ECE 252 / CPS 220
Advanced Computer Architecture I

Lecture 17
Vectors

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www.duke.edu/~bcl15
www.duke.edu/~bcl15/class/class_ece252fall11.html

ECE252 Administrivia

15 November – Homework #4 Due

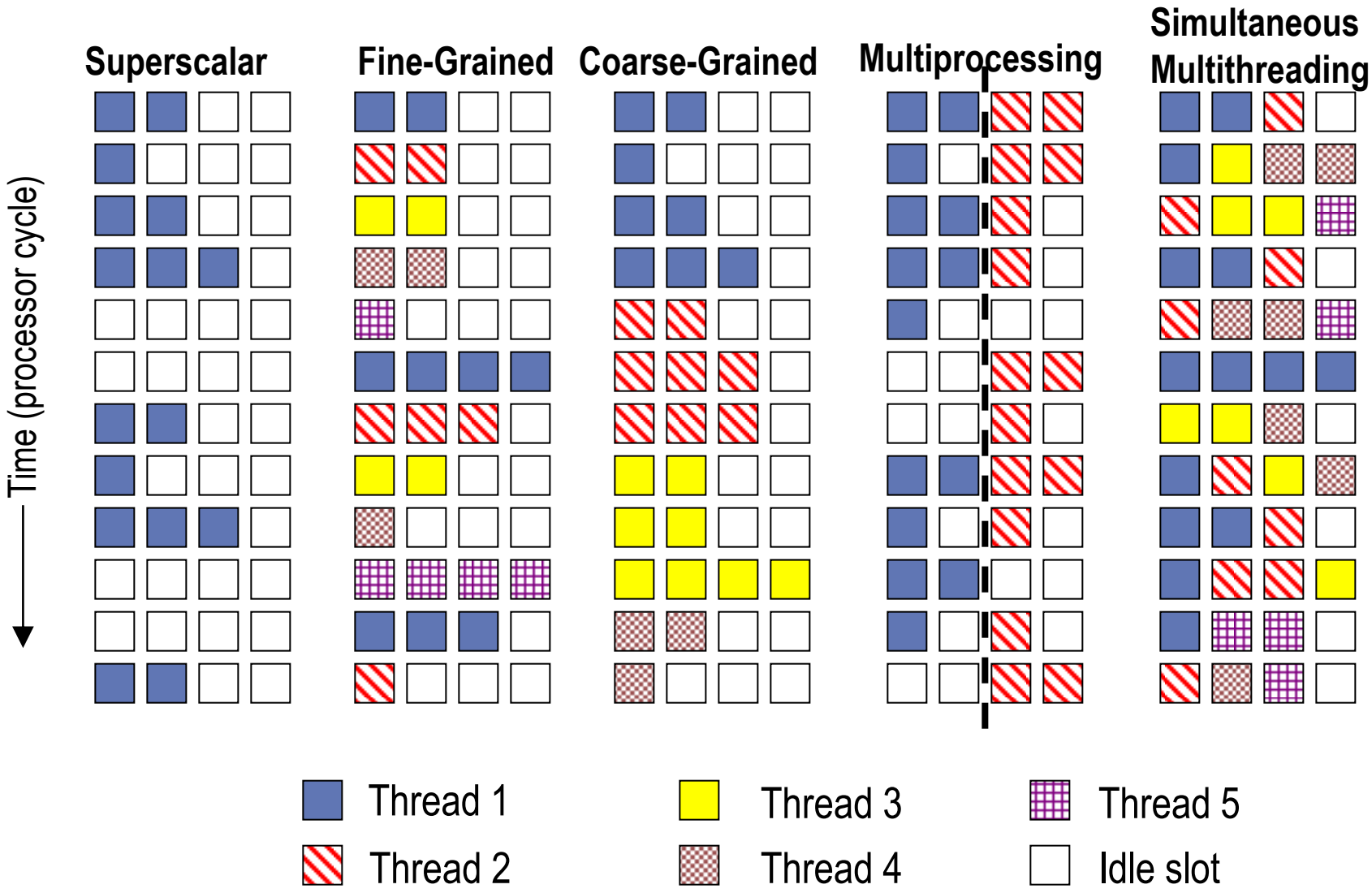
Project Status

- Plan on having preliminary data or infrastructure

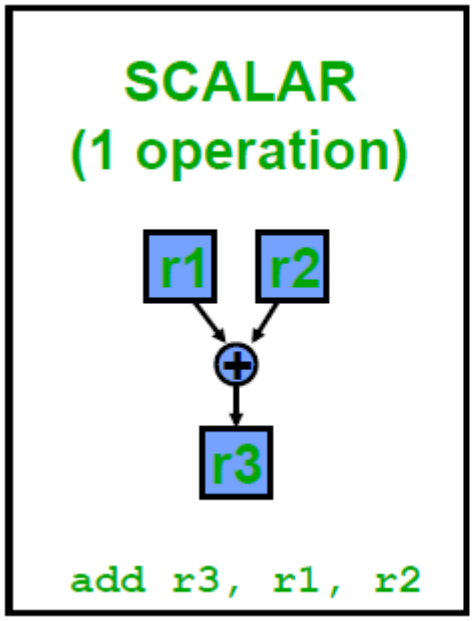
ECE 299 – Energy-Efficient Computer Systems

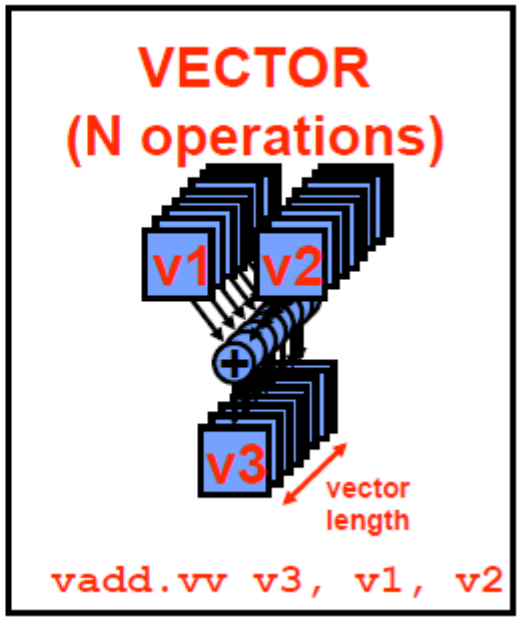
- www.duke.edu/~bcl15/class/class_ece299fall10.html
- Technology, architectures, systems, applications
- Seminar for Spring 2012.
- Class is paper reading, discussion, research project
- In Fall 2010, students read >35 research papers.
- In Spring 2012, read research papers.
- In Spring 2012, also considering textbook "The Datacenter as a Computer: An Introduction to the Design of Warehouse-scale Machines."

