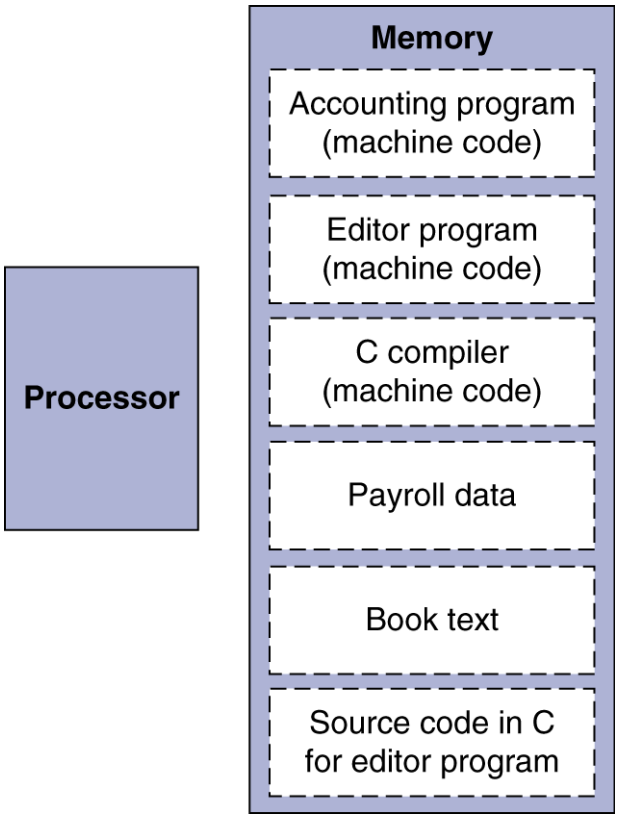
Topic 3

Assembly Programming
- Function (Procedure) Call

Stored Program

The BIG Picture

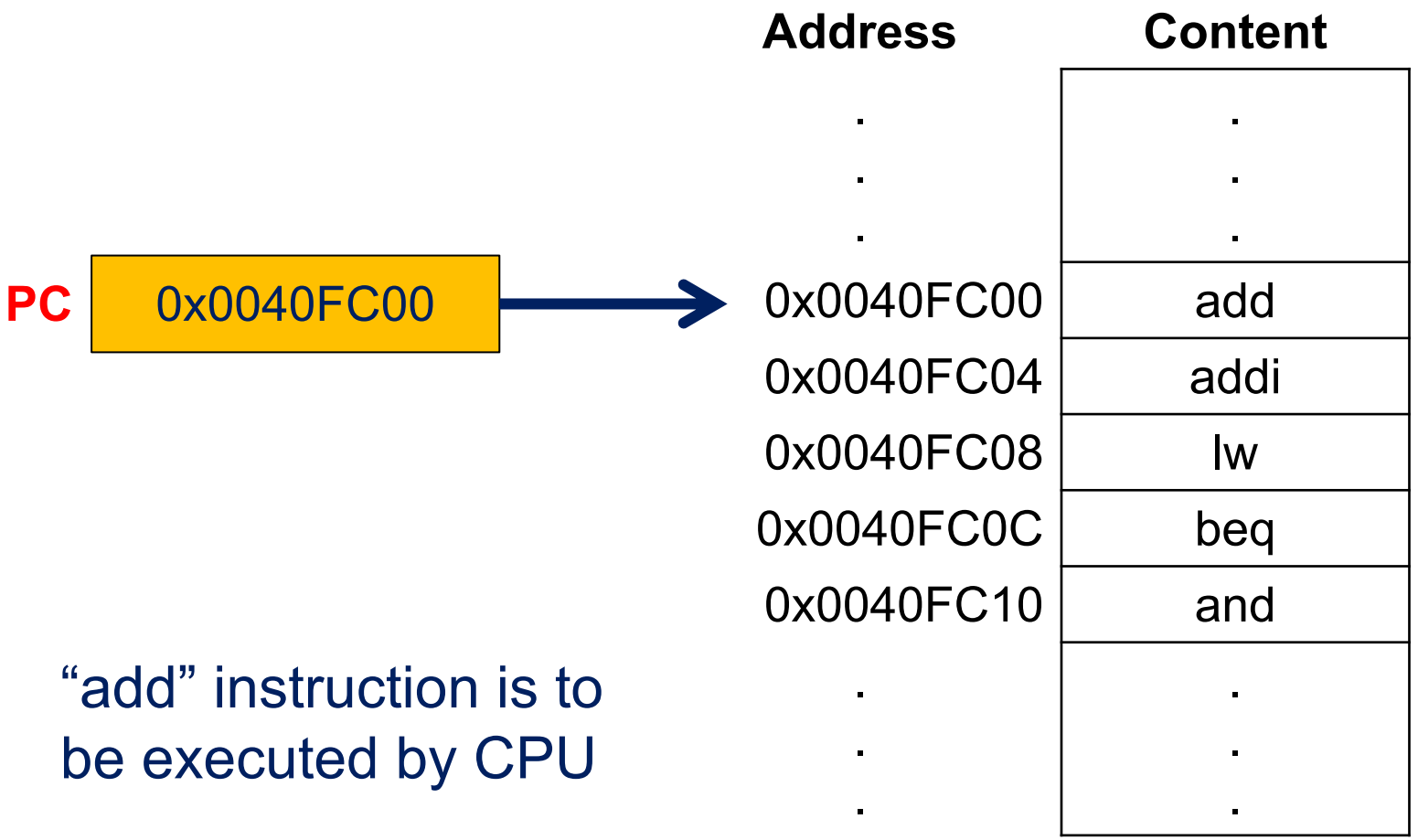


- Instructions are represented in binary, just like data
- Instructions and data are both stored in memory – stored program

Program Counter (PC)

- Each instruction is stored as a 32-bit word in program memory
  - has an address
  - when labeled, the label is equal to the address
- PC holds address of an instruction to be executed
  - 32 bits register
  - Increased by 4 for RV32
- PC is a special register in CPU
  - Different from the registers in register file

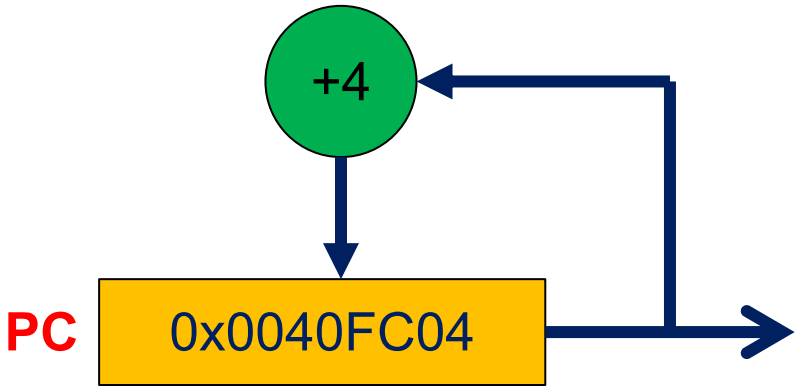
Program Counter (PC)



"add" instruction is to be executed by CPU

Program stored in memory

Program Counter (PC)

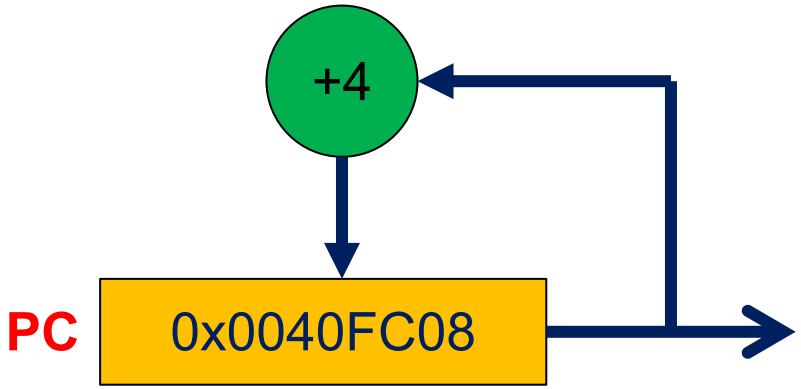


Address	Content
.	.
.	.
.	.
0x0040FC00	add
0x0040FC04	addi
0x0040FC08	lw
0x0040FC0C	beq
0x0040FC10	and
.	.
.	.
.	.

