University of Pennsylvania
Department of Electrical and System Engineering
System-on-a-Chip Architecture

ESE532, Fall 2019 — Midterm — Wednesday, October 9

- Exam ends at 11:50AM; begin as instructed (target 10:30AM)
  Do not open exam until instructed.
- Problems weighted as shown.
- Calculators allowed.
- Closed book = No text or notes allowed.
- Show work for partial credit consideration.
- Unless otherwise noted, answers to two significant figures are sufficient.
- Sign Code of Academic Integrity statement (see last page for code).

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I certify that I have complied with the University of Pennsylvania's Code of Academic Integrity in completing this exam.

Name: Solution

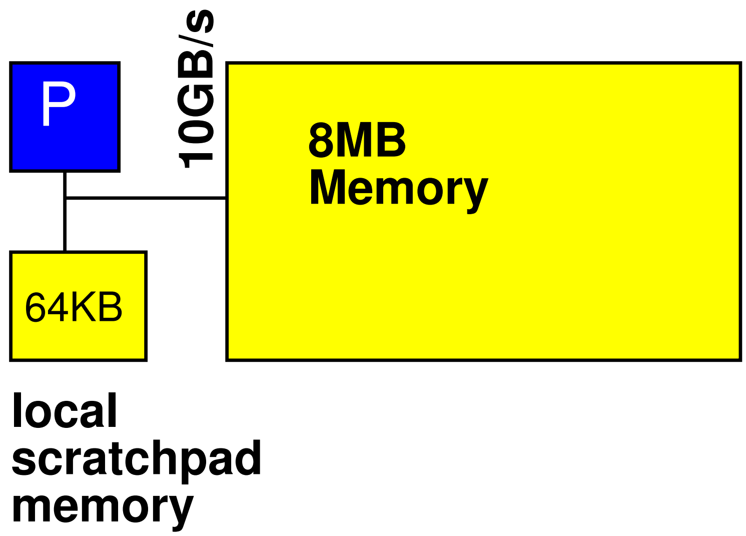
1	2a	2b	3	4	5	6	7	8	Total
10	5	5	10	10	10	10	20	20	100

Consider the following code to pick a set of nearest-neighbor assignments (e.g., Ride Share Drivers to Passengers or Fire Trucks to Fires).

```
code_assign.c        Wed Oct 09 20:33:13 2019        1

void assign() {
    // these are all in the main memory
    uint32_t driver_x[AVAILABLE];
    uint32_t driver_y[AVAILABLE];
    uint16_t passenger_x[TARGETS];
    uint16_t passenger_y[TARGETS];
    uint64_t distances[TARGETS][AVAILABLE];
    uint16_t matches[TARGETS][TARGETS];
    uint16_t match[TARGETS];

    get_drivers(driver_x,driver_y); // in 10*AVAILABLE cycles all memory
    get_passengers(passenger_x,passenger_y); // in 10*TARGETS cycles all memory
    compute_distances(driver_x,driver_y,passenger_x,passenger_y,distances);
    best_matches(distances,matches);
    assign_matches(matches,match);
    //TYPO: send_assignments(match); // in 10*TARGET cycles all memory
    send_assignments(match); // in 10*TARGETS cycles all memory
  }
```

```
code_operators.c        Wed Oct 09 20:37:09 2019        1

#define TARGETS 100
#define AVAILABLE  1000

uint64_t distance(uint32_t x1, uint32_t y1, uint32_t x2, uint32_t y2) {
     int32_t dx=x1-x2;
     int32_t dy=y1-y2;
     return(dx*dx+dy*dy);
   }

void compute_distances(uint32_t driver_x[AVAILABLE],
                       uint32_t driver_y[AVAILABLE],
                       uint16_t passenger_x[TARGETS],
                       uint16_t passenger_y[TARGETS],
                       uint64_t distances[TARGETS][AVAILABLE]) {
    for (int p=0;p<TARGETS;p++) // loop A
       for (int d=0;d<AVAILABLE;d++) // loop B
          distances[p][d]=distance(driver_x[d],driver_y[d],
                                   passenger_x[p],passenger_y[p]);
    return;
   } // compute_distances

void best_matches(uint64_t distances[TARGETS][AVAILABLE],
                  uint16_t matches[TARGETS][TARGETS])      {

    uint64_t p_distances[AVAILABLE]; // in scratchpad memory
    uint16_t p_matches[TARGETS];     // in scratchpad memory
    for (int p=0;p<TARGETS;p++) {  // loop C
       for (int d=0;d<AVAILABLE;d++) // stream copy distances for p
          p_distances[d]=distances[p][d];
       closest_available(p_distances,p_matches);
       for (int m=0;m<TARGETS;m++) // stream copy matches for p
          matches[p][m]=p_matches[m];
       } // for p
    return;
} // best_matches

void closest_available(uint64_t distances[AVAILABLE],
                       uint16_t matches[TARGETS]) {
   // the matches result is an ordered list (smallest to largest)
   //  of the TARGETS nearest(smallest distance) available resources (drivers)

   // implementation omitted -- we will ask you to supply in Question 7.

   // for Question 1--5, assume
   // closest_available requires 4*TARGETS*AVAILABLE compute cycles
   //                            and 4*TARGETS*AVAILABLE memory cycles
   //                       critical path is TARGETS cycles (or, equivalently, ns)
}

void assign_matches(uint16_t matches[TARGETS][TARGETS], uint16_t match[TARGETS])
{
    // ERROR in exam: uint16_t driver_match[DRIVERS];  // in scratchpad memory
    uint16_t driver_match[AVAILABLE];  // in scratchpad memory
    for (int d=0;d<AVAILABLE;d++) driver_match[d]=0; // assume free
    for (int p=0;p<TARGETS;p++) // loop F
         for (int m=0;m<TARGETS;m++) // loop G
             if (driver_match[matches[p][m]]==0) {
                 match[p]=matches[p][m];
                 driver_match[matches[p][m]]=p;
                 break; // out of the for m loop
              } // if driver available
    return;
}
```

