RISC-V Assembly Programming

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Lecture 6

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Contents

1. Assembly Programming
2. Example Startup File
3. Function Call Conventions

Data Processing Instructions

- Example data processing instructions and their descriptions

```
add   x3, x4, x5      // x3 = x4 + x5
addi  x3, x4, 9       // x3 = x4 + 9
xor   x1, x2, x3      // x1 = x2 ^ x3
slt   x2, x4, x6      // x2 = (x4 < x6) ? 1:0
```

```
// load upper immediate (lui) used to build 32-bit constants
lui   x3, imm         // x3 = imm << 12 (20-bit ‘imm’ value)

// add upper immediate to PC (auipc)
auipc x4, imm         // x4 = PC + (imm << 12)
```

Data Processing Instructions Cont'd

- Generating 32-bit constants

```
// Generating 32-bit constant
y = 0x12345678;
```

```
// Assume x6 = y
lui   x6, 0x12345
addi  x6, x6, 0x678
```

Data Processing Instructions Cont'd

- Generating 32-bit constants

```
// Generating 32-bit constant
y = 0x12345678;
```

```
// Assume x6 = y
lui   x6, 0x12345
addi  x6, x6, 0x678
```

```
// Generating 32-bit constant
y = 0x12345A78;
```

```
// Assume x6 = y
lui   x6, 0x12346
addi  x6, x6, 0xFFFFA78
```

Data Transfer Instructions

- Example data transfer instructions and their descriptions

```
lw   x3, 0x23(x5)       // x3 = Mem[x5 + 0x23][31:0]

// loads byte/halfword and sign extends it
lb   x2, 0x34(x4)       // x2 = Mem[x4 + 0x34][7:0]
lh   x2, 0x34(x4)       // x2 = Mem[x4 + 0x34][15:0]

// loads halfword and zero extends it
lhu  x2, 0x34(x4)       // x2 = Mem[x4 + 0x34][15:0]

sh   x8, 0x45(x7)       // Mem[x7 + 0x45][15:0] = x8[15:0]
```

Data Transfer Instructions

- Example data transfer instructions and their descriptions

```
lw   x3, 0x23(x5)      // x3 = Mem[x5 + 0x23][31:0]

// loads byte/halfword and sign extends it
lb   x2, 0x34(x4)      // x2 = Mem[x4 + 0x34][7:0]
lh   x2, 0x34(x4)      // x2 = Mem[x4 + 0x34][15:0]

// loads halfword and zero extends it
lhu  x2, 0x34(x4)      // x2 = Mem[x4 + 0x34][15:0]

sh   x8, 0x45(x7)      // Mem[x7 + 0x45][15:0] = x8[15:0]
```

- Loading a global variable (beyond 12-bit offset range)

```
auipc  x7, 23456      // rd = mem[PC + 0x23456789]
lw     x9, 789(x7)
```

Flow Control Instructions

- Unconditional (jump) and conditional (branch) instructions and their descriptions

```
beq   rs1, rs2, Label       // if(rs1 == rs2) {PC = PC + imm}
blt   rs1, rs2, Label       // if(rs1 < rs2) {PC = PC + imm}

// if x10 >= x11 or x10 < 0, then goto OutOfBound
bgeu  x10, x11, OutOfBound

jal   x1, Label             // x1 = PC + 4; PC = PC + imm
jalr  x1, imm(rs1)          // x1 = PC + 4; PC = rs1 + imm
```

```
ecall                        // Transfer control to OS
ebreak                       // Transfer control to debugger
```

Flow Control Instructions Cont'd

- Calling a nearby (within 12-bit offset range) function

```
jal    ra, Label      // ra = PC + 4; PC = PC + imm = Label
```

Flow Control Instructions Cont'd

- Calling a nearby (within 12-bit offset range) function

```
jal   ra, Label     // ra = PC + 4; PC = PC + imm = Label
```

