The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2065-28

Advanced Training Course on FPGA Design and VHDL for Hardware Simulation and Synthesis

26 October - 20 November, 2009

Starting to make an FPGA Project

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Starting to make an FPGA project

FPGA specifications

- **How to make an FPGA?**
  - What should it do?
  - How should it do it?

- **Systems / Requirements define detailed implementation scheme/architecture**

- **Specification need to be worked out before even one thinks about the FPGA type or code.**
  - Specification: understand user needs
  - define specification of system together with user/costumer

- **re-discuss, re-negotiate**
  - understand
  - task of designer to understand and translate specifications

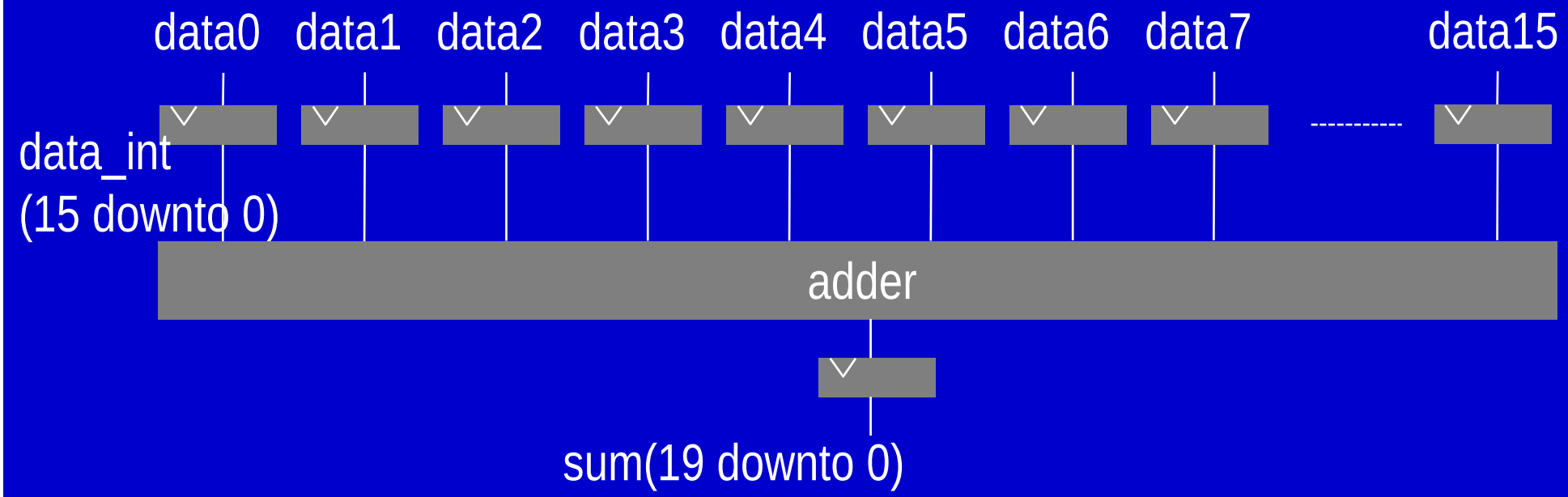
FPGA specifications

- **Costumer/boss says:**
  “I need a system which can calculate the value each 25 ns.”

- **What you might understand is:**
  “The calculation needs to be finished within 25 ns”

Adder

- **Example:**
  - add 16 16-bit values in 25 ns



add16.vhd - /Volumes/akluge/cadence/div/test_vhdl/mult_trig/

File Edit Search Preferences Shell Macro Windows Help

/Volumes/akluge/cadence/div/test_vhdl/mult_trig/add16.vhd 3271 bytes L: 50 C: 51

```
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;

entity add16x28bit is
   port (
         clk          :in std_logic;
         reset_i      :in std_logic;
         data0        :in integer range 0 to 2 ** 16 - 1;
         data1        :in integer range 0 to 2 ** 16 - 1;
         data2        :in integer range 0 to 2 ** 16 - 1;
         data3        :in integer range 0 to 2 ** 16 - 1;
         data4        :in integer range 0 to 2 ** 16 - 1;
         data5        :in integer range 0 to 2 ** 16 - 1;
         data6        :in integer range 0 to 2 ** 16 - 1;
         data7        :in integer range 0 to 2 ** 16 - 1;
         data8        :in integer range 0 to 2 ** 16 - 1;
         data9        :in integer range 0 to 2 ** 16 - 1;
         data10       :in integer range 0 to 2 ** 16 - 1;
         data11       :in integer range 0 to 2 ** 16 - 1;
         data12       :in integer range 0 to 2 ** 16 - 1;
         data13       :in integer range 0 to 2 ** 16 - 1;
         data14       :in integer range 0 to 2 ** 16 - 1;
         data15       :in integer range 0 to 2 ** 16 - 1;

         sum          :out integer range 0 to 2 ** 20 - 1
         );

end add16x28bit;

architecture behavioral of add16x28bit is

signal   data0_int       :integer range 0 to 2 ** 16 - 1;
signal   data1_int       :integer range 0 to 2 ** 16 - 1;
signal   data2_int       :integer range 0 to 2 ** 16 - 1;
signal   data3_int       :integer range 0 to 2 ** 16 - 1;
signal   data4_int       :integer range 0 to 2 ** 16 - 1;
signal   data5_int       :integer range 0 to 2 ** 16 - 1;
signal   data6_int       :integer range 0 to 2 ** 16 - 1;
signal   data7_int       :integer range 0 to 2 ** 16 - 1;
signal   data8_int       :integer range 0 to 2 ** 16 - 1;
signal   data9_int       :integer range 0 to 2 ** 16 - 1;
signal   data10_int      :integer range 0 to 2 ** 16 - 1;
signal   data11_int      :integer range 0 to 2 ** 16 - 1;
signal   data12_int      :integer range 0 to 2 ** 16 - 1;
signal   data13_int      :integer range 0 to 2 ** 16 - 1;
signal   data14_int      :integer range 0 to 2 ** 16 - 1;
signal   data15_int      :integer range 0 to 2 ** 16 - 1;

signal   sum_int         :integer range 0 to 2 ** 20 - 1;
```

```
process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         data0_int   <= 0;
         data1_int   <= 0;
         data2_int   <= 0;
         data3_int   <= 0;
         data4_int   <= 0;
         data5_int   <= 0;
         data6_int   <= 0;
         data7_int   <= 0;
         data8_int   <= 0;
         data9_int   <= 0;
         data10_int  <= 0;
         data11_int  <= 0;
         data12_int  <= 0;
         data13_int  <= 0;
         data14_int  <= 0;
         data15_int  <= 0;
      else
         data0_int   <= data0;
         data1_int   <= data1;
         data2_int   <= data2;
         data3_int   <= data3;
         data4_int   <= data4;
         data5_int   <= data5;
         data6_int   <= data6;
         data7_int   <= data7;
         data8_int   <= data8;
         data9_int   <= data9;
         data10_int  <= data10;
         data11_int  <= data11;
         data12_int  <= data12;
         data13_int  <= data13;
         data14_int  <= data14;
         data15_int  <= data15;
      end if;
   end if;
end process;
```

```
end process;
process (clk)
begin
    if (clk'event and clk = '1') then
        if (reset_i = '0') then
            sum_int      <=  0;
        else
            sum_int      <= data0_int +
                            data1_int +
                            data2_int +
                            data3_int +
                            data4_int +
                            data5_int +
                            data6_int +
                            data7_int +
                            data8_int +
                            data9_int +
                            data10_int +
                            data11_int +
                            data12_int +
                            data13_int +
                            data14_int +
                            data15_int;
        end if;
    end if;
end process;
sum <= sum_int;
end behavioral;
```

Adder

- 533 logic elements, 6%
- 278 pins, 74%
- 29.7 MHz => 33.6 ns

- 33.6 ns > 25 ns -> too slow

Adder

- 533 logic elements, 6%
- 278 pins, 74%
- 29.7 MHz => 33.6 ns

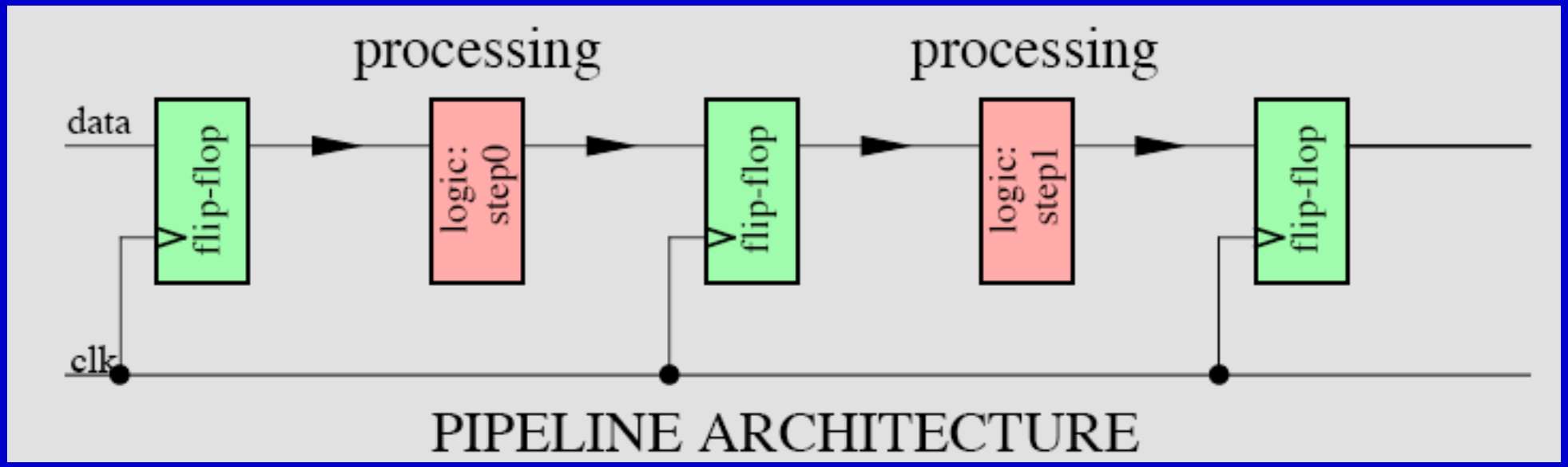
- 33.6 ns > 25 ns -> too slow

- Ask boss to buy faster, more expensive FPGA
- Work (manually) on FPGA placing&routing
- Help synthesizer to make fater adder
- Ask whether you have understood specification

FPGA specifications

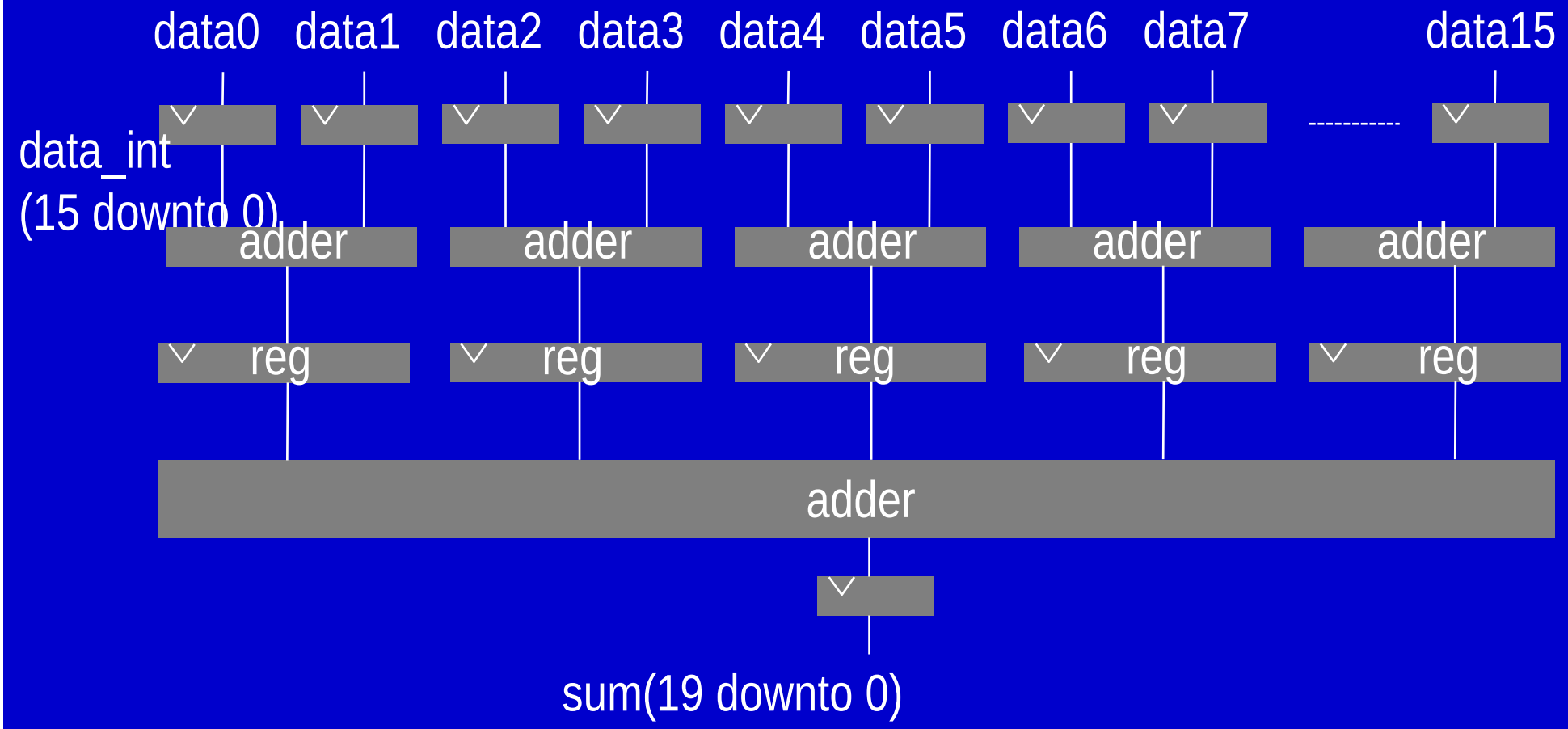
- **Costumer/boss says:**
  “I need a system which can calculate the value each 25 ns.”
- **What you might understand is:**
  “The calculation needs to be finished within 25 ns”
- **What he means is:**
  “A new value needs to be processed every 25 ns. How long it takes to present the result does not matter”
- **First case: might be impossible, maybe not.**
  Second case: Processors in parallel or in pipeline

Pipeline architecture



Adder with pipeline

- **Example:**
  - add 16 16-bit values every 25 ns



```
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;

entity add16Pipeline is
   port (
         clk          :in std_logic;
         reset_i      :in std_logic;
         data0        :in integer range 0 to 2 ** 16 - 1;
         data1        :in integer range 0 to 2 ** 16 - 1;
         data2        :in integer range 0 to 2 ** 16 - 1;
         data3        :in integer range 0 to 2 ** 16 - 1;
         data4        :in integer range 0 to 2 ** 16 - 1;
         data5        :in integer range 0 to 2 ** 16 - 1;
         data6        :in integer range 0 to 2 ** 16 - 1;
         data7        :in integer range 0 to 2 ** 16 - 1;
         data8        :in integer range 0 to 2 ** 16 - 1;
         data9        :in integer range 0 to 2 ** 16 - 1;
         data10       :in integer range 0 to 2 ** 16 - 1;
         data11       :in integer range 0 to 2 ** 16 - 1;
         data12       :in integer range 0 to 2 ** 16 - 1;
         data13       :in integer range 0 to 2 ** 16 - 1;
         data14       :in integer range 0 to 2 ** 16 - 1;
         data15       :in integer range 0 to 2 ** 16 - 1;

         sum          :out integer range 0 to 2 ** 20 - 1
         );

end add16Pipeline;

architecture behavioral of add16Pipeline is

signal   data0_int       :integer range 0 to 2 ** 16 - 1;
signal   data1_int       :integer range 0 to 2 ** 16 - 1;
signal   data2_int       :integer range 0 to 2 ** 16 - 1;
signal   data3_int       :integer range 0 to 2 ** 16 - 1;
signal   data4_int       :integer range 0 to 2 ** 16 - 1;
signal   data5_int       :integer range 0 to 2 ** 16 - 1;
signal   data6_int       :integer range 0 to 2 ** 16 - 1;
signal   data7_int       :integer range 0 to 2 ** 16 - 1;
signal   data8_int       :integer range 0 to 2 ** 16 - 1;
signal   data9_int       :integer range 0 to 2 ** 16 - 1;
signal   data10_int      :integer range 0 to 2 ** 16 - 1;
signal   data11_int      :integer range 0 to 2 ** 16 - 1;
signal   data12_int      :integer range 0 to 2 ** 16 - 1;
signal   data13_int      :integer range 0 to 2 ** 16 - 1;
signal   data14_int      :integer range 0 to 2 ** 16 - 1;
signal   data15_int      :integer range 0 to 2 ** 16 - 1;

signal   sum_int         :integer range 0 to 2 ** 20 - 1;
signal   sum_int0        :integer range 0 to 2 ** 17 - 1;
signal   sum_int1        :integer range 0 to 2 ** 17 - 1;
signal   sum_int2        :integer range 0 to 2 ** 17 - 1;
signal   sum_int3        :integer range 0 to 2 ** 17 - 1;
signal   sum_int4        :integer range 0 to 2 ** 17 - 1;
signal   sum_int5        :integer range 0 to 2 ** 17 - 1;
signal   sum_int6        :integer range 0 to 2 ** 17 - 1;
signal   sum_int7        :integer range 0 to 2 ** 17 - 1;

begin
```

```
process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         data0_int   <= 0;
         data1_int   <= 0;
         data2_int   <= 0;
         data3_int   <= 0;
         data4_int   <= 0;
         data5_int   <= 0;
         data6_int   <= 0;
         data7_int   <= 0;
         data8_int   <= 0;
         data9_int   <= 0;
         data10_int  <= 0;
         data11_int  <= 0;
         data12_int  <= 0;
         data13_int  <= 0;
         data14_int  <= 0;
         data15_int  <= 0;

      else
         data0_int   <= data0;
         data1_int   <= data1;
         data2_int   <= data2;
         data3_int   <= data3;
         data4_int   <= data4;
         data5_int   <= data5;
         data6_int   <= data6;
         data7_int   <= data7;
         data8_int   <= data8;
         data9_int   <= data9;
         data10_int  <= data10;
         data11_int  <= data11;
         data12_int  <= data12;
         data13_int  <= data13;
         data14_int  <= data14;
         data15_int  <= data15;
      end if;
   end if;
end process;
```

```
process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         sum_int0    <=  0;
      else
         sum_int0    <= data0_int +
                        data1_int;
      end if;
   end if;
end process;

process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         sum_int1    <=  0;
      else
         sum_int1    <= data2_int +
                        data3_int;
      end if;
   end if;
end process;

process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         sum_int2    <=  0;
      else
         sum_int2    <= data4_int +
                        data5_int;
      end if;
   end if;
```

```
        end if;
    end if;
end process;

process (clk)
begin
    if (clk'event and clk = '1') then
        if (reset_i = '0') then
            sum_int3    <=  0;
        else
            sum_int3    <= data6_int +
                           data7_int;
        end if;
    end if;
end process;

process (clk)
begin
    if (clk'event and clk = '1') then
        if (reset_i = '0') then
            sum_int4    <=  0;
        else
            sum_int4    <= data8_int +
                           data9_int;
        end if;
    end if;
end process;
```

```
process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         sum_int5    <=  0;
      else
         sum_int5    <= data10_int +
                        data11_int;
      end if;
   end if;
end process;

process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         sum_int6    <=  0;
      else
         sum_int6    <= data12_int +
                        data13_int;
      end if;
   end if;
end process;

process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         sum_int7    <=  0;
      else
         sum_int7    <= data14_int +
                        data15_int;
      end if;
   end if;
end process;
```

```
process (clk)
begin
   if (clk'event and clk = '1') then
      if (reset_i = '0') then
         sum_int     <=  0;
      else
         sum_int     <= sum_int0 +
                        sum_int1 +
                        sum_int2 +
                        sum_int3 +
                        sum_int4 +
                        sum_int5 +
                        sum_int6 +
                        sum_int7
                        ;
      end if;
   end if;
end process;


sum <= sum_int;

end behavioral;
```

