

IN3160, IN4160 Digital system design

Introduction

HDL, PL and Design flow

Yngve Hafting



Overview

- General information
 - Course management
 - Schedule
 - Course Goals
 - Curriculum
 - Lab assignments
 - Who are we
- Motivation
 - Why Digital Design?
 - Why HDL?
- Assignments and suggested reading for this week
- Intro to programmable Logic
 - What is programmable logic?
 - Why choose programmable logic?
- Design Flow for digital designs
- Intro to our hardware....:
 - Zedboard
 - Architecture
 - Documentation
 - «Our» HDL: VHDL

Course Management

- Lecturers:
 - **Alexander Wold** (II'er)
 - **Yngve Hafting** (Universitetslektor)
- Lab supervisors / teachers:
 - **Elias Ringkjøb** (student)
 - **Jonas Wenberg** (student)
 - **Øystein Øverbø** (student)



Lectures

Tuesday 10:15 -12:00, OJD Caml

Friday 10:15-12:00, OJD Caml

Lab

LISP (2428): TBD- lab will be manned certain time slots- poll next slide

<https://www.mn.uio.no/ifi/om/finn-fram/apningstider/>

Tid (.15)	Monday	Tuesday	Wednesday	Thursday	Friday
8					
10		Lecture 10-12			Lecture 10-12
12				IN3050 Lecture	
14		Øystein		Elias	Jonas
16					

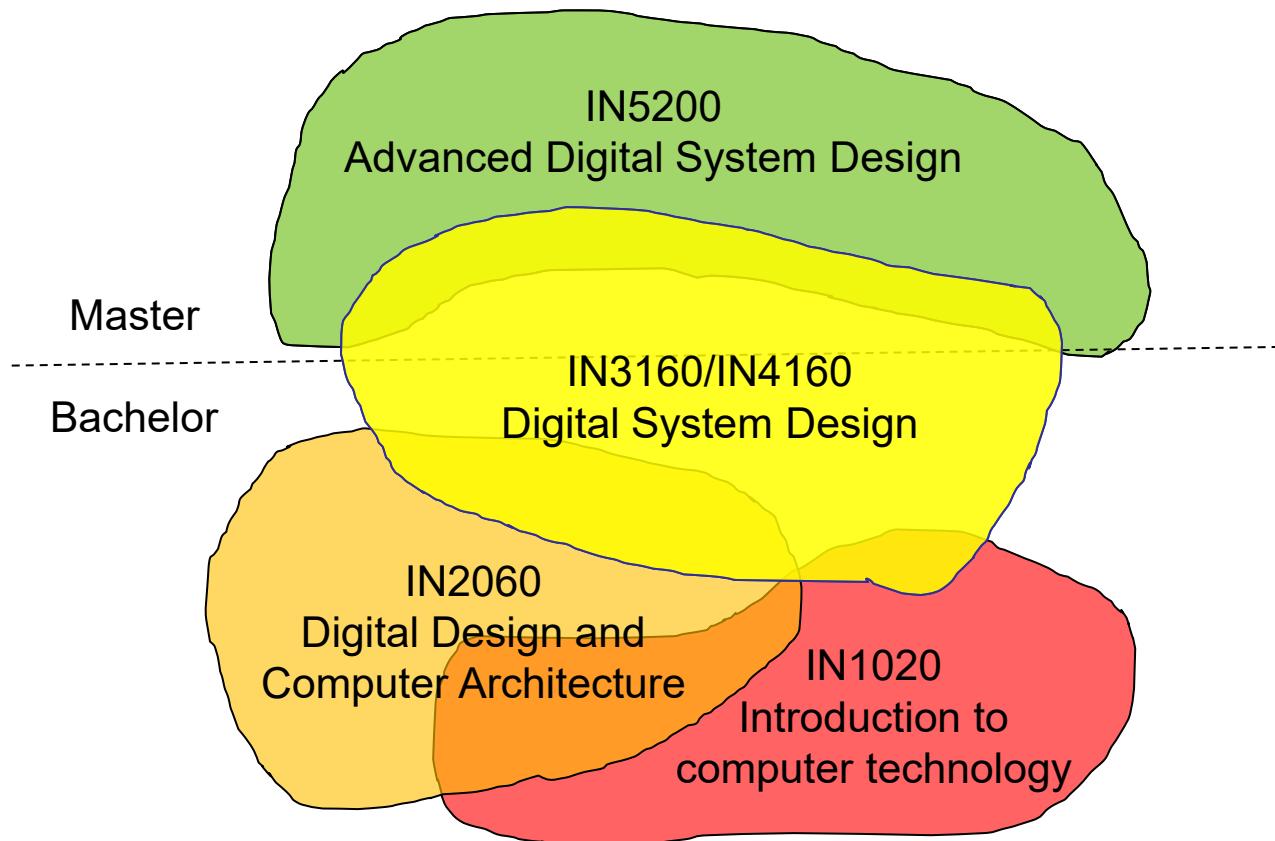
<http://www.uio.no/studier/emner/matnat/ifi/IN3160/>

(covers also INF4160)

Where do we stand + lab supervision poll?

- www.menti.com
- Code 2536 2149

(ROBIN) Study program connections



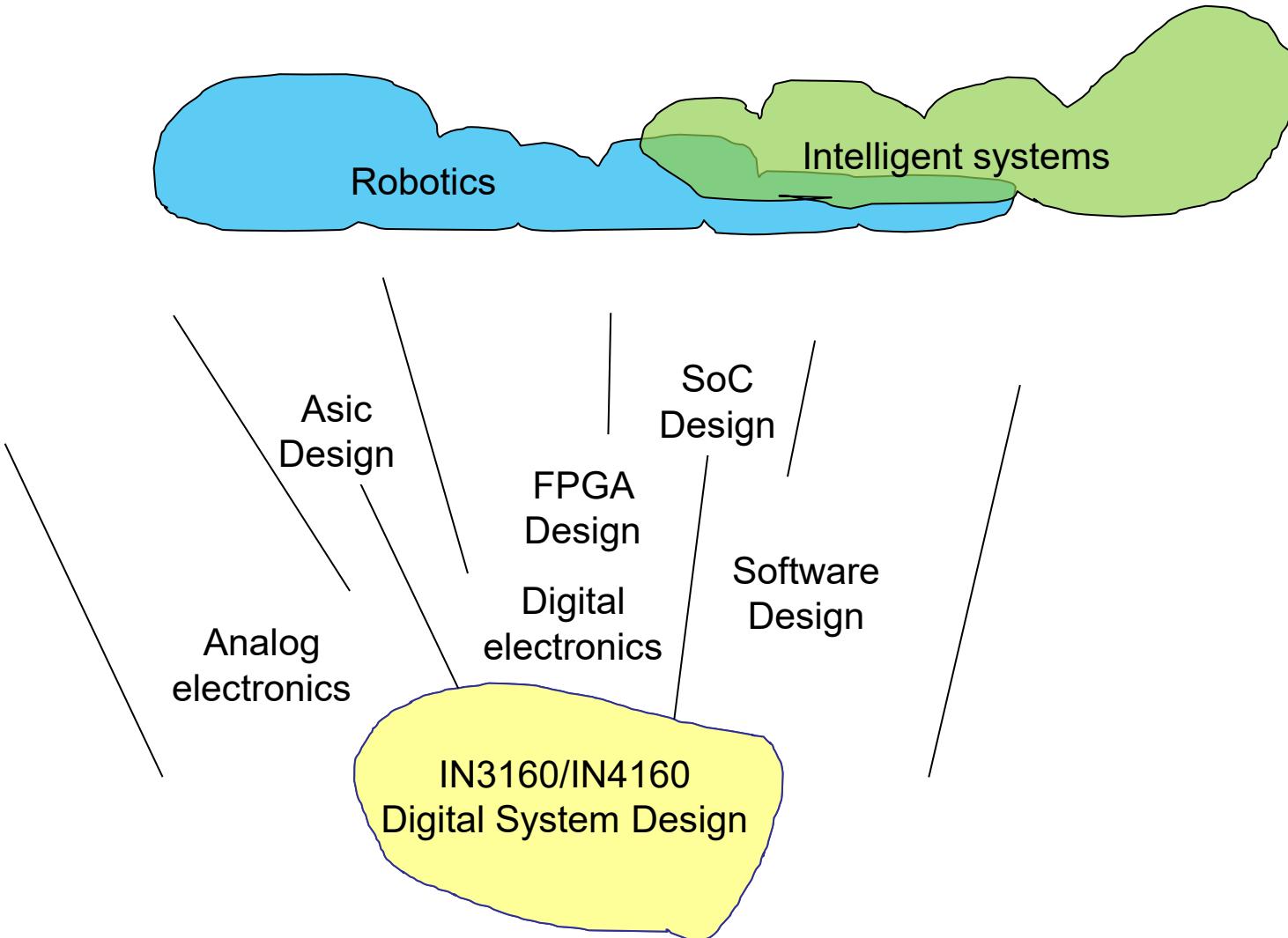
Courses in electronics and circuit theory, such as

FYS1210 - Electronics
FYS3220 - Linear circuit theory
FYS3240 - Data acquisition and control

provide a complementary background that may help understanding digital systems in general.

FYS4220 - Real time and Embedded Data Systems overlaps with 6p

Relevancy



Finishing this course you will be able to do work within the field of digital design.

Course Goals and Learning Outcome

<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

- In this course you will learn about the design of advanced digital systems.
- This includes programmable logic circuits, a hardware design language and system-on-chip design (processor, memory and logic on a chip).
- Lab assignments provide practical experience in how real design can be made.
- After completion of the course you'll:...

... IN3160 vs IN4160 ...

IN3160

- After completion of the course you'll:
 - understand important principles for design and testing of digital systems
 - understand the relationship between behavior and different construction criteria
 - be able to describe advanced digital systems at different levels of detail
 - be able to perform simulation and synthesis of digital systems.

IN4160

- After completion of the course you'll:
 - understand important principles for design and testing of digital systems
 - understand the relationship between behavior and different construction criteria
 - be able to describe advanced digital systems at different levels of detail
 - be able to perform **advanced** simulation and synthesis of digital systems
 - **be able to perform advanced implementation and analysis techniques**

NOTE: these are MINIMUM requirements for passing an exam.

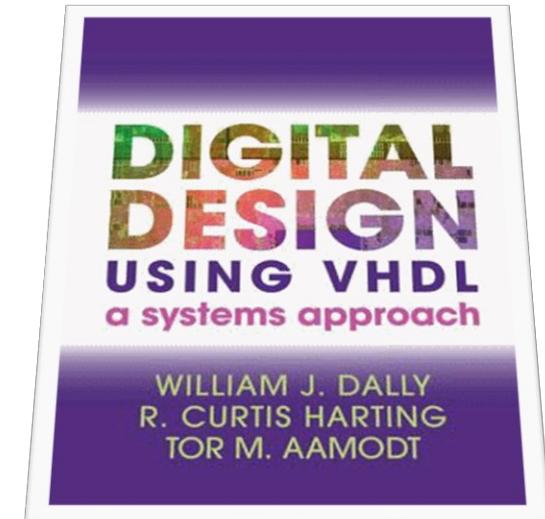
- You will be given the same opportunities to learn, and the curriculum is the same.
- *Grading will be (slightly) stricter for IN4160 due to added minimum requirements*
- Otherwise, this course will be held as one.

Our approach (*compared to other studies*)

- Focus on relevancy for students with programming skills
 - less physics and maths oriented
 - less transistor and PCB technology
 - less focus on mathematical proofs and methods
 - less focus on tweaking (IN2060 covered this)
- Focus on design strategies
 - High level code (New -24: Testbenches in python)
 - Schematics / Diagrams
 - Verifiability
 - State machines
- Focus on physical realization on FPGA
 - Full tool chain used in industry

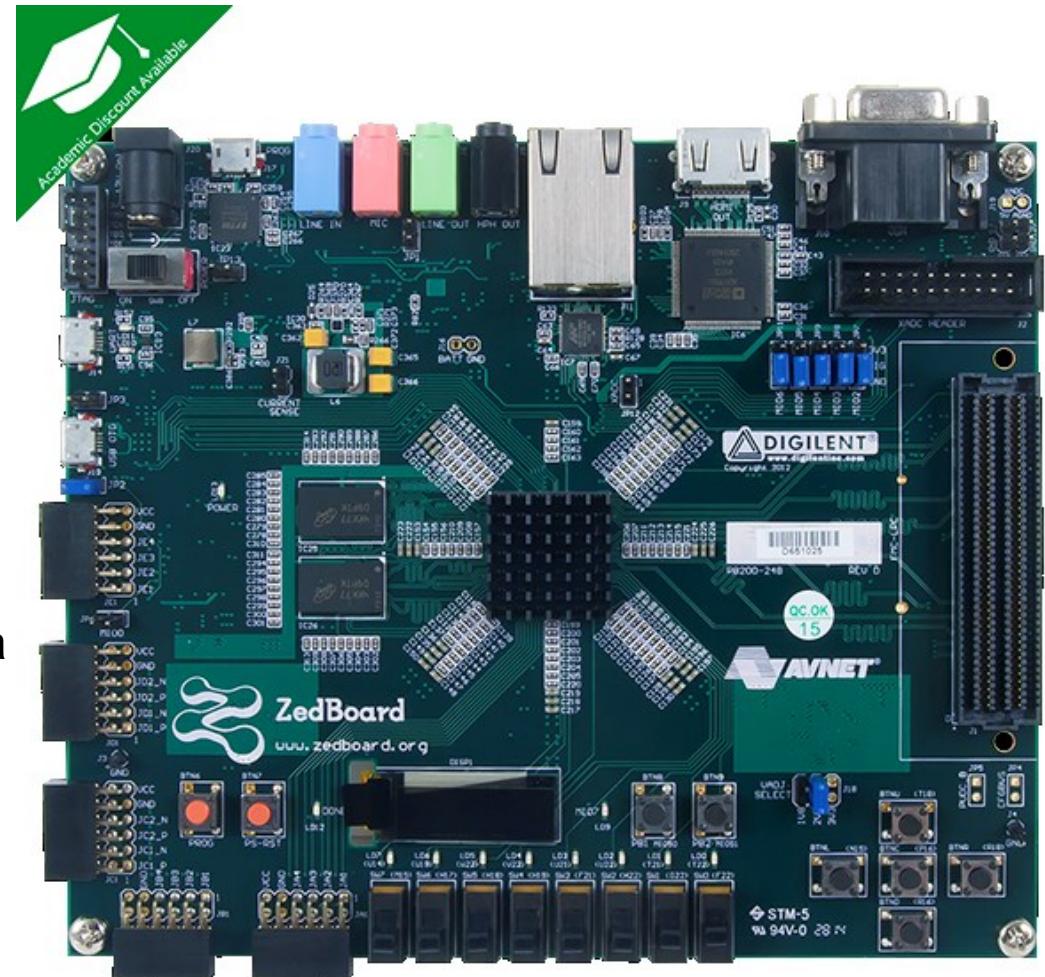
Syllabus

- Dally, William J. - Harting, R. Curtis - Aamodt, Tor M.
Digital Design Using VHDL A Systems Approach
Cambridge University Press 2016
ISBN9781107098862
- Lectures and lecture slides
- Mandatory assignments
- Handouts – Will be made available digitally on semester page
(Link from 2022 can be used until the 2023 link is ready)
 - Cookbook
 - Articles (Reset Circuits, Steve Kilts)



Lab assignments

- There are 10 obligatory lab assignments.
 - *The book has chapter-exercises that can be used for self-study.*
 - All assignments must be completed to take the exam.
 - *Lab workload and complexity increases through the semester*
 - Lectures are prerequisite for some assignments
 - Lectures most intensive in the beginning
 - The lab assignments utilises the digilent Zedboard, featuring a Xilinx Zynq 7020 device that includes both a hardcoded ARM processor and FPGA fabric.
 - You will be introduced to tools and board first.
 - By the end of this course you will design a system, using both processor and FPGA fabric, that will both regulate, read and display the speed of an electric motor connected to the board.



<https://store.digilentinc.com/zedboard-zynq-7000-arm-fpqa-soc-development-board/>

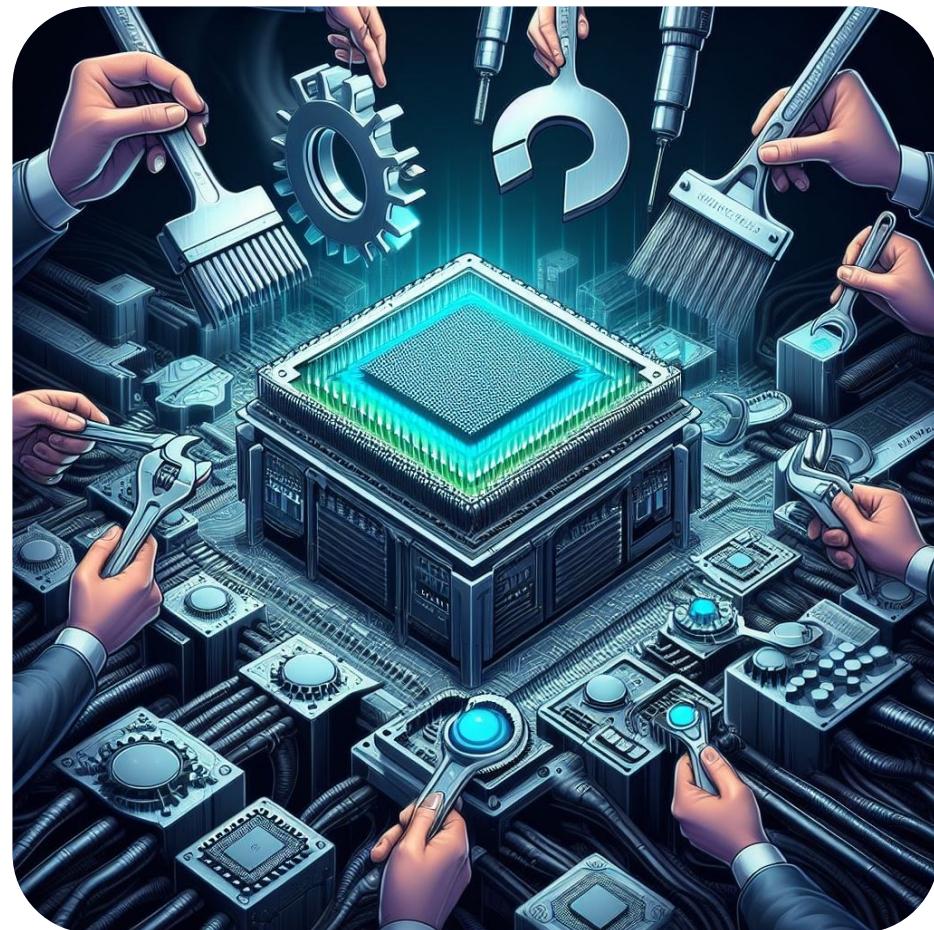
LAB

- Lab starts now!
 - **Assignments are available in Canvas!**
 - Assignments are individual.
 - WHAT ABOUT...
 - Collaboration?
 - Previously approved assignments?
 - ChatGPT?
 - There will be one assignment (3) using peer review only.
 - Your reviews are mandatory for your approval!
 - Some assignments may require that you show your setup to the lab supervisor.
 - *Labs can be done entirely remote, but on-site is strongly advised.*
- **LISP (2428) is the LAB.**
 - Both hardware and software will be available in LISP.
 - 4 boards with camera will be available online for those in quarantine/ isolation / specieal needs.
- Questions..?



Software

- Vivado, Vitis
 - Floorplanning and Programming FPGA boards
 - <https://www.xilinx.com/products/design-tools/vivado.html>
 - Standard edition is free and should be sufficient up to assignment 9.
- Tool chain for Python Testbenches = Vivado + these
<https://robin.wiki.ifi.uio.no/Cookbook> (Not complete, but has installation guide)
 - GHDL
 - Open source VHDL simulation, used together with CocoTB below.
 - GTKWave
 - Open source waveform viewer
 - CocoTB
 - Cosimulation framework for Python testbenches
 - This is invoked when using "make" when using python based testbenches.
- Questa=Modelsim (Fallback solution if GHDL fails)
 - Compilation, Simulation, waveform viewer
 - "industry standard"
 - Not open source. Access may be limited
- All software can be accessed from Linux machines on IFI, and IFI-digital-electronics
- GHDL+ GTKWave and Cocotb



Resources

- Semester page/ course web "Vortex"
 - Course information
 - Exam date, lecture schedule, etc.
- Canvas (link from semester page)
 - Assignment-files, delivery and -feedback
 - Some links to external content
- in3160-discourse
 - Communication and discussion:
 - Requires login, allows anonymous posting.
 - Both students and staff can answer ☺
 - Note: Use the manned lab hours as much as possible for questions.
- <https://robin.wiki.ifi.uio.no/Cookbook>

HDL & PL

Hardware **D**escription **L**anguage & **P**rogrammable **L**ogic

Yngve Hafting



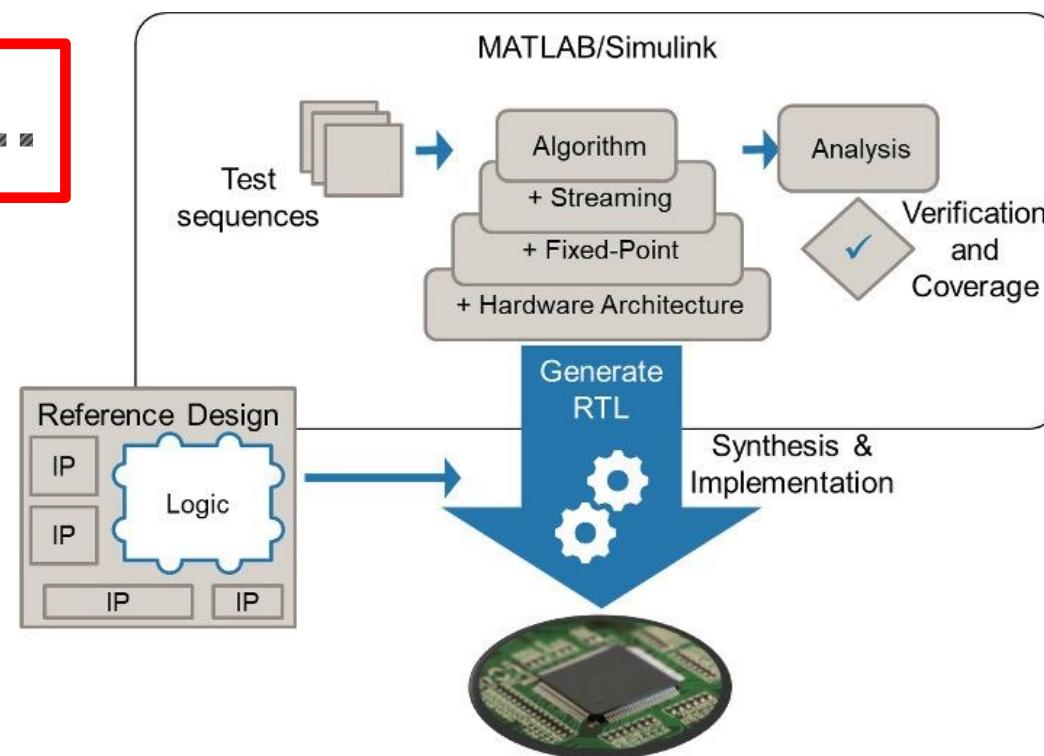
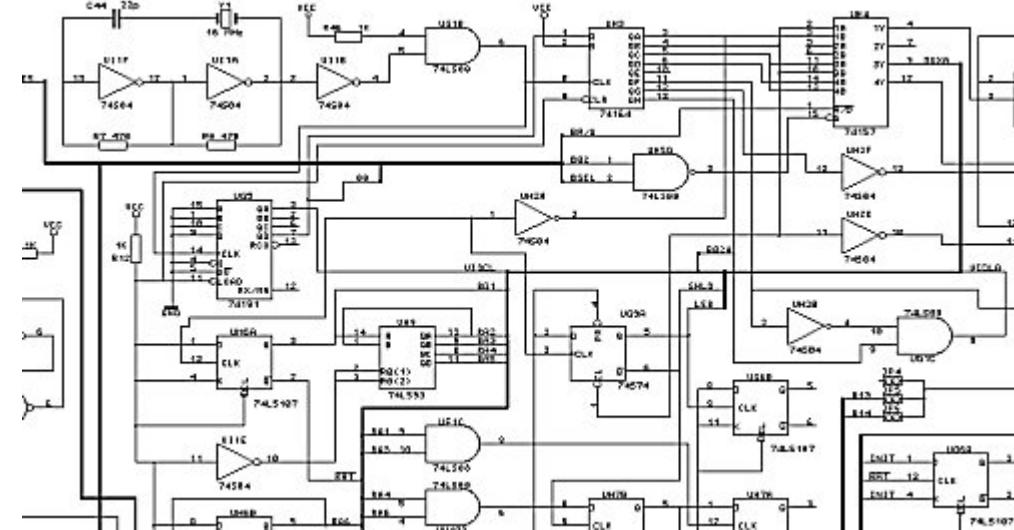
Overview

- How to implement digital designs?
- HDL vs schematics
- **Why use HDL...**
- HDL vs Software
- Hardware
 - ASICs vs PL
 - Some types of PL

How to implement digital designs..?

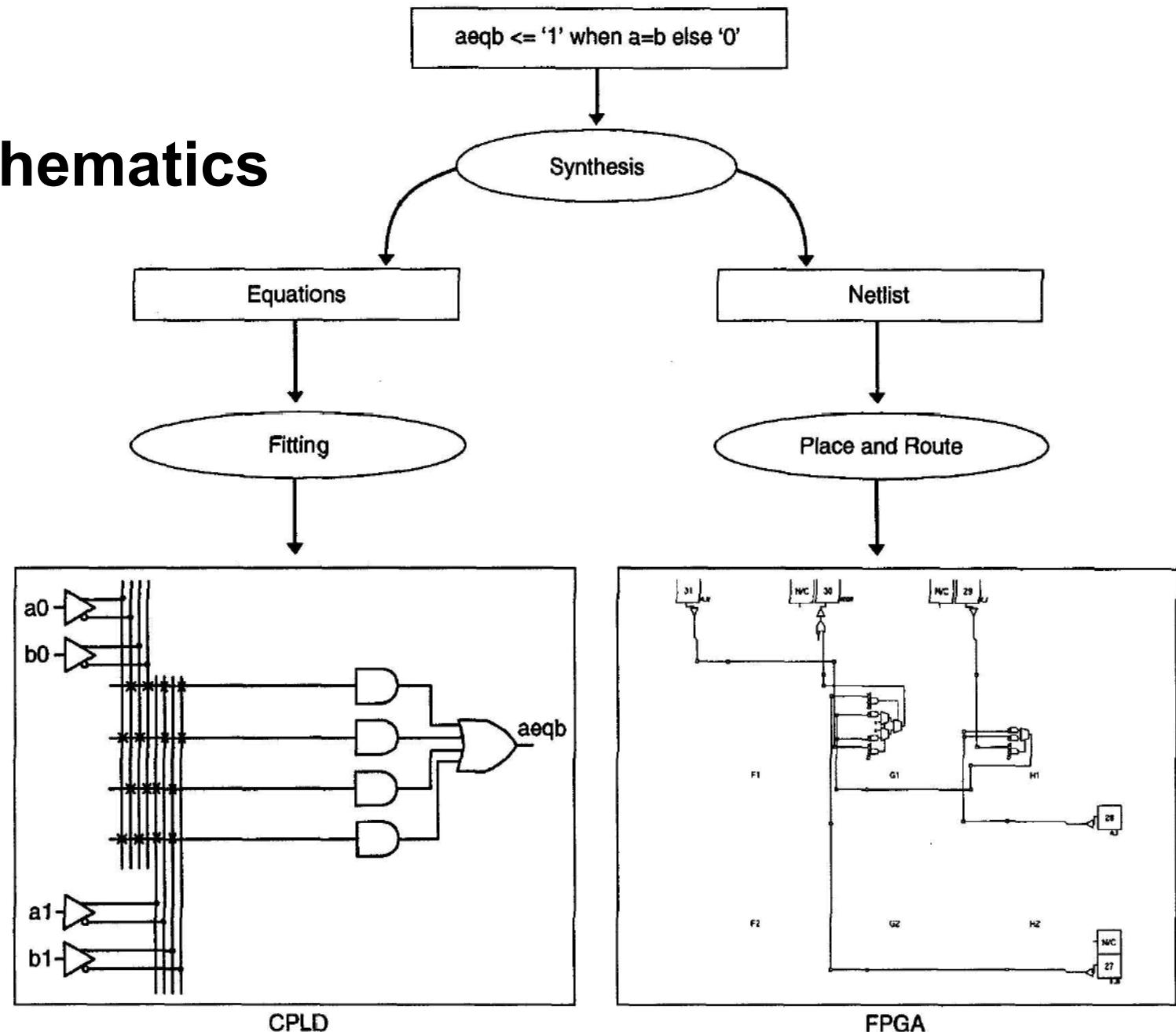
- Low Level
 - Netlists
 - Schematic diagrams
 - Programming using hardware description languages (HDL programming)
 - High Level
 - HDL programming (RTL)
 - Block diagrams
 - Connecting premade models (IP's)
 - High level synthesis...
 - Code Generators (Matlab/Simulink)
 - Uses IP's
 - Generates HDL/ Netlists

The diagram consists of three black arrows originating from the right side of the slide. The top arrow points from the 'IN3160...' text box to the 'HDL programming' item under the 'Low Level' section. The middle arrow points from the same text box to the 'High level synthesis...' item under the 'High Level' section. The bottom arrow points from the same text box to the 'Code Generators (Matlab/Simulink)' item under the 'High level synthesis...' section.



HDL vs netlists/ Schematics

- Synthesis enables
 - One design
 - Several physical implementations



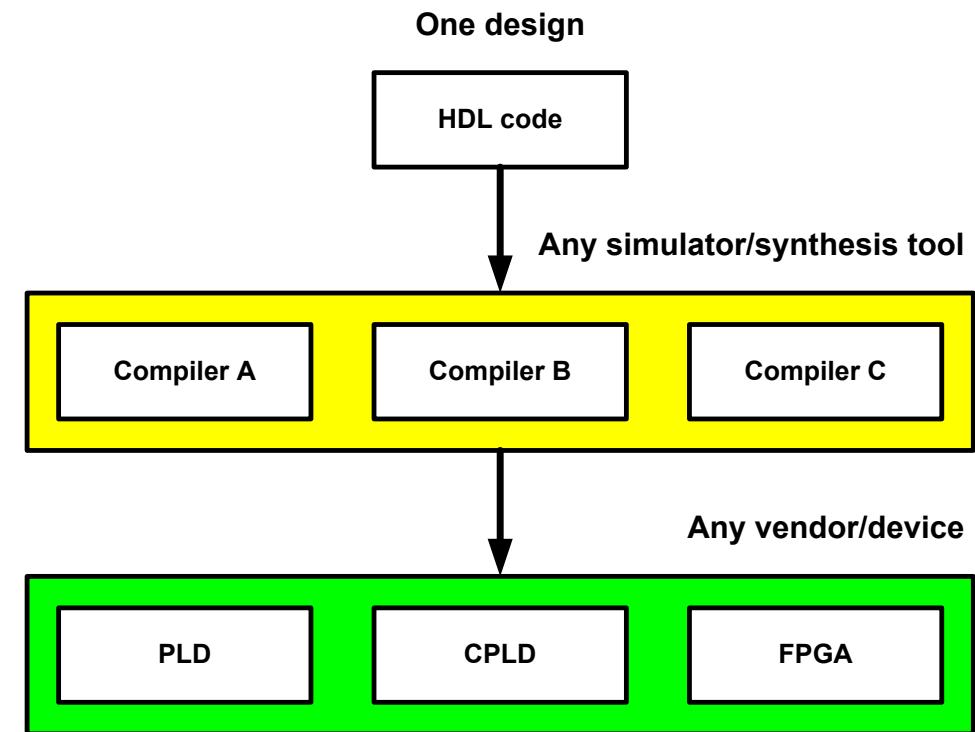
Why HDL?

- Technology independent code
- Different abstraction layers

Netlist: U1: xor2 port map(a(0), b(0), x(0)); U2: xor2 port map(a(1), b(1), x(1)); U3: nor2 port map(x(0), x(1), aeqb);	Boolean equations: aeqb <= (a(0) xor b(0)) nor (a(1) xor b(1));
Concurrent statements: aeqb <= '1' when a=b else '0';	Sequential statements: if a=b then aeqb <= '1'; else aeqb <= '0'; end if;

Why HDL?

- Portability
 - Tool and device independency
- IEEE Standards
 - VHDL and System Verilog
 - Both IEEE standards
(Institute of Electrical and Electronics Engineers)
 - VHDL - IEEE 1076
 - System Verilog - IEEE 1364



Why HDL?

- Example :
Simple maintenance/expansion of a counter

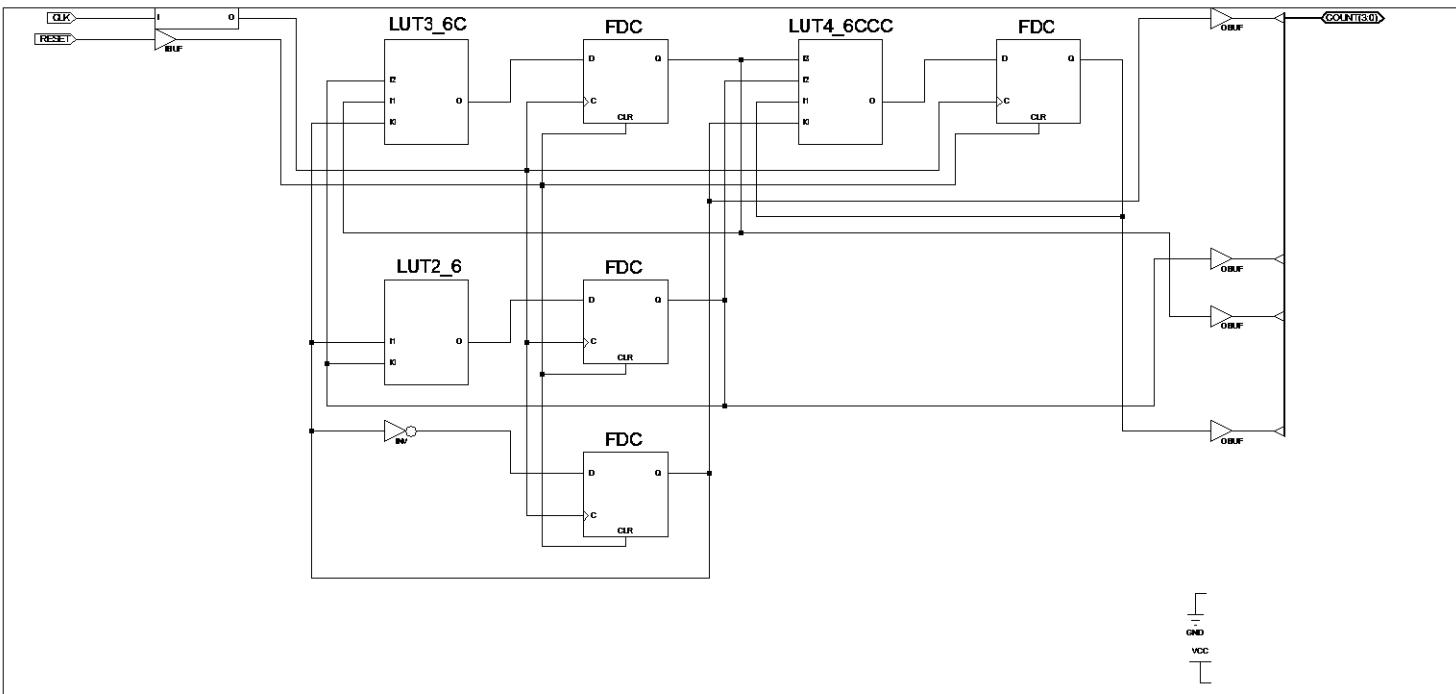
```
signal r_count, next_count : unsigned(N-1 downto 0);
---
next_count <= r_count+1;

REGISTER_UPDATE: process(clk) is
begin
  if rising_edge(clk) then
    r_count => (others => '0') when reset else next_count;
  end if;
end process;
```

Why HDL?

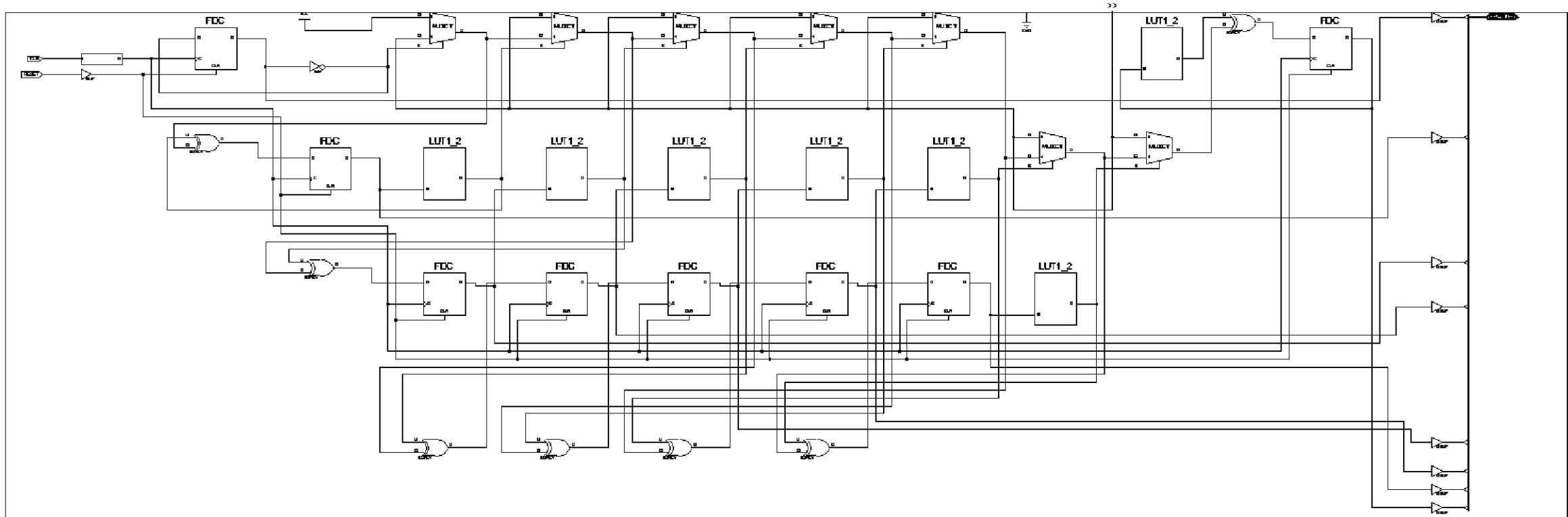
4 bit counter:

```
signal r_count, next_count : unsigned(3 downto 0);
```



8 bit ...

```
signal r_count, next_count : unsigned(7 downto 0);
```



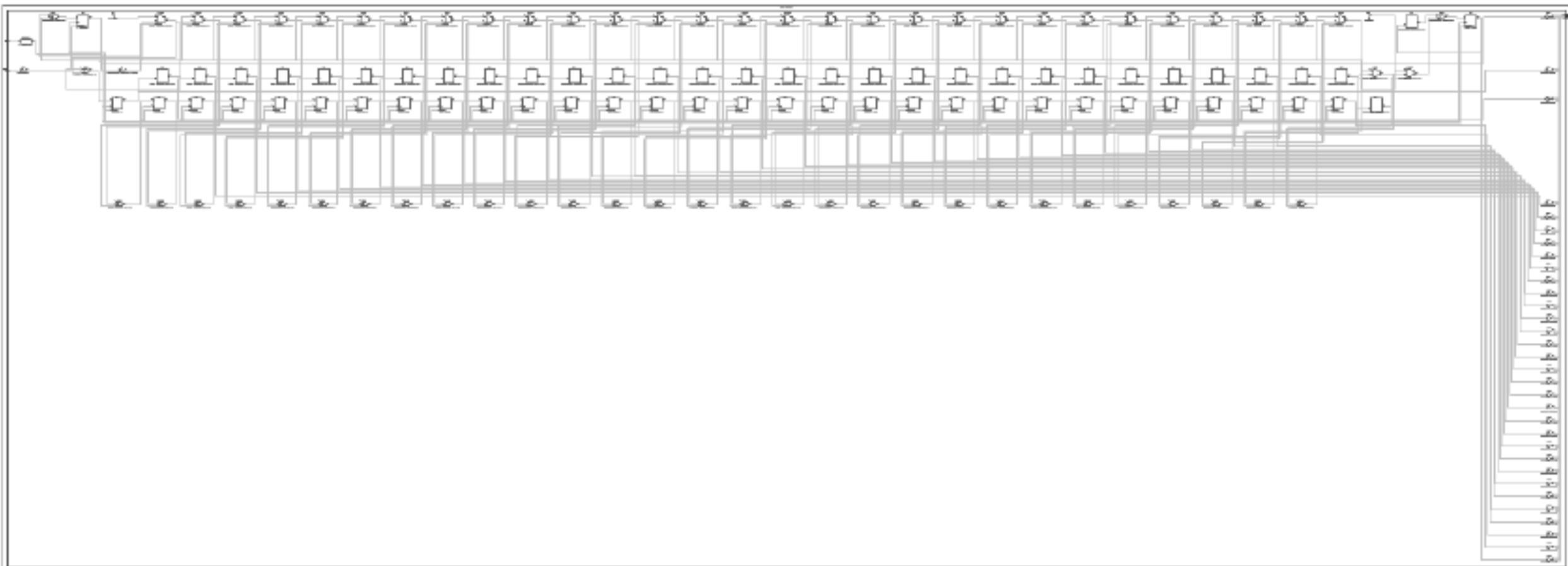
16 bit ...

```
signal r_count, next_count : unsigned(15 downto 0);
```



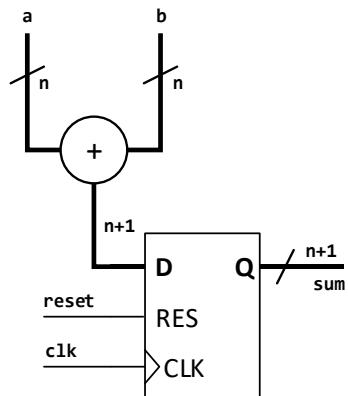
32 bit...

```
signal r_count, next_count : unsigned(31 downto 0);
```



HDL vs software

```
next_sum <= a+b;
r_sum <=
(others => '0') when reset else
next_sum when rising_edge(clk);
```



Hardware description languages	Software languages
Defines the logic function of a circuit	Defines the sequence of instructions and which data shall be used for one or more processors or processor cores
CAD tools syntetizes designs to enable realization using physical gates.	A compiler translates program code to machine code instructions that the processor can read sequentially from memory
<i>Implemented in Programmable Logic</i> (FPGA, CPLD, PLD, PAL, PLA, ...) or ASICs (application specific circuits) ("ASICs", processors, ..-chips,.. etc.)	Is stored in computer memory
Verilog (SystemVerilog) VHDL (VHDL 2008) (System C m. fl.)	C, C++, C#, Python, Java, assemblere (ARM, MIPS, x86, ...) Fortran, LISP, Simula, Pascal, osv...

```
int sum(int a, int b){
    int s;
    s = a + b;
    return s;
}

sum(int, int):
    push    rbp
    mov     rbp, rsp
    mov     DWORD PTR [rbp-0x14],edi
    mov     DWORD PTR [rbp-0x18],esi
    mov     edx, DWORD PTR [rbp-0x14]
    mov     eax, DWORD PTR [rbp-0x18]
    add     eax, edx
    mov     DWORD PTR [rbp-0x4],eax
    mov     eax, DWORD PTR [rbp-0x4]
    pop    rbp
    ret

55
48 89 e5
89 7d ec
89 75 e8
8b 55 ec
8b 45 e8
01 d0
89 45 fc
8b 45 fc
5d
c3
```

What is HDL

- VHDL = VHSIC HDL:
 - Very High Speed Integrated Circuit **Hardware Description Language**
 - The purpose is to generate circuits, and verify their function through simulation.
 - **Synthesizable** (realizable) **code work concurrently** (in parallel, always on).
 - Code for simulation include things such as file I/O which cannot be synthesized.
 - Testbenches can use synthesizable elements, but will use sequential statements, and is only run as software.

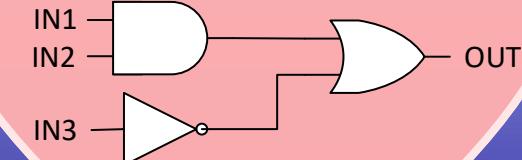
This may be confusing at times...

HDL

Code for generating and parsing simulation data
(Test benches)

code for generating multiple instances or variants of entities

Synthesizable code



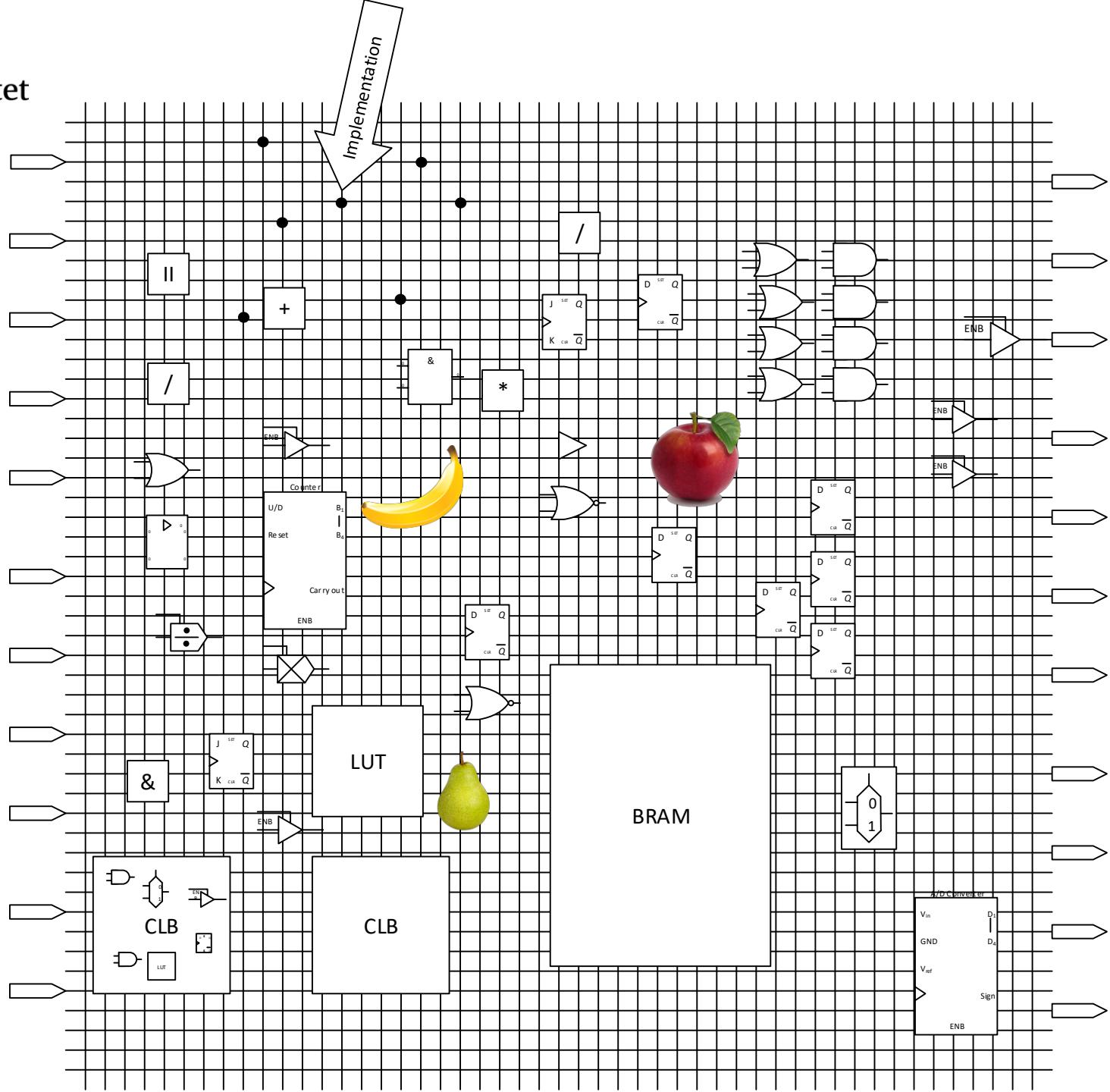
What hardware..?

- **ASIC** : Application Specific Integrated Circuit
 - Processors, microcontrollers, GPUs (x86, ARM, GeForce)
 - Customized chips
- **PL** : Programmable logic
 - PLA, PAL "Programmable Logic Array" / .."Array Logic"
 - CPLD "Complex Programmable Logic Device" = Several PAL/PLAs, FFs
 - FPGA "Field Programmable Gate Array" = More complex array of primitives

IN3160...

What is PL and FPGA ? (Programmable Logic)

- PL = FPGA, CPLD, PLA...
(Field Programmable Gate Array,
Complex Programmable logic Device)
- PL vs processor
(FPGA vs CPU, MCU) ?
- PL vs ASIC (Application
Specific Integrated circuit)?



When or why choose programmable logic?

- (Verify behavior of ASIC)
- Prototyping flexibility
 - Lots of multi purpose IO
 - Reprogrammable
- Small batch production
- Parallelism
- Custom / fast
- Runtime reconfigurability
- ...

When to avoid programmable logic?

- High Volume + low cost
- When dedicated HW is well suited.
- When extreme speed is required => ASIC
- ...

IN3160

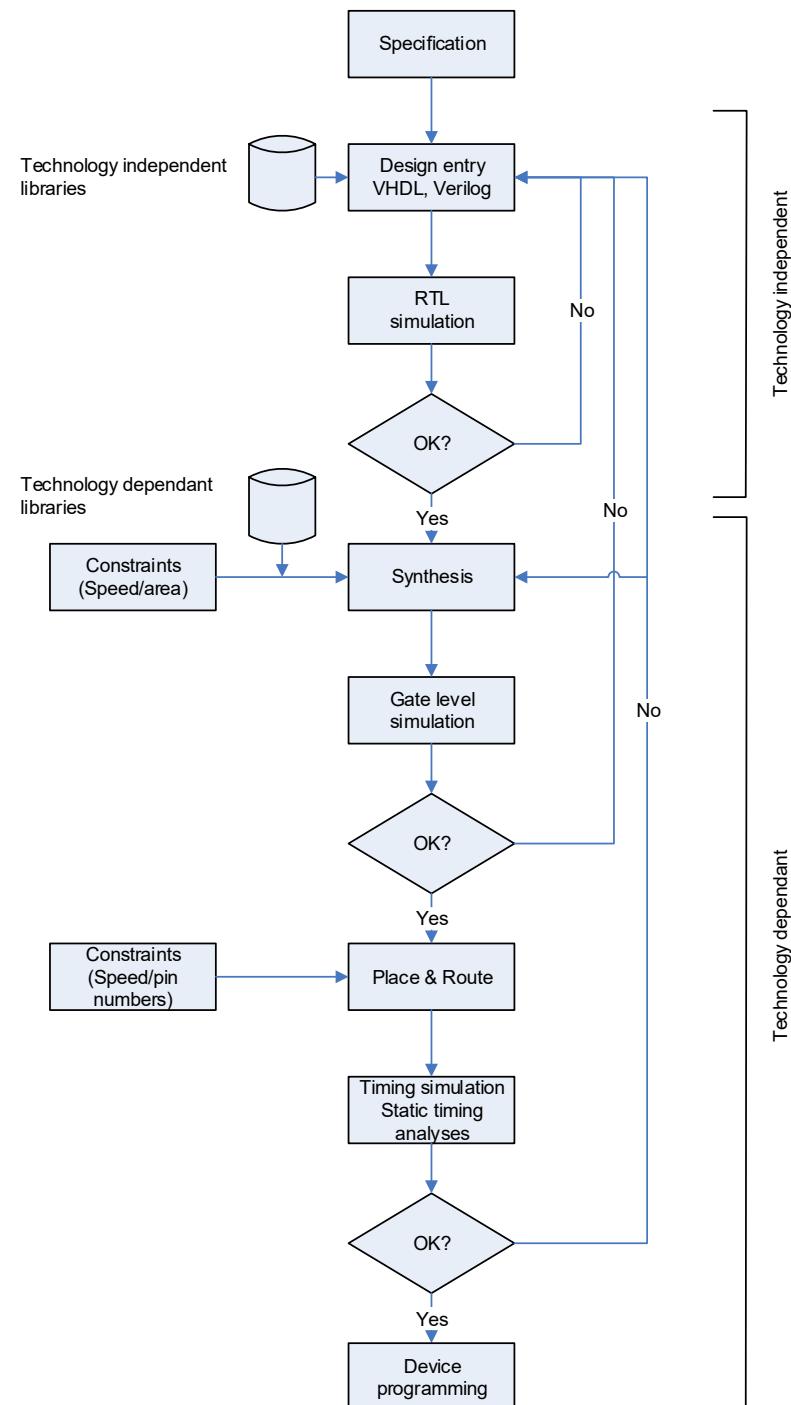
Digital Design Flow

Yngve Hafting



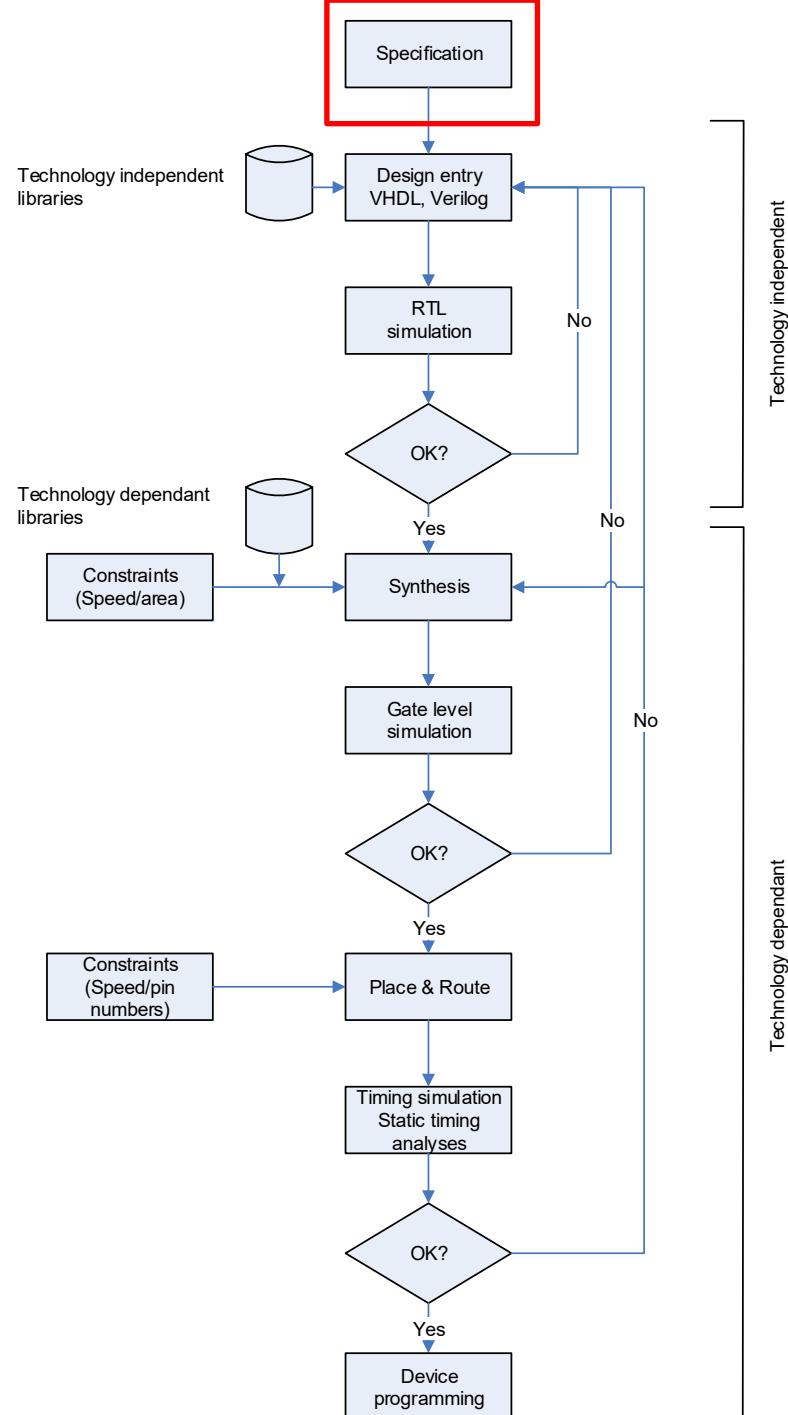
Overview

- Digital design tools.
- Specification
- Design entry, synthesis and PAR
- Timing analysis
- Timing simulation
- Testing



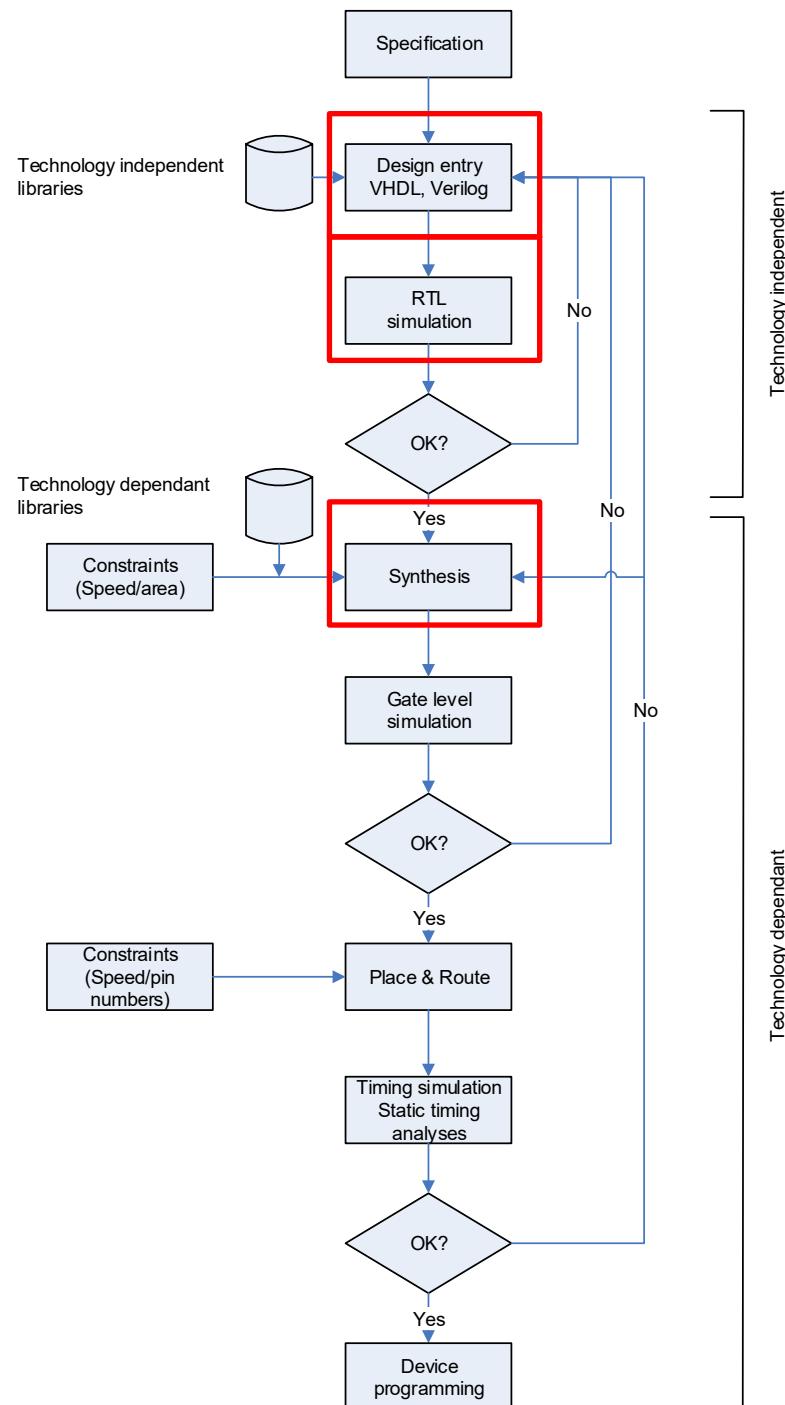
Digital Design Flow: Specification

1. Define the problem
2. Draw a functional diagram
 - block diagram with major components and connections
3. Identify IO requirements
4. Identify necessary interface circuits
5. Decide on HDL (VHDL, Verilog, System C,...)
6. Draw a program flowchart (ASM diagram)
 - Defines how the design shall work logically.
 - By hand or using tools such as:
 - Visio, Draw.io, Lucid chart, etc.



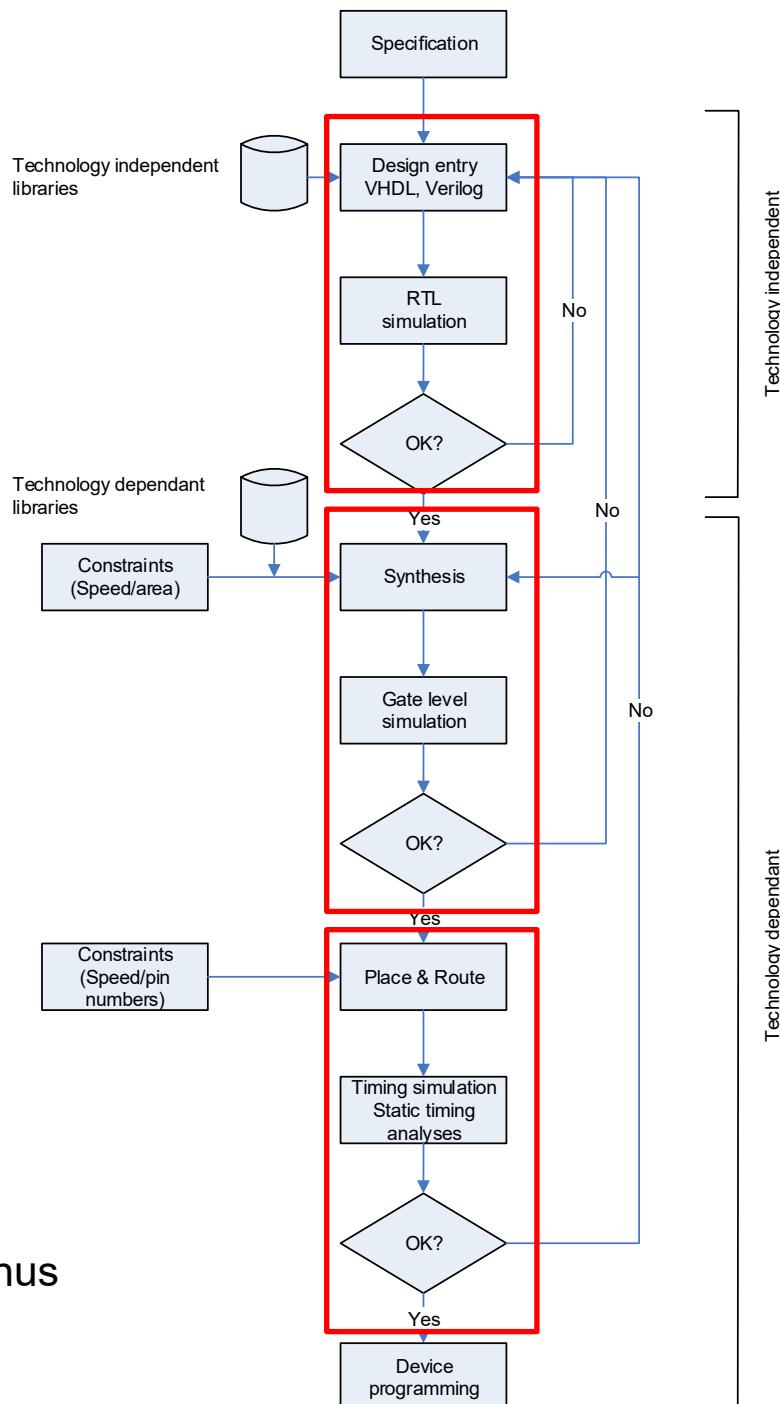
Digital Design tools...

