

ESE5320: System-on-a-Chip Architecture

Day 14: October 16, 2024
Orchestrating Data in Memories

Midterm Average: 58
Std. Dev.: YY
Will take max(midterm,final)
for midterm grade



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Today

- DRAM (Part 1)
- DRAM Implications (Part 2)
- Tricks for working with DRAM and generally minimizing use of large memories
 - Data Reuse in Images (Part 3)
 - Sort (time permitting) (Part 4)

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Message

- How we access data matters
- Reuse data to avoid access to large memories
- Think about how organize computation and data to minimize
 - Use of large memory
 - Data movement
- ...and think about what you expect, so can diagnose unnecessary data bottlenecks

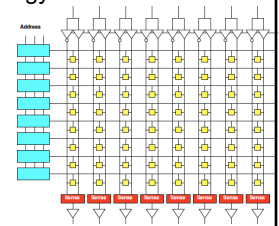
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Day 3: Memory Scaling

- Small memories are fast
 - Large memories are slow
- Small memories low energy
 - Large memories high energy
- Large memories dense
 - Small memories cost more area per bit
- Combining:
 - Dense memories are slow



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Day 3: Lesson

- Cheaper to access wide/contiguous blocks memory
 - In hardware
 - From the architectures typically build
- Can achieve higher bandwidth on large block data transfer
 - Than random access of small data items

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DRAM
Dynamic
Random Access Memory
Usually the largest memory

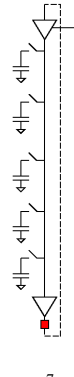
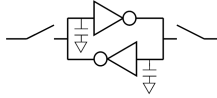
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Dynamic RAM

- Shares even more logic among bits
- Share refresh/restoration logic as well
- Minimal storage is a capacitor
- “Feature” DRAM process is ability to make capacitors efficiently
- Denser, but slower



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DRAM

- 1GB DDR3 SDRAM from Micron

- <http://www.micron.com/products/dram/ddr3/>
- 96 pin package
- 16b datapath IO
- Operate at 500+MHz
- 37.5ns random access latency

- Options**
- Configuration
 - 64 Meg x 16 (8 Meg x 16 x 8 banks)
 - 128 Meg x 8 (16 Meg x 8 x 8 banks)
 - 256 Meg x 4 (32 Meg x 4 x 8 banks)
 - FBGA package (lead-free)
 - x4, x6, 96-ball FBGA (9mm x 15.5mm)
 - x16, 96-ball FBGA (9mm x 15.5mm)
 - Timing - cycle time
 - 2.5ns @ CL = 8 (DDR3-800)
 - 2.5ns @ CL = 5 (DDR3-800)
 - 1.87ns @ CL = 8 (DDR3-1066)
 - 1.87ns @ CL = 7 (DDR3-1066)
 - 1.5ns @ CL = 10 (DDR3-1333)
 - 1.5ns @ CL = 9 (DDR3-1333)

Marking

64M16
128M8
256M4

Table 1: Key Timing Parameters

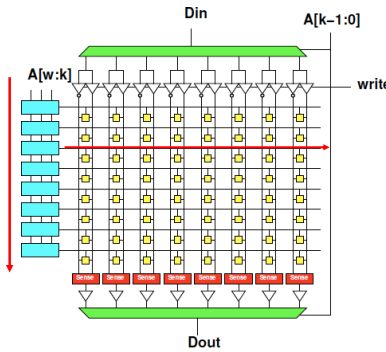
Speed Grade	Data Rate (Mbits)	Target RCD/TP/CL	^t RCD (ns)	^t RP (ns)	CL (ns)
-25E	800	5-5-5	12.5	12.5	12.5
-25	800	6-6-6	15	15	15
-187E	1,066	7-7-7	13.1	13.1	13.1
-187	1,066	9-8-8	15	15	15
-15E	1,333	9-9-9	13.5	13.5	13.5
-15	1,333	10-10-10	15	15	15

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Memory Access Timing

- Access:
 1. Address (RCD)

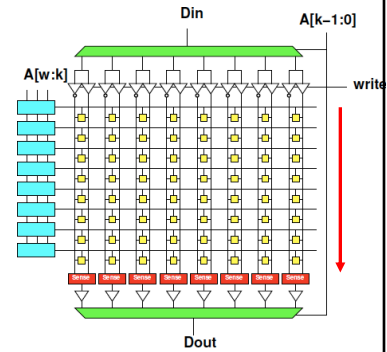


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Memory Access Timing

- Access:
 1. Address (RCD)
 2. Row fetch (RP)