Adder with pipeline

- Adder without pipeline
- 533 logic elements, 6%
- 278 pins, 74%
- 29.7 MHz => 33.6 ns

- Adder with pipeline
- 526 logic elements, 6%
- 278 pins, 74%
- 45.4 MHz => 22 ns

- 22ns < 25 ns, fast enough and less logic

FPGA specifications

- **re-discuss, re-negotiate**
  - understand
  - task of designer to understand and translate specifications

Readout Processors

Read-out processors

- **Specification**
  - Challenge - many parallel inputs –
    25 ns intervall - short processing time
  - Storage during trigger decision time
  - Data reduction/encoding (zero suppression)
  - pipelining, buffering (FIFO, dual port RAM)

Pixel detector

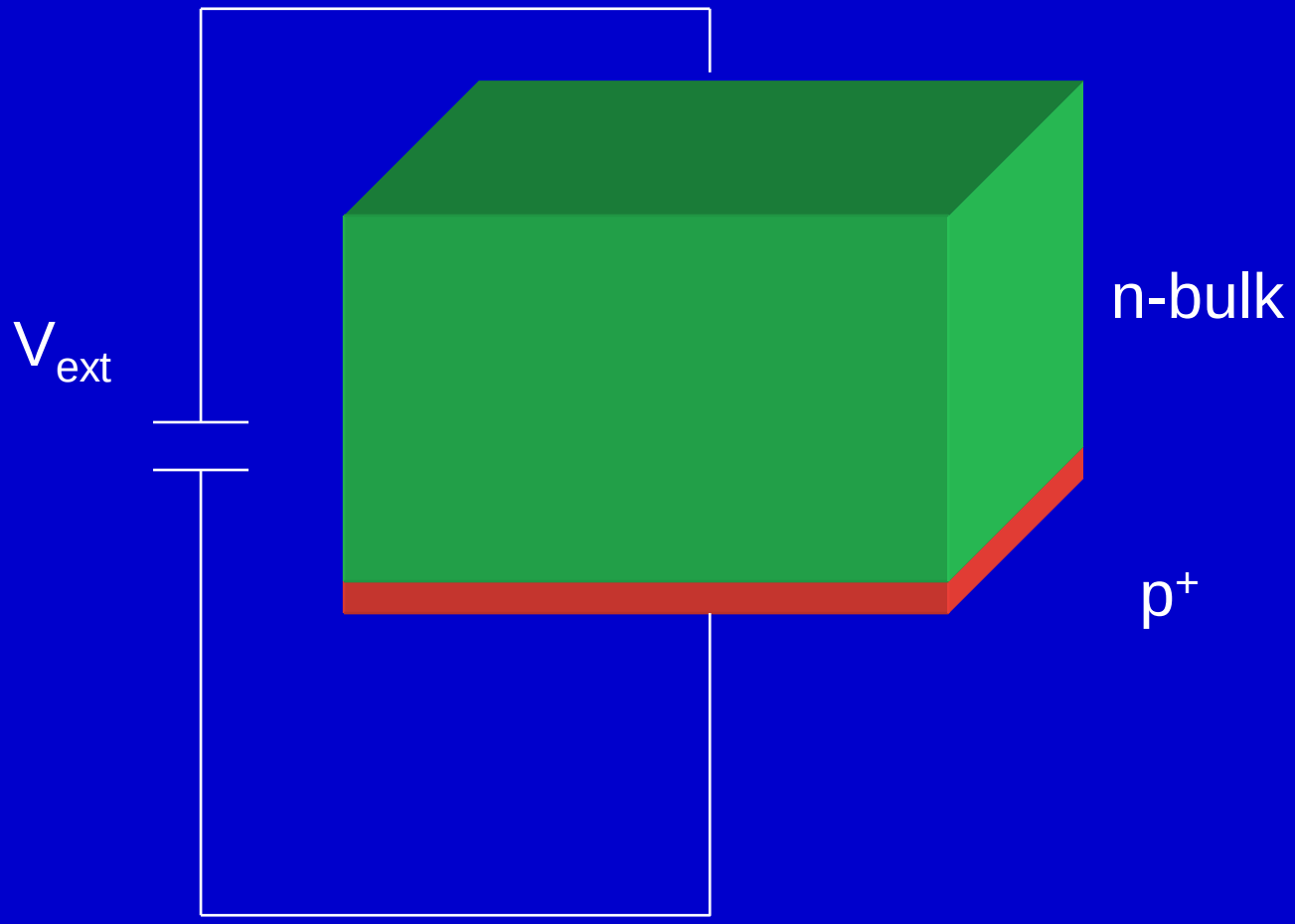
What do we need to know?

Silicon Sensor

Position resolution: 10 µm

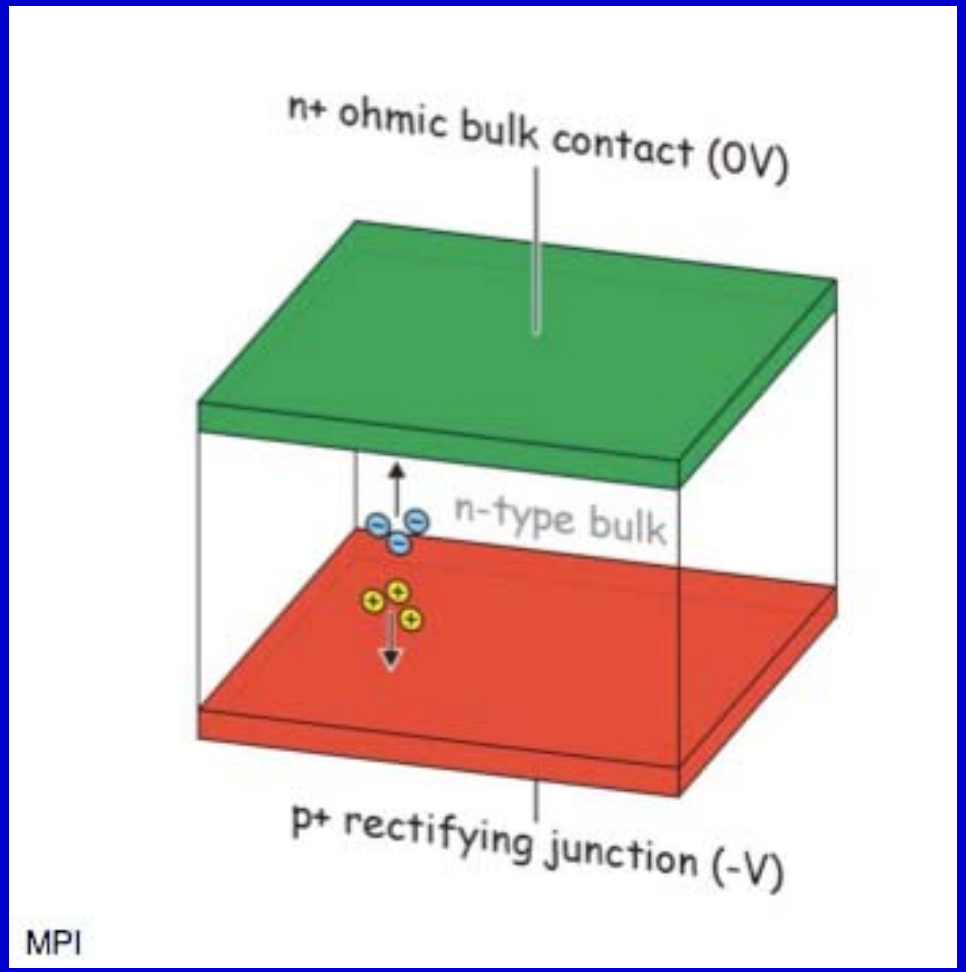
light material: 1 % X_0 oder 2 mm

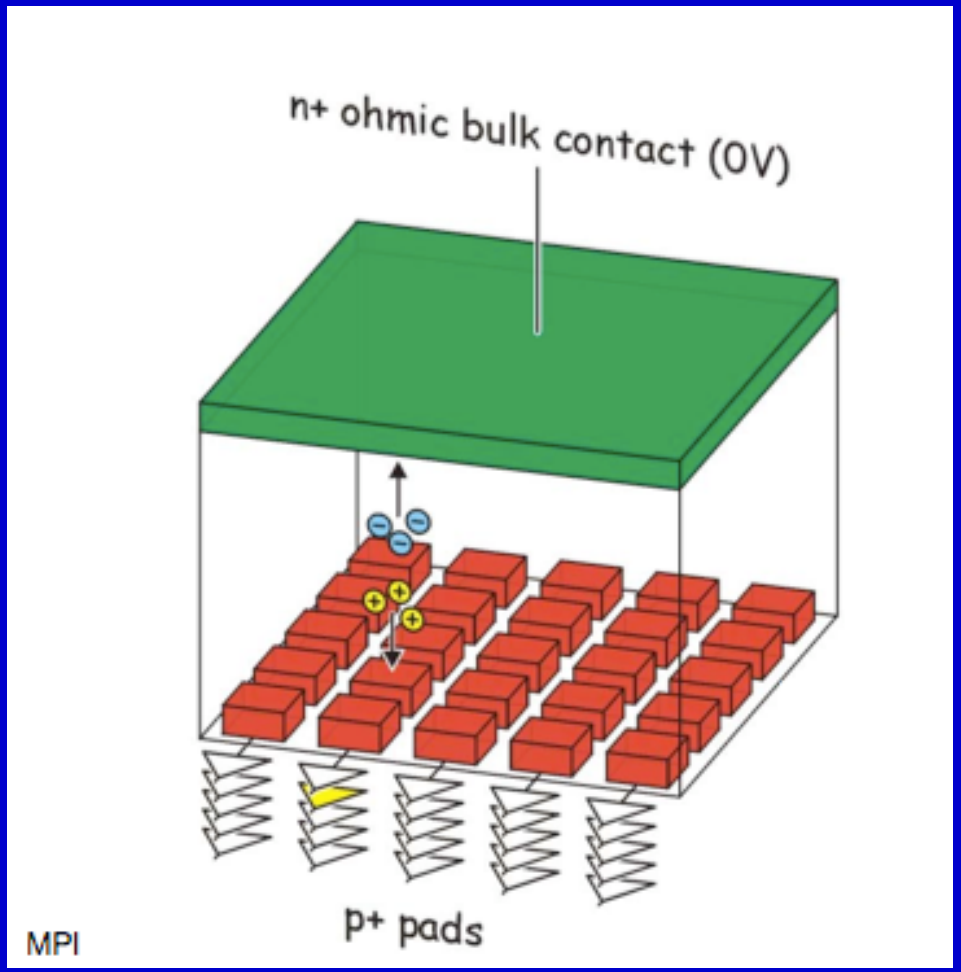
Silicon Sensors



P. Riedler
A. Kluge

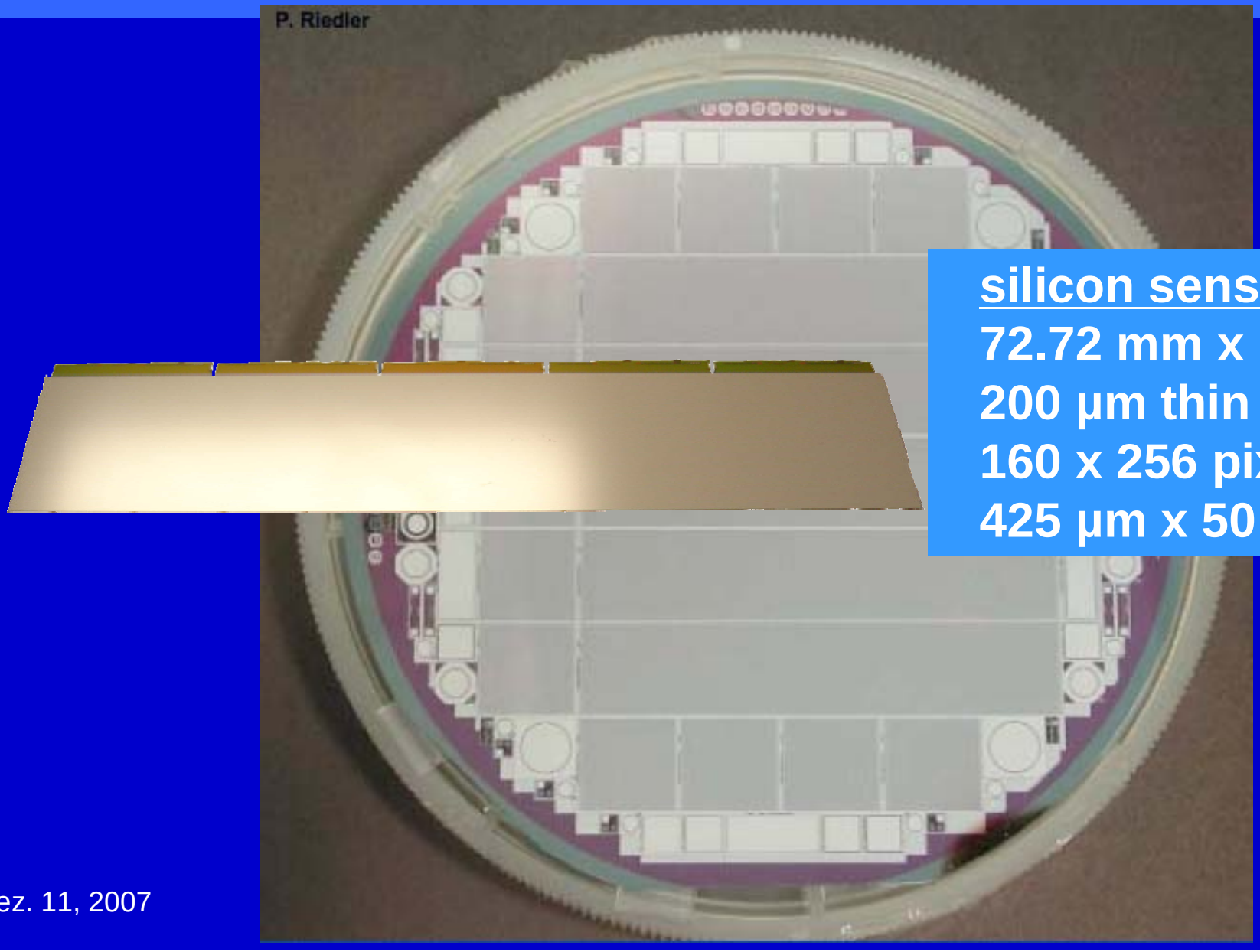
Silicon Pixel sensors





P. Riedler
A. Kluge

Silicon Pixel Wafers



silicon sensor
72.72 mm x 13.92 mm
200 µm thin
160 x 256 pixel
425 µm x 50 µm

P. Riedler
A. Kluge

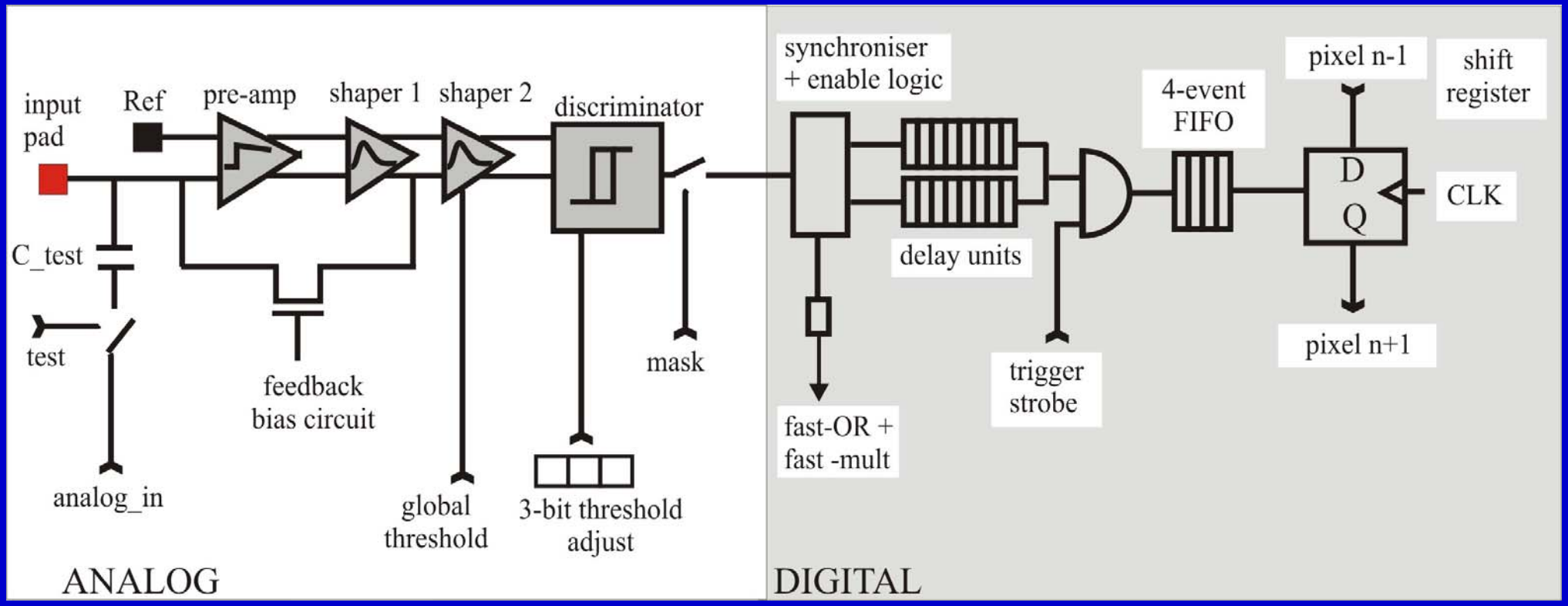
Pixel read out chip

Time resolution: 25 ns

Repetition frequency: 40 MHz

Storage time: > 3.2 µs

Pixel chip


input pad
Ref
pre-amp
shaper 1
shaper 2
discriminator
C_test
test
analog_in
feedback bias circuit
global threshold
3-bit threshold adjust
mask
ANALOG
synchroniser + enable logic
delay units
fast-OR + fast -mult
trigger strobe
4-event FIFO
pixel n-1
shift register
D
Q
CLK
pixel n+1
DIGITAL

