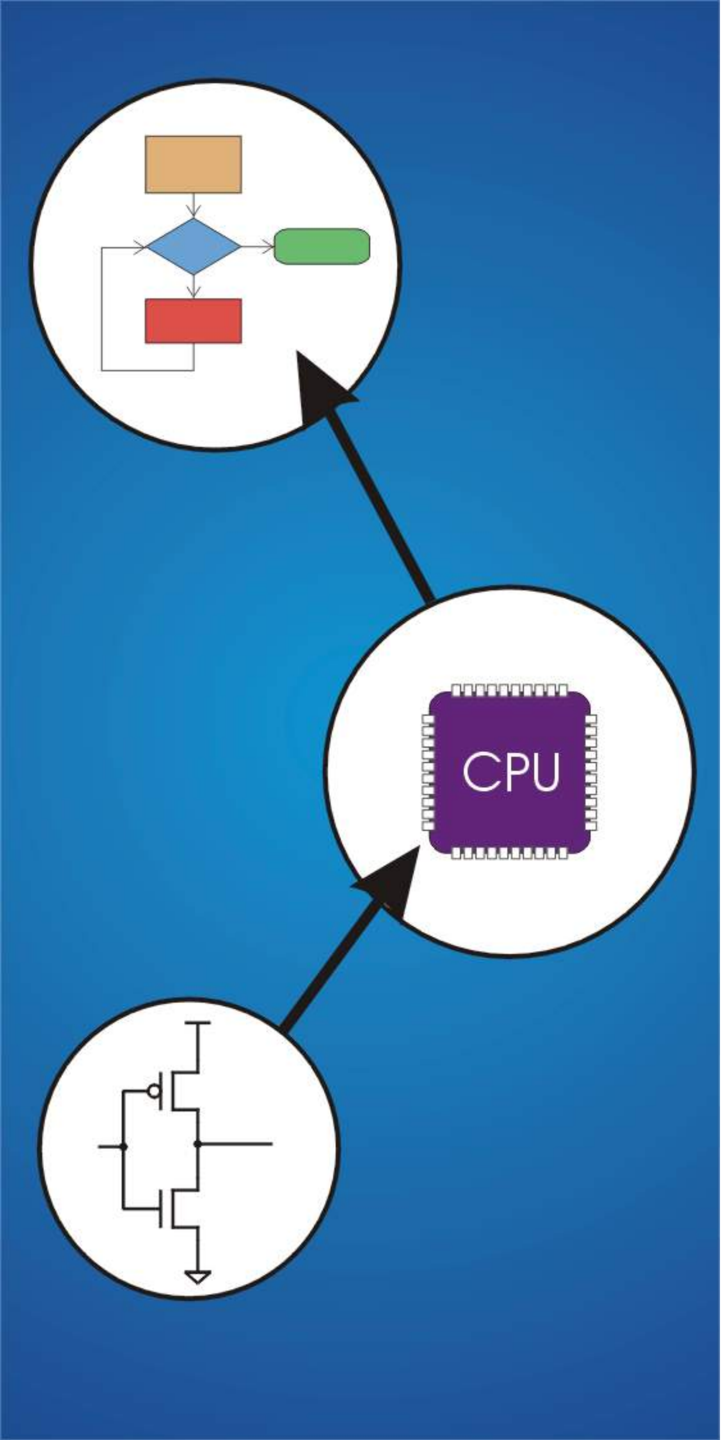


Chapter 10
And, Finally...
The Stack

Stack: An Abstract Data Type

An important abstraction that you will encounter in many applications.

We will describe three uses:

Interrupt-Driven I/O

- **The rest of the story…**

Evaluating arithmetic expressions

- **Store intermediate results on stack instead of in registers**

Data type conversion

- **2's comp binary to ASCII strings**

Stacks

A LIFO (last-in first-out) storage structure.

- **The first thing you put in is the last thing you take out.**
- **The last thing you put in is the first thing you take out.**

This means of access is what defines a stack, not the specific implementation.

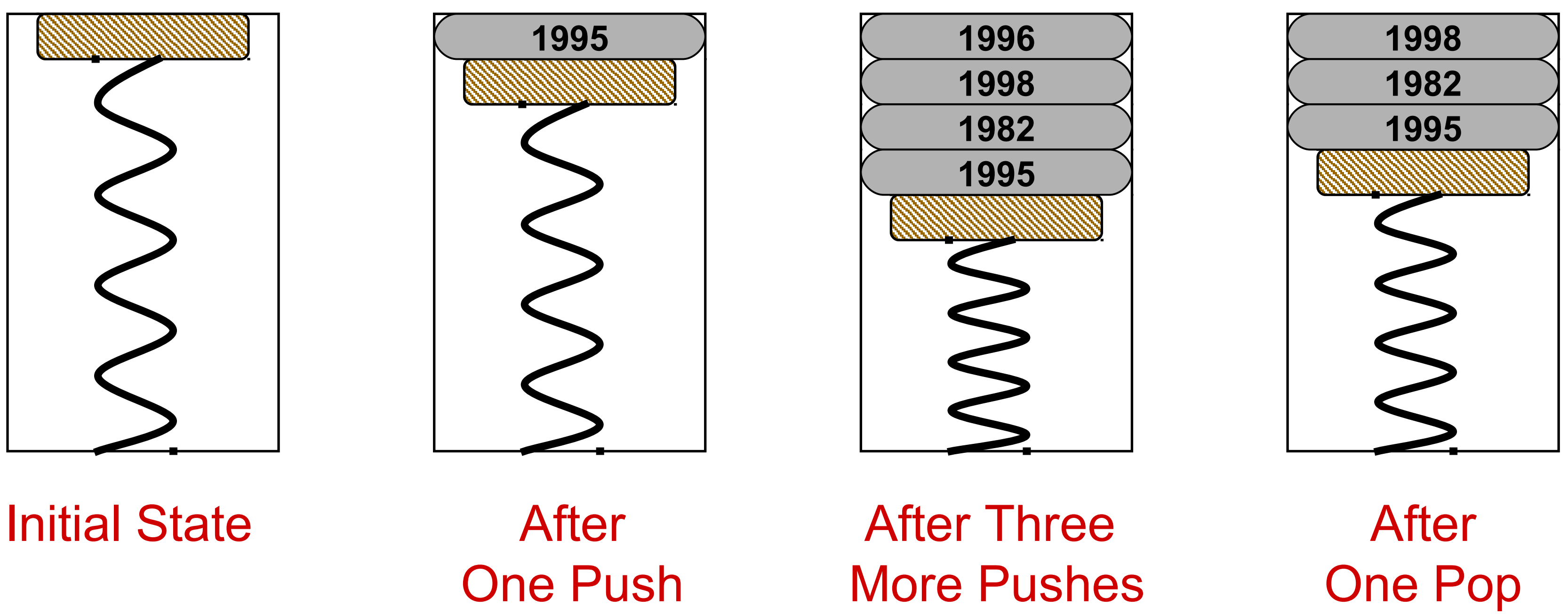
Two main operations:

