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

ESE5320, Fall 2022 — Final — Friday, December 16

- Exam ends at 2:00PM; begin as instructed (target 12:00PM)
  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. All answers here.
- 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	6a	6b	6c	7	8	Total
10	5	5	10	10	15	10	5	10	10	10	100

Consider the following code to align (rotate, scale, translate) an image to best match a reference image and identify the largest connected region that differs from the reference (likely an object) on a real-time video stream:

```
#include <stdint.h>
#include <stdlib.h>

#define WIDTH 1000
#define HEIGHT 1000
#define COLORS 3
#define MASK 3

#define VPARAMS 5
#define VP_X 0
#define VP_Y 1
#define VP_XS 2
#define VP_YS 3
#define VP_ROT 4

#define XOFF 2
#define YOFF 2
#define ROT 2
#define XSCALE 2
#define XSFACT 2
#define YSCALE 2
#define YSFACT 2

#define REGION_PARAMS 4
#define XMIN 0
#define XMAX 1
#define YMIN 2
#define YMAX 3

#define NODIFF 0
#define DIFFERENT 1
#define THRESHOLD 10

uint16_t reference[HEIGHT][WIDTH][COLORS];
int16_t sintable[360]; // -1 to 1 -- scaled by 2^14
int16_t costable[360];

// treat as single cycle operations
uint16_t max(uint16_t a, uint16_t b) {if (a<b) return(b); else return(a);}
uint16_t min(uint16_t a, uint16_t b) {if (a<b) return(a); else return(b);}

void get_image(uint16_t image[HEIGHT][WIDTH][COLORS]) {
  static uint16_t image_in[HEIGHT][WIDTH][COLORS];
  for (int iy=0;iy<HEIGHT;iy++)
    for (int ix=0;ix<WIDTH;ix++)
      for (int c=0;c<COLORS;c++)
        image[iy][ix][c]=image_in[iy][ix][c];
}

void copy_viewpoint(int16_t orig[VPARAMS], int16_t copy[VPARAMS]) {
  for(int i=0;i<VPARAMS;i++) copy[i]=orig[i];
}
```

```
void compute_viewpoint(uint16_t image[HEIGHT][WIDTH][COLORS],
                       uint16_t reference[HEIGHT][WIDTH][COLORS],
                       int16_t  old[VPARAMS], int16_t current[VPARAMS]) {
  uint64_t best_score=1<<62; // large integer
  for (int rot=old[VP_ROT]-ROT;rot<=old[VP_ROT]+ROT;rot+=1) { // loop A
    int16_t sr=sintable[rot]; // result is a fraction
    int16_t cr=costable[rot];
    for (int x=old[VP_X]-XOFF;x<=old[VP_X]+XOFF;x++) // loop B
      for (int y=old[VP_Y]-YOFF;y<=old[VP_Y]+YOFF;y++) // loop C
        for (int xs=old[VP_XS]/XSCALE;xs<=old[VP_XS]*XSCALE;xs*=XSFACT) // loop D
          for (int ys=old[VP_YS]/YSCALE;ys<=old[VP_YS]*YSCALE;ys*=YSFACT) // loop E
            {
              uint64_t score=0;
              for (int iy=0;iy<HEIGHT;iy++) // loop F
                for (int ix=0;ix<WIDTH;ix++) // loop G
                  {
                    uint16_t tx=(((ix*cr+iy*sr)*xs)>>(14+8))+x; // 14 to scale sr, cr
                    uint16_t ty=(((ix*sr+iy*cr)*ys)>>(14+8))+y; // +8 for xscale, ysc
                    if ((tx>=0) && (tx<WIDTH) && (ty>=0) && (ty<HEIGHT))
                      for (int c=0;c<COLORS;c++) // loop H
                        score+=abs(image[iy][ix][c]-reference[ty][tx][c]);
                  }
              if (score<best_score)
                {
                  best_score=score;
                  current[VP_ROT]=rot;
                  current[VP_X]=x;
                  current[VP_Y]=y;
