18-447: Computer Architecture
Lecture 16: Approaches to Concurrency
(SIMD and VLIW)

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Carnegie Mellon University
Spring 2012, 3/21/2012
Reminder: Homeworks

- Homework 5
  - Due April 2
  - Topics: Out-of-order execution, dataflow, vector processing, memory, caches
Reminder: Lab Assignments

- Lab Assignment 4
  - Due this Friday (March 23)
  - Implementing control flow and branch prediction in your pipelined simulator
  - You can get extra credit by optimizing your design to be the fastest
    - Just make sure you have one of the Top 3 lowest execution times

- Lab Assignment 5
  - Will be out today/tomorrow
  - Implementing caches and branch prediction in a high-level timing simulator of a pipelined processor
  - Due April 6
Don’t Forget

- Please turn in your feedback sheet
  - Until the end of this weekend (March 25)

- Attend discussion sessions this week and the next
  - TAs will go over exam solutions
  - TAs will describe the timing simulator for Lab 5

- Pick up your exams and HW3 at the end of class today
# Prizes for Lab 3 Competition

- 8 students had fully-correct designs
- 4 students shared the “fastest” design
  - Earned 10% extra credit
  - Top 3 will soon earn a book each

<table>
<thead>
<tr>
<th>Student</th>
<th>Cycles</th>
<th>Cycle Time (ns)</th>
<th>Execution Time (ns)</th>
<th>Ranking</th>
<th>Relative Exec. Time</th>
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</table>
Prizes for Lab 3 Competition

- Rui Cai
- Jason Lin
- Tyler Huberty
Readings for Next Time

- Cache chapters from P&H: 5.1-5.3
- Memory/cache chapters from Hamacher+: 8.1-8.7
- First cache paper by Maurice Wilkes, 1965
Review of Last Lecture

- Wrap up out-of-order execution
  - Memory disambiguation
  - Design choices and combining concepts

- Data flow
  - Dataflow graphs
  - Irregular parallelism

- Vector processing
Today

- Vector processing
- VLIW
Vector Processing:
Exploiting Regular (Data) Parallelism
Flynn’s Taxonomy of Computers


- **SISD**: Single instruction operates on single data element
- **SIMD**: Single instruction operates on multiple data elements
  - Array processor
  - Vector processor
- **MISD**: Multiple instructions operate on single data element
  - Closest form: systolic array processor, streaming processor
- **MIMD**: Multiple instructions operate on multiple data elements (multiple instruction streams)
  - Multiprocessor
  - Multithreaded processor
Review: Data Parallelism

- Concurrency arises from performing the **same operations on different pieces of data**
  - Single instruction multiple data (SIMD)
  - E.g., dot product of two vectors

- Contrast with thread ("control") parallelism
  - Concurrency arises from executing different threads of control in parallel

- Contrast with data flow
  - Concurrency arises from executing different operations in parallel (in a data driven manner)

- SIMD exploits instruction-level parallelism
  - Multiple instructions concurrent: instructions happen to be the same
Review: SIMD Processing

- Single instruction operates on multiple data elements
  - In time or in space
- Multiple processing elements

- Time-space duality
  - **Array processor**: Instruction operates on multiple data elements at the same time
  - **Vector processor**: Instruction operates on multiple data elements in consecutive time steps
Array vs. Vector Processors

**Instruction Stream**
- LD  VR ← A[3:0]
- ADD VR ← VR, 1
- MUL VR ← VR, 2
- ST  A[3:0] ← VR

**Time**
- ARRAY PROCESSOR:
  - Same op @ same time
  - Different ops @ same space
- VECTOR PROCESSOR:
  - Different ops @ time
  - Same op @ space
Review: SIMD Array Processing vs. VLIW

- VLIW
Review: SIMD Array Processing vs. VLIW

- Array processor

Diagram:
- Program Counter
- add VR, VR, 1
- VLEN = 4
- Instruction Execution:
  - add VR[0],VR[0],1
  - add VR[1],VR[1],1
  - add VR[2],VR[2],1
  - add VR[3],VR[3],1

PE PE PE PE
Vector Processors

- A vector is a one-dimensional array of numbers
- Many scientific/commercial programs use vectors
  
  ```c
  for (i = 0; i<=49; i++)
    C[i] = (A[i] + B[i]) / 2
  ```

- A vector processor is one whose instructions operate on vectors rather than scalar (single data) values

