

## Chapter 10 And, Finally... The Stack

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### Stack: An Abstract Data Type

- An important abstraction that you will encounter in many applications.
- The fundamental model for execution of C, Java, Fortran, and many other languages.
- We will describe three uses of the stack:
  - **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

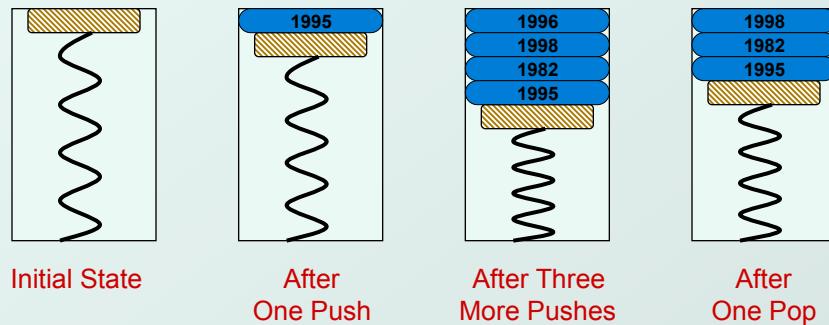
- A LIFO (last-in first-out) storage structure.
  - The **first** thing you put in is the **last** thing you take out.
  - The **last** thing you put in is the **first** thing you take out.
- This means of access is what defines a stack, not the specific implementation.
- Two main operations:

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

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

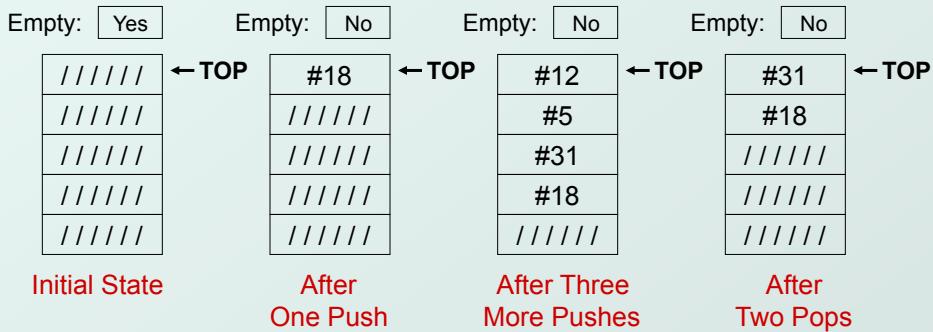
## A Physical Stack

- Coin rest in the arm of an automobile



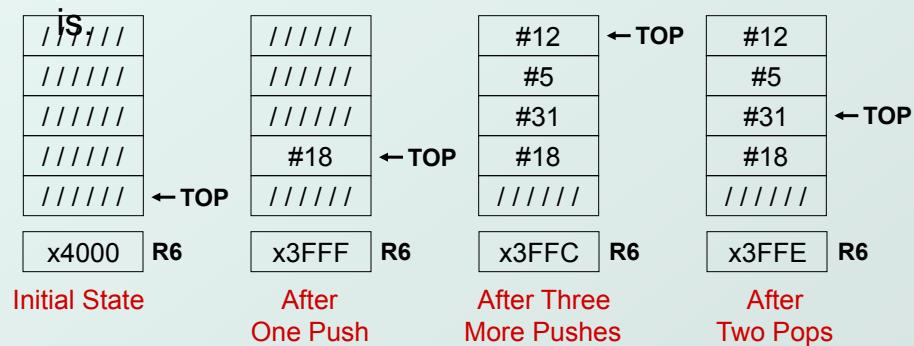
# A Hardware Implementation

- Data items move between registers



# A Software Implementation

- Data items don't move in memory, just our idea about where 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 Rx

```
ADD  R6, R6, #-1 ; decrement stack pointer
STR  Rx, R6, #0  ; store data (Rx) to TOS
```