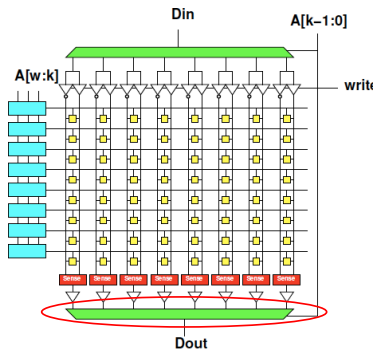


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Memory Access Timing

- Access:
 1. Address (RCD)
 2. Row fetch (RP)
 3. Column select (CL)

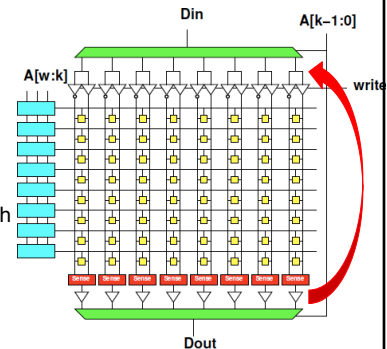


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Memory Access Timing

- Access:
 1. Address (RCD)
 2. Row fetch (RP)
 3. Column select (CL)
 4. writeback/refresh

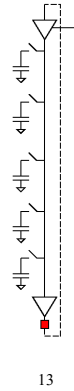
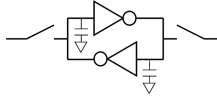


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Dynamic RAM

- Shares even more logic among bits
- Share refresh/restoration logic as well
- Minimal storage is a capacitor
- “Feature” DRAM process is ability to make capacitors efficiently
- Denser, but slower



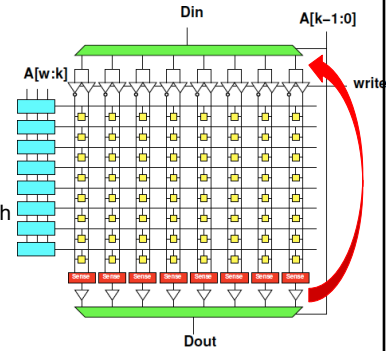
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Memory Access Timing

- Access:
 1. Address (RCD)
 2. Row fetch (RP)
 3. Column select (CL)
 4. writeback/refresh



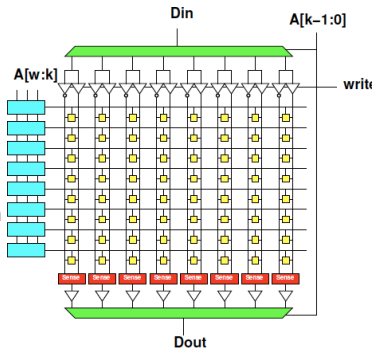
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Memory Access Timing

- Access:
 1. Address (RCD)
 2. Row fetch (RP)
 3. Column select (CL)
 4. writeback/refresh
- Optimization for access within a row



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DRAM

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- 96 pin package
- 16b datapath IO
- Operate at 500+MHz
- 37.5ns random access latency

- | | |
|--------------------------------------|----------------|
| Options | Marking |
| • Configuration | |
| – 64 Meg x 16 (8 Meg x 16 x 8 banks) | 64M16 |
| – 128 Meg x 8 (16 Meg x 8 x 8 banks) | 128M8 |
| – 256 Meg x 4 (32 Meg x 4 x 8 banks) | 256M4 |
| • FBGA package (lead-free) | |
| – 84, 96-ball FBGA (9mm x 15.5mm) | BY |
| – x16, 96-ball FBGA (9mm x 15.5mm) | LA |

Table 1: Key Timing Parameters

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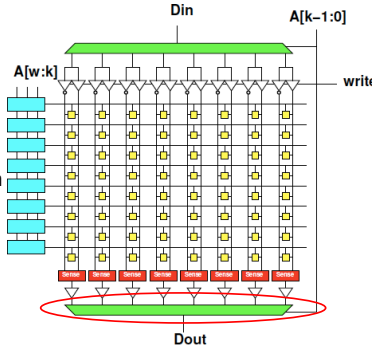
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Memory Access Timing

- Access
 1. Address (RCD)
 2. Row fetch (RP)
 3. Column select
 - CL: Can repeat
 4. writeback/refresh
- Row
 - 1024b—8192b
- Faster to access within row