- Calling a far away (beyond 12-bit offset range) function
- `call` is the corresponding pseudo-assembly instruction

```
auipc ra, 0x12345    // offset = Label - PC = 0x12345678
jalr  ra, 0x678(ra)  // ra = PC + 4; PC = ra + 0x678
```

Assembly Programming: if-else Construct

- if-else in C and assembly
- Assume f $\sim$ x10, g $\sim$ x11, h $\sim$ x12, i $\sim$ x13, j $\sim$ x14

```
if (i == j)
  f = g + h;
else
  f = g - h;
```

Listing 1: C code.

```
  bne    x13, x14, label    # if (i == j)
  add    x10, x11, x12      # f = g + h;
  j      exit

label:
  sub x10,x11,x12           # f = g - h;
exit:
```

Listing 2: Assembly code for if-else.

Assembly Programming: `while` Loop

- GCD algorithm in C and assembly
- Assume a ∼ x8 and b ∼ x9

```c
// GCD implementation based on
    Euclid algorithm
int gcd(int a, int b)
{
    while (a != b)
    {
        if (a > b)
            a = a - b;
        else
            b = b - a;
    }
    return a;
}
```

Listing 3: C code for GCD.

```
    addi   x8, x0, 12
    addi   x9, x0, 9

gcd:
    beq    x8, x9, stop
    blt    x8, x9, less
    sub    x8, x8, x9
    j      gcd
less:
    sub    x9, x9, x8
    j      gcd

stop:
    j      stop
```

Listing 4: GCD assembly code.

Pseudo Assembly Instructions

Table 1: Selected pseudo assembly instructions.

Pseudo Instruction		Base	Instruction	Description
nop		addi	x0, x0, 0	No operation
neg	rd, rs	sub	rd, x0, 0	Two’s complement
j	offset	jal	x0, offset	Jump
mv	rd, rs	addi	rd, rs, 0	Copy register
not	rd, rs	xori	rd, rs,-1	One’s complement
li	rd, imm	lui	rd, imm	Load immediate uses
		addi	rd, rs1, imm	lui and addi
ret		jalr	x0, ra, 0	return from function

Example Startup File

```
.equ CSR_MSTATUS, 0x300
.equ MSTATUS_MIE, 0x00000008
.equ CSR_MTVEC,   0x305

 # Main interrupt vector table entries
.global vtable
.type vtable, %object
.section .text.vector_table,"a",%progbits

# this entry is to align reset_handler at address 0x04
  .word    0x00000013
  j        reset_handler
  .align   2
vtable:
  j        default_interrupt_handler
  .word    0
  .word    0
  j        msip_handler
  .word    0
  .word    0
```

Example Startup File Cont'd

```
    .word     0
    j         mtip_handler
    .word     0
    .word     0
    .word     0
    .word     0
    .word     0
    .word     0
    .word     0
    .word     0
    j         user_handler
    .word     0
    .word     0
```

Example Startup File Cont'd

```
# Weak aliases to point each exception handler to the
# 'default_interrupt_handler', unless the application defines
# a function with the same name to override the reference.

  .weak msip_handler
  .set  msip_handler, default_interrupt_handler
  .weak mtip_handler
  .set  mtip_handler, default_interrupt_handler
  .weak user_handler
  .set  user_handler, default_interrupt_handler

# Assembly 'reset handler' function to initialize core CPU registers.
.section .text.default_interrupt_handler,"ax",%progbits

.global reset_handler
.type reset_handler,@function

reset_handler:
# Set mstatus bit MIE = 1 (enable M mode interrupts)
  li      t0, 8
  csrrs   zero, CSR_MSTATUS, t0
```

Example Startup File Cont'd

```
# Load the initial stack pointer value.
  la   sp, _sp

# Set the vector table's base address.
  la   a0, vtable
  addi a0, a0, 1
  csrw CSR_MTVEC, a0

# Call user 'main(0,0)' (.data/.bss sections initialized there)
  li   a0, 0
  li   a1, 0
  call main

# A 'default' handler, in case an interrupt triggers without its
    handler defined
default_interrupt_handler:
  j default_interrupt_handler
```