                  current[VP_XS]=xs;
                  current[VP_YS]=ys;
                }
            }
  }
}
void compute_diff(uint16_t raw[HEIGHT][WIDTH][COLORS],
                  uint16_t reference[HEIGHT][WIDTH][COLORS],
                  int16_t current[VPARAMS],
                  uint16_t difference[HEIGHT][WIDTH]) {
  int16_t rot=current[VP_ROT];
  int16_t x=current[VP_X];
  int16_t y=current[VP_Y];
  int16_t xs=current[VP_XS];
  int16_t ys=current[VP_YS];
  int16_t sr=sintable[rot]; // result is a fraction
  int16_t cr=costable[rot];
  for (int iy=0;iy<HEIGHT;iy++) // loop I
    for (int ix=0;ix<WIDTH;ix++) // loop J
      difference[iy][ix]=NODIFF; // assume this runs like streaming data copy
  for (int iy=0;iy<HEIGHT;iy++) // loop K
    for (int ix=0;ix<WIDTH;ix++) // loop L
        {
          uint16_t tx=(((ix*cr+iy*sr)*xs)>>(14+8))+x; // 14 to scale sr, cr
          uint16_t ty=(((ix*sr+iy*cr)*ys)>>(14+8))+y; // +8 for xscale, yscale
          if ((tx>=0) && (tx<WIDTH) && (ty>=0) && (ty<HEIGHT))
            {
              int diff=0;
              for (int c=0;c<COLORS;c++) // loop M
                diff+=abs(raw[ty][tx][c]-reference[ty][tx][c]);
              if (diff>THRESHOLD)
                difference[iy][ix]=DIFFERENT;
            }
        }
}
```

```
void update(uint16_t label[HEIGHT][WIDTH][REGION_PARAMS],
            uint16_t difference[HEIGHT][WIDTH], int x, int y)
{
  if (difference[y][x]==DIFFERENT)
    for (int xoff=-1;xoff<2;xoff++) // loop S
      for (int yoff=-1;yoff<1;yoff++) // loop T
        if (difference[y+yoff][x+xoff]==DIFFERENT)
          {
            label[y][x][XMIN]=min(label[y][x][XMIN],label[y+yoff][x+xoff][XMIN]);
            label[y][x][YMIN]=min(label[y][x][YMIN],label[y+yoff][x+xoff][YMIN]);
            label[y][x][XMAX]=max(label[y][x][XMAX],label[y+yoff][x+xoff][XMAX]);
            label[y][x][YMAX]=max(label[y][x][YMAX],label[y+yoff][x+xoff][YMAX]);
          }
}
void largest_region(uint16_t difference[HEIGHT][WIDTH],
                    uint16_t  region[REGION_PARAMS]) {
  uint16_t label[HEIGHT][WIDTH][REGION_PARAMS];
  int best_area=0;
  for (int iy=0;iy<HEIGHT;iy++) // loop N
    for (int ix=0;ix<WIDTH;ix++) // loop O
      if (difference[iy][ix]==DIFFERENT)
          {
            label[iy][ix][XMIN]=ix;
            label[iy][ix][XMAX]=ix;
            label[iy][ix][YMIN]=iy;
            label[iy][ix][YMAX]=iy;
          }
  for (int iy=0;iy<HEIGHT;iy++) // loop P
    {
      for (int ix=0;ix<WIDTH;ix++) // loop Q
        update(label,difference,iy,ix);
      for (int ix=WIDTH;ix>-1;ix--) // loop R
        update(label,difference,iy,ix);

    }
  for (int iy=0;iy<HEIGHT;iy++) // loop U
    {
      for (int ix=0;ix<WIDTH;ix++) // loop V
        {
          int area=(label[iy][ix][XMAX]-label[iy][ix][XMIN])*
            (label[iy][ix][YMAX]-label[iy][ix][YMIN]);
          if (area>best_area)
            {
              best_area=area;
              region[XMIN]=label[iy][ix][XMIN];
              region[XMAX]=label[iy][ix][XMAX];
              region[YMIN]=label[iy][ix][YMIN];
              region[YMAX]=label[iy][ix][YMAX];
            }
        }
    }
  return;
}
```