- Design entry:
 - Use your favourite HDL text editor
VScode, Notepad++, Emacs, ...
- Simulation (RTL)
 - Here: Typically using GHDL
- Synthesis, Implementation, Programming
 - Vendor specific tools,
 - Here: Vivado by Xilinx
 - Also possible: Digilent tools for programming.



Design entry, synthesis and PAR

- RTL = Register Transfer Level
 - RTL does not use specific gates or technology
 - Designs are *mostly* done in RTL
 - RTL simulation can be used to verify logic function.
- Gate level synthesis
 - Technology specific gates are selected for all components in the design.
 - Typically a synthesizer will pick gates specific for the (FPGA) chip family we use.
 - Once we have a gate level design we can
 - calculate gate-, but not propagation delays
 - Simulate using gate delays.
- Place and route
 - After synthesis gates can be placed within a specific (FPGA) chip.
 - When place and route is performed propagation delays may also be simulated thus
 - We can do all timing simulation, including propagation delays.



Static timing analysis

- Performed by EDA tools on synthesized or routed designs
- Will attempt to
 - find critical path(s) and
 - check if timing requirements (constraints) can be met.

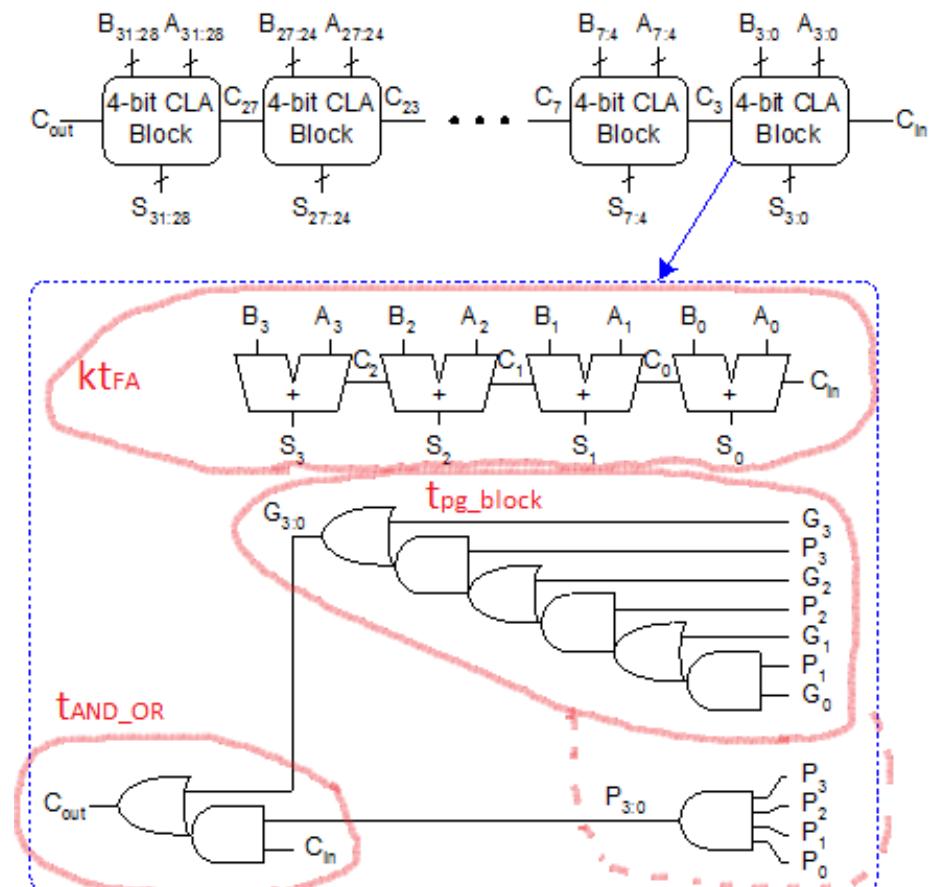
IN2060: Carry-Lookahead Adder Delay

For N -bit CLA with k -bit blocks:

$$t_{CLA} = t_{pg} + t_{pg_block} + (N/k - 1)t_{AND_OR} + kt_{FA}$$

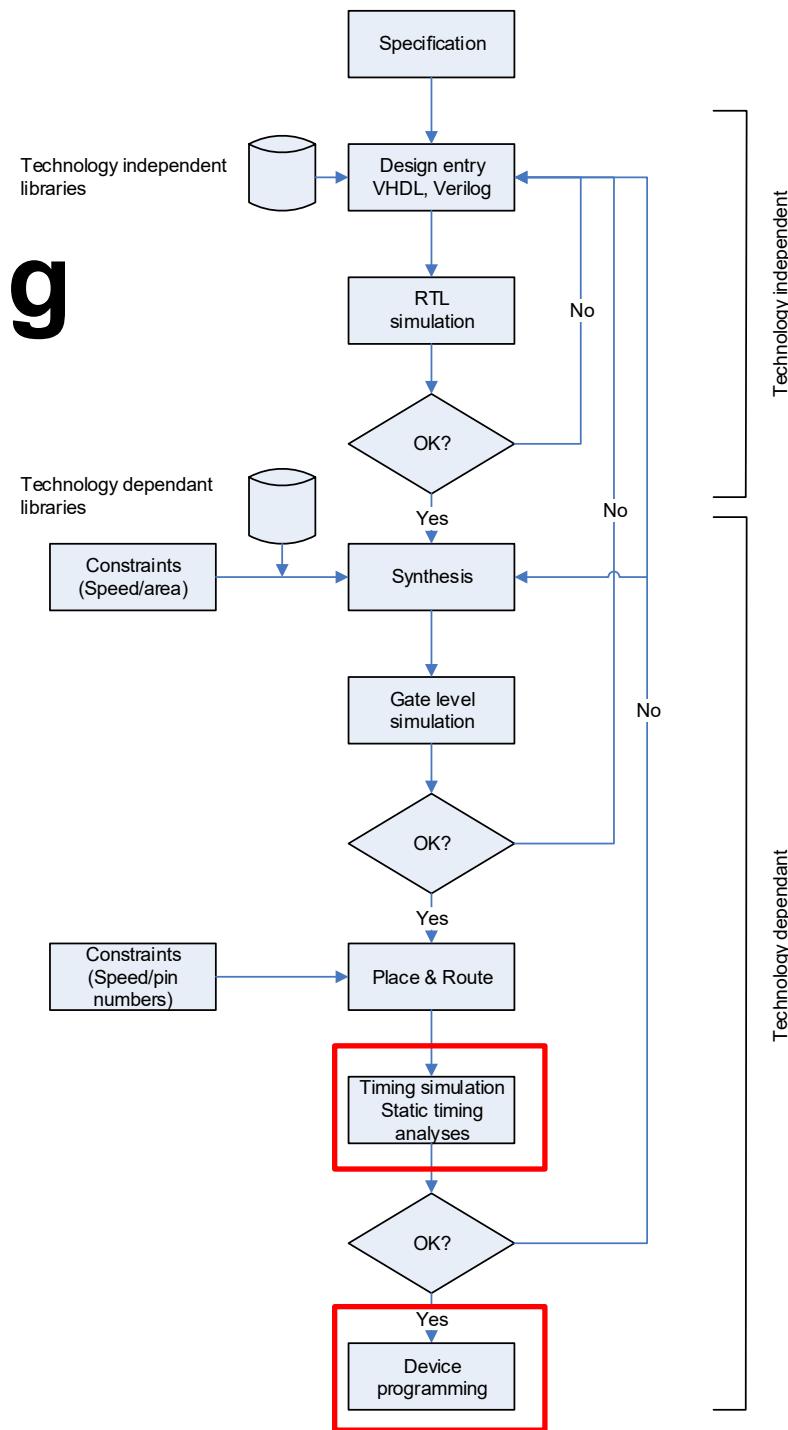
- t_{pg} : delay to generate all P_i, G_i
- t_{pg_block} : delay to generate all $P_{i:j}, G_{i:j}$
- t_{AND_OR} : delay from C_{in} to C_{out} of final AND/OR gate in k -bit CLA block

An N -bit carry-lookahead adder is generally much faster than a ripple-carry adder for $N > 16$



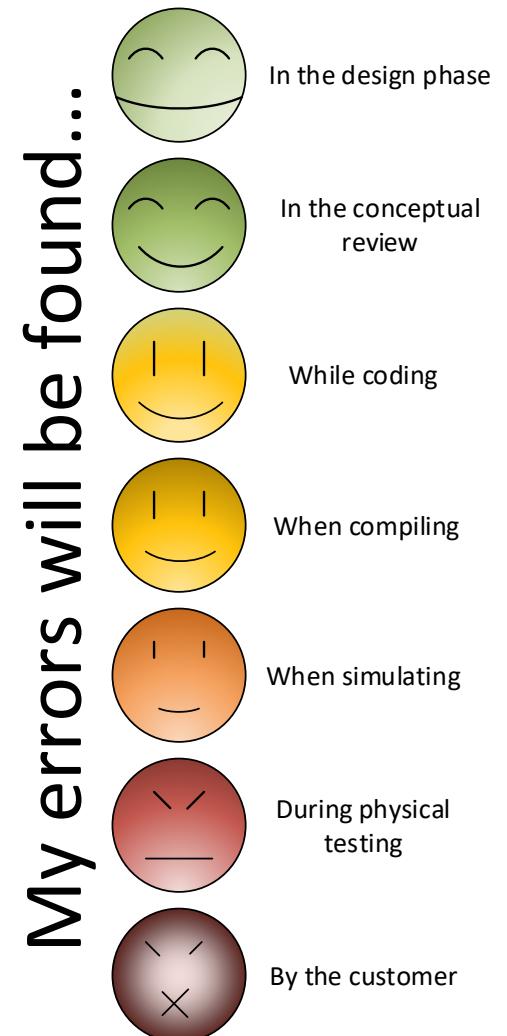
Timing simulation, programming

- Simulating synthesized or routed designs
 - Not common for FPGA design, but for ASIC and analog
 - *IN3160 does not use timing simulation:
Static timing analysis is mostly sufficient*
 - Uses timing information for every component in use.
 - Requires much more resources than RTL simulation.
 - Can be slow for complex designs
 - Hence the option to simulate at gate level, before performing PAR.
- Device programming...
 - (Usually done from vivado, but third part tools *may* be used).
 - Download bit stream to FPGA



Testing and verification

- «*Testing*» is to find *physical errors* in a device.
 - Built in self-tests
 - Ex: Memory tests in BIOS
 - Design for testability
 - Means that we design for physical testing.
 - We *may* touch this later in the course.
- «*Verification*» is to check the *design*
 - Reading the code...
 - Simulation
 - Testbenches
 - HDL
 - Scripts
 - Co-simulation using normal programming languages
 - Analysis:
 - Compilation
 - Timing Analysis
 - Implementation reports
 - *Spend more time in early phases!*

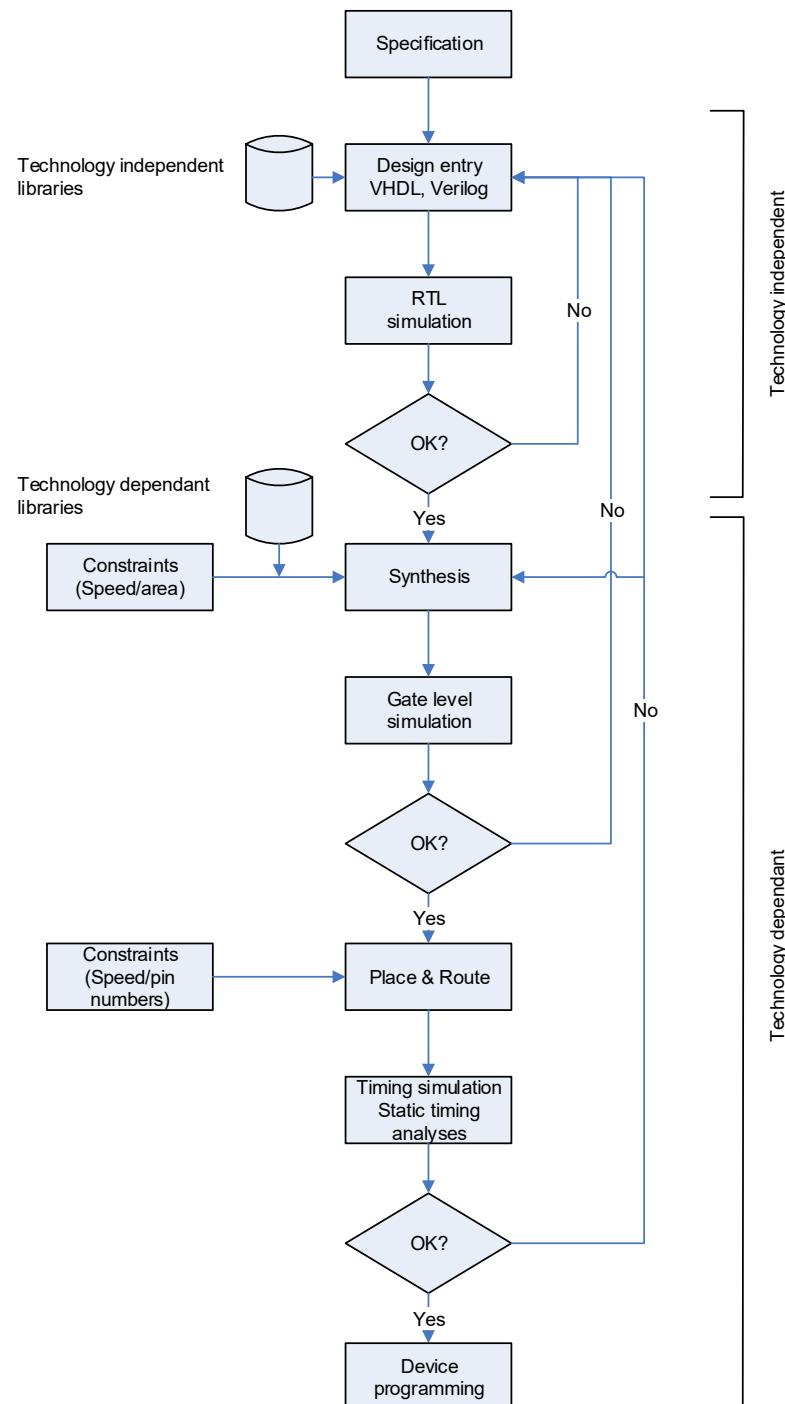


Introduction to course hardware and software tools

- Zedboard
- Questa
- Vivado
- ROBIN wiki:
<https://robin.wiki.ifi.uio.no/Hovedside>
 - Software
 - FPGA tools
https://robin.wiki.ifi.uio.no/FPGA_tools (See VSCode)
 - https://robin.wiki.ifi.uio.no/Cocotb,_GHDL_and_GTKWave
 - Cook book and ZedBoard documentation
 - Canvas – IN3160
 - Cookbook_v3_5.pdf
 - ZedBoard HW UG vX_X.pdf
 - Zynq intro video:
<https://www.xilinx.com/video/soc/zedboard-overview-featuring-zynq.html>

Digital Design tools...

- Design entry:
 - Use your favourite HDL text editor
Vscode Notepad++, Emacs, Vivado.
- Simulation (RTL, Gate Level, Timing)
 - GHDL
 - (Questa= Modelsim)
- Synthesis, Implementation, Programming
 - Vendor specific tools...
 - Here: Vivado by AMD/Xilinx, (*Vitis for SoC designs*)



Simulation and test benches

Simulation can be run several ways:

1. Manually setting inputs and specifying time intervals in the GUI or console
 - Tedious and not really practical at all
 - *Normally this is only done only initially.*
2. To make scripts (tcl for Questa) in a separate (.do) file.
 - The *script commands will be added to the console during manual use, and can be copied as text into a .do file.*
 - setting up the simulation windows can be done reusing script commands.

3. Using test benches written in HDL
 - possible in combination with running scripts
 - VHDL can be used to generate code for applying test vectors sequentially to the inputs of an entity for simulating.
 - *Test bench code is SW even if it is written in an HDL* (not synthesizable)
 - VHDL has built in test-specific attributes
4. Using Co-Simulation (cocotb)
 - runs simulation and coroutines in parallel
 - Environment switches back and forth between coroutines and simulation
 - Test vectors are generated in software coroutines
 - Checks and reporting is done in coroutines
 - Python can be used for test-benches
 - not built for hardware testing initially
 - scale better with large design and complex testing
 - non-HDL-specific issues has (way) better support

Suggested reading, Mandatory assignments

- D&H:
 - 1.4 p 11-13
 - 1.5 p 13-16
 - 1.6 p 16-17
 - 2.1 p 22-28
 - 2.2 p 28-30
 - 2.3 p 30-34
 - 3.1-3.5 p 43-51 = repetition (known from previous courses)
- Oblig 1: «Design Flow»
 - See canvas for further instruction.

Note: Some of this content will be covered in depth in later lectures.

- *Read this to familiarize yourself with content, form and language.*

IN3160

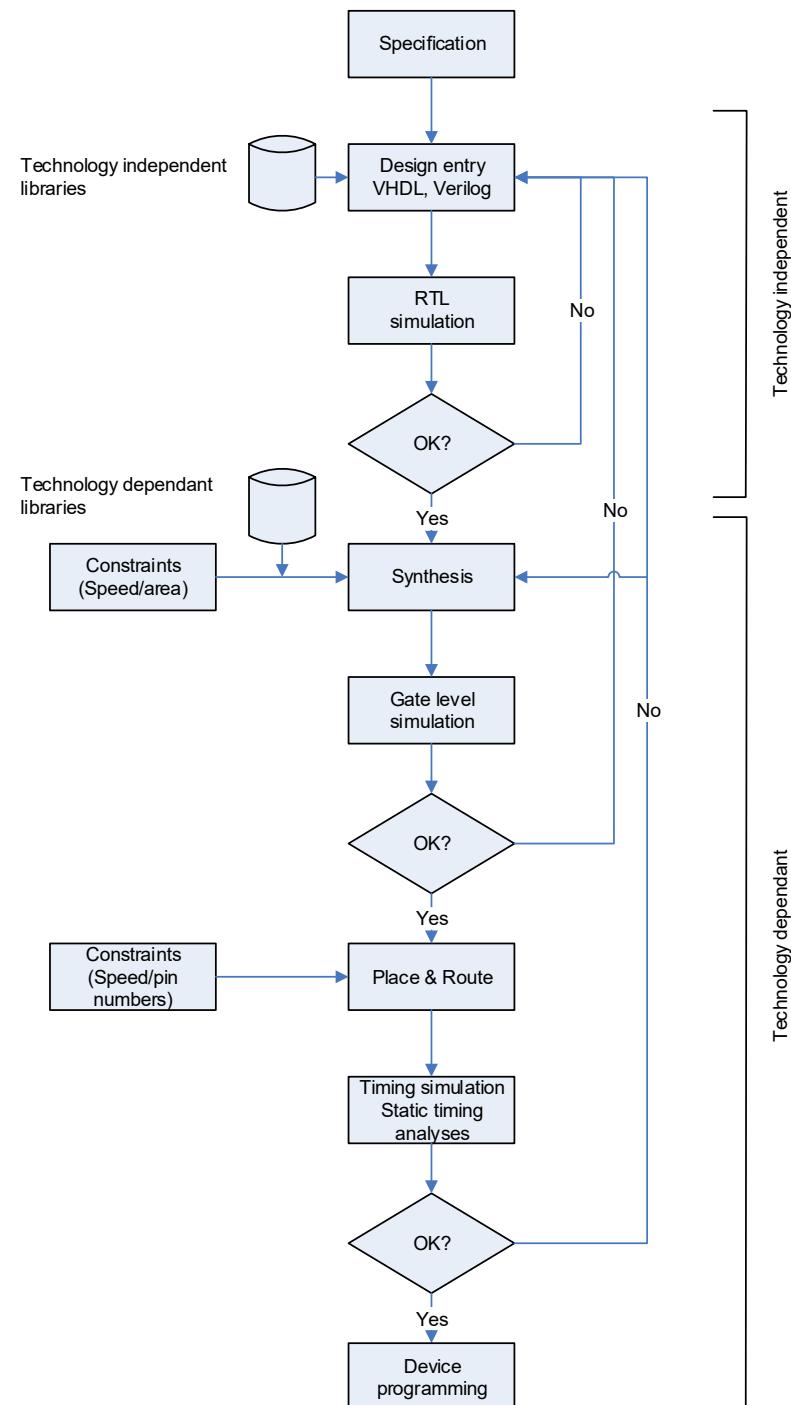
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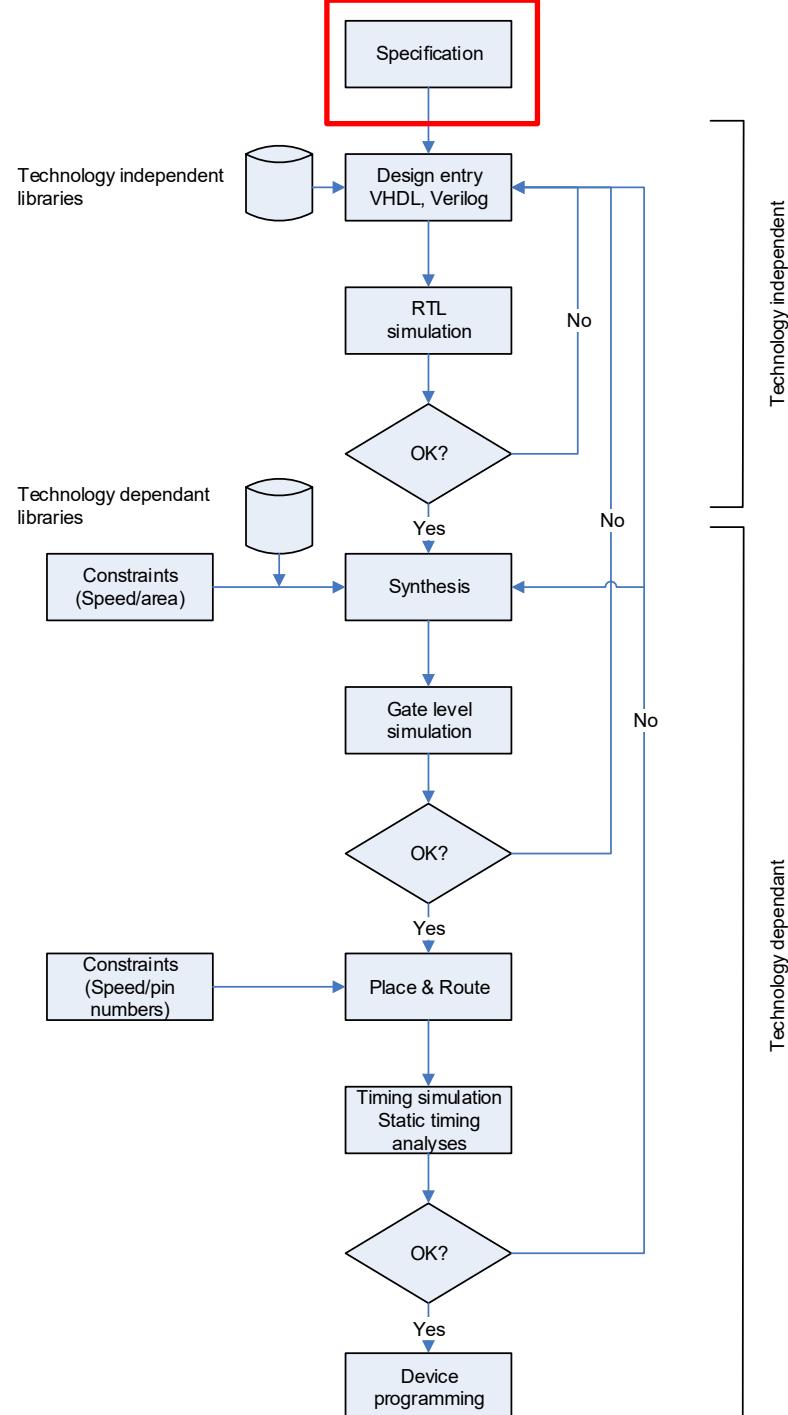
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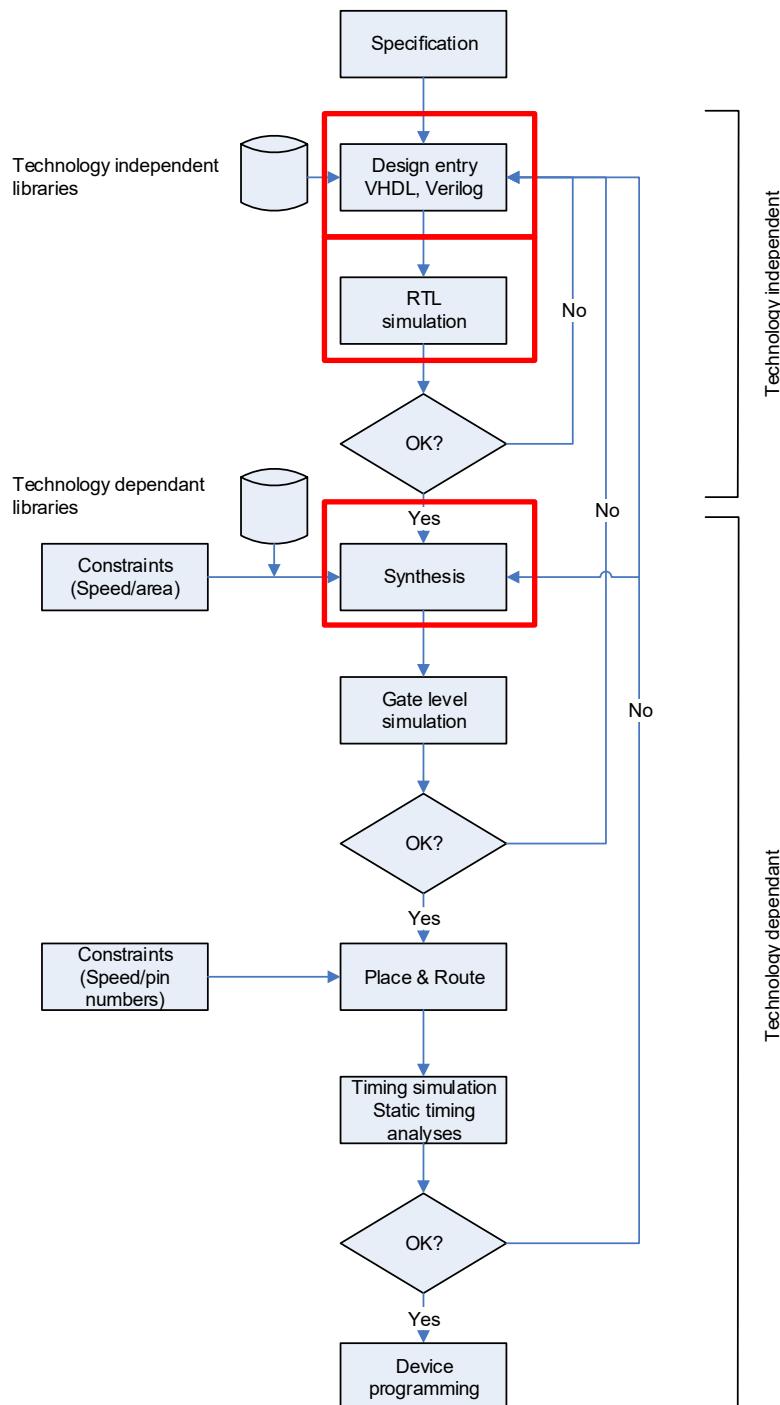
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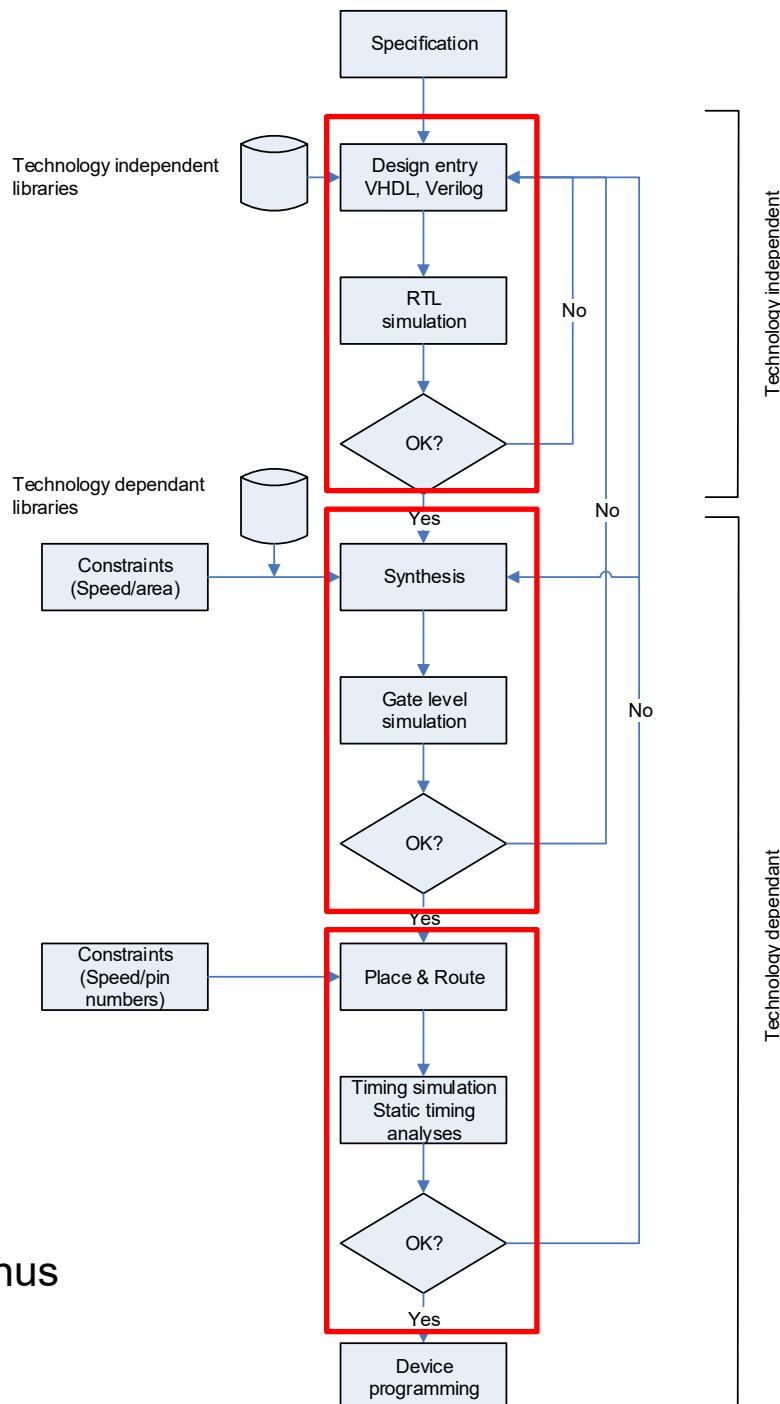
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 - Simulate using gate delays.
- Place and route
 - After synthesis gates can be placed within a specific (FPGA) chip.
 - When place and route is performed propagation delays may also be simulated thus
 - We can do all timing simulation, including propagation delays.



Static timing analysis

- Performed by EDA tools on synthesized or routed designs
- Will attempt to
 - find critical path(s) and
 - check if timing requirements (constraints) can be met.

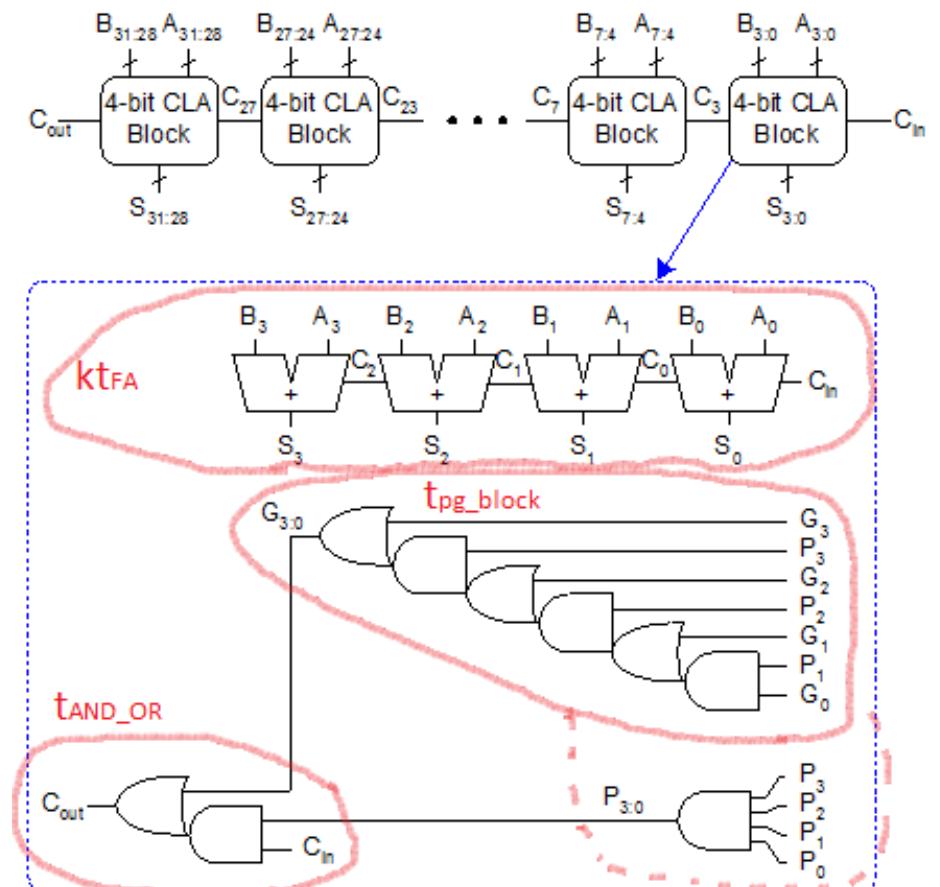
IN2060: Carry-Lookahead Adder Delay

For N -bit CLA with k -bit blocks:

$$t_{CLA} = t_{pg} + t_{pg_block} + (N/k - 1)t_{AND_OR} + kt_{FA}$$

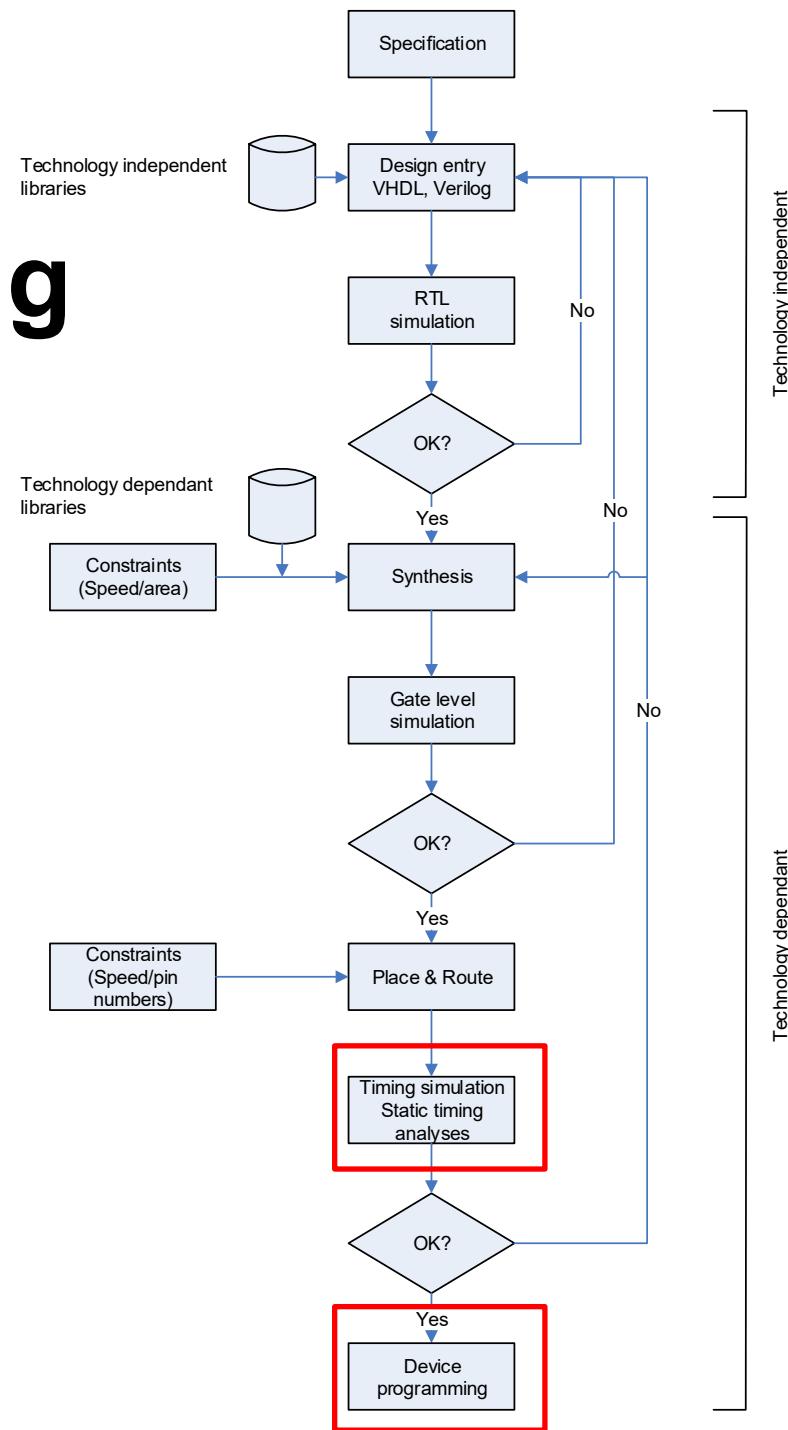
- t_{pg} : delay to generate all P_i, G_i
- t_{pg_block} : delay to generate all $P_{i:j}, G_{i:j}$
- t_{AND_OR} : delay from C_{in} to C_{out} of final AND/OR gate in k -bit CLA block

An N -bit carry-lookahead adder is generally much faster than a ripple-carry adder for $N > 16$



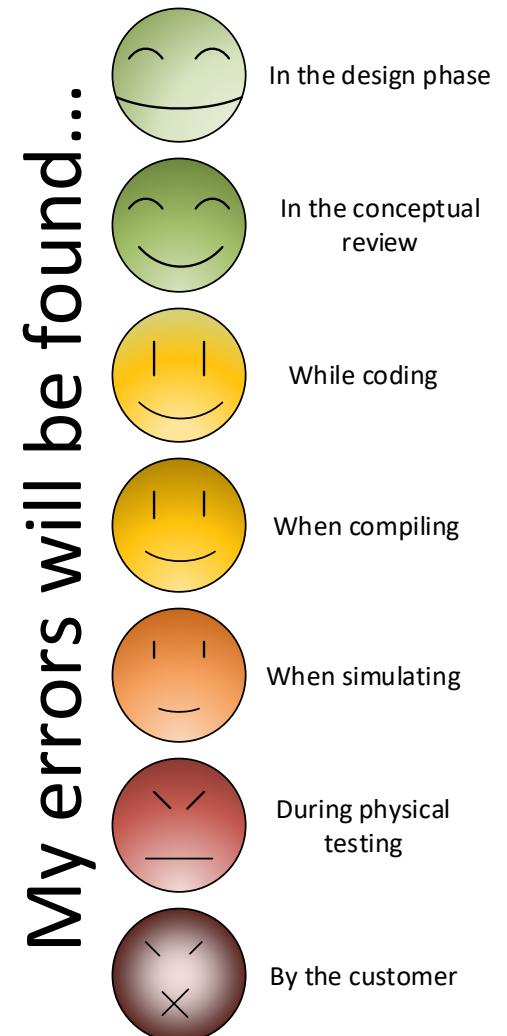
Timing simulation, programming

- Simulating synthesized or routed designs
 - Not common for FPGA design, but for ASIC and analog
 - *IN3160 does not use timing simulation:
Static timing analysis is mostly sufficient*
 - Uses timing information for every component in use.
 - Requires much more resources than RTL simulation.
 - Can be slow for complex designs
 - Hence the option to simulate at gate level, before performing PAR.
- Device programming...
 - (Usually done from vivado, but third part tools *may* be used).
 - Download bit stream to FPGA



Testing and verification

- «*Testing*» is to find *physical errors* in a device.
 - Built in self-tests
 - Ex: Memory tests in BIOS
 - Design for testability
 - Means that we design for physical testing.
 - We *may* touch this later in the course.
- «*Verification*» is to check the *design*
 - Reading the code...
 - Simulation
 - Testbenches
 - HDL
 - Scripts
 - Co-simulation using normal programming languages
 - Analysis:
 - Compilation
 - Timing Analysis
 - Implementation reports
 - *Spend more time in early phases!*

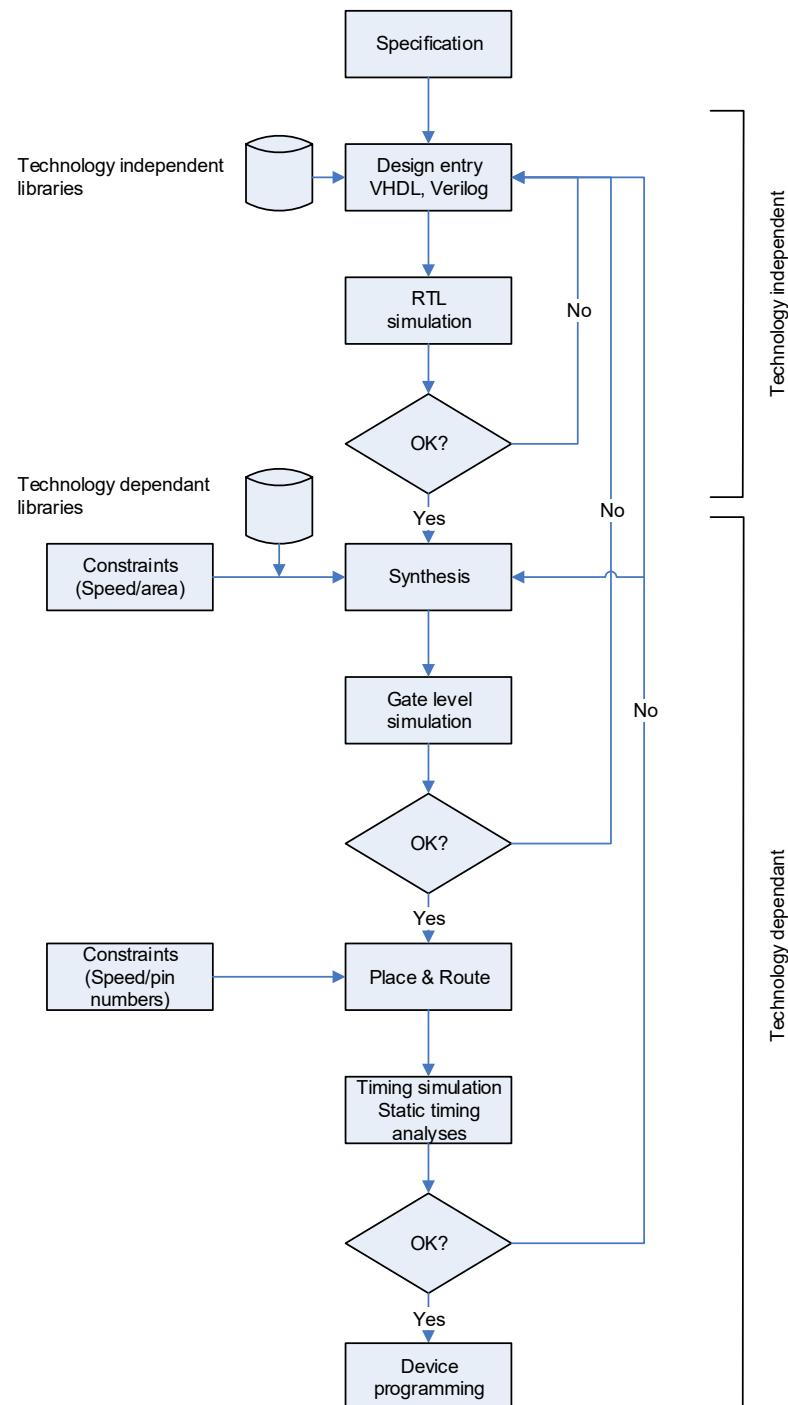


Introduction to course hardware and software tools

- Zedboard
- Questa
- Vivado
- ROBIN wiki:
<https://robin.wiki.ifi.uio.no/Hovedside>
 - Software
 - FPGA tools
https://robin.wiki.ifi.uio.no/FPGA_tools (See VSCode)
 - https://robin.wiki.ifi.uio.no/Cocotb,_GHDL_and_GTKWave
 - Cook book and ZedBoard documentation
 - Canvas – IN3160
 - Cookbook_v3_5.pdf
 - ZedBoard HW UG vX_X.pdf
 - Zynq intro video:
<https://www.xilinx.com/video/soc/zedboard-overview-featuring-zynq.html>

Digital Design tools...

- Design entry:
 - Use your favourite HDL text editor
Vscode Notepad++, Emacs, Vivado.
- Simulation (RTL, Gate Level, Timing)
 - GHDL
 - (Questa= Modelsim)
- Synthesis, Implementation, Programming
 - Vendor specific tools...
 - Here: Vivado by AMD/Xilinx, (*Vitis for SoC designs*)



Simulation and test benches

- Four different approaches:
 1. Manually setting inputs and specifying time intervals in the GUI or console
 - This way is tedious if much testing is to be done. Normally this is only done initially.
 2. Run the simulator using scripts (tcl) {Tikl}
 - Automating 1.
 - Can be combined with other solutions
 3. Create a test bench in VHDL
 - *This was the preferred method for IN3160 up to 2023*
 - *VHDL 2008 is created with testing in mind*
 - *Test benches and simulation code is software..!*
 - » *Can be confusing*
 - *Uses simulator only = runs fast*
- 4. *Co simulating using or python)*
(possible in combination with running scripts)
 - This is the preferred method
 - VHDL can be used to generate code for applying test vectors sequentially to the inputs of an entity for simulating.
 - Test bench code is not synthesizable
 - easy to read and use test data for each particular design,
 - Can be used both prior and post synthesis or implementation

Suggested reading, Mandatory assignments

- D&H:
 - 1.4 p 11-13
 - 1.5 p 13-16
 - 1.6 p 16-17
 - 2.1 p 22-28
 - 2.2 p 28-30
 - 2.3 p 30-34
 - 3.1-3.5 p 43-51 = repetition (known from previous courses)
- Oblig 1: «Design Flow»
 - See canvas for further instruction.

Note: Some of this content will be covered in depth in later lectures.

- *Read this to familiarize yourself with content, form and language.*

IN3160, IN4160

Infrastructure and tool introduction

Yngve Hafting 2022



Overview

- Demo
 - VSCode setup info
 - Remote access solution
 - Vmware / VDI
 - Ifi Digital Electronics
-
- Assignments and suggested reading for this week

Demos (Own PC / VmWare)

- Try :
 - Live-demo for cocotb + gtkwave
 - Show how to
 - Run
 - Display Waveform in gtkwave (+ analog step)
 - Modify vhdl / errors
 - Modify python to get weird behavior
 - Vivado + vhdl-eksempel or live-demo
 - elaborate and create schematic
 - Synthesize
 - New project?

VSCode with VHDL?

- VHDL using VSCode
 - https://robin.wiki.ifi.uio.no/FPGA_tools#VHDL_using_VSCode
- Notepad ++
 - <https://notepad-plus-plus.org>

Access through VDI

- <https://www.mn.uio.no/ifi/tjenester/it/hjelp/>
 - => Linux->Virtuell arbeidsstasjon (VDI) Virtual Desktop Interface(?)
 - If you don't have the Vmware client already, check
 - <https://www.uio.no/tjenester/it/maskin/vdi/hjelp/vdi-installer-og-bruk.html>
 - Start Vmware horizon client
 - Enter view.uio.no
 - Use ifi-Digital-Electronics
 - *Run vivado, make og gtkwave from Xterm / command line*
 - Ifi digital electronics can be used for everything... *until programming*

Remote access using Xwin?

- login.ifi.uio.no
 - Ssh -Y
 - X-win

IN3160, IN4160

**Introduction to VHDL
+Basic layout for VHDL**

Yngve Hafting



Messages:

- Timeplan -> Im working on it...
- Questions before we start?
- Today:
 - VHDL structure
 - Layout (only in slides) <- Hvis tid – også egnet for selvstudium.
- Friday: Basic verification and test-benches

Course Goals and Learning Outcome

<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

In this course you will learn about the **design of advanced digital systems**. This includes programmable logic circuits, a **hardware design language** and system-on-chip design (processor, memory and logic on a chip). **Lab assignments provide practical experience in how real design can be made.**

After completion of the course you will:

- understand important **principles for design** and testing of digital systems
- understand the **relationship between behavior and different construction criteria**
- be able to **describe advanced digital systems** at different levels of detail
- be able to perform simulation and synthesis of digital systems.

Goals for this lesson:

- Know the basic structure of VHDL
 - Know which design entities there are
 - Know how assignment and statements works
 - Know the basic functionality of processes
 - Be able to create designs using VHDL
 - Know the relation between physical signals and their declaration.
 - Know the difference between basic coding styles
- Know basic layout principles
 - Guidelines for capital letters
 - Basic layout types
 - Principles for indentation, commenting, naming, punctuations

Overview

- Repetition
- VHDL Structure (*Partly repetition from IN2060*)
 - Design entities
 - Statements
 - Signals, variables, vectors
 - Processes
 - Libraries
 - STD_LOGIC
 - Operators
 - String literals
- Code layout principles
- Next lesson: Combinational logic
 - Assignments and suggested reading for this week

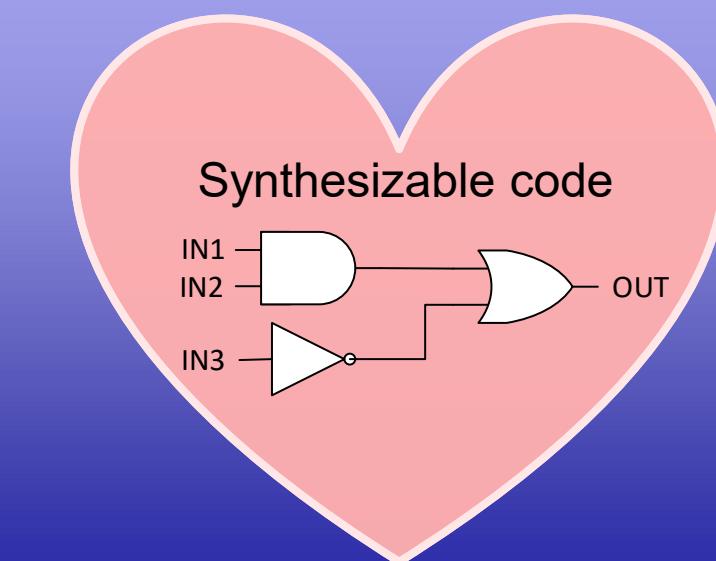
HDL

- VHDL = VHSIC HDL:
 - Very High Speed Integrated Circuit Hardware Description Language
 - **The purpose is to generate digital circuits, and verify their function through simulation.**
 - **Synthesizable (realizable) code generates circuits that are always on = work concurrently (in parallel).**
 - Code for simulation include things such as file I/O which cannot be synthesized.
 - Testbenches can and will use some synthesizable elements, but will in general look more like other sequential languages, and use sequential statements.
This may be confusing at times...

HDL

Code for generating and parsing simulation data
(Test benches)

code for generating multiple instances or variants of entities



VHDL structure

- Design entities
- Architecture styles
- Ports and signals
- Vectors
- Assignment
- Libraries
- STD_LOGIC data type
- Operators

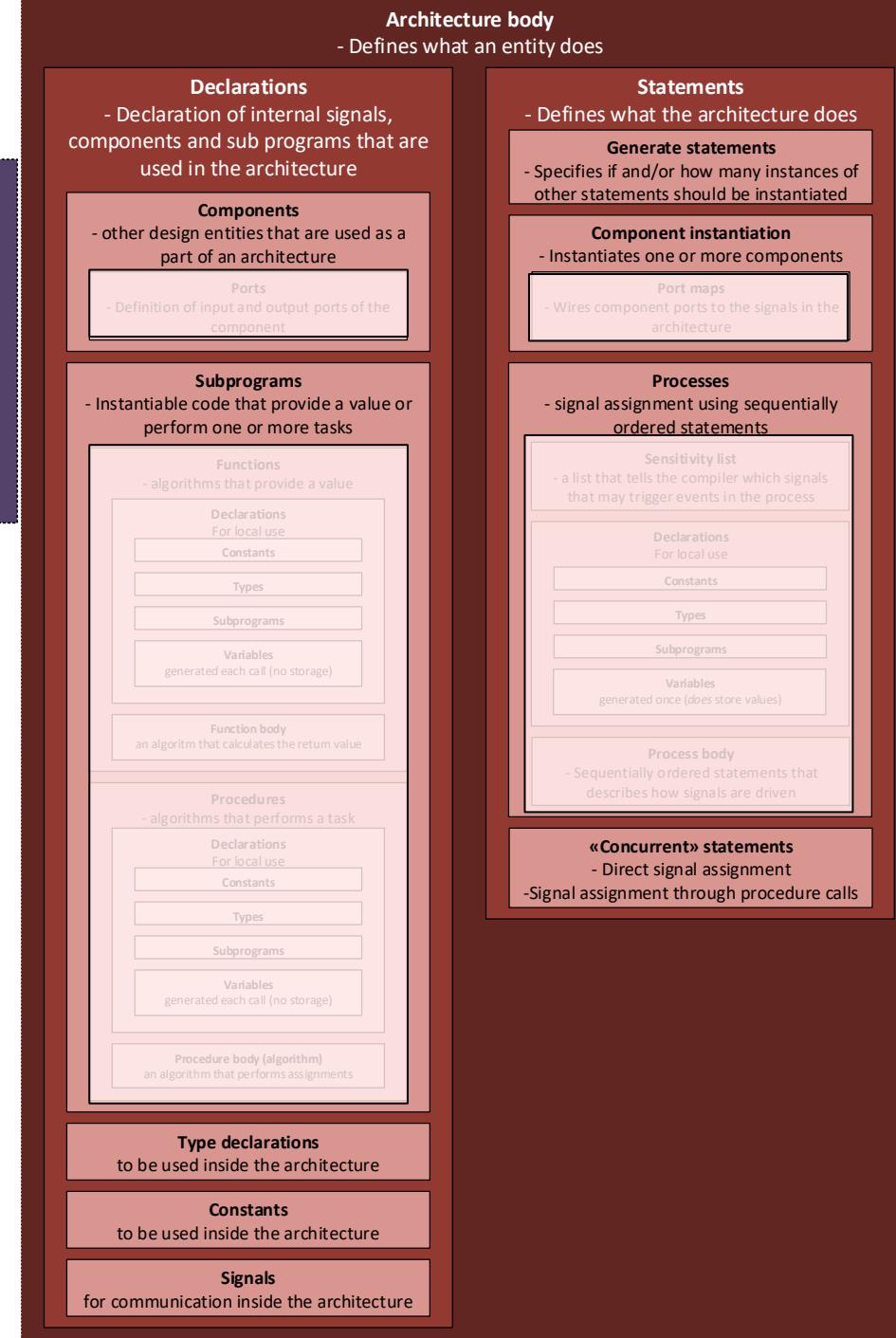
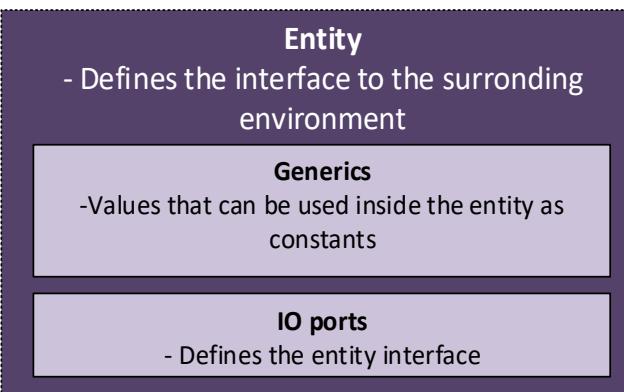
Design entities in VHDL

- 5 types of design entities
 - Entity
 - Architecture *body*
 - Package
 - Package body
 - Configuration
- Each entity can have its own file...

Design-entities:

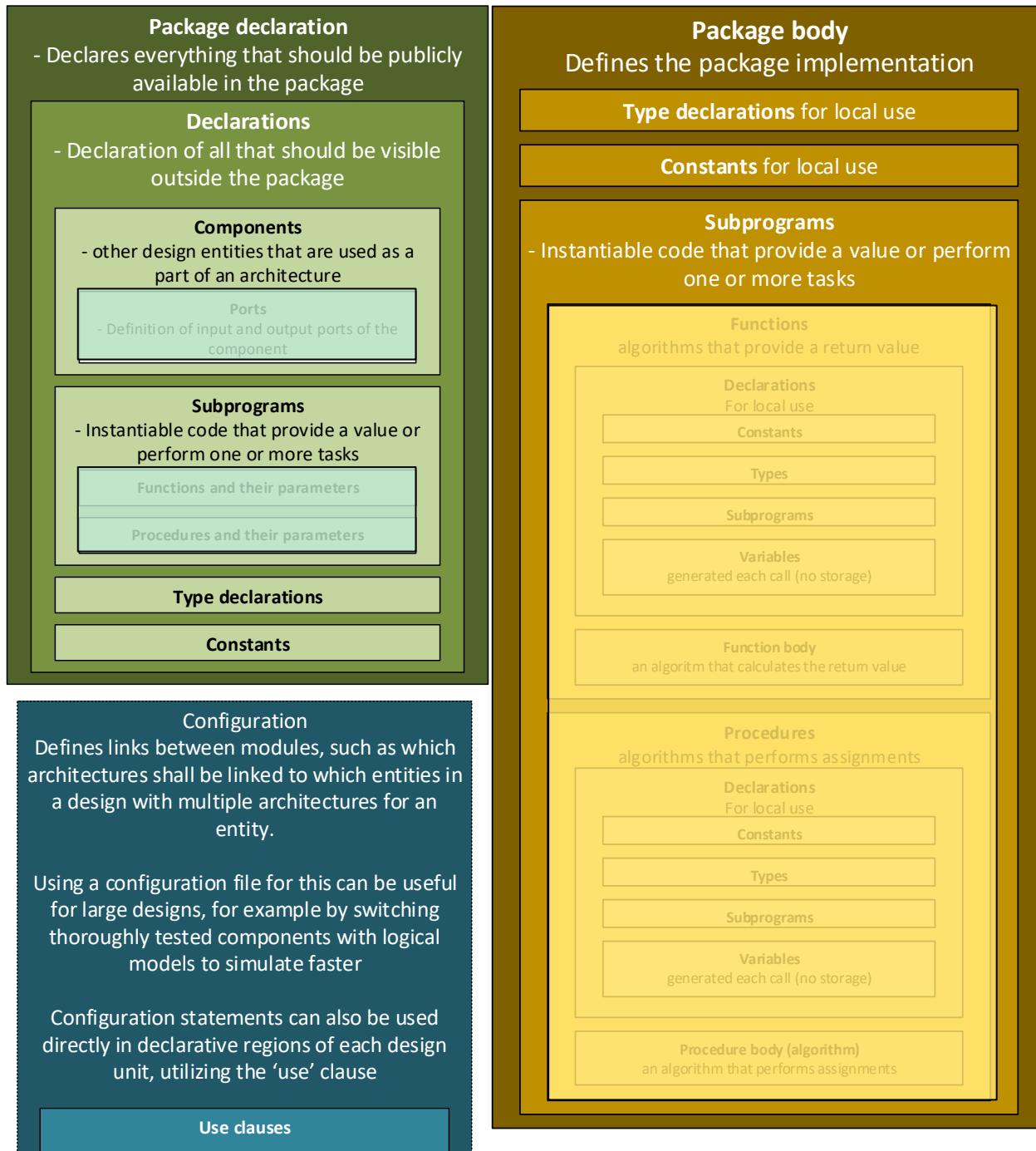
Entity and architecture

- E. and A. is often put into the same file
- In larger designs these may be separated, several architectures can be used for one entity.
 - Simulation vs modules for synthesis
- *Details will be revealed later..*



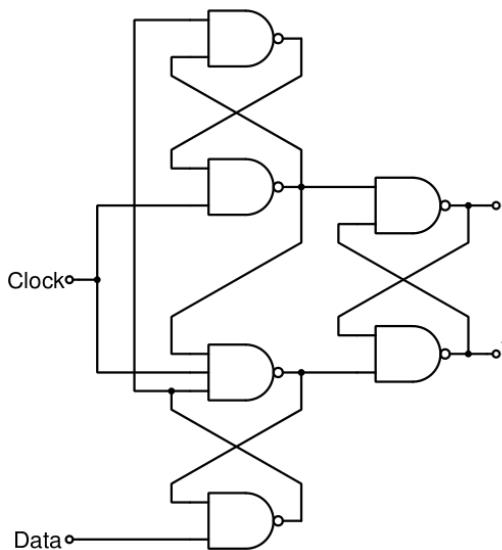
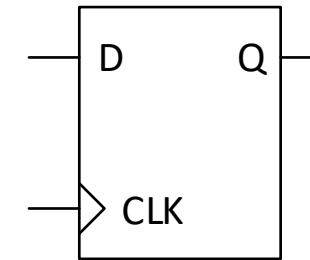
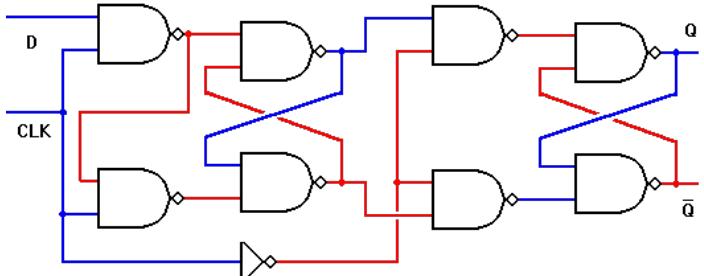
Design entities: Package, P.body, Configuration

- VHDL uses and can be used to create packages
- We will almost always use packages in precompiled libraries.
- *Configuration files* can be used to specify which components or architectures that shall be used in (large) designs
 - (Not a primary concern for in3160)



VHDL Entity and Architecture

- Entity defines Input and Output ports in the design
 - There is only one entity in a vhdl file..
- Architecture defines what the design does.
 - There can be several architectures for an entity
 - Architectures, may be defined using different styles (next slide)
 - “RTL” and “Dataflow” are names providing information;
 - changing these names would not change function.



