Stack in LC3 & Interrupt Processing (Chapters 10)

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Subroutines in LC3

- we covered TRAP routines
  - System calls to process I/O (or other system tasks)
  - Written by system, called by user
    - ➢ Resides as part of system code
  - Steps: Call, Process, Return
- Subroutines – i.e., functions
  - Written by user
  - Called by user program
  - Steps: Call, Process, Return

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Finally. . last concept at Machine Level. . The Stack: An abstract data type (ADT)

- An important abstraction you will encounter in many applications
- Abstract Data Type
  - Defined by behavior not implementation
- Stack
  - Last in/First Out
  - Many ways to implement
  - Many uses in CS
    - ➢ Interrupt drive I/O, Saving state of Processor, function calls, etc.
  - Push/Pop

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Stack: An Abstract Data Type

•An important abstraction that you will encounter in many applications.

•Example: three uses --

•Interrupt-Driven I/O
- The rest of the story…

•Evaluating arithmetic expressions
- Store intermediate results on stack instead of in registers
  - ➢ Do this in HW 5

•Data type conversion
- 2's comp binary to ASCII strings
- You will read this on your own and use it in HW5 and Project 2

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Stacks

•Simplest form of storage ?

•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

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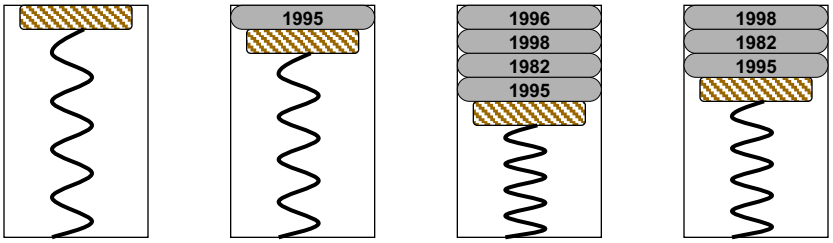
A Physical Stack

•Coin rest in the arm of an automobile



Initial State | After One Push | After Three More Pushes | After One Pop

•First quarter out is the last quarter in.

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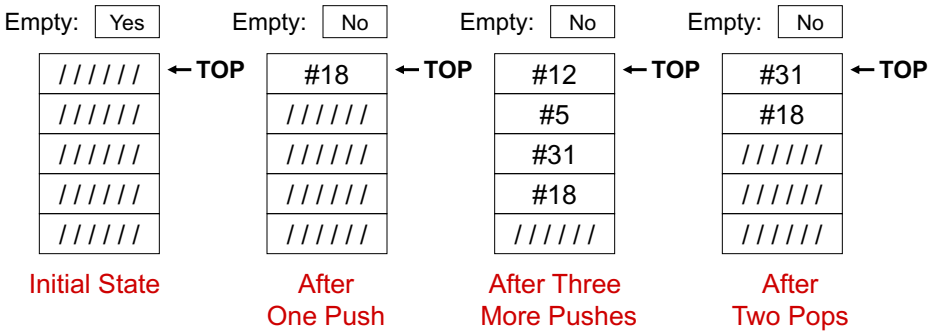
A Hardware Implementation

•Data items move between registers to memory

•



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Problems….

- Implement a stack as an array.
  - Push will involve moving each element over 1:
  - a(n+1) = a(n)
  - a(0) = new_element
  - Etc.
- So what's the solution….

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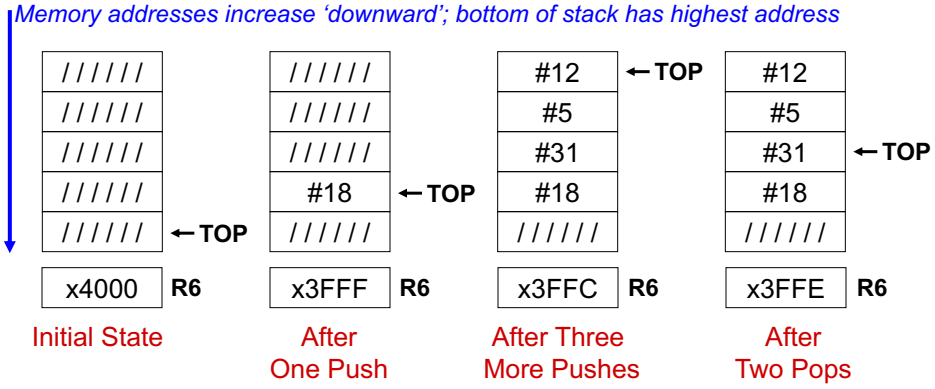
A Software Implementation

