

Static Compiler Optimization Techniques

- We examined the following static ISA/compiler techniques aimed at improving pipelined CPU performance:
 - Static pipeline scheduling.
 - Loop unrolling.
 - Static branch prediction.
 - Static multiple instruction issue: VLIW.
 - Conditional or predicted instructions/predication. e.g. IA-64 (EPIC)
 - Static speculation

- Here we examine two additional static compiler-based techniques:

- 1 – Loop-Level Parallelism (LLP) analysis: + relationship to Data Parallelism
 - Detecting and enhancing loop iteration parallelism
 - Greatest Common Divisor (GCD) test.
 - 2 – Software pipelining (Symbolic loop unrolling).
- In addition a brief introduction to vector processing (Appendix G) is included to emphasize the importance/origin of LLP analysis. } FYI

4th Edition: Appendix G.1-G.3, vector processing: Appendix F
(3rd Edition: Chapter 4.4, vector processing: Appendix G)

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Data Parallelism & Loop Level Parallelism (LLP)

- **Data Parallelism:** Similar independent/parallel computations on different elements of arrays that usually result in independent (or parallel) loop iterations when such computations are implemented as sequential programs.
- A common way to increase parallelism among instructions is to exploit data parallelism among independent iterations of a loop (e.g exploit Loop Level Parallelism, LLP).
 - One method covered earlier to accomplish this is by **unrolling the loop** either statically by the compiler, or dynamically by hardware, which increases the size of the basic block present. This resulting larger basic block provides more instructions that can be scheduled or re-ordered by the compiler/hardware to eliminate more stall cycles.
- The following loop has parallel loop iterations since computations in each iterations are data parallel and are performed on different elements of the arrays.

Usually: Data Parallelism → LLP

Example

```
for (i=1; i<=1000; i=i+1;)  
    z[i] = x[i] + y[i];
```

4 vector instructions:

LV	Load Vector X
LV	Load Vector Y
ADDV	Add Vector Z, X, Y
SV	Store Vector Z

- In supercomputing applications, data parallelism/LLP has been traditionally exploited by vector ISAs/processors, utilizing vector instructions
 - Vector instructions operate on a number of data items (vectors) producing a vector of elements not just a single result value. The above loop might require just four such instructions.

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Loop Unrolling Example

From Lecture #3 (slide # 11) ←

When scheduled for pipeline

Loop:	L.D	F0, 0(R1)
	L.D	F6,-8 (R1)
	L.D	F10, -16(R1)
	L.D	F14, -24(R1)
	ADD.D	F4, F0, F2
	ADD.D	F8, F6, F2
	ADD.D	F12, F10, F2
	ADD.D	F16, F14, F2
	S.D	F4, 0(R1)
	S.D	F8, -8(R1)
	DADDUI	R1, R1,# -32
	S.D	F12, 16(R1),F12
	BNE	R1,R2, Loop
	S.D	F16, 8(R1), F16 ;8-32 = -24

Note:
Independent Loop Iterations
Resulting from data parallel
operations on elements of array X

for (i=1000; i>0; i=i-1)
x[i] = x[i] + s;

Usually: Data Parallelism → LLP

The execution time of the loop
has dropped to 14 cycles, or $14/4 = 3.5$
clock cycles per element
compared to 7 before scheduling
and 6 when scheduled but unrolled.

$$\text{Speedup} = 6/3.5 = 1.7$$

Unrolling the loop exposed more
computations that can be scheduled
to minimize stalls by increasing the
size of the basic block from 5 instructions
in the original loop to 14 instructions
in the unrolled loop.

i.e more ILP
exposed

Loop unrolling exploits data parallelism
among independent iterations of a loop

Larger Basic Block → More ILP

Exposed

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Loop unrolled four times and scheduled

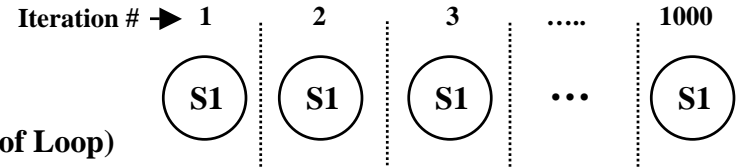
Loop-Level Parallelism (LLP) Analysis

- Loop-Level Parallelism (LLP) analysis focuses on whether data accesses in later iterations of a loop are data dependent on data values produced in earlier iterations and possibly making loop iterations independent (parallel).

e.g. in **for (i=1; i<=1000; i++)**

x[i] = x[i] + s;

S1
(Body of Loop)



Dependency Graph

the computation in each iteration is independent of the previous iterations and the loop is thus parallel. The use of **X[i]** twice is within a single iteration.

⇒ Thus loop iterations are parallel (or independent from each other).

Classification of Data Dependencies in Loops:

Between iterations or inter-iteration

1 **Loop-carried Data Dependence:** A data dependence between different loop iterations (data produced in an earlier iteration used in a later one).

2 **Not Loop-carried Data Dependence:** Data dependence within the same loop iteration.

Within an iteration or intra-iteration

- LLP analysis is important in software optimizations such as loop unrolling since it usually requires loop iterations to be independent (and in vector processing).
- LLP analysis is normally done at the source code level or close to it since assembly language and target machine code generation introduces loop-carried name dependence in the registers used in the loop.
 - Instruction level parallelism (ILP) analysis, on the other hand, is usually done when instructions are generated by the compiler.

