The Andrew and Erna Viterbi Faculty of ELECTRICAL & COMPUTER ENGINEERING

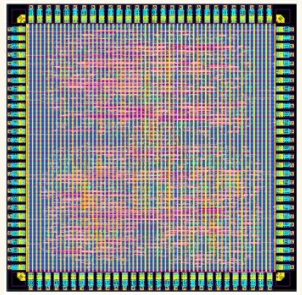
VLSI המעבדה ל- Laboratory

# Accelerator for Genetic Local Sequence Alignment

## Frontend Design Review

**Students: Niv Bar-Tov, Dor Lerman**

**Supervisor: Goel Samuel**



# Outline

- Sequence Alignment
- Smith-Waterman Algorithm
- Project's Requirements and Specifications
- High-Level Overview
- Architectural Design
- Next Steps

# Sequence Alignment

- Method of arranging sequences of DNA, RNA or proteins
- Aims to identify regions of similarity that may indicate on a relationship between the sequences
- Can be used also for non-biological sequences

# Sequence Alignment

TACGCTTG

CTACCTAG

TAC−CT

TACGCT

# Global Alignment VS. Local Alignment

- Align the entire sequence (all letters)
- Suitable for closely related sequences
- Needleman-Wunsch Algorithm

- Align regions (substrings) having highest similarities
- Suitable for more divergent sequences
- Smith-Waterman Algorithm

# Smith-Waterman Algorithm

- Dynamic Programming algorithm used for local sequence alignment
- Compares segments of all possible lengths and optimizes the similarity measure
- Time complexity: $O(n^2)$
- Space complexity: $O(n^2)$

# Smith-Waterman Main Stages

1. Initialization: Construct a scoring matrix and initialize its first row and column with zeros
2. Scoring: Calculate score for each cell based on the scoring scheme
3. Traceback: Determine the optimal alignment by trace back from the highest-scoring cell in the matrix to a cell with a score of zero

# Smith-Waterman Algorithm

## Initialization

$$H_{i,j} = max \begin{cases} H_{i-1,j-1} + MATCH/MISMTACH \\ H_{i-1,j} + GAP\_PENALTY \\ H_{i,j-1} + GAP\_PENALTY \\ 0 \end{cases}$$

| S | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | | | | | | | | |
| T | 0 | | | | | | | | |
| A | 0 | | | | | | | | |
| C | 0 | | | | | | | | |
| C | 0 | | | | | | | | |
| T | 0 | | | | | | | | |
| A | 0 | | | | | | | | |
| G | 0 | | | | | | | | |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Scoring

$$H_{i,j} = max \begin{cases} H_{i-1,j-1} + MATCH/MISMTACH \\ H_{i-1,j} + GAP\_PENALTY \\ H_{i,j-1} + GAP\_PENALTY \\ 0 \end{cases}$$

| S | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | | | | | | | |
| T | 0 | | | | | | | | |
| A | 0 | | | | | | | | |
| C | 0 | | | | | | | | |
| C | 0 | | | | | | | | |
| T | 0 | | | | | | | | |
| A | 0 | | | | | | | | |
| G | 0 | | | | | | | | |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Scoring

$$H_{i,j} = max \begin{cases} H_{i-1,j-1} + MATCH/MISMTACH \\ H_{i-1,j} + GAP\_PENALTY \\ H_{i,j-1} + GAP\_PENALTY \\ 0 \end{cases}$$

| S | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | | | | | | |
| T | 0 | 1 | | | | | | | |
| A | 0 | | | | | | | | |
| C | 0 | | | | | | | | |
| C | 0 | | | | | | | | |
| T | 0 | | | | | | | | |
| A | 0 | | | | | | | | |
| G | 0 | | | | | | | | |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Scoring

$$H_{i,j} = max \begin{cases} H_{i-1,j-1} + MATCH/MISMTACH \\ H_{i-1,j} + GAP\_PENALTY \\ H_{i,j-1} + GAP\_PENALTY \\ 0 \end{cases}$$

| S | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | | | | | |
| T | 0 | 1 | 0 | | | | | | |
| A | 0 | 0 | | | | | | | |
| C | 0 | | | | | | | | |
| C | 0 | | | | | | | | |
| T | 0 | | | | | | | | |
| A | 0 | | | | | | | | |
| G | 0 | | | | | | | | |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Scoring

$$H_{i,j} = max \begin{cases} H_{i-1,j-1} + MATCH/MISMTACH \\ H_{i-1,j} + GAP\_PENALTY \\ H_{i,j-1} + GAP\_PENALTY \\ 0 \end{cases}$$

| | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 |
| C | 0 | 0 | 0 | 3 | 1 | 1 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 2 | 2 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 1 | 3 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 0 |
| G | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 3 |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Traceback

| S | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 |
| C | 0 | 0 | 0 | 3 | 1 | 1 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 2 | 2 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 1 | 3 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 0 |
| G | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 3 |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Traceback

**TAC**
**TAC**

| | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 |
| C | 0 | 0 | 0 | 3 | 1 | 1 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 2 | 2 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 1 | 3 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 0 |
| G | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 3 |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
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# Smith-Waterman Algorithm

## Traceback

| S | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 |
| C | 0 | 0 | 0 | 3 | 1 | 1 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 2 | 2 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 1 | 3 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 0 |
| G | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 3 |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Traceback

**TAC–CT**
**TACGCT**

| | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 |
| C | 0 | 0 | 0 | 3 | 1 | 1 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 2 | 2 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 1 | 3 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 0 |
| G | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 3 |

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Traceback

| S | | T | A | C | G | C | T | T | G |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 |
| C | 0 | 0 | 0 | 3 | 1 | 1 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 1 | 2 | 2 | 0 | 0 | 0 |
| T | 0 | 1 | 0 | 0 | 0 | 1 | 3 | 1 | 0 |
| A | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 0 |
| G | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 3 |

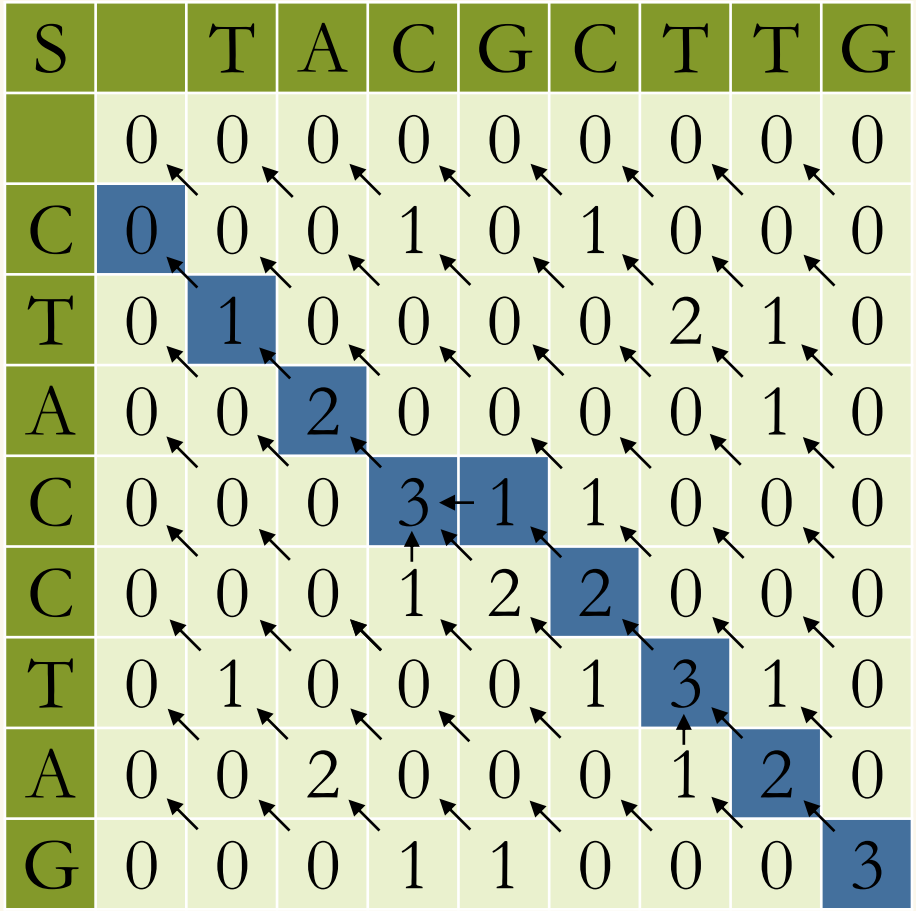
| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |

# Smith-Waterman Algorithm

## Traceback

**TAC–CTAG**
**TACGCTTG**

| | |
|---|---|
| Match | +1 |
| Mismatch | –1 |
| Gap Penalty | –2 |



# High-Level Overview

# Requirements & Specifications

- Technology process: TSMC 65 nm
- Sequences length: 32 residues
- Maximum area efficiency (1.0x1.0 sq. mm)
- Maximum of 40 I/O pins
- Clock frequency: up to 300 MHz
- Minimal on-chip memory
- Performance efficiency