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Preclass 4

- Preclass 4 toy warmup
 - Reading n 16b words takes: 10+n cycles
 - 10 cycles for access latency (RCD, RP)
 - 1 cycle to select each word (CL)
 - n cycles for n of them
- % time in access latency
 - Reading 1 word
 - Reading 16 words
 - Reading 128 words

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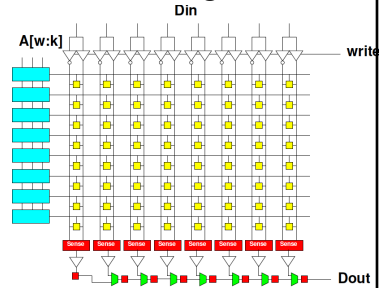
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BY
LA

-25
-25E
-187
-187E
-15
-15E |

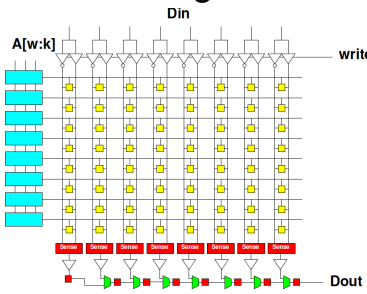
DRAM Streaming

- Can design to shift out large data from row



DRAM Streaming

- Reading row is 2x12.5ns
 - (RCD,RP)
- 16b @ 500MHz
- 1024b row
- 1024/16
 - 64 words per row



- How long (ns) to provide full row (64, 16b words) from address?

DRAM Streaming

- Can read from wide memory, but only have 16 pins to bring off chip
- But, can clock across those 16 pins at high clock rate compared to memory reference (2ns vs. 12.5ns)
- So, can sequentially shift the data out the 16 pins, if grabbing all the data for the row

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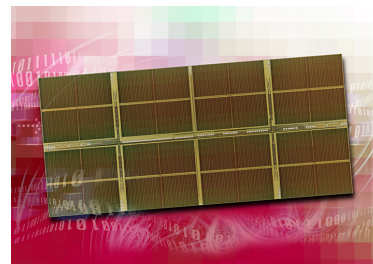
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BY
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-25E
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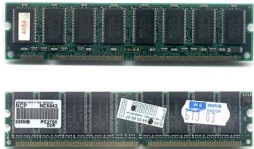
1 Gigabit DDR2 SDRAM



[Source: <http://www.elpida.com/en/news/2004/11-18.html>]

DIMMS multi-DRAM

- DIMMs usually pack multiple DRAM chips, c, in parallel
 - Can access $c \cdot 16b$ per transfer
 - Typically 64, 128, 256b wide
 - 8 chips = 128b wide



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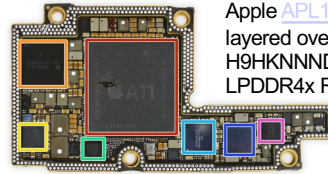
<https://commons.wikimedia.org/wiki/File:DIMMs.jpg>

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Smart Phone

- Will use single DRAM chip
- iPhone/iPod – flip chip in package with SoC Processor



Apple [APL1W72](#) A11 Bionic SoC layered over SK Hynix H9HKNNDBMAUUR 3 GB LPDDR4x RAM

Source:

<https://www.ifixit.com/Teardown/iPhone+X+Teardown/98975>

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Xilinx/Vitis DMA?

- This section focused on what the **DRAM** can do
 - What should happen with an optimized DRAM controller
 - Only DRAM is contributing latency

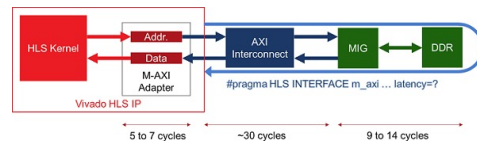
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Xilinx AXI Connection to DRAM

- Additional Latency from on-chip interconnect and interface



Source: https://www.xilinx.com/html_docs/xilinx2020_1/vitis_doc/programmingvitis_hls.html

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Xilinx/Vitis DMA?