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

• Note: stack "grows" towards lower numbered addresses



By convention, **in LC3 R6 holds the Top of Stack (TOS) pointer.**

every ISA specifies such a register

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Question…State of stack

• R6 points to top of stack

•What happens after a push ?

•What happens after a pop ?

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Basic Push and Pop Code

•For our implementation, stack grows downward in address space

- (when item added, TOS moves closer to 0)

•Push: value in register R0 into the stack

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

•Pop: value at top of stack into register R0

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

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Anything missing…?

•Detect underflow

- Trying to pop from empty stack

•Detect overflow

- Trying to push into a "full" stack

•Need to send a "signal" back to calling program indicating success or failure of pop or push operations

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Pop subroutine with Underflow Detection

•If we try to pop too many items,an underflow condition occurs.

- Check for underflow by checking TOS before removing data.
- Return status code in R5 (0 for success, 1 for underflow)
- Return value at TOS into R0

```
•POP    LD  R1, EMPTY  ; EMPTY = -x4000
       ADD R2, R6, R1 ; Compare stack pointer
       BRz FAIL       ;
       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
```

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Push Subroutine with Overflow Detection

•If we try to push too many items,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 value in R0 onto the stack

```
•PUSH   LD  R1, MAX    ; MAX = -x3FFB
       ADD R2, R6, R1 ; Compare stack pointer
       BRz FAIL       ;
       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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More Stack Use examples

- Simple calculator program
  - Also illustrates use of subroutines
- Converting ASCII to Binary
  - System always reads ASCII characters from terminal/input
  - System operates on binary numbers
  - Who does the conversion ?
    - ➢ Need a subroutine
- Interrupts
  - Interrupt driven I/O

Will need to understand stack concept and use it later to implement high level language program execution

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HW: Calculator using Stack

- Simulate a calculator using LC3
- You MUST read the Example in Chapter 10
  - You will be required to implement it in Team homework
  - various portions of the source code have been provided, but you have to put them together and get them to work
    - ➢ There are some integration issues you need to worry about – i.e., ignoring them will lead to bugs
  - Source code can help with your Project 4 (and Homework 5)
    - ➢ You can use any of the code provided
    - ➢ Available in electronic reserves on Blackboard

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Arithmetic Using a Stack

•Instead of registers, some ISA's used 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:

•(A,B,+)(C,D,+)*

- (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.

Historical note: HP calculators used reverse polish notation…similar to this

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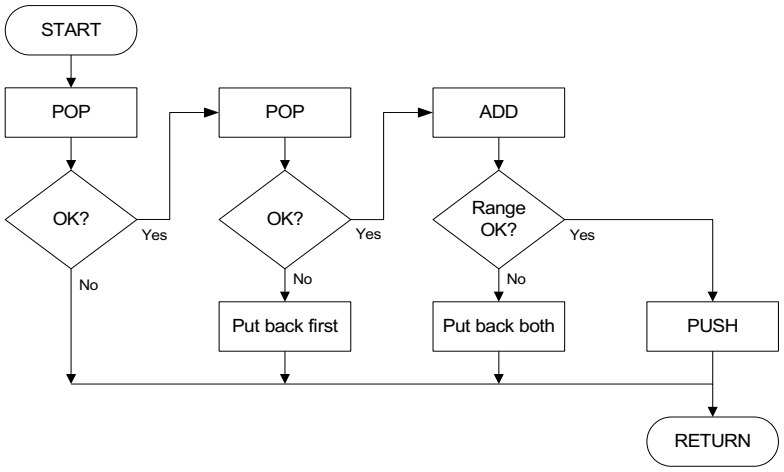
Example: So how does Add operation (OpAdd) work on this calculator ?

•POP two values, ADD, then PUSH result.



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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
```

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Data Type Conversion

- LC3 keyboard input routines read ASCII characters, not binary values.
- Similarly, LC3 output routines write ASCII.
- You've seen this program:

```
     IN ; input from keybd into R0
     ADD   R1, R0, #0  ; move to R1
     IN  ; read next input from keybd
     ADD   R2, R0, #0  ; move to R2 add two inputs
     ADD    R0, R1,R2 ; add the two inputs
     OUT ; print result
```

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

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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.

