GCC for MMIX

the ABI

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This document is a webbification of some slides and notes presented at the MMIXfest 2001, October 6 in Munich, Germany, hosted by the Computer Science and Mathematics Department, Munich University of Applied Sciences.

You are encouraged to report errors in the original document or opinions about it to hp@bitrange.com.

Contents

Location of the original

The original of this document is located at http://bitrange.com/mmix/mmixfest-2001/mmixabi.html.

Summary of changes

(No changes since the original webbification on 2001-10-10.)

Abstract

I'll present an ABI based on Knuth's documents. I want your opinions about some details where I'm undecided. I'll also sketch a few details of an alternative ABI.

Goals for the GCC MMIX port

Performance of programs for the MMIX architecture relies on keeping as many variables as possible in registers, to minimize memory accesses by other means than through the register stack and instruction fetches. So first hand, registers should be used rather than a traditional memory stack.

Another goal is for the assembly code to be usable as input for further modification by a human. The generated code should as far as possible be compatible with mmixal and conventions in Knuth's texts. There are currently (2001-10-10) some non-conformance issues, which will be fixed wherever possible.

Function call conventions as implied by Knuth's texts

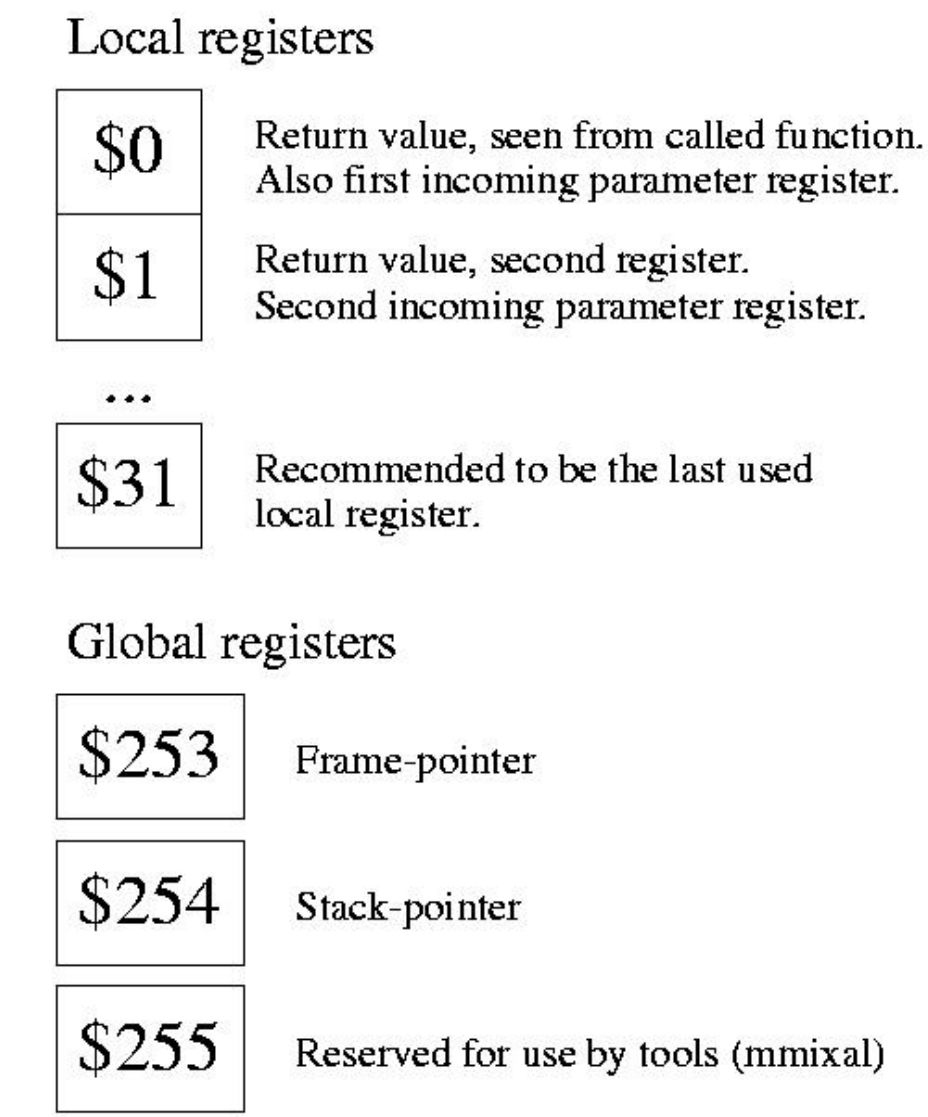
```
long zz = 0;

void x (void)
{
 zz = fn (3, 2, 1);
}

long fn (long a, long b, long c)
{
 return a + b * c;
}
```

```
zz   OCTA 0

x    GET $0,rJ
     SETL $2,#3
     SETL $3,#2
     SETL $4,#1
     PUSHJ $1,fn
     PUT rJ,$0
     GETA $0,zz
     STOU $1,$0,0
     POP 0,0

fn   MULU $1,$1,$2
     ADDU $0,$0,$1
     POP 1,0
```

