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
- from the ALU or memory

Von Neumann Execution Model

Program is 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

Operands reside in a centralized, global memory (GPRs)

Dataflow Execution Model

Instructions are already in the processor:

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

Dataflow Computers

Motivation:

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

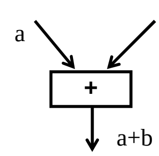
Believed this was possible if:

- expose instruction-level parallelism by using a functional-style programming language
  - no side effects; only restrictions were producer-consumer
- scheduled code for execution on the hardware greedily
- hardware support for data-driven execution

Dataflow Execution

All computation is **data-driven**.

- binary is represented as a directed graph
  - nodes are operations
  - values travel on arcs



- WaveScalar instruction

opcode	destination1	destination2

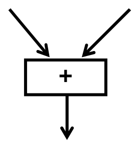
Dataflow Execution

Data-dependent operations are connected, producer to consumer

Code & initial values loaded into memory

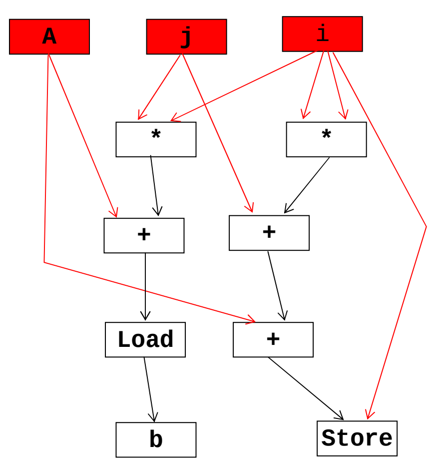
Execute according to the **dataflow firing rule**

