

Procedure Calls

Young W. Lim

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1 Introduction

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- Transferring Control
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- Procedure Definition Example
- Direct / Indirect Call Examples
- Recursive Procedure Example

- ① "Self-service Linux: Mastering the Art of Problem Determination",

Mark Wilding

- ① "Computer Architecture: A Programmer's Perspective", Bryant & O'Hallaron

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Compiling 32-bit program on 64-bit gcc

- `gcc -v`
- `gcc -m32 t.c`
- `sudo apt-get install gcc-multilib`
- `sudo apt-get install g++-multilib`
- `gcc-multilib`
- `g++-multilib`
- `gcc -m32`
- `objdump -m i386`

- procedure calls
 - passing procedure arguments
 - storing return informations
 - saving registers for later restoration
 - local storage
- stack frame:
 - the portion of the stack allocated for a single procedure call

Descending full stack

- Descending stack
 - stack grows toward lower addresses
 - push decreases %esp (growing stack)
 - pop increases %esp (shrinking stack)
- Full stack
 - contains a valid data at %esp address

Stack frame pointers

- Frame Pointer (%ebp)
 - the highest address of a stack frame
 - bottom of a stack frame
- Stack Pointer (%esp)
 - the lowest address of a stack frame
 - top of a stack frame
- read access via %ebp
 - the stack pointer can move while the procedure is executing
 - most information is accessed relative to the frame pointer

Stack frame structures (1)

- suppose procedure P (caller) calls procedure Q (callee)

the stack frame for P (caller)	<ul style="list-style-type: none">- argument values to Q- return address to P
the stack frame for Q (callee)	<ul style="list-style-type: none">- P's frame pointer (%ebp)- saved registers- local variables- temporaries- Q's arguments to other functions

Stack frame structures (2)

- the stack frame for P (caller)
 - the **argument** to Q are contained within the stack frame for P
 - the **return address** within P is pushed on the stack forming the end of P's stack frame
- the stack frame for Q (callee)
 - starts with the saved value of the **frame pointer** for P
 - followed by copies of any other saved values of **registers** (callee saved)
 - **local variables**

- procedure Q also uses the stack for any local variables that cannot be stored in registers
 - when there are not enough registers to hold all of the local data
 - when the local variables are arrays or structures and hence must be accessed by array or structure references
 - the address operator & is applied to one of the local variables and hence we must be able to generate an address for it
- Q will use the stack frame for storing arguments to any procedure it calls

Caller's Viewpoint

————— H.I.G.H. A.D.D.R.E.S.S. —————

- frame pointer (%ebp)
- saved registers
- local variables
- temporaries

-
- arguments for a function call to the callee
 - return address
 - stack pointer (%esp)

————— L.O.W. A.D.D.R.E.S.S. —————

local variables > function arguments > return address

Callee's Viewpoint

H.I.G.H. A.D.D.R.E.S.S.

- `%ebp+c`: argument 2 from the caller
- `%ebp+8`: argument 1 from the caller
- `%ebp+4`: return address of the caller

-
- frame pointer (`%ebp`) : caller's `%ebp` stored
 - saved registers of the callee
 - local variables of the callee
 - temporaries of the callee

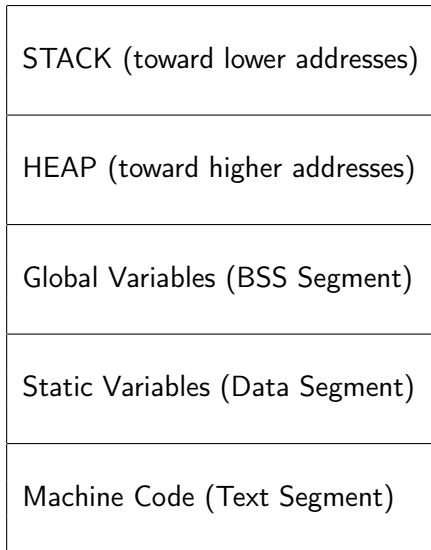
L.O.W. A.D.D.R.E.S.S.

