

MIPSpro™ 64-Bit Porting and Transition Guide

Document Number 007-2391-004

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64-bit ABI and Compiler Overview

This chapter gives a brief overview of the 64-bit application binary interface (ABI) and describes the MIPSpro™ 7.2 32-bit, 64-bit and high performance 32-bit (N32) compilers. It contains six sections:

- The first section introduces the 64-bit ABI and describes the compatibility of old IRIX 5.x programs with IRIX 6.x (see Figure 1-1).
- The second section describes the various components of both the 64-bit compiler system and the 32-bit compiler.
- The third section gives an overview of interprocedural analysis (IPA), a new feature introduced in the MIPSpro™ 7.0 64-bit and N32 compilers.
- The fourth section gives an overview of the loop nest optimizer (LNO), another new feature of the MIPSpro™ 7.0 64-bit and N32 compilers.
- The fifth section describes the Auto Parallelizing Option which, as of MIPSpro 7.2, replaces the Kuck and Associates Preprocessor (KAP), as a means of converting programs to parallel code.
- The last section introduces the multiprocessing support provided by the MIPSpro™ compilers.

64-bit ABI Overview

Currently, three different ABIs are supported on IRIX platforms:

- o32** The old 32-bit ABI generated by the ucode compiler.
- n32** The new 32-bit ABI generated by the MIPSpro 64-bit compiler. N32 is described in the *MIPSpro N32 ABI Handbook*.
- n64** The new 64-bit ABI generated by the MIPSpro 64-bit compiler.

Introduced in IRIX 6.0, the 64-bit ABI was designed to exploit the high performance capabilities and 64-bit virtual addressing provided by the MIPS R8000 processor. These capabilities include:

- The ability to execute MIPS1 user code, compatible with the R3000.
- The ability to execute MIPS2 instruction set extensions introduced in the R4000.
- The ability to execute MIPS3 64-bit addressing and instructions introduced in the R4400.
- The ability to execute new instructions which improved floating point and integer performance (MIPS4 instructions).

The MIPS3 and MIPS4 64-bit capabilities provide both 64-bit virtual addressing and instructions which manipulate 64-bit integer data. Processor registers are 64 bits in size. Also provided was the ability to use 32 64-bit floating point registers.

Table 1-1 compares the various ABIs.

Table 1-1 ABI Comparison Summary

| | o32 | n32 | n64 |
|------------------------|------------|------------|------------|
| Compiler Used | ucode | MIPSpro | MIPSpro |
| Integer Model | ILP32 | ILP32 | LP64 |
| Calling Convention | mips | new | new |
| Number of FP Registers | 16 (FR=0) | 32 (FR=1) | 32 (FR=1) |

Table 1-1 (continued) ABI Comparison Summary

| | o32 | n32 | n64 |
|------------------------------|------------|-------------|------------|
| Number of Argument Registers | 4 | 8 | 8 |
| Debug Format | mdebug | dwarf | dwarf |
| ISAs Supported | mips1/2 | mips3/4 | mips3/4 |
| 32/64 Mode | 32 (UX=0) | 64 (UX=1) * | 64 (UX=1) |

* UX=1 implies 64-bit registers and also indicates that MIPS3 and MIPS4 instructions are legal. N32 uses 64-bit registers but restricts addresses to 32 bits.

Compatibility and Supported ABIs

All versions of IRIX 6.x support development for o32, n32 and n64 programs. All IRIX 6.x systems also support execution of o32 and n32 programs. However, in order to execute 64-bit programs you must be running on IRIX 6.4 or a 64-bit version of IRIX 6.2. IRIX 6.3 and the 32-bit version of IRIX 6.2 do not support execution of 64-bit programs. You can tell whether you are running on a system capable of executing 64-bit programs by running the *uname* command. If it returns `IRIX64`, you are on a 64-bit version of IRIX. If it returns `IRIX`, you are on a 32-bit version.

On 64-bit versions of IRIX you can execute programs conforming to any of the following Application Binary Interfaces (ABIs):

- An o32 program built under IRIX 5.x or IRIX 6.x (32-bit MIPS1 or MIPS2 ABI). COFF is no longer supported as of IRIX 6.2.
- A 64-bit program (64-bit MIPS3 or MIPS4 ABI).
- An N32 program (N32 MIPS3 or MIPS4 ABI).

Figure 1-1 illustrates the ABIs supported by IRIX 6.x.

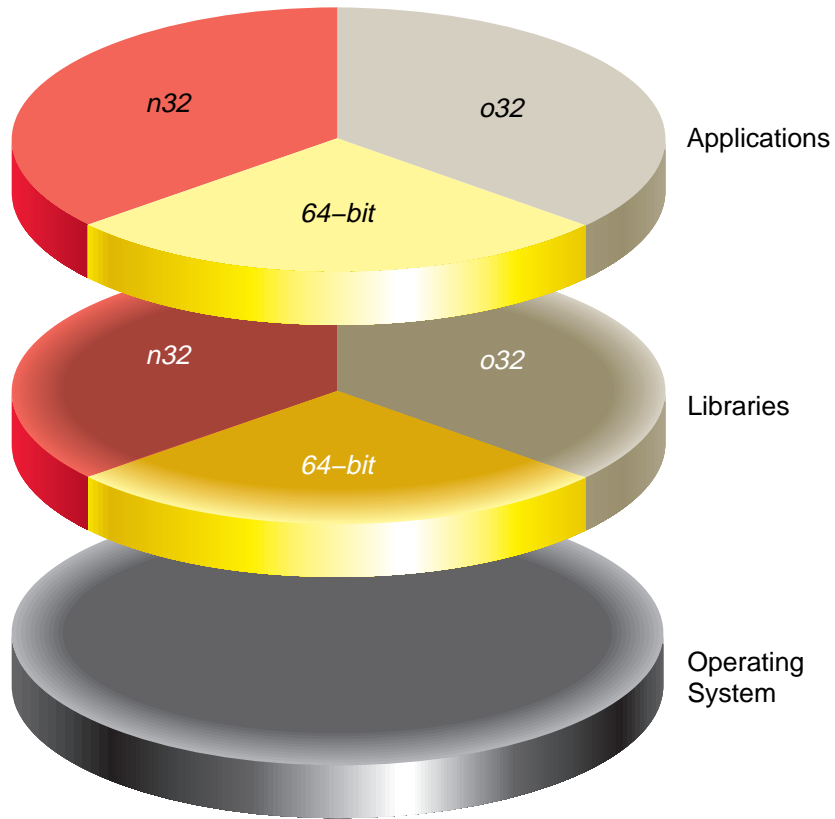


Figure 1-1 ABIs supported by IRIX 6.x

More specifically, the execution and development environments under IRIX 6.x provide the following functionality:

- 32-bit IRIX 5.x binaries and Dynamic Shared Objects (DSOs) execute under IRIX 6.x
- IRIX 6.x has a set of compilers (32-bit Native Development Environment) that generate 32-bit code. You can mix objects and link with objects produced on IRIX 5.x. (We do not, however, guarantee that this code runs on current IRIX 5.x systems.)
- IRIX 6.x also has a set of compilers (64-bit Native Development Environment) that generates either 64-bit or N32 code. This code **cannot** run on current IRIX 5.x systems.

- You can specify which compiler you want to run by using the **-64**, **-n32** or **-32 (-o32)** flags on the compiler command line.

The compiler driver then executes the appropriate compiler binaries and links with the correct libraries. This also applies to the assembler, linker, and archiver. If these switches are not present, the driver checks for an `/etc/compiler.defaults` file and an environment variable, `SGI_ABI`, for these values. See the `cc(1)` man pages.

- All of the compiler-related tools (`dbx`, `nm`, `dis`) can work with either 32-bit, N32 or 64-bit binaries. *Prof* functionality is rolled into a new product, *SpeedShop*.
- You **cannot** mix objects and DSOs produced by the 32-bit compilers with objects and DSOs produced by the 64-bit compilers. In Figure 1-1, this is illustrated by the lines separating the 32-bit, N32 and 64-bit libraries.

This means:

- You **cannot** link 32-bit objects with 64-bit or N32 objects and shared libraries
- You **cannot** link 64-bit objects with 32-bit or N32 objects and shared libraries
- You **cannot** link N32 objects with 64-bit or 32-bit objects and shared libraries
- The `/usr/lib` directory on IRIX 6.x systems contains the 32-bit libraries and `.sos`. The 64-bit `.sos` are located in `/usr/lib64`. The N32 `.sos` are located in `/usr/lib32`. The complete layout looks like this:

32-bit: This is the IRIX 5.x `/usr/lib`, including compiler components:

```
/usr/lib/
    *.so
    mips2/
    *.so
/usr/lib/
    cfe
    fcom
    ugen
    uopt
    as
```

64-bit: These are the 64-bit-specific libraries:

```
/usr/lib64/
    *.so
    mips3/
    *.so
    mips4/
    *.so
```

N32: These are the N32-specific libraries and components:

```
/usr/lib32/  
    *.so  
    mips3/  
    *.so  
    mips4/  
    *.so  
  
/usr/lib32/cmplrs  
    be  
    fec  
    mfef77  
    as
```

Known Compatibility Issues

The following issues are known to cause trouble for 32-bit programs running on IRIX 6.x:

- Any access to kernel data structures, for example, through */dev/kmem*. Many of these structures have changed in size. Programs making these kinds of accesses must be ported to 64-bit. 32-bit programs cannot access all of kernel memory, hence probably must also be ported to 64-bit.
- Use of **nlist()** does not work on any 64-bit *.o* or *a.out*. A new **nlist64()** is supplied for 64-bit ELF.
- Any assumption that the page size is 4Kbytes (for example, using **mmap()** and specifying the address). The page size is no longer 4Kbytes. Programs must use **getpagesize()**.
- Ada programs which catch floating point exceptions do not work.
- Any program using */proc* must have some interfaces changed.

It is possible for a program to determine whether it is running on a 64-bit capable kernel in order to work around the issues listed above. Use **sysconf(_SC_KERN_POINTERS)**, which returns 32 or 64.

Compiler System Components

As explained earlier, the MIPSpro compiler system on IRIX 6.x consists of two independent compiler systems. One system supports the 64-bit and high performance 32-bit (N32) ABIs. The other supports the old 32-bit ABI. This section describes and compares them.

Fortran

The MIPSpro Fortran 77 compilers support 32-bit, 64-bit and N32 compiler modes. The components of the two systems are described in the section that follows.

Fortran 64-Bit and N32 System

The 64-bit Fortran compiler consists of the following components:

| | |
|--------------------|---|
| <i>f77</i> | Fortran driver: Executes the appropriate components below. |
| <i>mfe77</i> | Fortran 77 front end: Parses the source file into an intermediate representation. It also performs scalar optimization and automatic parallelization. |
| <i>be</i> | Back end: Generates code and assembles it into an object file. It also performs a variety of optimizations which are described in Chapter Four of this book, <i>Compilation Issues</i> . It also automatically performs scalar optimizations and inter procedural optimizations. Available with the MIPSpro Auto Parallelizing Option product, is the ability to automatically convert programs to parallel code. |
| <i>dsm_prelink</i> | Prelinker for routines that use distributed shared memory. If a reshaped array is passed as a parameter to another subroutine, <i>dsm_prelink</i> automatically propagates the <i>distribute_reshape</i> directive to the called subroutine. |
| <i>ld64</i> | Linker: Links the object file(s) with any libraries. |

When you run 64-bit compilations for single processor applications, the following components are executed by the compiler driver:

```
%f77 -64 foo.f
%f77 -64 -O foo.f
mfef77 --> be --> ld64
```

When you run 64-bit compilations for multiprocessor applications an additional step invoking *dsm_prelink* is done just before the final linking step:

```
%f77 -64 -mp foo.f
%f77 -64 -pfa foo.f
mfef77 --> be --> dsm_prelink --> ld64
```

Under the MIPSpro 64-bit compiler, optimizations are performed in the back end. Note that **-O3** is available with **-c**. Unlike the *ucode* compilers, **-O3** does not result in interprocedural optimizations being performed. Use the **-IPA:...** control group to perform interprocedural optimizations with the 64-bit compiler.

The **-sopt** switch is NOT supported on the 64-bit compiler. Use the **-LNO: ...** control group flags to perform the desired scalar optimizations.

The **-mp** switch is supported on the 64-bit compiler and causes **mfef77** to recognize inserted parallelization directives.

The **-pfa** switch is supported on the 64-bit compiler (when the MIPSpro Auto Parallelizing Option is obtained) and causes *be* to perform automatic parallelization.

Fortran 32-Bit System

The 32-bit (*ucode*) Fortran compiler systems contain the following components:

| | |
|-------------|--|
| <i>f77</i> | Fortran driver: Executes the appropriate components below. |
| <i>cpp</i> | C preprocessor: Handles #include statements and other <i>cpp</i> constructs such as #define , #ifdef , and so on, in the source file. |
| <i>fopt</i> | Special scalar optimizer: Performs scalar optimization on the Fortran source. |

| | |
|-------------|---|
| <i>pfa</i> | Power Fortran Accelerator™: Automatically parallelizes Fortran source code and performs scalar optimizations. Available with the Power Fortran product. |
| <i>fcom</i> | Fortran front end: Parses the source file into intermediate code (<i>ucode</i>). |
| <i>uopt</i> | Optimizer: Performs optimizations on the intermediate file. |
| <i>ugen</i> | Code generator: Generates binary assembly code from the intermediate file. |
| <i>as1</i> | Binary assembler: Assembles the <i>binasm</i> code into an object file. |
| <i>ld</i> | Linker: Links the object file(s) with any libraries. |

When you run simple examples through the *ucode* Fortran compilers, the following components are executed by the compiler driver:

```
%f77 -32 foo.f
      cpp --> fcom --> ugen --> as1 --> ld
```

The command

```
%f77 -32 -O foo.f
      cpp --> fcom --> uopt --> ugen --> as1 --> ld
```

also invokes the *ucode* optimizer, *uopt*. The command

```
%f77 -32 -sopt foo.f
      cpp --> fopt --> fcom --> ugen --> as1 --> ld
```

invokes the scalar optimizer but does not invoke the *ucode* optimizer.

The **-mp** option signals *fcom* to recognize inserted parallelization directives:

```
%f77 -32 -mp foo.f
      cpp --> fcom --> ugen --> as1 --> ld
```

The Power Fortran option, **-pfa**:

```
%f77 -32 -pfa foo.f
      cpp --> pfa --> fcom --> ugen --> as1 --> ld
```

invokes the Power Fortran Accelerator to convert programs to parallel code automatically.

C

For C, the respective compiler systems are similar to their Fortran counterparts. The front ends, of course, are different in each system.

C 64-Bit and N32 System

The MIPSpro (64-bit) C compiler systems contain the following components:

| | |
|--------------------|--|
| <i>cc</i> | C driver: Executes the appropriate components below. |
| <i>fec</i> | C front end: Preprocesses the C file, and then parses the source file into an intermediate representation. |
| <i>be</i> | Back end: Generates code and assembles it into an object file. It also performs a variety of optimizations which are described in Chapter Four of this book, <i>Compilation Issues</i> . It also automatically performs scalar optimizations and inter procedural optimizations. Available with the MIPSpro AutoParallelizing Option product, is the ability to automatically convert programs to parallel code. |
| <i>dsm_prelink</i> | Prelinker for routines that use distributed shared memory. If a reshaped array is passed as a parameter to another subroutine, <i>dsm_prelink</i> automatically propagates the <i>distribute_reshape</i> directive to the called subroutine. |
| <i>ld</i> | Linker: Links the object file(s) with any libraries. |

When you run simple examples through the 64-bit C compilers, the following components are executed by the compiler driver:

```
%cc -64 foo.c
%cc -64 -O foo.c
      fec --> be --> ld64
```

When you run 64-bit compilations for multiprocessor applications an addition step invoking *dsm_prelink* is done just before the final linking step:

```
%cc -64 -mp foo.c
%cc -64 -pca foo.c
      fec --> be --> dsm_prelink --> ld64
```

C 32-Bit System

The 32-bit (*ucode*) C compiler systems contain the following components:

| | |
|-----------------|---|
| <i>cc</i> | C driver: Executes the appropriate components below. |
| <i>acpp</i> | ANSI C preprocessor: Handles #include statements and other <i>cpp</i> constructs such as #define , #ifdef , and so on, in the source file. |
| <i>cfe</i> | C front end: Preprocesses the C file, and then parses the source file into intermediate code (<i>ucode</i>). |
| <i>ccom_mp</i> | C front end for Power C: Interprets parallel directives (K & R version). |
| <i>accom_mp</i> | C front end for Power C: Interprets parallel directives (ANSI version). |
| <i>copt</i> | C scalar optimizer: Performs scalar optimization. |
| <i>pca</i> | Power C analyzer: Automatically parallelizes C source code and performs scalar optimizations. Available with the Power C product. |
| <i>uopt</i> | Optimizer: Performs optimizations on the intermediate file. |
| <i>ugen</i> | Code Generator: Generates binary assembly code from the intermediate file. |
| <i>as1</i> | Binary assembler: Assembles the <i>binasm</i> code into an object file. |
| <i>ld</i> | Linker: Links the object file(s) with any libraries. |

When you run simple examples through the *ucode* C compiler, the following components are executed by the compiler driver:

```
%cc -32 foo.c
    cfe --> ugen --> as1 --> ld
```

Note: *cfe* has a built-in C preprocessor.

The command

```
%cc -32 -O foo.c
    cfe --> uopt --> ugen --> as1 --> ld
```

also invokes the *ucode* optimizer, *uopt*.

The command

```
%cc -32 -sopt foo.c
    acpp --> copt --> cfe --> ugen --> as1 --> ld
```

invokes the scalar optimizer but does not invoke the *ucode* optimizer.

The C preprocessor has to be run before *copt* can do its source-to-source translation:

```
%cc -32 -mp foo.c
  acpp --> accom_mp --> ugen --> as1 --> ld
```

-mp signals *accom_mp* to recognize inserted parallelization directives.

The command

```
%cc -32 -pca foo.c
  acpp --> pca --> accom_mp --> ugen --> as1 --> ld
```

invokes the Power C accelerator to convert programs to parallel code automatically.

Fortran and C 64-Bit Components

Table 1-2 summarizes the major components of both the Fortran and C compilers of the new MIPSpro (64-bit and N32) compiler system.

Table 1-2 Major Components of 64-Bit and N32 Fortran and C Compilers

| Fortran | | C |
|--------------------|--|--------------------|
| <i>f77</i> | Driver | <i>cc</i> |
| <i>mfef77</i> | Preprocessor | <i>fec</i> |
| <i>mfef77</i> | Front end | <i>fec</i> |
| <i>be</i> | Scalar optimizer | <i>be</i> |
| <i>mfef77</i> | MP directive interpreter | <i>fec</i> |
| <i>be</i> | Automatic parallelizer | <i>be</i> |
| <i>be</i> | Back end | <i>be</i> |
| <i>dsm_prelink</i> | Distributed Shared Memory Prelinker | <i>dsm_prelink</i> |
| <i>ld64</i> | Linker | <i>ld</i> |

Interprocedural Analysis (IPA)

As of version 7.0, the MIPSpro 64-bit or N32 compilers can perform interprocedural analysis and optimization when invoked with the `-IPA` command line option. Current IPA optimizations include: inlining, interprocedural constant propagation, dead function, dead call and dead variable elimination and others. For more information about IPA and its optimization options, refer to the *MIPSpro Compiling, Debugging and Performance Tuning Guide*.

An important difference between the 64-bit compiler's use of `-IPA` and `-c` and the 32-bit compilers use of `-O3` and `-j` is that the intermediate files generated by the 64-bit compiler have the `.o` suffix. This can greatly simplify *Makefiles*. For example:

```
% cc -n32 -O -IPA -c main.c
% cc -n32 -O -IPA -c foo.c
% ls
foo.c  foo.o  main.c  main.o
% cc -n32 -IPA main.o foo.o
```

An analogous 32-bit compilation would look like:

```
% cc -32 -O3 -j main.c
% cc -32 -O3 -j foo.c
% ls
foo.c  foo.u  main.c  main.u
% cc -32 -O3 main.u foo.u
```

Note: Use of the non-standard `-j` option and non-standard `.u` (*u*code) files leads to more complicated *Makefiles*.

Loop Nest Optimizer (LNO)

The loop nest optimizer performs high-level optimizations that can greatly improve program performance by exploiting instruction level parallelism and caches. LNO is run by default at the `-O3` optimization level. LNO is integrated into the compiler back end (*be*) and is not a source to source preprocessor. As a result, LNO will optimize C++, C and Fortran programs, although C and C++ often include features that make them inherently more difficult to optimize. For more information about LNO and its optimization options, refer to the *MIPSpro Compiling, Debugging and Performance Tuning Guide*.