Last Time


Superscalar
Fine-Grained
Coarse-Grained
Multiprocessing
Simultaneous Multithreading
Time (processor cycle)
Thread 1
Thread 2
Thread 3
Thread 4
Thread 5
Idle slot

Vector Processors





Data-level Parallelism

Vectors effective for data-level parallelism (DLP)

-- Vectors are most efficient way to exploit DLP

-- Superscalar (e.g., DLP as instruction-level parallelism) is less efficient

-- Multiprocessor (e.g., DLP as thread-level parallelism) is less efficient

Scientific Computing

-- Weather forecasting, car-crash simulation, biological modeling

-- Vector processors were invented for supercomputing, but fell out of favor after the advent of multiprocessors

Multimedia Computing

-- Identical ops on streams or arrays of sound samples, pixels, video frames

-- Vector processors were revived for multimedia computing

Vector Processor History

Vectors widely used for supercomputing (1970s-1990s)

-- Cray, CDC, Convex, TI, IBM

Transition away from vectors (1980s-1990s)

-- Fitting a vector processor into a single chip was difficult

-- Building supercomputers from commodity components was easier

Vectors are re-emerging as SIMD

-- SIMD – single instruction multiple data

-- SIMD provides short vectors in all ISAs

-- Provides multimedia acceleration

Parts of a Vector Processor

Scalar processor

-- Scalar register file (e.g., 32 registers)

-- Scalar functional units (arithmetic, load/store, etc…)

Vector register file

-- Each register is an array of elements

-- Example: 32 registers, each with 32 64-bit elements

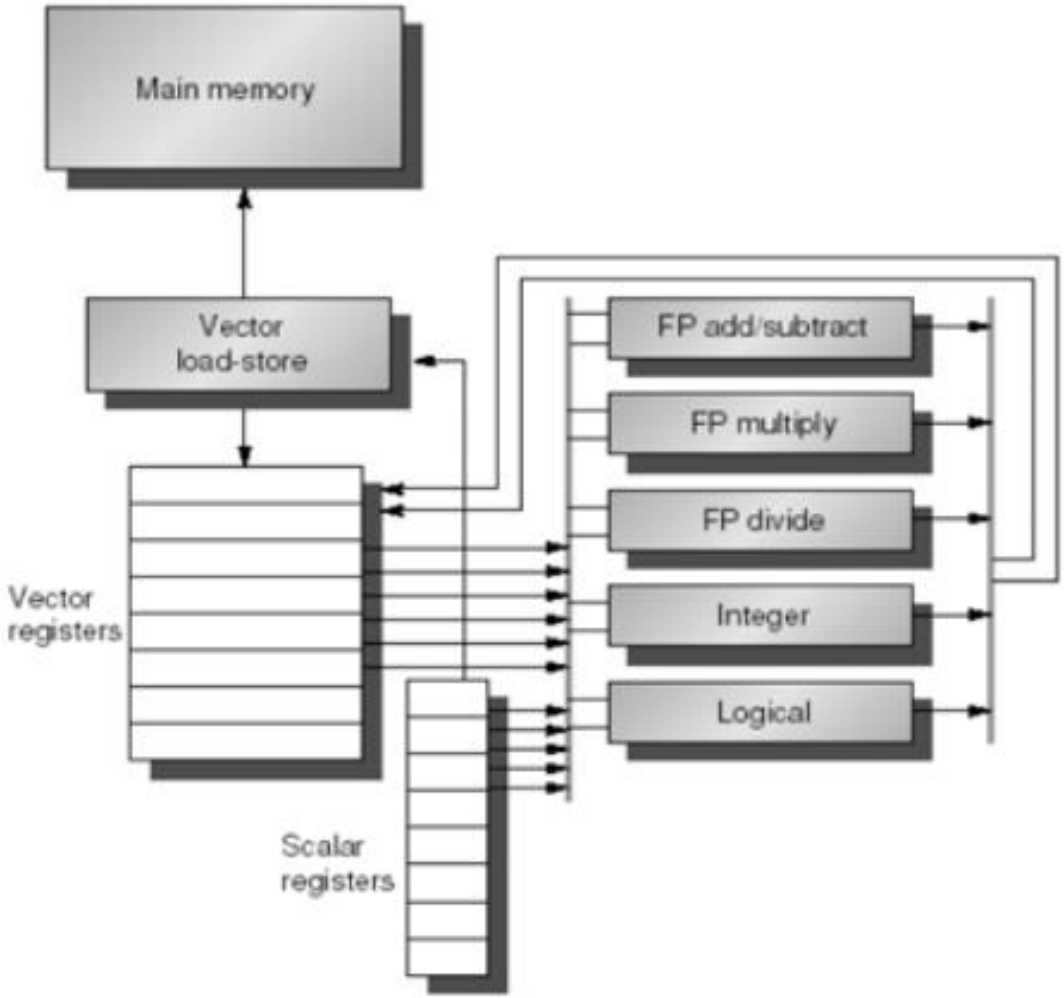
-- MVL – maximum vector length = max # of elements per register

