TSEA44: Computer hardware – a system on a chip

Kent Palmkvist, Erik Bertilsson
http://www.isy.liu.se/edu/kurs/TSEA44
Based on slides by Andreas Ehliar

LINKÖPING UNIVERSITY

What is the course about?

- How to build a complete embedded computer using an FPGA and a few other components. Why?
  - Only one chip
  - The computer can easily be tailored to your needs.
    - Special instructions
    - Accelerators
    - DMA transfer
  - The computer can be simulated
  - A logic analyzer can be added in the FPGA
    - Add performance counters
  - It's fun!

Prerequisites (expected knowledge!)

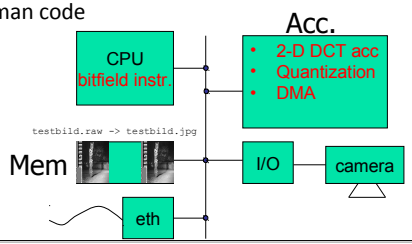
- Digital logic design. You will design both a data path and a control unit for an accelerator.
- Binary arithmetic. Signed/unsigned numbers.
- VHDL or Verilog. SystemVerilog (SV) is the language used in the course.
- Computer Architecture. It is extremely important to understand how a CPU executes code. You will also design part of a DMA-controller. Bus cycles are central.
- ASM and C programming. Most of the programming is done in C, with a few cases of inline asm.

Course organisation

- Lab 0: learn enough Verilog, 4 hours
  - Individual work and demonstration
- Lab course: 4 mini projects
  - 1-3 people/labgroup
- Lectures: 8*2 hours
- Examination 6 credits:
  - 3 written reports/group
  - Oral individual questions

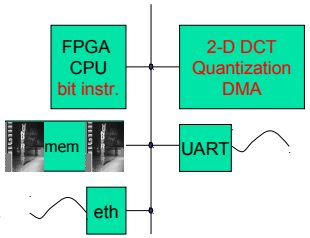
Lab course is based on an application: JPEG compression

- Take 2-D DCT on 8x8-blocks
- Quantize = Divide and set small values to zero
- RLE + Huffman code



Lab info

- 0) Build an UART in Verilog
- 1) Interface your UART
  Test performance counters
  Test a SW-DCT2 application
- 2+3) Build an HW accelerator for 2-D DCT and add a DMA controller
- 4) Design your own instruction to handle bitfields



Lab tasks and examination

- Lab 0 (individual work and demonstration)
  - Build an UART in Verilog
  - Demonstration
  - Deadline 14 November
- Lab 1 (in groups of 2 or 3 students)
  - Interface to the Wishbone bus
  - Demonstration (individual questions)
    Written report

Lab tasks and examination, cont.

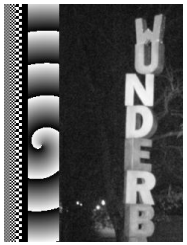
- Lab 2+3
  - Design a JPEG accelerator + DMA
  - Demonstration (with individual questions)
    Written report
- Lab 4
  - Custom Instruction
  - Demonstration (with individual questions)
    Written report

Written report requirements

- A readable short report typically consisting of
  - Introduction
  - Design, where you explain with text and diagrams how your design works
  - Results, that you have measured
  - Conclusions
  - Appendix: All Verilog and C code with comments!

Competition – fastest JPEG compression

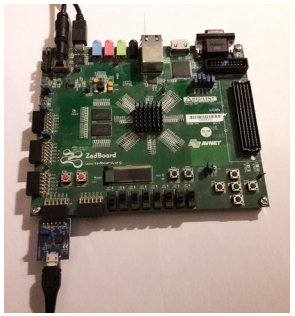
- An unaccelerated JPEG compression (using jpegfiles) takes roughly 13.0 Mcycles (@ 25MHz) ≃ 2 FPS (Frames Per Second)
- Our record: ~ 100 000 cycles (everything in hardware)
- Goal: Highest framrate. Exception: At over 25 FPS, the smallest implementation wins
- Deadline: 21/12 2018