In order to view the transformations that LNO performs, you can use the **-CLIST:=ON** or **-FLIST:=ON** options to generate C or Fortran listing files respectively. The listing files are generated with the *.w2.f* (or *.w2.c*) suffix. For example:

```
%cat bar.f
subroutine bar(a,b,c,d,j)
real*4 a(1024),b(1024),c(1024)
real*4 d,e,f

sum = 0
do m= 1,j
do i=1,1024
b(i) = b(i) * d
enddo
enddo

call foo(a,b,c)
end

%f77 -64 -O3 -FLIST:=ON foo.f
%cat foo.w2.f
C *****
C Fortran file translated from WHIRL Fri May 17 12:07:56 1997
C *****

        SUBROUTINE bar(a, b, c, d, j)
        IMPLICIT NONE
        REAL*4 a(1024_8)
        REAL*4 b(1024_8)
        REAL*4 c(1024_8)
        REAL*4 d
        INTEGER*4 j
C
C**** Variables and functions ****
C
        INTEGER*4 m
        INTEGER*4 i
        EXTERNAL foo
C
C**** Temporary variables ****
C
        INTEGER*4 wd_m
        INTEGER*4 i0
C
```



```
C**** statements ****
C
      DO m = 1, j + -1, 2
        DO i = 1, 1024, 1
          b(i) = (b(i) * d)
          b(i) = (b(i) * d)
        END DO
      END DO
      DO wd_m = m, j, 1
        DO i0 = 1, 1024, 1
          b(i0) = (b(i0) * d)
        END DO
      END DO
      CALL foo(a, b, c)
      RETURN
      END ! bar
```

MIPSpro Auto Parallelizing Option

The MIPSpro Auto Parallelizing Option analyzes data dependence to guide automatic parallelization. For the 7.2 compiler release this functionality is implemented in the 64-bit and N32 compiler back end (*be*). It replaces KAP (Kuck and Associates Preprocessor) which was implemented as a separate preprocessor. An advantage to being built into the backend is that automatic parallelization is now available for C++ as well the previously supported C, Fortran 77 and Fortran 90. Another advantage to this design, is that a separate (and orthogonal) set of optimization options is no longer necessary.

Compiling with Automatic Parallelization

To compile with automatic parallelization you must obtain the *MIPSpro Auto Parallelizing Option* and install its license. The syntax for compiling programs with automatic parallelization is as follows:

For Fortran 77 and Fortran 90 compilations use **-pfa** on your compilation command line. For C and C++ use **-pca**. For example:

```
%f77 -pfa foo.f
```

If you link separately, you must also add **-mp** to the link line.

Automatic Parallelization Listings

The auto-parallelizer provides a listing mechanism via the **-pfa list** or **-pca list** option. This will cause the compiler to generate a *.l* file. The *.l* file will list the original loops in the program along with messages telling whether or not the loops were parallelized. For loops that were not parallelized, an explanation will be given. For example:

```
%cat test.f

      program test
      real*8 a, x(100000),y(100000)
      do i = 1,2000
         y(i) = y(i-1) + x(i)
      enddo
      do i = 1,2000
         call daxpy(3.7,x,y,100000)
      enddo
      stop
      end

      subroutine daxpy( a, x, y, nn)
      real*8 a, x(*), y(*)
      do i = 1, nn,1
         y(i) = y(i) + a*x(i)
      end do
      return
      end

%f77 -64 -mp list test.f

%cat test.l

Parallelization Log for Subprogram MAIN__
  3: Not Parallel
      Array dependence from y on line 4 to y on line 4.
  6: Not Parallel
      Call daxpy on line 7.
Parallelization Log for Subprogram daxpy_
 14: PARALLEL (Auto) __mpdo_daxpy_1
```

The **-mplist** option will, in addition to compiling your program, generate a *.w2f.f* file (for Fortran 77, *.w2c.c* file for C) that represents the program after the automatic parallelization phase. These programs should be readable and in most cases should be valid code suitable for recompilation. The **-mplist** option can be used to see what portions of your code were parallelized. Continuing our example from above:

```
%f77 -64 -pfa -mplist test.f
%cat test.w2f.f
C *****
C Fortran file translated from WHIRL Sat Jul 26 12:05:52 1997
C *****

        PROGRAM MAIN
        IMPLICIT NONE

C
C      **** Variables and functions ****
C
        REAL*8 x(100000_8)
        REAL*8 y(100000_8)
        INTEGER*4 i

C
C      **** statements ****
C
        DO i = 1, 2000, 1
            y(i) = (x(i) + y(i + -1))
        END DO
        DO i = 1, 2000, 1
            CALL daxpy(3.7000000477, x, y, 100000)
        END DO
        STOP
        END ! MAIN

        SUBROUTINE daxpy(a, x, y, nn)
        IMPLICIT NONE
        REAL*8 a
        REAL*8 x(*)
        REAL*8 y(*)
        INTEGER*4 nn

C
C      **** Variables and functions ****
C
        INTEGER*4 i
        INTEGER*4 __mp_sug_numthreads_func$
        EXTERNAL __mp_sug_numthreads_func$

C
C      **** statements ****
C
        DOACROSS will be converted to SUBROUTINE __mpdo_daxpy_1
```

```
C$DOACROSS if(((DBLE(__mp_sug_numthreads_func$() + -1)) * (DBLE(nn) *
C$& 9.0D00)) .GT. (DBLE(__mp_sug_numthreads_func$()) * ((DBLE(
C$& __mp_sug_numthreads_func$()) * 1.23D+02) + 2.6D+03))))), local(i),
C$& shared(y, x, a, nn)
    DO i = 1, nn, 1
        y(i) = (y(i) +(x(i) * a))
    END DO
RETURN
END ! daxpy
```

The **-pfa keep** option generates a *.I* file, a *.anl* file that used by the *Workshop ProMPF* tool, and a *.m* file. The *.m* file is similar to the *.w2f.for* or *.w2c.c* file except that the file is annotated with some information used by *Workshop ProMPF*.

For Fortran 90 and C++, automatic parallelization happens after the source program has been converted into an internal representation. It is not possible to regenerate Fortran 90 or C++ after parallelization.

Multiprocessing Support

IRIX 6.x and the MIPSpro compilers support multiprocessing primitives for 32-bit, N32 and 64-bit applications. The 64-bit (and N32) multiprocessor programming environment is a superset of the 32-bit one. It also contains enhancements.

MP Compatibility

This section describes 64-bit and 32-bit Fortran MP compiler compatibility:

- The 64-bit Fortran compiler supports all of the parallelization directives (such as *C\$DOACROSS*, *C\$&*, *C\$MP_SCHEDTYPE*, *C\$CHUNK*, *C\$COPYIN*) supported by the 32-bit Fortran compiler.
In addition, *mfe77* supports PCF style parallel directives, which are documented in the *MIPSpro Fortran 77 Programmer's Guide*.
- The 64-bit Fortran compiler supports the same set of multiprocessing utility subroutine calls (such as **mp_block** and **mp_unblock**) as the 32-bit compiler.

The 64-bit Fortran compiler supports the same set of environment variables (such as *MP_SET_NUMTHREADS* and *MP_BLOCKTIME*) as the 32-bit compiler.

- The **-mp** and **-pfa** switches are supported on both the 32-bit compilers and the 64-bit compilers.
 - **-mp** allows LNO to recognize hand-inserted parallelization directives in the 64-bit compiler.
 - **-pfa** enables automatic parallelization by the MIPSpro Auto Parallelizing Option (64-bit and N32).

MP Enhancements

The MIPSpro 64-bit Fortran MP I/O library has been enhanced to allow I/O from parallel regions. In other words, multiple threads can read and write to different files as well as read and write to the same file. The latter case, of course, encounters normal overhead due to file locking. The MIPSpro 64-bit compilers also have been enhanced to allow parallel C and parallel Fortran programs to share a common runtime. This allows you to link parallel C routines with parallel Fortran routines and have a single master. Figure 1-2 illustrates this.

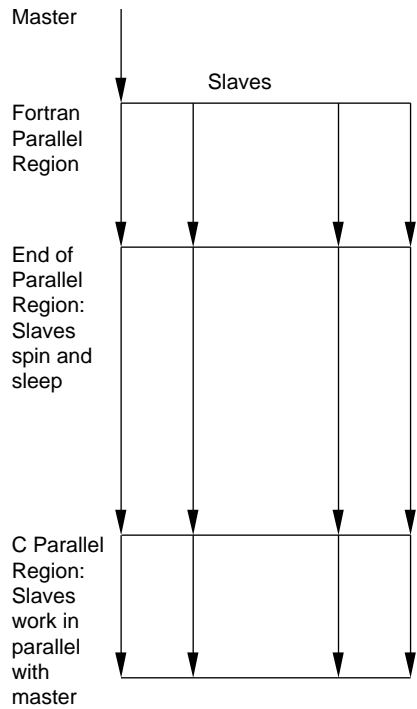


Figure 1-2 Running Parallel C and Parallel Fortran Programs Together

The MIPSpro 64-bit compilers also have been enhanced to provide a variety of primitive synchronization operations. The operations are guaranteed to be atomic (typically achieved by implementing the operation using a sequence of load-linked/store-conditional instructions in a loop). Associated with each operation are certain memory barrier properties that restrict the movement of memory references to *visible* data across the intrinsic operation (by either the compiler or the processor). For more information, please consult Chapter 5 of the *MIPSpro Fortran77 Programmer's Guide* and the sync(3f) and sync(3c) man pages.

New Directives for Tuning on Origin2000

The Origin2000 provides cache-coherent, shared memory in the hardware. Memory is physically distributed across processors. Consequently, references to locations in the remote memory of another processor take substantially longer (by a factor of two or

more) to complete than references to locations in local memory. This can severely affect the performance of programs that suffer from a large number of cache misses.

The new programming support consists of extensions to the existing multiprocessing Fortran and C directives (pragmas) as well as support for C++. Also provided are intrinsic functions that can be used to manage and query the distribution of shared memory. For more information, please consult Chapter 6 of the *MIPSpro Fortran77 Programmer's Guide*, and *MIPSpro C and C++ Pragmas*.

MP Application Testing

In general, to test 64-bit MP applications, follow these guidelines:

- First, get the application to run with no parallelization at the highest optimization level.
- When testing the parallel version, first run it with only one thread (either on a single CPU machine or by setting the environment variable `MP_SET_NUMTHREADS` to 1).
- Go down to the `-g` optimization level for the first MP test, and run that version with one thread, then with multiple threads. Then go up the optimization scale, testing both single and multi-threaded versions.

You can, of course, skip as many steps as you like. In case of failure, however, this method of incremental iterations can help you narrow down and identify the problem.

Language Implementation Differences

This chapter describes where the 32-bit and 64-bit compilers differ with respect to calling conventions and language implementations. The first section describes the 64-bit subprogram interface. The next two sections identify differences in the 32-bit and 64-bit implementations of the Fortran 77 and C programming languages, respectively.

Native 64-Bit Subprogram Interface for MIPS Architectures

This section describes the internal subprogram interface for native 64-bit programs. It assumes some familiarity with the current 32-bit interface conventions as specified in the MIPS application binary interface (ABI). The transition to native 64-bit code on the MIPS R8000 requires subprogram interface changes due to the changes in register and address size.

The principal interface for 64-bit native code is similar to the 32-bit ABI standard, with all 32-bit objects replaced by 64-bit objects. In particular, this implies:

- All integer parameters are promoted (that is, sign- or zero-extended to 64-bit integers and passed in a single register). Normally, no code is required for the promotion.
- All pointers and addresses are 64-bit objects.
- Floating point parameters are passed as single- or double-precision according to the ANSI C rules.
- All stack parameter slots become 64-bit doublewords, even for parameters that are smaller (for example, floats and 32-bit integers).

In more detail, the 64-bit native calling sequence has the following characteristics. Square brackets are used to indicate different 32-bit ABI conventions.

- All stack regions are quadword-aligned. (The 32-bit ABI specifies only doubleword alignment.)

- Up to eight integer registers (**\$4 .. \$11**) may be used to pass integer arguments. [The 32-bit ABI uses only the four registers *\$4 .. \$7*.]
- Up to eight floating point registers (*\$f12 .. \$f19*) may be used to pass floating point arguments. [The 32-bit ABI uses only the four registers *\$f12 .. \$f15*, with the odd registers used only for halves of double-precision arguments.]
- The argument registers may be viewed as an image of the initial eight doublewords of a structure containing all of the arguments, where each of the argument fields is a multiple of 64 bits in size with doubleword alignment. The integer and floating point registers are distinct images, that is, the first doubleword is passed in either *\$4* or *\$f1*, depending on its type; the second in either *\$5* or *\$f1*; and so on. [The 32-bit ABI associates each floating point argument with an even/odd pair of integer or floating point argument registers.]
- Within each of the 64-bit save area slots, smaller scalar parameters are right-justified, that is, they are placed at the highest possible address (for big-endian targets). This is relevant to float parameters and to integer parameters of 32 or fewer bits. Of these, only **int** parameters arise in C except for prototyped cases – **floats** are promoted to **doubles**, and smaller integers are promoted to **int**. [This is true for the 32-bit ABI, but is relevant only to prototyped small integers since all the other types were at least register-sized.]
- 32-bit integer (*int*) parameters are always sign-extended when passed in registers, whether of signed or unsigned type. [This issue does not arise in the 32-bit ABI.]
- Quad-precision floating point parameters (C **long double** or Fortran **REAL*16**) are always 16-byte aligned. This requires that they be passed in even-odd floating point register pairs, even if doing so requires skipping a register parameter and/or a 64-bit save area slot. [The 32-bit ABI does not consider long double parameters, since they were not supported.]
- **Structs**, **unions**, or other composite types are treated as a sequence of doublewords, and are passed in integer or floating point registers as though they were simple scalar parameters to the extent that they fit, with any excess on the stack packed according to the normal memory layout of the object. More specifically:
 - Regardless of the **struct** field structure, it is treated as a sequence of 64-bit chunks. If a chunk consists solely of a double float field (but not a **double**, which is part of a **union**), it is passed in a floating point register. Any other chunk is passed in an integer register.

- A **union**, either as the parameter itself or as a **struct** parameter field, is treated as a sequence of integer doublewords for purposes of assignment to integer parameter registers. No attempt is made to identify floating point components for passing in floating point registers.
- Array fields of **structs** are passed like **unions**. Array parameters are passed by reference (unless the relevant language standard requires otherwise).
- Right-justifying small scalar parameters in their save area slots notwithstanding, all **struct** parameters are always left-justified. This applies both to the case of a **struct** smaller than 64 bits, and to the final chunk of a **struct** which is not an integral multiple of 64 bits in size. The implication of this rule is that the address of the first chunk's save area slot is the address of the **struct**, and the **struct** is laid out in the save area memory exactly as if it were allocated normally (once any part in registers has been stored to the save area). [These rules are analogous to the 32-bit ABI treatment – only the chunk size and the ability to pass double fields in floating point registers are different.]
- Whenever possible, floating point arguments are passed in floating point registers regardless of whether they are preceded by integer parameters. [The 32-bit ABI allows only leading floating point (FP) arguments to be passed in FP registers; those coming after integer registers must be moved to integer registers.]
- Variable argument routines require an exception to the previous rule. Any floating point parameters in the variable part of the argument list (leading or otherwise) are passed in integer registers. There are several important cases involved:
 - If a **varargs** prototype (or the actual definition of the callee) is available to the caller, it places floating point parameters directly in the integer register required, and there are no problems.
 - If no prototype is available to the caller for a direct call, the caller's parameter profile is provided in the object file (as are all global subprogram formal parameter profiles), and the linker (*ld/rld*) generates an error message if the linked entry point turns out to be a *varargs* routine.

Note: If you add `-TENV:varargs_prototypes=off` to the compilation command line, the floating point parameters appear in both floating point registers and integer registers. This decreases the performance of not only **varargs** routines with floating point parameters, but also of any unprototyped routines that pass floating point parameters. The program compiles and executes correctly; however, a warning message about unprototyped **varargs** routines still is present.

- If no prototype is available to the caller for an indirect call (that is, via a function pointer), the caller assumes that the callee is not a *varargs* routine and places floating point parameters in floating point registers (if the callee is *varargs*, it is not ANSI-conformant).
- The portion of the argument structure beyond the initial eight doublewords is passed in memory on the stack and pointed to by the stack pointer at the time of call. The caller does not reserve space for the register arguments; the callee is responsible for reserving it if required (either adjacent to any caller-saved stack arguments if required, or elsewhere as appropriate.) No requirement is placed on the callee either to allocate space and save the register parameters, or to save them in any particular place. [The 32-bit ABI requires the caller to reserve space for the register arguments as well.]
- Function results are returned in **\$2** (and **\$3** if needed), or **\$f0** (and **\$f2** if needed), as appropriate for the type. Composite results (**struct**, **union**, or **array**) are returned in **\$2/\$f0** and **\$3/\$f2** according to the following rules:
 - A **struct** with only one or two floating point fields is returned in **\$f0** (and **\$f2** if necessary). This is a generalization of the Fortran **COMPLEX** case.
 - Any other *struct* or *union* results of at most 128 bits are returned in **\$2** (first 64 bits) and **\$3** (remainder, if necessary).
 - Larger composite results are handled by converting the function to a procedure with an implicit first parameter, which is a pointer to an area reserved by the caller to receive the result. [The 32-bit ABI requires that all composite results be handled by conversion to implicit first parameters. The MIPS/SGI Fortran implementation has always made a specific exception to return *COMPLEX* results in the floating point registers.]
- There are eight callee-saved floating point registers, **\$f24..\$f31**. [The 32-bit ABI specifies the six even registers, or even/odd pairs, **\$f20..\$f31**.]
- Routines are not be restricted to a single exit block. [The 32-bit ABI makes this restriction, though it is not observed under all optimization options.]

There is no restriction on which register must be used to hold the return address in exit blocks. The **.mdebug** format was unable to cope with return addresses in different places, but the DWARF format can. [The 32-bit ABI specifies **\$3**, but the implementation supports **.mask** as an alternative.]

PIC (position-independent code, for DSO support) is generated from the compiler directly, rather than converting it later with a separate tool. This allows better compiler

control for instruction scheduling and other optimizations, and provides greater robustness.

In the 64-bit interface, **gp** becomes a callee-saved register. [The 32-bit ABI makes **gp** a caller-saved register.]

Table 2-1 specifies the use of registers in native 64-bit mode. Note that “caller-saved” means only that the caller may not assume that the value in the register is preserved across the call.

Table 2-1 Native 64-Bit Interface Register Conventions

| Register Name | Software Name | Use | Saver |
|---------------|---------------|-----------------------------------|--------------|
| \$0 | zero | Hardware zero | |
| \$1 or \$at | at | Assembler temporary | Caller-saved |
| \$2..\$3 | v0..v1 | Function results | Caller-saved |
| \$4..\$11 | a0..a7 | Subprogram arguments | Caller-saved |
| \$12..\$15 | t4..t7 | Temporaries | Caller-saved |
| \$16..\$23 | s0..s7 | Saved | Callee-saved |
| \$24 | t8 | Temporary | Caller-saved |
| \$25 | t9 | Temporary | Caller-saved |
| \$26..\$27 | kt0..kt1 | Reserved for kernel | |
| \$28 or \$gp | gp | Global pointer | Callee-saved |
| \$29 or \$sp | sp | Stack pointer | Callee-saved |
| \$30 | s8 | Frame pointer (if needed) | Callee-saved |
| \$31 | ra | Return address | Caller-saved |
| hi, lo | | Multiply/divide special registers | Caller-saved |
| \$f0, \$f2 | | Floating point function results | Caller-saved |

Table 2-1 (continued) Native 64-Bit Interface Register Conventions

| Register Name | Software Name | Use | Saver |
|---------------|---------------|----------------------------|--------------|
| \$f1, \$f3 | | Floating point temporaries | Caller-saved |
| \$f4..\$f11 | | Floating point temporaries | Caller-saved |
| \$f12..\$f19 | | Floating point arguments | Caller-saved |
| \$f20..\$f23 | | Floating point temporaries | Caller-saved |
| \$f24..\$f31 | | Floating point | Callee-saved |

Table 2-2 gives several examples of parameter passing. It illustrates that at most eight values can be passed through registers. In the table note that:

- **d1..d5** are double precision floating point arguments
- **s1..s4** are single precision floating point arguments
- **n1..n3** are integer arguments

Table 2-2 Native 64-Bit C Parameter Passing

| Argument List | Register and Stack Assignments |
|---------------|--------------------------------|
| d1,d2 | \$f12, \$f13 |
| s1,s2 | \$f12, \$f13 |
| s1,d1 | \$f12, \$f13 |
| d1,s1 | \$f12, \$f13 |
| n1,d1 | \$4,\$f13 |
| d1,n1,d1 | \$f12, \$5,\$f14 |
| n1,n2,d1 | \$4, \$5,\$f14 |
| d1,n1,n2 | \$f12, \$5,\$6 |
| s1,n1,n2 | \$f12, \$5,\$6 |

| Table 2-2 (continued) | |
|-----------------------------------|---|
| Native 64-Bit C Parameter Passing | |
| Argument List | Register and Stack Assignments |
| d1,s1,s2 | \$f12, \$f13, \$f14 |
| s1,s2,d1 | \$f12, \$f13, \$f14 |
| n1,n2,n3,n4 | \$4,\$5,\$6,\$7 |
| n1,n2,n3,d1 | \$4,\$5,\$6,\$f15 |
| n1,n2,n3,s1 | \$4,\$5,\$6, \$f15 |
| s1,s2,s3,s4 | \$f12, \$f13,\$f14,\$f15 |
| s1,n1,s2,n2 | \$f12, \$5,\$f14,\$7 |
| n1,s1,n2,s2 | \$4,\$f13,\$6,\$f15 |
| n1,s1,n2,n3 | \$4,\$f13,\$6,\$7 |
| d1,d2,d3,d4,d5 | \$f12, \$f13, \$f14, \$f15, \$f16 |
| d1,d2,d3,d4,d5,s1,s2,s3,s4 | \$f12, \$f13, \$f14, \$f15, \$f16, \$f17, \$f18,\$f19,stack |
| d1,d2,d3,s1,s2,s3,n1,n2,s4 | \$f12, \$f13, \$f14, \$f15, \$f16, \$f17, \$10,\$11, stack |

Fortran Implementation Differences

This section lists differences between the 32-bit and the 64-bit Fortran implementations. Command line argument compatibility is described in Chapter 4. The 32-bit Fortran front end is called *fcom* and the 64-bit front end is called *mfe77*.

