Mac OS X Runtime Architecture

This manual describes Enterprise Objects Framework Release 1.0

Writing: A. Matt Rollefson, Jun Suzuki
Book design: Karin Stroud
Production: Glen Frank
Illustration: Stephen Osborn
Art and Production management: Terri FitzMaurice
With help from: Kevin Enderby
Technical publications management: Ron Hayden

Contents

Table of Contents

Chapter 1

PowerPC Runtime Conventions

This chapter covers specific low-level details of the PowerPC runtime environment, including the following:

- data storage types
- stack structure
- routine calling conventions

These conventions may be useful for low-level programming (if you are writing in assembly language, for example) or for optimizing higher-level code.

Data Types

The following table lists the binary data types and their sizes in the PowerPC runtime environment.

Type	Size (bytes)	Alignment (bytes)	Range	Notes
UInt8	1	1	0 to 255	
SInt8	1	1	–128 to 127	
SInt16	2	2	–32,768 to 32,767	
UInt16	2	2	0 to 65,535	
SInt32	4	4	-2^{-31} to $2^{31} -1$	
UInt32	4	4	0 to $2^{32}-1$	
Boolean	1	1		0 = false, nonzero = true
float	4	4	±(2^{-149} to 2^{127})	IEEE 754 standard
double	8	8	±(2^{-1074} to 2^{1023})	IEEE 754 standard
Pointer	4	4	0 to FFFFFFFF	

All numeric and pointer data types are stored in big-endian format (that is, high bytes first, then low bytes). Signed integers use two's-complement representation.

Data Alignment

The PowerPC runtime environment supports multiple data alignment modes. These alignments fall into two categories:

- the **natural alignment**, which is the alignment of a data type when allocated in memory or assigned a memory address
- the **embedding alignment**, which is the alignment of a data type within a composite data item

For example, the alignment of a `UInt16` variable may differ from that of a `UInt16` data item embedded in a data structure.

Note: Data items passed as parameters in a routine call have their own special alignment rules. See "Routine Calling Conventions," beginning on page 16, for more information.

The binary data type table shows the natural alignment of each data type, which is simply the size of the data type. This alignment is fixed.

In data structures, you can specify an embedding alignment that varies depending on the alignment mode selected. Typically you can select the alignment mode using compiler options or pragmas. The table below shows the possible alignment modes.

Data type	PowerPC	68K	Packed	Natural
SInt8 UInt8 Boolean	1	1	1	1
SInt16 UInt16	2	2	1	2
SInt32 UInt32	4	2	1	4
float	4	2	1	4
double	4 or 8	2	1	8
Pointer	4	2	1	4
Composite	4 or 8	2	1	16

In all but the 68K alignment mode, the embedding alignment of a composite (for example, a data structure or an array) is determined by the largest embedding alignment of its members. The total size of a composite is rounded up to be a multiple of its embedded alignment.

In 68K alignment mode, the embedded alignment of a composite is always 2 bytes. The total size of the composite is rounded up to a multiple of two.

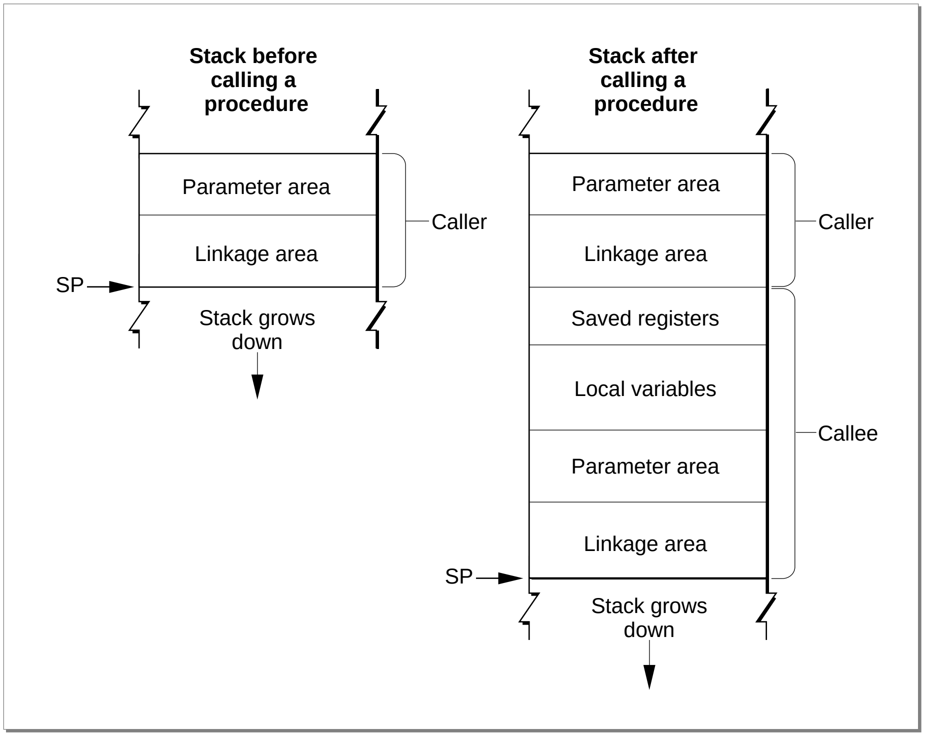
In PowerPC alignment mode, if the first embedded element in a data structure is type `double`, then the embedding alignment of all type `double` members in the structure is 8. In such cases, the embedding alignment for the entire structure is also 8 bytes.