- Basic requirements
  - Need to load/store vectors → vector registers (contain vectors)
  - Need to operate on vectors of different lengths → vector length register (VLEN)
  - Elements of a vector might be stored apart from each other in memory → vector stride register (VSTR)
    - Stride: distance between two elements of a vector
Vector Processors (II)

- A vector instruction performs an operation on each element in consecutive cycles
  - Vector functional units are pipelined
  - Each pipeline stage operates on a different data element

- Vector instructions allow deeper pipelines
  - No intra-vector dependencies → no hardware interlocking within a vector
  - No control flow within a vector
  - Known stride allows prefetching of vectors into cache/memory
Vector Processor Advantages

+ No dependencies within a vector
  - Pipelining, parallelization work well
  - Can have very deep pipelines, no dependencies!

+ Each instruction generates a lot of work
  - Reduces instruction fetch bandwidth

+ Highly regular memory access pattern
  - Interleaving multiple banks for higher memory bandwidth
  - Prefetching

+ No need to explicitly code loops
  - Fewer branches in the instruction sequence
Vector Processor Disadvantages

-- Works (only) if parallelism is regular (data/SIMD parallelism)
  ++ Vector operations
-- Very inefficient if parallelism is irregular
  -- How about searching for a key in a linked list?

To program a vector machine, the compiler or hand coder must make the data structures in the code fit nearly exactly the regular structure built into the hardware. That’s hard to do in first place, and just as hard to change. One tweak, and the low-level code has to be rewritten by a very smart and dedicated programmer who knows the hardware and often the subtleties of the application area. Often the rewriting is

Vector Processor Limitations

-- Memory (bandwidth) can easily become a bottleneck, especially if
  1. compute/memory operation balance is not maintained
  2. data is not mapped appropriately to memory banks
Vector Registers

- Each vector data register holds $N$ $M$-bit values
- Vector control registers: VLEN, VSTR, VMASK
- Vector Mask Register (VMASK)
  - Indicates which elements of vector to operate on
  - Set by vector test instructions
    - e.g., $VMASK[i] = (V_k[i] == 0)$
- Maximum VLEN can be $N$
  - Maximum number of elements stored in a vector register
Vector Functional Units

- Use deep pipeline (=> fast clock) to execute element operations
- Simplifies control of deep pipeline because elements in vector are independent

Slide credit: Krste Asanovic
Vector Machine Organization (CRAY-1)

- CRAY-1

- Scalar and vector modes
- 8 64-element vector registers
- 64 bits per element
- 16 memory banks
- 8 64-bit scalar registers
- 8 24-bit address registers
Memory Banking

- Example: 16 banks; can start one bank access per cycle
- Bank latency: 11 cycles
- Can sustain 16 parallel accesses if they go to different banks

Slide credit: Derek Chiou
Vector Memory System

Vector Registers

Address Generator

Memory Banks

Slide credit: Krste Asanovic
Scalar Code Example

- For I = 0 to 49
  - C[i] = (A[i] + B[i]) / 2

- Scalar code
  
  MOV R0 = 50
  MOVA R1 = A
  MOVA R2 = B
  MOVA R3 = C

  LD R4 = MEM[R1++]
  LD R5 = MEM[R2++]
  ADD R6 = R4 + R5
  SHFR R7 = R6 >> 1
  ST MEM[R3++] = R7

  DECBNZ --R0, X

304 dynamic instructions

;autoincrement addressing

;decrement and branch if NZ
Scalar Code Execution Time

- Scalar execution time on an in-order processor with 1 bank
  - First two loads in the loop cannot be pipelined $2 \times 11$ cycles
  - $4 + 50 \times 40 = 2004$ cycles

- Scalar execution time on an in-order processor with 16 banks (word-interleaved)
  - First two loads in the loop can be pipelined
  - $4 + 50 \times 30 = 1504$ cycles

- Why 16 banks?
  - 11 cycle memory access latency
  - Having 16 (>11) banks ensures there are enough banks to overlap enough memory operations to cover memory latency
Vectorizable Loops

- A loop is *vectorizable* if each iteration is independent of any other
- For I = 0 to 49
  - C[i] = (A[i] + B[i]) / 2
- Vectorized loop:
  
  MOVI VLEN = 50
  MOVI VSTR = 1
  VLD V0 = A
  VLD V1 = B
  VADD V2 = V0 + V1
  VSHFR V3 = V2 >> 1
  VST C = V3

  7 dynamic instructions
Vector Code Performance

- No chaining
  - i.e., output of a vector functional unit cannot be used as the input of another (i.e., no vector data forwarding)
- One memory port (one address generator)
- 16 memory banks (word-interleaved)

```
1 1 11 49 11 49 4 49 1 49 11 49
```