PUSH: **add an item to the stack**

POP: **remove an item from the stack**

A Physical Stack

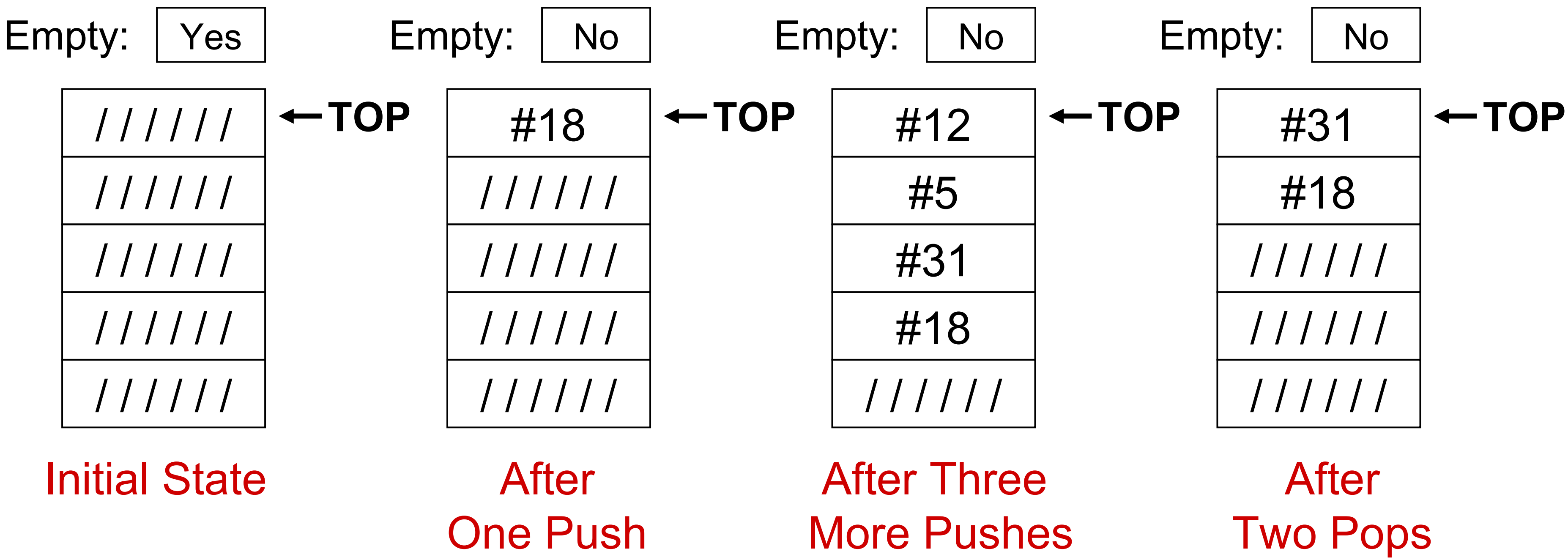
Coin rest in the arm of an automobile



First quarter out is the last quarter in.

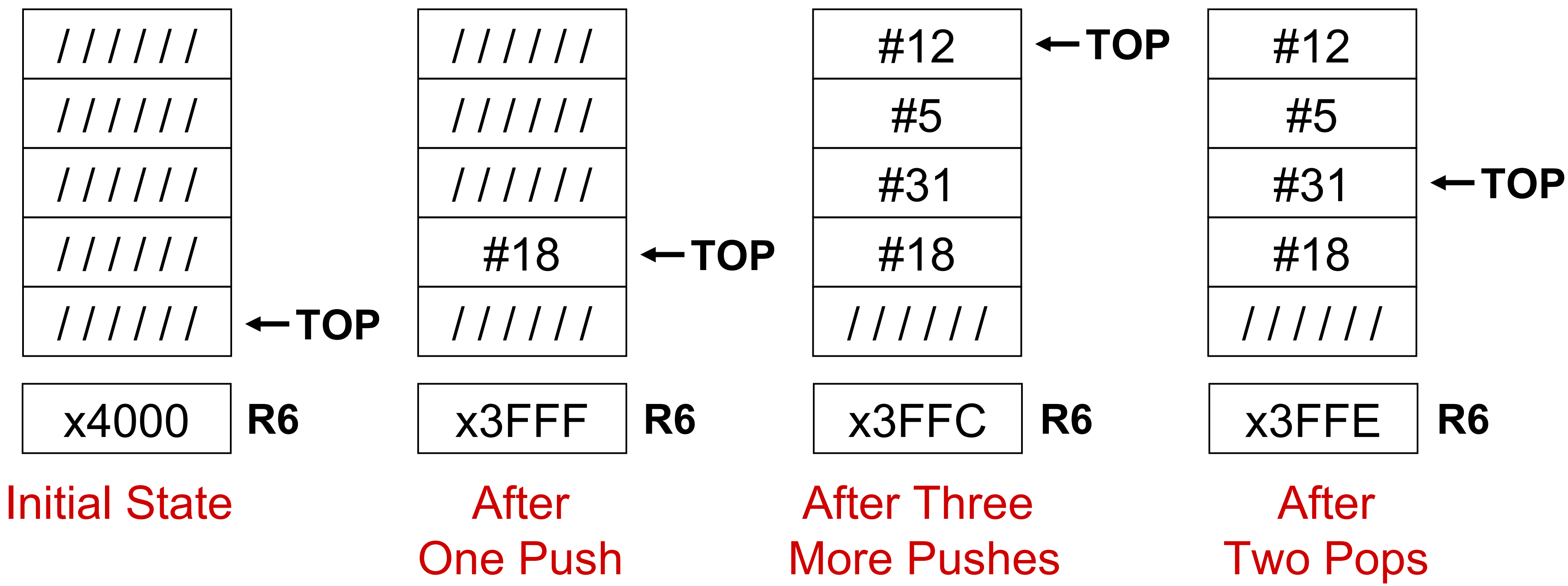
A Hardware Implementation

Data items move between registers



A Software Implementation

**Data items don't move in memory,
just our idea about there the TOP of the stack is.**



By convention, R6 holds the Top of Stack (TOS) pointer.