`wunderb.jpg`
`320 x 240`

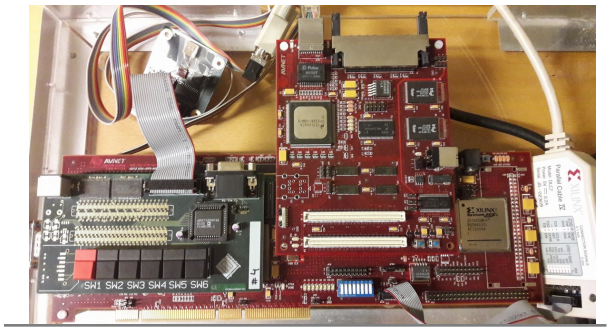
The hardware, lab0

- Zedboard
  - Programming connection at top of the board
  - Serial port at bottom of the board
  - Only use PL part of of the chip



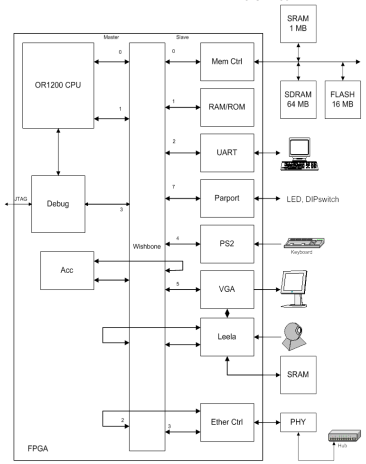
The hardware, lab0 - lab4

- 6 boxes with FPGA boards



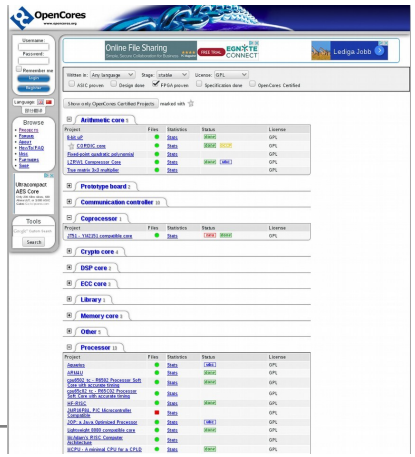
The soft computer

- OR1200 CPU
- Memory
  - RAM (+ SDRAM)
  - ROM (+ FLASH)
- I/O
  - Serial
  - Parallel
  - Ethernet
  - Camera



Opencores

- Open source initiative for hardware models
- From simple to very complex models
- Note page is showing only FPGA proven LGPL licensed models



Processor core: Openrisc 1200

- Initially developed within opcores initiative
- Split into a new website
  - Openrisc.io
- Complete risc processor including synthesizable code, instructions set simulator etc.

(System)Verilog

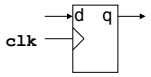
- The course uses SystemVerilog
- SystemVerilog is easy to learn if you know VHDL/C
- Our soft computer (80% downloaded from OpenCores) is written in Verilog
- It is possible to use both languages in a design
- You need to understand parts of the computer

(System)Verilog vs VHDL

An edge-trigged D-flip/flop

C-like syntax

```
module dff(
  input clk, d,
  output reg q);

  always_ff @(posedge clk)
   q <= d;

endmodule
```

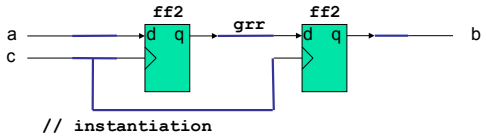


Ada-like syntax

```
entity dff is
port (clk,d : in std_logic;
      q: out std_logic);
end dff;

architecture firsttry of dff is
begin
process (clk) begin
 if rising_edge(clk) then
   q <= d;
 end if;
end process;
end firsttry;
```


