CSCE 611:
Execution and Write Back Stages:
I-Type Branch, R/J-Type JUMP Instructions

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Schedule

- Final exam:
  - Final exam slots:
    - Monday, Dec. 5 at 2:00-4:00
    - Monday, Dec. 5 at 4:00-6:00 (regular time)
  - An example exam and grading rubric are posted on Dropbox
- Lab 5: Schedule your demos ASAP!
- Lab 6: No demos, require standard testbench
  - Due Fri. 12/2 (end of next week)
  - I will be out of town next week except Monday
- Lab 7:
  - Must be submitted and demonstrated to Dr. Bakos by Monday, Dec. 12
  - Both group members must be present at demo

Branch Instructions

- Examples:
  - beq $1, $2, loop
  - bgez $1, loop
- Target address is encoded as a signed value indicating number of instructions to skip relative to next instruction
- New PC =
  - Program counter in FETCH + sign extended immediate of instruction in EX
- Resolve branch in EX, depends on ALU

Jump Instructions

- R-type JUMP
  - Example:
    - jr $31
  - Unconditional
  - New PC = Regs[RS]

- J-type JUMP
  - Example:
    - j exit
  - Unconditional
  - New PC = instruction_EX bits 9:0

Three Stage Pipeline

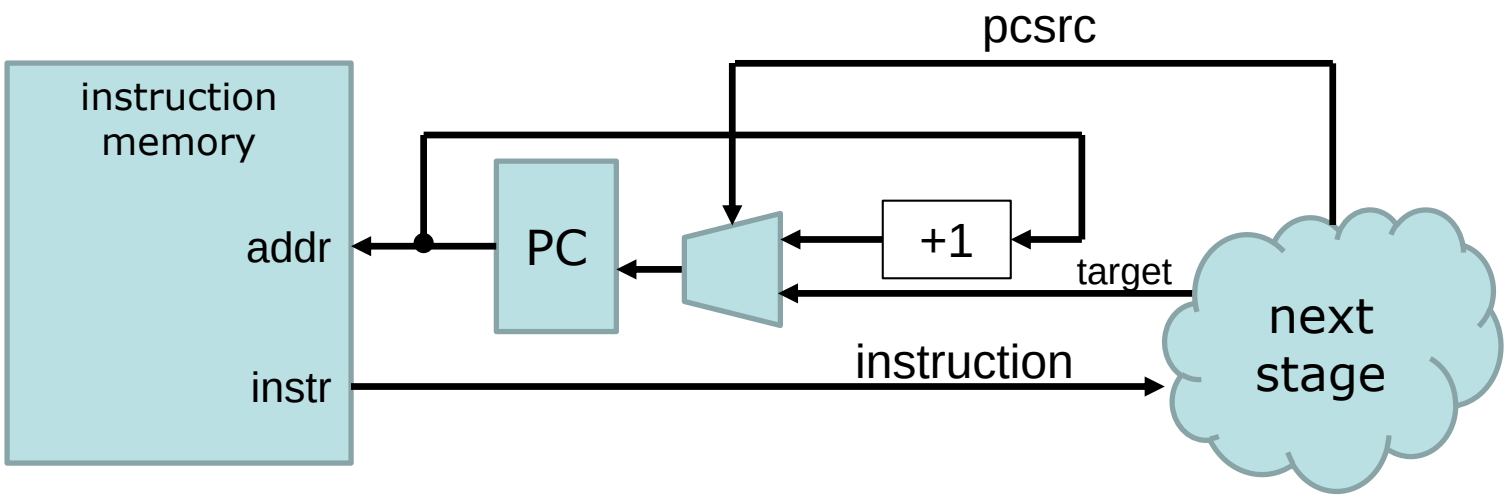
cycle	0	1	2	3	4	5	6	7
add	F	E	W					
add		F	E	W				
branch (t)			F	E	W			
fall through				F	E(S)	W(S)		
target					F	E	W	
branch(nt)						F	E	W

EX Stage: Branch/Jump

- New datapaths for EX stage:
  - **[NEW PC TARGET]**
    Need to compute **branch_addr**, **jtype_addr**, **reg_addr** and feed back to FETCH
  - **[BRANCH RESOLUTION]**
    - bgez: sign bit of R[rs]
    - beq, bne: perform subtract, use ALU's 'zero' output
  - **[LINK ADDRESSES]**
    For and-link branches and jumps:
    - Add registered version of PC_FETCH as possible register write value
      - Expand regsel_EX to allow this value to be written to the register file
    - Expand rdrt_EX to allow a hardcoded 31 to be chosen as the destination register