New Fortran Features

mfe77 implements **REAL*16** and **COMPLEX*32** and all associated intrinsics as 16-byte floating point entities. *fcom* recognizes them, but converts them to **REAL*8** and **COMPLEX*16** respectively.

Incompatibilities and Differences

- *fcom* and *mef77* are incompatible in the way they fold **REAL*4** constants. *fcom* promotes them internally to **REAL*8**. *mef77* however, provides the **-r8const** flag to simulate the *fcom* behavior.
- *mef77* allows more constant expressions in parameter statements than *fcom*.
- *mef77* allows parameters (which are ignored with a warning message) to the program statement.
- *mef77* accepts PCF-style parallel directives in addition to the directives such as **C\$DOACROSS**, which *fcom* accepts. PCF-style directives are documented in the *MIPSpro Fortran 77 Programmer's Guide*.

C Implementation Differences

This section lists differences between the 32-bit and the 64-bit C implementations. Because both compilers adhere to the ANSI standard, and because C is a rigorously defined language designed to be portable, there are not many differences between the 32-bit and 64-bit compiler implementations. The only areas where differences can occur are in data types (by definition) and in areas where ANSI does not define the precise behavior of the language.

Table 2-3 summarizes the differences in data types under the 32-bit and 64-bit data type models.

Table 2-3 Differences in Data Type Sizes

| C type | 32-bit | 64-bit |
|---------------|---------------|---------------|
| char | 8 | 8 |
| short int | 16 | 16 |
| int | 32 | 32 |
| long int | 32 | 64 |
| long long int | 64 | 64 |
| pointer | 32 | 64 |
| float | 32 | 32 |

Table 2-3 (continued) Differences in Data Type Sizes

| C type | 32-bit | 64-bit |
|--------------------------|--------|--------|
| double | 64 | 64 |
| long double ^a | 64 | 128 |

a. On 32-bit compiles the *long double* data type generates a warning message indicating that the *long* qualifier is not supported.

Table 2-3 shows that **long ints**, **pointers** and **long doubles** are different under the two models.

Structure and Union Layout Examples

Simple examples illustrate the alignment and size issues of C structures and unions.

Example 1: Structure Smaller Than a Word

```
struct c {
    char c;
} c1;
```

Byte-aligned, `sizeof` struct is 1.

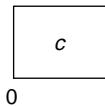


Figure 2-1 Structure Smaller Than a Word

Example 2: Structure With No Padding

```
struct s {
    char c;
    char d;
    short s;
    int i;
} s1;
```

Word-aligned, **sizeof** struct is 8.

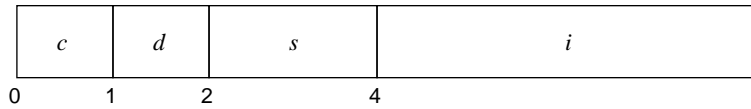


Figure 2-2 Structure With No Padding

Example 3: Structure With Internal Padding

```
struct t {  
    char c;  
    char d;  
    short s;  
    long l;  
} t1;
```

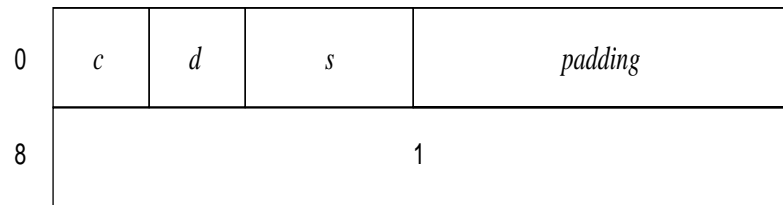


Figure 2-3 Structure With Internal Padding

Example 4: Structure With Internal and Tail Padding

```
struct l {  
    char c;  
    long l;  
    short s;  
} l1;
```

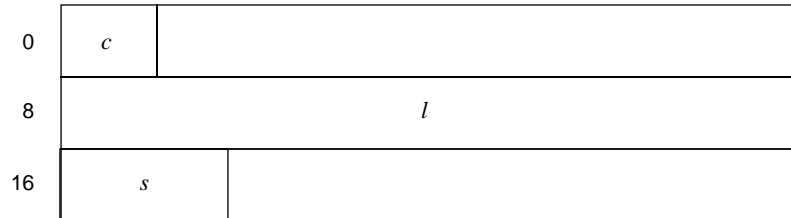


Figure 2-4 Structure With Internal and Tail Padding

Example 5: Union Allocation

```
union u {  
    char c;  
    short s;  
    int i;  
    long l;  
} ul;
```

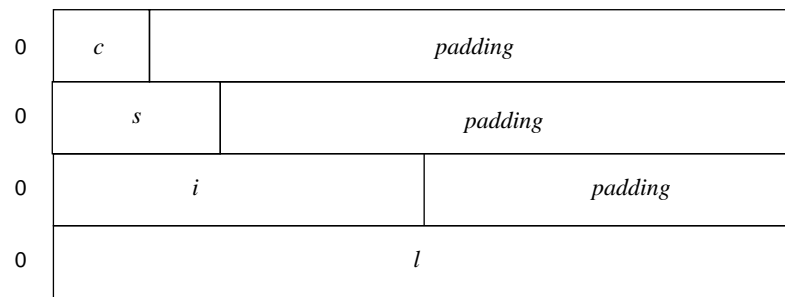


Figure 2-5 Union Allocation

Portability Issues

If code was originally written with portability in mind, the type size differences should not be difficult to reconcile. However, production code is often written without regard for portability. When porting code written without regard to portability the following areas should be handled carefully:

- Equivalence of **pointers** and **ints**
- Equivalence of **long ints** and **ints**
- Code without prototypes

These areas are covered in depth in Chapter 3, “Source Code Porting.”

Source Code Porting

This chapter describes changes you must make to your application source code to port it from a 32-bit to a 64-bit system. The first section outlines changes to Fortran code. The second and third sections deal with C source code issues. The fourth section provides guidelines on writing portable assembly language and C code (with respect to 32-bit and 64-bit systems).

64-Bit Fortran Porting Guidelines

This section describes which sections of your Fortran source code you need to modify to port to a 64-bit system.

Standard ANSI Fortran 77 code should have no problems, but the following areas need attention:

- Code that uses **REAL*16** could get different runtime results due to additional accuracy in the QUAD libraries.
- *fcom* and *fef77* are incompatible with regard to real constant folding.
- Integer variables which were used to hold addresses need to be changed to **INTEGER*8**.
- C interface issues (Fortran passes by reference).
- **%LOC** returns 64-bit addresses.
- **%VAL** passes 64-bit values.

Source code modifications are best done in phases. In the first phase, try to locate all of the variables affected by the size issues mentioned above. In the second phase, locate variables that depend on the variables changed in the first phase. Depending on your code, you may need to iterate on this phase as you track down long sets of dependencies.

Examples of Fortran Portability Issues

The following examples illustrate the variable size issues outlined above:

Example 1: Changing Integer Variables

Integer variables used to hold addresses must be changed to **INTEGER*8**.

32-bit code:

```
integer iptr, asize  
  
iptr = malloc(asize)
```

64-bit code:

```
integer asize  
integer*8 iptr  
  
iptr = malloc(asize)
```

Example 2: Enlarging Tables

Tables which hold integers used as pointers must be enlarged by a factor of two.

32-bit code:

```
integer tableptr, asize, numptrs  
numptrs = 100  
asize = 100 * 4  
  
tableptr = malloc(asize)
```

64-bit code:

```
integer asize, numptrs  
integer*8 tableptr  
  
numptrs = 100  
asize = 100 * 8  
  
tableptr = malloc(asize)
```

Example 3: Using #if Directives with Predefined Variables.

You should use *#if* directives so that your source code can be compiled either **-32** or **-64**. The compilers support predefined variables such as `_MIPS_SZPTR` or `_MIPS_SZLONG`, which can be used to differentiate 32-bit and 64-bit source code. A later section provides a more complete list of predefined compiler variables and their values for 32-bit and 64-bit operation. For example, the set of changes in the previous example could be coded:

```
integer asize, numptrs

#if (_MIPS_SZPTR==64)
    integer*8 tableptr
    asize = 100 * 8
#else
    integer*4 tableptr
    asize = 100 * 4
#endif

tableptr = malloc(asize)
```

Example 4: Storing %LOC Return Values

`%LOC` returns 64-bit addresses. You need to use an `INTEGER*8` variable to store the return value of a `%LOC` call.

```
#if (_MIPS_SZLONG==64)
    INTEGER*8 HADDRESS
#else
    INTEGER*4 HADDRESS
#endif
```

```
C determine memory location of dummy heap array
    HADDRESS = %LOC(HEAP)
```

Example 5: Modifying C Routines Called by Fortran

C routines which are called by Fortran where variables are passed by reference must be modified to hold 64-bit addresses. Typically, these routines used `ints` to contain the addresses in the past. For 64-bit use, at the very least, they should use **long ints**. There are no problems if the original C routines simply define the parameters as **pointers**.

Fortran:

```
call foo(i,j)
```

C:

```
foo_( int *i, int *j) or at least  
foo_( long i, long j)
```

Example 6: Declaring Fortran Arguments as *long ints*

Fortran arguments passed by %VAL calls to C routines should be declared as *long ints* in the C routines.

Fortran:

```
call foo(%VAL(i))
```

C:

```
foo_( long i )
```

Example 7: Changing Argument Declarations in Fortran Subprograms

Fortran subprograms called by C where *long int* arguments are passed by address need to change their argument declarations.

C:

```
long l1, l2;  
foo_(&l1, &l2);
```

Fortran:

```
subroutine foo(i, j)  
#if (_MIPS_SZLONG==64)  
    INTEGER*8 i,j  
#else  
    INTEGER*4 i,j  
#endif
```


64-Bit C Porting Guidelines

This section details the issues involved in porting 32-bit C application code to 64 bits. It addresses both the porting of existing code and guidelines for writing code to be ported at a later date.

Porting programs written in C to a Silicon Graphics 64-bit MIPS architecture platform, using the native 64-bit C compilers and related tools, should be straightforward. However, depending on assumptions made in writing the original C code, it may require some changes.

The C integer data types historically have been sized based on matching desired functionality with the target architecture's ability to efficiently implement integers of various sizes.

The SGI 64-bit platforms support the LP64 model for native 64-bit programs. In this model, **pointers** and **long** integers are 64 bits.

In the sections below, we discuss what problems to expect in porting existing C code to the LP64 native model, and suggest approaches for avoiding porting problems in new code.

Porting to the LP64 Model

For code which currently runs on SGI 32-bit platforms, porting to the LP64 model is straightforward. (It may also be unnecessary. Unless the program requires a 64-bit address space, 64-bit data, or other native-only functionality, it may still be run as a 32-bit program.)

Porting requires, at minimum, recompiling and relinking the program. You must specify a 64-bit target if you are doing this on a 32-bit workstation; on a 64-bit workstation this is the default (and you must request the 32-bit compatibility model if you want it). In some cases, the differences between the models imply changes in SGI-provided system header files and/or libraries; in such cases, your selection of the 32-bit or LP64 model selects the correct version automatically.

Within your code, most porting problems arise from assumptions, implicit or explicit, about either absolute or relative sizes of the **int**, **long int**, or **pointer** types. The most common are likely to be:

- **sizeof(void *) == 4**

This assumption is analogous to the previous one. But mappings to external data structures should seldom be a problem, since the external definition should also assume 64-bit pointers in the LP64 model.

- constants

The change in type sizes may yield some surprises related to constants. You should be especially careful about using constants with the high-order (sign) bit set. For instance, the hex constant `0xffffffff` yields different results in the expression:

```
long x;  
... ( (long) ( x + 0xffffffff ) ) ...
```

In both models, the constant is interpreted as a 32-bit *unsigned int*, with value 4,294,967,295. In the 32-bit model, the addition result is a 32-bit **unsigned long**, which is cast to **type long** and has value $x-1$ because of the truncation to 32 bits. In the LP64 model, the addition result is a 64-bit *long* with value $x+4,294,967,295$, and the cast is redundant.

- arithmetic assumptions

Related to some of the above cases, code which does arithmetic (including shifting) which may overflow 32 bits, and assumes particular treatment of the overflow (for example, truncation), may exhibit different behavior in the LP64 model, depending on the mix of types involved (including signedness).

Similarly, implicit casting in expressions which mix *int* and *long* values may behave unexpectedly due to sign/zero extension. In particular, remember that integer constants are sign or zero extended when they occur in expressions with *long* values.

Once identified, each of these problems is easy to solve. Change the relevant declaration to one which has the desired characteristics in both target environments, add explicit type casts to force the correct conversions, use function prototypes, or use type suffixes (for example, 'l' or 'u') on constants to force the correct type.

Writing Code Portable to 64-Bit Platforms

The key to writing new code which is compatible with the 32-bit and LP64 data models described is to avoid those problems described above. Since all of the assumptions described sometimes represent legitimate attributes of data objects, this requires some tailoring of declarations to the target machines' data models.

We suggest observing the following guidelines to produce code without the more common portability problems. They can be followed from the beginning in developing new code, or adopted incrementally as portability problems are identified.

In a header file which can be included in each of the program's source files, define (**typedef**) a type for each of the following functions:

- For each specific integer data size required, that is, where exactly the same number of bits is required on each target, define a *signed* and *unsigned* type, for example:

```
typedef signed char int8_t
typedef unsigned char uint8_t
...
typedef unsigned long long uint64_t
```
- If you require a large scaling integer type, that is, one which is as large as possible while remaining efficiently supported by the target, define another pair of types, for example:

```
typedef signed long intscaled_t
typedef unsigned long uintscaled_t
```
- If you require integer types of at least a particular size, but chosen for maximally efficient implementation on the target, define another set of types, similar to the first but defined as larger standard types where appropriate for efficiency.

Having constructed the above header file, use the new **typedef**ed types instead of the standard C type names. You need (potentially) a distinct copy of this header file (or conditional code) for each target platform supported. As a special case of this, if you are providing libraries or interfaces to be used by others, be particularly careful to use these types (or similar application specific types) chosen to match the specific requirements of the interface. Also in such cases, you should choose the actual names used to avoid name space conflicts with other libraries doing the same thing. If this is done carefully, your clients should be able to use a single set of header files on all targets. However, you generally need to provide distinct libraries (binaries) for the 32-bit compatibility model and the LP64 native model on 64-bit SGI platforms, though the sources may be identical.

Be careful that constants are specified with appropriate type specifiers so that they extend to the size required by the context with the values that you require. Bit masks can be particularly troublesome in this regard: avoid using constants for negative values. For example, `0xffffffff` may be equivalent to a -1 on 32-bit systems, but it is interpreted as 4,294,967,295 (*signed* or *unsigned*) on 64-bit systems. The *inttypes.h* header file provides *cpp* macros to facilitate this conversion.

Defining constants which are sensitive to type sizes in a central header file may help in modifying them when a new port is done. Where **printf()**/**scanf()** are used for objects whose types are **typedef**ed differently among the targets you must support, you may need to define constant format strings for each of the types defined in step (1), for example:

```
#define _fmt32 "%d"  
#define _fmt32u "%u"  
#define _fmt64 "%ld"  
#define _fmt64u "%lu"
```

The *inttypes.h* header file also defines **printf()**/**scanf()** format extensions to standardize these practices.

Fundamental Types for C

This section discusses 'fundamental types' useful in converting C code from 32-bit to 32- or 64-bit. These take the form of **typedefs**, and are available in the file *<sgidefs.h>*. These typedefs are enabled by compiler predefines, which are also described. This discussion is entirely from the C point of view, although the predefines discussed are also emitted by the other compilers.

It is desirable to have source code that can be compiled either in 32-bit mode or 64-bit mode. An example is *libc*, which we provide in both 32-bit and 64-bit form. (In this discussion, 32-bit code means **mips1** or **mips2**, 64-bit code means **mips3** or **mips4**.)

As previously mentioned, the compilation model chosen for 64-bit objects is referred to as LP64, where **longs** and **pointers** are 64 bits, and **ints** remain at 32 bits. Since **ints** and **pointers** are no longer the same size, and **ints** and **longs** are not the same size, a lot of code can break in this compilation model.

The **typedefs** discussed, in their naming convention, explicitly call out certain attributes of the **typedef**. The goal of this, by naming those attributes, is to ease the long term maintenance of code which has to compile in both the 32-bit and 64-bit models.

The **typedefs** are enabled by predefines from the compilers. The predefines that the compilers emit are:

For MIPS1executables:

```
-D_MIPS_FPSET=16
-D_MIPS_ISA=_MIPS_ISA_MIPS1
-D_MIPS_SIM=_MIPS_SIM_ABI32
-D_MIPS_SZINT=32
-D_MIPS_SZLONG=32
-D_MIPS_SZPTR=32
```

For MIPS3 executables:

```
-D_MIPS_FPSET=32
-D_MIPS_ISA=_MIPS_ISA_MIPS3
-D_MIPS_SIM=_MIPS_SIM_ABI64
-D_MIPS_SZINT=32
-D_MIPS_SZLONG=64
-D_MIPS_SZPTR=64
```

For MIPS4 executables:

```
-D_MIPS_FPSET=32
-D_MIPS_ISA=_MIPS_ISA_MIPS4
-D_MIPS_SIM=_MIPS_SIM_ABI64
-D_MIPS_SZINT=32
-D_MIPS_SZLONG=64
-D_MIPS_SZPTR=64
```

The explanation of these predefines is as follows:

- `MIPS_ISA` is Mips Instruction Set Architecture. `MIPS_ISA_MIPS1` and `MIPS_ISA_MIPS3` would be the most common variants for kernel level assembler code.
- `MIPS_ISA_MIPS4` is the ISA for R8000 applications. `MIPS_SIM` is Mips Subprogram Interface Model -- this describes the subroutine linkage convention and register naming/usage convention.
- `_MIPS_FPSET` describes the number of floating point registers. The MipsIII compilation model makes use of the extended floating point registers available on the R4000.
- `_MIPS_SZINT`, `_MIPS_SZLONG`, and `_MIPS_SZPTR` describe the size of each of those types.

An example of the use of these predefined variables:

```
#if (_MIPS_SZLONG == 32)
    typedef int    ssize_t;
```

```
#endif
#if (_MIPS_SZLONG == 64)
    typedef long    ssize_t;
#endif
```

The **typedefs** following are largely self-explanatory. These are from `<sgidefs.h>`:

```
__int32_t    Signed 32 bit integral type
__uint32_t   Unsigned 32 bit integral type
__int64_t    Signed 64 bit integral type
__uint64_t   Unsigned 64 bit integral type
```

These are “pointer-sized **int**” and “pointer-sized **unsigned int**” respectively. As such, they are guaranteed to have the same number of bits as a pointer.

```
__psint_t
__psunsigned_t
```

These are 'scaling **int**' and 'scaling **unsigned**' respectively, and are intended for variables that you want to grow as the code is compiled in the 64-bit model.

```
__scint_t
__scunsigned_t
```

The usefulness of these types is that they free the coder from having to know the underlying compilation model -- indeed, that model can change, and the code should still work. In this respect, use of these **typedefs** is better than replacing the assumption, that an **int** and a **pointer** are the same size with the new assumption, that a **long** and a **pointer** are the same size.'

Assembly Language Coding Guidelines

This section describes techniques for writing assembler code which can be compiled and run as either a 32-bit or 64-bit executable. These techniques are based on using certain predefined variables of the compiler, and on macros defined in `sys/asm.h` and `sys/regdef.h` which rely on those compiler predefines. Together, they enable a fairly easy conversion of existing assembly code to run in either the 32-bit or LP64 compilation model. They also allow retargeted assembler code to look fairly uniform in the way it is converted.

Overview and Predefined Variables

There are two sets of issues: the LP64 model, and the new calling conventions. Each of these issues is solved by a combination of predefined variables that the compiler emits, and macros in `<sys/asm.h>` and `<sys/regdef.h>`, that use those predefined variables to define macros appropriately.

The predefines that the assembler emits are:

For MIPS1/2 executables:

```
-D_MIPS_FPSET=16
-D_MIPS_ISA=_MIPS_ISA_MIPS1
-D_MIPS_SIM=_MIPS_SIM_ABI32
-D_MIPS_SZINT=32
-D_MIPS_SZLONG=32
-D_MIPS_SZPTR=32
```

For MIPS3 executables:

```
-D_MIPS_FPSET=32
-D_MIPS_ISA=_MIPS_ISA_MIPS3
-D_MIPS_SIM=_MIPS_SIM_ABI64
-D_MIPS_SZINT=32
-D_MIPS_SZLONG=64
-D_MIPS_SZPTR=64
```

For MIPS4 executables:

```
-D_MIPS_FPSET=32
-D_MIPS_ISA=_MIPS_ISA_MIPS4
-D_MIPS_SIM=_MIPS_SIM_ABI64
-D_MIPS_SZINT=32
-D_MIPS_SZLONG=64
-D_MIPS_SZPTR=64
```

The explanation of these predefined variables is as follows:

- *MIPS_ISA* is MIPS Instruction Set Architecture. *MIPS_ISA_MIPS1* and *MIPS_ISA_MIPS3* would be the most common variants for kernel-level assembler code.
- *MIPS_ISA_MIPS4* is the ISA for R8000 applications. *MIPS_SIM* is MIPS Subprogram Interface Model – this describes the subroutine linkage convention and register naming/usage convention.

- `_MIPS_FPSET` describes the number of floating point registers. The MipsIII compilation model makes use of the extended floating point registers available on the R4000.
- `_MIPS_SZINT`, `_MIPS_SZLONG`, and `_MIPS_SZPTR` describe the size of each of those types.

