Von Neumann Execution Model

Fetch:
- send PC to memory
- transfer instruction from memory to CPU
- increment PC

Decode & read ALU input sources

Execute
- an ALU operation
- memory operation
- branch target calculation

Store the result in a register or memory

Von Neumann Execution Model

Execution is comprised of a linear series of addressable instructions
- next instruction to be executed is pointed to by the PC
- send PC to memory
- next instruction to execute depends on what happened during the execution of the current instruction

Instruction operands reside in a centralized processor memory (GPRs)

Dataflow Execution Model

Instructions & initial input values are already in the processor:

Source operands arrive from a producer instruction via a network

Check to see if all an instruction's operands are there

Execute
- an ALU operation
- memory operation
- branch target calculation

Send the result
- to the consumer instructions or memory

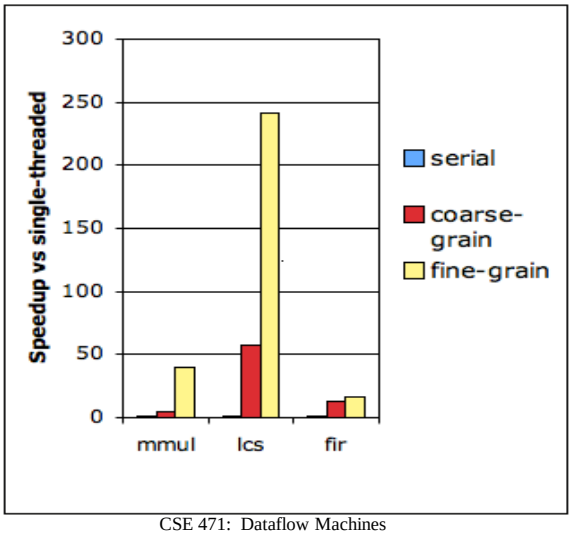
Dataflow Execution Model

Execution is driven by the availability of input operands
- operands are consumed
- output is generated
- **no PC**

Result operands are passed directly to consumer instructions
- **no register file**

Parallel execution only hindered by data dependences
- entire execution cycle is out-or-order, not just the execution core
- all instructions can execute in parallel, not just those in the instruction queue

Promise of Dataflow Parallelism



Dataflow Computers

Motivation:

- exploit **instruction-level parallelism** on a massive scale
- more fully utilize all processing elements

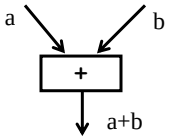
Believed this was possible if:

1. expose instruction-level parallelism by using a functional-style programming language
   - no side effects wrt generating new values
   - only restrictions were producer-consumer
2. scheduled code for execution on the hardware greedily
3. hardware support for data-driven execution

Dataflow Execution

All computation is **data-driven**.

- binary is represented as a directed graph of data dependences
  - nodes are operations executing in a logical processor
  - values travel on arcs



- WaveScalar instruction

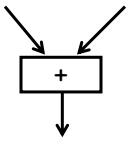
Dataflow Execution

Data-dependent operations are connected, producer to consumer

Code & initial values loaded into memory

Execute according to the **dataflow firing rule**

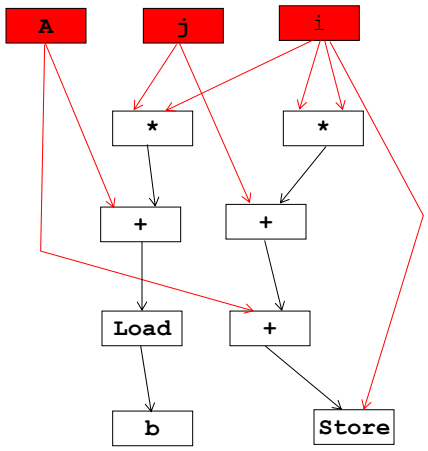
- when operands of an instruction have arrived on all input arcs, instruction may execute
- value on input arcs is removed
- computed value placed on output arc