Recommended MMIX function call convention,
as derived from Knuth's texts.

It is described (in [ref 1]) that parameters are usually passed in registers $0 and up, as seen by the called function. Further, the return address is passed in rJ, using PUSHJ and PUSHGO for function calls and POP for returning ([ref 3]). Return values are put in $0 and up, as seen by the returning (called) function.

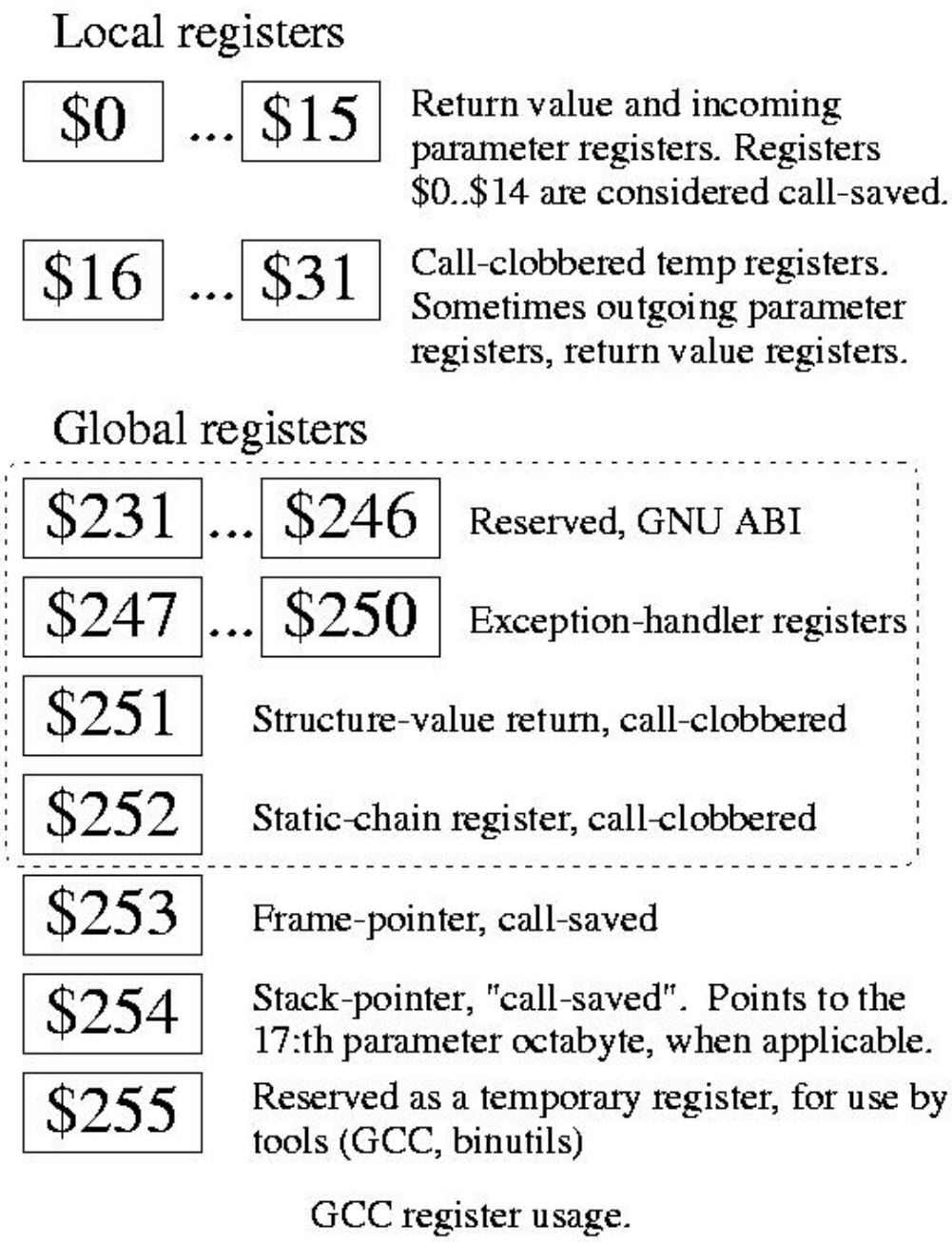
Register usage as implied by Knuth's texts