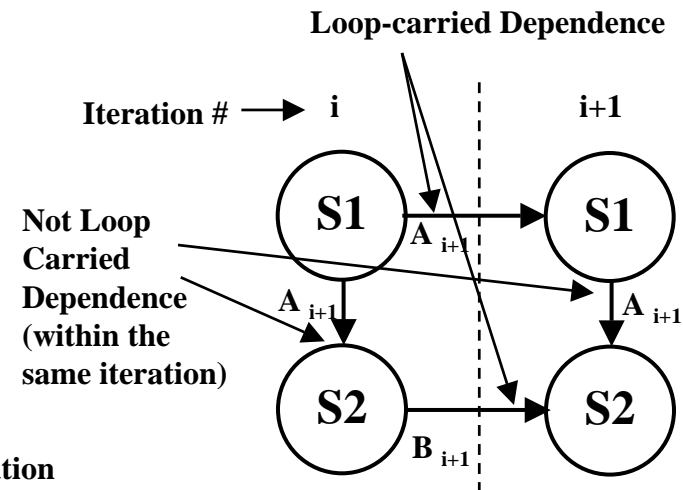
LLP Analysis Example 1

- In the loop:

```

for (i=1; i<=100; i=i+1) {
    A[i+1] = A[i] + C[i]; /* S1 */
    B[i+1] = B[i] + A[i+1]; /* S2 */
}
    
```

(Where **A**, **B**, **C** are distinct non-overlapping arrays)
 Produced in previous iteration Produced in same iteration



Dependency Graph

- **S2** uses the value **A[i+1]**, computed by **S1** in the same iteration. This data dependence is within the same iteration (not a loop-carried data dependence).

i.e. S1 → S2 on A[i+1] Not loop-carried data dependence

⇒ does not prevent loop iteration parallelism.

- **S1** uses a value computed by **S1** in the earlier iteration, since iteration **i** computes **A[i+1]** read in iteration **i+1** (loop-carried dependence, prevents parallelism). The same applies for **S2** for **B[i]** and **B[i+1]**

Loop-level

i.e. S1 → S1 on A[i] Loop-carried data dependence
 S2 → S2 on B[i] Loop-carried data dependence

⇒ These two data dependencies are loop-carried spanning more than one iteration (two iterations) preventing loop parallelism.

In this example the loop carried dependencies form two dependency chains starting from the very first iteration and ending at the last iteration

LLP Analysis Example 2

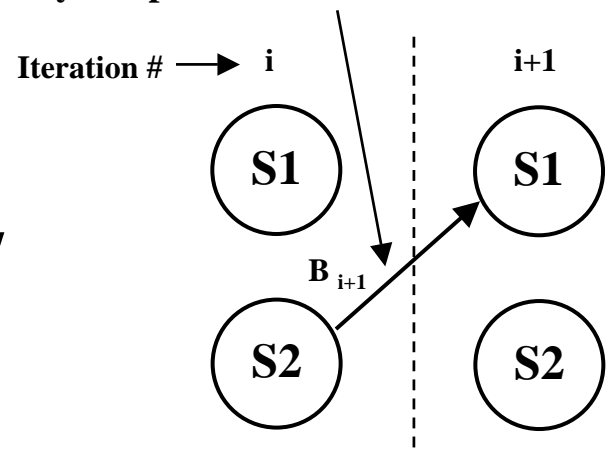
• In the loop:

```

for (i=1; i<=100; i=i+1) {
    A[i] = A[i] + B[i];      /* S1 */
    B[i+1] = C[i] + D[i];   /* S2 */
}
    
```

Dependency Graph

Loop-carried Dependence



– S1 uses the value B[i] computed by S2 in the previous iteration (loop-carried dependence) i.e. S2 → S1 on B[i] Loop-carried data dependence

– This dependence is not circular: And does not form a data dependence chain

• S1 depends on S2 but S2 does not depend on S1.

i.e. loop

– Can be made parallel by replacing the code with the following:

Very First S1

```

A[1] = A[1] + B[1];      Loop Start-up code
    
```

```

for (i=1; i<=99; i=i+1) {
    B[i+1] = C[i] + D[i];   S2
    A[i+1] = A[i+1] + B[i+1];
}
    
```

Very Last S2

```

B[101] = C[100] + D[100]; Loop Completion or Finish code
    
```

Parallel loop iterations
(data parallelism in computation
exposed in loop code)

S1 (From Next Iteration)

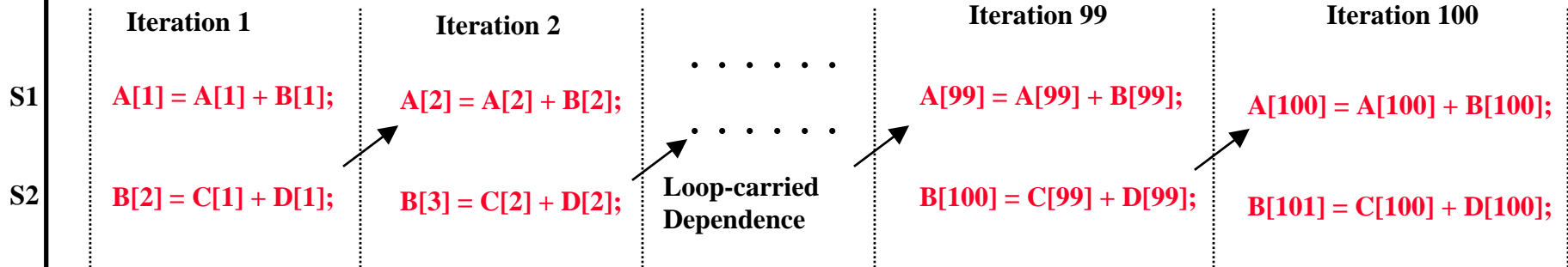
→
Illustrated
Next Slide

LLP Analysis Example 2

Original Loop:

```

for (i=1; i<=100; i=i+1) {
    A[i] = A[i] + B[i];    /* S1 */
    B[i+1] = C[i] + D[i]; /* S2 */
}
    
```