We start with a baseline, single processor system as shown.



- For simplicity throughout, we will treat non-memory indexing adds (subtracts count as adds), compares, and multplies as the only compute operations. We'll assume the other operations take negligible time or can be run in parallel (ILP) with the adds, multiplies, and memory operations. (Some consequences: You may ignore loop and conditional overheads in processor runtime estimates; you may ignore computations in array indecies.)
- Baseline processor can execute one multiply, compare, or add per cycle and runs at 1 GHz.
- Data can be transfered from the 8MB main memory at 10 GB/s when streamed in chunks of at least 192B. Assume `for` loops that only copy data can be auto converted into streaming operations.
- Non-streamed access to the main memory takes 10 cycles.
- Baseline processor has a local scratchpad memory that holds 64KB of data. Data can be streamed into the local scratchpad memory at 10 GB/s. Non-streamed accesses to the local scratchpad memory take 1 cycle.
- By default, all arrays live in the main memory.
- Arrays `p_distances`, `p_matches`, and `driver_match` live in local scratchpad memory.
- Assume scalar (non-array) variables can live in registers.
- Assume all additions are associative.
- Assume comparisons, adds, and multiplies take 1 ns when implemented in hardware accelerator, so fully pipelined accelerators also run at 1 GHz. A compare-mux operation can also be implemented in 1 ns.
- Data can be transfered to accelerator local memory at the same 10 GB/s when streamed in chunks of at least 256B.

1. Simple, Single Processor Resource Bounds

   Give the single processor resource bound time for each function.

function	Compute	Memory
compute_distances	5×10^5	5×10^6
best_matches	4×10^7	$4.0082 \times 10^7+$
assign_matches	10^4	2.2×10^5
assign	4.1×10^7	4.5×10^7

compute_distances compute: TARGETS*AVAILABLE*5

compute_distances memory: TARGETS*AVAILABLE*5*10

best_matches compute: TARGETS*4*TARGETS*AVAILABLE

best_matches memory: TARGETS(AVAILABLE*(8/10) + 4*TARGETS*AVAILABLE + TARGETS*(2/10))
(8/10) and (2/10) terms are for streaming transfers before and after closest_available calls

assign_matches compute: TARGETS*TARGETS*1

assign_matches memory: TARGETS*TARGETS*(2+2*10)
first 2 is readers to driver_match; second is to match and matches assuming only read matches[p][m] once from memory and use 3 times. Otherwise second 2 will be 4.
rest of assign is 10*AVAILABLE+20*TARGETS for 1.2×10^4

2. Based on the simple, single processor mapping from Problem 1:

   (a) What function is the bottleneck? (circle one)

   compute_distances

   (best_matches)

   assign_matches

   (b) What is the Amdahl's Law speedup if you only accelerate the identified function?