Pixel detector

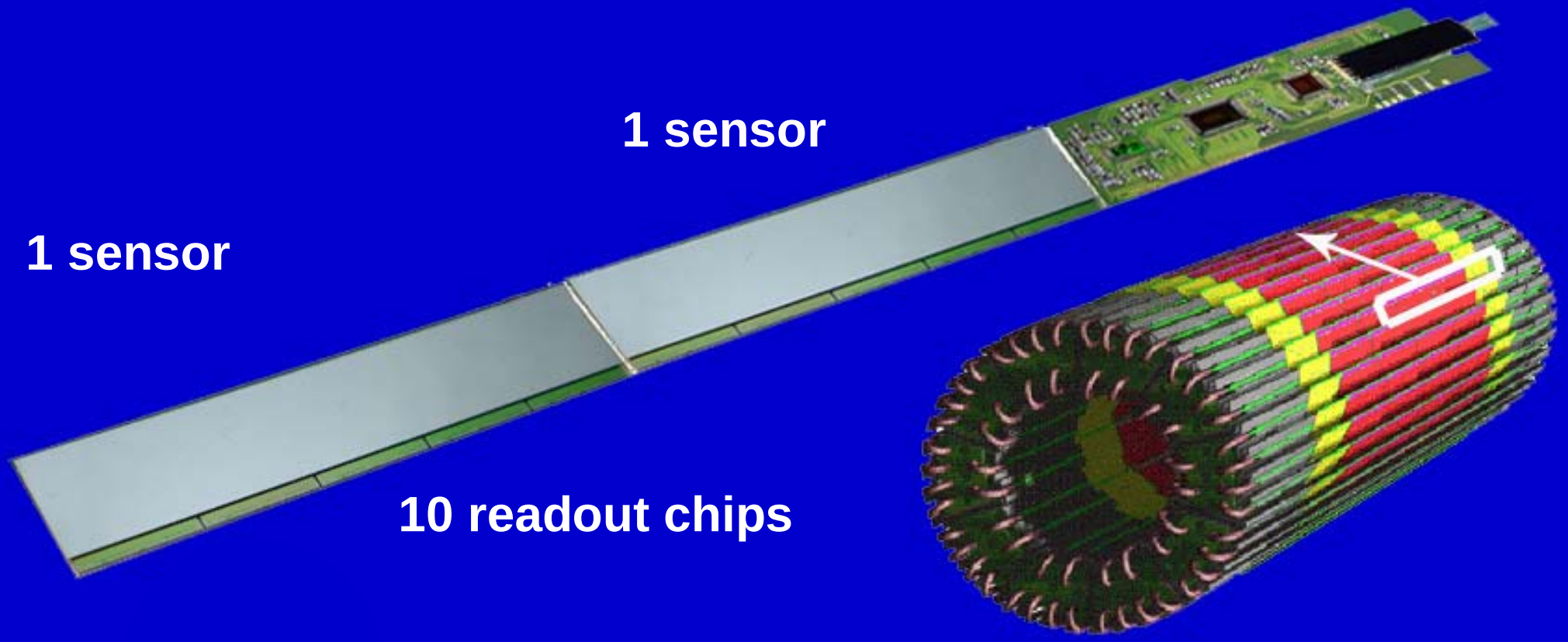


Image:INFN(Padova)

Pixel detector

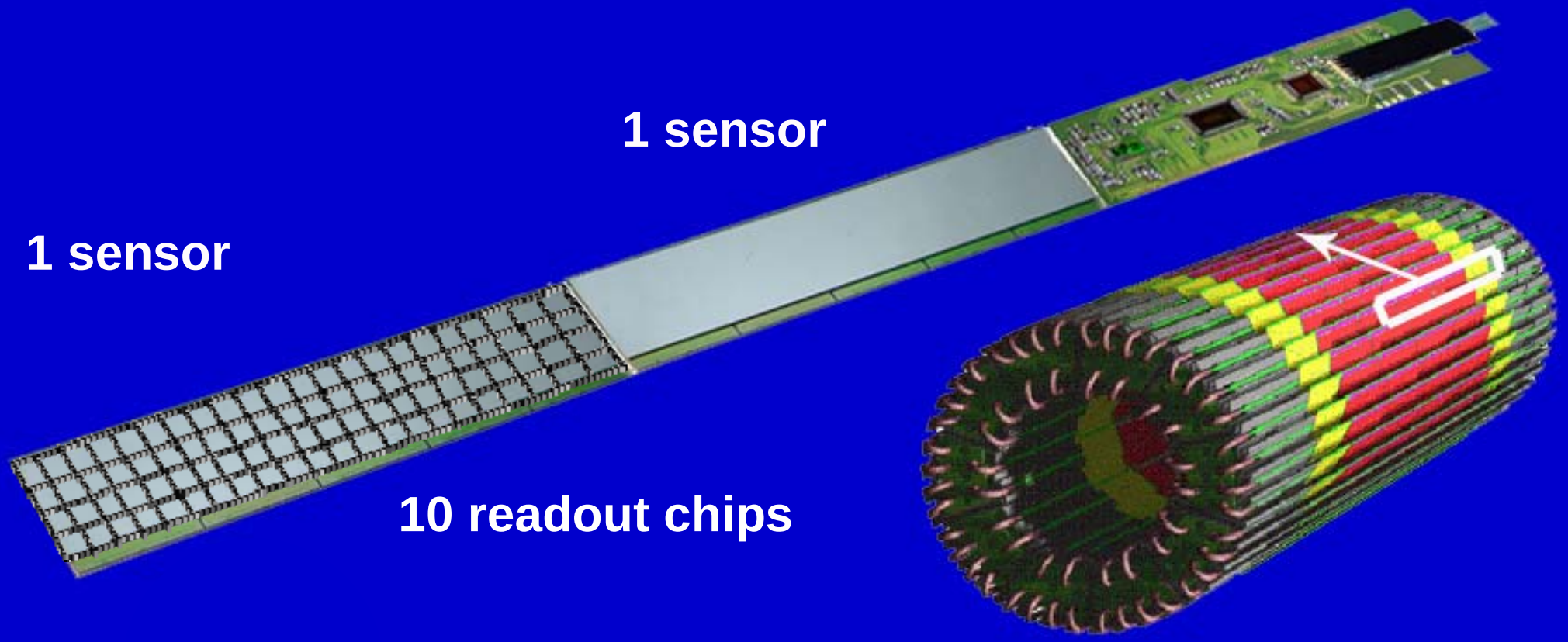


Image:INFN(Padova)

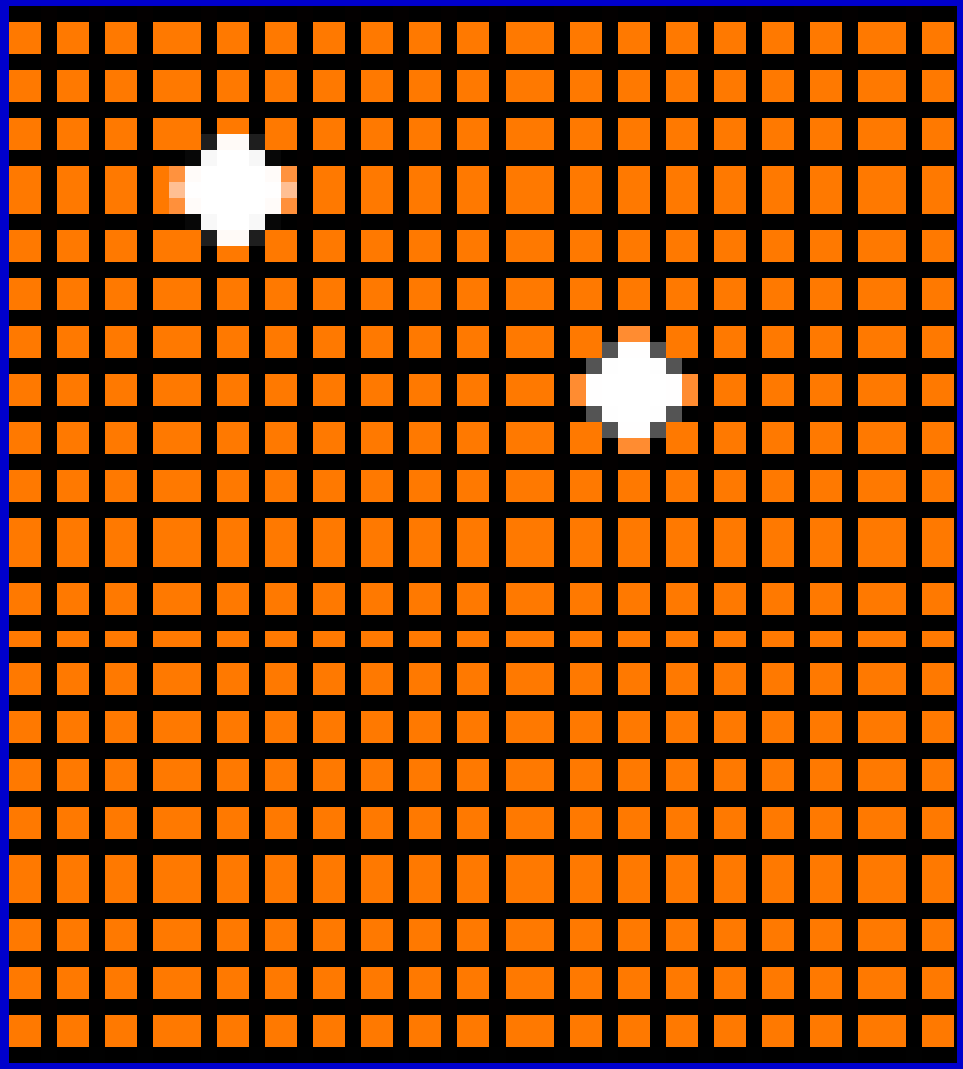
Pixel detector

0000100000000000000000000

0000000000000000100000000

0000000000100000010000010 0

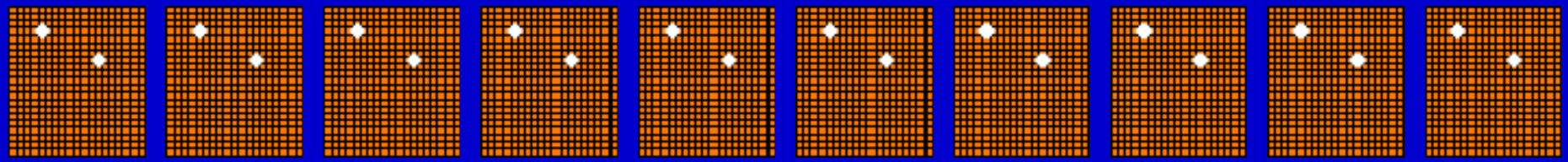
0000000000000000000000000



Pixel detector

Full detector 120 x 2560 x 32 bits @ 10 MHz (100ns) =
~ 100 Gbits/s

Separate read-out for each detector module



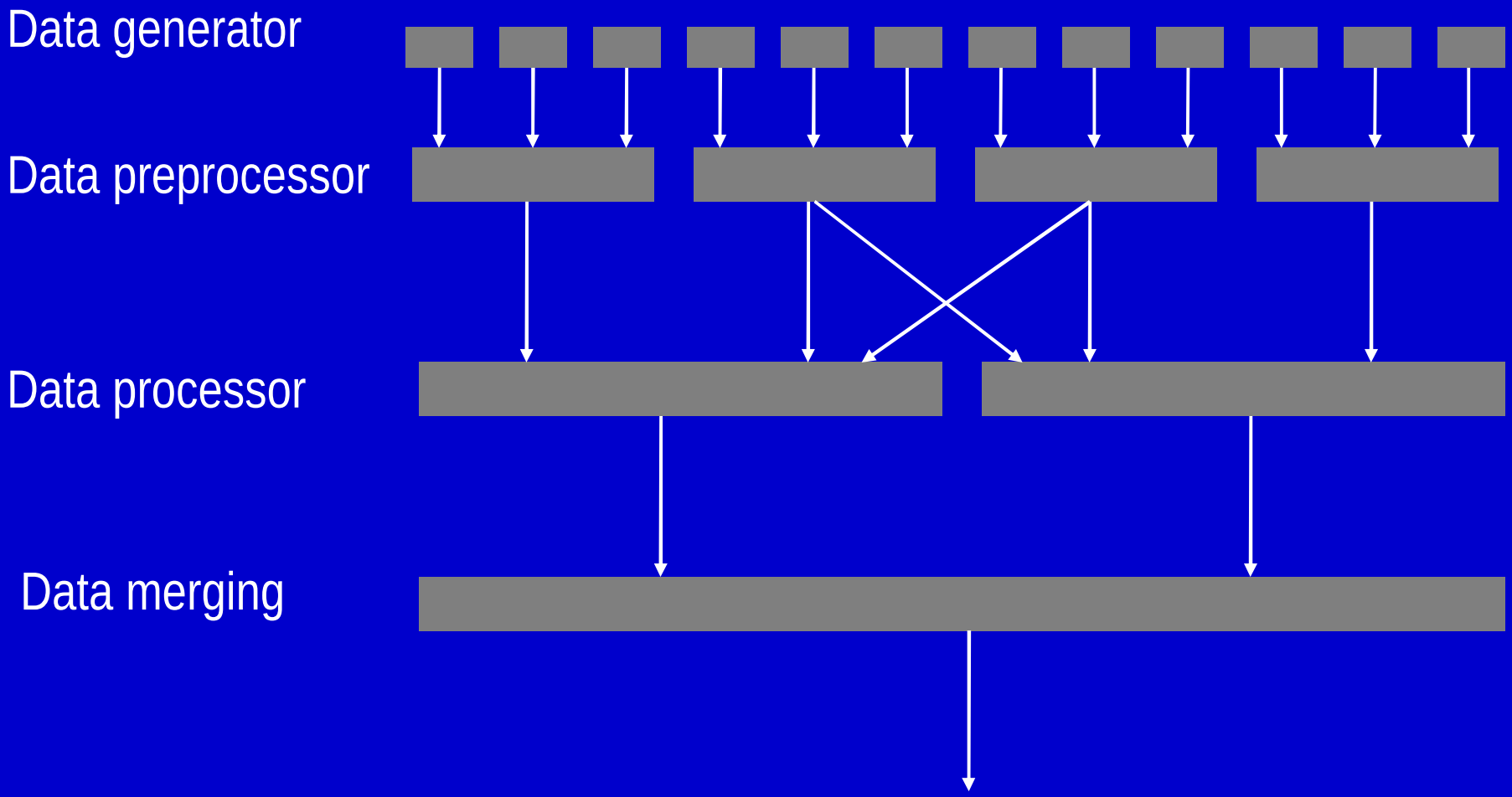
Each detector module (10 chips) 1 x 2560 x 32 bits @ 10 MHz

00001000000000000000000000000000

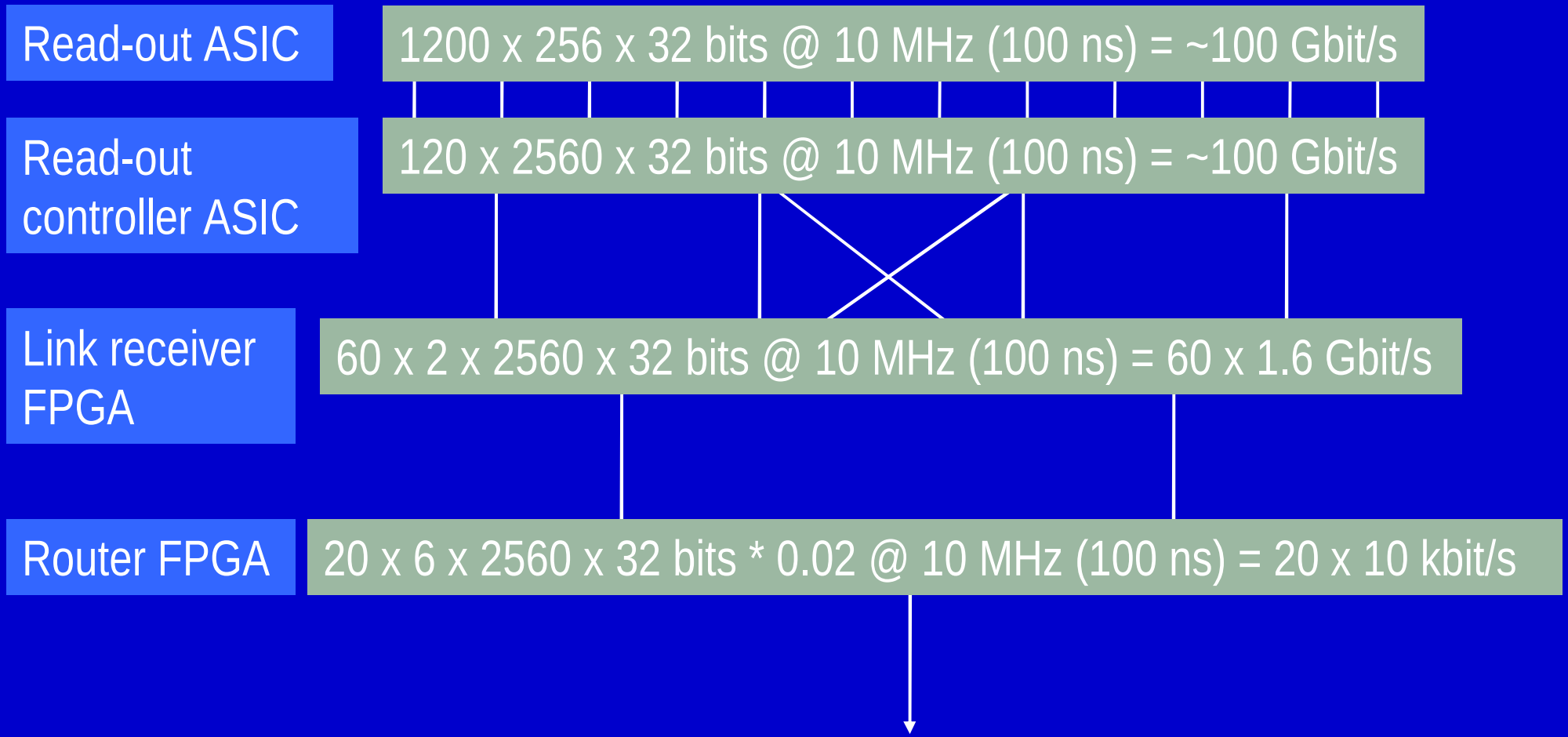
00000000000000001000000000000000

00000000010000001000001000000000

Data funnel


Data generator
Data preprocessor
Data processor
Data merging

Data funnel


Read-out ASIC
1200 x 256 x 32 bits @ 10 MHz (100 ns) = ~100 Gbit/s
Read-out controller ASIC
120 x 2560 x 32 bits @ 10 MHz (100 ns) = ~100 Gbit/s
Link receiver FPGA
60 x 2 x 2560 x 32 bits @ 10 MHz (100 ns) = 60 x 1.6 Gbit/s
Router FPGA
20 x 6 x 2560 x 32 bits * 0.02 @ 10 MHz (100 ns) = 20 x 10 kbit/s