Basic Push and Pop Code

For our implementation, stack grows downward (when item added, TOS moves closer to 0)

Push

```
ADD  R6, R6, #-1 ; decrement stack ptr
STR  R0, R6, #0  ; store data (R0)
```

Pop

```
LDR  R0, R6, #0  ; load data from TOS
ADD  R6, R6, #1  ; decrement stack ptr
```

Pop with Underflow Detection

If we try to pop too many items off the stack, an underflow condition occurs.

- Check for underflow by checking TOS before removing data.
- Return status code in R5 (0 for success, 1 for underflow)

```
POP    LD   R1, EMPTY   ; EMPTY = -x4000
       ADD R2, R6, R1 ; Compare stack pointer
       BRz FAIL         ; with x3FFF
       LDR R0, R6, #0
       ADD R6, R6, #1
       AND R5, R5, #0 ; SUCCESS: R5 = 0
       RET
FAIL   AND R5, R5, #0 ; FAIL: R5 = 1
       ADD R5, R5, #1
       RET
EMPTY .FILL xC000
```

Push with Overflow Detection

If we try to push too many items onto the stack, an overflow condition occurs.

- **Check for underflow by checking TOS before adding data.**
- **Return status code in R5 (0 for success, 1 for overflow)**

```
PUSH   LD   R1, MAX     ; MAX = -x3FFB
       ADD R2, R6, R1 ; Compare stack pointer
       BRz FAIL        ; with x3FFF
       ADD R6, R6, #-1
       STR R0, R6, #0
       AND R5, R5, #0 ; SUCCESS: R5 = 0
       RET
FAIL   AND R5, R5, #0 ; FAIL: R5 = 1
       ADD R5, R5, #1
       RET
MAX    .FILL xC005
```

Interrupt-Driven I/O (Part 2)

Interrupts were introduced in Chapter 8.

1. **External device signals need to be serviced.**
2. **Processor saves state and starts service routine.**
3. **When finished, processor restores state and resumes program.**

Interrupt is an ***unscripted subroutine call****,*
triggered by an external event.

Chapter 8 didn't explain how (2) and (3) occur, because it involves a stack.

Now, we're ready…

Processor State

What state is needed to completely capture the state of a running process?

Processor Status Register

- **Privilege [15], Priority Level [10:8], Condition Codes [2:0]**

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
P						PL							N	Z	P

Program Counter

- **Pointer to next instruction to be executed.**

Registers

- **All temporary state of the process that's not stored in memory.**

Where to Save Processor State?

Can't use registers.

- Programmer doesn't know when interrupt might occur, so she can't prepare by saving critical registers.
- When resuming, need to restore state exactly as it was.

Memory allocated by service routine?

- Must save state <u>before</u> invoking routine, so we wouldn't know where.
- Also, interrupts may be nested – that is, an interrupt service routine might also get interrupted!

Use a stack!

- Location of stack "hard-wired".
- Push state to save, pop to restore.

Supervisor Stack

A special region of memory used as the stack for interrupt service routines.

- **Initial Supervisor Stack Pointer (SSP) stored in Saved.SSP.**
- **Another register for storing User Stack Pointer (USP): Saved.USP.**

Want to use R6 as stack pointer.

- **So that our PUSH/POP routines still work.**

When switching from User mode to Supervisor mode (as result of interrupt), save R6 to Saved.USP.

Invoking the Service Routine – The Details

1. **If Priv = 1 (user),**
   Saved.USP = R6, then R6 = Saved.SSP.
2. **Push PSR and PC to Supervisor Stack.**
3. **Set PSR[15] = 0 (supervisor mode).**
4. **Set PSR[10:8] = priority of interrupt being serviced.**
5. **Set PSR[2:0] = 0.**
6. **Set MAR = x01vv, where vv = 8-bit interrupt vector provided by interrupting device (e.g., keyboard = x80).**
7. **Load memory location (M[x01vv]) into MDR.**
8. **Set PC = MDR; now first instruction of ISR will be fetched.**

Note: This all happens between the STORE RESULT of the last user instruction and the FETCH of the first ISR instruction.

Returning from Interrupt

Special instruction – RTI – that restores state.

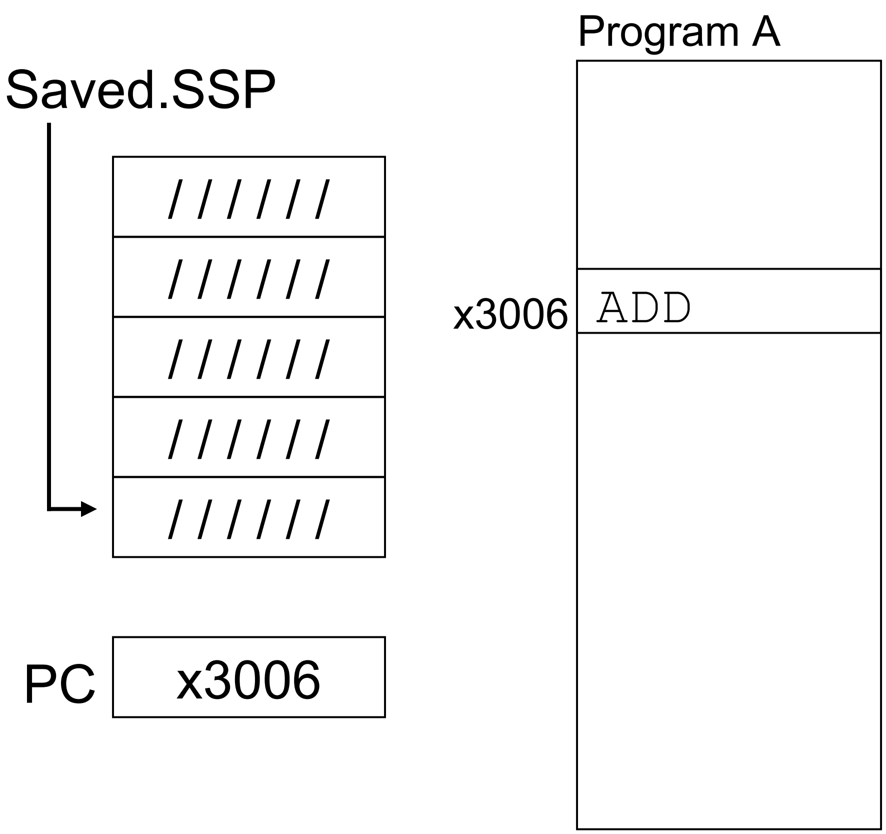
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
RTI	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1. **Pop PC from supervisor stack.** (PC = M[R6]; R6 = R6 + 1)
2. **Pop PSR from supervisor stack.** (PSR = M[R6]; R6 = R6 + 1)
3. **If PSR[15] = 1, R6 = Saved.USP.**
   (If going back to user mode, need to restore User Stack Pointer.)