(System)Verilog vs VHDL

Using the D-flip/flop, instantiation

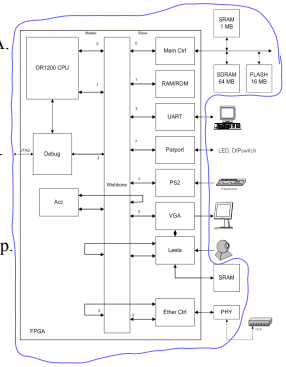



```
// instantiation

wire a,b,c,grr;
...

dff ff1(.clk(c),.d(a), .q(grr));

dff ff2(.clk(c), .d(grrr) .q(b));
```

Watch out! Verilog allows implicit declarations (but this can be disabled)

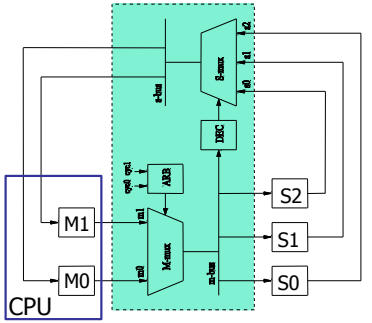
You get a lab skeleton

- **dafk_tb.sv** . Testbench.
  - **dafk_top.sv** . To be synthesized in the FPGA.
    - **eth_top.sv**. Ethernet controller.
    - **pkmc_top.sv**. Memory controller.
    - **or1200_top.sv**. The OR1200 CPU.
    - **parport.sv**. Simple parallel port.
    - **romram.sv** . The boot code resides here.
    - **uart_top.sv** . UART 16550.
    - **dvga_top.sv** . VGA controller.
    - **wb_top.sv** . The wishbone bus.
  - **eth_phy.v** Simulation model for the PHY chip.
  - **flash.v** Simulation model.
  - **sdram.v** Simulation model.
  - **sram.v** . Simulation model

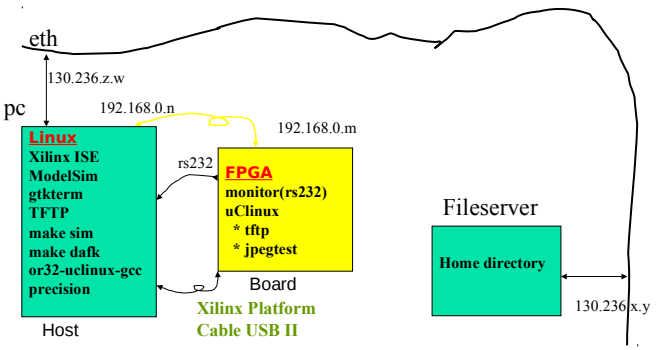


The Wishbone bus

- A multi-master bus
  - Signals: adress (32), data_out (32), data_in (32), control
  - Two data buses and muxes are used instead of tristate



The environment



Software under linux

- C-compiler (GNU tool chain)
  - or-32-uclinux-gcc
- Software simulator
  - or-32-uclinux-sim

host

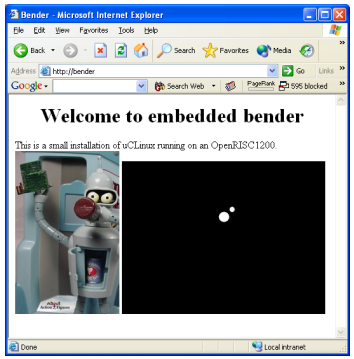
- A very simple boot monitor (24 kB + 8 kB RAM inside FPGA)
  - dct_sw, dma_dct_sw, jpegtest
- uClinux boots from flash
  - jpegtest