"addi" instruction is to be executed by CPU

Program stored in memory

Program Counter (PC)



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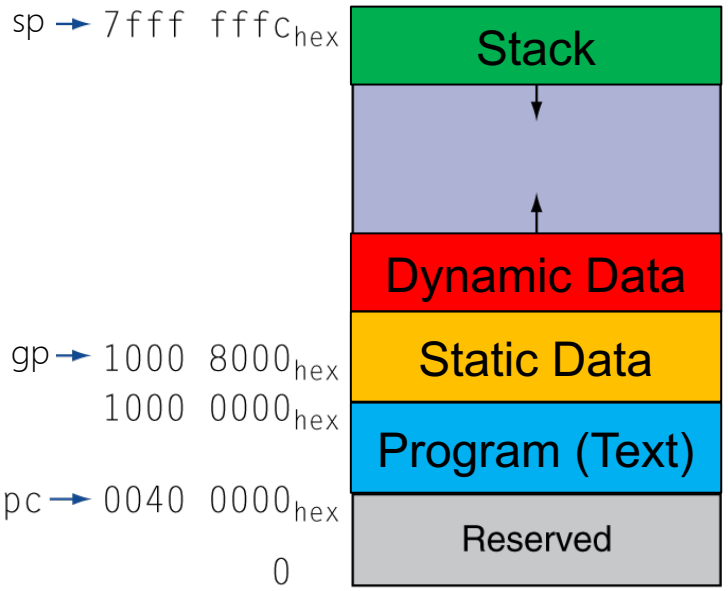
0x0040FC00	add
0x0040FC04	addi
0x0040FC08	lw
0x0040FC0C	beq
0x0040FC10	and
.	.
.	.
.	.

"lw" instruction is to be executed by CPU

Program stored in memory

Memory Layout

- Text: program code
- Static data: global/static variables
  - x3 (global pointer) initialized to the middle of this segment, 0x10008000 allowing ±offset
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: storage for temporary variable in functions
  - x2 (sp, stack pointer) initialized to 0x7ffffffc, growing towards low address



Function Calling

- Functions are used to improve reusability and manageability
- Steps for function calling operation
  1. Place parameters in registers x10 to x17
  2. Call function and transfer control to function
  3. Acquire storage on stack for the function
  4. Save (push) important registers on the stack
  5. Perform function's operations
  6. Place result in register x10 and x11 for caller
  7. Restore (pop) important registers from the stack
  8. Return storage on stack
  9. Return to the place of function call (using x1)

Function Call Instructions

- Function call: jump and link

  `jal x1, ProcedureLabel`

  - x1 <= PC + 4, x1 is called **return address** reg.
  - PC <= ProcedureLabel
- Function return: jump and link register

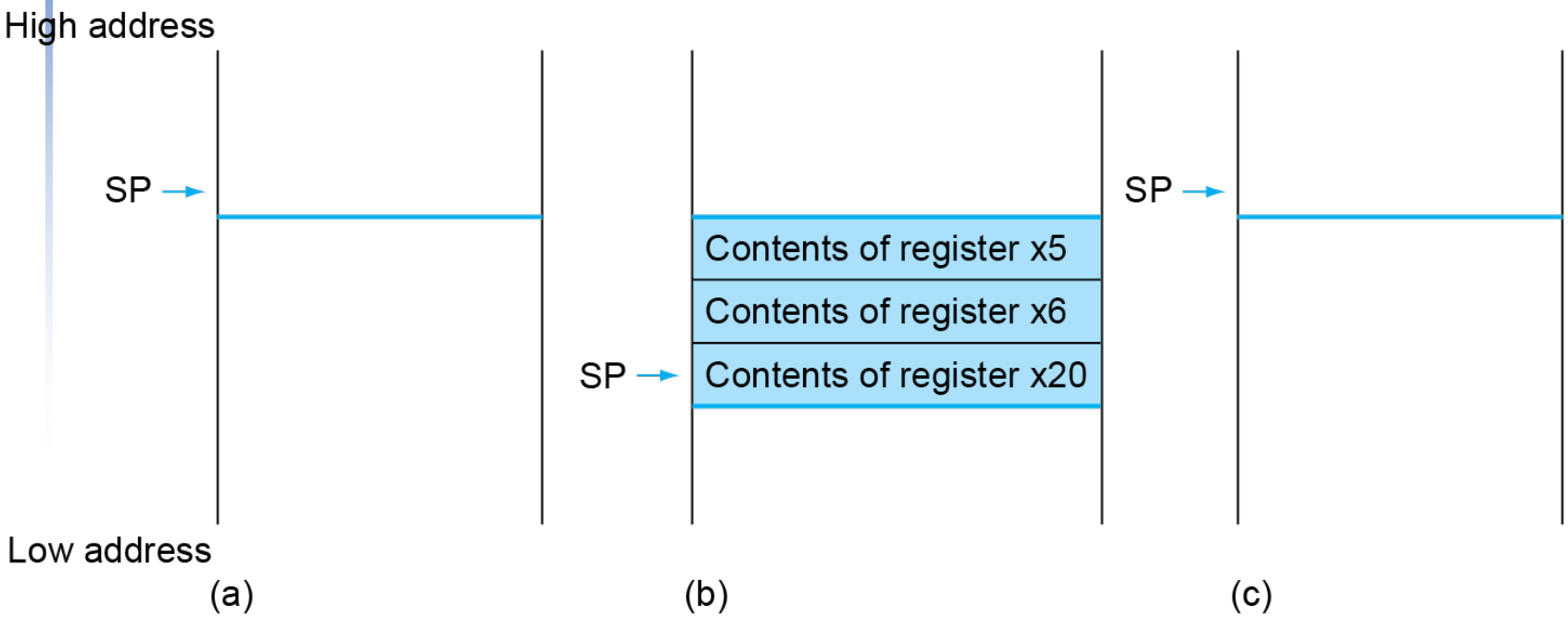
  `jalr x0, offset(x1)`

  - x0 <= PC + 4 (x0≡0, nothing happens)
  - PC <= offset + return address stored in x1, offset usually is 0 for function return
  - Can also be used for computed jumps

Register Usage

- x0: the constant value 0
- x1: return address
- x2: stack pointer
- x3: global pointer
- x4: thread pointer
- x5 – x7, x28 – x31: temporaries
- x8: frame pointer
- x9, x18 – x27: saved registers
- x10 – x11: function arguments/results
- x12 – x17: function arguments

Uses of Stack in Function Call



Before calling

During function
- **For storing important registers**
- **For temporary variables**

After calling
- **Important registers restored**
- **Temporary variables destroyed**