# Sequences Representation

**Input**

| | |
|---|---|
| A | 00 |
| G | 01 |
| T | 10 |
| C | 11 |

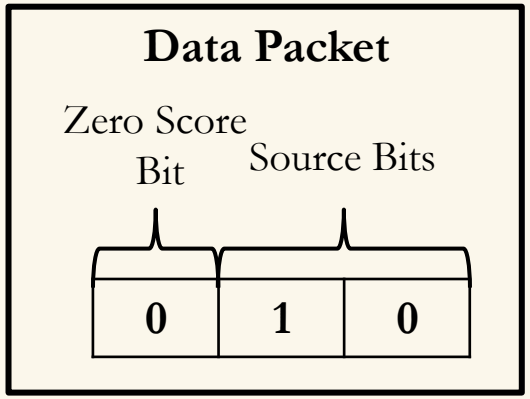
**Output**

| | |
|---|---|
| A | 000 |
| G | 001 |
| T | 010 |
| C | 011 |
| – | 100 |
| Don't Care | 101 |
| Don't Care | 110 |
| Start/End Signal | 111 |

# Data Packet

**We need to keep in each cell:**

1. Zero Score Bit – Indicates if the score of the cell equals zero
2. Source Bits – 2 bits indicate the neighbor cell from where the maximum score has been determined (left, top or diagonally located)



# High-Level Architecture Stages

**Consists of 3 main stages:**

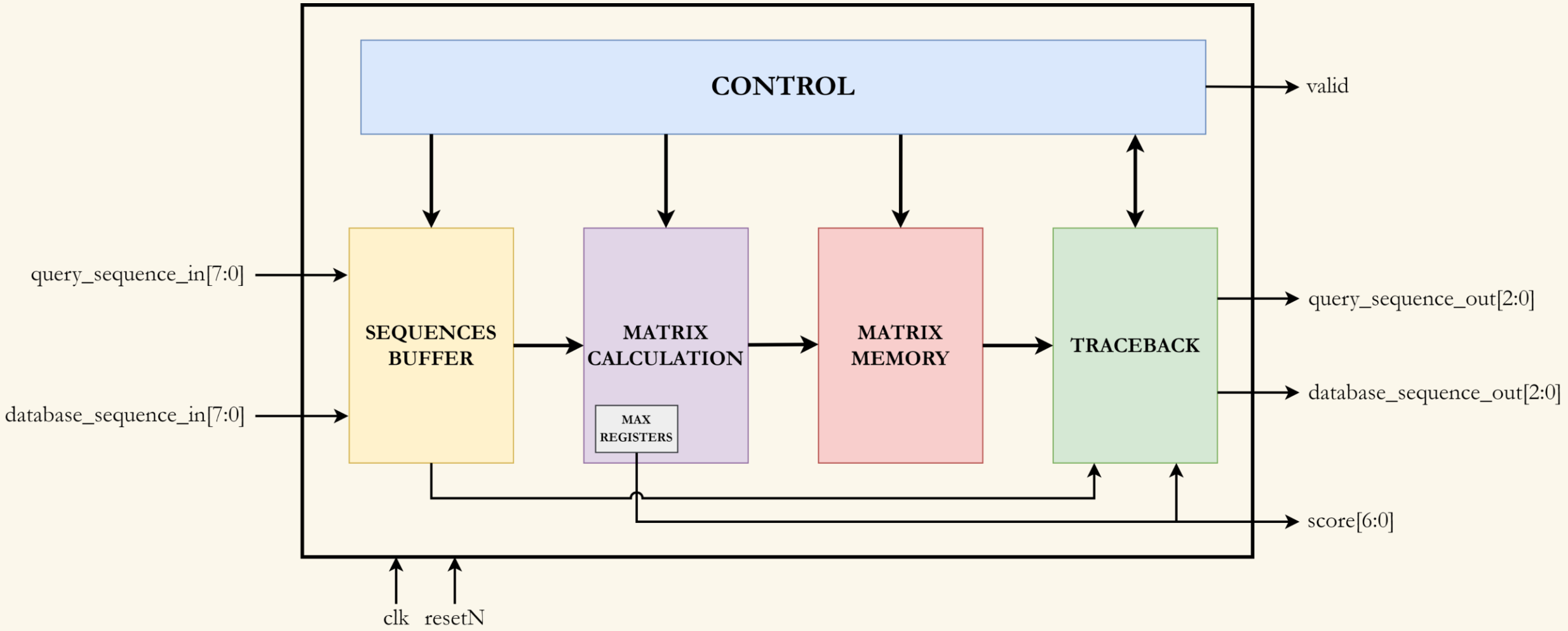
1. **Load Sequences**: Load the two input sequences into the Sequences Buffer unit (4 residues from each sequence in parallel in each cycle).
2. **Score Matrix Computation**: Initializing the Matrix Memory unit with zeros and then iteratively filling it according to the Matrix Calculation unit, while updating the Matrix Memory and Max Score Register.
3. **Traceback**: Starting at the highest-scoring cell in the matrix and following a path of highest-scoring cells until zero cell score is reached.