Example Interrupt Service Routine

```
# RISC-V Interrupt Service Routines (ISRs)
# ALL supported ISRs should be put here

.section .text.isr

# User interrupt handler
.globl user_handler
user_handler:
  nop
  # you can call user ISR here and then return using 'mret'
  mret
```

Function Call Conventions

- Function parameters and return values conventions
  - Put parameters in a place where the function being called (`callee`) can access them
  - Transfer control to the callee
  - Acquire (local) resources required by the callee
  - Perform desired task of the callee
  - Put result(s) in a place where `caller` (point of origin) can access it
  - Return control to caller

Function Call Conventions Cont'd

- Registers for parameter passing
  - Registers are faster than memory, use them for parameter passing and return values
  - a0–a7 (x10-x17): eight registers for passing parameters
  - a0–a1 (x10-x11): two registers for return values
  - ra (x1): return address register to return to point of origin

Function Call Conventions Cont'd

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  - ra (x1): return address register to return to point of origin
- Registers preserved across function calls
  - sp, gp, tp, s0- s11 (saved registers, s0 is also frame pointer (fp))

Function Call Conventions Cont'd

- Registers for parameter passing
  - Registers are faster than memory, use them for parameter passing and return values
  - a0–a7 (x10-x17): eight registers for passing parameters
  - a0–a1 (x10-x11): two registers for return values
  - ra (x1): return address register to return to point of origin
- Registers preserved across function calls
  - sp, gp, tp, s0- s11 (saved registers, s0 is also frame pointer (fp))
- Registers that are not preserved across function calls
  - a0-a7 (argument and return registers), ra, t0-t6 (temporary registers)

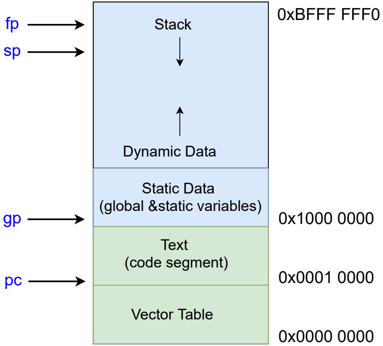
Function Call Conventions Cont'd

Table 2: Assembler mnemonics and register conventions for RV32I.

Register	ABI Name	Description	Saver
x0	zero	Hardwired to 0	—
x1	ra	Return address for subroutine calls	Caller
x2	sp	Stack pointer	Callee
x3	gp	Global Pointer	—
x4	tp	Thread pointer	—
x5-x7	t0-t2	Memory temporary registers	Caller
x8	s0/fp	Frame pointer	Callee
x9	s1	Saved register	Callee
x10-x11	a0-a1	Arguments to subroutines/return values	Caller
x12-x17	a2-a7	Arguments to subroutines	Caller
x18-x27	s2-s11	Saved registers	Callee
x28-x31	t3-t6	Temporary registers	Caller

Memory Allocation

- An example memory allocation for program and data



Caller-Callee Working Example

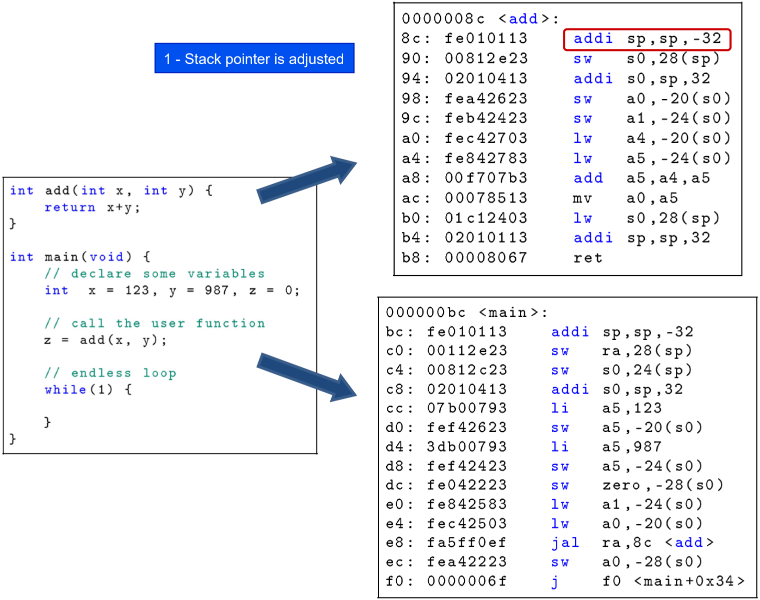
```
int add(int x, int y) {
 return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

    // call the user function
    z = add(x,y);

    // endless loop
    while(1){}
}
```