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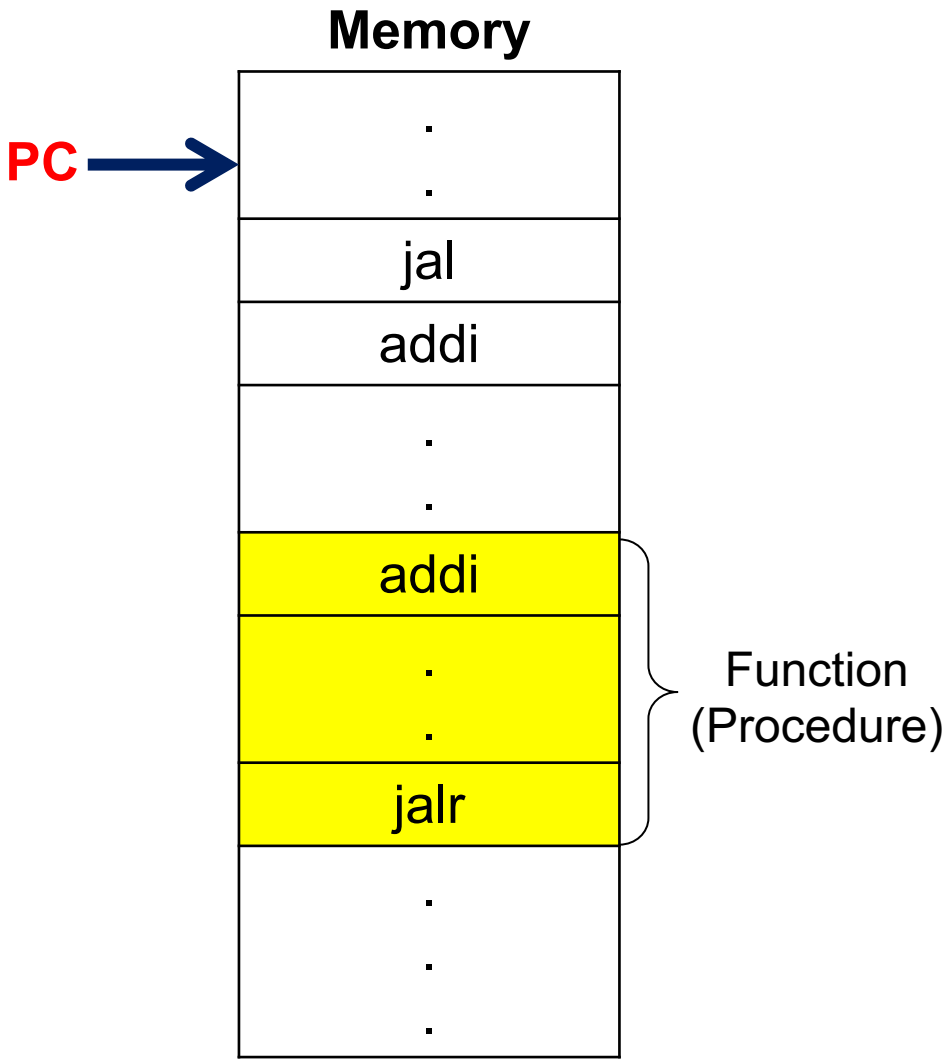

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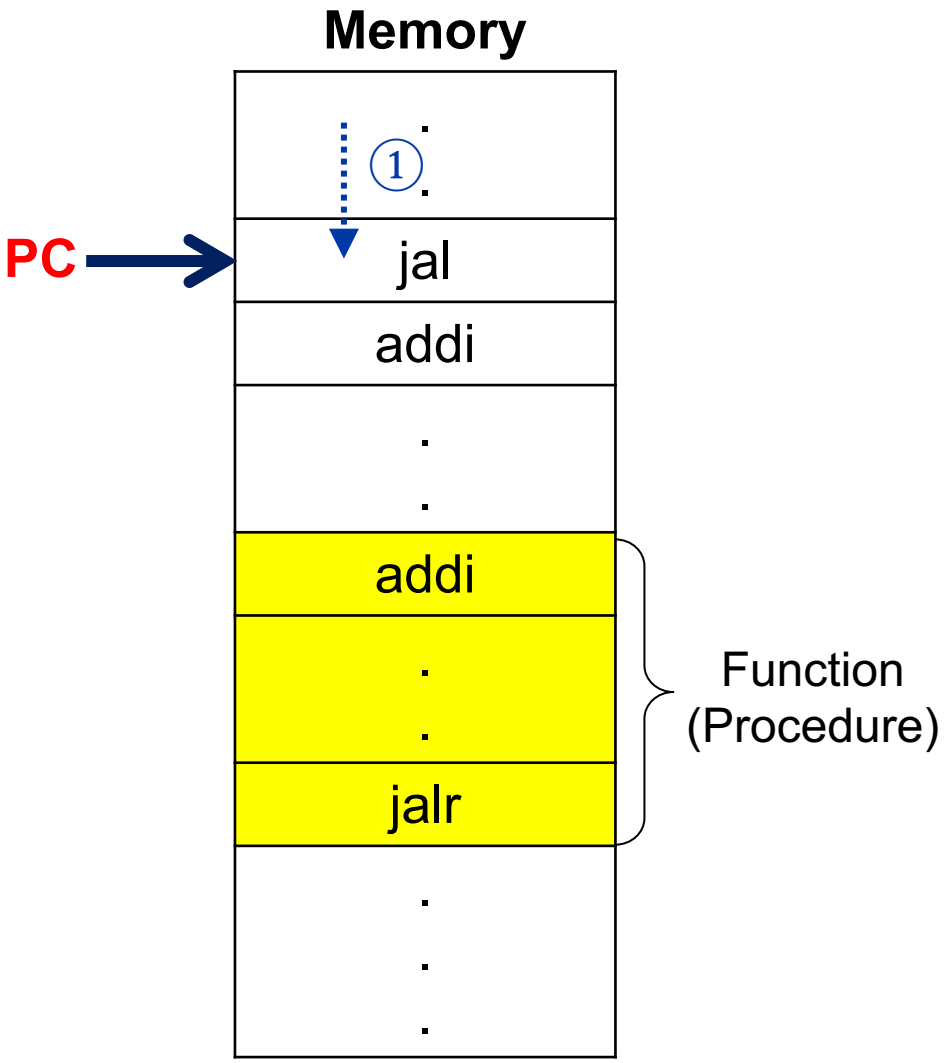

