Name: Jacob Branaugh **CS/ECE 472/572 Midterm 2**

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1. (10 points) 9.23
   When a CPU writes to the cache, both the item in the cache and the corresponding item in the memory must be updated. If data is not in the cache, it must be fetched from memory and loaded in the cache. If t_1 is the time taken to reload the cache on a miss, show that the effective average access time of the memory system is given by
   $t_{ave} = ht_c + (1-h)t_m + (1-h)t_1$

- Assuming the cache does not have to be reloaded, the average access time is equal to
  $t_{ave} = ht_c + (1-h)t_m$
  In this case, the cache does take time to reload. For a single access, the time taken to reload the cache must be added to the no-miss access time. Since we are concerned about the average time, the cache reload time multiplied by the cache miss ratio must be added to the prior equation. This gives us
  $t_{ave} = ht_c + (1-h)t_m + (1-h)t_1$
  which is the hit ratio multiplied by the cache access time plus the miss ratio multiplied the memory access time plus the miss ratio multiplied by cache reload time.

2. (10 points) 9.26
   A system has a level 1 cache and a level 2 cache. The hit rate of the level 1 cache is 90%, and the hit rate of the level 2 cache is 80%. An access to level 1 cache requires one cycle, an access to level 2 cache requires four cycles, and an access to main memory requires 50 cycles. What is the average access time?

- The average access time can be expressed as a sum of the various access times multiplied by their respective occurrence rates:
  $t_{avg} = h_1 t_{c1} + (1-h_1)h_2 t_{c2} + (1-h_1)(1-h_2)t_m$
  where h_1 is the l1 cache hit rate, h_2 is the l2 cache hit rate, t_{c1} is the l1 cache access time, t_{c2} is the l2 cache access time, and t_m is the main memory access time. On average, the l1 cache access occurs as frequently as the l1 hit rate, the l2 cache access occurs as frequently as the l1 miss rate, and the main memory access occurs as frequently as the l2 miss rate and the l1 miss rate. Plugging in values gives:
  $t_{avg} = .9 \times 1 + .1 \times .8 \times 4 + .1 \times .2 \times 50 =$ **2.22 cycles**

3. (10 points) 9.35
   A 64-bit processor has an 8-MB, four-way set-associative cache with 32-byte lines. How is the address arranged in terms of set, line, and offset bits?

- With a four way set associative 8MB cache, each set will be 2MB in size. 32 byte lines means the number of lines will be $\frac{2^{30}}{2^6}$, or 2^{24}. This means that 24 of the 64 bits will be required for the line number. Since the line size is 32 bytes, or 2^6, 6 bits will be required for the line offset. Since the cache has four, or 2^2, sets, 2 bits will be required for the set number.

4. (10 points) Assume a 64-bit virtual address and a 64-bit physical address. The page size is 4KB. How many total entries are there in the page table? Express your answer in powers of 2.

- The page size is given as $4KB = 4 * 2^{10} = 2^2 * 2^{10} = 2^{12}$ bytes.
- Since the physical and virtual addresses are the same size, the addresses map one to one.

- This means that the page table must contain a page for each address, meaning the number of entries will be $\frac{2^{64}}{2^{12}} = 2^{52}$ **entries**.

5. (10 points) 7.16
   Derive an expression for the speedup ratio (i.e., the ratio of the execution time without pipelining to the execution time with pipelining) of a pipelined processor in terms of the number of stages in the pipeline m and the number of instructions to be executed N.

- $t_{no} = m \times N$ (each instruction executes sequentially)
- $t_{piped} = m + (N-1)$ (the first instruction of m stages has to finish, then an instruction of the remaining N-1 finishes every cycle)
- $S = \frac{t_{piped}}{t_{no}} = \frac{mN}{m+N-1}$

6. (10 points) 9.12
   How is data in main store mapped on to each of the following?

   a) Direct-mapped Cache:
   In a direct mapped cache, the main store is split into a number of equal sets, where each set is the size of the cache. From there, the sets are divided into lines, where the number of lines in the set is equal to the total number of lines in the cache.

   b) Fully-Associative Cache:
   In a fully associative cache, lines are taken from main memory and stored directly in cache. Each line's location is tagged with an address, and each line has an associated data validity bit.

   c) Set-Associative Cache:
   In a set associative cache, the cache is broken up into n sets for an n-way associative cache. A line has the same address across all n sets. When searching for an item, the sets are searched in parallel. When a match is found in any set, the search ends.

7. (10 points) 7.18
   A processor executes an instruction in the following six stages. The time required by each stage in picoseconds is given for each stage.

IF	Instruction Fetch	300ps
ID	Instruction Decode	150ps
OF	Operand Fetch	250ps
OE	Execute	350ps
M	Memory Access	700ps
OS	Operand Store (writeback)	200ps

   a. What is the time to execute an instruction if the processor is not pipelined?
   If the processor is not pipelined, each instruction will have to go through the whole fetch/execute process before the next can start. This gives the time to execute an instruction as:
   $300ps + 150ps + 250ps + 350ps + 700ps + 200ps =$ **1950ps**

   b. What is the time taken to fully execute an instruction assuming that this structure is pipelined in six stages and that there is an additional 20ps per stage due to the pipeline latches?
   Since the processor is in the act of filling the pipeline, the clock must be able to accomodate the slowest stage. This means that the clock rate will be 700ps, as this is the slowest stage. At this point, the time to execute a single instruction will be 700ps times the number of stages, plus 20ps per stage. This gives $(700ps + 20ps) \times 6 =$ **4320ps**