4 main abstraction levels

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;
```

```
entity D_flipflop is
  port(
    clk: in std_logic;
    D: in std_logic;
    Q: out std_logic
  );
end entity D_flipflop;
```

```
architecture RTL of D_flipflop is
begin
  process (clk) is
  begin
    if rising_edge(clk) then
      Q <= 'D';
    end if;
  end process;
end architecture RTL;
```

```
architecture data_flow of D_flipflop is
  signal e, f, g, h, i, j, k, l: std_logic;
begin
  -- concurrent statements
  e <= not (D and clk);
  f <= not (e and clk);
  g <= not (e and h);
  h <= not (f and g);
  i <= not (g and not clk);
  j <= not (h and not clk);
  k <= not (l and i);
  l <= not (k and j);
  Q <= k;
end architecture data_flow;
```

RTL, register transfer level

- high level
- easy to read
- describes registers and what happens between them
- «default» for sequential logic

Data Flow

- typically used for optimization
- will easily become unreadable if used extensively.
- *Use higher level code unless absolutely necessary*

Behavioral

- *Simulation models only = Software*
- Not for synthesis or implementation

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;
entity my_thing is
  port (
    A: in std_logic;
    B: in std_logic_vector(5 downto 0);
    C, D, E, F: in std_logic;
    G: out std_logic;
    H: out std_logic_vector(64 downto 0);
    I: out std_logic
  );
end entity my_thing;
```

```
architecture structural of my_thing is
  signal js: std_logic;
  signal ks: std_logic_vector(64 downto 0);
  signal ls: std_logic;
  component apple is
    port (
      A: in std_logic;
      B: in std_logic_vector(5 downto 0);
      C: out std_logic;
      D: out std_logic_vector(64 downto 0)
    );
  end component;
```

```
component pear is
  port (
    A, B, C: in std_logic;
    D, E: out std_logic
  );
end component;
```

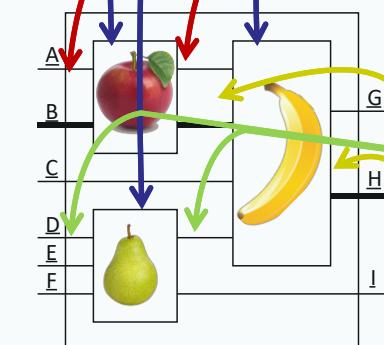
```
component banana is
  port (
    smurf: in std_logic_vector(64 downto 0);
    cat, dog, donkey: in std_logic;
    horse: out std_logic;
    monkey: out std_logic_vector(64 downto 0)
  );
end component;
```

```
begin
  -- port map (component => My_thing)
  U1: apple port map(
    A => A,
    B => B,
    C => js,
    D => ks
  );
```

```
U2: pear port map(
  A => D,
  B => E,
  C => F,
  D => ls,
  E => I
);
```

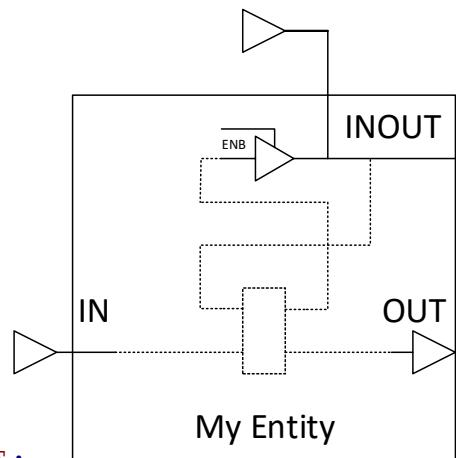
```
U3: banana port map(
  smurf => ks,
  cat => js,
  dog => C,
  donkey => ls,
  horse => G,
  monkey => H
);
```

```
end architecture structural;
```



Ports and signals

- Ports define the entity interface
 - IN:
 - *can only be read*
 - cannot be driven or assigned internally
 - OUT:
 - *should be driven from the architecture*
 - *It is bad practice not to do so.*
 - *prior to VHDL2008 output ports could not be read*
 - INOUT
 - *Can be both driven and read*
(typical use is for buses)
- Signals are internal
 - For connecting internal modules, subprograms and processes.



Ports continued

INOUT is for tying input and output to the same pin

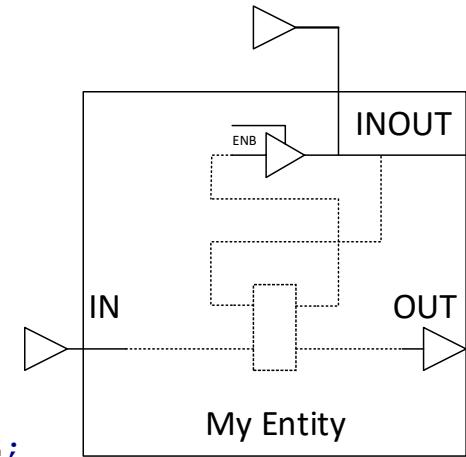
- **should implement tristate functionality.**
- ‘Z’ means it is not driven (tristate)
- Typically to be used when connecting a bus with multiple drivers.

DO NOT use INOUT for convenience!

- The compiler will not alert you if you are driving from two sources simultaneously.
 - *May cause undetected electrical faults*
- INOUT may infer inferior structures (long delays)

Even if it is used safely, it will require special resources, usually only found near the package boundaries.

(Can create timing or availability issues, and other..)



```

library IEEE;
use IEEE.std_logic_1164.all;

entity my_entity is
port(
    Ain      : in     std_logic;
    Binout  : inout  std_logic;
    Cout    : out    std_logic
);
end entity my_entity;

architecture dataflow of my_entity is
signal enb, s1, s2, s3, s4 : std_logic;

begin
    -- ...
    s1 <= Ain;
    Cout <= s2;
    -- reading INOUT is OK
    s3 <= Binout;
    -- setting INOUT should implement tri-state
    Binout <= s4 when enb else 'Z';

end architecture dataflow;

```

Statements and assignments

- Statements and processes
 - defines how a digital circuit works
 - assign drivers to signals
- All statements must be valid at all times
 - A circuit may have sequential behavior...
 - But all logic is present and functional at all times
- Processes are complex statements
 - Assigns values to one or more signals
 - Can have local variables.. (more on those later)
- A signal can only be assigned once in an architecture
 - We do not want two circuits to apply voltage on the same wire...

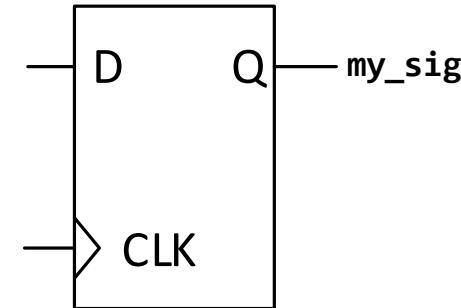
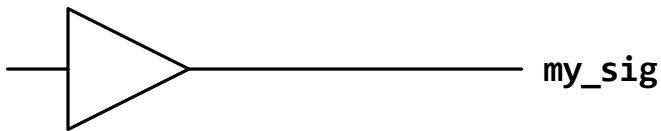
Examples:

```
with input select isprime <=
  '1' when x"1" | x"2" | x"3" | x"5" | x"7" | d"11" | x"d",
  '0' when others;
```

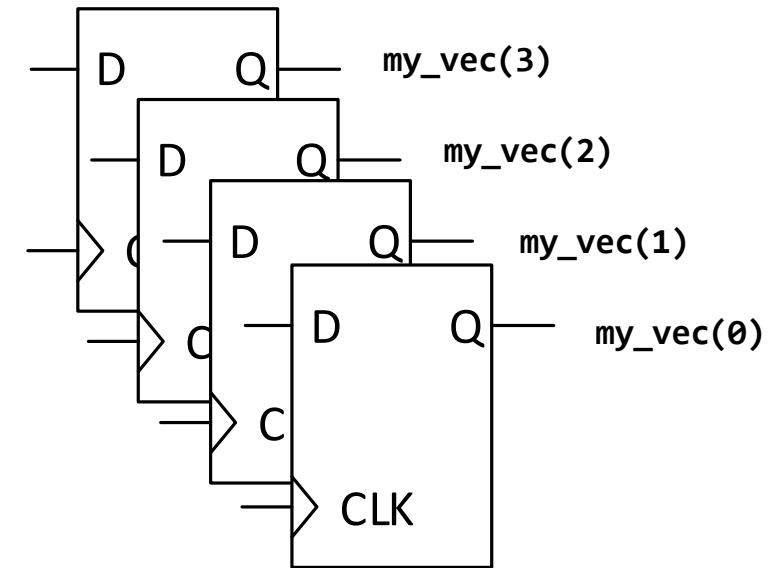
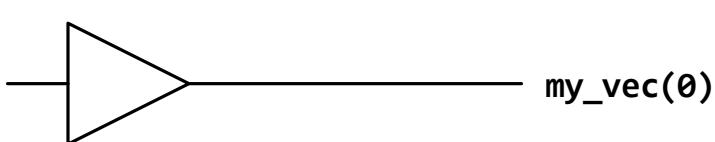
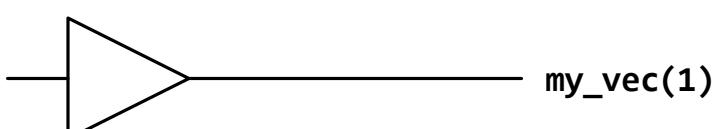
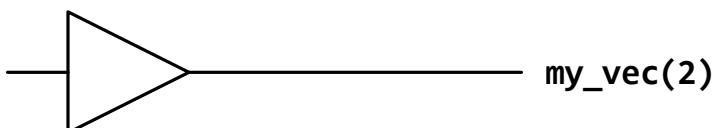
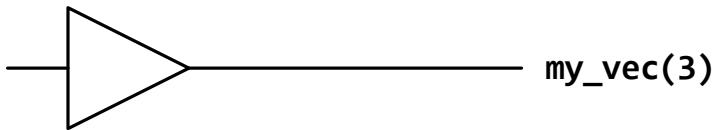
```
process(Reset, Clock) is
  variable Q : Unsigned(7 downto 0);
begin
  if Reset = '0' then
    Count <= zero_byte;
  elsif rising_edge(Clock) then
    Q := 
      unsigned(Count) when Enable else
      unsigned(Data) when not Load else
      unsigned(Count) + 1 when not Mode else
      dec_count(unsigned(Count));
    Count <= std_logic_vector(Q);
  end if;
end process;
```

«Vectors»

- `signal my_sig std_logic;`



- `signal my_vec std_logic_vector(3 downto 0);`



Signals and variables

- **signals** are for *inter-architecture* communication
 - Between processes, modules and subprograms
- **variables** are subprogram(or process)-internal
 - To make code clearer, and more local.
- Example note:
 - placement of s&v declarations
 - Signal assignment order is irrelevant outside processes

```
architecture example of sigvar is
  -- (signal) declarations
  signal S, T : std_logic;

begin
  -- statements
  S <= A and B;

process (A, B) is
  -- (variable) declarations
  variable V : std_logic;
begin
  -- process body
  V := '0';
  --
end process;

X <= S XOR T;
end architecture;
```

Signal and variable assignment

- Signals are assigned concurrently in statements
 - both in and outside processes
 - Signals are assigned using `<=`
 - Signals uses event based updates
 - ie after a process is complete.
- Variables can only be used inside processes and subprograms
 - Variables are assigned using `:=`
 - Variables are updated immediately in simulation
 - *Processes can have variables store values*
 - *Initialized at the beginning of simulation*
 - *Subprograms (procedure, function) can not have variables store values*
 - *initialized on every call*

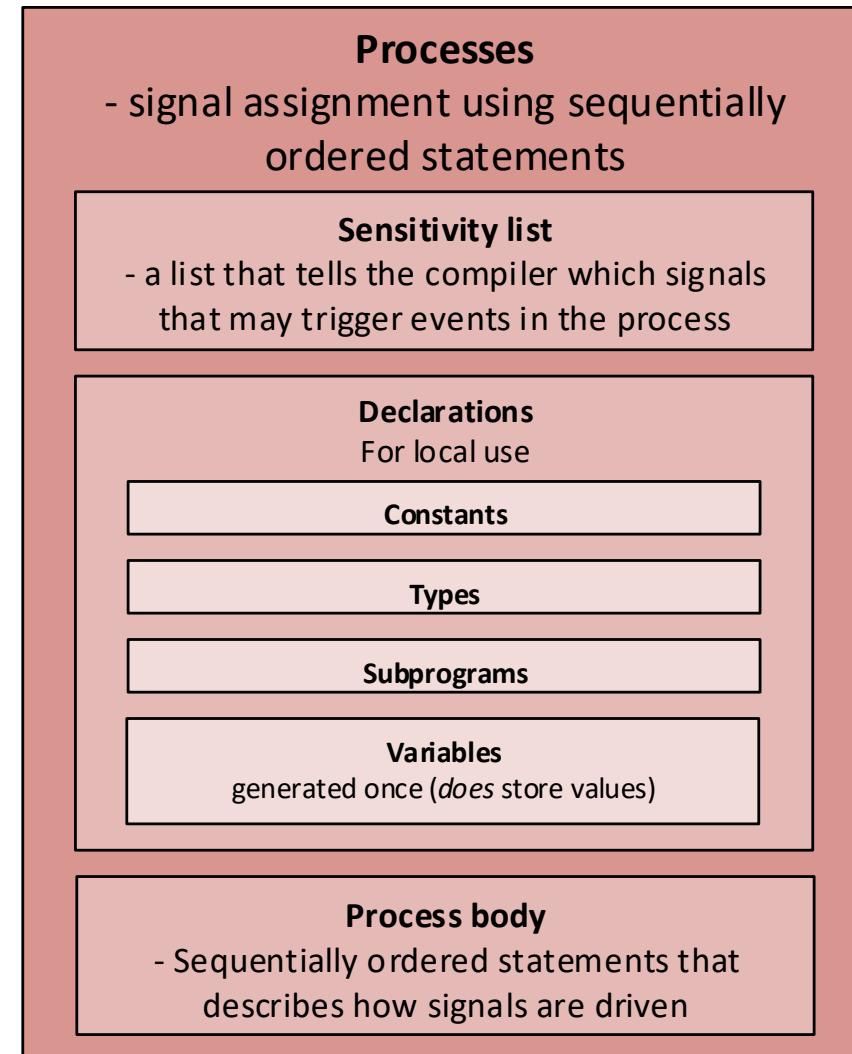
```
A <= B; -- A reads B, or A is assigned to B's ouput,  
-- (A is a signal)
```

```
D(6 downto 0) <= E(3 downto 1) & (others => '0');  
-- D is a vector having 7 input signals  
-- D(6) <= E(3)  
-- D(5) <= E(2)  
-- D(4) <= E(1)  
-- D(3 downto 0) <= "0000"
```

```
C := B; -- C is given B's value, C is a variable  
-- variables are used internally in processes.
```

Processes

- A process is one (concurrent) statement
 - Ensures one driver for each signal by using priority.
 - "Signals are only updated only once"...
 - The process body has sequential *priority*
 - Last assignment takes precedence over previous.
 - Variables *can* be assigned multiple times within a process body(!)
 - They *can* act as several signals
 - » Generally this should be avoided
 - sensitivity list
 - determines when the process body is invoked *during simulation*
 - *Event triggered*
 - *Can* be used to make sequential logic
 - Clocked events infers flipflops (or latches)



Process example (avoid this style)

```
library IEEE;
use IEEE.std_logic_1164.all;

entity sigvar is
  port(
    A, B : in std_logic;
    X    : out std_logic
  );
end entity sigvar;
```

- The use of V would not be allowed a signal outside a process.
- A variable can be used in place of multiple physical signals within a process. (= bad practice...)
- Signals will be assigned one driver in a process.

```
architecture bad of sigvar is
  -- declarations
  signal S, T : std_logic;

begin
  -- statements
  S <= A and B;

  process (A,B) is
    -- decalarations
    variable V : std_logic;

  begin
    -- process body
    V := '0';
    if (A = '1') then
      V := '1';
    end if;
    if (B = '1') then
      V:= '1';
    end if;
    T <= V;
  end process;

  X <= S XOR T;
end architecture;
```

Process example

(template code = can be used)

```

library IEEE;
use IEEE.std_logic_1164.all;
use IEEE.numeric_std.all;

entity adder is
port(
    clk, reset : in std_logic_vector;
    a, b : in std_logic_vector(7 downto 0);
    sum : out std_logic_vector(8 downto 0)
);
end entity adder;

```

- Process for
 - Registry update
 - Complex combinational assignments
- Variables
 - Only used for clarifying

```

architecture RTL of adder is
    signal r_sum, next_sum : unsigned(sum'range);
begin
    -- concurrent statements
    SUM <= std_logic_vector(r_sum);

    REG_UPDATE: process(clk)
    begin
        if rising_edge(clk) then
            if reset then
                r_sum <= (others => '0');
            else
                r_sum <= next_sum;
            end if;
        end if;
    end process;

    COMB_PROCESS: process(all)
        variable va, vb : unsigned(sum'range);
    begin
        -- variables used for clarification
        va <= unsigned("0" & a);
        vb <= unsigned("0" & b);
        next_sum <= va + vb;
    end process;
end architecture;

```

Libraries and Data types

- VHDL is built upon use of libraries and packages.
- You can both use existing ones, and create your own.
- The **library IEEE**, contains the most used data types and functions
 - *The built-in standard (std) package*, containing:
 - `bit`, `integer`, `natural`, `positive`, `boolean`, `string`, `character`, `real`, `time`, `delay_length`
 - `std_logic_1164`
 - defines the `std_logic` type
 - `numeric_std`
 - numeric operations for «`std_logic_vectors`»: `unsigned`, `signed`
 - `std_logic_textio`
 - to provide IO during simulation (ie VHDL testbenches)
 - *Can be used with synthesizable VHDL (=unlikely)*
 - `numeric_bit`
 - numeric operations for bit vectors
 - etc.

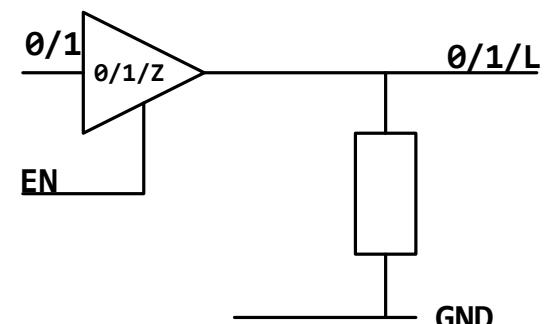
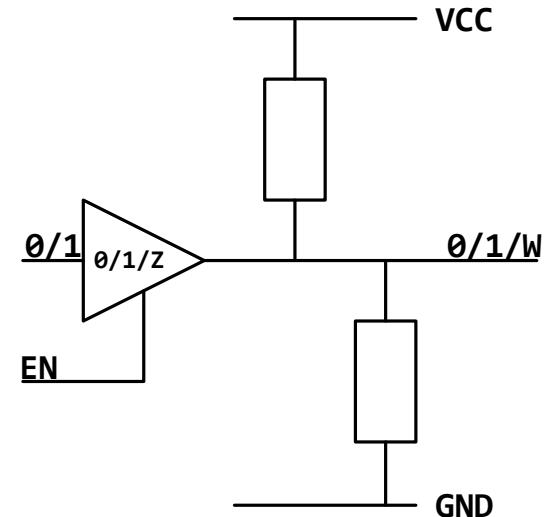
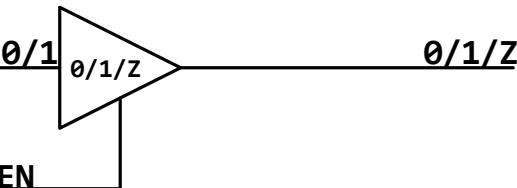
STD_LOGIC TYPE

(requires std_logic_1164 package from IEEE library)

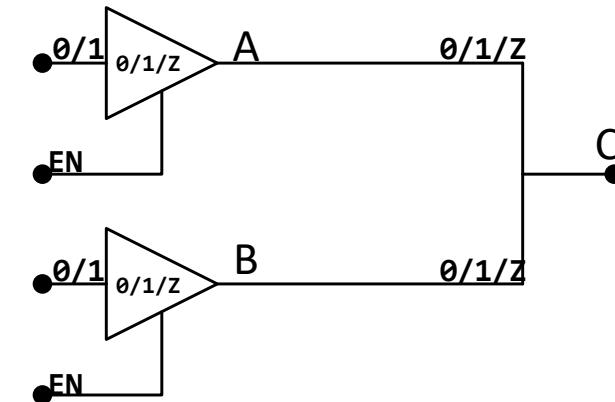
- STD_LOGIC is a **type** that has the following possible values
 - ‘U’ Uninitialized (Typically seen in simulation before initializing values)
 - ‘X’ Unknown (typically when a signal is driven to both 0 and 1 simultaneously)
 - ‘0’ **Driven low**
 - ‘1’ **Driven High**
 - ‘Z’ **Tristate**
 - ‘W’ Weak unknown (when driven by two different weak drivers)
 - ‘L’ Weak ‘0’ (Typically for simulating a pulldown resistor)
 - ‘H’ Weak ‘1’ (Typically for simulating a pullup resistor)
 - ‘_’ Don’t care (Typically for assessing results in simulator).
- You will only assign synthesizable signals to ‘0’, ‘1’ and ‘Z’
- Type STD_LOGIC_VECTOR is array (NATURAL range <>) of STD_LOGIC
 - STD logic vector is used for hardware. For simulation, other types (such as integer) may be faster. Thus we use STD_LOGIC for hardware interactions, and other types when possible for test bench code.

std_logic -- values

Value	Name	Usage
'U'	Uninitialized state	Used as a default value
'X'	Forcing unknown	Bus contentions, error conditions, etc.
'0'	Forcing zero	Transistor driven to GND
'1'	Forcing one	Transistor driven to VCC
'Z'	High impedance	3-state buffer outputs
'W'	Weak unknown	Bus terminators
'L'	Weak zero	Pull down resistors
'H'	Weak one	Pull up resistors
'_'	Don't care	Used for synthesis and advanced modeling



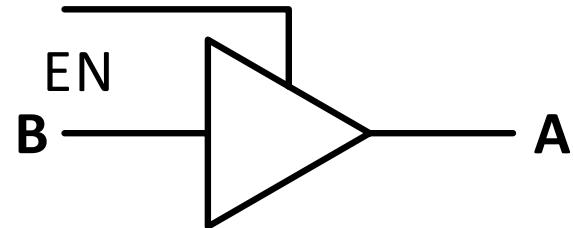
-- multiple drivers
signal c : std_logic;



Signal A/B	'U'	'X'	'0'	'1'	'Z'	'W'	'L'	'H'	'_'
'U'	'U'	'U'	'U'	'U'	'U'	'U'	'U'	'U'	'U'
'X'	'U'	'X'							
'0'	'U'	'X'	'0'	'X'	'0'	'0'	'0'	'0'	'X'
'1'	'U'	'X'	'X'	'1'	'1'	'1'	'1'	'1'	'X'
'Z'	'U'	'X'	'0'	'1'	'Z'	'W'	'L'	'H'	'X'
'W'	'U'	'X'	'0'	'1'	'W'	'W'	'W'	'W'	'X'
'L'	'U'	'X'	'0'	'1'	'L'	'W'	'L'	'W'	'X'
'H'	'U'	'X'	'0'	'1'	'H'	'W'	'W'	'H'	'X'
'_'	'U'	'X'							

Tri-state buffer

- Digital logic *reads only either '0' or '1'*
- We can set tristate (high impedance) to allow other sources to drive a bus.
- Simulation tools can use all possible **STD_LOGIC** values.



```
A <= B when EN = '1' else 'Z';  
-- ekvivalent med  
TRISTATE:  
process (B,EN)  
begin  
    if EN = '1' then  
        A <= B;  
    else  
        A <= 'Z';  
    end if;  
end process;
```

VHDL operator priority

- Functions are interpreted from left to right (in reading order).
- **Use parenthesis to govern priority!**

Prioritet	Operator klasse	Operatorer
1 (first)	miscellaneous	<code>**, abs, not</code>
2	multiplying	<code>*, /, mod, rem</code>
3	sign	<code>+, -</code>
4	adding	<code>+, -, &</code>
5	Shift	<code>sll, srl, sla, sra, rol, ror</code>
6	relational	<code>=, /=, <, <=, >, >=, ?=, ?/=, ?<, ?<=, ?>, ?>=</code>
7	logical	<code>And, or, nand, nor, xor, xnor</code>
8 (last)	condition	<code>??</code>

Examples (elaboration on next page):

`a <= a or b and c;` == `a <= (a or b) and c;`

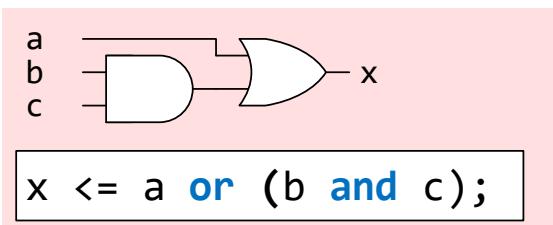
`z <= a and not b and c;` == `z <= a and (not b) and c;` == `z <= c and (a and (not b));`

`y <= a and not (b and c);` -- *z=1 kun for a=1, b=0, c=1.* *y=1 for a=1 og (b eller c)=0.*

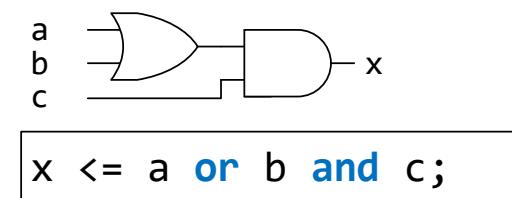
VHDL operator priority

Examples:

`x <= a or b and c;` == `x <= (a or b) and c;`

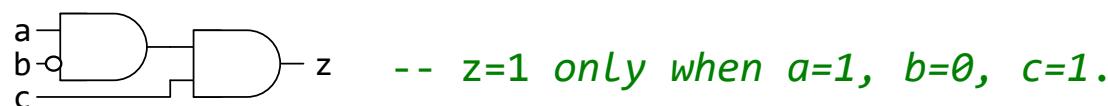


(What you might want)



(what you actually will get)

Try
a := '1'
b := '1'
c := '0'



`z <= a and not b and c;` == `z <= a and (not b) and c;` == `z <= c and (a and (not b));`
`y <= a and not (b and c);`



Bit operators and reduction operator

- **and, or, not, xor, xnor** operators will work at bit level when they are placed between two signals or vectors.

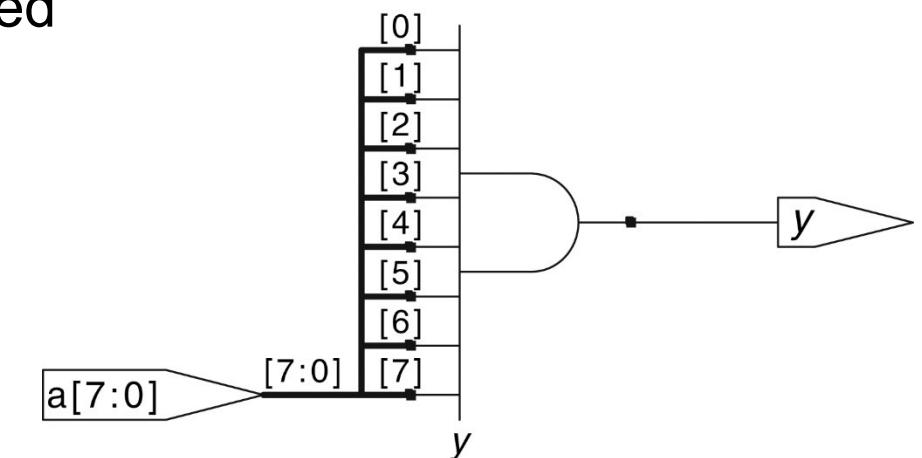
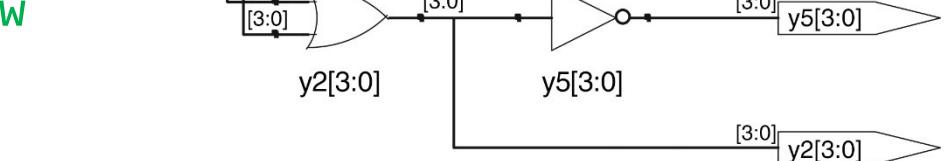
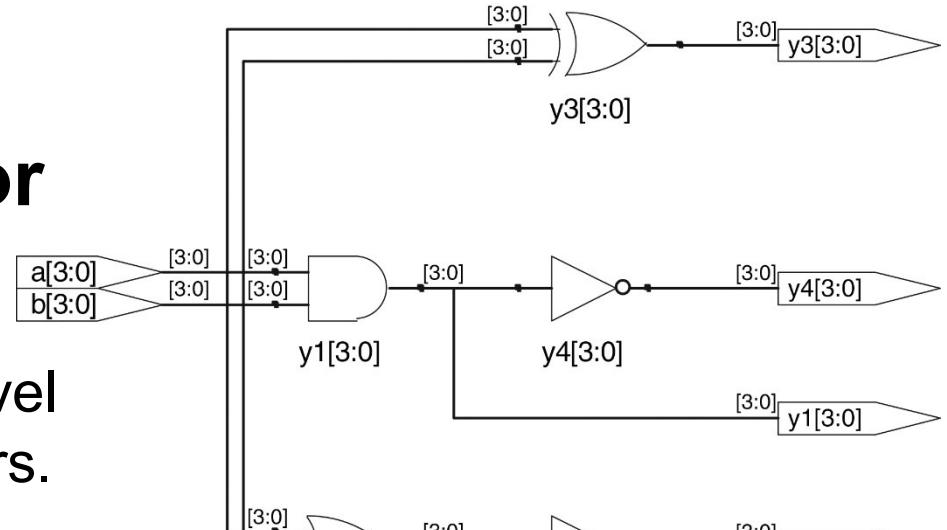
- $y1 \leq a \text{ and } b$; -- is equal to the lines below

$$\begin{aligned}y1(3) &\leq a(3) \text{ and } b(3); \\y1(2) &\leq a(2) \text{ and } b(2); \\y1(1) &\leq a(1) \text{ and } b(1); \\y1(0) &\leq a(0) \text{ and } b(0);\end{aligned}$$

- In VHDL2008 (not earlier) these operators can be used for reduction

$y \leq \text{and } a$; -- is equal to the figure ->

- **xor** can be used this way to generate (even) parity for a signal.



VHDL Bit String Literals

Binary, Decimal, heXadecimAl, Octal, Unsigned, Signed

<ant bit><U/S><B/D/O/X><numbers of type B/D/O/X >

B"1111_1111_1111"	-- Equivalent to the string literal "111111111111".	12UB"X1"	-- Equivalent to B"0000_0000_00X1"
X"FFF"	-- Equivalent to B"1111_1111_1111".	12SB"X1"	-- Equivalent to B"XXXX_XXXX_XXX1"
O"777"	-- Equivalent to B"111_111_111".	12UX"F-"	-- Equivalent to B"0000_1111_----"
X"777"	-- Equivalent to B"0111_0111_0111".	12SX"F-"	-- Equivalent to B"1111_1111_----"
B"XXXX_01LH"	-- Equivalent to the string literal "XXXX01LH"	12D"13"	-- Equivalent to B"0000_0000_1101"
UO"27"	-- Equivalent to B"010_111"	12UX"000Www"	-- Equivalent to B"www_www_www"
UO"2X"	-- Equivalent to B"011_XXX"	12SX"FFFC00"	-- Equivalent to B"1100_0000_0000"
SX"3W"	-- Equivalent to B"0011_WWW"	12SX"XXXX00"	-- Equivalent to B"XXXX_0000_0000"
D"35"	-- Equivalent to B"100011"	8D"511"	- Error ($> 2^8$)
		8UO"477"	- Error ($> 2^8$)
		8SX"0FF"	- Error (cannot have 255 using 8 bit signed)
		8SX"FX"	- Error (cannot extend beyond 8 bit)

IN3160
Code Layout (15 min)



Kilde: Ricardo Jasinski: Effective Coding with VHDL, Chapter 18

Overview

- Why bother thinking about layout?
- What constitutes a good layout scheme?
- Basic layout types
- Indentation
- Paragraphs and spaces

Why bother thinking of layout?

```
pRoCeSS(clock,reset) bEGIN iF resET then oUTpuT <="0000"; e1SE IF RISING_edge  
(Cl0ck) tHEN cASE s Is When 1=>outPUT<= "0001"; wHEN 2046=> oUTpuT <="0010";wheN  
31=>OutPut<="0100";when OTHERs=>OUTput <= «1111"; end CASe; END if;END proCESS; --  
Q.E.D.
```

A good layout scheme...

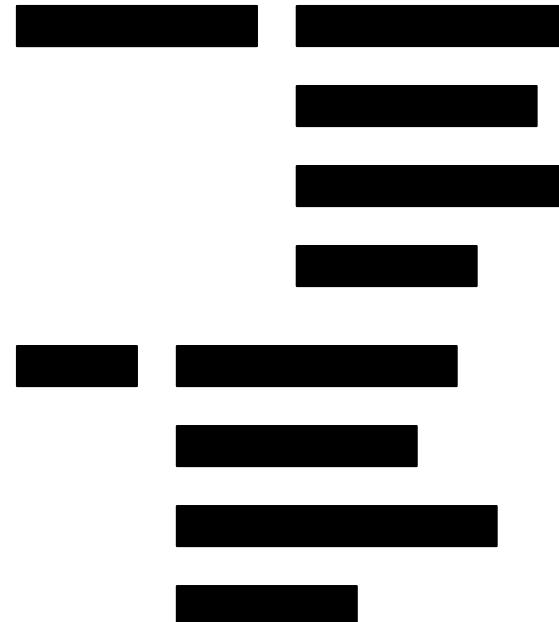
1. ...accurately matches the structure of the code
2. ...improves readability
3. ...affords changes
4. ...is consistent (few exceptions)
5. ...is simple (few rules)
6. ...is easy to use
7. ...is economic

Basic layout types

Block layout



Endline layout



Column layout



Block layout (What you should use *most of the time*)

- Accurately matches structure
- relatively tidy
- readable,
- easy to maintain, etc.

```
process (clock, reset)
begin
    if reset then
        output <= "0000";
    else if rising_edge(clock) then
        case s is
            when 1 => output <= "0001";
            when 2046 => output <= "0010";
            when 31 => output <= "0100;
            when others => output <= "1111";
        end case;
    end if;
end process;
```

Endline layout (*avoid this*)

- Harder to maintain when code changes.
- Looks tidier, but isn't faster than pure block
- Will get messy- poor match of code hierarchy
- Long lines..!

```
process (clock, reset)
begin
    if reset then output <= "0000";
    else if rising_edge(clock) then case s is
        when 1 => output <= "0001";
        when 2046 => output <= "0010";
        when 31 => output <= "0100";
        when others => output <= "1111";
    end case;
end if;
end process;
```

Column layout (use sparingly)

- Can be easier to read than pure block layout (scanning vertically)
- Harder to maintain.
- Best to use when columns are unlikely to change, and statements are related.
 - Typically used for 2D arrays.

```
process (clock, reset)
begin
    if reset then
        output <= "0000";
    else if rising_edge(clock) then
        case s is
            when      1 => output <= "0001";
            when      2 => output <= "0010";
            when    333 => output <= "0100";
            when others => output <= "1111";
        end case;
    end if;
end process;
```

Indentation

- *Use indentation to match code hierarchy*
- 2-4 spaces has been proven most efficient
 - *Along with a monospace font, such as courier, consolas..*
- Use space rather than tabulator sign.
 - Tabulator spaces may be interpreted differently in different editors.
 - Most editors can be set up for this.
- Example:

```
entity ent_name is
  generic (
    generic_declaration_1;
    generic_declaration_2;
  );
  port(
    port_declaration_1;
    port_declaration_2;
  );
end entity ent_name;
.
.
.
process (sensitivity_list)
  declaration_1;
  declaration_2;
begin
  statement_1;
  statement_2;
end process;
```

Paragraphs and comments

- Paragraphs should be used to separate chunks that does not need to be read all at once.
- Paired with comments that this make for good readability
- Comments should be indented as according to the code it is referring to.

```
-- Find character in text RAM corresponding to x, y
text_ram_x := pixel_x / FONT_WIDTH;
text_ram_y := pixel_y / FONT_HEIGHT;
display_char := text_ram(text_ram_x, text_ram_y);

-- Get character bitmap from ROM
ascii_code := character'pos(display_char);
char_bitmap := FONT_ROM(ascii_code);

-- Get pixel value from character bitmap
x_offset := pixel_x mod FONT_WIDTH;
y_offset := pixel_y mod FONT_HEIGHT;
pixel := char_bitmap(x_offset)(y_offset);
```

Line length and wrapping

- Try to keep line length within reasonable limits
 - 80, 100 and 120 characters is widely used.
- When wrapping lines:
 - break at a point that clearly shows it is incomplete, such as
 - after opening parenthesis
 - after operators or commas (`&`, `+`, `-`, `*`, `/`)
 - after keywords such as `«and»` or `«or»`
 - consider one item per line...

```
-- one item/line + named association
Paddle <= update_sprite(
    sprite => paddle,
    sprite_x => paddle_position.x + paddle_increment.x,
    sprite_y => paddle_position.x + paddle_increment.y,
    raster_x => vga_raster_x,
    raster_y => vga_raster_y,
    sprite_enabled => true
);
```

```
-- several items/line
paddle <= update_sprite(paddle, paddle_position.x + paddle_increment.y,
    paddle_position.y + paddle_increment.y, vga_raster_x, vga_raster_y, true);
```

Spaces

- Punctuation symbols
(comma, colon, semicolon)

- use spaces as you would in regular prose:
 - Never add space before punctuation symbols
 - Always add space after punctuation symbols
 - *no exceptions*

- Parentheses
 - Add a space before opening parenthesis.
 - Add a space or punctuation symbol after closing parenthesis
 - Except:
 - array indices and routine parameters;
 - *expressions*.

```
-- too much
function add ( addend : signed ; augend : signed ) return signed ;

-- better
function add(addend: signed; augend: signed) return signed;
```

```
-- consider this expression:
a + b mod c sll d;

-- better
(a + (b mod c)) sll d;
```

```
-- consider
(-b+sqrt(b**2-4*a*c))/2*a;

-- better
(-b + sqrt(b**2 - 4*a*c)) / 2*a;

-- too much
( - b + sqrt( b ** 2 - 4 * a * c ) ) / 2 * a;
```

Naming conventions - Letter case and underscores

```
noconventionnaming -- don't go there  
UpperCamelCase -- OK used consequently  
lowerCamelCase -- OK used consequently  
snake_case or underscore_case  
SCREAMING_SNAKE_CASE or ALL_CAPS
```

- Do not use ALL_CAPS too frequently.
- Use editor **colors**/ **bold** for highlighting **keywords**
- Try to avoid mixing snakes_andCamels.
- Treat acronyms/ abbreviations as words
 - "UDPHDRFromIPPacket" **vs**
"UdpHdrFromIpPacket" **vs**
"udp_hdr_from_ip_packet"
- VHDL packages tend to favour snake_case and ALL_CAPS
- *Suggestion:*
 - Use **snake_case** for all **names** except **constants** and **generics** that use **ALL_CAPS**

Suggested reading, Mandatory assignments

- D&H:
 - 1.5 p 13-16
 - 3.6 p 51-54
 - 6.1 p 105-106
- Oblig 1: «Design Flow»
- Oblig 2: «VHDL»
 - See canvas for further instruction.

Layout is slides only

IN3160
Combinational logic design
Verification 1:
Compilation and Simulation
Basic Test benches.



Messages:

- <https://github.uio.no/in3160>
 - Intend to bring more content there
- Implement?
 - Oblig 1, 2
 - yes (follow assignment instructions)
- Demonstrate / show lab supervisor?
 - Yes:
 - Simplifies approval and feedback process
 - If not possible...
 - Video -> filesender. <https://filesender.uio.no/>
 - Can be used to show the same
 - *Feedback in canvas only*
 - *...remember to check...*

Course Goals and Learning Outcome

<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

In this course you will learn about the **design of advanced digital systems**. This includes programmable logic circuits, a **hardware design language** and system-on-chip design (processor, memory and logic on a chip). Lab assignments provide practical experience in how real design can be made.

After completion of the course you will:

- understand important **principles for design** and testing of digital systems
- understand the **relationship between behavior and different construction criteria**
- be able to **describe advanced digital systems** at different levels of detail
- be able to perform simulation and synthesis of digital systems.

Goals for CL part:

- Know how to create combinational logic (CL)
 - What is CL and non combinational logic?
 - What is hazards in CL
 - How to manage hazards in CL
-
- Verification

Overview

- What is combinational logic circuits
- CL vs Sequential logic
- What is and how to deal with hazards

Combinational vs Combinatorial

Combinational

Combinatorial



combinational logic circuit
combines inputs to generate
an output

mathematics of counting

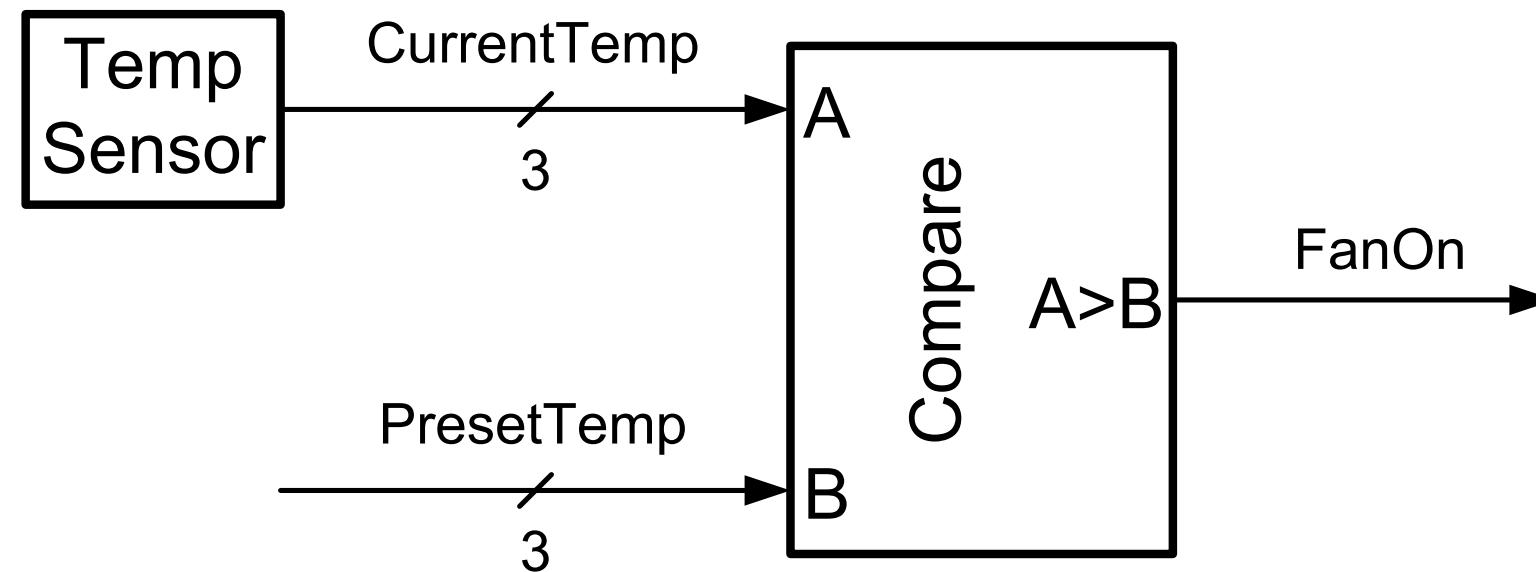
Norsk: Kombinasjonslogikk / kombinatorisk logikk)

Varierende bruk forekommer...

I all hovedsak brukes “kombinatorisk” på norsk..

Combinational Logic Circuit

- Output is a function of current input
- Example – digital thermostat

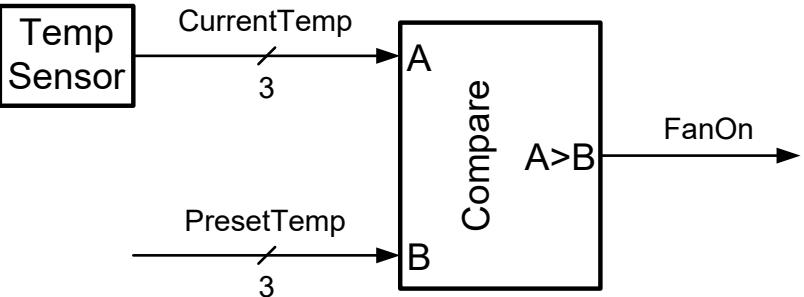


VHDL code

```
library IEEE;
use IEEE.std_logic_1164.all;

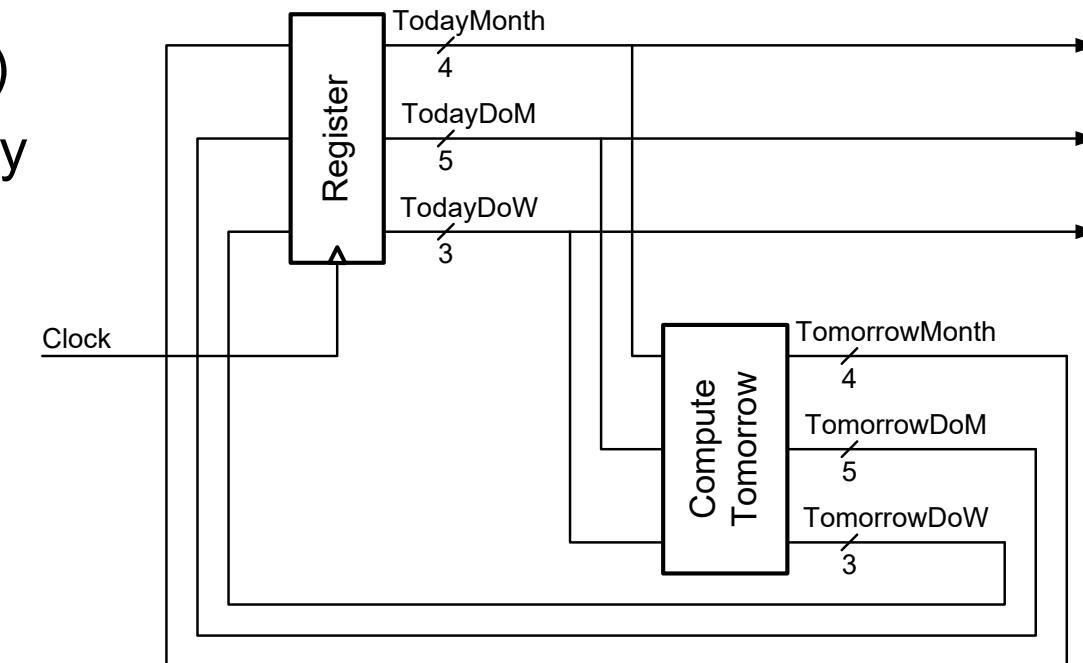
entity compare is
port(
    current_temp : in std_logic_vector(2 downto 0);
    preset_temp  : in std_logic_vector(2 downto 0);
    fan_on       : out std_logic
);
end entity compare;

architecture combinational of compare is
-- declarations (none)
begin
-- statements
fan_on <= '1' when (current_temp > preset_temp) else '0';
end architecture;
```



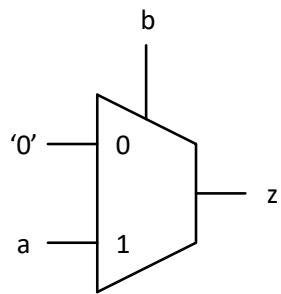
Sequential logic circuit

- Includes state (memory, storage)
- Makes output a function of history as well as current inputs
- Synchronous sequential logic uses a *clock*
- Example: calendar circuit
 - (1 clock / day...)
 - "Compute Tomorrow" is CL
 - Register stores state



Combinational vs sequential code example

```
COMBINATIONAL: process (all) is
begin
    z <= '0';
    if b then
        z <= a;
    end if;
end process;
```



-- «all» can be replaced by b here

NOTE:

Using IF, we get latches unless all options are covered.

Here: $z \leq '0'$ (default value) solves this issue.

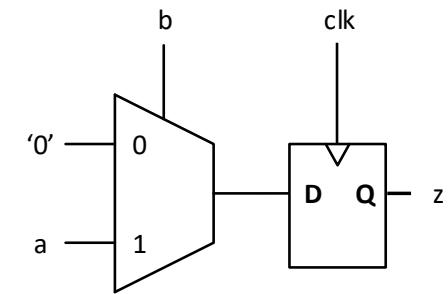
Using 'when-else' is another option

-- concurrent statement is more compact...

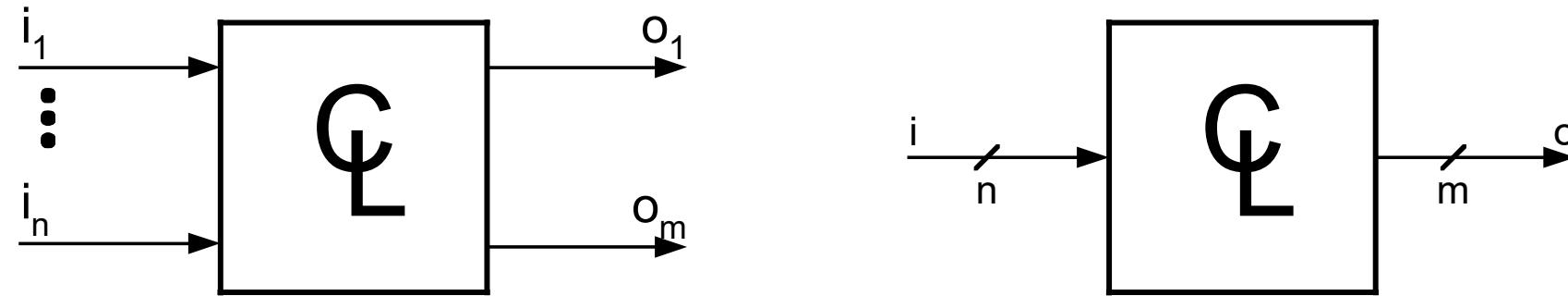
```
z<= a when b else '0';
```

```
SEQUENTIAL: process (clk) is
begin
    if rising_edge(clk) then
        z <= '0';
        if b then
            z <= a;
        end if;
    end if;
end process;
```

-- quite often we have both reset and clk



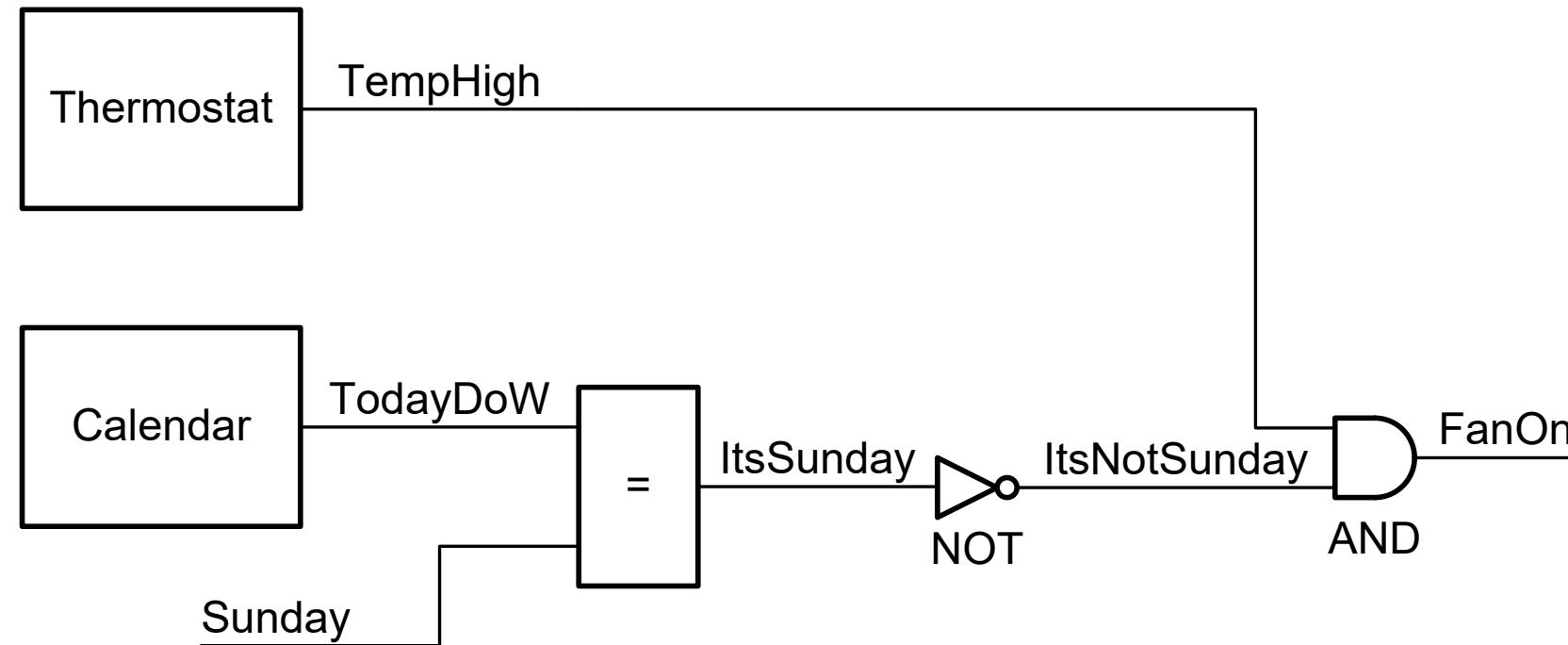
Combinational logic is memoryless



$$o = f(i)$$

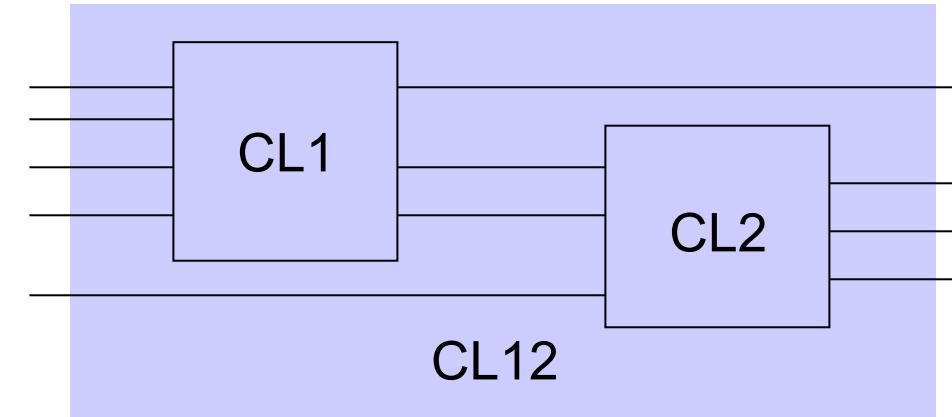
Input determines output

Can compose digital circuits

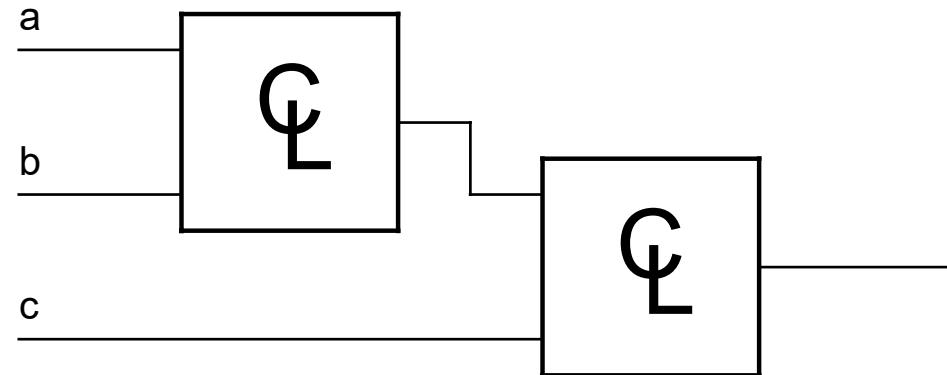


Closure

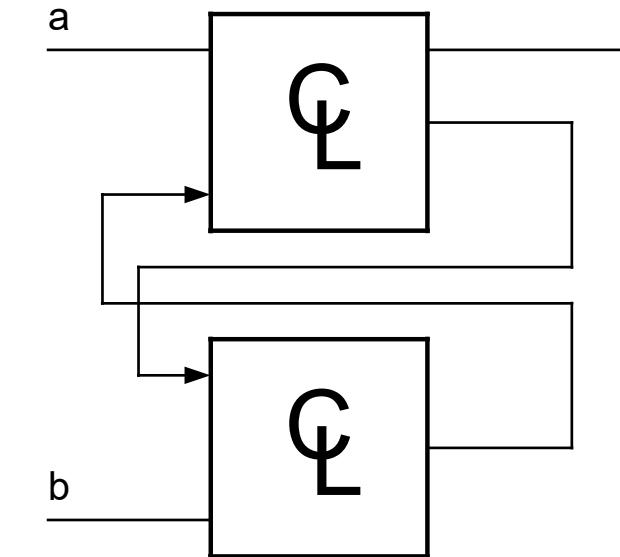
- "Combinational logic circuits are closed under acyclic composition".
 - Norsk: Vi får CL når vi kobler CL etter CL (uten tilbakekobling)



- Ie. As long as there are **no loops**:
 - A module of modules *of combinational logic* is combinational



YES



NO

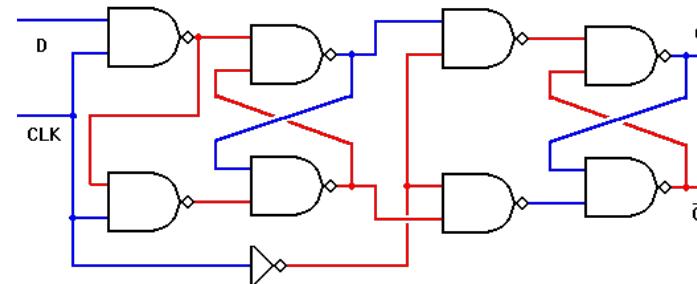
Code that refers back to itself infers latches and is not combinational.

Inferring latches (not intended as RAM/ROM) is bad practice,
and should be shunned at all costs unless strictly necessary.

If you think you need latches (*rather than FFs*) you most likely should rethink the design...

Non CL example :

- Can be hard to spot in dataflow code
- => Use high level code
 - Unless strictly necessary
 - for *readability (& modifiability)*

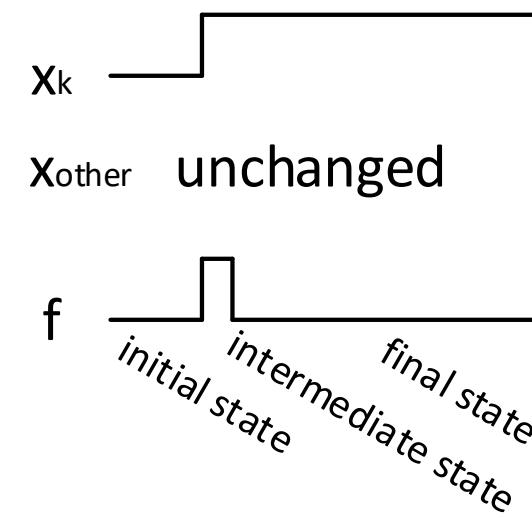
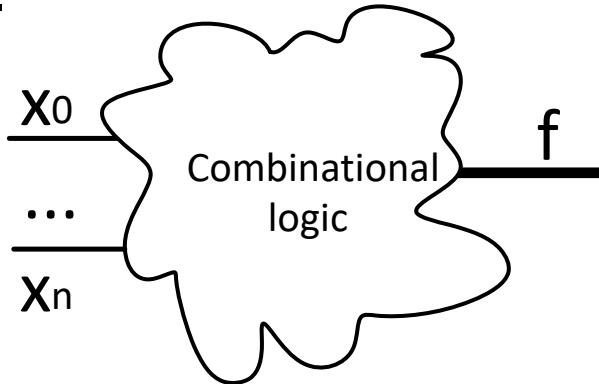


```
architecture data_flow of D_flipflop is
  signal e, f, g, h, i, j, k, l: std_logic;
begin
  -- concurrent statements
  e <= not (D and clk);
  f <= not (e and clk);
  g <= not (e and h);
  h <= not (f and g);
  i <= not (g and not clk);
  j <= not (h and not clk);
  k <= not (l and i);
  l <= not (k and j);
  Q <= k;
end architecture data_flow;
```

Hazards (glitches) in combinational circuits

- Definition of hazard in a combinational circuit:
 - Output goes through an (unwanted) intermediate state when input changes

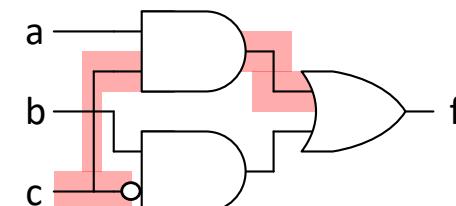
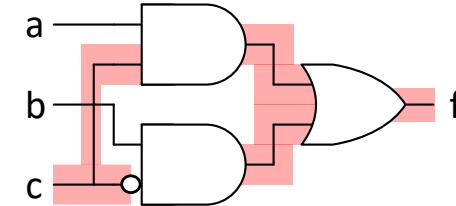
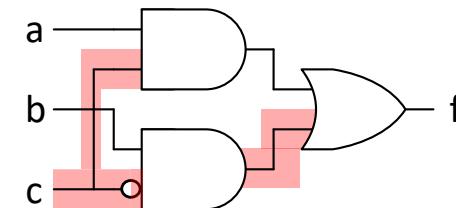
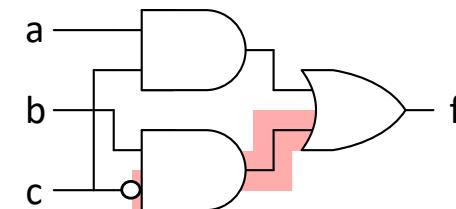
– e.g.