# I/O Diagram


**18 input pins, 14 output pins**

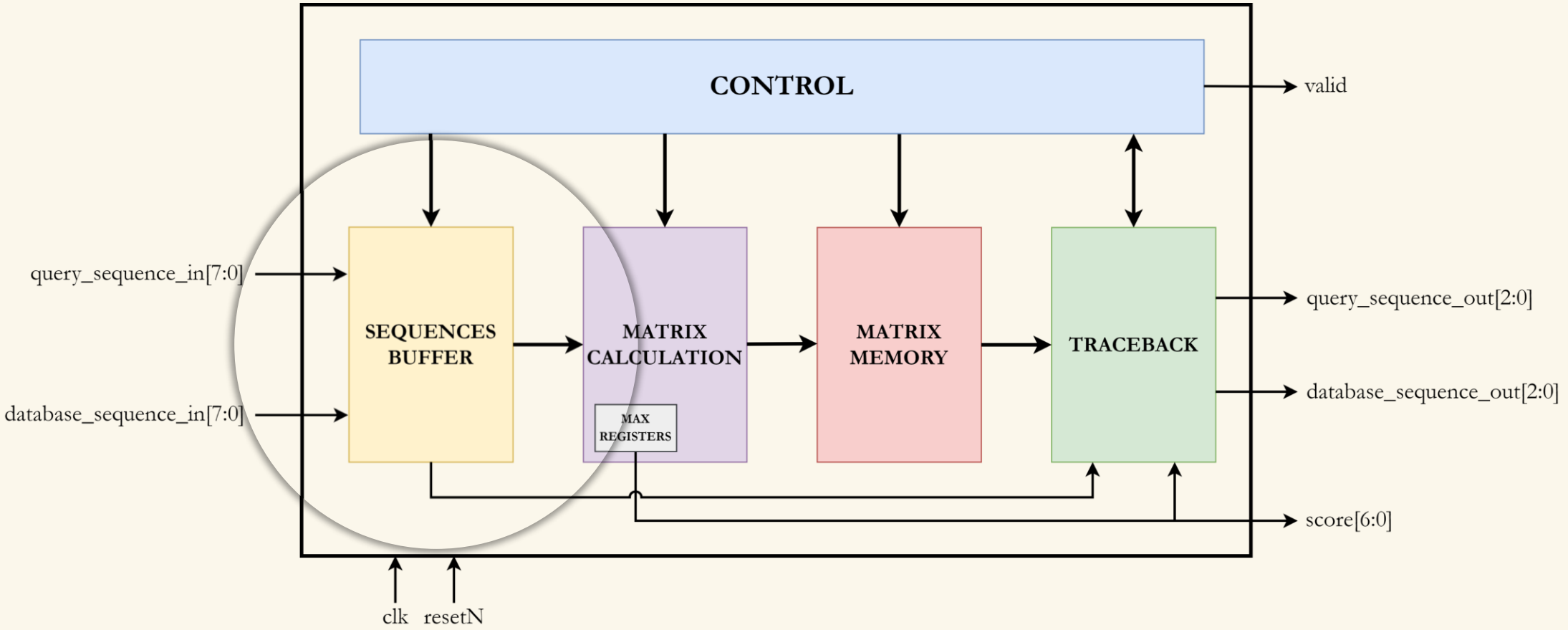
**(+8 pins for $V_{DD}$ and $V_{SS}$)**

# Top Level Architecture

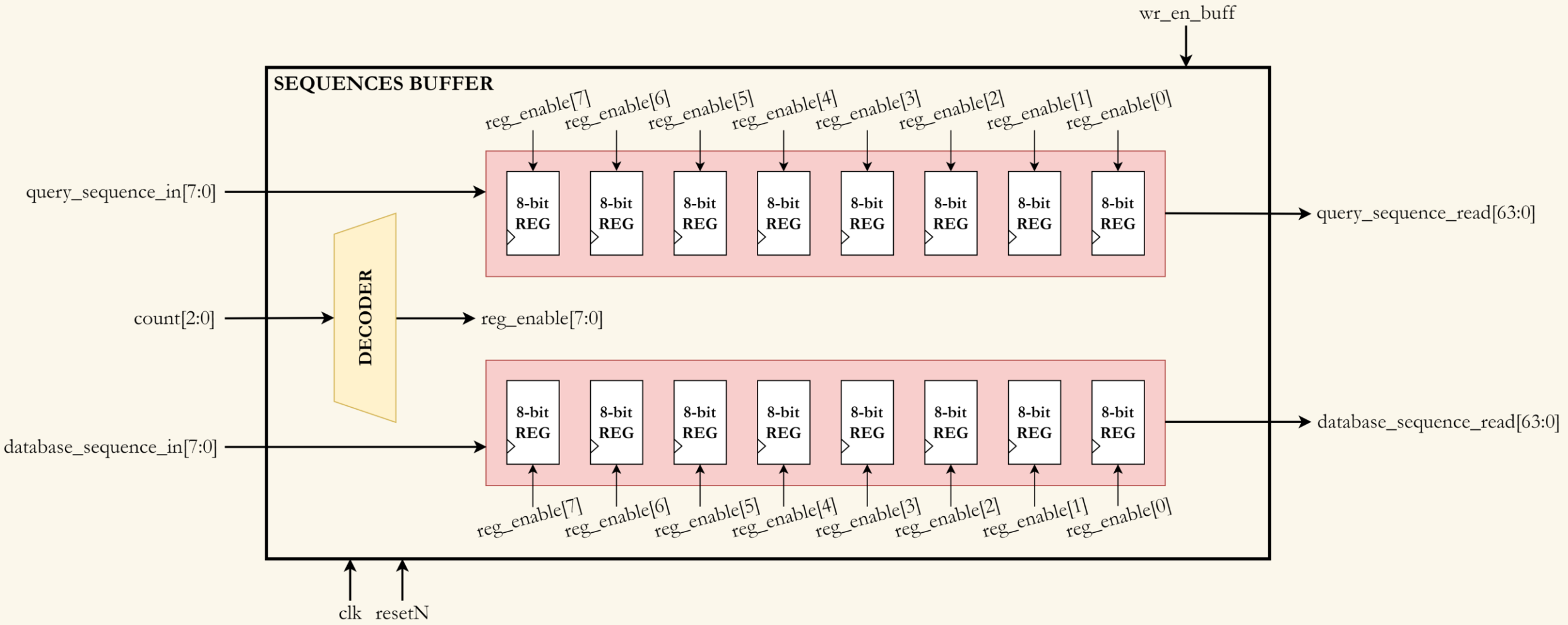


# Architectural Design

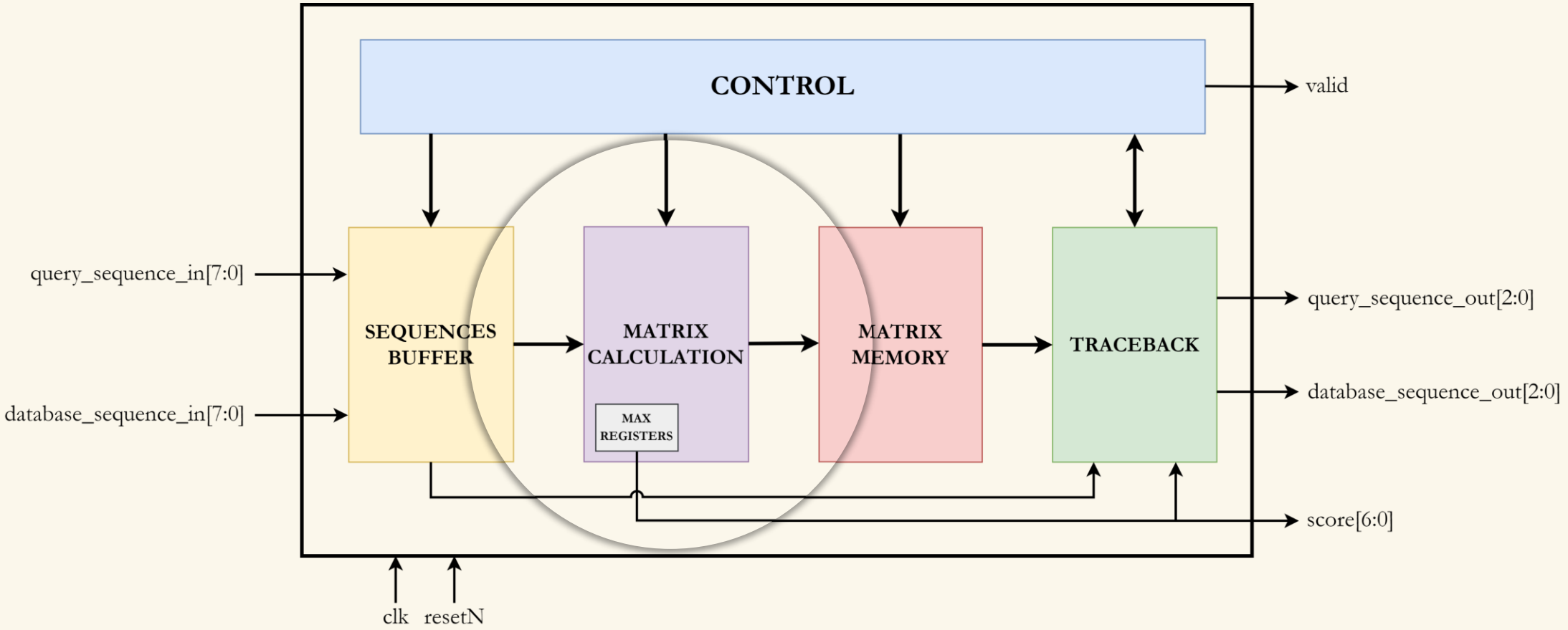
# Sequences Buffer



# Sequences Buffer



# Matrix Calculation



# Score Matrix Computation

| S | | T | G | G | C | A | T | A | C | C | G | T | A | C | T | G | G | A | C | T | G | G | A | T | A | T | C | G | A | T | C | C | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

# Score Matrix Computation

| S | | T | G | G | C | A | T | A | C | C | G | T | A | C | T | G | G | A | C | T | G | G | A | T | A | T | C | G | A | T | C | C | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

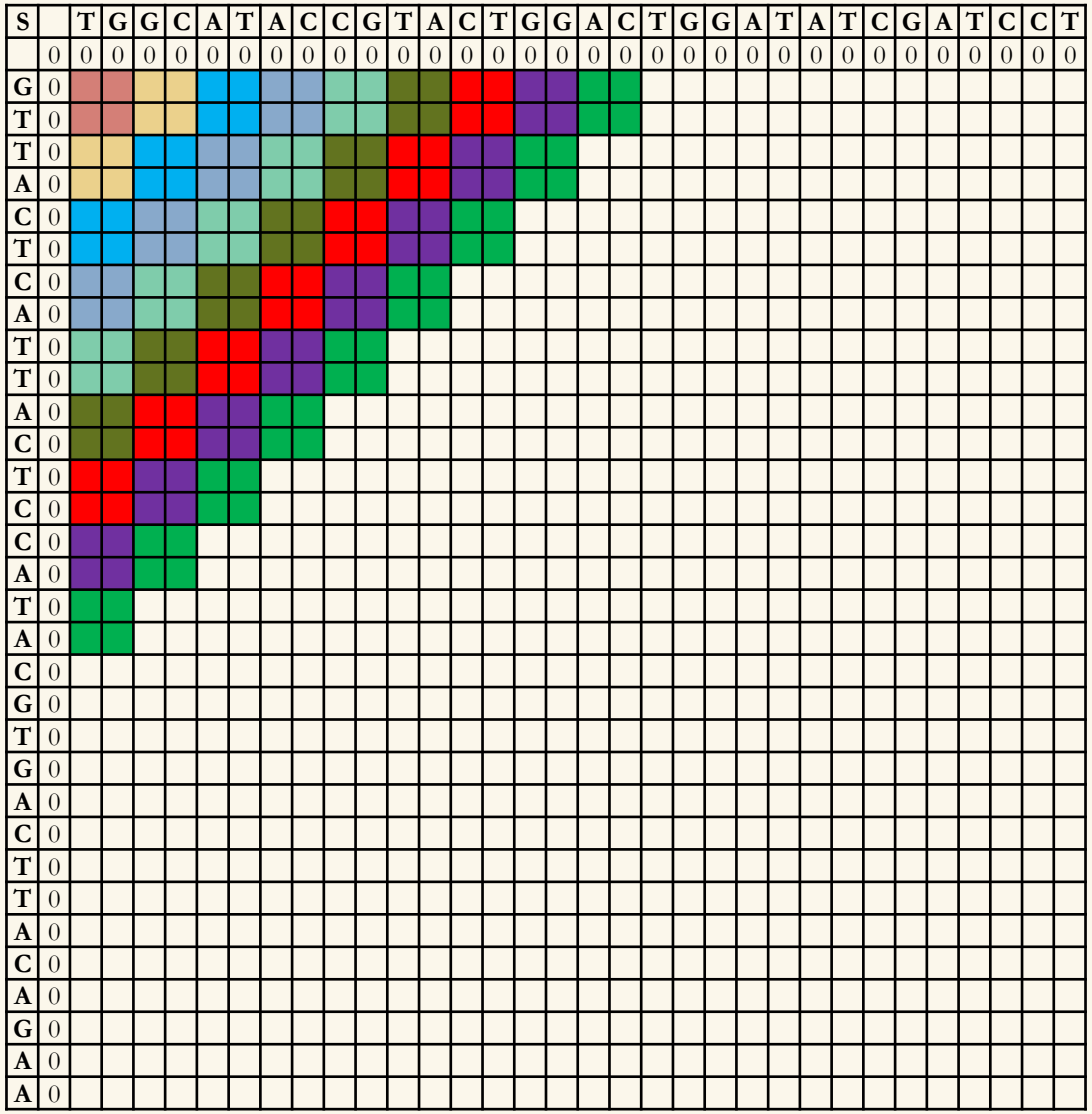
# Score Matrix Computation

| S | | T | G | G | C | A | T | A | C | C | G | T | A | C | T | G | G | A | C | T | G | G | A | T | A | T | C | G | A | T | C | C | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