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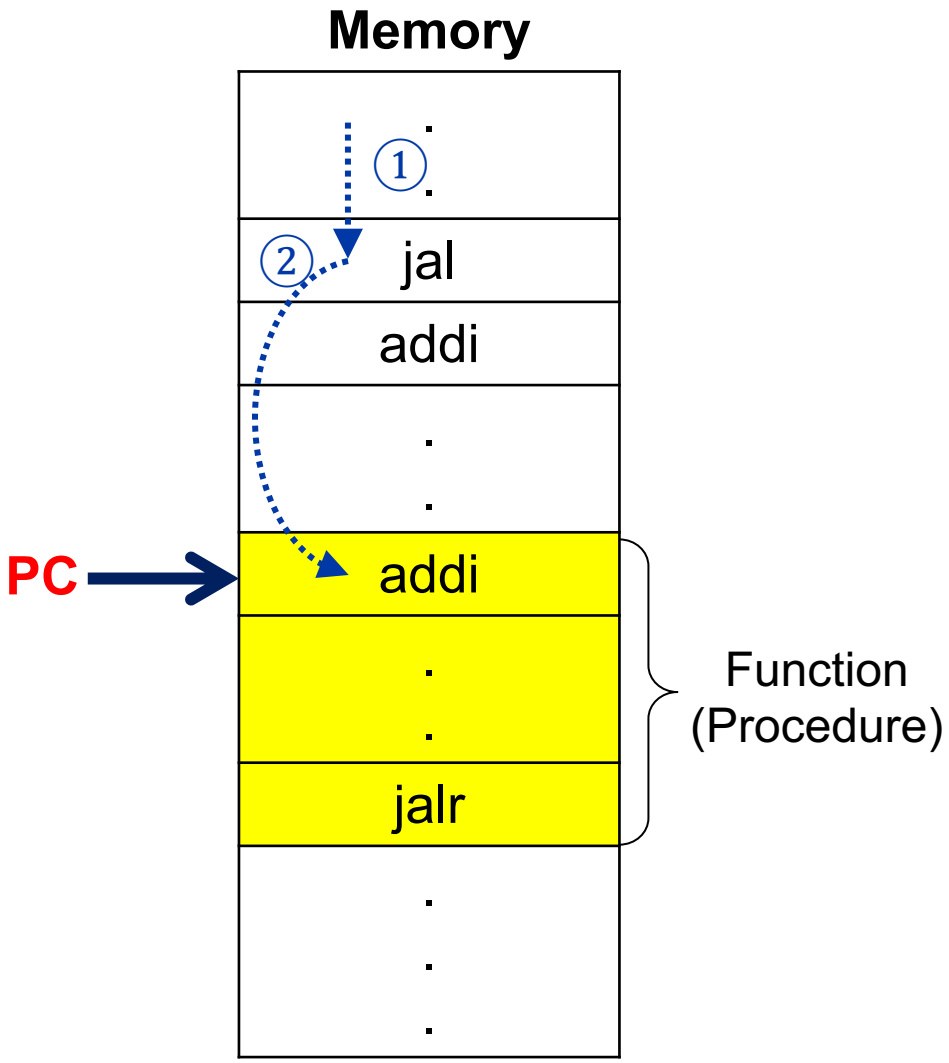

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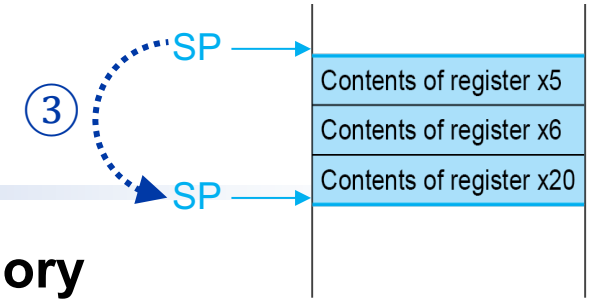

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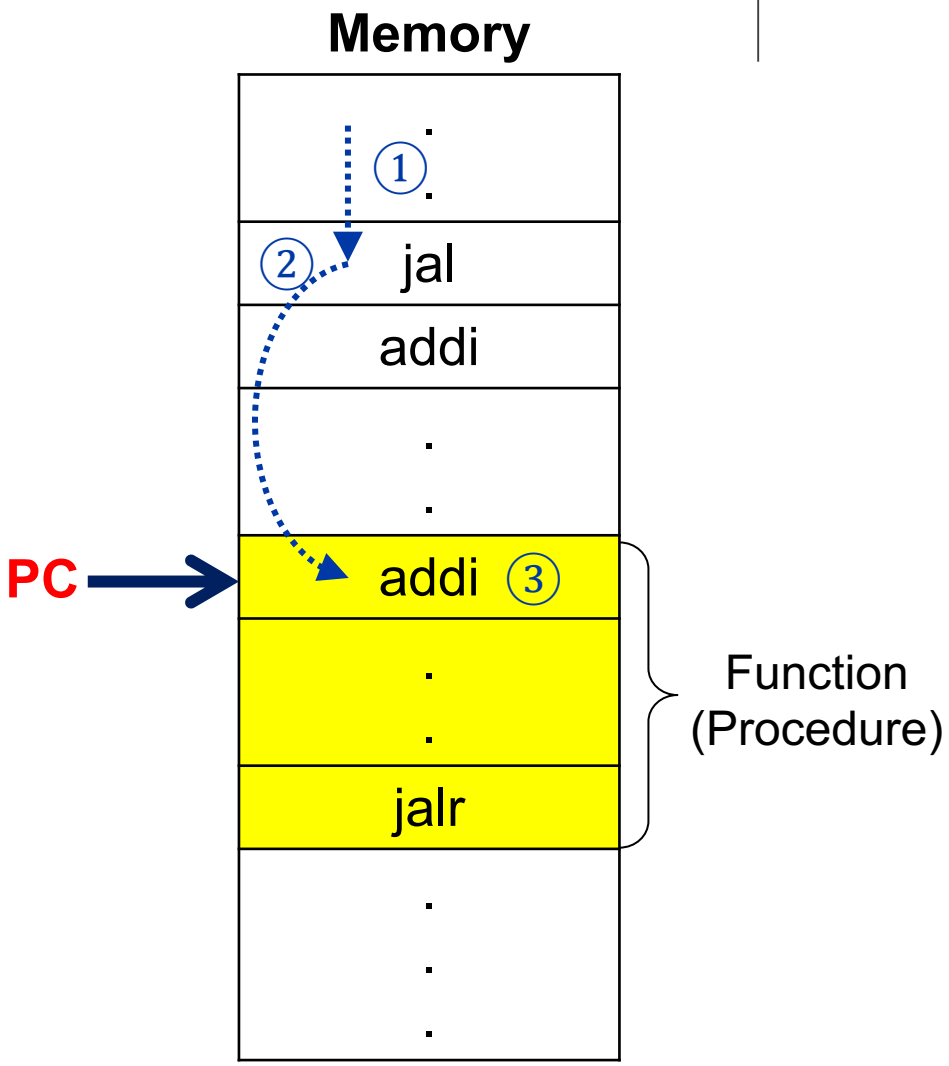

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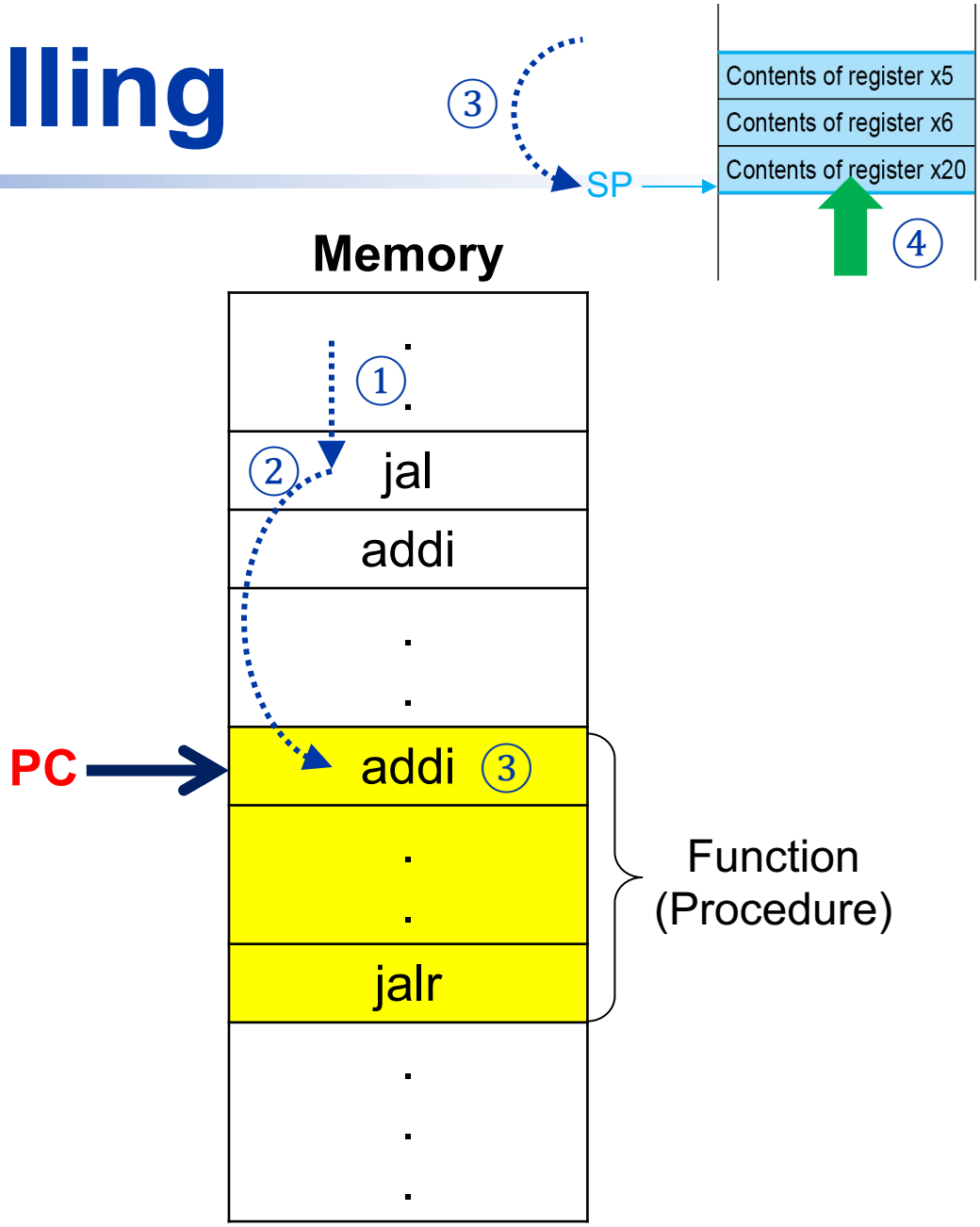