Note that you may need to adjust embedded alignments if you are converting code from the classic 68K environment to the PowerPC (or CFM-68K) runtime environments. If you wish to enforce classic 68K alignment on your PowerPC code, you can often specify compiler pragmas or options to do so. Note, however, that the PowerPC processor is less efficient when accessing data that is not placed according to its natural alignment.

PowerPC Stack Structure

The PowerPC runtime environment uses a grow-down stack that contains linkage information, local variables, and a routine's parameter information as shown in Figure 1..

Figure 1. The PowerPC stack

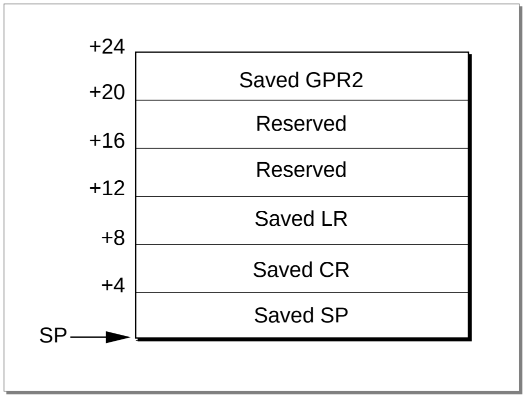


The typical PowerPC stack conventions use only a stack pointer (held in register GPR1) and no frame pointer. This configuration assumes a fixed stack frame size, which is known at compile time. Parameters are not passed by pushing them onto the stack.

The calling routine's stack frame includes a parameter area and some linkage information. The **parameter area** has space for the parameters of any routines the caller calls (*not* the parameters of the caller itself). Since the calling routine might call several different routines, the parameter area must be large enough to accomodate the largest parameter list of all the routines the caller calls. It is the calling routine's responsibility for setting up the parameter area before each call to some other routine, and the called routine's responsibility for accessing the parameters placed within it. See “Routine Calling Conventions,” beginning on page 16, for more information about the calling conventions.

The calling routine’s **linkage area** holds a number of values, some of which are saved by the calling routine and some by the called routine. Figure 2. shows the structure of the linkage area.

Figure 2. A stack frame’s linkage area



The elements within the linkage area are as follows:

- The base register (GPR2) value is saved at `20(SP)` by the calling routine prior to the call if the call is to an imported routine or the call is a pointer-based call (which may or may not be cross-fragment). This ensures that the calling routine can still access its own direct data area upon return. Local calls do not need to save this value.

- The Link Register (LR) value is saved at `8(SP)` by the *called routine* if it chooses to do so.

- The Condition Register (CR) value may be saved at `4(SP)` by the *called routine*. As with the Link Register value, the called routine is not required to save this value.

- The stack pointer is always saved by the calling routine as part of its stack frame.

Note that the linkage area is at the top of the stack, adjacent to the stack pointer. This positioning is necessary so the calling routine can find and restore the values stored there and also to enable the called routine to find the caller’s parameter area. This placement means that a routine cannot push and pop parameters from the stack once the stack frame is set up.

The stack frame also includes space for the called routine's local variables. In general, the general-purpose registers GPR13 through GPR31 and the floating-point registers FPR14 through FPR31 are reserved for the routine's local variables. However, if the routine contains more local variables than would fit in the registers, it uses additional space on the stack. The size of the local variable area is determined at compile time; once a stack frame is allocated, the size of the local variable area cannot change.