Vector functional units

-- Integer, floating-point, load/store, etc…

-- Some datapaths (e.g., ALUs) shared by vector, scalar units

Parts of a Vector Processor



Vector Supercomputers

Cray-1, 1976

Scalar Unit

- Load/Store architecture

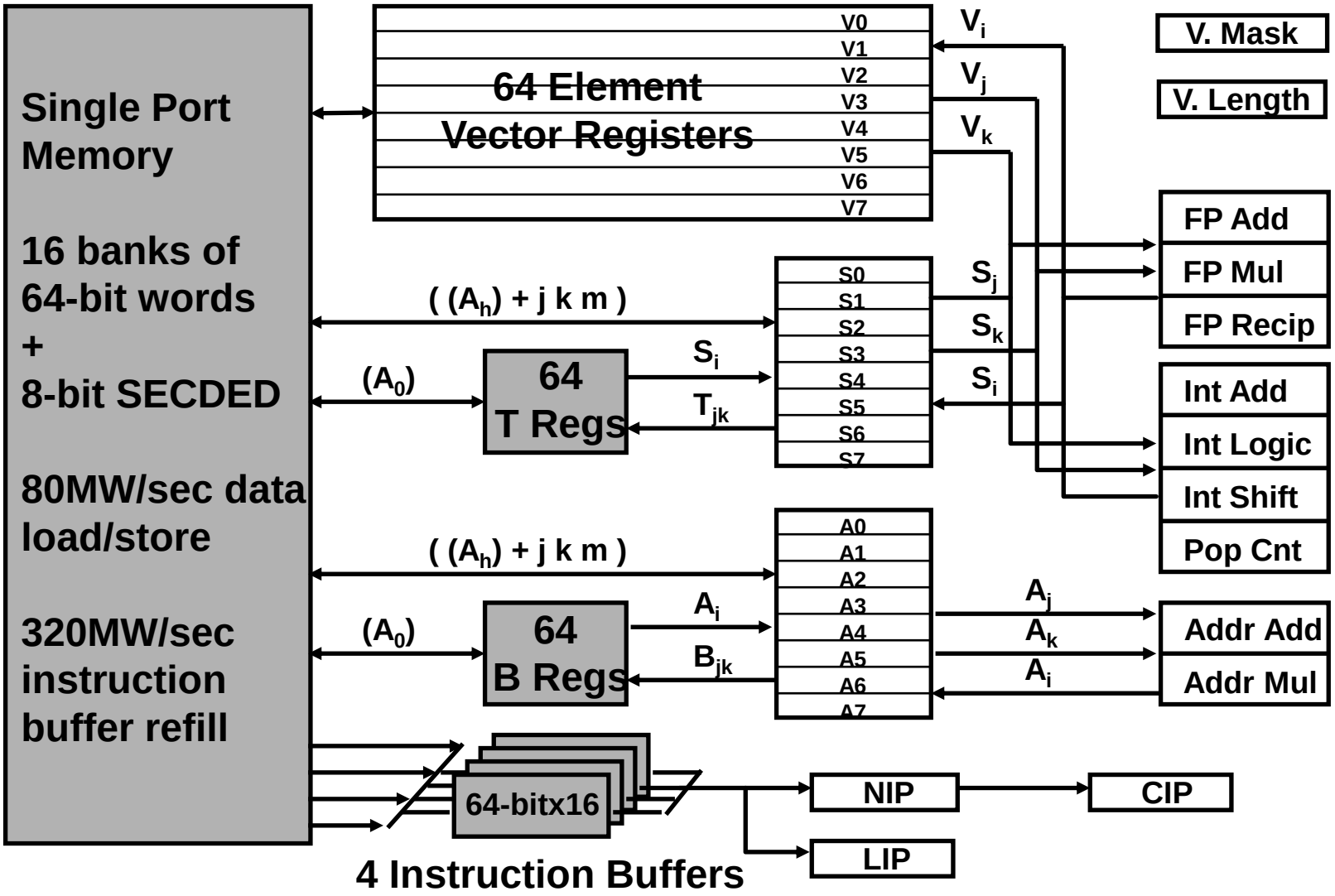
Vector Extension

- Vector registers
- Vector instructions

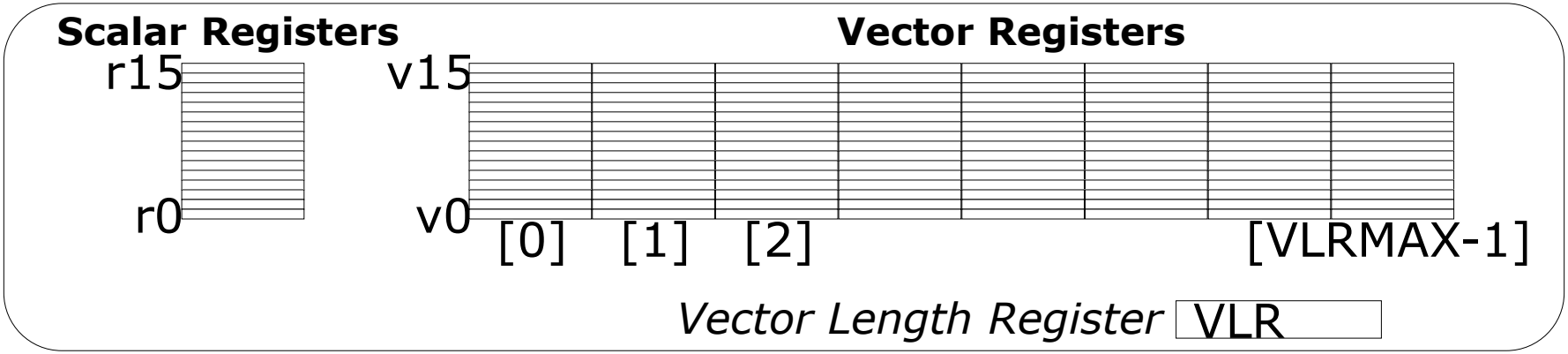
Implementation

- Hardwired control (no microcode)
- Pipelined functional units
- Interleaved memory system
- No data caches
- No virtual memory

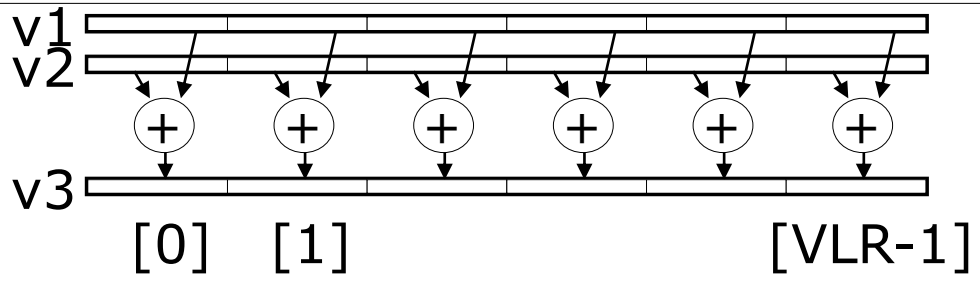
Cray-1 (1976)