RTI is a privileged instruction.

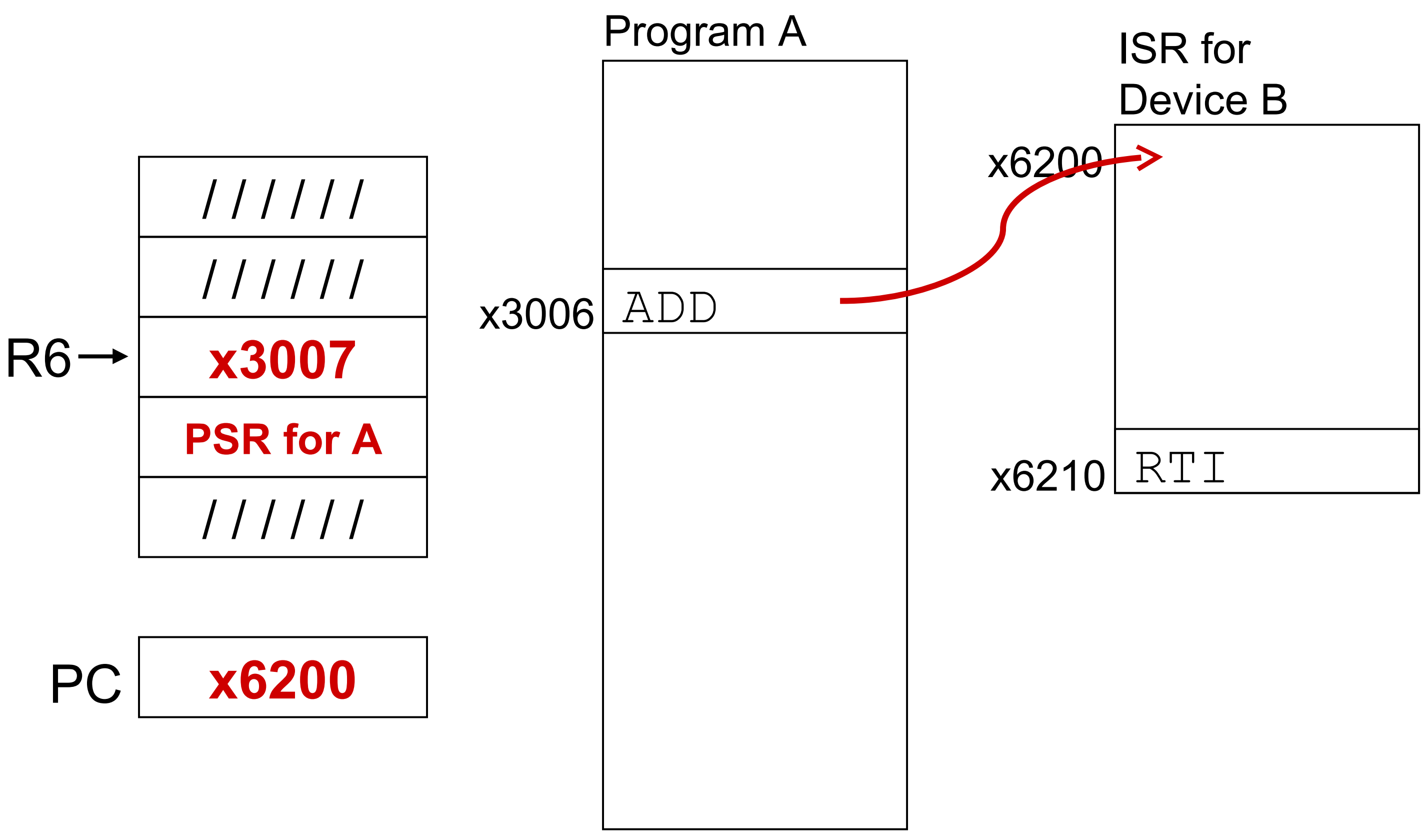
- **Can only be executed in Supervisor Mode.**
- **If executed in User Mode, causes an exception.**
  (More about that later.)

Example (1)