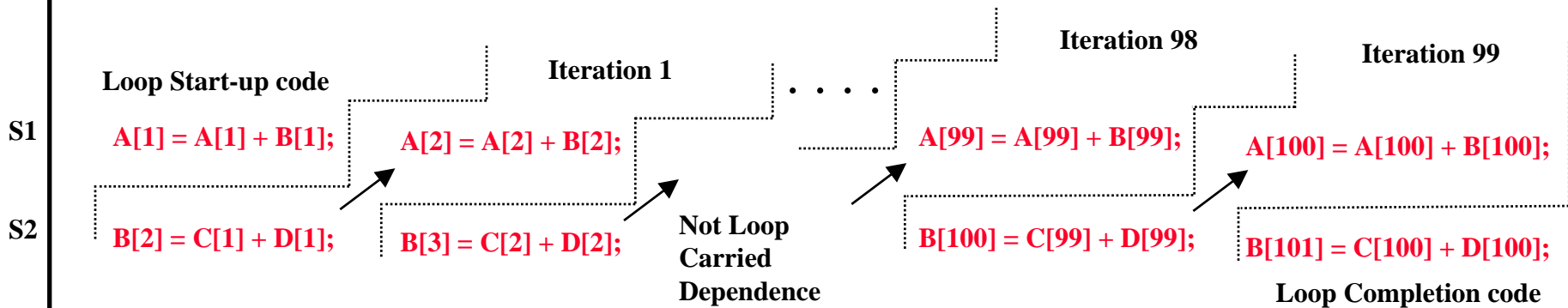


Modified Parallel Loop:

(one less iteration)

```

A[1] = A[1] + B[1];    // Loop Start-up code
for (i=1; i<=99; i=i+1) {
    B[i+1] = C[i] + D[i];
    A[i+1] = A[i+1] + B[i+1];
}
B[101] = C[100] + D[100]; // Loop Completion or Finish code
    
```



ILP Compiler Support:

For access to elements of an array

Loop-Carried Dependence Detection

- To detect loop-carried dependence in a loop, **the Greatest Common Divisor (GCD) test** can be used by the compiler, which is based on the following:

- If an array element with **index: $a \times i + b$** is stored and element: **$c \times i + d$** of the same array is loaded later where **index** runs from **m** to **n**, a dependence exists if the following two conditions hold:

1 There are two iteration indices, **j** and **k**, **$m \leq j, k \leq n$** (i.e. within iteration limits)

2 The loop stores into an array element indexed by: m, n

$a \times j + b$ Produce or write (store) element with this Index

and later loads from the same array the element indexed by:

$c \times k + d$ Later read (load) element with this index

Thus:

$$a \times j + b = c \times k + d$$

$$j < k$$

i.e later iteration

Index of element written (stored) earlier

Index of element read(loaded) later

Here a, b, c, d are constants

The Greatest Common Divisor (GCD) Test

- If a loop carried dependence exists, then :

For access to elements of an array in a loop

$$\text{GCD}(c, a) \text{ must divide } (d-b)$$

The GCD test is sufficient to guarantee no loop carried dependence

However there are cases where GCD test succeeds but no dependence exists because GCD test does not take loop bounds into account

Example:

```
for(i=1; i<=100; i=i+1) {
    x[2*i+3] = x[2*i] * 5.0;
}
```

$$a = 2 \quad b = 3 \quad c = 2 \quad d = 0$$

$$\text{GCD}(a, c) = 2$$

$$d - b = -3$$

2 does not divide -3 \Rightarrow No loop carried dependence possible.

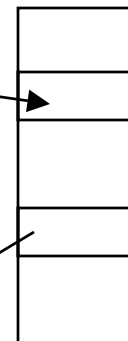
In an earlier iteration

Index of element stored:
 $a \times i + b$
Index of element loaded:
 $c \times i + d$

In a later iteration

Index of written element:
 $a \times i + b = 2i + 3$

Index of read element:
 $c \times i + d = 2i$



Showing Last Example Loop Iterations to Be Independent

```
for(i=1; i<=100; i=i+1) {
    x[2*i+3] = x[2*i] * 5.0;
}
```

Index of element stored:
 $a \times i + b$
 Index of element loaded:
 $c \times i + d$

$$c \times i + d = 2 \times i + 0$$

$$a \times i + b = 2 \times i + 3$$

$$a=2 \quad b=3 \quad c=2 \quad d=0$$

Iteration i	Index of x loaded	Index of x stored
1	2	5
2	4	7
3	6	9
4	8	11
5	10	13
6	12	15
7	14	17

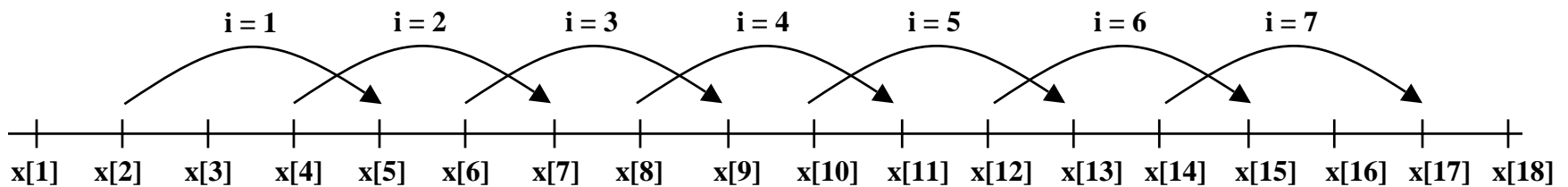
$$\text{GCD}(a, c) = 2$$

$$d - b = -3$$

2 does not divide -3

⇒ No dependence possible.

What if GCD (a, c) divided d - b ?