Single Port Memory
16 banks of 64-bit words + 8-bit SECDED
80MW/sec data load/store
320MW/sec instruction buffer refill
64 Element Vector Registers
V0
V1
V2
V3
V4
V5
V6
V7
V_i
V_j
V_k
V. Mask
V. Length
FP Add
FP Mul
FP Recip
((A_h) + j k m)
(A_0)
64 T Regs
S_i
T_{jk}
S0
S1
S2
S3
S4
S5
S6
S7
S_j
S_k
S_i
Int Add
Int Logic
Int Shift
Pop Cnt
((A_h) + j k m)
(A_0)
64 B Regs
A_i
B_{jk}
A0
A1
A2
A3
A4
A5
A6
A7
A_j
A_k
A_i
Addr Add
Addr Mul
64-bitx16
NIP
CIP
LIP
4 Instruction Buffers

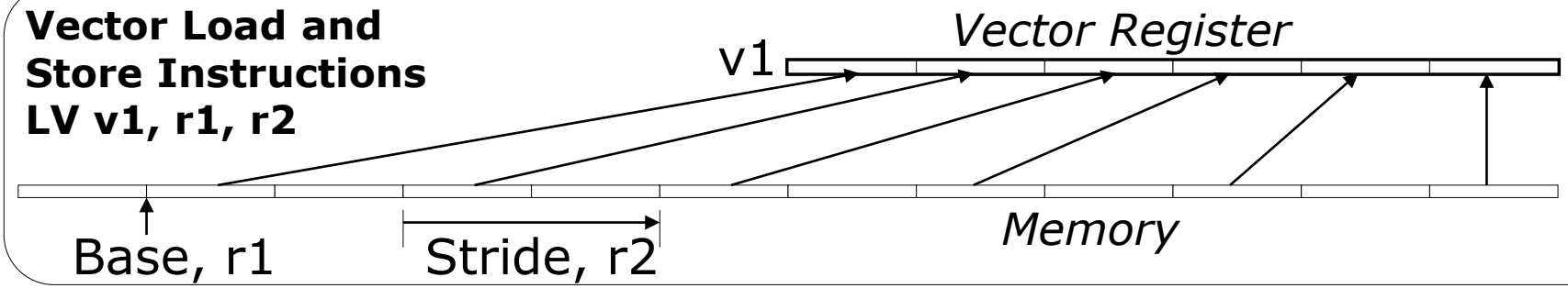
Vector Programming Model



Vector Arithmetic Instructions
ADDV v3, v1, v2



Vector Load and Store Instructions
LV v1, r1, r2



Vector ISA Benefits

Compact – single instruction defines N operations

-- also fewer branches

Parallel – N operations are (data) parallel

-- no dependencies between vector elements

-- like VLIW, no complex hardware for dynamic scheduling

-- scalable; additional functional units give additional performance

Expressive – memory ops describe access patterns

-- vector memory ops exhibit continuous or regular access patterns

-- vector memory ops can prefetch and/or effectively use memory banks

-- amortize high latency for 1st element over large sequential pattern (bursts of data transfer…1st element incurs a long latency….subsequent elements are pipelined to produce a new element per cycle)

Basic Vector Instructions

Suppose 64-element vectors

Instr	Operands	Operation	Comment
VADD.VV	V1, V2, V3	V1 = V2 + V3	vector + vector
VADD.SV	V1, R0, V2	V1 = R0 + V2	scalar + vector
VMUL.VV	V1, V2, V3	V1 = V2 * V3	vector x vector
VMUL.SV	V1, R0, V2	V1 = R0 * V2	scalar x vector
VLD	V1, R1	V1 = M[R1,...R1+63]	load, stride=1
VLDS	V1, R1, R2	V1 = M[R1,...R1+63*R2]	load, stride=R2
VLDX	V1, R1, V2	V1 = M[R1+V2(i), i=0 to 63]	indexed gather
VST	V1, R1	M[R1...R1+63] = V1	store, stride=1
VLDS	V1, R1, R2	M[R1,...R1+63*R2] = V1	store, stride=R2
VLDX	V1, R1, V2	M[R1+V2(i), i=0 to 63] = V1	indexed scatter

Vector Code Example

```
# C code
for (i=0 ; i<64 ; i++)
C[i] = A[i] + B[i];
```

```
# Scalar Code
LI R4, 64
loop:
L.D F0, 0 (R1)
L.D F2, 0 (R2)
ADD.D F4, F2, F0
S.D F4, 0 (R3)
DADDIU R1, 8
DADDIU R2, 8
DADDIU R3, 8
DSUBIU R4, 1
BNEZ R4, loop
```

```
# Vector Code
LI VLR, 64
VLD V1, R1
VLD V2, R2
ADD.VV V3, V1, V2
VST V3, R3
```

-- Load immediate (LI) with length of vector (64)
-- Vector length register (VLR)

Vector Length

Vector register holds a max number of elements

-- MVL: Maximum vector length (e.g., 64)

-- But application vectors may not match MVL

Vector length register

-- VL: controls length of any vector operation (add, multiply, load, store)

-- Example: vadd.vv with VL10 is equivalent to:

for(i=0; i<10; i++) {V1[i] = V2[i] + V3[i]}

-- Before vector instructions, VL is set to number less than or equal to MVL

How can we code applications where the vector length is not known until run-time?