V0 = A[0..49]  V1 = B[0..49]  ADD  SHIFT  STORE

- 285 cycles
Vector Chaining

- **Vector chaining**: Data forwarding from one vector functional unit to another

\[
\begin{align*}
&\text{LV } v1 \\
&MULV v3, v1, v2 \\
&ADDV v5, v3, v4
\end{align*}
\]
Vector Code Performance - Chaining

- **Vector chaining**: Data forwarding from one vector functional unit to another

1 1 11 49 11 49

- Each memory bank has a single port (memory bandwidth bottleneck)

These two VLDs cannot be pipelined. WHY?

- 182 cycles

VLD and VST cannot be pipelined. WHY?
Vector Code Performance – Multiple Memory Ports

- Chaining and 2 load ports, 1 store port in each bank

- 79 cycles
Questions (I)

- What if # data elements > # elements in a vector register?
  - Need to break loops so that each iteration operates on # elements in a vector register
    - E.g., 527 data elements, 64-element VREGs
    - 8 iterations where VLEN = 64
    - 1 iteration where VLEN = 15 (need to change value of VLEN)
  - Called vector stripmining

- What if vector data is not stored in a strided fashion in memory? (irregular memory access to a vector)
  - Use indirection to combine elements into vector registers
  - Called scatter/gather operations
Gather/Scatter Operations

Want to vectorize loops with indirect accesses:

```c
for (i=0; i<N; i++)
    A[i] = B[i] + C[D[i]]
```

Indexed load instruction (Gather)

```assembly
LV vD, rD       # Load indices in D vector
LVI vC, rC, vD  # Load indirect from rC base
LV vB, rB       # Load B vector
ADDV.D vA,vB,vC # Do add
SV vA, rA       # Store result
```
Gather/Scatter Operations

- Gather/scatter operations often implemented in hardware to handle sparse matrices
- Vector loads and stores use an index vector which is added to the base register to generate the addresses

<table>
<thead>
<tr>
<th>Index Vector</th>
<th>Data Vector</th>
<th>Equivalent</th>
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<tbody>
<tr>
<td>1</td>
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<td>3.14</td>
</tr>
<tr>
<td>3</td>
<td>6.5</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>71.2</td>
<td>6.5</td>
</tr>
<tr>
<td>8</td>
<td>2.71</td>
<td>0.0</td>
</tr>
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</table>
Conditional Operations in a Loop

What if some operations should not be executed on a vector (based on a dynamically-determined condition)?

```plaintext
loop: if (a[i] != 0) then b[i]=a[i]*b[i]
goto loop
```

Idea: Masked operations

- VMASK register is a bit mask determining which data element should not be acted upon
  - VLD V0 = A
  - VLD V1 = B
  - VMASK = (V0 != 0)
  - VMUL V1 = V0 * V1
  - VST B = V1

- Does this look familiar? This is essentially **predicated execution**.
Another Example with Masking

for (i = 0; i < 64; ++i)
    if (a[i] >= b[i]) then c[i] = a[i]
    else c[i] = b[i]

Steps to execute loop

1. Compare A, B to get VMASK
2. Selective store of A, VMASK into C
3. Complement VMASK
4. Selective store of B, VMASK into C

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>VMASK</th>
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<tbody>
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<td>2</td>
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<td>0</td>
<td>-3</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>-7</td>
<td>-8</td>
<td>1</td>
</tr>
</tbody>
</table>
Masked Vector Instructions

Simple Implementation
- execute all N operations, turn off result writeback according to mask

\[
\begin{align*}
M[1] &= 1 & C[1] & \text{Write data port} \\
M[0] &= 0 & C[0] & \text{Write data port}
\end{align*}
\]

Density-Time Implementation
- scan mask vector and only execute elements with non-zero masks

\[
\begin{align*}
M[0] &= 0 & C[0] & \text{Write data port}
\end{align*}
\]
Some Issues

- Stride and banking
  - As long as they are relatively prime to each other and there are enough banks to cover bank access latency, consecutive accesses proceed in parallel.

- Storage of a matrix
  - Row major: Consecutive elements in a row are laid out consecutively in memory.
  - Column major: Consecutive elements in a column are laid out consecutively in memory.
  - You need to change the stride when accessing a row versus column.
Matrix multiplication

A & B, both in row-major order

A:

Load A0 into a vector register V1

→ Each time you need to increment the address by 1 to access the next column
→ First matrix accesses have a stride of 1

B:

Load B0 into a vector register V2.