   $(8.6 \times 10^7)/(5.7 \times 10^6) = 15$

3. Parallelism in Loops

   (a) Classify the following loops as data parallel or not? (loop bodies could be executed concurrently)

   (b) Explain why or why not?

Loop	Data Parallel?	Why or why not?
A	Y	all drivers, targets independent
B	Y	all drivers, targets independent
C	Y	each target closest_available independent
F	N	availability of closest drivers impacted by previous selections; must resolve previous selection before can process target p
G	N	each choice depends on previous availability check; must check each in turn to make selection. We could do parallel-prefix selection to do this in log-time, but that's beyond what we've discussed in class.

4. Identify streaming opportunties between functions. When streaming is possible, what granularity of data can be usefully sent between the functions? [i.e., producer can generate and consumer can operate upon without waiting for additional data from the producer.] Report as a size in bytes and the logical data structure (or part of a data structure) to which this corresponds.

   (a) compute_distances → best_matches

   8*AVAILABLE=8000 Bytes for rows of **`distance`**.
   While **`compute_distances`** can produce each distance independently, **`best_matches`** needs an entire row for a particular passenger to stream to **`closest_match`**. Each **`closest_match`** call is independent, so can operate concurrent with **`compute_distances`** computing the next row.

   (b) best_matches → assign_matches

   2*TARGETS=200 Bytes for rows of **`matches`**.
   `best_matches` is producing each passenger match row indepdently and streaming them as a group into memory. As each match row is available, **`assign_matches`** can process it and identify a match. Since matches are assigned in the same order as produced by **`best_matches`**, **`assign_matches`**, we can process a passenger assignment while **`best_matches`** is producing the ordered matches for the next driver.

5. What is the critical path for the entire computation as captured in the `assign` function?

compute_distances: 3 (subracts, multiplies, add)

best_matches: closest_available= TARGETS
assign_matches: TARGETS^2
Total critical path: 10,103

Depending on why the times for get_drivers, get_passengers, send_assignments are what they are, we could include get_drivers, get_passengers, send_assignments for another 10*(AVAILABLE+2*TARGETS)=10,200. Omitting them assumes they are memory bottlenecks that could be avoided with appropriate engineering.

---

assign_matches using parallel-prefix could be $TARGETS * (1 + \log_2(TARGETS)) = 800$, making total around 903

6. Rewrite the body of `compute_distances` to minimize the memory resource bound by exploiting the scratchpad memory.

   - Annotate what arrays live in the local scratchpad
   - Account for total memory usage in the local scratchpad
   - use for loops that only copy data to denote the streaming operations

   Estimate the new memory resource bound for your optimized `compute_distances`.

   Code on facing page.

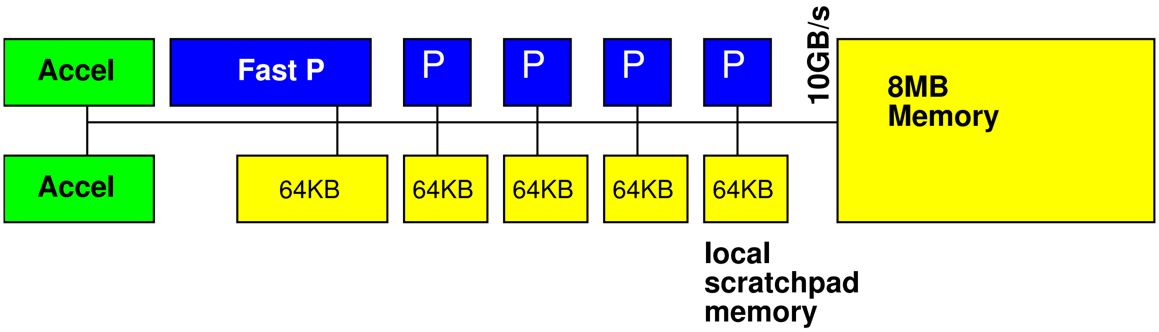
   Uses 16,400 B of scratchpad memory.