Prologs and Epilogs

The called routine is responsible for allocating its own stack frame, making sure to preserve 16-byte alignment on the stack. This action is accomplished by the prolog before entering the actual routine. The compiler-generated prolog code does the following:

- Decrements the stack pointer to account for the new stack frame.
- Writes the previous value of the stack pointer to its own linkage area. This procedure ensures that the stack can be restored to its original state after returning from the call.
- Saves all nonvolatile general-purpose and floating-point registers into the saved-registers area. Note that if the called routine does not change a particular nonvolatile register, it does not save it.
- Saves the Link Register and Condition Register values in the caller's linkage area, if needed.

Note: The order in which the prolog executes these actions is determined by convention, not by any requirements of the PowerPC runtime architecture.

The following is a sample of prolog code. Note that the order of these actions differs from the order previously described.

```
linkageArea: set 24           ; size in PowerPC environment
params: set 32                ; callee parameter area
localVars: set 0              ; callee local variables
numGPRs: set 0                ; volatile GPRs used by callee
numFPRs: set 0                ; volatile FPRs used by callee)

spaceToSave: set linkageArea + params + localVars
spaceToSave: set spaceToSave + 4*numGPRs + 8*numFPRs

.moo:                         ; PROLOG
  mflr   r0,                  ; extract return address
  stw    r0,8(SP)             ; save the return address
  stwu   SP, -spaceToSave(SP) ; skip over caller save area
```

After the called routine exits, the epilog code executes, which does the following:

- Restores the nonvolatile general-purpose and floating-point registers that were saved in the stack frame.
- Restores the Condition Register and Link Register values that were stored in the linkage area.
- Restores the stack pointer to its previous value.
- Returns to the calling routine using the address stored in the Link Register.

Below is some sample epilog code.

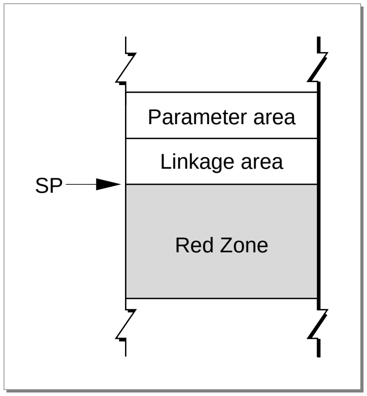
```
                                        ; EPILOG
    lwz     r0,spaceToSave(SP)+8        ; get the return address
    mtlr    R0                          ; reset Link Register
    addic   SP,SP,spaceToSave           ; restore stack pointer
    blr                                 ; return
```

The calling routine is responsible for restoring its GPR2 value immediately after returning from the called routine.

The Red Zone

The space beneath the stack pointer, where a new stack frame would normally be allocated, is called the Red Zone. This area, as shown in Figure 3., may be used for any purpose as long as a new stack frame does not need to be added to the stack.

Figure 3. The Red Zone



For example, the Red Zone may be used by a leaf procedure. A leaf procedure is a routine that does not call any other routines. Since it does not call any other routines, it does not need to allocate a parameter area on the stack. Furthermore, if it does not need to use the stack to store local variables, it need save and restore only the nonvolatile registers that it uses for local variables. Since by definition no more than one leaf procedure is active at any time, there is no possibility of multiple leaf procedures competing for the same Red Zone space.

A leaf procedure does not allocate a stack frame nor does it decrement the stack pointer. Instead it stores the Link Register and Condition Register values in the linkage area of the routine that calls it (if necessary) and stores the values of any nonvolatile registers it uses in the Red Zone. This streamlining means that a leaf procedure's prolog and epilog do only minimal work; they do not have to set up and take down a stack frame.

When an exception handler is called, the Exception Manager automatically decrements the stack pointer by 224 bytes (the largest possible area used to save registers), to skip over any possible Red Zone information, and then restores the stack pointer when the handler exits. The Exception Manager does this because an exception handler cannot know in advance if a leaf procedure is executing at the time the exception occurs. If you are writing code that modifies the stack at interrupt time, you must similarly decrement the stack pointer by 224 bytes to preserve any Red Zone information and restore it after the interrupt call.

Note: The value of 224 bytes is the space occupied by nineteen 32-bit general-purpose registers plus eighteen 64-bit floating-point registers, rounded up to the nearest 16-byte boundary. If a leaf procedure's Red Zone usage would exceed 224 bytes, then it must set up a stack frame just like routines that call other routines.

Routine Calling Conventions

This section details the process of passing parameters or other information to a routine in the PowerPC runtime environment.