→ Each time you need to increment by 10
→ Stride of 10

Different strides can lead to bank conflicts.

→ How do you minimize them?
Array vs. Vector Processors, Revisited

- Array vs. vector processor distinction is a “purist’s” distinction

- Most “modern” SIMD processors are a combination of both
  - They exploit data parallelism in both time and space
Remember: Array vs. Vector Processors

**ARRAY PROCESSOR**

Instruction Stream:
- LD  VR ← A[3:0]
- ADD  VR ← VR, 1
- MUL  VR ← VR, 2
- ST  A[3:0] ← VR

Same op @ same time:
- LD0
- LD1
- LD2
- LD3
- AD0
- AD1
- AD2
- AD3
- MU0
- MU1
- MU2
- MU3
- ST0
- ST1
- ST2
- ST3

Different ops @ same space:
- LD0 → AD0 → MU0 → ST0
- LD1 → AD1 → MU1
- LD2 → AD2 → MU2 → ST1
- LD3 → AD3 → MU3 → ST2
- ST3

**VECTOR PROCESSOR**

Same op @ space:
- LD0
- ADD
- MUL
- ST

Different ops @ time:
- LD0
- AD0
- AD1
- MU0
- AD2
- MU1
- ST0
- AD3
- MU2
- ST1
- MU3
- ST2
- ST3

Time

Space
Vector Instruction Execution

ADDV C,A,B

Execution using one pipelined functional unit


Execution using four pipelined functional units


Slide credit: Krste Asanovic
Vector Unit Structure

Function Unit

Vector Registers

Elements 0, 4, 8, ...

Elements 1, 5, 9, ...

Elements 2, 6, 10, ...

Elements 3, 7, 11, ...

Memory Subsystem

Lane

Slide credit: Krste Asanovic
Vector Instruction Level Parallelism

Can overlap execution of multiple vector instructions
- example machine has 32 elements per vector register and 8 lanes
- Complete 24 operations/cycle while issuing 1 short instruction/cycle

Load Unit Multiply Unit Add Unit

Instruction issue

Slide credit: Krste Asanovic
Automatic Code Vectorization

Scalar Sequential Code

Vectorized Code

Vectorization is a compile-time reordering of operation sequencing
⇒ requires extensive loop dependence analysis

Slide credit: Krste Asanovic
Vector/SIMD Processing Summary

- Vector/SIMD machines good at exploiting regular data-level parallelism
  - Same operation performed on many data elements
  - Improve performance, simplify design (no intra-vector dependencies)

- Performance improvement limited by vectorizability of code
  - Scalar operations limit vector machine performance
  - Amdahl’s Law
  - CRAY-1 was the fastest SCALAR machine at its time!

- Many existing ISAs include (vector-like) SIMD operations
  - Intel MMX/SSEn, PowerPC AltiVec, ARM Advanced SIMD
SIMD Operations in Modern ISAs
Intel Pentium MMX Operations

- Idea: One instruction operates on multiple data elements simultaneously
  - Ala array processing (yet much more limited)
  - Designed with multimedia (graphics) operations in mind

No VLEN register
Opcode determines data type:
8 8-bit bytes
4 16-bit words
2 32-bit doublewords
1 64-bit quadword

Stride always equal to 1.

**MMX Example: Image Overlaying (I)**

Figure 8. Chroma keying: image overlay using a background color.

```
<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
</tr>
<tr>
<td>MM3</td>
<td>X7!=blue</td>
<td>X6!=blue</td>
<td>X5=blue</td>
<td>X4=blue</td>
<td>X3!=blue</td>
<td>X2!=blue</td>
<td>X1=blue</td>
</tr>
<tr>
<td>MM1</td>
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<td>0x0000</td>
<td>0xFFFF</td>
<td>0xFFFF</td>
<td>0x0000</td>
<td>0x0000</td>
<td>0xFFFF</td>
</tr>
</tbody>
</table>
```

Bitmask

Figure 9. Generating the selection bit mask.
**MMX Example: Image Overlaying (II)**

Figure 10. Using the mask with logical MMX instructions to perform a conditional select.

```
Movq    mm3, mem1  /* Load eight pixels from woman’s image
Movq    mm4, mem2  /* Load eight pixels from the blossom image
Pcmpeqb mm1, mm3
Pand    mm4, mm1.
Pandn   mm1, mm3
Por     mm4, mm1
```

Figure 11. MMX code sequence for performing a conditional select.
Graphics Processing Units
SIMD not Exposed to Programmer (SIMT)
High-Level View of a GPU
Concept of “Thread Warps” and SIMT

- Warp: A set of threads that execute the same instruction (on different data elements) → SIMT (Nvidia-speak)
- All threads run the same kernel
- Warp: The threads that run lengthwise in a woven fabric ...