board

Booting uClinux

```
uClinux/OR32
Flat model support (C) 1998,1999 Kenneth Albanowski, D. Jeff Dionne
Calibrating delay loop.. ok - 2.00 BogoMIPS
Memory available: 53000k/62325k RAM, 0k/0k ROM (667892k kernel data, 2182k code)
Swansea University Computer Society NET3.035 for Linux 2.0
NET3: Unix domain sockets 0.13 for Linux NET3.035.
Swansea University Computer Society TCP/IP for NET3.034
IP Protocols: ICMP, UDP, TCP
uClinux version 2.0.38.1pre3 (olles@kotte) (gcc version 3.2.3) #180 Sat Sep 11 0
9:01:55 CEST 2004
Serial driver version 4.13pl with no serial options enabled
ttyS00 at 0x90000000 (irq = 2) is a 16550A
Ramdisk driver initialized : 16 ramdisks of 2048K size
Blkmem copyright 1998,1999 D. Jeff Dionne
Blkmem copyright 1998 Kenneth Albanowski
Blkmem 0 disk images:
loop: registered device at major 7
eth0: Open Ethernet Core Version 1.0
RAMDISK: Romfs filesystem found at block 0
RAMDISK: Loading 1608 blocks into ram disk... done.
VFS: Mounted root (romfs filesystem).
Executing shell ...
Shell invoked to run file: /etc/rc
Command: #!/bin/sh
Command: setenv PATH /bin:/sbin:/usr/bin
Command: hostname bender
Command: #
Command: mount -t proc none /proc
... More of the same
Command: #
Command: # start web server
Command: /sbin/boa -d &
[12]
/>
```


Web server



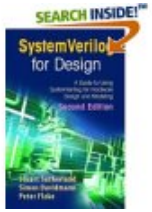
Lecture info

1 Course Intro, FPGA
2 Verilog (lab0)
3 A soft CPU
4 A soft computer (lab1)
5 HW acceleration (lab2)
6 FPGAs
7 Test benches, SV
8 Custom instructions (lab4)

Books

Lilja,Saptnekar: *Designing Digital Computer Systems with Verilog*, Cambridge University Press

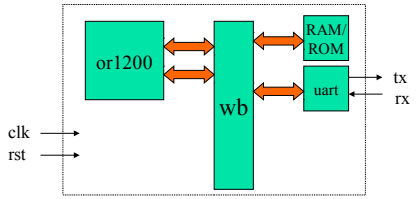
Sutherland et al: *SystemVerilog for Design*, Springer



Spear: *SystemVerilog for Verification*, Springer

How we built our first FPGA computer

1. Download CPU OR1200, roughly 60 Verilog files
2. Download Wishbone bus 3 Verilog files
3. Download UART 16550, 9 Verilog files
4. Figure out a computer



How we built our first FPGA computer

5. Write top file (”wire wrap in emacs”)

Size 35 kB in Verilog, 13 kB in SV
(Verilog does not have struct)

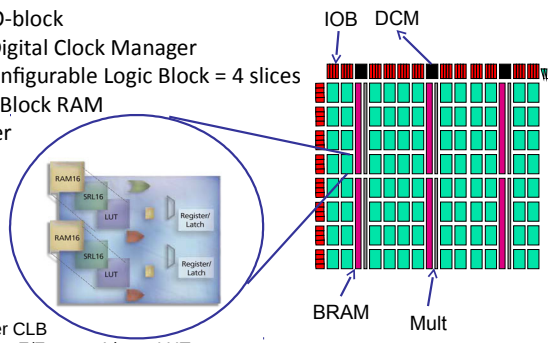
```
module myfirstcomputer(clk,rst,rx,tx)
  input clk,rst,rx;
  output tx;

  wishbone Mx[0:1], Sx[0:1];

  or1200cpu cpu0(.iwb(Mx[0]), … );
  wb_conbus wb0(clk, rst, Mx, Sx);
  romram rom0(Sx[1]);
  uart uart0(Sx[0], …);
end module
```

How we built our first FPGA computer

6. Download the cross compiler
7. Write a small monitor and place in ROM
8. ModelSim. Does it boot? Anything on tx?
9. Test with the simulator or32-uclinux-sim
10. Synthesize for 10 minutes (originally 40 minutes, note that simulation are quite important in this course)

Xilinx – Virtex II Overview

IOB = I/O-block
DCM = Digital Clock Manager
CLB = Configurable Logic Block = 4 slices
BRAM = Block RAM
Multiplier