- 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



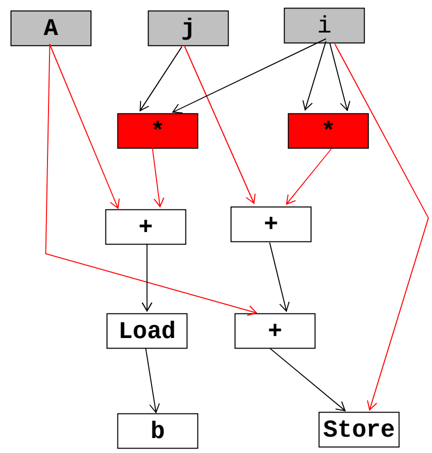
Dataflow Example

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

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



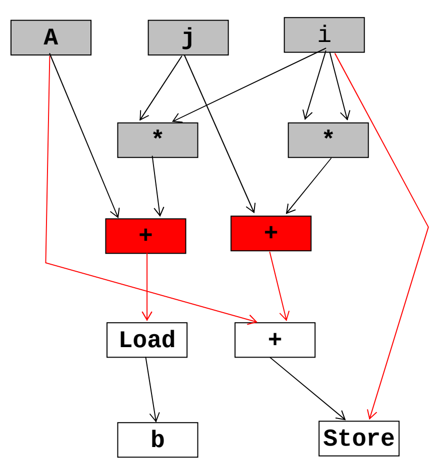
Dataflow Example

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

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



Dataflow Example

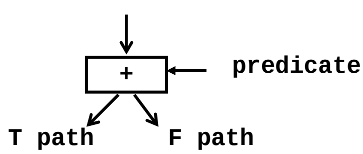
```
A[j + i*i] = i;

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



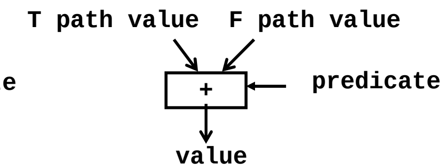
Dataflow Execution

Control

- steer (ρ)



merge (ϕ)



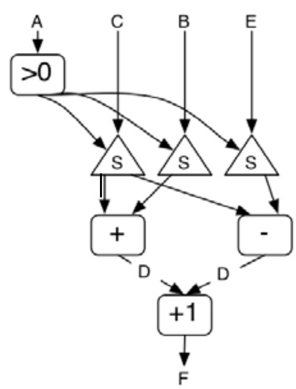
- convert control dependence to data dependence with value-steering instructions
- execute one path after condition variable is known (steer)
  or
- execute both paths & pass values at end (merge)

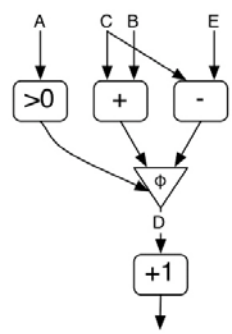
WaveScalar Control

ρ (steer)

ϕ (merge)

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





Dataflow Computer ISA

Instructions
- operation
- destination instructions

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

Types of Dataflow Computers

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

Types of Dataflow Computers

dynamic

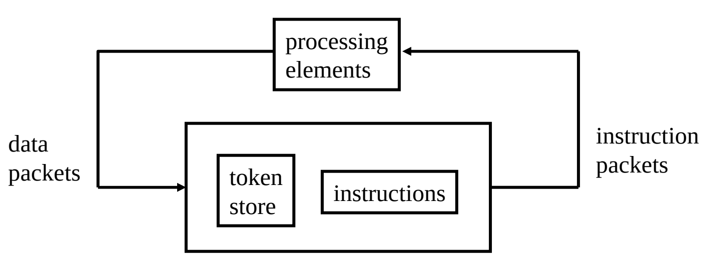
- multiple copies of each instruction
- better performance
- gate counting technique to prevent instruction explosion:

k-bounding

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

Prototypical Early Dataflow Computer

Original implementations were centralized.



Performance cost

- large token store (long access)
- long wires
- arbitration both for PEs and storing of result

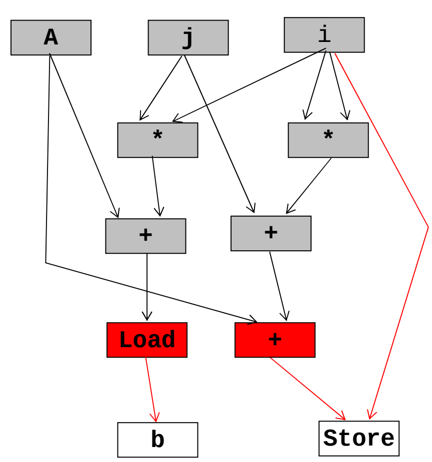
Problems with Dataflow Computers

Language compatibility
- dataflow cannot guarantee a correct ordering of memory operations
- dataflow computer programmers could not use mainstream programming languages, such as C
- developed special languages in which order didn't matter

Scalability: large 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
- aggravated by the state of processor technology at the time
  - delays in processing (only so many functional units, arbitration delays, etc.) meant delays in operand arrival
  - associative search impossible; accessed with slower hash function

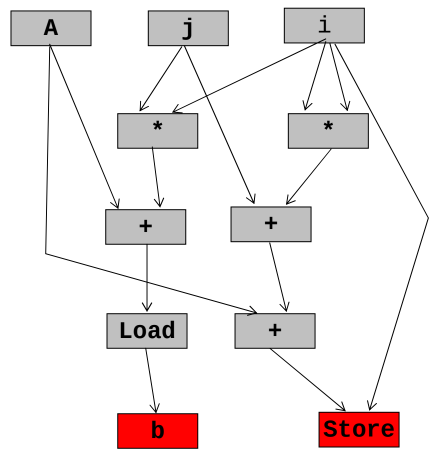
Example to Illustrate the Memory Ordering Problem

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

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



Example to Illustrate the Memory Ordering Problem

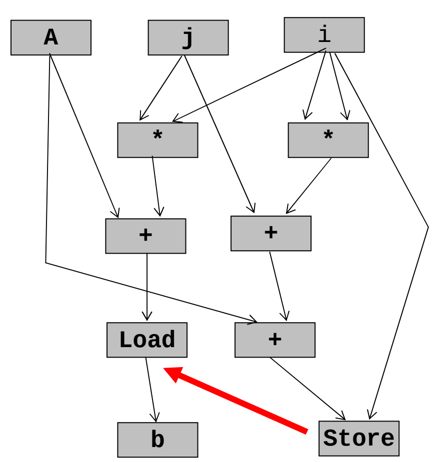
```
A[j + i*i] = i;

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



Example to Illustrate the Memory Ordering Problem

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

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

Load-store ordering issue



Partial Solutions

Solutions led away from pure dataflow execution

Data representation in memory

- **I-structures**:
  - write once; read many times
  - early reads are deferred until the write
- **M-structures**:
  - multiple reads & writes, but they must alternate
  - reusable structures which could hold multiple values

Partial Solutions

Local (register) storage for back-to-back instructions

Frames of sequential instruction execution

- create "frames", each of which stored the data for one iteration or one thread
- not have to search entire token store (offset to frame)
- like having dataflow execution among coarse-grain threads rather than instructions

Physically partition token store & place each partition with a PE