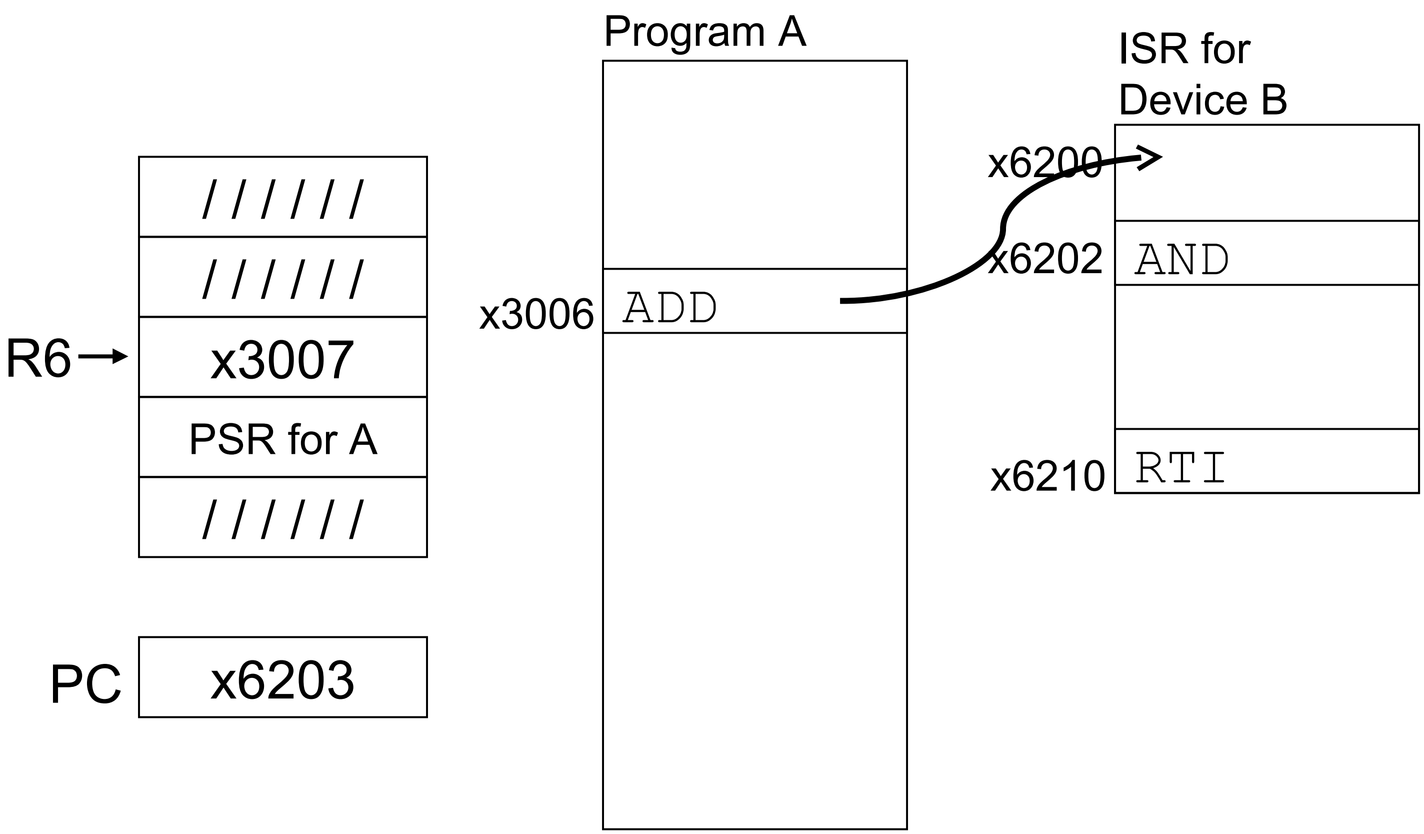
Executing ADD at location x3006 when Device B interrupts.

Example (2)



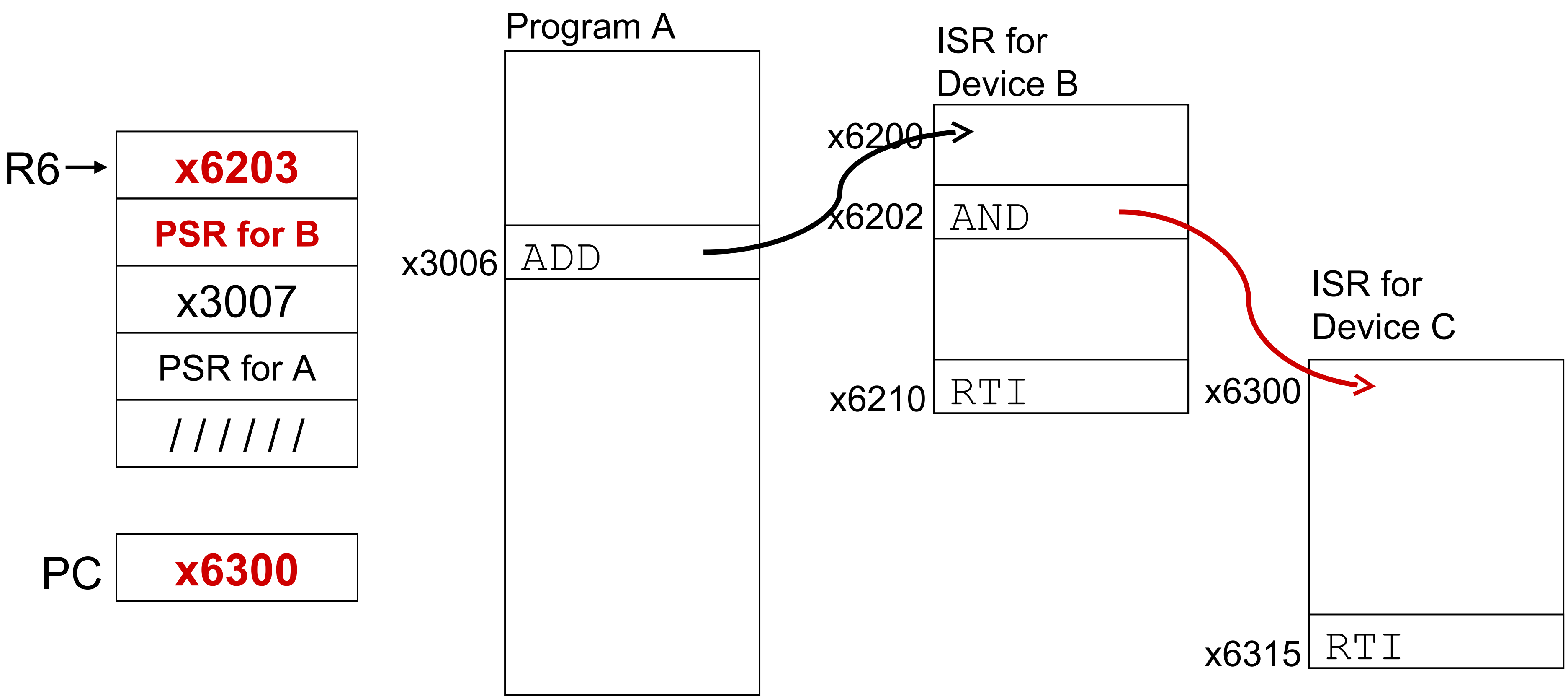
Saved.USP = R6. R6 = Saved.SSP.
Push PSR and PC onto stack, then transfer to Device B service routine (at x6200).