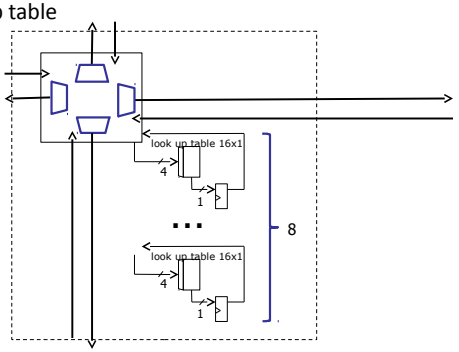


4 Slices per CLB
1 slice = two F/F + two 4-input LUT

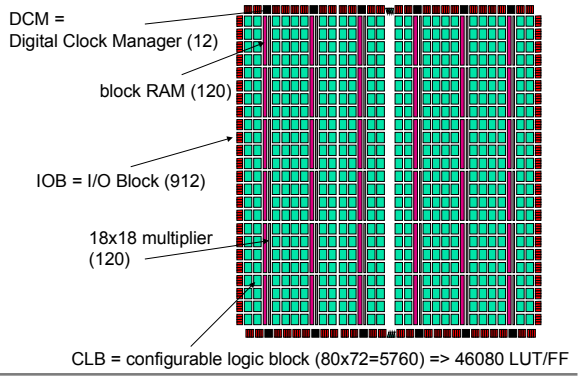
CLB = configurable logic block

LUT = look up table

1 CLB = 4 slices
1 slice = 2*(LUT+FF)



Our FPGA



Xilinx – Virtex II Overview

Device XC2V	40	80	250	500	1000	1500	2000	3000	4000	6000	8000
CLB Array	8 x 8	16 x 8	24 x 16	32 x 24	40 x 32	48 x 40	56 x 48	64 x 56	80 x 72	96 x 88	112 x 104
18Kb BRAM	4	8	24	32	40	48	56	96	120	144	168
Multiplier	4	8	24	32	40	48	56	96	120	144	168
DCM	4	4	8	8	8	8	8	12	12	12	12
Max IOB	88	120	200	264	432	528	624	720	912	1,104	1,296

2 Columns BRAM & Multipliers

4 Columns BRAM & Multipliers

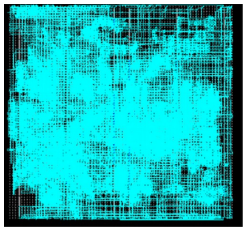
6 Columns BRAM & Multipliers

Our FPGA has 5760 CLBs = 23.040 slices = 46080 LUTs+FFs

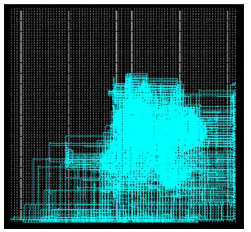
Synthesis result

Module	LUT	FF	RAMB16	MULT_18x18	IOB
/	64				216
cpu	5029	1345	12	4	
dvga	813	755	4		
eth3	3022	2337	4		
jpg0	2203	900	2	13	
leela	685	552	4	2	
pia	2	5			
pkmc_mc	218	122			
rom0	82	3	12		
sys_sig_gen		6			
uart2	825	346			
wb_conbus	616	11			
Total	**13559**	**6382**	**38**	**19**	**216**
Available	46080	46080	120	120	912

Floorplan from FPGA Editor



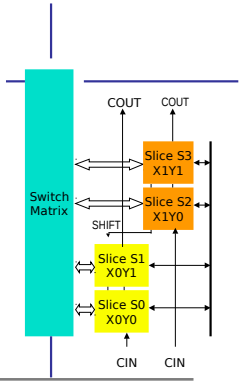
Computer



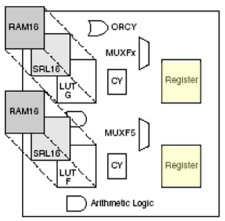
CPU OR1200

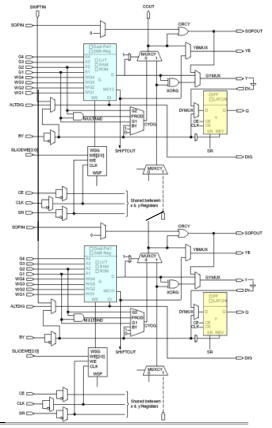
CLB contains four slices

- Each CLB is connected to one switch matrix
  - 1 slice = 2 LUT/FF + ...
- High level of logic integration
  - Wide-input functions
    - 16:1 multiplexer in 1 CLB
    - 32:1 multiplexer in 2 CLBs
  - Fast arithmetic functions
    - 2 look-ahead carry chains per CLB column
  - Adressable shift register in LUT
    - 16-b shift register in 1 LUT
    - 128-b shift register in 1 CLB



