

DESIGN OF DIGITAL CIRCUITS (252-0028-00L), SPRING 2018
OPTIONAL HW 5: VECTOR PROCESSORS AND GPUS

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1 Vector Processing

Consider the following piece of code:

```
for (i = 0; i < 100; i ++)  
  A[i] = ((B[i] * C[i]) + D[i])/2;
```

- (a) Translate this code into assembly language using the following instructions in the ISA (note the number of cycles each instruction takes is shown next to each instruction):

Opcode	Operands	Number of Cycles	Description
LEA	Ri, X	1	$R_i \leftarrow \text{address of } X$
LD	Ri, Rj, Rk	11	$R_i \leftarrow \text{MEM}[R_j + R_k]$
ST	Ri, Rj, Rk	11	$\text{MEM}[R_j + R_k] \leftarrow R_i$
MOVI	Ri, Imm	1	$R_i \leftarrow \text{Imm}$
MUL	Ri, Rj, Rk	6	$R_i \leftarrow R_j \times R_k$
ADD	Ri, Rj, Rk	4	$R_i \leftarrow R_j + R_k$
ADD	Ri, Rj, Imm	4	$R_i \leftarrow R_j + \text{Imm}$
RSHFA	Ri, Rj, amount	1	$R_i \leftarrow \text{RSHFA}(R_j, \text{amount})$
BRcc	X	1	Branch to X based on condition codes

Assume one memory location is required to store each element of the array. Also assume that there are 8 registers (R0 to R7).

Condition codes are set after the execution of an arithmetic instruction. You can assume typically available condition codes such as zero, positive, and negative.

How many cycles does it take to execute the program?

- (b) Now write Cray-like vector assembly code to perform this operation in the shortest time possible. Assume that there are 8 vector registers and the length of each vector register is 64. Use the following instructions in the vector ISA:

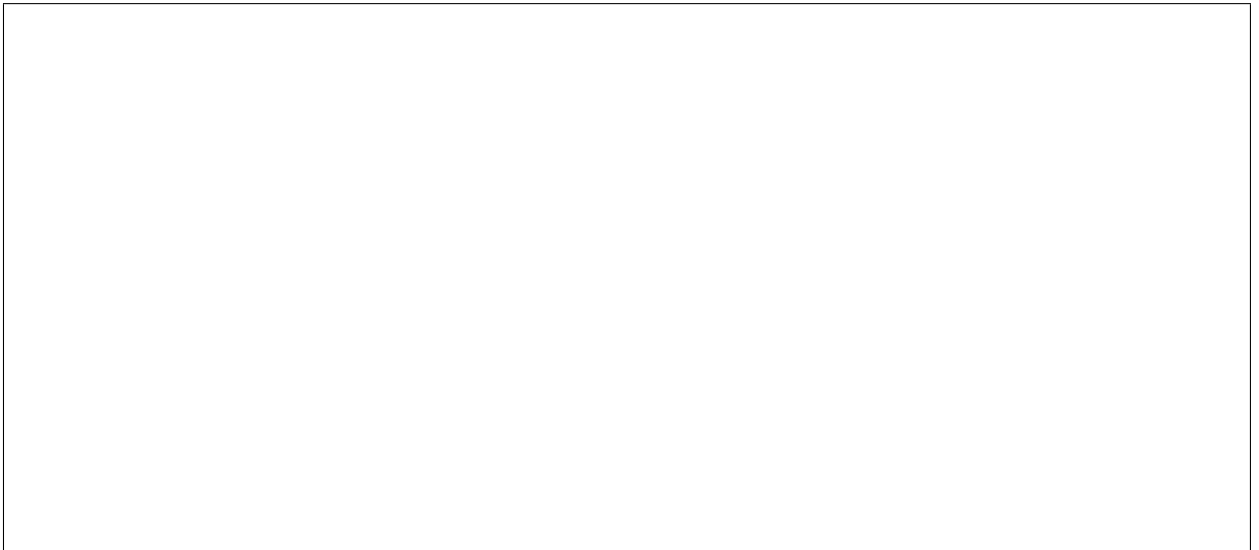
Opcode	Operands	Number of Cycles	Description
LD	Vst, #n	1	Vst ← n (Vst = Vector Stride Register)
LD	Vln, #n	1	Vln ← n (Vln = Vector Length Register)
VLD	Vi, X	11, pipelined	
VST	Vi, X	11, pipelined	
Vmul	Vi, Vj, Vk	6, pipelined	
Vadd	Vi, Vj, Vk	4, pipelined	
Vrshfa	Vi, Vj, amount	1	

How many cycles does it take to execute the program on the following processors? Assume that memory is 16-way interleaved.

