

ESE5320: System-on-a-Chip Architecture

Day 6: September 18, 2024
Data-Level Parallelism

Preclass



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Today

Data-level Parallelism

- For Parallel Decomposition (Part 1)
- Architectures (Part 2)
- Concepts (Part 3)
- NEON

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Message

- Data Parallelism easy basis for decomposition
 - When things are data parallel, exploiting for parallelism relatively easy
- Data Parallel architectures can be compact
 - pack more computations onto a fixed-size Integrated Circuit chip
 - OR perform computation in less area

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Preclass 1

- 500 news articles
 - 3000 words each
- Count total occurrences of a string
- How can we exploit data-level parallelism on task?
- How much parallelism can we exploit?
 - If don't exploit parallelism within article?
 - If do exploit parallelism within article?

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Parallel Decomposition

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Data Parallel

- Data-level parallelism can serve as an organizing principle for parallel task decomposition
- Run computation on independent data in parallel

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Exploit

- Can exploit with
 - Threads
 - Pipeline Parallelism
 - Instruction-level Parallelism
 - Fine-grained Data-Level Parallelism

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Performance Benefit

- Ideally linear in number of processors (resources)
- Resource Bound:
 - $T_{dp} = (T_{single} \times N_{data}) / P$
- T_{single} = Latency on single data item
- $T_{dp} = T_{single} \times [N_{data} / P]$

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Vector

- In Math – 1D array of numbers
- Vector A = [2, 3, 5, 7]
- Vector B = [4, 6, 8, 9]
- A+B = [6, 9, 13, 16]

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Preclass 2 Common Examples

- What are common examples of DLP?
 - Numerical Linear Algebra
 - E.g. Vector Add, Matrix-Vector Multiplication
 - Simulation
 - Signal or Image Processing
 - Optimization

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Hardware Architectures

Part 2

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Idea

- If we're going to perform the same operations on different data, exploit that to reduce area, energy
- Reduced area means can have more computation on a fixed-size IC chip.

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SIMD

- Single Instruction Multiple Data

Shared Instruction

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Ripple Carry Addition

- Can define logic for each bit, then assemble:
– bit slice

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Arithmetic Logic Unit (ALU)

- Observe:
– with small tweaks can get many functions with basic adder components

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Arithmetic and Logic Unit

ALU

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ALU Functions

- A+B w/ Carry
- B-A
- A xor B (squash carry)
- A*B (squash carry)
- /A

Key observation: every ALU bit does the same thing on different bits of the data word(s).

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ARM v7 Core

- ALU is Key compute operator in a processor

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W-bit ALU as SIMD

- Familiar idea
- A W-bit ALU (W=8, 16, 32, 64, ...) is SIMD
- Each bit of ALU works on separate bits
 - Performing the same operation on it
 - Trivial to see bitwise AND, OR, XOR
 - Also true for ADD (each bit performing Full Adder)
- Share one instruction across all ALU bits

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ALU Bit Slice

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Preclass 4

- What do we get when add 65280 to 257
 - 32b unsigned add?
 - 16b unsigned add?

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ALU vs. SIMD ?

- What's different between
 - 128b wide ALU
 - SIMD datapath supporting eight 16b ALU operations

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ALU vs. SIMD Example

- Concretely show:
 - 16b wide ALU
 - SIMD datapath with two 8b wide ALUs

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ALU vs. SIMD ?

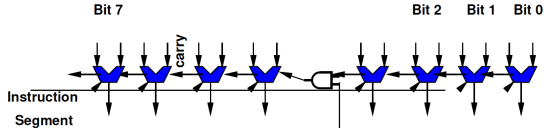
- How could we get both operations from the same hardware?
 - 128b wide ALU
 - SIMD datapath supporting eight 16b ALU operations

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Segmented Datapath

- Add a few gates to convert a wide datapath into one supporting a set of smaller operations
 - Just need to squash the carry at points



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Segmented Datapath

- Add a few gates to convert a wide datapath into one supporting a set of smaller operations
 - Just need to squash the carry at points
- But need to keep instructions (description) small
 - So typically have limited, homogeneous widths supported

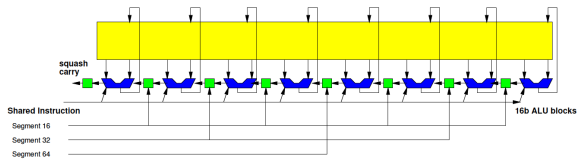
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Segmented 128b Datapath