![Diagram of Thread Warps and SIMD Pipeline]
Loop Iterations as Threads

for (i=0; i < N; i++)
C[i] = A[i] + B[i];

Scalar Sequential Code

Vectorized Code

Slide credit: Krste Asanovic
**SIMT Memory Access**

- Same instruction in different threads uses thread id to index and access different data elements

Let's assume $N=16$, $blockDim=4 \rightarrow 4$ blocks

![Diagram showing memory access in SIMT](image-url)

Slide credit: Hyesoon Kim
Sample GPU SIMT Code (Simplified)

CPU code

```c
for (ii = 0; ii < 100; ++ii) {
}
```

CUDA code

```c
// there are 100 threads
__global__ void KernelFunction(...) {
    int tid = blockDim.x * blockIdx.x + threadIdx.x;

    int varA = aa[tid];
    int varB = bb[tid];

    C[tid] = varA + varB;
}
```

Slide credit: Hyesoon Kim
Sample GPU Program (Less Simplified)

**CPU Program**

```c
void add_matrix
  ( float *a, float* b, float *c, int N) {
    int index;
    for (int i = 0; i < N; ++i)
      for (int j = 0; j < N; ++j) {
        index = i + j*N;
        c[index] = a[index] + b[index];
      }
}

int main () {
  add_matrix (a, b, c, N);
}
```

**GPU Program**

```c
__global__ add_matrix
  ( float *a, float *b, float *c, int N) {
    int i = blockIdx.x * blockDim.x + threadIdx.x;
    int j = blockIdx.y * blockDim.y + threadIdx.y;
    int index = i + j*N;
    if (i < N && j < N)
      c[index] = a[index] + b[index];
  }

int main() {
  dim3 dimBlock( blocksize, blocksize ) ;
  dim3 dimGrid (N/dimBlock.x, N/dimBlock.y);
  add_matrix<<<<<dimGrid, dimBlock>>>( a, b, c, N);
}
```
Latency Hiding with “Thread Warps”

- **Warp**: A set of threads that execute the same instruction (on different data elements)

- **Fine-grained multithreading**
  - One instruction per thread in pipeline at a time (No branch prediction)
  - Interleave warp execution to hide latencies

- Register values of all threads stay in register file

- No OS context switching

- Memory latency hiding
  - Graphics has millions of pixels
Warp-based SIMD vs. Traditional SIMD

- Traditional SIMD contains a single thread
  - Lock step
  - Programming model is SIMD (no threads) \(\rightarrow\) SW needs to know vector length
  - ISA contains vector/SIMD instructions

- Warp-based SIMD consists of multiple scalar threads executing in a SIMD manner (i.e., same instruction executed by all threads)
  - Does not have to be lock step
  - Each thread can be treated individually (i.e., placed in a different warp) \(\rightarrow\) programming model not SIMD
    - SW does not need to know vector length
    - Enables memory and branch latency tolerance
  - ISA is scalar \(\rightarrow\) vector instructions formed dynamically
  - Essentially, it is SPMD programming model implemented on SIMD hardware
SPMD

- Single procedure/program, multiple data
  - This is a programming model rather than computer organization

- Each processing element executes the same procedure, except on different data elements
  - Procedures can synchronize at certain points in program, e.g. barriers

- Essentially, multiple instruction streams execute the same program
  - Each program/procedure can 1) execute a different control-flow path, 2) work on different data, at run-time
  - Many scientific applications programmed this way and run on MIMD computers (multiprocessors)
  - Modern GPUs programmed in a similar way on a SIMD computer
Branch Divergence Problem in Warp-based SIMD

- SPMD Execution on SIMD Hardware
  - NVIDIA calls this “Single Instruction, Multiple Thread” (“SIMT”) execution

Slide credit: Tor Aamodt
Control Flow Problem in GPUs/SIMD

- GPU uses SIMD pipeline to save area on control logic.
  - Group scalar threads into warps