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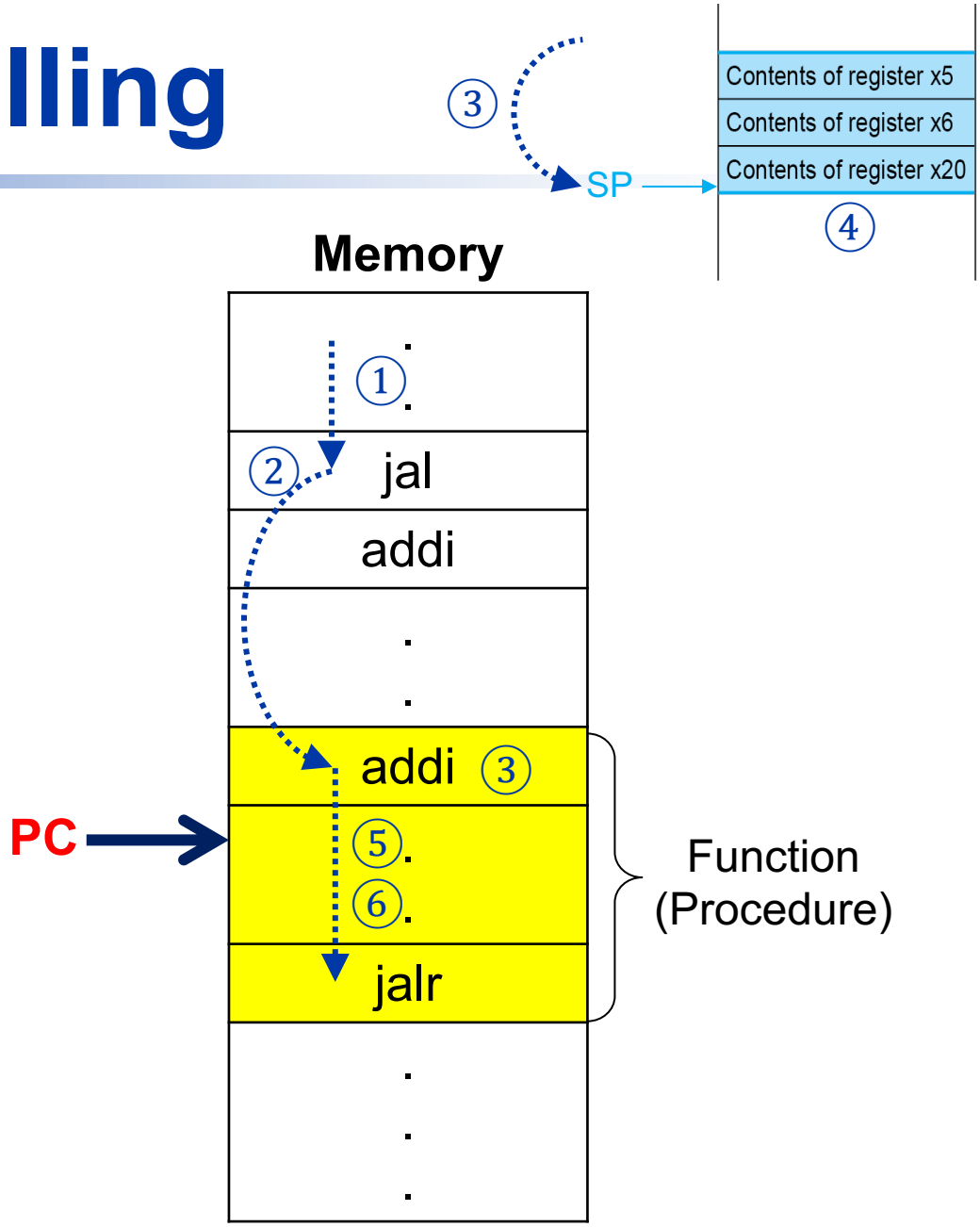

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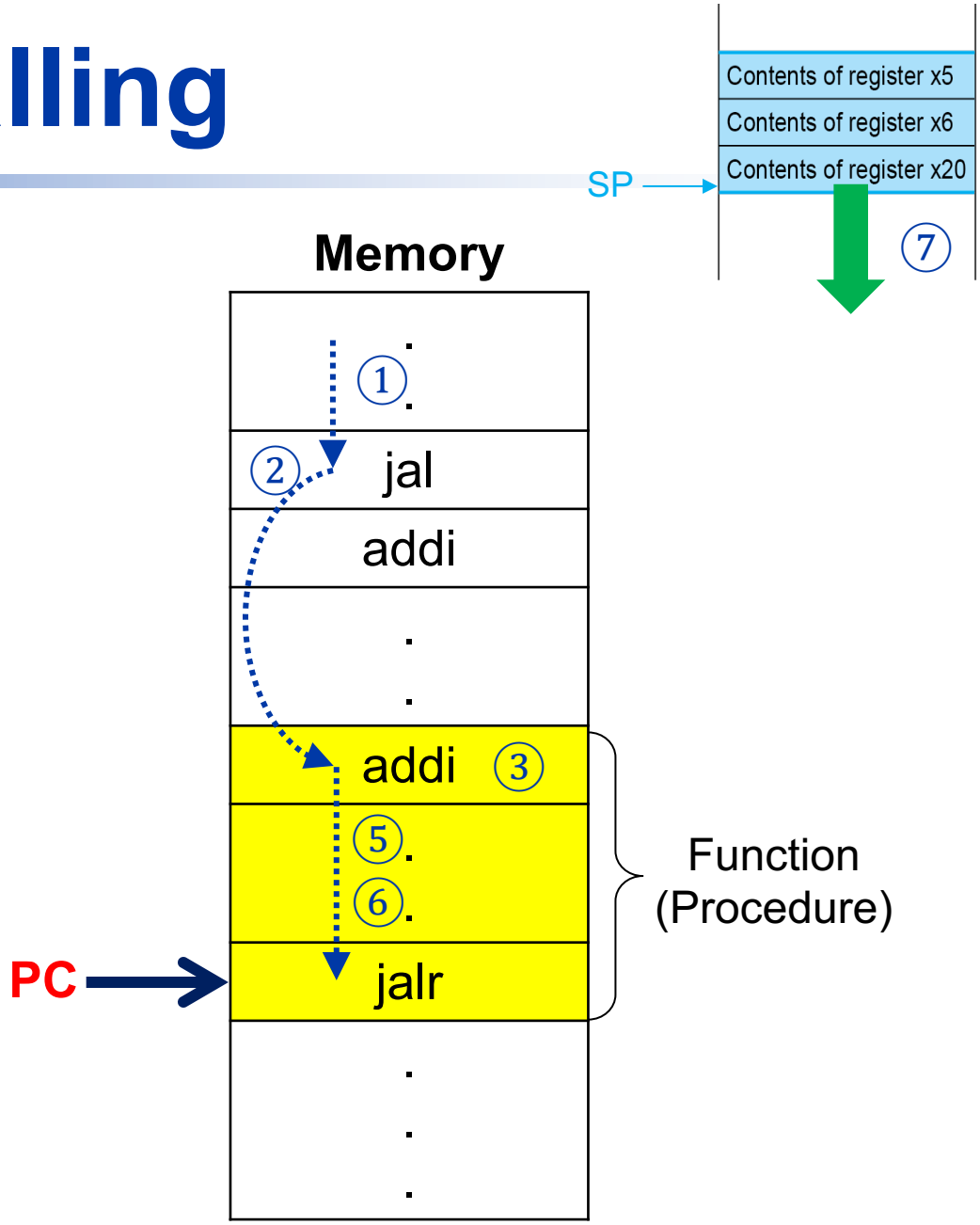