- This section focused on what the **DRAM** can do
 - What should happen with an optimized DRAM controller
- Vitis DMA requires setup time
 - Which will be **in addition** to DRAM access time
 - High overhead [as you will see on HW6]
 - Even higher premium for large block transfers

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DRAM Implications

Part 2

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Terminology Watch

- Need to talk about
 - DRAM Rows
 - Image Rows
 - Relation between DRAM and Image Rows

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Preclass 1

```
uint16_b dram_image[1024*1024]; // assume
for (y=0; y<1024;y++)
    for (x=0; x<1024;x++)
        astream.write(dram_image[1024*y+x])
```

- How many cycles to run loop?
 - 10 cycle on dram row change (RCD,RP,CL)
 - 3 cycles same row (CL)
 - 128 uint16_b per DRAM row (2048b)

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Image Row and DRAM Rows

Address	MSB -- DRAM Row Bytes	-- LSB
0x027FF0	[y-1,1023]	
0x028000	[y,127]	[y,0]
0x028100		[y,128]
0x028200		
0x028300		
0x028400		
0x028500		
0x028600		
0x028700	[y,1023]	[y,896]
0x028800		[y+1,0]
0x028900		
0x028a00		

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Preclass 2

```
uint16_b dram_image[1024*1024];
for (x=0; x<1024;x++)
    for (y=0; y<1024;y++)
        astream.write(dram_image[1024*y+x]);
```

Note loop interchange

- How many cycles to run loop?
 - 10 cycle on row change
 - 3 cycles same row
 - 128 uint16_b per DRAM row (2048b)

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Preclass 3

```
uint16_b dram_image[1024*1024];
for (y=0; y<1024;y++)
    for (x=0; x<1024;x+=128)
        // assume the following for loop can be converted to a stream
        // as noted above, so takes 10+n cycles for n uint16_b's
        for(i=0;i<128;i++) astream.write(dram_image[1024*y+x+i])
```

- How many cycles to run loop?
 - 10+n cycles to fetch n<=128 Half-words on row

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DRAM

- Latency is large (10s of ns)
- Throughput can be high (GB/s)
 - If accessed sequentially
 - If exploit wide-word block transfers
- Throughput low on random accesses
 - As we saw for random access on wide-word memory
- Integer factor – order of magnitude -- difference

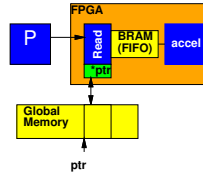
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Day 13: Data Movement (Options)

- DMA burst copy into BRAM memories
 - Built on top of other with DMA copy loop



```
hls::stream<datatype_t> str;
INPUT_READ: for(int i=0; i<INPUT_SIZE; i++) {
  #pragma HLS PIPELINE
  str.write(inp[i]); // Reading from Input interface
}
```

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Maximize Reuse Part 3

Minimize need to go to large memory

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Data Management

- Large, central memory
 - Bottleneck
 - High energy
- Minimize need to return to it

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Window Filter

- Compute based on neighbors
 - $F(d[y-1][x-1], d[y-1][x], d[y-1][x+1], d[y][x-1], d[y][x], d[y][x+1], d[y+1][x-1], d[y+1][x], d[y+1][x+1])$
- Common idiom
 - Image filtering
 - CNN (Convolution stage in Deep Neural Network)
 - Numerical simulation
 - Cellular automata
 - Search, matching

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Window Filter

- Compute based on neighbors
 - $F(d[y-1][x-1], d[y-1][x], d[y-1][x+1], d[y][x-1], d[y][x], d[y][x+1], d[y+1][x-1], d[y+1][x], d[y+1][x+1])$
- Generalize for different neighborhood sizes
 - for (yoff=YMIN; yoff<YMAX;yoff++)
 - for (xoff=XMIN; xoff<XMAX;xoff++)
 - res=fun(res,d[y+yoff][x+xoff]);

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Window Filter

- Compute based on neighbors
- for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++)
 - $o[y][x]=F(d[y-1][x-1], d[y-1][x], d[y-1][x+1], d[y][x-1], d[y][x], d[y][x+1], d[y+1][x-1], d[y+1][x], d[y+1][x+1]);$
- How work with image in DRAM
 - As written references
 - Reads per row?

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Window Filter

- Compute based on neighbors
- for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++)
 - $o[y][x]=F(d[y-1][x-1],d[y-1][x],d[y-1][x+1],$
 $d[y][x-1],d[y][x],d[y][x+1],$
 $d[y+1][x-1],d[y+1][x],d[y+1][x+1]);$
- Data reused between inner loop invocations when x increments?
 - How many of the 9 values are reused at x+1?

