Question 1 (20 points): Provide concise answers to the following question.

1. (**5 points**) What were two important motivations for the creation of virtual-memory systems in computers?

   - To provide access protection to private data of a process and to data used by the kernel.
   - To facilitate the execution of programs that need more space (code and data) than can be stored simultaneously in the physical memory of the system.

2. (**5 points**) Consider two cache-memory designs with the same cache storage capacity. What is the relationship between the associativity of the cache and the number of bits used for indexing the cache?

   Every time that the associativity is doubled, the number of sets in the cache is reduced in half, and therefore one fewer bit is used to index a set in the cache.

3. (**5 points**) Consider the following sequence of MIPS instructions:

   ```
   lw    $t0, 0($a0)
   addi  $t1, $t0, 4
   ```

   When these two instructions are executed in sequence in a five-stage MIPS pipeline there will be a delay, also referred to as a bubble, in the pipeline execution. Explain why.

   The value produced by the load instruction is not available until the end of the MEM stage and this value is needed by the `addi` instruction one cycle earlier. Therefore forwarding cannot be used to send the value from the MEM stage to the EXE stage in time. The only solution is to delay the execution of the `addi` instruction by one cycle.

4. (**5 points**) Given the following C-language code

```
indCopy(int **p, int **q){
**p = **q;
}
```

Assume that `p` and `q` are in `$a0` and `$a1`, respectively, when the `indCopy` function starts executing. How many load instructions and how many store instructions are needed to execute this function?

Three loads and one store:

```
lw $t0, 0($a0)   # $t0 <- *q
lw $t1, 0($t0)   # $t1 <- **q
lw $t2, 0($a1)   # $t2 <- *p
sw $t1, 0($t2)   # *pp <- **q
```