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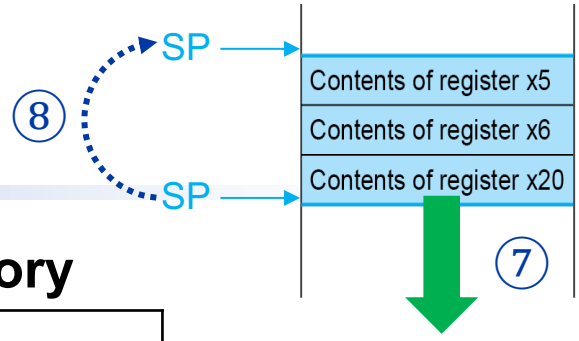

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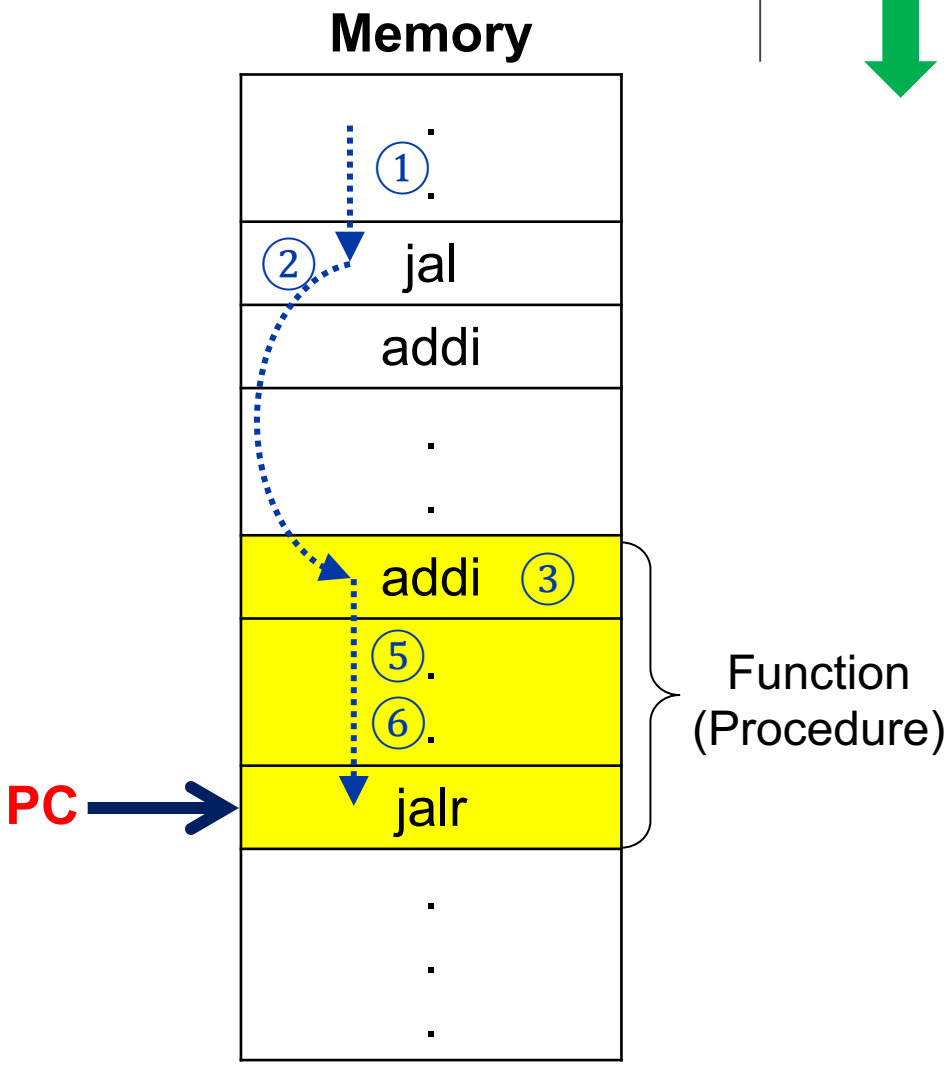

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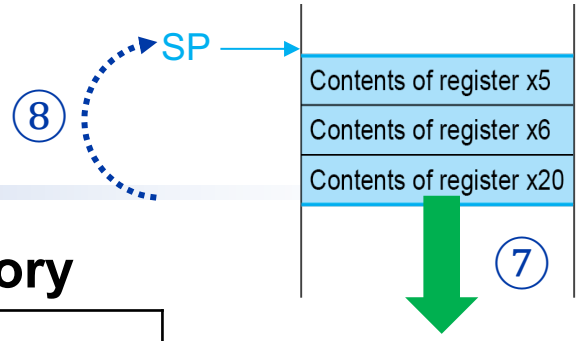

