles.
- $IT, DT, I, D, \text{ or } S$ : Show current contents of a cache.
- $D^*$  or  $S^*$ : Show dirty blocks of a cache.
- $p$ : Show current contents of the pipeline.
- $s$ : Show current statistics on branch prediction and speed of instruction issue.
- $h$ : Help (show the possibilities for interaction).
- $q$ : Quit.

$\langle \text{Run the simulation interactively } 13 \rangle \equiv$

```
while (1) {
    printf("mmmix>"); fflush(stdout);
    fgets(buffer, BUF_SIZE, stdin);
    switch (buffer[0]) {
        default: what_say: printf("Eh? Sorry, I don't understand. (Type h for help)\n");
            continue;
        case 'q': case 'x': goto done;
         $\langle \text{Cases for interaction } 14 \rangle$ 
    }
}
```

done:

This code is used in section 2.



14.  $\langle$  Cases for interaction 14  $\rangle \equiv$ 

```

case 'h': case '?': printf("The interactive commands are as follows:\n");
    printf("_<n>_to_run_for_n_cycles\n");
    printf("_0<x>_to_take_next_instruction_from_location_x\n");
    printf("_k_____to_change_the_sign_bit_of_the_instruction_location\n");
    printf("_b<x>_to_pause_when_location_x_is_fetched\n");
    printf("_v<x>_to_print_specified_diagnostics_when_running;\n");
    printf("_____x=1[insts_enter/leave_pipe]+2[whole_pipeline_each_cycle]+\n");
    printf("_____4[coroutine_activations]+8[coroutine_scheduling]+\n");
    printf("_____10[uninitialized_read]+20[online_I/O_read]+\n");
    printf("_____40[I/O_read/write]+80[branch_prediction_details]+\n");
    printf("_____100[invalid_cache_blocks_displayed_too]\n");
    printf("_<n>_to_deissue_n_instructions\n");
    printf("_l<n>_to_print_current_value_of_local_register_n\n");
    printf("_g<n>_to_print_current_value_of_global_register_n\n");
    printf("_m<x>_to_print_current_value_of_memory_address_x\n");
    printf("_f<x>_to_insert_instruction_x_into_the_fetch_buffer\n");
    printf("_i<n>_to_initiate_a_timer_interrupt_after_n_cycles\n");
    printf("_IT,_DT,_I,_D,_or,_S_to_print_current_cache_contents\n");
    printf("_D*_or,_S*_to_print_dirty_blocks_of_a_cache\n");
    printf("_p_to_print_current_pipeline_contents\n");
    printf("_s_to_print_current_stats\n");
    printf("_h_to_print_this_message\n");
    printf("_q_to_exit\n");
    printf("(Here<n>_is_a_decimal_integer,_<x>_is_hexadecimal.)\n");
continue;

```

See also sections 15, 18, 19, 21, 22, 23, and 24.

This code is used in section 13.

15.  $\langle$  Cases for interaction 14  $\rangle + \equiv$ 

```

case '0': case '1': case '2': case '3': case '4': case '5': case '6': case '7': case '8':
    case '9':
        if (sscanf(buffer, "%d", &n)  $\neq$  1) goto what_say;
        printf("Running_d_at_time_d", n, ticks.l);
        if (bp.h  $\equiv$  (tetra) - 1  $\wedge$  bp.l  $\equiv$  (tetra) - 1) printf("\\n");
        else printf("_with_breakpoint_%08x%08x\\n", bp.h, bp.l);
        MMIX_run(n, bp); continue;
case '@': inst_ptr.o = read_hex(buffer + 1); goto new_inst_ptr;
case 'k': inst_ptr.o.h  $\oplus=$  #80000000; /* shortcut to kernel mode */
    if ( $\neg$ ticks.l  $\wedge$  head) head-loc.h  $\oplus=$  #80000000; /* fix the UNSAVE loc */
new_inst_ptr: if (inst_ptr.o.h & #80000000) g[rK].o.h &= -2; /* disable interrupts on P_BIT */
    inst_ptr.p =  $\Lambda$ ; continue;
case 'b': bp = read_hex(buffer + 1); continue;
case 'v': verbose = read_hex(buffer + 1).l; continue;

```

16.  $\langle$  Global variables 5  $\rangle + \equiv$ 

```

int n, m; /* temporary integer */
octa bp = {-1, -1}; /* breakpoint */
octa tmp; /* an octabyte of temporary interest */
static unsigned char d[BUF_SIZE];

```

17. Here's a simple program to read an octabyte in hexadecimal notation from a buffer. It changes the buffer by storing a null character after the input.

```

⟨Subroutines 10⟩ +=
  octa read_hex ARGS((char *));
  octa read_hex(p)
    char *p;
  {
    register int j, k;
    octa val;
    val.h = val.l = 0;
    for (j = 0; ; j++) {
      if (p[j] ≥ '0' ∧ p[j] ≤ '9') d[j] = p[j] - '0';
      else if (p[j] ≥ 'a' ∧ p[j] ≤ 'f') d[j] = p[j] - 'a' + 10;
      else if (p[j] ≥ 'A' ∧ p[j] ≤ 'F') d[j] = p[j] - 'A' + 10;
      else break;
    }
    p[j] = '\0';
    for (j--, k = 0; k ≤ j; k++) {
      if (k ≥ 8) val.h += d[j - k] << (4 * k - 32);
      else val.l += d[j - k] << (4 * k);
    }
    return val;
  }