Note: These parameter passing conventions are part of Apple's standard for procedural interfaces. Object-oriented languages may use different rules for their own method calls. For example, the conventions for C++ virtual function calls may be different from those for C functions.

Indirect Calls

A routine that branches indirectly to another routine must store the target of the call in the GPR12 register. This convention applies to all code used with the dynamic compiler flag, which is on by default for all user code. It does not apply to kernel or driver code. Standardizing the register used to store the target address makes it possible to optimize dynamic code generation in the future. All code must adhere to this standard from the very first release of Mac OS X compilers in order to take advantage of it later.

As an example, the following code:

```
foo() {
  bar();
}
```

Compiled with this command:

```
% cc -arch ppc -S -O foo.c
```

Produces the following assembly output:

```
.text
  .align 2
.globl _foo
_foo:
  mflr r0
  stw r0,8(r1)
  stwu r1,-64(r1)
# end prolog
  bl L_bar$stub
# start epilog
  addi r1,r1,64
  lwz r0,8(r1)
  mtlr r0
  blr

.picsymbol_stub
L_bar$stub:
  .indirect_symbol _bar
  mflr r0
  bl L0$_bar
L0$_bar:
  mflr r11
  mtlr r0
# load value to branch to into r12 from lazy pointer location
  addis r11,r11,ha16(L_bar$lazy_ptr-L0$_bar)
  lwz r12,lo16(L_bar$lazy_ptr-0L0$_bar)(r11)
# move branch location to the counter register
  mtctr r12
```

```
    addi r11,r11,lo16(L_bar$lazy_ptr-L0$_bar)
    bctr
  .lazy_symbol_pointer
  L_bar$lazy_ptr:
    .indirect_symbol _bar
    .long dyld_stub_binding_helper
```

Because the target address needs to be stored in a register in any event, this convention simply standardizes what register to use. Routines that may have been called directly should not depend on the value of GR12, because in the case of a direct call its value is not defined.

Parameters

A routine can have a fixed or variable number of arguments. In an ANSI-style C syntax definition, a routine with a variable number of arguments typically appears with ellipsis points (…) at the end of its input parameter list.

A variable-argument routine may have several required (that is, fixed) parameters preceding the variable parameter portion. For example, the routine definition

`mooColor(`*number*`,` [*color1. . .*]`)`

gives no restriction on the number of *color* arguments, but you must always precede them with a *number* argument. Therefore, *number* is a fixed parameter.

Typically the calling routine passes parameters in registers. However, the compiler generates a parameter area in the caller's stack frame that is large enough to hold all parameters passed to the called routine, regardless of how many of the parameters are actually passed in registers. There are several reasons for this scheme:

- It provides the callee with space to store a register-based parameter if it wants to use one of the parameter registers for some other purpose (for instance, to pass parameters to a subroutine).
- Routines with variable-length parameter lists must often access their parameters from RAM, not from registers. Such routines must reserve eight registers (32 bytes) in the parameter area to hold the parameter values.
- To simplify debugging, some compilers may write parameters from the parameter registers into the parameter area in the stack frame; this allows you to see all the parameters by looking only at that parameter area.

You can think of the parameter area as a data structure that has space to hold all the parameters in a given call. The parameters are placed in the structure from left to right according to the following rules:

- All parameters are aligned on 4-byte (word) boundaries.
- Noncomposite parameters smaller than 4 bytes occupy the low order bytes of their word.
- Composite parameters (such as data structures) are followed by padding to make a multiple of 4 bytes, with the padding bytes being undefined.

For a routine with fixed parameters, the first 8 words (32 bytes) of the data structure, no matter the size of the individual parameters, are passed in registers according to the following rules:

- The first 8 words are placed in GPR3 through GPR10 unless a floating-point parameter is encountered.
- Floating-point parameters are placed in the floating-point registers FPR1 through FPR13.
- If a floating-point parameter appears before all the general-purpose registers are filled, the corresponding GPRs that match the size of the floating-point parameter are skipped. For example, a `float` item causes one (4-byte) GPR to be skipped, while an item of type `double` causes two GPRs to be skipped.
- If the number of parameters exceeds the number of usable registers, the calling routine writes the excess parameters into the parameter area of its stack frame.

Note: Currently the parameter area must be at least 8 words (32 bytes) in size.