An example of the use of these macros:

```
#if (_MIPS_ISA == _MIPS_ISA_MIPS1 || _MIPS_ISA == _MIPS_ISA_MIPS2)
#define SZREG          4
#endif

#if (_MIPS_ISA == _MIPS_ISA_MIPS3 || _MIPS_ISA == _MIPS_ISA_MIPS4)
#define SZREG          8
#endif
```

LP64 Model Implications for Assembly Language Code

Four implications to writing assembly language code for LP64 are:

- The first deals with different register sizes as explained in “Different Register Sizes.”
- The second requires you to use a different subroutine linkage convention as explained in “Using a Different Subrouting Linkage.”
- The third requires you to use a different convention to save the global pointer register (`$gp`) as explained in “Caller `$gp` (o32) vs. Callee Saved `$gp` (LP64).”
- The fourth restricts your use of `lwc1` instructions to access floating point register pairs but allows you to use more floating point registers as described in “Using More Floating Point Registers.”

Different Register Sizes

The MIPSpro 64-bit C compiler generates code in the LP64 model -- that is, **pointers** and **longs** are 64 bits, **ints** are 32 bits. This means that all assembler code which deals with either **pointers** or **longs** needs to be converted to using doubleword instructions for MipsIII/IV code, and must continue to use word instructions for MipsI/II code.

Macros in `<sys/asm.h>`, coupled with the compiler predefines, provide a solution to this problem. These macros look like `PTR_<op>` or `LONG_<op>`, where `op` is some operation such as `L` for load, or `ADD`, etc.. These `ops` use standard defines such as `_MIPS_SZPTR` to

resolve to doubleword opcodes for MIPS3, and word opcodes for MIPS1. There are specific macros for PTR ops, for LONG ops, and for INT ops.

Using a Different Subrouting Linkage

The second implication of LP64 is that there is a different subroutine linkage convention, and a different register naming convention. The compiler predefine `_MIPS_SIM` enables macros in `<sys/asm.h>` and `<sys/regdef.h>`. Some important ramifications of that linkage convention are described below.

In the `_MIPS_SIM_ABI64` model there are 8 argument registers – `$4 .. $11`. These additional 4 argument registers come at the expense of the temp registers in `<sys/regdef.h>`. In this model, there are no registers `t4 .. t7`, so any code using these registers does not compile under this model. Similarly, the register names `a4 .. a7` are not available under the `_MIPS_SIM_ABI32` model. (It should be pointed out that those temporary registers are not lost -- the argument registers can serve as scratch registers also, with certain constraints.)

To make it easier to convert assembler code, the new names `ta0`, `ta1`, `ta2`, and `ta3` are available under both `_MIPS_SIM` models. These alias with `t4 .. t7` in the 32-bit world, and with `a4 .. a7` in the 64-bit world.

Another facet of the linkage convention is that the caller no longer has to reserve space for a called function to store its arguments in. The called routine allocates space for storing its arguments on its own stack, if desired. The `NARGSAVE` define in `<sys/asm.h>` helps with this.

Caller `$gp` (o32) vs. Callee Saved `$gp` (LP64)

The `$gp` register is used to point to the Global Offset Table (GOT). The GOT stores addresses of subroutines and static data for runtime linking. Since each DSO has its own GOT, the `$gp` register must be saved across function calls. Two conventions are used to save the `$gp` register.

Under the first convention, called caller saved `$gp`, each time a function call is made, the calling routine saves the `$gp` and then restores it after the called function returns. To facilitate this two assembly language pseudo instructions are used. The first, `.cpload`, is used at the beginning of a function and sets up the `$gp` with the correct value. The second, `.cprestore`, saves the value of `$gp` on the stack at an offset specified by the user. It also causes the assembler to emit code to restore `$gp` after each call to a subroutine.

The formats for correct usage of the `.cpload` and `.cprestore` instructions are shown below:

```
.cpload reg      reg is t9 by convention
.cprestore offset offset refers to the stack offset where $gp is saved
```

Under the second convention, called callee saved `$gp`, the responsibility for saving the `$gp` register is placed on the called function. As a result, the called function needs to save the `$gp` register when it first starts executing. It must also restore it, just before it returns. To accomplish this the `.cpsetup` pseudo assembly language instruction is used. Its usage is shown below:

```
.cpsetup reg, offset, proc_name
                reg is t9 by convention
                offset refers to the stack offset where $gp is saved
                proc_name refers to the name of the subroutine
```

You must create a stack frame by subtracting the appropriate value from the `$sp` register before using the directives which save the `$gp` on the stack.

In order to facilitate writing assembly language code for both conventions several macros have been defined in `<sys/asm.h>`. The macros `SETUP_GP`, `SETUP_GPX`, `SETUP_GP_L`, and `SAVE_GP` are defined under `o32` and provide the necessary functionality to support a caller saved `$gp` environment. Under `LP64`, these macros are null. However, `SETUP_GP64`, `SETUP_GPX64`, `SETUP_GPX64_L`, and `RESTORE_GP64` provide the functionality to support a callee saved environment. These same macros are null for `o32`.

In conclusion, predefines from the compiler enable a body of macros to generate 32/64-bit asm code. Those macros are defined in `<sys/asm.h>`, `<sys/regdef.h>`, and `<sys/fpregdef.h>`

The following example handles assembly language coding issues for `LP64` and `KPIC` (`KPIC` requires that the `asm` coder deals with `PIC` issues). It creates a template for the start and end of a generic assembly language routine.

The template is followed by relevant defines and macros from `<sys/asm.h>`.

```
LOCALSZ=      4                # save a0, a1, ra, gp
FRAMESZ=      ((NARGSAVE+LOCALSZ)*SZREG)+ALSZ)&ALMASK
RAOFF=        FRAMESZ-(1*SZREG)
A0OFF=        FRAMESZ-(2*SZREG)
A1OFF=        FRAMESZ-(3*SZREG)
GPOFF=        FRAMESZ-(4*SZREG)
```

```

NESTED(asmfunc, FRAMESZ, ra)
    move t0, gp    # save entering gp
                  # SIM_ABI64 has gp callee save
                  # no harm for SIM_ABI32
    SETUP_GPX(t8)
    PTR_SUBU sp, FRAMESZ
    SETUP_GP64(GPOFF, _sigsetjmp)
    SAVE_GP(GPOFF)
/* Save registers as needed here */
    REG_S ra, RAOFF(sp)
    REG_S a0, A0OFF(sp)
    REG_S a1, A1OFF(sp)
    REG_S t0, T0OFF(sp)

/* do real work here */
/* safe to call other functions */

/* restore saved registers as needed here */
    REG_L ra, RAOFF(sp)
    REG_L a0, A0OFF(sp)
    REG_L a1, A1OFF(sp)
    REG_L t0, T0OFF(sp)

/* setup return address, $gp and stack pointer */
REG_L    ra, RAOFF(sp)
RESTORE_GP64
PTR_ADDU sp, FRAMESZ

    bne    v0, zero, err
    j      ra

    END(asmfunc)

```

The *.cpload/.cprestore* is only used for generating KPIC code -- and tells the assembler to initialize, save, and restore the **gp**.

The following are relevant parts of *asm.h*:

```

#if (_MIPS_SIM == _MIPS_SIM_ABI32)
#define NARGSAVE    4
#define ALSZ        7
#define ALMASK      ~7
#endif

```

```
#if (_MIPS_SIM == _MIPS_SIM_ABI64)
#define NARGSAVE      0
#define ALSZ          15
#define ALMASK        ~0xf
#endif

#if (_MIPS_ISA == _MIPS_ISA_MIPS1 || _MIPS_ISA == _MIPS_ISA_MIPS2)
#define SZREG         4
#endif

#if (_MIPS_ISA == _MIPS_ISA_MIPS3 || _MIPS_ISA == _MIPS_ISA_MIPS4)
#define SZREG         8
#endif

#if (_MIPS_ISA == _MIPS_ISA_MIPS1 || _MIPS_ISA == _MIPS_ISA_MIPS2)
#define REG_L        lw
#define REG_S        sw
#endif

#if (_MIPS_ISA == _MIPS_ISA_MIPS3 || _MIPS_ISA == _MIPS_ISA_MIPS4)
#define REG_L        ld
#define REG_S        sd
#endif

#if (_MIPS_SZINT == 32)
#define INT_L        lw
#define INT_S        sw
#define INT_LLEFT    lwl
#define INT_SLEFT    swl
#define INT_LRIGHT   lwr
#define INT_SRIGHT   swr
#define INT_ADD      add
#define INT_ADDI     addi
#define INT_ADDIU    addiu
#define INT_ADDU     addu
#define INT_SUB      sub
#define INT_SUBI     subi
#define INT_SUBIU    subiu
#define INT_SUBU     subu
#define INT_LL       ll
#define INT_SC       sc
#endif

#if (_MIPS_SZINT == 64)
#define INT_L        ld

```

```
#define INT_S    sd
#define INT_LLEFT    ld1
#define INT_SLEFT    sdl
#define INT_LRIGHT    ldr
#define INT_SRIGHT    sdr
#define INT_ADD    dadd
#define INT_ADDI    daddi
#define INT_ADDIU    daddiu
#define INT_ADDU    daddu
#define INT_SUB    dsub
#define INT_SUBI    dsubi
#define INT_SUBIU    dsubiu
#define INT_SUBU    dsubu
#define INT_LL    lld
#define INT_SC    scd
#endif

#if (_MIPS_SZLONG == 32)
#define LONG_L    lw
#define LONG_S    sw
#define LONG_LLEFT    lwl
#define LONG_SLEFT    swl
#define LONG_LRIGHT    lwr
#define LONG_SRIGHT    swr
#define LONG_ADD    add
#define LONG_ADDI    addi
#define LONG_ADDIU    addiu
#define LONG_ADDU    addu
#define LONG_SUB    sub
#define LONG_SUBI    subi
#define LONG_SUBIU    subiu
#define LONG_SUBU    subu
#define LONG_LL    ll
#define LONG_SC    sc
#endif

#if (_MIPS_SZLONG == 64)
#define LONG_L    ld
#define LONG_S    sd
#define LONG_LLEFT    ld1
#define LONG_SLEFT    sdl
#define LONG_LRIGHT    ldr
#define LONG_SRIGHT    sdr
#define LONG_ADD    dadd
#define LONG_ADDI    daddi
```

```
#define LONG_ADDIU      daddiu
#define LONG_ADDU      daddu
#define LONG_SUB       dsub
#define LONG_SUBI      dsubi
#define LONG_SUBIU     dsubiu
#define LONG_SUBU     dsubu
#define LONG_LL        lld
#define LONG_SC        scd
#endif

#if (_MIPS_SZPTR == 32)
#define PTR_L      lw
#define PTR_S      sw
#define PTR_LLEFT  lwl
#define PTR_SLEFT  swl
#define PTR_LRIGHT lwr
#define PTR_SRIGHT swr
#define PTR_ADD    add
#define PTR_ADDI   addi
#define PTR_ADDIU  daddiu
#define PTR_ADDU   addu
#define PTR_SUB    sub
#define PTR_SUBI   subi
#define PTR_SUBIU  subiu
#define PTR_SUBU   subu
#define PTR_LL     ll
#define PTR_SC     sc
#endif

#if (_MIPS_SZPTR == 64)
#define PTR_L      ld
#define PTR_S      sd
#define PTR_LLEFT  ldl
#define PTR_SLEFT  sdl
#define PTR_LRIGHT ldr
#define PTR_SRIGHT sdr
#define PTR_ADD    dadd
#define PTR_ADDI   daddi
#define PTR_ADDIU  daddiu
#define PTR_ADDU   daddu
#define PTR_SUB    dsub
#define PTR_SUBI   dsubi
#define PTR_SUBIU  dsubiu
#define PTR_SUBU   dsubu
#define PTR_LL     lld
#define PTR_SC     scd
#endif
```

Using More Floating Point Registers

On the R4000 and later generation MIPS microprocessors, the FPU provides:

- 16 64-bit Floating Point registers (FPRs) each made up of a pair of 32-bit floating point general purpose register when the FR bit in the Status register equals 0, or
- 32 64-bit Floating Point registers (FPRs) each corresponding to a 64-bit floating point general purpose register when the FR bit in the Status register equals 1

For more information about the FPU of the R4000 refer to Chapter 6 of the *MIPS R4000 User's Manual*.

Under o32, the FR bit is set to 0. As a result, o32 provides only 16 registers for double precision calculations. Under o32, double precision instructions must refer to the even numbered floating point general purpose register. A major implication of this is that code written for the MIPS I instruction set treated a double precision floating point register as an odd and even pair of single precision floating point registers. It would typically use sequences of the following instructions to load and store double precision registers.

```
lwc1 $f4, 4(a0)
lwc1 $f5, 0(a0)
...
swc1 $f4, 4(t0)
swc1 $f5, 0(t0)
```

Under LP64, however, the FR bit is set to 1. As a result, LP64 provides all 32 floating point general purpose registers for double precision calculations. Since *\$f4* and *\$f5* refer to different double precision registers, the code sequence above will not work under LP64. It can be replaced with the following:

```
l.d $f14, 0(a0)
...
s.d $f14, 0(t0)
```

The assembler will automatically generate pairs of LWC1 instructions for MIPS I and use the LDC1 instruction for MIPS II and above.

On the other hand, you can use these additional odd numbered registers to improve performance of double precision code.

Compilation Issues

This chapter outlines the issues dealt with at compile and link times. It covers environment variable usage, compile-time switches, error messages and how to link correctly.

Environment Variables

The *SGI_ABI* environment variable can be used to specify whether you want an old 32-bit, high performance 32-bit (N32) or 64-bit compilation environment. It is overridden by using the *-32* (or *-o32*), *-64* or *-n32* option on the command line.

Because there are three distinct ABIs used by programs with accompanying libraries, there are three distinct sets of *rld* search paths and three sets of environment variables.

The default library search path for o32 (old 32-bit ABI) programs is *(/usr/lib:/usr/lib/internal:/lib)*, which can be overridden by either of the environment variables *_RLD_ROOT* or *LD_LIBRARY_PATH*.

The default library search path for 64 (64-bit ABI) programs is *(/usr/lib64:/usr/lib64/internal:/lib64)*, which can be overridden by either of the environment variables *_RLD64_ROOT* or *LD_LIBRARY64_PATH*.

The default library search path for n32 (new 32-bit ABI) programs is *(/usr/lib32:/usr/lib32/internal:/lib32)*, which can be overridden by either of the environment variables *_RLDN32_ROOT* or *LD_LIBRARYN32_PATH*.

For n32 or 64-bit programs, if *LD_LIBRARYN32_PATH* or *LD_LIBRARY64_PATH* is not specified, then *rld* will honor *LD_LIBRARY_PATH* if specified.

Command Line Switches

This section lists the differences between the supported switches of the 32-bit and 64-bit compilers.

If you use the **-32** switch on the compiler command line, the 32-bit (*ucode*) compiler is invoked. If you use **-64** or **-n32**, the 64-bit compiler is run.

The default switches on all R8000 based platforms are **-64 -mips4**. On all other platforms the default switches are **-32 -mips2** unless the */etc/compiler.defaults* file is present. If it is, its contents will specify what the default values are.

Although they are two separate and different compiler systems, the 32-bit and 64-bit compilers have similar command line interfaces. The following list summarizes the differences between the compilers in the switches that they support. A full list can be found in the *cc(1)* and *f77(1)* man pages:

Fortran Switch Differences

The 32-bit compiler supports the following switches which the 64-bit compiler does not:

| | |
|---------------------|--|
| -32, -o32 | By definition. |
| -mips1 | Generate code using the MIPS1 instruction set (the default for the 32-bit compiler). |
| -mips2 | Generate code using the MIPS2 instruction set. |
| -66 | Suppress extensions that enhance FORTRAN 66 compatibility. |
| -[no]kpicopt | Asks <i>uopt</i> to perform the special treatment for global variables to optimize their program accesses regardless of the shared or non-shared compilation mode. |
| -j | Compile the specified source program and leave the <i>ucode</i> object file in a <i>.u</i> file. |
| -w66 | Suppress only FORTRAN 66 compatibility warnings messages. |
| -usefpidx | Force the compiler to use the floating point DO loop variable as the loop counter. |
| -vms_cc | Use VMS Fortran carriage control interpretation on unit 6. |

- vms_endfile** Write a VMS endfile record to the output file when **ENDFILE** statement is executed and allow subsequent reading from an input file after an endfile record is encountered.
- vms_library** Treat subroutines/functions starting with **LIB\$, OTSS,** and **SMG\$** as VMS runtime library routines which take a variable number of arguments.
- vms_stdin** Allow rereading from *stdin* after **EOF** has been encountered.

The 64-bit compiler supports the following switches which the 32-bit compiler does not:

- 64** By definition.
- n32** Generate code for the high performance 32-bit (N32) ABI.
- mips3** Generate code using the MIPS3 instruction set.
- mips4** Generate code using the MIPS4 instruction set (the default for the 64-bit compiler on Power Challenge).

C Switch Differences

The 32-bit compiler supports the following switches which the 64-bit compiler does not:

- 32, -o32, -mips1, -mips2**
As in 32-bit Fortran above.
- [no]kpicopt** Asks *uopt* to perform the special treatment for global variables to optimize their program accesses regardless of the shared or non-shared compilation mode.
- j** As in 32-bit Fortran above.
- hpath** Use *path* rather than the directory where the name is normally found.
- Bstring** Append *string* to all names specified by the **-t** option.

The 64-bit compiler supports the following switches which the 32-bit compiler does not:

- 64, -n32, -mips3 -mips4**
As in 64-bit Fortran above.
- help** Print a list of possible options.
- keep** Keep intermediate files.

- show1** Show phases but don't have phases print additional info.
- showt** Show time taken by each phase.
- unsigned** Characters are unsigned by default.
- woffall** Turn off all warnings.

The following switches are accepted by both compilers but have different semantics:

- O3** On the 32-bit compiler, a *ucode* object file is created and left in a *.u* file. Inter-procedural optimization is done on the resulting *ucode* linked file and an *a.out* file is created. On the 64-bit compiler interprocedural optimization is carried out when the **-IPA** flag is present and can be done at optimization levels less than **-O3**.
- v** On the 32-bit compiler, it's the same as **-show**, whereas it means verbose warnings on the 64-bit compiler.
- woff** Turn off named warnings, but the warning numbers are different between the compilers.
- Wc,arg1,[,arg2...]** Designate to which pass, **c**, of the compiler the arguments are to be passed.

Optimization Switches of the 64-Bit Compilers

In addition to the switches listed above, both the 64-bit Fortran and 64-bit C compilers support many more switches. These switches are used to control the types of optimizations the compilers perform. This section outlines the various optimizations that the 64-bit compilers can perform, and lists the switches used to control them. To get a summary of the flags and their values set the **-LIST:all_options=ON** flags on the command line. For example:

```
%f77 -64 -O3 -mips4 -LIST:all_options=ON foo.f
```

This creates a *.l* file which contains a summary of all the flags used in the compilation including the default values of flags not explicitly set on the command line.

The optimizations and switches fall into the following categories:

- General Optimizations
- Floating Point Optimizations
- Processor Specific Tuning Options
- Inter-Procedural Analysis (IPA) Optimizations
- Loop Nest Optimization (LNO)
- Miscellaneous Optimizations
- Target Environment Issues

The list of options described below is not exhaustive. For a complete list, see the `cc(1)` and `f77(1)` man pages.

General Optimizations

-O0

Perform no optimization that may complicate debugging (this is the default). User data is kept in memory, and little or no attempt is made to eliminate redundant code.

-O1

Perform local optimizations which do not significantly affect compile-time performance. Most user data is still kept in memory, but much of the locally redundant code is removed.

-O2

-O

Perform extensive global optimization. The optimizations at this level are generally conservative in the sense that they:

- Provide code improvements commensurate with the compile time spent
- Are almost always beneficial
- Avoid changes which affect such things as floating point results.

-O3

Perform aggressive optimization. The additional optimization at this level is distinguished by a focus on maximizing code quality even if that requires extensive compile-time or relaxing language rules. It is more likely to use transformations that are usually beneficial but can hurt performance in isolated cases. This level may cause noticeable changes in floating point results due to relaxing expression evaluation rules. See the discussion of the **-OPT:roundoff** option below.

-Ofast[=ipxx]

Use optimizations selected to maximize performance for the given SGI target platform (IPxx). The selected optimizations may differ between releases of the compiler, and among the supported platforms. They will always enable the full instruction set of the target platform (e.g. **-mips4** for an R10000). Although the optimizations are generally safe, they may affect floating point accuracy due to rearrangement of computations. Typical optimizations selected include **-O3**, **-IPA**, **-TARG:platform=ipxx**, **-n32**, and **-OPT:Olimit=0:roundoff=3:div_split=ON:alias=typed**. See the description of **-TARG:platform=ipxx** in the `cc(1)` man pages for information about the optional argument. To determine precisely what options are set by **-Ofast**, use **-LIST:options=ON**. The default is an R10000 Power Challenge, IP25.

Floating Point Optimizations

Floating point numbers (Fortran's **REAL*n**, **DOUBLE PRECISION**, and **COMPLEX*n**, and C's **float**, **double**, and **long double**) are inexact representations of ideal real numbers. The operations performed on them are also necessarily inexact. However, the MIPS processors conform to the IEEE 754 floating point standard, producing results as precise as possible given the constraints of the IEEE 754 representations. The MIPSpro 64-bit compilers generally preserve this conformance. (Note, however, that 128-bit floating point, such as Fortran's **REAL*16** and C's **long double**, is not precisely IEEE-compliant.)