Strip Mining

Strip Mining

-- Suppose application VL > MVL

-- Generate loop that handles MVL elements per iteration

-- Translate each loop iteration into a single vector instruction

Example: AX+Y

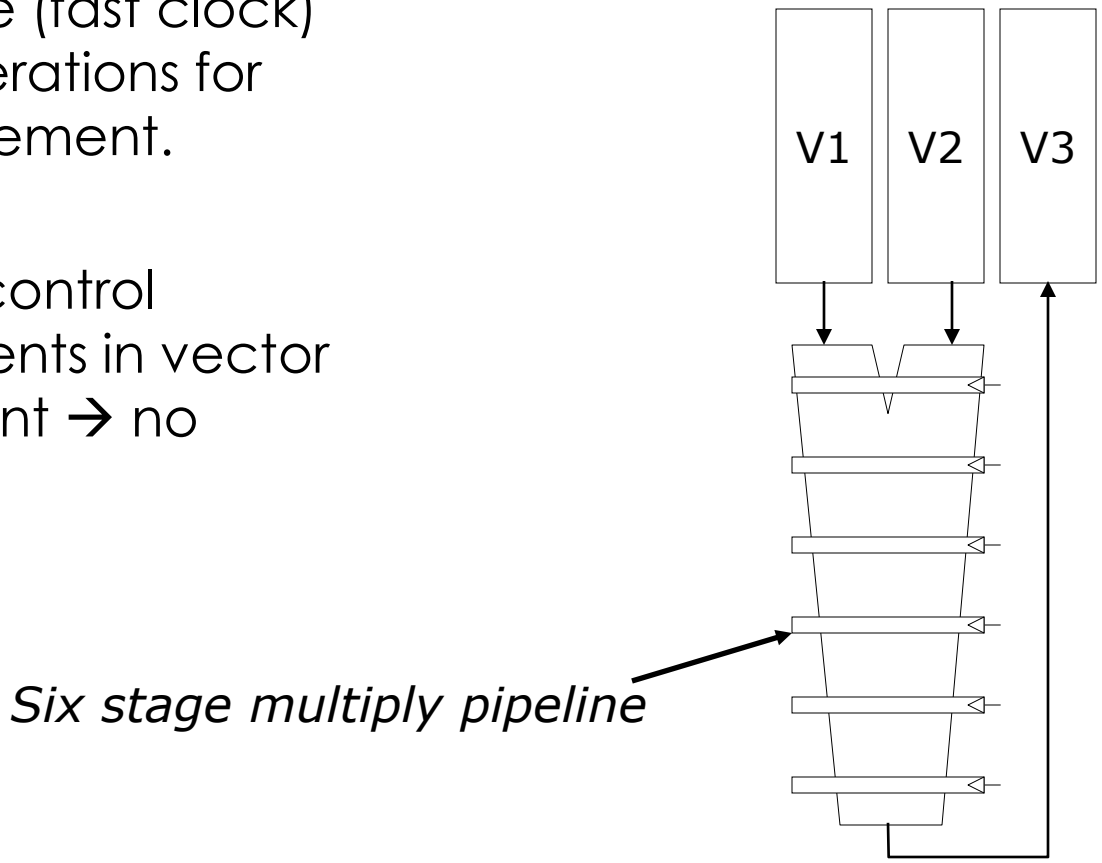
-- First loop for (N mod MVL) elements. Remaining loops for MVL elements

```
VL = (N mod MVL);                 # set VL to be a smaller vector
for (i=0 ; i<VL ; i++)            # 1st-loop translates into a single set
        Y[i] = A*X[i] + Y[i];     # of vector instructions
low = (N mod MVL)                 # low – strips off beginning elements
VL = MVL                          # set VL to be max vector length
for (i=low ; i<N ; i++);          # 2nd-loop translates into N/MVL sets
        Y[i] = A * X[i] + Y[i];   # of vector instructions
```

Vector Instruction Execution

Use deep pipeline (fast clock) to execute operations for each vector element.

Simplify pipeline control because elements in vector are independent → no hazards.



V3 ← V1 * V2

Opt 1 – Chaining

Consider the following code with vector length of 32

```
vmul.vv     V1, V2, V3
vadd.vv     V4, V1, V5          # very long RAW hazard
```

Chaining

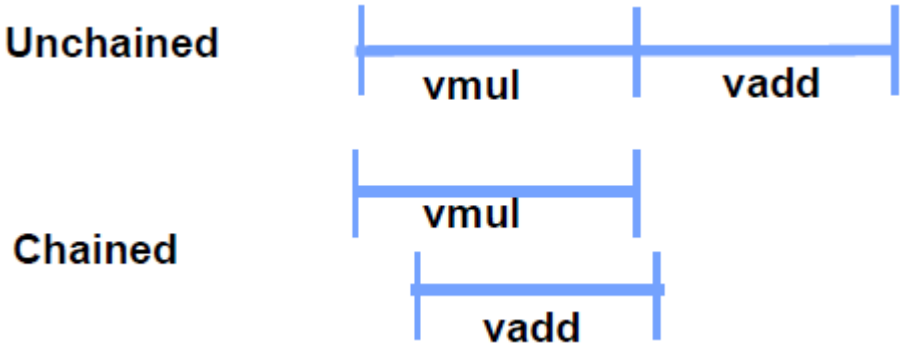
-- V1 is not a single entity, but a vector of individual elements