function arguments > return address > caller's `%ebp` > local variables

Stack Frames & Heap

```
----- H.I.G.H. A.D.D.R.E.S.S. -----  
STACK (stack frame grows toward lower addresses)  
.....  
stack Frame #1      v v v v  
.....  
stack Frame #2      v v v v  
.....  
                    v v v v  
.....  
stack Frame #n      v v v v  
-----  
  
-----  
                    ^ ^ ^ ^  
                    ^ ^ ^ ^  
                    ^ ^ ^ ^  
-----  
- HEAP (heap grows toward higher address)  
-----
```

Stack Frames & Memory Map



Procedure Instructions

Procedure Call	<code>call</code> label	direct call
	<code>call</code> *operand	indirect call
Procedure Return	<code>leave</code>	stack preparation
	<code>ret</code>	return from call

Direct / indirect call / jump

- direct call / jump
 - `call label` or `jmp label`
- indirect call / jump
 - `call *%eax` or `jmp *%eax`
uses the value in register `%eax` as the call/jump target
 - `call *(%eax)` or `jmp *(%eax)`
reads the call/jump target from memory
using the value in `%eax` as the read address

<code>call label</code>	direct call
<code>call *operand</code>	indirect call

<code>jmp label</code>	direct jump
<code>jmp *operand</code>	indirect jump

Operand Addressing Modes

Imm		M[Imm]	Absolute
Imm	(Eb)	M[Imm + R[Eb]]	Base + displace
Imm	(Eb, Ei)	M[Imm + R[Eb] + R[Ei]]	Indexed
Imm	(, Ei, s)	M[Imm + R[Ei]*s]		Scaled Indexed
Imm	(Eb, Ei, s)	M[Imm + R[Eb] + R[Ei]*s]		Scaled Indexed
	(Ea)	M[R[Ea]]	Indirect
	(Eb, Ei)	M[R[Eb] + R[Ei]]	Indexed
	(, Ei, s)	M[R[Ei]*s]		Scaled Indexed
	(Eb, Ei, s)	M[R[Eb] + R[Ei]*s]		Scaled Indexed

call Instruction

- **call label** : direct call (without memory reference)
- **call *operand** : indirect call (with memory reference)
 - operand address modes : **Imm (Eb, Ei, s)**
offset **Imm** (base reg **Eb**, index reg **Ei**, scale factor **s**)
- *return address*: the address of the instruction immediately following the call instruction

call instruction

- 1 **pushl** *return addr* : push a return address
- 2 **jmp** *procedure* : jump to the start the called function

ret Instruction

- stack pointer must points to the return address

ret instruction

- 1 `popl return addr`
pops the return address from the stack
- 2 `jmp return addr`
jump to the return address location

- prepare the stack for returning

leave instruction

- `mov %ebp, %esp`
set stack pointer to the beginning of callee's stack
- `pop %ebp`
restore saved `%ebp`
set the stack pointer to the end of caller's stack

- to return the value of any function that returns an integer or pointer register `%eax` is used

Procedure Instruction Summary

<code>call</code>	push a return address jump to a procedure	<code>pushl return addr</code> <code>jmp procedure</code>
<code>ret</code>	pops a retrun address jump to this address	<code>popl return addr</code> <code>jmp return addr</code>
<code>leave</code>	set SP to BP restore BP	<code>movl %ebp, %esp</code> <code>popl %ebp</code>

Setup and finish code in a procedure

call	push a return address jump to a procedure	<code>pushl <i>return addr</i></code> <code>jmp <i>procedure</i></code>
setup	save old %ebp set %esp to %ebp	<code>pushl %ebp</code> <code>movl %esp, %ebp</code>

	function body	function body

finish (leave)	restore %esp restore %ebp	<code>movl %ebp, %esp</code> <code>popl %ebp</code>
ret	pops a retrun address jump to this address	<code>popl <i>return addr</i></code> <code>jmp <i>return addr</i></code>

IA32 conventions for register usage

- the callee should not overwrite some registers that the caller is going to use later

%eax	Caller save register
%ebx	Callee save register
%ecx	Caller save register
%edx	Caller save register
%esi	Callee save register
%edi	Callee save register
%ebp	Frame Pointer
%esp	Stack Pointer

Caller save registers	Callee save registers
%eax	%ebx
%ecx	%esi
%edx	%edi

IA32 conventions for register usage

Caller Save Registers	%eax %ecx %edx	the callee can overwrite these registers
Callee Save Registers	%ebx %esi %edi	the callee must save these registers before using and restore them before returning

