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:

1	2a	2b	3	4	5	6	Total
20	5	5	10	20	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).

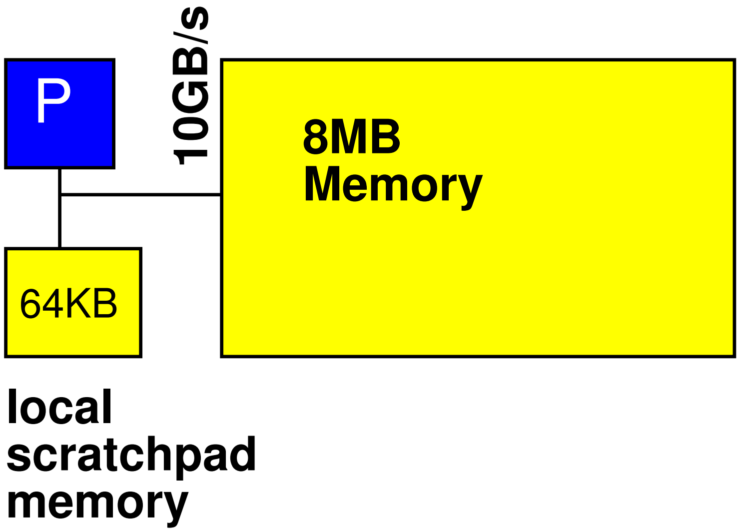
code_assign.c Thu Oct 03 12:18:34 2024 1

```
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

```c
#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		
best_matches		
assign_matches		
assign		

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?

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		
B		
C		
F		
G		

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

(This page intentionally left mostly blank for answers.)

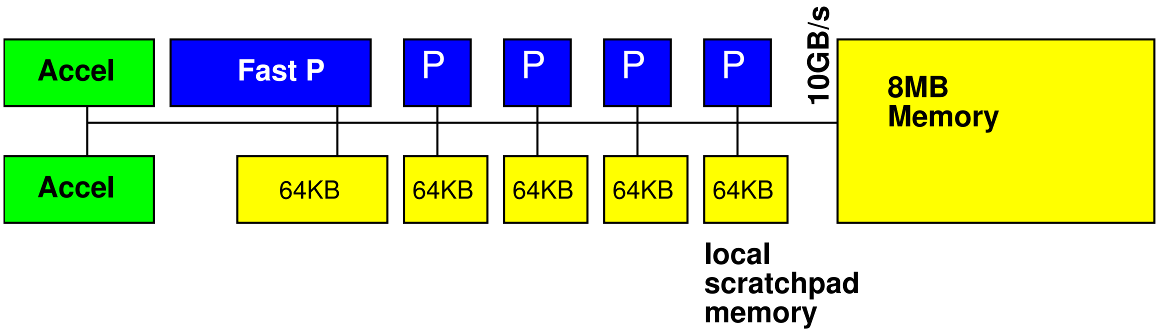
5. Rewrite the body of `compute_distances` to minimize the memory resource bound by exploiting the scratchpad memory.

    - 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`.

(This page intentionally left mostly blank for answers.)

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.



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