- 1x128b, 2x64b, 4x32b, 8x16b



(only 4 cases, so can decode from 2b)

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Vector

- In Math – 1D array of numbers
- Here – 1D array of numbers that we operate upon with SIMD operations
 - Perform the same operations on
- Vector A = [2, 3, 5, 7]
- Vector B = [4, 6, 8, 9]
- A+B = [6, 9, 13, 16]

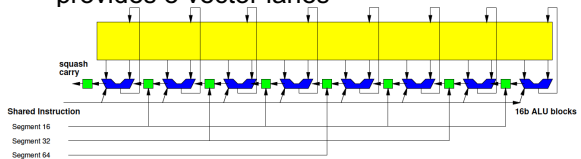
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Terminology: Vector Lane

- Each of the separate segments called a **Vector Lane**
 - Length of vector hardware natively supports
- For 16b data on 128b datapath, this provides 8 vector lanes



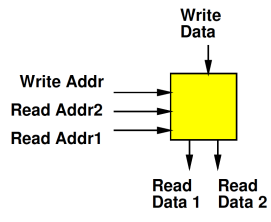
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Register File

- Small Memory
- Usually with multiple ports
 - Ability to perform multiple reads and writes simultaneously
- Small
 - To make it fast (small memories fast)
 - Multiple ports are expensive

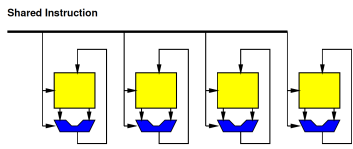
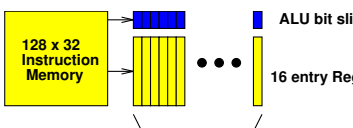


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SIMD Datapath

- Logical View: 
- Layout View: 

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Preclass 3: Opportunity

- Don't need 64b variables for lots of things
- Natural data sizes?
 - Audio samples?
 - Input from A/D?
 - Video Pixels?
 - X, Y coordinates for 4K x 4K image?

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Preclass 5

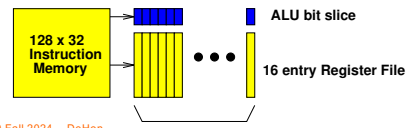
- Look at Area of datapath
- Imagine filling an IC die with copies (instances) of datapath
 - If datapath smaller, can fit more of them into fixed die area
- Look at computation this provides

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Preclass 5

W	A(W)	% datapath	Instances	Peak 16b ops
16				
64				
128				
256				



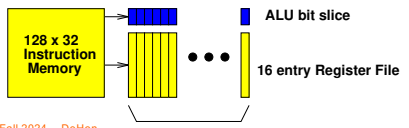
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Preclass 5

W	A(W)	% datapath	Instances	Peak 16b ops	Ratio
16	1.1	9	91	91	1.0
64					
128	1.8	43	56	448	4.9
256					

Complete: 64, 256



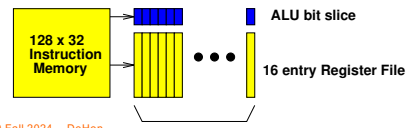
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Preclass 5

W	A(W)	% datapath	Instances	Peak 16b ops	Ratio
16	1.1	9	91	91	1.0
64					
128	1.8	43	56	448	4.9
256					

Complete: 64, 256



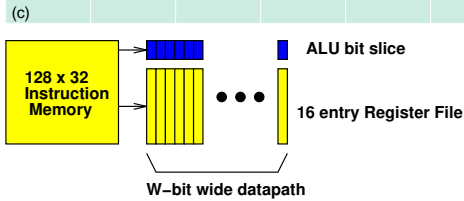
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Preclass 5

Why?

W	A(W) x10 ⁶	% datapath	Instances	Peak 16b ops	Ratio
16	1.1	9	91	91	1.00
64	1.4	28	71	284	3.16
128	1.8	43	56	448	4.90
256	2.5	60	39	640	6.85