Curious ? Look up atoi function in C…

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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.

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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.

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More Stack uses…

•Interrupt processing

•Will need to understand stack concept and use it later to implement high level language program execution

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Recall: Interrupt-Driven I/O

- Two ways to process I/O
  - Polling: CPU waits for input device
  - Interrupt driven: device signals when it is ready
- Why?
  - Polling consumes a lot of cycles,
    especially for rare events – these cycles could be used to do useful computations.
  - Example: Process previous input while waiting for network/disk.

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Interrupt Processing

External device can:

(1) Force currently executing program to stop;

(2) Have the processor satisfy the device's needs; and

(3) Resume the stopped program as if nothing happened.

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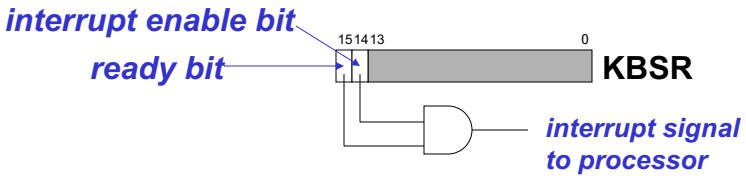
Interrupt-Driven I/O

•To implement an interrupt mechanism, we need:

- A way for the I/O device to signal the CPU that an interesting event has occurred.
- A way for the CPU to test whether the interrupt signal is set and whether its priority is higher than the current program.

•Generating Signal

- Software sets "interrupt enable" bit in device register.
- When ready bit is set and IE bit is set, interrupt is signaled.



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Priority

•Every instruction executes at a stated level of urgency.

•LC-3: 8 priority levels (PL0-PL7)

- Example:
  - email program runs at PL0.
  - Nuclear power correction program runs at PL6.
- It's OK for PL6 device to interrupt PL0 program, but not the other way around.

•Priority encoder selects highest-priority device, compares to current processor priority level, and generates interrupt signal if appropriate.

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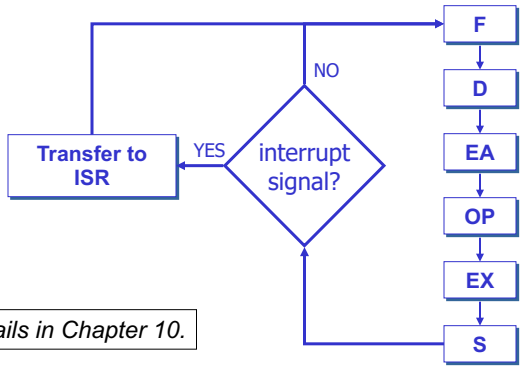
Testing for Interrupt Signal

- CPU looks at signal between STORE and FETCH phases.
- If not set, continues with next instruction.
- If set, transfers control to interrupt service routine.



More details in Chapter 10.

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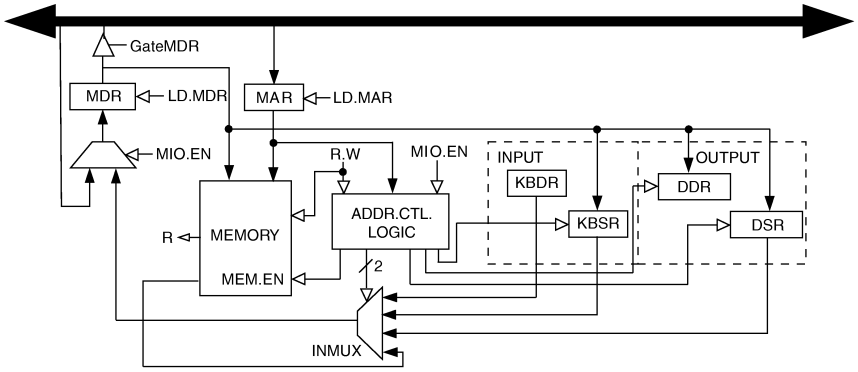
Full Implementation of LC-3 Memory-Mapped I/O



Because of interrupt enable bits, status registers (KBSR/DSR) must be written, as well as read.