In addition, the source language standards imply rules about how expressions are to be evaluated. However, most code that has not been written with careful attention to floating point behavior does not require precise conformance to either the source language expression evaluation standards or to IEEE 754 arithmetic standards. Therefore, the MIPSpro 64-bit compilers provide a number of options which trade off source language expression evaluation rules and IEEE 754 conformance against better performance of generated code. These options allow transformations of calculations specified by the source code that may not produce precisely the same floating point result, although they involve a mathematically equivalent calculation.

Two of these options are the preferred controls. **-OPT:roundoff** deals with the extent to which language expression evaluation rules are observed, generally affecting the transformation of expressions involving multiple operations. **-OPT:IEEE_arithmetic** deals with the extent to which the generated code conforms to IEEE 754 standards for discrete IEEE-specified operations (for example, a divide or a square root). The remaining options in this class may be used to obtain finer control, but they may disappear or change in future compiler releases.

The first general option provides control over floating point accuracy and overflow/underflow exception behavior relative to the source language rules:

-OPT:roundoff=n

The roundoff option specifies the extent to which optimizations are allowed to affect floating point results, in terms of both accuracy and overflow/underflow behavior. The roundoff value, **n**, has a value in the range 0..3 with the following meaning:

- **roundoff=0**

Do no transformations which could affect floating point results. This is the default for optimization levels **-O0** to **-O2**.

- **roundoff=1**

Allow transformations with limited effects on floating point results. For roundoff, limited means that only the last bit or two of the mantissa are affected. For overflow (underflow), it means that intermediate results of the transformed calculation may overflow within a factor of two of where the original expression might have overflowed (underflowed). Note that limited effects may be less limited when compounded by multiple transformations.

- **roundoff=2**

Allow transformations with more extensive effects on floating point results. Allow associative rearrangement, even across loop iterations, and distribution of multiplication over addition/subtraction. Disallow only transformations known to cause cumulative roundoff errors or overflow/underflow for operands in a large range of valid floating point values.

Re-association can have a substantial effect on the performance of software pipelined loops by breaking recurrences. This is therefore the default for optimization level **-O3**.

- **roundoff=3**

Allow any mathematically valid transformation of floating point expressions. This allows floating point induction variables in loops, even when they are known to cause cumulative roundoff errors, and fast algorithms for complex absolute value and divide, which overflow (underflow) for operands beyond the square root of the representable extremes.

The second general option controls conformance to IEEE 754 arithmetic standards for discrete operators:

-OPT:IEEE_arithmetic=n

The **IEEE_arithmetic** option specifies the extent to which optimizations must preserve IEEE floating point arithmetic. The value *n* must be in the range 1..3, with the following meaning:

- **IEEE_arithmetic=1**

No degradation: do no transformations which degrade floating point accuracy from IEEE requirements. The generated code may use instructions like **madds** which provide greater accuracy than required by IEEE 754. This is the default.

- **IEEE_arithmetic=2**

Minor degradation: allow transformations with limited effects on floating point results, as long as exact results remain exact. This option allows use of the MIPS 4 **recip** and **rsqrt** operations.

- **IEEE_arithmetic=3**

Conformance not required: allow any mathematically valid transformations. For instance, this allows implementation of x/y as $x*\text{recip}(y)$. As an example, consider optimizing the Fortran code fragment:

```
INTEGER i, n
REAL sum, divisor, a(n)
sum = 0.0
DO i = 1,n
    sum = sum + a(i)/divisor
END DO
```

At **roundoff=0** and **IEEE_arithmetic=1**, the generated code must do the *n* loop iterations in order, with a **divide** and an **add** in each.

Using **IEEE_arithmetic=3**, the **divide** can be treated like $a(i)*(1.0/divisor)$. On the MIPS R8000, the reciprocal can be done with a **recip** instruction. But more importantly, the reciprocal can be calculated once before the loop is entered, reducing the loop body to a much faster multiply and add per iteration, which can be a single *madd* instruction on the R8000.

Using **roundoff=2**, the loop may be reordered. The original loop takes at least 4 cycles per iteration on the R8000 (the latency of the *add* or *madd* instruction). Reordering allows the calculation of several partial sums in parallel, adding them together after loop exit. With software pipelining, a throughput of nearly 2 iterations per cycle is possible on the R8000, a factor of 8 improvement.

Consider another example:

```
INTEGER i,n
COMPLEX c(n)
REAL r
DO i = 1,n
    r = 0.1 * i
    c(i) = CABS ( CMPLX(r,r) )
END DO
```

Mathematically, **r** can be calculated by initializing it to 0.0 before entering the loop and adding 0.1 on each iteration. But doing so causes significant cumulative errors because the representation of 0.1 is not exact. The complex absolute value mathematically is equal to $\text{SQRT}(r*r + r*r)$. However, calculating it this way causes an overflow if $2*r*r$ is greater than the maximum REAL value, even though a representable result can be calculated for a much wider range of values of **r** (at greater cost). Both of these transformations are forbidden for **roundoff=2**, but enabled for **roundoff=3**.

There are several other options which allow finer control of floating point behavior than is provided by **-OPT:roundoff**.

-OPT:div_split[=(ON|OFF)]

Enable/disable the calculation of x/y as $x*(1.0/y)$, normally enabled by **IEEE_arithmetic=2**. See **-OPT:recip**.

-OPT:fast_complex[=(ON|OFF)]

Enable/disable the fast algorithms for complex absolute value and division, normally enabled by **roundoff=3**.

-OPT:fast_exp[=(ON|OFF)]

Enable/disable the translation of exponentiation by integers or halves to sequences of multiplies and square roots. This can change **roundoff** and can make these functions produce minor discontinuities at the exponents where it applies. Normally enabled by **roundoff>0** for Fortran, or for C if the function **exp()** is labelled intrinsic in *<math.h>* (the default in **-xansi** and **-cckr** modes).

-OPT:fast_sqrt[=(ON|OFF)]

Enable/disable the calculation of square root as **x*rsqrt(x)** for MIPS4 and above. Note that this optimization produces a *NaN* instead of 0.0 for a 0 operand.

-OPT:fold_reassociate[=(ON|OFF)]

Enable/disable transformations which reassociate or distribute floating point expressions, normally enabled by **roundoff>1**.

-OPT:fold_unsafe_relops[=(ON|OFF)]

Enable/disable folding of relational operators in the presence of possible integer overflow.

-OPT:fold_unsigned_relops[=(ON|OFF)]

Enable/disable folding of unsigned relational operators in the presence of possible integer overflow.

-OPT:IEEE_comparisons[=ON]

Force comparisons to yield results conforming to the IEEE 754 standard for *NaN* and *Inf* operands, normally disabled. Setting this option disables certain optimizations like assuming that a comparison **x==x** is always TRUE (since it is FALSE if *x* is a *NaN*).

It also disables optimizations which reverse the sense of a comparison, for example, turning **x < y** into **!(x >= y)**, since both **x < y** and **x >= y** may be FALSE if one of the operands is a *NaN*.

-OPT:recip[=(ON|OFF)]

Allow use of the MIPS4 reciprocal instruction for $1.0/y$, normally enabled by **IEEE_arithmetic** ≥ 1 . See **-OPT:div_split**.

-OPT:rsqrt[=(ON|OFF)]

Allow use of the MIPS4 reciprocal square root instruction for $1.0/\sqrt{y}$, normally enabled by **IEEE_arithmetic** ≥ 1 .

-TARG:madd[=(ON|OFF)]

The MIPS 4 architecture supports fused multiply-add instructions, which add the product of two operands to a third, with a single roundoff step at the end. Because the product is not rounded separately, this can produce slightly different (but more accurate) results than a separate multiply and add pair of instructions. This is normally enabled for **-mips4**.

Processor Specific Tuning Options

These options instruct the compiler to schedule code for the given processor and to use processor specific math libraries (e.g. `/usr/lib64/mips4/r10000/libm.so`) when linking. The resulting code may be optimized for a particular platform, but may not be optimal for use across all platforms.

-r8000 | -r10000 | -r5000

These options schedule code (including software pipelining at **-O3**) for an R8000, R10000 or R5000 respectively and use the corresponding math library for linking if necessary.

Inter-procedural Analysis (IPA) Optimizations

The stand-alone inliner option group control the application of subroutine inlining done within a file by the stand-alone inliner, or by the main inliner, if **-IPA** options are enabled. Normally, the calls to be replaced by an inlined copy of the called subprogram are chosen by heuristics internal to the inliner. For more information about IPA, please consult Chapter 4 of the *MIPSpro Compiling, Debugging and Performance Tuning Guide*.

Most of the options in this group provide control over those choices. The individual controls in this group are:

-INLINE:[=(ON|OFF)]

Enable/disable inlining (e.g. **-INLINE:=OFF** disables inlining). Forcibly turn on or off stand-alone inline processing; ignored with a warning for compiles which invoke main IPA processing. When both are seen in the command line (for a compile which will not invoke main IPA processing), **-INLINE:=OFF** is processed and **-INLINE=ON** is overridden with a warning. If used within a *specfile* read by the stand-alone inliner, **-INLINE=OFF** will skip inline processing within the stand-alone inliner and **-INLINE=ON** is ignored with a warning.

-INLINE:all

Change the default inlining heuristic. Attempt to inline all routines which are not excluded by a **-INLINE:never** option or a pragma suppressing inlining, either for the routine or for a specific call site. This option conflicts with **-INLINE:none**; the earlier option takes precedence if both are specified.

-INLINE:alloca[=(ON|OFF)]

Enable saving and restoring of the stack when inlining calls with *alloca* (default ON).

-INLINE:dfe[=(ON|OFF)]

Enable or disable dead function elimination. The goal is to remove subprograms which are never called from the program (default ON for C++, otherwise OFF).

-INLINE:file=filename

Search for routines specified with **-INLINE:must** in *filename* to perform cross file inlining. *Filename* must be generated using **-IPA -c**.

-INLINE:keep_pu_order[=(ON|OFF)]

Preserve source subprogram ordering (default OFF).

-INLINE:library=filename

Search for routines specified with **-INLINE:must** in *filename* to perform cross file inlining. *Filename* must be a library or archive file created from object files that were compiled with **-IPA -c**.

-INLINE:list[=(ON|OFF)]

List inlining actions to *stderr* as they occur. (default OFF).

-INLINE:must[=name1{name2...}]

Independent of the default inlining heuristic, always attempt to inline any routines with names *name1*, *name2*, etc. For C++, the names given must be the mangled names. For Fortran, the name given may be either the original name, or the external name with an underscore appended by the compiler. In all cases, the option occurs to any and all routines encountered with the given name, whether **static** or **extern**. A pragma suppressing inlining at a particular call site takes precedence over this option.

-INLINE:never[=name1{name2...}]

Independent of the default inlining heuristic, never attempt to inline any routines with names *name1*, *name2*, etc. For C++, the names given must be the mangled names. For Fortran, the name given may be either the original name, or the external name with an underscore appended by the compiler. In all cases, the option occurs to any and all routines encountered with the given name, whether **static** or **extern**. A pragma suppressing inlining at a particular call site takes precedence over this option.

-INLINE:none

Change the default inlining heuristic. Do not attempt to inline any routines which are not specified by a **must** option or a pragma requesting inlining, either for the routine or for a specific call site. This option conflicts with **-INLINE:all**; the earlier option takes precedence if both are specified.

-INLINE:preempt[=(ON|OFF)]

Enable inlining of functions marked preemptible in the stand-alone inliner. Such inlining prevents another definition of such a function in another DSO from pre-empting the definition of the function being inlined (default OFF).

-INLINE:static[=(ON|OFF)]

Perform inlining of static functions (default ON for C, C++ at **-O2** and higher optimization levels, otherwise OFF).

-INLINE:specfile=filename

Open *filename* to read additional options. The specification file contains zero or more lines with inliner options in the form expected on the command line. For instance, it might contain a single line like: **-INLINE:never=errfunc:must=accessor,solver** or, multiple lines like: **-INLINE:all** and **-INLINE:never=errfunc**. The **specfile** option cannot occur in a specification file, so specification files cannot invoke other specification files.

The **-IPA** option group controls the interprocedural analyses and transformations performed. Note that giving just the group name, **-IPA**, without any options will invoke IPA with the default settings. The individual controls in this group are:

-IPA:addressing[=(ON|OFF)]

Enable or disable the analysis of address operator usage. **-IPA:alias=ON** is a prerequisite (default OFF).

-IPA:aggr_cprop[=(ON|OFF)]

Enable or disable aggressive interprocedural constant propagation. Attempt to avoid passing constant parameters, replacing the corresponding formal parameters by the constant values. By default, less aggressive interprocedural constant propagation is done (default OFF).

-IPA:alias[=(ON|OFF)]

Enable or disable alias, modification and reference analysis (default OFF).

-IPA:autognum[=(ON|OFF)]

Determine the optimal value of the **-Gnum** option. The goal is to identify a size bound below which data can be allocated relative to the global pointer and accessed cheaply. This optimization is turned off when **-multigot** is specified in the linker command line. (default ON).

-IPA:cgi[=(ON|OFF)]

Enable or disable constant global variable identification. The goal is to mark non-scalar global variables which are never modified as constant, and propagate their constant values to all files (default ON).

-IPA:cprop[=(ON|OFF)]

Enable or disable interprocedural constant propagation. The goal is to identify formal parameters which always have a specific constant value (default ON; see also **-IPA:aggr_cprop**).

-IPA:dfe[=(ON|OFF)]

Enable or disable dead function elimination. The goal is to remove subprograms which are never called from the program (default ON).

-IPA:dve[=(ON|OFF)]

Enable or disable dead variable elimination. The goal is to remove variables which are never referenced from the program (default ON).

-IPA:echo[=(ON|OFF)]

Echo to *stderr* the back-end compilation commands and the final link command which are invoked from IPA (default OFF).

-IPA:forcedepth=n

Instead of the default inlining heuristics, attempt to inline all functions at a depth of at most *n* in the call graph, where functions which make no calls are at depth 0, those which call only depth 0 functions are at depth 1, and so on. Ignore the default heuristic limits on inlining. (See also **-IPA:maxdepth**.)

-IPA:Gfactor=n

Use *n* as the value of the percentage used to multiply the number of estimated external GOT (Global Offset Table) entries. A value of 200 means that IPA will multiply the number of estimated external GOT entries by 2 to estimate the total *.got* size (default 200).

-IPA:Gnum=n

Use *n* as the value of the **-Gnum** option. The goal is to identify a size bound below which data can be allocated relative to the global pointer and accessed cheaply (default is no limit).

-IPA:Gspace=n

Use *n* as the size in bytes of the area where IPA can allocate data that can be referenced relative to the global pointer. (default 64 kilobytes, which is the maximum value)

-IPA:gp_partition[=(ON|OFF)]

Enable partitioning for achieving different GP-groups, as specified by the user externally or determined by IPA internally. This option basically enables PICOPT in the presence of **-multigot** (default OFF).

-IPA:inline[=(ON|OFF)]

Perform inter-file subprogram inlining during main IPA processing (default ON; does not affect the stand-alone inliner).

-IPA:Intrinsics=n

Use *n* as the number of Fortran intrinsic functions that may have entries in the GOT area. This number is added to the estimated number of external GOT entries to get the estimated total number of Fortran intrinsic functions that will be added after IPA.

-IPA:keeplight[=(ON|OFF)]

Force IPA not to pass the **-keep** option to the compiler back end in order to save disk space (default OFF).

-IPA:{max}depth=n

In addition to the default inlining heuristics, don't attempt to inline functions at a depth of more than *n* in the call graph, where functions which make no calls are at depth 0, those which call only depth 0 functions are at depth 1, and so on. Inlining remains subject to overriding limits on code expansion (also see **-IPA:forcedepth**, **-IPA:space** and **-IPA:plimit**).

-IPA:max_job=n

Limit the maximum parallelism when invoking the compiler back end after IPA to at most n compilations running at once (default 2 on a uniprocessor host, 4 on a multiprocessor host).

-IPA:map_limit=n

Use n as the maximum number of input files that are mapped before IPA does `sp_partition`.

-IPA:opt_alias[=(ON|OFF)]

Transfer the results of alias/mod/ref analysis to the global optimizer. (default OFF; Forces `-IPA:alias=ON` if set.)

-IPA:picopt[=(ON|OFF)]

Perform position independent code optimizations, e.g. identify names which cannot be preempted (default ON).

-IPA:plimit=n

Stop inlining into a particular subprogram once it reaches size n in the intermediate representation (default 2500).

-IPA:space=n

Stop inlining once the program size has increased by $n\%$. For example, $n=20$ will limit code expansion due to inlining to approximately 20%. (default is 100%.)

-IPA:sp_partition[=(ON|OFF)]

Enable partitioning for disk space saving purposes. Mainly used for building huge applications (default OFF).

-IPA:specfile=filename

Use *filename* to read more IPA options. The *specfile* may contain zero or more IPA options. A *specfile* may not reference another *specfile*.

-IPA:use_intrinsic[=(ON|OFF)]

Enable loading of the intrinsic version of standard library functions (default OFF).

Loop Nest Optimizations (LNO)

The loop nest optimizer (LNO) option control group controls optimizations and transformations performed by LNO. For more information about LNO and its associated functionality such as loop fission, loop fusion, cache blocking and loop unrolling, please consult Chapter 4 of the *MIPSpro Compiling, Debugging and Performance Tuning Guide*.

The individual controls in this group are:

-LNO:opt[=(0|1)]

General control over the LNO optimization level.

- **opt=0**
Compute the dependence graph to be used by later passes. Remove inexecutable loops and if statements.
- **opt=1**
Perform full LNO transformations.

-LNO:override_pragmas

By default, pragmas within a file override the command-line options. This command-line options allows the user to have the command-line options override the pragmas in the file.

-LNO:fission[=(0|1|2)]

Control loop fission. The default value is 1.

- **fission=0**
No fission will be performed.
- **fission=1**
Do normal fission as necessary.
- **fission=2**
Try fission before fusion.
- **fission=3**
Fission inner loop as much as possible. If **-LNO:fission** and **-LNO:fusion** (see below) are both set to 1 or to 2, fusion is preferred.

-LNO:fusion[=(0|1|2)]

Control loop fusion. The default value is 1.

- **fusion=0**
No fusion will be performed.
- **fusion=1**
Do normal outer loop fusion.
- **fusion=2**
Fuse outer loops even if it means partial fusion. If **-LNO:fission** and **-LNO:fusion** are both set to 1 or to 2, fusion is preferred.

-LNO:fusion_peeling_limit=n

Set the limit ($n \geq 0$) for number of iterations allowed to be peeled in fusion. By default, $n=5$.

-LNO:outer[=(ON|OFF)]

Enable or disable outer loop fusion. LNO fuses two outermost loops to reuse them and to reduce loop overhead. By default, **outer=ON**.

-LNO:vintr[=(ON|OFF)]

Replace mathematical intrinsic calls in loops with vectorized versions of the intrinsics. The transformation is done by taking intrinsic calls out of the loops and modifying the fissioned loops to use vector intrinsic calls. Vector intrinsic calls are described in Chapter 6. By default, **vintr=ON**.

LNO Cache Memory Modeling Options

The following options may also be specified to model the cache memory system. The numbering starts with the cache level closest to the processor and works outward. For all of the options, setting a value to zero indicates that there is no cache at that level.

-LNO:(cache_size1|cs1)=n
-LNO:(cache_size2|cs2)=n
-LNO:(cache_size3|cs3)=n
-LNO:(cache_size4|cs4)=n

The size of the cache. The value *n* may either be 0, or it must be a positive integer followed by exactly one of the letters k, K, m or M. This specifies the cache size in kilobytes or megabytes.

-LNO:(line_size1|ls1)=n
-LNO:(line_size2|ls2)=n
-LNO:(line_size3|ls3)=n
-LNO:(line_size4|ls4)=n

The line size in bytes. This is the number of bytes that are moved from the memory hierarchy level further out to this level on a miss.

-LNO:(associativity1|assoc1)=n
-LNO:(associativity2|assoc2)=n
-LNO:(associativity3|assoc3)=n
-LNO:(associativity4|assoc4)=n

The cache set associativity. Large values are equivalent. For example, when blocking for main memory, it's adequate to set **LNO:assoc3=128**.

-LNO:(clean_miss_penalty1|cmp1)=n
-LNO:(clean_miss_penalty2|cmp2)=n
-LNO:(clean_miss_penalty3|cmp3)=n
-LNO:(clean_miss_penalty4|cmp4)=n
-LNO:(dirty_miss_penalty1|dmp1)=n
-LNO:(dirty_miss_penalty2|dmp2)=n
-LNO:(dirty_miss_penalty3|dmp3)=n
-LNO:(dirty_miss_penalty4|dmp4)=n

In processor cycles, the time for a clean or dirty miss to the next outer level of the memory hierarchy. This number is obviously approximate, since it depends upon a clean or dirty line, read or write miss, etc.

-LNO:(is_memory_level1|is_mem1)=ON|OFF
-LNO:(is_memory_level2|is_mem2)=ON|OFF
-LNO:(is_memory_level3|is_mem3)=ON|OFF
-LNO:(is_memory_level4|is_mem4)=ON|OFF

Does not need to be specified. Default is OFF. If specified, the corresponding associativity is ignored and needn't be specified. Model this memory hierarchy level as a memory, not a cache. This means that blocking may be attempted for this memory hierarchy level, and that blocking appropriate for a memory rather than cache would be applied. This implies no prefetching, no need to worry about conflict misses.

LNO TLB Modeling Options

The following options may also be specified to model the TLB. The TLB is assumed to be fully associative.

-LNO:(tlb_entries1|tlb1)=n
-LNO:(tlb_entries2|tlb2)=n
-LNO:(tlb_entries3|tlb3)=n
-LNO:(tlb_entries4|tlb4)=n

The size of the TLB for this cache level.