Dataflow Example

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

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



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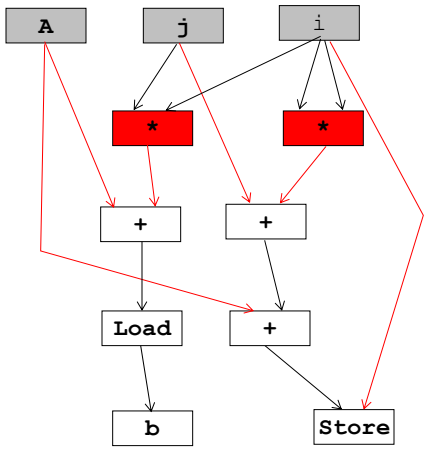

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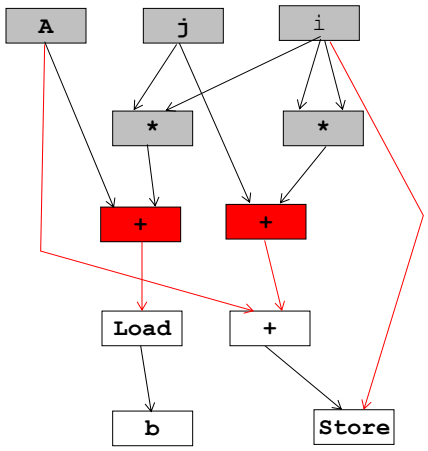
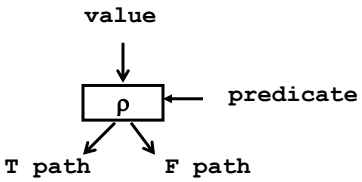
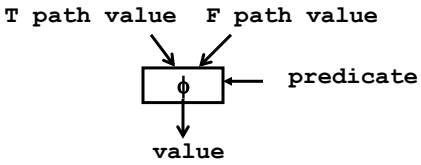


Dataflow Execution

Control

- **steer** (ρ) **merge** (ϕ)



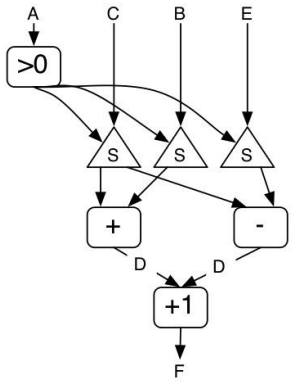


- execute one path after the condition variable is known (steer)
  or
- execute both paths & pass one set of values at the end (merge)
- convert control dependence to data dependence

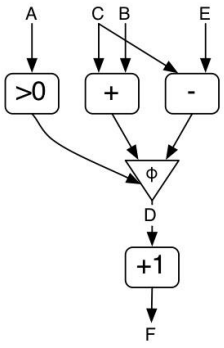
WaveScalar Control

```
if (A > 0)
      D = C + B;
else
      D = C - E;
F = D + 1;
```

ρ (steer)



ϕ (merge)



ISA for a Dataflow Computer

Instructions
- operation
- names of destination instructions

Data packets, called **Tokens**
- value
- tag to identify the operand & match it with its fellow operands in the same dynamic instruction
  - architecture dependent
    - instruction number
    - iteration number
    - activation/context number (for functions, especially recursive)
    - thread number
- Dataflow computer executes a program by receiving tokens, matching tags, computing & sending out tokens.

Types of Dataflow Computers

static:

- one copy of each instruction
- no simultaneously active iterations, no recursion

Types of Dataflow Computers

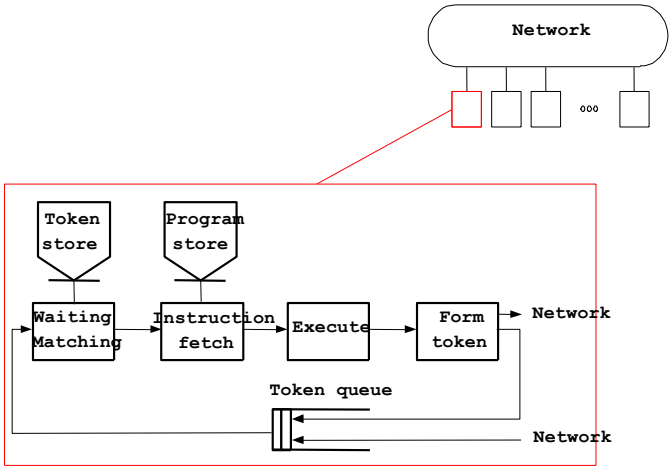
dynamic

- multiple copies of each instruction
- better performance from increased ILP
- gate counting technique to prevent instruction explosion

k-bounding

- extra instruction with K tokens on its input arc; passes a token to 1st instruction of a loop iteration
- 1st instruction consumes a token (needs one extra operand to execute)
- last instruction in loop iteration produces another token at end of iteration
- limits active iterations to k