Example 1 (1)

- example code 1

```
int P() {  
    int x = f();  
  
    Q(x);  
    return x;  
}
```

- procedure P wants the value it has computed for $x = f()$ to remain valid across the call to $Q(x)$ then to return x

Example 1 (2)

- if x is in a **caller save** register,
then P (the caller) must save the value x
before calling $Q(x)$
and restore x *after* Q *returns*
- if x is in a **callee save** register,
and Q must save the value x
before using the register
and restore x *before returning*
- in either case,
 - saving : pushing the register value onto the stack
 - restoring : popping from the stack back to the register

Example 2 (1)

- example code 2

```
int P (int x)
{
    int y = x*x;           // y is computed here
    int z = Q(y);         // y is passed as an argument

    return y + z;         // y is accessed here also
}
```

- P compute $y=x*x$ before calling $Q(y)$,
but it must also ensure that
the value of y is available
in return $y+z$ after Q returns

Example 2 (2)

- two ways to ensure that the value of y is available in return $y+z$ after Q returns
 - 1 **Caller P** saves y in its own stack frame
 - 2 **Callee Q** saves y in a callee save register
- most commonly, gcc uses the latter conventions, since it tends to reduce the total number of stack accesses

Example 2 (3)

- 1 **Caller P** saves y in its own **stack frame**
 - before calling $Q(y)$,
P can store the value of $y=x*x$ in its own **stack frame**
 - when Q returns, in $z=Q(y)$
P can then retrieve the value of y from the **stack**

Example 2 (4)

- ② Callee Q saves y in a **callee save** register
 - P can store the value of $y=x*x$ in a **callee save** register
 - if Q or any procedures called by Q wants to use this register, it must save the register value in its **stack frame** and restore the value before it returns.
 - thus, when $Q(y)$ returns to P, the value of $z=Q(y)$ will be in the **callee save** register,
 - either because the register was never altered or because it was saved and restored

GCC Example for a procedure call

- the beginning part of an assembly code

```
pushl %edi           ; callee save %edi
pushl %esi           ; callee save %esi
pushl %ebx           ; callee save %ebx
movl 24(%ebp), %eax  ; caller save %eax
imull 15(%ebp), %eax
leal 0(,%eax,4), %ecx ; caller save %ecx
addl 8(%ebp), %ecx
movl %ebx, %edx      ; caller save %edx
```

- the callee save register (%edi, %esi, %ebx)
 - to use the callee save registers in the procedure, they should be save on its stack frame and be restored before returning to the caller
- the caller save register (%eax, %ecx, %edx)
 - these can be modified without saving nor restoring

Procedure definition example code

caller P source code

```
int P() {  
    int a1 = 55;  
    int a2 = 77;  
    int sum = Q( &a1, &a2 );  
    int diff = a1 - a2;  
  
    return sum * diff;  
}
```

callee Q source code

```
int Q(int *xp, int *yp) {  
    int x = *xp;  
    int y = *yp;  
  
    *xp = y;  
    *yp = x;  
    return x+y;  
}
```

Stack Frames contents for P & Q

before calling Q

```
+-----+-----+
%ebp -> | %ebp+0 | saved %ebp |
+-----+-----+
      | %ebp-4 | a2      |
+-----+-----+
      | %ebp-8 | a1      |
+-----+-----+
      | %ebp-12| &a2     |
+-----+-----+
%esp -> | %ebp-16 | &a1     |
+-----+-----+
      |      |      |
+-----+-----+
      |      |      |
+-----+-----+
      |      |      |
+-----+-----+
```

in the body of Q

```
+-----+-----+
      | %ebp+24| saved %ebp |
+-----+-----+
      | %ebp+20| a2      |
+-----+-----+
      | %ebp+16| a1      |
+-----+-----+
      | %ebp+12| &a2     |
+-----+-----+
      | %ebp+ 8| &a1     |
+-----+-----+
      | %ebp+ 4| return adr |
+-----+-----+
%ebp -> | %ebp+ 0 | saved %ebp |
+-----+-----+
%esp -> | %ebp- 4 | saved %ebx |
+-----+-----+
```