   Memory Resource Bound: $4000/10 + 4000/10 + 200/10 + 200/10$ $+100*1000*5+100*(8000/10)=580840=5.8 \times 10^5$

(This page intentionally left mostly blank for answers.)

```
void compute_distances(uint32_t driver_x[AVAILABLE],
                       uint32_t driver_y[AVAILABLE],
                       uint16_t passenger_x[TARGETS],
                       uint16_t passenger_y[TARGETS],
                       uint64_t distances[TARGETS][AVAILABLE]) {

    uint32_t local_driver_x[AVAILABLE]; // scratchpad 4000 B
    uint32_t local_driver_y[AVAILABLE]; // scratchpad 4000 B
    uint16_t local_passenger_x[TARGETS]; // scratchpad 200 B
    uint16_t local_passenger_y[TARGETS]; // scratchpad 200 B
    uint64_t p_distances[AVAILABLE]; // scratchpad  8000 B

    // streaming read into locals
    for (int d=0;d<AVAILABLE;d++) local_driver_x[d]=driver_x[d];
    for (int d=0;d<AVAILABLE;d++) local_driver_y[d]=driver_y[d];
    for (int p=0;p<TARGETS;p++) local_passenger_x[p]=passenger_x[p];
    for (int p=0;p<TARGETS;p++) local_passenger_y[p]=passenger_y[p];


    for (int p=0;p<TARGETS;p++)  { // loop A
       for (int d=0;d<AVAILABLE;d++) // loop B
          p_distances[d]=distance(local_driver_x[d],local_driver_y[d],
                                  local_passenger_x[p],local_passenger_y[p]);
           // streaming write of distances row
           for (int d=0;d<AVAILABLE;d++) distances[p][d]=p_distances[d];
          }
    return;
   } // compute_distances
```

7. Consider a substrate with 4 simple processors (1 GHz as previously outlined), 1 fast processor (3 GHz, with everything running 3× as fast except data transfer from main memory), and 2 accelerators. The accelerators are pipelined and designed to start one call to `closest_available` each cycle;[1] pipeline depth is TARGETS. (You wlll look at the accelerator in Problem 8, but do not need to know its internal details to solve this problem). Describe how you would map the computation onto these heterogeneous computing resources. Describe how you would use the scratchpad memories as necessary beyond what you've already answered in Problem 6. Estimate the performance your mapping achieves.



Accelerators perform best_match in 100 cycles plus 100 cycles to drain pipeline. Place on two and this runs in 50+100=150 cycles. All but final call to closest_available overlapped with compute_distances.

Consistent with Problem 8, accelerators run in 100,000 cycles. With 2, it takes 50,000 cycles. Only non-overlapped call takes 1000+100 cycles.

Use 3 simple processors and fast processor for compute_distances. With Problem 6, compute_distance total is $(5 + 5.8) \times 10^5$ cycles. Divided by 6 for 3 simple + one 3× processors, 10.8/6=1.8×10^5 cycles.

Use 1 slow processor for everything else.

Use streaming to optimize memory references in assign_matches. Create local for match and a p_matches for one row of matches at a time. Stream in matches[p] into a local p_matches inside each F loop body. Stream out match at end. Memory in assign_matches (assuming read once from local version of matches[p][m] and use 3 times) goes to 100*(200/10)+4*100*100+200/10=4.2×10^4, bringing assign_matches to a total time of 4.2×10^4. Since 4.2×10^4 is less than the time on accelerators or compute_distances processors, this isn't the bottleneck. Streaming overlap means only the final 200/10+(4+1)*100+200/10 cycles for completing assign_matches adds time.

So, total time is 12,000 for get_drivers, get_passengers, and send_assignments, 1.8×10^5 for the compute_distances, and a final 540 cycles for the end of assign_matches.

[1] Error: to be consistent, should be every AVAILABLE cycles.

