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

ESE5320, Fall 2024 — Midterm — Wednesday, October 9

- Exam ends at 11:45AM; begin as instructed (target 10:15AM)
  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	Total
20	5	5	10	20	20	20	100

Mean: 58, Std. Dev. 17

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

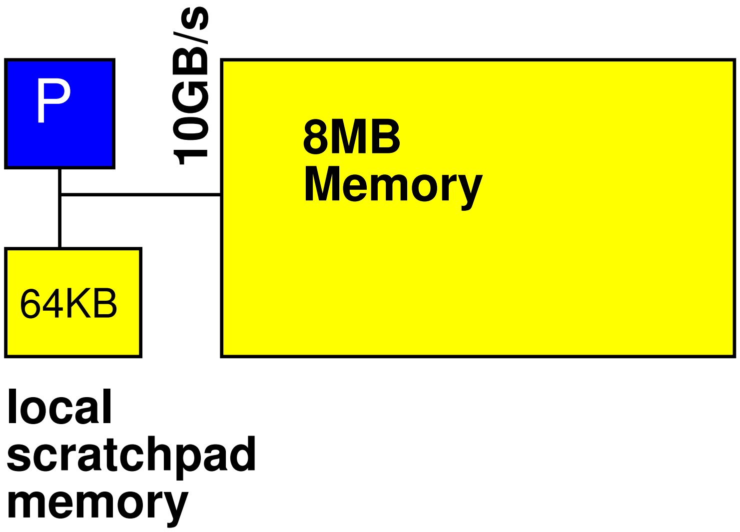
code_assign.c   Thu Oct 03 12:18:34 2024   1

```
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);
    send_assignments(match); // in 10*TARGETS cycles all memory
  }
```

code_operators.c Thu Oct 03 13:13:22 2024 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)

   // to be implemented as an accelerator on Question 6
   //    implementation not shown

   // 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])
{
    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	4.0082×10^7
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

deduct two point for each of 8 answers (so 4 free points); partial credit for consistent mistakes – e.g. if swap up TARGETS and AVAILABLE and otherwise consistent, only take off 2 points.

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

   grade consistent with answers for Problem 1

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

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

   grade consistent with answers for Problem 1 if performing correct calculation

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. accept Y with parallel-prefix/log-reduce/associativity explanation

4 points each

4. 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_assignmen 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.

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

6 points for each of compute_distances, best_match, and assign_match, 2 points for total. If get correct parallelism (which will be correct use of TARGET and AVAILABLE terms), that gets most credit (5 or 6 of 6 points). E.g. if compute_distances is any small constant with no TARGET or AVAILABLE term, it gets full credit.

(This page intentionally left mostly blank for answers.)

5. 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: $4000/10+4000/10+200/10+200/10$ $+100*1000*5+100*(8000/10)=580840=5.8\times10^{5}$

(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
```

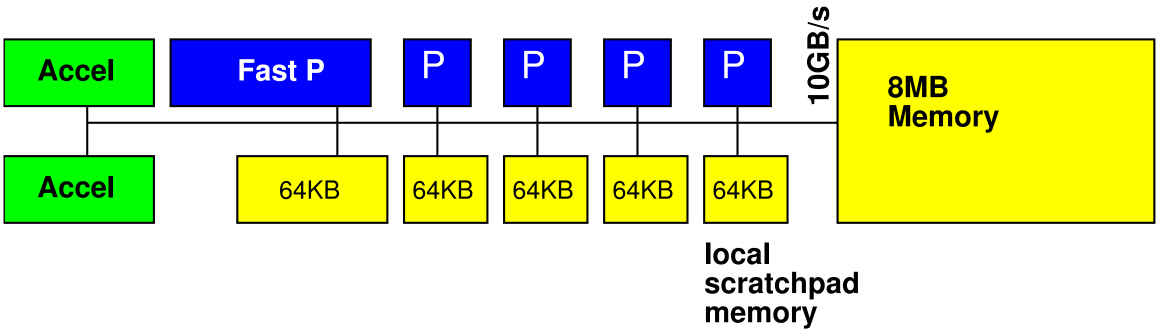
Solutions which exceed the space get at most 5 points out of the 20.

Solutions that only get a small speedup (e.g. less than factor of 4) get at most 10 points.

We don't deduct for small coding errors as long as the intended strategy is clear and sensible.

To get full credit, must have memory usage roundup and new memory resouce bound calculation. Given a plausible strategy and code, 5 points for correct/consitent memory usage roundup and 5 points for final (consistent) calculation.

6. 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` every AVAILABLE cycles; pipeline depth is TARGETS. 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 5. Estimate the performance your mapping achieves.



Accelerators perform best_match in 100,000 cycles plus 100 cycles to drain pipeline. Place on two and this runs in 50,000+100≈50,000 cycles. All but final call to closest_available overlapped with compute_distances.

Use 3 simple processors and fast processor for compute_distances. With Problem 5, 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. Less than the accelerators, and as noted above, mostly overlapped.

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, 5×10^5 for the accelerators, and a final 540 cycles for the end of assign_matches. This makes final time about: 5.1×10^5.

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Full credit requires, (i) understanding what time accelerators require (5pts), (ii) properly identifying and assigning fast processors for next bottleneck (compute_distance (5pts), (iii) understanding concurrency overlaps in computing time (5pts), (iv) providing final time estimate (5pts).

Fine details of calculations less important. Should get correct TARGET and AVAILABLE factors. Should be consistent with Problem 5.

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