- Branch divergence occurs when threads inside warps branch to different execution paths.
NVIDIA GeForce GTX 285 “core”

64 KB of storage for fragment contexts (registers)

- = SIMD functional unit, control shared across 8 units
  - = multiply-add
  - = multiply
- = instruction stream decode
- = execution context storage

Slide credit: Kayvon Fatahalian
NVIDIA GeForce GTX 285 “core”

- Groups of 32 **threads** share instruction stream (each group is a Warp)
- Up to 32 warps are simultaneously interleaved
- Up to 1024 thread contexts can be stored

64 KB of storage for thread contexts (registers)

Slide credit: Kayvon Fatahalian
There are 30 of these things on the GTX 285: 30,720 threads

Slide credit: Kayvon Fatahalian
VLIW
VLIW (Very Long Instruction Word)

- A very long instruction word consists of multiple independent instructions packed together by the compiler
  - Packed instructions can be logically unrelated (contrast with SIMD)

- Idea: Compiler finds independent instructions and statically schedules (i.e. packs/bundles) them into a single VLIW instruction

- Traditional Characteristics
  - Multiple functional units
  - Each instruction in a bundle executed in lock step
  - Instructions in a bundle statically aligned to be directly fed into the functional units

ELI: Enormously longword instructions (512 bits)
SIMD Array Processing vs. VLIW

- Array processor

Program Counter → add VR, VR, 1

Instruction Execution

PE

add VR[0], VR[0], 1
add VR[1], VR[1], 1
add VR[2], VR[2], 1
add VR[3], VR[3], 1

VLEN = 4
VLIW Philosophy

- Philosophy similar to RISC (simple instructions)
  - Except multiple instructions in parallel

- RISC (John Cocke, 1970s, IBM 801 minicomputer)
  - Compiler does the hard work to translate high-level language code to simple instructions (John Cocke: control signals)
    - And, to reorder simple instructions for high performance
  - Hardware does little translation/decoding → very simple

- VLIW (Fisher, ISCA 1983)
  - Compiler does the hard work to find instruction level parallelism
  - Hardware stays as simple and streamlined as possible
    - Executes each instruction in a bundle in lock step
    - Simple → higher frequency, easier to design
VLIW Philosophy (II)

More formally, VLIW architectures have the following properties:

There is one central control unit issuing a single long instruction per cycle.

Each long instruction consists of many tightly coupled independent operations.

Each operation requires a small, statically predictable number of cycles to execute.

Operations can be pipelined. These properties distinguish VLIWs from multiprocessors (with large asynchronous tasks) and dataflow machines (without a single flow of control, and without the tight coupling). VLIWs have none of the required regularity of a vector processor, or true array processor.
Commercial VLIW Machines

- Multiflow TRACE, Josh Fisher (7-wide, 28-wide)
- Cydrome Cydra 5, Bob Rau
- Transmeta Crusoe: x86 binary-translated into internal VLIW
- TI C6000, Trimedia, STMicro (DSP & embedded processors)
  - Most successful commercially

- Intel IA-64
  - Not fully VLIW, but based on VLIW principles
  - EPIC (Explicitly Parallel Instruction Computing)
  - Instruction bundles can have dependent instructions
  - A few bits in the instruction format specify explicitly which instructions in the bundle are dependent on which other ones
VLIW Tradeoffs

**Advantages**
+ No need for dynamic scheduling hardware → simple hardware
+ No need for dependency checking within a VLIW instruction → simple hardware for multiple instruction issue + no renaming
+ No need for instruction alignment/distribution after fetch to different functional units → simple hardware

**Disadvantages**
-- Compiler needs to find N independent operations
   -- If it cannot, inserts NOPs in a VLIW instruction
   -- Parallelism loss AND code size increase
-- Recompilation required when execution width (N), instruction latencies, functional units change (Unlike superscalar processing)
-- Lockstep execution causes independent operations to stall
   -- No instruction can progress until the longest-latency instruction completes
VLIW Summary

- VLIW simplifies hardware, but requires complex compiler techniques
- VLIW architectures have not been commercially successful in the general-purpose computing market. Why?
  - Too many NOPs (not enough parallelism discovered)
  - Static schedule intimately tied to microarchitecture
    - Code optimized for one generation performs poorly for next
    - No tolerance for variable or long-latency operations (lock step)

++ Most compiler optimizations developed for VLIW employed in optimizing compilers (for superscalar compilation)
  - Enable code optimizations
++ VLIW successful in embedded markets, e.g. DSP