**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

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**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

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

```
  a  b
  +   +
    a+b
```
- WaveScalar instruction

```plaintext
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

\[ A[j + i\times i] = i; \]
\[ b = A[i\times j]; \]
**Dataflow Execution**

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

merge (\( \phi \))

**WaveScalar Control**

\( \rho \) (steer)

\( \phi \) (merge)

\[
\begin{align*}
\text{if } (A > 0) & : D = C + B; \\
\text{else} & : D = C - E; \\
F &= D + 1;
\end{align*}
\]
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

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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 1st instruction of loop body
- 1st 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

Dataflow Example

\[ A[j + i*i] = i; \]
\[ b = A[i*j]; \]
Example to Illustrate the Memory Ordering Problem

\[ A[j + i \times i] = i; \]
\[ b = A[i \times j]; \]
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 for distinct 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