-LNO:(page_size1|ps1)=n
-LNO:(page_size2|ps2)=n
-LNO:(page_size3|ps3)=n
-LNO:(page_size4|ps4)=n

The number of bytes in a page.

-LNO:(tlb_clean_miss_penalty1|tlbcmp1)=n
-LNO:(tlb_clean_miss_penalty2|tlbcmp2)=n
-LNO:(tlb_clean_miss_penalty3|tlbcmp3)=n
-LNO:(tlb_clean_miss_penalty4|tlbcmp4)=n
-LNO:(tlb_dirty_miss_penalty1|tlbdmp1)=n
-LNO:(tlb_dirty_miss_penalty2|tlbdmp2)=n
-LNO:(tlb_dirty_miss_penalty3|tlbdmp3)=n
-LNO:(tlb_dirty_miss_penalty4|tlbdmp4)=n

The number of processor cycles to service a clean or dirty tlb miss.

The following option controls aides in modeling, but is not required. The default depends upon the target processor.

-LNO:(non_blocking_loads|nb1)[=(ON|OFF)]

Specify OFF if the processor blocks on loads. If not set, takes the default of the current processor. This is not associated with a cache level, and does not have to be defined when defining a cache level.

LNO Transformation Control Options

The following options control which transformations to apply.

-LNO:interchange[=(ON|OFF)]

Specify OFF to disable the interchange transformation. By default,

-LNO:interchange=ON.

-LNO:blocking[=(ON|OFF)]

Specify OFF to disable the cache blocking transformation. Note that loop interchange to improve cache performance could still be applied. By default, **-LNO:blocking=ON.**

-LNO:blocking_size=n1[,n2]

Specify a blocksize that the compiler must use when performing any blocking.

-LNO:(outer_unroll,ou)=n

-LNO:(outer_unroll_max,ou_max)=n

-LNO:(outer_unroll_prod_max,ou_prod_max)=n

If **-LNO:outer_unroll** (abbreviation **-LNO:ou**) is specified, neither

-LNO:outer_unroll_max nor **-LNO:outer_unroll_prod_max** may be.

-LNO:outer_unroll indicates that every outer loop for which unrolling is legal should be unrolled by exactly *n*. The compiler will either unroll by this amount or not at all.

-LNO:outer_unroll_max indicates that the compiler may unroll as many as *n* per loop, but no more. **-LNO:outer_unroll_prod_max** indicates that the product of unrolling of the various outer loops in a given loop nest is not to exceed **-LNO:outer_unroll_prod_max**.

-LNO:(outer_unroll_further,ou_further)=n

When generating wind-down code from outer loop unrolling, the compiler sometimes will attempt to generate additional register tiling of unrolling factor two. For example, rather than transforming:

```
for (i=0; i<n; i++) {
    for (j=0; j<n; j++) {
        S[i][j];
    }
}
```

into

```
for (i=0; i<n-5; i+=6) {
    for (j=0; j<n; j++) {
        S[i][j]; S[i+1][j];
        S[i+2][j]; S[i+3][j];
        S[i+4][j]; S[i+5][j];
    }
}
for (i=i; i<n; i++) {
    for (j=0; j<n; j++) {
        S[i][j];
    }
}
```

the compiler may choose to generate

```
for (i=0; i<n-5; i+=6) {
    for (j=0; j<n; j++) {
        S[i][j]; S[i+1][j];
        S[i+2][j]; S[i+3][j];
        S[i+4][j]; S[i+5][j];
    }
}
for (i=i; i<n-1; i+=2) {
    for (j=0; j<n; j++) {
        S[i][j]; S[i+1][j];
    }
}
for (i=i; i<n; i++) {
    for (j=0; j<n; j++) {
        S[i][j];
    }
}
```

The compiler will not always do this. It is guaranteed not to do this when the unrolling factor (six in the above example) is less than the number supplied in this parameter. Thus, the additional unrolling as illustrated above is disabled by specifying **-LNO:ou_further=999999**, and is enabled as much as is sensible by specifying **-LNO:ou_further=3**.

-LNO:(outer_unroll_deep|ou_deep)=n

When ON, for 3-deep or deeper nests, we outer unroll the wind-down loops that result from outer unrolling loops further out. This results on larger code, but generates much better code whenever wind down loop execution costs are significant. The default is ON.

-LNO:pwr2[=(ON|OFF)]

When the leading dimension of an array is a power of two, the compiler makes an extra effort to make the inner loop stride one, and is less likely to block since it'll be harder to take advantage of reuse. Set **-LNO:pwr2=OFF** to disable this, so that the leading dimension is ignored.

-LNO:gather_scatter[=(0|1|2)]

Specify to control the gather-scatter optimization.

- **gather_scatter=0**
No gather-scatter will be performed.
- **gather_scatter=1**
Gather-scatter non-nested IF statements.
- **gather_scatter=2**
Perform multi-level gather-scatter.

-LNO:prefetch[=(0|1|2)]

Specify level of prefetching.

- **prefetch=0**
Prefetch disabled. This is the default on all systems that are not based on the R10000.
- **prefetch=1**
Prefetch enabled but conservative.
- **prefetch=2**
Prefetch enabled and aggressive. This is the default on R10000 systems.

-LNO:prefetch_level n [(OFF|ON)]

-LNO:pf n [(OFF|ON)]

Selectively disable or enable prefetching for cache level n , where n ranges from 1 to 4.

-LNO:prefetch_manual[(ON|OFF)]

Specify whether manual prefetches (through pragmas) should be respected or ignored.

- **prefetch_manual=OFF**
Ignore manual prefetches (default for all systems based on the R8000 and earlier)
- **prefetch_manual=ON**
Respect manual prefetches (default for all systems based on the R10000 and beyond)

-LNO:prefetch Ahead=*n*

Specify *n* number of lines to prefetch ahead of the reference. The default is 2 lines.

Miscellaneous Optimizations

The **-OPT** group allows control over a variety of other optimization choices.

-OPT:Olimit=n

Any routine above the **Olimit** size will not be optimized. If the optimization level is **-O2** or above, and a routine is so big that the compile speed may be slow, then the compiler will print a message about what **Olimit** value is needed to compile with optimization. You can recompile with that value or you can use **-OPT:Olimit=0** to avoid having any **Olimit** cutoff.

-OPT:space

The MIPSpro 64-bit compilers normally make optimization decisions based strictly on the expected execution time effects. If code size is more important, use this option. One of its effects is to cause most subprogram exits to go through a single exit path, with a single copy of register restores, result loads, and so on.

-OPT:swp=OFF

Disable the software pipelining optimization which is enabled at **-O3**. Software pipelining is discussed in Chapter 6.

-OPT:alias=name

The compilers must normally be very conservative in optimization of memory references involving pointers (especially in C), since aliases (different ways of accessing the same memory) may be very hard to detect. This option may be used to specify that the program being compiled avoids aliasing in various ways. The choices are:

- **alias=any**

The compiler assumes that any pair of memory references may be aliased unless it can prove otherwise (the default).

- **alias=disjoint**

The compiler assumes that any pair of memory references to distinct named pointers in the program do not alias with each other. It also assumes that different depths of dereferences of the same named pointers also do not alias with each other. For example, if *p* and *q* are pointers, **p* does not alias with **q*. Nor does **p* alias with ***p*. Nor does **p* alias with ***q*.

- **alias=typed**

The compiler assumes that any pair of memory references which reference distinct types in fact reference distinct data. For example, consider the code:

```
void dbl ( int *i, float *f )
{
    *i = *i + *i;
    *f = *f + *f;
}
```

The compiler assumes that *i* and *f* point to different memory, and produces an overlapped schedule for the two calculations.

- **alias=no_typed**

The compiler assumes that pointers to different base types may point to the same object.

- **alias=unnamed**

The compiler assumes that pointers never point to named objects. For example, consider the code:

```
float g;
void dbl ( float *f )
{
    *g = g + g;
    *f = *f + *f;
}
```

The compiler assumes that *f* cannot point to *g*, and produces an overlapped schedule for the two calculations. This option also implies the *alias=typed* assumption. Note that this is the default assumption for the pointers implicit in Fortran dummy arguments according to the ANSI standard.

- **alias=no_unnamed**

The compiler assumes that *f* can point to *g* in the example above.

- **alias=restrict**

The compiler assumes a very restrictive model of aliasing, where no two pointers ever point to the same memory area. For example, consider the code:

```
void dbl ( int *i, int *j )
{
    *i = *i + *i;
    *j = *j + *j;
}
```

The compiler assumes that *i* and *j* point to different memory, and produces an overlapped schedule for the two calculations.

Although this is a very dangerous option to use in general, it may produce significantly better code when used for specific well-controlled cases where it is known to be valid.

- **alias=no_restrict**

The compiler assumes that distinct pointers may point to overlapping storage.

Loop Unrolling Optimizations

The following options control loop unrolling in the MIPSpro 64-bit optimizer, that is, making multiple copies of a loop body to minimize the loop overhead or to expose more instruction parallelism. Unrolling is subject to a number of limits in the optimizer, intended to balance the runtime benefits against code expansion. These options allow the user to modify those limits when they can be improved.

-OPT:unroll_times_max=n

The optimizer normally unrolls loops at most 2 times (**-mips4**) or 4 times (**-mips3**), unless it can unroll them completely. This option modifies the default limit.

-OPT:unroll_size=n

The optimizer normally unrolls loops only to the extent that the resulting unrolled loop body contains at most 320 instructions. This option modifies the default limit.

Target Environment Issues

Generated code is affected by a number of assumptions about the target software environment. The options in this group tell the compiler what assumptions it can make, and sometimes what assumptions it should enforce.

-TENV:check_div=n

Insert checks for divide by zero or overflow.

- **n=0**
No checks are performed.
- **n=1**
Perform checks for divide by zero. This is the default.
- **n=2**
Perform checks for both divide by zero and overflow.

-TENV:large_GOT[=(ON|OFF)]

-TENV:small_GOT[=(ON|OFF)]

Shared code and dynamic shared objects (DSOs) require the use of a global offset table (GOT) containing addresses of static data and subprograms at runtime. A dedicated register (*\$gp*) points to the GOT at runtime, and the code can load these addresses from the GOT without being dependent on its actual virtual address. If the GOT is less than 64KB in size, those loads can all be single instructions; otherwise they require adding a constructed offset to *\$gp*. These options choose one of those cases (default **small_GOT**).

-TENV:X=n

Specify the level (0 to 5, default 1) of enabled traps that is assumed (and enforced) for purposes of performing speculative code motion. At level 0, no speculation is done. At level 1, only safe speculative motion may be done, assuming that the IEEE 754 underflow and inexact traps are disabled. At level 2, all IEEE 754 floating point traps are disabled except divide by zero. At level 3, divide by zero traps are disabled. At level 4, memory traps may be disabled or dismissed by the operating system. At level 5, any exceptions may be disabled or ignored. Non-default levels should be used with great care. Disabling traps eliminates a useful debugging tool, since the problems which cause traps are detected later (often much later) in the execution of the program. In addition, many

memory traps can't be avoided outright, but must be dismissed by the operating system after they occur. As a result, level 4 or 5 speculation can actually slow a program down significantly if it causes frequent traps.

Disabling traps in one module requires disabling them for the entire program. Programs which make use of level 2 or above should not attempt explicit manipulation of the hardware trap enable flags.

Data Alignment Options

The last set of environment options are concerned with the alignment of data:

-align32 | -align64

The MIPS architectures perform memory references much more efficiently if the data referenced is naturally aligned, that is, if 4-byte objects are at 4-byte-aligned address, etc. By default, the compilers allocate well-aligned data, and that is a requirement of the ABI for C. However, code ported from other architectures without alignment constraints may require less restricted alignment. The ANSI Fortran standard essentially requires maximum alignment of 4 bytes (32 bits), although it is unusual for code to actually depend on this. These options specify a maximum alignment (in bits) to be forced in allocating data. The MIPSpro 64-bit compilers default to **-align64** for MIPS3 or MIPS4 Fortran, and to ABI alignment (up to 128 bits for long double) for C.

-TENV:align_aggregates=n

The ABI specifies that aggregates (that is, **structs** and **arrays**) be aligned according to the strictest requirements of their components (that is, fields or elements). Thus, an array of **short ints** (or a **struct** containing only **short ints** or **chars**) is normally 2-byte aligned. However, some non-ANSI-conforming code may reference such objects assuming greater alignment, and some code (for example, **struct** assignments) may be more efficient if the objects are better aligned). This option specifies that any aggregate of size at least *n* is at least n-byte aligned. It does not affect the alignment of aggregates which are themselves components of larger aggregates.

Compilation Messages

Because they are two separate and different compiler systems, the 32-bit and 64-bit MIPSpro compilers have different warning and error messages.

The 32-bit C compiler emits errors as follows: the phase of the compiler which detects an error or warning, identifies itself first, then it prints whether it found an error or warning. The next printed items are the file name, line number and description of the error.

Fortran error messages are similar except the compiler phase name is omitted.

Two examples illustrate this:

C:

```
%cc -32 test.c
cfe: Error: test.c, line 4: Syntax Error
```

Fortran:

```
% f77 -32 err.f
Error on line 6 of err.f: syntax error
```

Under the 64-bit compiler, back end warning messages start with the string “!!!”. Error messages start with the string “###”. This allows easier searches in log files. C error messages are similar to the 32-bit compiler’s error messages, although they are usually more descriptive.

Here the same files compiled with the 64-bit compiler result in the following error messages:

C:

```
%cat test.c
#include <stdio.h>
main ()
{
    printf ("help")
}
%cc -64 test.c
"test.c", line 4: error(1065): expected a ";"
}
```


Fortran:

```
%cat err.f
      program test
c
c
2      write(6,8)
8      formatr('This is a test')
      end

% f77 -64 err.f
"err.f", line 6: error(2080): expected a "("
8      formatr('This is a test')
      ^

1 error detected in the compilation of "err.f"
Important Warning Messages
```

When porting a 32-bit application to 64-bits use the **-fullwarn** option to expose variable size related issues. Two warnings in particular emitted by the 64-bit C compiler are helpful in this respect. They allow you to locate faulty assumptions that integers and pointers are the same size.

warning(1412): destination type of cast is too small to hold all pointers: truncation possible

For example, the following code fragment generates this warning when compiled **-64**.

```
unsigned i, *p;
i = (unsigned) p;
```

In this example, the unsigned integer variable *i* is set to only the low order 32 bits of *p*. If *p* contains an address greater than 32 bits, that address is truncated in *i*.

remark(1413): source type of cast is too small to hold all pointers:

The following code fragment generates this warning when compiled **-64 -fullwarn**.

```
int i, *p;
p = (int *) i;
```

In this example, if *i* is negative, the sign bit is extended throughout the high-order 32 bits of *p*. The result is that *p* contains an invalid address.

Linking Your Application

The *cc* driver automatically picks the correct compiler, linker, and library paths if you use the **-32**, **-n32** or **-64** switches on the command line. If you compile and link separately, you must use these switches on both the *cc* driver and *ld* command lines. If you link with libraries that are not included with IRIX or the compiler, you must make sure that they are of the proper type. Remember, you can't link 32-bit applications with N32 or 64-bit *.so*'s.

To create your own N32, 64-bit or 32-bit libraries, you must supply the correct switch on the archiver command line.

Libraries

The 32-bit and 64-bit compilers include some different libraries. Whereas, the 32-bit compiler includes *libftn.so*, *libF77.a*, *libI77.a*, *libU77.a* and *libisam.a* under */usr/lib*, the 64-bit compiler has one library, *libftn.so*, under */usr/lib64* and */usr/lib32*.

The 64-bit compiler also introduces routines which do QUAD precision (128-bit) floating point calculations into existing libraries.

The 64-bit compiler provides a united runtime library for parallel C and parallel Fortran programs (*/usr/lib64/libmp.so*), as opposed to two (*/usr/lib/libc_mp.a*, */usr/lib/libkapio.a*) libraries under the 32 code compiler. This united library allows you to mix parallel C with parallel fortran programs.

The 64-bit compiler also does not include *libmld.a*, but provides *libdwarf.a*.

Runtime Issues

This chapter outlines why your 32-bit and 64-bit applications may run differently, due both to compiler differences and to architectural modes. It describes the Performance and Precise Exception Modes of the R8000 microprocessor architecture and how they affect the calculations of applications. This chapter also briefly outlines a methodology to bring up and debug applications.

Runtime Differences

Your 64-bit application may produce slightly different floating point calculations on the R8000 than on its 32-bit counterpart. There can be a variety of causes for this. These include reassociation of operations by optimizations, algorithm changes in libraries and hardware changes.

Reassociation of Operations by Optimizations

The order in which equivalent floating point expressions are executed can cause differences in their results. The 32-bit and 64-bit compiler systems perform different optimizations which can cause reordering of instructions leading to slightly different results. The compilers may also perform operation reductions which can affect the results.

Algorithm Changes in Libraries

The 64-bit compiler comes with new math libraries which use different algorithms than those used with the 32-bit compiler to improve their performance. The values which they return can cause potentially noticeable differences in application results.

Hardware Changes

The R8000 microprocessor includes four floating point multiply/add / subtract instructions which allow two floating point computations to be performed with one instruction. The intermediate result is calculated to infinite precision and is not rounded prior to the addition or subtraction. The result is then rounded according to the rounding mode specified by the instruction. This can yield slightly different calculations than a multiply instruction (which is rounded) and an add instruction (which is rounded again).

The R8000 microprocessor architecture also defines two execution environments which can affect your application if it generates floating point exceptions such as underflow. Performance Mode enhances the execution speed of floating point applications, by rounding denormalized numbers to zero and allowing the hardware to trap exceptions imprecisely. Precise Exception Mode, on the other hand, is fully compatible to the existing MIPS floating point architecture.

It should be emphasized that running in Performance Mode does not affect those applications which don't cause floating point exceptions.

A program, *fpmode*, allows you to run your application in either Performance (imprecise) or Precise Mode. Its usage is as follows:

```
%fpmode precise commandargs
```

or

```
%fpmode imprecise commandargs
```

A full discussion of the Extended MIPS Floating Point Architecture is provided as a reference.

Extended MIPS Floating-Point Architecture

The MIPS architecture fully complies with the ANSI/IEEE Standard 754-1985, *IEEE Standard for Binary Floating-Point Arithmetic*. Most application programs utilize only a fraction of all the features required by the Standard. These applications can gain additional performance if executed in an environment that supports only those features of the Standard that are actually necessary for the correct execution of the application. The Extended MIPS Floating-Point Architecture defines two execution environments:

- Performance Mode enhances the execution speed of most applications by rounding denormalized numbers to zero and by allowing the hardware to trap exceptions imprecisely. This mode requires compiler and library support to fully comply with the Standard.

In Performance Mode, the hardware and operating system are relieved of the requirements to precisely trap floating-point exceptions and to compute using denormalized operands. This mode is defined in such a way that it is adequate for a majority of application programs in use today, yet it can also be used in conjunction with compiler and library support to fully implement the Standard in the future.

Performance Mode improves the floating-point execution speed of processors. On the R4000, Performance Mode enables flushing operands to zero, thus avoiding the software emulation overhead of denormalized computations. On the R8000, Performance Mode enables floating-point instructions to execute out-of-order with respect to integer instructions, improving performance by a factor of two or more.

Performance Mode is the standard execution environment on R8000 based Power Challenge systems.

- Precise Exception Mode fully complies with the Standard and is compatible in every way to the preexisting MIPS floating-point architecture.

In Precise Exception Mode the responsibility for compliance lies entirely with the hardware and operating system software; no compiler support is assumed. Since there is no information about the application, the hardware must assume the most restrictive features of the Standard applies at all times. The result is lost performance opportunities on applications that utilize only a subset of the features called for by the Standard.

Performance Mode

The purpose of this section is to define Performance Mode and explain why it is necessary and desirable.

Background

The IEEE Standard defines floating-point numbers to include both normalized and denormalized numbers. A denormalized number is a floating-point number with a minimum exponent and a nonzero mantissa which has a leading bit of zero. The vast majority of representable numbers in both single and double precision are normalized numbers. An additional small set of very tiny numbers (less than 2^{-126} ($\sim 10^{-38}$) in single precision, less than 2^{-1022} (10^{-308}) in double precision) are represented by denormalized numbers. The importance of approximating tiny real values by denormalized numbers, as opposed to rounding them to zero, is controversial. It makes no perceptible difference to many applications, but some algorithms need them to guarantee correctness.

Figure 5-1 shows pictorially the IEEE definition of floating-point numbers. Only the positive side of the real number line is shown, but there is a corresponding negative side also. The tick marks under the real number line denote example values that can be precisely represented by a single or double precision binary number. The smallest representable value larger than zero is *minD*, a denormalized number. The smallest normalized number is *minN*. The region between zero and just less than *minN* contains tiny values. Larger values starting with *minN* are not tiny.

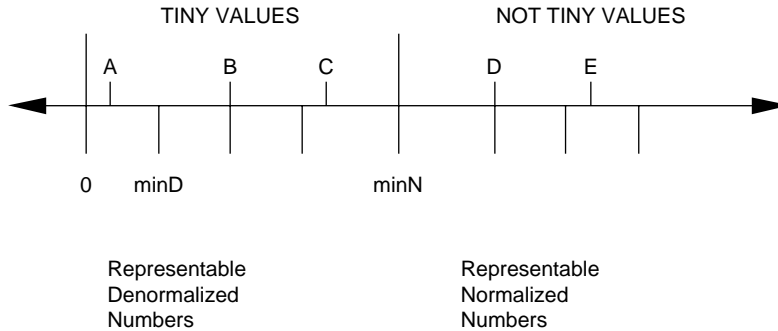


Figure 5-1 Floating Point Numbers

The different cases that must be considered are represented by the values A-E. According to the IEEE Standard, the behavior of an operation that produces these result values is defined as shown in Table 5-1.