For example from last slide

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ILP Compiler Support: Software Pipelining (Symbolic Loop Unrolling)

- A compiler technique where loops are reorganized:
 - Each new iteration is made from instructions selected from a number of independent iterations of the original loop.

i.e parallel iterations

Why?

- The instructions are selected to **separate dependent** instructions within the original loop iteration.
- No actual loop-unrolling is performed.
 - A software equivalent to the Tomasulo approach?
- Requires:
 - Additional **start-up code** to execute code left out from the first original loop iterations.
 - Additional **finish code** to execute instructions left out from the last original loop iterations.

By one or more new iterations

This static optimization is done at machine code level

Software Pipelining (Symbolic Loop Unrolling)

Longest chain of data dependence
[Within original loop iteration]

Iteration 0 Original Loop Iterations (Parallel)
Iteration 1

Iteration 2

Iteration 3

Iteration 4

New Iteration

Software-pipelined iteration

Start new iteration
With last instruction
of dependency chain

New loop iteration body is made from instructions selected from a number of independent iterations of the original loop.
Purpose: Separate dependent instructions by one or more loop iterations.

A software-pipelined loop chooses instructions from different loop iterations, thus separating the dependent instructions within one iteration of the original loop.

4th Edition: Appendix G.3 (3rd Edition: Chapter 4.4)

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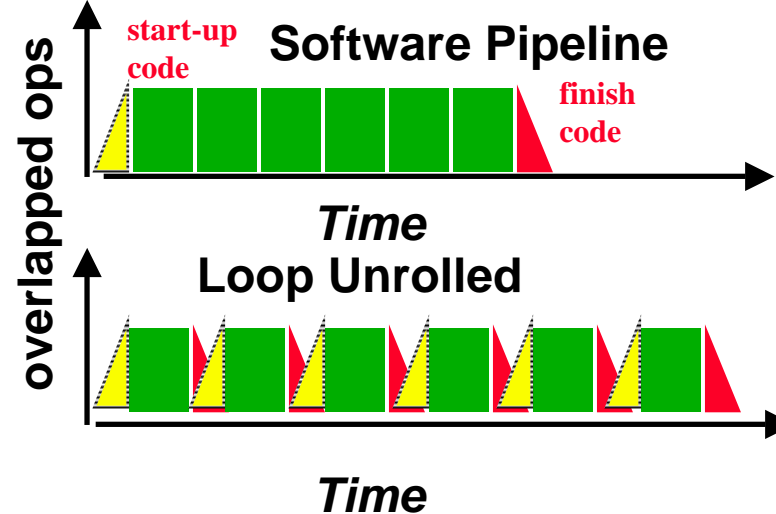
Software Pipelining (Symbolic Loop Unrolling) Example

Show a software-pipelined version of the code:

```

Loop:  L.D      F0,0(R1)
        ADD.D   F4,F0,F2
        S.D     F4,0(R1)
        DADDUI  R1,R1,#-8
        BNE    R1,R2,LOOP
    
```

3 times because chain of dependence of length 3 instructions exist in body of original loop i.e. L.D → ADD.D → S.D



Iteration

Before: Unrolled 3 times

1	L.D	F0,0(R1)
2	ADD.D	F4,F0,F2
3	S.D	F4,0(R1)
4	L.D	F0,-8(R1)
5	ADD.D	F4,F0,F2
6	S.D	F4,-8(R1)
7	L.D	F0,-16(R1)
8	ADD.D	F4,F0,F2
9	S.D	F4,-16(R1)
10	DADDUI	R1,R1,#-24
11	BNE	R1,R2,LOOP

After: Software Pipelined Version

```

LOOP:
L.D      F0,0(R1)
ADD.D   F4,F0,F2
L.D     F0,-8(R1)
S.D     F4,0(R1) ;Stores M[i]
ADD.D   F4,F0,F2 ;Adds to M[i-1]
L.D     F0,-16(R1);Loads M[i-2]
DADDUI  R1,R1,#-8
BNE    R1,R2,LOOP
S.D     F4,0(R1)
ADD.D   F4,F0,F2
S.D     F4,-8(R1)
    
```