- With several inputs, there can be several unwanted transitions
 - It doesn't have to be 0 1 0, it can be $X \rightarrow Y \rightarrow Z$ or $X \rightarrow Y_1 \rightarrow \dots \rightarrow Y_n \rightarrow Z$

Hazards in combinational design

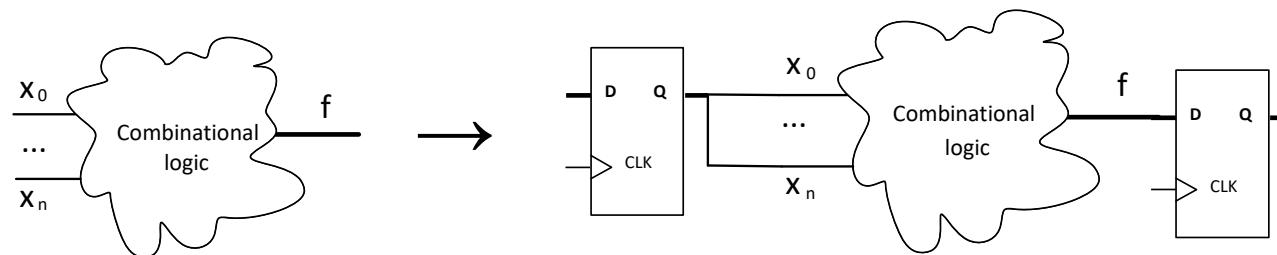
- Ex: $f(a,b,c) = (a \wedge c) \vee (b \wedge c')$
 $f \leq (a \text{ and } c) \text{ or } (b \text{ and not } c);$
- $a = '1'$, $b = '1'$, c changes from ' 1 ' to ' 0 '
- f goes from 1 to 0 to 1
(the inverted input of the second and-gate..)
- Possible solutions: (next page)



Solutions

- 1: add registers... (we'll get back to this one in oblig 8)

- This is what we normally do..
 - Left => stable input
 - Right => stable output

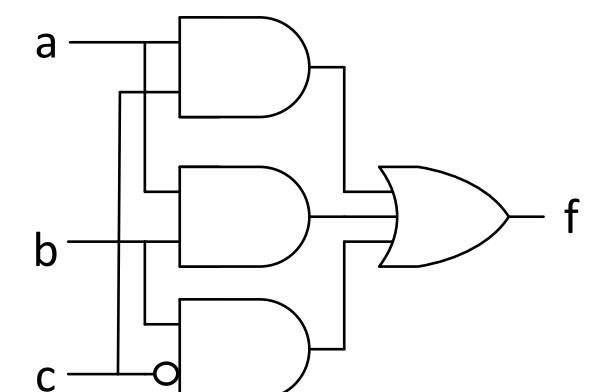


- 2: Manually design a solution

- D&H goes through that process
 - Laborious process:
 - Typically last resort (ASIC design)
 - Technology dependant solutions
 - *Know it is there*: We do not use this method in this course.

- 3: (Use high level code!)

- **may not solve every possible issue, but**
 - Allows synthesizer to decide
 - Synthesizing for FPGAs, = LUTs (problem occurs first at > 4 inputs)



Designer vs tool- example:

Create this circuit:

- $F(d,c,b,a)$ is true if input d,c,b,a is prime

$$f = \sum_{dcba} m(1,2,3,5,7,11,13)$$

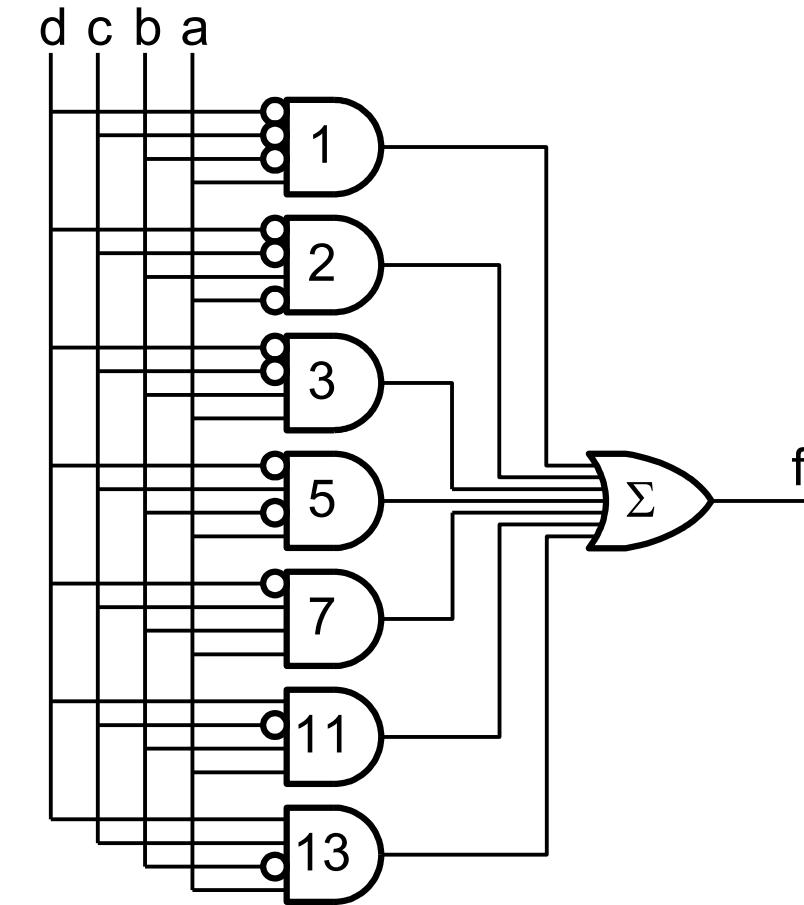
No	dcba	q
0	0000	0
1	0001	1
2	0010	1
3	0011	1
4	0100	0
5	0101	1
6	0110	0
7	0111	1
8	1000	0
9	1001	0
10	1010	0
11	1011	1
12	1100	0
13	1101	1
14	1110	0
15	1111	0

Schematic Logic Diagram

Equation:

$$f = \sum_{dcba} m(1,2,3,5,7,11,13)$$

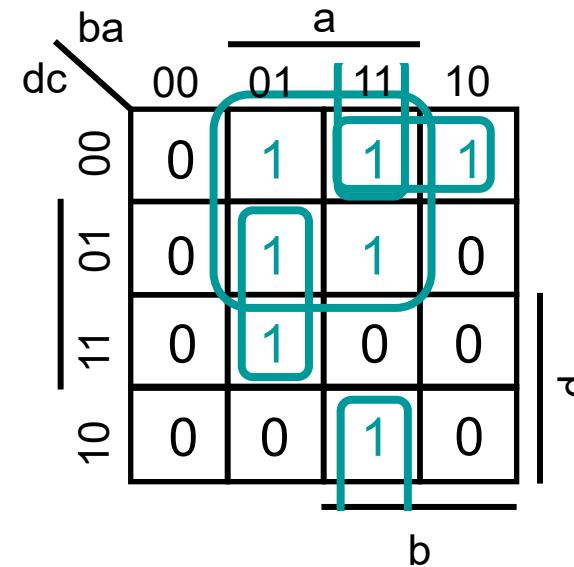
Schematic Logic Diagram:



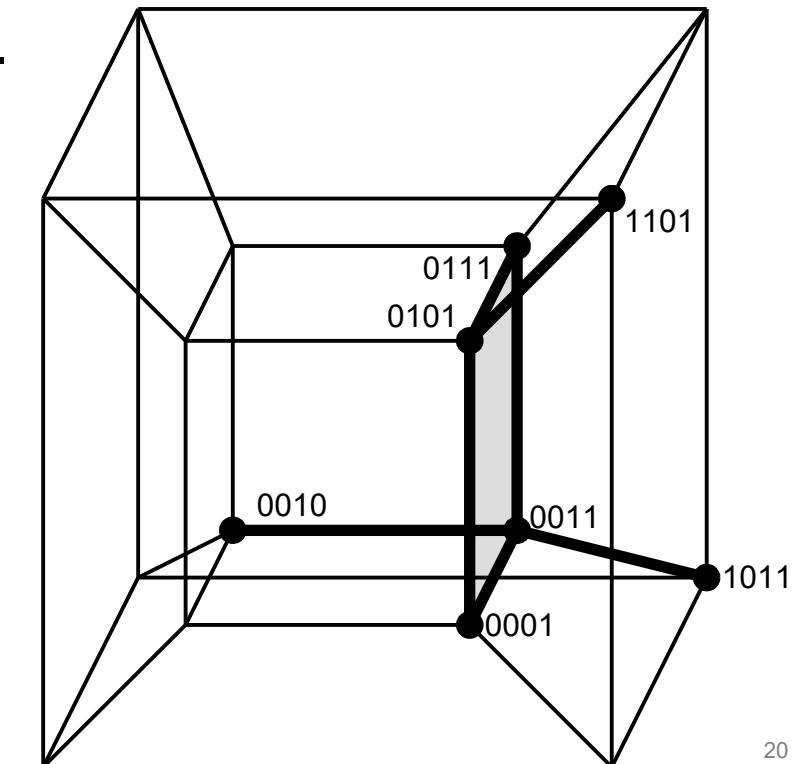
Manual optimization

- Minimalistic and Hazard free implementations can be found using implicant cubes and Karnaugh diagrams
 - The result will be a specific dataflow structure
- Method is laborious and can normally be skipped entirely.*
- D&H covers this in 6.4-6.9, we will not go in-depth.

$$f = \sum_{dcba} m(1,2,3,5,7,11,13)$$



Leads to a dataflow (or structural) design.



High level (RTL)

VHDL that implement the prime function (F)

- Note that these do not address any hazard issue.

$$f = \sum_{dcba} m(1,2,3,5,7,11,13)$$

VHDL Solution using case

```

library IEEE;
use IEEE.std_logic_1164.all;

entity prime is
port(
  input:  in std_logic_vector(3 downto 0);
  isprime: out std_logic
);
end entity prime;

architecture case_impl of prime is begin
process(input) begin
  case input is
    when x"1" | x"2" | x"3" | x"5" | x"7" | x"b" | x"d" => isprime <= '1';
    when others => isprime <= '0';
  end case;
end process;
end case_impl;

```

The vertical bar ‘|’ can be used to list multiple choices

No	dcba	q
0	0000	0
1	0001	1
2	0010	1
3	0011	1
4	0100	0
5	0101	1
6	0110	0
7	0111	1
8	1000	0
9	1001	0
10	1010	0
11	1011	1
12	1100	0
13	1101	1
14	1110	0
15	1111	0

Solution using «Matching case» = case?

```
library ... (same as previous slide)
```

```
entity ...
```

```
architecture mcase_impl of prime is
begin
  process(all) begin
    case? input is
      when "0--1" => isprime <= '1';
      when "0010" => isprime <= '1';
      when "1011" => isprime <= '1';
      when "1101" => isprime <= '1';
      when others => isprime <= '0';
    end case?;
  end process;
end mcase_impl;
```

$$f = \sum_{dcba} m(1,2,3,5,7,11,13)$$

No	dcba	q
0	0000	0
1	0001	1
2	0010	1
3	0011	1
4	0100	0
5	0101	1
6	0110	0
7	0111	1
8	1000	0
9	1001	0
10	1010	0
11	1011	1
12	1100	0
13	1101	1
14	1110	0
15	1111	0

Matching case can be used with '-'
('-' = don't-care bit)

Note:
Each option should only be listed once

$$f = \sum_{dcba} m(1,2,3,5,7,11,13)$$

Solutions using concurrent signal assignment

```
architecture dataflow of prime is
begin
    isprime <=
        (input(0) and (not input(3))) or
        (input(1) and (not input(2)) and (not input(3))) or
        (input(0) and (not input(1)) and input(2)) or
        (input(0) and input(1) and not input(2));
end architecture dataflow;
```

```
architecture selected of prime is
begin
    with input select isprime <=
        '1' when x"1" | x"2" | x"3" | x"5" | x"7" | d"11" | x"d",
        '0' when others;
end architecture selected;
```



Avoid pure dataflow unless strictly necessary



Selected statements will not infer latches unless explicitly designed for that purpose

No	dcba	q
0	0000	0
1	0001	1
2	0010	1
3	0011	1
4	0100	0
5	0101	1
6	0110	0
7	0111	1
8	1000	0
9	1001	0
10	1010	0
11	1011	1
12	1100	0
13	1101	1
14	1110	0
15	1111	0

Which one would you prefer reading?

More on case and case? «matching case»

- Case requires all possible outcomes to be defined
 - «when others»
 - Will cover other outcomes, but may also cover errors
 - i.e. we added a subtype to a type, and should extend a case...
- If you have many options that do the same
 - Use «matching case» case?
 - Allows for don't cares to cover options with the same outcome.

```
type holiday is (Xmas, easter, summer);
signal min_holiday: holiday;
type temperature is (freezing, cold, mild, warm);
signal weather : temperature;

...
case my_holiday is
  when Xmas    => weather <= freezing;
  when easter  => weather <= cold;
  when others  => weather <= warm;
end case;

-- add 'autumn' to holiday type...
-- will compilation bug you?
-- should autumn be considered warm...?
```

IN3160, IN4160

Verification part 1 : Simulation

Yngve Hafting

Code examples can be found at

<https://github.uio.no/in3160/lectures/>



In this course you will learn about the **design of advanced digital systems**. This includes programmable logic circuits, a **hardware design language** and system-on-chip design (processor, memory and logic on a chip). **Lab assignments provide practical experience in how real design can be made.**

After completion of the course you will:

- understand important **principles for** design and **testing** of digital systems
- understand the relationship between behaviour and different construction criteria
- be able to describe advanced digital systems at different levels of detail
- **be able to perform simulation** and **synthesis of digital systems.**

Course Goals and Learning Outcome

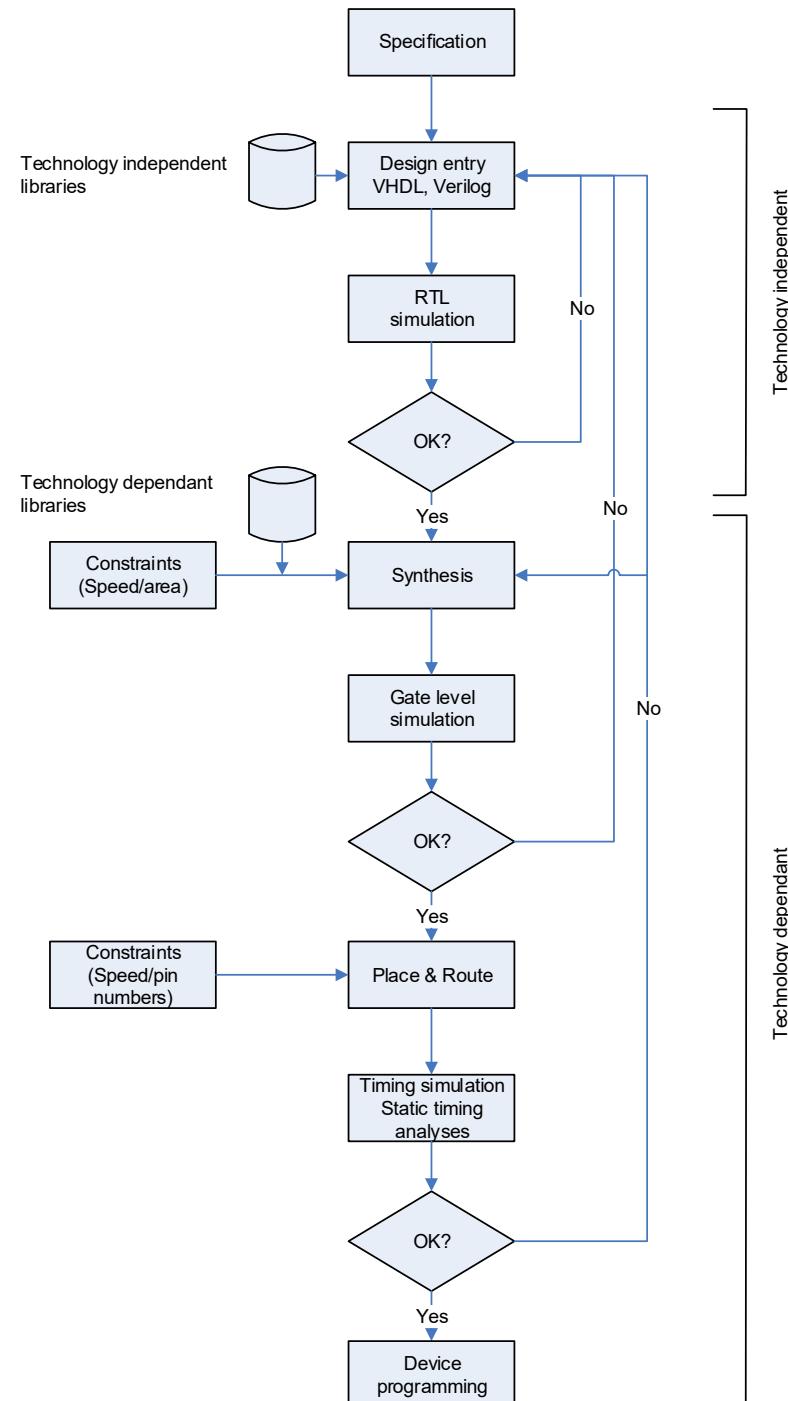
<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

Goals for this lesson:

- Know what we mean by ‘verification’ and ‘test’
 - Functional verification
 - Formal verification
 - Compilation
 - Simulation
 - Coverage
- Know how to perform verification
 - Manual stimuli
 - Script based stimuli
 - **Test benches**
- Know basic simulation principles for digital systems
 - Know how event based simulation works
 - Know the difference between event based and cycle based simulation.
- Know how basic VHDL structures will be simulated
 - Compilation steps
 - Process sensitivity list

Overview

- Verification part 1:
 - Compilation
 - Simulation
 - Types
 - RTL (functional)
 - Timing
 - » Static timing analysis
 - » dynamic
 - Execution
 - Cycle based
 - Event based
 - Assignments and suggested reading



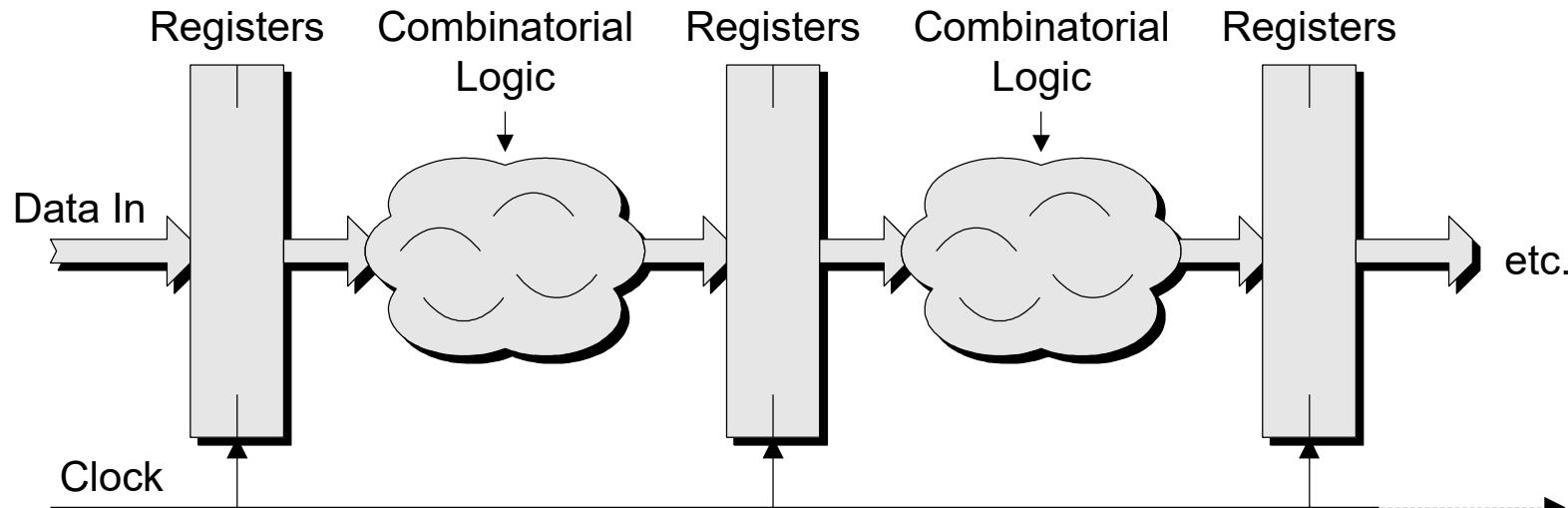
Compilation: Analysis and Elaboration

- Analysis
 - **The compiler reads all the files, check syntax, semantics**
 - Compiled result is
 - translated to an intermediate representation
 - stored in (work) library
- Elaboration (requires error free analysis)
 - **Creates design hierarchy**
 - Instantiates entities
 - Creates connections
 - Checks that types does match for connected signals

Simulation

- The Simulator
 - knows all signal dependencies
 - *Unless there are errors in signal sensitivity lists.*
 - keeps track of all signal values
 - Both external and internal to the design
 - has an event queue
 - Every change in a signal is an event scheduled at a specific time step.
 - Events may be queued to happen at the same simulation step
 - But they are resolved one by one.
- Simulation types (upcoming slides)
 - Cycle based
 - Event based

Cycle based simulation



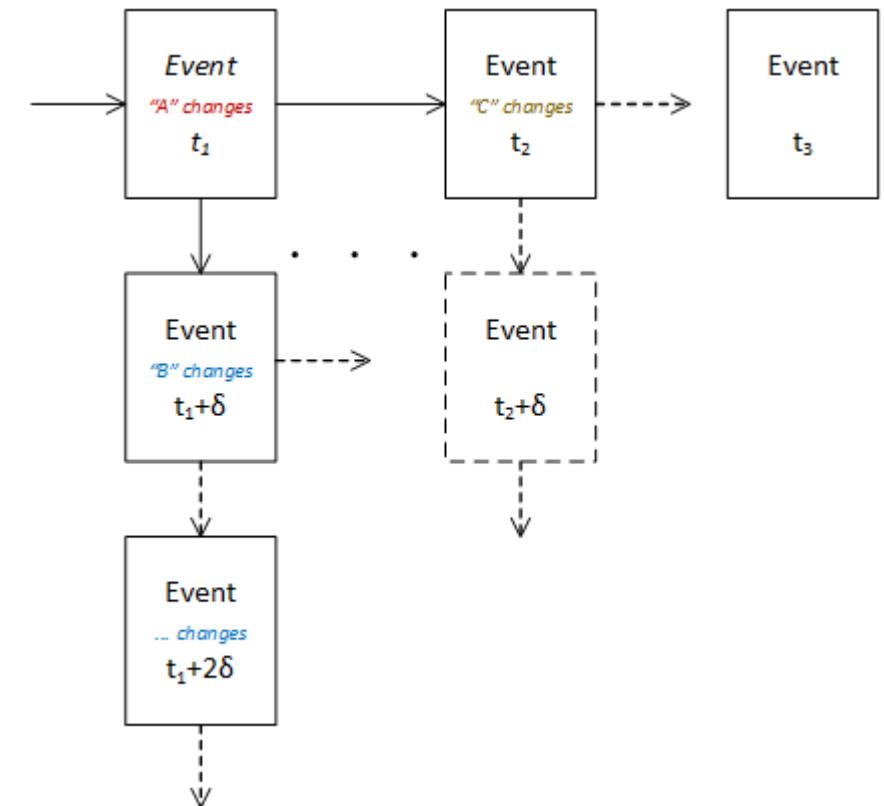
- No notion of time within a single clock cycle
- Only evaluate boolean functions for each component once
- Very fast, but *can produce simulation errors*
- Not widely used, but can be used in some parts of designs with high simulation times
 - This is *almost* what we get when using "clk" as sensitivity in a process

Event driven simulation

- «event driven» => time is driven by events
 - Change in inputs (stimuli)
 - Change in outputs that propagate to other changes
- All signal drivers are modelled with a delay called «delta delay»
 - A delta delay is a delay of 0 time-
 - a mechanism for queuing of events

Event driven simulation

- An event occurs in a time-step when a signal changes (Ex. an input is set from the testbench)
 - All signals that depend on the signal is evaluated
 - Changes are put in the event queue
 - When timing information is provided (post synthesis)
 - » Timing delays are used to schedule events
 - With no timing information (RTL-simulation)
 - » Output is queued at the same time-step
 - » A delay of 0 time is called a delta delay (δ)
 - All events in the queue for a time step is evaluated
 - Until there are no more changes left
 - The simulation proceeds to the next time-step when there are no more events to be evaluated
 - Event driven simulation ensures all simulators get the same result.



Event queue example : Glitch

Full code (for ref)

```

library IEEE;
use IEEE.std_logic_1164.all;

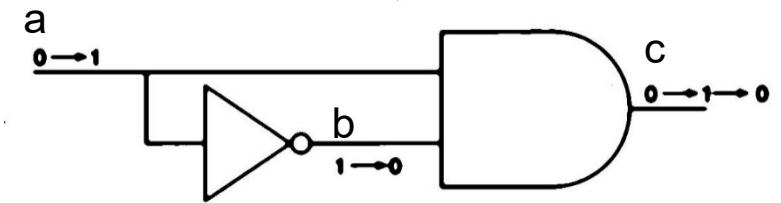
entity delta is
port(
  a : in std_logic;
  c : out std_logic
);
end entity delta;

architecture dataflow of delta is
  signal b : std_logic;
begin
  b <= not a;
  c <= b and a;
end architecture;

import cocotb
from cocotb import start_soon
from cocotb.triggers import Edge, Timer, First
from cocotb.utils import get_sim_time

async def monitor(dut):
    while True:
        ta = Edge(dut.a)
        tb = Edge(dut.b)
        tc = Edge(dut.c)
        await First(ta, tb, tc)
        print(f"{get_sim_time(units='ps'):{9}.0f}ps  ",
              f"a:{(dut.a.value)}  ",
              f"b:{(dut.b.value)}  ",
              f"c:{(dut.c.value)}")

@cocotb.test()
async def main_test(dut):
    dut.a.value = 0
    start_soon(monitor(dut))
    for i in range(5):
        await Timer(100, units='ps')
        dut.a.value = not dut.a.value
  
```



0ps	a:0	b:U	c:U
0ps	a:0	b:1	c:0
100ps	a:1	b:1	c:0
100ps	a:1	b:0	c:1
200ps	a:0	b:0	c:0
200ps	a:0	b:1	c:0
300ps	a:1	b:1	c:0
300ps	a:1	b:0	c:1
300ps	a:1	b:0	c:0
400ps	a:0	b:0	c:0
400ps	a:0	b:1	c:0

Waiting for ReadOnly()

0ps	a:0	b:1	c:0
100ps	a:1	b:0	c:0
200ps	a:0	b:1	c:0
300ps	a:1	b:0	c:0
400ps	a:0	b:1	c:0

IN a physical circuit
We *may* see all glitches

Glitches can be hidden in simulation results
and waveform diagrams

*Post synthesis- will much more likely show
these type of effects than RTL-simulation*

```
import cocotb
from cocotb import start_soon
from cocotb.triggers import Edge, Timer, First, ReadOnly
from cocotb.utils import get_sim_time

async def monitor(dut):
    while True:
        ta = Edge(dut.a)
        tb = Edge(dut.b)
        tc = Edge(dut.c)
        await First(ta, tb, tc)
        await ReadOnly()
        print(f'{get_sim_time(units="ps"):.9f}ps',
              f'a:{(dut.a.value)}',
              f'b:{(dut.b.value)}',
              f'c:{(dut.c.value)}')

@cocotb.test()
async def main_test(dut):
    dut.a.value = 0
    start_soon(monitor(dut))
    for i in range(5):
        await Timer(100, units='ps')
        dut.a.value = not dut.a.value
```

Cocotb Triggers -- `await <trigger>`

ReadOnly ()

Waits until all delta delays has settled
useful for *most* checks

ReadWrite ()

get out of `ReadOnly` before next value are set

Edge (*signal*)

Waits for any change in the signal

RisingEdge (*signal*) , **FallingEdge** (*signal*)

Timer (*value*, *unit*="ps")

Waits the exact simulation time

ClockCycles (*signal*, *num_cycles*, *rising=True*)

Waits a number of (rising) edges

First (**triggers*)

Waits for the first trigger in the list

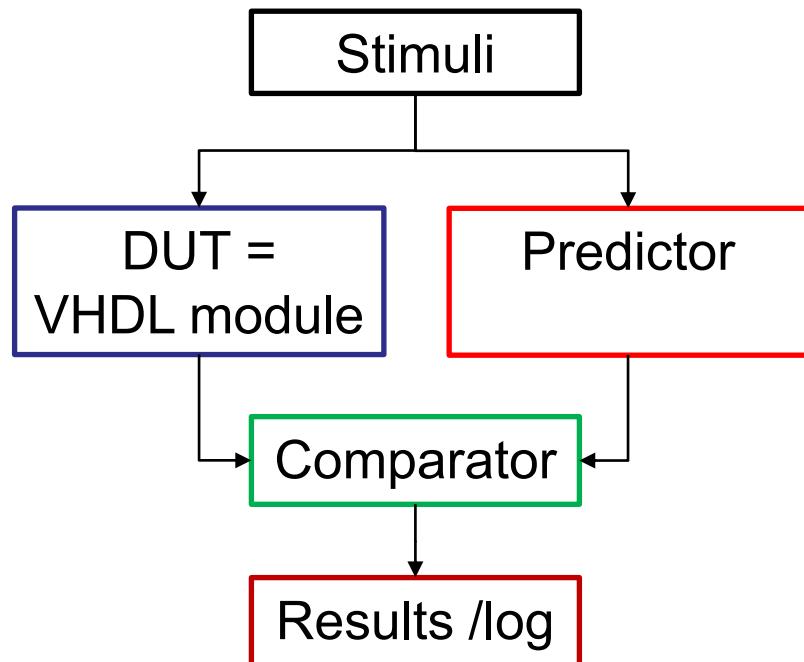
Combine (**triggers*)

Waits for all triggers in the list

RTL simulation practical example

- Modelsim / Questa:
 - Creating test benches
 - Example ([tb_xor.vhd](#))
 - See [..//verification...](#)

General testbench layout



- **Stimuli**
 - Generate or read stimuli from a file
 - Use procedures rather than repeating lines
- **DUT**
 - Device under test (Device, Module, ...)
 - Connect DUT input to stimuli to create simulation results
- **Predictor**
 - Predicts what the output should be
 - Calculates from input or reads from file
- **Comparator**
 - Compares simulation result with predicted result and reports to screen or file.

Cocotb testbench

```

import cocotb
from cocotb import start_soon
from cocotb.triggers import Edge, Timer, ReadOnly
import random

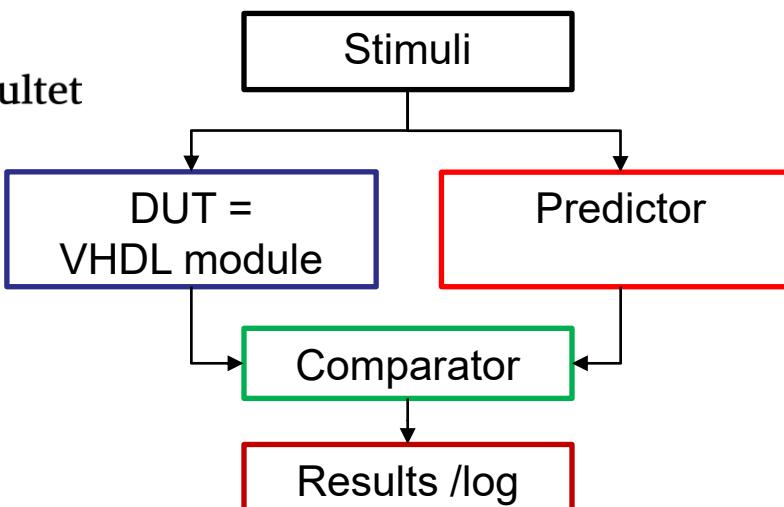
# bitwise XOR of input (a subroutine for predictor)
def xor(input):
    result = 0
    for i in range(input.n_bits):
        result = result^(input & 1)
        input = input >> 1
    return result

# Predicts or calculates what the output should be
def predictor(dut):
    return xor(dut.input.value)

# Compares simulated output with predicted output
async def compare(dut):
    while True:
        # Test on new input, then let output settle.
        await Edge(dut.input)
        await ReadOnly()
        assert dut.output == predictor(dut), (
            "output ({out}) is not as predicted: XOR({inp})"
            .format(out=dut.output.value, inp=dut.input.value))

    dut._log.info("output ({out}) is XOR({inp})"
        .format(out=dut.output.value, inp=dut.input.value))

```



```

# Generate all data
async def stimuli_generator(dut):
    for i in range( 2**len(dut.input)):
        dut.input.value = vector
        await Timer(1, units= 'ns')

@cocotb.test()
async def main_test(dut):
    """Try accessing the design."""
    dut._log.info("Running test...")
    start_soon(compare(dut))
    await stimuli_generator(dut)

    dut._log.info("Running test...done")

```

```

# Makefile
# defaults
SIM ?= ghdl
TOPLEVEL_LANG ?= vhdl

# VHDL 2008
EXTRA_ARGS +---std=08

# TOPLEVEL is the name of the
# toplevel module in your VHDL file
TOPLEVEL ?= xor

# VHDL_SOURCES +=
# $(PWD)/../src/$(TOPLEVEL).vhdl
VHDL_SOURCES += $(PWD)/../src/*.vhdl

# SIM_ARGS is Simulation arguments.
# --wave determines name and type of
waveform
SIM_ARGS +---wave=$(TOPLEVEL).ghw

# -g<GENERIC> is used to set generics
# defined in the toplevel entity
SIM_ARGS +--gWIDTH=5

# MODULE is the basename of the
# Python test file
MODULE ?= tb_xor

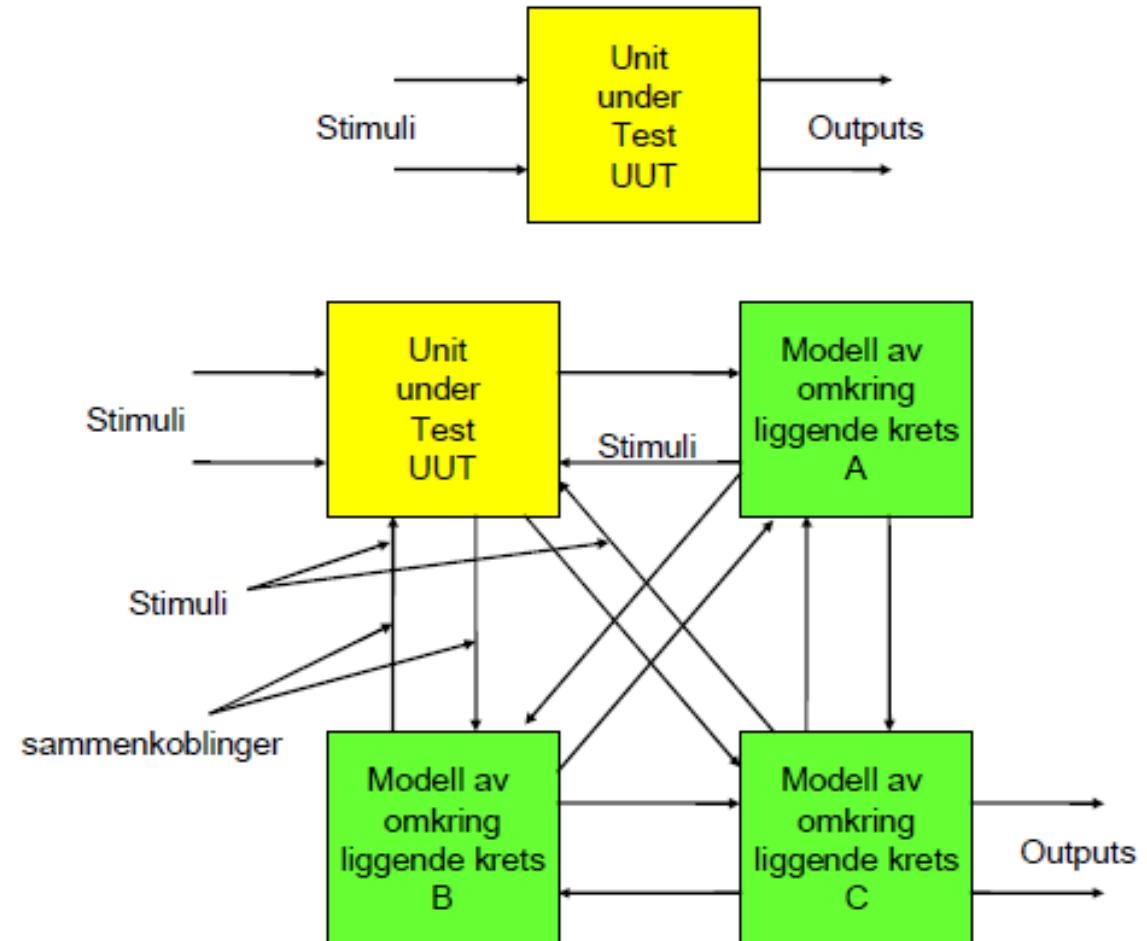
# include cocotb's make rules to
# take care of the simulator setup
include $(shell cocotb-config --
makefiles)/Makefile.sim

# removing generated binary of top
# entity and .o-file on make clean
clean:::
    -@rm -f $(TOPLEVEL)
    -@rm -f e~$(TOPLEVEL).o

```

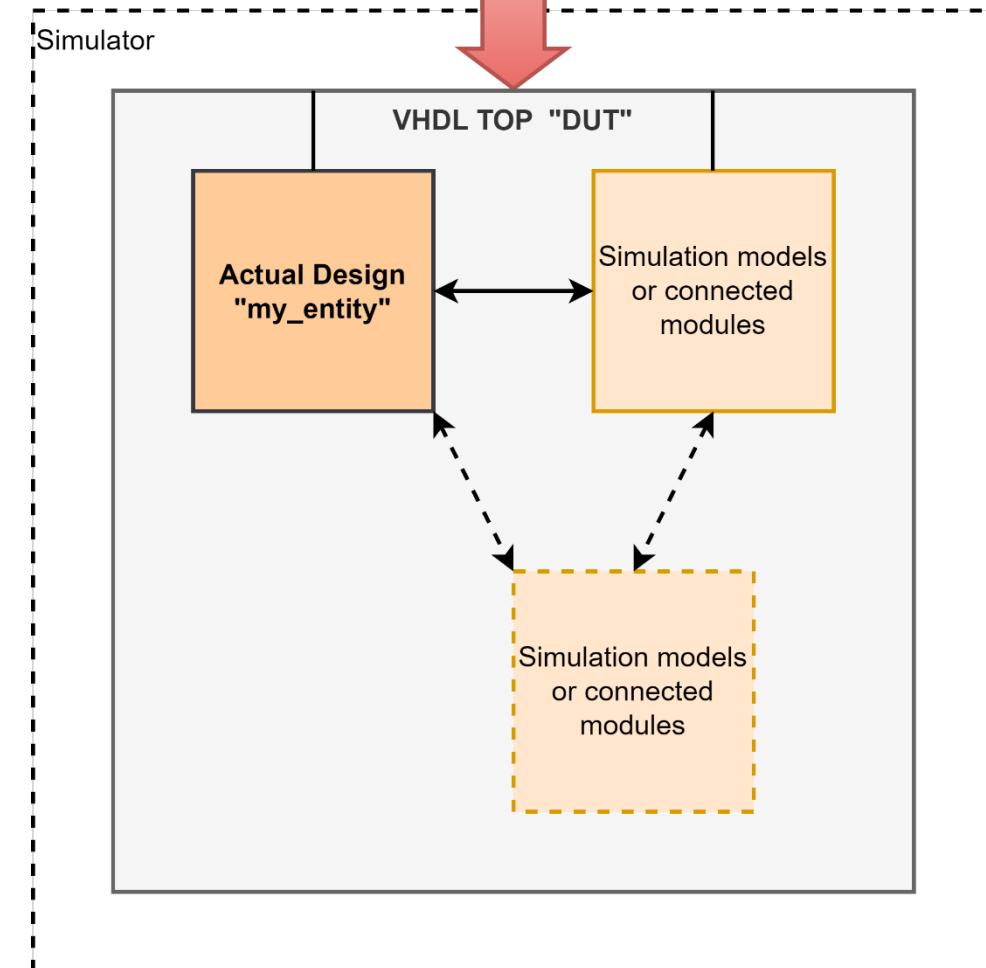
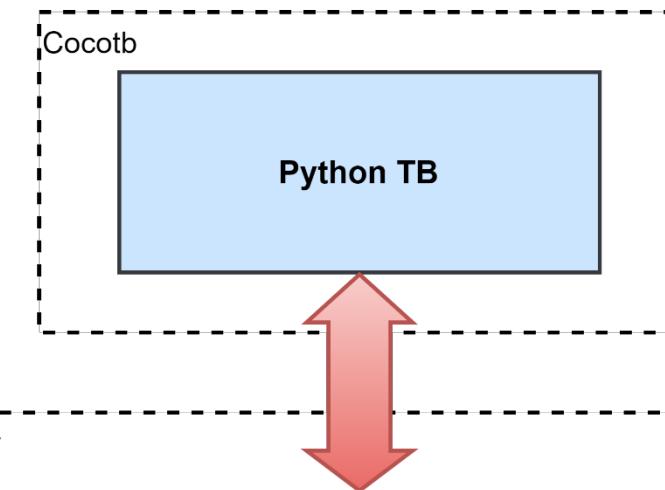
Testbench structures

- Multiple modules are often required to be tested together
 - Other design modules
 - Premade modules (Ips)
 - Bus functional models etc.
 - *Can be required to achieve certifications in industry..*



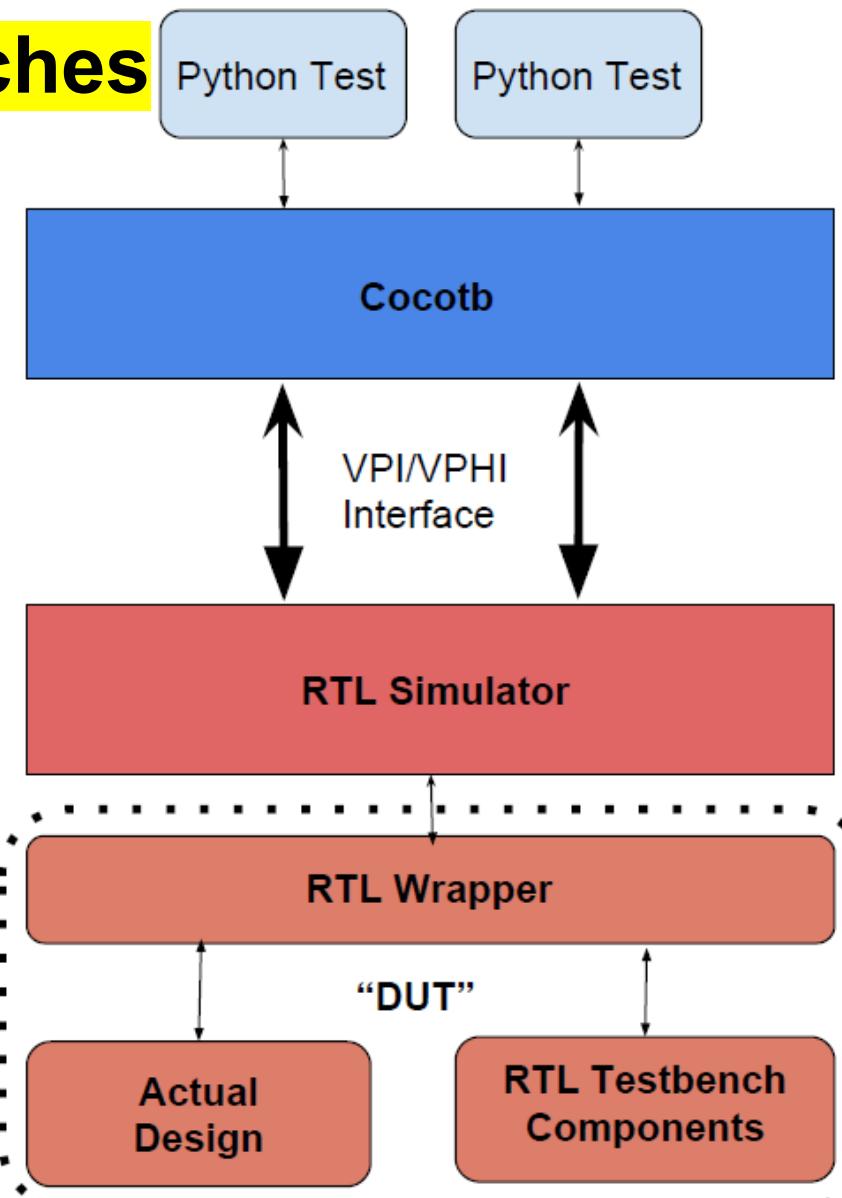
Multiple modules in cocotb

- Only one toplevel can be used
 - Multiple modules =>
 - Create a top entity connecting all modules.
- Python TB can access all hierarchy
 - "Dut.my_entity.my_signal.value = ..."
 - Use dot notation to go deeper in hierarchy



Cosimulation: Cocotb and python testbenches

- *Cosimulation*: Design and testbench simulated independently
- Communication through VPI/VHPI interfaces, represented by cocotb "triggers".
- When the Python code is executing, **simulation time is not advancing**.
- When a trigger is awaited, the testbench waits until the triggered condition is satisfied before resuming execution.
- Available triggers include:
 - Timer(time, unit): waits for a certain amount of simulation time to pass.
 - Edge(signal): waits for a signal to change state (rising or falling edge).
 - **RisingEdge(signal)**: waits for the rising edge of a signal.
 - **FallingEdge(signal)**: waits for the falling edge of a signal.
 - **ClockCycles(signal, num)**: waits for some number of clocks (transitions from 0 to 1).



Cocotb: Coroutines, tasks and triggers

- All signals in the design hierarchy can be probed and set in python
- "async def" is used when defining coroutines
- Multiple triggers can be used
 - enable tests running independently
 - `start_soon(<coroutine>)`
 - Starts the coroutine as soon when "awaiting" the next time
 - Used to start clock generation,
 - `await <task/trigger>` <https://docs.python.org/3/library/asyncio-task.html>
 - Waits until the task is finished or trigger condition occurs
 - `await ReadOnly()` is used to let signals settle after other triggers such as `await Edge(<dut.signal>)`
 - » Normally all delta delays should finish before reading

```
async def stimuli_generator(dut):
    ''' Generates all data for this tesbench '''
    for i in range( 2**len(dut.input)):
        dut.input.value = i
        await Timer(1, units= 'ns')

async def compare(dut):
    ''' Compares simulated output with predicted output '''
    while 1:
        await Edge(dut.input)    # Test on each new input
        await ReadOnly()         # Wait for output to settle
        assert dut.output == predictor(dut), (
            "output ({out}) is not as predicted: XOR({inp})"
            .format(out=dut.output.value, inp=dut.input.value))
        dut._log.info(
            "output ({out}) is XOR({inp})"
            .format(out=dut.output.value, inp=dut.input.value))

@cocotb.test()
async def main_test(dut):
    """ Starts comparator and stimuli """
    dut._log.info("Running test...")
    start_soon(compare(dut))
    await stimuli_generator(dut)
    dut._log.info("Running test...done")
```

More Cocotb...

- Cocotb documentation:
 - <https://docs.cocotb.org/en/stable/>
- Coroutines generally in python:
 - <https://docs.python.org/3/library/asyncio-task.html>

Suggested reading, corresponding assignments

Combinational logic

- D&H
 - 3.6
 - 6.1, 6.2, 6.3 (p105-109)
 - (6.4-6.9 p110- 120 .. Not syllabus)
 - 6.10 p121-123
 - 7.1 p 129-143
 -

Verification

- D&H:
 - 2.1.4 p 27
 - 7.2 p 143-148
 - 7.3 p 148-153
 - 20.1 p 453 – 456
- Oblig 1: «Design Flow»
 - See canvas for further instruction.
- Oblig 2: «VHDL»

IN 3160, IN4160

More VHDL:
Processes, signals and variables
conditional statements
Structural design

Yngve Hafting



Messages

Content

- How VHDL processes work
 - Example with
 - Sensitivity
 - Signals
 - Variables
 - Compared to cocotb testbench code

VHDL processes

- A process must work in a predictable, deterministic way for both creating and simulating circuits
- Process sensitivity
 - Decides when a process is invoked in *simulation*
 - «*should not*» interfere with how HW is made...
 - *Do not trust this..!*
 - Good practice:
 - Use keyword `all` for combinational logic: `process(all) is...`
 - Use clock for sequential logic: `process(clk)...`
 - or (clk, reset) when asynchronous reset is desired

```

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity My_thing is
    port(A: in STD_LOGIC;
         F: out STD_LOGIC
        );
end entity My_thing;

architecture Behavioral of My_thing is
    signal b : STD_LOGIC;
begin
    signal_update: process(a)
    begin
        if A = '1' then b <= '1';
        else b <= '0';
        end if;

        if b = '1' then F <= '1';
        else F <= '0';
        end if;

    end process;
end architecture Behavioral;

```

/my_thing/A	-No Data-		
/my_thing/F	-No Data-		
/my_thing/b	-No Data-		

Sensitivity list

What happens with F?

Assume a changes from '0' to '1'

```

signal_update: process(a,b)
begin
    if a = '1' then
        b <= '1';
    else
        b <= '0';
    end if;

    if b = '1' then f <= '1';
    else f <= '0';
    end if;
end process;

```

/my_thing/A	-No Data-		
/my_thing/F	-No Data-		
/my_thing/b	-No Data-		

Signals and variables

- Signals
 - A signal can be used within the **whole architecture**
 - *Changes value when simulation exits a process (or statement)*
- Variables
 - Can only be **used locally**
 - within a process, function or procedure
 - Assigned using “:=“ (Ex: var := ‘1’ ;)
 - Changes value **immediately** in simulation
 - Immediately = based on position, *read from top to bottom.*
 - *can have multiple values* within one process.
 - Variables are useful to keep intermediate results in algorithms
 - Subprograms initialize variables every run.
 - Process variables initialize once, *when simulation starts*
- Both signals and variables can be used for storage
 - Both FFs and latches.
 - Variables that are read «before» written will accomplish this = BAD PRACTICE!...

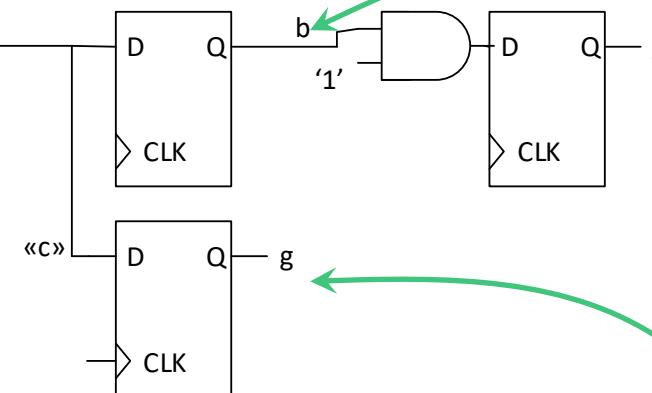
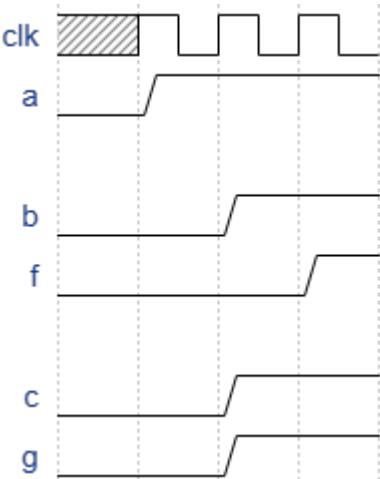
Signals vs. variables (sequential logic example)

- Exercise:
- Assume all signals are 0, then
 - signal a changes from 0 to 1.
- On which clock cycles does f and g change value; first, second, third?

Try for 1 minute:

Time's up...

```
signal_var_update : process(clk)
  variable c : std_logic;
begin
  if rising_edge(clk) then
    if a = '1' then
      b <= '1';
      c := '1';
    else
      b <= '0';
      c := '0';
    end if;
    if b = '1' then
      f <= '1';
    else
      f <= '0';
    end if;
    if c = '1' then
      g <= '1';
    else
      g <= '0';
    end if;
  end if;
end process;
```



NOTE: c could be assigned multiple places in the process.

How would that affect the diagram..?

Variables update «immediately»

Signals are assigned «where» the process ends
when the process statement updates as a whole

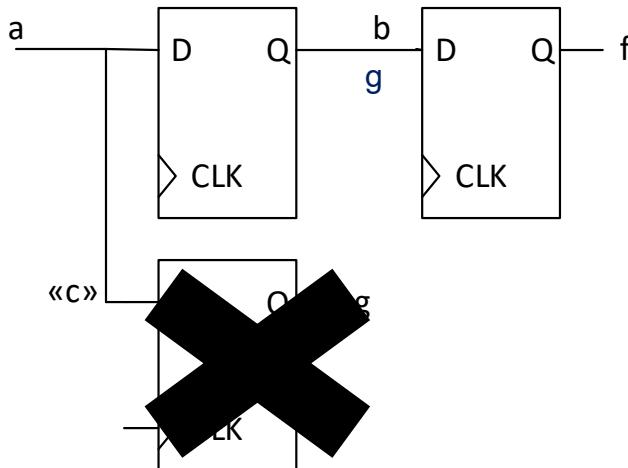
```

signal_var_update :
process(clk)
variable c : std_logic;
begin
if rising_edge(clk) then
if a = '1' then
b <= '1';
c := '1';
else
b <= '0';
c := '0';
end if;
if b = '1' then
f <= '1';
else
f <= '0';
end if;
if c = '1' then
g <= '1';
else
g <= '0';
end if;
end if;
end process;

```

Digression:

- Simplified...



```

signal_var_update :
process(clk)
    variable c : std_logic;
begin
    if rising_edge(clk) then
        if a = '1' then
            b <= '1';
            c := '1';
        else
            b <= '0';
            c := '0';
        end if;
        if b = '1' then
            f <= '1';
        else
            f <= '0';
        end if;
        if c = '1' then
            g <= '1';
        else
            g <= '0';
        end if;
    end if;
end process;

```

```

signal_var_update :
process(clk)
    variable c : std_logic;
begin
    if rising_edge(clk) then
        if a = '1' then
            b <= '1';
            c := '1';
        else
            b <= '0';
            c := '0';
        end if;
        if b = '1' then
            f <= '1';
        else
            f <= '0';
        end if;
        if c = '1' then
            g <= '1';
        else
            g <= '0';
        end if;
    end if;
end process;

```

Default values and positional priority in processes

```
architecture Sequential2 of priority is
begin
  process (a) is
  begin
    valid <= '1';
    if a(3)='1' then
      y <= "11";
    elsif a(2)='1' then
      y <= "10";
    elsif a(1)='1' then
      y <= "01";
    elsif a(0)='1' then
      y <= "00";
    else
      valid <= '0';
      y <= "00";
    end if;
  end process;
end architecture Sequential2;
```

- Default values
 - Ensures we always "have an output value" (*avoiding latches*).
 - The last assignment of a signal takes precedence
 - This works because processes are compiled sequentially...
- Only use default values on top in processes
 - Don't bury them in nested if's...
 - Readability and maintainability suffer if you do..
- Default values are commonly used for state machine outputs
- Using positional priority except for default values
 - is bad practice

How processes work with signals and variables...

- Signals
 - Represent physical wires and drivers in the architecture
 - A wire can only have a single voltage at any given time.
 - Are updated once in a process invocation
 - This happens only at process exit.
 - No intermediate values are held.
 - A value that has been changed cannot be read as changed within the process.
 - When assigned multiple times within a process, the latest will be given priority
 - Allows for default values
 - Makes inferring storage elements (FFs+latches) deterministic and comprehensible.

How processes work with signals and variables...

- Variables
 - Variables are *local* to the process.
 - They must be both assigned and read within a process
 - Their value is *intended for intermediate purposes*
 - Making code more readable by turning complex statements into several simpler statements
 - By taking value(s) that can be used within the process
 - They *can* be given values multiple times within a single process invocation
 - *Doing so- is generally not a good idea*
 - **Placement determines whether they will infer storage elements (latches and flipflops)!**
 - *Reading before writing to* = storage
 - **Using variables for storage is considered bad practice** in most circumstances

Processes and the event queue (in simulation)

- Simulation uses an event queue to keep track of what happens.
- A process is invoked as a result of a change in one of the signals in the sensitivity list.
 - The whole process is "run" through «within that delta delay».
 - Each **signal** assignment is added to the queue of delta delays
 - Only changes in signals that are in the sensitivity list will trigger the process again.
 - **variable** updates does *not* create new events.
 - (They are updated immediately...)

Cocotb and the event queue

- Cocotb code only runs within a delta delay
 - From triggered to next wait statement (ie **await** <trigger>)
 - Similar to a vhdl process but
 - **await** statements may be put almost anywhere
 - VHDL processes are always run through completely
- Each cocotb output (`dut.value = <new value>`) creates a new event in the simulation.

IN 3160, IN4160

**VHDL
conditional statements and structural design**

Yngve Hafting



In this course you will learn about the design of advanced digital systems. This includes programmable logic circuits, a hardware design language and system-on-chip design (processor, memory and logic on a chip). Lab assignments provide practical experience in how real design can be made.

After completion of the course you will:

- understand important principles for design and testing of digital systems
- **understand the relationship between behaviour and different construction criteria**
- **be able to describe advanced digital systems at different levels of detail**
- **be able to perform simulation and synthesis of digital systems.**

Goals for this lesson:

- Know conditional statements in VHDL
 - .
- how to implement these structures using VHDL
 - *If, case, when-else, select*
 - *Loops*
 - *Type casting*
 - *Shift operators*
 - *Dataflow vs RTL descriptions*
- Know how to generate complex structures in VHDL
 - generate

Section overview

- VHDL:
 - Sensitivity list
 - Signals and variables example
 - If, case, when-else, select
 - Loops
 - Structural coding
 - Generate
 - Generics

Next lesson: Building blocks

Decoders vs encoders
Decoder
Multiplexer
Encoders
Arbiters
Shifters
Comparators
ROM
RAM

If and case in VHDL Processes

- **if** and **case** are used much like in other programming languages like C, Java etc.
 - *Their similarity in syntax may lead to errors if we do not understand how they work in digital circuits...*
 - If-tests can test on multiple signals/variables
 - built in priority
 - Case-tests uses single signal/variable (vector=OK)
 - No built in priority because the same signal are being used everywhere in the test

If

- Must be in process
 - **Multiple conditions**
 - **Multiple targets**
 - prioritizes
-
- First option has priority
 - (think of two-input multiplexers)
 - Can be used to infer latches and Flipflops
 - FF when edge triggered (`if rising_edge(clk) then...`)
 - **Latch when not sufficiently specified!**
 - This is a trap, avoid this!
 - Can be nested using «`elsif`»
 - Can replace any other conditional statement
 - *Not recommended!*
 - Avoid deep nesting
 - ~4 degrees should be maximum...

If example (*all input specified*):

inp1	inp2	a	b
1	1	1	1
1	0	1	0
0	1	0	Latched
0	0	0	Latched

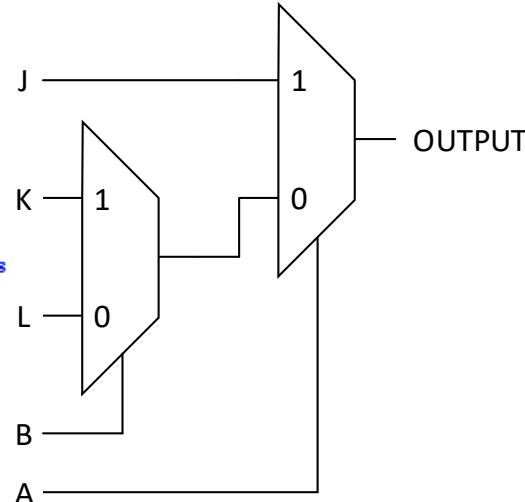
```
process(all) is
begin
    if inp1 then
        if inp2 then
            a <= '1';
            b <= '1';
        else
            a <= '1';
            b <= '0';
        end if;
    else
        a <= '0';
    end if;
end process;
```

```
process(all) is
begin
    if inp1 then
        a <= '1';
        b <= inp2;
    else
        a <= '0';
        -- b ass. missing
    end if;
end process;
```

Always specify all outputs for all conditions of inputs!

```
entity My_thing is
  port(A,B,J,K,L: in STD_LOGIC;
       OUTPUT: out STD_LOGIC);
end entity My_thing;
```

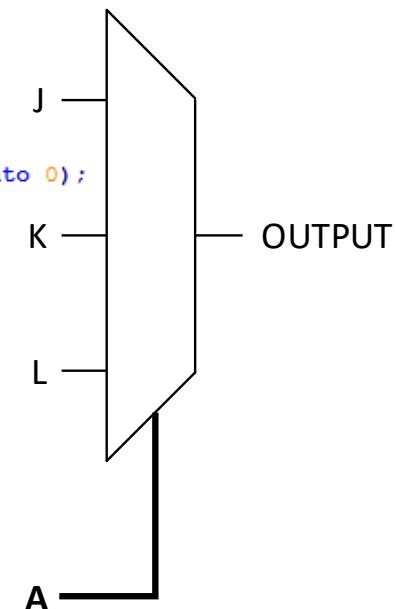
```
architecture prioritized of My_thing is
begin
  process(all)
  begin
    if A = '1' then
      OUTPUT <= J;
    elsif B = '1' then
      OUTPUT <= K;
    else
      OUTPUT <= L;
    end if;
  end process;
end architecture prioritized;
```



if..../case..

```
entity My_thing is
  port(A : in STD_LOGIC_VECTOR(1 downto 0);
       J,K,L: in STD_LOGIC;
       OUTPUT: out STD_LOGIC);
end entity My_thing;

architecture nonpri of My_thing is
begin
  case A is
    when "01" =>
      OUTPUT <= J;
    when "10" =>
      OUTPUT <= K;
    when others =>
      OUTPUT <= L;
  end case;
end architecture nonpri;
```



If nesting vs. chaining (using `elsif`)

```
process(all) is
begin
    if (input = 4d"1") then
        isprime <= '1';
    else
        if (input = 4d"2") then
            isprime <= '1';
        else
            if (input = 4d"3") then
                isprime <= '1';
            ...
            end if;
        end if;
    else
        isprime <= '0';
    end if;
end process;
```

```
process(all) is
begin
    if (input = 4d"1") then isprime <= '1';
    elsif (input = 4d"2") then isprime <= '1';
    elsif (input = 4d"3") then isprime <= '1';
    ...
    else isprime <= '0';
    end if;
end process;
```

If nesting for priority – danger zone

Sometimes it can make sense to use nesting

- clocked processes and state machines
- It is easy infer latches
 - When not all input options are covered
 - When some output is not covered for all options

Consider other options when creating CL

- *improve readability*
- *Reduce risk for latches*
- *It is OK to nest other statements within if...*
 - *select ...*
 - *when ... else*
 - *case ...*

```
process(all) is
begin
    if (inp1 = a) then
        if (inp2 = b) then
            if (inp3 = c) then
                <statement 1>
                <statement 2>
            else
                <statement 3>
            end if;
        end if;
    else
        <statement 4>
    end if;
end process;
```

Example

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

entity latches is
port(
    invec : in std_logic_vector(1 downto 0);
    outvec : out std_logic_vector(3 downto 0);

    input : in std_logic;
    out1, out2 : out std_logic
);
end entity latches;
```

- **Nesting if-statements will conceal these errors easily, thus providing an endless source of errors**

```
architecture poor of latches is
begin
    -- if invec = "11" => outvec is latched
    missing_input: process(all) is
    begin
        if invec = "00" then
            outvec <= "0000";
        elsif invec = "01" then
            outvec <= "1110";
        elsif invec = "10" then
            outvec <= "0110";
        end if;
    end process;

    -- if input='1' then out2 is latched.
    -- if input='0' then out1 is latched.
    missing_output: process(all) is
    begin
        if input then
            out1 <= '1';
        else
            out2 <= '0';
        end if;
    end process;

end architecture poor;
```

Case

- Must be in process
 - **single input vector**
 - **Multiple targets**
 - Every alternative has same priority
-
- Every option for *input* must be declared
 - ‘**when others**’ can be used
 - be wary of changes in input *type*...
 - Can infer latches too...
 - When not defining all outputs for all inputs
 - Matching case- «case?»
 - Allowes for don’t care’s

```
process(input) is
begin
  case input is
    when x"1" | x"2" | x"3" | x"5" | x"7" |x"b" | x"d" =>
      isprime <= '1';
    when others => isprime <= '0';
  end case;
end process;
```

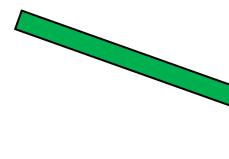
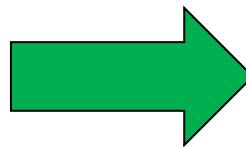
The typical use-case for case is state machines.

Case is excellent when you want to set several output vectors depending on one state vector.

Case creating latches:

Default values can be a good solution when using case statements.

'null' statement should only be used in CL when using default values for all outputs.