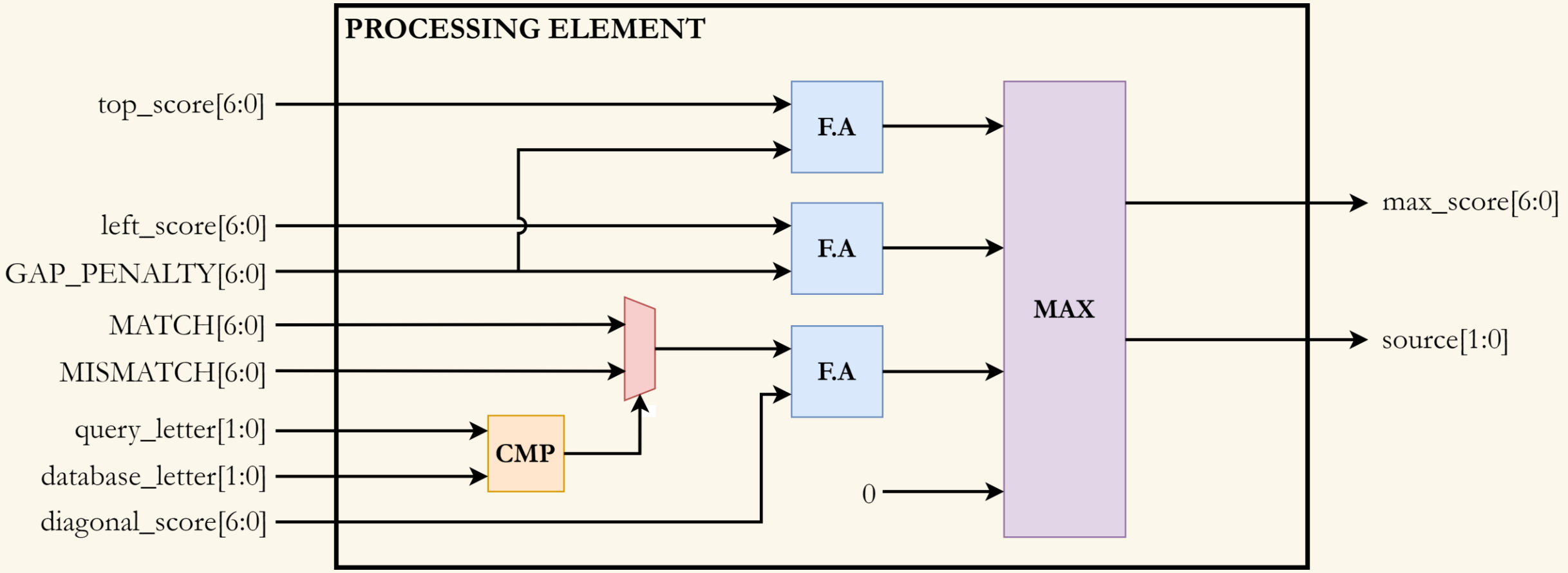
# Score Matrix Computation

| S | | T | G | G | C | A | T | A | C | C | G | T | A | C | T | G | G | A | C | T | G | G | A | T | A | T | C | G | A | T | C | C | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