2 fewer loop iterations

No Branch delay slot in this example

New Loop

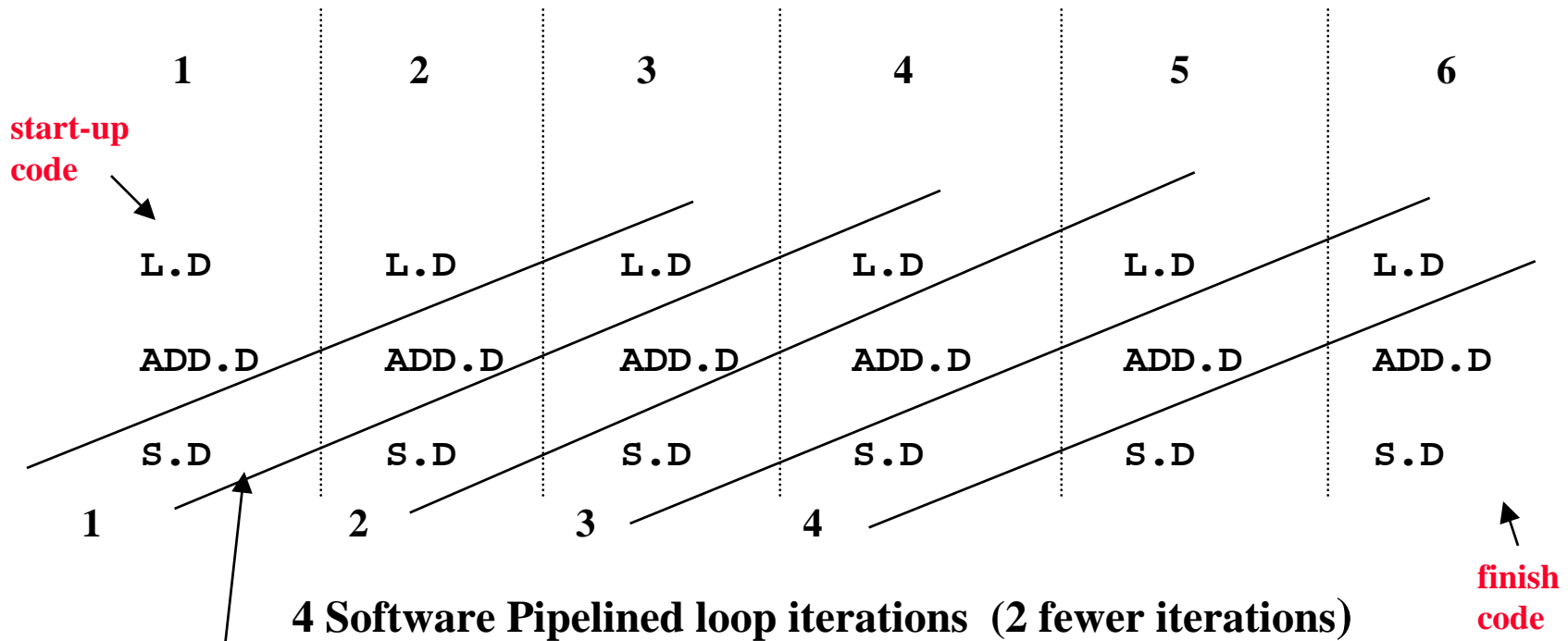
No actual loop unrolling is done (do not rename registers)

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Software Pipelining Example Illustrated

Assuming 6 original iterations
(for illustration purposes):

L.D	F0,0(R1)	Body of original loop
ADD.D	F4,F0,F2	
S.D	F4,0(R1)	



Loop Body of software Pipelined Version

Problems with Superscalar approach

- **Limits to conventional exploitation of ILP:**
 - 1) **Pipelined clock rate**: Increasing clock rate requires deeper pipelines with longer pipeline latency which increases the CPI increase (longer branch penalty, other hazards).
 - 2) **Instruction Issue Rate**: Limited instruction level parallelism (ILP) reduces actual instruction issue/completion rate. (vertical & horizontal waste)
 - 3) **Cache hit rate**: Data-intensive scientific programs have very large data sets accessed with poor locality; others have continuous data streams (multimedia) and hence poor locality. (poor memory latency hiding).
 - 4) **Data Parallelism**: Poor exploitation of data parallelism present in many scientific and multimedia applications, where similar independent computations are performed on large arrays of data (Limited ISA, hardware support).
- As a result, actual achieved performance is much less than peak potential performance and low computational energy efficiency (computations/watt)

Flynn's 1972 Classification of Computer Architecture

SISD

- **Single Instruction stream over a Single Data stream**
(SISD): Conventional sequential machines
(e.g single-threaded processors: Superscalar, VLIW ..).

SIMD

- **Single Instruction stream over Multiple Data streams (SIMD):**
Vector computers, array of synchronized processing elements.
(exploit data parallelism) AKA Data Parallel Systems e.g. GPUs?

MISD

- **Multiple Instruction streams and a Single Data stream (MISD):**
Systolic arrays for pipelined execution.

MIMD

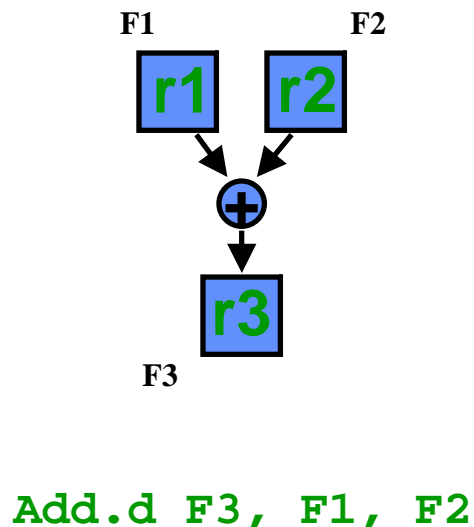
- **Multiple Instruction streams over Multiple Data streams (MIMD):**
Parallel computers: Parallel Processor Systems: Exploit Thread Level Parallelism (TLP)
 - Shared memory multiprocessors (e.g. SMP, CMP, NUMA, SMT)
 - Multicomputers: Unshared distributed memory, message-passing used instead (e.g Computer Clusters)

Vector Processing

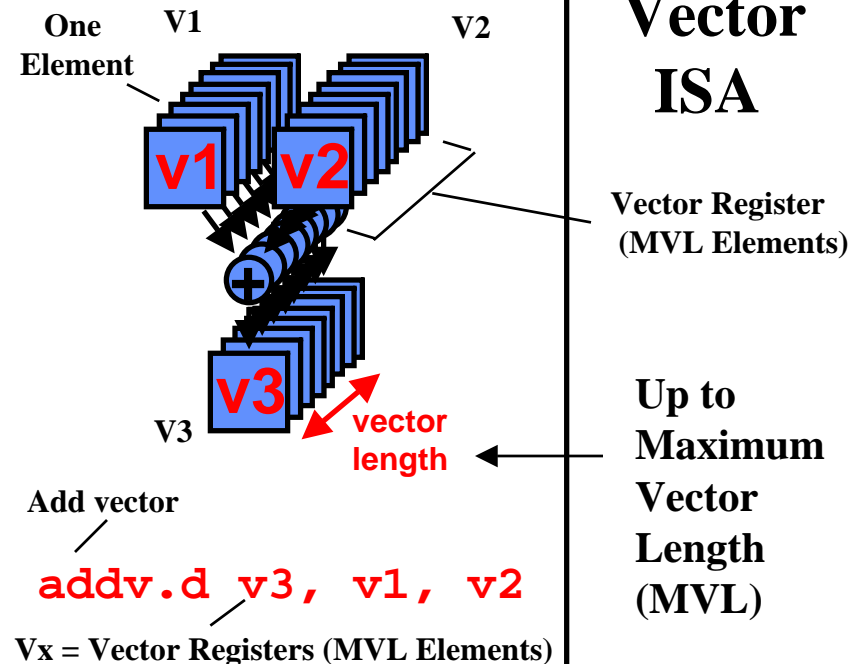
- Vector processing exploits data parallelism by performing the same computation on linear arrays of numbers "vectors" using one instruction.
- The maximum number of elements in a vector supported by a vector ISA is referred to as the Maximum Vector Length (MVL).