-- Pipeline forwarding can work for individual elements

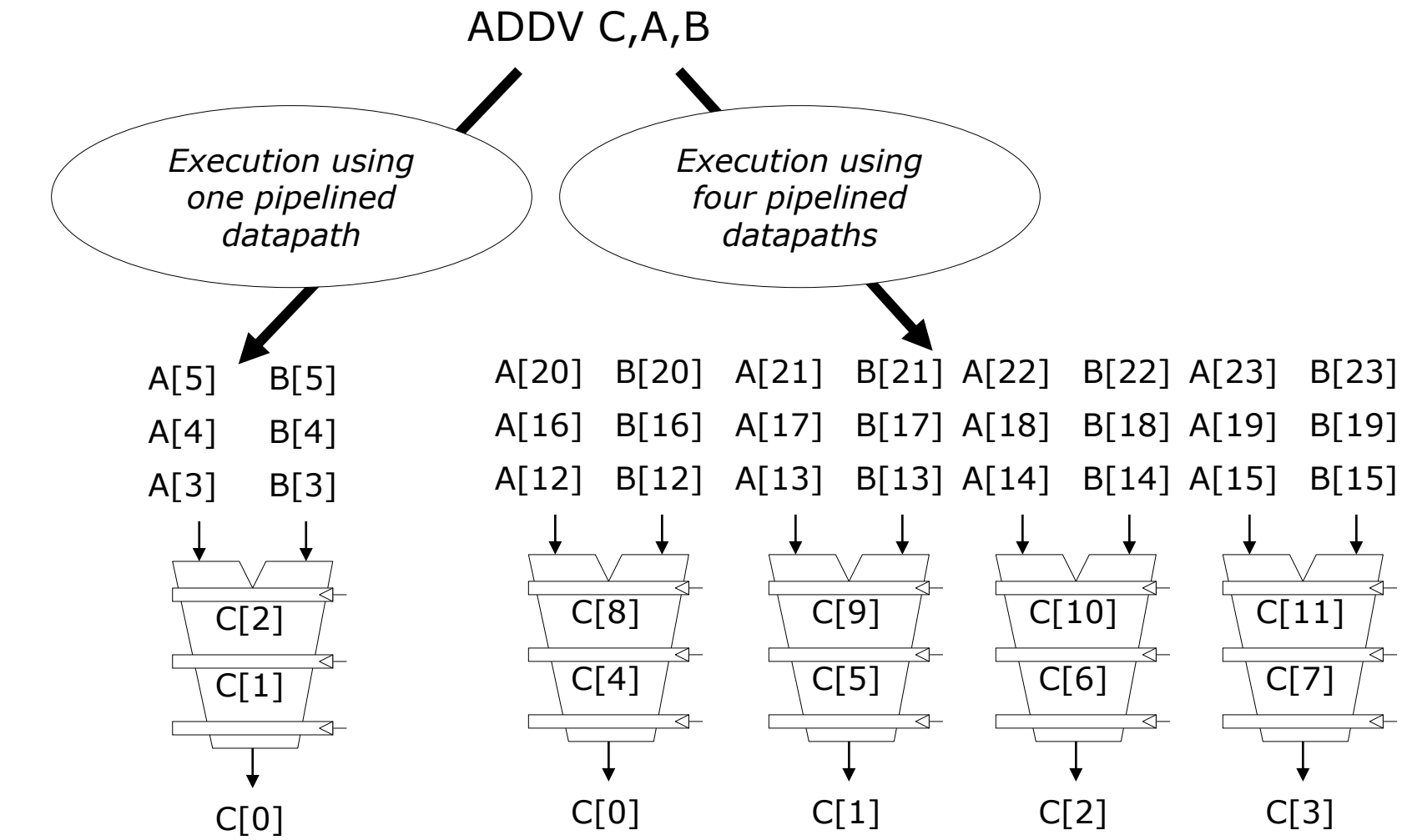
Flexible Chaining

-- Chain any vector to any other active vector operation

-- Requires more read/write ports in the vector register file



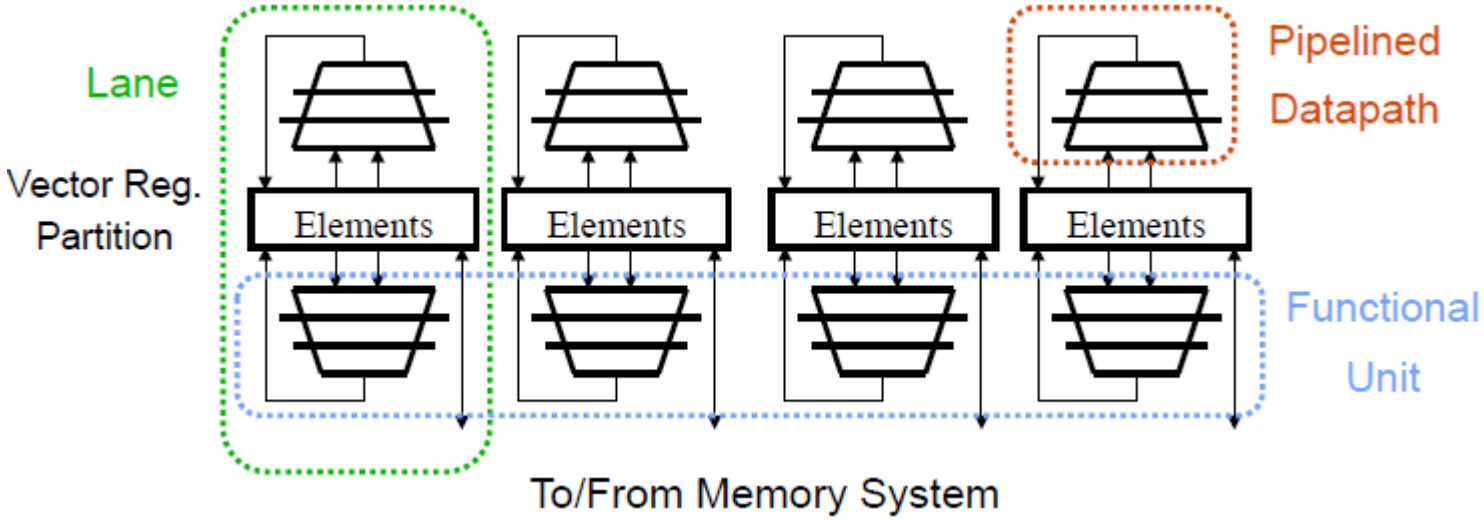
Opt 2 – Multiple Datapaths



1 adder → 1 element / cycle
N cycles

4 adders → 4 elements / cycle
N/4 cycles

Opt 2+: Multiple Lanes



-- Vector elements interleaved across lanes
-- Example: V[0, 4, 8, …] on Lane 1, V[1, 5, 9,…] on Lane 2, etc.

-- Compute for multiple elements per cycle
-- Example: Lane 1 computes on V[0] and V[4] in one cycle

-- Modular, scalable design
-- No inter-lane communication needed for most vector instructions

Opt 3 – Conditional Execution

Suppose you want to vectorize this code:

```
for (i=0 ; i<N ; i++) {
    if(A[i] != B[i]) {A[i] -= B[i]; } }
```