Caller-Callee Working Example Cont'd



1 - Stack pointer is adjusted

```
0000008c <add>:
8c: fe010113    addi  sp,sp,-32
90: 00812e23    sw    s0,28(sp)
94: 02010413    addi  s0,sp,32
98: fea42623    sw    a0,-20(s0)
9c: feb42423    sw    a1,-24(s0)
a0: fec42703    lw    a4,-20(s0)
a4: fe842783    lw    a5,-24(s0)
a8: 00f707b3    add   a5,a4,a5
ac: 00078513    mv    a0,a5
b0: 01c12403    lw    s0,28(sp)
b4: 02010113    addi  sp,sp,32
b8: 00008067    ret
```

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

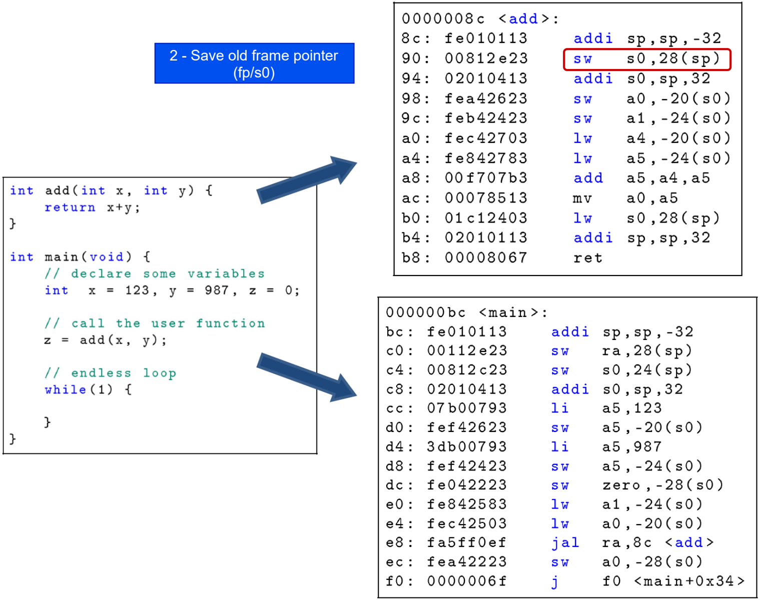
    // call the user function
    z = add(x, y);

