**Problem No. 1**

(a) The 7-bit data packet (P1 through P7) could be arranged as follows with the 3 check bits (R1, R2 and R3) placed at the $2^N$ positions and the data bits (D1, D2, D3 and D4) placed in the remaining positions:

<table>
<thead>
<tr>
<th>Bit Pos</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>001</td>
<td>010</td>
<td>011</td>
<td>100</td>
<td>101</td>
<td>110</td>
<td>111</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bit</th>
<th>R1</th>
<th>R2</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rcv’d bits</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Data word = 1100  
ECC check bits = 100

(b) To determine whether the data word was received correctly or not, we need to re-compute the check bits based on the received data. The calculations are as follows:

\[
R1 = P_{001} = D1 \oplus D2 \oplus D4 = 1 \oplus 1 \oplus 0 = 0 \\
R2 = P_{010} = D1 \oplus D3 \oplus D4 = 1 \oplus 0 \oplus 0 = 1 \\
R3 = P_{100} = D2 \oplus D3 \oplus D4 = 1 \oplus 0 \oplus 0 = 1
\]

Since the calculated check bits (011) do not match the received check bits (100), we can conclude that the data word was **not received correctly**.

(c) To determine which bit is incorrect, we take the XOR of the received check bits and the re-computed check bits. In this case, we calculate 100 $\oplus$ 011 = 111 which indicates that P7 (bit#7 in the received packet) is incorrect. Referring to the table above, P7 refers to D4. We can correct the error by inverting D4 (from 0 to 1). Therefore, the correct data word is \{D1, D2, D3, D4\} = 1101.

We can confirm this by re-computing the check bits with what we feel is the correct data (1101):  

\[
R1 = P_{001} = D1 \oplus D2 \oplus D4 = 1 \oplus 1 \oplus 1 = 1 \\
R2 = P_{010} = D1 \oplus D3 \oplus D4 = 1 \oplus 0 \oplus 1 = 0 \\
R3 = P_{100} = D2 \oplus D3 \oplus D4 = 1 \oplus 0 \oplus 1 = 0
\]

This matches the received check bits.

**Problem No. 2**

(a) Loop-A is expected to have more instruction cache hits. This is because loop-A has more iterations and thus the same instructions keep on getting accessed over and over again. Furthermore, loop-A has fewer instructions in each iteration, causing the instruction footprint to easily fit in a small cache.
(b) Increasing the cache block size results in more data being transferred from the main memory to the cache on every cache miss.

**Advantage:** This can result in a higher cache hit ratio, if the application exhibits high spatial locality.

**Disadvantages:** (i) This can increase the cache miss latency and put more bandwidth pressure on the next level cache (or memory), (ii) It can result in fragmentation and wastage of capacity, if the program does not exhibit high spatial locality.

**Problem No. 3**

(a) Block size = 64 bytes = $2^6$ bytes

Therefore, Number of bits in the _Byte Select_ field = 6

Cache size = 32K-byte = $2^{15}$ bytes

Total number of cache blocks = Cache size / Block size = $2^{15} / 2^6 = 2^9 = 512$

Number of cache blocks per set = 1 (Direct-mapped cache)

Number of sets = $2^9 / 1 = 2^9$

Therefore, Number of bits in the _Index_ field = 9

Total number of address bits = 48

Therefore, Number of bits in the _Tag_ field = 48 - 6 - 9 = 33

(b) Each cache block requires the following SRAM bits:

33 bits for tag, 1 valid bit, 1 dirty bit and 512 data bits

Total SRAM bits in the cache = Total number of blocks * (SRAM bits needed for each block)

= $512 * (33 + 1 + 1 + 512) = 280,064$ bits

**Problem No. 4**

(a) Block size = 128 bytes = $2^7$ bytes

Therefore:

Number of bits in the _Byte Select_ field = 7

Cache size = 4Mbyte = $2^{22}$ bytes

Total number of cache blocks = Cache size / Block size = $2^{22} / 2^7 = 2^{15} = 32768$

Number of cache blocks per set = 16 = $2^4$

Number of sets = $2^{15} / 2^4 = 2^{11}$

Therefore, Number of bits in the _Index_ field = 11

Total number of address bits = 48

Therefore, Number of bits in the _Tag_ field = 48 - 7 - 11 = 30

(b) Each cache block requires the following SRAM bits:

30 bits for tag, 1 valid bit, 1 dirty bit and 1024 data bits

Therefore:

Number of SRAM bits needed for each block = $30 + 1 + 1 + 1024 = 1056$

Total SRAM bits in the cache = Total number of blocks * (SRAM bits needed for each block)