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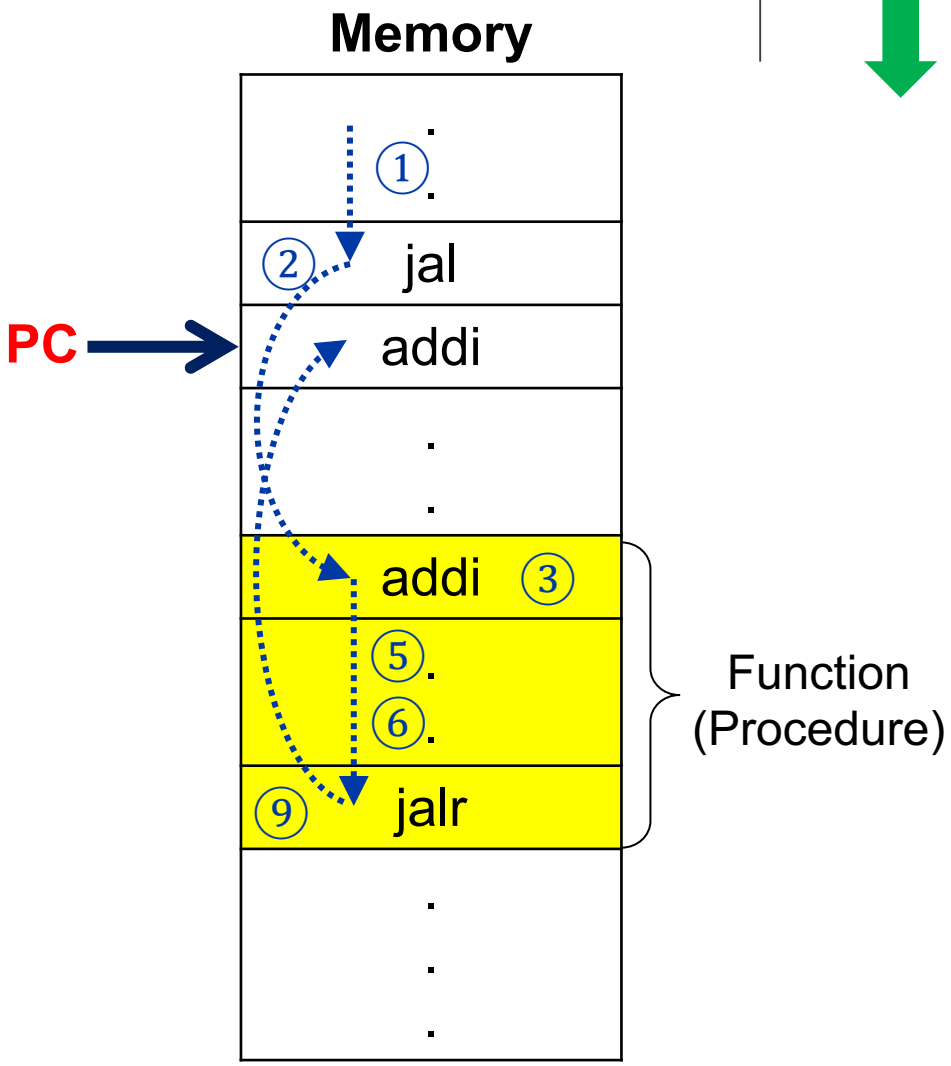


Register Usage

- x5 – x7, x28 – x31: temporary registers
  - Not preserved by the callee
- x8 – x9, x18 – x27: saved registers
  - If used, the callee saves and restores them

Leaf Function

- Functions that don't call other functions
- C code:

```
int leaf_example (int g, h, i, j)
{ int f;
  f = (g + h) - (i + j);
  return f;}
```

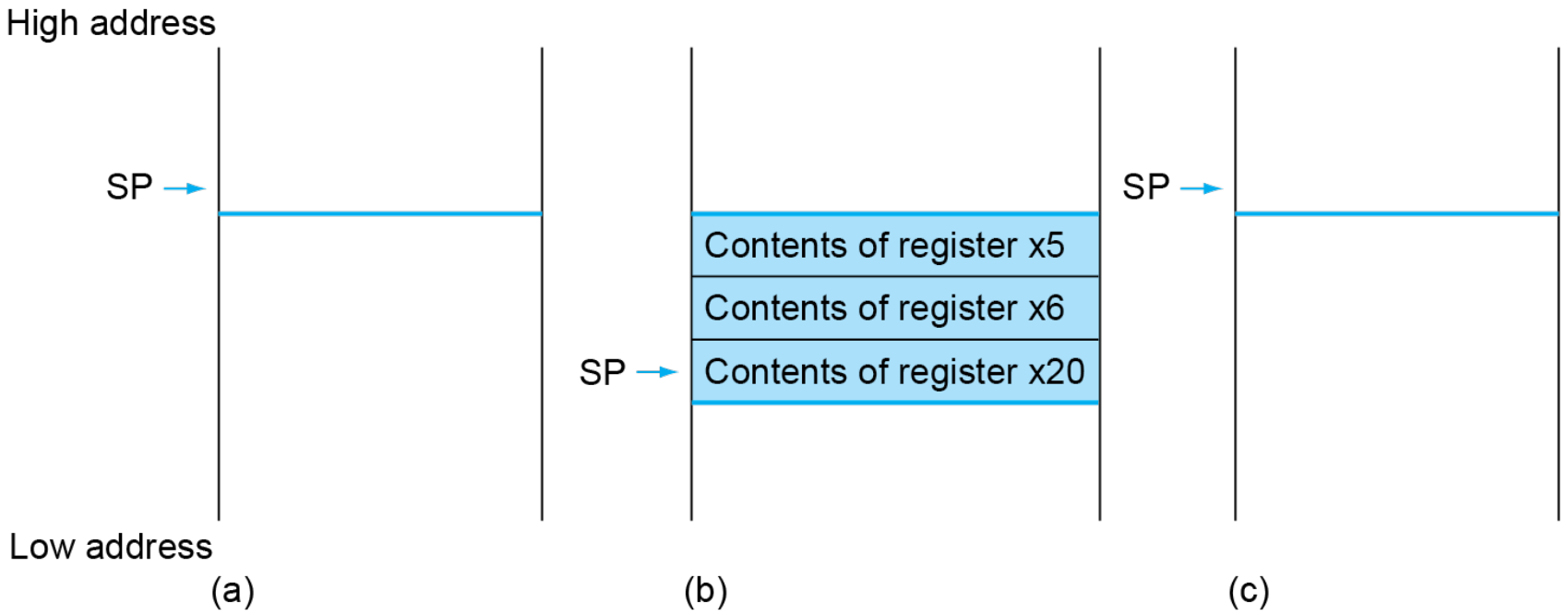
- Assumptions:
  - Arguments g, …, j in x10, …, x13
  - f in x20
  - temporaries x5, x6
  - If we decide to save x5, x6, x20 all on stack

Leaf Function Example

- RISC-V code:

```
leaf_example:
   addi sp,sp,-12    #create spaces on stack  ③
   sw   x5,8(sp)     #Save x5, x6, x20 on stack
   sw   x6,4(sp)     ④
   sw   x20,0(sp)
   add  x5,x10,x11   #x5 = g + h
   add  x6,x12,x1    #x6 = i + j    ⑤
   sub  x20,x5,x6    #f = x5 - x6
   addi x10,x20,0    #copy f to return register  ⑥
   lw   x20,0(sp)    #Resore x5, x6, x20 from stack
   lw   x6,4(sp)     ⑦
   lw   x5,8(sp)
   addi sp,sp,12     #release space on stack ⑧
   jalr x0,0(x1)     #return to caller  ⑨
```

Local Data on the Stack



Leaf Function Example

- RISC-V code:

Unnecessary, because they are temporary registers, no need to save them by the callee

```
leaf_example:
   addi sp,sp,-12     #create spaces on stack
   sw   x5,8(sp)      #Save x5, x6, x20 on stack
   sw   x6,4(sp)
   sw   x20,0(sp)     #only need to store saved regs
   add  x5,x10,x11    #x5 = g + h
   add  x6,x12,x1     #x6 = i + j
   sub  x20,x5,x6     #f = x5 - x6
   addi x10,x20,0     #copy f to return register
   lw   x20,0(sp)     #Resore x5, x6, x20 from stack
   lw   x6,4(sp)
   lw   x5,8(sp)
   addi sp,sp,12      #release space on stack
   jalr x0,0(x1)      #return to caller
```

String Copy Example

- C code:
  - Null-terminated string

```
void strcpy (char x[], char y[])
{ int i;
  i = 0;
  while ((x[i]=y[i])!='\0')
    i += 1;
}
```