    // endless loop
    while(1) {

    }
}
```

```
000000bc <main>:
bc: fe010113    addi  sp,sp,-32
c0: 00112e23    sw    ra,28(sp)
c4: 00812c23    sw    s0,24(sp)
c8: 02010413    addi  s0,sp,32
cc: 07b00793    li    a5,123
d0: fef42623    sw    a5,-20(s0)
d4: 3db00793    li    a5,987
d8: fef42423    sw    a5,-24(s0)
dc: fe042223    sw    zero,-28(s0)
e0: fe842583    lw    a1,-24(s0)
e4: fec42503    lw    a0,-20(s0)
e8: fa5ff0ef    jal   ra,8c <add>
ec: fea42223    sw    a0,-28(s0)
f0: 0000006f    j     f0 <main+0x34>
```

Caller-Callee Working Example Cont'd



2 - Save old frame pointer (fp/s0)

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

    // call the user function
    z = add(x, y);

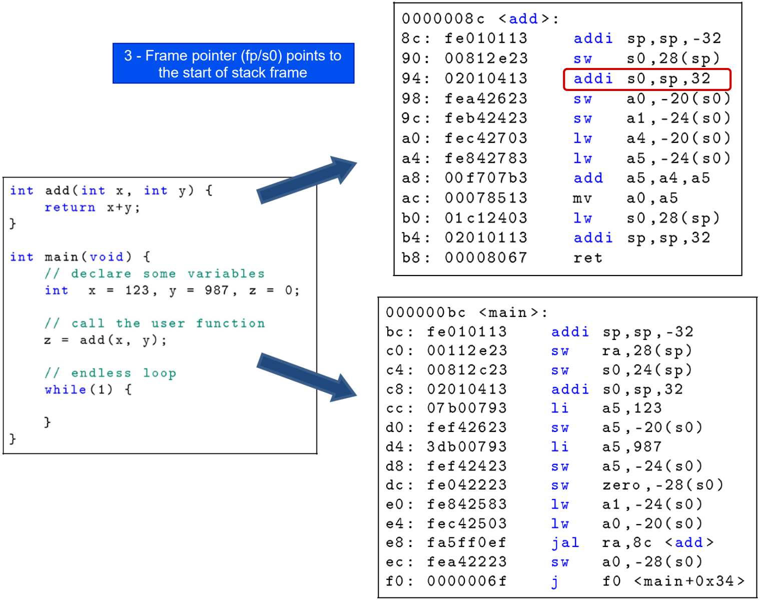
    // endless loop
    while(1) {

    }
}
```

```
0000008c <add>:
8c:  fe010113     addi  sp,sp,-32
90:  00812e23     sw    s0,28(sp)
94:  02010413     addi  s0,sp,32
98:  fea42623     sw    a0,-20(s0)
9c:  feb42423     sw    a1,-24(s0)
a0:  fec42703     lw    a4,-20(s0)
a4:  fe842783     lw    a5,-24(s0)
a8:  00f707b3     add   a5,a4,a5
ac:  00078513     mv    a0,a5
b0:  01c12403     lw    s0,28(sp)
b4:  02010113     addi  sp,sp,32
b8:  00008067     ret
```

```
000000bc <main>:
bc:  fe010113     addi  sp,sp,-32
c0:  00112e23     sw    ra,28(sp)
c4:  00812c23     sw    s0,24(sp)
c8:  02010413     addi  s0,sp,32
cc:  07b00793     li    a5,123
d0:  fef42623     sw    a5,-20(s0)
d4:  3db00793     li    a5,987
d8:  fef42423     sw    a5,-24(s0)
dc:  fe042223     sw    zero,-28(s0)
e0:  fe842583     lw    a1,-24(s0)
e4:  fec42503     lw    a0,-20(s0)
e8:  fa5ff0ef     jal   ra,8c <add>
ec:  fea42223     sw    a0,-28(s0)
f0:  0000006f     j     f0 <main+0x34>
```

Caller-Callee Working Example Cont'd



3 - Frame pointer (fp/s0) points to the start of stack frame

```
0000008c <add>:
8c: fe010113    addi  sp,sp,-32
90: 00812e23    sw    s0,28(sp)
94: 02010413    addi  s0,sp,32
98: fea42623    sw    a0,-20(s0)
9c: feb42423    sw    a1,-24(s0)
a0: fec42703    lw    a4,-20(s0)
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b0: 01c12403    lw    s0,28(sp)
b4: 02010113    addi  sp,sp,32
b8: 00008067    ret
```

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

    // call the user function
    z = add(x, y);