Recommended MMIX register usage,
derived from Knuth's texts.

In [ref 2], it is mentioned that $255 is used by mmixal for instruction expansion under control of the -x option. This happens when loading out-of-range addresses, making register $255 unsuitable for literal use in assembly programs. At the same place, it is suggested that functions that need a memory stack can use $254 as a stack pointer and when necessary, $253 as a frame-pointer.

Register usage by the GCC port



GCC register usage.

The number of local registers (the value of special register rG), is defined to never be lower than 32. It is also recommended (in [ref 1]) that a program should not assume more than 32 available local registers. This number is higher than most human-written C-functions will use anyway. Therefore, the number of incoming or outgoing registers used for parameters cannot reasonably be higher than 32. In an attempt to keep things simple (and to work around restrictions in GCC), it seemed best to split that number even for incoming and outgoing parameters; the number of registers used for parameters is 16.

Hopefully, this should also minimize the number of register moves necessary to get incoming registers "out-of-the-way" when calling other functions.

Please note that register $16 being an outgoing parameter register is just a first approximation. I'll explain briefly the GCC-related issues later. The 17:th parameter and beyond are passed on the stack, with $254 (the stack-pointer) pointing to the first parameter in the called function.

Just as mmixal does, the GNU binutils uses register $255 for its own purposes when loading addresses. GCC also uses it for temporary purposes in some cases, but only for instructions that the assembler and linker will not expand.

The stack pointer $254 is set up in the code between Main and main, and must have the same value when a function returns as when it was entered.

If register $253, the suggested frame-pointer, is used in a function, it must likewise be saved so it has the same value at function exit as at function entry.

The GCC implementation reserves a few registers.

There's a GCC extension for nested functions, that for some codes circumstances need to pass a context pointer; a pointer to the local variables of the enclosing function when a pointer to a nested function is passed to another function[1]. That pointer is passed in register $252.

Register $251 is used for the structure return pointer. Registers $247..$250 are used for C++ exception handling, and registers $231.. $246 are reserved for the GNU ABI. There is no need for a function to preserve these register values, but it must be prepared that a called function may change them.

This is just the current (2001-10-10) work-in-progress mapping. These allocations are not final, and some of the uses can certainly share the same register. For the imaginary typical MMIX programmer these allocations should not matter, as they do not collide with GREG-allocated registers (unless the program is short on registers).

Type layout

C/C++	MMIX
char	byte
short int	wyde
int	tetra
long int	octa
long long	octa
float	"single float": 32-bit IEEE
double	64-bit IEEE
long double	64-bit IEEE

MMIX fundamental C and C++ type mapping

MMIX can handle 8, 16, 32 and 64-bit data. A reasonable mapping of C types exposes all these sizes so e.g. a C programmer wanting to write for MMIX can do it simply by using standard types[2]. The fundamental address unit type in C is char (sizeof char is always 1), so BYTE maps naturally to it. The C "char" type is by default signed, because this is the case for most gcc ports and therefore would presumably lead to the fewest compatibility problems. The rest of the normal C integer types are "short int", "int" and "long int". They naturally map to wyde, tetrabyte and octabyte. Incidentally, this is the same mapping as the alpha gcc port uses. The gcc type "long long"[3] has to map to octabyte, otherwise cross-compilation from a 32-bit host is not possible. This is a gcc restriction, but might not matter too much, since on a "long long" is usually also 64 bits, this being natural for existing 32-bit hosts.