Solution: vector conditional execution

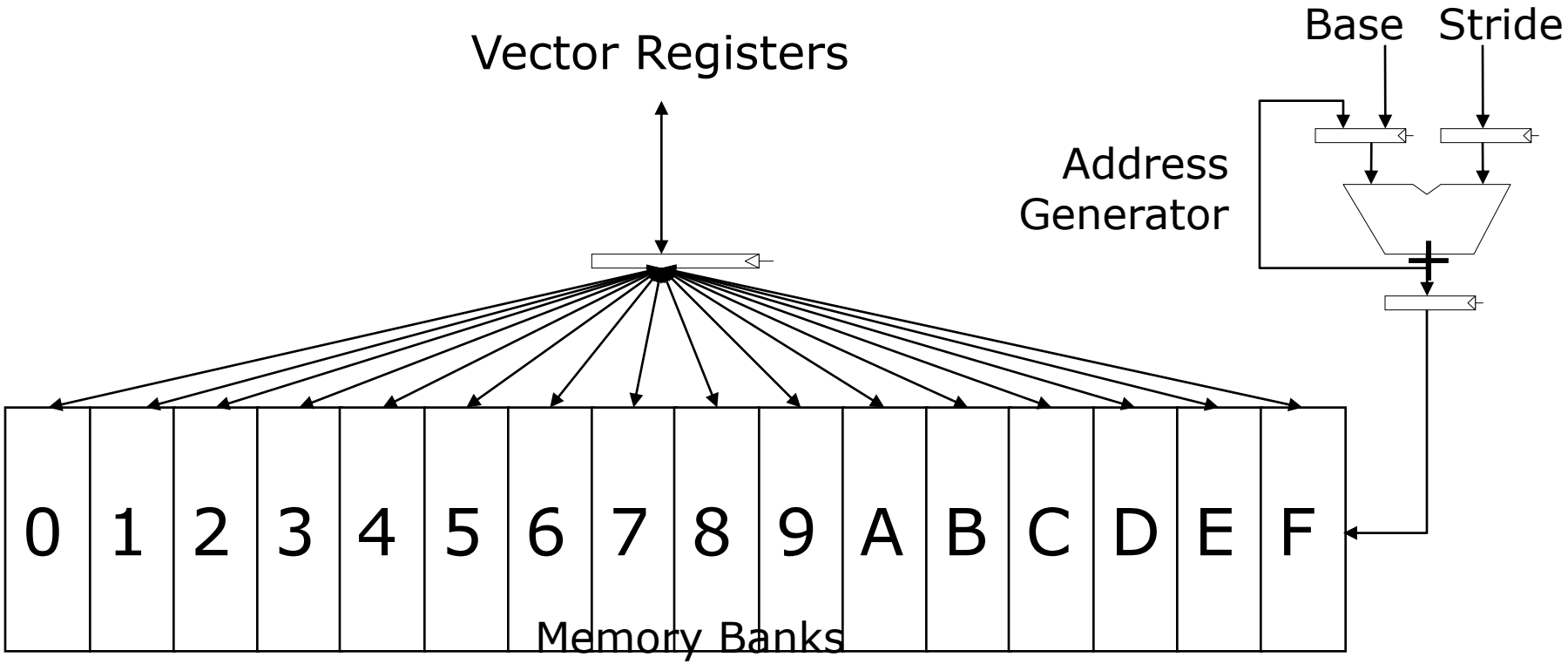
-- Add vector flag registers, single-bit mask per vector element
-- Use vector-compare to set the vector flag register
-- Use vector flag register to control vector-sub
-- Vector op executed only if corresponding flag element is set

```
vld             V1, Ra
vld             V2, Rb
vcmp.neq.vv     M0, V1, V2      # vector compare for mask
vsub.vv         V3, V2, V1, M0  # conditional vadd
vst             V3, Ra
```

Vector Memory

Multiple, interleaved memory banks (16)

Bank busy time (e.g., 4 cycles) is time before bank ready to accept next request



Supercomputing to Multimedia

Support narrow data types

-- Allow each vector registers to store 16-, 32-, or 64-bit elements

-- Use a control register to indicate width of register elements

Support saturated and fixed-point arithmetic

-- Minor modification to functional units

Support element permutations for vector reductions

-- for(i=0 ; i<N ; i++) {S += A[i]}

-- Rewrite as:

```
for(i=0 ; i<N ; i+=VL) {S[0:VL-1]+=A[i:i+VL-1];}      # S[…], A[…] are
for(i=0 ; i<VL ; i++) {S+=[S[i];}                     # vectors of VL elements
```

-- First loop trivially vectorizable

-- Second loop vectorizable by splitting vector register S into two vector registers. Take a binary-tree approach to reduction

SIMD in Superscalar Processors

SIMD extends conventional ISA

-- SIMD – single instruction, multiple data

-- MMX, SSE, SSE-2, SSE-3, 3D-Now, Altivec, VIS

Objective: Accelerate multimedia processing

-- Define vectors of 16-, 32-bit elements in regular registers

-- Apply SIMD arithmetic on these vectors

Advantages

-- No vector register file, which would require additional area

-- Simple extensions (new opcodes, modified datapath)

SIMD Challenges

SIMD Vectors are short with fixed size

-- Cannot capture data parallelism wider than 64 bits

-- Recent shift from 64-bit to 128-bit vectors (SSE, Altivec)

SIMD does not support vector memory accesses

-- Strided or indexed access require equivalent multi-instruction sequences

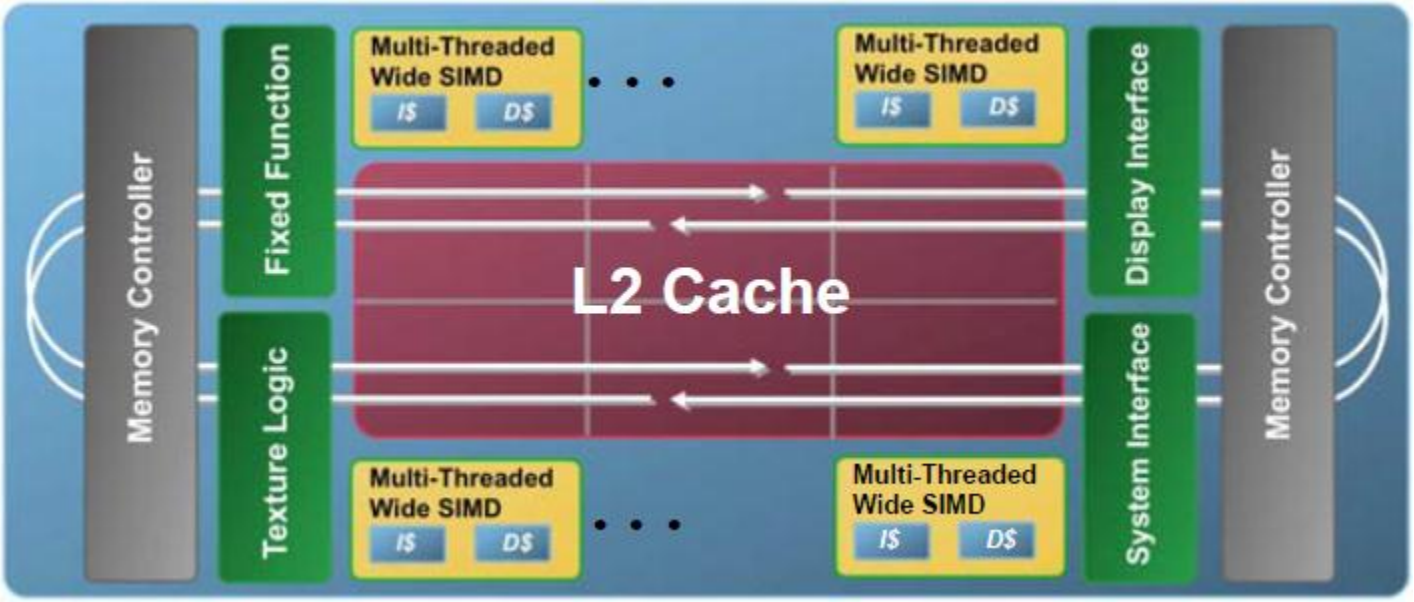
-- With vector memory accesses, much lower benefits in performance and code density