Example (3)



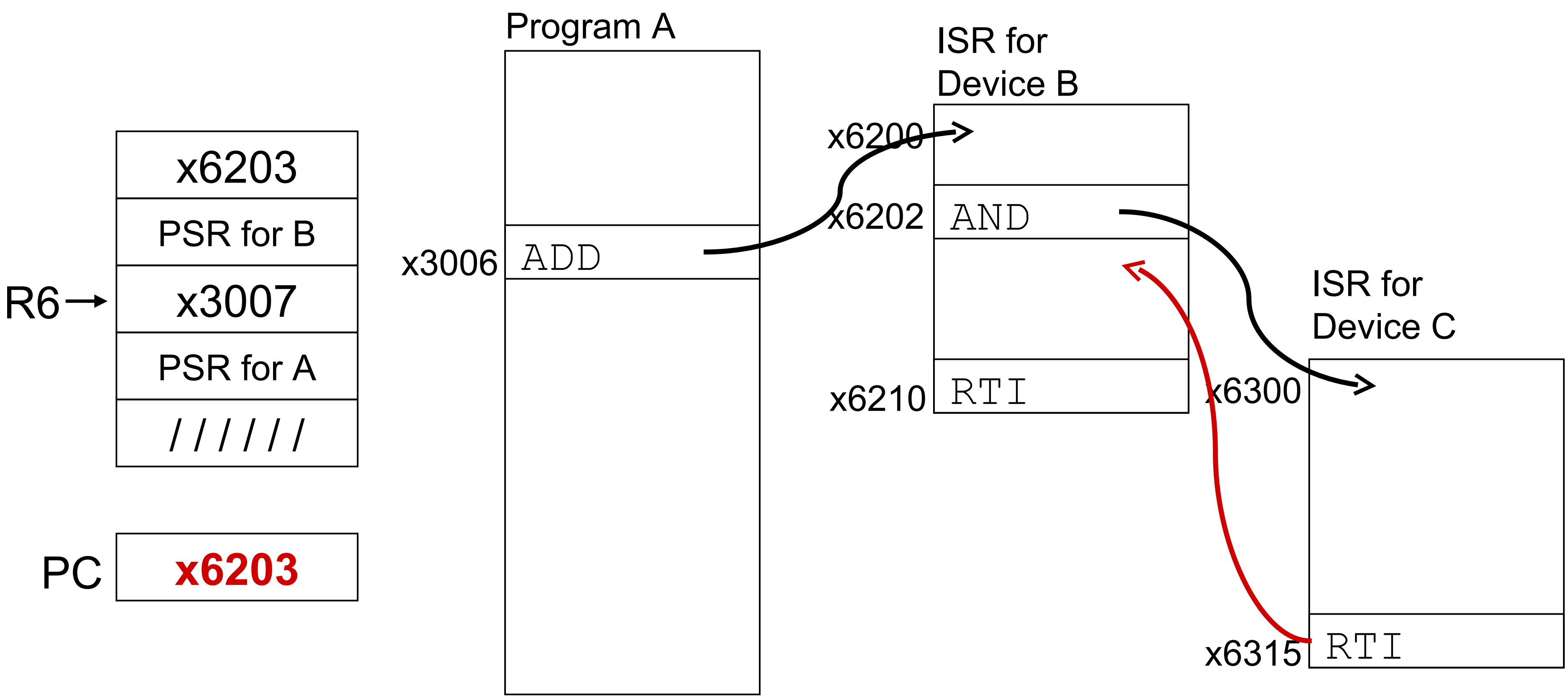
Executing AND at x6202 when Device C interrupts.

Example (4)



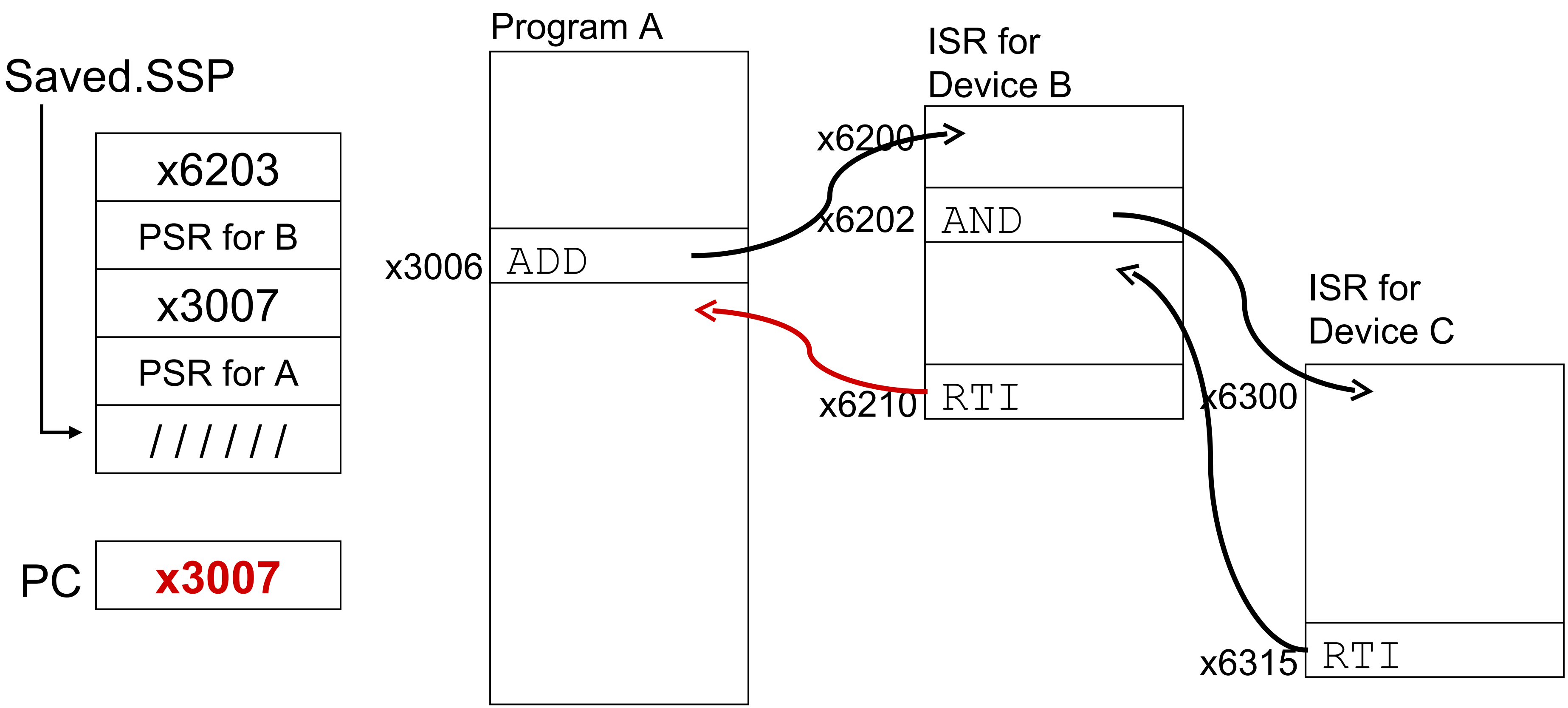
Push PSR and PC onto stack, then transfer to Device C service routine (at x6300).