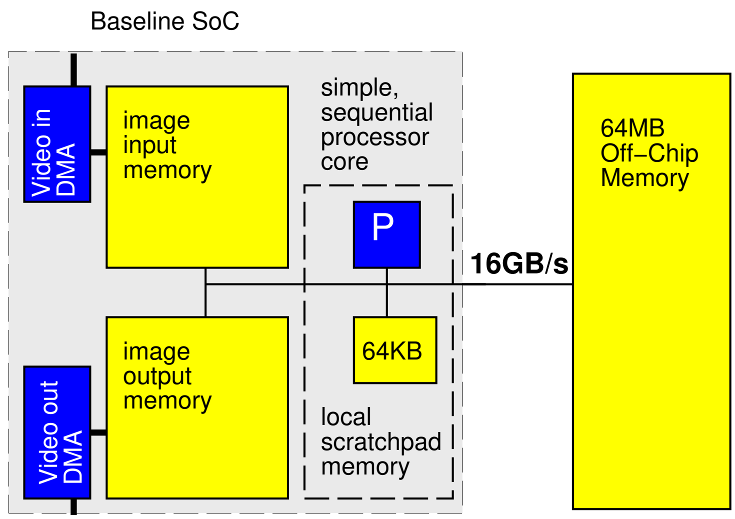
```
void send_region(uint16_t region[REGION_PARAMS], int16_t current[VPARAMS],
                 uint16_t image[HEIGHT][WIDTH][COLORS])
{
  static uint16_t image_out[HEIGHT][WIDTH][COLORS];
  int16_t rot=current[VP_ROT];
  int16_t x=current[VP_X];
  int16_t y=current[VP_Y];
  int16_t xs=current[VP_XS];
  int16_t ys=current[VP_YS];
  int16_t sr=sintable[rot]; // result is a fraction
  int16_t cr=costable[rot];

  int basey=region[YMIN];
  int basex=region[XMIN];
  for (int iy=basey;iy<=region[YMAX];iy++) // W
    for (int ix=basex;ix<=region[XMAX];ix++)
      {
        uint16_t tx=(((ix*cr+iy*sr)*xs)>>(14+8))+x; // 14 to scale sr, cr
        uint16_t ty=(((ix*sr+iy*cr)*ys)>>(14+8))+y; // +8 for xscale, yscale
        if ((tx>=0) && (tx<WIDTH) && (ty>=0) && (ty<HEIGHT))
            for (int c=0;c<COLORS;c++)
              image_out[iy-basey][ix-basex][c]=image[ty][tx][c];
      }
}

void extract_region() {
  uint16_t raw[HEIGHT][WIDTH][COLORS]; // uint16_t for 16b (2 byte) color per pixel
  uint16_t difference[HEIGHT][WIDTH];
  int16_t viewpoint[VPARAMS];
  int16_t old_viewpoint[VPARAMS];
  uint16_t region[REGION_PARAMS];
  get_image(raw);
  copy_viewpoint(viewpoint,old_viewpoint);
  compute_viewpoint(raw,reference,old_viewpoint,viewpoint);
  compute_diff(raw,reference,viewpoint,difference);
  largest_region(difference,region);
  send_region(region,viewpoint,raw);
}

int main() {
  while (1) { // loop Z
    extract_region();
  }
}
```

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, abs, shifts, max, min, and multplies as the only compute operations. We'll assume the other operations take negligible time or can be run in parallel (ILP) with these compute operations and memory operations. (Some consequences: You may ignore loop and conditional overheads in processor runtime estimates; you may ignore computations in array indecies.)
- Baseline (simple, sequential) processor can execute one add, compare, shift, abs, max, min, or multiply per cycle and runs at 1 GHz.
- Data can be transfered between pairs of memory (including main memory) at 16 GB/s when streamed in chunks of at least 1000B. Assume `for` loops that only copy data can be auto converted into streaming operations.
- Non-streamed access to image and 64 MB off-chip memories takes 10 cycles and can move 8B.
- Baseline processor has a local scratchpad memory that holds 64KB of data. Data can be streamed into the local scratchpad memory at 16 GB/s. Non-streamed accesses to the local scratchpad memory take 1 cycle.
- Baseline processor is 1 mm^2 of silicon including its 64KB local scratchpad.
- By default, all arrays live in the 64 MB off-chip memory.
- `image_in` and `image_out` live in the respective image input and image output memories.
- Arrays for `sintable`, `costable`, viewpoints (`old_viewpoint`, `viewpoint`), and `region` live in local scratchpad memory.
- Assume scalar (non-array) variables can live in registers.
- Assume all additions are associative.
- Assume comparisons, max, min, 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. Consider abs and shift free in hardware.
- Data can be transfered to accelerator local memory at the same 16 GB/s when streamed in chunks of at least 1000B.