The normal C floating point types are float, double and long double. MMIX has 64-bit IEEE floating point quantities and limited operations on 32-bit quantities, "short floats". They naturally map to double and float, with long double an alias for double.

Memory layout

Each of the fundamental types must be mapped to an address at least a multiple of its size, so called "naturally aligned". To be theoretically addressable with a GETA, individual variables are aligned to tetrabyte alignment.

```
struct x {
  char a;
  int b;
  long c;
  char d;
} x1 = {                LOC @+(8-@)&7
  1,            x1      BYTE 1
                        LOC @+3
  2,                    TETRA 2
  3,                    OCTA 3
  4                     BYTE 4
};                      LOC @+7

    sizeof (struct x) == 24
```

MMIX GCC structure layout example

Similarly for structures, the structure layout has members naturally aligned, with padding inserted where necessary. The alignment of a structure is that of its largest contained type. The size is a multiple of that type, with padding inserted at the end of the structure.

Parameter passing in the GCC port

If a parameter fits in a register, it is passed by-value, with integer types extended to 64 bits by the caller. Otherwise, it is passed by reference (as a pointer to the original), and the called function has to copy it, in case it needs a local modifiable copy.

The same goes for parameters passed on the stack; integer types are promoted, passed as 64 bits, with larger-than-64-bit types passed by reference.

Returning function values in the GCC port

Scalar values are returned in $0 as seen by the calling function. We usually don't have to worry about the register hole.

There is an exception: complex values together larger than 64 bits are returned in $0 and $1 as seen by the calling function. For these multi-register return values, the called function compensates for the hole, so the calling function sees the register with $0 being the natural first part; like the order allocated for registers.

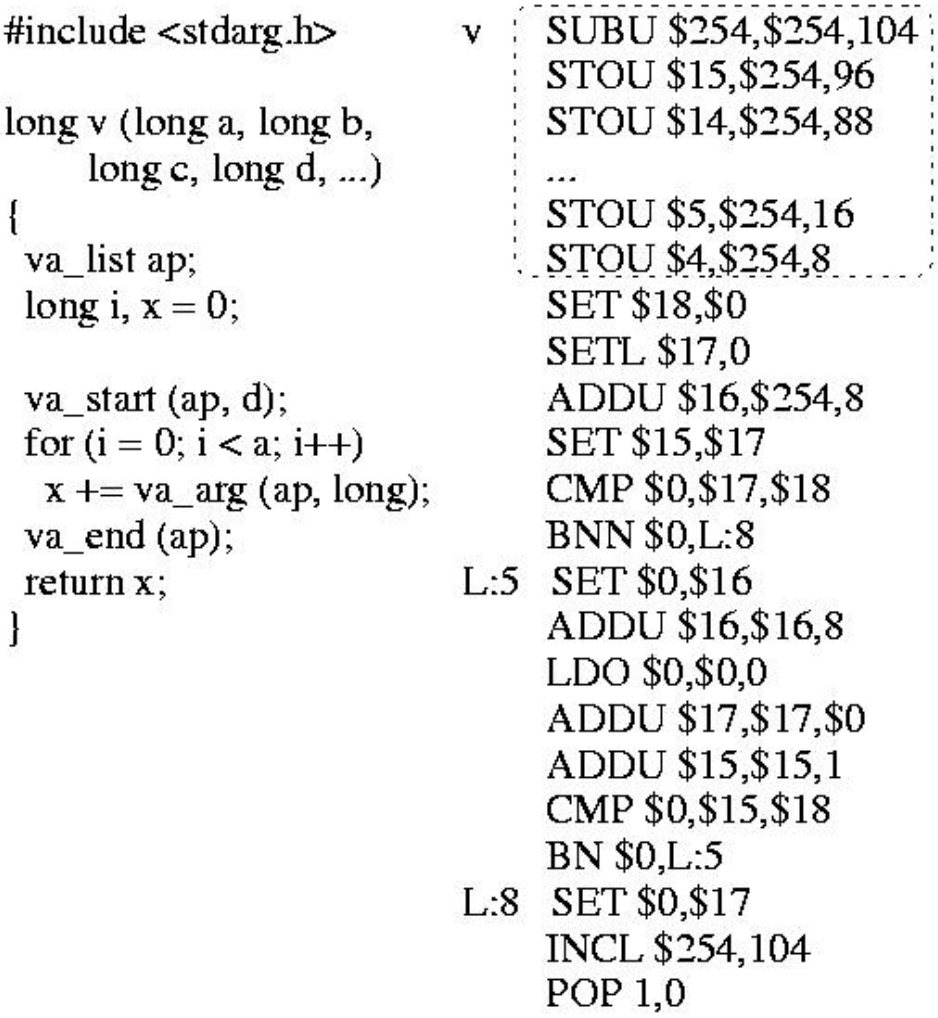
```
struct s { char a; char b; };

struct s
sf (struct s ps)
{
 ps.a++;
 return ps;
}
```

```
sf   SUBU $254,$254,16
     SET $1,$254
     STWU $0,$1,0
     LDB $2,$1,0
     ADDU $0,$2,1
     STBU $0,$1,0
     STBU $0,$251,0
     LDB $1,$1,1
     STBU $1,$251,1
     SET $0,$251
     INCL $254,16
     POP 1,0
```