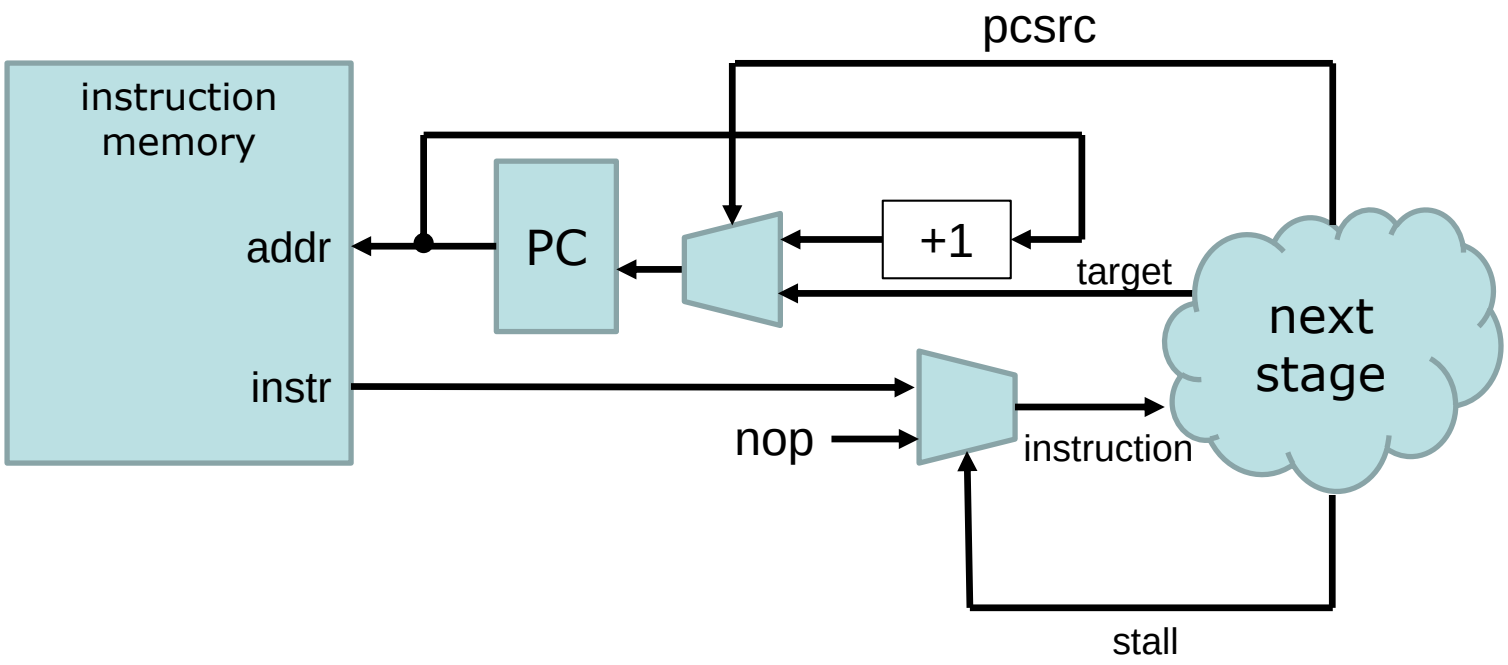
Fetch Stage

- Need to accept a branch/jump target from next stage for taken branches or jumps