SIMD versus Vectors

	Vector	MMX
iDCT	0.75	3.75 (5.0x)
Color Conversion	0.78	8.00 (10.2x)
Image Convolution	1.23	5.49 (4.5x)
QCIF (176x144)	7.1M	33M (4.6x)
CIF (352x288)	28M	140M (5.0x)

-- QCIF and CIF numbers are in clock cycles per frame
-- All other numbers are in clock cycles per pixel
-- MMX results assume no first-level cache misses
-- Courtesy: Christos Kozyrakis, Stanford

Intel Larrabee



Vector Multiprocessor

-- 2-way superscalar, 4-way multi-threaded, in-order cores with vectors

-- Cores communicate on a wide ring bus

-- L2 cache is partitioned among the cores

-- Provides high aggregate bandwidth

-- Allows data replication and sharing

Larrabee x86 Core

-- separate scalar, vector units with separate registers

-- scalar unit: in-order x86 core

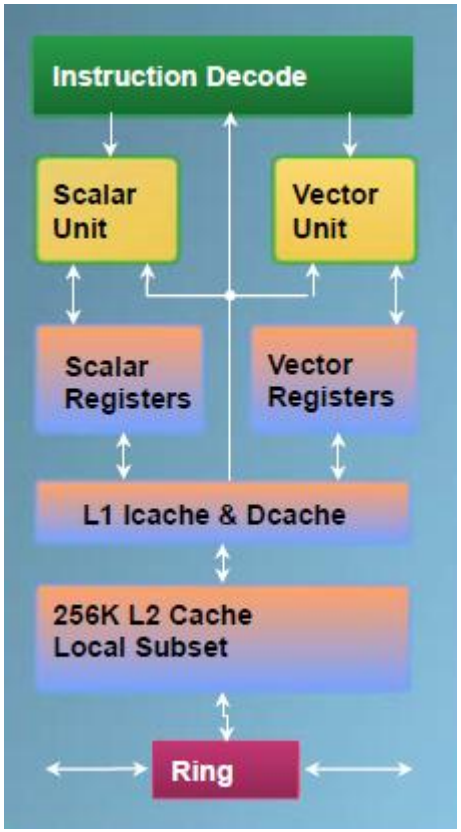
-- vector unit: 16 32-bit ops/clock

-- short execution pipelines

-- fast access to L1 cache

-- direct connection to L2 cache subset

-- instructions support prefetch into L1 and L2 caches



Larrabee Vector Unit

Vector Instruction Set

-- 32 vector registers (512 bits each)

-- vector load/store with scatter/gather

-- 8 mask registers for conditional exec.

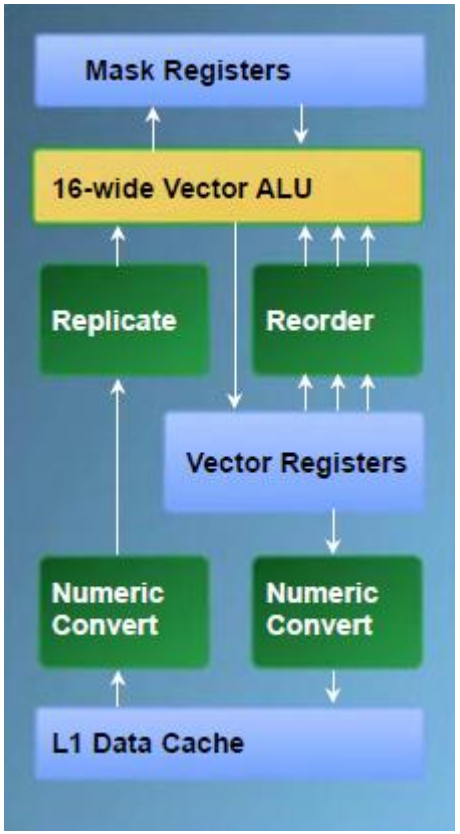
-- mask registers select lanes for an instruction

-- mask registers allow separate execution kernels in each lane

Vector Instruction Support

-- Fast read from L1 cache

-- Numeric type conversion and replication in memory path



Vector Power Efficiency

Power and Parallelism

-- Power(1-lane) = [capacitance] x [voltage]^2 x [frequency]
-- If we double number of lanes, we double peak performance
-- Then, if we halve frequency, we return to original peak performance.
-- But, halving frequency allows us to halve voltage
-- Power (2-lane) = [2 x capacitance] x [voltage/2]^2 x [frequency/2]
-- Power (2-lane) = Power(1-lane)/4 @ same peak performance

Simpler Logic

-- Replicate control logic for all lanes
-- Avoid logic for multiple instruction issue or dynamic out-of-order execution

Clock Gating

-- Turn-off clock when hardware is unused
-- Vector of given length uses specific resources for specific # of cycles
-- Conditional execution (masks) further exposes unused resources

Summary

Vector Processors

-- Express and exploit data-level parallelism (DLP)

SIMD Extensions

-- Extensions for short vectors in superscalar (ILP) processors

-- Provide some advantages of vector processing at less cost