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Window Shift x++

	23	24	25	26	27
17					
18			Y-1,X-1	Y-1,X	Y-1,X+1
19			Y,X-1	Y,X	Y,X+1
20			Y+1,X-1	Y+1,X	Y+1,X+1
21					

	23	24	25	26	27
17					
18				Y-1,X-1	Y-1,X
19				Y,X-1	Y,X
20				Y+1,X-1	Y+1,X
21					

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Window Filter

- Compute based on neighbors
- for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++)
 - $o[y][x]=F(d[y-1][x-1],d[y-1][x],d[y-1][x+1],$
 $d[y][x-1],d[y][x],d[y][x+1],$
 $d[y+1][x-1],d[y+1][x],d[y+1][x+1]);$
- Data reused between y values in outer loop?
 - How many of 9 values reused for y+1?

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Window Shift y++

	23	24	25	26	27
17					
18			Y-1,X-1	Y-1,X	Y-1,X+1
19			Y,X-1	Y,X	Y,X+1
20			Y+1,X-1	Y+1,X	Y+1,X+1
21					

	23	24	25	26	27
17					
18					
19			Y-1,X-1	Y-1,X	Y-1,X+1
20			Y,X-1	Y,X	Y,X+1
21			Y+1,X-1	Y+1,X	Y+1,X+1

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Window Filter

- Compute based on neighbors
- for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++)
 - $o[y][x]=F(d[y-1][x-1],d[y-1][x],d[y-1][x+1],$
 $d[y][x-1],d[y][x],d[y][x+1],$
 $d[y+1][x-1],d[y+1][x],d[y+1][x+1]);$
- Data reused between y values in outer loop?
 - How many of 9 values reused for y+1?
 - Reuse distance [in cycles]?
 - ...assume II=1 pipeline inner loop
 - i.e. how many $o[y][x]$'s do we compute between using as $d[y+1][x]$ and $d[y][x]$?

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Window Filter

- Compute based on neighbors
- for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++)
 - $o[y][x]=F(d[y-1][x-1],d[y-1][x],d[y-1][x+1],$
 $d[y][x-1],d[y][x],d[y][x+1],$
 $d[y+1][x-1],d[y+1][x],d[y+1][x+1]);$
- How much data need to store to hold on to $d[y]$ values that will use again?
- Where can we store?

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Line Buffers

- Only need to save last 2 rows ($d[y][*]$)
 - General case: $(\text{window_height}-1)$ rows
- Store in local buffers
 - Call them $\text{dy}[\text{XMAX}]$, $\text{dym}[\text{XMAX}]$;
 - dym for dy minus 1
 - Stick value there between uses.

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Variable Naming

	+xm		+xp	
dym	Y-1,X-1	Y-1,X	Y-1,X+1	
dy	Y,X-1	Y,X	Y,X+1	
dyp	Y+1,X-1	Y+1,X	Y+1,X+1	

	+xm		+xp	
dym	Y-1,X-1	Y-1,X	Y-1,X+1	
dy	Y,X-1	Y,X	Y,X+1	
dyp	dypxm	dypx	dnew	

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Window Filter

- With line buffers dy , dym
- for ($y=0; y<YMAX; y++$)
 - for ($x=0; x<XMAX; x++$) {
 - $\text{dypxm}=\text{dypx}$; $\text{dypx}=\text{dnew}$; $\text{dnew}=\text{d}[y+1][x+1]$;
 - $\text{o}[y][x]=\text{F}(\text{dym}[x-1], \text{dym}[x], \text{dym}[x+1],$
 $\text{dy}[x-1], \text{dy}[x], \text{dy}[x+1],$
 $\text{dypxm}, \text{dypx}, \text{dnew})$;
 - $\text{dym}[x-1]=\text{dy}[x-1]$;
 - $\text{dy}[x-1]=\text{dypxm}$;

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Lines in Buffers

	+xm		+xp	
dym	Y-1,X-1	Y-1,X	Y-1,X+1	
dy	Y,X-1	Y,X	Y,X+1	
dyp	Y+1,X-1	Y+1,X	Y+1,X+1	

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Window Filter

- With line buffers dy , dym
- for ($y=0; y<YMAX; y++$)
 - for ($x=0; x<XMAX; x++$) {
 - $\text{dypxm}=\text{dypx}$; $\text{dypx}=\text{dnew}$; $\text{dnew}=\text{d}[y+1][x+1]$;
 - $\text{o}[y][x]=\text{F}(\text{dym}[x-1], \text{dym}[x], \text{dym}[x+1],$
 $\text{dy}[x-1], \text{dy}[x], \text{dy}[x+1],$
 $\text{dypxm}, \text{dypx}, \text{dnew})$;
 - $\text{dym}[x-1]=\text{dy}[x-1]$; $\text{dy}[x-1]=\text{dypxm}$; }

- Avoid multiple read dy , dym ?