```
process(input) is
begin
    isprime <= '0';
    isfour <= '0';
    case input is
        when x"1" | x"2" | x"3" | x"5" | x"7" | x"b" | x"d" =>
            isprime <= '1';
            isfour <= '0';
        when x"4" =>
            isprime <= '0';
            isfour <= '1';
        when others =>
            null;
    end case;
end process;
```

= latch inferred

When ... else

- Can be used concurrently (outside processes).
- **Multiple conditions**
- **Single target**
- prioritizes

- Can replace if statements for *single target*
- Can infer FF's/latches
- Compact
 - Suitable when complexity is low

```
isprime <=
  '1' when input = x"1" else
  '1' when input = x"2" else
  '1' when input = x"3" else
  '1' when input = x"5" else
  '1' when input = x"7" else
  '1' when input = x"b" else
  '1' when input = x"d" else
  '0';
```

```
q <= '0' when reset else 'd' when rising_edge(clk);
a <= b when en;
```

^^ always keep '**else**' in mind...

with ... select "Selected statement"

- Can be used concurrently
- **single input vector**
- **Single target**
 - Must have all input cases defined
- Can also infer latches
 - *Least likely*
 - Feedback obvious ☺
- Compact and readable

```
with input select isprime <=
  '1' when x"1" | x"2" | x"3" | x"5" | x"7" | x"b" | x"d",
  '0' when others;
```

```
with a select g <=
  16d"1" when 16d"1",
  16d"4" when 16d"2",
  16d"8" when 16d"3",
  g when others;
```

If, case, when ... else, with select - summary

- When in doubt...
 - Try '`with...select`'
 - This will force you to make visible choices.
- Only use '`if`'...
 - When you need to prioritize conditions...
 - and have multiple targets
 - Typically used for clocked processes.
- It is fine to `use select...` or `when/else` inside `if` and `case`
 - *Do you need if inside if?..*
 - *Case inside case? ..*
 - Readability suffers when nesting several levels of if or case

Statement	Targets	Conditions	Process
<code>if</code>	<i>Multiple</i>	<i>Multiple</i>	Required
<code>case</code>	<i>Multiple</i>	Single	Required
<code>when ... else</code>	Single	<i>Multiple</i>	Optional
<code>with ... select</code>	Single	Single	Optional

Whatever you choose,
keep the following in mind:

define

- all outputs for
- all conditions

Structural Design

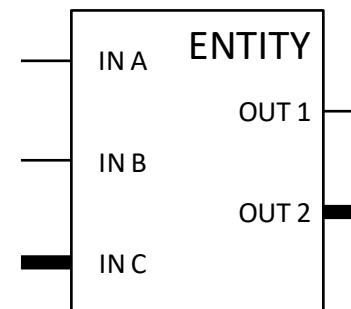
Entity/architecture

- Entity and architecture are the two most fundamental building blocks in VHDL
- Entity
 - Connection to the surroundings
 - Port description
 - Input/output/bi-directional signals
- Architecture
 - Describes behavior
 - An entity can have many architectures
 - Can be used to describe the circuit on several levels of abstraction:
 - Behavioral (for simulation)
 - RTL (Register Transfer Level)
 - Dataflow
 - Structural
 - Post synthesis (netlist)
 - Post Place & Route (netlist + timing)

REPETITION

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity My_thing is
    generic(width: integer := 8);
    port(INA, INB : in STD_LOGIC;
         INC : in STD_LOGIC_VECTOR(width-1 downto 0);
         OUT1: out STD_LOGIC;
         OUT2: out STD_LOGIC_VECTOR( width/2 - 1 downto 0));
end entity My_thing;
```



Generics

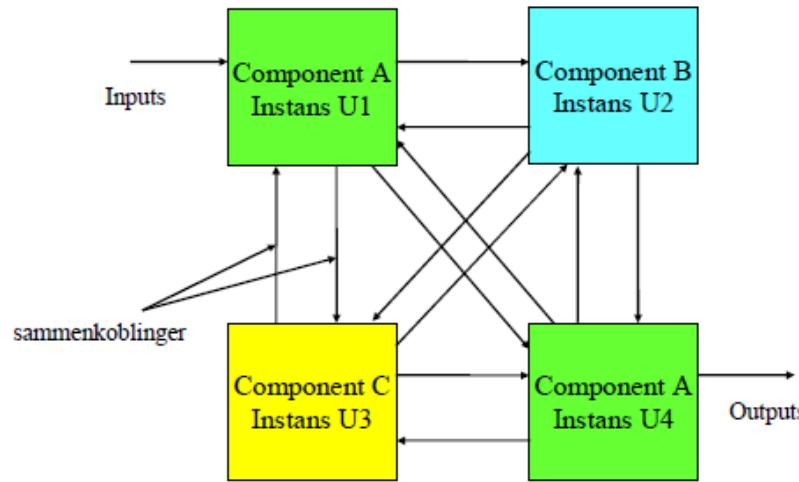
- In addition to the port description an entity can have a generic description
- Generics** can be used to make parameterized components (generic)
 - can be used for structural information
 - both synthesis and simulation
 - can be used for timing information
 - for simulation only
 - Example 1:
 - Time delay can vary between circuits, but the behavior is the same
 - Example 2:
 - The number of bits can vary between circuits, but the behavior is the same

```
24: entity And2 is
25:   generic (delay : DELAY_LENGTH := 10 ns);
26:   port (x, y : in BIT; z: out BIT);
27: end entity And2;
28:
29: architecture ex2 of And2 is
30: begin
31:   z <= x and y after delay;
32: end architecture ex2;
```

```
architecture Structural of My_tb is
  component And2
    port( x,y : in BIT; z : out BIT);
  end component;
  signal a,b,c : BIT;
begin
  MY_COMP1: And2
    generic map(delay => 1 us);
    port map(x=>a, y=>b, z=>c);
end architecture Structural;
```

DELAY_LENGTH is a subtype of the type time from the predefined (always in use) package “std”

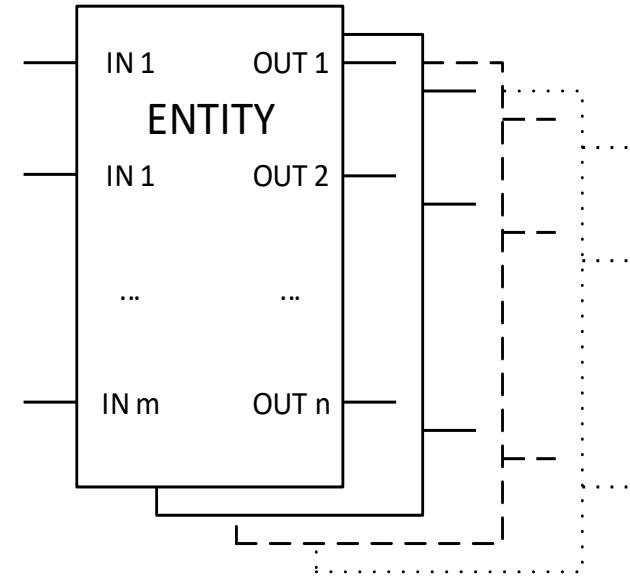
Structural design



- Every Component has an underlying Entity/architecture pair
- Components can be used multiple times
- We *can* make a hierachic design with as many levels we want
 - Try keep design hierarchy manageable...
 - Structural top layer is the norm (for multiple modules)

Structural design

- Reuse of modules (entities and architectures)
- Generic modules (generics)
 - For example scalable bus widths
 - Configurable functionality
- Breaking up big designs to smaller and more manageable building blocks
 - Think functional blocks
 - Connection of functional blocks (entities/components/modules)
- Easier to collaborate within a design team
 - Well defined interface between modules
- Any entity-/architecture pair can be used as a building block in a structural description
 - Pairing of components



Structural design (netlist)

```
25: architecture netlist2 of comb_function is
26:
27:   component And2 is
28:     port (x, y : in BIT; z: out BIT);
29:   end component And2;
30:
31:   component Or2 is
32:     port (x, y : in BIT; z: out BIT);
33:   end component Or2;
34:
35:   component Not1 is
36:     port (x : in BIT; z: out BIT);
37:   end component Not1;
38:
39:   signal p, q, r : BIT;
40:
41: begin
42:   g1: Not1 port map (a, p);
43:   g2: And2 port map (p, b, q);
44:   g3: And2 port map (a, c, r);
45:   g4: Or2 port map (q, r, z);
46: end architecture netlist2;
```

- A netlist is a description of components used, and their connections
 - Synthesizing *is* creating a netlist using the available primitives for a (PL/ASIC) device.
 - The top level in larger designs is normally purely structural
- Component declaration pick up entities from «work» library
- The last compiled architecture are being used unless specified different
- Port mapping:
 - «Association» *can* be done by position
 - Will lead to disasters when making changes.
 - named association is less error prone. ex:
`g1: Not1 port map (x=>a, z=>p);`

Component instantiation

- Instantiation of a declared component

Label: **component** <name> **generic map**(...) **port map**(...);

- The entity of the component is not required for compilation (**for sim: yes**)
- Preferred method in medium to large projects

- Direct instantiation

Label: **entity** <library>.<name>(<arch>) **generic map**(...) **port map**(...);

- The instantiated entity must be compiled before use.

Example in next slide

Instantiation example 1/2

Direct instantiation

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

entity adder is
generic(N: positive := 5);
port(
    a, b : in std_logic_vector(N-1 downto 0);
    sum : out std_logic_vector(N downto 0)
);
end entity adder;

architecture RTL of adder is
begin
    sum <= std_logic_vector(
        signed(a(a'left) & a) +
        signed(b(b'left) & b)
    );
end architecture RTL;
```

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

entity instantiate is
port(
    addend, augend : in integer;
    sum : out integer
);
end entity instantiate;

architecture direct of instantiate is
constant size : positive := 8;
signal std_sum : std_logic_vector(size downto 0);
begin
direct_inst: entity work.adder(rtl)
generic map(N => size)
port map(
    a => std_logic_vector(to_signed(addend,size)),
    b => std_logic_vector(to_signed(augend,size)),
    sum => std_sum
);
    sum <= to_integer(signed(std_sum));
end architecture direct;
```

2/2 Using component

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

entity instantiate is
  port(
    addend, augend : in integer;
    sum : out integer
  );
end entity instantiate;
```

```
architecture structural of instantiate is
  constant size : positive := 8;
  component adder is
    generic(
      N: positive := 8
    );
    port(
      a, b : in std_logic_vector(N-1 downto 0);
      sum : out std_logic_vector(N downto 0)
    );
  end component;

  signal std_sum : std_logic_vector(size downto 0);
begin
  -- "component" is optional
  direct_inst: component adder
    generic map(N => size)
    port map(
      a => std_logic_vector(to_signed(addend,size)),
      b => std_logic_vector(to_signed(augend,size)),
      sum => std_sum
    );
  sum <= to_integer(signed(std_sum));
end architecture structural;
```

Loops in VHDL

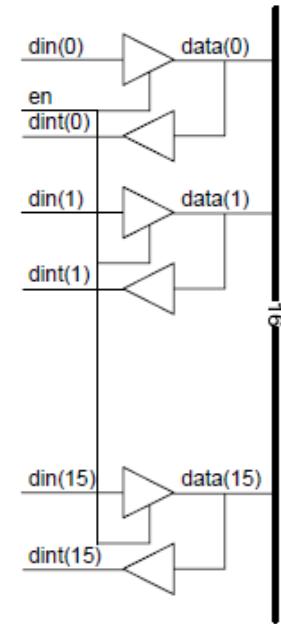
- Both simulation and synthesizable code
- Three types
 - Simple loop- until exit
 - While- loop condition is true
 - For loop
 - Counted
 - Numbers or elements/ ‘range
 - Loop parameter static
 - Can be increased using ‘next’
 - ‘next when <condition>’
- ‘exit’+(optional loop_label)
 - Can be used in all loops
 - Innermost loop is default
 - Nested loops: use label

```
--SIMPLE LOOP--  
variable i: integer := 0;  
...  
loop  
    statements;  
    i := i + 1;  
    exit when i = 10;  
end loop;  
  
--WHILE LOOP--  
variable i: integer := 0;  
...  
while i < 10 loop  
    statements;  
    i := i + 1;  
end loop;  
  
--FOR LOOP--  
for i in 1 to 10 loop  
    statements;  
end loop;  
  
--FOR LOOP2--  
type frukt_type is (eple, pære, banan);  
...  
frukt_loop: for f in frukt_type loop  
    statements;  
    when <condition1> next frukt_loop;  
    when <condition2> exit frukt_loop;  
end loop;
```

Structural design with generate statement

- **generate** - loop
 - can build multiple components .
 - requires indexable parameters in some connected signals
 - non-indexable signals will be connected to all instances
- Example: Bidirectional bus
- **generate**
 - can be used to conditionally build structures
 - **if** and **case + generate**
 - **Conditions must be resolved at compile-time**
 - only constants/generics, *no signals involved*
 - *This is not runtime-reconfiguration...*

```
bidir_bus_inst: for i in 0 to 15 generate
    buft_inst: buft port map (data(i),en,din(i));
    ibuf_inst: ibuf port map (dint(i),data(i));
end generate;
```



Suggested reading

- D&H 7.1- 7.3 p129-153
 - (The testbench code in 7.2 is not curriculum).
- The instantiation code can be found on
<https://github.uio.no/in3160/lectures/tree/main/week03/instantiation>

IN 3160, IN4160

Combinational building blocks (and their VHDL)

Yngve Hafting



Messages

- Draw.io / Diagrams.net
 - Online tool <https://app.diagrams.net>
 - Download <https://www.drawio.com>
 - editor for diagrams
 - Will be available on this years exam!
 - *replaces hand drawing*
- Access to Lisp...
 - With card: 0500-2400
 - <https://www.mn.uio.no/ifi/om/finn-fram/apningstider/>
 - Do contact studieinfo@ifi.uio.no if this does not work

In this course you will learn about the design of advanced digital systems. This includes programmable logic circuits, a hardware design language and system-on-chip design (processor, memory and logic on a chip). Lab assignments provide practical experience in how real design can be made.

After completion of the course you will:

- understand important principles for design and testing of digital systems
- **understand the relationship between behaviour and different construction criteria**
- **be able to describe advanced digital systems at different levels of detail**
- **be able to perform simulation and synthesis of digital systems.**

Goals for this lesson:

- Know the basic structure and function of widely used combinational structures.
 - Multiplexers
 - Encoders
 - Decoders
 - Arbiter
 - Comparator
 - Shifters
 - ROM

Today: Building blocks

- About dataflow representations
- **Encoders vs Decoders**
- Decoder
- **Multiplexer**
- Encoders
- Arbiters
- **Shifters**
- Comparators
 - VHDL: dataflow vs RTL examples
- **ROM**
- **RAM**

Next lecture:

- Subroutines
- Packages & Libraries
- Sequential (clocked) statements.

Goal:
Recognising & describing
Building blocks

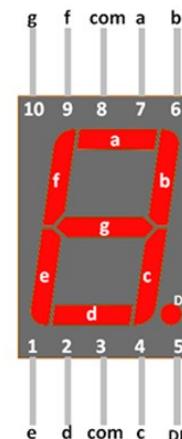
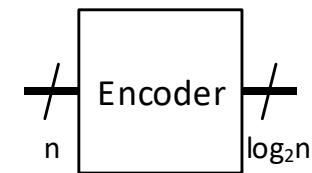
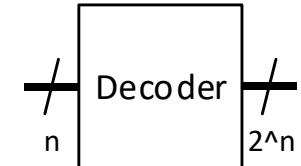
Getting to know more VHDL
techniques...

Data flow representations

- Dataflow
 - Matches port/gate schematics
 - Use *when this is the only way* to achieve desired function
 - Tweaking (speed / area / power).
- *To show how building blocks are made,*
this presentation uses low level representations
 - *Normally we want our code to be at a higher level*
 - easier to read,
 - easier to maintain
 - synthesis tool decide primitives

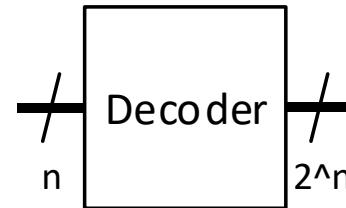
Encoders and decoders

- ... convert signals from one type to another
- Encoder = inverse decoder
- Several types:
 - One hot decoder " $n \rightarrow 2^n$ "
 - Typical use: in multiplexers, memory arrays (RAM, ROM)
 - Binary encoder " $n \rightarrow \log_2(n)$ "
 - Priority encoder
 - Arbiter
- Conditional statements generally creates decoders as needed...
- De-/encoders not considered "building blocks"
 - Seven segment decoder
 - 4-5 bit Binary / BCD (binary coded decimal) to 8 bit... (Assignment 6)
 - Quadrature encoder
 - Converts rotational position/ speed to a two-bit pulse train (Assignment 8)



N to 2^N Decoder

- Ex: generic N to 2^N decoder
 - (binary to *one hot* converter)
- Demonstrates strict type check in VHDL
 - numeric_std is required for ‘`unsigned`’ and ‘`integer`’ conversions



```

library IEEE;
use IEEE.std_logic_1164.all;
use IEEE.numeric_std.all;

entity decoder is
  generic(n : positive := 4);
  port(
    a: in std_logic_vector(n-1 downto 0);
    z: out std_logic_vector(2**n-1 downto 0)
  );
end entity decoder;

architecture rotate of decoder is
  constant one_vector : unsigned(z'range):= to_unsigned(1, z'high+1);
begin
  z <= std_logic_vector(one_vector sll to_integer(unsigned(a)));
end architecture rotate;

-- signal shift: integer;
-- shift <= to_integer(unsigned(a));
-- z <= std_logic_vector(one sll shift);
  
```

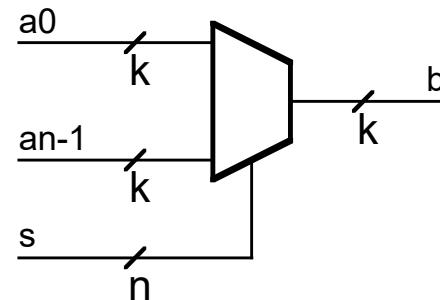
Total amount of bits

integer 1

Annotations highlight the use of `to_unsigned` and `to_integer` conversions.

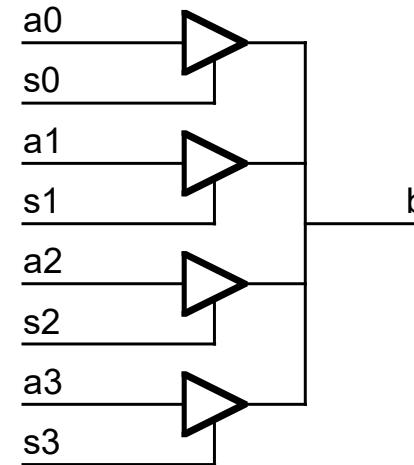
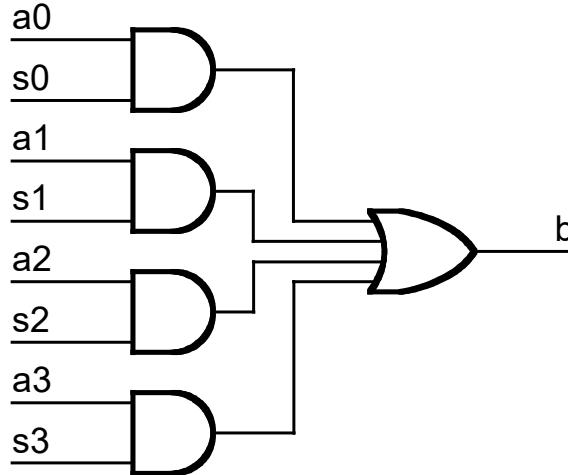
Multiplexer

- k-bit Binary-Select Multiplexer:
 - n k-bit inputs
 - n-bit one-hot select signal s
 - Multiplexers are commonly used as *data selectors*

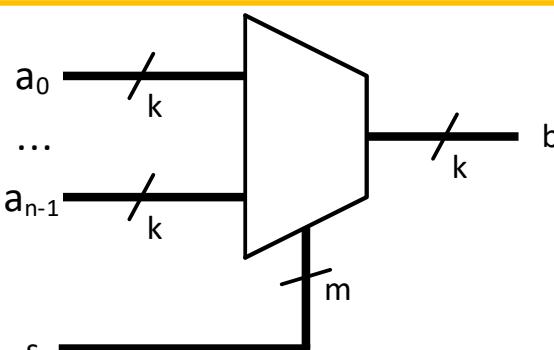
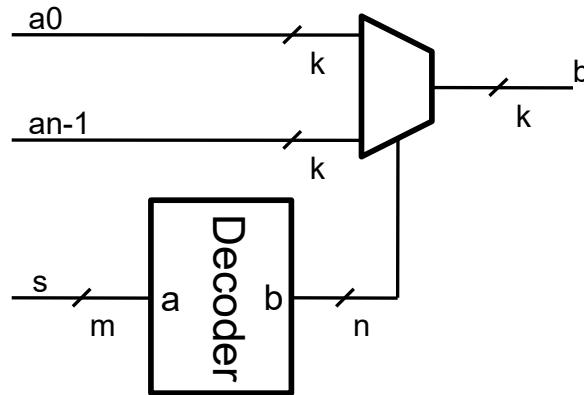


Selects one of n k-bit inputs
s must be one-hot
 $b = a[i] \text{ if } s[i]=1$

Multiplexer Implementation

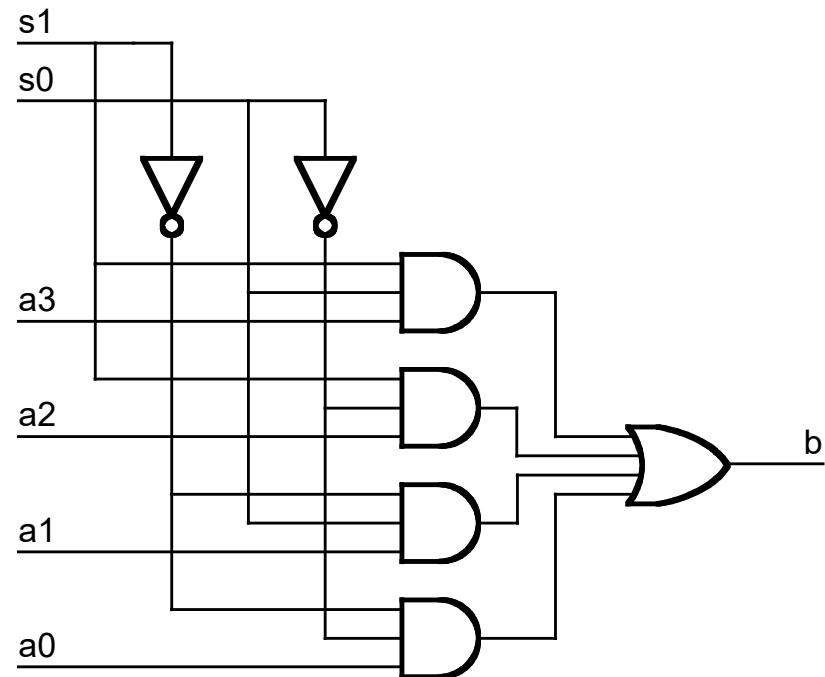


k-bit Binary-Select Multiplexer (Cont)



Normally, the decoder part is taken for granted

Ex: select 1 out of 4 bit (4 to 1 bit mux)
 $k=1$, $m=2$, $n=4$



```
-- three input mux with one-hot select (arbitrary width)
library ieee;
use ieee.std_logic_1164.all;

entity Mux3a is
    generic( k : integer := 1 );
    port( a2, a1, a0 : in std_logic_vector( k-1 downto 0 ); -- inputs
          s : in std_logic_vector( 2 downto 0 ); -- one-hot select
          b : out std_logic_vector( k-1 downto 0 ) );
end Mux3a;

architecture case_impl of Mux3a is
begin
    process(all) begin
        case s is
            when "001" => b <= a0;
            when "010" => b <= a1;
            when "100" => b <= a2;
            when others => b <= (others => '-');
        end case;
    end process;
end case_impl;
```

```
architecture select_impl of Mux3a is
begin
    with s select b <=
        a0 when "001",
        a1 when "010",
        a2 when "100",
        (others => '-') when others;
end select_impl;
```

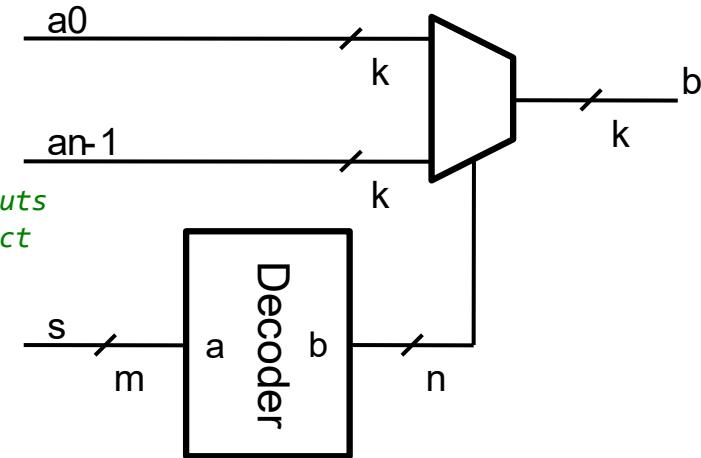
- Can this be implemented using ‘**select**’ statement?
 - Single input vector
 - Single output vector...
 - QED...

Structural Implementation of k-bit Binary-Select Multiplexer

```
-- 3:1 multiplexer with binary select (arbitrary width)
library ieee;
use ieee.std_logic_1164.all;
use work.ch8.all; -- D&H Library with generic decoder

entity Muxb3 is
    generic(k : integer:= 1);
    port(
        a2, a1, a0 : in std_logic_vector(k-1 downto 0); -- 3 k-bit inputs
        sb         : in std_logic_vector(1 downto 0);    -- binary select
        b          : out std_logic_vector(k-1 downto 0)
    );
end Muxb3;

architecture struct_impl of Muxb3 is
    signal s: std_logic_vector(2 downto 0);
begin
    -- decoder converts binary to one-hot
    d: Dec generic map(2,3) port map(sb,s);
    -- multiplexer selects input
    mx: Mux3 generic map(k) port map(a2,a1,a0,s,b);
end struct_impl;
```



Binary Encoder (*output is the number of most significant bit set*)

Don't cares vs ordered priority:

```
architecture dont_care of priority is
begin
    with a select y <=
        "00" when "0001",
        "01" when "001-",
        "10" when "01--",
        "11" when "1---",
        "00" when others;

    with a select valid <=
        '1' when "1---" | "01--" | "001-" | "0001",
        '0' when others;
end architecture dont_care;
```

A3	A2	A1	A0	Y1	Y0	Valid
0	0	0	0	0	0	0
0	0	0	1	0	0	1
0	0	1	-	0	1	1
0	1	-	-	1	0	1
1	-	-	-	1	1	1

```
architecture ordered of priority is
begin
    y <=
        "11" when a(3) else
        "10" when a(2) else
        "01" when a(1) else
        "00" when a(0) else
        "00";

    valid <= or a;

    --valid <='0' when a="0000" else '1';
end architecture ordered;
```

Selected and when-else statement

- Two checks on the same signal
 - = Small maintainability issue compared to *case*
- Don't cares in dataflow representations-
 - may help the synthesizer pick glitch free implementations (ref. karnaugh diagrams)

Don't cares vs sequential ordered priority

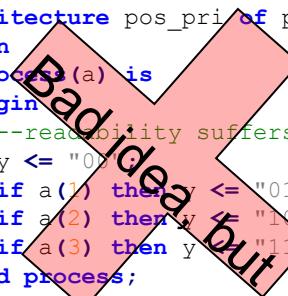
```
architecture mcase of priority is
begin
  process(a) is
    begin
      --default values
      y <= "00";
      valid <= '1';
      case? a is
        when "0001" => y <= "00";
        when "001-" => y <= "01";
        when "01--" => y <= "10";
        when "1---" => y <= "11";
        when others => valid <= '0';
      end case?;
    end process;
  end architecture mcase;
```

```
architecture default_if of priority is
begin
  process(a) is
    begin
      --default values
      y <= "00";
      valid <= '1';
      if a(3) then y <= "11";
      elsif a(2) then y <= "10";
      elsif a(1) then y <= "01";
      elsif a(0) then y <= "00";
      else valid <= '0';
      end if;
    end process;
  end architecture default_if;
```

```
architecture non_default of priority is
begin
  process(a) is
    begin
      --no default values
      if a(3) then
        y <= "11";
        valid <= '1';
      elsif a(2) then
        y <= "10";
        valid <= '1';
      elsif a(1) then
        y <= "01";
        valid <= '1';
      elsif a(0) then
        y <= "00";
        valid <= '1';
      else
        y <= "00";
        valid <= '0';
      end if;
    end process;
  end architecture non_default;
```

Sequential priority (if):

- Easy to forget specifying all outputs for all input options
- Readability suffers as complexity grows



```
architecture pos_pri of priority is
begin
  process(a) is
    begin
      --readability suffers- don't do
      y <= "00";
      if a(1) then y <= "01"; end if;
      if a(2) then y <= "10"; end if;
      if a(3) then y <= "11"; end if;
    end process;
    valid <= or a;
  end architecture pos_pri;
```

Case- or selected- statement is preferred

A3	A2	A1	A0	Y1	Y0	Valid
0	0	0	0	0	0	0
0	0	0	1	0	0	1
0	0	1	-	0	1	1
0	1	-	-	1	0	1
1	-	-	-	1	1	1

Positional priority

- Not normally used in processes
 - Difficult to read
 - Mixing with sequential priority makes it worse
- Can make sense when using loops..
 - => Next page

Generic priority encoder

```

library IEEE;
use IEEE.std_logic_1164.all;
use IEEE.numeric_std.all;

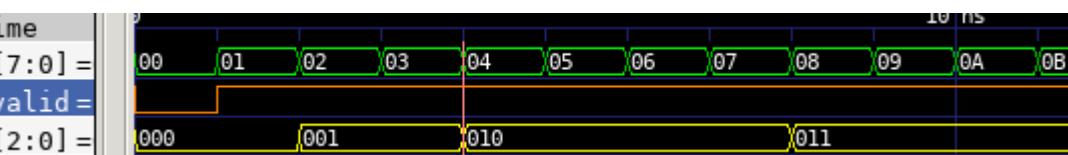
entity priority is
  generic ( n : positive := 2);
  port(
    a : in std_logic_vector(2**n-1 downto 0);
    y : out std_logic_vector(n-1 downto 0);
    valid : out std_logic
  );
end entity priority;

architecture range_iterative of priority is
begin
  process(a) is
  begin
    -- default values
    valid <= '0';
    y <= (others => '0');

    -- iterate i from 2**n - 1 down to 0
    -- set y to i when the highest bit is true
    for i in a'range loop
      if a(i) = '1' then
        y <= std_logic_vector(to_unsigned(i,n));
        valid <= '1';
        exit; -- without exit (loop exit),
        end if; -- lower bits would be prioritized
      end loop;
    end process;
  end architecture range_iterative;

```

These architectures are equivalent = Does the same



```

architecture reverse_range_iterative of priority is
begin
  process(a) is
  begin
    -- default values
    valid <= '0';
    y <= (others => '0');

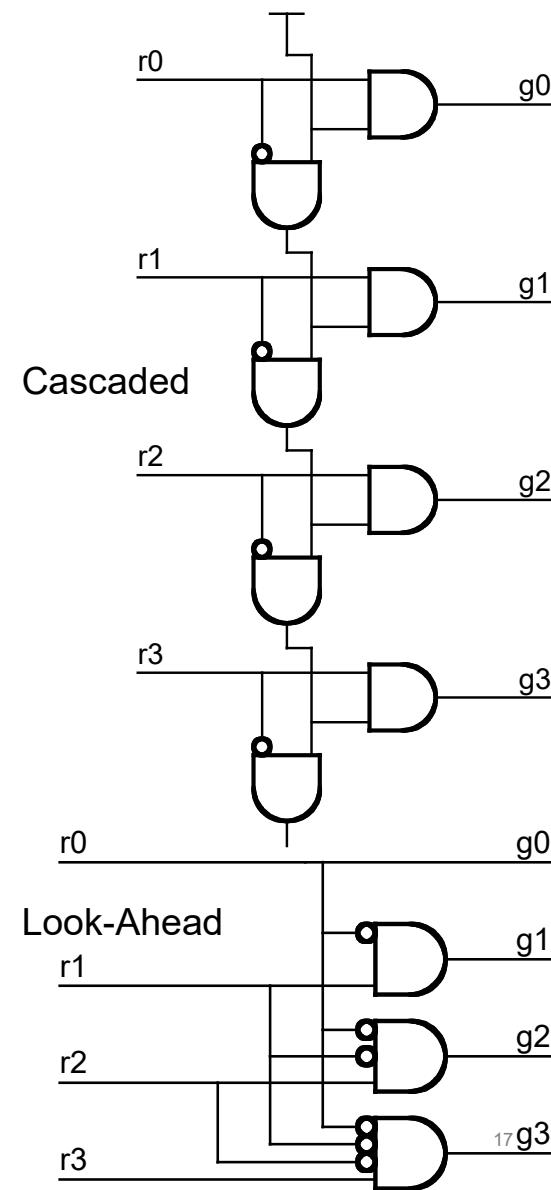
    -- iterate from 0 to 2**n-1
    for i in a'reverse_range loop
      if a(i) = '1' then
        y <= std_logic_vector(to_unsigned(i,n));
        valid <= '1';
      end if; -- no exit, means the last iteration (i=2**n-1)
    end loop;
  end process;
end architecture reverse_range_iterative;

```

NOTE: All iterations create HW
how we iterate determine priority
There is no "conditional execution"

Arbiter

- Arbiters are used to sort requests for resources
 - interrupt handling in a CPU or microprocessor
 - Finds the least (or most significant) one-bit
 - cascaded vs look-ahead principle
 - VHDL = priority encoder (previous page).
 - Normally we let synthesis tool decide
 - FPGA => mostly LUT based
 - Structural code may bind a solution
 - Is it a critical feature?
 - Does not synthesis provide desired result?



Priority encoder test bench

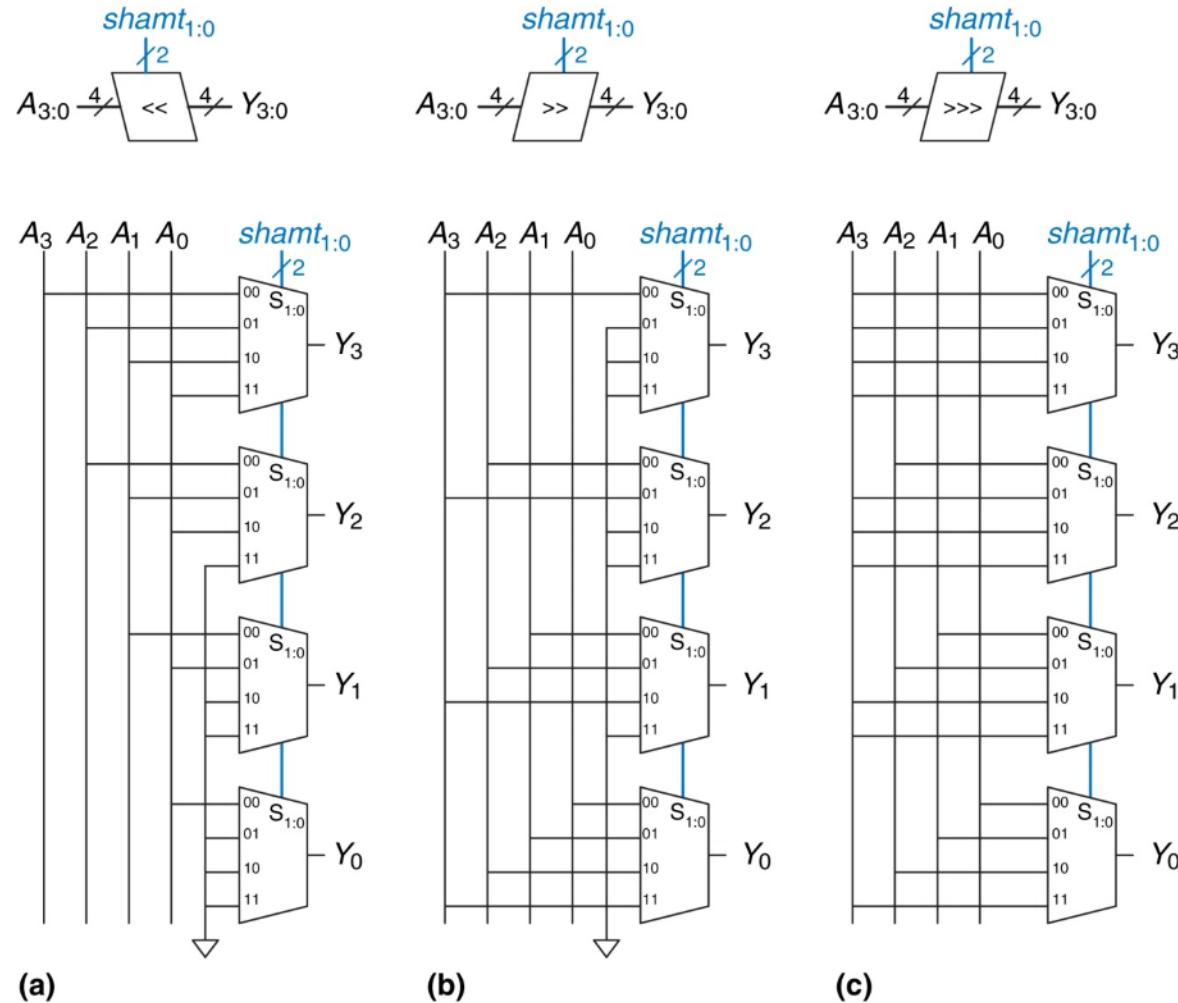
- The example makes stimuli to a combinational function independent of number of bits
- The attribute x'high gives the highest bit number to the vector x and x'low the lowest bit number
- Python equivalent tb code:

```
STIMULI :  
process  
    variable ain : integer := 0;  
begin  
    loop  
        for ain in 0 to 2**(a'high-a'low+1)-1 loop  
            a <= std_logic_vector  
                (TO_UNSIGNED(ain, a'high-a'low+1));  
            wait for 50 ns;  
        end loop;  
    end loop;  
end process;
```

```
async def stimuli_generator(dut):  
    ''' Generates all data for this tesbench'''  
    for i in range( 2**len(dut.a)):  
        dut.a.value = i  
        await Timer(1, units= 'ns')
```

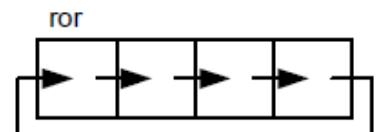
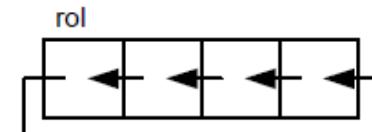
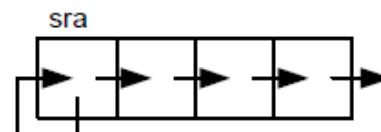
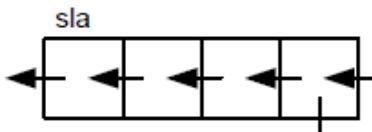
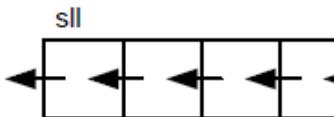
Shifters

- Ex, 4 bit :
 - a) SLL
 - b) SRL
 - c) SRA



Shift operators in VHDL

- The shift operators are defined for **bit_vector** (originally)
 - and **unsigned** and **signed** in **numeric_std**
- If you are defining shift operators for other types, you have to make so called “overload”-operators
- By overload we mean that there are an already existing operator with the same name, but is written for another data type



```
-- simple shift left operation in VHDL
variable n : positive := 5;
...
a(31 downto n) <= a(31-n downto 0); -- a'high is 31,
a(n-1 downto 0) <= (others => '0'); -- a'low is 0.
```

```
-- using sll (requires numeric_std library)
a <= std_logic_vector( to_unsigned(a) sll(n) );
```

Shift operators

- The standard libraries does not define shift operators for `std_logic_vector`
- The standard synthesis library `numeric_std` defines two data types which are sub types of `std_logic`:
 - `unsigned`
 - `signed`
 - For these two it exists shift operators (overload)
- Use type casting to go between `std_logic_vector` and `signed` / `unsigned`

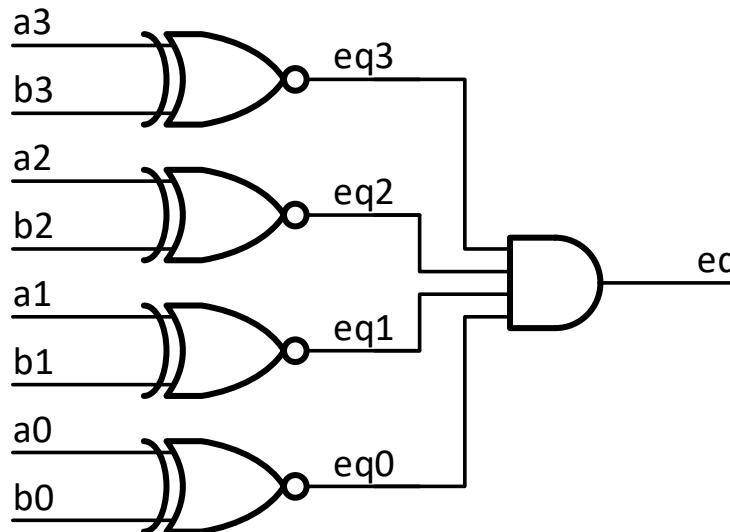
```
-- a is std_logic_vector.  
a <= std_logic_vector( to_unsigned(a) sll (n) );
```

Comparators

- Equality ‘=’
- Magnitude ‘<’, ‘>’

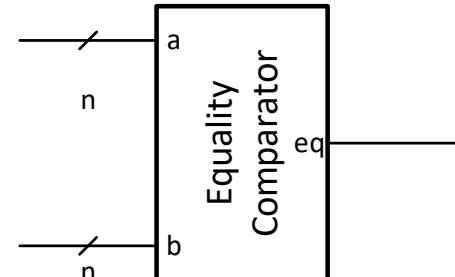
Equality Comparator

Is true when both input vectors are equal



```
eq <= '1' when (a = b) else '0';
```

```
-- Dataflow: eq <= and (a xnor b);
```



```
-- high level comparator usage, IF (inside process)
if (a = b) then
    p <= q;
else
    p <= (others => '0');
end if;

-- high level comparator usage, WHEN ... ELSE
p <= q when (a = b) else (others => '0');
```

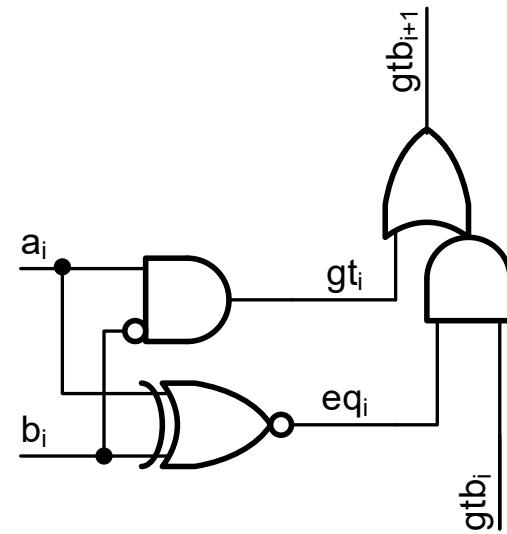
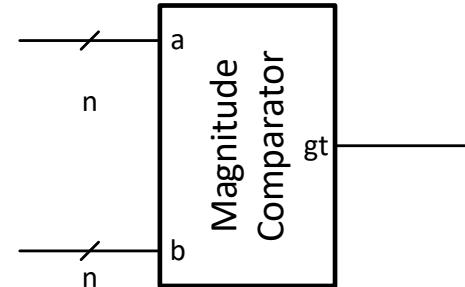
Magnitude Comparator

- **if** ($a > b$) **then** ...'
- will infer what you need most of the time
- Dataflow example.

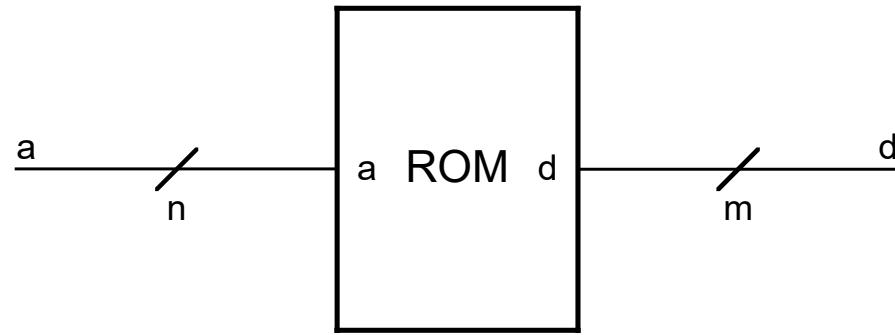
```
library ieee;
use ieee.std_logic_1164.all;

entity MagComp is
  generic( k: integer := 8 );
  port( a, b: in std_logic_vector(k-1 downto 0);
        gt: out std_logic );
end MagComp;

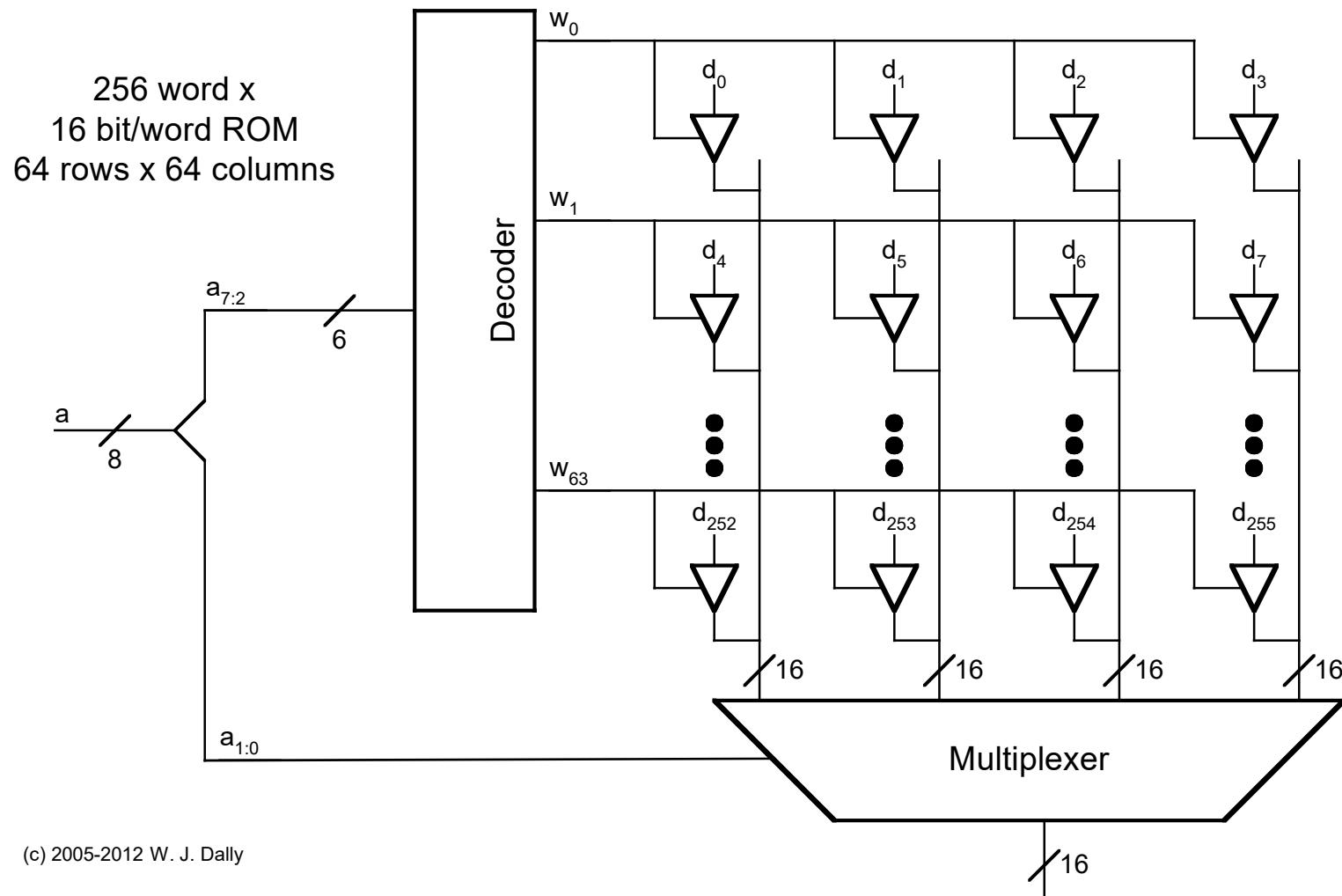
architecture impl of MagComp is
  signal eqi, gti : std_logic_vector(k-1 downto 0);
  signal gtb: std_logic_vector(k downto 0);
begin
  begin
    eqi <= a xnor b;
    gti <= a and not b;
    gtb <= (gti or (eqi and gtb(k-1 downto 0))) & '0';
    gt <= gtb(k);
  end impl;
```



Read-only memory (ROM)



2-D array implementation



ROM using VHDL

- ROM can be implemented using
 - `select`'ed statement
 - `case`
 - D&H demonstrates this.
 - `constant`'s
 - Example next slide
- File IO can be used to store ROM values.
 - Tools may be picky about implementations.
 - *We will look into that later.*

Example: ROM

```

library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;

entity ROM is
  generic(
    data_width: natural := 8;
    addr_width: natural := 2);
  port(
    address: in std_logic_vector(addr_width-1 downto 0);
    data: out std_logic_vector(data_width-1 downto 0));
end entity;

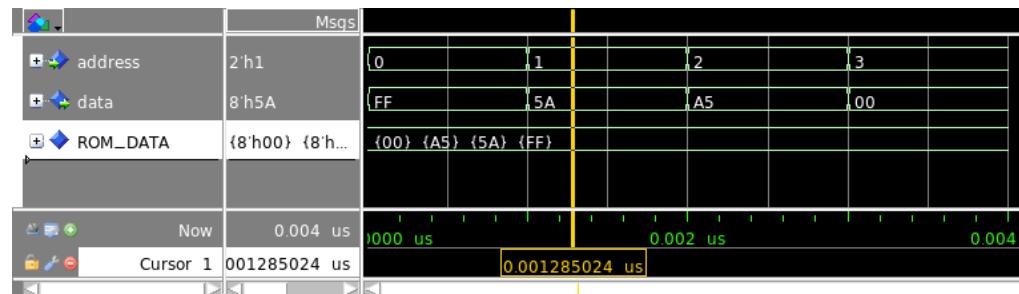
architecture synth of ROM is
  type memory_array is array(2**addr_width-1 downto 0) of
    std_logic_vector(data_width-1 downto 0);

  constant ROM_DATA: memory_array := (
    8x"00", -- address 3 (from 'left to 'right)
    8x"A5", -- address 2
    8x"5A", -- address 1
    8x"FF" -- address 0
  );

begin
  data <= ROM_DATA(to_integer(unsigned(address)));
end architecture synth;

```

- 4 byte ROM example
 - 8 bit data
 - 2 bit address
- We can define array types in VHDL
- Constants are set using :=
- Array data is listed in the sequence given by the type (array) definition
 - Here: $(2^{addr_width-1} \text{ downto } 0) \Rightarrow 3, 2, 1, 0$
- Indexing requires conversion to integer



RAM using VHDL

```

library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;

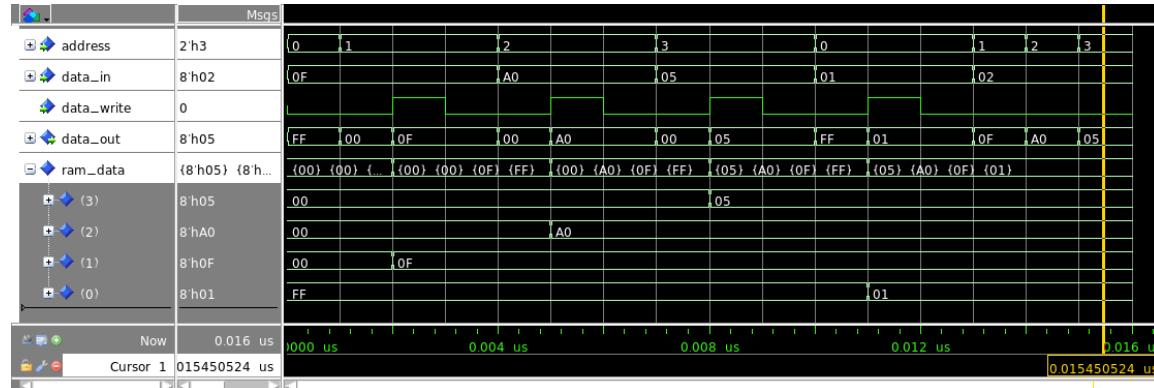
entity RAM is
generic(
    data_width: natural := 8;
    addr_width: natural := 2
);
port(
    address: in std_logic_vector(addr_width-1 downto 0);
    data_in: in std_logic_vector(data_width-1 downto 0);
    data_write: in std_logic;
    data_out: out std_logic_vector(data_width-1 downto 0)
);
end entity RAM;

architecture synth of RAM is
type memory_array is array(2**addr_width-1 downto 0) of
    std_logic_vector(data_width-1 downto 0);

signal ram_data: memory_array :=
    (8x"00", 8x"00", 8x"00", 8x"FF");
begin
    data_out <=
        ram_data(to_integer(unsigned(address)));
    ram_data(to_integer(unsigned(address))) <=
        data_in when data_write; -- else latched
end architecture synth;

```

- 4 Byte RAM example
- Mostly like the ROM example
 - Added write and data_in
 - Data is a **signal**, not **constant**
- Signals *may* have default values in synthesis (RAM based FPGAs)
- Writing is latched
 - *not combinational*



Suggested reading

- D&H 8.1- 8.9 p157-192
- *(8.10 PLA -> Architecture)*

IN3160, IN4160

1: Subroutines, packages and libraries

2: Clocked statements



Messages

- Remember to **log out** after using the lab machines
 - Reduces the need for reboot (USB port locked to user)
- Peer review oblig 3
 - In time = automatically assigned
 - Late = manual assignment Monday
 - On sick leave = by appointment
 - Be polite!
 - Reviewing others work is frequently used in industry.

Goal

- Learn how to create subroutines using VHDL
- Learn good practice for writing subroutines
- Learn which packages are most used in VHDL
- Learn how to use and create libraries and packages in VHDL

Overview

- Subroutine types
 - Functions
 - Procedures
- Functions and operators
- Procedures
- Overloading in VHDL
- Libraries
 - Package/package body
- Standard libraries
- **Clocked statements**

Next: Verification & file IO ⁴

Why Subroutines

- *avoid duplicating code*
 - Make the code more readable
 - Reduce code complexity
 - Make the code easier to maintain
 - Make code easier to test or verify

VHDL Subroutine types and practice:

- Two types:
 - Functions – *returns one value*
 - = *CL*
 - Procedures – *a group of statements*
- General good practice:
 - **use functions!**
 - Limit the use of procedures to structural code or testbenches
 - Consider functions, entities or processes before using procedures

Functions-

- take one or more parameters
 - Parameters in functions
 - Can not be changed/manipulated
 - always mode “in”
 - (only) *constant, signal or file*
 - constant is default*
 - Parameters are separated by ‘;’
(a: **bit**; b: **my_type**; ...)
- return only a single value
 - The value can be of any *type*
 - Including vectors and custom types*
- pure* functions use only their input parameters => CL
- Impure* functions make use of data visible where they are declared (as parameters)
 - Ex: File IO (next lecture)
- Cannot have wait- statements. (single event / completes within a single delta delay)
- Cannot have internal signals (no storage)



```

function sum_function(vect: integer_vector) return integer is
    variable sum: integer := 0;
begin
    for i in vect'range loop
        sum := sum + vect(i);
    end loop;
    return sum;
end;
  
```

```

b <= std_logic_vector(to_signed(
    sum_function(( ←
        to_integer(signed(a2)),
        to_integer(signed(a1)),
        to_integer(signed(a0)) )),
    b'high - b'low + 1 ) );
  
```

The «extra» parenthesis is needed to make one vector out of the three integers. Without, they will be interpreted as three separate parameters of wrong type

Function usage example:

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

entity subprogram is
    generic( k: positive := 4 );
    port(
        a2, a1, a0: in std_logic_vector(k-1 downto 0);
        b : out std_logic_vector(k-1 downto 0) );
end subprogram;

architecture example of subprogram is
    function sum_function(vect: integer_vector)
        return integer is
        variable sum: integer := 0;
    begin
        for i in vect'range loop
            sum := sum + vect(i);
        end loop;
        return sum;
    end;

begin
    local: process(all) is
        variable v: integer_vector(2 downto 0);
        variable sum: integer;
        variable s: signed(b'high-b'low downto b'low);
    begin
        v:=( 
            to_integer(signed(a2)),
            to_integer(signed(a1)),
            to_integer(signed(a0)) );

        sum := sum_function(v);

        s := to_signed(sum, b'high - b'low + 1);
        b <= std_logic_vector(s);
    end process local;
end architecture example;
```

More Functions...

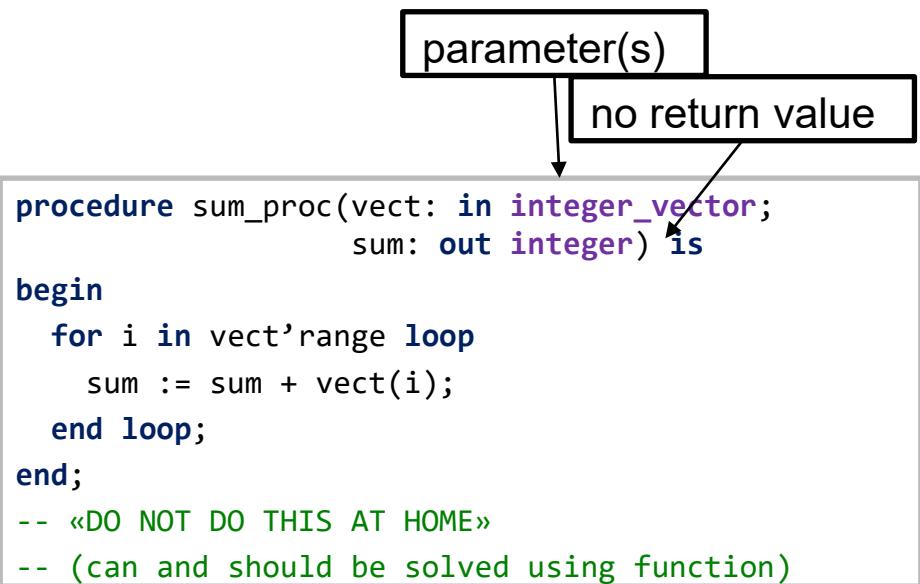
- Can be used for both synthesis and simulation
- Can (also) be *overloaded* (two or more functions having same name)
 - different parameters and or return type
- Are declared in the declarative region of
 - architectures
 - processes
 - packages (declaration and body – example later)
- Are frequently used for
 - Computation
 - Type converting
- Packages in libraries we use typically define functions
 - IEEE (library)
 - std_logic_1164 (package)
 - numeric_std
 - ...
 - *We use these all the time...*

```
architecture func_arch of functest is
    -- declarations
    function bool2bit(a: boolean) return bit is
        begin
            if a then
                return '1';
            else
                return '0';
            end if;
        end bool2bit;

    -- statements
    begin
        ...
    end func_arch;
```

Procedures...

- do not have a return value
- can have
 - **in** and **out** parameters
 - in is default
 - out parameters (must be set)
 - **wait** statements
 - signals
 - file access
- cannot be used in a statement
 - Only standalone «calls»
- Are typically used in test benches
 - Reading test vectors from file
 - Applying test vectors
 - Writing test results to file



- ! • Can manipulate both **out**-parameters and other **signals** declared in the same (underlying) region...
- !

Example- when not to use procedure:

```

process(all) is
  variable v: integer_vector(2 downto 0);
  variable sum: integer;
  variable s: signed(b'high-b'low downto b'low);
begin
  v:=(
    to_integer(signed(a2)),
    to_integer(signed(a1)),
    to_integer(signed(a0)) );
  sum := sum_function(v);
  s := to_signed(sum, b'high - b'low + 1);
  c <= std_logic_vector(s);
end process local;

```

Only difference apart from declarations (previous slides)

```

process(all) is
  variable v: integer_vector(2 downto 0);
  variable sum: integer;
  variable s: signed(b'high-b'low downto b'low);
begin
  v:=(
    to_integer(signed(a2)),
    to_integer(signed(a1)),
    to_integer(signed(a0)) );
  sum_proc(v,sum);
  s := to_signed(sum, b'high - b'low + 1);
  d <= std_logic_vector(s);
end process;

```

a2	-4'd3	X	3		-3
a1	4'd2	X	2		
a0	-4'd1	X	-1	1	-1
c	-4'd2	0	4	6	-2
d	-4'd8	0	4	-6	-8

- Why aren't c and d equal?

- the procedure is not CL.
 - sum accumulates
 - process variable -> single instantiation
- In HW, d would be unstable due to this feedback loop, since the process is not clocked.
- -6 and -8 is the result of the 4 digit two-complement representation.

Functions vs Procedures

Functions	Procedures
Returns a value (<i>can be vector</i>) of any type	A collection of statements (Sets signals)
Can only use variables, no signals.	Can contain both signals and variables that will be hidden from the outside. May use signals from the underlying structure.
Cannot replace procedures fully	<i>Can</i> replace functions (DON'T DO THAT!)
Much used in conversions (from bit to STD_LOGIC, from some_type to my_type, etc).	Much used for repetitive tasks- particularly in test benches.
Typically found in libraries and packages	<i>Mostly used for simulation/ test benches.</i>
Always “instant” (CL), never time based	Can use “wait” and timing information.
Can be used in statements... <code>a <= my_func(...);</code>	Can only be used standalone... <code>my_procedure(..);</code>

Neither can store internal values between calls.

Parameters for subprograms

Parameters or «interface objects» have up to five parts

1. Class : **constant** (default), **variable**, **signal**, **file**
2. Identifier: the name you decide must be defined
3. Mode: **in** (default) or **out**
4. Type: **std_logic**, **integer**, **bit**, **text**, ... must be defined
5. Default value := optional

Ex:

```
procedure apply_vectors(
    file vector_input : text;
    addend : integer := 42;
    signal valid : out boolean;
    file vector_output : text);
```

Good practice

- When considering to create a subprogram:
 - Is it possible to do this using a function?
 - Yes: **use function**
 - No:... Is it for creating HW?
 - If yes: consider a process, or a separate entity + architecture
 - Is it for simulation only, and a function will not do:
 - Use a procedure
- Subprograms generally should have a single purpose.
 - Try see if the purpose can be said in one sentence without use of “and” or “or”...

Good practice

- Use functions when you can
 - Limitations in functions makes it easier to achieve well structured code
 - readable
 - maintainable
 - short
- Limit procedures to structural code (or testbenches)
 - It is easy to create messy code using procedures since they allow
 - multiple in and out parameters
 - to use signals and create storage elements

Packages

- In a package declarative region you can add:
 - Component declarations
 - Data type definitions
 - Constants
 - Subprogram declarations
 - Functions
 - Procedures
- The declarative region is publicly visible
 - similar to header files in C
- Package body-
 - declarations is not publicly visible
 - typically contains content of-
 - subprograms
 - components

```
package my_pkg is
    -- publicly visible declarations
    type imb_vec is record
        re: bit_vector;
        im: bit_vector;
    end record;

    constant IMB_VEC1: imb_vec := (re => "010", im => "001");
    function bool2bit(a: boolean) return bit;
    ...
end;

Package body my_pkg is
    -- non visible, internal declarations
    function bool2bit(a: boolean) return bit is
        begin
        ...
    end bool2bit;
    ...
end my_pkg;
```

Packages

Save and compile your package in the work folder

To use package contents, include these two lines:

```
1 library work;  
2 use work.my_package.all;
```

```
1 -- Package Declaration Section  
2 package my_package is  
3  
4     constant c_PIXELS : integer := 65536;  
5  
6     type t_my_rec is record  
7         full: std_logic;  
8         empty: std_logic;  
9     end record t_my_rec;  
10  
11    component my_component is  
12        port (i_data : in std_logic; o_res : out std_logic);  
13    end component my_component;  
14  
15    function Bit_OR (i_vec : in std_logic_vector(3 downto 0))  
16        return std_logic;  
17  
18 end package my_package;  
19  
20 -- Package Body Section  
21 package body my_package is  
22  
23     function Bit_OR (i_vec : in std_logic_vector(3 downto 0))  
24         return std_logic is  
25     begin  
26         return (i_vec (0) or i_vec (1) or i_vec (2) or i_vec (3));  
27     end;  
28  
29 end package body my_package;
```

Typical use of packages

- Typically packages is organized such that it contains
 - custom or abstract data types
 - Ex: I have a project that will incorporate calendar data
 - => lets make a package for all types used
 - functions that work on these abstract data types.
- Create packages when you have
 - function(s) that may be used by more than one design unit.
 - Types that may be used in several design units
 - Components that may be used in several designs
 - Simulation -models, -procedures and -functions that can be re-used

Use of functions library

- A “package/body” pair can be compiled to work or to another library.
 - This needs to have a logic name. Here: mylib
- The logic name is given in the current tool and is reflected in the directory structure of the tool

```
use work.my_func.all;
-- eller
-- use.work.my_func.bl2bit;
-- dersom bare bl2bit skal gjøres synlig

entity .....
architecture ...
signal a: BOOLEAN;
signal b: bit;
begin
  b <= bl2bit(a);
end architecture ...;
```

```
library mylib;
use my_lib.my_func.all;
-- eller
-- use.my_lib.my_func.bl2bit;
-- dersom bare bl2bit skal gjøres synlig
```

Operators

- Operators are defined in the same way as functions, but by “<operator name>”
- Operators are being used differently from functions
- You can create overloaded operators (ie ‘+’ for my_type),
 - *but not create new*

```
-- package declaration (overload)
function "+" (a,b :std_logic_vector) return std_logic_vector;
...
-- usage
sum <= a + b;

-- package declaration (non overload)
function add (a,b :std_logic_vector) return std_logic_vector;
...
-- usage
sum <= add(a, b);
```

Overloading

- **Overloading** means defining the same operator-, function- or procedure-name for different data types or a mix of data types.
- Overloaded subprograms (operators, functions and procedures) may have different number of parameters
- Synthesis tools separates the usage of overloaded subprograms by comparing actual parameters (those in use) with formal parameters (in the subprogram declaration)

Overloading

- There are a lot of standard libraries with overload operators, functions and procedures in IEEE 1164 and IEEE 1076.3
 - IEEE 1164
 - **Package std_logic_1164**
 - Synopsis libraries (compiled to IEEE, but not standard)
 - Package std_logic_unsigned
 - Package std_logic_signed
 - Package std_logic_arith
 - Package std_logic_textio
 - *Don't use these in this course.*
 - » Std libraries covers the usage and there are some differences.
 - IEEE 1076.3
 - **Package numeric_std**
 - Use the package IEEE.numeric_std for integer arithmetics with the use of the data types **signed** and **unsigned**

IN 3160, IN4160

Clocked processes and statements

Yngve Hafting



Course Goals and Learning Outcome

<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

In this course you will learn about the design of advanced digital systems. This includes programmable logic circuits, a hardware design language and system-on-chip design (processor, memory and logic on a chip). Lab assignments provide practical experience in how real design can be made.

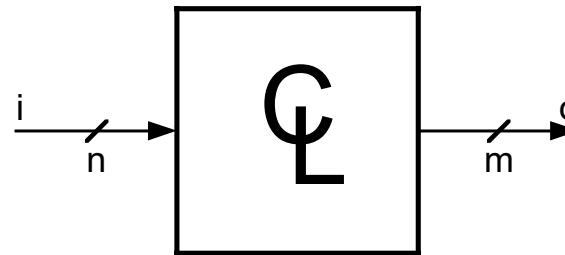
After completion of the course you will:

- understand important principles for design and testing of digital systems
- **understand the relationship between behaviour and different construction criteria**
- **be able to describe advanced digital systems at different levels of detail**
- be able to perform simulation and synthesis of digital systems.

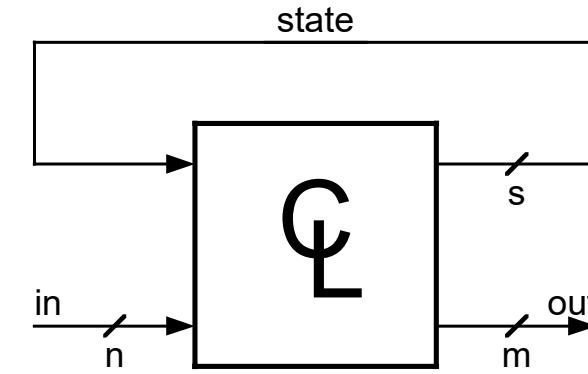
Goals for this lesson:

- Know different approaches to achieve clocked logic in VHDL
 - Why they exists
 - Benefits and pitfalls
 - ...

Sequential logic has state



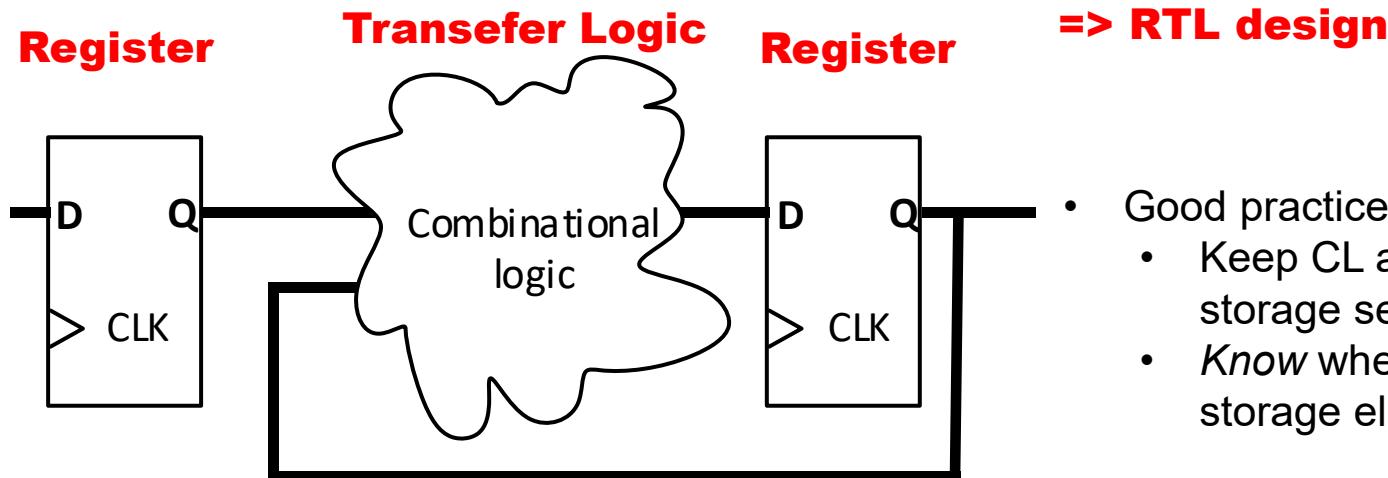
Combinational Logic



Sequential Logic

Do not use feedback into CL without using flipflops!

Sequential design = CL + FFs

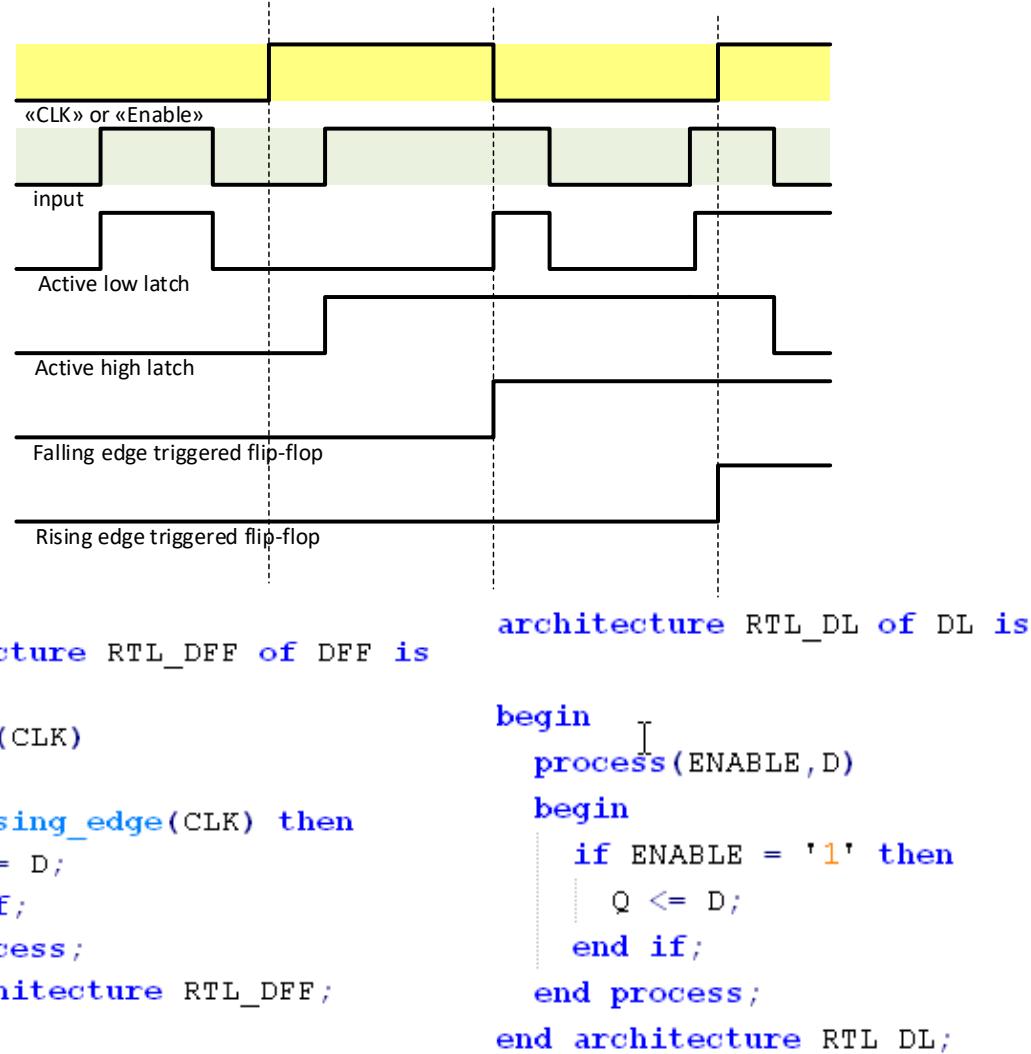


- Sequential designs are state machines
 - Sometimes they have other names
 - *Counters*
 - *Shift Registers*
 - *LFSR – Linear Feedback shift Registers*
 - ...

- Good practice:
 - Keep CL and register storage separate
 - Know when you infer storage elements!

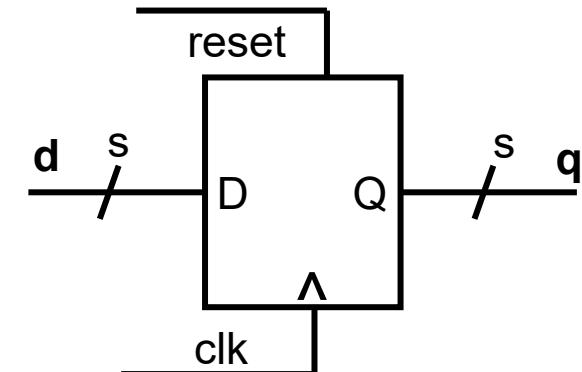
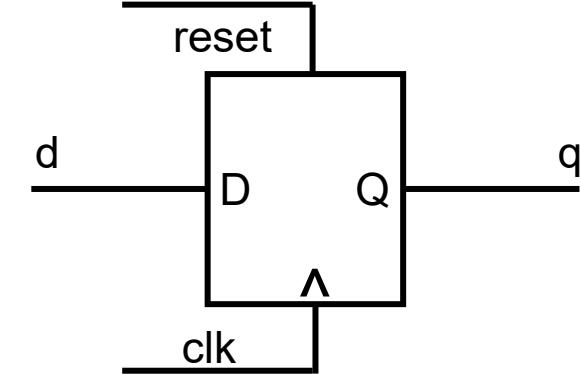
Latch vs Flip-flop

- The functions `rising_edge` and `falling_edge` gives a true (0->1 or 1->0) edge detection
 - `if CLK'event and CLK = '1' then` reacts on all transitions to '1', for example U->1 (*simulation*)
- NB! An *incomplete** conditional statement will be synthesized to a latch (implied memory)
 - *complete defines all outputs for all conditions of the input variable(s).



D Flip-Flop

- Input: D
 - Output: Q
 - Clock
-
- Q outputs a steady value
 - Edge on Clock changes Q to be D
 - Flip-flop stores state
 - Allows sequential circuits to iterate

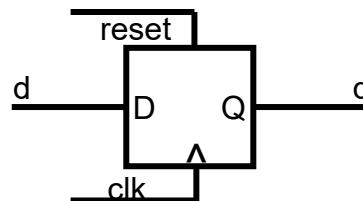


D-flip-flop with asynchronous reset

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

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

```
architecture signal_and_process of DFF is
begin
  process(clk, reset) is
  begin
    if reset then
      q <= '0';
    elsif rising_edge(clk) then
      q <= d;
    end if;
  end process;
end architecture;
```



one-liner... (VHDL 2008 style)

- Use for single async. register assignment.

```
architecture oneliner of DFF is
begin
  q <= '0' when reset else d when rising_edge(clk);
end architecture;
```

- reset has priority
- Both clk and reset in sensitivity lists
 - NEVER use 'all' for clocked sensitivity lists

Variables *can* be used for FF instantiation, but...

No FF is created unless a signal is assigned to the state variable

```
architecture variabled of DFF is
begin
  process(clk, reset) is
    variable state;
  begin
    if reset then
      state := '0';
    elsif rising_edge(clk) then
      state := d;
    end if;
    Q <= state;
  end process;
end architecture;
```

Use when assigning multiple registers in a process

Synchronous D-flip-flop

- Clock has priority
- Only clk in sensitivity list
 - (not reset, and *definitely not 'all'*)

```
architecture synchronous_reset of DFF is
begin
  process(clk) is
  begin
    if rising_edge(clk) then
      if reset then
        q <= '0';
      else
        q <= d;
      end if;
    end if;
  end process;
end architecture;
```

```
architecture sync_compact of DFF is
begin
  process(clk) is
  begin
    if rising_edge(clk) then
      q <= '0' when reset else d;
    end if;
  end process;
end architecture;
```

```
architecture separate_CL of DFF is
  signal next_state : std_logic;
begin
  next_state <= '0' when reset else q;
  q <= next_state when rising_edge(clk);
end architecture;
```

- Use this style when assigning multiple registers

Generally when writing RTL code:

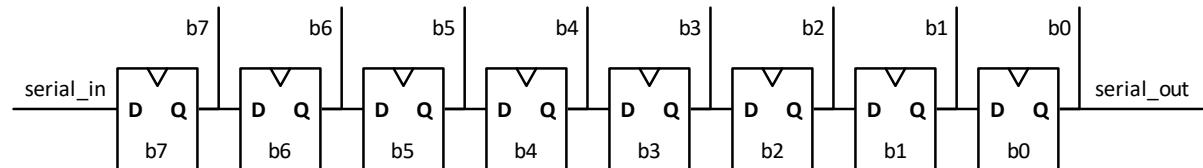
- Separate use of CL and clocked processes
 - Keep (all) register assignment in one process
 - Use one process for each purpose : ex
 - process for state assignment
 - process for state output
 - process for registers
- Avoid unintentional states by not combining CL and registers(!)
- Use synchronous reset unless specific reasons for async reset.
 - (reset circuits will be covered later)
- Simple statements can be written concurrently
 - Use only for 1 or 2 registers

```
architecture RTL of my_entity is
  signal r_x, next_x : std_logic_vector(7 downto 0);
  signal r_y, next_y : <your type>;
begin
  CL: process(all)is
  begin
    -- Create next based on input and registers>
    next_x <= ...
    next_y <= ...
  end process;

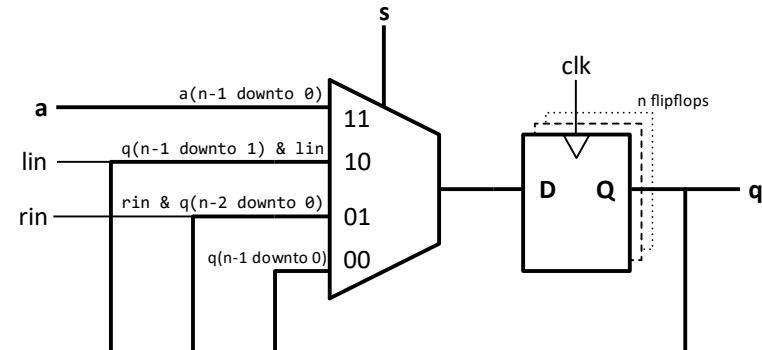
  REG_ASSIGNMENT: process(clk) is
  begin
    if rising_edge(clk) then
      if reset then
        r_x <= (others => '0');
        r_y <= ...; -- depending on your type
      else
        r_x <= next_x;
        r_y <= next_y;
      end if;
    end process;

end architecture;
```

Shift registers (not shifters)



- Shifter = CL
- Shift register = Flipflops connected in series
 - Used to parallelize serial input
 - Serial data transfer is used for high speed IO over distance
 - If largest parallel high speed io is memory buses on a PC main board
 - Can sometimes be used both ways
 - If both serial and parallel in/out
 - Assignment 4 lets you attempt this using structural code.



Parity calculation in VHDL 2008

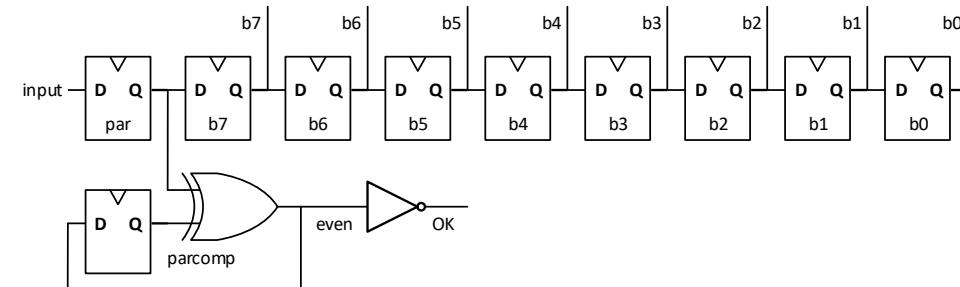
- VHDL-2008 adds Unary Reduction Operators of the form:

```
function "xor" ( anonymous: BIT_VECTOR) return BIT;
```

- Defined for arrays of bit and std_ulogic
- Defined for all binary logic operators:
 - AND, OR, XOR, NAND, NOR, XNOR
- Simplifies parity calculation

```
signal data : std_logic_vector(7 downto 0) ;
signal parity : std_logic;
.
.
parity <= xor data; -- even parity
```

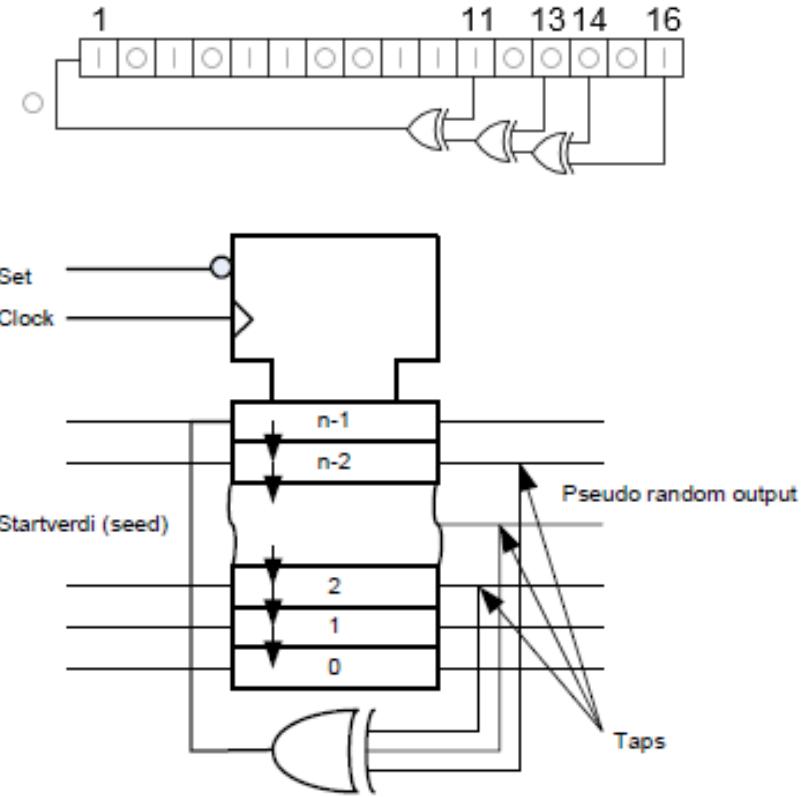
Serial parity check



- Even parity
 - parity bit is even ('0') when there is an even number of bits that are '1'
 - Using even parity bit, each byte transmission (*including parity bit*) should always have even parity.
 - OK signal is high when even is '0'.
- Odd parity is «not even»

Linear Feedback Shift Register(LFSR)

- Made by xor-ing one and one bit that are connected back to MSB
- Apparently a random counting sequence
 - Nicknamed “Pseudo-random generator” since the counting sequence looks random
- It can be shown that it's not needed more than three xor gates to make a random sequence
- *Some combinations are better*
https://web.archive.org/web/20161007061934/http://courses.cse.tamu.edu/csce680/walker/lfsr_table.pdf
- Used in testing of communication lines and buses
- Used in encryption



Oblig 3, Recommended reading

- Oblig 3:
 - Peer review is required for passing
 - 2 peer review will be assigned to each
 - When in trouble, call the lab-assistant.
 - Be polite!
- Subprograms: This lecture
- Clocked processes and statements:
 - D&H:
 - 14.1-2 p 305-309,
 - 16.1-2 p 344-356

Challenge next page..

(If-15 min...) challenge:

- 5 different architectures...
- Fill in what X is based on the input signals (in the table)
- How many FF's are created here?
- What type of circuit is this / What does it do?
- Raise you hand when finished...
- We will discuss and elaborate after

```
entity XXX is
  port (Clock : in Std_logic;
        Reset : in Std_logic;
        Enable: in Std_logic;
        Load : in Std_logic;
        Mode : in Std_logic;
        Data : in Std_logic_vector(7 downto 0);
        X    : out Std_logic_vector(7 downto 0));
end;
```

Enable	Load	Mode	X
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

To be revealed in the lecture

IN 3160, IN4160

File IO and more verification

Yngve Hafting



Messages

- *Peer reviews assigned?*

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After completion of the course you will:

- understand important **principles for design** and **testing** of digital systems
- understand the relationship between behaviour and different construction criteria
- be able to describe advanced digital systems at different levels of detail
- **be able to perform simulation** and **synthesis of digital systems**.

Goals for this lesson:

- To write self-testing testbenches
 - What is self-testing test benches
 - File IO in VHDL
 - VHDL attributes used in test benches
 - Assertions
- To understand set-up and hold-time
 - Be able to check for violations
- To generate test-bench clocks that emulate real world clocks

Next lesson

- Finite state machines (FSM's)

Outline

- Special vs generic code-
 - dcounter example
- File IO and text io
 - Example synthesizable File IO
- Verification
 - Self checking testbenches
 - Blackbox and whitebox
 - Called vs triggered tests
- Assertions in VHDL
- Attributes in VHDL
 - Attributes in cocotb Python
 - Example PWM module testbench
- *Post synthesis testing*
- *Set-up / hold time for FFs*
- *Timing checks*
 - *Relevant attributes for assertions*

Example code – dcounter

- 8 bit decade counter
- Generic decade counter, RTL style
 - Observe complexity
 - What ways are there to reduce complexity?

```
entity XXX is
  port (Clock : in Std_logic;
        Reset : in Std_logic;
        Enable: in Std_logic;
        Load : in Std_logic;
        Mode : in Std_logic;
        Data : in Std_logic_vector(7 downto 0);
        X : out Std_logic_vector(7 downto 0));
end;
```

Enable	Load	Mode	X
0	0	0	Data
0	0	1	Data
0	1	0	X+1 (bin)
0	1	1	X+1 (dec)
1	0	0	X
1	0	1	X
1	1	0	X
1	1	1	X

```
architecture when_else_function of XXX is
  constant zero_byte: std_logic_vector(7 downto 0) := "00000000";
  signal Q : Unsigned(7 downto 0);
  function dec_count(input: Unsigned) return Unsigned is
    constant decade_max : Unsigned(3 downto 0) := "1001";
    constant zero_nibble: Unsigned(3 downto 0) := "0000";
    variable output : unsigned(input'range);
  begin
    output :=
      input + 1
        when input(3 downto 0) /= decade_max else
      (input(7 downto 4) + 1) & zero_nibble
        when input(7 downto 4) /= decade_max else
      unsigned(zero_byte);
    return output;
  end function dec_count;
begin
  Q <=
    unsigned(X)
      when Enable else
    unsigned(Data)
      when not Load else
    unsigned(X) + 1
      when not Mode else
    dec_count(unsigned(X));
  X <= zero_byte
    when not reset
    else std_logic_vector(Q)
      when rising_edge(Clock);
end;
```

TASK

Fill in what X is based on the input signals
(in the table)

How many FF's are created here?

8

What type of circuit is this / What does it do?

8 bit Binary/Decade counter with load and active low signals and reset

```
-- Generic n digit counter (n*4 bit)
-- synchronous, positive edge
-- binary/decade mode (0,1)
-- synchronous reset, active high
-- synchronous parallel load, active high
-- synchronous enable, active high
-- reset has priority over enable over load
-- By Yngve Hafting 2024

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

entity dcounter is
    generic( digits : natural := 3);
    port (clk, reset : in std_logic;
        enable, load, mode : in std_logic;
        data : in std_logic_vector(digits*4-1 downto 0);
        count : out std_logic_vector(digits*4-1 downto 0)
    );
end;
```

Enable	Load	Mode	next_count
1	-	0	X+1 (bin)
1	-	1	X+1 (dec)
0	1	-	Data
0	0	-	r_count

```
architecture RTL of dcounter is
    function digcount(r_count: unsigned; dig_mode : std_logic) return unsigned is
        variable full : std_logic_vector(digits-1 downto -1);
        variable next_count : unsigned(r_count'range);
        variable hi, lo : integer;
        variable dig : unsigned(3 downto 0);
    begin
        full(-1) := '1';
        for i in 0 to digits-1 loop
            lo := i*4;
            hi := lo+3;
            dig := r_count(hi downto lo);
            full(i) := '1' when (dig_mode = '1') and (dig = 9) else and dig;
            if and full(i-1 downto 0) then
                next_count(hi downto lo) := (others => '0') when full(i) else dig+1;
            else
                next_count(hi downto lo) := dig;
            end if;
        end loop;
        return next_count;
    end function;

    signal r_count, next_count : unsigned(count'range);
begin
    count <= std_logic_vector(r_count);

    REG_ASSIGNMENT: process(clk)
    begin
        if rising_edge(clk) then
            r_count <= (others => '0') when reset else next_count;
        end if;
    end process;

    next_count <=
        digcount(r_count, mode) when enable else
        unsigned(data) when load else
        r_count;
    end architecture;
```

Example code – dcounter

- Partial testbench
 - Not complete, but showcases use
 - What would it take to make this complete?

```
# Testbench for decade counter circuit
# Uses a structure with separate compare and stimuli
# By Yngve Hafting IN3160/4160 2024
import cocotb
from cocotb.clock import Clock
from cocotb import start_soon
from cocotb.triggers import FallingEdge,
    RisingEdge, Timer, ReadOnly, ClockCycles

async def reset(dut):
    ''' Reset DUT and apply initial input'''
    dut._log.info("Resetting module... ")
    dut.reset.value = 1
    dut.enable.value = 0
    dut.Load.value = 0
    dut.Mode.value = 0
    dut.Data.value = 0x00
    await ClockCycles(dut.clk, 2)
    dut.reset.value = 0
    dut._log.info("Reset finished... ")

async def load_check(dut):
    ''' Check that Data is loaded when appropriate'''
    while True:
        await RisingEdge(dut.clk)
        if dut.load.value == 1 :
            if dut.enable.value == 0:
                data = dut.data.value
                await ReadOnly();
                assert dut.count.value == data,
                    "Did not load data"

```

```
async def compare(dut):
    ''' Compares simulated output with predicted output '''
    start_soon(load_check(dut))
    # Create more checkers to be run from here , based on
    specification
    # counting
    # priority

async def stimuli_generator(dut):
    ''' Generates all data for this tesbench'''
    dut._log.info("Start stimuli... ")
    await ClockCycles(dut.clk, 3)
    dut.data.value = 0x92
    dut.load.value = 1
    await ClockCycles(dut.clk, 3)
    dut.enable.value = 1
    dut.data.value = 0x85
    await ClockCycles(dut.clk, 20)
    dut.enable.value = 0
    await ClockCycles(dut.clk, 4)
    dut.Mode.value = 1
    dut.enable.value = 1
    await ClockCycles(dut.clk, 20)

@cocotb.test()
async def main_test(dut):
    """ Starts comparator and stimuli """
    dut._log.info("Running test...")
    PERIOD_NS = 10          #100MHz
    start_soon(Clock(dut.clk, PERIOD_NS, 'ns').start())
    await reset(dut)
    start_soon(compare(dut))
    await stimuli_generator(dut)
    dut._log.info("Running test...done")
```

File IO in VHDL

- Synthesis
 - Mostly used for reading ROM content
 - Strictly not supported by VHDL-> vendor specific solutions
 - *Vivado synthesis (2020) can only use std_logic or bit, no integers*
- Simulation
 - Stimuli (input)
 - Response (logging)
 - Data output
 - Errors and other messages

File IO

- Binary files
 - Can output whole types (custom types, records / anything)
 - Only one type per file
 - *Tool specific* (non portable code)
- Text files
 - Can contain anything
 - Human readable
 - A bit trickier to use (text to type conversions...)
- *We will use text files*

VHDL libraries for file IO

- std.textio from IEEE contains procedures for reading from and writing to file
- (see next page for package declaration)
- Standard VHDL package declarations can be found by searching the web
(if you do know their name)

```
package TEXTIO is
    type LINE is access string;
    type TEXT is file of string;
    type SIDE is (right, left);
    subtype WIDTH is natural;
```

```
file input : TEXT open READ_MODE is "STD_INPUT";
file output : TEXT open WRITE_MODE is "STD_OUTPUT";
```

```
procedure READLINE(file F: TEXT; L: inout LINE);
```

```
procedure READ(L:inout LINE; VALUE: out bit; GOOD : out BOOLEAN);
procedure READ(L:inout LINE; VALUE: out bit);
```

```
procedure READ(L:inout LINE; VALUE: out bit_vector; GOOD : out BOOLEAN);
procedure READ(L:inout LINE; VALUE: out bit_vector);
```

```
procedure READ(L:inout LINE; VALUE: out BOOLEAN; GOOD : out BOOLEAN);
procedure READ(L:inout LINE; VALUE: out BOOLEAN);
```

```
procedure READ(L:inout LINE; VALUE: out character; GOOD : out BOOLEAN);
procedure READ(L:inout LINE; VALUE: out character);
```

```
procedure READ(L:inout LINE; VALUE: out integer; GOOD : out BOOLEAN);
procedure READ(L:inout LINE; VALUE: out integer);
```

```
procedure READ(L:inout LINE; VALUE: out real; GOOD : out BOOLEAN);
procedure READ(L:inout LINE; VALUE: out real);
```

```
procedure READ(L:inout LINE; VALUE: out string; GOOD : out BOOLEAN);
procedure READ(L:inout LINE; VALUE: out string);
```

```
procedure READ(L:inout LINE; VALUE: out time; GOOD : out BOOLEAN);
procedure READ(L:inout LINE; VALUE: out time);
```

L (**line**) is the **access** (pointer) to the «current» position in a text
Note: L is **inout** since it is both read and set by the procedure

```
procedure WRITELINE(file F : TEXT; L : inout LINE);
procedure WRITE(L :inout LINE; VALUE : in bit;
JUSTIFIED: in SIDE := right;
FIELD: in WIDTH := 0);
procedure WRITE(L : inout LINE; VALUE : in bit_vector;
JUSTIFIED: in SIDE := right;
FIELD: in WIDTH := 0);
procedure WRITE(L : inout LINE; VALUE : in BOOLEAN;
JUSTIFIED: in SIDE := right;
FIELD: in WIDTH := 0);
procedure WRITE(L : inout LINE; VALUE : in character;
JUSTIFIED: in SIDE := right;
FIELD: in WIDTH := 0);
procedure WRITE(L : inout LINE; VALUE : in integer;
JUSTIFIED: in SIDE := right;
FIELD: in WIDTH := 0);
procedure WRITE(L : inout LINE; VALUE : in real;
JUSTIFIED: in SIDE := right;
FIELD: in WIDTH := 0;
DIGITS: in NATURAL := 0);
procedure WRITE(L : inout LINE; VALUE : in string;
JUSTIFIED: in SIDE := right;
FIELD: in WIDTH := 0);
procedure WRITE(L : inout LINE; VALUE : in time;
JUSTIFIED: in SIDE := right;
FIELD: in WIDTH := 0;
UNIT: in TIME := ns);
end TEXTIO;
```

Example: File IO for synthesis of ROM 1/2

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;
use STD.textio.all;

entity ROM is
  generic(
    data_width: natural := 8;
    addr_width: natural := 2;
    filename: string := "ROM data bits.txt"
  );
  port(
    address: in std_logic_vector(addr_width-1 downto 0);
    data:   out std_logic_vector(data_width-1 downto 0));
end entity;
```

- 4 byte ROM example
 - 8 bit data
 - 2 bit address
- Libraries
 - Remember std.textio
- File name
 - Assuming project (work) directory

Example: File IO for synthesis of ROM 2/2

```

type memory_array is array(2**addr_width-1 downto 0) of
  std_logic_vector(data_width-1 downto 0);

impure function initialize_ROM(file_name: string)
  return memory_array is
    file init_file: text open read mode is file name;
    variable current_line: line;
    variable result: memory_array;
  begin
    for i in result'range loop
      readline(init_file, current_line);
      read(current_line, result(i));
    end loop;
    return result;
  end function;

--initialize rom:
constant ROM_DATA: memory_array := initialize_ROM(filename);

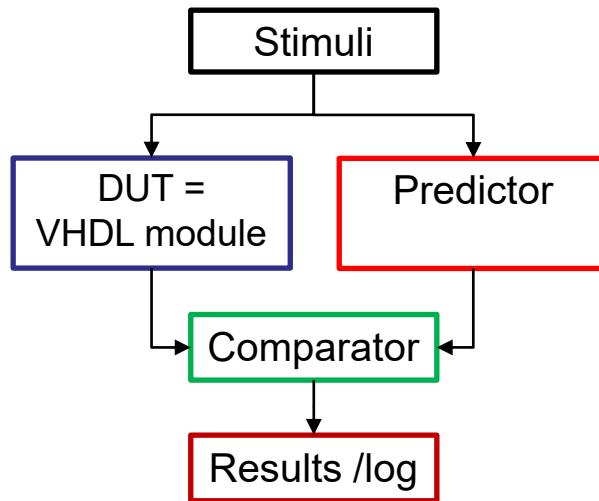
begin
  data <= ROM_DATA(to_integer(unsigned(address)));
end;

```

Combinational implementation

- Tool specific: Vivado won't allow for integers being read from file or strings
 - Integer data will have to be converted to '1' and '0' (without '_').
- Impure:
 - Does not always return the same result using same input parameters (due to file usage)
- *File is a text we open in read mode*
- Line is “access” type which means
 - A pointer to a position in the file
- Readline
 - Sets the line pointer to the beginning of the (first or) next line
- Read
 - Sets the data parameter
 - Sets the line pointer to the next data (or end of line)
 - Whitespace is delimiter
- *What do we get if we set ROM_DATA to a signal?*
- By initializing as default value this memory can be synthesized with file usage

General testbench layout (R)



- **Stimuli**

- Generate or read stimuli from a file
- Use procedures rather than repeating lines

- **DUT**

- Device under test (Device, Module, ...)
- Connect DUT input to stimuli to create simulation results

- **Predictor**

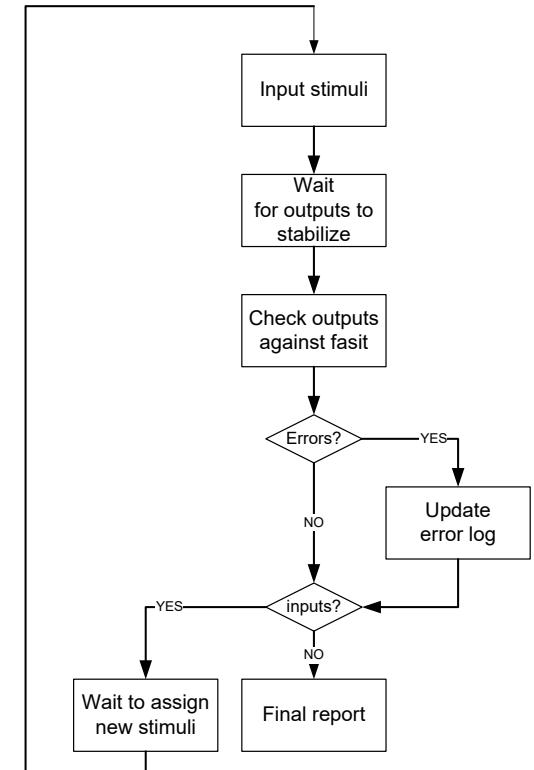
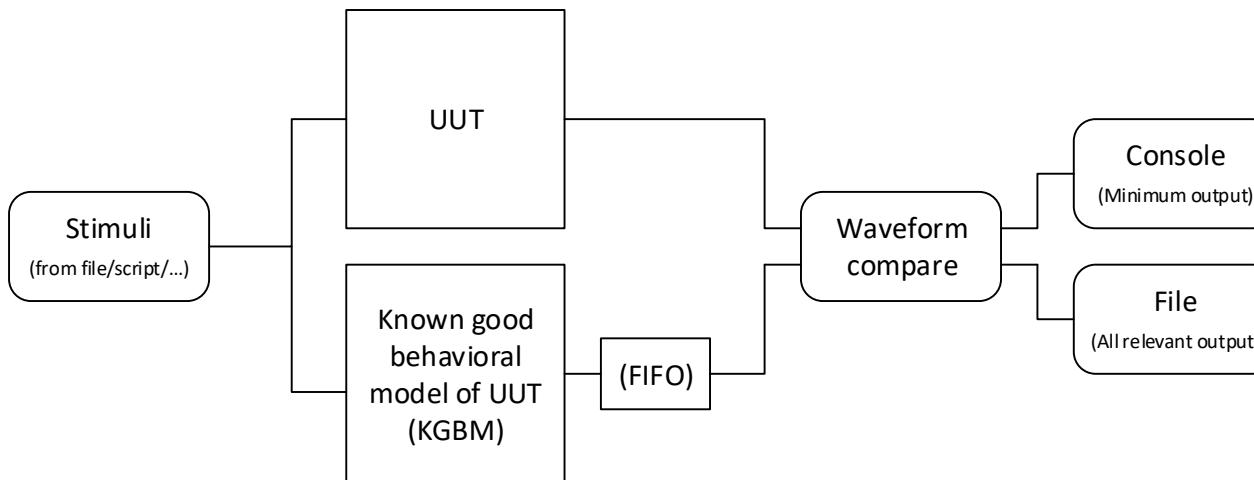
- Predicts what the output should be
 - Calculates from input or reads from file

- **Comparator**

- Compares simulation result with predicted result and reports to screen or file.

Self checking test benches

- performs tests and reports to screen or file (*timing diagram is only used when debugging*)
- Two perspectives
 - As a system of modules (below)
 - As a finite state machine (to the right)
 - *Does not reflect stimuli independent testing*



Blackbox vs Whitebox testing

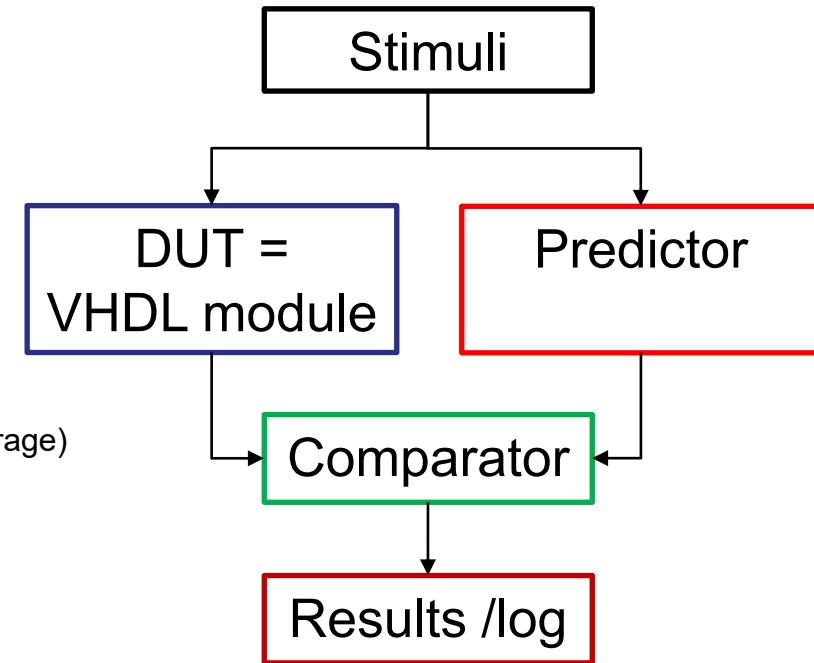
- Whitebox
 - either sets or reads internal signals
 - Requires knowledge of the internal structure in a module
 - Gtk wave (our setup) show signals from the whole hierarchy (not considered a part of a test)
 - Will require more maintenance
 - Architectural changes may void test results
- Blackbox
 - communicates to a module through the entity interface
 - Internal signals are left alone / not considered
 - Blackbox testbenches are usually easy to maintain

Called or triggered checks

- Checks can be performed when called for or when triggered
 - Called tests run manually, inserted at certain timeslots
 - May miss important failure conditions because it was not performed at correct time.
 - May cause the code to become a long list of *applying data -> test output -> apply data -> test output -> ...*
 - Such a list in itself is hard to verify
 - » Did we cover all necessary situations?
- Better: Use triggers for (all) tests
 - Make the test latently wait for their trigger while testing any data.
 - Trigger conditions can be fixed (in one spot)
 - Test can be fixed in one spot
 - Data can be generated once.

A good testbench:

- Tests should
 - run independently of stimuli
 - run throughout simulation
 - cover all (100%) specified behaviour
 - Catch all deviations from known good behavior
- Stimuli
 - Should cover all types of behavior
 - All design (VHDL) code should be run (100% code coverage)
 - All corner cases or
 - Formal verification : All possible input
 - » = not possible in most cases
 - » (eg 32 bit adder = $(2^{32})^2$ combinations)
 - Use blackbox testing when possible
 - avoid overwriting signals inside DUT
 - => create and test submodules separately if this seems needed...
 - Internal signals in waveform is OK
 - Checks (assert statements) on output = less maintenance



Test bench output

- Report (console or log file)
 - which tests are performed
 - what stimuli are applied
 - \neq all stimuli
 - successful completion of
 - Stimuli series
 - Tests
 - Errors
 - Expected vs simulation result
 - Timing

Relevant waveforms

(we do not automate this)

- Before errors or deviations occur
 - Relevant input, output
 - Internal states (preferably with names)
- Log files
 - Report
 - Relevant verification data not already in wave
 - Depending on verification goals

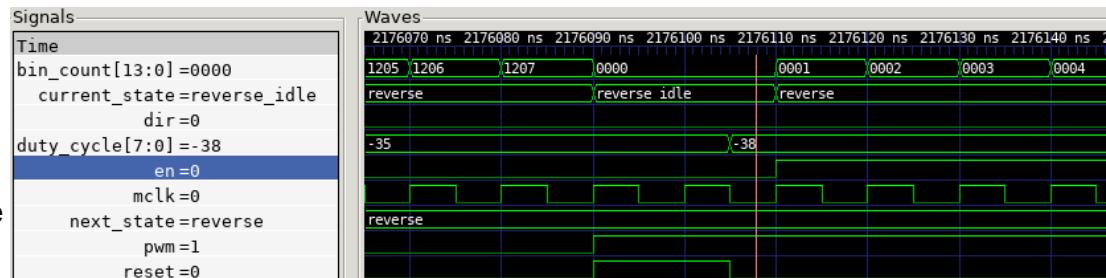
Example (not perfect):

```

1.00ns INFO cctb.pwm Starting monitoring events
1.00ns INFO cctb.pwm Starting duty cycle tests
15.00ns INFO cctb.pwm Passed: Reset test
163850.00ns INFO cctb.pwm Duty cycles: Set dc: 50.0%, Measured dc: 49.0%, period = 163.8us, f = 6.11kHz
327690.00ns INFO cctb.pwm Duty cycles: Set dc: -50.0%, Measured dc: -49.0%, period = 163.8us, f = 6.10kHz
327690.00ns INFO cctb.pwm Sequential duty tests complete
491530.00ns INFO cctb.pwm Duty cycles: Set dc: 27.3%, Measured dc: 27.0%, period = 163.8us, f = 6.10kHz
819210.00ns INFO cctb.pwm Duty cycles: Set dc: 50.0%, Measured dc: 49.0%, period = 163.8us, f = 6.10kHz
983050.00ns INFO cctb.pwm Duty cycles: Set dc: -84.4%, Measured dc: -84.0%, period = 163.8us, f = 6.10kHz
1310730.00ns INFO cctb.pwm Duty cycles: Set dc: -33.6%, Measured dc: -33.0%, period = 163.8us, f = 6.10kHz
1474570.00ns INFO cctb.pwm Duty cycles: Set dc: 41.4%, Measured dc: 41.0%, period = 163.8us, f = 6.10kHz
1638410.00ns INFO cctb.pwm Duty cycles: Set dc: -23.4%, Measured dc: -23.0%, period = 163.8us, f = 6.10kHz
1966090.00ns INFO cctb.pwm Duty cycles: Set dc: -27.3%, Measured dc: -27.0%, period = 163.8us, f = 6.10kHz
2129930.00ns INFO cctb.pwm Duty cycles: Set dc: -27.3%, Measured dc: -27.0%, period = 163.8us, f = 6.10kHz
2176090.00ns INFO cctb.pwm Random duty tests 1/2 complete
2176090.00ns INFO cctb.pwm Resetting module...
2176105.00ns INFO cctb.pwm Reset between duties complete
2176105.00ns INFO cctb.pwm Passed: Reset test
2339940.00ns INFO cctb.pwm Duty cycles: Set dc: -29.7%, Measured dc: -29.0%, period = 163.8us, f = 6.10kHz
2667620.00ns INFO cctb.pwm Duty cycles: Set dc: -69.5%, Measured dc: -69.0%, period = 163.8us, f = 6.10kHz
2831460.00ns INFO cctb.pwm Duty cycles: Set dc: 27.3%, Measured dc: 27.0%, period = 163.8us, f = 6.10kHz
2943460.00ns INFO cctb.pwm Random duty tests 2/2 complete
2943460.00ns INFO cctb.regr main_test passed
*****
** TEST STATUS SIM TIME (ns) REAL TIME (s) RATIO (ns/s) **
***** PASS 2943460.00 11.54 255164.53 **
** tb_pwm.main_test *****
** TESTS=1 PASS=1 FAIL=0 SKIP=0 2943460.00 11.66 252500.41 **
*****

```

Signals	
Time	
bin_count[13:0]	=0000
current_state	=reverse_idle
dir	=0
duty_cycle[7:0]	=-38
en	=0
mclk	=0
next_state	=reverse
pwm	=1
reset	=0



How to organize a medium sized testbench

- Create separate classes for
 - Generic signal monitoring
 - replaces use of 'attributes in VHDL
 - can be much more extensive than attributes
 - DUT Monitoring
 - Contains all tests, their trigger and reports
 - Stimuli generation
 - Creates all input sequentially
 - Either timed or based on response
 - Uses DUT-inputs
 - *Fault injection (to analyze tests)*
 - can be run with DUT being an empty entity.
 - Forces/overrides signals used in tests
 - *GHDL + forced signals = False?*
- Separate location for classes will ensure better readability
- Allow the simulator to run as much as possible...
 - Test only on appropriate triggers
 - everything on every clock => slow test.
 - No need to store values that can be easily calculated

Assertions - «To ensure a model is working with valid inputs»*

- Syntax

```
assert <boolean condition> -- report when false
      report <string>
      severity <note, warning, error, failure>;
```
- Compilation
 - Can be used to check for size mismatches at compile time.
- RTL Simulation
 - Compare simulated and expected outcome values (behavior)
- Post Synthesis simulation
 - Checks on signal timing attributes in addition to behavior
- Severity levels
 - **failure** means «simulation should be stopped»
 - Usually when a module can't be initiated correctly, something doesn't compile...
 - **error** – when the model provides wrong output or goes into wrong state
 - **warning** – «*unexpected conditions that do not affect the state of the model*»
 - **note** – to report when everything went well (default for report)

Signal Attributes for simulation 1/2

These attributes are predefined for any signal X:

Name	Definition
X'event	True when X changes (boolean)
X'active	True when X assigned to (boolean)
X'last_event	When X last changed (time)
X'last_active	When X was last assigned to (time)
X'last_value	Previous value of X (same type as X)

- These are signal only!
 - Each signal maintains these throughout simulation
 - *Variables don't have these*
 - => v. faster in simulation
- 'event used in **rising_edge()**
 - (other use not intended for synthesis)
- 'last...
 - Can be useful in testbenches
 - Example (oblig 8):

```
assert en'last_event < LONG_PWM_CYCLE/2
  report "PWM is not happening,..." severity error;
```

Signal Attributes for simulation 2/2

These attributes create a **new signal**, based on signal X:

Name	Definition
X'delayed(T)	X, delayed by T (same type as X)
X'stable(T)	True if X unaltered for time T (boolean)
X'quiet(T)	True if X unassigned for time T (boolean)
X'transaction	"Toggles" when X is assigned (bit)

- May be used to create simulation logic and tests
 - (not synthesizable)

Attributes in cocotb?

- Cocotb and GHDL does not (Jan. 2023) have built in support for VHDL signal attributes.
 - Other simulators may have an API for this...
- Solution: create a signal monitor class
 - It will run slightly slower than a pure VHDL simulation due to added context switching
- Alternative: build a new top layer in VHDL with signal attributes as outputs along with the other signals.
 - Downside for this is spreading testbench code into multiple modules and languages

```
import cocotb
from cocotb import start_soon
from cocotb.triggers import Edge, ReadOnly
from cocotb.utils import get_sim_time

# Conversion to pico-seconds using dictionary
ps_conv = {'fs': 0.001, 'ps': 1, 'ns': 1000, 'us': 1e6, 'ms': 1e9}

class SignalEventMonitor():
    """ Tracks a signal's last event. """
    def __init__(self, signal):
        self.signal = signal
        self.last_event = get_sim_time('ps')
        self.last_rise = self.last_event
        self.last_fall = self.last_event
        start_soon(self.update())

    @async def update(self):
        while 1:
            await Edge(self.signal)
            # Avoid multiple triggers on a single event
            await ReadOnly()
            self.last_event = get_sim_time('ps')
            if self.signal == 1: self.last_rise = self.last_event
            else: self.last_fall = self.last_event

    def stable_interval(self, units='ps'):
        # convert last_event to the prefix in use
        last_event_c = self.last_event / ps_conv[units]
        # calculate stable interval
        stable = get_sim_time(units) - last_event_c
        return stable

    #... Monitoring a signal ...
en_mon = SignalEventMonitor(self.dut.en)
PERIOD_NS = 10
#...
assert en_mon.stable_interval('ns') > PERIOD_NS-1, (
    "not stable long enough!")
```

core "attributes"

Monitoring service

Secondary attribute calculation on demand

Example

- Testbench for PWM module
 - Checks that
 - PWM is performed
 - Not too fast (can cause short circuit condition)
 - Not too slow
 - Duty cycle is as specified (within a few percent)
 - Has tests for checking that the checkers find errors (disabled)
 - Note: These checks may or may not work with GHDL if enabled

Example: DUT-Monitor 1/2

- Each test has its own triggers (more on triggers next slide)
- Each test run throughout all stimuli
- Example is used in later assignment.
 - *Look at structure, not each test in particular*

```
class Monitor:  
    """ Contains all tests checking signals in and from DUT """  
    def __init__(self, dut):  
        self.dut = dut  
        self.dut._log.info("Starting monitoring events")  
        self.en_mon = SignalEventMonitor(self.dut.en)  
        self.duty_mon = SignalEventMonitor(self.dut.duty_cycle)  
        self.reset_mon = SignalEventMonitor(self.dut.reset)  
        start_soon(self.reset())  
        start_soon(self.dir_stability())  
        start_soon(self.timeout())  
        start_soon(self.duty_dir_cohesion())  
        start_soon(self.duty_checks())  
  
    async def reset(self):  
        ''' Checks that PWM pulse (en) is deasserted when reset is applied '''  
        while 1:  
            await FallingEdge(self.dut.reset)  
            assert self.dut.en.value == 0,  
                "PWM enable has not been deasserted during reset"  
            self.dut._log.info("Passed: Reset test")  
  
    async def dir_stability(self):  
        ''' Checks that we are not short-circuiting the  
        half-bridge by switching direction while pulsing '''  
        while 1:  
            await Edge(self.dut.dir)  
            if self.dut.reset.value == 0:  
                assert self.dut.en.value == 0, (  
                    "HALF-BRIDGE SHORT CIRCUITED: en active when changing direction")  
                assert self.en_mon.stable_interval('ns') > PERIOD_NS-1, (  
                    "SHORT CIRCUIT DANGER:  
                    en deactivated less than one cycle before dir change")  
                wait_task = Timer(PERIOD_NS-1, 'ns')  
                event_task = Edge(self.dut.en)  
                result = await First(wait_task, event_task)  
                assert result == wait_task, (  
                    "SHORT CIRCUIT DANGER: En was not stable for {per} {uni}"  
                    .format(per=PERIOD_NS, uni='ns'))  
  
    async def timeout(self):  
        ''' Checks that the PWM signal is actually driven  
        within a reasonable timeframe'''  
        while 1:  
            if self.dut.duty_cycle.value == 0 : await Edge(self.dut.duty_cycle)  
            await with_timeout(Edge(self.dut.en), PWM_TIMEOUT_MS, 'ms')
```

Example: DUT-Monitor 2/2

```

async def duty_dir_cohesion(self):
    ''' Checks that the pwm drives the motor in the correct direction'''
    while 1:
        await Edge(self.dut.duty_cycle)
        await ClockCycles(self.dut.mclk, 2) # Trigger two clock edges after duty cycle was changed
        await ReadOnly() # Wait for all signals to settle (all delta delays)
        duty = int(self.dut.duty_cycle.value) # Check if sign and dir matches
        if np.int8(duty) > 0:
            assert self.dut.dir.value == 1, (
                "DIR is not '1' within 2 clock cycles of positive duty cycle: {DU} = {D}"
                .format(DU=np.int8(duty), D=self.dut.duty_cycle.value))
        if np.int8(duty) < 0:
            assert self.dut.dir.value == 0, (
                "DIR is not '0' within 2 clock cycles of negative duty cycle: {DU} = {D}"
                .format(DU=np.int8(duty), D=self.dut.duty_cycle.value))

async def duty_checks(self):
    ''' Checks that pwm pulses are not happening too fast for the PMOD module '''
    await RisingEdge(self.dut.en)
    while 1:
        # Wait until we have a full period after reset
        if self.dut.reset.value == 1:
            await FallingEdge(self.dut.reset)
            await RisingEdge(self.dut.en)
        await RisingEdge(self.dut.en)

        # Find the interval/period
        start = self.en_mon.last_rise/ps_conv['us']
        interval = get_sim_time('us') - start

        # Trigger only when duty cycle has been stable for the last period
        if self.duty_mon.stable_interval('us') > interval:
            assert interval > TOO_FAST_PWM_US, (
                "PWM period too short!: {iv:.2f}us, f={f:.3f}kHz Minimum period: {per} us, f<{maxf:.2f}kHz "
                .format(iv=interval, f=(1000/interval), per=TOO_FAST_PWM_US, maxf=(1000/TOO_FAST_PWM_US)))

            # Calculate duty cycle
            mid = self.en_mon.last_fall/ps_conv['us']
            high = mid-start
            measured_duty = np.int8((high*100)/interval)
            set_duty = np.int8(self.dut.duty_cycle.value.integer)*100/128

            # Report duty cycle and check correspondens between input and output
            sign = "-" if self.dut.dir.value == 0 else " "
            self.dut._log.info(
                "Duty cycles: Set dc: {S:.1f}%, Measured dc: {Sig}{M:.1f}%, period = {P:.1f}us, f = {F:.2f}kHz"
                .format(S=set_duty, Sig = sign, M = measured_duty, P = interval, F = 1000/interval))
            abs_duty = abs(set_duty)
            deviation = np.int8(abs(abs_duty - measured_duty))
            assert deviation < 5, (
                "Set and measured duty cycle deviates by more than 5% ({D}%) "
                .format(D=deviation))

```

Example: Stimuli Generator

- Feeds DUT with all data for the test
 - run-method provides all data sequentially

```
class StimuliGenerator():
    ''' Generates all stimuli used in the normal tests '''
    def __init__(self, dut):
        self.dut = dut
        self.dut._log.info("Starting clock")
        start_soon(Clock(self.dut.mclk, PERIOD_NS, 'ns').start())
        self.dut.duty_cycle.value = 0
        start_soon(self.reset_module())

    async def reset_module(self):
        self.dut._log.info("Resetting module... ")
        self.dut.reset.value = 1
        await Timer(15, 'ns')
        self.dut.reset.value = 0

    async def run(self):
        self.dut._log.info("Starting duty cycle tests ")
        await Timer(20, 'ns')
        await self.sequential_duty_tests()
        self.dut._log.info("Sequential duty tests complete ")
        await self.random_duties(7)
        self.dut._log.info("Random duty tests 1/2 complete ")
        await self.reset_module()
        self.dut._log.info("Reset between duties complete ")
        await self.random_duties(3)
        self.dut._log.info("Random duty tests 2/2 complete ")

    def set_duty(self, duty_cycle):
        self.dut.duty_cycle.value= int((duty_cycle*128)/100)

    async def sequential_duty_tests(self):
        self.set_duty(50)
        for i in range(3):
            await RisingEdge(self.dut.en)
        self.set_duty(-50)
        for i in range(2):
            await RisingEdge(self.dut.en)

    async def random_duties(self, tests):
        duties = list(range(-90+1,-10)) + list(range(10+1,90))
        for x in range(tests):
            random_duty = random.choice(duties)
            duties.remove(random_duty)
            self.set_duty(random_duty)
            for i in range(2):
                await RisingEdge(self.dut.en)
        interval = random.randint(1,300)
        await Timer(interval, units='us')
```

Example: Fault injector

```

class FaultInjector():
    """ Contain tests to verify that each assertion will
    trigger """
    def __init__(self, dut):
        self.dut = dut
        self.dut._log.info("/** TRIP-BENCH INITIALIZED ***)")

    async def run(self):
        # TESTS run, comment out when working
        #await self.reset()
        #await self.dir_stability_1()
        #await self.dir_stability_2()
        #await self.dir_stability_3()
        #await self.timeout()
        #await self.duty_dir_cohesion()
        #await self.too_fast_pwm()
        #await self.duty()
        assert False, "Trip run came to an end without
tripping anything else!"

    def release(self):
        """ Releases all Forced values. """
        self.dut.reset.value = Release()
        self.dut.en.value = Release()
        self.dut.dir.value = Release()
        self.dut.duty_cycle.value = Release()

    async def disable_reset(self):
        self.dut.reset.value = Force(0)
        await Timer(20, 'ns')

    async def reset(self):
        """ Enable asserted while reset is deasserted"""
        self.dut.reset.value = Force(1)
        self.dut.en.value = Force(1)
        await RisingEdge(self.dut.mclk)
        self.dut.reset.value = Force(0)
        await RisingEdge(self.dut.mclk)
        self.release()

```

```

async def dir_stability_1(self):
    """ Enable is not deasserted when dir changes"""
    await self.disable_reset()
    self.dut.dir.value = Force(0)
    self.dut.en.value = Force(1)
    await Timer(1, 'ns')
    self.dut.dir.value = Force(1)
    await Timer(30, 'ns')
    self.release()

async def dir_stability_2(self):
    """ Enable is deasserted within one clock cycle of
dir changing"""
    await self.disable_reset()
    self.dut.en.value = Force(1)
    await Timer(1, 'ns')
    self.dut.en.value = Force(0)
    await Timer(8, 'ns')
    self.dut.dir.value = Force(not self.dut.dir.value)
    await Timer(10, 'ns')
    self.release()

async def dir_stability_3(self):
    """ Enable asserted within one clock cycle after
dir changing """
    await self.disable_reset()
    self.dut.en.value = Force(0)
    await Timer(20, 'ns')
    self.dut.dir.value = Force(not self.dut.dir.value)
    await Timer(8, 'ns')
    self.dut.en.value = Force(1)
    await Timer(1, 'ns')
    self.release()

async def timeout(self):
    """ Prevents pulsing although a nonzero duty
cycle"""
    await self.disable_reset()
    self.dut._log.info("/** timeout test started: this
may take minutes ***)")
    self.dut.duty_cycle.value = Force(0x50)
    # Stopping clock might be useful to reduce time
spent here.
    # Requires a pointer/handle to the process.
    self.dut.en.value = Force(0)
    await Timer(PWM_TIMEOUT_MS+1, 'ms')
    self.release()

async def duty_dir_cohesion(self):
    """ To not have dir correspond to duty
cycle within two clock cycles"""
    await self.disable_reset()
    self.dut.dir.value = Freeze()
    self.dut.duty_cycle.value = Force(0xEE)
    await ClockCycles(self.dut.mclk, 3)
    self.dut.duty_cycle.value = Force(0x11)
    await ClockCycles(self.dut.mclk, 3)
    self.release()

async def too_fast_pwm(self):
    """ Runs PWM signal (en) faster than
allowed by TB """
    await self.disable_reset()
    for i in range(4):
        self.dut.en.value = Force(1)
        await RisingEdge(self.dut.mclk)
        self.dut.en.value = Force(0);
        await RisingEdge(self.dut.mclk)
    self.release()

async def duty(self):
    """ Asserts one duty cycle, and pulses
another"""
    await self.disable_reset()
    self.dut.en.value = Force(0)
    await ClockCycles(self.dut.mclk, 10)
    self.dut.duty_cycle.value = Force(-32) #
25% as hex (128 = 100%)
    await ClockCycles(self.dut.mclk, 10)
    for i in range(4):
        self.dut.en.value = Force(1)
        await ClockCycles(self.dut.mclk, 8001)
        self.dut.en.value = Force(0);
        await ClockCycles(self.dut.mclk, 8001)
    self.release()

```

- All tests still present although disabled.

More on VHDL attributes

- There are attributes for
 - Signals
 - (previous slides)
 - Types
 - Notable:
 - ‘image(v) returns a string ex : `report("current value is: ", integer'image(my_int));`
 - ‘value(s) returns a value (opposite of ‘image)
 - Array types/objects (vectors)
 - ‘left, ‘right, ‘low, ‘high, ‘range, ‘reverse_range, ‘length, ‘ascending (= false when «downto»), ‘element (== subtype of the vector)
 - Entities
 - attributes to get compiled name hierarchy- as seen in simulator when selecting signals

Post synthesis, post implementation simulation and testbenches

- Mostly relevant for ASIC design
- Post synthesis, post route
 - Using the same testbench may be difficult
 - Simulation information in design files will normally be stripped during synthesis.
 - Assertions will be gone
 - Adaptations may be necessary to compile
 - Generics may be frozen/ not generic
 - Timing information will be there
 - Much more to test on...
 - Signal attributes next slide
 - Does not replace static timing analysis and constraints
 - Timing constraints are used for synthesis...

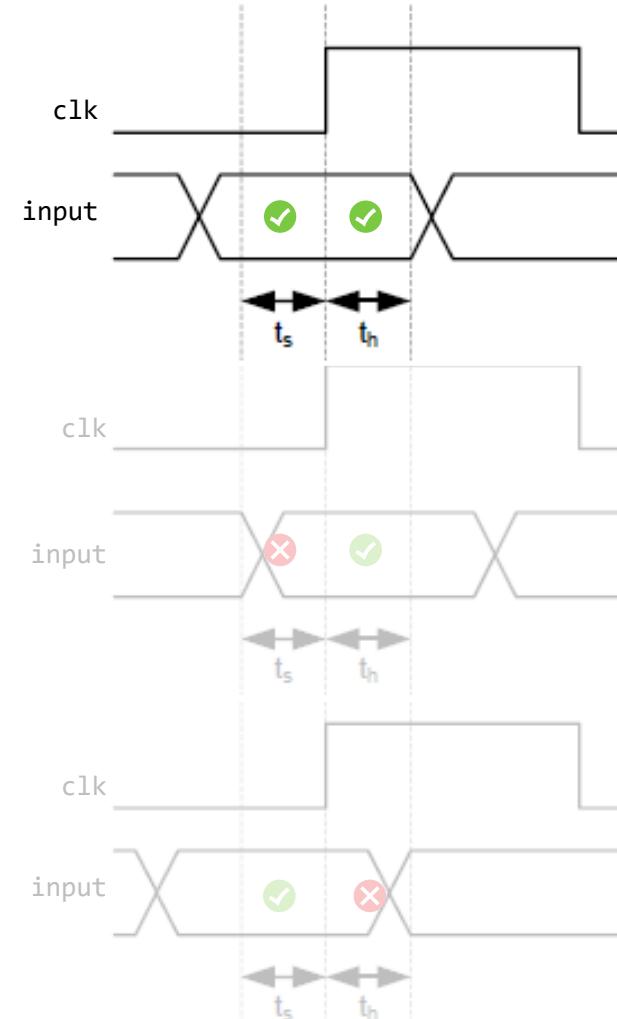
<https://docs.xilinx.com/r/en-US/ug900-vivado-logic-simulation/Post-Synthesis-Simulation>

Performing a thorough timing simulation ensures that the completed design is free of defects that could otherwise be missed, such as:

- functionality changes that are caused by:
 - Synthesis properties or constraints that create mismatches
 - UNISIM properties applied in the Xilinx Design Constraints (XDC) file
 - The interpretation of language during simulation by different simulators
 - Dual port RAM collisions
 - Missing, or improperly applied timing constraints
 - Operation of asynchronous paths
 - Functional issues due to optimization techniques

Testcase: Set-up/hold time in flipflops

- To avoid metastability (neither 0 nor 1), inputs must be stable some time before (set-up) and after (hold) clock edge
- Output (not shown) will return to 0 or 1 after being in the metastable state, but it's not given which one.
 - This means; the system is no longer deterministic.



Timing and logic check

```
27: entity D_FF is
28:
29:   port (D, Clk, Set, Reset: in std_logic;
30:         Q : out std logic);
31: begin
32:   assert (not(Clk ='1' and Clk'EVENT and not D'STABLE(Setup)))
33:     report "Setup time violation" severity WARNING;
34:   assert (not(Clk ='1' and D'EVENT and not Clk'STABLE(Hold)))
35:     report "Hold time violation" severity WARNING;
36:   assert (not(Set ='0' and Reset = '0'))
37:     report "Set and Reset are both asserted"
38:   severity ERROR;
39: end entity D_FF;
```

- The stable attribute can be used to check set-up- and hold times
 - Returns true if a signal has been stable \geq time given as input parameter
- Assert in an entity =>
checking is being done for all architectures that belongs to this entity.

CAUTION! Care should be taken using asserts. Vivado can only support static asserts that do not create, or are created by, behavior. For example, performing an assert on a value of a constant or a operator/generic works; however, an assert on the value of a signal inside an if statement will not work.

Suggested reading

- D&H
 - File access, ROM
 - 8.8 p184-189
 - Attributes
 - B.8 p 638-640
 - Timing constraints:
 - 15.1-3 p 328 - 334
 - 15.4-6 p 334- 340

IN3160 IN4160
Finite State Machines
Yngve Hafting



Messages

- Assignment 6
 - beta is posted
 - Progress in 6, 8 and 10 are tied
 - *Read specifications, not only task*
 - Start early (greater task = longer time)
- FSM-videos from 2017 re-posted with text (autotext)
 - Mostly very good (se last pages)
 - use the newer source code for reference:
 - <https://www.uio.no/studier/emner/matnat/ifi/IN3160/v23/fsm-videoer/src-traffic.zip>

Course Goals and Learning Outcome

<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

In this course you will learn about the **design of advanced digital systems**. This includes programmable logic circuits, a **hardware design language** and system-on-chip design (processor, memory and logic on a chip). **Lab assignments provide practical experience in how real design can be made.**

After completion of the course you will:

- understand important **principles for design** and testing of digital systems
- understand the relationship between behaviour and different construction criteria
- **be able to describe advanced digital systems at different levels of detail**
- be able to perform simulation and synthesis of digital systems.

Goals for this lesson:

- Know different types of state machines
 - What is a state machine
 - Moore type machines
 - Mealy type machines
- To specify state machine functionality using
 - State tables
 - State diagrams
 - Algorithmic state machine diagrams
 - VHDL
- To know pro's and con's for
 - Moore and Mealy
 - Different state machine representations

Overview Today

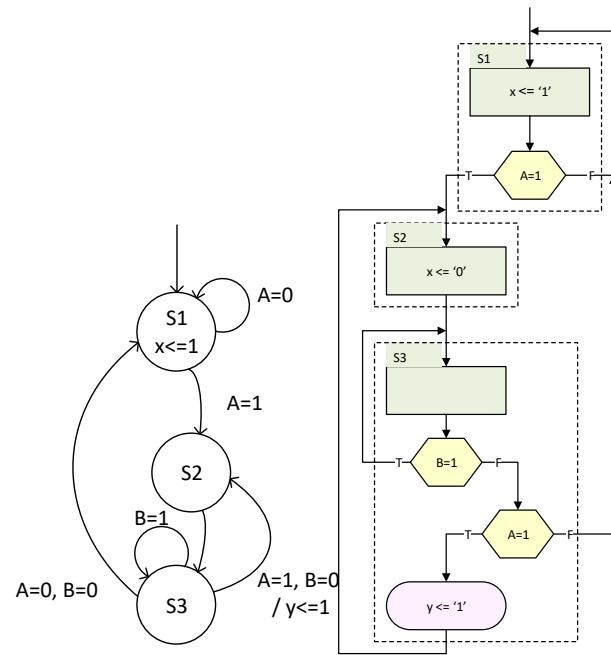
- What is finite state machines (FSM)?
 - General FSM
 - Moore type FSM
 - Mealy
 - Synchronized Mealy
- FSM representations
 - State diagram
 - State output table
 - Algorithmic State Machine (ASM) diagrams
- FSM example with VHDL and testbench

Next:

- Datapath state machines

Why/What is an FSM?

- Names
 - Finite State Machine "FSM"
 - Finite State Automaton "FSA"
 - State Machine (*Never seen "SM" used for this*)
 - Finite automaton
- A description of something that happens in a more or less fixed sequence
 - Going through a set of states
- Not an FSM? "ISM" / "ESM"?
 - Near *infinite* or *endless* amount of states...
 - Any computer program *could* be called an "FSM",
– we do not use the term FSM for SW in general
- Example FSM?
 - Traffic light implementation*
 - Pushbutton user interfaces*
 - Vending machine
 - Washing machine program
 - Bus controller
 - Arbitration algorithm
 - Microprocessors, etc
- FSMs *can* be made in HW, FW or SW. (We'll cover HW)

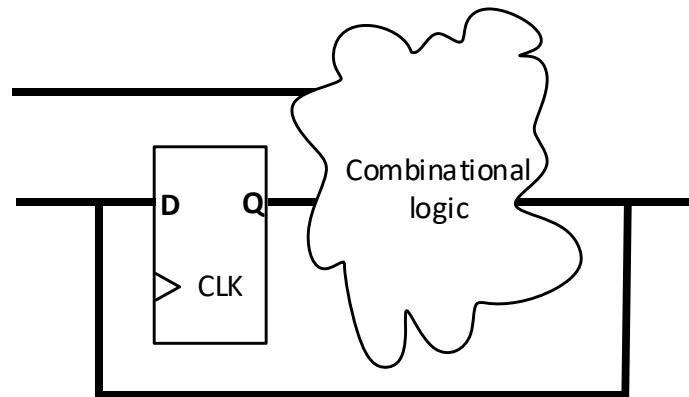
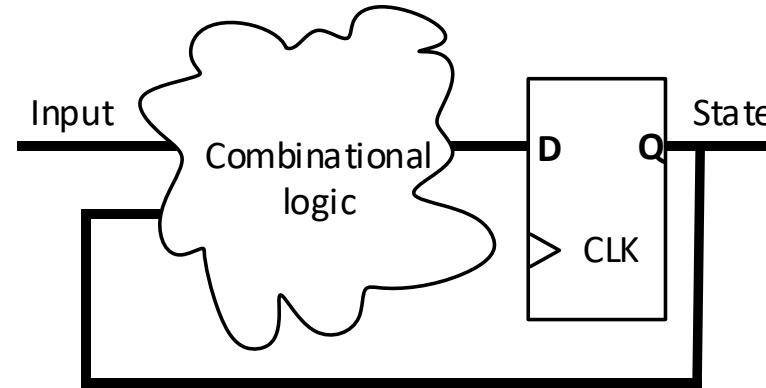


FSM-diagrams and descriptions:
We'll get to these...

Input(BA) /State	11	10	01	00	x	y
S1	S2	S1	S2	S1	1	0
S2	S3	S3	S3	S3	0	0
S3	S3	S3	S2	S1	0	1 or 0

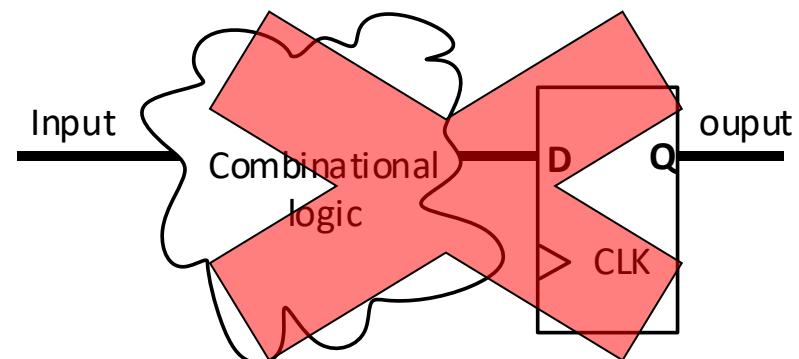
General FSM in HW

- General FSM
 - Combinational logic connected to registers with feedback
 - *Can be nearly any clocked logic*
 - Counter
 - LFSR
 - Shiftregister
 - Timer
 - Microprocessor
 - Vending machines...
 - Etc.



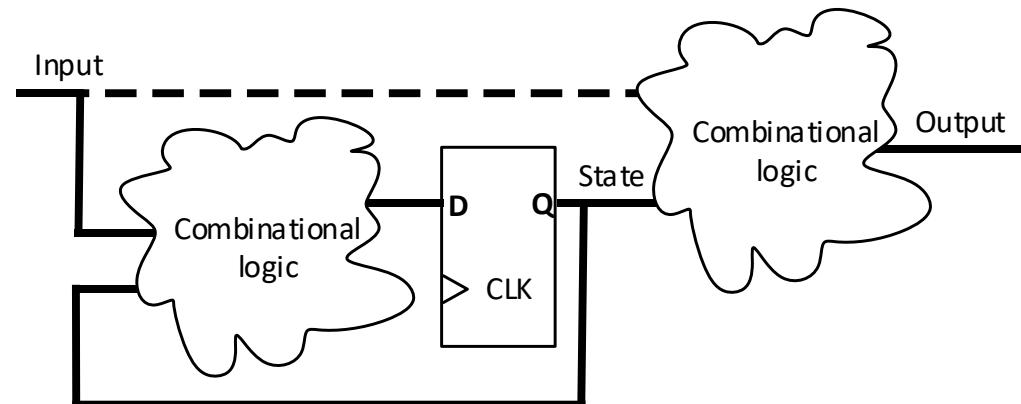
Non FSM sequential logic?

- *Strictly speaking* any logic using registers (FFs) are FSMs, but...
- We usually don't refer to things as FSMs when they
 - Have well known names or near-infinite states
 - Shift registers,
 - Counters, Timers
 - LFSR (linear feedback shift registers)
 - Microprocessors
 - ...
 - are pure datapath representations
 - No feedback after registers

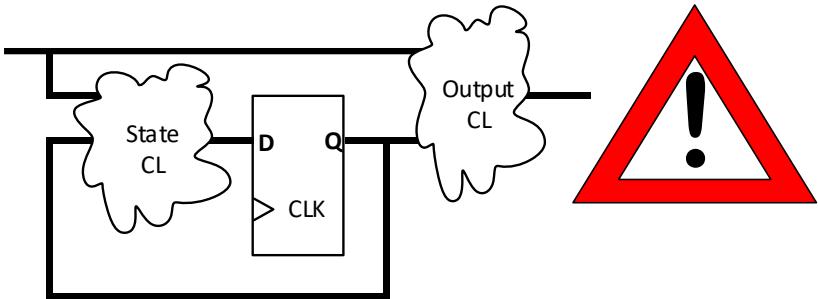


Output decoding in FSM

- Two types:
 - Moore
 - Output is entirely decoded from state registers
 - Mealy
 - Output is decoded from input and state registers



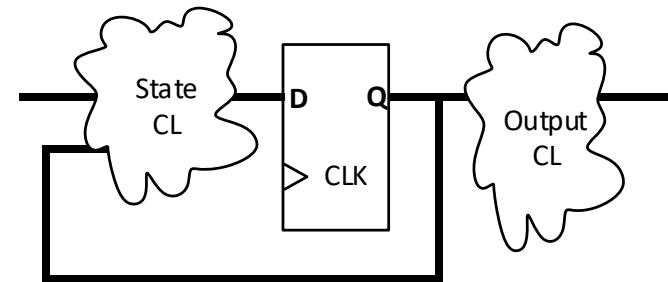
Mealy FSM



- Fast output
 - Asynchronous output!
- Hazards!



Moore FSM

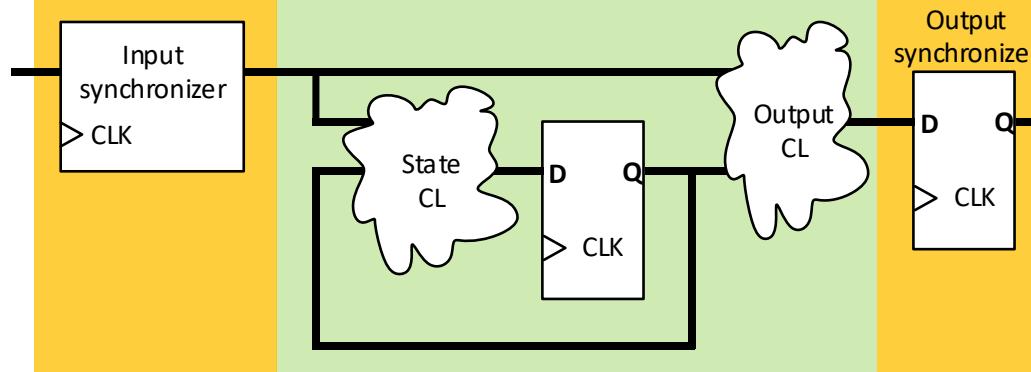


- Output will always be delayed by at least one clock cycle
 - Requires more states



Output hazards still present, although synchronized

Solution: Fully synchronized Mealy FSM



- Input synchronizer: Synchronizes signals from other clock domains
- Output synchronizer: Removes hazards from output
- Technically this is a «Moore» type machine altogether
 - But we operate with **minimum delay within the state machine** design
 - **Synchronizers can be** added in **separate** modules, processes or statements
 - Thus it makes sense to refer to the state machine inside as Mealy type

Moore vs mealy conclusion:

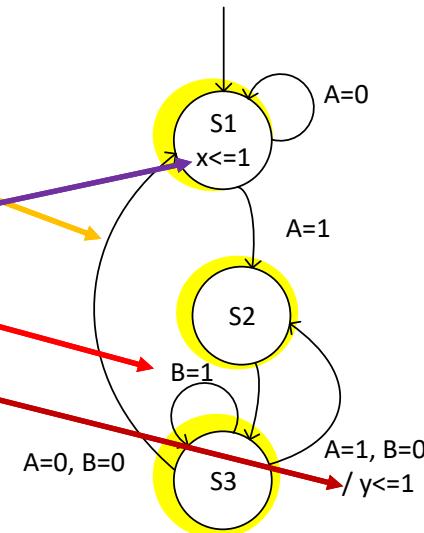
- Can we afford having synchronization:
 - MEALY
- If we cannot have other synchronization:
 - Moore will be the safest option
- Some FSMs will inherently be Moore type = OK!

Three ways of representing state machines

- State diagram
- State (output) table
- Algorithmic state machine (ASM) diagram

State diagram

- States
- Transitions between states
- Beside transition arc:
 - Decision parameter
 - / Mealy output
- Inside bubble:
 - Moore output
- Frequently used, but not always with all parameters.
- Note: *Default values often omitted*
 - Here: default: $x, y = 0$ (boolean false)



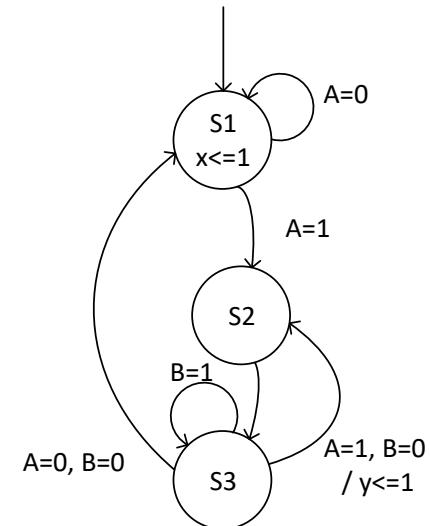
State output table, input & state table

Input(BA) /State	11	10	01	00	x	y
S1	S2	S1	S2	S1	1	0
S2	S3	S3	S3	S3	0	0
S3	S3	S3	S2	S1	0	A and \bar{B}

Input (AB) v	S1		S2		S3		< Current state
00	S1	x=1	S3	y=1	S1		< Next state / output
01	S1		S3		S3		
10	S2		S3		S2	y=1	
11	S2		S3		S3		

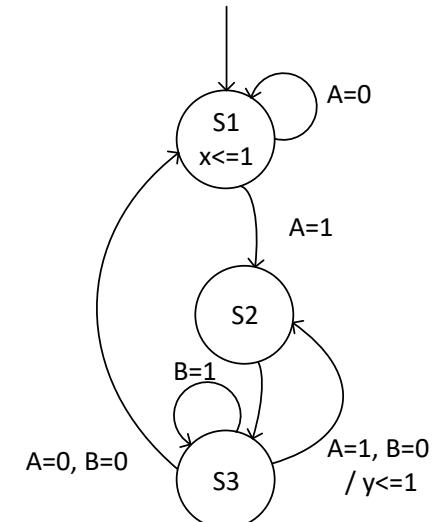
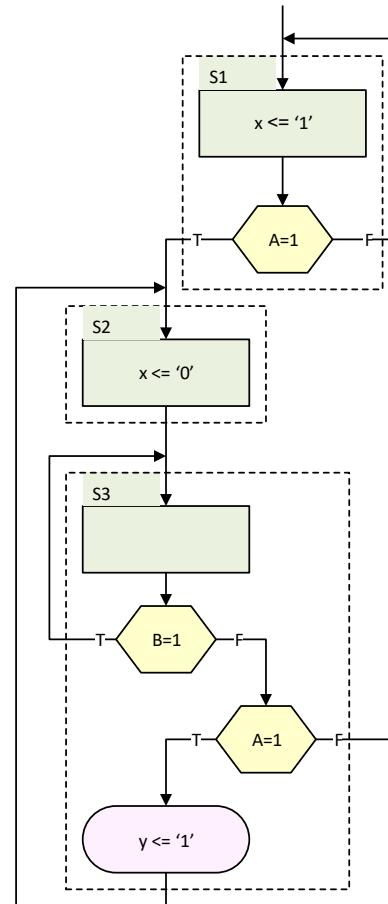
- *Next state and output as a function of input vs current state..?*
- There are many ways to organize tables to get output, but no clear winner
 - State and input should intersect to create next state
 - Output must be stated in a comprehensible manner...
 - Complex decisions could be named and explained outside table

- State ouput table
 - Moore output is simple
 - Mealy outputs becomes functions or table must be extended



ASM chart (Algorithmic state machine)

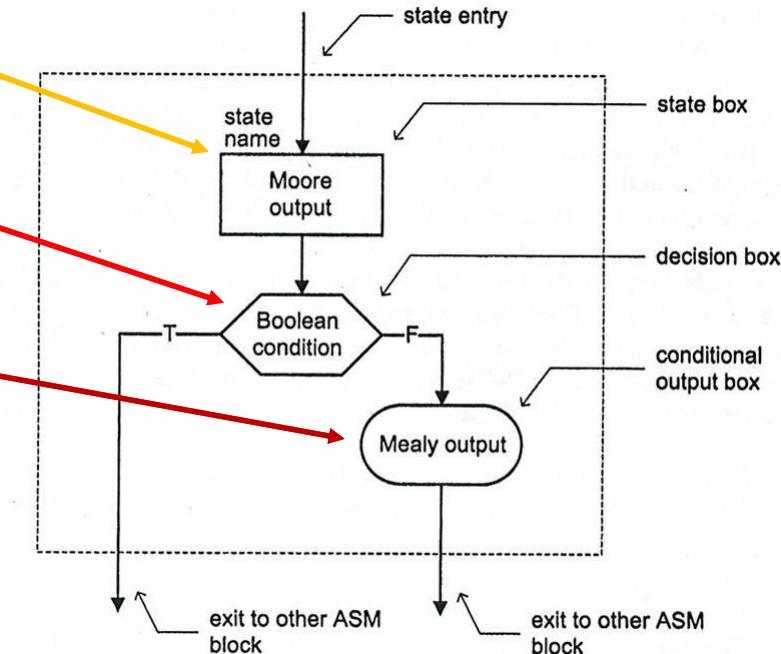
- Standardized way of displaying FSMs
 - Developed for digital ICs at Berkeley in the 1960's
- More descriptive than state diagram?
 - More structured
 - Same information
 - Always prioritized conditions
 - = Synthesizable
- Works well with boolean conditions for transitions and assignment
- *Can become very large*
 - when having multiple exit paths for each state.



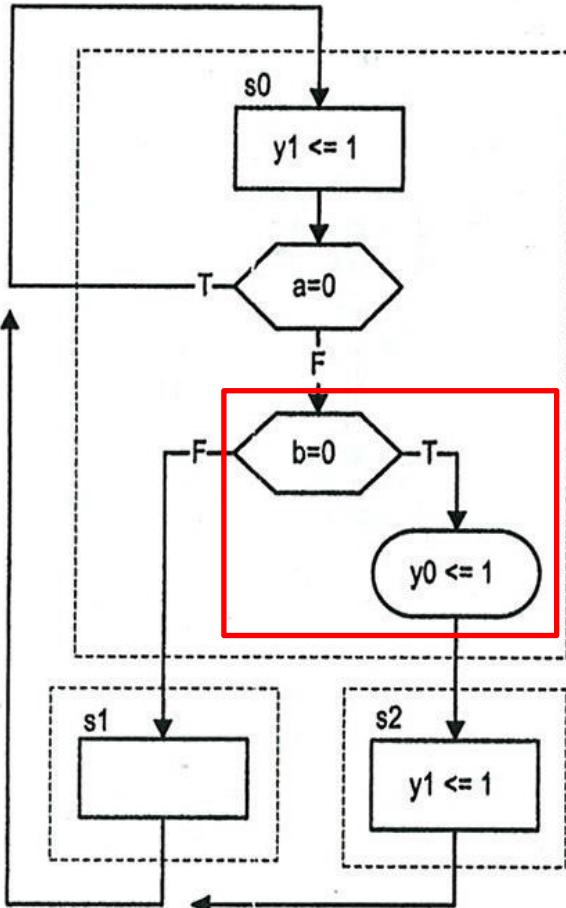
ASM (Algorithmic State Machine) block

Source: RTL hardware design using VHDL, Pong P.Chu

- The **state box "Tilstandsboks"** represents a state in the FSM
 - State based output is shown inside (i.e. the **Moore outputs**).
- The **decision box "Beslutningsboks"** tests an input condition to determine the exit path of the current ASM block.
- A **conditional output box "Mealy boks"**
 - lists conditionally asserted signals.
 - Can only be placed after an exit path of a decision box
 - (i.e. the **Mealy outputs** that depends on the state and input values).

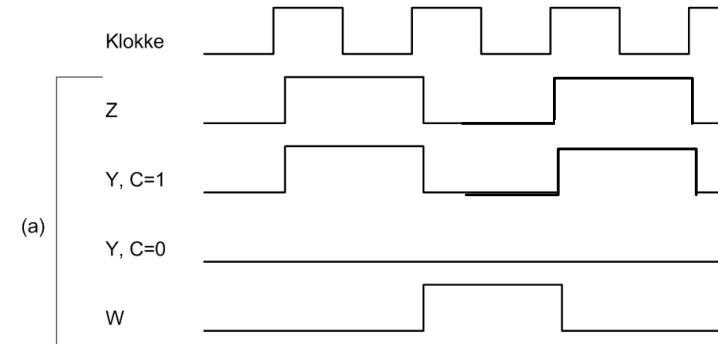
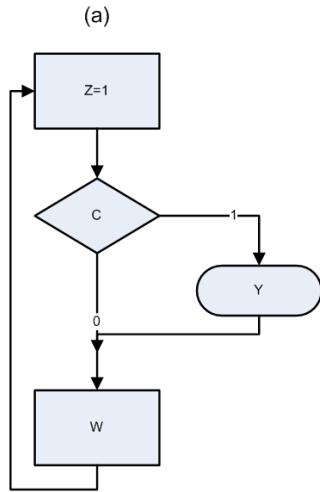


ASM Chart Example 1



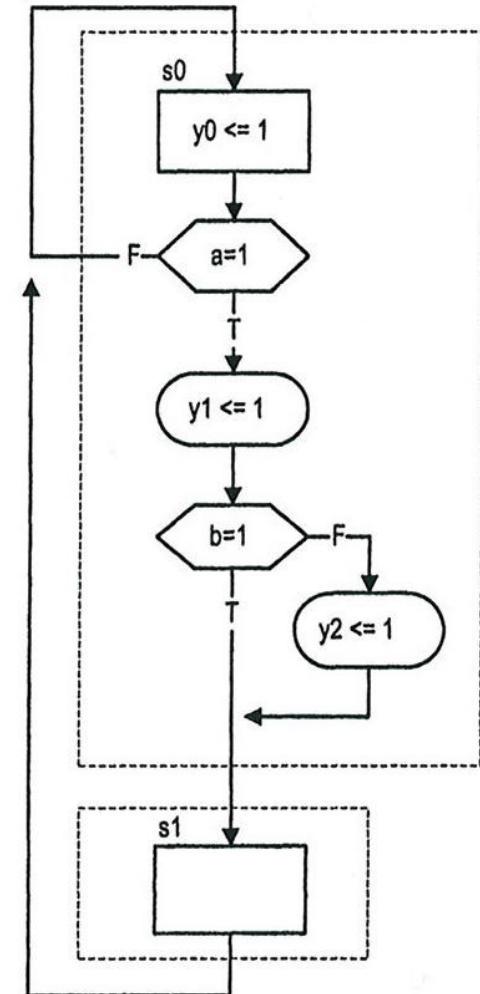
- Conditional output (Mealy box) can only be placed after an exit path of a decision box.
- \leq is used for assigning signal values
 - Don't expect full consistency... some will use "="*
- Unless specified (assigned) values are assumed to take their default values
 - Except register operations which is noted with ' \leftarrow '
 - Registers will be updated on the next clock cycle
 - This can cause great confusion (be careful)
 - ASMD lecture covers this
- Signals that are boolean are assumed set or found active ('1') when mentioned alone.
 - Here: we could have seen
 - " y_1 " in place of " $y_1 \leq 1$ " and
 - "not b " in place of " $b=0$ "

ASM chart example 2, Mealy vs Moore output

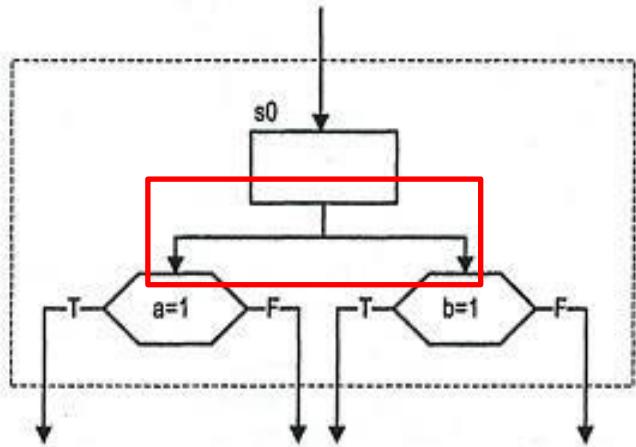


Two ASM FSM rules apply

1. For any given input combination, there is one unique exit path from the current ASM block.
2. The exit path of an ASM block must always lead to a state box.
 - Can be the state box of the current or any other ASM block.

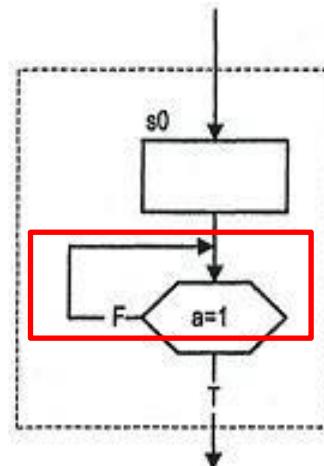


Common Errors in ASM Charts



This case violates rule one since it is two exit paths that are not governed by an input

You cannot enter two states at the same time in one state machine...

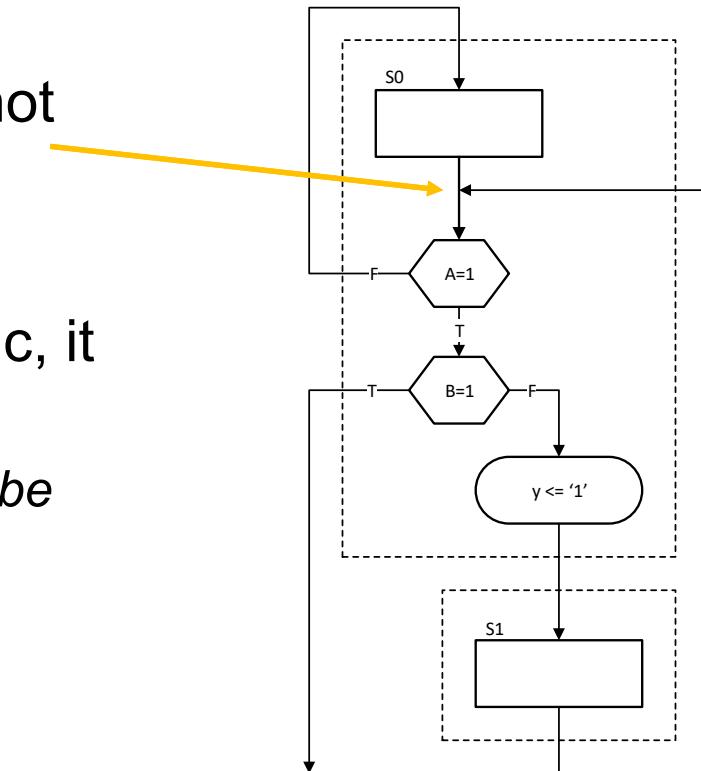


The case above violates the first rule since there is no exit path when the condition in the decision box is false.

A state shall be entered each clock cycle...

Common errors in ASM charts (2/2):

- exit path of the S1 block does not go into a state box
- If we need the same output logic, it must be copied for S1.
 - *(unless S1 is redundant and can be removed entirely)*

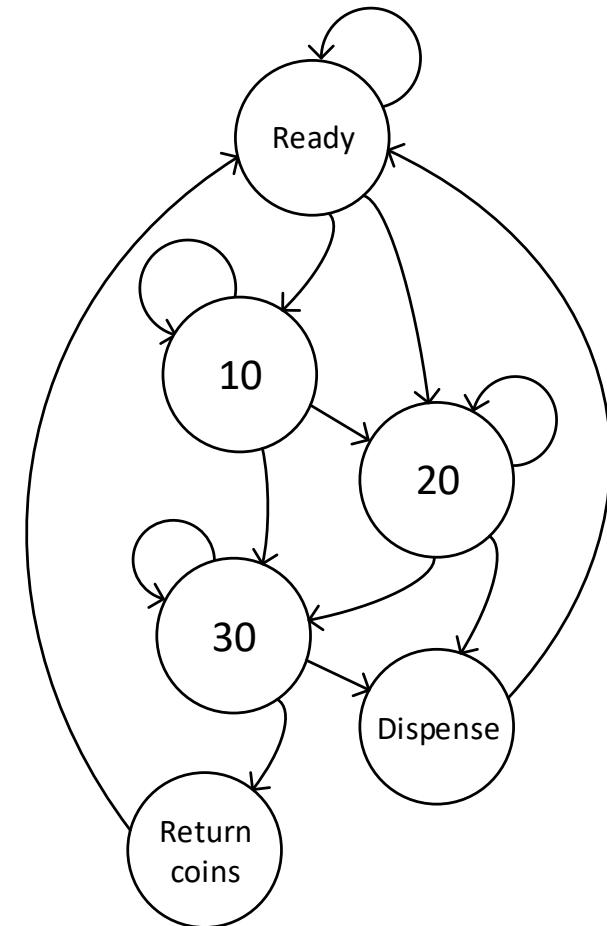
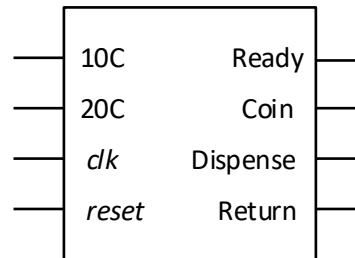


Example State Machine: Vending Machine

- Specification:
 - We want to design a vending machine that sells drinks for 40c.
 - The machine accepts 20c and 10c coins (all others will be rejected mechanically).
 - If 40c are inserted a drink shall be dispensed
 - If more than 40c is inserted all coins are returned
 - The machine has two lights
 - One to show that it is ready
 - One to show that further coins are needed
- Work order:
 - Define the entity
 - Find/Define the states
 - State diagram, ASM chart or both?
 - How to find redundant states?
 - Create an ASM chart
 - Be aware of Moore and mealy output
 - Once you have the ASM chart, with as few possible states: start coding
 - Decide before synthesizing:
 - One hot?
 - (FF's are cheap in an FPGA)
 - Binary counter?
 - Gray code?
 - (minimum noise / switching current)
 - *can the synthesizer decide for me?*

Example: Vending machine

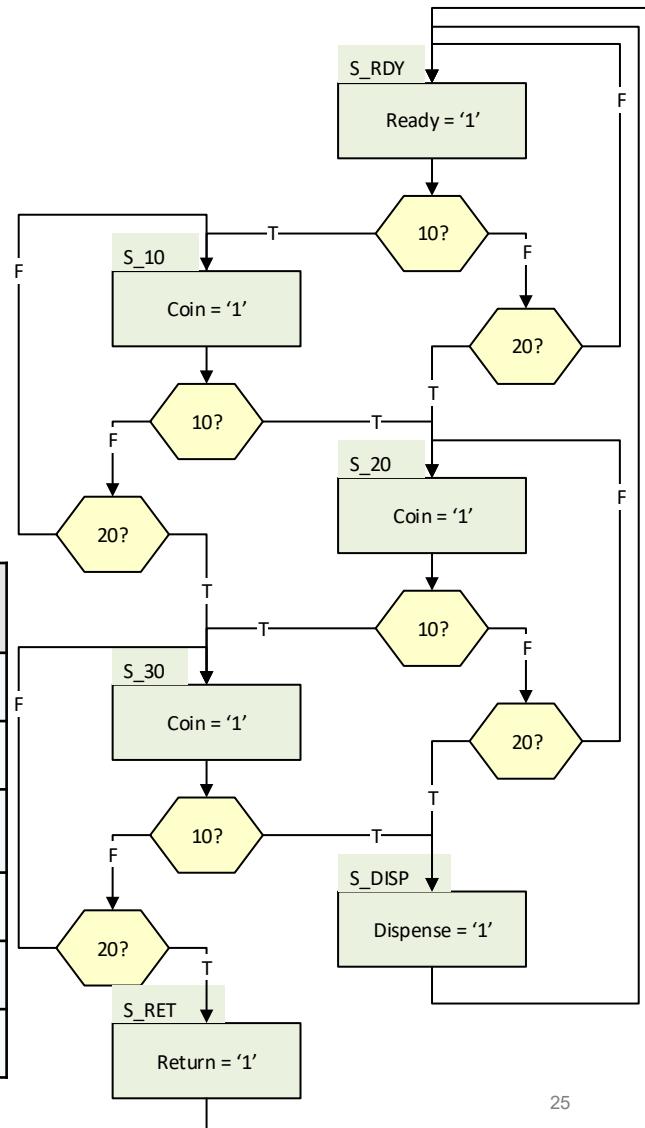
- Sketch state diagram and entity
- May give you enough overview that you can simplify



ASM diagram & State and output table

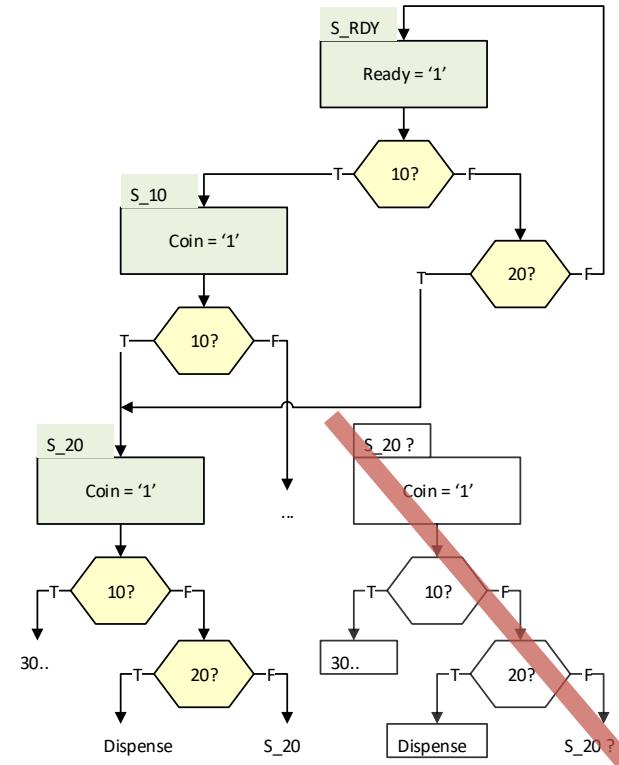
- If possible- simplify early.
 - Both state and output tables and ASM charts can be used to find redundancy

State	10c	20c	No coin	Ready	Coin	Dispense	Return
S_RDY	S_10	S_20	Self	1	0	0	0
S_10	S_20	S_30	Self	0	1	0	0
S_20	S_30	S_DISP	Self	0	1	0	0
S_30	S_DISP	S_RET	Self	0	1	0	0
S_DISP	S_RDY	S_RDY	S_RDY	0	0	1	0
S_RET	S_RDY	S_RDY	S_RDY	0	0	0	1



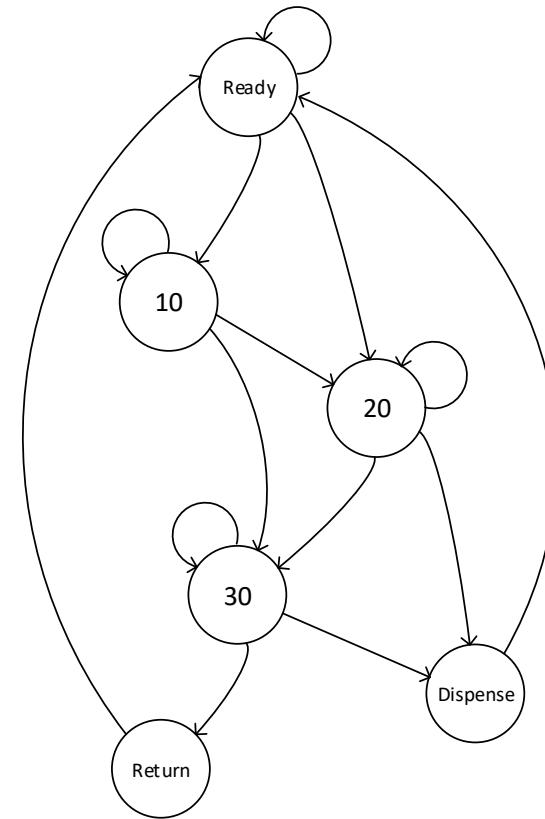
Redundant states in ASM

- If we start out as a decision tree
-always branching to new states-
we will get redundant states.
- State can be removed when
 - (decisions for) next state and output is equal to another state



Redundant states in state diagram

- Can be easier to spot
 - We need to know all output based on state to be sure



Redundant states in output table

- Can be difficult to spot...
 - Names may confound
 - Both state and output must be checked
 - Here: otherwise DISP = RET ..?
 - It may be useful to use «self» rather than state name when going to the same state.
 - States that we only sweep through are candidates for creating mealy outputs...

The diagram illustrates the identification of redundant states in an output table. Two sets of arrows point to specific rows in the table:

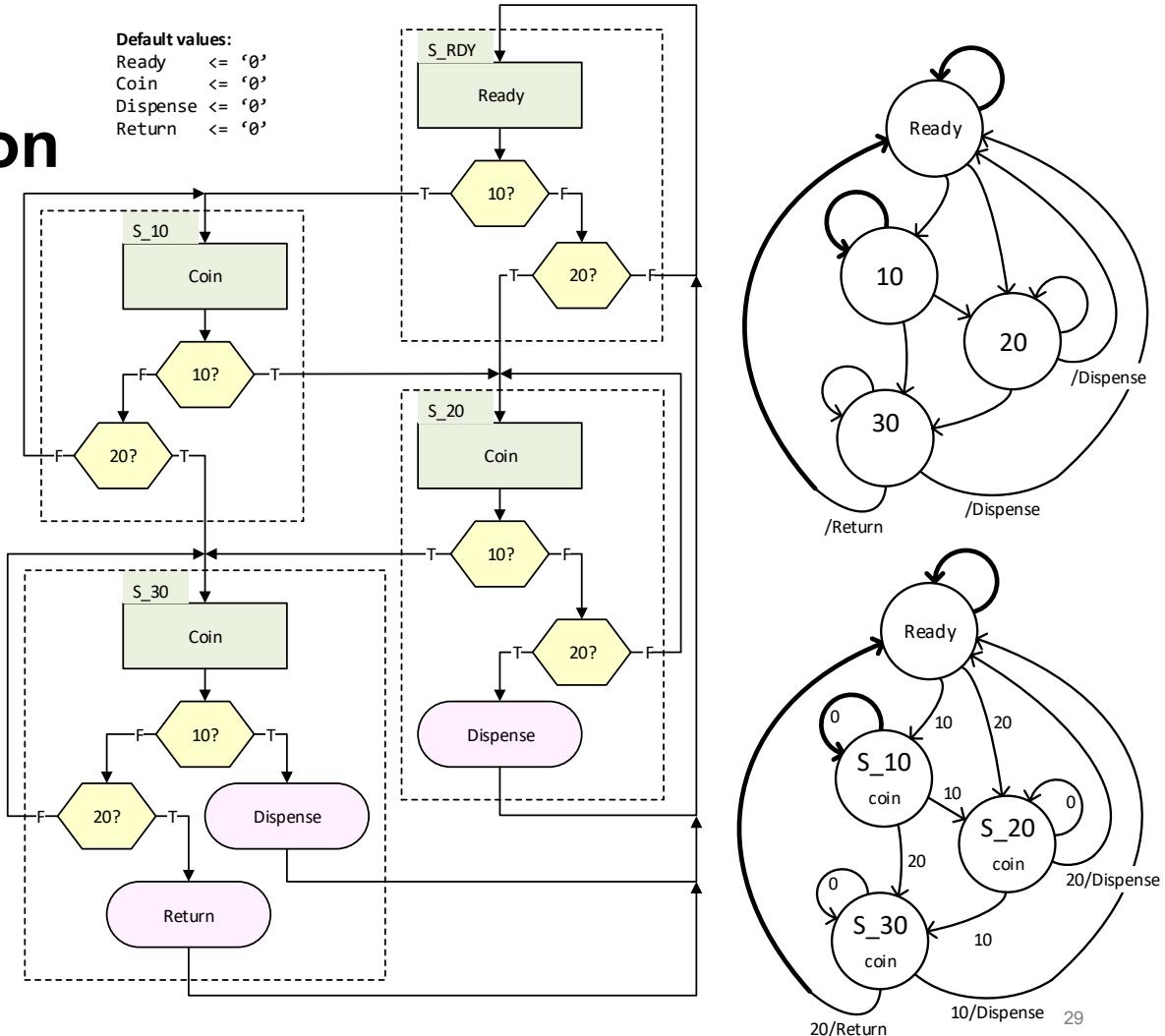
- Yellow arrows:** Point to the rows for S_RDY, S_10, S_20, and S_20_2. These rows represent states that transition to themselves ('Self') and have other transitions (e.g., 10c to S_10, 20c to S_20) which may be redundant or indicate a different behavior than intended.
- Red arrows:** Point to the rows for S_DISP and S_RET. These rows represent states that are only swept through (indicated by '-' in the 10c and 20c columns) and serve as candidates for creating mealy outputs.

State	10c	20c	No coin	Transition to self	Ready	Coin	Dispense	Return
S_RDY	S_10	S_20	Self	Yes	1	0	0	0
S_10	S_20_2	S_30	Self	Yes	0	1	0	0
S_20	S_30	S_DISP	Self	Yes	0	1	0	0
S_20_2	S_30_2	S_DISP	Self	Yes	0	1	0	0
S_30	S_DISP	S_RET	Self	Yes	0	1	0	0
S_30_2	S_DISP	S_RET	Self	Yes	0	1	0	0
S_DISP	-	-	S_RDY	No	0	0	1	0
S_RET	-	-	S_RDY	No	0	0	0	1

Mealy optimization

Identify states that are run through in one clock cycle without decision boxes

1. Is the output depending on being decoded in a different state than the previous?
 2. Does timing requirements that dictates a separate state?
- If no on both:
create a Mealy-output box, in place of the old state



Coding state machine using VHDL

- Make your own states as «enumerated» type.
 - This simplifies reading a lot (example next slide)
- Use three processes / statements
 1. One for assigning the state = declaring FF's
 - based clock (and *reset when asynchronous reset*)
 2. One for deciding the next state (*next_state* CL).
 - based on previous state and inputs
 3. One for setting outputs (output CL)
 - based present state (and inputs if Mealy type)
- Sometimes 2. and 3. can be combined
 - In simple cases where the output has very little decoding

FSM in VHDL 1/2

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;

entity vending is
port(
    clk, reset, twenty, ten : in std_logic;
    ready, coin, dispense, ret : out std_logic);
end entity vending;

architecture asm of vending is
type state_type is (S_RDY, S_10, S_20, S_30);
signal present_state, next_state : state_type;
begin
```

```
-- 1: sequential state assignment:
REGISTER_ASSIGNMENT: process(clk) is
begin
    if rising_edge(clk) then
        present_state <= S_RDY when reset else next_state;
    end if;
end process;

-- 2: combinatorial next_state logic
next_state_CL: process(twenty, ten, present_state) is
begin
    --default
    next_state <= present_state;
    case present_state is
        when S_RDY =>
            next_state <=
                S_10 when ten else
                S_20 when twenty;
        when S_10 =>
            next_state <=
                S_20 when ten else
                S_30 when twenty;
        when S_20 =>
            next_state <=
                S_30 when ten else
                S_RDY when twenty;
        when S_30 =>
            next_state <= S_RDY when ten or twenty;
    end case;
end process next_state_CL;
```

- Continues next slide

FSM in VHDL 2/2

```
-- 3: combinatorial output logic
output_CL: process(all) is
begin
    --default output values
    ready    <= '0';
    dispense <= '0';
    ret      <= '0';
    coin     <= '0';
    -- state based assignment
    case present_state is
        when S_RDY =>
            ready    <= '1';
        when S_10 =>
            coin     <= '1';
        when S_20 =>
            coin     <= '1';
            dispense <= '1' when twenty;
        when S_30 =>
            coin     <= '1';
            dispense <= '1' when ten;
            ret      <= '1' when twenty;
    end case;
end process output_CL;
end architecture asm;

-- ALTERNATIVE ouput_CL:
ready <= '1' when present_state = S_RDY else '0';
coin  <= not ready;
dispense <= '1' when
    (present_state = S_20 and twenty = '1') or
    (present_state = S_30 and ten = '1') else '0';
ret   <= '1' when (present_state = S_30 and twenty = '1') else '0';
```

- *Optional alternative replaces 3*
 - Consider how compactness affects readability

Test bench for FSM

- Uses file I/O template from previous lecture-
- Input procedural
- Output in a separate process

```

library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;
use STD.textio.all;

entity tb_vending is
end entity;

architecture behavioral of tb_vending is
component vending is
port(
    clk, reset, twenty, ten : in std_logic;
    ready, coin, dispense, ret : out std_logic);
end component;
signal clk, reset, twenty, ten: std_logic := '0';
signal ready, coin, dispense, ret: std_logic;
constant CLK_PERIOD : time := 10 ns;

begin
DUT: vending
port map(
    clk => clk,
    reset => reset,
    twenty => twenty,
    ten => ten,
    ready => ready,
    coin => coin,
    dispense => dispense,
    ret => ret);

clk <= not clk after CLK_PERIOD/2;

check_output: process(clk) is
variable in_machine: integer := 0;
constant COIN_DIGITS : integer := 3;
constant SPACER : integer := 1;
-- log output file
file log_file: text open write_mode is "vending_log.txt";
variable log_line: line;

begin
if rising_edge(clk) then
    --keep track of coins
    if ret = '1' or dispense = '1' then
        in_machine := 0;
    elsif ten then
        in_machine := in_machine + 10;
    elsif twenty then
        in_machine := in_machine + 10;
    end if;
    --report errors to console
    assert (in_machine < 40)
        report ("coin overflow: ", integer'image(in_machine))
        severity error;
    -- report to file
    write(log_line, in_machine, field => COIN_DIGITS);
    write(log_line, ready, field => + 2*SPACER);
    write(log_line, coin, field => + 2*SPACER);
    write(log_line, dispense, field => + 2*SPACER);
    write(log_line, ret, field => + 2*SPACER);
    writeline(log_file, log_line);
end if;
end process;

```

TB stimuli:

- Usually one main process for stimuli
 - Except for clock generation
- Use procedures for file IO
- Testing can be done for each new input data or in a separate process...

```

process is
    type t_coin is (te, tw); -- ten, twenty abbreviated
    file stimuli_file: text open read_mode is "vending_stimuli.txt";
    variable stimuli_line: line;
    variable stimuli_coin: t_coin;
    variable stimuli_periods: integer := 0;
    variable str : string(2 downto 1);

procedure set_stimuli is
begin
    readline(stimuli_file, stimuli_line);
    read(stimuli_line, str);
    stimuli_coin := t_coin'value(str);
    read(stimuli_line, stimuli_periods);
    ten <= '1' when stimuli_coin = te else '0';
    twenty <= '1' when stimuli_coin = tw else '0';
end procedure;

begin
    -- initial reset:
    wait for CLK_PERIOD/2;
    reset <= '1';
    wait for CLK_PERIOD;
    reset <= '0';
    wait for CLK_PERIOD;

    while not endfile(stimuli_file) loop
        set_stimuli;
        wait for CLK_PERIOD;
        ten <= '0';
        twenty <= '0';
        wait for CLK_PERIOD*stimuli_periods;
    end loop;
    file_close(stimuli_file);
    -- file_close(log_file);
    report ("Testing finished!");
    std.env.stop;
end process;

end architecture;

```

Libraries and main

```
import cocotb
from cocotb.triggers import RisingEdge, FallingEdge, ReadOnly,
ClockCycles
from cocotb.clock import Clock

@cocotb.test()
async def main_test(dut):
    dut._log.info("Starting test...")
    cocotb.start_soon(Clock(dut.clk, 10, units='ns').start())
    await reset_dut()
    cocotb.start_soon(compare(dut))
    log_file = open("vending_log.txt", "a")
    cocotb.start_soon(io_log(dut, log_file))
    stimuli_file = open("vending_stimuli.txt", "r")
    await stimuli_generator(dut, stimuli_file)
    stimuli_file.close()
    log_file.close()
    dut._log.info("Testing finished")

async def reset_dut():
    ''' Set all device input and output in a known state '''
    dut._log.info("Resetting...")
    dut.twenty.value = 0
    dut.ten.value = 0
    dut.reset.value = 0
    await FallingEdge(dut.clk)
    dut.reset.value = 1
    await RisingEdge(dut.clk)
    dut.reset.value = 0
    dut._log.info("Reset finished")
```

Stimuli and log

- Stimuli out on falling edge to avoid confusion?

```
async def stimuli_generator(dut, stimuli_file):
    dut._log.info("Generating test patterns..")
    for line in stimuli_file:
        #await FallingEdge(dut.clk)
        await RisingEdge(dut.clk)
        items = line.split()
        dut.ten.value = 1 if items[0] == 'te' else 0
        dut.twenty.value = 1 if items[0] == 'tw' else 0
        await RisingEdge(dut.clk)
        dut.ten.value = 0
        dut.twenty.value = 0
        await ClockCycles(dut.clk, int(items[1]))
```

```
async def io_log(dut, logfile):
    dut._log.info("Starting IO log")
    logfile.write("Logging input and output \n")
    while True:
        await FallingEdge(dut.clk)
        line = (f"twenty: {dut.twenty.value} " +
                f"ten: {dut.ten.value} " +
                f"ready: {dut.ready.value} " +
                f"coin: {dut.coin.value} " +
                f"ret: {dut.ret.value} " +
                f"dispense: {dut.dispense.value} " +
                f"\n")
        logfile.write(line)
```

Helping methods

```
# Conversion tables
# type state_type is (S_RDY, S_10, S_20, S_30);
state = {
    0:'S_RDY',
    1:'S_10',
    2:'S_20',
    3:'S_30'
}
def should_dispense(dut, in_machine):
    if in_machine == 20 and dut.twenty.value == 1: return True
    if in_machine == 30 and dut.ten.value     == 1: return True
    return False

def should_return(dut, in_machine):
    if in_machine == 30 and dut.twenty.value == 1: return True
    return False
```

compare

- Note:

- Avoid parenthesis on assert

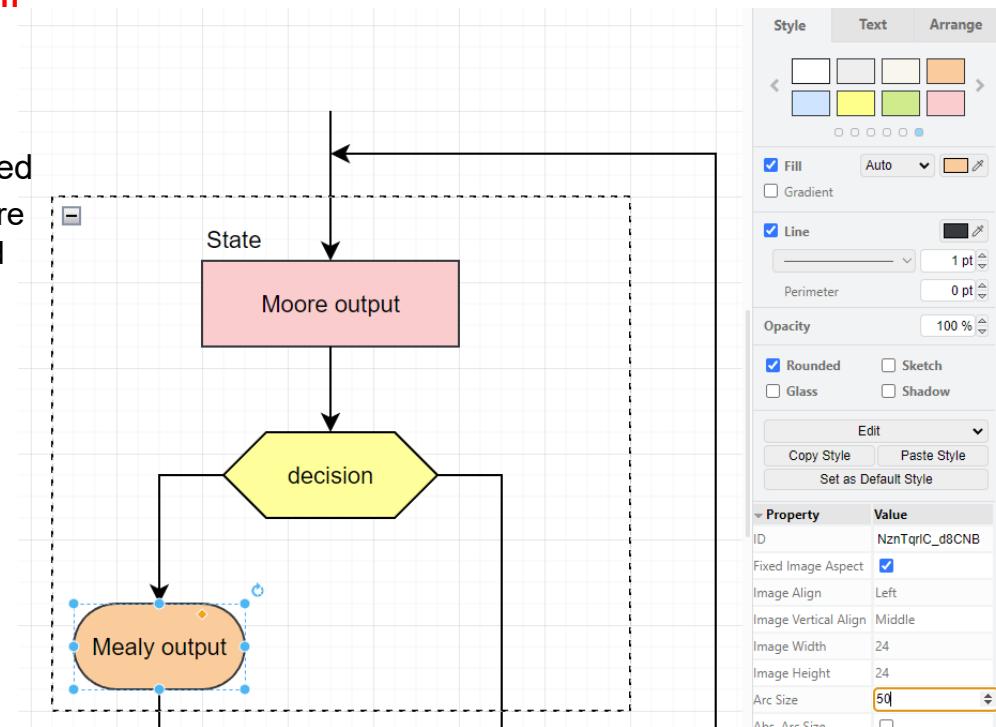
```
async def compare(dut):
    dut._log.info("Launching checks")
    in_machine = 0
    while True:
        await RisingEdge(dut.clk)
        # Before ReadOnly- tests on what was present when clock arrived
        if dut.ten.value == 1: in_machine += 10
        elif dut.twenty.value == 1: in_machine += 20
        # print(in_machine)
        if dut.ret.value == 1: in_machine = 0
        if dut.dispense.value == 1: in_machine = 0

        await ReadOnly()
        # Blackbox checks (requires only entity + requirements )
        assert dut.dispense.value == int(should_dispense(dut, in_machine)), \
               "Dispense failed"
        assert dut.ret.value == int(should_return(dut, in_machine)), \
               "Coin return failed"

        assert in_machine < 40, f"Machine has too much coin: {in_machine}"
        #Whitebox check (requires architecture knowledge)
        if in_machine > 0:
            assert int(dut.present_state.value) == in_machine/10, \
                   f"Coin ({in_machine}) and state "+" \
                   f"({state[int(dut.present_state.value)]}) mismatch"
```

Diagram tools: Draw.io (Check availability)

- Draw.io (diagrams.net) will be available on the exam
 - Get used to the interface
 - General tab has all you need
 - "Containers" does not interfere with arrows, and can be used for state boundary
 - Making use of style:
 - Use 50% Arc size for mealy boxes
 - Light colouring is OK, *avoid dark colours*
 - Edit -> copy as image
 - *Will do for documentation.*
 - SVG available through export
 - File export *may not be available during exam*



Video resources

(Created for INF3430, updated with autotext 2023)

- FSM intro (37s)
 - <https://www.uio.no/studier/emner/matnat/ifi/IN3160/v23/fsm-videoer/0-fsm-intro.mp4?vrtx=view-as-webpage>
- FSM Basics (2:05)
 - <https://www.uio.no/studier/emner/matnat/ifi/IN3160/v23/fsm-videoer/1-fsm.mp4?vrtx=view-as-webpage>
- ASM State Diagrams (7:44)
 - <https://www.uio.no/studier/emner/matnat/ifi/IN3160/v23/fsm-videoer/2-asm.mp4?vrtx=view-as-webpage>
 - Note: 3:50 register operation ‘←’ not sufficiently described
- ASM Examples (5:30)
 - <https://www.uio.no/studier/emner/matnat/ifi/IN3160/v23/fsm-videoer/2b-asm-examples.mp4?vrtx=view-as-webpage>
- FSM Synthesis to VHDL (4:43)
 - <https://www.uio.no/studier/emner/matnat/ifi/IN3160/v23/fsm-videoer/3-fsm-synthesis.mp4?vrtx=view-as-webpage>

Suggested reading

- D&H:
 - 14 p305-324
 - 16 p344-372

Some (free) tools for making charts

- <https://app.diagrams.net/> (browser based or downloadable <https://www.drawio.com>)
- <http://mermaid.live/> (browser+ code based, OK for bubble-diagram, not ASM – 2023-0306 *cannot specify exit direction of boxes*)
www.lucidchart.com (browser based, signup)
- [Dia](#) (Small, requires installation, all platform GNU)
- [LibreOffice](#) (large, GNU)
- <http://diagrammo.com/> (browser based, signup)

IN3160 IN4160
Datapath state machines
Yngve Hafting



Messages:

Course Goals and Learning Outcome

<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

In this course you will learn about the **design of advanced digital systems**. This includes programmable logic circuits, a **hardware design language** and system-on-chip design (processor, memory and logic on a chip). **Lab assignments provide practical experience in how real design can be made.**

After completion of the course you will:

- understand important **principles for design** and testing of digital systems
- understand the relationship between behaviour and different construction criteria
- **be able to describe advanced digital systems at different levels of detail**
- be able to perform simulation and synthesis of digital systems.