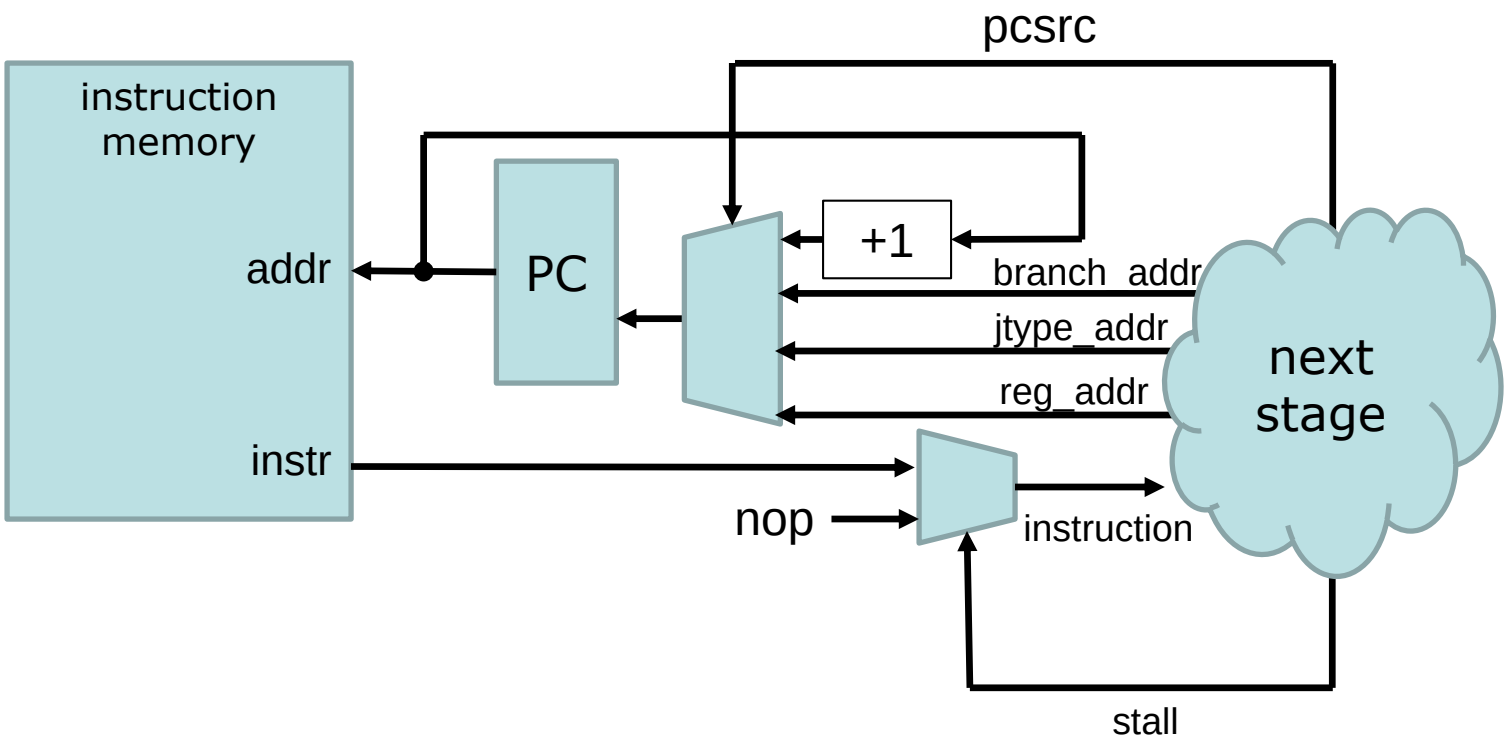
Fetch Stage

- Need to add a stall for instruction following a taken branch or jump



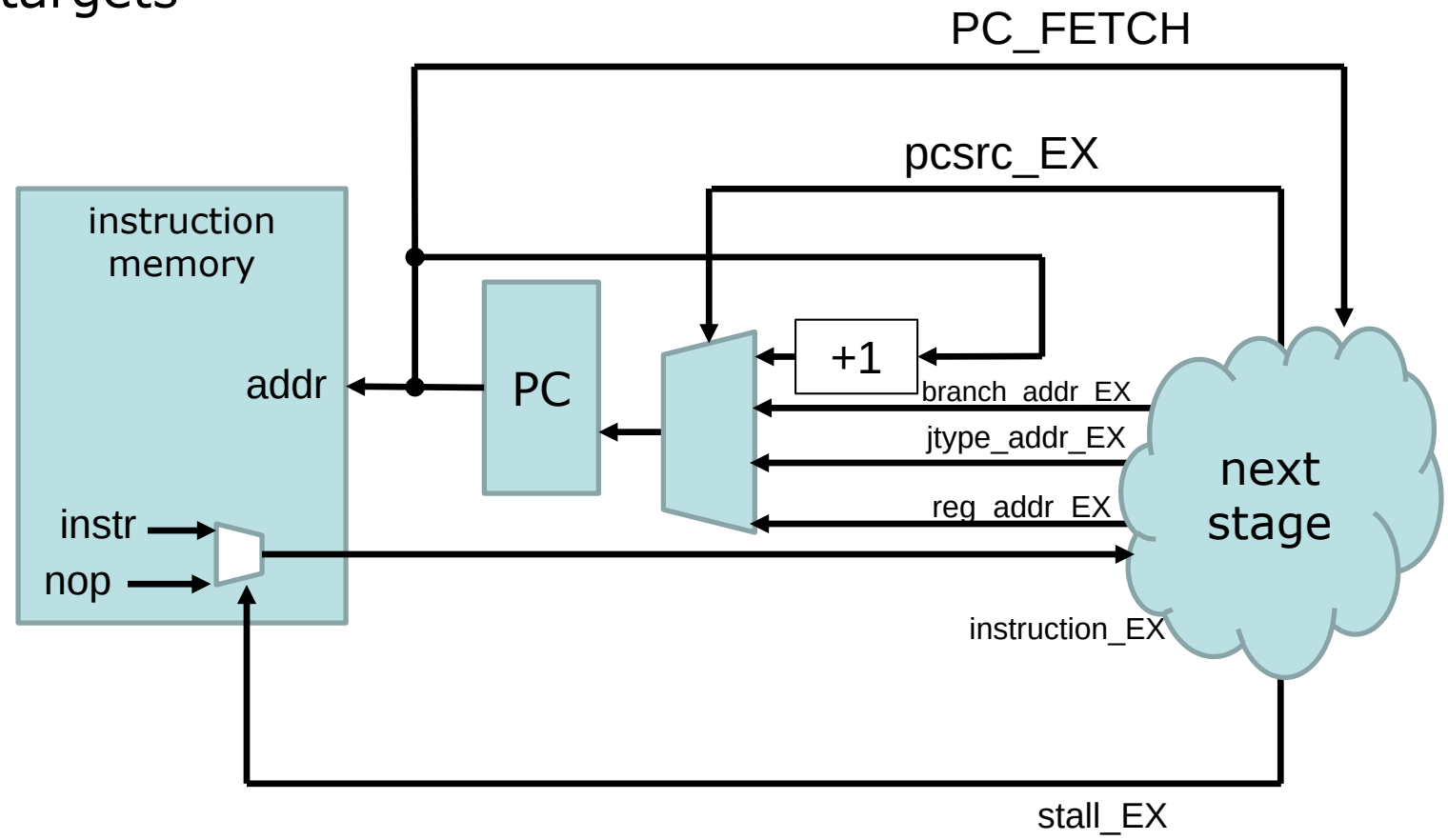
Fetch Stage