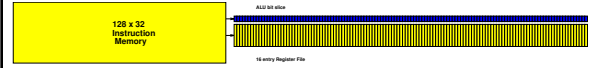


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To Scale Comparison

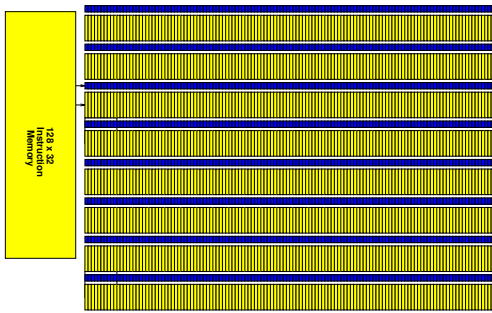


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To Scale W=1024



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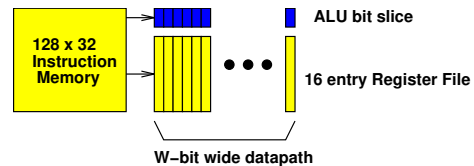
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Preclass 5

W	A(W) x10 ⁶	% datapath	Instances	Peak 16b ops	Ratio
16	1.1	9	91	91	1.00
64	1.4	28	71	284	3.16
128	1.8	43	56	448	4.90
256	2.5	60	39	640	6.85
(c)	100				

What get for 5c?



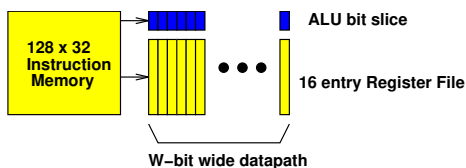
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Preclass 5

W	A(W) x10 ⁶	% datapath	Instances	Peak 16b ops	Ratio
16	1.1	9	91	91	1.00
64	1.4	28	71	284	3.16
128	1.8	43	56	448	4.90
256	2.5	60	39	640	6.85
(c) 16,500	100	100-epsilon	1	1031	11.32



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Take Away

- Wider SIMD → greater potential density
 - More compute per cm² of silicon
- There is a point of diminishing return
 - Once over half the area in datapath
- Wider SIMD may be inefficient if do not have enough data-level parallelism

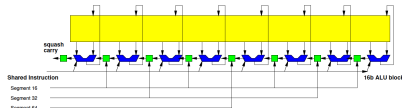
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Preclass 6: Vector Length

- May not match physical hardware length
 - Logical (application need): Vector Length
 - Physical (hardware provide): Vector Lanes
- ```
vadd(int *a, int *b, int *res,
 int vector_length) {
 for (int i=0;i<vector_length;i++)
 res[i]=a[i]+b[i];
}
```



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## Preclass 6: Vector Length

- May not match physical hardware length
  - Logical (application need): Vector Length
  - Physical (hardware provide): Vector Lanes
- Efficiency (utilization) when
  - Vector length < Vector Lanes? (5, 8)
  - Vector length > Vector Lanes? (24, 8)
  - Vector length % (Vector Lanes) != 0 (13, 8)
    - E.g. vector length 13, for 8 vector lanes

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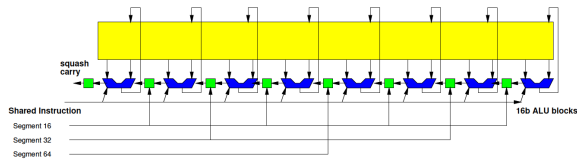
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## Performance

- Resource Bound

$$T_{\text{vector}} = \lceil N_{\text{op}}/VL \rceil \times T_{\text{cycle}}$$



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## Vector Computation

- Easy to map to SIMD flow if can express computation as operation on vectors
  - Vector Add
  - Vector Multiply
  - Dot Product

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## Concepts

### Part 3

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## Terminology: Scalar

- Simple: non-vector
- When we have a vector unit controlled by a normal (non-vector) processor core often need to distinguish:
  - Vector operations that are performed on the vector unit
  - Normal=non-vector=scalar operations performed on the base processor core

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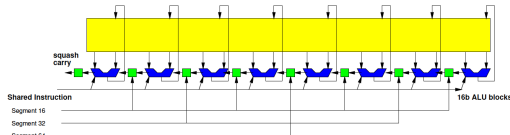
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## Vector Register File

- Need to be able to feed the SIMD compute units
  - Not be bottlenecked on data movement to the SIMD ALU
- Wide RF (register file) to supply
- With wide path to memory

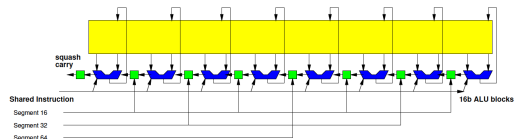


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## Point-wise Vector Operations

- Easy – just like wide-word operations (now with segmentation)



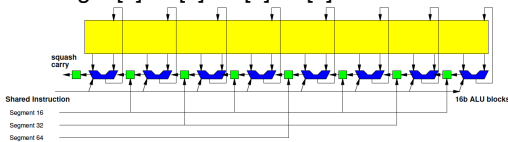
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## Point-wise Vector Operations

- ...but alignment matters.
- If not aligned, need to perform data movement operations to get aligned
  - E.g.  $a[0] \dots a[7] + b[1] \dots b[8]$



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## Ideal

- for  $(i=0; i<64; i=i++)$ 
  - $c[i]=a[i]+b[i]$
- No data dependencies
- Access every element
- Number of operations is a multiple of number of vector lanes

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## Skipping Elements?