For example, consider a routine `mooFunc` with this declaration:

```
void mooFunc (SInt32 i1, float f1, double d1, SInt16 s1, double d2,
                UInt8 c1, UInt16 s2, float f2, SInt32 i2);
```

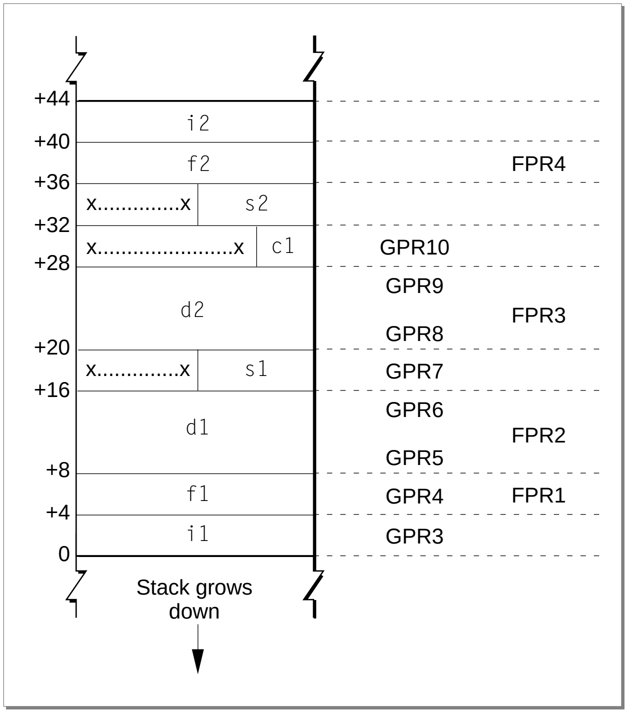
To see how the parameters of `mooFunc` are arranged in the parameter area on the stack, first convert the parameter list into a structure, as follows:

```
struct params {
  SInt32                p_i1;
  float                 p_f1;
  double                p_d1;
  SInt16                p_s1;
  double                p_d2;
  UInt8                 p_c1;
  UInt16                p_s2;
  float                 p_f2;
  SInt32                p_i2;
};
```

This structure serves as a template for constructing the parameter area on the stack. (Remember that, in actual practice, many of these variables are passed in registers; nonetheless, the compiler still allocates space for all of them on the stack, for the reasons just mentioned.)

The "top" position on the stack is for the field pi_1 (the structure field corresponding to parameter i1). The floating-point field p_f1 is assigned to the next word in the parameter area. The 64-bit double field p_d1 is assigned to the next two words in the parameter area. Next, the short integer field p_s1 is placed into the following 32-bit word; the original value of p_s1 is in the lower half of the word, and the padding is in the upper half. The remaining fields of the params structure are assigned space on the stack in exactly the same way, with unsigned values being extended to fill each field to make it a 32-bit word. The final arrangement of the stack is illustrated in Figure 4.. (Because the stack grows down, it looks as though the fields of the params structure are upside down.)

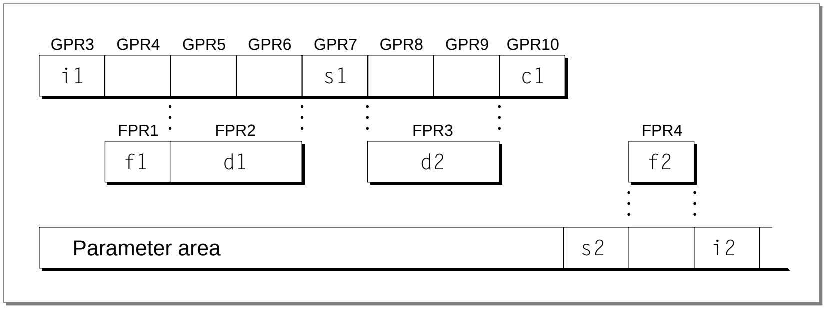
Figure 4. The organization of the parameter area of the stack



To see which parameters are passed in registers and which are passed on the stack, you need to map the stack, as illustrated in Figure 4., to the available general-purpose and floating-point registers. Therefore, the parameter i1 is passed in GPR3, the first available general-purpose register. The floating-point parameter f1 is passed in FPR1, the first available floating-point register. This action causes GPR4 to be skipped.