Table 5-1 Operation Results According to IEEE Standard

| Value | Result | Flags |
|-----------------|-----------------|--|
| A:TooSmall | $\text{rnd}(A)$ | $U=1, I=1$ |
| B:ExactDenorm | B | $U=1, I=0$ if Enable $U=U=0,$ $I=0$ if Enable $U=0$ |
| C:InexactDenorm | $\text{rnd}(C)$ | $U=1, I=1$ |
| D:ExactNorm | D | $U=0, I=0$ |
| E:InexactNorm | $\text{rnd}(E)$ | $U=0, I=1$ |

The flags U and I abbreviate Underflow and Inexact, respectively. The function $\text{rnd}()$ rounds the operand to the nearest representable floating point number based on the current rounding mode, which can be round-to-zero, round-to-nearest, round-to-plus-infinity, and round-to-minus-infinity. For example, $\text{rnd}(A)$ is either zero or $\text{min}D$. A trap occurs if a flag is set and the corresponding enable is on. For example, if an operation sets $I=1$ and $\text{Enable}I=1$, then a trap should occur. Note that there is a special case for representable tiny values: the setting of the U flag depends on the setting of its enable.

Supporting denormalized numbers in hardware is undesirable because many high performance hardware algorithms are designed to work only with normalized numbers, and so a special case using additional hardware and usually additional execution time is needed to handle denormalized numbers. This special case hardware increases the complexity of the floating-point unit and slows down the main data path for normalized numbers, but is only rarely used by a few applications. Therefore most processor designers have generally deemed it not cost effective to support computations using denormalized numbers in hardware. To date no implementation of the MIPS architecture supports denormalized number in hardware.

Computations using denormalized numbers can also be supported by software emulation. Whenever a floating-point operation detects that it is about to either generate a denormalized result or begin calculating using a denormalized operand, it can abort the operation and trap to the operating system. A routine in the kernel, called *softfp*, emulates the computation using an algorithm that works correctly for denormalized numbers and deposits the result in the destination register. The operating system then

resumes the application program, which is completely unaware that a floating-point operation has been emulated in software rather than executed in hardware. Emulation via *softfp* is the normal execution environment on all IRIX platforms today.

The problem with the software emulation approach is two-fold. Firstly, emulation is slow. Computations using denormalized operands frequently generate denormalized results. So, once an application program creates a denormalized intermediate value, the execution speed of the application drastically slows down as it propagates more and more denormalized intermediate results by software emulation. If the application truly requires representation of denormalized numbers in order to perform correctly, then the slowdown is worthwhile. But in many cases the application also performs correctly if all the denormalized intermediate results were rounded to zero. For these applications software emulation of denormalized computations is just a waste of time.

The second problem with software emulation is that it demands precise floating-point exceptions. In order for *softfp* to substitute the result of an arbitrary floating-point instruction, the hardware must be capable of aborting an already-executing floating-point instruction based on the value of the input operand or result, aborting any subsequent floating-point instruction that may already be in progress, and trapping to the operating system in such a way that the program can be resumed. Providing precise exceptions on floating-point operations is always difficult since they take multiple cycles to execute and should be overlapped with other operations. It becomes much more difficult when, to achieve higher performance, operations are executed in a different order than that specified in the program. In this case instructions logically after a floating-point operation that needs to be emulated may have already completed execution! While there are known techniques to allow *softfp* to emulate the denormalized operation, all these techniques require considerable additional hardware.

Performance Mode Definition

In defining a new floating-point execution environment there are several goals:

- Give sufficient latitude to facilitate the design of all conceivable future high performance processors.
- Fully comply with the IEEE Standard via a combination of compiler, library, operating system and hardware.
- Preserve the correct operation of a broad subset of existing applications compiled under the preexisting floating-point environment (which we now call Precise Exception Mode).
- Provide a software-only solution to retrofit the new mode on existing hardware.

The first goal is important because we do not want to be changing floating-point architectures with every implementation. The second goal is important because we want to continue to say we have "IEEE arithmetic" machines. The third goal gives our customers a smooth transition path. The fourth goal lets our customers upgrade their old machines.

Performance mode is defined by omitting denormalized numbers from the IEEE Standard and by deleting the requirement to precisely trap floating-point exceptions. Referring to Table 5-2, the behavior of an operation that produces result values A-E in Performance Mode is defined as follows.

Table 5-2 Operation Results Using Performance Mode

| Value | Input | Result | Flags |
|------------------|----------|-----------|----------|
| A: TooSmall | - | 0 or minN | U=1, I=1 |
| B: ExactDenorm | 0 or min | 0 or minN | U=1, I=1 |
| C: InexactDenorm | - | 0 or minN | U=1, I=1 |
| D: ExactNorm | D | D | U=0, I=0 |
| E: InexactNorm | - | rnd(E) | U=0, I=1 |

Tiny results are mapped to either zero or the minimum normalized number, depending on the current Rounding Mode. Note that the inexact flag *I* is set in case *B* because although there is an exact denormalized representation for that value, it is not being used. Denormalized input operands, *B*, are similarly mapped to zero or *minN*. Note that there are no inexact inputs since they cannot be represented. The normalized cases are identical to those in Precise Exception mode.

All IEEE Standard floating-point exceptions are trapped imprecisely in Performance Mode. Regardless of whether the exceptions are enabled or disabled, the result register specified by the offending instruction is unconditionally updated as if all the exceptions are disabled, and the exception conditions are accumulated into the flag bits of the *FSR*, the floating point control and status register.

There are two classes of exceptions in Performance Mode. If any flag bit (invalid operation, division by zero, overflow, underflow, inexact) and its corresponding enable bit are both set, then an imprecise trap occurs at or after the offending instruction up to the next trap barrier. In addition, if *FS*=0 (*FS* is a special control bit in the *FSR*) then an imprecise trap occurs when a tiny result that would be represented as a denormalized

number gets mapped into zero or $\min N$. $FS=0$ also causes an imprecise trap if an input operand is a denormalized number that gets trapped into zero or $\min N$.

A floating-point trap barrier is defined by a code sequence that begins with an instruction moving the *FSR* to an integer register and concludes with an instruction that uses the integer register containing the *FSR* contents. Any number of other instructions are allowed in between as long as they are not floating-point computation instructions (that is, they cannot set flag bits). All imprecise floating-point traps that occur on behalf of an instruction before the barrier are guaranteed to have occurred before the conclusion of the barrier. At the conclusion of the barrier the flag bits accurately reflect the accumulated results of all floating point instructions before the barrier. The floating-point barrier is defined in this way to give implementations maximum flexibility in overlapping integer and floating-point operations serialization of the two units is deferred as late as possible to avoid performance loss.

The cause bits of the *FSR* present a serious problem in Performance Mode. Ideally they should contain the result of the latest floating-point operation. However, this may be very difficult or expensive to implement when floating-point instructions are issued or even completed out of order. In order to maximize the opportunity for correctly running existing binaries and yet retain full flexibility in future out-of-order implementations, the cause bits of the *FSR* are defined to be cleared by each floating-point operation. Future applications, however, should avoid looking at the cause bits, and instead should use the flag bits.

The selection of Performance or Precise Exception Mode is defined as a protected or kernel-only operation. This is necessary for several reasons. When executing existing binaries that operate correctly in Performance Mode, we do not want the program to accidentally go into Precise Exception Mode. Since existing programs regularly clear the entire *FSR* when they want to clear just the rounding mode bits, Performance Mode cannot be indicated by setting a bit in the *FSR*. On the other hand, existing programs that must run in Precise Exception Mode must not accidentally go into Performance Mode. Thus Performance Mode cannot be indicated by clearing a bit in the *FSR* either. We cannot use a new user-accessible floating-point control register to indicate Performance Mode because when a new program running on an existing processor that does not understand Performance Mode writes to this nonexistent control register, it is undefined what happens to the floating-point unit. Finally, on the R8000 there are implementation restrictions on what instructions may proceed and follow a mode change, so such changes can only be done safely by the kernel.

R8000 and R4400 Implementations

The R4000 already made a step in the direction of Performance Mode by defining the *FS* bit in the *FSR*, the floating-point control and status register. When *FS* is set, denormalized results are flushed to zero or *minN* depending on current Rounding Mode instead of causing an unimplemented operation exception. This feature eliminates the most objectionable aspect of Precise Exception Mode, namely the slow propagation of denormalized intermediate results via *softfp*. However, it does not eliminate the need to precisely trap floating-point exceptions because denormalized input operands must still be handled by *softfp*.

The R8000 extends the R4000 floating-point architecture to include another control bit whose states are labeled *PERF* and *PREX*, for Performance Mode and Precise Exception Mode, respectively. In Performance Mode the R8000 hardware (see Table 5-3) does the following:

Table 5-3 R8000 Performance Mode

| Value | Input | Result | Flags |
|-----------------|-------|-----------|----------------------|
| A:TooSmall | - | 0 or minN | U=1, I=1 E=1 if FS=0 |
| B:ExactDenorm | 0 | 0 or minN | U=1, I=1 E=1 if FS=0 |
| C:InexactDenorm | - | 0 or minN | U=1, I=1 E=1 if FS=0 |
| D:ExactNorm | D | D | U=0, I=0 |
| E:InexactNorm | - | rnd(E) | U=0, I=1 |

The *E* bit, which becomes sticky in Performance Mode, signifies that a denormalized number was mapped to 0 or *minN*. Note that the R8000 can only flush denormalized input operands to zero, as opposed to either zero or *minN*. This deviation is unfortunate but unlikely to be noticeable and is not scheduled to be fixed.

In Precise Exception Mode the R8000 hardware (see Table 5-4) does the following:

Table 5-4 R8000 Precise Exception Mode

| Value | Input | Result | Flags |
|-----------------|-------|--------|----------|
| A:TooSmall | - | trap | U=1, I=1 |
| B:ExactDenorm | trap | trap | U=1, I=1 |
| C:InexactDenorm | - | trap | U=1, I=1 |
| D:ExactNorm | D | D | U=0, I=0 |
| E: InexactNorm | - | rnd(E) | U=0, I=1 |

Unlike the R4400, the R8000 totally ignores the *FS* bit in this case and relies on **softfp** to emulate the result. This simplification degrades the performance of Precise Exception Mode but does not alter the results.

Performance Mode is retrofitted on the R4400 by enhancing the kernel and **softfp**. The emulation of Performance Mode deviates from the definition in that the cause bits of the *FSR* are not cleared by every floating-point operation, but instead continue to be updated based on the result of the operation. This deviation is necessary to achieve acceptable performance.

Full IEEE Compliance in Performance Mode

Full IEEE Standard compliance including precise exceptions and support for denormalized computations is possible in Performance Mode with help from the compiler. Although most applications never need it, some programming languages (for example, Ada) require more precision in exception reporting than what the hardware provides in Performance Mode. Also, a small number of algorithms really do need to perform computations on denormalized numbers to get accurate results.

The concept behind achieving precise exceptions in Performance Mode relies on two observations. Firstly, a program can be divided into a sequence of blocks, each block containing a computation section followed by an update section. Computation sections can read memory, calculate intermediate results, and store to temporary locations which are not program variables, but they cannot modify program visible state. Update sections store to program visible variables, but they do not compute. Floating-point exceptions can only occur on behalf of instructions in computation sections, and can be confined to

computation sections by putting a floating-point exception barrier at the end of computation sections.

Secondly, it is always possible to partition the computation and update sections in such a way that the computation sections are infinitely reexecutable. We call such computation sections Idempotent Code Units.

Intuitive, an ICU corresponds to the right hand side of an assignment statement, containing only load and compute instructions without cyclic dependencies. In practice ICUs can also contain stores if they spill to temporary locations. As long as the input operands remain the same, the result generated by an ICU remains the same no matter how many times the ICU is executed. We achieve precise exceptions in Performance Mode by compiling the program (or parts of the program) into blocks of the following form (registers are marked with %):

```
restart = current pc      #restart point
. . .                   #Idempotent Code Unit
%temp = FSR              #trap barrier
%add %r0 = %r0 + %temp   #end of trap barrier
    Fixup:nop             #break point inserted here
    . . .                 #update section
```

A map specifying the locations of all ICU's and their Fixup point is included in the binary file, and the program is linked with a special floating-point exception handler.

When a floating-point exception trap occurs, the handler switches the processor to Precise Exception mode, inserts a break point at location Fixup, and re-executes the ICU by returning to the program counter in *%restart*. This time the exception(s) are trapped precisely, and denormalized computations can be emulated. When the program reaches the break point inserted at **Fixup**, another trap occurs to allow the handler to remove the break point, reinsert the nop, and return to Performance Mode.

Application Bringup and Debugging

The first step in bringing up applications is to compile and run them at the lowest optimization level. Once a stable baseline of code is established, you can compare it with code that does not run, to isolate problems. This methodology is expanded upon as follows:

- Use the source base of a 32-bit working application which is compiled *-mips2* (compiled with the *ucode* compilers).
- Compile **-64 -mips4 -g** and fix source problems. Refer to other sections in this Guide for help on general porting issues.
- Run the **-64 -mips4 -g** binaries on a PowerChallenge, R8000 IRIX 6 system. At this point the *ucode* 32-bit binaries, should also be run, side by side, on the PowerChallenge system to help isolate where the problems are creeping in.
- Repeat the previous step, going up the optimization scale.
- Compile **-64, -mips4, -O3** and tune applications on Power Challenge to get the best performance. Refer to Chapter 6 in this Guide for help on tuning for the R8000.

The good news is that if you can get everything working **-64 -mips4 -g**, then you have a 64-bit baseline with which to compare non-working code. The MIPSpro compiler allows you to link object files compiled at different optimizations. By repeatedly linking objects from the working baseline, with those of the non-working set and testing the resulting application, you should be able to identify which objects from the non-working set are bad.

Once you have narrowed down your search to a small area of code, use the *dbx* debugger. You can then compare the variables and program behavior of your working application against the variables and program behavior of the code that fails. By isolating the problem to a line of code, you can then find the cause of the failure.

Performance Tuning for the R8000 and R10000

This chapter outlines techniques for tuning the performance of your R8000 and R10000 applications. It contains five sections:

- The first section provides an architectural overview of the R8000 and R10000. This will serve as background for the software pipelining discussion.
- The second section presents the compiler optimization technique of software pipelining, which is crucial to getting optimal performance on the R8000. It shows you how to read your software pipelined code and how to understand what it does.
- The third section uses matrix multiplies as a case study on loop unrolling.
- The fourth section describes how the *IVDEP* directive can be used in Fortran to gain performance.
- The final section describes how using vector intrinsic functions can improve the performance of your program.

Architectural Overview

Table 6-1 illustrates the main architectural features of the R8000 and R10000 microprocessors. Both can execute the MIPS IV instruction set and both can issue up to four instructions per cycle, of which two can be integer instructions and two can be floating point instructions. The R8000 can execute up to two *madd* instructions per cycle, while the R10000 can only execute one per cycle. The R8000 can issue two memory instructions per cycle while the R10000 can issue one per cycle. On the other hand, the R10000 operates at a much faster clock frequency and is capable of out-of-order execution. This makes it a better candidate for executing programs that were not explicitly tuned for it.

Table 6-1 Architectural Features of the R8000 and R10000

| Feature | R8000 | R10000 |
|---|---------|---------|
| ISA | MIPS IV | MIPS IV |
| Frequency | 90 Mhz | 200 Mhz |
| Peak MFLOPS | 360 | 400 |
| Total Number of Instructions per cycle | 4 | 4 |
| Number of Integer Instructions per cycle | 2 | 2 |
| Number of Floating Point Instructions per cycle | 2 | 2 |
| Number of Multiply-Add Instructions per cycle. | 2 | 1 |
| Number of Load/Store Instructions per cycle | 2 | 1 |
| Out-of-order Instruction execution | No | Yes |

Software Pipelining

The purpose of this section is to give you an overview of software pipelining and to answer these questions:

- Why software pipelining delivers better performance
- How software pipelined code looks
- How to diagnose what happened when things go wrong

Why Software Pipelining Delivers Better Performance

To introduce the topic of software pipelining, let's consider the simple DAXPY loop (double precision a times x plus y) shown below.

```
DO i = 1, n
    v(i) = v(i) + X * w(i)
ENDDO
```


On the MIPS IV architecture, this can be coded as two load instructions followed by a *madd* instruction and a store. See Figure 6-1.

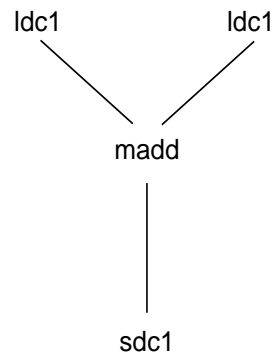


Figure 6-1 A Simple DAXPY Implementation

This simplest schedule achieves the desired result after five cycles. Since the R8000 architecture can allow up to two memory operations and two floating point operations in the same cycle, this simple example uses only one tenth of the R8000's peak megaflops. There is also a delay of three cycles before the results of the *madd* can be stored.

```

0: ldc1 ldc1 madd
1:
2:
3:
4: sdc1
  
```

A loop unrolling by four schedule improves the performance to one quarter of the R8000's peak megaflops.

```

0: ldc1    ldc1    madd
1: ldc1    ldc1    madd
2: ldc1    ldc1    madd
3: ldc1    ldc1    madd
4: sdc1
5: sdc1
6: sdc1
7: sdc1
  
```

But this schedule does not take advantage of the R8000's ability to do two stores in one cycle. The best schedule that could be achieved would look like the following:

```

0: ldc1    ldc1
1: ldc1    ldc1    madd    madd
2: sdc1    sdc1

```

It uses 1/3 of the R8000's peak megaflops. But there still is a problem with the *madd sdc1* interlock delay. Software pipelining addresses this problem.

Software pipelining allows you to mix operations from different loop iterations in each iteration of the hardware loop. Thus the store instructions (which would interlock) in the above example could be used to store the results of different iterations. This can look like the following:

```

L1:
0: t1 = ldc1    t2 = ldc1    t3 = madd t1 X t2
1: t4 = ldc1    t5 = ldc1    t6 = madd t4 X t5
2: sdc1 t7      sdc1 t8      beq DONE

3: t1 = ldc1    t2 = ldc1    t7 = madd t1 X t2
4: t4 = ldc1    t5 = ldc1    t8 = madd t4 X t5
5: sdc1 t3      sdc1 t6      bne L1

DONE:

```

The stores in this loop are storing the *madd* results from previous iterations. But, in general, you could mix any operations from any number of different iterations. Also, note that every loop replication completes two loop iterations in 3 cycles.

In order to properly prepare for entry into such a loop, a windup section of code is added. The windup section sets up registers for the first stores in the main loop. In order to exit the loop properly, a winddown section is added. The winddown section performs the final stores. Any preparation of registers needed for the winddown is done in the compensation section. The winddown section also prevents speculative operations.

```

windup:
0: t1 = ldc1    t2 = ldc1    t7 = madd t1 X t2
1: t4 = ldc1    t5 = ldc1    t8 = madd t4 X t5
L1:
0: t1 = ldc1    t2 = ldc1    t3 = madd t1 X t2
1: t4 = ldc1    t5 = ldc1    t6 = madd t4 X t5
2: sdc1 t7      sdc1 t8      beq compensation1

3: t1 = ldc1    t2 = ldc1    t7 = madd t1 X t2
4: t4 = ldc1    t5 = ldc1    t8 = madd t4 X t5
5: sdc1 t3      sdc1 t6      bne L1

```

```
winddown:
0: sdc1 t7      sdc1 t8      br ALLDONE
```

```
compensation1:
0: t7 = t3      t8 = t6
1: br winddown
```

```
ALLDONE:
```

Our example loop always does loads from at least 4 iterations, so we don't want to start it if we don't want speculative operations and if the trip count is less than 4. The following generalizes our example into a map of a software pipelined loop:

```
/* Precondition for unroll by 2 */
do i = 1, n mod 2
    original loop
enddo

    if ( n-i < 4 ) goto simple_loop
windup:
    ...
/* fp - fence post */
    fp = fp - peel_amount
    ...

swp replication 0:
    ...
    if ( i == fp ) goto compensation 0
    ...
swp replication n - 1:
    ...
    if ( i != fp ) goto swp replication 0

compensation n-1:

winddown:
    ...
    goto done

compensation 0:
/* Move registers to set up winddown */
    rx = ry
    ...
```

```
        goto winddown
        ...

compensation n - 2:
    ...
/* Move registers to set up winddown */
    rx = ry
    goto winddown

simple_loop:

    do i = i,n
        original_loop
    enddo

done:
```

In practice, software pipelining can make a huge difference. Sample benchmark performances see more than 100% improvement when compiled with software pipelining. This makes it clear that in order to get the best performance on the R8000 (**-mips4**), you should compile your application to use software pipelining (**-O3 -r8000**).

Software Pipelining on the R10000

Scheduling for the R10000 (**-r10000**) is somewhat different. First of all, since the R10000 can execute instructions out-of-order, static scheduling techniques are not as critical to its performance. On the other hand, the R10000 supports the prefetch (*pref*) instruction. This instruction is used to load data into the caches before it is needed, reducing memory delays for programs that access memory predictably. In the schedule below, the compiler generates prefetch instructions.

Since the R10000 can execute only one memory instruction and only one *madd* instruction per cycle, there are two open slots available for integer instructions. The R10000 has a delay of three cycles before the results of the *madd* can be stored. It also has delays of three cycles and one cycle before the *madd* can use the result of a load for multiplication and addition, respectively.