### POP Rx

```
LDR  Rx, R6, #0  ; load data (Rx) from TOS
ADD  R6, R6, #1  ; increment stack pointer
```

## Pop with Underflow Detection

- If we try to pop too many items off the stack, an **underflow** condition occurs.
  - Check for underflow 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 overflow 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 x3FFB
      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
```

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## 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...

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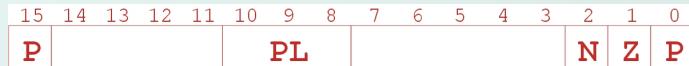
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## Processor State

- 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]



- **Program Counter**

- Pointer to next instruction to be executed.

- **Registers**

- Temporary process state 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 before 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 (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 = x01 $\text{v}\text{v}$ , where  $\text{v}\text{v}$  = 8-bit interrupt vector provided by interrupting device (e.g., keyboard = x80).
7. Load memory location (M[x01 $\text{v}\text{v}$ ]) 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.**

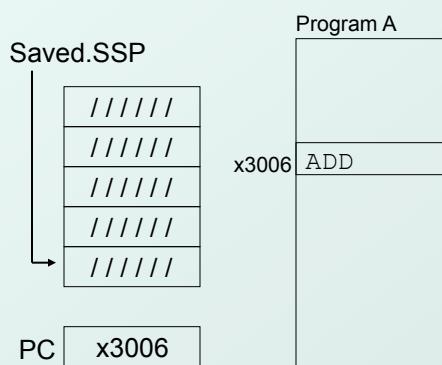
## Returning from Interrupt

- Special instruction – RTI – that restores state.

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 going back to user mode, need to restore User Stack Pointer:  
 $(if PSR[15] = 1, R6 = Saved.USP)$

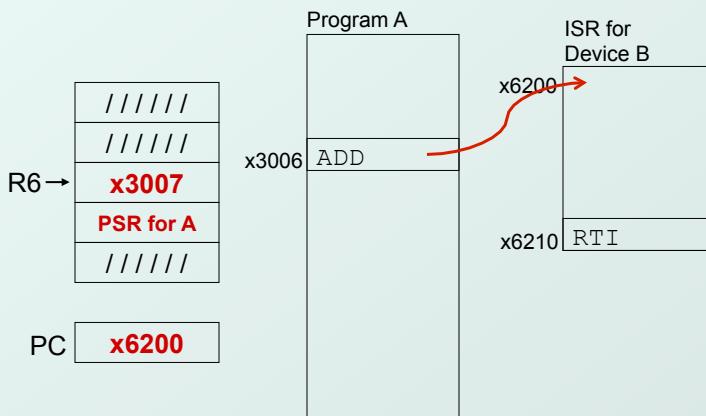
- RTI is a privileged instruction.
  - Can only be executed in Supervisor Mode.
  - If executed in User Mode, causes an exception.  
(More about that later.)

## Example (1)



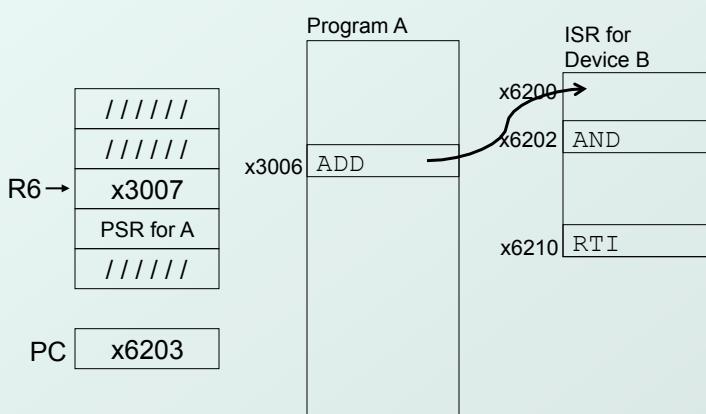
Executing ADD at location x3006 when Device B interrupts.

## Example (2)



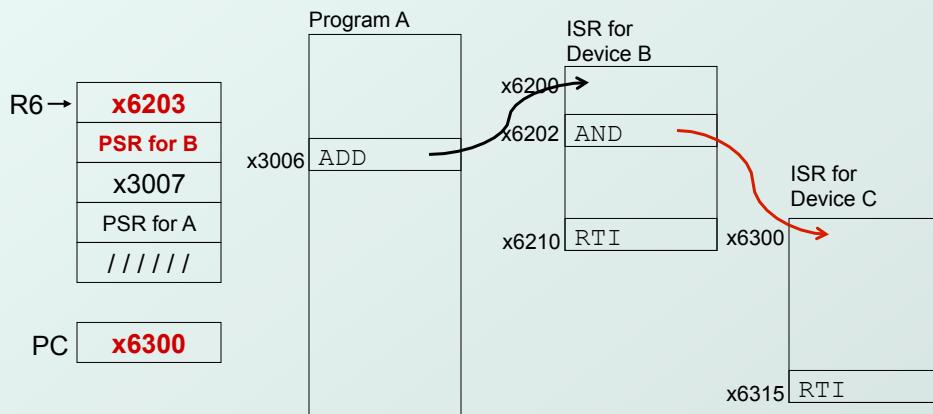