Example (5)



Execute RTI at x6315; pop PC and PSR from stack.

Example (6)



Execute RTI at x6210; pop PSR and PC from stack.
Restore R6. Continue Program A as if nothing happened.

Exception: Internal Interrupt

When something unexpected happens *inside* the processor, it may cause an exception.

Examples:

- **Privileged operation (e.g., RTI in user mode)**
- **Executing an illegal opcode**
- **Divide by zero**
- **Accessing an illegal address (e.g., protected system memory)**

Handled just like an interrupt

- **Vector is determined internally by type of exception**
- **Priority is the same as running program**

Arithmetic Using a Stack

Instead of registers, some ISA's use a stack for source and destination operations: a zero-address machine.

- **Example:**
  ADD instruction pops two numbers from the stack, adds them, and pushes the result to the stack.

Evaluating (A+B)·(C+D) using a stack:

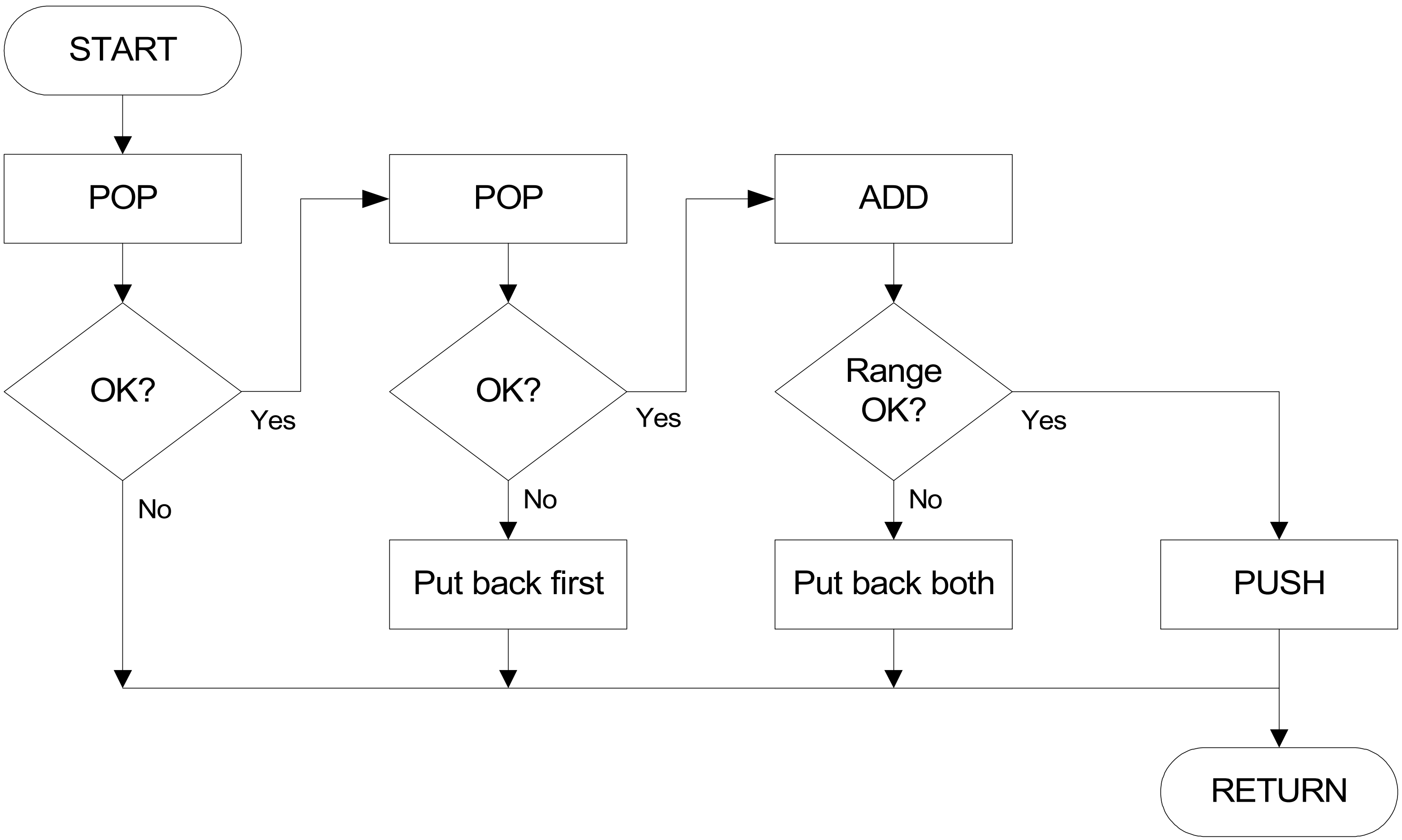
(1) push A
(2) push B
(3) ADD
(4) push C
(5) push D
(6) ADD
(7) MULTIPLY
(8) pop result

Why use a stack?

- Limited registers.
- Convenient calling convention for subroutines.
- Algorithm naturally expressed using FIFO data structure.

Example: OpAdd

POP two values, ADD, then PUSH result.



Example: OpAdd

```
OpAdd     JSR POP         ; Get first operand.
          ADD R5,R5,#0    ; Check for POP success.
          BRp Exit        ; If error, bail.
          ADD R1,R0,#0    ; Make room for second.
          JSR POP         ; Get second operand.
          ADD R5,R5,#0    ; Check for POP success.
          BRp Restore1    ; If err, restore & bail.
          ADD R0,R0,R1    ; Compute sum.
          JSR RangeCheck  ; Check size.
          BRp Restore2    ; If err, restore & bail.
          JSR PUSH        ; Push sum onto stack.
          RET
Restore2  ADD R6,R6,#-1   ; Decr stack ptr (undo POP)
Restore1  ADD R6,R6,#-1   ; Decr stack ptr
Exit      RET
```

Data Type Conversion

Keyboard input routines read ASCII characters, not binary values.