– Save memory ports

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Variable Naming

	+xm		+xp	
dym	Y-1,X-1	Y-1,X	Y-1,X+1	
dy	Y,X-1	Y,X	Y,X+1	
dyp	Y+1,X-1	Y+1,X	Y+1,X+1	

	+xm		+xp	
dym	dymxm	dymx	dymxp	
dy	dypxm	dypx	dypx	
dyp	dypxm	dypx	dnew	

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Window Filter

- Single read and write from dym, dy
- for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++) {
 - dypxm=dypx; dypx=dnew; dnew=d[y+1][x+1];
 - dyxm=dyx; dyx=dyxp; dyxp=dy[x+1];
 - dymxm=dymx; dymx=dymxp; dymxp=dym[x+1];
 - o[y][x]=F(dymxm,dymx,dymxp,
 - dyxm,dyx,dyxp,
 - dypxm,dypx,dnew);
 - dym[x-1]=dyxm;dy[x-1]=dypxm; }

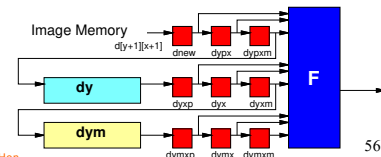
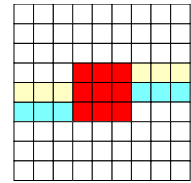
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Pipelined Circuit

- Single **sequential** read from big memory (DRAM) per result
- Shift registers
- Line buffers



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Window Filter

- Convert to stream ... use Preclass 3 load
- for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++) {
 - dypxm=dypx; dypx=dnew; **astream.read(dnew);**
 - dyxm=dyx; dyx=dyxp; dyxp=dy[x+1];
 - dymxm=dymx; dymx=dymxp; dymxp=dym[x+1];
 - o[y][x]=F(dymxm,dymx,dymxp,
 - dyxm,dyx,dyxp,
 - dypxm,dypx,dnew);
 - dym[x-1]=dyxm;dy[x-1]=dypxm; }

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Window Filter

- Convert to stream ... use Preclass 3 load
- for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++) {
 - dypxm=dypx; dypx=dnew; **astream.read(dnew);**
 - dyxm=dyx; dyx=dyxp; dyxp=dy[x+1];
 - dymxm=dymx; dymx=dymxp; dymxp=dym[x+1];
 - ostream.write(F(dymxm,dymx,dymxp,**
 - dyxm,dyx,dyxp,
 - dypxm,dypx,dnew));
 - dym[x-1]=dyxm;dy[x-1]=dypxm; }

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Multiple Filters

- What if want to run multiple filters?
- for (f=0;f<FMAX;f++)
 - for (y=0;y<YMAX;y++)
 - for (x=0;x<XMAX;x++)
 - o[f][y][x]=fun[f](d[y-1][x-1],d[y-1][x],d[y-1][x+1],**
 - d[y][x-1],d[y][x],d[y][x+1],
 - d[y+1][x-1],d[y+1][x],d[y+1][x+1]);
- Forces multiple reads through d
- **Avoidable?**

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Take-Away

- Can process with a single, streaming read through data in large memory
 - Specifically for window filters on images
 - General goal to try to achieve
- Careful to orchestrate data in small, local buffers
- DMA/streaming transfers to achieve near peak DRAM bandwidth

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Sort Part 4

Cover in lecture session if time permits

[Skip to wrapup](#)

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Sort

- Order data
 - 7 3 4 2 1 9 8 0 → 0 1 2 3 4 7 8 9
- Data movement can be challenging
 - Last value may become first (vice-versa)
 - Especially when not fit in small memories
- Many sequential sort solutions access data irregularly
 - Want to avoid with DRAM
- Example illustrates can reformulate as streaming

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Observation: Merge

- Merging two sorted list is a streaming operation
- int aptr; int bptr;
- for (i=0;i<MCNT;i++)
 - If ((aptr<ACNT) && (bptr<BCNT))
 - If (a[aptr]>b[bptr])
 - { o[i]=a[aptr]; aptr++; }
 - Else
 - { o[i]=b[bptr]; bptr++; }
 - Else // copy over remaining from a or b

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Merge Memory Access

- for (i=0;i<MCNT;i++)
 - If ((aptr<ACNT) && (bptr<BCNT))
 - If (a[aptr]>b[bptr])
 - { o[i]=a[aptr]; aptr++; }
 - Else
 - { o[i]=b[bptr]; bptr++; }
 - Else // copy over remaining from a or b
- How work with DRAM rows?