Calling code of the caller P (1)

- the stack frame for P includes storage for local variables a1 and a2, at position %ebp-8 and %ebp-4
- Q retrieves its arguments &a1 and &a2 from the stack frame for P

caller P code

```
int P() {  
    int a1 = 55;  
    int a2 = 77;  
    int sum = Q( &a1, &a2 );  
    int diff = a1 - a2;  
  
    return sum * diff;  
}
```

before calling Q

	+-----+-----+
%ebp ->	%ebp+0 saved %ebp
	+-----+-----+
	%ebp-4 a2
	+-----+-----+
	%ebp-8 a1
	+-----+-----+
	%ebp-12 &a2
	+-----+-----+
%esp ->	%ebp-16 &a1
	+-----+-----+

Calling code of the caller P (3)

- the local variable a1 and a2 must be stored on the stack since the addresses &a1 and &a2 need to be computed using leal instruction
- local variables (a2, a1) and arguments (&a2, &a1) are pushed on the stack in the order

calling Q

```
leal  -4(%ebp), %eax    ; compute &a2 (the address value of %ebp-4)
pushl %eax              ; push &a2
leal  -8(%ebp), %eax    ; compute &a1 (the address value of %ebp-8)
pushl %eax              ; push &a1
call  Q                 ; call Q() function
```

Function code of the callee Q

the compiled code for a function has 3 parts

- 1 the **setup** part
the stack frame is initialized
- 2 the **body** part
the actual computation of the procedure is performed
- 3 the **finish** part
the stack state is restored and the procedure returns

Setup code for the callee Q

Setup code for the callee Q

```
Q:
; %ebp : frame pointer of P

; save this old %ebp
pushl %ebp

; set %ebp as a new frame pointer
movl %esp, %ebp

; save %ebx
pushl %ebx
```

- %ebx is used in the callee Q
- %ebx is a callee save register
- %ebx is pushed on the stack

Stack frame of the callee Q

	+-----+-----
	%ebp+24 saved %ebp
	+-----+-----+
	%ebp+20 a2
	+-----+-----+
	%ebp+16 a1
	+-----+-----+
	%ebp+12 &a2
	+-----+-----+
	%ebp+ 8 &a1
	+-----+-----+
	%ebp+ 4 return adr
	+-----+-----+
%ebp ->	%ebp+ 0 saved %ebp
	+-----+-----+
%esp ->	%ebp- 4 saved %ebx
	+-----+-----+

Body code for the callee Q (1)

Body Code for Q

```
;      %edx holds xp
movl  8(%ebp), %edx
;      %ecx holds yp
movl  12(%ebp), %ecx
;      %ebx holds x
movl  (%edx), %ebx
;      %eax holds y
movl  (%ecx), %eax

;      assign y to *xp
movl  %ecx, (%edx)
;      assign x to *yp
movl  %ebx, (%ecx)
;      %eax holds x+y
addl  %ebx, %eax
```

- return value is at %eax

Stack frame of the callee Q

```
+-----+-----+
| %ebp+24 | saved %ebp |
+-----+-----+
| %ebp+20 | a2         |
+-----+-----+
| %ebp+16 | a1         |
+-----+-----+
| %ebp+12 | &a2        |
+-----+-----+
| %ebp+ 8 | &a1        |
+-----+-----+
| %ebp+ 4 | return adr |
+-----+-----+
%ebp -> | %ebp+ 0 | saved %ebp |
+-----+-----+
%esp -> | %ebp- 4 | saved %ebx |
+-----+-----+
```


Body code for the callee Q (2)

Body Code for Q

```
;      %edx holds xp
movl   8(%ebp), %edx
;      %ecx holds yp
movl   12(%ebp), %ecx
;      %ebx holds x
movl   (%edx), %ebx
;      %eax holds y
movl   (%ecx), %eax

;      assign y to *xp
movl   %ecx, (%edx)
;      assign x to *yp
movl   %ebx, (%ecx)
;      %eax holds x+y
addl   %ebx, %eax
```

- return value is at %eax

callee Q source code

```
int Q(int *xp, int *yp) {
    int x = *xp;
    int y = *yp;

    *xp = y;
    *yp = x;
    return x+y;
}
```