**Saved.USP = R6. R6 = Saved.SSP.**  
**Push PSR and PC onto stack, then transfer to**  
**Device B service routine (at x6200).**

## Example (3)



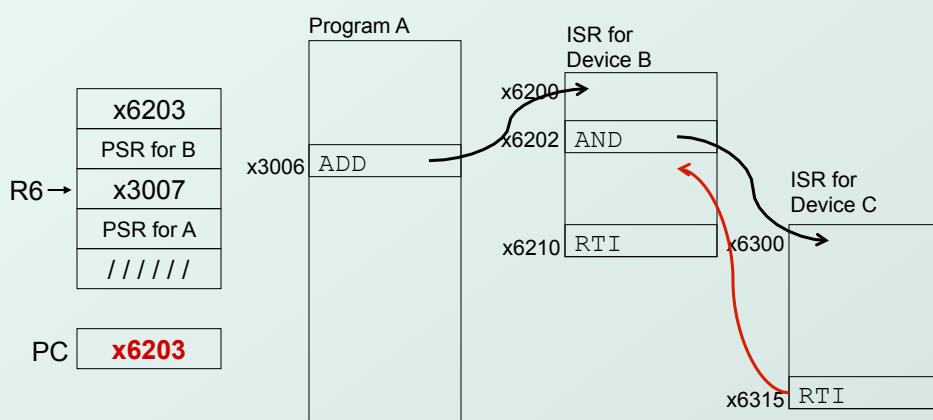
**Executing AND at x6202 when Device C interrupts.**

## Example (4)



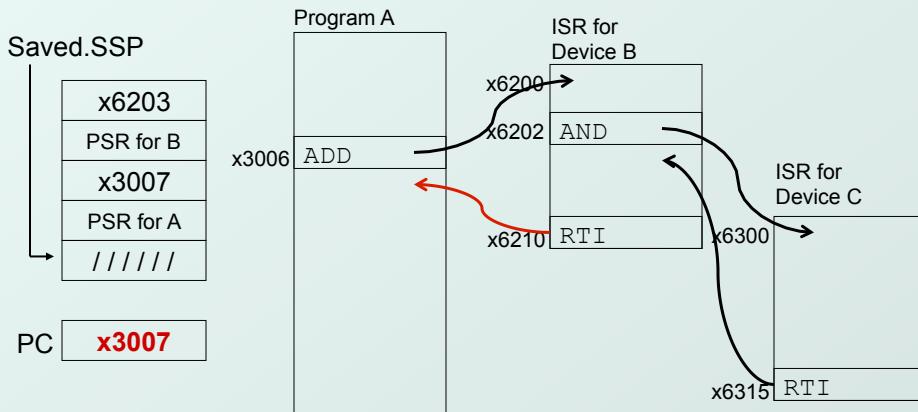
Push PSR and PC onto stack, then transfer to Device C service routine (at x6300).

## 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/destination ops (**zero-address** machine).
  - Example: ADD instruction pops two numbers from the stack, adds them, and pushes the result to the stack.

Evaluating  $(A+B) \cdot (C+D)$  using a stack:

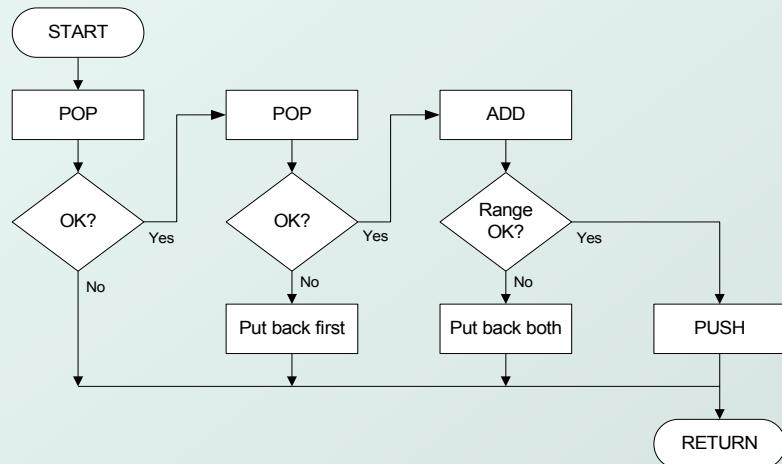
- (1) push A
- (2) push B
- (3) ADD
- (4) push C
- (5) push D
- (6) ADD
- (7) MULTIPLY
- (8) pop Result

### 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 ; undo first POP
Restore1 ADD R6,R6,#-1 ; undo second POP
Exit RET
```

## Data Type Conversion

- Keyboard input routines read ASCII characters, not binary values, 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 multi-digit decimal numbers
- Assume we've read three ASCII digits (e.g., "259") into memory.

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

- How do we convert this to a number we can use?
  - Convert first character to digit 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:  $0 \times 100 = 0$

Entry 1:  $1 \times 100 = 100$

Entry 2:  $2 \times 100 = 200$

Entry 3:  $3 \times 100 = 300$

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
```

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## Complete Conversion Routine (1 of 3)

```
; Three-digit buffer at ASCIIIBUF.
; 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, ASCIIIBUF
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 1's
```

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## 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 10's
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
Done   RET

NegZero  .FILL xFFD0      ; -0x30
ASCIIIBUF .BLKW 4
Lookup10  .FILL 0
        .FILL 10
...
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.