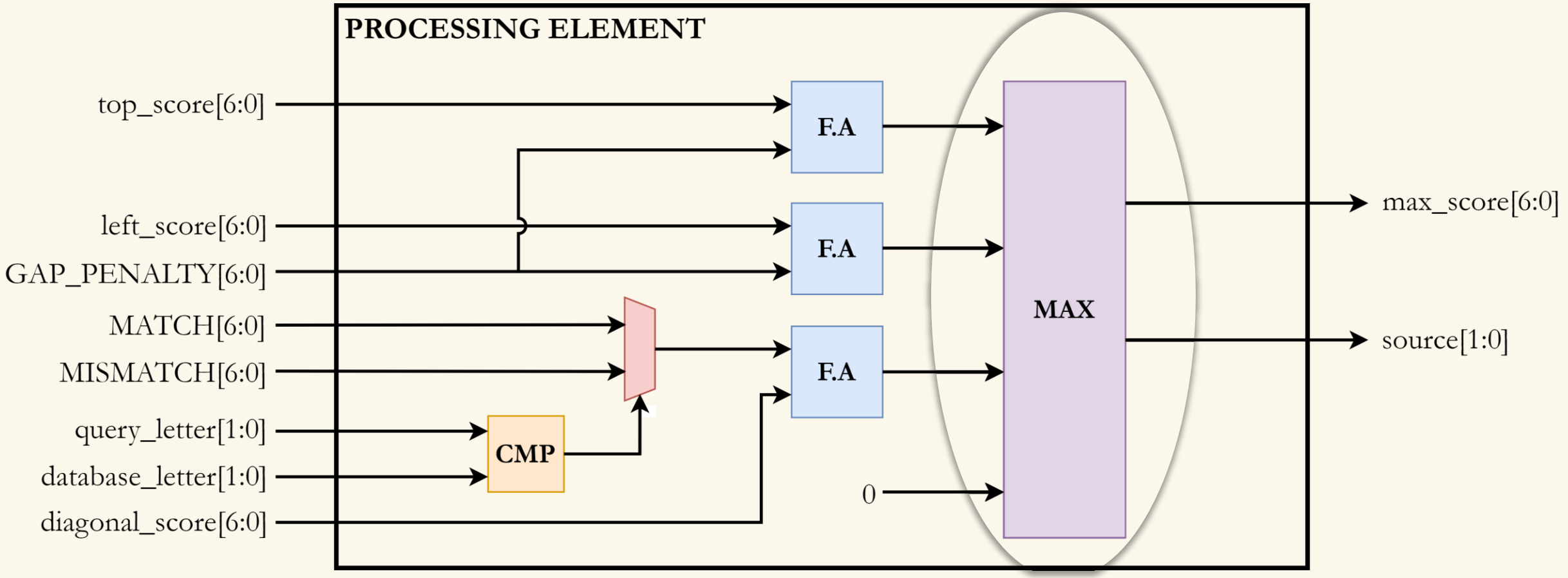
# Score Matrix Computation



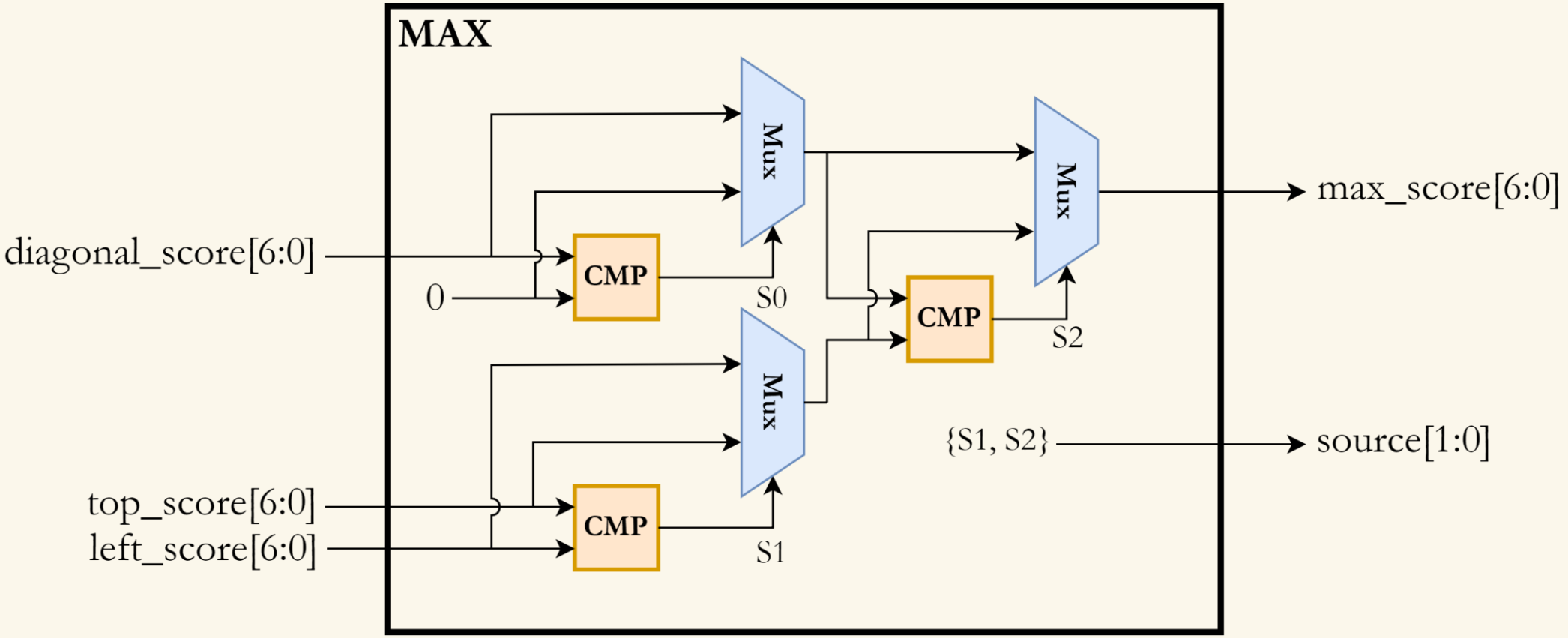
# Processing Element



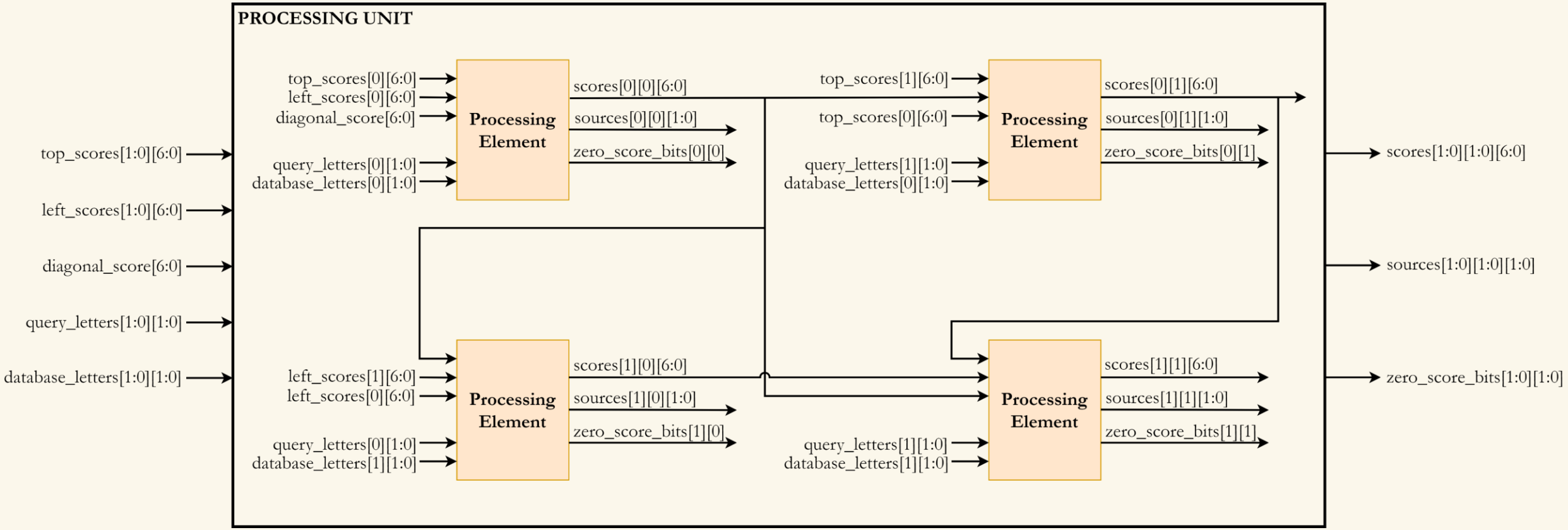
# Processing Element



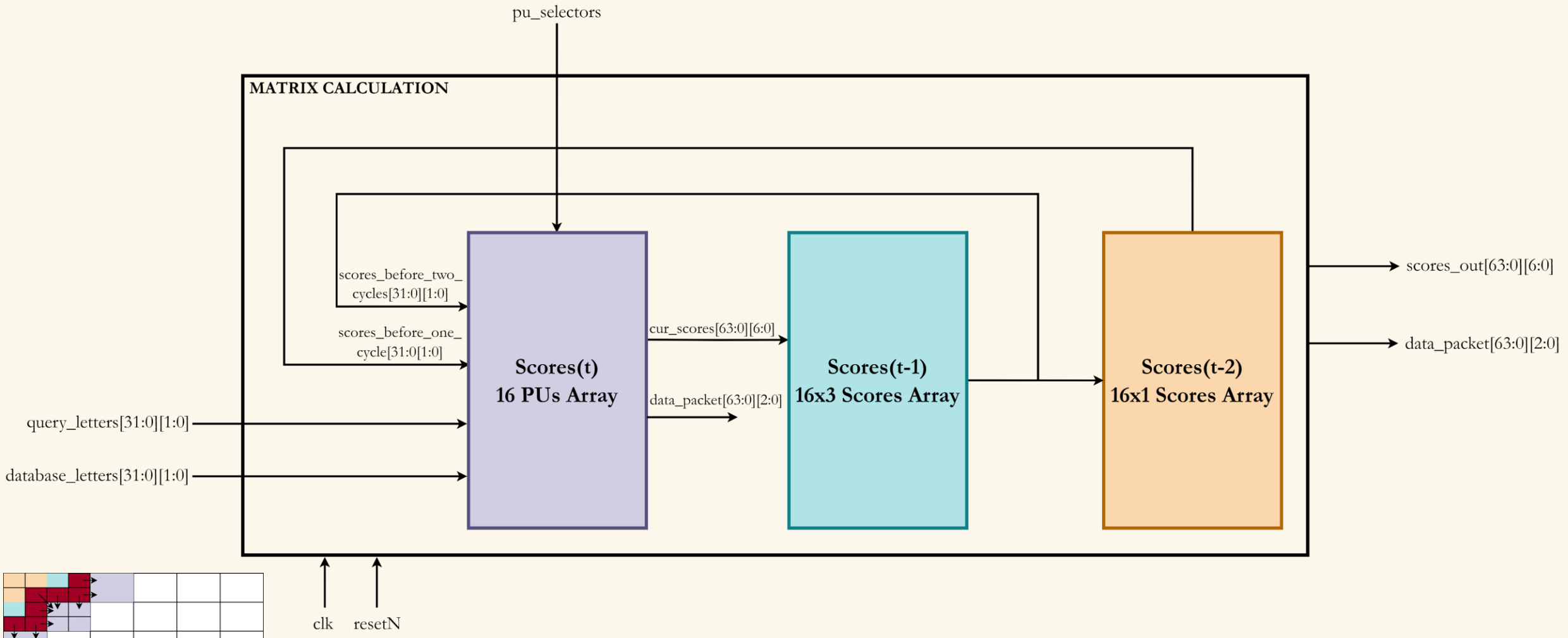
# Max Unit

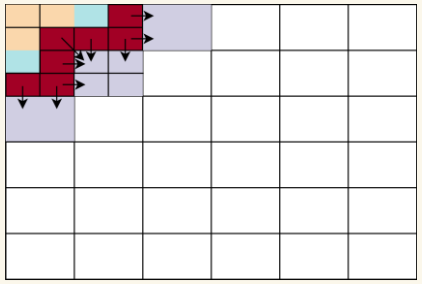

MAX
Mux
Mux
Mux
CMP
CMP
CMP
diagonal_score[6:0]
0
top_score[6:0]
left_score[6:0]
S0
S1
S2
{S1, S2}
max_score[6:0]
source[1:0]