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Interrupt-Driven I/O

•Interrupts processing:

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.*

•How do steps (2) and (3) occur, involves a stack.

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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

- All temporary state of the process that's not stored in memory.
  - Can be saved by Interrupt processing routine (similar to TRAP routines)

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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.

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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.

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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.

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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.)

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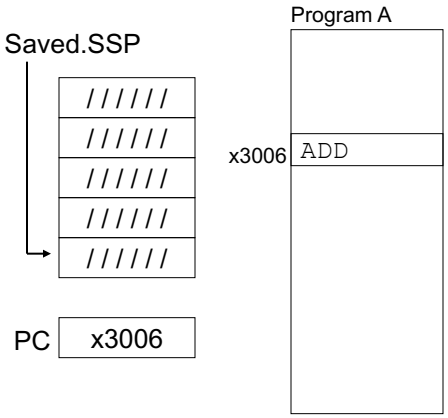
Example (1)



Executing ADD at location x3006 when Device B interrupts.

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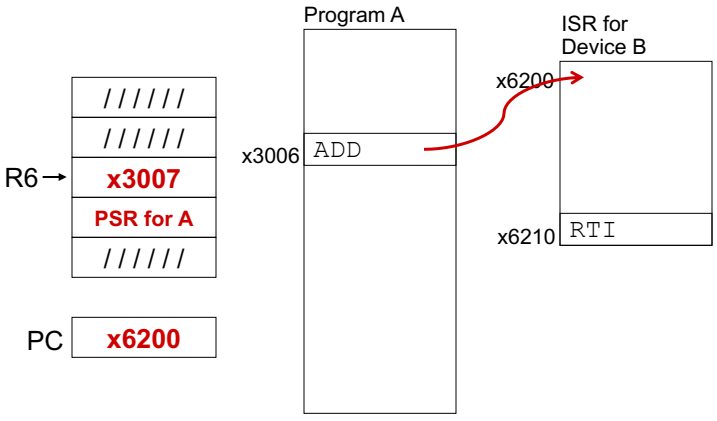
Example (2)



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

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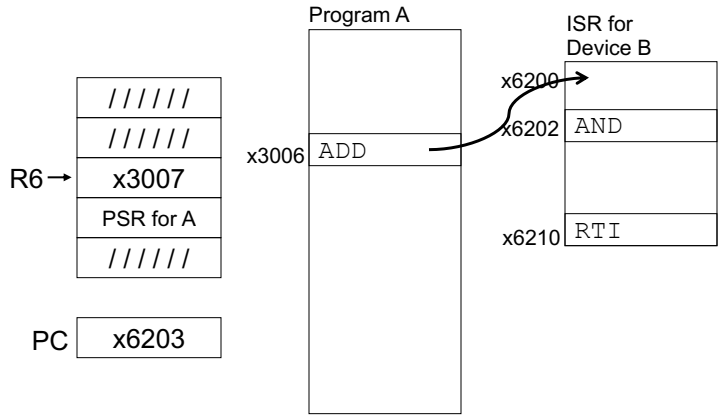
Example (3)



Executing AND at x6202 when Device C interrupts.

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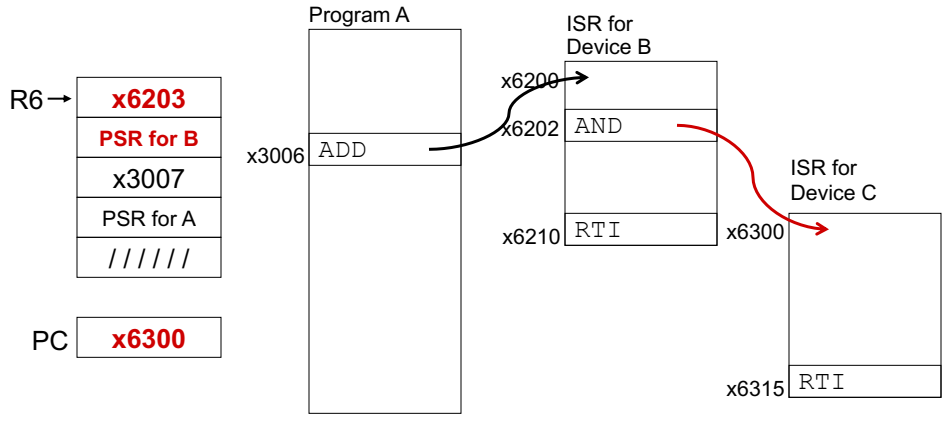
Example (4)