- (i) Vector processor without chaining, 1 port to memory (1 load or store per cycle).

A large, empty rectangular box with a thin black border, intended for the student to write their answer for part (i).

- (ii) Vector processor with chaining, 1 port to memory.

A large, empty rectangular box with a thin black border, intended for the student to write their answer for part (ii).

(iii) Vector processor with chaining, 2 read ports and 1 write port to memory.



2 More Vector Processing

You are studying a program that runs on a vector computer with the following latencies for various instructions:

- VLD and VST: 50 cycles for each vector element; fully interleaved and pipelined.
- VADD: 4 cycles for each vector element (fully pipelined).
- VMUL: 16 cycles for each vector element (fully pipelined).
- VDIV: 32 cycles for each vector element (fully pipelined).
- VRSHF (right shift): 1 cycle for each vector element (fully pipelined).

Assume that:

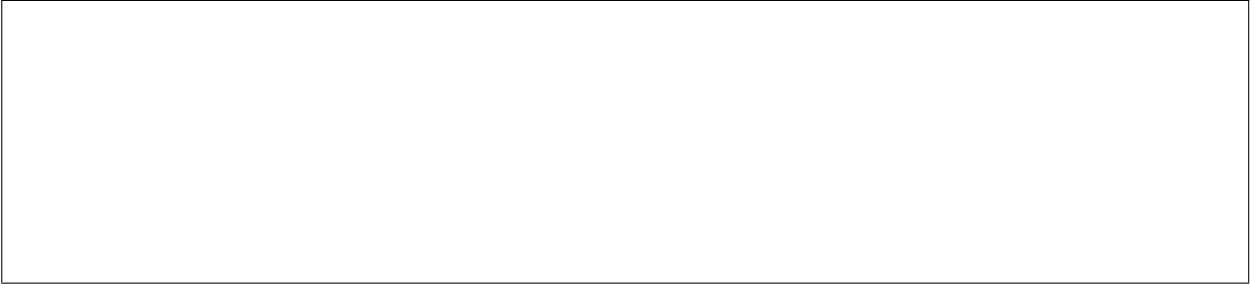
- The machine has an in-order pipeline.
 - The machine supports chaining between vector functional units.
 - In order to support 1-cycle memory access after the first element in a vector, the machine interleaves vector elements across memory banks. All vectors are stored in memory with the first element mapped to bank 0, the second element mapped to bank 1, and so on.
 - Each memory bank has an 8 KB row buffer.
 - Vector elements are 64 bits in size.
 - Each memory bank has two ports (so that two loads/stores can be active simultaneously), and there are two load/store functional units available.
- (a) What is the minimum power-of-two number of banks required in order for memory accesses to never stall? (Assume a vector stride of 1.)

- (b) The machine (with as many banks as you found in part a) executes the following program (assume that the vector stride is set to 1):


```
VLD V1 ← A
VLD V2 ← B
VADD V3 ← V1, V2
VMUL V4 ← V3, V1
VRSHF V5 ← V4, 2
```

It takes 111 cycles to execute this program. What is the vector length?