# Processing Unit

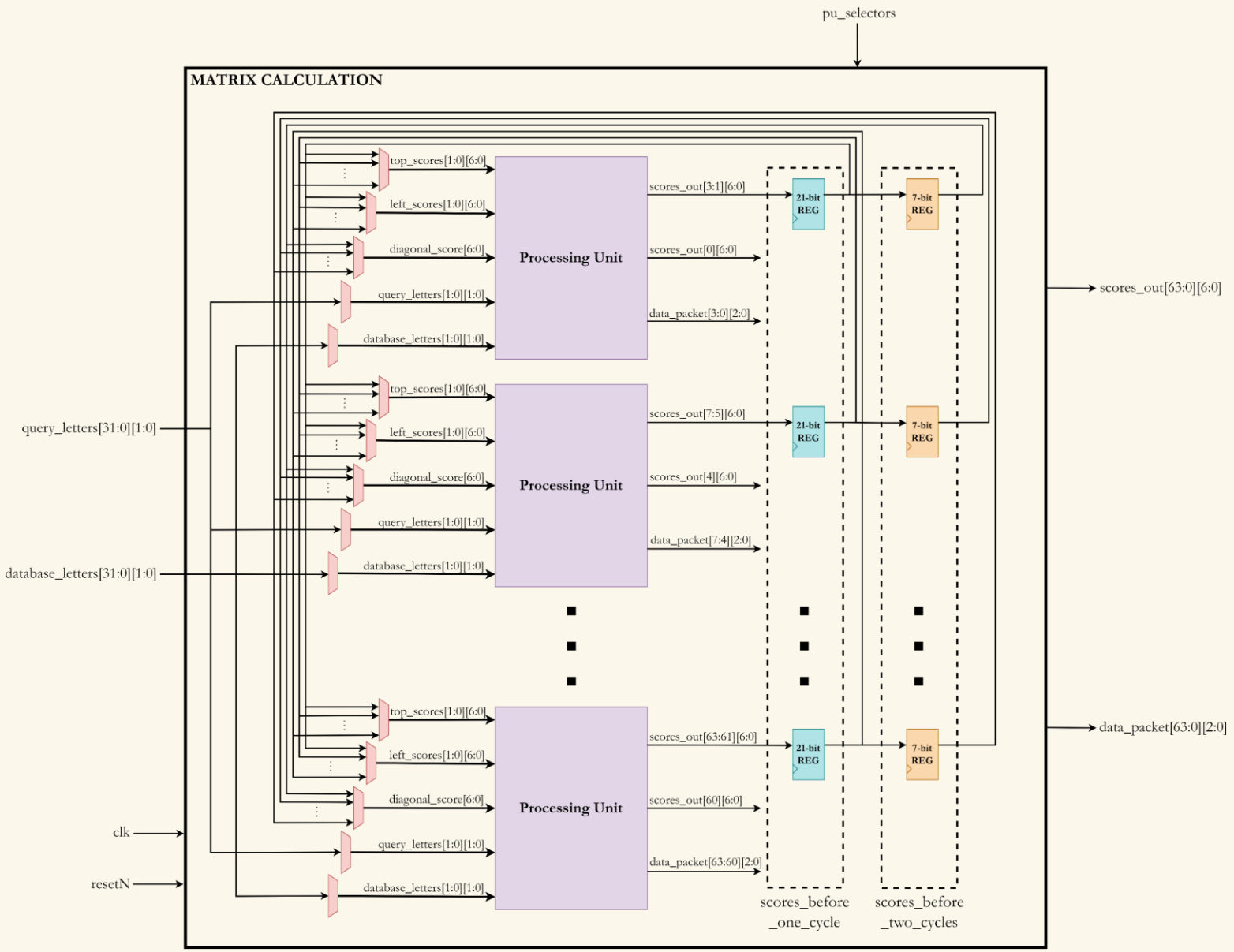


# Score Matrix Computation

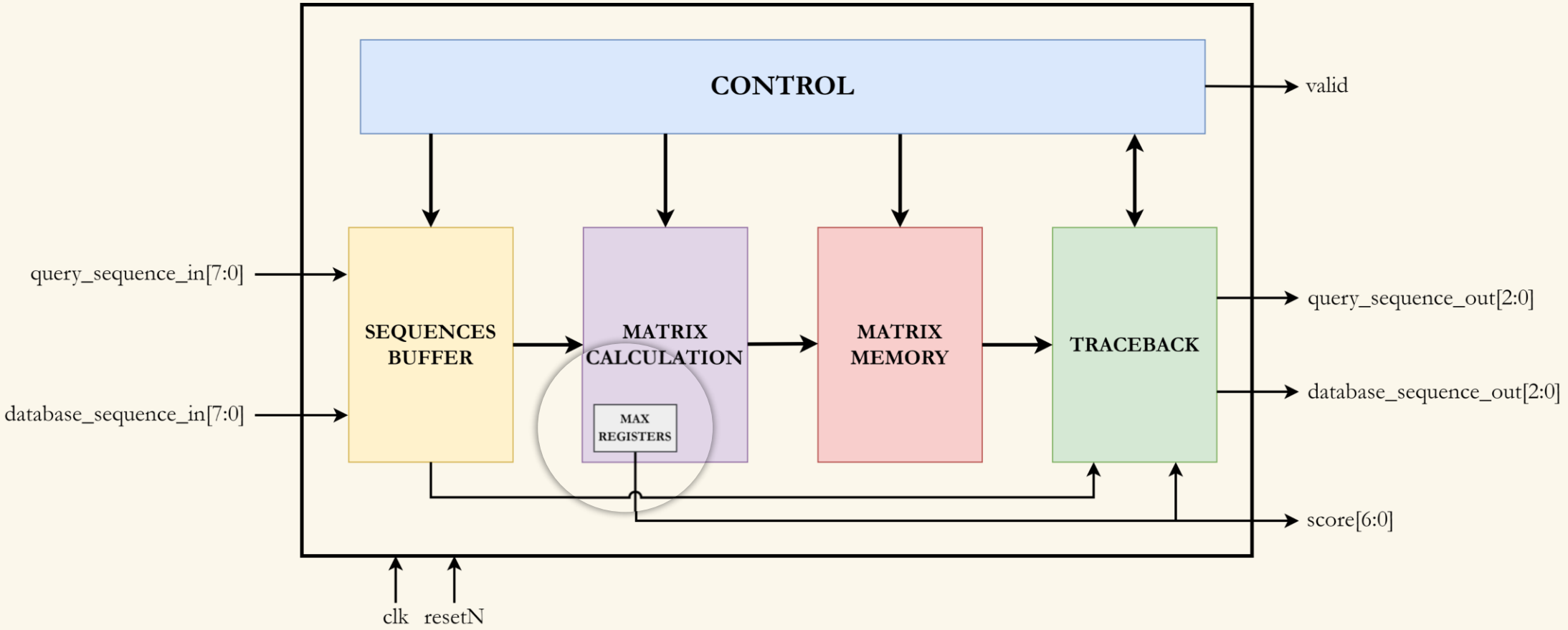


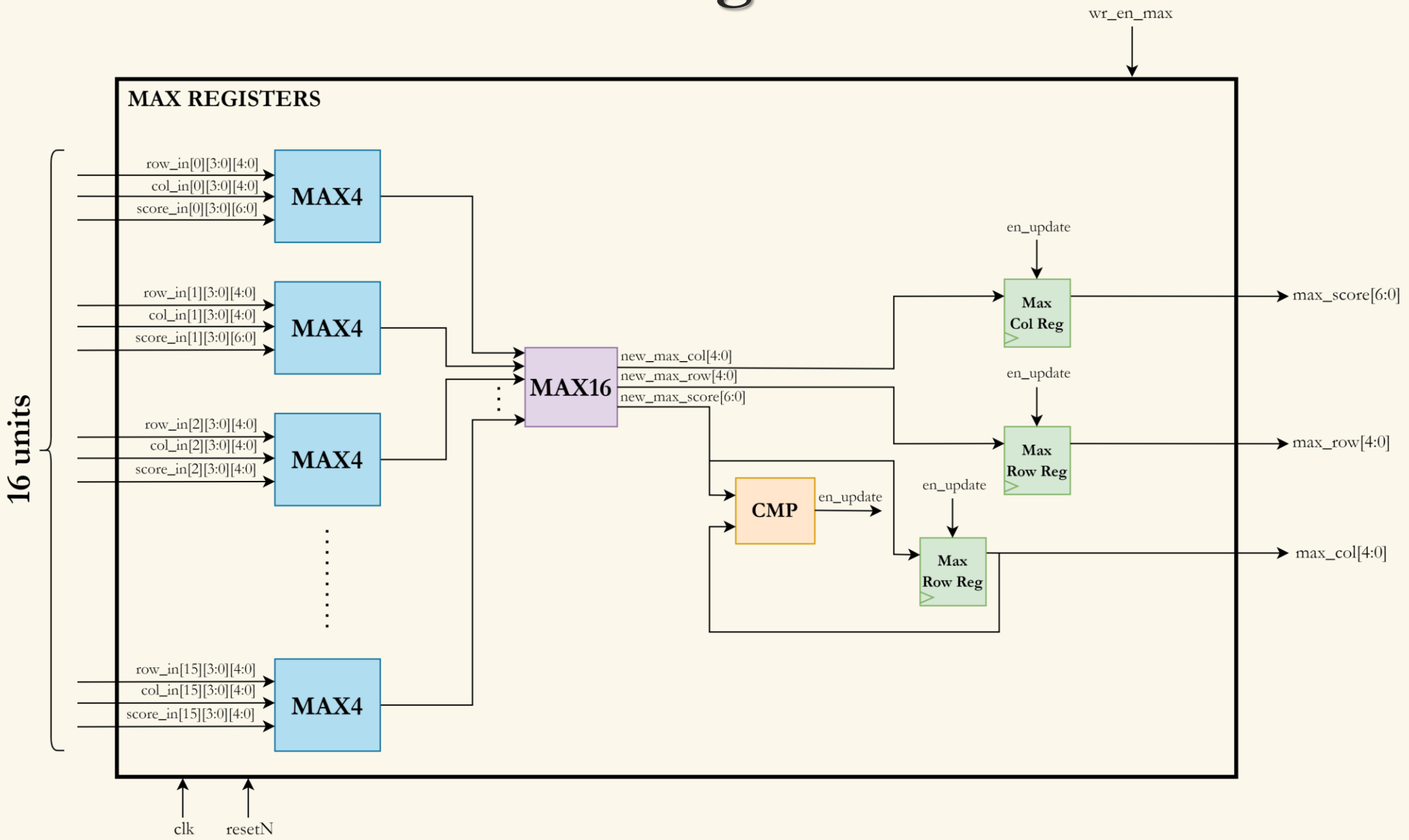
# Score Matrix Computation



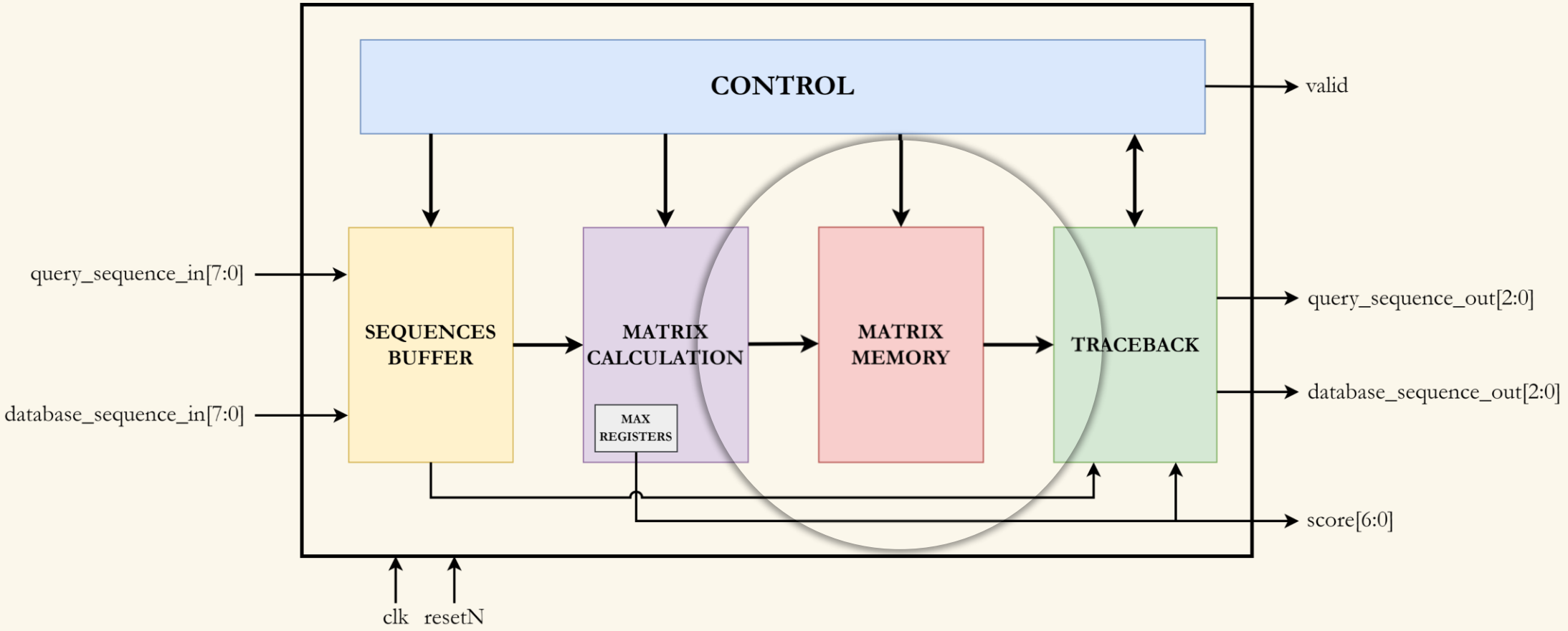
# Max Registers



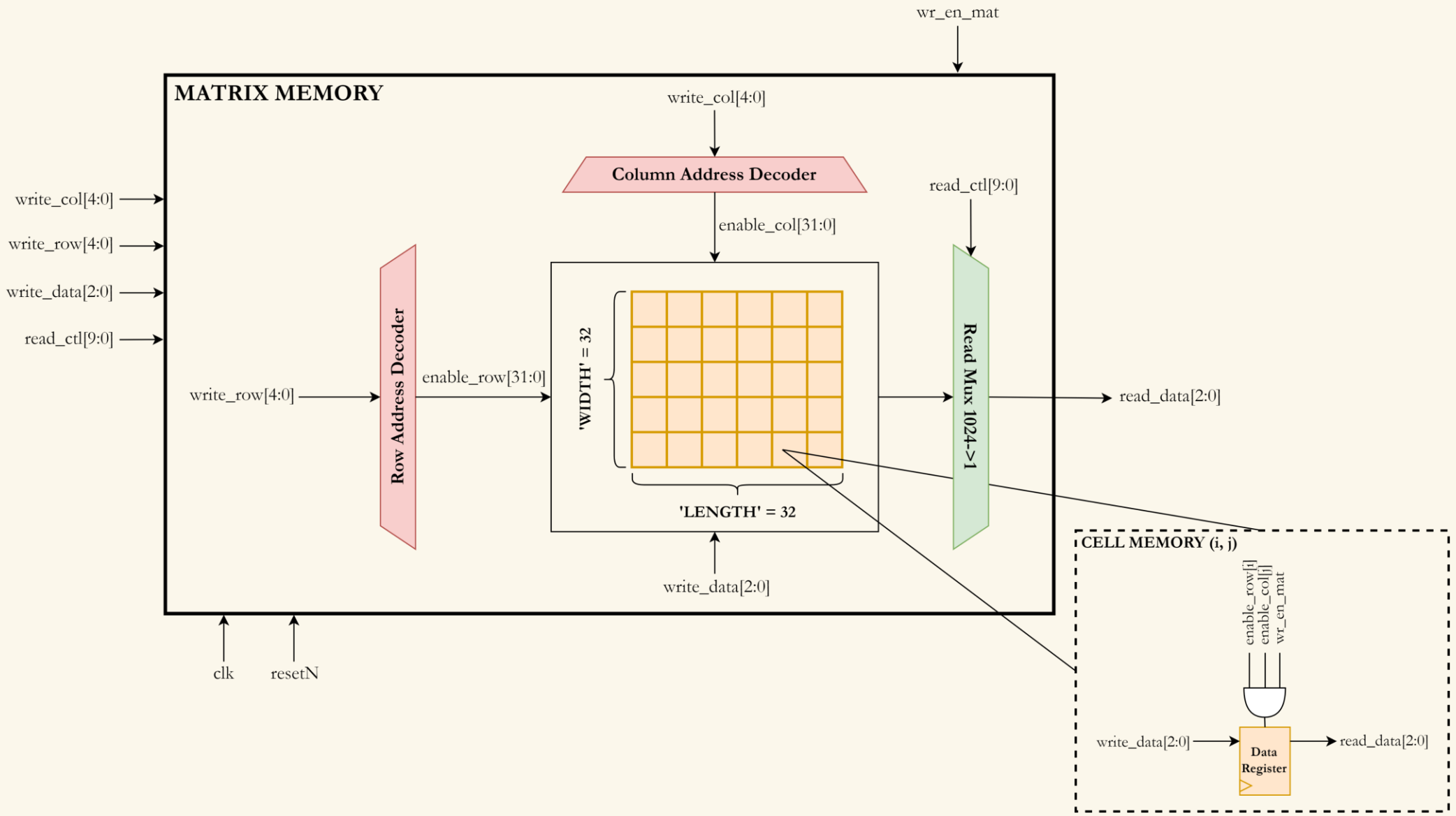
# Max Registers



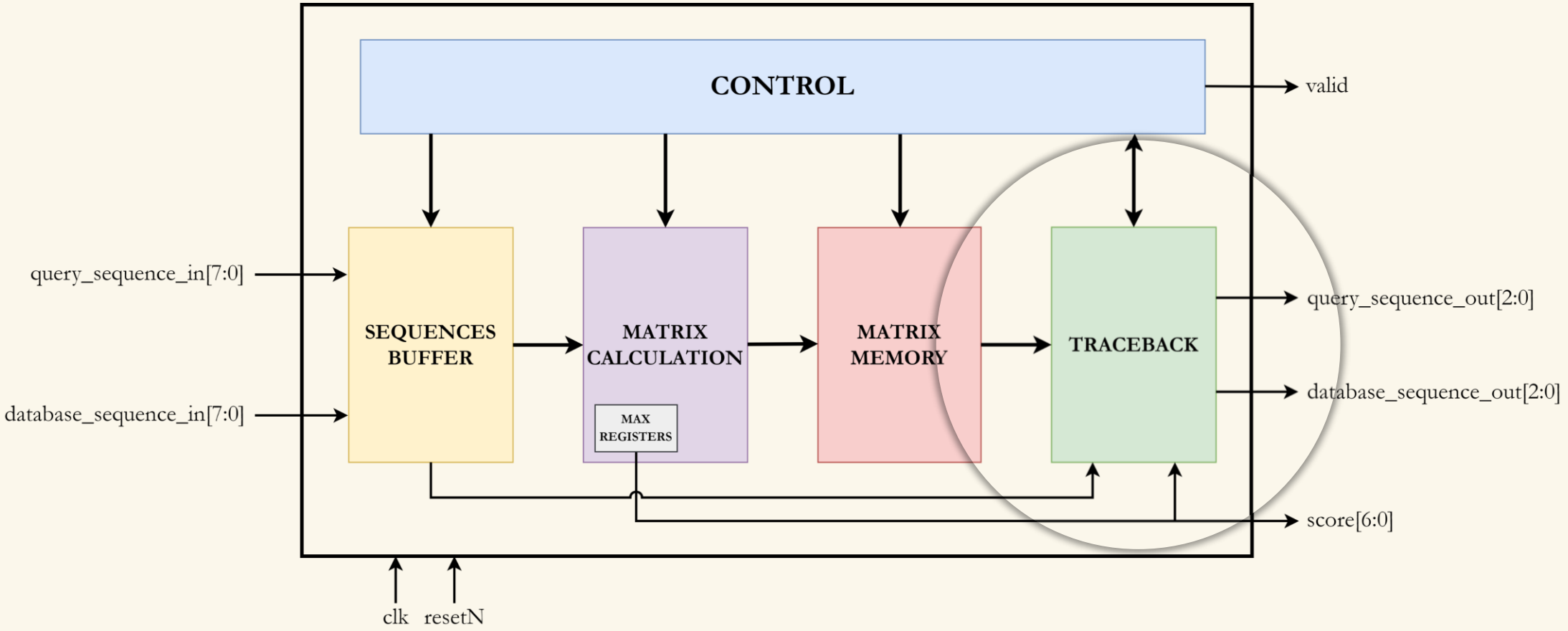
# Matrix Memory



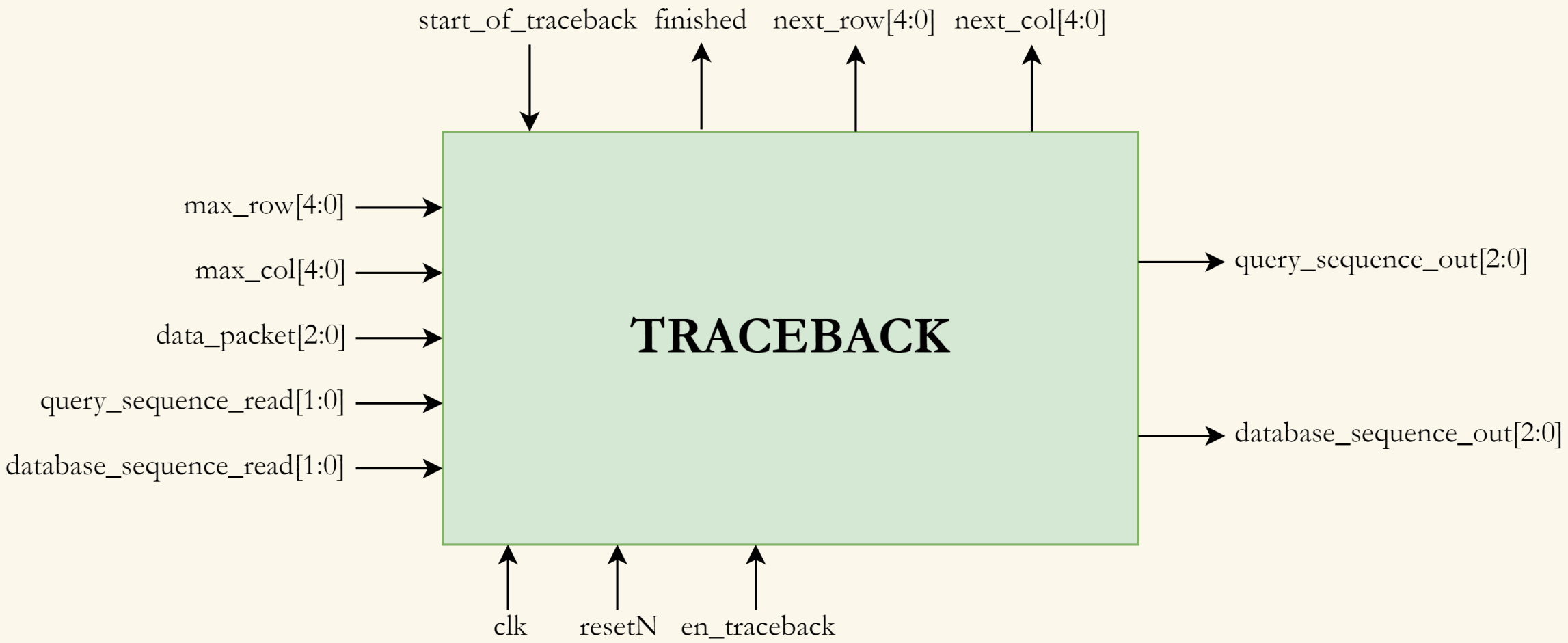
# Matrix Memory



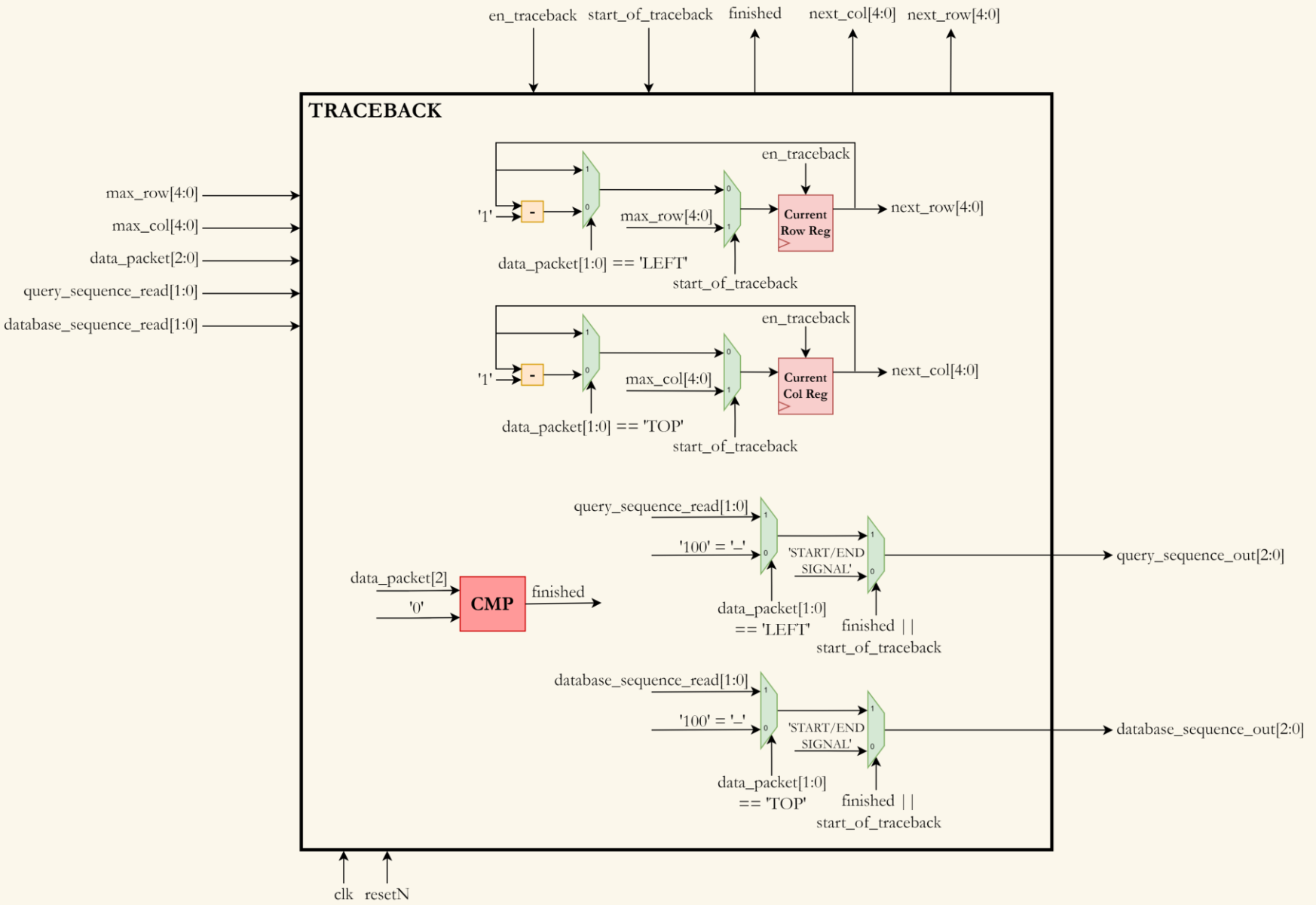
# Traceback


CONTROL
valid
query_sequence_in[7:0]
database_sequence_in[7:0]
SEQUENCES BUFFER
MATRIX CALCULATION
MAX REGISTERS
MATRIX MEMORY
TRACEBACK
query_sequence_out[2:0]
database_sequence_out[2:0]
score[6:0]
clk
resetN

# Traceback – Interface



# Traceback


en_traceback
start_of_traceback
finished
next_col[4:0]
next_row[4:0]
TRACEBACK
max_row[4:0]
max_col[4:0]
data_packet[2:0]
query_sequence_read[1:0]
database_sequence_read[1:0]
en_traceback
'1'
-
max_row[4:0]
Current Row Reg
next_row[4:0]
data_packet[1:0] == 'LEFT'
start_of_traceback
en_traceback
'1'
-
max_col[4:0]
Current Col Reg
next_col[4:0]
data_packet[1:0] == 'TOP'
start_of_traceback
query_sequence_read[1:0]
'100' = '–'
'START/END SIGNAL'
query_sequence_out[2:0]
data_packet[2]
'0'
CMP
finished
data_packet[1:0] == 'LEFT'
finished | | start_of_traceback
database_sequence_read[1:0]
'100' = '–'
'START/END SIGNAL'
database_sequence_out[2:0]
data_packet[1:0] == 'TOP'
finished | | start_of_traceback
clk
resetN

# Next Steps

- Finalize full system RTL simulations
- Synthesis
- Physical design
- Tape out (by end of December 2023)
- Post-silicon Testing

The Andrew and Erna Viterbi Faculty of
ELECTRICAL & COMPUTER
ENGINEERING

VLSI
המעבדה ל-
Laboratory

# THANK YOU!