Similarly, output routines write ASCII.

Consider this program:

```
TRAP   x23              ; input from keybd
ADD    R1, R0, #0       ; move to R1
TRAP   x23              ; input from keybd
ADD    R0, R1, R0       ; add two inputs
TRAP   x21              ; display result
TRAP   x25              ; HALT
```

User inputs 2 and 3 -- what happens?

Result displayed: e

Why? ASCII '2' (x32) + ASCII '3' (x33) = ASCII 'e' (x65)

ASCII to Binary

Useful to deal with mult-digit decimal numbers

Assume we've read three ASCII digits (e.g., "259") into a memory buffer.

x32	'2'
x35	'5'
x39	'9'

How do we convert this to a number we can use?

- Convert first character to digit (subtract x30) and multiply by 100.
- Convert second character to digit and multiply by 10.
- Convert third character to digit.
- Add the three digits together.

Multiplication via a Lookup Table

How can we multiply a number by 100?

- **One approach:**
  Add number to itself 100 times.
- **Another approach:**
  Add 100 to itself <number> times. (Better if number < 100.)

Since we have a small range of numbers (0-9), use number as an index into a lookup table.

Entry 0: 0 x 100 = 0
Entry 1: 1 x 100 = 100
Entry 2: 2 x 100 = 200
Entry 3: 3 x 100 = 300
etc.

Code for Lookup Table

```
; multiply R0 by 100, using lookup table
;
           LEA   R1, Lookup100    ; R1 = table base
           ADD   R1, R1, R0       ; add index (R0)
           LDR   R0, R1, #0       ; load from M[R1]
           ...
Lookup100  .FILL 0   ; entry 0
           .FILL 100 ; entry 1
           .FILL 200 ; entry 2
           .FILL 300 ; entry 3
           .FILL 400 ; entry 4
           .FILL 500 ; entry 5
           .FILL 600 ; entry 6
           .FILL 700 ; entry 7
           .FILL 800 ; entry 8
           .FILL 900 ; entry 9
```

Complete Conversion Routine (1 of 3)

```
; Three-digit buffer at ASCIIBUF.
; R1 tells how many digits to convert.
; Put resulting decimal number in R0.
ASCIItoBinary  AND  R0, R0, #0   ; clear result
               ADD  R1, R1, #0   ; test # digits
               BRz  DoneAtoB     ; done if no digits
;
               LD   R3, NegZero  ; R3 = -x30
               LEA  R2, ASCIIBUF
               ADD  R2, R2, R1
               ADD  R2, R2, #-1  ; points to ones digit
;
               LDR  R4, R2, #0   ; load digit
               ADD  R4, R4, R3   ; convert to number
               ADD  R0, R0, R4   ; add ones contrib
```

Conversion Routine (2 of 3)

```
            ADD  R1, R1, #-1    ; one less digit
            BRz  DoneAtoB       ; done if zero
            ADD  R2, R2, #-1    ; points to tens digit
;
            LDR  R4, R2, #0     ; load digit
            ADD  R4, R4, R3     ; convert to number
            LEA  R5, Lookup10   ; multiply by 10
            ADD  R5, R5, R4
            LDR  R4, R5, #0
            ADD  R0, R0, R4     ; adds tens contrib
;
            ADD  R1, R1, #-1    ; one less digit
            BRz  DoneAtoB       ; done if zero
            ADD  R2, R2, #-1    ; points to hundreds
                                ; digit
```

Conversion Routine (3 of 3)

```
                LDR   R4, R2, #0    ; load digit
                ADD   R4, R4, R3    ; convert to number
                LEA   R5, Lookup100 ; multiply by 100
                ADD   R5, R5, R4
                LDR   R4, R5, #0
                ADD   R0, R0, R4    ; adds 100's contrib
;
DoneAtoB        RET
NegZero         .FILL xFFD0   ; -x30
ASCIIBUF        .BLKW 4
Lookup10        .FILL 0
                .FILL 10
                .FILL 20
...
Lookup100       .FILL 0
                .FILL 100
...
```

Binary to ASCII Conversion

Converting a 2's complement binary value to a three-digit decimal number

- **Resulting characters can be output using OUT**

Instead of multiplying, we need to divide by 100 to get hundreds digit.

- **Why wouldn't we use a lookup table for this problem?**
- **Subtract 100 repeatedly from number to divide.**

First, check whether number is negative.

- **Write sign character (+ or -) to buffer and make positive.**

Binary to ASCII Conversion Code (part 1 of 3)

```
; R0 is between -999 and +999.
; Put sign character in ASCIIBUF, followed by three
; ASCII digit characters.

BinaryToASCII  LEA R1, ASCIIBUF   ; pt to result string
               ADD R0, R0, #0     ; test sign of value
               BRn NegSign
               LD  R2, ASCIIplus ; store '+'
               STR R2, R1, #0
               BRnzp  Begin100
NegSign        LD  R2, ASCIIneg   ; store '-'
               STR R2, R1, #0
               NOT R0, R0         ; convert value to pos
               ADD R0, R0, #1
```

Conversion (2 of 3)

```
Begin100        LD   R2, ASCIIoffset
                LD   R3, Neg100
Loop100         ADD R0, R0, R3
                BRn End100
                ADD R2, R2, #1    ; add one to digit
                BRnzp  Loop100
End100          STR R2, R1, #1    ; store ASCII 100's digit
                LD   R3, Pos100
                ADD R0, R0, R3    ; restore last subtract
;
                LD   R2, ASCIIoffset
                LD   R3, Neg10
Loop100         ADD R0, R0, R3
                BRn End10
                ADD R2, R2, #1    ; add one to digit
                BRnzp  Loop10
```

Conversion Code (3 of 3)

```
End10           STR R2, R1, #2   ; store ASCII 10's digit
                ADD R0, R0, #10  ; restore last subtract
;
                LD  R2, ASCIIoffset
                ADD R2, R2, R0   ; convert one's digit
                STR R2, R1, #3   ; store one's digit
                RET


;
ASCIIplus   .FILL x2B    ; plus sign
ASCIIneg    .FILL x2D    ; neg sign
ASCIIoffset .FILL x30    ; zero
Neg100      .FILL xFF9C  ; -100
Pos100      .FILL #100
Neg10       .FILL xFFF6  ; -10
```