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Merge and DRAM

- May alternate between DRAM rows
- Int aptr; int bptr;
- For (i=0;i<MCNT;i++)
 - If ((aptr<ACNT) && (bptr<BCNT))
 - If (a[aptr]>b[bptr])
 - { o[i]=a[aptr]; aptr++; }
 - Else
 - { o[i]=b[bptr]; bptr++; }
 - Else // copy over remaining from a or b

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Merge and DRAM

- Want to fetch a as block into local memory (into stream), then can do this
- Int aptr; int bptr;
- For (i=0;i<MCNT;i++)
 - If ((aptr<ACNT) && (bptr<BCNT))
 - If (a[aptr]>b[bptr])
 - { o[i]=a[aptr]; aptr++; }
 - Else
 - { o[i]=b[bptr]; bptr++; }
 - Else // copy over remaining from a or b

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Merge using Streams

- Merging two sorted list is a streaming operation
- int aptr; int bptr;
- astream.read(ain); bstream.read(bin)
- for (i=0;i<MCNT;i++)
 - If ((aptr<ACNT) && (bptr<BCNT))
 - If (ain>bin)
 - { ostream.write(ain); aptr++; astream.read(ain);}
 - Else
 - { ostream.write(bin) bptr++; bstream.read(bin);}
- Else // copy over remaining from astream/bstream

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Merge using Streams and DRAM

- Streaming accomplishes if Streaming is implemented to fetch row into FIFO buffer
- Int ptr; int bptr;
- astream.read(ain); bstream.read(bin)
- For (i=0;i<MCNT;i++)
 - If ((aptr<ACNT) && (bptr<BCNT))
 - If (ain>bin)
 - { ostream.write(ain); aptr++; astream.read(ain);}
 - Else
 - { ostream.write(bin) bptr++; bstream.read(bin);}
- Else // copy over remaining from astream/bstream

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Building from Merge

- Know how to get sorted data of length N given two, independently sorted lists of length N/2
- A list of length 1 is sorted.
- Merging two lists of length 1 gives us?
 - How many lists of what length?
- Merging two lists of length 2 gives us?

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Merge Sort

- Strategy
 - For i=1 to passes
 - Pass over data creating merged sequences of length 2^i from pairs of length 2^{i-1}
 - What is passes?
- Can, at least, limit to passes reads through data from large memory.

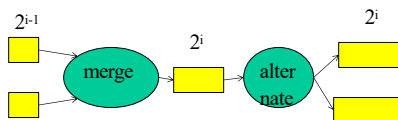
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On-chip Merge

- As long as can fit sequence (2^i) on chip, can stream merge stages without going back to big memory (DRAM)



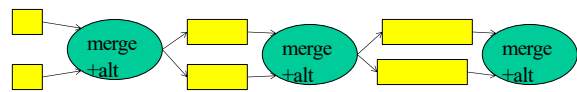
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On-chip Merge

- As long as can fit sequence (2^i) on chip, can stream merge stages without going back to big memory (DRAM)
 - E.g. with 36Kb BRAMs ~ first 10-12 stages
 - Up to ~16 using multiple BRAMs



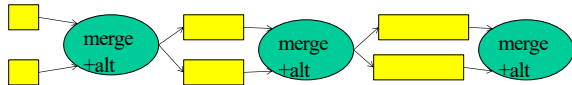
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On-chip Merge

- For sorts up to ~100K elements may be able to cover in one read/write stream to/from DRAM
- Larger: $\sim \log_2(N) - 15$ read/writes



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Big Ideas

- Must pay attention to orchestrate data movement
 - How we access and reuse data
- Minimize use of large memories
- Regular (sequential) access to large memories higher performance
 - Easier to get bandwidth on wide-word reads

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Admin

- Feedback
- HW6 due Friday
- Reading for Monday on web
- HW7: out

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