- How does this work with datapath?
  - Assume loaded  $a[0], a[1], \dots, a[63]$  and  $b[0], b[1], \dots, b[63]$  into vector register file
- for  $(i=0; i<64; i=i+2)$ 
  - $c[i/2]=a[i]+b[i]$

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## Stride

- Stride: the distance between vector elements used
- for  $(i=0; i<64; i=i+2)$ 
  - $c[i/2]=a[i]+b[i]$
- Accessing data with stride=2

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## Load/Store

- Strided load/stores
  - Some architectures will provide strided memory access that compact when read into register file
- Scatter/gather
  - Some architectures will provide memory operations to grab data from different places to construct a dense vector

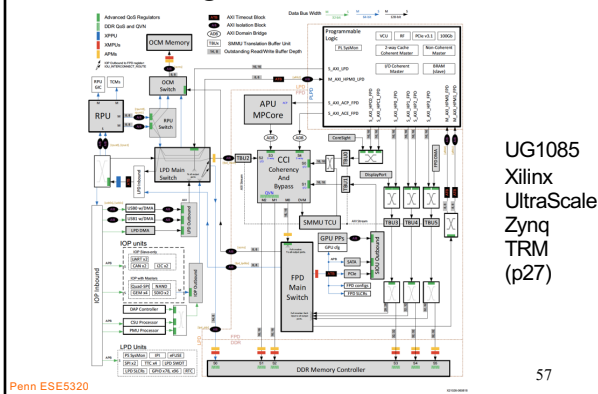
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## Neon

ARM Vector Accelerator

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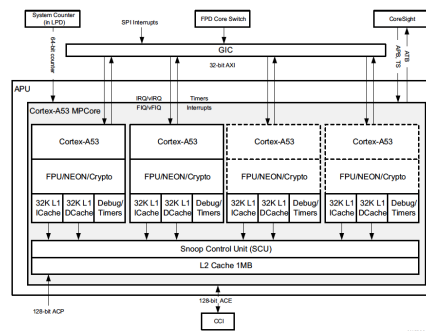
## Programmable SoC



UG1085  
Xilinx  
UltraScale  
Zynq  
TRM  
(p27)

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## APU MPcore



UG1085  
Xilinx  
UltraScale  
Zynq  
TRM  
(p53)

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## Neon Vector

- 128b wide register file, 16 registers
- Support
  - 2x64b
  - 4x32b (also Single-Precision Float)
  - 8x16b
  - 16x8b

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## Sample Instructions

- VADD – basic vector
- VCEQ – compare equal
  - Sets to all 0s or 1s, useful for masking
- VMIN – avoid using if's
- VMLA – accumulating multiply
- VPADAL – maybe useful for reduce
  - Vector pair-wise add
- VEXT – for “shifting” vector alignment
- VLDn – deinterleaving load

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## ARM Cortex A53 (Ultra96) (similar to A-7 Pipeline)

2-issue  
In-order  
1 NEON pipe  
128b wide  
8-stage pipe

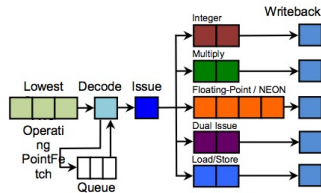


Figure 1 Cortex-A7 Pipeline

<https://www.anandtech.com/show/8718/the-samsung-galaxy-note-4-exynos-review/3>

<https://arstechnica.com/gadgets/2011/10/arms-new-cortex-a7-is-tailor-made-for-android-superphones/>  
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## Big Ideas

- Data Parallelism easy basis for decomposition
- Data Parallel architectures can be compact – pack more computations onto a chip
  - SIMD, Pipelined
  - Benefit by sharing (instructions)
  - Performance can be brittle
    - Drop from peak as mismatch

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## Admin

- Remember feedback
- Reading for Day 7 online
- HW3 due Friday
- HW4 out
  - Including partner assignments
    - Board holders – contact partner soon

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