1. Simple, Single Processor Resource Bounds

   Give the single processor resource bound time for compute operations and memory access for operations inside `extract_region`.

routine	Compute	Memory
compute_viewpoint		
compute_diff		
largest_region		
send_region		
extract_region		

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

   (a) Considering both compute and memory cycles, what routine is the bottleneck? (circle one)

   compute_viewpoint

   compute_diff

   largest_region

   send_region

   (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, reduce, or sequential?

   (b) Explain why or why not?

Loop	circle one	Why?
A	Data Parallel Reduce Sequential	
F	Data Parallel Reduce Sequential	
K	Data Parallel Reduce Sequential	
N	Data Parallel Reduce Sequential	
P	Data Parallel Reduce Sequential	
Q	Data Parallel Reduce Sequential	
U	Data Parallel Reduce Sequential	

4. What is the critical path (latency bound) `largest_region`?

(This page intentionally left mostly blank for answers.)

5. How would you modify `compute_viewpoint` to minimize the memory resource bound by exploiting the scratchpad memory and streaming memory operations.

    - Annotate what arrays live in the local scratchpad.
    - Account for total memory usage in the local scratchpad (use provided table).
    - Describe your modifications to the code.
        - Use **for** loops that only copy data to denote the streaming operations
    - Estimate the new memory resource bound for your optimized `compute_viewpoint`.

Variable	Size (Bytes)

(This page intentionally left mostly blank for answers.)

6. Considering a custom hardware accelerator implementation for loops A–H of `compute_viewpoint` where you are designing both the compute operators and the associated memory architecture. How would you use loop unrolling and array partitioning to achieve guaranteed throughput of 30 frames per second while minimizing area?
Use the following area model in units of mm^2:

- n-bit adder or absolute value: $n \times 10^{-5}$
- p-port, w-bit wide memory holding d words: $w(1+p)(d+6) \times 10^{-7}$

Make the (probably unreasonable) assumption that reads from these memories can be completed in one cycle.

(a) Unrolling for each loop?

Loop	Unroll Factor
A	
B	
C	
D	
E	
F	
G	
H	

(b) For the unrolling, how many absolute value units, adders, and multipliers?

Absolute Value	
Adders	
Multipliers	

(c) Array partitioning for each array used in local memories in the accelerator?

Note: local arrays may be ones added when optimizing memory in Question 5. If add additional memories, describe as necessary.

Array	Replicas	Array Partition	Ports	Width	Depth per Partition (in Width words)

7. Data Streaming:

   (a) Can the producer and consumer operate concurrently on the same input image? or must the consumer work on a different (earlier) input image? ("Same Image?" column)

   (b) How big (minimum size) does the buffer (or other data storage space) need to be between the identified loops in order to allow the loops to profitably execute concurrently?

   (c) What data is being transfered in each such quanta? Identify the variable, array, or portion of an array that is needed for the consuming loop to operate.

   (Hint: Based on data dependencies, under what scenarios and granularity can the identified loops act as a producer-consumer pair in a pipeline.)

Loop Pair	(a) Same Image?	(b) Size (bytes)	(c) Data
`compute_viewpoint` → `compute_diff`			
`compute_diff` → `largest_region`			
`largest_region` → `send_region`			

Explain size choices for partial credit consideration.

8. Assuming you start with the accelerator from Problem 6, and building on your previous answers, what else do you need on an SoC to achieve real-time (30 frame/second) operation for `main`?

    - What processor(s) do you need to run the remaining code? (how many? any particular properties)?
    - If necessary, how is the remaining code divided among the processors?
    - What changes (if any) are needed to memory organization and data movement?

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