Scalar
ISA
(RISC
or CISC)

SCALAR
(1 operation)



MVL **VECTOR**
(N operations)



Vector
ISA

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Properties of Vector Processors/ISAs

- **Each result in a vector operation is independent of previous results (Data Parallelism, LLP exploited)**
=> Multiple pipelined Functional units (lanes) usually used, vector compiler ensures no dependencies between computations on elements of a single vector instruction
=> higher clock rate (less complexity)
- **Vector instructions access memory with known patterns**
=> Highly interleaved memory with multiple banks used to provide the high bandwidth needed and hide memory latency.
=> Amortize memory latency of over many vector elements
=> No (data) caches usually used. (Do use instruction cache)
- **A single vector instruction implies a large number (up to MVL) of computations (replacing loops or reducing number of iterations needed).** By a factor of MVL
=> Fewer instructions fetched/executed.
=> Reduces branches and branch problems (control hazards) in pipelines.

As if loop-unrolling by default MVL times?

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Changes to Scalar Processor to Run Vector Instructions

1

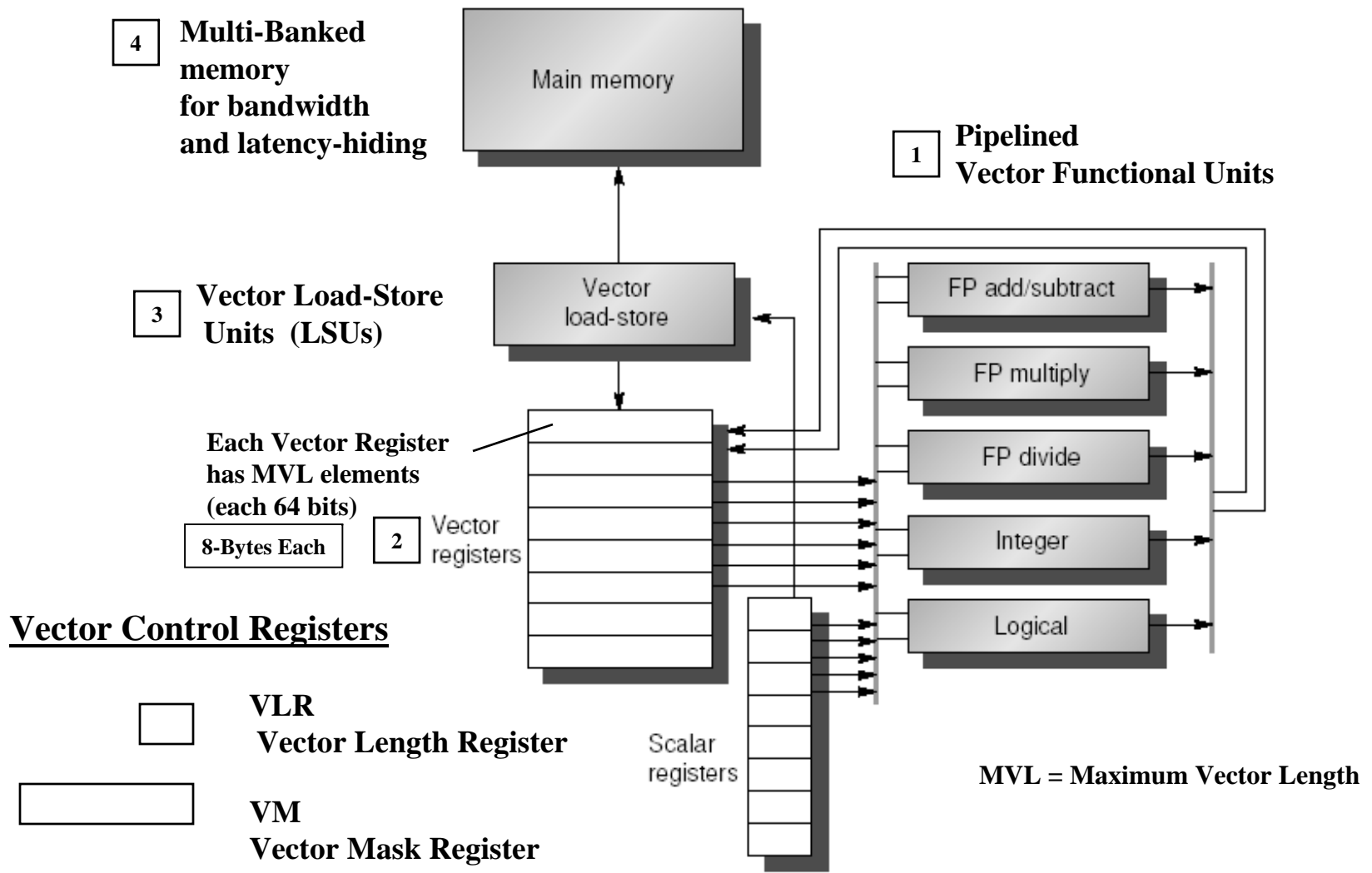
- A vector processor typically consists of an ordinary pipelined scalar unit plus a vector unit.
- The scalar unit is basically not different than advanced pipelined CPUs, commercial vector machines have included both out-of-order scalar units (NEC SX/5) and VLIW scalar units (Fujitsu VPP5000).
- Computations that don't run in vector mode don't have high ILP, so can make scalar CPU simple (e.g in-order).
- The vector unit supports a vector ISA including decoding of vector instructions which includes:
 - 1 – Vector functional units.
 - 2 – ISA vector register bank, vector control registers (vector length, mask)
 - 3 – Vector memory Load-Store Units (LSUs).
 - 4 – Multi-banked main memory (to support the high data bandwidth needed, data cache not usually used)
- Send scalar registers to vector unit (for vector-scalar ops).
- Synchronization for results back from vector register, including exceptions.