- Add a separate bus for branch vs. j-type jumps vs. r-type jumps



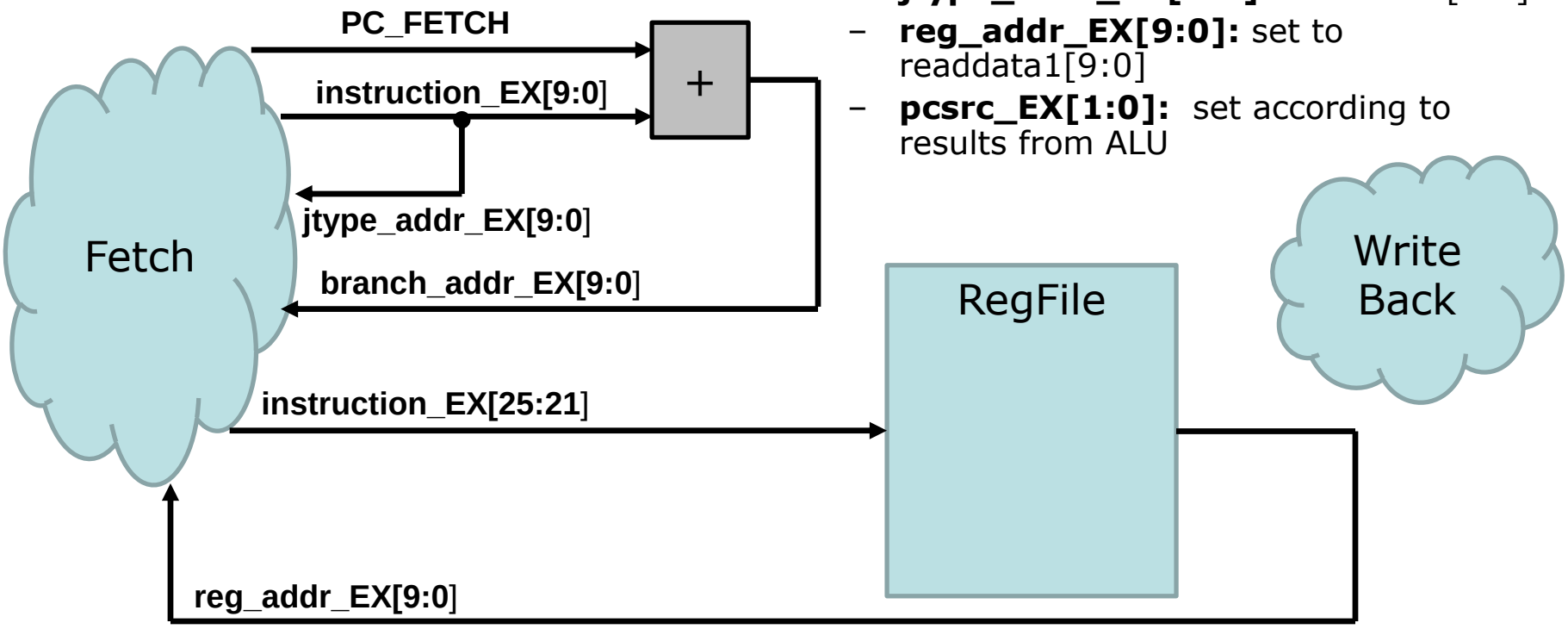
Fetch Stage

- Need to provide PC to next stage to compute branch targets