```

18. ⟨Cases for interaction 14⟩ +=

```

case '-': if (sscanf(buffer + 1, "%d", &n) ≠ 1 ∨ n < 0) goto what_say;
  if (cool ≤ hot) m = hot - cool; else m = (hot - reorder_bot) + 1 + (reorder_top - cool);
  if (n > m) deissues = m; else deissues = n;
  continue;
case '1': if (sscanf(buffer + 1, "%d", &n) ≠ 1 ∨ n < 0) goto what_say;
  if (n ≥ lring_size) goto what_say;
  printf("␣␣1[%d]=%08x%08x\n", n, l[n].o.h, l[n].o.l); continue;
case 'm': tmp = mem_read(read_hex(buffer + 1));
  printf("␣␣m[%s]=%08x%08x\n", buffer + 1, tmp.h, tmp.l); continue;

```

19. The register stack pointers, rO and rS, are not kept up to date in the *g* array. Therefore we have to deduce their values by examining the pipeline.

⟨Cases for interaction 14⟩ +=

```

case 'g': if (sscanf(buffer + 1, "%d", &n) ≠ 1 ∨ n < 0) goto what_say;
  if (n ≥ 256) goto what_say;
  if (n ≡ rO ∨ n ≡ rS) {
    if (hot ≡ cool) /* pipeline empty */
      g[rO].o = sl3(cool_O), g[rS].o = sl3(cool_S);
    else g[rO].o = sl3(hot-cur_O), g[rS].o = sl3(hot-cur_S);
  }
  printf("␣␣g[%d]=%08x%08x\n", n, g[n].o.h, g[n].o.l);
  continue;

```

20.  $\langle$  Subroutines 10  $\rangle + \equiv$

```
static octa sl3 ARGS((octa));
static octa sl3(y) /* shift left by 3 bits */
    octa y;
{
    register tetra yhl = y.h << 3, ylh = y.l >> 29;
    y.h = yhl + ylh; y.l <<= 3;
    return y;
}
```

21.  $\langle$  Cases for interaction 14  $\rangle + \equiv$

```
case 'I': print_cache(buffer[1] == 'T' ? ITcache : Icache, false); continue;
case 'D': print_cache(buffer[1] == 'T' ? DTcache : Dcache,
    buffer[1] == '*'); continue;
case 'S': print_cache(SCache, buffer[1] == '*'); continue;
case 'p': print_pipe(); print_locks(); continue;
case 's': print_stats(); continue;
case 'i': if (sscanf(buffer + 1, "%d", &n) == 1) g[rI].o = incr(zero_octa, n);
    continue;
```

22.  $\langle$  Cases for interaction 14  $\rangle + \equiv$

```
case 'f': tmp = read_hex(buffer + 1);
{
    register fetch *new_tail;
    if (tail == fetch_bot) new_tail = fetch_top;
    else new_tail = tail - 1;
    if (new_tail == head) printf("Sorry, the fetch buffer is full!\n");
    else {
        tail-loc = inst_ptr.o;
        tail-inst = tmp.l;
        tail-interrupt = 0;
        tail-noted = false;
        tail = new_tail;
    }
    continue;
}
```

23. A hidden case here, for me when debugging. It essentially disables the translation caches, by mapping everything to zero.

$\langle$  Cases for interaction 14  $\rangle + \equiv$

```
case 'd': if (ticks.l) printf("Sorry: I disable ITcache and DTcache only at the beginning!\n");
    else {
        ITcache-set[0][0].tag = zero_octa;
        ITcache-set[0][0].data[0] = seven_octa;
        DTcache-set[0][0].tag = zero_octa;
        DTcache-set[0][0].data[0] = seven_octa;
        g[rK].o = neg_one;
        page_bad = false;
        page_mask = neg_one;
        inst_ptr.p = (specnode *) 1;
    } continue;
```

24. And another case, for me when kludging. At the moment, it simply lists the functional unit names.  
But I might decide to put other stuff here when giving a demo.

⟨ Cases for interaction 14 ⟩ +≡

```
case '!': {
    register int j;
    for (j = 0; j < funit_count; j++) printf("unit_%s_%d\n", funit[j].name, funit[j].k);
}
continue;
```

25. ⟨ Global variables 5 ⟩ +≡

```
bool silent = false;
bool bad_address;
extern bool page_bad;
extern octa page_mask;
extern int page_r, page_s, page_b[5];
extern octa zero_octa;
extern octa neg_one;
octa seven_octa = {0, 7};
extern octa incr ARGS((octa y, int delta));    /* unsigned y + δ (δ is signed) */
extern void mmix_io_init ARGS((void));
extern void MMIX_config ARGS((char *));
```

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