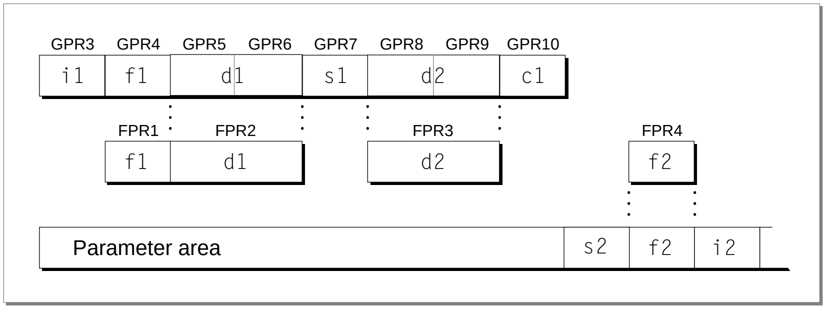
The parameter d1 is placed into FPR2 and the corresponding general-purpose registers GPR5 and GPR6 are unused. The parameter s1 is placed into the next available general-purpose register, GPR7. Parameter d2 is placed into FPR3, with GPR8 and GPR9 masked out. Parameter c1 is placed into GPR10, which fills out the first 8 words of the data structure. Parameter s2 is then passed in the parameter area of the stack. Parameter f2 is passed in FPR4, since there are still floating-point registers available. Finally, parameter i2 is passed on the stack. Figure 5. shows the final layout of the parameters in the registers and the parameter area.

Figure 5. Parameter layout in registers and the parameter area



If you have a C routine with a variable number of parameters (that is, one that does not have a fixed prototype), the compiler cannot know whether to pass a parameter in the variable portion of the routine in the general-purpose (that is, fixed-point) registers or in the floating-point registers. Therefore, the compiler passes the parameter in both the floating-point and the general-purpose registers, as shown in Figure 6..

Figure 6. Passing a variable number of parameters



The called routine can access parameters in the fixed portion of the routine definition as usual. However, in the variable-argument portion of the routine, the called routine must copy the GPRs to the parameter area and access the values from there. The code below shows a routine that accesses values by walking through the stack.

```
double dsum (int count, ...)
{
  double sum = 0.0;
  double * arg = (double *) (&count + 1 /* pointer arithmetic */);
  while (count > 0 ) {
      sum += *arg;
      arg += 1;   /* pointer arithmetic */
      count -= 1;
  }
  return sum;
}
```

Function Return

In the PowerPC runtime environment, floating-point function values are returned in register FPR1 (or FPR1 and FPR2 for long double values). Other values are returned in GPR3 as follows:

- Functions returning simple values smaller than 4 bytes (such as type `SInt8`, `Boolean`, or `SInt16`) place the return value in the least significant byte or bytes of GPR3. The most significant bytes in GPR3 are undefined.

- Functions returning 4-byte values (such as pointers, including array pointers, or types `SInt32` and `UInt32`) return them normally in GPR3.

- If a function returns a composite value (for example, a `struct` or `union` data type) or a value larger than 4 bytes, a pointer must be passed as an implicit left-most parameter before passing all the user-visible arguments (that is, the address is passed in GPR3, and the actual parameters begin with GPR4). The address of the pointer must be a memory location large enough to hold the function return value. Since GPR3 is treated as a parameter in this case, its value is not guaranteed on return.

Register Preservation

The following table lists registers used in the PowerPC runtime environment and their volatility in routine calls. Registers that retain their value after a routine call are called *nonvolatile*. All registers are 4 bytes long.

Type	Register	Preserved by a routine call?	Notes
General- purpose register	GPR0	No	
	GPR1	See next column	Used as the stack pointer to store parameters and other temporary data items.
	GPR2	See next column	Used as the base register to access the direct data area. GPR2 is preserved by direct calls; for indirect calls the caller must restore the value after the call.
	GPR3	See next column	Holds the return value or the address of the return value in function calls. For routine calls that do not return a value, GPR3 is used to pass parameter values.
	GPR4-GPR10	No	Used to pass parameter values in routine calls.
	GPR11	No	
	GPR12	No	Set to the value of the target before an indirect call for dynamic code generation. Unless a routine knows it's been called indirectly, it should not depend on the value of this register.
	GPR13-GPR31	Yes	
Floating- point register	FPR0	No	
	FPR1-FPR13	No	Used to pass floating- point parameters in routine calls.
	FPR14-FPR31	Yes	
Link Register	LR	No	Stores the return address of the calling routine during a routine call.
Count Register	CTR	No	
Fixed-point exception register	XER	No	
Condition Registers	CR0-CR1	No	

Type	Register	Preserved by a routine call?	Notes
Condition Registers *(continued)*	CR2-CR4	Yes	
	CR5-CR7	No	