A function returning a structure through the structure-return register, $251.

Structures are returned specially. The caller passes a pointer to an area where the structure contents is to be stored by the called function, regardless of the structure size. The structure-return pointer is passed in register $251.

Functions with a variable number of parameters



```
#include <stdarg.h>

long v (long a, long b,
        long c, long d, ...)
{
  va_list ap;
  long i, x = 0;

  va_start (ap, d);
  for (i = 0; i < a; i++)
    x += va_arg (ap, long);
  va_end (ap);
  return x;
}
```

```
v   SUBU $254,$254,104
    STOU $15,$254,96
    STOU $14,$254,88
    ...
    STOU $5,$254,16
    STOU $4,$254,8
    SET $18,$0
    SETL $17,0
    ADDU $16,$254,8
    SET $15,$17
    CMP $0,$17,$18
    BNN $0,L:8
L:5 SET $0,$16
    ADDU $16,$16,8
    LDO $0,$0,0
    ADDU $17,$17,$0
    ADDU $15,$15,1
    CMP $0,$15,$18
    BN $0,L:5
L:8 SET $0,$17
    INCL $254,104
    POP 1,0
```

Example function with a variable number of arguments.

While it's certainly possible to implement special calling conventions for functions declared to take a variable number of parameters, like printf, there is no need to. The called stdarg function will arrange to map parameter registers to be accessible as a va_list (usually an array). The called function will have to push the parameters that were passed in registers onto the stack before processing them. There's an implicit assumption that stdarg functions don't have to be optimal in terms of speed. Also, this yields simple, easy-to-understand code.

How to get addresses into registers

Using GREG to get an address base

```
        GREG @
buffer1 BYTE 0,0,0,0,0,0,0,0
buffer2 BYTE 0,0,0,0,0,0,0,0
        ...
Main    LDA $0,buffer2
! (or individual GREG:s)
```

The constant-pool approach

```
buffer1 BYTE 0,0,0,0,0,0,0,0
buffer2 BYTE 0,0,0,0,0,0,0,0
            ...
pool    OCTA buffer1
        OCTA buffer2
            ...
Main    GETA $0,pool+8
        LDOU $0,$0,0
```

The GETA approach

```
buffer1 BYTE 0,0,0,0,0,0,0,0
buffer2 BYTE 0,0,0,0,0,0,0,0
        ...
Main    GETA $0,buffer2
        ! May expand to:
        ! SETL $0,buffer2&65535
        ! INCML $0,(buffer2>>16)&65535
        ! INCMH $0,(buffer2>>32)&65535
        ! INCH $0,(buffer2>>48)
```

Different approaches to getting an address into a register.