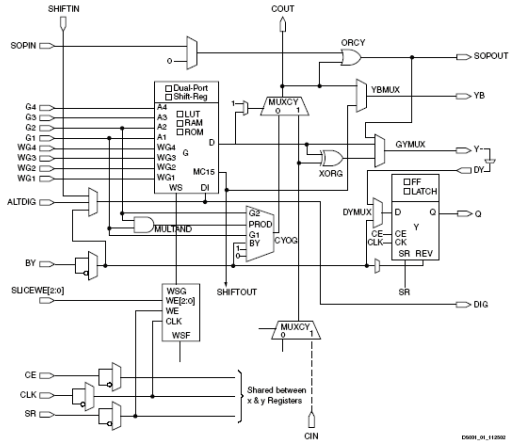
1 slice (out of 23 040)





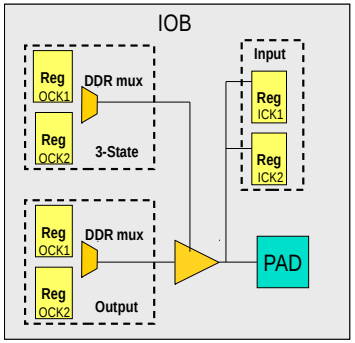
1/2 slice

- Top half
- One of 46 080



IOB element

- Input path
  - Two DDR registers
- Output path
  - Two DDR registers
  - Two 3-state DDR registers
- Separate clocks for I & O
- Set and reset signals are shared
  - Separated sync/async
  - Separated Set/Reset attribute per register



Embedded 18 kb Block RAM

- Up to 3 Mb on-chip block RAM
- High internal buffering bandwidth
- Clocked write and read

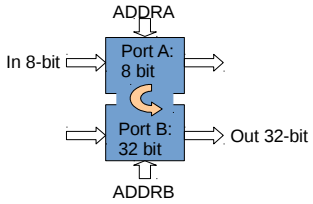
✓	18Kbit block RAM
✓	Parity bit locations (parity in/out busses)
✓	Data width up to 36 bits
✓	3 WRITE modes
✓	Output latches Set/Reset
✓	True Dual-Port RAM
✓	Independent clock (async.) & control

True Dual-Port™ configurations

- Configurations available on each port:

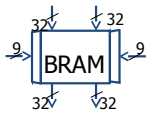
Configuration	Depth	Data bits	Parity bits
16K x 1	16Kb	1	0
8K x 2	8Kb	2	0
4K x 4	4Kb	4	0
2K x 9	2Kb	8	1
1K x 18	1Kb	16	2
512 x 36	512	32	4

- Independent port A and B configuration.
  - Support for data width conversion including parity bits (same memory array!)



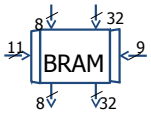
How to use Block RAM: Just Instantiate template

2-port 512x32(+4)




```
RAMB16_S36_S36 inmem
    (// port A
     .CLKA(wb.clk), .SSRA(wb.rst),
     .ADDRA(bram_addr),
     .DIA(bram_data), .DIPA(4'h0),
     .ENA(bram_ce), .WEA(bram_we),
     .DOA(doa), .DOPA(),
     // port B
     .CLKB(wb.clk), .SSRB(wb.rst),
     .ADDRB({3'h0,rdc}),
     .DIB(32'h0), .DIPB(4'h0),
     .ENB(1'b1),.WEB(1'b0),
     .DOB(dob), .DOPB());
```

2048x8 512x32



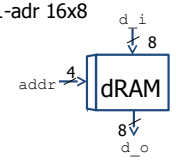

```
RAMB16_S9_S36 inmem
    (// port A
     …
     // port B
     … );
```