Basic Types of Vector Architecture

(ISAs)

- Types of architecture for vector ISAs/processors:
 - **Memory-memory vector ISAs/processors:**
All vector operations are memory to memory
 - **Vector-register ISAs/processors:**
All vector operations between vector registers (except load and store)
 - Vector equivalent of load-store architectures (ISAs)
 - Includes all vector machines since the late 1980
Cray, Convex, Fujitsu, Hitachi, NEC

Basic Structure of Vector Register Architecture (Vector MIPS)



Typical MVL = 64 (Cray)
MVL range 64-4096 (4K)

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#21 Fall 2017 lec#7 10-17-2017

Example Vector-Register Architectures

First Vector
Supercomputer
Cray 1 (1976)
133 MFLOPS/s
(Peak)

Processor (year)	Clock rate (MHz)	Vector registers	Elements per register (64-bit elements)	Vector arithmetic units	Vector load-store units	Lanes
Cray-1 (1976)	80	8	64	6: FP add, FP multiply, FP reciprocal, integer add, logical, shift	1	1
Cray X-MP (1983)	118	8	64	8: FP add, FP multiply, FP reciprocal, integer add, 2 logical, shift, population count/parity	2 loads 1 store	1
Cray Y-MP (1988)	166	8	64	5: FP add, FP multiply, FP reciprocal/sqrt, integer add/shift/population count, logical	1	1
Cray-2 (1985)	244	8	64	5: FP add, FP multiply, FP reciprocal/sqrt, integer add/shift/population count, logical	1	1
Fujitsu VP100/VP200 (1982)	133	8-256	32-1024	3: FP or integer add/logical, multiply, divide	2	1 (VP100) 2 (VP200)
Hitachi S810/S820 (1983)	71	32	256	4: FP multiply-add, FP multiply/divide-add unit, 2 integer add/logical	3 loads 1 store	1 (S810) 2 (S820)
Convex C-1 (1985)	10	8	128	2: FP or integer multiply/divide, add/logical	1	1 (64 bit) 2 (32 bit)
NEC SX/2 (1985)	167	8 + 32	256	4: FP multiply/divide, FP add, integer add/logical, shift	1	4
Cray C90 (1991)	240	8	128	8: FP add, FP multiply, FP reciprocal, integer add, 2 logical, shift, population count/parity	2 loads 1 store	2
Cray T90 (1995)	460	8	128	8: FP add, FP multiply, FP reciprocal, integer add, 2 logical, shift, population count/parity	2 loads 1 store	2
NEC SX/5 (1998)	312	8 + 64	512	4: FP or integer add/shift, multiply, divide, logical	1	16
Fujitsu VPP5000 (1999)	300	8-256	128-4096	3: FP or integer multiply, add/logical, divide	1 load 1 store	16
Cray SV1 (1998)	300	8	64	8: FP add, FP multiply, FP reciprocal, integer add, 2 logical, shift, population count/parity	1 load-store 1 load	2 8 (MSP)
SV1ex (2001)	500	8	64	8: FP add, FP multiply, FP reciprocal, integer add, 2 logical, shift, population count/parity	1 load-store 1 load	2 8 (MSP)
→ VMIPS (2001)	500	8	64	5: FP multiply, FP divide, FP add, integer add/shift, logical	1 load-store	1

VMIPS = Vector MIPS

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8 Vector Registers
V0-V7
MVL = 64
(Similar to Cray)

The VMIPS Vector FP Instructions

VMIPS = Vector MIPS

Vector FP

Instruction	Operands	Function
ADDV.D	V1, V2, V3	Add elements of V2 and V3, then put each result in V1.
ADDVS.D	V1, V2, F0	Add F0 to each element of V2, then put each result in V1.
SUBV.D	V1, V2, V3	Subtract elements of V3 from V2, then put each result in V1.
SUBVS.D	V1, V2, F0	Subtract F0 from elements of V2, then put each result in V1.
SUBSV.D	V1, F0, V2	Subtract elements of V2 from F0, then put each result in V1.
MULV.D	V1, V2, V3	Multiply elements of V2 and V3, then put each result in V1.
MULVS.D	V1, V2, F0	Multiply each element of V2 by F0, then put each result in V1.
DIVV.D	V1, V2, V3	Divide elements of V2 by V3, then put each result in V1.
DIVVS.D	V1, V2, F0	Divide elements of V2 by F0, then put each result in V1.
DIVSV.D	V1, F0, V2	Divide F0 by elements of V2, then put each result in V1.