Finish code for the callee Q

Finish code for Q

```
; restore %ebx
popl %ebx

; restore %esp
movl %ebp, %esp

; restore %ebp
popl %ebp

; return to the caller
ret
```

Stack frame of the callee Q

```
+-----+-----|
| %ebp+24 | saved %ebp |
+-----+-----+
| %ebp+20 | a2         |
+-----+-----+
| %ebp+16 | a1         |
+-----+-----+
| %ebp+12 | &a2        |
+-----+-----+
| %ebp+ 8 | &a1        |
+-----+-----+
| %ebp+ 4 | return adr |
+-----+-----+
%ebp -> | %ebp+ 0 | saved %ebp |
+-----+-----+
%esp -> | %ebp- 4 | saved %ebx |
+-----+-----|
```

direct / indirect procedure source code

direct procedure

```
int foo(int a) {
    return a;
}

int direct() {
    int i, b = 0;

    for (i = 0; i < INT_MAX; ++i) {
        b = foo(b);
    }

    return b;
}
```

indirect procedure

```
int indirect(int (*fn)(int)) {
    int i, b = 0;

    for (i = 0; i < INT_MAX; ++i) {
        b = fn(b);
    }

    return b;
}
```

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

main procedure

```
int foo(int a) {
    return a;
}

int main(int argc, char *argv[]) {
    if (argc == 2 && argv[1][0] == 'd') {
        return direct();
    }
    else {
        return indirect(&foo);
    }
}
```

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

Direct / indirect call

direct call	indirect call
<code>foo(int a)</code>	<code>int (*fn)(int)</code>
<code>b = foo(b);</code>	<code>b = fn(b);</code>
<code>call _foo</code>	<code>call *%esi</code>

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

direct / indirect procedure assembly code

direct version

```
_foo:
    movl    4(%esp), %eax
    ret

_direct_version:
    subl   $4, %esp
    movl   $2147483647, %edx
    xorl   %eax, %eax
L3:
    movl   %eax, (%esp)
    call  _foo
    subl   $1, %edx
    jne   L3
    addl   $4, %esp
    ret
```

indirect version

```
_indirect_version:
    pushl  %esi
    pushl  %ebx
    xorl   %eax, %eax
    movl   $2147483647, %ebx
    subl   $20, %esp
    movl   32(%esp), %esi
L8:
    movl   %eax, (%esp)
    call  *%esi
    subl   $1, %ebx
    jne   L8
    addl   $20, %esp
    popl   %ebx
    popl   %esi
    ret
```

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

direct procedure source and assembly code

direct procedure

```
int foo(int a) {
    return a;
}

int direct() {
    int i, b = 0;

    for (i = 0; i < INT_MAX; ++i) {
        b = foo(b);
    }

    return b;
}
```

direct version

```
_foo:
    movl    4(%esp), %eax
    ret

_direct_version:
    subl   $4, %esp
    movl   $2147483647, %edx
    xorl   %eax, %eax
L3:
    movl   %eax, (%esp)
    call  _foo
    subl   $1, %edx
    jne   L3
    addl   $4, %esp
    ret
```

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

indirect procedure source and assembly code

indirect procedure

```
int indirect(int (*fn)(int)) {
    int i, b = 0;

    for (i = 0; i < INT_MAX; ++i) {
        b = fn(b);
    }

    return b;
}
```

indirect version

```
_indirect_version:
    pushl   %esi
    pushl   %ebx
    xorl    %eax, %eax
    movl    $2147483647, %ebx
    subl    $20, %esp
    movl    32(%esp), %esi
L8:
    movl    %eax, (%esp)
    call    *%esi
    subl    $1, %ebx
    jne    L8
    addl    $20, %esp
    popl    %ebx
    popl    %esi
    ret
```

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

foo procedure assembly code

- `movl 4(%esp), %eax`
copy argument from stack into %eax
to store the return value from a function

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

direct procedure assembly code

- `subl $4, %esp`
allocate 4 bytes of stack space
to hold the argument when we call `foo()`
- `movl $2147483647, %edx`
`%edx` is the 'i' variable of the for loop
Initialized to `MAX_INT`
- `xorl %eax, %eax`
`%eax` is the 'b' variable
xor will set `eax` to 0.
- `movl %eax, (%esp)`
copy 'b' onto the stack space reserved
to hold the argument for `foo()`.