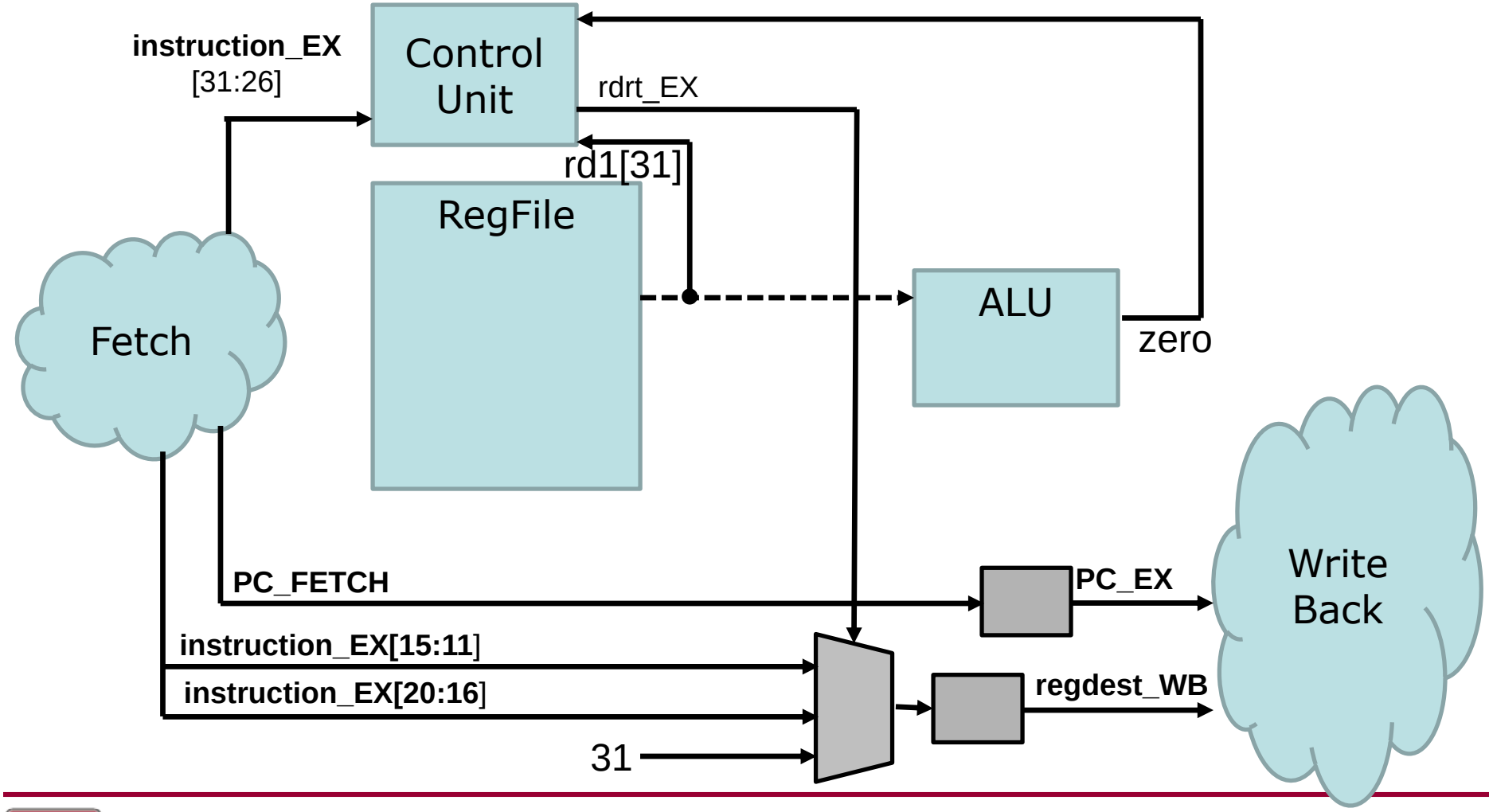


EX Stage: New Signals for Branch/Jump

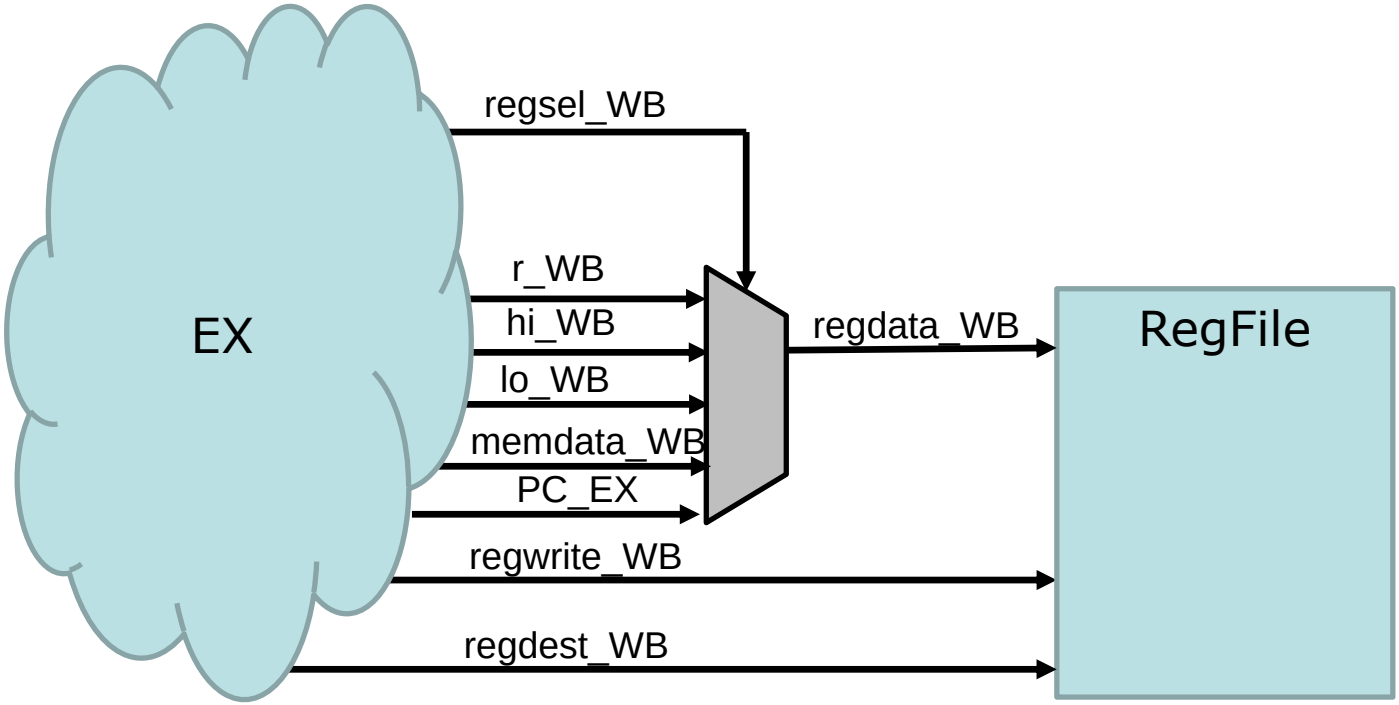
- In execute stage:
  - **branch_addr_EX[9:0]:** set to PC_FETCH + instr[9:0]
  - **jtype_addr_EX[9:0]:** set to inst[9:0]
  - **reg_addr_EX[9:0]:** set to readdata1[9:0]
  - **pcsrc_EX[1:0]:** set according to results from ALU