When accessing memory, the address has to get into a register somehow. A common convention is to allocate a register with GREG at the start of a number of memory variables, and use a base-plus-offset expression to translate the address into a register plus offset. That method is restricted to about two hundred such variables (or areas of variables, 256 bytes long) per program.

The ARM, Hitachi SH and others use "constant pools", where each far-away address is kept nearby the code; *its* address loaded with a GETA equivalent, then using a LDOU to load the real address. On the other hand, these memory accesses appear out of sequence compared to instruction fetches and the "real" memory accesses, a reason to avoid that solution, at least when modeling real hardware. Also, that would mean a GETA and LDOU with the address taking up an octabyte: disregarding possible sharing of addresses, this equals a four-instruction sequence, at least in size.

I chose to use GETA for address loading, leaving it to the assembler and linker to expand it when necessary. This is counter to the goal of using the same conventions as for manually written assembly code. Therefore I'll implement the

GREG/base-plus-offset approach as an option, default for standard applications. Anyway, it seems good to at least *optionally* be lean on GREG allocations, using the GETA approach.

Assembly label conventions

Some ports prepend symbols with underscores to disambiguate register names, but there's no need for that with MMIX. Some use dollar signs ($) or dots (.) to protect compiler-generated symbols; the MMIX port uses colon (:) at strategic places. (See the static chain example.)

GCC register allocation restrictions

A few properties and limitations of gcc affect the MMIX port badly.

```
extern long i;
long g (void);
long g2 (long);
long h (long);

long f (long p)
{
 long y = g();
 long x = h(y + p);
 i = x+y;
 return i;
}

long f2 (long p)
{
 long y = g2(i);
 long x = h(y + p);
 i = x+y;
 return i;
}
```

```
f    SET $15,$15
     GET $2,rJ
     PUSHJ $15,g
     SET $1,$15
     ADDU $0,$1,$0
     SET $16,$0
     PUSHJ $15,h
     PUT rJ,$2
     SET $0,$15
     ADDU $0,$0,$1
     GET $1,i
     STOU $0,$1,0
     POP 1,0

f2   GET $3,rJ
     GETA $2,i
     LDO $16,$2,0
     PUSHJ $15,g2
     SET $1,$15
     ADDU $0,$1,$0
     SET $16,$0
     PUSHJ $15,h
     PUT rJ,$3
     SET $0,$15
     ADDU $0,$0,$1
     STOU $0,$2,0
     POP 1,0
```

Example of fixed-set register allocation,
along related forcing of L=15.

As a rule, GCC considers the set of registers that can hold parameters and the set of return-value registers constant. Two other important sets, are the set of call-saved registers and call-clobbered registers. While GCC is written for these sets being constant, they should be chosen dynamically for best MMIX code (even per-call within a function), to e.g. avoid setting L higher than necessary. Unfortunately the possibility of making these properties dynamic, or one a function of the other, is limited at best. For the GCC MMIX port, these properties *are* currently (2001-10-10) constant: registers $0..$14 are call-saved, and $16..$31 are call-clobbered.

Changing these parts of gcc would be a major rewrite.

It is reasonably simple, that at a final pass "rename" registers, for example to close an unused gap between the end of the call-saved registers and the outgoing parameter registers. There's hope that the end result will be reasonably near an optimal register allocation, like the one a skilled human would do.

GCC global registers

After mentioning the register allocation limitations, I think I should cheer you up by mentioning that GCC has some provisions for allocating global variables in registers. It doesn't do it automatically, but it should be reasonably simple to interface global register definitions with GREG allocations. I have however not investigated this thoroughly.