Canonical Dataflow Computer



Problems with Dataflow Computers

1. Memory ordering
   - dataflow cannot guarantee a correct ordering of memory operations

2. Language compatibility
   - dataflow computer programmers could not use mainstream programming languages, such as C
   - could not handle “complex” data structures
   - developed special languages in which order didn’t matter

Dataflow Example

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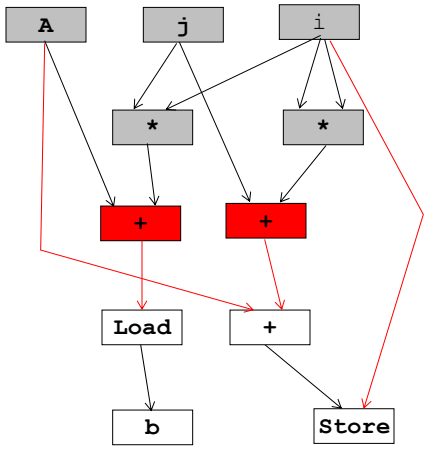

Example to Illustrate the Memory Ordering Problem

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

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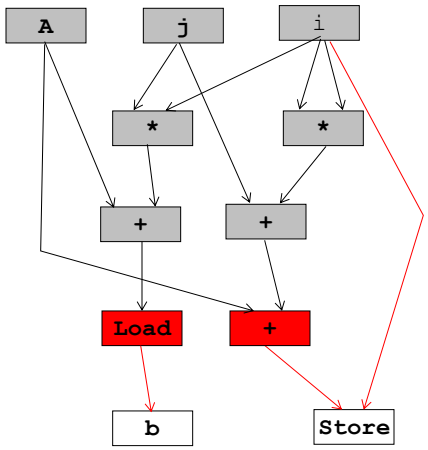

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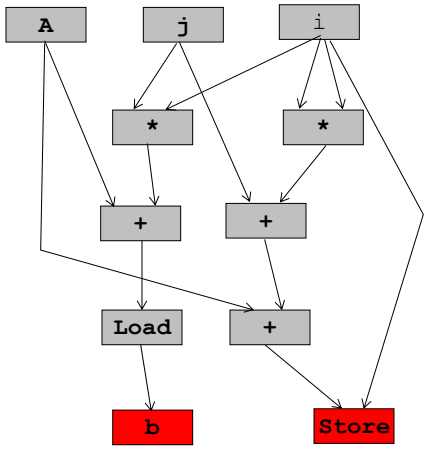

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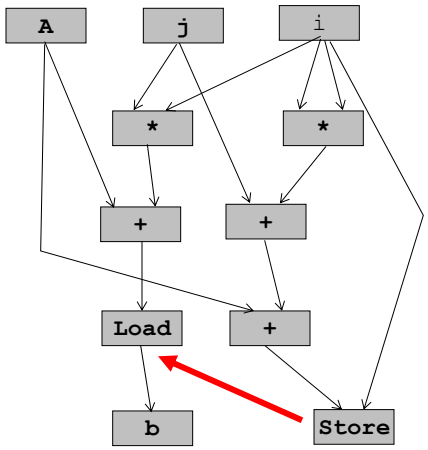
Load-store ordering issue



Problems with Dataflow Computers

3. Scalability:
   - big token store
     - side-effect-free programming language with no mutable data structures
       - each update creates a new data structure
       - 1000 tokens for 1000 data items even if the same value
   - slow access
     - aggravated by the state of processor technology at the time
     - associative search impossible; accessed with slower hash function
     - delays in processing (only so many functional units, arbitration both for PEs and storing of result, long wires)