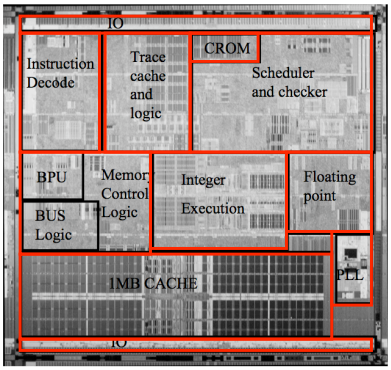
WaveScalar [MICRO 03]

Dataflow machine
- good at exploiting ILP
- dataflow parallelism + traditional coarser-grain parallelism
  - cheap thread management
- low operand latency because of a hierarchical organization
- memory ordering enforced through **wave-ordered memory**
  - no special languages

WaveScalar

Additional motivation:
- increasing disparity between computation (fast transistors) & communication (long wires)
- increasing circuit complexity
- decreasing fabrication reliability

Monolithic von Neumann Processors



A phenomenal success today.
But in 2016?

☹ Performance
Centralized processing & control, e.g., operand broadcast networks

☹ Complexity
40-75% of "design" time is design verification

☹ Defect tolerance
1 flaw -> paperweight

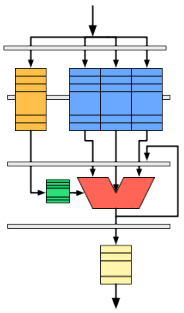
WaveScalar's Microarchitecture

Good performance via distributed microarchitecture ☺
- hundreds of PEs
- dataflow execution – no centralized control
- short point-to-point communication
- organized hierarchically for fast communication between neighboring PEs
- scalable

Low design complexity through simple, identical PEs ☺
- design one & stamp out thousands

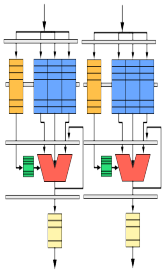
Defect tolerance ☺
- route around a bad PE

Processing Element



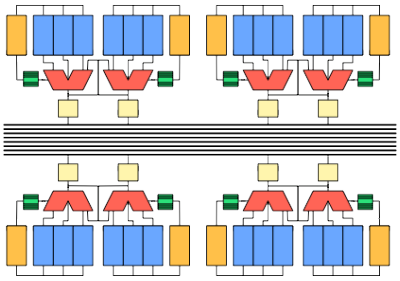
- Simple, small (.5M transistors)
- 5-stage pipeline (receive input operands, match tags, instruction schedule, execute, send output)
- Holds 64 (decoded) instructions
- 128-entry token store
- 4-entry output buffer

PEs in a Pod

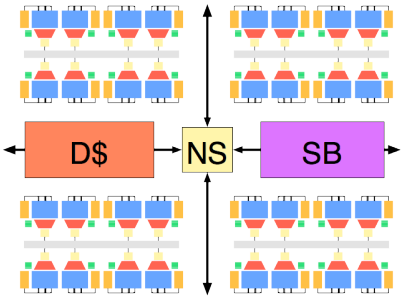


- Share operand bypass network
- Back-to-back producer-consumer execution across PEs
- Relieve congestion on intra-domain bus

Domain

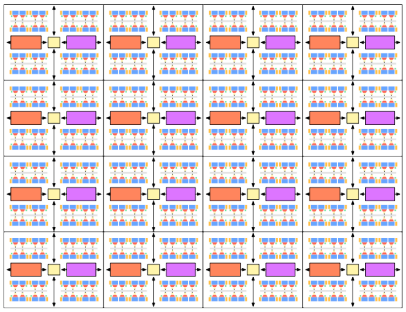


Cluster



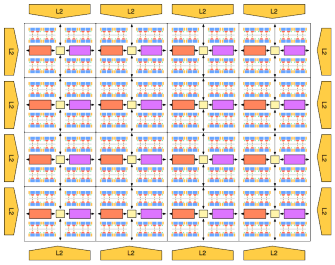
WaveScalar Processor

Long distance communication
- dynamic routing
- grid-based network
- 2-cycle hop/cluster



Whole Chip

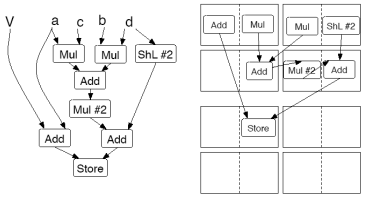
- Can hold 32K instructions
- Normal memory hierarchy
- Traditional directory-based cache coherence
- ~400 mm^2 in 90 nm technology
- 1GHz.
- ~85 watts



WaveScalar Instruction Placement

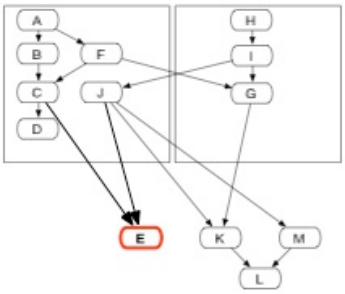
```
int *V;
int a, b;
int c, d, r;

r = a*c + b*d;
V[a] = 2*r + d << 2;
```



Instruction Placement Trade-offs

operand latency vs.
parallelism (resource conflicts)



WaveScalar Instruction Placement

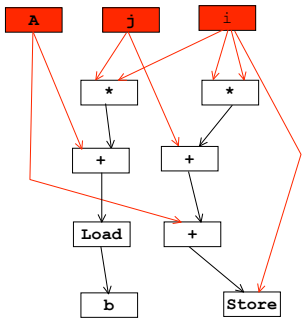
Place instructions in PEs to maximize data locality & instruction-level parallelism.