An alternative ABI

GNU ABI difference:

$231 ... $246 Parameters and return value

```
long f2 (long p)
{
 long y = g2(i);
 long x = h(y + p);
 i = x+y;
 return i;
}
```

```
f2  GET $3,rJ
    GETA $2,i
    LDO $16,$2,0
    PUSHJ $15,g2
    SET $1,$15
    ADDU $0,$1,$0
    SET $16,$0
    PUSHJ $15,h
    PUT rJ,$3
    SET $0,$15
    ADDU $0,$0,$1
    STOU $0,$2,0
    POP 1,0
```

```
f2  GET $3,rJ
    SET $0,$231
    GETA $2,i
    LDO $231,$2,0
    PUSHJ $4,g2
    SET $1,$231
    ADDU $0,$1,$0
    SET $231,$0
    PUSHJ $4,h
    PUT rJ,$3
    ADDU $231,$231,$1
    STOU $231,$2,0
    POP 0,0
```

Example compiled for the MMIXware ABI along one compiled for the GNU ABI.

To simplify development of the port, I started with a traditional ABI, one where parameters are passed in call-clobbered global registers (same for called and calling function) and where the return value is returned in primarily the first parameter registers. I call this the GNU ABI.

At the moment I don't have any performance figures. Though in my experience, the number of register moves are kept to a minimum if incoming and outgoing parameter register and the primary return value register are the same. On the other hand MMIX instructions being three-operand lessens the importance of that.

Request for comments

- Structures passed and returned by value (in multiple registers)?
- ... with a size threshold?
- Parameters passed extended to octabyte?
- Is mmixal compatibility of interest?
- Thoughts about the GNU ABI?
- Your favorite issue here.

Call for opinions

Should structures be passed by-value in multiple registers?

If so, there should preferably be a size-threshold. What should be the structure-size threshold for that?

Who should extend passed integers, caller or called function? The 64-bit extension of passed integer types is mainly for ease of use; the programmer who interfaces assembly code to compiler-generated code does not have to remember the

exact type passed, "it's an integer, extend or truncate it and pass it in a register" is sufficient for most use. I haven't showed you actual examples of this, because there are some related bugs that cause the code to be quite ugly. That's why I've used "long" in most examples.

Is it useful that the generated code is as mmixal-compatible as possible, even if it results in non-optimal code?

What are your thoughts about the GNU ABI?

References

The sources for these references can be found at http://www-cs-staff.Stanford.EDU/~knuth/mmix-news.html and (probably, I have not checked) in the MMIX book.

1. mmix-doc.ps, section 29, page 23
2. mmixal-intro.ps, section 18, page 8
3. mmix-doc.ps, section 18, page 13

Footnotes

1. The static chain register is necessary when a function pointer to the nested function is passed to another function, the nested function accessing variables in the enclosed function. The passed function pointer for the nested function is actually points to another piece of code, a *trampoline*, where the static chain register is loaded. The trampoline then jumps to the nested function, as can be seen in the figure below:

```
extern void f0 (void (*)(void));
long f1 (void)
{
 long i = 0;

 void f2 (void)
 {
  i++;
 }

 f0 (f2);

 return i;
}
```

```
f1    SUBU $254,$254,56       f2::0 SUBU $252,$252,8
      GET $2,rJ                     LDO $0,$252,0
      SET $0,$254                   ADDU $0,$0,1
      GETA $1,LTRAMP:0              STOU $0,$252,0
      <copy trampoline template     POP 0,0
       to the stack>
      <setup the trampoline>  LTRAMP:0      GETA $255,1F
      ADDU $0,$254,40               LDOU $252,$255,0
      STCO 0,$0,0                   LDOU $255,$255,8
      SET $16,$254                  GO $255,$255,0
      PUSHJ $15,f0              1H  OCTA 0  ! Static chain.
      PUT rJ,$2                     OCTA 0  ! Address of the nested f2::0.
      LDO $0,$0,0
      INCL $254,56
      POP 1,0
```

A nested function using the static-chain register, $252.

2. In the "new" C99 standard, there can be names for types of specific sizes, like int64_t, accessible through the <stdint.h> header file. Mapping ordinary C types to specific sizes may therefore not strictly be necessary.

3. The type *long long* and its unsigned variant are standard types in the C99 standard.

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