EX Stage: New Signals for Branch/Jump



WB Stage: New Signals for Branch/Jump



EX Stage: Branch/Jump

- Example control unit code for branch:

```
if (opcode == 6'b000001) begin // bgez
    alu_op = 4'b1100; // slt
    alu_shamt = 5'bX;
    enhilo = 1'b0;
    regsel = 3'bX;
    regwrite = 1'b0;
    alusrc = ??; // varies per design
    rdrt = 2'bX; // now 2 bits!
    if (readdata1_EX[31] == 0) begin
      pcsrc = 2'b01; // take branch and invalidate instruction being fetched
      stall = 1;
    else begin
      pcsrc = 2'b00;
      stall = 0;
    end
```

Lab 6: Branch/Jump Instructions

- Objectives:
  1. Implement MIPS processor that implements instructions:
     `beq, bne, bgez, j, jal, jr`

  2. Test with test program

  3. Write a MIPS test program:
     - Computes square root of a value on switches
     - Displays value on 7-segment LEDs
     - Implement on DE2

     - Value on switches is (18,0) value
     - Solution stored as (32,24) internally
     - Value displayed on HEXs is (8,5)
     - You can't light up decimal point on HEXs (not connected on DE2 board)

Test Program

```
                li $4,1
                li $5,2
                beq $4,$5,target1    # not taken
b:              bne $4,$5,target2    # taken
c:              bgez $4,target3      # taken
d:              jal target4
                j exit
target1:        j b
target2:        j c
target3:        j d
target4:        jr $31
exit:
```

Square Root

- Basic idea:
  - For a input value ***S***
  - Write a problem that solves equation $x^2 - S = 0$
  - Simplest solution: use binary search
    1. Choose initial guess for X = 0.0
    2. Choose initial step size ***step*** (solution must be within ***step***^{2})
    3. Repeat until step == 0:
       1. val = $x^2 - S$
       2. if val < 0 then x = x+step else x = x-step
       3. step = step / 2
  - Example: find sqrt(2)

X	val	step	action
0	-2	2	add
2	2	1	sub
1	-1	.5	add
1.5	0.25	.25	sub
1.25	-0.4375	.125	add
1.375	-0.1093	.0625	add
1.4375	0.0664	.03125	sub
1.40625	-0.0224	0.01563	sub
…			

Fractional Conversion

- Switches allow a value from 0 to (2^{18}-1)
  - 0 <= x <= 262143
  - 0 <= $x^{.5}$ < 512
- Assume our BCD display is (8,5)
  - Need 3 digits to left of decimal point
  - Gives precision of 1/100000 (least significant BCD value is 10^{-5})
  - Roughly equivalent to 2^{-14} (2^-14 = 6.1x10^{-5})
- Binary representation: (32,14) fixed-point
  - shift initial step 14 bits to left
  - initial guess = 0, initial step = 256.0
- Use same algorithm as in lab 4, but first:
  - Multiply value by 10^5 (100000)
  - Shift 13 bits to the right
  - If bit 0 is set then add 2
  - Shift one bit to the right

Input and Output

- CPUs need a mechanism by which to communicate with external devices (peripherals)

- There are three mechanisms for this:
  - **Programmed I/O:** CPU and peripheral communicate through load and store instructions to special memory addresses
    - Generally used only for short control messages and status updates
  - **Direct Memory Access:** an external device is used to allow peripherals to directly access system memory, without CPU involvement
    - Used for bulk data -- disk drives, network interfaces, video cards
  - **Interrupts:** special signals that peripherals can send to the CPU in order to notify it that an I/O, error, or timer event has occurred

Programmed I/O

- Loads and stores to specially-mapped address ranges can be used to:
  - Read a word from a **status register**
    - Used to poll the state of a peripheral
  - Write a word to a **control register**
    - Used to send an "instruction" to a peripheral
- In this course, your CPU must interface with:
  - VGA video memory

CSELib VGA Interface

- We have designed a VGA interface for you
- Our VGA interface has the following characteristics:
  - Output VGA signal for 640x480 frame
  - Each pixel is 24 bit color
    - 8 bits each for RED, GREEN, and BLUE
- Nominally, this would require 640x480x3 = 921600 bytes
- We don't have this much on-chip memory, so we will *downsample* the frame data:
  - The frame size will be 80 x 60
  - 8x8 on 640x480 field

Writing Control Registers

- Although modern computers use DMA for sending data to video memory, we will treat each location in video memory as a control register