- Instruction placement algorithm based on a performance model that captures the important performance factors [SPAA 06]
- Depth-first traversal of dataflow graph to make chains of dependent instructions
- Broken into segments [ASPLOS 06]
- Snakes segments across the chip on demand
- K-loop bounding to prevent instruction "explosion"

Example to Illustrate the Memory Ordering Problem

```
A[j + i*i] = i;

b = A[i*j];
```



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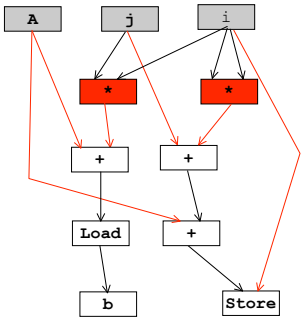

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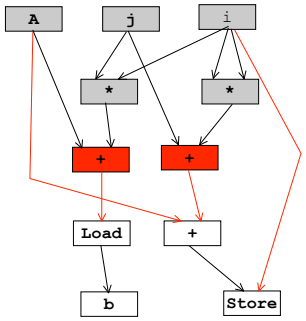

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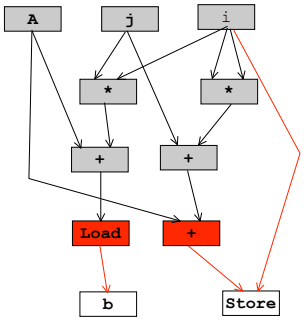

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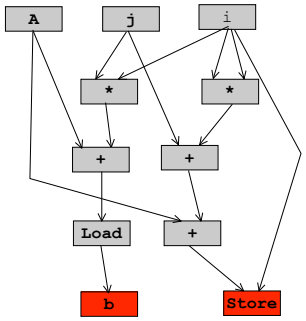

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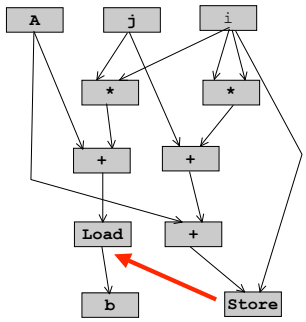
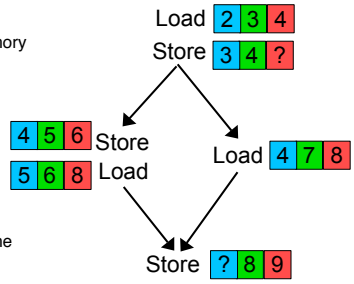
Global load-store ordering issue

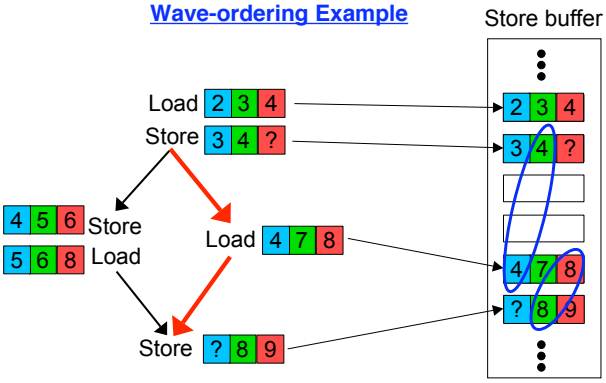


Wave-ordered Memory

- Compiler annotates memory operations
  - Sequence #
  - Successor
  - Predecessor
- Send memory requests in any order
- Hardware reconstructs the correct order



Wave-ordering Example

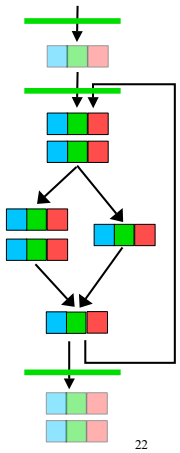


Wave-ordered Memory

Waves are loop-free sections of the dataflow graph

Each dynamic wave has a **wave number**
Wave number is incremented between waves

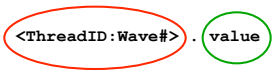
Ordering memory:
- wave-numbers
- sequence number within a wave