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

indirect procedure assembly code

- `pushl %esi, pushl %ebx`
push `%esi` and `%ebx` on to the stack
- `xorl %eax, %eax`
`%eax` is the 'b' variable
xor will set `eax` to 0.
- `movl $2147483647, %edx`
`%edx` is the 'i' variable of the for loop
Initialized to `MAX_INT`
- `subl $20, %esp`
allocate 20 bytes of stack space
to hold the argument when we call `foo()`
- `movl 32(%esp), %esi`
`M[%esp+32] -> %esi`

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

Direct and indirect call examples (6)

- differences between the direct and indirect versions
 - the direct version uses 3 instructions to setup before it gets to the for-loop.
the indirect version uses 6.
 - the loop itself is 4 instructions in both cases, but the direct version uses 3 registers (eax, esp and edx) while the indirect version uses 4 (eax, esp, esi, and ebx).
If there were no more registers free, the indirect version would have to add extra code to move variables on and off the stack.

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

Direct and indirect call examples (7)

- The extra setup overhead doesn't matter much, unless the loop count is tiny.
- But the extra register use does matter.
- In real code, register contention is often a problem - it is more of a problem on x86 than instruction sets with more registers, but I don't think we should ignore this cost in any case.

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

Direct and indirect call examples (8)

- To investigate the cost, the code is changed to use additional copies of foo().
- timing the resulting executable, the indirect version is 3.4x slower.

direct procedure ver 2

```
int foo(int a) { return a; }

int bar(int a) { return a; }

int baz(int a) { return a; }

int direct_version() {
    int i, b = 0;
    for (i = 0; i < INT_MAX; ++i) {
        b = foo(b) + bar(b) + baz(b);
    }
    return b;
}
```

indirect procedure ver 2

```
int indirect_version
    (int (*fn)(int),
     int (*fn2)(int),
     int (*fn3)(int)) {
    int i, b = 0;

    for (i = 0; i < INT_MAX; ++i) {
        b = fn(b) + fn2(b) + fn3(b);
    }

    return b;
}
```

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

Direct and indirect call examples (9)

main procedure ver 2

```
int main(int argc, char *argv[]) {
    if (argc == 2 && argv[1][0] == 'd') {
        return direct_version();
    }
    else {
        return indirect_version(&foo, &bar, &baz);
    }
}
```

https://gist.github.com/rianhunter/0be8dc116b120ad5fdd4#file-call_overhead-c-L17

Fibonacci Sequence

```
int fibo(int n) {
    int prev, val;

    if (n <= 2) return 1;
    prev = fibo(n-2);
    val = fibo(n-1);
    return prev + val;
}
```

- multiple outstanding calls
- each call has its own local variables
- allocated only when the procedure is called
- deallocated when it returns

Stack Frames for the caller and the callee

```
%ebp+8 : n
%ebp+4 : return address
%ebp+0 : saved %ebp
...
...
%ebp-20: saved %esi
%ebp-24: saved %ebp
```

after initial setup

```
%ebp+8 : n
%ebp+4 : return address
%ebp+0 : saved %ebp
...
...
%ebp-20: saved %esi
%ebp-24: saved %ebp
...
...
%ebp-40: n-2
```

just before the 1st recursive call

Setup Code for fibo()

fibo:

```
    pushl %ebp
    movl  %esp, %ebp
    subl  $16, %esp
    pushl %esi
    pushl %ebx
```

Set up code

%ebp: frame pointer

alloc 16 bytes on stack

save %esi (-20)

save %ebx (-24)

Body Code for fibo()

```
movl 8(%ebp), %ebx
cmpl $2, %ebx
jle .L24
addl $-12, %esp
leal -2(%ebx), %eax
pushl %eax
call fibo
movl %eax, %esi
addl $-12, %esp
leal -1(%ebx), %eax
pushl %eax
call fibo
addl %esi, %eax
jmp .L25
```

Finish Code for Q()

```
popl %ebx  
movl %ebp, %esp  
popl %ebp  
ret
```

```
restore %ebx  
restore %esp  
restore %ebp  
return to the caller
```