c. Once the pipeline is full, what is the average instruction rate?
If the pipeline is full, an instruction will be completed every cycle. On average, the limiting factor will be the slowest cycle, with the addition of the time taken to latch the pipeline. Since the slowest cycle is the memory access at 700ps, an instruction will be completed every **720ps**

d. Suppose that 25% of instructions are branch instructions that are taken and cause a 3 cycle penalty, what is the effective instruction execute time?
Assuming the added conditions have carried through the problem, non branching instructions will take 720ps (from part c) and occur 75% of the time. Branching instructions will take an additional 3 cycles on top of the existing instruction cycle, giving 720ps 4 times (or 2880ps) occurring 25% of the time. Averaging this gives
$\frac{720+720+720+2880}{4} = \mathbf{1260ps}$

8. (10 points) 6.13
A computer has the following parameters:

Operation	Frequency	Cycles
Arithmetic/logic instructions	65%	1
Register load operations	10%	5
Register store operations	5%	2
All branch instructions	20%	8

If the average performance of the computer (in terms of its CPI) is to be increased by 20% while executing the same instruction mix, what target must be achieved for the cycles per conditional branch instruction?

- The CPI for branch instructions executed by machine A is as follows:
$CPI_A = \frac{freq_{ar}}{100} \times cyc_{ar} + \frac{freq_{ld}}{100} \times cyc_{ld} + \frac{freq_{st}}{100} \times cyc_{st} + \frac{freq_{br}}{100} \times cyc_{br}$
When values are plugged in, we get:
$CPI_A = .65 + .5 + .1 + 1.6 = 2.85$

- We know that a 20% performance increase is desired. This means our new CPI will be equal to our old CPI multiplied by 1.2, or
$CPI_B = \frac{CPI_A}{1.2} = 2.375$

- If we reorder the equation from the first bullet for finding the branch instruction cycles using our new CPI, we get:
$cyc_{br} = \frac{CPI_B - \frac{freq_{ar}}{100} \times cyc_{ar} - \frac{freq_{ld}}{100} \times cyc_{ld} - \frac{freq_{st}}{100} \times cyc_{st}}{freq_{br}}$
Plugging values in gives us:
$cycles_{branch} = \frac{2.375 - .65 - .5 - .1}{.2} = 5.625$
We can only have integer multiples of clock cycles. Since 5.625 is our minimum target, 6 cycles will be too slow. This means that to see a 20% performance increase, we need to see branch instructions being executed in **5 cycles**

9. (15 points) 7.35
A RISC processor has an eight-stage pipeline: F D O E1 E2 MR MW WB (fetch, decode, register read operands, execute 1, execute 2, memory read, memory write, result writeback to register). Simple logical and arithmetic operations are complete by the end of E1. Multiplication is complete by the end of E2. How many cycles are required to execute the following code assuming that internal forwarding is not used?

```
(1) MUL   r0, r1, r2
(2) ADD   r3, r1, r4
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(3) ADD   r5, r1, r6
(4) ADD   r6, r5, r7
(5) LDR   r1, [r2]
```

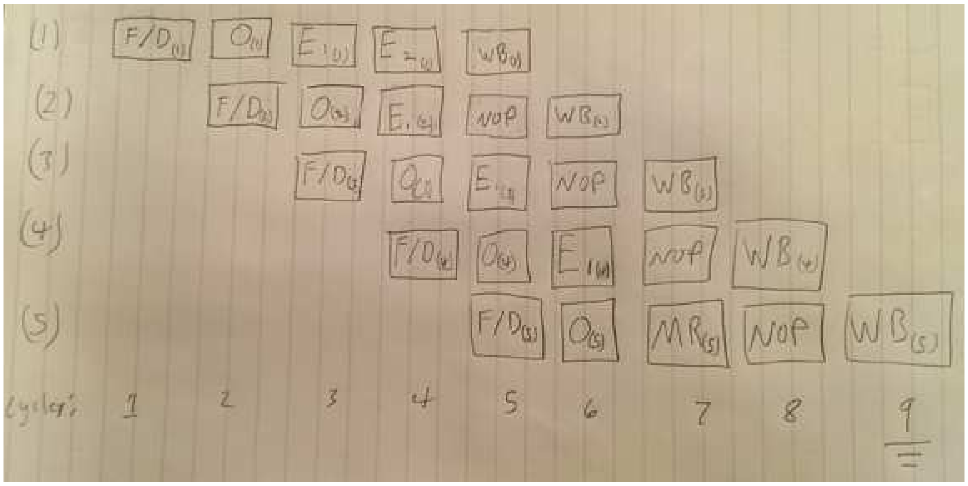

9 cycles

10. (15 points) 7.38
the following table gives a sequence of instructions that are performed on a four-stage pipelined computer. Detect all hazards. For example, if instruction m uses operand r2 generated by instruction m-1, the write m-1,r2 in the RAW column in line m.
NOTE: I am assuming that no out of order execution is happening here. Because of this, WAR and WAW will never cause hazards, as they are only hazardous to code being executed out of order. Work is shown below the table.

Number	Instruction	RAW	WAR	WAW
1	ADD r1, r2, r3			
2	ADD r4, r1, r3	1, r1		
3	ADD r5, r1, r2	1, r1		
4	ADD r1, r2, r3			
5	ADD r5, r2, r3			
6	ADD r1, r6, r6			
7	ADD r8, r1, r5	6, r1		