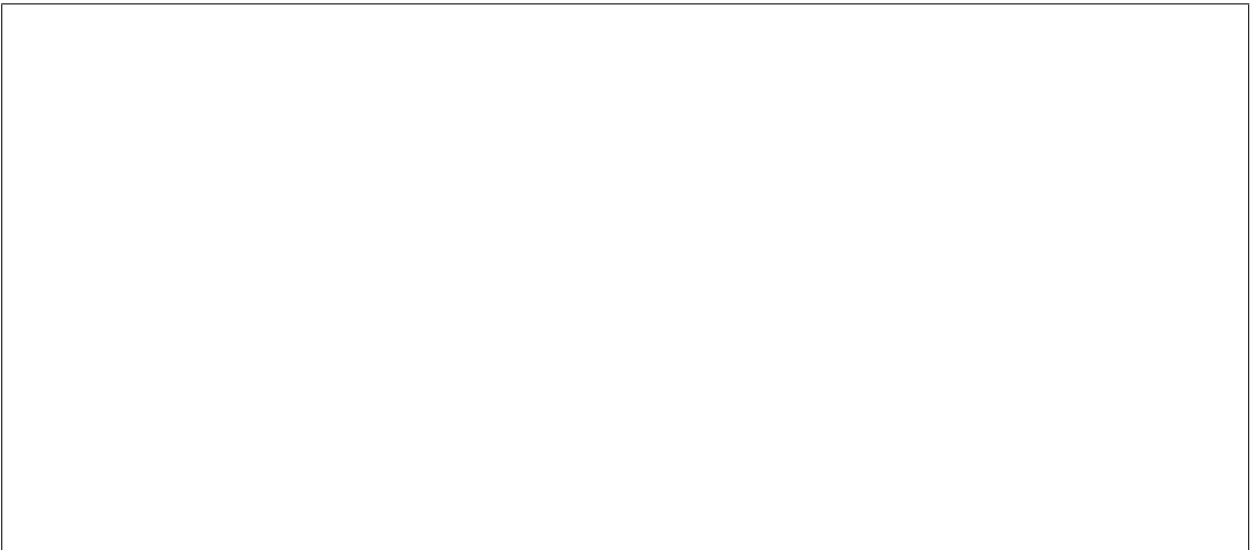
If the machine did not support chaining (but could still pipeline independent operations), how many cycles would be required to execute the same program?



- (c) The architect of this machine decides that she needs to cut costs in the machine's memory system. She reduces the number of banks by a factor of 2 from the number of banks you found in part (a) above. Because loads and stores might stall due to bank contention, an *arbiter* is added to each bank so that pending loads from the oldest instruction are serviced first. How many cycles does the program take to execute on the machine with this reduced-cost memory system (but with chaining)?



Now, the architect reduces cost further by reducing the number of memory banks (to a lower power of 2). The program executes in 279 cycles. How many banks are in the system?



- (d) Another architect is now designing the second generation of this vector computer. He wants to build a multicore machine in which 4 vector processors share the same memory system. He scales up the number of banks by 4 in order to match the memory system bandwidth to the new demand. However, when he simulates this new machine design with a separate vector program running on every core, he finds that the average execution time is longer than if each individual program ran on the original single-core system with 1/4 the banks. Why could this be? Provide concrete reason(s).

What change could this architect make to the system in order to alleviate this problem (in less than 20 words), while *only* changing the shared memory hierarchy?

3 SIMD Processing

Suppose we want to design a SIMD engine that can support a vector length of 16. We have two options: a traditional vector processor and a traditional array processor.

Which one is more costly in terms of chip area (circle one)?

The traditional vector processor

The traditional array processor

Neither

Explain:

Assuming the latency of an addition operation is five cycles in both processors, how long will a VADD (vector add) instruction take in each of the processors (assume that the adder can be fully pipelined and is the same for both processors)?

For a vector length of 1:

The traditional vector processor:

The traditional array processor:

For a vector length of 4:

The traditional vector processor:

The traditional array processor:

For a vector length of 16:

The traditional vector processor:

The traditional array processor:

4 GPUs and SIMD I

We define the *SIMD utilization* of a program run on a GPU as the fraction of SIMD lanes that are kept busy with *active threads* during the run of a program.

The following code segment is run on a GPU. Each thread executes **a single iteration** of the shown loop. Assume that the data values of the arrays A and B are already in vector registers so there are no loads and stores in this program. (Hint: Notice that there are 2 instructions in each thread.) A warp in the GPU consists of 32 threads, there are 32 SIMD lanes in the GPU. Assume that each instruction takes the same amount of time to execute.

```
for (i = 0; i < N; i++) {  
    if (A[i] % 3 == 0) {    // Instruction 1  
        A[i] = A[i] * B[i]; // Instruction 2  
    }  
}
```

- (a) How many warps does it take to execute this program? Please leave the answer in terms of N .

- (b) Assume integer arrays A have a repetitive pattern which have 24 ones followed by 8 zeros repetitively and integer arrays B have a different repetitive pattern which have 48 zeros followed by 64 ones. What is the SIMD utilization of this program?

- (c) Is it possible for this program to yield a SIMD utilization of 100% (circle one)?

YES NO

If YES, what should be true about arrays A for the SIMD utilization to be 100%?

What should be true about arrays B?

If NO, explain why not.

(d) Is it possible for this program to yield a SIMD utilization of 56.25% (circle one)?