    // endless loop
    while(1) {

    }
}
```

```
000000bc <main>:
bc: fe010113    addi  sp,sp,-32
c0: 00112e23    sw    ra,28(sp)
c4: 00812c23    sw    s0,24(sp)
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dc: fe042223    sw    zero,-28(s0)
e0: fe842583    lw    a1,-24(s0)
e4: fec42503    lw    a0,-20(s0)
e8: fa5ff0ef    jal   ra,8c <add>
ec: fea42223    sw    a0,-28(s0)
f0: 0000006f    j     f0 <main+0x34>
```

Caller-Callee Working Example Cont'd

4 - Save the function arguments

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

    // call the user function
    z = add(x, y);

    // endless loop
    while(1) {

    }
}
```

```
0000008c <add>:
8c: fe010113    addi  sp,sp,-32
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b0: 01c12403    lw    s0,28(sp)
b4: 02010113    addi  sp,sp,32
b8: 00008067    ret
```

```
000000bc <main>:
bc: fe010113    addi  sp,sp,-32
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dc: fe042223    sw    zero,-28(s0)
e0: fe842583    lw    a1,-24(s0)
e4: fec42503    lw    a0,-20(s0)
e8: fa5ff0ef    jal   ra,8c <add>
ec: fea42223    sw    a0,-28(s0)
f0: 0000006f    j     f0 <main+0x34>
```

Caller-Callee Working Example Cont'd

5 - Make a local copy of the function arguments

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

    // call the user function
    z = add(x, y);

    // endless loop
    while(1) {

    }
}
```

```
0000008c <add>:
8c: fe010113    addi  sp,sp,-32
90: 00812e23    sw    s0,28(sp)
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a0: fec42703    lw    a4,-20(s0)
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a8: 00f707b3    add   a5,a4,a5
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bc: fe010113    addi  sp,sp,-32
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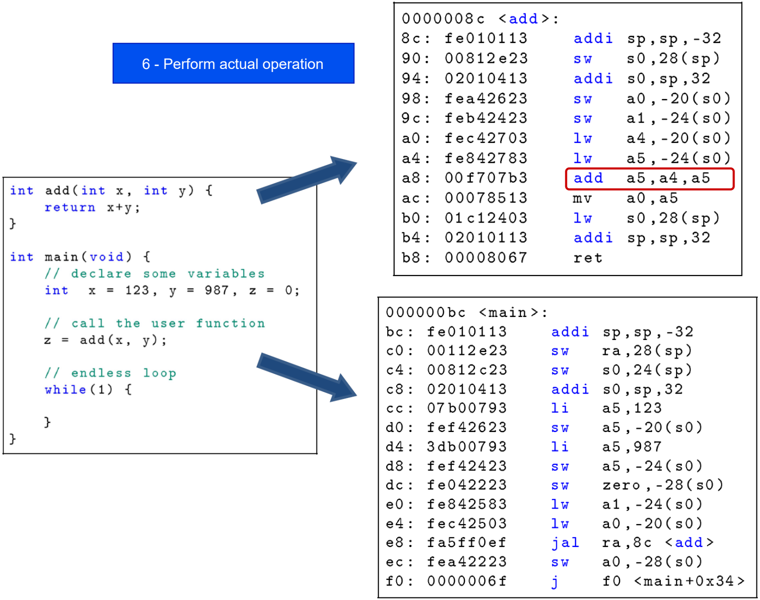
Caller-Callee Working Example Cont'd



6 - Perform actual operation

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

    // call the user function
    z = add(x, y);

    // endless loop
    while(1) {

    }
}
```

```
0000008c <add>:
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a4:  fe842783     lw    a5,-24(s0)
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d8:  fef42423    sw    a5,-24(s0)
dc:  fe042223    sw    zero,-28(s0)
e0:  fe842583    lw    a1,-24(s0)
e4:  fec42503    lw    a0,-20(s0)
e8:  fa5ff0ef    jal   ra,8c <add>
ec:  fea42223    sw    a0,-28(s0)
f0:  0000006f    j     f0 <main+0x34>
```

Caller-Callee Working Example Cont'd

7 - Return the result

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

    // call the user function
    z = add(x, y);

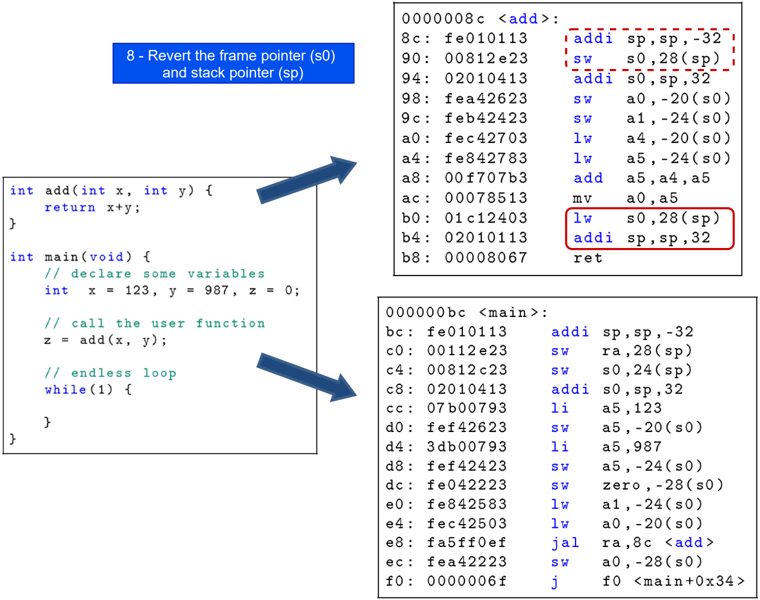
    // endless loop
    while(1) {

    }
}
```

```
0000008c <add>:
8c: fe010113    addi  sp,sp,-32
90: 00812e23    sw    s0,28(sp)
94: 02010413    addi  s0,sp,32
98: fea42623    sw    a0,-20(s0)
9c: feb42423    sw    a1,-24(s0)
a0: fec42703    lw    a4,-20(s0)
a4: fe842783    lw    a5,-24(s0)
a8: 00f707b3    add   a5,a4,a5
ac: 00078513    mv    a0,a5
b0: 01c12403    lw    s0,28(sp)
b4: 02010113    addi  sp,sp,32
b8: 00008067    ret
```

```
000000bc <main>:
bc: fe010113    addi  sp,sp,-32
c0: 00112e23    sw    ra,28(sp)
c4: 00812c23    sw    s0,24(sp)
c8: 02010413    addi  s0,sp,32
cc: 07b00793    li    a5,123
d0: fef42623    sw    a5,-20(s0)
d4: 3db00793    li    a5,987
d8: fef42423    sw    a5,-24(s0)
dc: fe042223    sw    zero,-28(s0)
e0: fe842583    lw    a1,-24(s0)
e4: fec42503    lw    a0,-20(s0)
e8: fa5ff0ef    jal   ra,8c <add>
ec: fea42223    sw    a0,-28(s0)
f0: 0000006f    j     f0 <main+0x34>
```

Caller-Callee Working Example Cont'd



8 - Revert the frame pointer (s0) and stack pointer (sp)

```
0000008c <add>:
8c:  fe010113    addi  sp,sp,-32
90:  00812e23    sw    s0,28(sp)
94:  02010413    addi  s0,sp,32
98:  fea42623    sw    a0,-20(s0)
9c:  feb42423    sw    a1,-24(s0)
a0:  fec42703    lw    a4,-20(s0)
a4:  fe842783    lw    a5,-24(s0)
a8:  00f707b3    add   a5,a4,a5
ac:  00078513    mv    a0,a5
b0:  01c12403    lw    s0,28(sp)
b4:  02010113    addi  sp,sp,32
b8:  00008067    ret
```