Distributed RAM

- Virtex-II LUT can implement
  - 16 x 1-bit synchronous RAM
  - Synchronous write
  - Asynchronous read
    - D flip-flop in the same slice can register the output
- Allow fast embedded RAM of any width
  - Only limited by the number of slices in each device
  - Example: RAM 16 x 48-bit fits in 48 LUTs

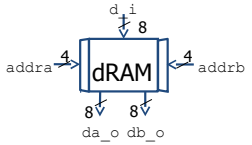
How to use

Distributed RAM : 8 LUTs
1-adr 16x8




```
logic [7:0] mem0[0:15];

always_ff @(posedge clk)
     if (wr) begin
       mem0[addr] <= d_i;
     end

assign d_o=(rd) ? mem0[addr] : 8'h0;
```

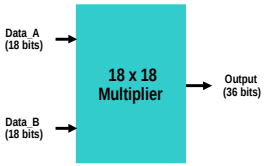
Distributed RAM : 16 LUTs
2-adr 16x8




```
logic [7:0] mem0[0:15];

always_ff @(posedge clk)
     if (wr) begin
       mem0[addra] <= d_i;
     end

assign db_o = (rdb) ? {mem0[addrb]}
                    : 8'h0;
assign da_o = (rda) ? {mem0[addra]}
                    : 8'h0;
```

18 x 18 Multiplier

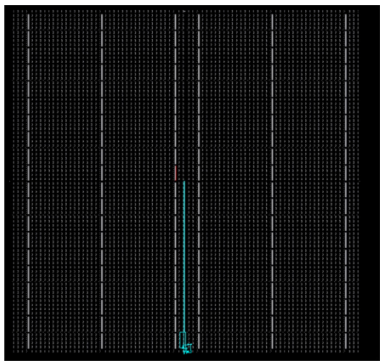
- Embedded 18-bit x 18-bit multipliers
  - 2's complement signed operation
- Multipliers are organized in columns



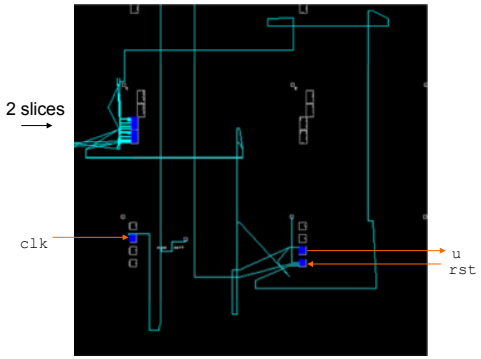
counter

```
module dec(
    input clk,rst
    output  u);

    reg u;
    reg [3:0] q;

    always_ff @(posedge clk or posedge rst)
      if (rst)
        q <= 4'h0;
      else if (q == 9)
        q <= 4'h0;
      else
        q <= q+1;

    always_ff @(posedge clk)
      if (q == 9)
        u <= 1'b1;
      else
        u <= 1'b0;
endmodule
```

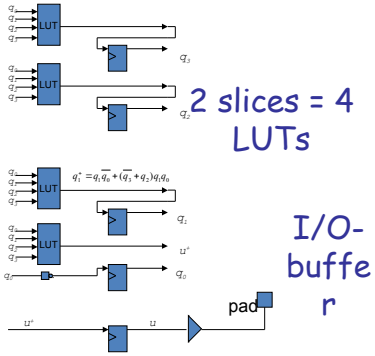

Synthesized counter, floorplan



Syntesized counter, detailed floorplan



Synthesized counter, logic description



2 slices = 4 LUTs

I/O-buffer

www.liu.se

LINKÖPING UNIVERSITY

Hints for lab work

- Remember to think hardware!
  - Draw block diagrams (required!)
  - Each block should be simple to translate to verilog
    - Counters
    - Registers
    - Boolean expressions, arithmetic operations
    - State machines
  - Use testbenches and simulate to verify behavor
  - Finally test on hardware