Vector Memory

LV	V1, R1	Load vector register V1 from memory starting at address R1.	1- Unit Stride Access
SV	R1, V1	Store vector register V1 into memory starting at address R1.	
LVWS	V1, (R1, R2)	Load V1 from address at R1 with stride in R2, i.e., $R1+i \times R2$.	2- Constant Stride Access
SVWS	(R1, R2), V1	Store V1 from address at R1 with stride in R2, i.e., $R1+i \times R2$.	
LVI	V1, (R1+V2)	Load V1 with vector whose elements are at $R1+V2(i)$, i.e., V2 is an index.	3- Variable Stride Access (indexed)
SVI	(R1+V2), V1	Store V1 to vector whose elements are at $R1+V2(i)$, i.e., V2 is an index.	

Vector Index

CVI	V1, R1	Create an index vector by storing the values $0, 1 \times R1, 2 \times R1, \dots, 63 \times R1$ into V1.
-----	--------	--

Vector Mask

S--V.D	V1, V2	Compare the elements (EQ, NE, GT, LT, GE, LE) in V1 and V2. If condition is true, put a 1 in the corresponding bit vector; otherwise put 0. Put resulting bit vector in vector-mask register (VM). The instruction S--VS.D performs the same compare but using a scalar value as one operand.
S--VS.D	V1, F0	

Vector Length

POP	R1, VM	Count the 1s in the vector-mask register and store count in R1.
CVM		Set the vector-mask register to all 1s.
MTC1	VLR, R1	Move contents of R1 to the vector-length register.
MFC1	R1, VLR	Move the contents of the vector-length register to R1.
MVTM	VM, F0	Move contents of F0 to the vector-mask register.
MVFM	F0, VM	Move contents of vector-mask register to F0.

Appendix F (4th)
Appendix G (3rd)

Vector Control Registers: VM = Vector Mask
VLR = Vector Length Register

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Scalar Vs. Vector
Code Example

DAXPY ($Y = \underline{a} * \underline{X} + Y$)

Does it have good data
Parallelism?
Indication?

Assuming vectors X, Y
are length 64 =MVL

Scalar vs. **Vector** →

VLR = 64
VM = (1,1,1,1 ..1)

```

L.D      F0,a      ;load scalar a
LV       V1,Rx     ;load vector X
MULVS.D  V2,V1,F0  ;vector-scalar mult.
LV       V3,Ry     ;load vector Y
ADDV.D   V4,V2,V3  ;add
SV       Ry,V4     ;store the result
    
```

```

L.D      F0,a
DADDIU   R4,Rx,#512 ;last address to load
loop: L.D  F2, 0(Rx) ;load X(i)
      MUL.D F2,F0,F2 ;a*X(i)
      L.D  F4, 0(Ry) ;load Y(i)
      ADD.D F4,F2,F4 ;a*X(i) + Y(i)
      S.D  F4,0(Ry) ;store into Y(i)
      DADDIU Rx,Rx,#8 ;increment index to X
      DADDIU Ry,Ry,#8 ;increment index to Y
      DSUBU R20,R4,Rx ;compute bound
      BNEZ R20,loop ;check if done
    
```

As if the scalar loop code was unrolled MVL = 64 times:
Every vector instruction replaces 64 scalar instructions.

Scalar Vs. Vector Code

**578 (2+9*64) vs.
321 (1+5*64) ops (1.8X)**

**578 (2+9*64) vs.
6 instructions (96X)**

**64 operation vectors +
no loop overhead
also 64X fewer pipeline
hazards**

Unroll? What does loop unrolling accomplish?

Vector Control Registers:
VM = Vector Mask
VLR = Vector Length Register

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Vector/SIMD/Multimedia Scalar ISA Extensions

- **Vector or Multimedia ISA Extensions: Limited vector instructions added to scalar RISC/CISC ISAs with MVL = 2-8**

Why? Improved exploitation of data parallelism in scalar ISAs/processors

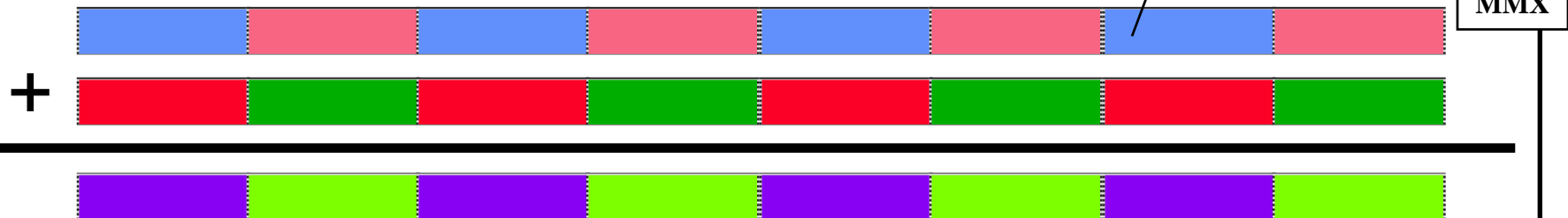
- **Example: Intel MMX: 57 new x86 instructions (1st since 386)**

- similar to Intel 860, Mot. 88110, HP PA-71000LC, UltraSPARC ...
- 3 integer vector element types: 8 8-bit (MVL =8), 4 16-bit (MVL =4) , 2 32-bit (MVL =2) in packed in 64 bit registers

- reuse 8 FP registers (FP and MMX cannot mix)

- short vector: load, add, store 8, 8-bit operands

MVL = 8
for byte elements



- **Claim: overall speedup 1.5 to 2X for multimedia applications (2D/3D graphics, audio, video, speech ...)**

- **Intel SSE (Streaming SIMD Extensions) adds support for FP with MVL =2 to MMX**
- **Intel SSE2 Adds support of FP with MVL = 4 (4 single FP in 128 bit registers), 2 double FP MVL = 2, to SSE**

Major Issue: Efficiently meeting the increased data memory bandwidth requirements of such instructions

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