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

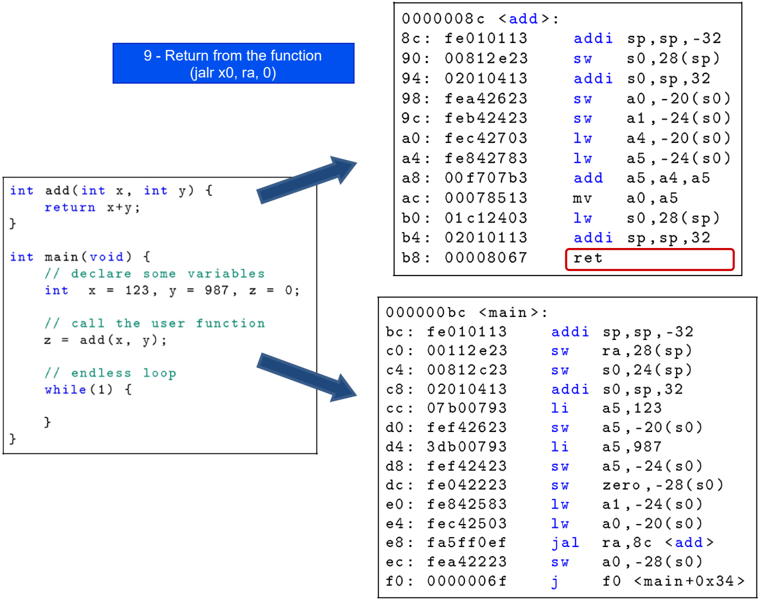
    // call the user function
    z = add(x, y);

    // endless loop
    while(1) {

    }
}
```

```
000000bc <main>:
bc:  fe010113    addi  sp,sp,-32
c0:  00112e23    sw    ra,28(sp)
c4:  00812c23    sw    s0,24(sp)
c8:  02010413    addi  s0,sp,32
cc:  07b00793    li    a5,123
d0:  fef42623    sw    a5,-20(s0)
d4:  3db00793    li    a5,987
d8:  fef42423    sw    a5,-24(s0)
dc:  fe042223    sw    zero,-28(s0)
e0:  fe842583    lw    a1,-24(s0)
e4:  fec42503    lw    a0,-20(s0)
e8:  fa5ff0ef    jal   ra,8c <add>
ec:  fea42223    sw    a0,-28(s0)
f0:  0000006f    j     f0 <main+0x34>
```

Caller-Callee Working Example Cont'd



9 - Return from the function
(jalr x0, ra, 0)

```
0000008c <add>:
8c: fe010113    addi  sp,sp,-32
90: 00812e23    sw    s0,28(sp)
94: 02010413    addi  s0,sp,32
98: fea42623    sw    a0,-20(s0)
9c: feb42423    sw    a1,-24(s0)
a0: fec42703    lw    a4,-20(s0)
a4: fe842783    lw    a5,-24(s0)
a8: 00f707b3    add   a5,a4,a5
ac: 00078513    mv    a0,a5
b0: 01c12403    lw    s0,28(sp)
b4: 02010113    addi  sp,sp,32
b8: 00008067    ret
```

```
int add(int x, int y) {
    return x+y;
}

int main(void) {
    // declare some variables
    int  x = 123, y = 987, z = 0;

    // call the user function
    z = add(x, y);

    // endless loop
    while(1) {

    }
}
```

```
000000bc <main>:
bc: fe010113    addi  sp,sp,-32
c0: 00112e23    sw    ra,28(sp)
c4: 00812c23    sw    s0,24(sp)
c8: 02010413    addi  s0,sp,32
cc: 07b00793    li    a5,123
d0: fef42623    sw    a5,-20(s0)
d4: 3db00793    li    a5,987
d8: fef42423    sw    a5,-24(s0)
dc: fe042223    sw    zero,-28(s0)
e0: fe842583    lw    a1,-24(s0)
e4: fec42503    lw    a0,-20(s0)
e8: fa5ff0ef    jal   ra,8c <add>
ec: fea42223    sw    a0,-28(s0)
f0: 0000006f    j     f0 <main+0x34>
```

Suggested Reading

- Read Chapter 2 of [Patterson and Hennessy, 2021].
- Read User Manual for the instruction set and its architecture [Waterman et al., 2016b].

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