Pixel detector

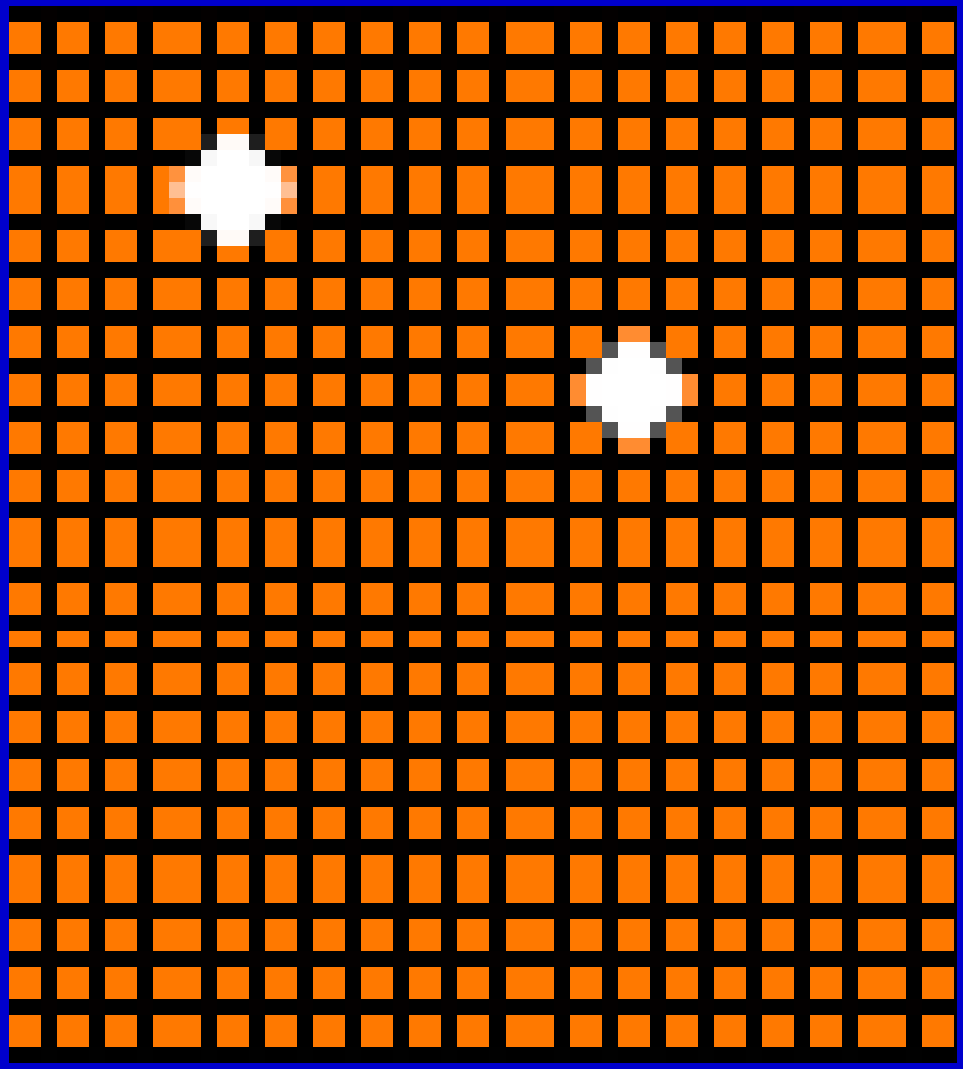
Data generator
2560 x 32 bits

00001000000000000000000000

00000000000000001000000000

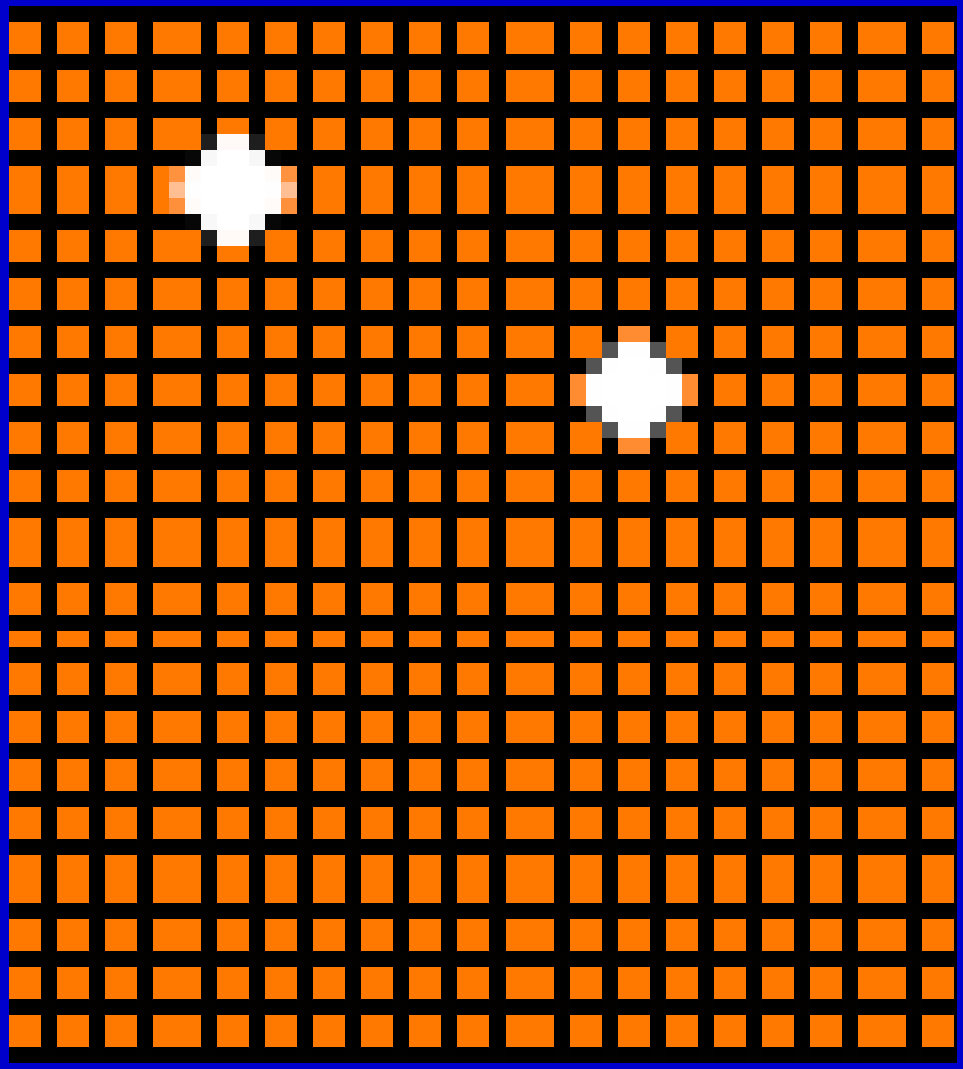
00000000001000000100000100

00000000000000000000000000



Pixel detector

What is the strategy?



0000100000000000000000000

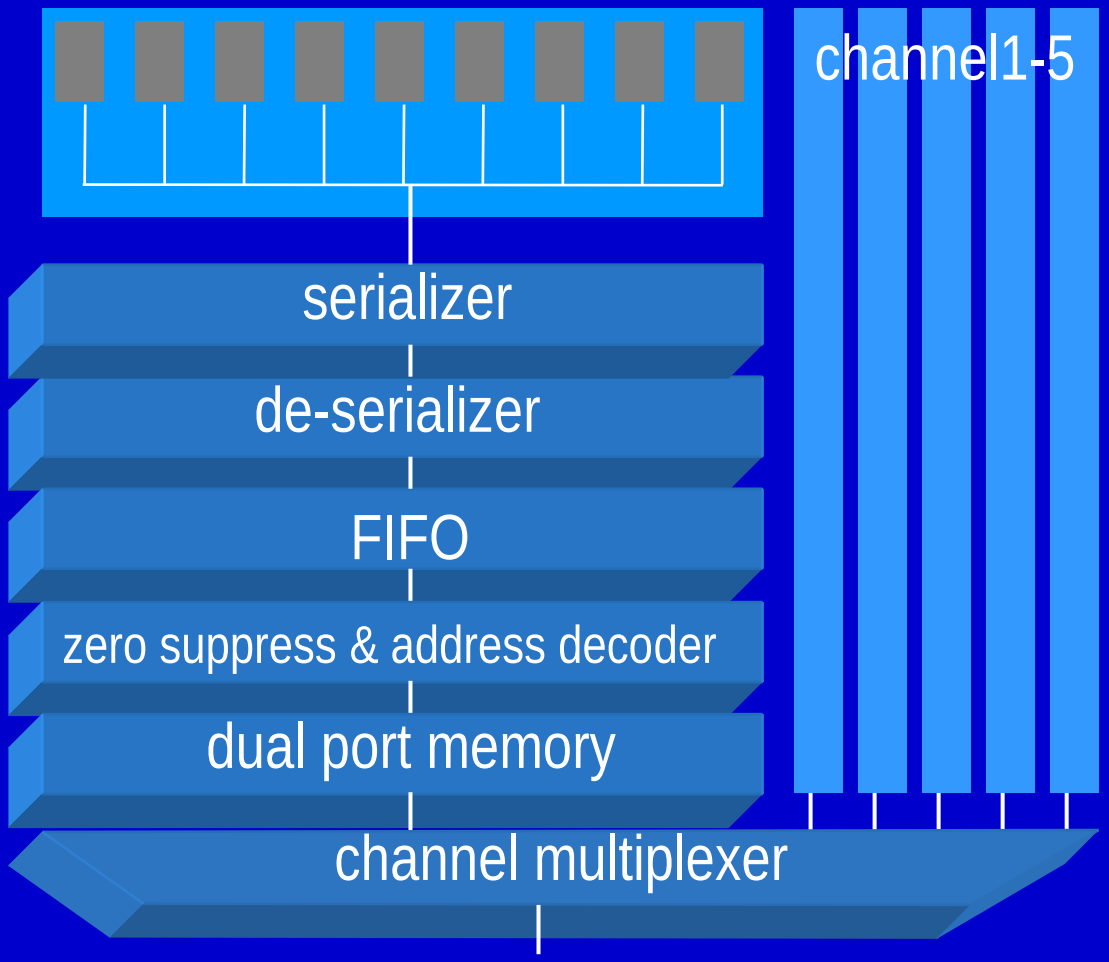
0000000000000000100000000

0000000000100000010000010 0

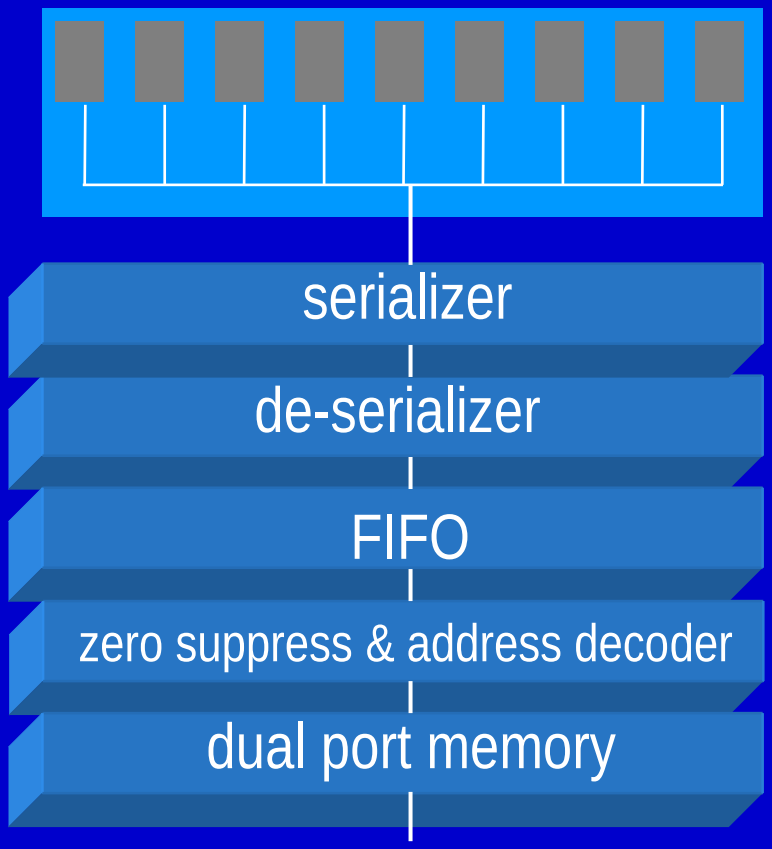
0000000000000000000000000

Some body counts values all the time, find out whether they can be divided by three, what to you do in real life? Include serial and dpm

Pixel detector



Pixel detector



Pixel detector data processing

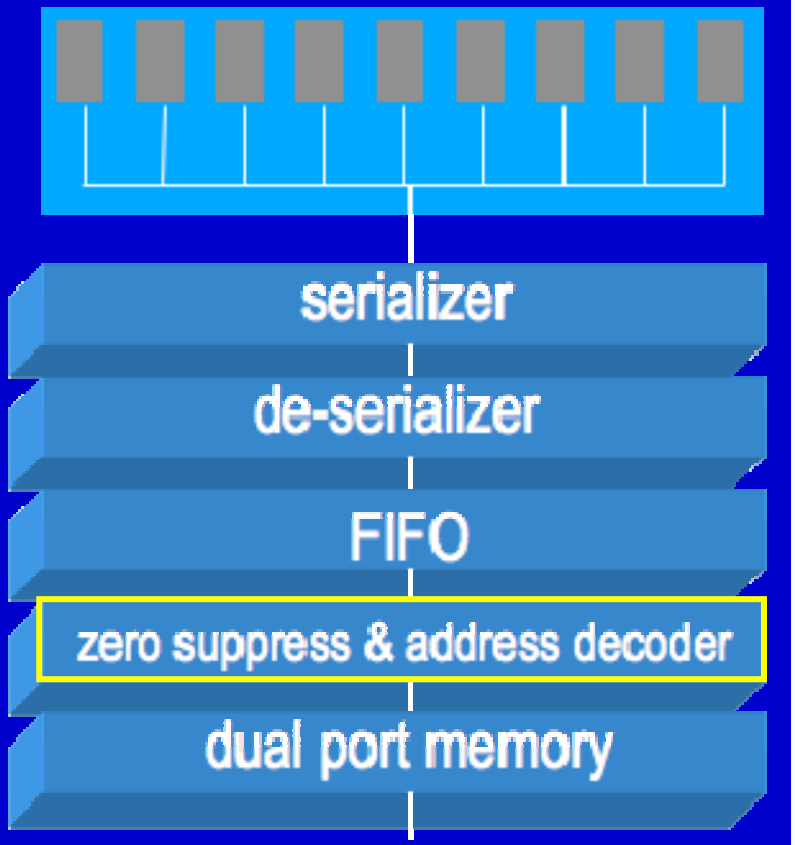
0	0	0	0	0	0	0	0	0	0	0	0	0

check if any hits

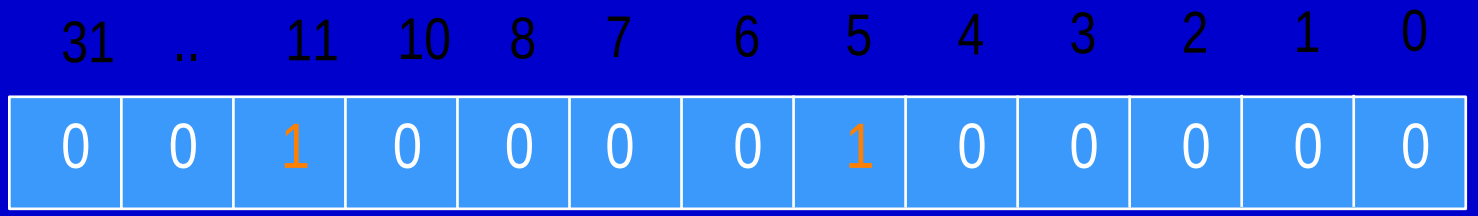
if no hits ->
load new value from FIFO

if 1 hit only ->
decode the hit &
request new value from FIFO

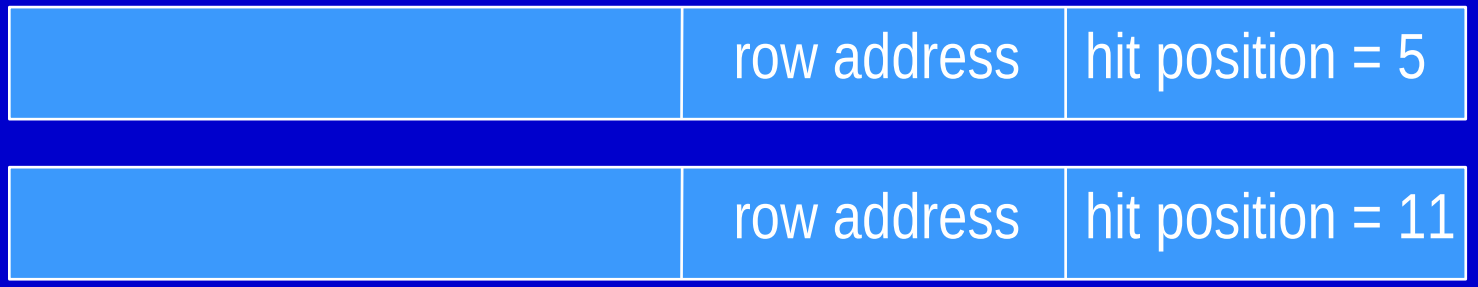
if more than one hit -> decode the hits



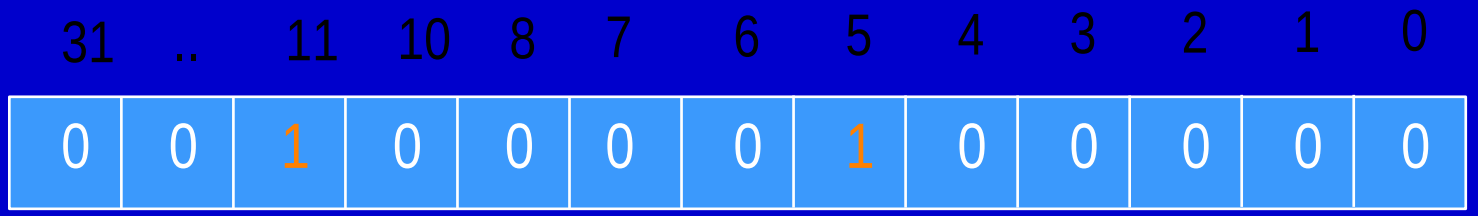
Pixel detector data processing



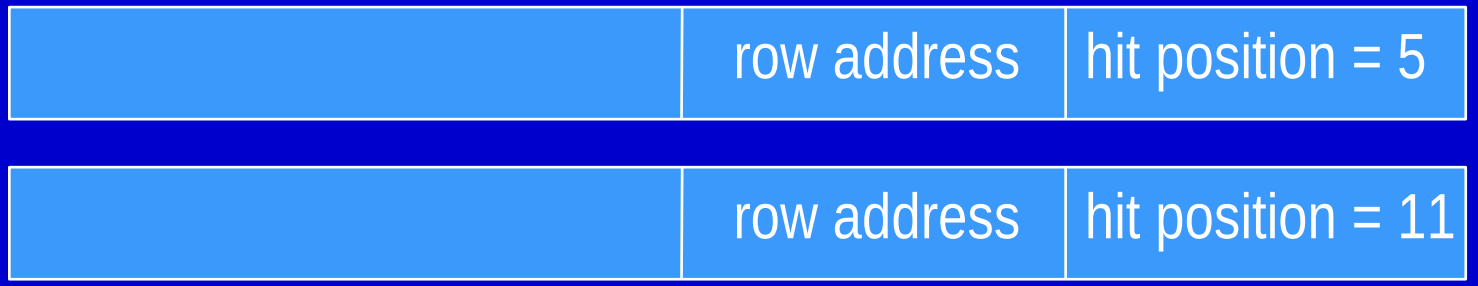
How to decode the address?
this line has two hits
the state machine must send two hits into the dual port memory



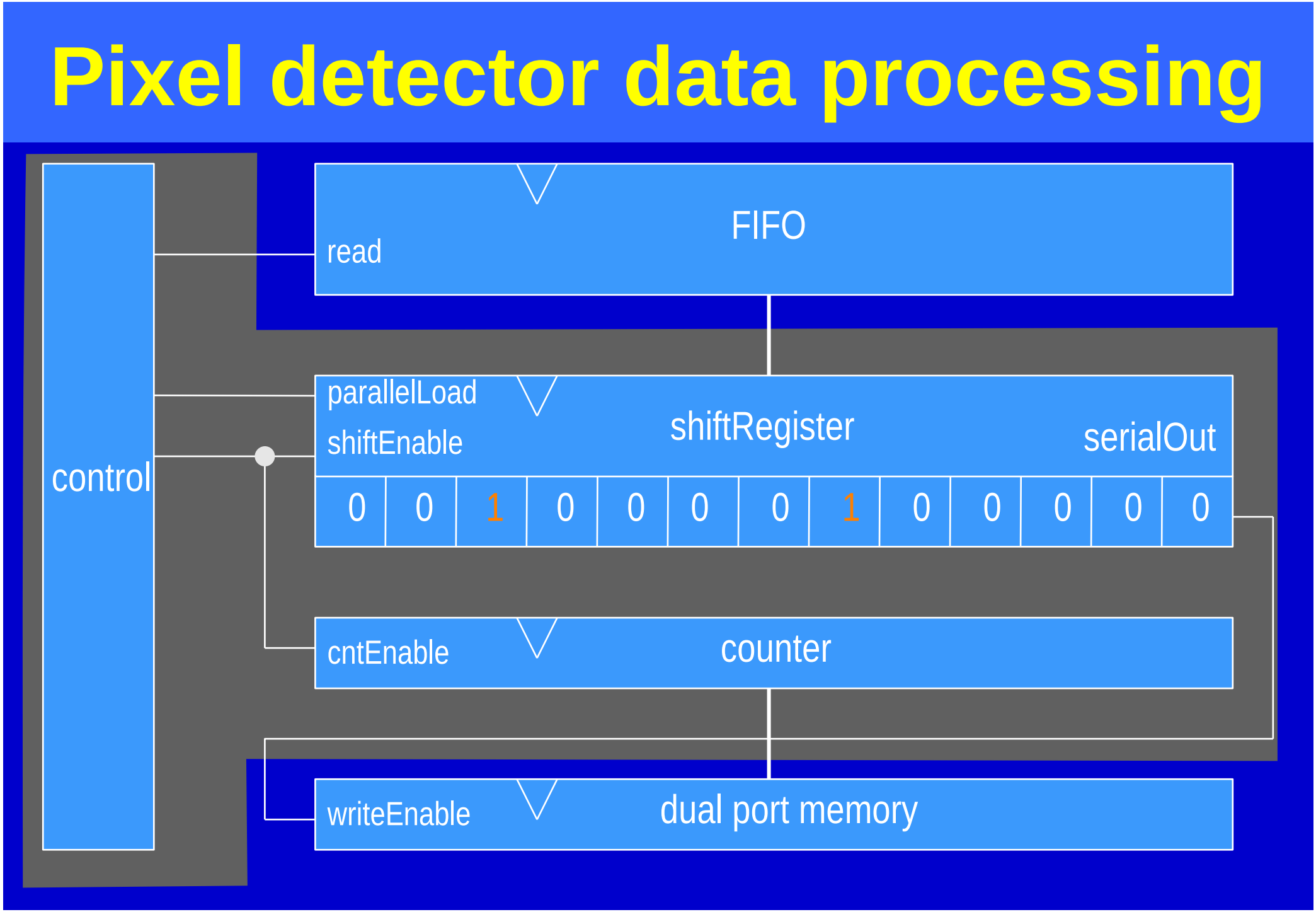
Pixel detector data processing



Do we know enough to start the project?
How do we encode the address?



Pixel detector data processing



Position decoder – shift register

positionDecoderSR.vhd - /Volumes/akluge/cadence/div/test_vhdl/

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/Volumes/akluge/cadence/div/test_vhdl/positionDecoderSR.vhd 1418 bytes L: 1 C: 16

```
library ieee;
use ieee.std_logic_1164.all;

entity positionDecoderSR is
port (   clk                    :in   std_logic;
         reset_i                :in   std_logic;
         new_value_available    :in   std_logic;
         new_value              :in   std_logic_vector (31 downto 0);
         data_word              :out  integer range 0 to 31;
         write_data_word        :out  std_logic);

end positionDecoderSR;

architecture behavioral of positionDecoderSR is


signal data_encode      :std_logic_vector (31 downto 0);
signal position_count   :integer range 0 to 31;
signal state_encoding   :std_logic;

begin

process (clk, reset_i)
begin

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_encode                <= (others => '0');
      position_count             <= 0;
      state_encoding             <= '0';
   elsif ((new_value_available = '1') and (state_encoding = '0')) then
      data_encode                <= new_value;
      state_encoding             <= '1';
   elsif ((state_encoding = '1') and (position_count /= 31)) then
      data_encode(30 downto 0)   <= data_encode(31 downto 1);
      data_encode(31)            <= '0';
      position_count             <= position_count - 1;
   elsif (position_count = 31) then
      state_encoding             <= '0';
   end if;
end if;

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_word                  <= 0;
      write_data_word            <= '0';
   elsif (data_encode(0) = '1') then
      data_word                  <= position_count;
      write_data_word            <= '1';
   else
      write_data_word            <= '0';
   end if;
end if;

end process;

end behavioral;
```

Position decoder – shift register

positionDecoderSR.vhd – /Volumes/akluge/cadence/div/test_vhdl/

File Edit Search Preferences Shell Macro Windows

/Volumes/akluge/cadence/div/test_vhdl/positionDecoderSR.vhd 1418 bytes

```
library ieee;
use ieee.std_logic_1164.all;

entity positionDecoderSR is
port (    clk                   :in   std_logic;
          reset_i               :in   std_logic;
          new_value_available   :in   std_logic;
          new_value             :in   std_logic_vector (31 downto 0);
          data_word             :out  integer range 0 to 31;
          write_data_word       :out  std_logic);

end positionDecoderSR;

architecture behavioral of positionDecoderSR is


signal data_encode       :std_logic_vector (31 downto 0);
signal position_count    :integer range 0 to 31;
signal state_encoding    :std_logic;

begin

process (clk, reset_i)
begin

if (clk'event and clk = '1') then
   if (reset_i = '0') then
```

```
begin

process (clk, reset_i)
begin

if (clk'event and clk = '1' ) then
   if (reset_i = '0') then
      data_encode                <= (others => '0');
      position_count             <= 0;
      state_encoding             <= '0';
   elsif ((new_value_available = '1') and (state_encoding = '0')) then
      data_encode                <= new_value;
      state_encoding             <= '1';
   elsif ((state_encoding = '1') and (position_count /= 31)) then
      data_encode(30 downto 0)   <= data_encode(31 downto 1);
      data_encode(31)            <= '0';
      position_count             <= position_count + 1;
   elsif (position_count = 31) then
      state_encoding             <= '0';
   end if;
end if;

if (clk'event and clk = '1' ) then
   if (reset_i = '0') then
      data_word                  <= 0;
      write_data_word            <= '0';
   elsif (data_encode(0) = '1' ) then
      data_word                  <= position_count;
      write_data_word            <= '1';
   else
      write_data_word            <= '0';
   end if;
end if;

end process;
```

```
begin

process (clk, reset_i)
begin

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_encode                   <= (others => '0');
      position_count                <= 0;
      state_encoding                <= '0';
   elsif ((new_value_available = '1') and (state_encoding = '0')) then
      data_encode                   <= new_value;
      state_encoding                <= '1';
   elsif ((state_encoding = '1') and (position_count /= 31)) then
      data_encode(30 downto 0)      <= data_encode(31 downto 1);
      data_encode(31)               <= '0';
      position_count                <= position_count + 1;
   elsif (position_count = 31) then
      state_encoding                <= '0';
   end if;
end if;

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_word                     <= 0;
      write_data_word               <= '0';
   elsif (data_encode(0) = '1') then
      data_word                     <= position_count;
      write_data_word               <= '1';
   else
      write_data_word               <= '0';
   end if;
end if;

end process;
```

shiftRegister

```
begin

process (clk, reset_i)
begin

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_encode                  <= (others => '0');
      position_count               <= 0;
      state_encoding               <= '0';
   elsif ((new_value_available = '1') and (state_encoding = '0')) then
      data_encode                  <= new_value;
      state_encoding               <= '1';
   elsif ((state_encoding = '1') and (position_count /= 31)) then
      data_encode(30 downto 0)     <= data_encode(31 downto 1);
      data_encode(31)              <= '0';
      position_count               <= position_count + 1;
   elsif (position_count = 31) then
      state_encoding               <= '0';
   end if;
end if;

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_word                    <= 0;
      write_data_word              <= '0';
   elsif (data_encode(0) = '1') then
      data_word                    <= position_count;
      write_data_word              <= '1';
   else
      write_data_word              <= '0';
   end if;
end if;

end process;

end behavioral;
```

counter

```
begin

process (clk, reset_i)
begin

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_encode                  <= (others => '0');
      position_count               <= 0;
      state_encoding               <= '0';
   elsif ((new_value_available = '1') and (state_encoding = '0')) then
      data_encode                  <= new_value;
      state_encoding               <= '1';
   elsif ((state_encoding = '1') and (position_count /= 31)) then
      data_encode(30 downto 0)     <= data_encode(31 downto 1);
      data_encode(31)              <= '0';
      position_count               <= position_count + 1;
   elsif (position_count = 31) then
      state_encoding               <= '0';
   end if;
end if;

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_word                    <= 0;
      write_data_word              <= '0';
   elsif (data_encode(0) = '1') then
      data_word                    <= position_count;
      write_data_word              <= '1';
   else
      write_data_word              <= '0';
   end if;
end if;

end process;

end behavioral;
```

control

```
begin

process (clk, reset_i)
begin

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_encode                  <= (others => '0');
      position_count               <= 0;
      state_encoding               <= '0';
   elsif ((new_value_available = '1') and (state_encoding = '0')) then
      data_encode                  <= new_value;
      state_encoding               <= '1';
   elsif ((state_encoding = '1') and (position_count /= 31)) then
      data_encode(30 downto 0)     <= data_encode(31 downto 1);
      data_encode(31)              <= '0';
      position_count               <= position_count + 1;
   elsif (position_count = 31) then
      state_encoding               <= '0';
   end if;
end if;

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_word                    <= 0;
      write_data_word              <= '0';
   elsif (data_encode(0) = '1') then
      data_word                    <= position_count;
      write_data_word              <= '1';
   else
      write_data_word              <= '0';
   end if;
end if;

end process;

end behavioral;
```

elsif invokes priority encoder -> more logic

state machine with case statement

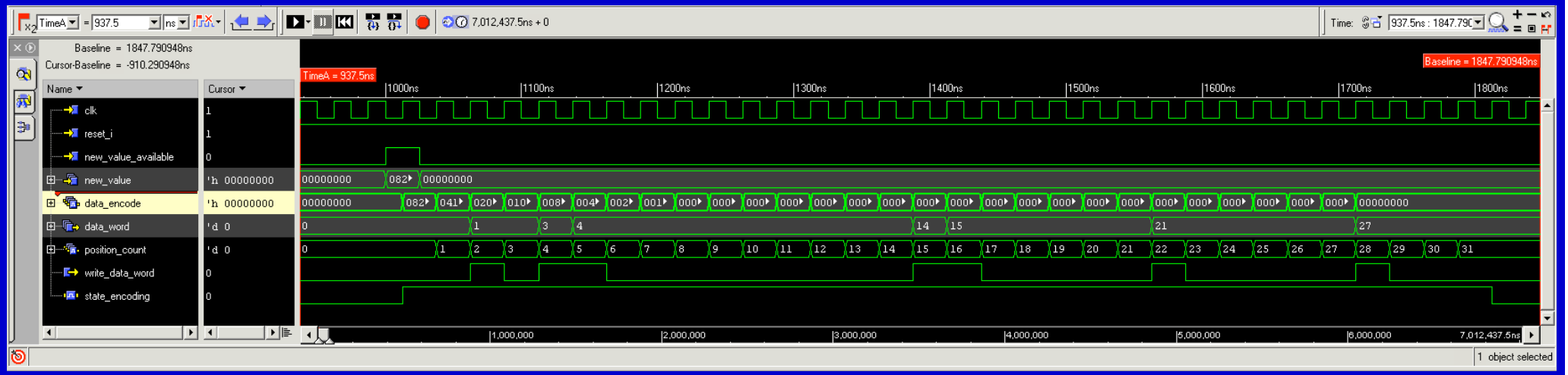
```
process (clk, reset_i)
begin
if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_encode                          <= (others => '0');
      position_count                       <= 0;
      state_encoding                       <= '0';
   else
      case (state_encoding) is
      when '0' =>
         if (new_value_available = '1') then
            data_encode                    <= new_value;
            state_encoding                 <= '1';
         end if;
      when '1' =>
         if (position_count /= 31) then
            data_encode(30 downto 0)       <= data_encode(31 downto 1);
            data_encode(31)                <= '0';
            position_count                 <= position_count + 1;
         elsif (position_count = 31) then
            state_encoding                 <= '0';
         end if;
      when others =>
         data_encode                       <= (others => '0');
         position_count                    <= 0;
         state_encoding                    <= '0';
      end case;
   end if;
end if;

if (clk'event and clk = '1') then
   if (reset_i = '0') then
```

- **Shift register is a parallel load register**

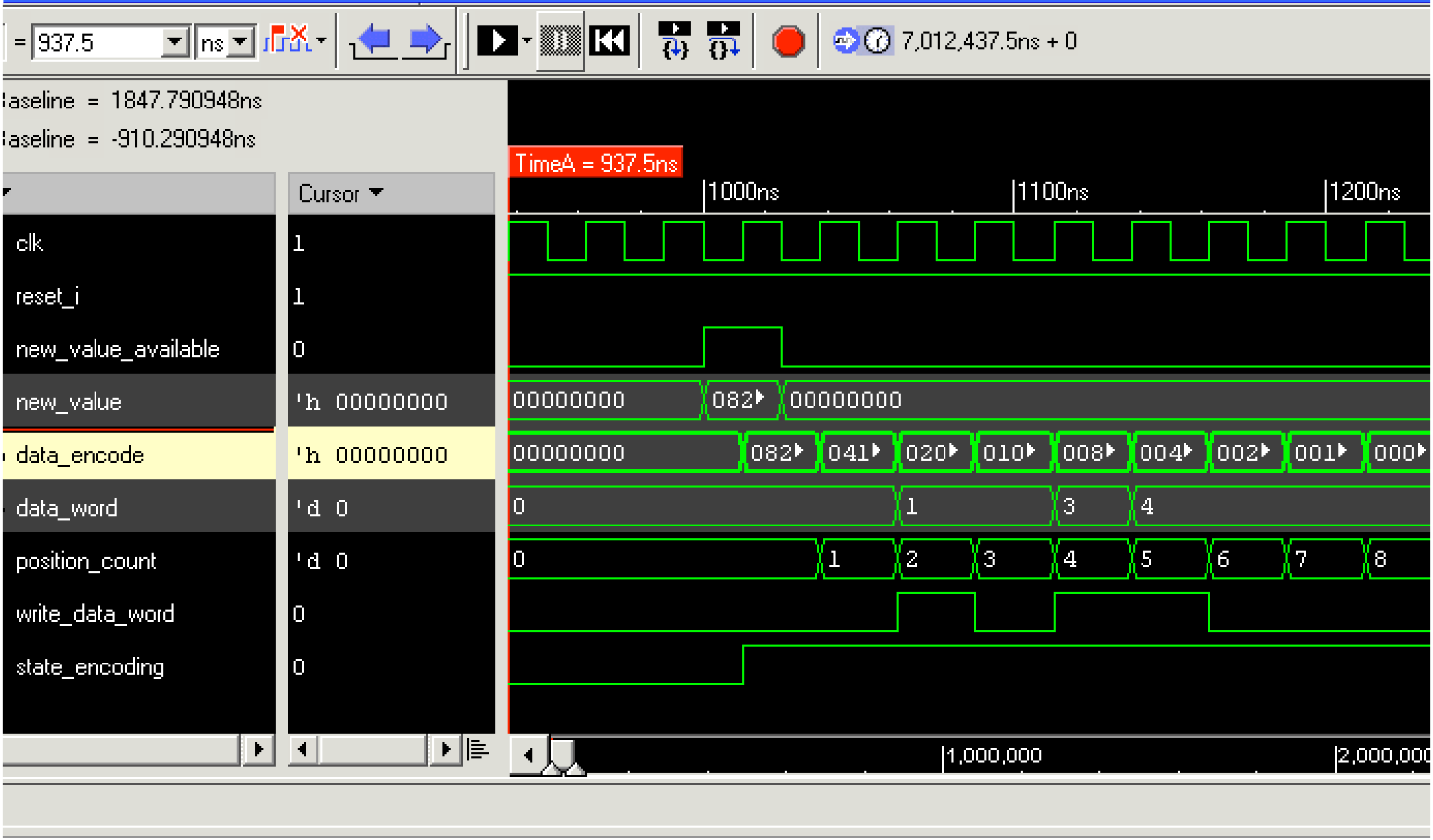
Position decoder – shift register

31	..	11	10	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	1	1	0	1	0

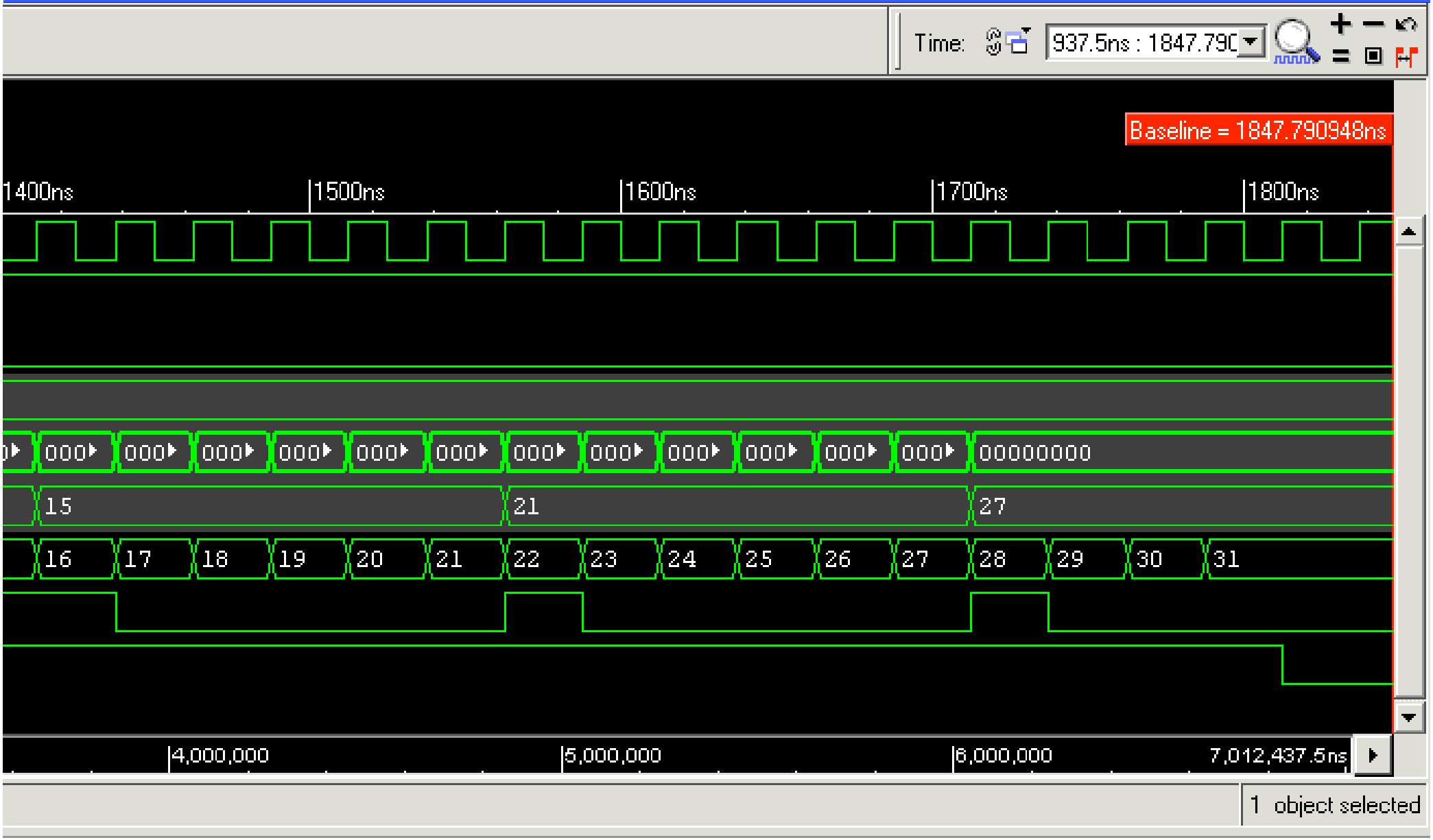
"00001000001000001100000000011010"



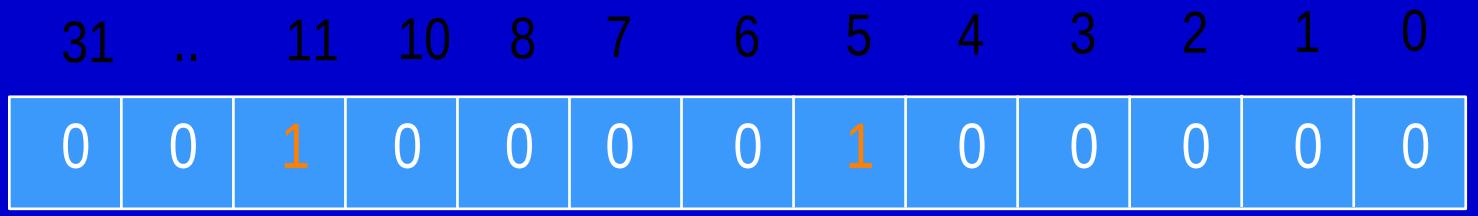
Position decoder – shift register



Position decoder – shift register



Position decoder – shift register



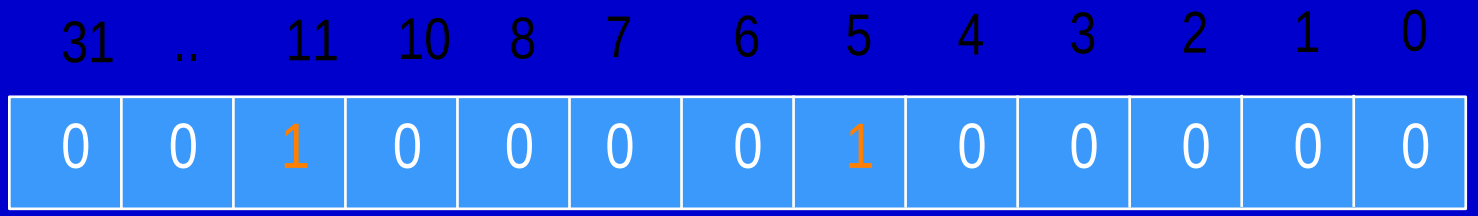
Shift register & counter (if then)
Result in an FPGA from 2002: (Altera EP20k200FC484-3)
81 out of 8320 logic elements
44 registers

11% (41/376) of pins

10.6 ns (94.5 MHz) position_count-> position_count

tco: 8.0 ns: data_word_reg -> data_word
tsu: 7.0 ns: new_value_available -> data_encode

Position decoder – shift register



Shift register & counter (case)
Result in an FPGA from 2002: (Altera EP20k200FC484-3)
50 out of 8320 logic elements (with case statement)
44 registers

11% (41/376) of pins

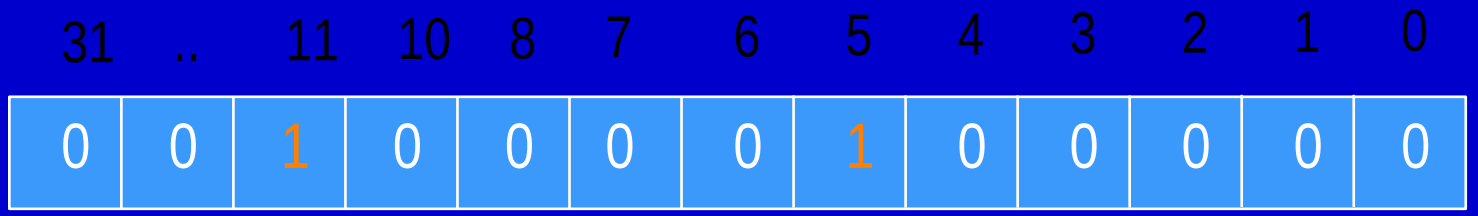
9.1 ns (109.9 MHz) position_count-> data_encode

tco: 7.0 ns: data_word_reg -> data_word
tsu: 6.3 ns: new_value_available -> data_encode

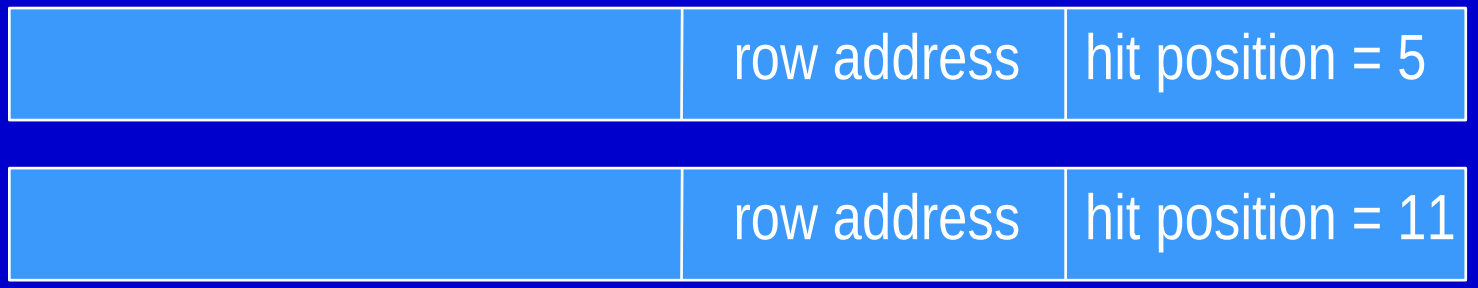
Position decoder – shift register

- **Task fulfilled?**
  - Few logic cells
  - Timing constraints fulfilled
- **User requirements fulfilled?**
  - Processing per 32 bit line takes:
    - 32 bits * 25 ns = 800 ns
    - Data comes each 100 ns -> 1 out of 2560 32 bit line
    - Decoding time for all lines is: 2560 * 800 ns => 2 ms
    - Within 2 ms => 20480 data lines arrive
      - input FIFO would need to be at least 20k * 32 bit deep
    - During 2 ms no other trigger acquisition can take place
      - dead time => max trigger rate: 488 Hz
- **User requirements not fulfilled**

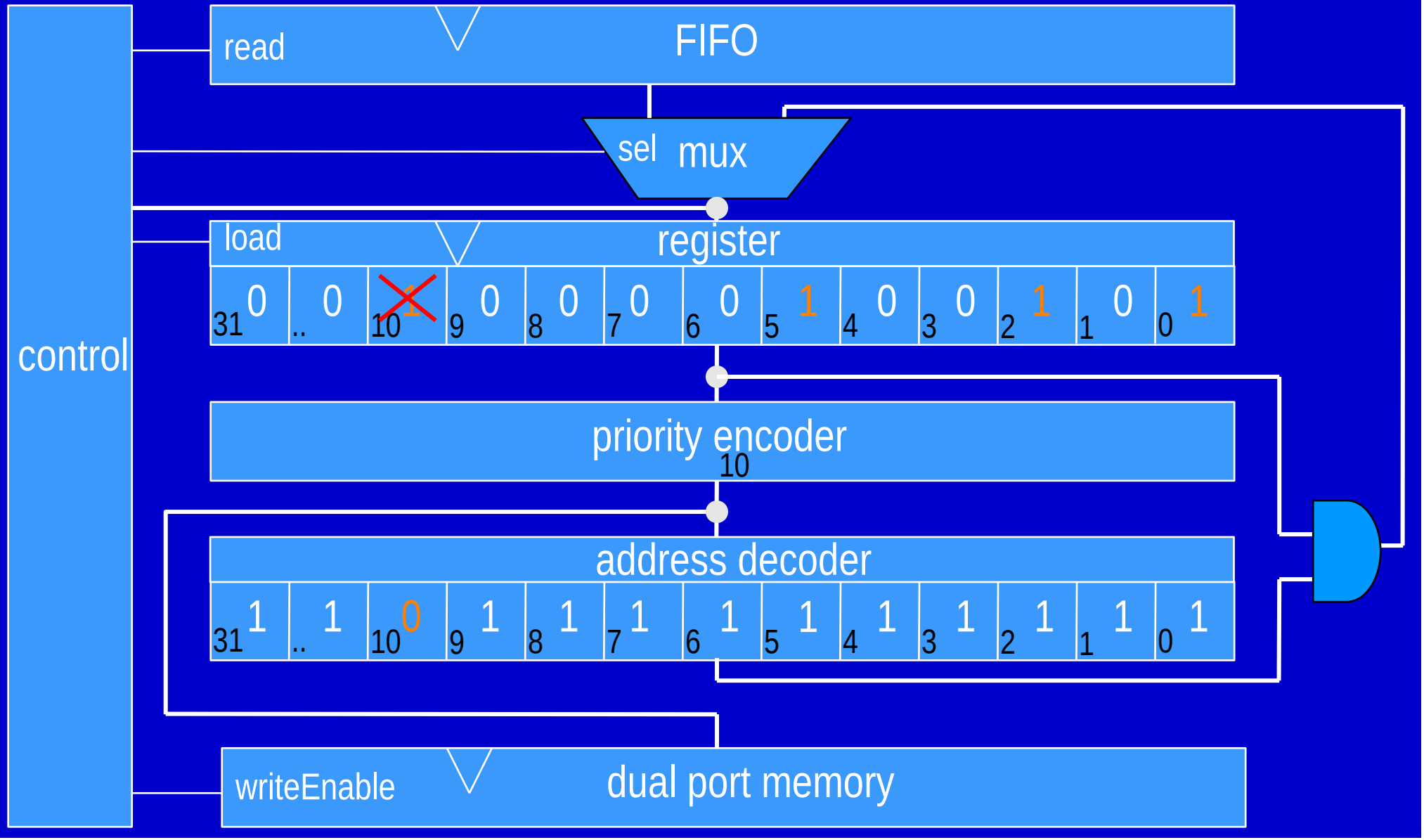
Position decoder – priority encoder



How to decode the address?
this line has two hits
the state machine must send two hits into the dual port memory



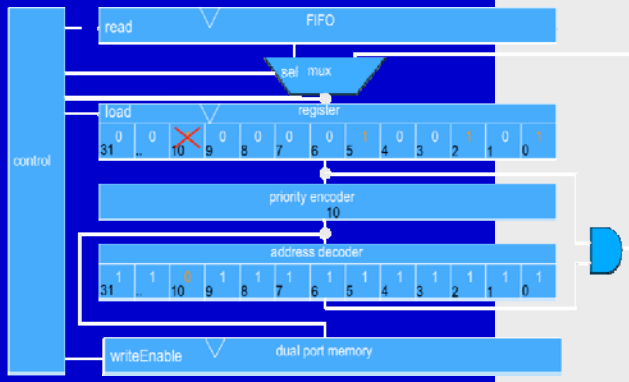
Position decoder – priority encoder



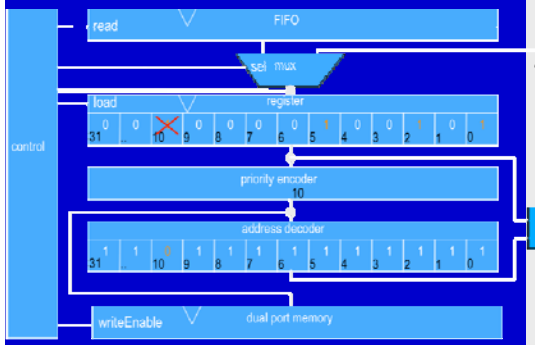
Position decoder – priority encoder

```
--*****************************************************************
--postionDecoderPri
--*****************************************************************

library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;

entity positionDecoder is
port (   clk                    :in   std_logic;
         reset_i                :in   std_logic;
         new_value_available    :in   std_logic;
         new_value              :in   std_logic_vector (31 downto 0);
         data_word              :out  integer range 0 to 31;
         write_data_word        :out  std_logic);

end positionDecoder;

architecture Priority of positionDecoder is

component prior32
port  (  inp       :in   std_logic_vector (31 downto 0);
         code      :out  std_logic_vector (4 downto 0));
end component;

component addressDecoder
port  (  inp       :in   std_logic_vector (4 downto 0);
         code      :out  std_logic_vector (31 downto 0));
end component;


signal data_encode             :std_logic_vector (31 downto 0);
signal state_encoding          :std_logic;
signal hit_address             :std_logic_vector (4 downto 0);
signal data_encode_actual      :std_logic_vector (31 downto 0);
signal data_encode_next        :std_logic_vector (31 downto 0);
signal data_encode_next_is_0   :std_logic;
signal new_value_is_0          :std_logic;
```

```
--*************************************************************
--postionDecoderPri
--*************************************************************

library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;

entity positionDecoder is
port (   clk                    :in   std_logic;
         reset_i                :in   std_logic;
         new_value_available    :in   std_logic;
         new_value              :in   std_logic_vector (31 downto 0);
         data_word              :out  integer range 0 to 31;
         write_data_word        :out  std_logic);

end positionDecoder;

architecture Priority of positionDecoder is

component prior32
port  (  inp       :in   std_logic_vector (31 downto 0);
         code      :out  std_logic_vector (4 downto 0));
end component;

component addressDecoder
port  (  inp       :in   std_logic_vector (4 downto 0);
         code      :out  std_logic_vector (31 downto 0));
end component;


signal data_encode             :std_logic_vector (31 downto 0);
signal state_encoding          :std_logic;
signal hit_address             :std_logic_vector (4 downto 0);
signal data_encode_actual      :std_logic_vector (31 downto 0);
signal data_encode_next        :std_logic_vector (31 downto 0);
signal data_encode_next_is_0   :std_logic;
signal new_value_is_0          :std_logic;
```




```
begin

process (clk, reset_i)
begin

if (clk'event and clk = '1') then
   if (reset_i = '0') then
      data_encode                          <= (others => '0');
      state_encoding                       <= '0';
   else case state_encoding is
      when '0' =>
         if (new_value_available = '1') then
            data_encode                    <= new_value;
            state_encoding                 <= not new_value_is_0;
         else
            state_encoding                 <= '0';
         end if;
      when '1' =>
         if (data_encode_next_is_0 = '0') then
            data_encode                    <= data_encode_next;
            state_encoding                 <= '1';
         elsif (data_encode_next_is_0 = '1') then
            data_encode                    <= data_encode_next;
            state_encoding                 <= '0';
         end if;
      when others =>
         data_encode                       <= (others => '0');
         state_encoding                    <= '0';
      end case;
   end if;
end if;

end process;

data_encode_next         <= data_encode and data_encode_actual;
write_data_word          <= state_encoding;
data_word                <= to_integer (unsigned(hit_address));

a_prior32:         prior32
   port map (data_encode, hit_address);

a_addressDecoder: addressDecoder
   port map (hit_address, data_encode_actual);
```

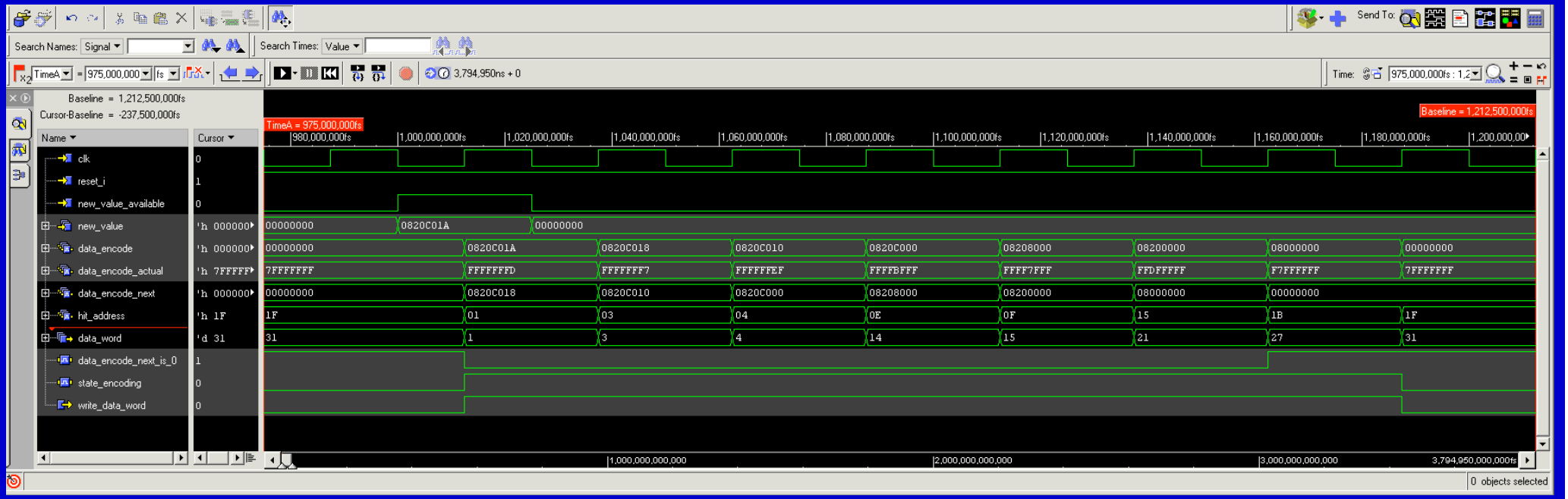



```
            data_encode                 <= data_encode_next;
            state_encoding              <= '0';
         end if;
      when others =>
         data_encode                    <= (others => '0');
         state_encoding                 <= '0';
      end case;
   end if;
end if;

end process;

data_encode_next        <= data_encode and data_encode_actual;
write_data_word         <= state_encoding;
data_word               <= to_integer (unsigned(hit_address));

a_prior32:         prior32
   port map (data_encode, hit_address);

a_addressDecoder: addressDecoder
   port map (hit_address, data_encode_actual);



process (data_encode_next)
begin
   if (data_encode_next = "00000000000000000000000000000000") then
      data_encode_next_is_0    <= '1';
   else
      data_encode_next_is_0    <= '0';
   end if;
end process;

process (new_value)
begin
   if (new_value = "00000000000000000000000000000000") then
      new_value_is_0 <= '1';
   else
      new_value_is_0 <= '0';
   end if;
end process;

end Priority;
```

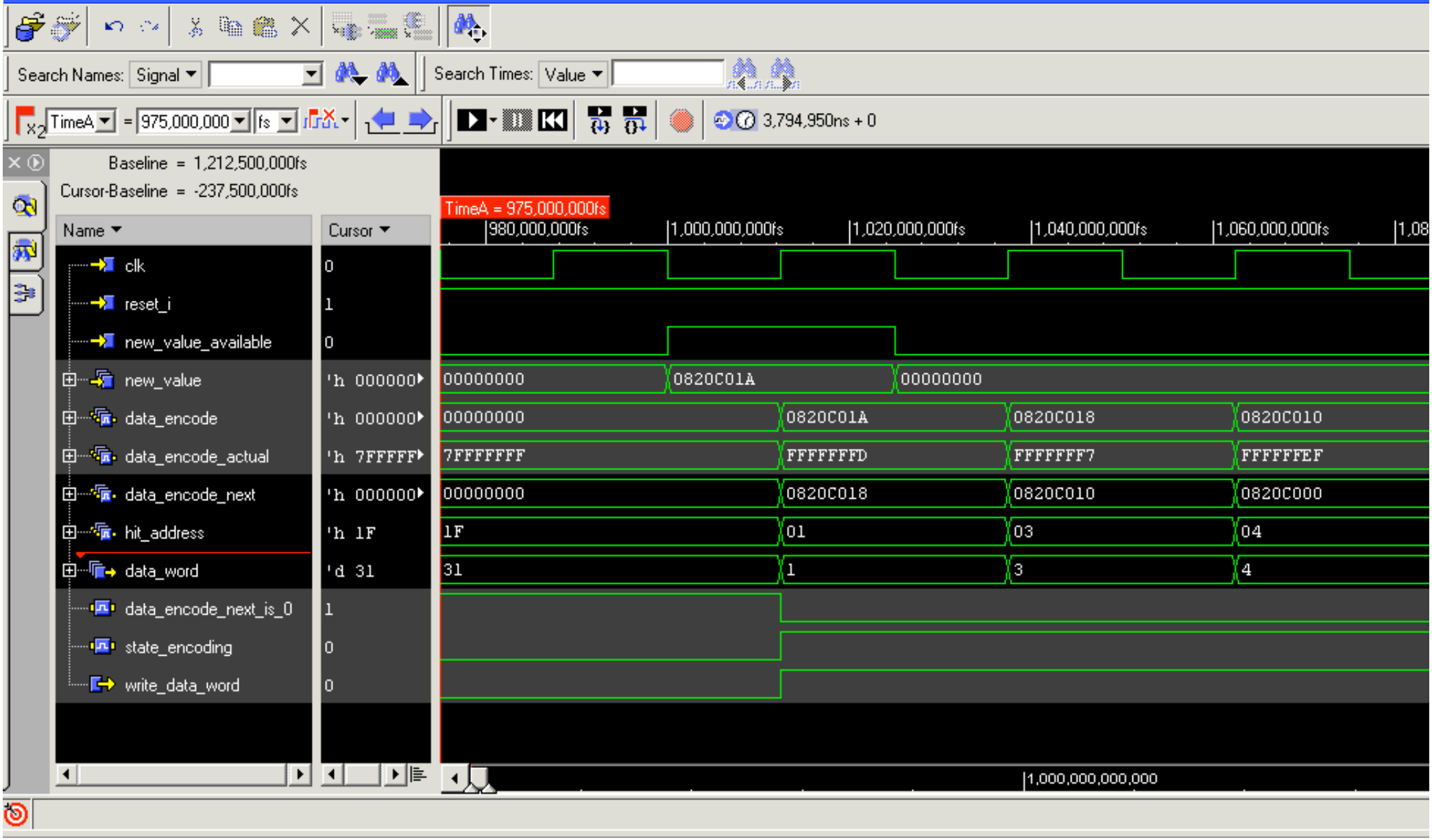
```
library ieee;
use ieee.std_logic_1164.all;

entity prior32 is
port  (  inp       :in   std_logic_vector (31 downto 0);
         code      :out  std_logic_vector (4 downto 0));
end prior32;

architecture behavioral0 of prior32 is

--------------------------------------------------------------
--prior32
--------------------------------------------------------------
begin

process (inp)
begin
   if    (inp(0) = '1') then      code <= "00000";
   elsif (inp(1) = '1') then      code <= "00001";
   elsif (inp(2) = '1') then      code <= "00010";
   elsif (inp(3) = '1') then      code <= "00011";
   elsif (inp(4) = '1') then      code <= "00100";
   elsif (inp(5) = '1') then      code <= "00101";
   elsif (inp(6) = '1') then      code <= "00110";
   elsif (inp(7) = '1') then      code <= "00111";
   elsif (inp(8) = '1') then      code <= "01000";
   elsif (inp(9) = '1') then      code <= "01001";
   elsif (inp(10) = '1') then     code <= "01010";
   elsif (inp(11) = '1') then     code <= "01011";
   elsif (inp(12) = '1') then     code <= "01100";
   elsif (inp(13) = '1') then     code <= "01101";
   elsif (inp(14) = '1') then     code <= "01110";
   elsif (inp(15) = '1') then     code <= "01111";
   elsif (inp(16) = '1') then     code <= "10000";
   elsif (inp(17) = '1') then     code <= "10001";
   elsif (inp(18) = '1') then     code <= "10010";
   elsif (inp(19) = '1') then     code <= "10011";
   elsif (inp(20) = '1') then     code <= "10100";
   elsif (inp(21) = '1') then     code <= "10101";
   elsif (inp(22) = '1') then     code <= "10110";
   elsif (inp(23) = '1') then     code <= "10111";
   elsif (inp(24) = '1') then     code <= "11000";
   elsif (inp(25) = '1') then     code <= "11001";
   elsif (inp(26) = '1') then     code <= "11010";
   elsif (inp(27) = '1') then     code <= "11011";
   elsif (inp(28) = '1') then     code <= "11100";
   elsif (inp(29) = '1') then     code <= "11101";
   elsif (inp(30) = '1') then     code <= "11110";
   elsif (inp(31) = '1') then     code <= "11111";
   else                           code <= "11111";
end if;

end process;

end behavioral0;
```

```
--**************************************************************************
--adressDecoder
--**************************************************************************

library ieee;
use ieee.std_logic_1164.all;

entity addressDecoder is
port  (  inp      :in   std_logic_vector (4 downto 0);
         code     :out  std_logic_vector (31 downto 0));
end addressDecoder;

architecture behavioral of addressDecoder is

begin

process (inp)
begin
   case (inp) is
      when "00000" =>    code  <= "11111111111111111111111111111110";
      when "00001" =>    code  <= "11111111111111111111111111111101";
      when "00010" =>    code  <= "11111111111111111111111111111011";
      when "00011" =>    code  <= "11111111111111111111111111110111";
      when "00100" =>    code  <= "11111111111111111111111111101111";
      when "00101" =>    code  <= "11111111111111111111111111011111";
      when "00110" =>    code  <= "11111111111111111111111110111111";
      when "00111" =>    code  <= "11111111111111111111111101111111";
      when "01000" =>    code  <= "11111111111111111111111011111111";
      when "01001" =>    code  <= "11111111111111111111110111111111";
      when "01010" =>    code  <= "11111111111111111111101111111111";
      when "01011" =>    code  <= "11111111111111111111011111111111";
      when "01100" =>    code  <= "11111111111111111110111111111111";
      when "01101" =>    code  <= "11111111111111111101111111111111";
      when "01110" =>    code  <= "11111111111111111011111111111111";
      when "01111" =>    code  <= "11111111111111110111111111111111";
      when "10000" =>    code  <= "11111111111111101111111111111111";
      when "10001" =>    code  <= "11111111111111011111111111111111";
      when "10010" =>    code  <= "11111111111110111111111111111111";
      when "10011" =>    code  <= "11111111111101111111111111111111";
      when "10100" =>    code  <= "11111111111011111111111111111111";
      when "10101" =>    code  <= "11111111110111111111111111111111";
      when "10110" =>    code  <= "11111111101111111111111111111111";
      when "10111" =>    code  <= "11111111011111111111111111111111";
      when "11000" =>    code  <= "11111110111111111111111111111111";
      when "11001" =>    code  <= "11111101111111111111111111111111";
      when "11010" =>    code  <= "11111011111111111111111111111111";
      when "11011" =>    code  <= "11110111111111111111111111111111";
      when "11100" =>    code  <= "11101111111111111111111111111111";
      when "11101" =>    code  <= "11011111111111111111111111111111";
      when "11110" =>    code  <= "10111111111111111111111111111111";
      when "11111" =>    code  <= "01111111111111111111111111111111";
      when others =>     code  <= "11111111111111111111111111111111";
   end case;

end process;

end behavioral;
```

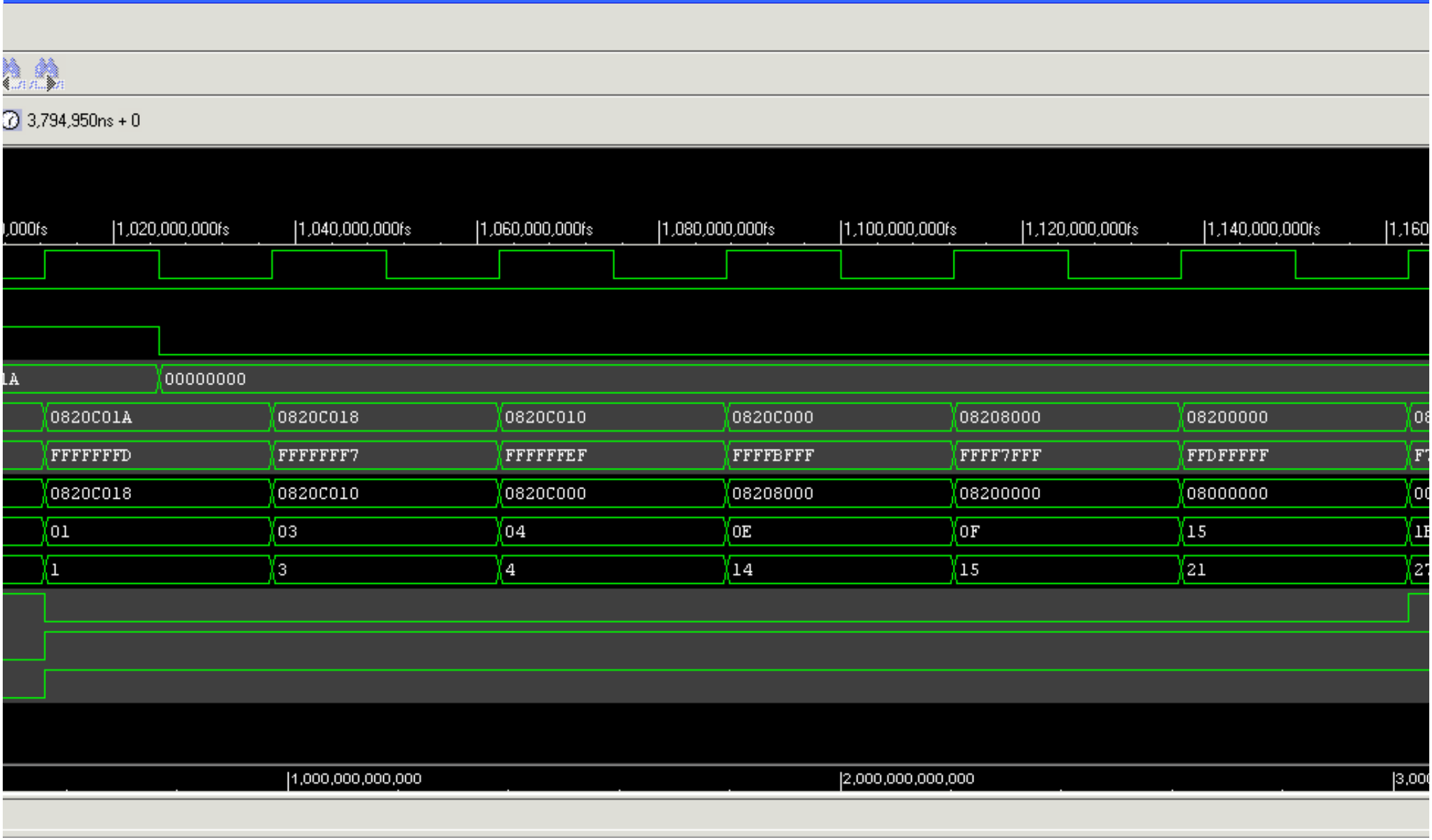
Position decoder – priority encoder



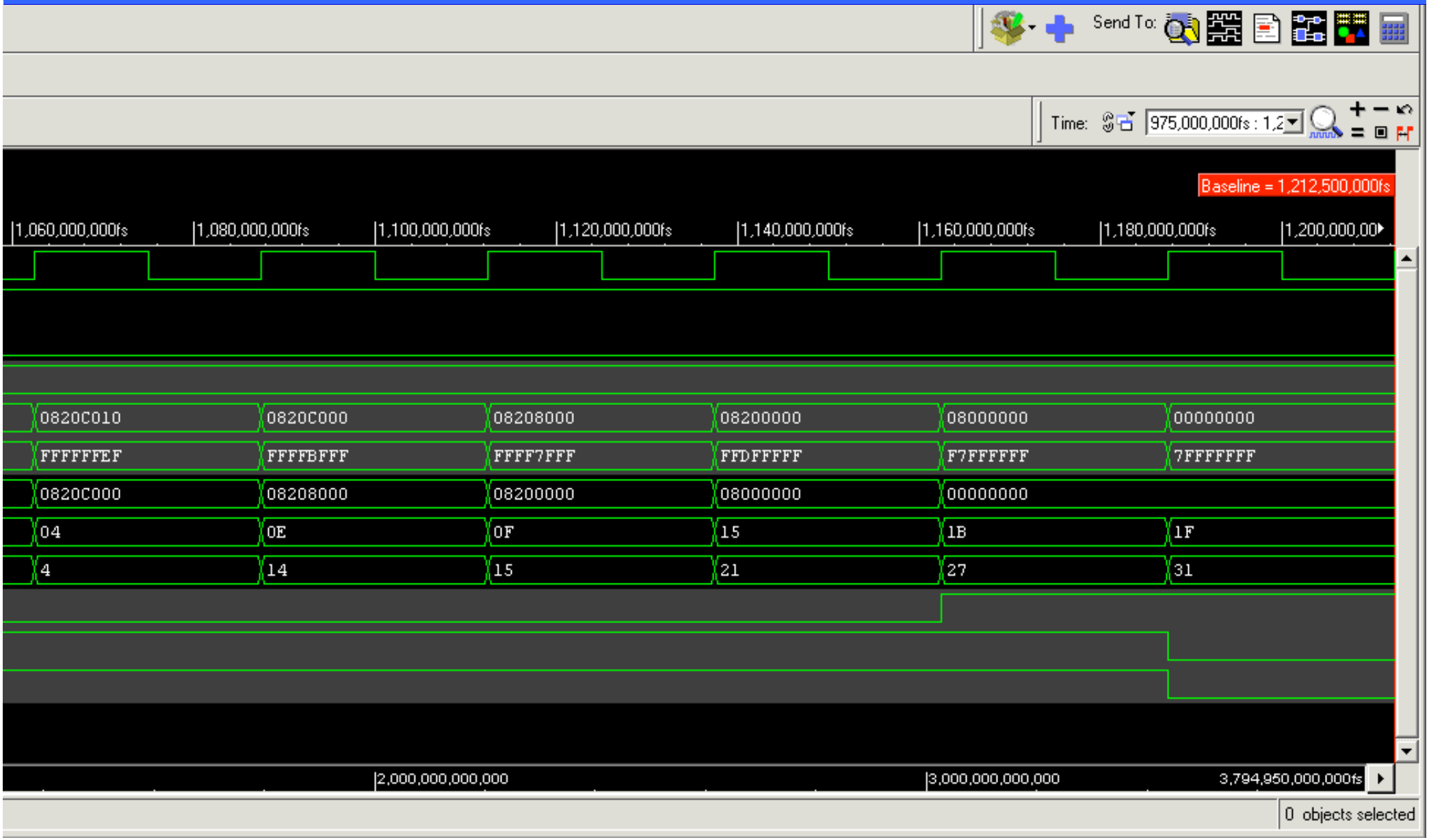
Position decoder – priority encoder



Position decoder – priority encoder



Position decoder – priority encoder



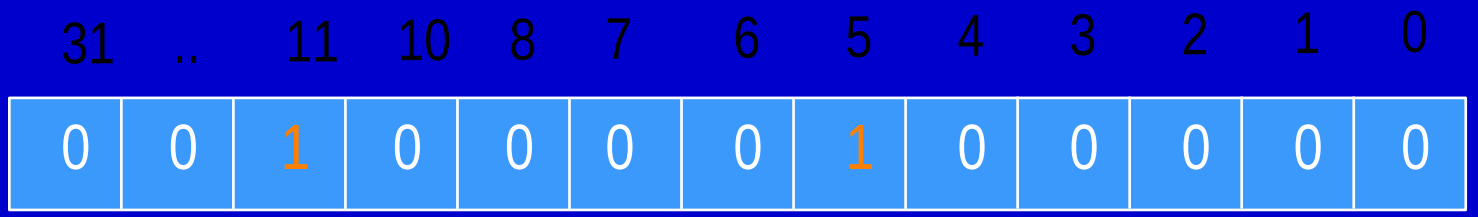
Shift register & counter (case)
Result in an FPGA from 2002: (Altera EP20k200FC484-3)
50 with case out of 8320 logic elements
44 registers

11% (41/376) of pins

9.1 ns (109.9 MHz) position_count-> data_encode

tco: 7.0 ns: data_word_reg -> data_word
tsu: 6.3 ns: new_value_available -> data_encode

Position decoder – priority encoder



Priority encoder
Result in an FPGA from 2002: (Altera EP20k200FC484-3)
172 (out of 8320) logic elements
33 registers
addressDecoder: 16
prior32: 54
11% (41/376) of pins

20.8 ns (48.0 MHz) data_encode -> state_encoding

tco: 17.1 ns: data_encode -> data_word
tsu: 14.9 ns: new_value -> state_encoding

Shift register & counter (case)
Result in an FPGA from 2002: (Altera EP20k200FC484-3)
50 with case out of 8320 logic elements
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11% (41/376) of pins

9.1 ns (109.9 MHz) position_count-> data_encode

tco: 7.0 ns: data_word_reg -> data_word
tsu: 6.3 ns: new_value_available -> data_encode

Position decoder – priority encoder

31	..	11	10	8	7	6	5	4	3	2	1	0
0	0	1	0	0	0	0	1	0	0	0	0	0

Priority encoder
Result in an FPGA from 2002: (Altera EP20k200FC484-3)
172 (out of 8320) logic elements -> more logic cells
33 registers
addressDecoder: 16
prior32: 54
11% (41/376) of pins

20.8 ns (48.0 MHz) data_encode -> state_encoding
-> slower state machine, but faster processing
tco: 17.1 ns: data_encode -> data_word
tsu: 14.9 ns: new_value -> state_encoding

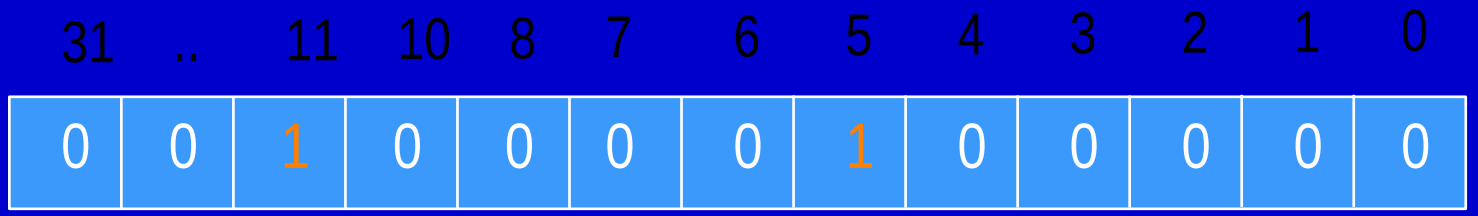
Position decoder – priority encoder

- **Task fulfilled?**
  - Many logic cells
  - FPGA Timing constraints fulfilled
- **User requirements fulfilled?**
  - Processing per 32 bit line takes:
    - numbHits per line * 25 ns = ?
    - Data comes each 100 ns -> one out of 2560 32 bit line
    - Decoding time for all lines is: 2560 * ? ns => ? ms
    - Within ? ms => ? data lines arrive
      - input FIFO would need to be at least ? * 32 bit deep
    - During ? ms no other trigger acquisition can take place
      - dead time => max trigger rate: ? Hz
- **User requirements fulfilled ?**

Position decoder – priority encoder

- **Task fulfilled?**
  - Physics simulation:
    - max 2% of all pixels will be hit in one acquisition
- **User requirements fulfilled?**
  - Processing per 32 bit line takes:
    - (numbHits per line) * 25 ns = (32 * 0.02) * 25 ns = <25 ns
    - Data comes each 100 ns -> one out of 2560 32 bit line
    - One line with up to 4 hits can be decoded before the next line arrives
    - Input FIFO of 1000 * 32 bits implemented to buffer statistical fluctuations or calibration sequences
    - Dead time defined by transmission of data stream
      - 2560 lines each 100 ns => 256 µs => 3900 Hz
      - dead time => max trigger rate: 3900 Hz
- **User requirements fulfilled: yes**

Position decoder – priority encoder



Priority encoder
Result in an FPGA from 2002: (Altera EP20k200FC484-3)
172 (out of 8320) logic elements -> more logic cells

20.8 ns (48.0 MHz) data_encode -> state_encoding
-> slower state machine, but faster processing

Slower and more logic can mean more elegant and effective

Position decoder – priority encoder

- User requirements fulfilled: yes
- Can we do better?
- Can we do faster or with less logic?
- Do we know something which the synthesizer does not know?

```vhdl
library ieee;
use ieee.std_logic_1164.all;

entity prior32 is
port  (  inp      :in   std_logic_vector (31 downto 0);
         code     :out  std_logic_vector (4 downto 0));
end prior32;

architecture behavioral0 of prior32 is

--*************************************************************
--prior32
--*************************************************************
begin

process (inp)
begin
   if    (inp(0) = '1') then     code <= "00000";
   elsif (inp(1) = '1') then     code <= "00001";
   elsif (inp(2) = '1') then     code <= "00010";
   elsif (inp(3) = '1') then     code <= "00011";
   elsif (inp(4) = '1') then     code <= "00100";
   elsif (inp(5) = '1') then     code <= "00101";
   elsif (inp(6) = '1') then     code <= "00110";
   elsif (inp(7) = '1') then     code <= "00111";
   elsif (inp(8) = '1') then     code <= "01000";
   elsif (inp(9) = '1') then     code <= "01001";
   elsif (inp(10) = '1') then    code <= "01010";
   elsif (inp(11) = '1') then    code <= "01011";
   elsif (inp(12) = '1') then    code <= "01100";
   elsif (inp(13) = '1') then    code <= "01101";
   elsif (inp(14) = '1') then    code <= "01110";
   elsif (inp(15) = '1') then    code <= "01111";
   elsif (inp(16) = '1') then    code <= "10000";
   elsif (inp(17) = '1') then    code <= "10001";
   elsif (inp(18) = '1') then    code <= "10010";
   elsif (inp(19) = '1') then    code <= "10011";
   elsif (inp(20) = '1') then    code <= "10100";
   elsif (inp(21) = '1') then    code <= "10101";
   elsif (inp(22) = '1') then    code <= "10110";
   elsif (inp(23) = '1') then    code <= "10111";
   elsif (inp(24) = '1') then    code <= "11000";
   elsif (inp(25) = '1') then    code <= "11001";
   elsif (inp(26) = '1') then    code <= "11010";
   elsif (inp(27) = '1') then    code <= "11011";
   elsif (inp(28) = '1') then    code <= "11100";
   elsif (inp(29) = '1') then    code <= "11101";
   elsif (inp(30) = '1') then    code <= "11110";
   elsif (inp(31) = '1') then    code <= "11111";
   else                          code <= "11111";
end if;

end process;

end behavioral0;
```

```
architecture behavioral1 of prior32 is
signal code0   :  std_logic_vector (2 downto 0);
signal code1   :  std_logic_vector (2 downto 0);
signal code2   :  std_logic_vector (2 downto 0);
signal code3   :  std_logic_vector (2 downto 0);
signal code4   :  std_logic_vector (2 downto 0);
signal code5   :  std_logic_vector (2 downto 0);
signal code6   :  std_logic_vector (2 downto 0);
signal code7   :  std_logic_vector (2 downto 0);
begin
process (inp)
begin
   if    (inp(0) = '1') then     code0 <= "000";
   elsif (inp(1) = '1') then     code0 <= "001";
   elsif (inp(2) = '1') then     code0 <= "010";
   elsif (inp(3) = '1') then     code0 <= "011";
   else                          code0 <= "100";
   end if;

   if    (inp(4) = '1') then     code1 <= "000";
   elsif (inp(5) = '1') then     code1 <= "001";
   elsif (inp(6) = '1') then     code1 <= "010";
   elsif (inp(7) = '1') then     code1 <= "011";
   else                          code1 <= "100";
   end if;

   if    (inp(8) = '1') then     code2 <= "000";
   elsif (inp(9) = '1') then     code2 <= "001";
   elsif (inp(10) = '1') then    code2 <= "010";
   elsif (inp(11) = '1') then    code2 <= "011";
   else                          code2 <= "100";
   end if;

   if    (inp(12) = '1') then    code3 <= "000";
   elsif (inp(13) = '1') then    code3 <= "001";
   elsif (inp(14) = '1') then    code3 <= "010";
   elsif (inp(15) = '1') then    code3 <= "011";
   else                          code3 <= "100";
   end if;
   if    (inp(16) = '1') then    code4 <= "000";
   elsif (inp(17) = '1') then    code4 <= "001";
   elsif (inp(18) = '1') then    code4 <= "010";
   elsif (inp(19) = '1') then    code4 <= "011";
   else                          code4 <= "100";
   end if;

   if    (inp(20) = '1') then    code5 <= "000";
   elsif (inp(21) = '1') then    code5 <= "001";
   elsif (inp(22) = '1') then    code5 <= "010";
   elsif (inp(23) = '1') then    code5 <= "011";
   else                          code5 <= "100";
   end if;

   if    (inp(24) = '1') then    code6 <= "000";
   elsif (inp(25) = '1') then    code6 <= "001";
   elsif (inp(26) = '1') then    code6 <= "010";
   elsif (inp(27) = '1') then    code6 <= "011";
   else                          code6 <= "100";
   end if;

   if    (inp(28) = '1') then    code7 <= "000";
   elsif (inp(29) = '1') then    code7 <= "001";
   elsif (inp(30) = '1') then    code7 <= "010";
   elsif (inp(31) = '1') then    code7 <= "011";
   else                          code7 <= "100";
   end if;
end process;
```

Position decoder – priority encoder

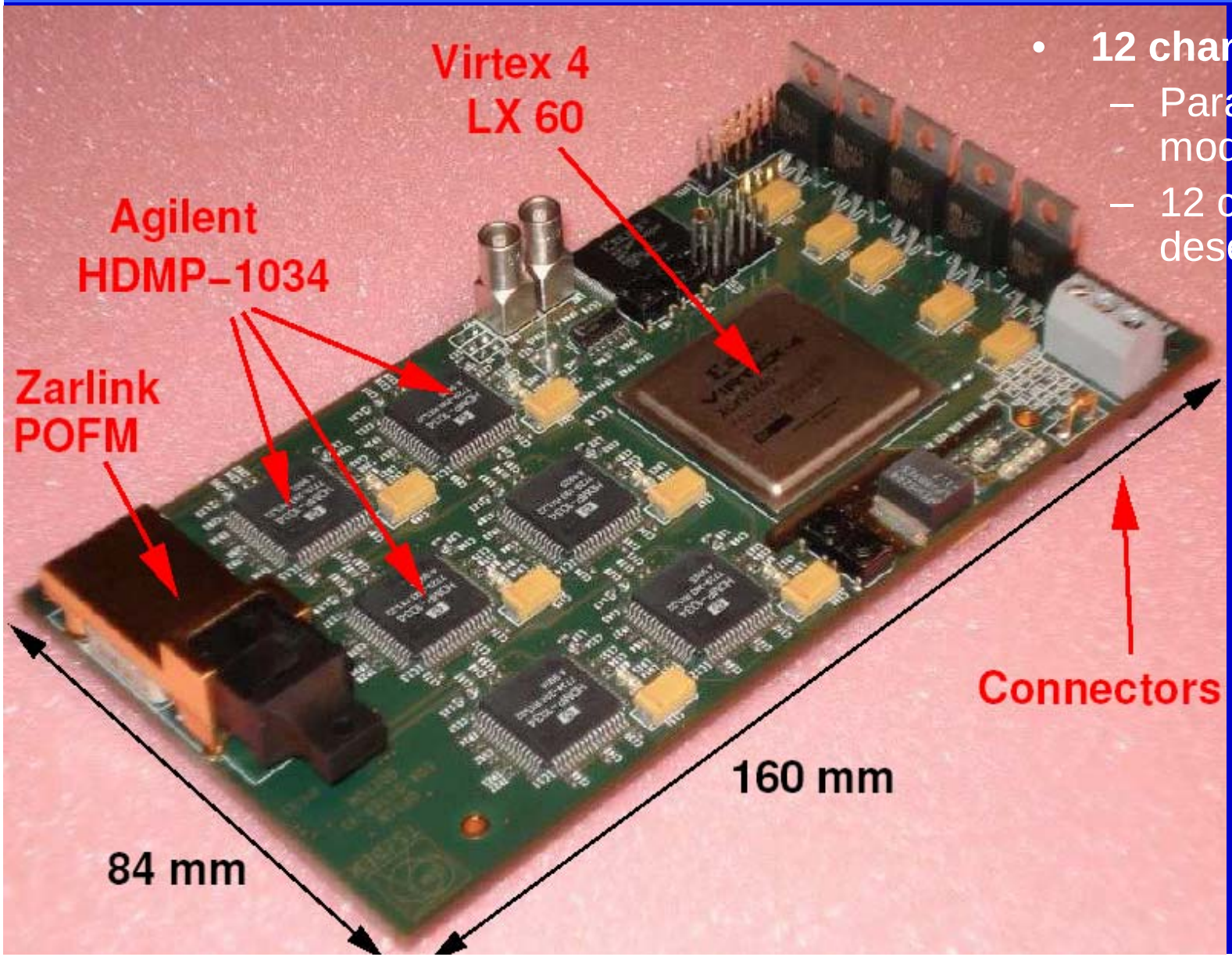
```
process (code0, code1, code2, code3, code4, code5, code6, code7)

begin
   if (code0(2) = '0') then
      code(4 downto 2)  <= "000";
      code(1 downto 0)  <= code0(1 downto 0);
   elsif(code1(2) = '0') then
      code(4 downto 2)  <= "001";
      code(1 downto 0)  <= code1(1 downto 0);
   elsif(code2(2) = '0') then
      code(4 downto 2)  <= "010";
      code(1 downto 0)  <= code2(1 downto 0);
   elsif(code3(2) = '0') then
      code(4 downto 2)  <= "011";
      code(1 downto 0)  <= code3(1 downto 0);
   elsif (code4(2) = '0') then
      code(4 downto 2)  <= "100";
      code(1 downto 0)  <= code4(1 downto 0);
   elsif(code5(2) = '0') then
      code(4 downto 2)  <= "101";
      code(1 downto 0)  <= code5(1 downto 0);
   elsif(code6(2) = '0') then
      code(4 downto 2)  <= "110";
      code(1 downto 0)  <= code6(1 downto 0);
   elsif(code7(2) = '0') then
      code(4 downto 2)  <= "111";
      code(1 downto 0)  <= code7(1 downto 0);
   else  code           <= "11111";
   end if;
end process;
```

Position decoder – priority encoder

- Knowledge of implementation in target technology is important
- Knowledge of what the synthesizer is doing is important

Processor board with optical inputs



- **12 channels**
  - Parallel optical receiver module
  - 12 closely packed G-link deserializer ASICs