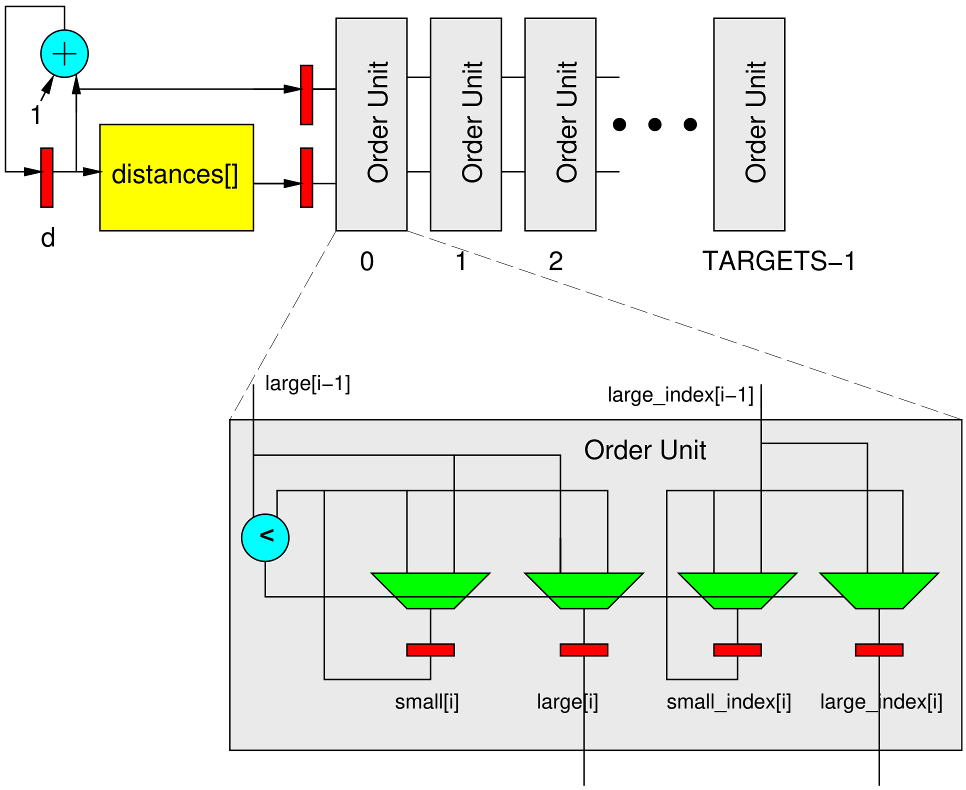
(This page intentionally left mostly blank for answers.)

compute_distances	3 simple + 1 fast	1.8×10^5
best_match	2 accelerators	adds 100 (as stated) adds 1100 (Problem 8)
everything else	1 slow	adds 12,540

Estimate total processing time as 1.8×10^5 cycles.

Same estimate if use consistent Problem 8 time for accelerators.

8. Consider the following accelerator for `closest_available` that processes one distance per cycle:



(Hint: this is performing an insertion sort one distance at a time, but keeping only the smallest TARGETS values.)

Assume:

- distances[] can be streamed from main memory into the local memory shown (with code already shown in best_matches)
- large[i] and small[i] can be reset to a maximum value, `MAX_VALUE`, in one cycle in hardware at the beginning of a call to `closest_available`; code for this reset in the C version is provided.
- small_index[i] and large_index[i] can be reset to a designated empty value, `EMPTY_VALUE`, in one cycle in hardware; code for this reset in the C version is provided.
- small_index[] becomes matches[] when the computation is completed and can be streamed into main memory (with code already shown in best_matches)

(a) Write C code that is consistent with the accelerator.

(b) Annotate the C code to explain how the C code was realized in the accelerator. (As appropriate, explain how unrolling, array partitioning, pipelining, dataflow streaming, and/or inlining were applied to the C code to get the implementation show.)

```
void closest_available(uint64_t distances[AVAILABLE],
                       uint16_t matches[TARGETS]) {

   uint16_t small_index[TARGETS]; // array partition complete
   uint16_t large_index[TARGETS]; // array partition complete
   uint 64_t small[TARGETS]; // array partition complete
   uint 64_t large[TARGETS]; // array partition complete

  for (int i=0;i<TARGETS;i++) small[i]=MAX_VALUE;
  for (int i=0;i<TARGETS;i++) small_index[i]=EMPTY_VALUE;
  for (int i=0;i<TARGETS;i++) large[i]=MAX_VALUE;
  for (int i=0;i<TARGETS;i++) large_index[i]=EMPTY_VALUE;

   for (int d=0;d<AVAILBLE;d++) { // pipeline
         if (distances[d]<small[0]) {
              large[0]=small[0];
              small[0]=distances[d];
              large_index[0]=small_index[0];
              small_index[0]=d;
           }
          else{
              small[0]=small[0];
              large[0]=distances[d];
              small_index[0]=small_index[0];
              large_index[0]=d;
           }
      for (int i=1;i<TARGETS;i++) { // unroll complete, pipeline
         if (large[i-1]<small[i]){
              large[i]=small[i];
              small[i]=large[i-1];
              large_index[i]=small_index[i];
              small_index[i]=large_index[i-1];
           }
          else {
              small[i]=small[i];
              large[i]=large[i-1];
              small_index[i]=small_index[i];
              large_index[i]=large_index[i-1];
           }
         } // i
       } // d
```

```
  for (int i=0;i<TARGETS;i++) matches[i]=small_index[i];
  return;
}
```

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