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

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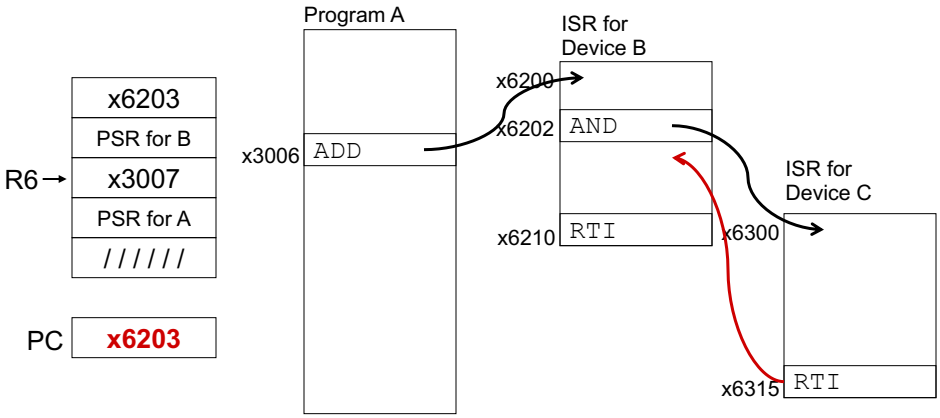
Example (5)



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

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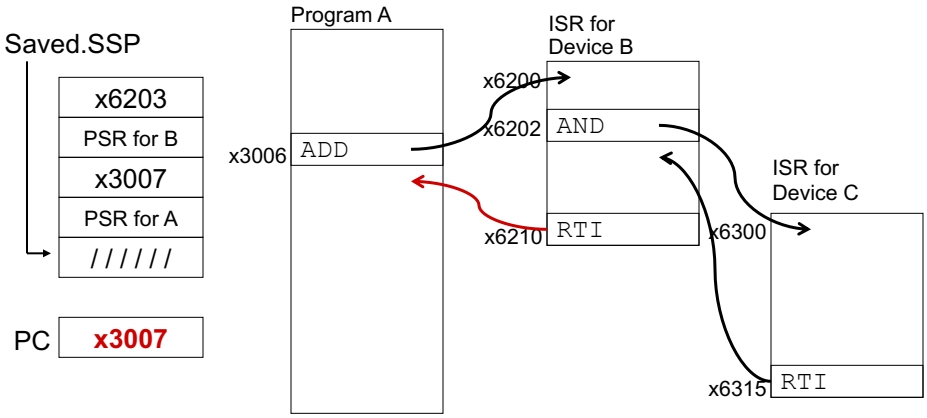
Example (6)



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

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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

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What Next ?

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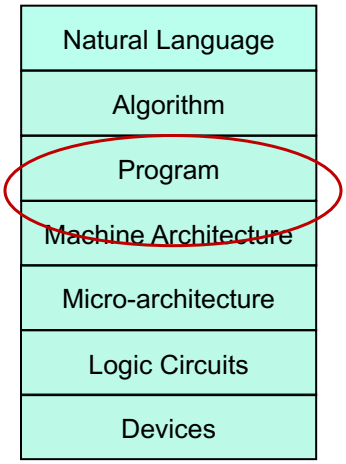
Problem Transformation - levels of abstraction

Interaction and Translation from High level to ISA



How do user programs get executed?

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What to study next..

- How are high level programs executed on the processor ?
  - Review some aspects of C
    - How are operators implemented?
  - Function calls and recursion
    - How does the system support this?
      - Any guesses?
  - Memory
    - Concept of virtual memory
- Performance
  - How "efficient is your program" ?

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