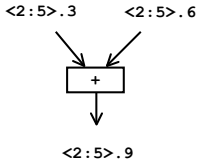


WaveScalar Tag-matching

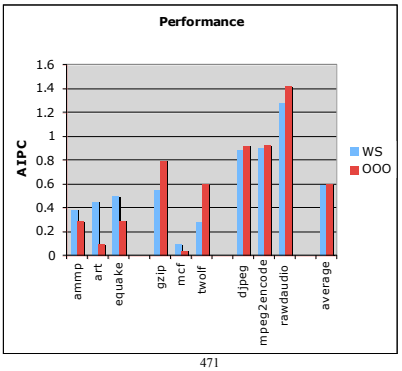
WaveScalar tag
- thread identifier
- wave number

Token: **tag** & **value**

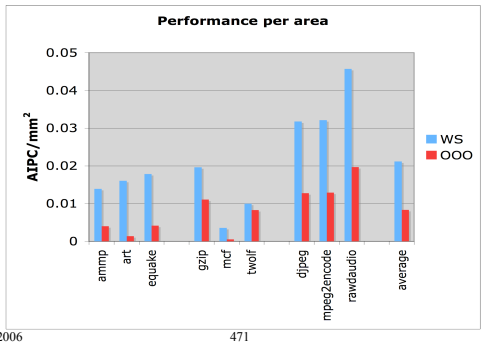




Single-thread Performance



Single-thread Performance per Area



Multithreading the WaveCache

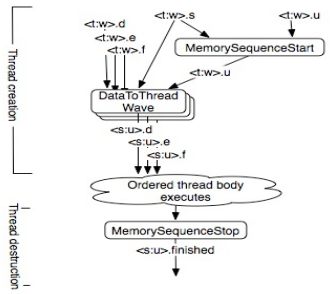
Architectural-support for WaveScalar threads

- instructions to start & stop memory orderings, i.e., threads
- memory-free synchronization to allow exclusive access to data (thread communicate instruction)
- fence instruction to allow other threads to see this one's memory ops

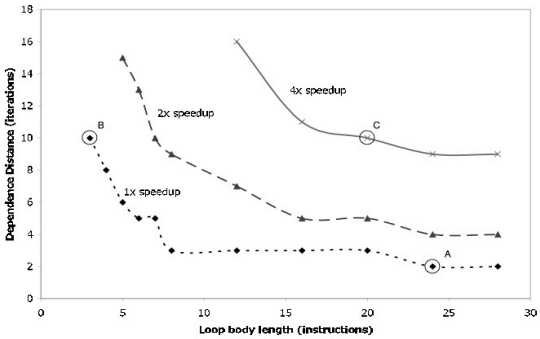
Combine to build threads with multiple granularities

- coarse-grain threads: 25-168X over a single thread; 2-16X over CMP, 5-11X over SMT
- fine-grain, dataflow-style threads: 18-242X over single thread
- combine the two in the same application: 1.6X or 7.9X -> 9X

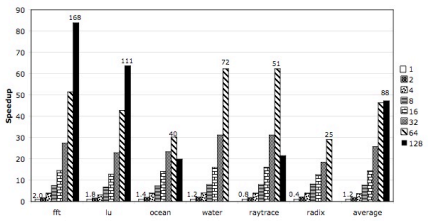
Creating & Terminating a Thread



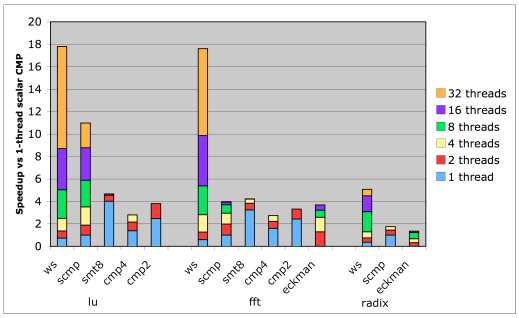
Thread Creation Overhead



Performance of Coarse-grain Parallelism

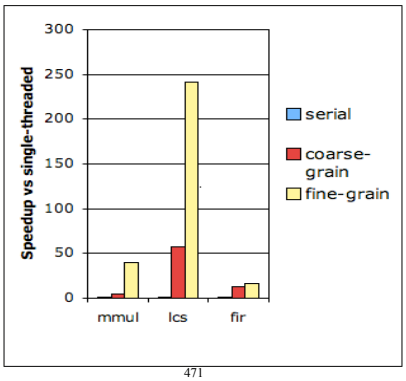


CMP Comparison



Relies on:
Cheap synchronization
Load once, pass data (not load/compute/store)

Performance of Fine-grain Parallelism



Building the WaveCache

RTL-level implementation [ISCA 06]

- some didn't believe it could be built in a normal-sized chip
- some didn't believe it could achieve a decent cycle time and load-use latencies
- Verilog & Synopsis CAD tools

Different WaveCache's for different applications

- 1 cluster: low-cost, low power, single-thread or embedded
  - 42 mm² in 90 nm process technology, 2.2 AIPC on Splash2
- 16 clusters: multiple threads, higher performance: 378 mm² , 15.8 AIPC

Board-level FPGA implementation

- OS & real application simulations

Compiling for the WaveCache

Eliminating dataflow control flow instructions [PACT 06]

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