- TODO:
  - Expand data address bus from 10 bits to 16 bits
  - Connect CPU's address output to both memories
  - Memory addresses 0xC000 to 0xF000 are mapped to video memory
  - Instantiate display interface into "My Computer" design
  - Video memory is 8K x 24 bits
  - External hardware used to **mask off** mem_we signal and enable video memory if store instruction falls into video memory range
    - Example:

```
assign mem_we = mem_addr[15:14] != 2'b11 ? mem_we_cpu : 1'b0;
assign video_we = mem_addr[15:14] == 2'b11 ? mem_we_cpu : 1'b0;
```

CSELib VGA Interface: display_IF

- The VGA interface outputs the current contents of the frame memory to the monitor

```
module display_if (
        input clk,
        input rst,
        input [12:0] mem_waddr,
        input [23:0] mem_wdata,
        input mem_web,

        output [7:0] VGA_R,
        output [7:0] VGA_G,
        output [7:0] VGA_B,
        output VGA_SYNC,
        output VGA_BLANK,
        output VGA_CLK,
        output VGA_HS,
        output VGA_VS);
```

- The 8 outputs must be wired to output pins on the top level design, named according to their corresponding pin names

display_IF

- Add files to your project from /usr/local/3rdparty/csce611/vga_interface:
  - display_if.v : top-level interface, instance this in your design
  - Display.v : downsamples 640x480x30 to 80x60x15
  - VGA_PLL.v : creates 25 MHz clock (for 640x480) from 50 MHz reference clock
  - VGA_Sync.v : generates synchronization signals
  - vmem8192x24.v : video (pixel) memory

- There is also a sample top-level file to test your VGA connection:
  - video_test.v

- To use:
  - Wire up clk, rst
  - To draw a pixel:
    - Assert mem_web
    - mem_waddr(12 downto 7) is the **ROW NUMBER**
    - mem_waddr(6 downto 0) is the **COLUMN NUMBER**
    - mem_wdata(23 downto 16) is the RED intensity
    - mem_wdata(15 downto 8) is the GREEN intensity
    - mem_wdata(7 downto 0) is the BLUE intensity

Project Objective

- Write an assembly program that implements an "orbiting cursor"
  - One pixel on screen
  - Foreground and background color at your discretion
  - Pixel should constantly follow a path in a clockwise circle around the center of screen
  - User can adjust the radius of the orbit, not exceeding the maximum or minimum sizes allowed by the screen

- Controls:
  - Add KEY inputs to REG30 input:
  - KEY3: while pressed, decrease radius
  - KEY2: while pressed, increase radius

Outline of Assembly Program

- Basic idea:
  - Keep track of cursor x-position: pos_x
  - Sweep it between +/- radius
  - Calculate y-position for each x position on circle
  - (Would be better to calculate both positions as a function of angle, but we don't want to implement trig functions)
  - Paint cursor on each iteration

- To slow the animation down:
  - Assign each pixel position a number of distance units, e.g. $2^{GRIDSIZE}$ units, per pixel
    - In other words (32,GRIDSIZE) fixed-point

Pseudocode

- Initialize registers:
  - pos_x = 0
  - direction_x = 1 (to the right)
  - radius = 30 << GRIDSIZE
  - center_x = 40 << GRIDSIZE
  - center_y = 30 << GRIDSIZE

Pseudocode

- Loop:
  - if pos_x<(-radius) or pos_x>radius then
    - direction_x = not direction_x
  - if direction_x then
    - new_pos_x = pos_x + 1
  - else
    - new_pos_x = pos_x - 1
  - new_pos_y = sqrt(radius^2-new_pos_x^2)
  - if direction_x==0 then new_pos_y = -new_pos_y
  - store background pixel to
    - (pos_x+center_x)>>GRIDSIZE, (pos_y+center_y)>>GRIDSIZE
  - store foreground pixel to
    - (new_pos_x+center_x)>>GRIDSIZE, (new_pos_y+center_y)>>GRIDSIZE
  - pos_x = new_pos_x
  - pos_y = new_pos_y
  - if KEY3 then increase radius
  - if KEY2 then decrease radius

Practical Considerations

- Square root input and output are (32,0) values
- x^2 must fit inside of 32 bits
  - limits $2^{GRIDSIZE}$ to sqrt(2^{32})/80 = 819.2 => 512
- Ball will move one x-position pixel after 512 iterations of loop
- Assume loop requires 100 cycles
- This means the ball will make a cycle (160 positions) in 160x100x512/50e6 s = .16 s at its max radius

Lab 7

- Design computer design with video interface
- Implement “orbit” code
- Due Dec. 12 (submission and demo)