String Copy Example

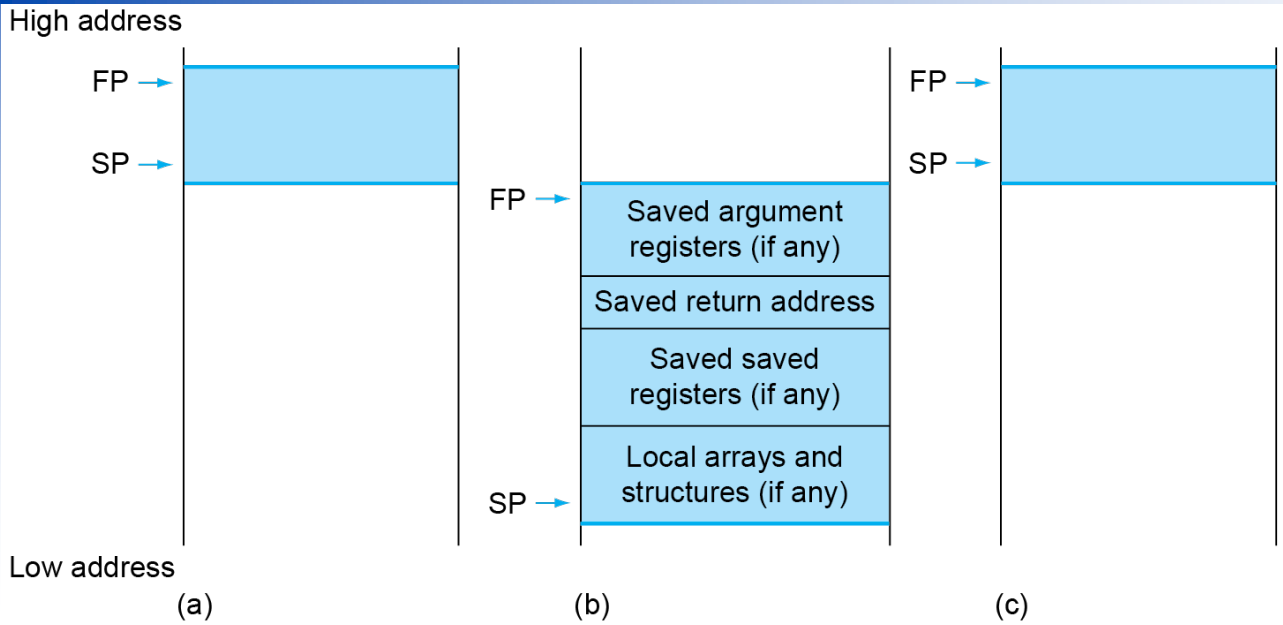
- RISC-V code:

```
strcpy:
     addi sp,sp,-4        # adjust stack for 1 word
     sw   x19,0(sp)       # push x19 (a saved register)
     add  x19,x0,x0       # i=0
L1:  add  x5,x19,x10      # x5 = addr of y[i]
     lbu  x6,0(x5)        # x6 = y[i]
     add  x7,x19,x11      # x7 = addr of x[i]
     sb   x6,0(x7)        # x[i] = y[i]
     beq  x6,x0,L2        # if y[i] == 0 then exit
     addi x19,x19,1       # i = i + 1
     jal  x0,L1           # next iteration of loop
L2:  lw   x19,0(sp)       # restore saved x19
     addi sp,sp,4         # pop 1 word from stack
     jalr x0,0(x1)        # and return
```

Non-Leaf Functions

- Functions that call other functions
- Before calling another function, caller needs to save on the stack :
  - Its return address
  - Any argument registers
  - Temporary registers needed after the call
- Restore from the stack after the call

Important Data on the Stack



SP manages entire stack

FP manages elements in each frame (optional)

- A frame (activation record) is a temporary memory space created for a function, it should always save:
  - Saved registers (x8, x9, x18-x27)
  - Local arrays and structures (if any)
- When it's a non-leaf function (caller) calling another function, it should also save:
  - Return address
  - Argument registers (if any)
  - Temporary registers (x5-x7, x28-x31) needed after the function call

Non-Leaf Function Example

- C code:

```
int fact (int n)
{
  if (n < 1) return f;
  else return n * fact(n - 1);
}
```

  - Argument n in x10
  - Result in x10

Non-Leaf Procedure Example

- RISC-V code:

```
fact:
    addi sp,sp,-8       Save return address and n on stack
    sw   x1,4(sp)
    sw   x10,0(sp)
    addi x5,x10,-1      x5 = n - 1
    bge  x5,x0,L1       if n >= 1, go to L1
    addi x10,x0,1       Else, set return value to 1
    addi sp,sp,8        Pop stack, don't bother restoring values
    jalr x0,0(x1)       Return
L1: addi x10,x10,-1     n = n - 1
    jal  x1,fact        call fact(n-1)
    addi x6,x10,0       move result of fact(n - 1) to x6
    lw   x10,0(sp)      Restore caller's n
    lw   x1,4(sp)       Restore caller's return address
    addi sp,sp,8        Pop stack
    mul  x10,x10,x6     return n * fact(n-1)
    jalr x0,0(x1)       return
```

More Examples: C Sort

- Illustrates use of assembly instructions for a C bubble sort function
- Swap procedure (leaf)

```
void swap(int v[],
          int k)
{
  int temp;
  temp = v[k];
  v[k] = v[k+1];
  v[k+1] = temp;
}
```

  - v in x10, k in x11, temp in x5

The Procedure Swap

```
swap:
  slli x6,x11,2     # reg x6 = k * 4
  add  x6,x10,x6    # reg x6 = v + (k * 4)
                    # (address of v[k])
  lw   x5,0(x6)     # reg x5 (temp) = v[k]
  lw   x7,4(x6)     # reg x7 = v[k + 1]
  sw   x7,0(x6)     # v[k] = reg x7 (v[k+1])
  sw   x5,4(x6)     # v[k+1] = reg x5 (temp)
  jalr x0,0(x1)     # return to calling routine
```

The Sort Procedure in C

- Non-leaf (calls swap)

```
void sort (int v[], int n)
{
  int i, j;
  for (i = 0; i < n; i += 1) {
    for (j = i - 1;
         j >= 0 && v[j] > v[j + 1];
         j -= 1) {
      swap(v,j);
    }
  }
}
```

  - v in x10, n in x11, i in x19, j in x20

The Outer Loop

- Skeleton of outer loop:
  - for (i = 0; i <n; i += 1) {

```
   li   x19,0       # i = 0, pseudo instruction
for1tst:
   bge  x19,x11,exit1   # go to exit1 if x19 ≥ x11 (i≥n)

   (body of outer for-loop)

   addi x19,x19,1         # i += 1
   j    for1tst           # branch to test of outer loop
                          # pseudo instruction
exit1:
```

The Inner Loop

- Skeleton of inner loop:
  - for (j = i − 1; j >= 0 && v[j] > v[j + 1]; j − = 1) {

```
    addi x20,x19,-1    # j = i –1
for2tst:
    blt  x20,x0,exit2  # go to exit2 if X20 < 0 (j < 0)
    slli x5,x20,2      # reg x5 = j * 4
    add  x5,x10,x5     # reg x5 = v + (j * 4)
    lw   x6,0(x5)      # reg x6 = v[j]
    lw   x7,4(x5)      # reg x7 = v[j + 1]
    ble  x6,x7,exit2   # go to exit2 if x6 ≤ x7, pseudo
    mv   x21, x10      # copy parameter x10 into x21, pseudo
    mv   x22, x11      # copy parameter x11 into x22
    mv   x10, x21      # first swap parameter is v
    mv   x11, x20      # second swap parameter is j
    jal  x1,swap       # call swap
    addi x20,x20,-1    # j –= 1
    j    for2tst       # branch to test of inner loop, pseudo
exit2:
```