The following schedule shows four replications from a daxpy inner loop scheduled for the R10000. Notice how the operands of the *madd* instruction are loaded well ahead of the actual execution of the instruction itself. Notice also that the final replication contains two prefetch instructions. Use of the prefetch instruction is enabled by default with the

-r10000 flag. The other replications each have a hole where the first prefetch instruction is placed. Had prefetch been turned off through the **-LNO:prefetch=0** option, each replication could have been scheduled in three cycles.

```
L1:
0: t0 = ldc1
1:
2: t7 = ldc1
3: sdc1 t2
4: t2 = madd t4 X t5    beq compensation0

0: t4 = ldc1
1:
2: t3 = ldc1
3: sdc1 t2
4: t2 = madd t0 X t1    beq compensation1

0: t0 = ldc1
1:
2: t5 = ldc1
3: sdc1 t2
4: t2 = madd t4 X t7    beq compensation2

0: t4 = ldc1
1: pref
2: t1 = ldc1
3: sdc1 t2
4: t2 = madd t0 X t3    bne L1    pref
```

Looking at the Code Produced by Software Pipelining

The proper way to look at the assembly code generated by software pipelining is to use the **-S** compiler switch. This is vastly superior to using the disassembler (*dis*) because the **-S** switch adds annotations to the assembly code which name out the sections described above.

The annotations also provide useful statistics about the software pipelining process as well as reasons why certain code did not pipeline. To get a summary of these annotations do the following:

```
%f77 -64 -S -O3 -mips4 foo.f
```

This creates an annotated *.s* file

```
%grep '#<swp' foo.s
```

#<swpf is printed for loops that failed to software pipeline. #<swps is printed for statistics and other info about the loops that did software pipeline.

Example 1: Output from Using the -S Compiler Switch

```
%cat test.f
    program test
    real*8 a x(100000),y(100000)
    do i = 1, 2000
        call daxpy(3.7, x, y, 100000)
    enddo
    stop
end

    subroutine daxpy(a, x, y, nn)
    real*8 a x(*),y(*)
    do i = 1, nn, 1
        y(i) = y(i) + a * x(i)
    enddo
    return
end

%f77 -64 -r8000 -mips4 -O3 -S test.f
%grep swps test.s
#<swps>
#<swps> Pipelined loop line 12 steady state
#<swps>
#<swps>    50 estimated iterations before pipelining
#<swps>    2 unrollings before pipelining
#<swps>    3 cycles per 2 iterations
#<swps>    4 flops      ( 33% of peak) (madds count as 2)
#<swps>    2 flops      ( 33% of peak) (madds count as 1)
#<swps>    2 madds      ( 33% of peak)
#<swps>    6 mem refs   (100% of peak)
#<swps>    3 integer ops ( 50% of peak)
#<swps>   11 instructions( 91% of peak)
#<swps>    2 short trip threshold
#<swps>    7 integer registers used
#<swps>    8 float registers used
#<swps>
```

This example was compiled with scheduling for the R8000. It shows that the inner loop starting at line 12 was software pipelined. The loop was unrolled two times before pipelining. It used 3 cycles for every two loop iterations and calculated the statistics as follows:

- If each *madd* counts as two floating point operations, the R8000 can do four floating point operations per cycle (two *madds*), so its peak for this loop is 12. Four floating point references are 4/12 or 33% of peak. The figure for *madds* is likewise calculated.
- If each *madd* counts as one floating point operation, the R8000 can do two floating point operations per cycle, so its peak for this loop is 6. Two floating point operations are 2/6 or 33% of peak.
- The R8000 can do two memory operations per cycle, so its peak for this loop is 6. Six memory references are 6/6 or 100% of peak.
- The R8000 can do two integer operations per cycle, so its peak for this loop is six. Three integer operations are 3/6 or 50% of peak.
- The R8000 can do four instructions per cycle, so its peak for this loop is 12. Eleven instructions are 11/12 or 91% of peak. The statistics also point out that loops of less than 2 iterations would not go through the software pipeline replication area, but would be executed in the **simple_loop** section shown above and that a total of seven integer and eight floating point registers were used in generating the code.

If the example would have been compiled with scheduling for the R10000, the following results would have been obtained.

```
%f77 -64 -r10000 -mips4 -O3 -S test.f
%grep swps test.s
#<swps>
#<swps> Pipelined loop line 12 steady state
#<swps>
#<swps> 25 estimated iterations before pipelining
#<swps> 4 unrollings before pipelining
#<swps> 14 cycles per 4 iterations
#<swps> 8 flops      ( 28% of peak) (madds count as 2)
#<swps> 4 flops      ( 14% of peak) (madds count as 1)
#<swps> 4 madds      ( 28% of peak)
#<swps> 12 mem refs  ( 85% of peak)
#<swps> 3 integer ops ( 10% of peak)
#<swps> 19 instructions( 33% of peak)
#<swps> 2 short trip threshold
#<swps> 7 integer registers used
#<swps> 15 float registers used
#<swps>
```

The statistics are tailored to the R10000 architectural characteristics. They show that the inner loop starting at line 12 was unrolled four times before being pipelined. It used 14 cycles for every four loop iterations and the percentages were calculated as follows:

- The R10000 can do two floating point operations per cycle (one *multiply* and one *add*), so its floating point operations peak for this loop is 28. If each *madd* instruction counts as a *multiply* and an *add*, the number of operations in this loop are 8/28 or 28% of peak.
- If each *madd* counts as one floating point instruction, the R10000 can do two floating point operations per cycle (one *multiply* and one *add*), so its peak for this loop is 28. Four floating point operations (four *madds*) are 4/28 or 14% of peak.
- The R10000 can do one *madd* operation per cycle, so its peak for this loop is 14. Four *madd* operations are 4/14 or 28% of peak.
- The R10000 can do one memory operation per cycle, so its peak for this loop is 14. Three memory references are 12/14 or 85% of peak.

Note: prefetch operations are sometimes not needed in every replication. The statistics will miss them if they are not in replication 0 and they will understate the number of memory references per cycle while overstating the number of cycles per iteration.

- The R10000 can do two integer operations per cycle, so its peak for this loop is 28. Three integer operations are 3/28 or 10% of peak.
- The R10000 can do four instructions per cycle, so its peak for this loop is 56. Nineteen instructions are 19/56 or 33% of peak. The statistics also point out that loops of less than 2 iterations would not go through the software pipeline replication area, but would be executed in the **simple_loop** section shown above and that a total of seven integer and fifteen floating point registers were used in generating the code.

How to Diagnose What Went Wrong

When you don't get much improvement in your application's performance after compiling with software pipelining, you should ask the following questions and consider some possible answers:

1. Did it software pipeline at all?

Software pipelining works only on inner loops. What is more, inner loops with subroutine calls or complicated conditional branches do not software pipeline.

2. How well did it pipeline?

Look at statistics in the `.s` file.

3. What can go wrong in code that was software pipelined?

Your generated code may not have the operations you expected.

4. Think about how you would hand code it.

What operations did it need?

Look at the loop in the .s file.

Is it very different? Why?

Sometimes this is human error. (Improper code, or typo.)

Sometimes this is a compiler error.

Perhaps the compiler didn't schedule tightly. This can happen because there are unhandled recurrence divides (Divides in general, are a problem) and because there are register allocation problems (running out of registers).

Matrix Multiply – A Tuning Case Study

Matrix multiplication illustrates some of the issues in compiling for the R8000 and R10000. Consider the simple implementation.

```
do j = 1,n
  do i = 1,m
    do k = 1 , p
      c(i,j) = c(i,j) - a(i,k)*b(k,j)
```

As mentioned before, the R8000 is capable of issuing two *madds* and two memory references per cycle. This simple version of matrix multiply requires 2 loads in the inner loop and one *madd*. Thus at best, it can run at half of peak speed. Note, though, that the same locations are loaded on multiple iterations. By unrolling the loops, we can eliminate some of these redundant loads. Consider for example, unrolling the outer loop by 2.

```
do j = 1,n,2
  do i = 1,m
    do k = 1 , p
      c(i,j) = c(i,j) - a(i,k)*b(k,j)
      c(i,j+1) = c(i,j+1) - a(i,k)*b(k,j+1)
```

We now have 3 loads for two *madds*. Further unrolling can bring the ratio down further. On the other hand, heavily unrolled loops require many registers. Unrolling too much can lead to register spills. The loop nest optimizer (LNO) tries to balance these trade-offs.

Below is a good compromise for the matrix multiply example on the R8000. It is generated by LNO using the **-O3** and **-r8000** flags. The listing file is generated using **-FLIST:=ON** option.

```
%f77 -64 -O3 -r8000 -FLIST:=ON mmul.f
%cat mmul.w2f.f
C *****
C Fortran file translated from WHIRL Fri May 17 15:51:30 1997
C *****

                PROGRAM MAIN
                IMPLICIT NONE

C
C**** Variables and functions ****
C
                REAL*8 a(100_8, 100_8)
                REAL*8 b(100_8, 100_8)
                REAL*8 c(100_8, 100_8)
                INTEGER*4 j
                INTEGER*4 i
                INTEGER*4 k

C
C**** Temporary variables ****
C
                REAL*8 mi0
                REAL*8 mi1
                REAL*8 mi2
                REAL*8 mi3
                REAL*8 mi4
                REAL*8 mi5
                REAL*8 mi6
                REAL*8 mi7

C
C**** statements ****
C
                DO j = 1, 10, 2
                  DO i = 1, 20, 4
                    mi0 = c(i, j)
                    mi1 = c(i + 3, j + 1)
                    mi2 = c(i, j + 1)
                    mi3 = c(i + 3, j)
                    mi4 = c(i + 2, j + 1)
                    mi5 = c(i + 1, j)
                    mi6 = c(i + 2, j)
```

```

mi7 = c(i + 1, j + 1)
DO k = 1, 20, 1
  mi0 = (mi0 -(a(i, k) * b(k, j)))
  mi2 = (mi2 -(a(i, k) * b(k, j + 1)))
  mi5 = (mi5 -(a(i + 1, k) * b(k, j)))
  mi7 = (mi7 -(a(i + 1, k) * b(k, j + 1)))
  mi6 = (mi6 -(a(i + 2, k) * b(k, j)))
  mi4 = (mi4 -(a(i + 2, k) * b(k, j + 1)))
  mi3 = (mi3 -(a(i + 3, k) * b(k, j)))
  mi1 = (mi1 -(a(i + 3, k) * b(k, j + 1)))
END DO
c(i + 1, j + 1) = mi7
c(i + 2, j) = mi6
c(i + 1, j) = mi5
c(i + 2, j + 1) = mi4
c(i + 3, j) = mi3
c(i, j + 1) = mi2
c(i + 3, j + 1) = mi1
c(i, j) = mi0
END DO
END DO
WRITE(6, '(F18.10)') c(9, 8)
STOP
END ! MAIN

```

The outermost loop is unrolled by two as suggested above and the second loop is unrolled by a factor of four. Note that we have not unrolled the inner loop. The code generation phase of the compiler back end can effectively unroll inner loops automatically to eliminate redundant loads.

In optimizing for the R10000, LNO unrolls both loops by a factor 2. LNO can also automatically tile the code to improve cache behavior. You can use the **-LNO:** option group flags to describe your cache characteristics to LNO. For more information, please consult the *MIPSpro Compiling, Debugging and Performance Tuning Guide*.

```

%f77 -64 -O3 -r10000 -FLIST:=ON mmul.f
%cat mmul.w2f.f
C *****
C Fortran file translated from WHIRL Fri May 17 15:54:13 1997
C *****

```

```

PROGRAM MAIN
IMPLICIT NONE

```

```

C
C**** Variables and functions ****
C
      REAL*8 a(100_8, 100_8)
      REAL*8 b(100_8, 100_8)
      REAL*8 c(100_8, 100_8)
      INTEGER*4 j
      INTEGER*4 i
      INTEGER*4 k

C
C**** Temporary variables ****
C
      REAL*8 mi0
      REAL*8 mi1
      REAL*8 mi2
      REAL*8 mi3

C
C**** statements ****
C
      DO j = 1, 10, 2
        DO i = 1, 20, 2
          mi0 = c(i, j)
          mi1 = c(i + 1, j + 1)
          mi2 = c(i, j + 1)
          mi3 = c(i + 1, j)
          DO k = 1, 20, 1
            mi0 = (mi0 -(a(i, k) * b(k, j)))
            mi2 = (mi2 -(a(i, k) * b(k, j + 1)))
            mi3 = (mi3 -(a(i + 1, k) * b(k, j)))
            mi1 = (mi1 -(a(i + 1, k) * b(k, j + 1)))
          END DO
          c(i + 1, j) = mi3
          c(i, j + 1) = mi2
          c(i + 1, j + 1) = mi1
          c(i, j) = mi0
        END DO
      END DO
      WRITE(6, '(F18.10)') c(9, 8)
      STOP
      END ! MAIN

```

Use of the IVDEP Directive

The *IVDEP* (Ignore Vector Dependencies) directive was started in Cray Fortran. It is a Fortran or C *pragma* that tells the compiler to be less strict when it is deciding whether it can get parallelism between loop iterations. By default, the compilers do the safe thing: they try to prove to that there is no possible conflict between two memory references. If they can prove this, then it is safe for one of the references to pass the other.

In particular, you need to be able to perform the load from iteration $i+1$ before the store from iteration i if you want to be able to overlap the calculation from two consecutive iterations.

Now suppose you have a loop like:

```
do i = 1, n
  a(l(i)) = a(l(i)) + ...
enddo
```

The compiler has no way to know that

```
&a(l(i)) != &a(l(i+1))
```

without knowing something about the vector l . For example, if every element of l is 5, then

```
&a(l(i)) == &a(l(i+1))
```

for all values of i .

But you sometimes know something the compiler doesn't. Perhaps in the example above, l is a permutation vector and all its elements are unique. You'd like a way to tell the compiler to be less conservative. The *IVDEP* directive is a way to accomplish this.

Placed above a loop, the statement:

```
cdir$ ivdep
```

tells the compiler to assume there are no dependencies in the code.

The MIPSpro v7.x compilers provide support for three different interpretations of the *IVDEP* directive, because there is no clearly established standard. Under the default interpretation, given two memory references, where at least one is loop variant, the compiler will ignore any loop-carried dependences between the two references. Some examples:

```
do i = 1,n
  b(k) = b(k) + a(i)
enddo
```

Use of *IVDEP* will not break the dependence since $b(k)$ is not loop variant.

```
do i=1,n
  a(i) = a(i-1) + 3.
enddo
```

Use of *IVDEP* does break the dependence but the compiler warns the user that it's breaking an obvious dependence.

```
do i=1,n
  a(b(i)) = a(b(i)) + 3.
enddo
```

Use of *IVDEP* does break the dependence.

```
do i = 1,n
  a(i) = b(i)
  c(i) = a(i) + 3.
enddo
```

Use of *IVDEP* does not break the dependence on $a(i)$ since it is within an iteration.

The second interpretation of *IVDEP* is used if you use the **-OPT:cray_ivdep=TRUE** command line option. Under this interpretation, the compiler uses Cray semantics. It breaks all lexically backwards dependences. Some examples:

```
do i=1,n
  a(i) = a(i-1) + 3.
enddo
```

Use of *IVDEP* does break the dependence but the compiler warns the user that it's breaking an obvious dependence.

```
do i=1,n
  a(i) = a(i+1) + 3.
enddo
```

Use of *IVDEP* does not break the dependence since the dependence is from the load to the store, and the load comes lexically before the store.

The third interpretation of *IVDEP* is used if you use the `-OPT:liberal_ivdep=TRUE` command line option. Under this interpretation, the compiler will break all dependences.

Note: *IVDEP* IS DANGEROUS! If your code really isn't free of vector dependences, you may be telling the compiler to perform an illegal transformation which will cause your program to get wrong answers. But, *IVDEP* is also powerful and you may very well find yourself in a position where you need to use it. You just have to be very careful when you do this.

Vector Intrinsic Functions

The MIPSpro 64-bit compilers support both single and double precision versions of the following vector intrinsic functions: `asin()`, `acos()`, `atan()`, `cos()`, `exp()`, `log()`, `sin()`, `tan()`, `sqrt()`. In C they are declared as follows:

```
/* single precision vector routines */
extern __vacosf( float *x, float *y, int count, int stridex, int stridey );
extern __vasinf( float *x, float *y, int count, int stridex, int stridey );
extern __vatanf( float *x, float *y, int count, int stridex, int stridey );
extern __vcosf( float *x, float *y, int count, int stridex, int stridey );
extern __vexpf( float *x, float *y, int count, int stridex, int stridey );
extern __vlogf( float *x, float *y, int count, int stridex, int stridey );
extern __vsinf( float *x, float *y, int count, int stridex, int stridey );
extern __vtanf( float *x, float *y, int count, int stridex, int stridey );
/* double precision vector routines */
extern __vacos( double *x, double *y, int count, int stridex, int stridey );
extern __vasin( double *x, double *y, int count, int stridex, int stridey );
extern __vatan( double *x, double *y, int count, int stridex, int stridey );
extern __vcos( double *x, double *y, int count, int stridex, int stridey );
extern __vexp( double *x, double *y, int count, int stridex, int stridey );
extern __vlog( double *x, double *y, int count, int stridex, int stridey );
extern __vsin( double *x, double *y, int count, int stridex, int stridey );
extern __vtan( double *x, double *y, int count, int stridex, int stridey )
```

The variables `x` and `y` are assumed to be pointers to non-overlapping arrays. Each routine is functionally equivalent to the following pseudo-code fragment:

```
do i = 1, count-1
    y[i*stridey] = func(x[i*stridex])
enddo
```

where `func()` is the scalar version of the vector intrinsic.

Performance and Accuracy

The vector intrinsics are optimized and software pipelined to take advantage of the R8000's performance features. Throughput is several times greater than that of repeatedly calling the corresponding scalar function though the result may not necessarily agree to the last bit. For further information about accuracy and restrictions of the vector intrinsics please refer to your *IRIX Compiler_dev Release Notes*.

Manual vs. Automatic Invocation

All of the vector intrinsics can be called explicitly from your program. In Fortran the following example invokes the vector intrinsic **vexpf0**.

```
real*4 x(N), y(N)
integer*8 N, i
i = 1
call vexpf$( %val(%loc(x(1))),
&           %val(%loc(y(1))),
&           %val(N),%val(i),%val(i))
end
```

The compiler at optimization level **-O3** also recognizes the use of scalar versions of these intrinsics on array elements inside loops and turns them into calls to the vector versions. If you need to turn this feature off to improve the accuracy of your results, add **-LNO:vint=OFF** to your compilation command line or switch to a lower optimization level.

Miscellaneous FAQ

This chapter summarizes important concepts found throughout this manual in the form of frequently asked questions and their answers.

Q. Why can't I link my 32-bit application with a 64-bit library?

A. There are differences in the subroutine calling interface.

Q. How can I see what LNO does to my code?

A. To view the file, use `-LNO:FLIST=ON` on your compile line
`%f77 -64 -LNO:FLIST=ON foo.f`

Q. How can I see what the automatic parallelizer does to my code when I add `-pfa` to my command line.?

A. To generate the listing file, use `-pfa keep` on your compile line
`%f77 -pfa keep foo.f`

Q. My `/tmp` directory becomes full when I do a compile. What should I do?

A. `%setenv TMP_DIR /directory` on a free partition.

Q. How do I know which compiler is being invoked?

A. `cc -show` will show each of the components as they are being run.

- Q. My 64-bit shared application gets mysterious messages from *rld* at runtime. What is the problem?
- A. It's possible that you are linking with 32-bit *.so*'s. Check and reset your *_RLD_ROOT* environment variable.
- Q. How can I avoid always setting **-32**, **-n32** or **-64** on my compilation command line?
- A. `%setenv SGI_ABI -32`
`%setenv SGI_ABI -n32` or
`%setenv SGI_ABI -64.`
- Q. How do I know if my code software pipelined OK?
- A. Compile your file (say *foo.f*) **-64 -O3 -mips4 -S**. Then `grep #<swp foo.s#`
#<swpf will be printed for loops that failed to software pipeline.
#<swps will be printed for statistics and other info about the loops that did software pipeline.
- Q. I compiled **-O**, but my code did not software pipeline. Why not?
- A. Software pipelining occurs at **-O3**. **-O** implies **-O2**.
- Q. Ok, I now compiled **-O3**. Why didn't my code software pipeline?
- A. Does it have a call or branch in the inner loop?
Is the inner loop too long?
Does the inner loop execute too few iterations?
Are there divide recurrences in your inner loop?
- Q. What predefine should my source code look at to know if its being compiled 32-bit or 64-bit.
- A. One way is:
`#if (_MIPS_SZLONG == 64)`

Q. How can I force a large loop to be unrolled by the compiler?

A. Add **-OPT:unroll_size=1000** to your command line?

Q. Why does my application gets different floating point numbers in 64-bit mode on an R8000 system?

A. If its compiled with optimization, the order of operations may different resulting in slightly different calculations due to rounding. *madd* instructions also round differently than a multiply and an add. The math libraries use different algorithms.

Q. If I just do **%cc hello.c** which ABI is the default?

A. If no */etc/compiler.defaults* file is present and *SGL_ABI* is not set, the 64-bit ABI is the default on R8000 systems. On all other systems, the 32-bit ABI is the default.

Q. What does the **-r10000** flag do?

A. It produces code scheduled for the R10000 microprocessor.
It enables use of the pre-fetch instruction.
It instructs the linker to use math libraries that are customized for the R10000.

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