YES NO

If YES, what should be true about arrays A for the SIMD utilization to be 56.25%?

What should be true about arrays B?

If NO, explain why not.

(e) Is it possible for this program to yield a SIMD utilization of 50% (circle one)?

YES NO

If YES, what should be true about arrays A for the SIMD utilization to be 50%?

What should be true about arrays B?

If NO, explain why not.

Now, we will look at the techniques in we learned in class that tries to improve SIMD utilization by merging diverge branch together. The key idea of dynamic warp formation is that threads in one warp can be swapped with threads in the other warp as long as the swapped threads has access to the associated registers (i.e., they are on the same SIMD lane).

Consider the following example of a program that consists of 3 warps *X*, *Y* and *Z* that are executing the same code segment specified at the top of this question. Assuming that the vector below specifies the direction of the branch of each thread within the warp and 1 means the branch in Instruction 1 is resolved to taken and 0 means the branch in Instruction 1 resolved to not taken.

```
X = {10000000000000000000000000000010}  
Y = {10000000000000000000000000000001}  
Z = {01000000000000000000000000000000}
```

- (f) Given the example above. Suppose that you perform dynamic warp formation on these three warps. What are the resulting outcome of each branch for the newly formed warps X' , Y' and Z' .

- (g) Given the specification for arrays A and B, is it possible for this program to yield a better SIMD utilization if dynamic warp formation is used? Explain your reasoning.

5 GPUs and SIMD II

We define the *SIMD utilization* of a program run on a GPU as the fraction of SIMD lanes that are kept busy with *active threads* during the run of a program.

The following code segment is run on a GPU. Each thread executes **a single iteration** of the shown loop. Assume that the data values of the arrays A, B, and C are already in vector registers so there are no loads and stores in this program. (Hint: Notice that there are 4 instructions in each thread.) A warp in the GPU consists of 64 threads, and there are 64 SIMD lanes in the GPU.

```
for (i = 0; i < 1024768; i++) {  
    if (B[i] < 4444) {  
        A[i] = A[i] * C[i];  
        B[i] = A[i] + B[i];  
        C[i] = B[i] + 1;  
    }  
}
```

- (a) How many warps does it take to execute this program?

- (b) When we measure the SIMD utilization for this program with one input set, we find that it is $67/256$. What can you say about arrays A, B, and C? Be precise (Hint: Look at the "if" branch, what can you say about A, B and C?).

A:

B:

C:

- (c) Is it possible for this program to yield a SIMD utilization of 100% (circle one)?

YES

NO

If YES, what should be true about arrays A, B, C for the SIMD utilization to be 100%? Be precise. If NO, explain why not.

(d) Is it possible for this program to yield a SIMD utilization of 25% (circle one)?

YES

NO

If YES, what should be true about arrays A, B, and C for the SIMD utilization to be 25%? Be precise.
If NO, explain why not.

6 GPUs and SIMD III

We define the *SIMD utilization* of a program run on a GPU as the fraction of SIMD lanes that are kept busy with *active threads* during the run of a program. As we saw in lecture and practice exercises, the SIMD utilization of a program is computed across the *complete run* of the program.

The following code segment is run on a GPU. Each thread executes **a single iteration** of the shown loop. Assume that the data values of the arrays A, B, and C are already in vector registers so there are no loads and stores in this program. (Hint: Notice that there are 6 instructions in each thread.) A warp in the GPU consists of 64 threads, and there are 64 SIMD lanes in the GPU. Please assume that all values in array B have magnitudes less than 10 (i.e., $|B[i]| < 10$, for all i).

```
for (i = 0; i < 1024; i++) {
    A[i] = B[i] * B[i];
    if (A[i] > 0) {
        C[i] = A[i] * B[i];
        if (C[i] < 0) {
            A[i] = A[i] + 1;
        }
        A[i] = A[i] - 2;
    }
}
```

Please answer the following five questions.

- (a) How many warps does it take to execute this program?

- (b) What is the maximum possible SIMD utilization of this program?

(c) Please describe what needs to be true about array B to reach the maximum possible SIMD utilization asked in part (b). (Please cover all cases in your answer)

B:

(d) What is the minimum possible SIMD utilization of this program?

(e) Please describe what needs to be true about array B to reach the minimum possible SIMD utilization asked in part (d). (Please cover all cases in your answer)

B: