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Problem statement

Realization of "Conway's game of life" using Logisim and Cdm-8.

"Conway's game of life" is a cellural automaton. This is a zero player game, player set an initial condition and then only can observe the development.

Rules:

1. The field of "Game of life" is a grid of square cells. Each cell has two conditions it can be live or dead.
2. Every cell has 8 neighbors, which are the cells that are horizontally, vertically, or diagonally adjacent.
3. Any live cell with less than two neighbors dies because of underpopulation.
4. Any dead cell with three neighbors becomes a live.
5. Any live cell with two or three neighbors continues to live.
6. Any live cell with more than three neighbors dies because of overpopulation.

We have made 2 powerful improvements and 2 concept changes from the basic technical task.

Improvements:

1. We have composed a toroidal cycled field with size `32*32`
2. We have extended simulation rules choice using 2 8-bit inputs as bit-arrays. Now you can set birth or surviving for any combination of neighbors count from `1` to `8`.

Concept changes:

1. We have decided to use Logisim keyboard handling circuit for cursor moving and cell changing instead of a joystick.
2. Video buffer (named random write buffer) has been made asynchronous. Besides, we have add `clear` input to it.

Other components wasn't mentioned in basic technical project. Here you can see our addition for the technical project.

Concept

Realization of "Conway's game of life" has two main parts, Logisim part and Assembler part.

Logisim part is responsible for:

1. User interface. Player can set his own simulation rules and start a new game or clean the field with special buttons.
2. Display. Display represented by matrix with size `32x32`. Matrix has two different colors for dead and alive cells.
3. Constructing environment data for current cell.
4. Storing current generation and new generation of our simulation.

Assembler:

1. Spreads simulation rules.
2. Iterates by all rows and skip null rows.
3. Iterates by cells in every row which have significant environment.
4. Gets cell's environment data and sends invert signal if it is necessary.
5. Interrupts field processing if static generation was reached.

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Analogues

We have found 3 interesting versions of "Conway's game of life" in the Internet

1. Version is full madden in Logisim with toroidal field `16*16`. Works fast but small field doesn't allow construct a lot of setups. For example "Pulsar" or "Copperhead":
2. Web version - fast and convenient. Has endless field. Alas, we do not have similar capacities
3. In this video you can see Turing machine, 1D and 3D version, CPU-like version and so on.

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User guide

Our version of "Conway's game of life" works with universal sets of conditions for birth and survival.

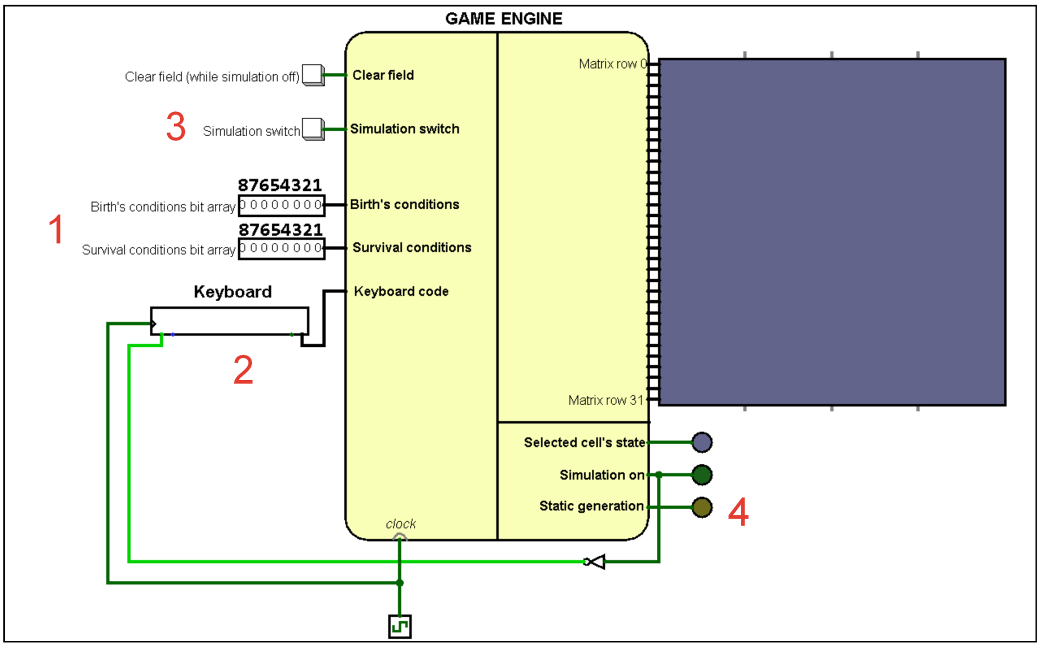
1. To set conditions switch bits in birth/survival 8-bit inputs where value 1 on position `N` means that birth/survival will be fulfilled when cell has `N` neighbors.
2. After this click on keyboard element and use one of two keyboard layouts to move blinking cursor and change cells' states.

KEY	DIRECTION
`NUM 1` / `Z`	bottom-left
`NUM 2` / `S`	bottom
`NUM 3` / `C`	bottom-right
`NUM 4` / `A`	left
`NUM 6` / `D`	right
`NUM 7` / `Q`	top-left
`NUM 8` / `W`	top
`NUM 9` / `E`	top-right

`NUM 5` / `Space` - change state of selected cell

3. When you have set initial field state press button "Simulation switch" and observe evolution! **You can stop simulation and edit field at any time. But if CPU cursor has processed some cells you would get half-counted generation**

4. If the next generation is the same as previous simulation will be interrupted with yellow LED-indicator lights up.



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Documentation

Special terms

There are some special terms that are used in different places below:

1. **Environment** is cell or cells' set with a border one cell wide on all sides. E.g.:
    - for cell `(Y, X)` environment will be `[(Y-1, X-1), (Y-1, X), (Y-1, X+1), (Y, X-1), (Y, X), (Y, X+1), (Y+1, X-1), (Y+1, X), (Y+1, X+1)]` with **centre bit** bit `(Y, X)` (term **centre bit** is meaningful only for one cell's environment)
    - environment for full row (`all X in range [0, 31]`) `Y` will be full rows `Y-1`, `Y` and `Y+1`
2. **Environment sum** is a sum of cells' values from environment border
3. **Significant environment** is an environment which has at least one cell with value `1` (**including border cells**)

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Assembler

Short description

Due to optimization reasons CdM-8 has only one main task - iteration by Y,X positions and determination whether cell should be changed. After the all cells' processing CdM-8 send signal to update generation `PSEUDO WRITE` register

In ASM code we use `asect` constants like this:

```
asect 8
constSample:

# ...

ldi r0, constSample  # r0 sets to 8
```

Often we save address value to its address:

```
ldi r0, IOAddr
st r0, r0
```

The reason for this action is `PSEUDO WRITE` mode for some I/O registers

RAM distribution

- `0xd0` - flag for checking non-static generation
- `0xe0` - birth's conditions first byte
- `0xe8` - death's conditions first byte

Stack initial position - `0xe0`

▼ Constants for this cells

```
# Internal data addresses
asect 0xe0
birthConditionsRowStart:

asect 0xe8
deathConditionsRowStart:

asect 0xd0
isNonStaticGeneration:
```

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Cells referring to I/O regs.

Cells from `0xf0` to `0xff` are allocated for I/O registers.

See detailed description in Logisim topic

▶ Constants for I/O cells

```
# Asects for I/O registers
asect 0xf0
IOGameMode:

asect 0xf1
IOBirthConditions:

asect 0xf2
IODeathConditions:

asect 0xf3
IOY:

asect 0xf4
IOX:

asect 0xf5
IOBit:

asect 0xf6
IOEnvSum:

asect 0xf7
IONullRowsEnv:

asect 0xf8
IONextSignificantX:

asect 0xf9
IOInvertBitSignal:

asect 0xfa
IOUpdateGeneration:
```

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Code description

Simulation start

This part just waits whilst user presses start button and after it loads game conditions to RAM using spreadByte subroutine

For optimized conditions checking survival conditions inverts to death's conditions. See how it works here

▶ Code

```
asect 0
br start

#==============================#
#     Place for subroutines    #
#==============================#
...
#===============================

start:
        # Move SP before I/O and field addresses
        setsp 0xd0


        # Waiting for IOGameMode I/O reg. != 0
        ldi r1, IOGameMode
        do
                ld r1, r0
                tst r0
        until nz

        ldi r1, gameMode
        st r1, r0

        # Read birth and death conditions from I/O regs.
        ldi r1, IOBirthConditions
        ld r1, r0
        ldi r1, birthConditionsRowStart
        jsr spreadByte
        ldi r1, IODeathConditions
        ld r1, r0
        ldi r1, deathConditionsRowStart
        jsr spreadByte
```

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Main cycle

This part will repeats while simulations stays on.

Before cycle we reset flag in cell `isNonStaticGeneration` and update stable generation's buffer using save signal to `IOUpdateGeneration` referred to Logisim. As a result, we can get correct data for processing cells.

Main cycle iterates by `Y` (row index) in decreasing order `[31, 0]`.

We use two optimizations for skipping meaningless iterations:

1. If rows `Y-1`, `Y` and `Y+1` (rows environment) are null (flag from `IONullRowsEnv` referred to I/O register will be `1`) $\rArr$ we decrement `Y`.
2. If rows environment isn't null we iterates by `X` with significant environment (surrounding sum > 0 or centre bit = 1) which are received from `IONextSignificantX` I/O register. When new received `X` >= current `X` we end cycle for this row

For every significant `(Y, X)` combination we get state of selected cell and its environment's sum using `IOBit` and `IOEnvSum` addresses which are referred to I/O registers

For zero sum:

- Alive cell is killed immediately using save signal `IOInvertBitSignal` referred to Logisim
- Empty cell is skipped

For non-zero sum we call subroutine `processBit`

If there are no changed cells (value in `isNonStaticGeneration` will stay `0`) we make a conclusion that there is a static generation so we stop simulation using save signal to game mode I/O register and interrupt main cycle.

▶ Code

```
main:

        # Update stable generation's buffer to get new data from env. data
constructor
        ldi r0, IOUpdateGeneration
        st r0, r0

        # Count new cells' states
        ldi r3, 31 # row iterator
        do
                # If game mode = 0 we interrupt cycle and go to start code part
                # NEW GENERATION CAN BE COUNTED PARTITIONALLY
                ldi r0, IOGameMode
                ld r0, r0
                tst r0
                bz start
```

```
                push r3 # Save row iterator

                # Send Y to logisim
                ldi r0, IOY
                st r0, r3

                # If all rows in env. are null => skip this row
                ldi r3, IONullRowsEnv
                ld r3, r3
                tst r3
                bnz rowProcessed

                ldi r1, 0 # Value for searching first significant X

                # Send X to Logisim
                ldi r0, IOX
                st r0, r1

                # Get the first X with significant env.
                ldi r3, IONextSignificantX
                ld r3, r2

                do
                        # Save currnt X
                        move r2, r1
                        push r1

                        # Send X to Logisim
                        ldi r0, IOX
                        st r0, r1

                        # Read data for this cell
                        ldi r0, IOEnvSum
                        ld r0, r0
                        ldi r1, IOBit
                        ld r1, r1

                        # Check birth or death conditions and save bit depends on
conditions
                        if
                                tst r0
                        is nz
                                jsr processBit
                        else
                                # If sum = 0 alive cell must die
                                if
                                        tst r1
                                is nz
                                        ldi r0, IOInvertBitSignal
                                        st r0, r0

                                        # Set flag for non-static generation to its
address (!= 0)
                                        ldi r0, isNonStaticGeneration
                                        st r0, r0
```

```
                        fi
                fi

                # Get the next X with significant env. lower than current
                pop r1
                ld r3, r2

                # If new X greater of equal => cycle ends
                cmp r2, r1
        until ge
        rowProcessed:

        # Get and decrement row iterator
        pop r3
        dec r3
    until mi
# Go to main cycle begin if generation isn't static
ldi r0, isNonStaticGeneration
ld r0, r0
tst r0
bnz main
# Otherwise reset game mode and go to start
ldi r0, IOGameMode
st r0, r0
br start
```

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Subroutines

`spreadByte`

- This subroutine spread byte from `r0` into cells from `r1` to `r1 + 7`. In other words `spreadByte` writes every bit of byte from `r0` to cells from `r1` to `r1 + 7`, writing the low order bit into `r1` and the high oreder bit into `r1 + 7`.
- `spreadByte` is used to write game settings to the memory.
- Thanks to `spreadByte` we can easily decide what we should do with current cell without using loops.

▶ Code

```
spreadByte:
        # Iterator
        ldi r3, 0b00001000 # 8
        while
                tst r3
        is nz
                # The process of spreading byte
                # Get lower bit and save to current cell
                ldi r2, 0b00000001
                and r0, r2
                st r1, r2

                # Increment cell address, shift data byte and decrement iterator
                inc r1
                shra r0
                dec r3
        wend
rts
```

`processBit`

- This subroutine gets neighbors' sum in `r0` and centre bit value in `r1`.
- Depending on bit value it chooses birth or death conditions
- Thanks to spreaded conditions we can simply add to conditions' begin address value `r0 - 1` and check data by new address
- If there is `1` we should change value in selected cell so we send this signal to Logisim and set flag in `isNonStaticGeneration` to non-zero value.

▶ Code

```
processBit:
        # r0 - sum
        # r1 - bit
        # Send save signal to PSEUDO reg. IOInvertBitSignal if bit should be
```

```
inverted (we count that IOX and IOY regs. contain correct coords.)
        if
                tst r1
        is z
                ldi r2, birthConditionsRowStart
        else
                ldi r2, deathConditionsRowStart
        fi
        # Check bit in spreaded space
        dec r0
        add r0, r2
        ld r2, r2
        # If there is 1 than we switch bit
        if
                tst r2
        is nz
                ldi r0, IOInvertBitSignal
                st r0, r0

                # Set flag for non-static generation to its address (!= 0)
                ldi r0, isNonStaticGeneration
                st r0, r0
        fi
rts
```

What to do if there is no neighbors?

We decided that alive cell should die and death cell cannot birth. Due to specific work with `sum = 0` this case for `bit = 1` is processed in main part:

```
...
        # Check birth or death conditions and save bit depends on conditions
        if
                tst r0
        is nz
                jsr processBit
        else
                # If sum = 0 alive cell must die
                if
                        tst r1
                is nz
                        ldi r0, IOInvertBitSignal
                        st r0, r0

                        # Set flag for non-static generation to its address (!= 0)
                        ldi r0, isNonStaticGeneration
                        st r0, r0
                fi
        fi
...
```

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Logisim

Main concept

Here you can see main jobs for Logisim part and logical ordered references for all of them:

1. Communication with user
    1. Controls
    2. Game screen
    3. Blinker for pretty cursor visualization
2. Storing game's data
    1. Random write buffer
    2. Stable generation's buffer
3. Constructing data for CPU
    1. Used I/O registers: cell and environment data
    2. Environment data constructor
4. Creating new generation by CPU signals
    1. Used I/O registers: cell and signals
    2. Row's bit invertor
    3. Random write buffer
    4. Stable generation's buffer

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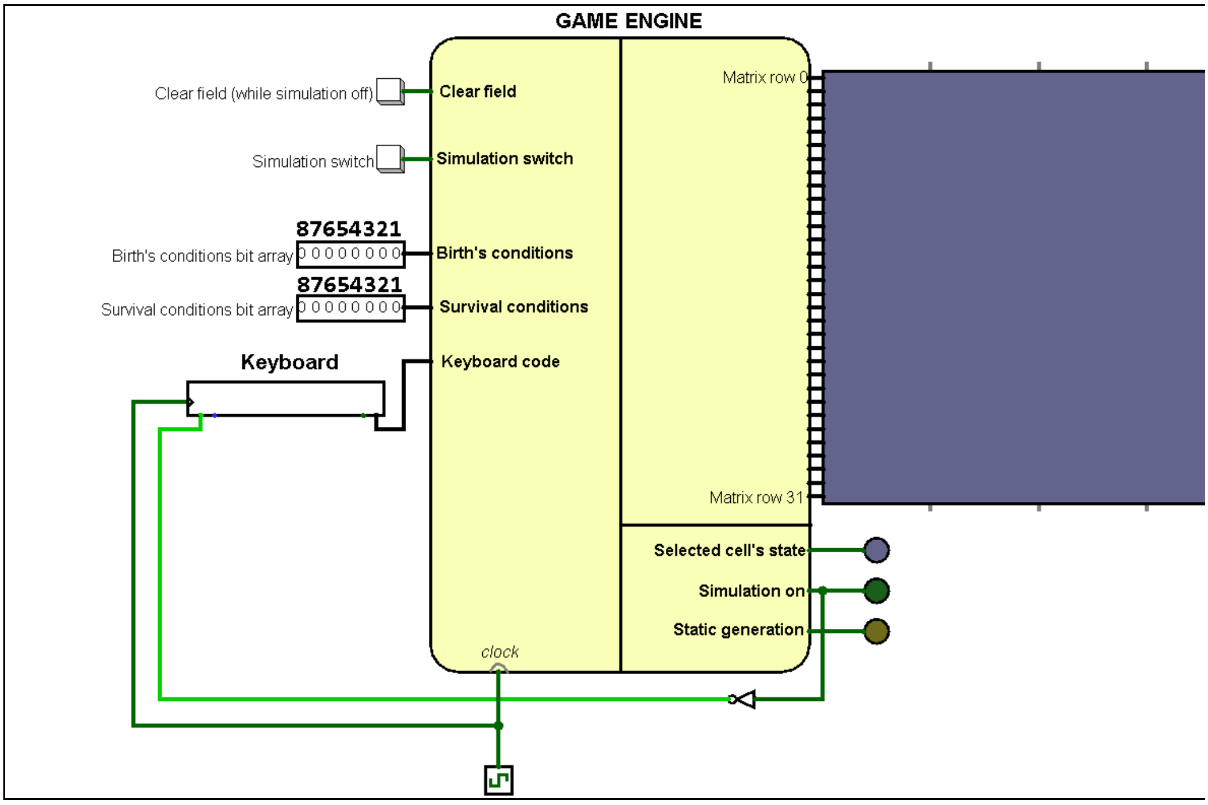
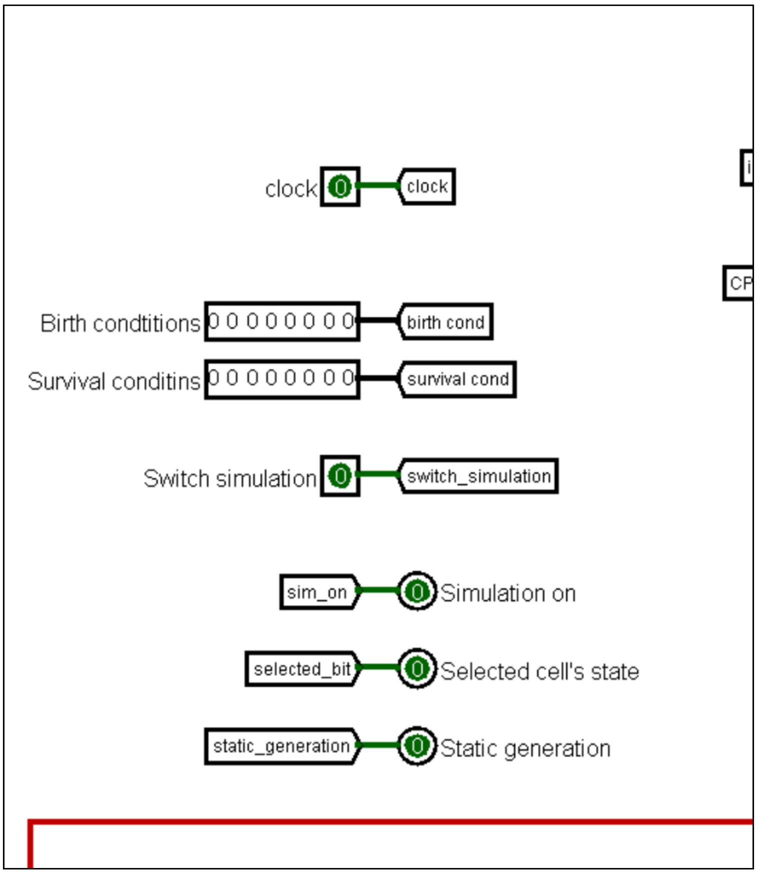
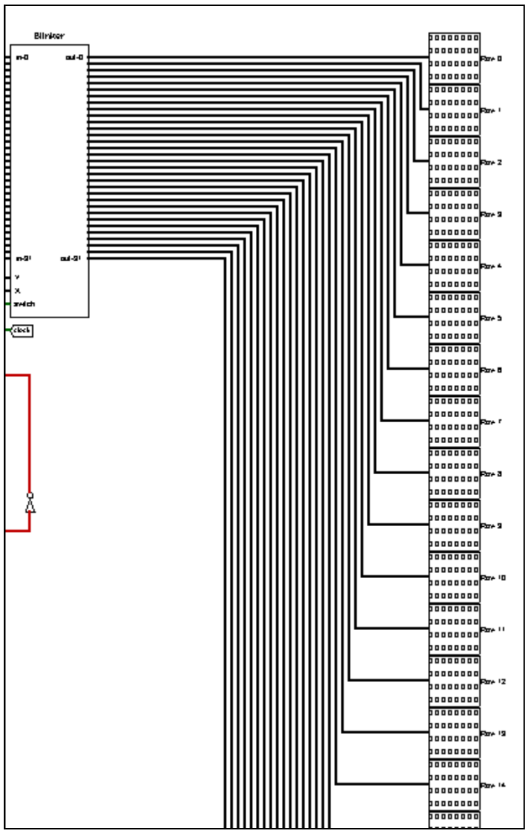
Engine circuit

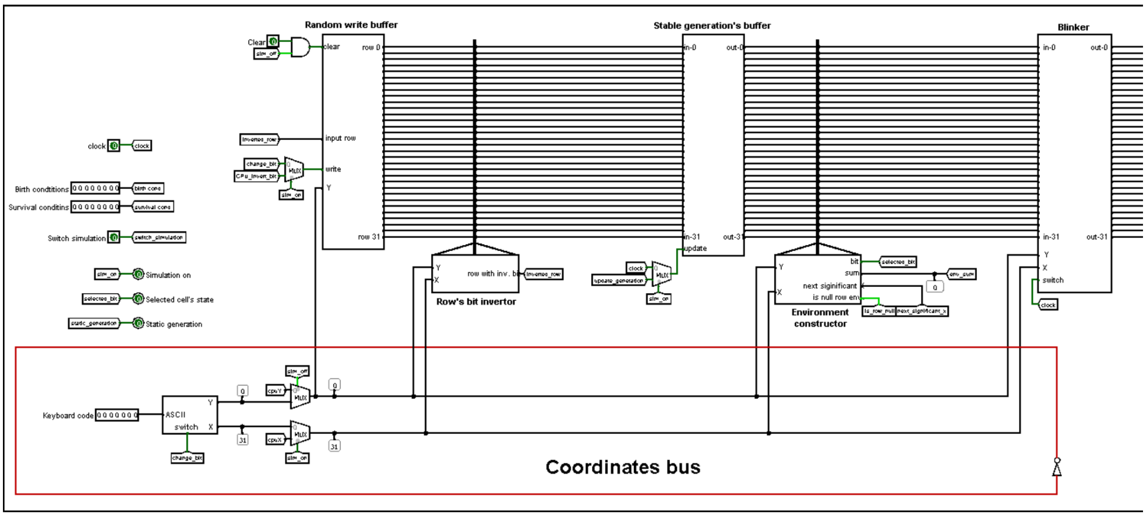


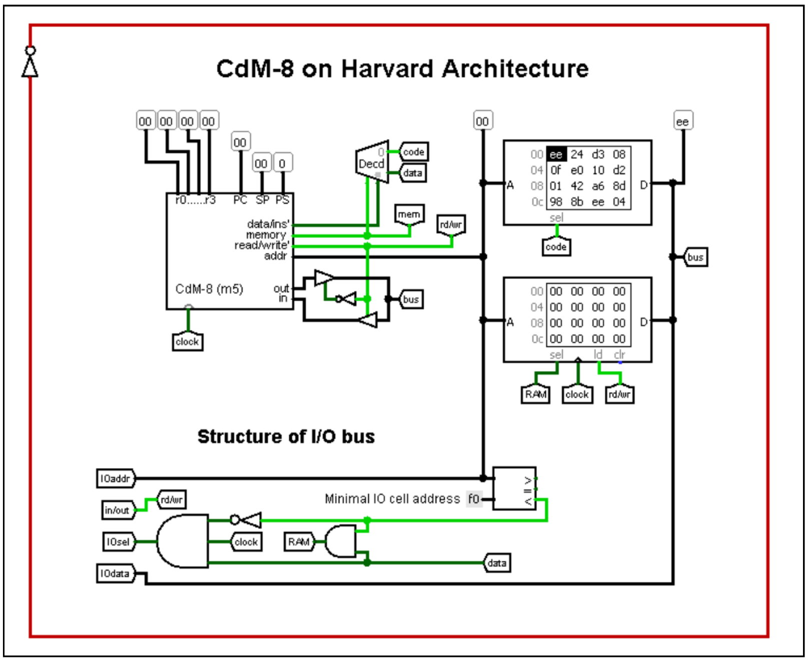
This circuit is main one element of game. It handles all inputs from user and gives finally 32 32-bit rows to matrix and outputs `simulation on`, `selected cell's state` and `static generation`.



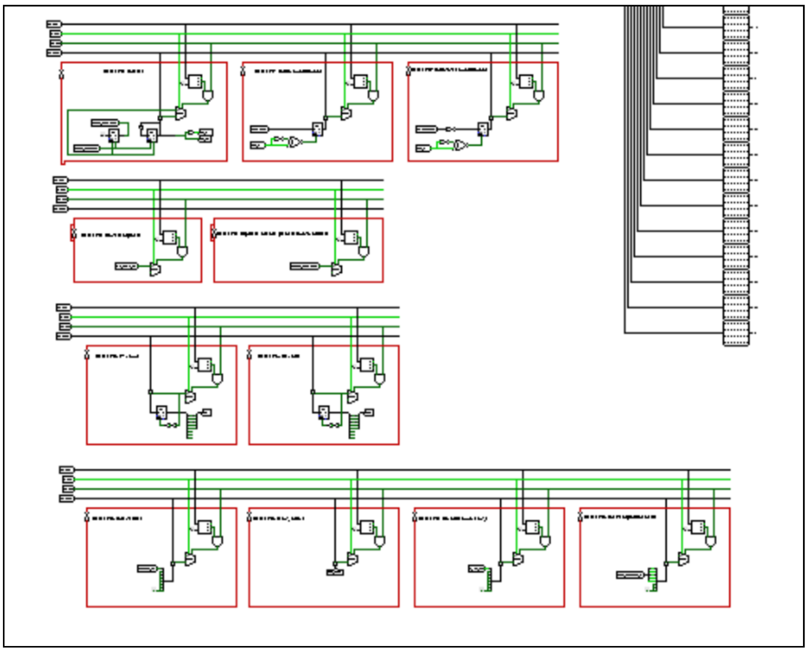


This circuit contains:

1. Most of all circuits below with connected to them coordinates bus (*excepting binary selector and row environment mask*):
    - 

2. CdM-8 integration scheme with Harvard architecture:
    - 

3. All I/O registers:

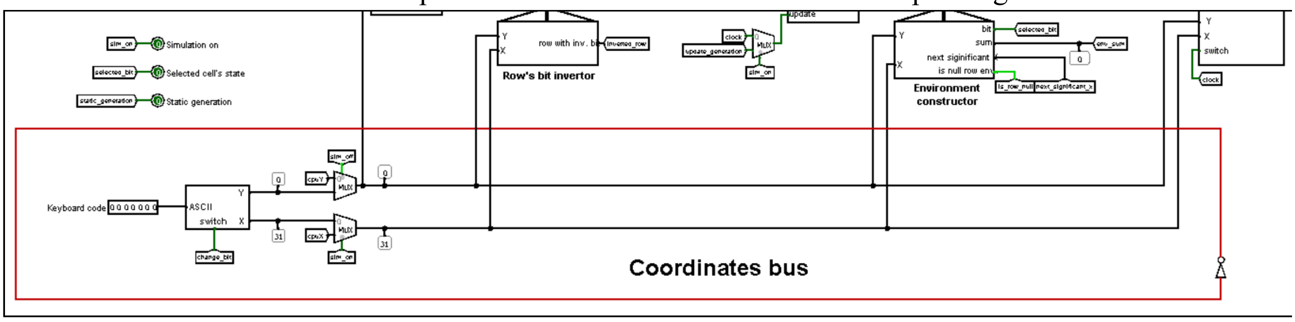


Coordinates bus

Most of circuits work with coordinates Y (row index) and X (bit index) and coordinates go from 2 sources:

- When simulation off they go from keyboard controller which handles user's inputs
- When simulation on they go from 2 I/O registers

Therefore we use two multiplexers that choose coordinates source depending on simulation state:



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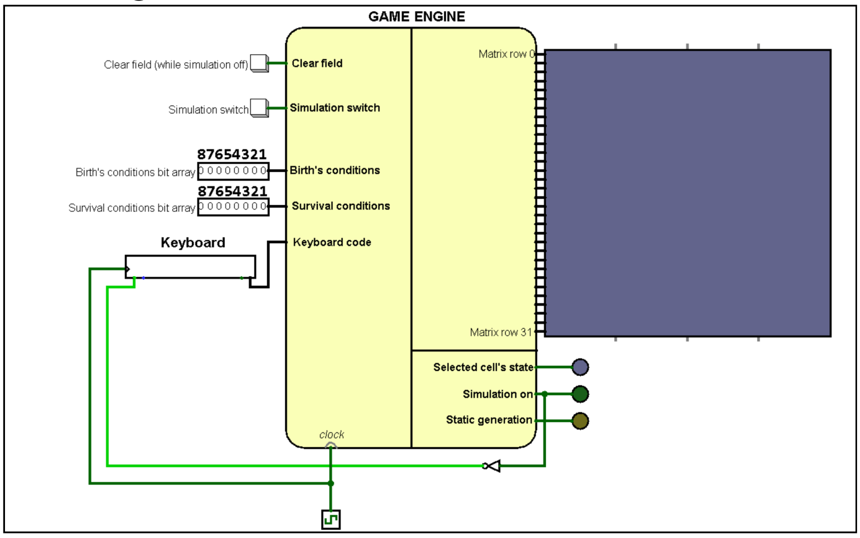
Controls

Main signals



Simulations switch button switches between simulation and setting modes. **When we turn from simulation to setting mode we can get unfinished new generation**

Two 8-bit inputs let us set different conditions for birth and survival. Bit value `1` on position `N` means fulfilling of conditions when cell has `N` neighbors so this inputs represent bit arrays.

Clear button clears all field when simulation is off.

Keyboard Logisim circuit sends keys' ASCII codes to engine. See more below.

On bottom-right side we can see two LED indicators:

1. State of cell under the blinking cursor
2. Simulation state (when simulation is on indicator will light)

Keyboard

Logisim circuits keyboard handles keys' presses and send 7-bit ASCII codes to Keyboard controller inside engine circuit

All keys are working only while we are in the `setting` game mode

Keyboard layouts

Cursor moving:

KEY	DIRECTION	X DELTA	Y DELTA
`NUM 1` / `Z`	bottom-left	`+1`	`+1`
`NUM 2` / `S`	bottom	`0`	`+1`

KEY	DIRECTION	X DELTA	Y DELTA
`NUM 3` / `C`	bottom-right	`-1`	`+1`
`NUM 4` / `A`	left	`+1`	`0`
`NUM 6` / `D`	right	`-1`	`0`
`NUM 7` / `Q`	top-left	`+1`	`-1`
`NUM 8` / `W`	top	`0`	`-1`
`NUM 9` / `E`	top-right	`-1`	`-1`

Deltas defined as shown above because in matrix top-left cell has `X = 31` and `Y = 0`

Cursor position on matrix is marked by blinker

`NUM 5` / `Space` - change state of selected cell in random write buffer using row's bit invertor

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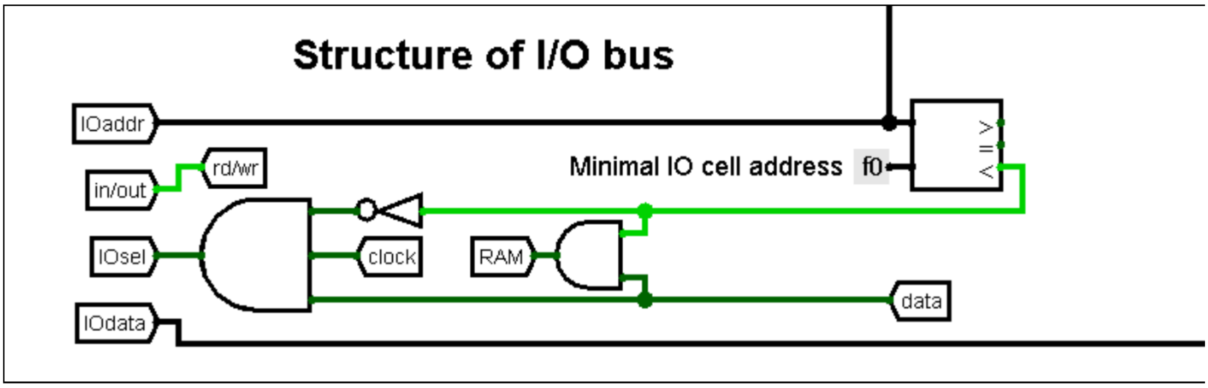
I/O registers

I/O bus have minor changes: selection of I/O addresses from CPU `addr` is detected by `less than` comparator's output with the second input `0xf0` (the first I/O cell address)



I/O registers' types

All types' names are regarding the CPU directions

Registers have trivial types of data direction: `READ ONLY` and `WRITE ONLY`.

`PSEUDO WRITE`

Besides these types we use one specific type - `PSEUDO WRITE`. CPU cannot write data to this "registers". Main goal for this type is handle `write` signal by CdM-8's `st` instruction.

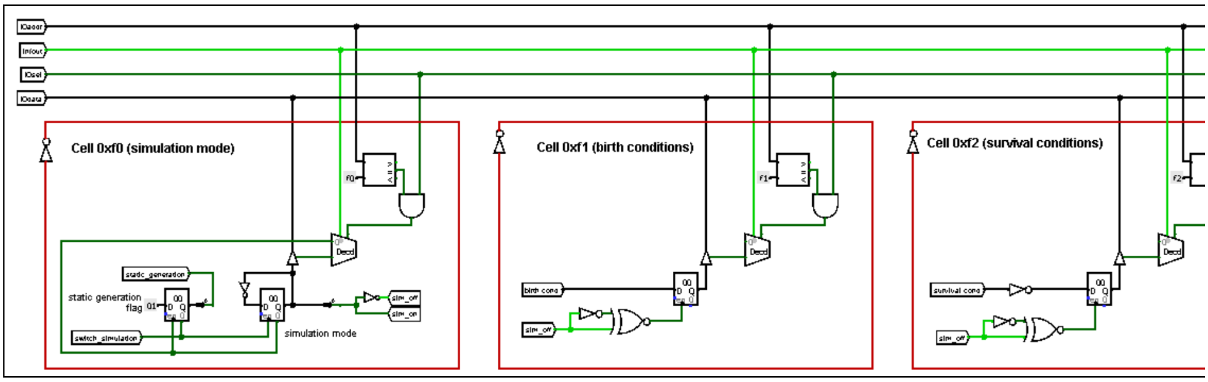
Short description table

CELL ADDR.	ASSEMBLER LABEL	DATA DIRECTION	EXPLANATION TOPIC
`0xf0`	`IOGameMode`	`READ ONLY` / `PSEUDO WRITE`	Link
`0xf1`	`IOBirthConditions`	`READ ONLY`	
`0xf2`	`IODeathConditions`	`READ ONLY`	
`0xf3`	`IOY`	`WRITE ONLY`	Link
`0xf4`	`IOX`	`WRITE ONLY`	
`0xf5`	`IOBit`	`READ ONLY`	Link
`0xf6`	`IOEnvSum`	`READ ONLY`	
`0xf7`	`IONullRowsEnv`	`READ ONLY`	
`0xf8`	`IONextSignificantX`	`READ ONLY`	
`0xf9`	`IOInvertBitSignal`	`PSEUDO WRITE`	Link
`0xfa`	`IOUpdateGeneration`	`PSEUDO WRITE`	

List with descriptions

Simulation rules

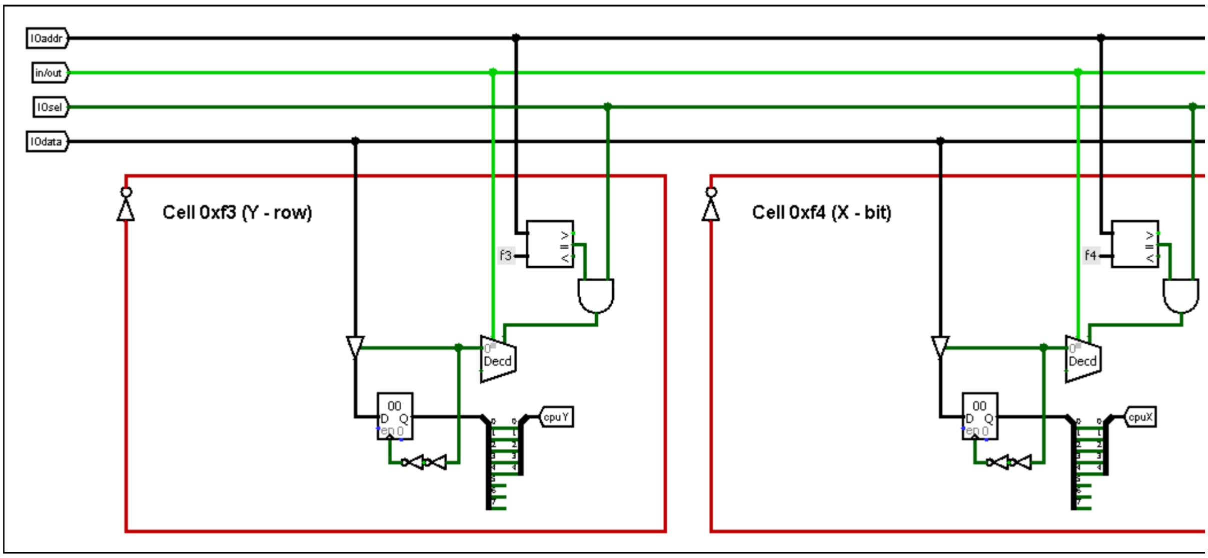
- `0xf0` - READ ONLY / PSEUDO WRITE - when simulation off this register will be `0`.
  - Trigger signal on this register will invert its value and reset static generation flag-register.
  - Tunnels from this register are used for control data origins on coordinates bus and some other cases.
  - Save signal from CPU will reset this register (turn off simulation) and set static generation flag-register to `1`. This feature is used in CPU main cycle for interrupting simulation
- `0xf1` - READ ONLY - birth conditions as bit array
- `0xf2` - READ ONLY - death conditions as bit array. This value is inverted version from survival conditions user input



Processed cell

Coordinates from these registers are used in all Logisim components to tell what cell CPU is processing. When simulation on they capture coordinates bus:

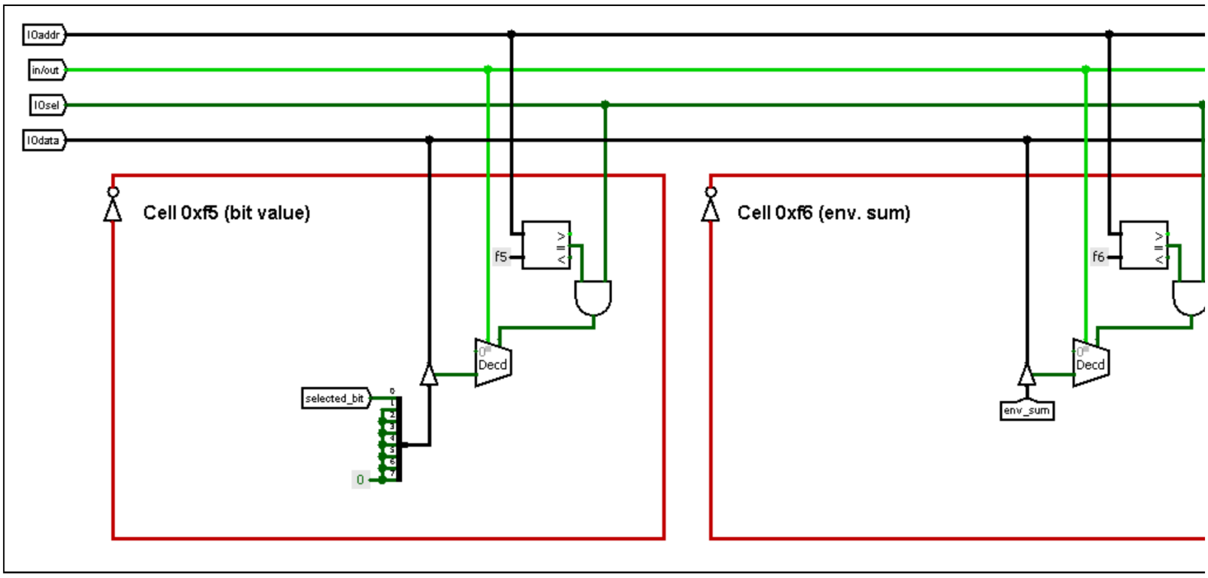
- `0xf3` - WRITE ONLY - Y coordinate (processing row)
- `0xf4` - WRITE ONLY - X coordinate (bit index in row)

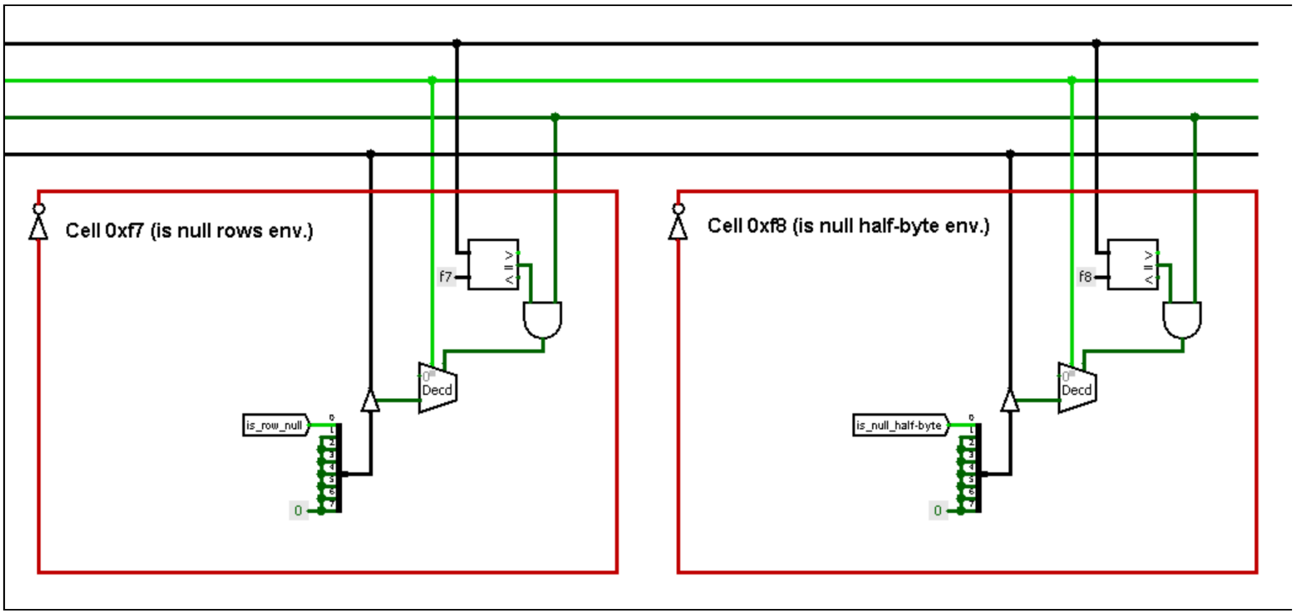


I/O "registers" with environment data

These "registers" aren't exist. There are just tunnels which are connected to environment constructor outputs:

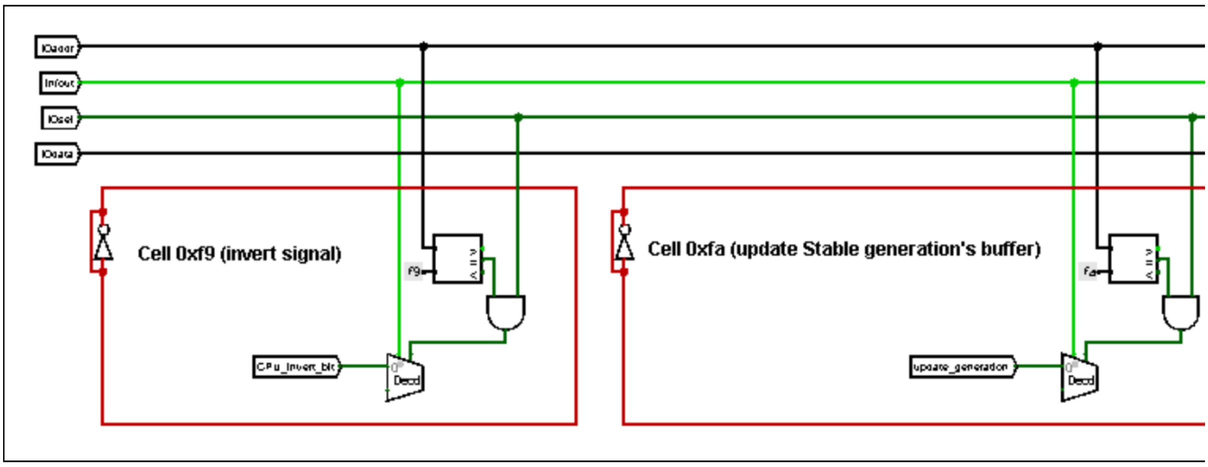
- `0xf5` - READ ONLY - 1 when bit on position `(Y, X)` is 1
- `0xf6` - READ ONLY - sum of bits around cell `(Y, X)`
- `0xf7` - READ ONLY - 1 when rows `Y-1`, `Y` and `Y+1` are null
- `0xf8` - READ ONLY - next `X` which satisfy some of conditions:
  - Cell `(Y, X)` isn't `0`
  - sum of bits around cell `(Y, X)` greater than `0`





I/O "registers" for changing field

- `0xf9` - PSEUDO WRITE - save signal to this cell will trigger random write buffer and change cell `(Y, X)` using row's bit invertor
- `0xfa` - PSEUDO WRITE - save signal to this cell will update generation buffer



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Elements description

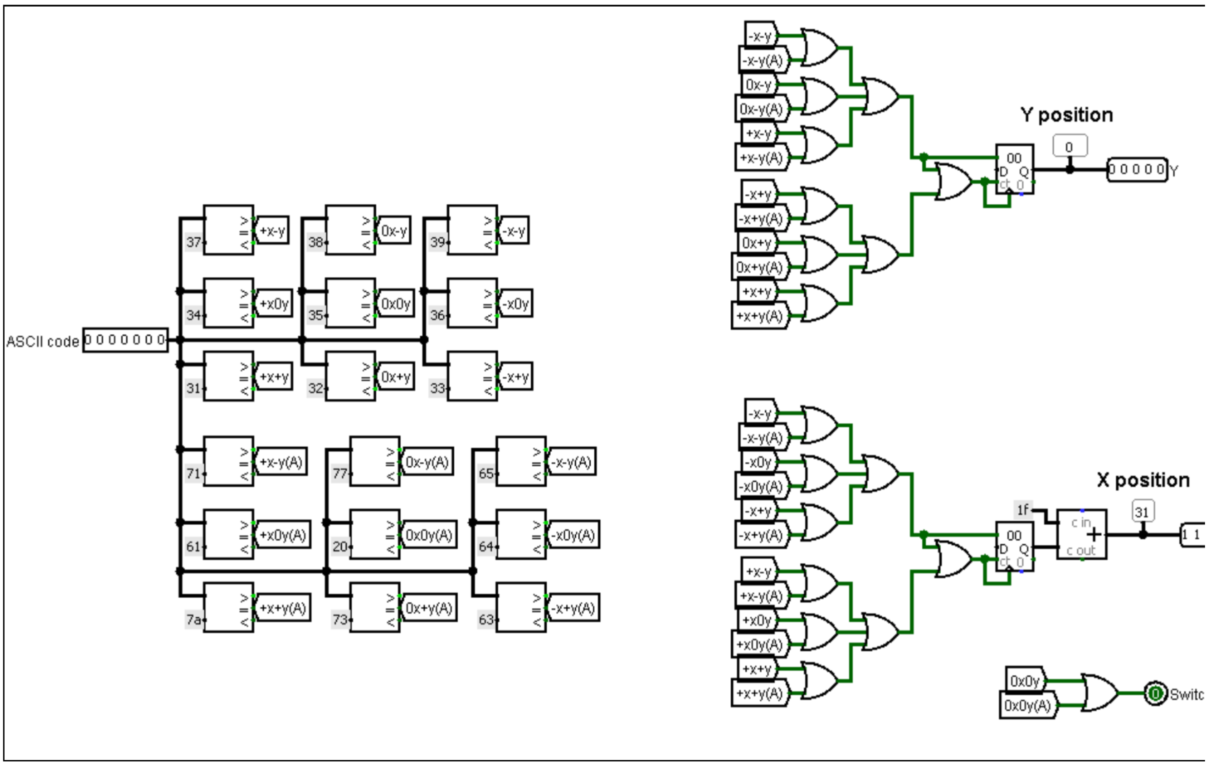
Keyboard controller

This circuit considers 7-bit ASCII input as ASCII code and compares it with constants related to some keys and make list of actions:

- Cycled increment/decrement X/Y of cursor
- Send switch signal for switching the cell's state

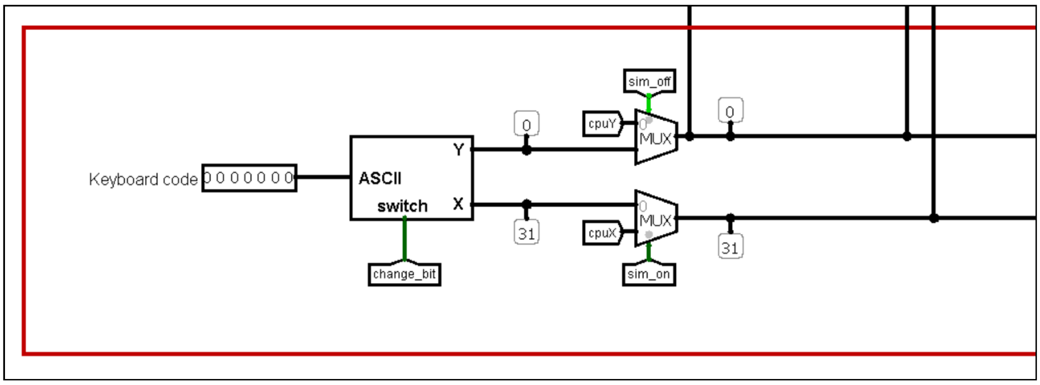
See keyboard layouts here

Circuit screenshot:



Usage in Engine circuit: Keyboard controller gives user signals that are used while simulation if off:

- Y and X for [coordinates bus]
- Switch signal which is implemented as `Write row` in random write buffer



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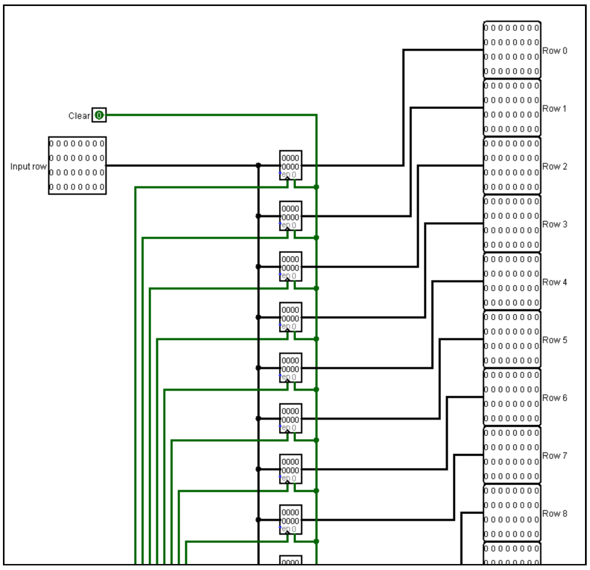
Random write buffer

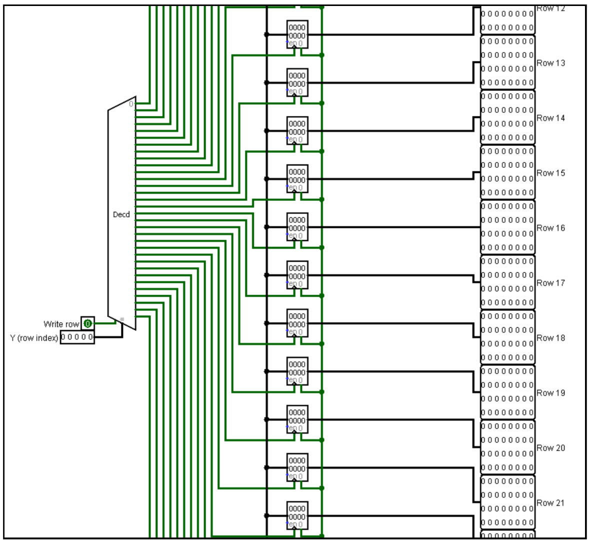
This circuit saves 32-bit row to one of 32 registers and sends all 32 saved rows to outputs.

Trigger for registers is decoder with 5-bit selector `Y (row index)` and `Write row` enable input. So, buffer will save row from `Input row` to `Y`th register on rising of `Write row`.

Clear signal resets all registers.

Circuit screenshots:





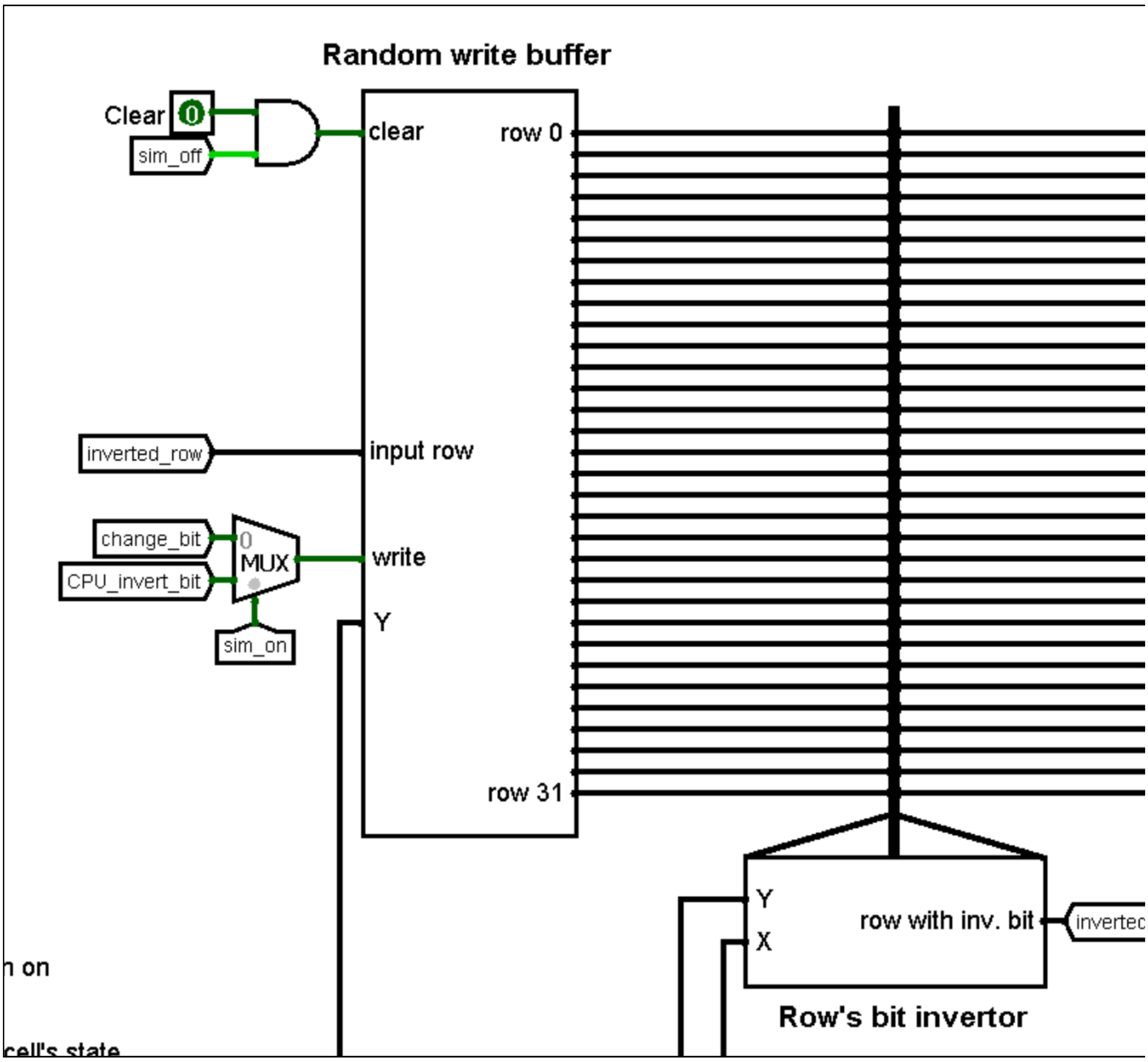
Usage in Engine circuit: In engine we get input row through tunnel from row's bit invertor

Clear signal works while simulation is off.

Y data goes from coordinates bus

Write row signal goes:

- From keyboard controller when simulation is off
- From Register `0xf9` when simulation is on



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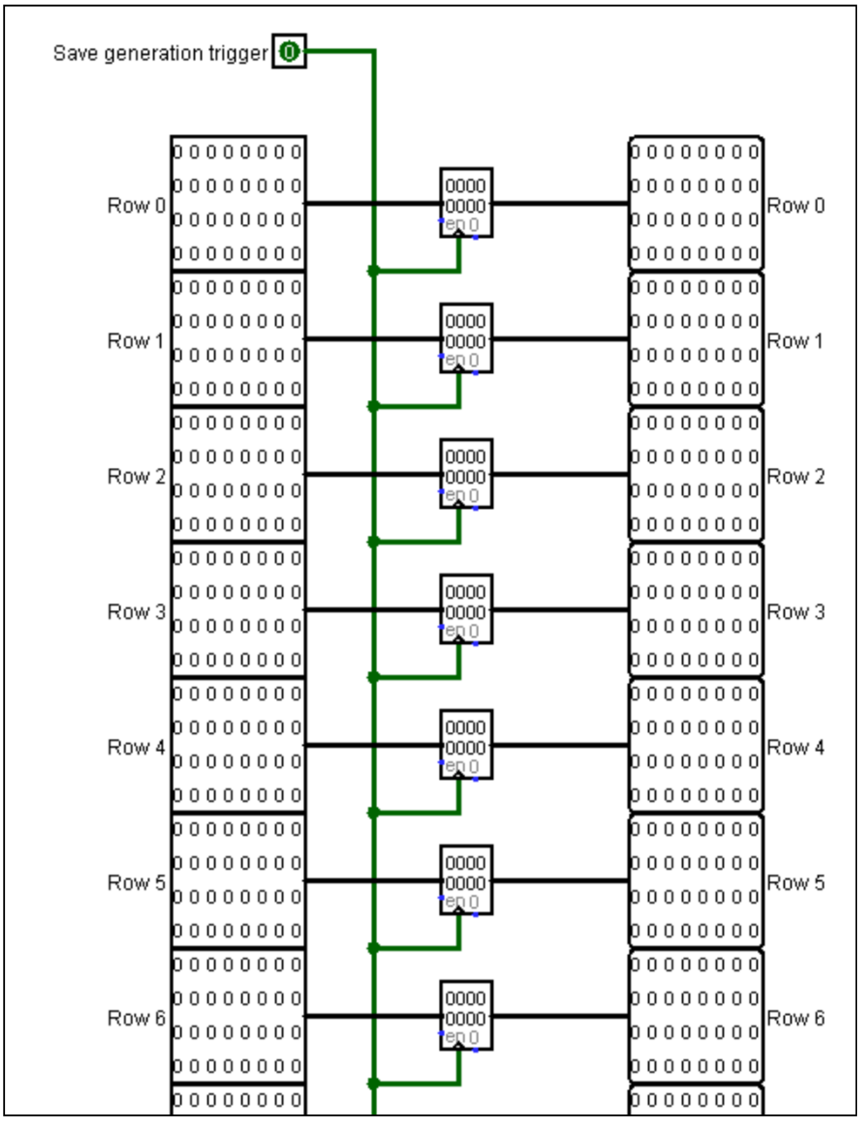
Stable generation's buffer

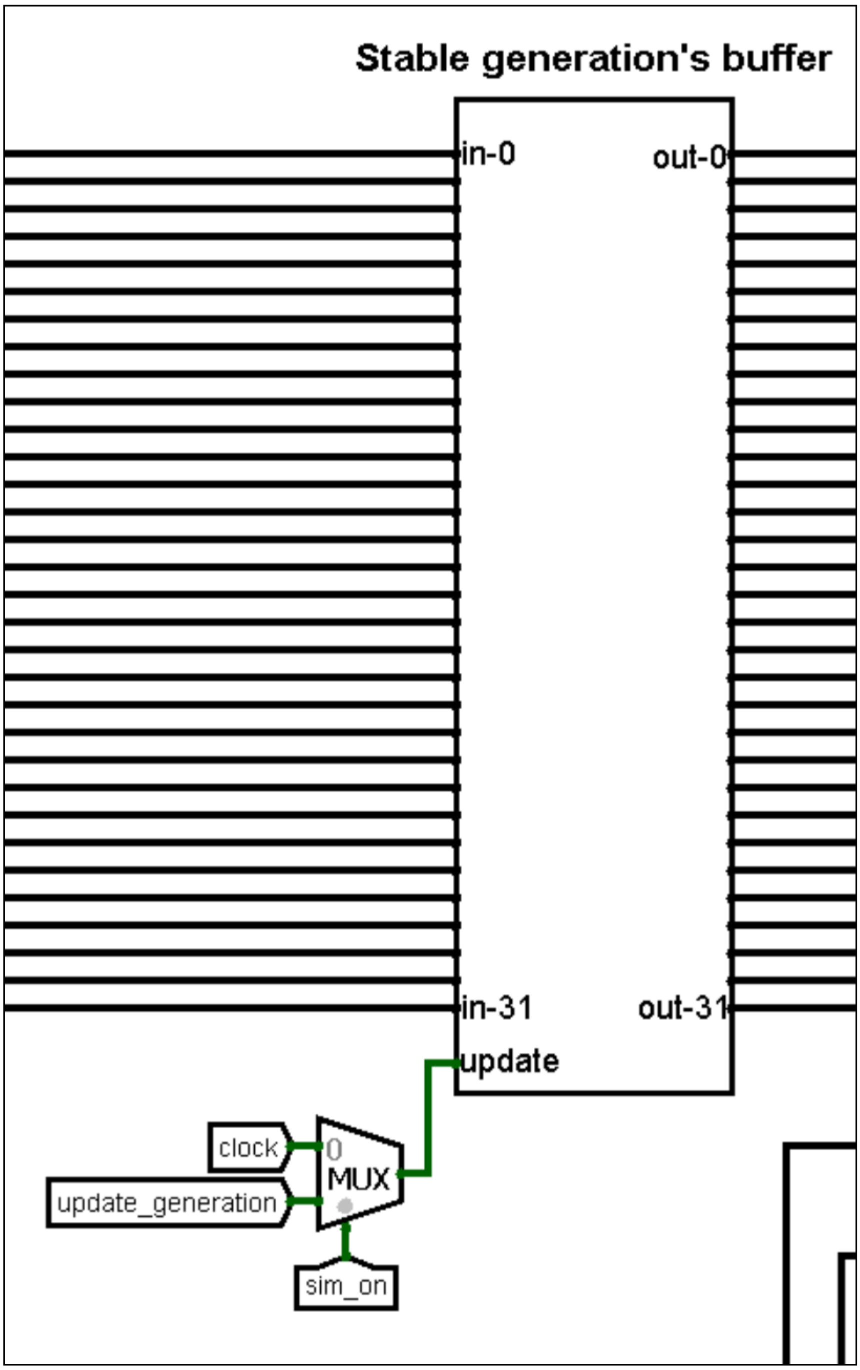
This buffer just saves 32 32-bit rows from inputs to registers and sends them to 32 outputs. Saving occurs on rising edge of input `Save generation trigger`

Circuit screenshot:



Circuit usage in Engine: Buffer update depends on simulation state:

- While simulation is off buffer is updated by `clock`
- While simulation is on buffer is updated after CdM-8 main cycle's full execution by signal from pseudo I/O register



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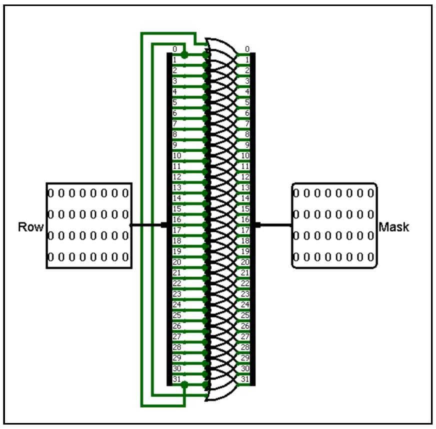
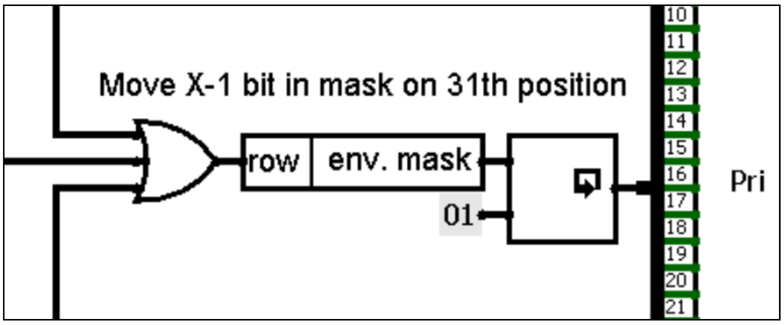
Row environment mask

This circuit gets 1 32-bit row and gives 1 32-bit row where `i` bit is `1` when in input row at least one of `i-1`, `i`, `i+1` bits is `1` (`OR` gate on splitter outputs). **So, result row let us easily detect bit with significant environment.**

Circuit screenshot and usage: this circuit is used in environment data constructor for detecting next `X` with significant environment by priority encoder.





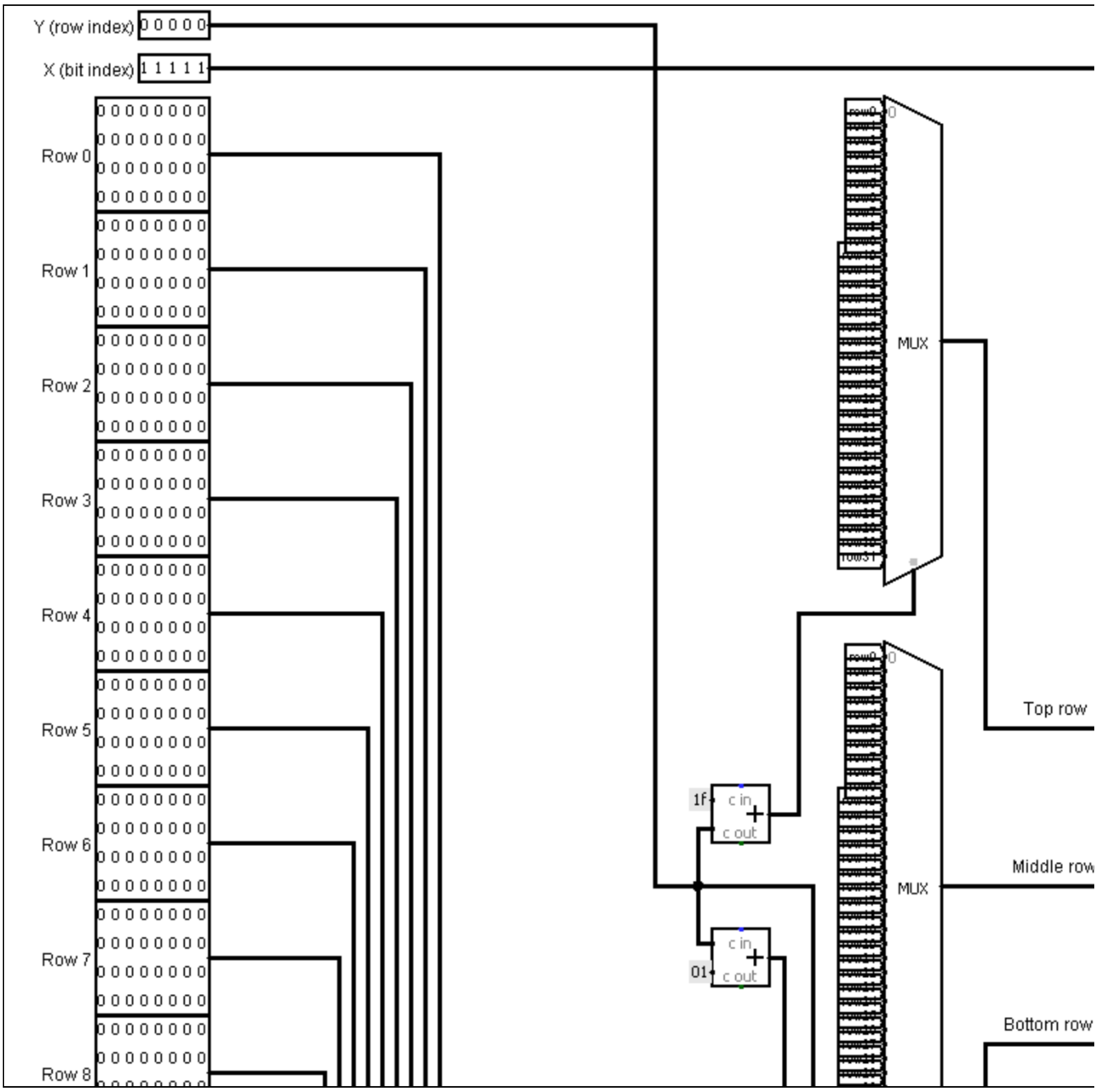
Environment data constructor

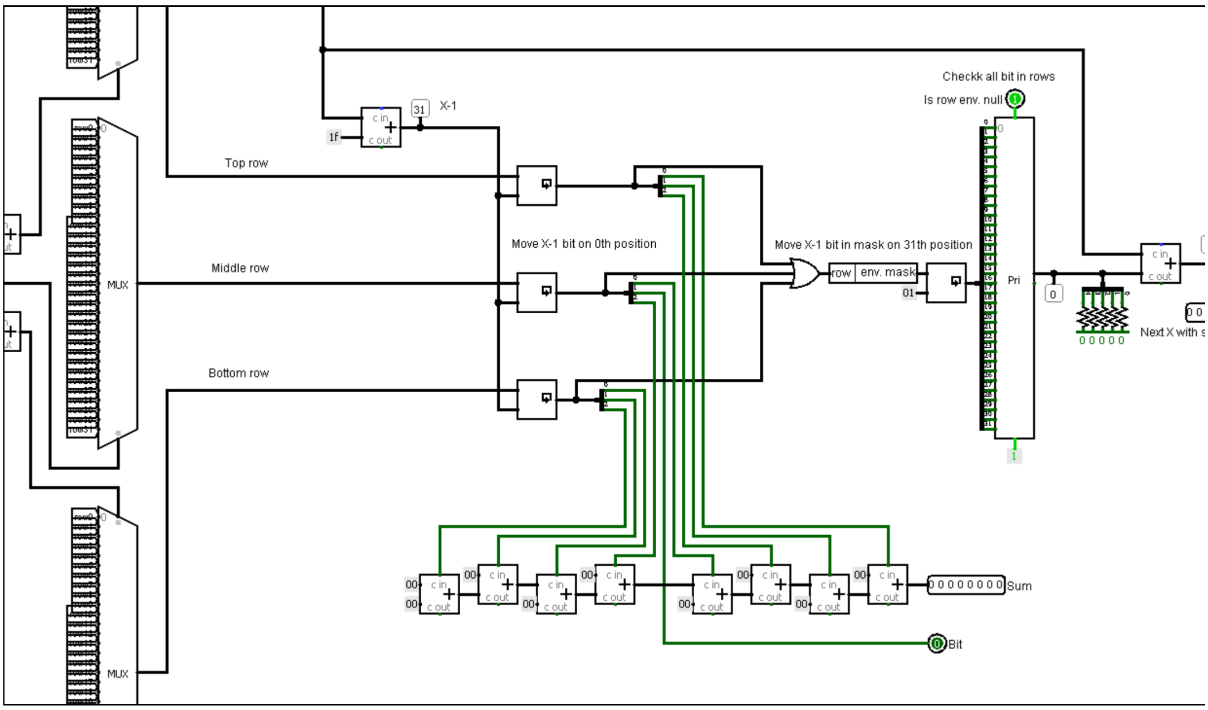
Job of this circuit is constructing data about cell's environment for optimized new generation's counting in CdM-8.

It has 32 32-bit inputs for rows and 5-bit `Y`, `X` inputs and works by this steps:

1. Get rows `Y-1`, `Y` and `Y` using multiplexers
2. Right cycled shift 3 rows on `X-1` positions to get `X-1`, `X` and `X+1` bits on `0`, `1` and `2`
    1. Send bit `1` from middle row to centre bit output
    2. Use bits `[0,2]` from top and bottom rows and bits `0` and `2` from middle row as carry signals for 8 8-bit adders to get sum of cells surrounding centre bit
3. Get common row from `Y-1`, `Y` and `Y+1` rows using `OR` gate for analyzing environment. It is name **environment row**
4. Construct environment mask from environment row using row environment mask circuit and shift it right on 1 bit to get `X-1` bit on `31`th position
5. This row goes to priority encoder that determines 2 values:
    1. If environment mask row is null encoder send true on `is row env. null` output
    2. Index of highest indexed bit which is `1` after sum with `X` input give us next `X` with significant environment. This value goes to `Next X with significant env.`

Circuit screenshots:

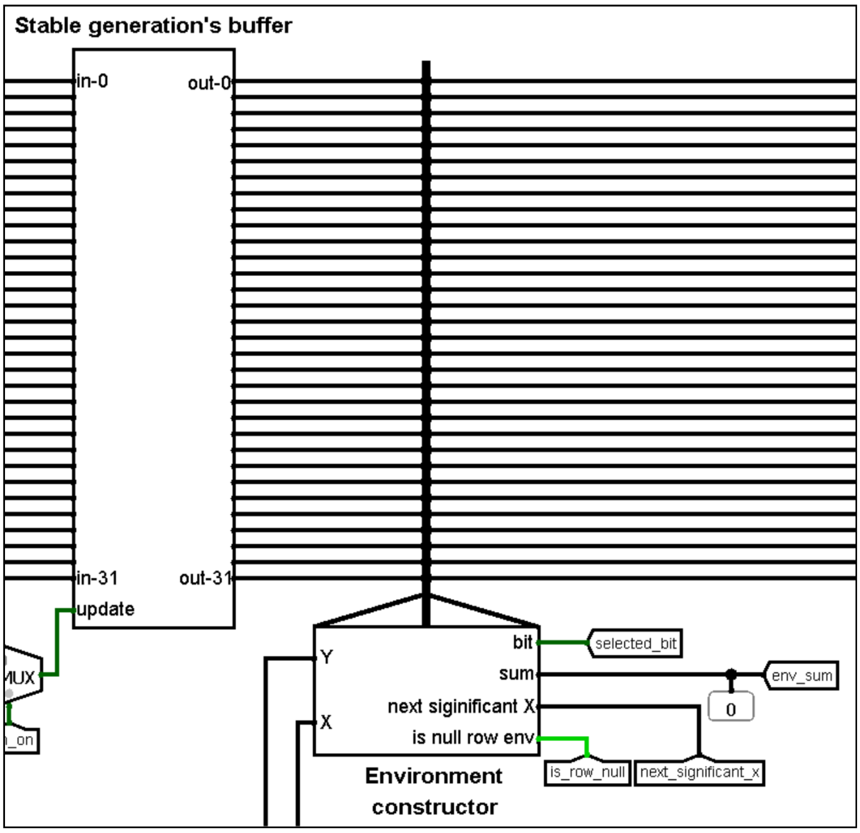

Y (row index)
X (bit index)
Row 0
Row 1
Row 2
Row 3
Row 4
Row 5
Row 6
Row 7
Row 8
MUX
MUX
Top row
Middle row
Bottom row
1f
01


X-1
Top row
Middle row
Bottom row
Move X-1 bit on 0th position
Move X-1 bit in mask on 31th position
Checkk all bit in rows
Is row env. null
env. mask
Pri
Sum
Bit

Usage in Engine circuit: Environment data constructor is connected to rows after stable generation's buffer to ensure that CPU works with stable generation.

All outputs go through tunnels to I/O registers that are used in ASM main cycle

Y and X go from coordinates bus but while simulation is off environment data isn't used.



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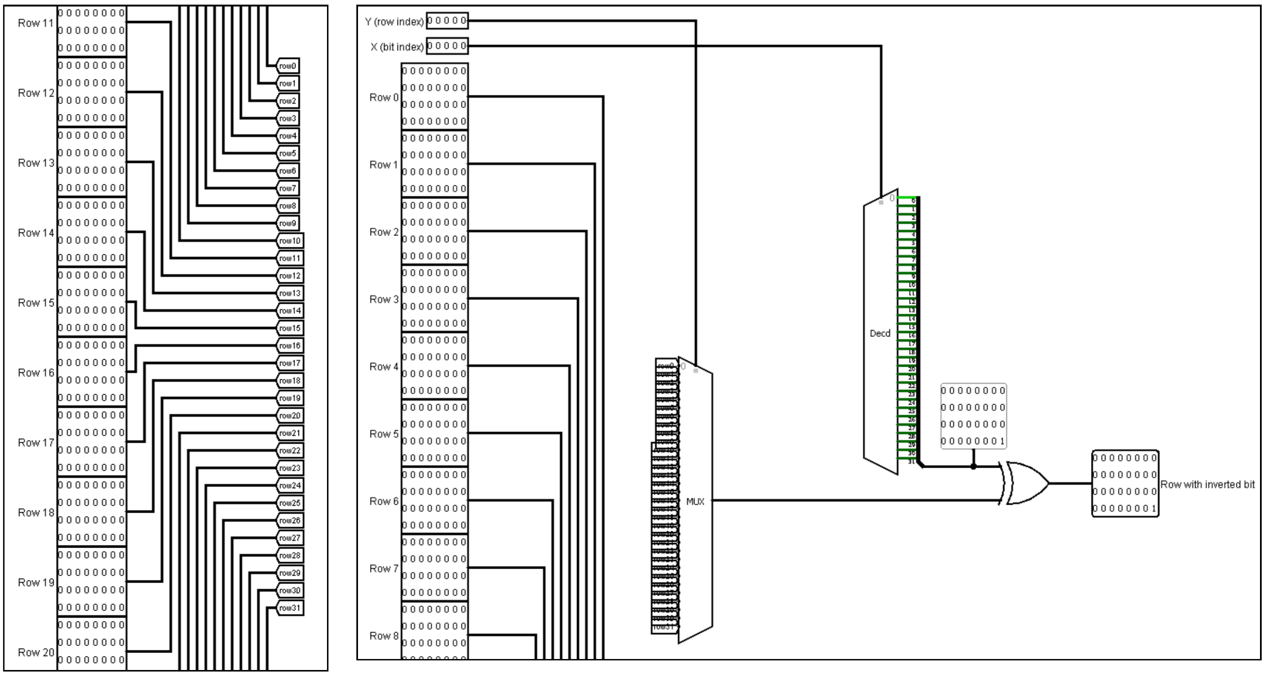
Row's bit invertor

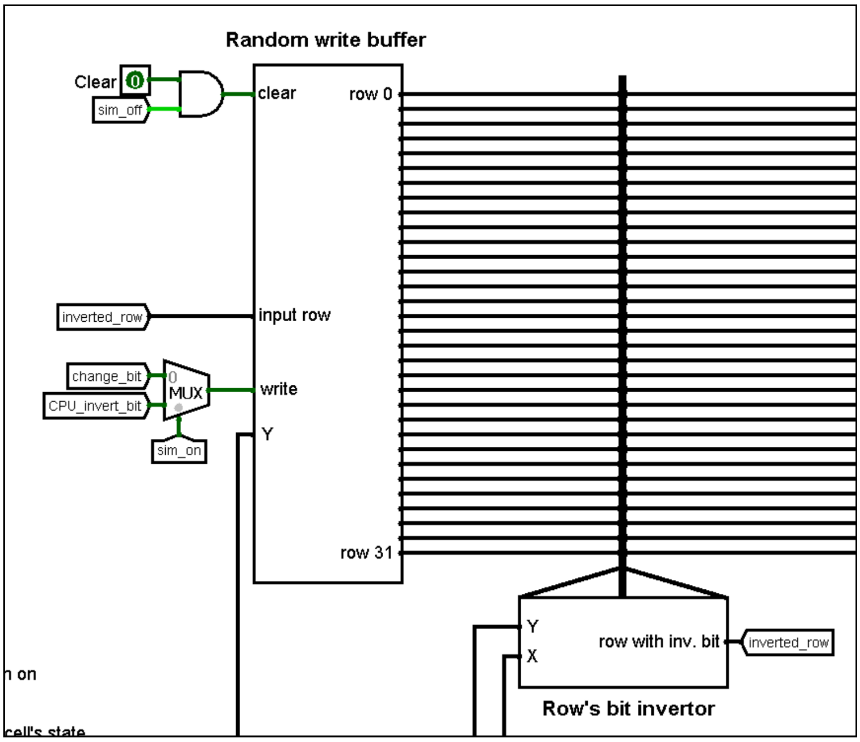
This circuit gets 32 32-bit rows and 5 bit coordinates Y and X. Returns Y row with inverted bit on position X. **For inversion we use decoder constructed bit mask and XOR**

Circuit screenshots:



Usage in Engine circuit: 32 input rows goes from random write buffer and inverted row goes through tunnel to `input row` of random write buffer

Y and X go from coordinates bus



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Binary selector

This circuit should choose one of two input values. `Binary selector` should choose second value if the `switch` input is `1` and first value otherwise.

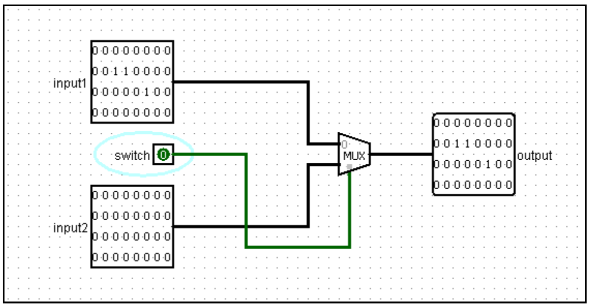
Inputs:

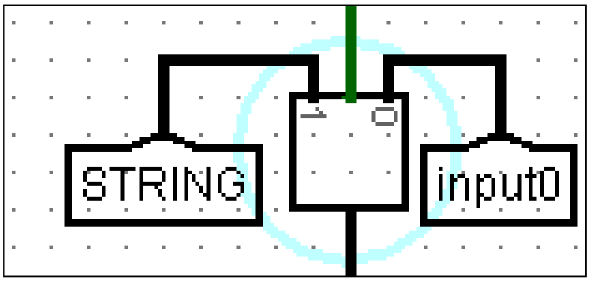
- input values: 2 32-bit rows
- `switch` - 1-bit

Outputs:

- selected value: 1 32-bit row

Circuit screenshot and its usage: Binary selector is used in blinker for convenient circuit composing.





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Blinker

`Blinker` must switch value of `X` bit in `Y` row to opposite if the `switch` input is raised and return new row between others unchanged. **It is important that this circuit should not store new values in itself.**

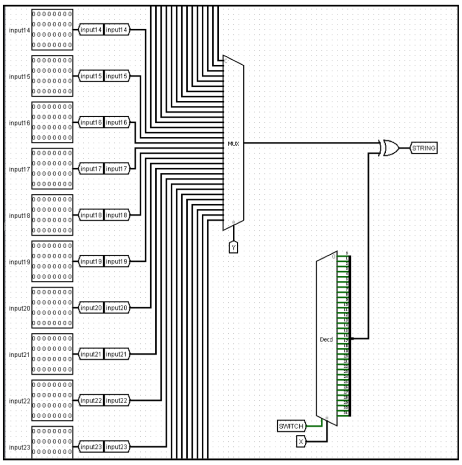
Inputs:

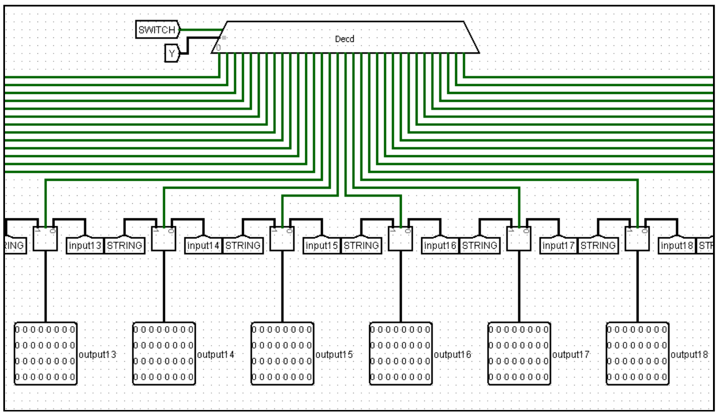
- matrix rows: 32 32-bit rows
- `Y` coordinate (row number) - 5-bit
- `X` coordinate (bit number in the row) - 5-bit
- `switch` - if this input is raised current bit must switch to opposite

Outputs:

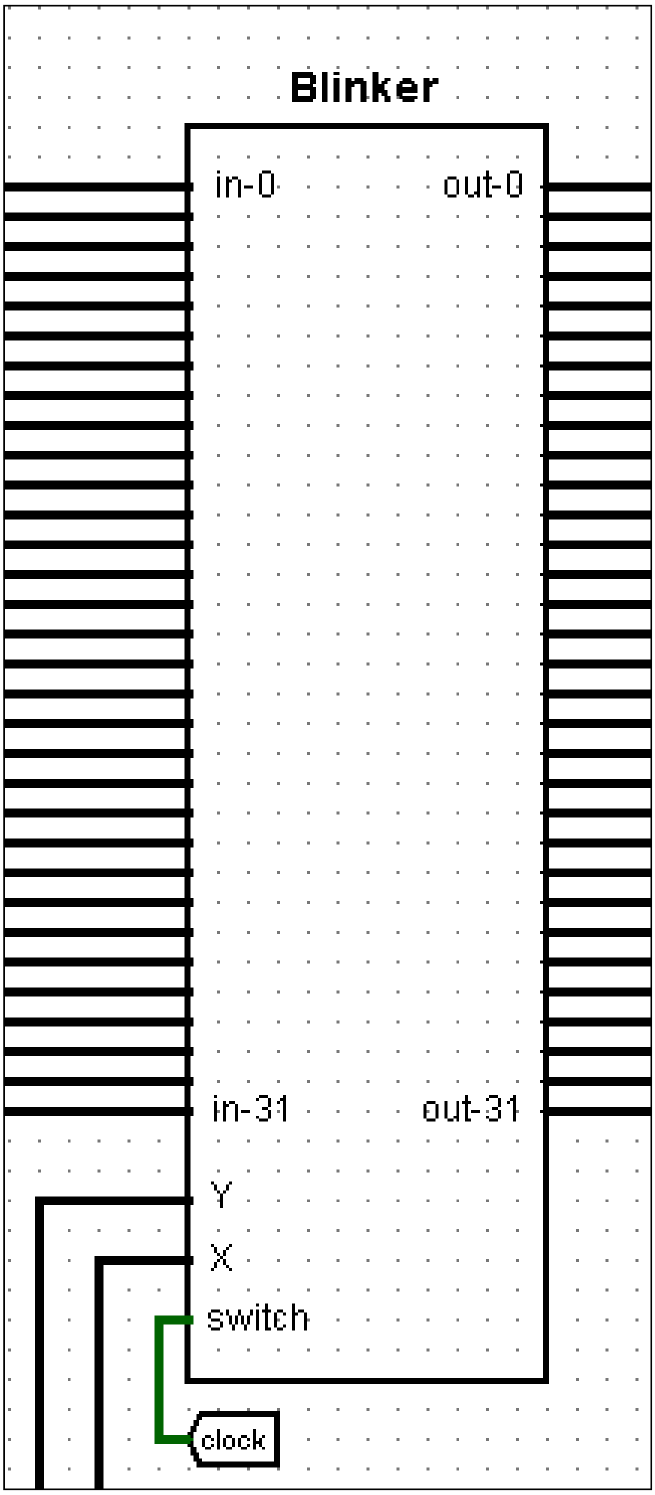
- 32 32-bit outputs, in one of which one bit was changed

Circuit screenshots:





Usage in Engine circuit: In `switch` handles clock signal. Y and X go from coordinates bus



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