= $32,768 * 1056 = 34,603,008$ bits
### Problem No. 5

Block size = 16 bytes = $2^4$ bytes
Therefore, Number of bits in the Byte Select field = 4
Total number of cache blocks = 8
Number of cache blocks per set = 2 (2-way set-associative cache)
Number of sets = $8 / 2 = 4 = 2^2$
Therefore, Number of bits in the Index field = 2
Total number of address bits = 12
Therefore, Number of bits in the Tag field = $12 - 4 - 2 = 6$

<table>
<thead>
<tr>
<th>CPU Operation</th>
<th>Tag</th>
<th>Index</th>
<th>Byte Select</th>
<th>H/M</th>
<th>Miss Type</th>
<th>Memory Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read 0x014</td>
<td>00</td>
<td>1</td>
<td>4</td>
<td>M</td>
<td>Compulsory</td>
<td>Read 16 bytes from 0x010 Set-1, way-0 marked valid, tag = 00</td>
</tr>
<tr>
<td>00000000101000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read 0x020</td>
<td>00</td>
<td>2</td>
<td>0</td>
<td>M</td>
<td>Compulsory</td>
<td>Read 16 bytes from 0x020 Set-2, way-0 marked valid, tag = 00</td>
</tr>
<tr>
<td>00000010000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Write 0x200</td>
<td>08</td>
<td>0</td>
<td>0</td>
<td>M</td>
<td>Compulsory</td>
<td>Read 16 bytes from 0x200 Set-0, way-0 marked valid &amp; dirty, tag = 08</td>
</tr>
<tr>
<td>00100000000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Write 0x0A0</td>
<td>02</td>
<td>2</td>
<td>0</td>
<td>M</td>
<td>Compulsory</td>
<td>Read 16 bytes from 0x0A0 Set-2, way-1 marked valid &amp; dirty, tag = 02</td>
</tr>
<tr>
<td>00001010000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read 0x024</td>
<td>00</td>
<td>2</td>
<td>4</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00000010010000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read 0x380</td>
<td>0E</td>
<td>0</td>
<td>0</td>
<td>M</td>
<td>Compulsory</td>
<td>Read 16 bytes from 0x380 Set-0, way-1 marked valid, tag = 0E</td>
</tr>
<tr>
<td>00111000000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Write 0x388</td>
<td>0E</td>
<td>0</td>
<td>0</td>
<td>H</td>
<td></td>
<td>No memory writes since this is a writeback cache, Set-0, way-1 marked dirty</td>
</tr>
<tr>
<td>00111000000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read 0x100</td>
<td>04</td>
<td>0</td>
<td>0</td>
<td>M</td>
<td>Compulsory</td>
<td>Read 16 bytes from 0x100 Evict the LRU line in set-0 (address 0x200 in way-0). Write the evicted line back to memory. New tag for set-0, way-0 = 04</td>
</tr>
<tr>
<td>00010000000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read 0x0A8</td>
<td>02</td>
<td>2</td>
<td>8</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00001010100000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read 0x200</td>
<td>08</td>
<td>0</td>
<td>0</td>
<td>M</td>
<td>Conflict</td>
<td>Read 16 bytes from 0x200 Evict the LRU line in set-0 (address 0x380 in way-1). Writeback the evicted line to memory</td>
</tr>
<tr>
<td>00100000000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Problem No. 6

(a) L1 cache miss ratio = 1 – L1 cache hit ratio = 1 – 96% = 4%

(b) L1 cache miss rate = L1 cache access rate * L1 cache miss ratio = 300 * 4% = 12 MPKI

(c) L2 cache miss rate = L2 cache access rate * L2 cache miss ratio
   Every time, there is an L1 cache miss, it results in an L2 cache access.
   Therefore, L2 cache access rate = 12 MPKI
   Hence, L2 cache miss rate = 12 * 40% = 4.8 MPKI

(d) AMAT of L2 cache = (L2 hit time * L2 hit ratio) + (L2 miss time * L2 miss ratio)
   = (20 * (1 – 40%)) + ((20 + 300) * 40%)
   = 140 cycles

(e) AMAT of L1 cache = (L1 hit time * L1 hit ratio) + (L1 miss time * L1 miss ratio)
   L1 hit time = 3 cycles
   L1 hit ratio = 96%
   L1 miss ratio = 4%
   L1 miss time = 3 + AMAT of L2 cache = 3 + 140 = 143 cycles
   Therefore:
   AMAT of L2 cache = (3 * 96%) + (143 * 4%) = 8.6 cycles