Goals for this lesson:

- Know what is
 - Datapath state machines (FSMD)
- Know how to divide larger designs and state machines
 - Principles
 - Design strategies
 - Divide and conquer-

Next lesson:

- Diagrams and reset circuits?
- ~~Microcoded state machines~~
- ~~Microcoded processors~~

Overview

- Register operations (example)
- What is data path finite state machines (FSMD)?
 - Example with code and diagrams
- Factoring state machines
 - When and how do we split
- Next lesson:
 - Examples with diagrams and code

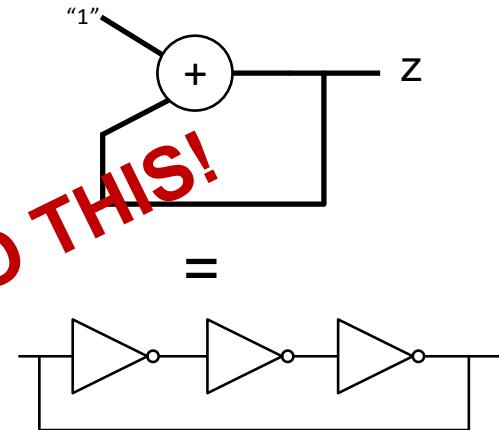
Register example: Simple counter

- Without the use of registers..?

- $z \leq z+1;$

- Not tied to clock => oscillator

DON'T DO THIS!



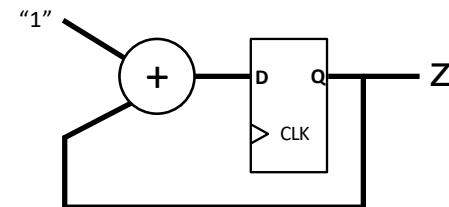
- Solution: use registers

- $z \leftarrow z + 1$ (ASMD notation)

=

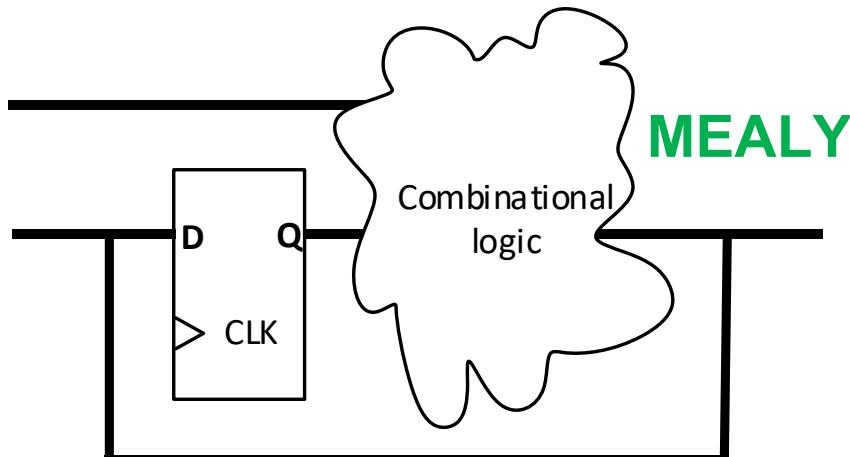
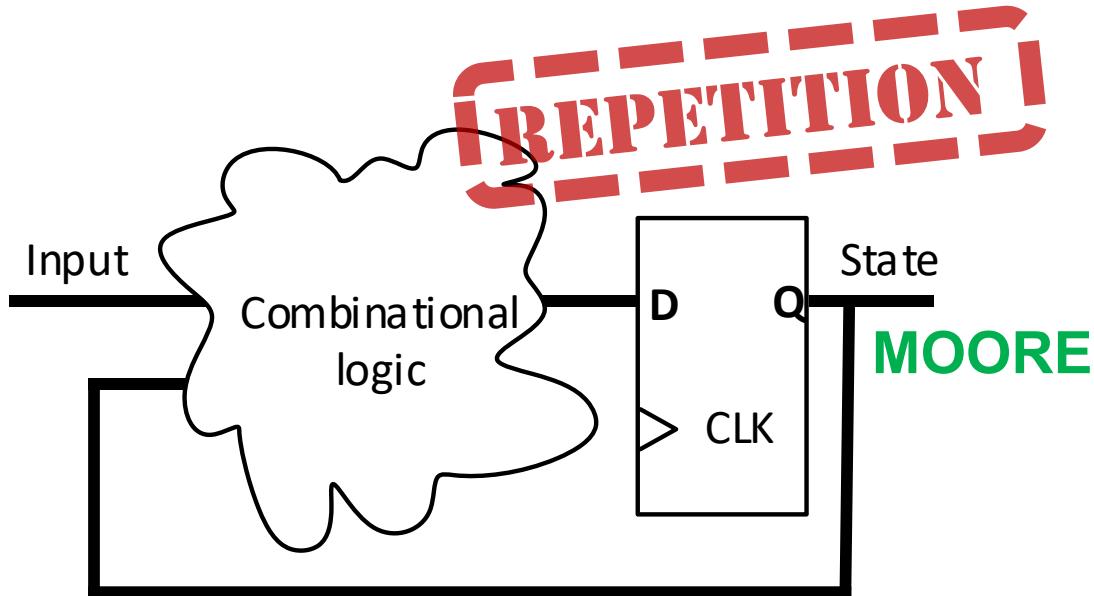
`next_z <= z+1;`

`z <= next_z when rising_edge(clk);`



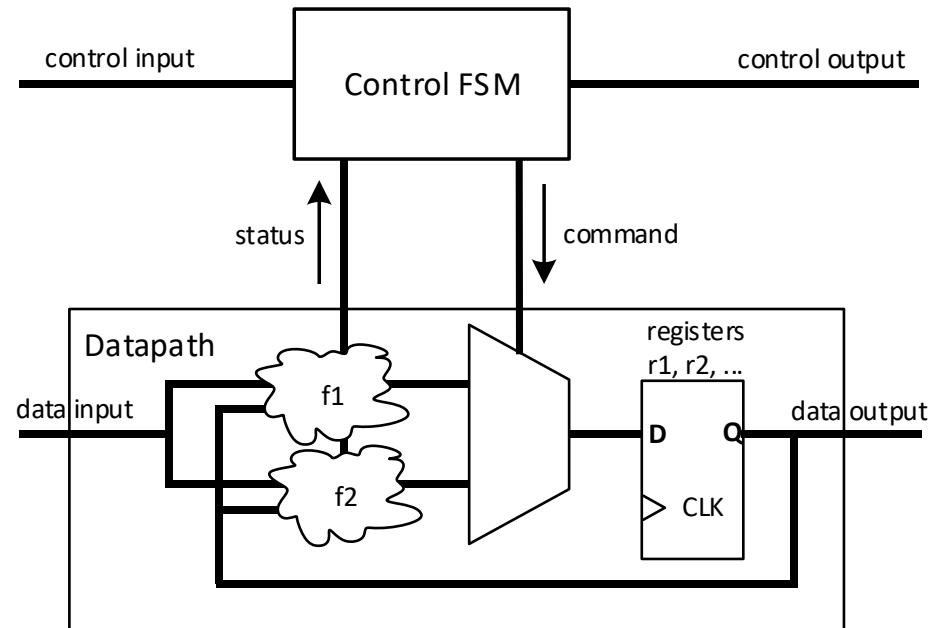
General FSM

- General FSM
 - Combinational logic connected to registers with feedback



«Datapath» FSM

- Datapath is described by a function rather than a table
 - Counters
 - Mathematical operations
 - Shift registers
 - Etc.
- We usually divide into control FSM and Datapath



«Register operations» in data-path FSM (FSMD) -and how to deal with it

- Common notations for register operations:

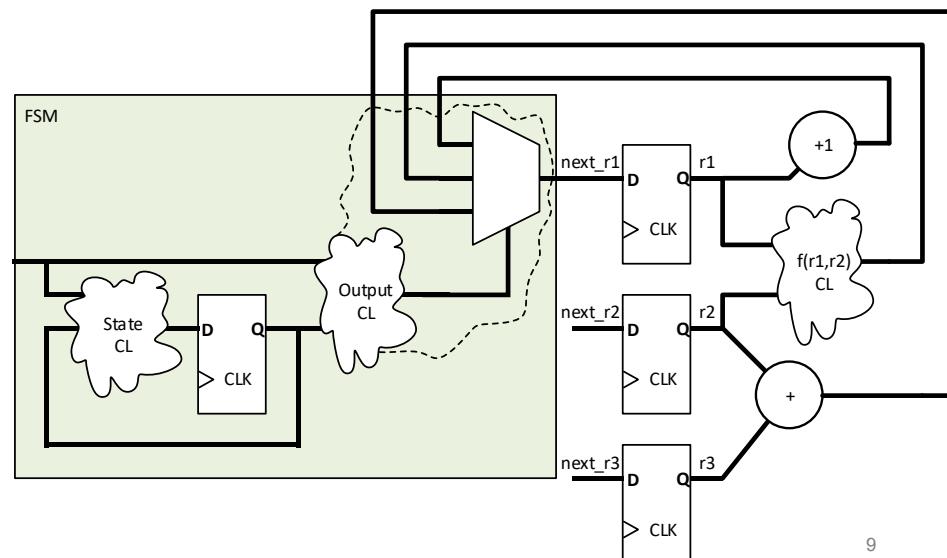
- on clock edge we increment $r1$  $r1 \leftarrow r1 + 1$
- on clock edge we update $r1$ based on a function of register outputs  $r1 \leftarrow f(r1, r2)$
- on clock edge, set $r1$ to $r2+r3$  $r1 \leftarrow r2 + r3$

This notation can be confusing, as it implies one clock delay if it is put into an ASM chart.

Solution:

Use '←' for datapath only (not for FSM)

Know that '←' implies the use of registers that are not a part of the FSM states



Use of register in decision box

We want to exit having n becomes 0..

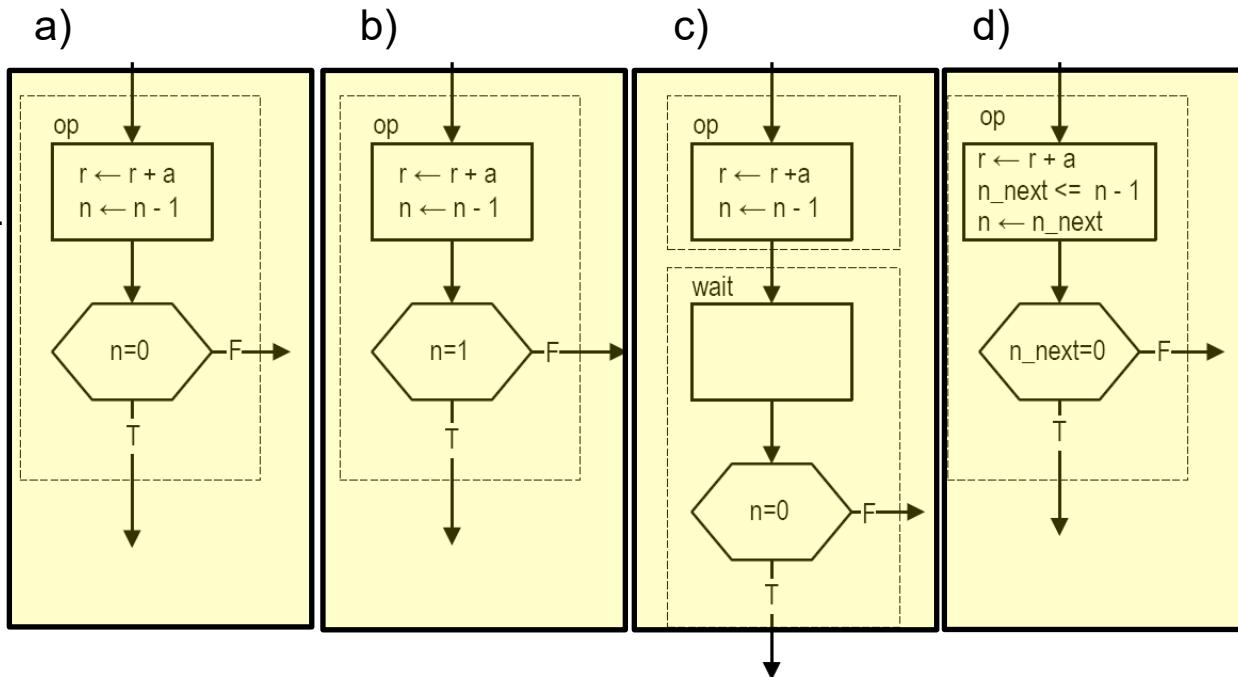
- a) n will be updated after $n=0$ check
- b) n will be updated after $n=1$ check...

- Even if we want this behavior...
 - it seems unclear what we want to achieve, as with a).

- c) Do we need to introduce single cycle wait states?..

- d) is clear about

- ***what we want*** and
- ***how we will do it***
- => ***no doubt on our intention***



- Register is updated when the FSM exits current state (#2017 Video)
 - NOTE: We “exit” current state each cycle- even if we re-enter...
- => Use solution d)!

Timer example

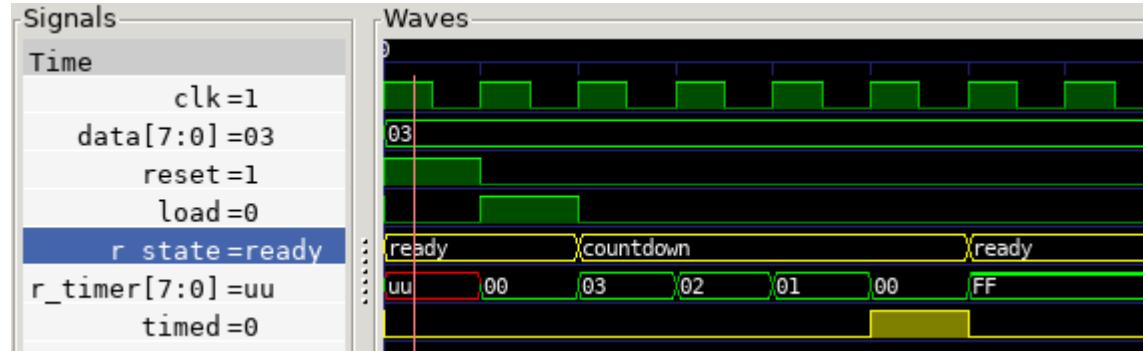
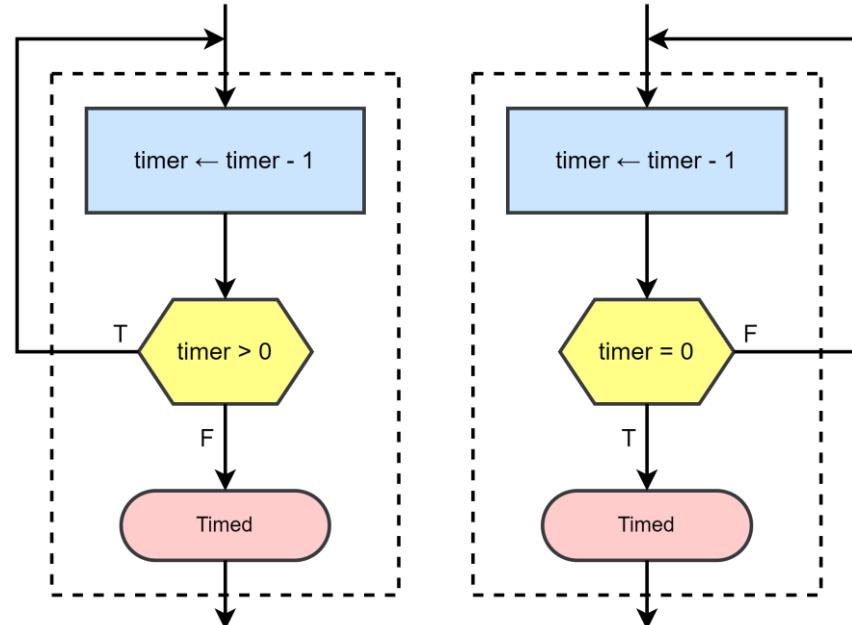
- Both diagrams here depict the same behavior
- Avoid setting the same output in both state box and mealy box

...CL

```
next_state <= ready when r_timer = 0;
-- next_state <= countdown when r_timer > 0 else ready;
```

...CL

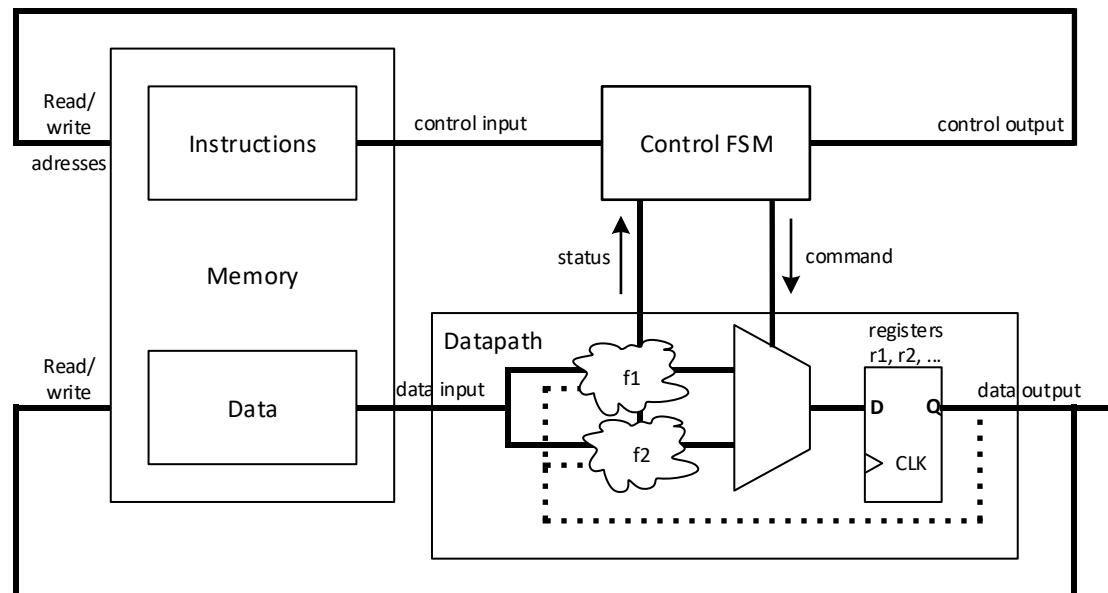
```
next_timer <= r_timer - 1;
timed <= '1' when r_timer = 0;
```



- Full example on github week 6
- <https://github.uio.no/in3160/lectures/tree/main/week06/timer-test>

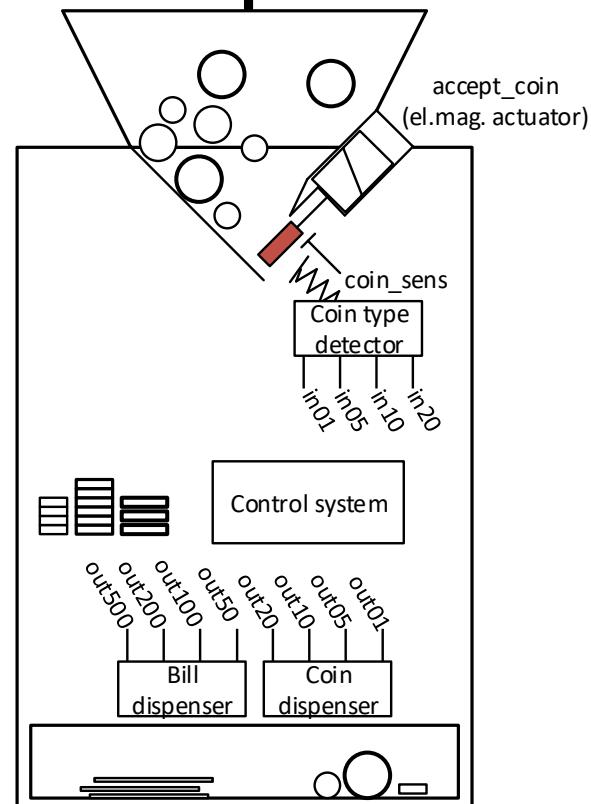
Processor system is a datapath FSM

- Control output is memory instructions
- FSM decodes instructions and decides which part of the datapath is used
 - Pipeline flushes, stalls etc.
- Datapath contains ALU, pipeline registers etc.



Example Factoring state machine with Datapath

- Exchange machine
 - Green LED ‘ready’/ can accept coins
 - Can take a number of up to 100 coins
 - Count each coin type
 - 1, 5, 10, 20 NOK
 - Close intake at maximum (! Green)
 - Close intake when counting
 - Close intake when no more coins (assume new coin each clock edge)
 - Give out the highest possible bills (assuming infinite supply)
 - 50, 100, 200 NOK
 - Return the least amount of coins
 - Use only coin from machine



When state count is nuts..

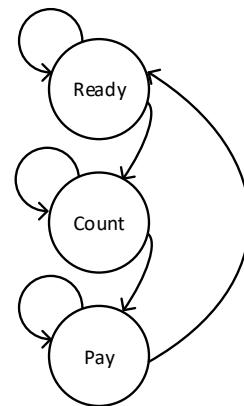
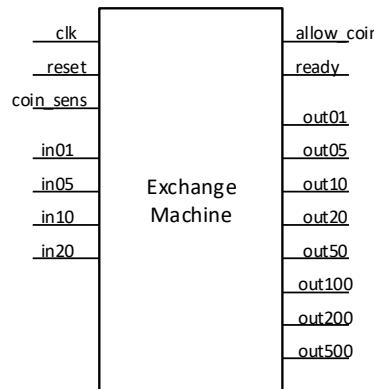
- Millions of states possible => Cannot make «one» FSM

=> several smaller state_machines or
state machine + data path with registers

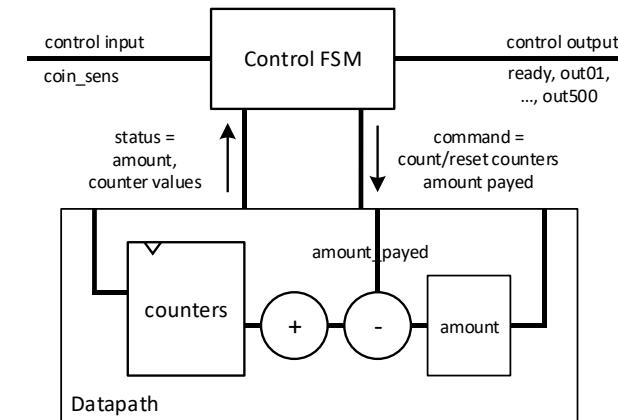
Method: Divide and conquer

Divide into models that can be conquered

- Partition by..?
 - State (FSMs vs datapath),
 - Task (counters, FSMs,...)
 - Interface (entities)
- Entity:
- FSM(s)

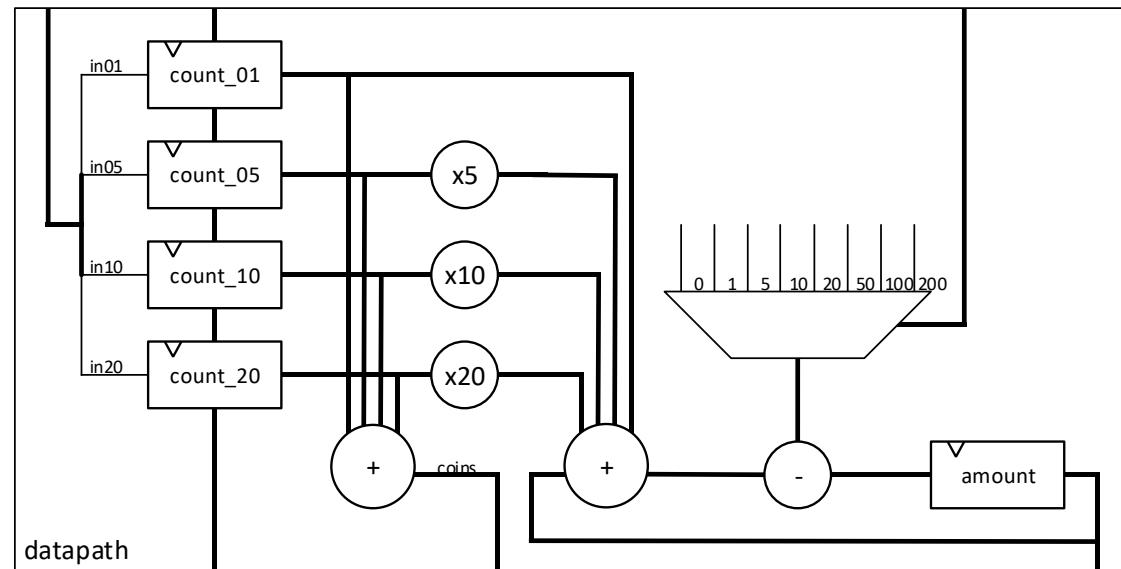


- Datapath



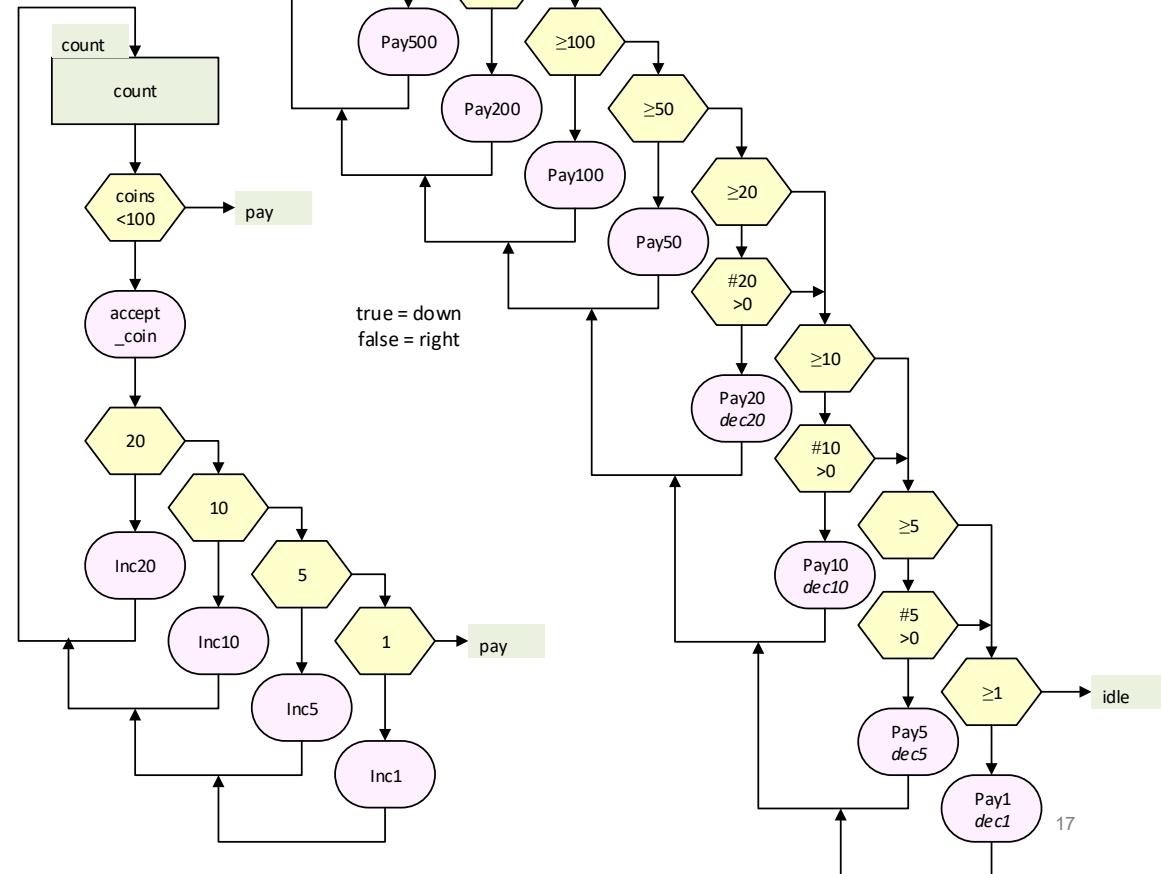
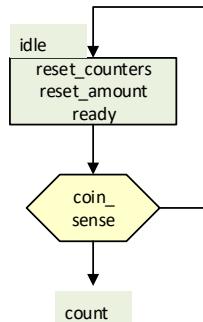
Detailed datapath

- 4 counters
 - Can they be of the same type?
 - Up/ down / reset
- «Coins» and «amount»
 - Why/ why not registers?



Detailed FSM = use ASM

- Make sure
 - all transition decisions are covered
 - all control output is set

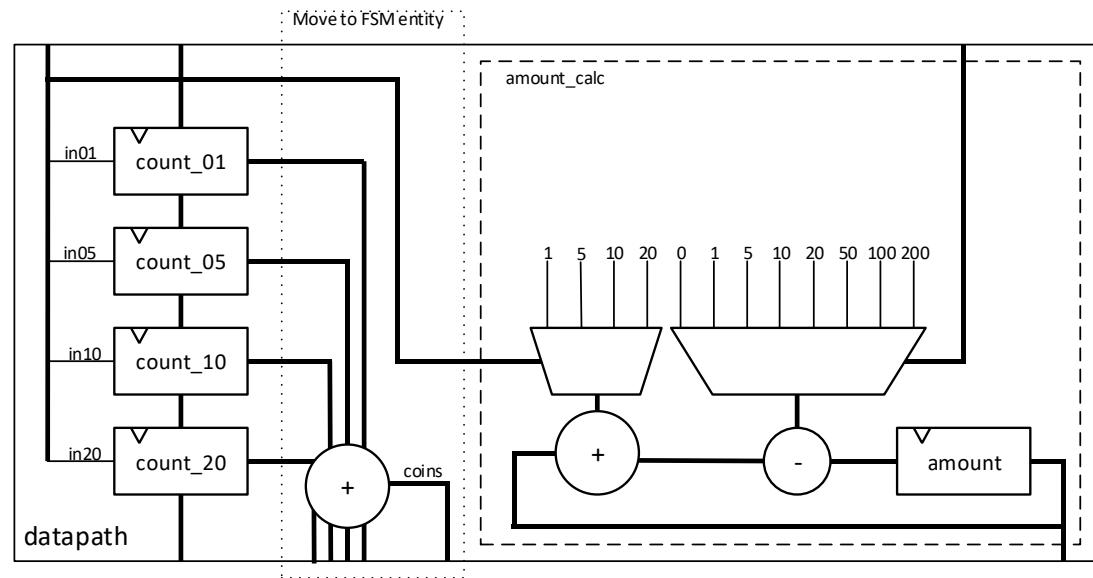


Reiterate and refine

- You will likely need a couple of rounds refining before deciding on VHDL modules
 - Entity
 - FSM(s)
 - Detailed datapath
 - ASM diagrams

Example reiteration

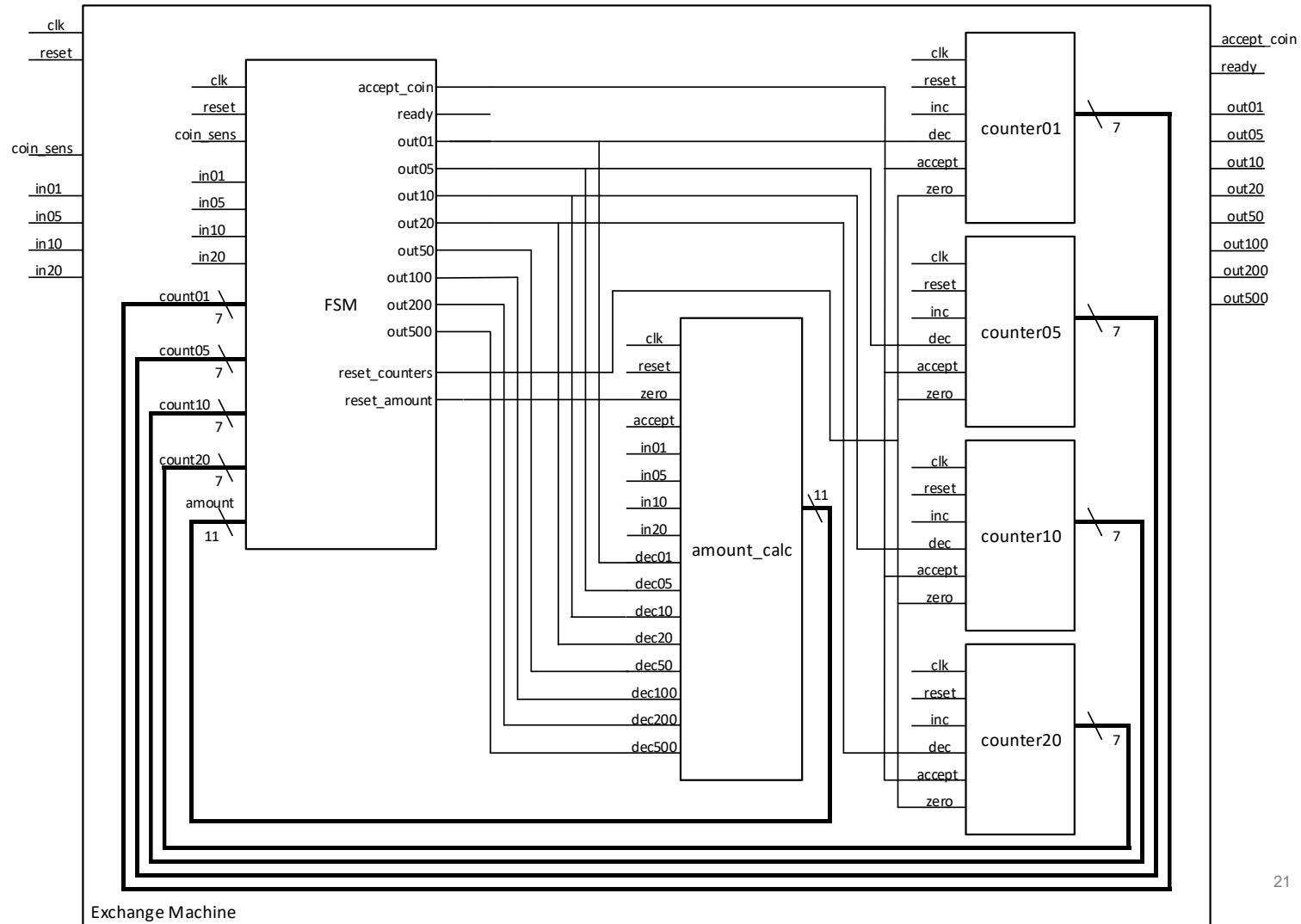
- Simpler by using
 - Only increments or decrements for amount calculation



VHDL modules and hierarchy

- What makes a good hierarchy?
 1. Structural top
 2. RTL
 3. data flow modules
 - Complex designs may have several structural layers
 - Do not overdo this
- What makes good modules..?
 - One type of code within module
 - (Structural vs RTL vs Data Flow)
 - One purpose for each module
 - Loosely coupled / few dependencies
 - Minimum communication between modules
 - Changes can be made within one module without changing another
 - Little or no duplicate code...
 - Use functions, loops, constants etc.
 - Scalable
- Example modules:
 - Toplevel (structural)
 - Control FSM
 - Counter(s)
 - One VHDL module, four instances
 - Datapath..?
 - (code reuse within toplevel...)
 - Datapath..?
 - *Amount calculation*

Top



Toplevel shell

- Filling in the rest should be easy once the modules are ready
- We need names for signals that go between modules.

```

library IEEE;
use IEEE.STD_LOGIC_1164.all;

entity exchange_machine is
port(
    clk, reset           : in std_logic;
    coin_sens, in01, in05, in10, in20 : in std_logic;
    ready, accept_coin      : out std_logic;
    out01, out05, out10, out20      : out std_logic;
    out50, out100, out200, out500     : out std_logic
);
end entity exchange_machine;

architecture toplevel of exchange_machine is
component control_FSM is
port(
    clk, reset : in std_logic);
component counter is
port(
    clk, reset : in std_logic);
component amount_calc is
port(
    clk, reset : in std_logic);
-- signal decl. for communication between modules
begin
    FSM: control FSM
    port map(
        clk => clk,
        reset => reset);

    count01: counter
    port map(
        clk => clk,
        reset => reset);

    count05: counter
    port map(
        clk => clk,
        reset => reset);

    count10: counter
    port map(
        clk => clk,
        reset => reset);

    count20: counter
    port map(
        clk => clk,
        reset => reset);

    amount: amount_calc
    port map(
        clk => clk,
        reset => reset);

end architecture toplevel;
```

Counter

- Processes can be used to sort priority by order
 - OK when conditions are mutually exclusive?
- When-else can do the same sorting explicitly
 - Less need for process..

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;

entity counter is
generic(
  COUNT_WIDTH : natural := 7);
port(
  clk, reset : in std_logic;
  inc, accept : in std_logic;
  dec, zero : in std_logic;
  count : out unsigned(COUNT_WIDTH-1 downto 0));
end entity counter;

architecture RTL of counter is
  signal next_count : unsigned(count'range);
begin
  -- registry update
  count <= (others => '0') when reset else next_count when rising_edge(clk);

  --next count CL
  next_count <=
    count + 1 when inc and accept else
    count - 1 when dec else
    (others => '0') when zero else
    count;

end architecture RTL;
```

amount_calc

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;

entity amount_calc is
generic(
    -- 100*20 = 2000 < 2048 = 2^11.
    AMOUNT_WIDTH : natural := 11);
port(
    clk, reset                  : in std_logic;
    in01, in05, in10, in20       : in std_logic;
    zero, accept_coin           : in std_logic;
    dec50, dec100, dec200, dec500 : in std_logic;
    dec20, dec10, dec05, dec01   : in std_logic;
    amount: out unsigned(AMOUNT_WIDTH-1 downto 0));
end entity amount_calc;
```

```
architecture RTL of amount_calc is
    signal next_amount : unsigned (amount'range);
begin
    -- registry update
    amount <=
        (others => '0') when reset else
        next_amount when rising_edge(clk);

    -- CL next_amount
    process(all) is
    begin
        -- default statement:
        next_amount <= amount;
        -- conditional statements (priority doesnt matter)
        if zero then
            next_amount <= (others => '0');
        elsif accept_coin then
            next_amount <= amount + 1 when in01;
            next_amount <= amount + 5 when in05;
            next_amount <= amount + 10 when in10;
            next_amount <= amount + 20 when in20;
        else
            next_amount <= amount - 500 when dec500;
            next_amount <= amount - 200 when dec200;
            next_amount <= amount - 100 when dec100;
            next_amount <= amount - 50 when dec50;
            next_amount <= amount - 20 when dec20;
            next_amount <= amount - 10 when dec10;
            next_amount <= amount - 5 when dec05;
            next_amount <= amount - 1 when dec01;
        end if;
    end process;

end architecture RTL;
```

- Process + if because..
 - Use of priority
 - Several levels
 - Single output can be resolved using when-else only
 - Readability/Maintainability would suffer
(...and accept_coin x 4)

FSM

```

library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;

entity control_FSM is
generic(
    COUNT_WIDTH : natural := 7;
    AMOUNT_WIDTH : natural := COUNT_WIDTH+4;
    COIN_LIMIT : natural := 100);
port(
    clk, rese : in std_logic;
    coin_sens, in01, in05, in10, in20 : in std_logic;
    count01 : in unsigned(COUNT_WIDTH-1 downto 0);
    count05 : in unsigned(COUNT_WIDTH-1 downto 0);
    count10 : in unsigned(COUNT_WIDTH-1 downto 0);
    count20 : in unsigned(COUNT_WIDTH-1 downto 0);
    amount : in unsigned(AMOUNT_WIDTH-1 downto 0);
    ready, accept_coin : out std_logic;
    out01, out05, out10, out20 : out std_logic;
    out50, out100, out200, out500 : out std_logic;
    reset_counters, reset_amount : out std_logic);
end entity control_FSM;

```

```

architecture RTL of control_FSM is
    type state_type is (idle, count, pay);
    signal current_state, next_state : state_type;
    signal coins : unsigned(COUNT_WIDTH-1 downto 0);
begin
    -- clocked logic
    current_state <=
        idle when reset else
        next_state when rising_edge(clk);

    -- CL (moved from datapath)
    coins <= count01 + count05 + count10 + count20;

    next_state_cl: process(all) is
    begin
        -- default value prevents latches
        next_state <= current_state;
        case current_state is
            when idle =>
                next_state <= count when coin_sens;
            when count =>
                next_state <= pay when coins > COIN_LIMIT-1;
                next_state <= pay when not (in01 or in05 or in10 or in20);
            when pay =>
                -- this should be equivalent to all tests listed
                next_state <= idle when or(amount) = '0';
        end case;
    end process;

    -- more next slide...

```

FSM 2/2

```
output_c1: process(all) is
begin
    -- default values to prevent latching
    reset_counters <= '0';
    reset_amount    <= '0';
    ready           <= '0';
    accept_coin    <= '0';
    out01          <= '0';
    out05          <= '0';
    out10          <= '0';
    out20          <= '0';
    out50          <= '0';
    out100         <= '0';
    out200         <= '0';
    out500         <= '0';
```

NOTE: with this prioritization order, the sequence becomes more complex than necessary.

- Readability?
 - What would happen if we mixed next_state CL into the output CL?
- Default values for all signals
 - => no latches
 - No need for `else` after `when` or `if` since default clause will apply.
- Use «`if`» to sort priorities, when having multiple conditions and multiple outputs
 - That are depending on each other..

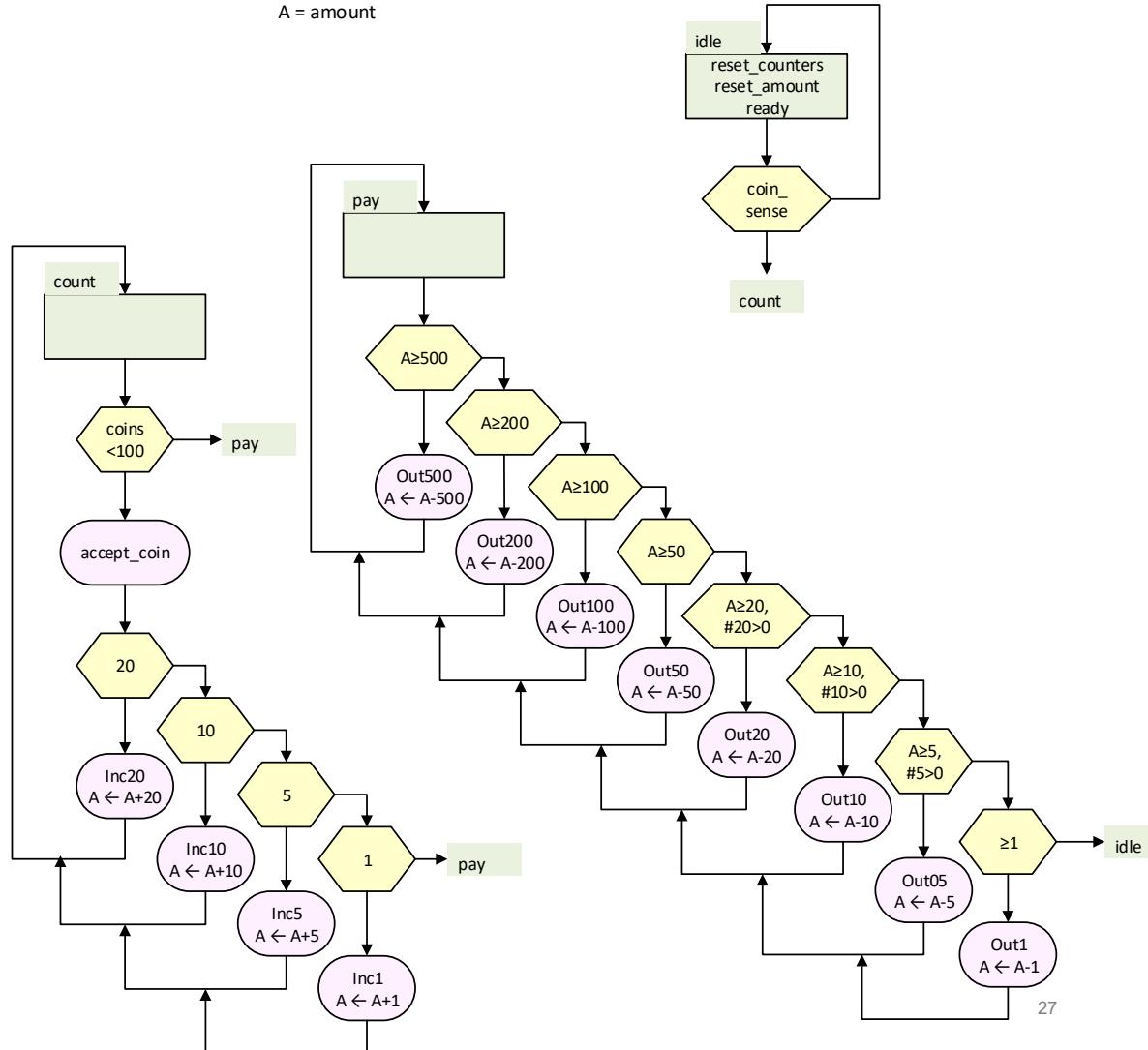
```
case current_state is
    when idle =>
        reset_counters <= '1';
        reset_amount    <= '1';
        ready           <= '1';
    when count =>
        accept_coin <= '1' when coins < COIN_LIMIT;
    when pay =>
        if amount >= 500 then out500 <= '1';
        elsif amount >= 200 then out200 <= '1';
        elsif amount >= 100 then out100 <= '1';
        elsif amount >= 50 then out50 <= '1';
        elsif amount < 50 and amount >= 20 then
            if count20 > 0 then out20 <= '1';
            elsif count10 > 0 then out10 <= '1';
            elsif count05 > 0 then out05 <= '1';
            else out01 <= '1';
            end if;
        elsif amount < 20 and amount >= 10 then
            if count10 > 0 then out10 <= '1';
            elsif count05 > 0 then out05 <= '1';
            else out01 <= '1';
            end if;
        elsif amount < 10 and amount >= 5 then
            if count05 > 0 then out05 <= '1';
            else out01 <= '1';
            end if;
        elsif amount < 5 and amount >= 1 then
            out01 <= '1';
            end if;
        end case;
    end process;

end architecture RTL;
```

true = down
false = right
A = amount

Recap ASMD

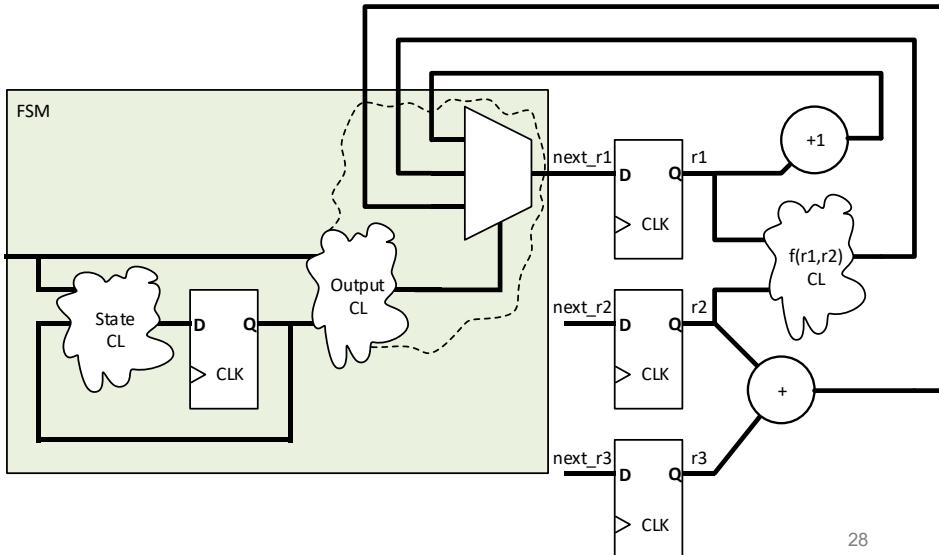
- D for datapath ASM
- ‘ \leftarrow ’ in a Mealy box?
 - OK because the register is a part of the data path (*and not the FSM itself*)
- Can we go without ‘ \leftarrow ’ ?
- Should we?



«Register operations» in data-path FSM (FSMD) -and how to deal with it

- Common notations for register operations:
 - on clock edge we update r_1 based on a function of register outputs
 - on clock edge we increment r_1 ,
 - on clock edge, set r_1 to r_1+r_2
- This notation can be confusing, as it implies one clock delay if it is put into an ASM chart.
- Solution:
 - Use ‘ \leftarrow ’ for datapath only** (not for FSM)
 - Know that ‘ \leftarrow ’ implies the use of additional registers

$$\begin{aligned} r_1 &\leftarrow r_1 + 1 \\ r_1 &\leftarrow f(r_1, r_2) \\ r_1 &\leftarrow r_2 + r_3 \end{aligned}$$

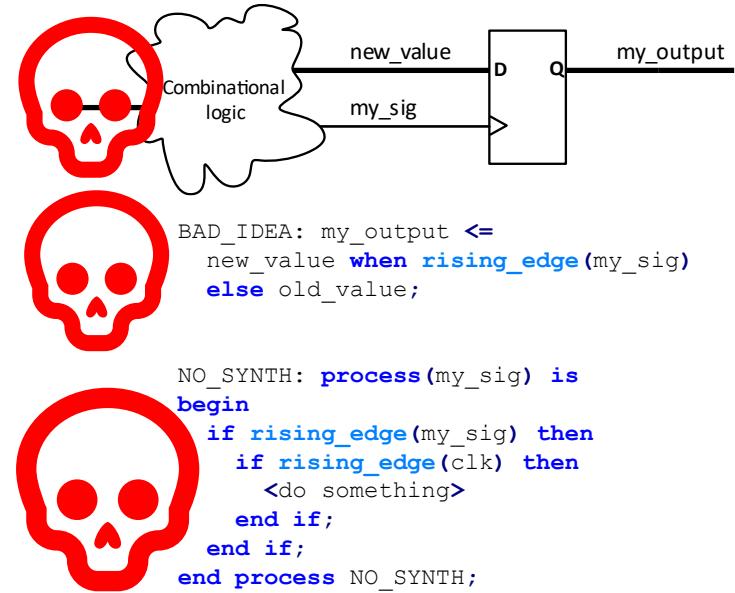


Suggested reading

- DHA:
 - 16 p 345-371
 - 17 p 375 - 393
- Hva nå? <=next_page **when** time_left > 15 min **else** questions ..?

Non-clock Edge detection

- We do not want to have registers triggered by other signals than clock
 - FPGA: messes up clock distribution networks
 - Synthesis will not understand timing
 - Will easily lead to non-synthesizable code

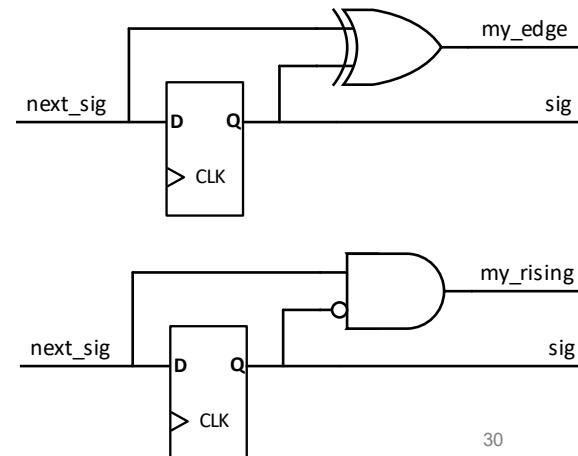


- Solution
 - Compare incoming signal with registered signal

```

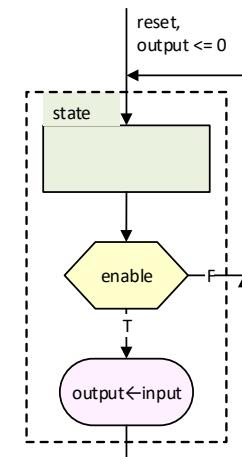
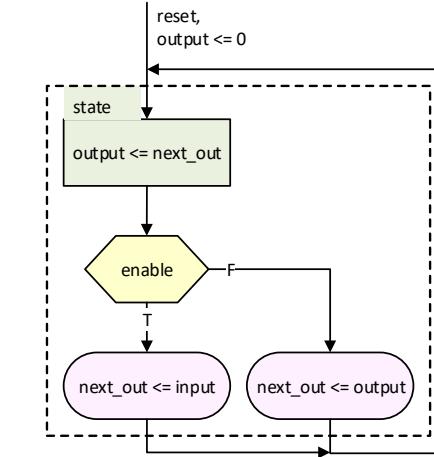
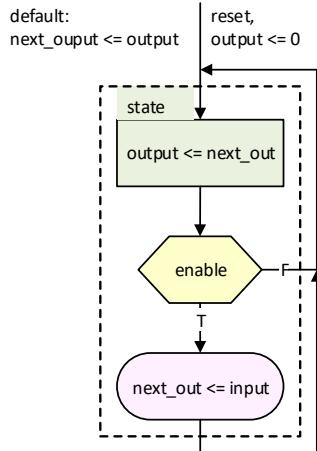
REG:
    sig      <= next_sig when rising_edge(clk);
CL:
    my_edge   <= '1' when sig /= next_sig else '0';
    my_rising <= '1' when (sig = '0') and (next_sig = '1') else '0';
-- <use my_edge or my_rising in combination with other signals> --

```



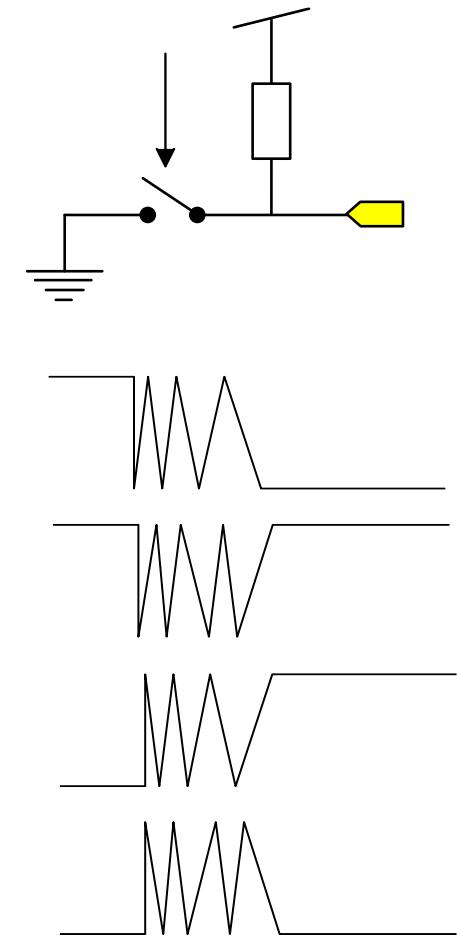
Pushbutton register storage

- Can be seen as a single state storage operation
- With default value
 - Without default
 - As a register operation



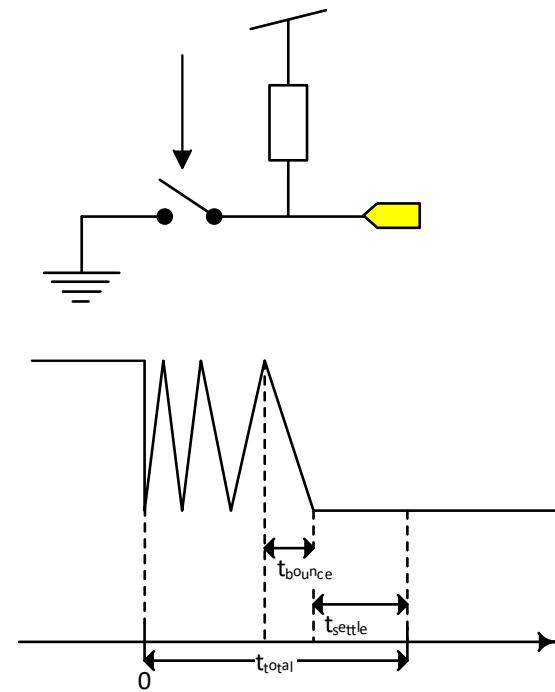
Challenges with pushbuttons

- Pushing a physical button can causes bounce ("prell"/"sprett")
 - Up to 10 actuations in a few of milliseconds
 - Time between each bounce varies
 - Different buttons have different settle time
- 4 different transitions
 - HbL
 - HbH (tap on switch)
 - LbH
 - LbL
- How and when should these be registered?
 - One/none/multiple times?
 - After settling or immediately?



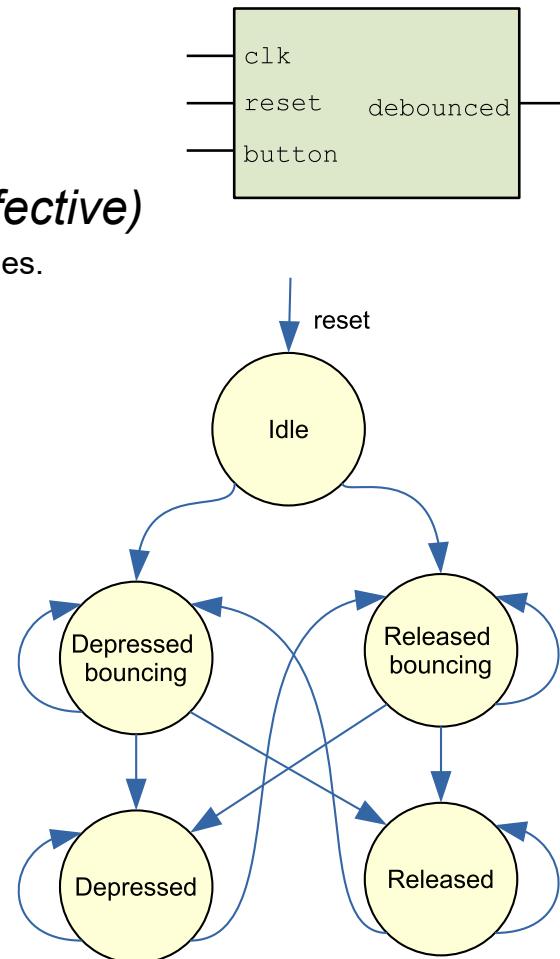
Pushbutton solutions...

- Ideally we want immediate response
- we do not want to record bouncing as several applications
- What are appropriate solutions?
 - Analog solution: can be solved with active filtering
 - Induces delay in response
 - Not always practical (board already made)
 - Check periodically?
 - What is a reasonable frequency?
 - Too low frequency = may miss short button strokes
 - Too high frequency = will register bounce multiple times
 - » Unless tied to a state machine
 - How do we deal with repeated strokes?
 - Create a state machine?



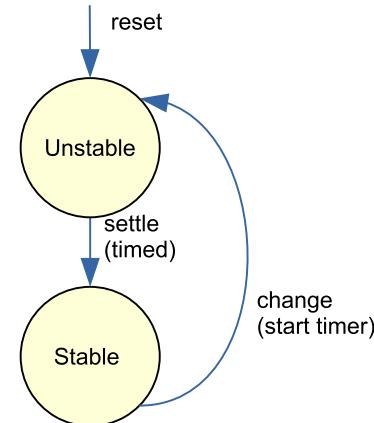
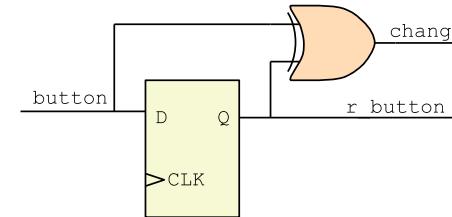
Pushbutton state machine

- Note: *This is for capturing a button being applied multiple times as efficient as possible (not cost effective)*
 - Solutions for capturing many keys may require other or added strategies.
- Initial thoughts:
 - I need something with states for bounce and press:
 - Looks OK, i can do this...
 - When should the keystroke be registered?
 - When depressed/released?
 - Too slow (several ms delay)
 - When bouncing?
 - The value for the key stroke is just 1 or 0
 - » Do we need 4 states for this?
 - How do i detect bounce?
 - Need edge detect on button stroke
 - What is the actual difference between the bounce-states?
 - Do we need an idle state?
 - Isn't released the normal –idle state?



Pushbutton reiteration

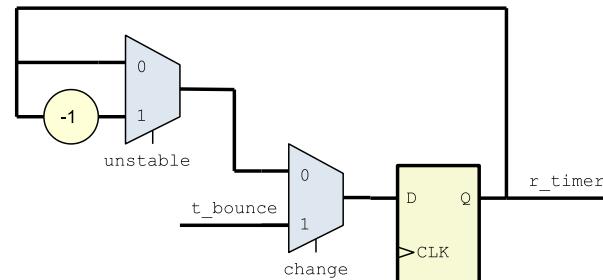
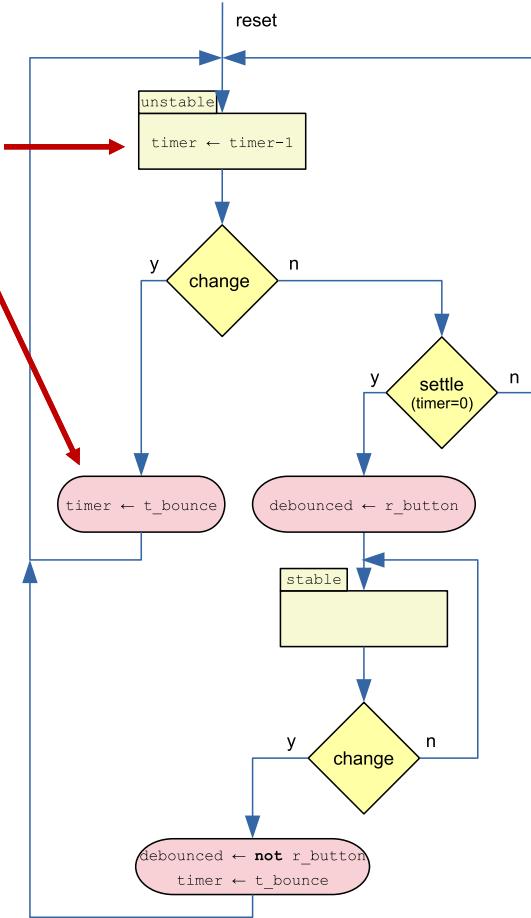
- Edge detection (= datapath not FSM)
- Simpler FSM
 - Detailed specification using ASM (next page)



Pushbutton reiteration

- ASM diagram
 - With timer integrated
 - Conflict can be resolved by using a mealy box assignment when not settle
 - Without timer integrated
 - Separate timer diagram
 - Easier to change timer/counter for sharing purposes (ie multi-button setup, ...)

Conflict..?



Example code

```

library IEEE;
use IEEE.std_logic_1164.all;
use IEEE.numeric_std.all;

entity debouncer is
  generic(
    t_bounce : positive:= (2**17)-1
  )
  port(
    clk, reset: in std_logic;
    button      : in std_logic;
    debounced   : out std_logic
  );
end entity debouncer;

architecture rtl of debouncer is
  type state_type is (unstable, stable);
  signal r_state, next_state : state_type;

  signal next_timer, r_timer: unsigned(23 downto 0);
  signal r_button, next_debounced : std_logic;
  signal change, settle          : std_logic;

begin
  change <= '1' when r_button /= button else '0';
  settle <= '1' when r_timer = 0 else '0';

  DEBOUNCE_FSM: process(all) is
  begin
    next_state <= r_state;
    case r_state is
      when unstable =>
        if not change then
          next_state <= stable when settle;
        end if;
      when stable =>
        next_state <= unstable when change;
    end case;
  end process;
end architecture rtl;

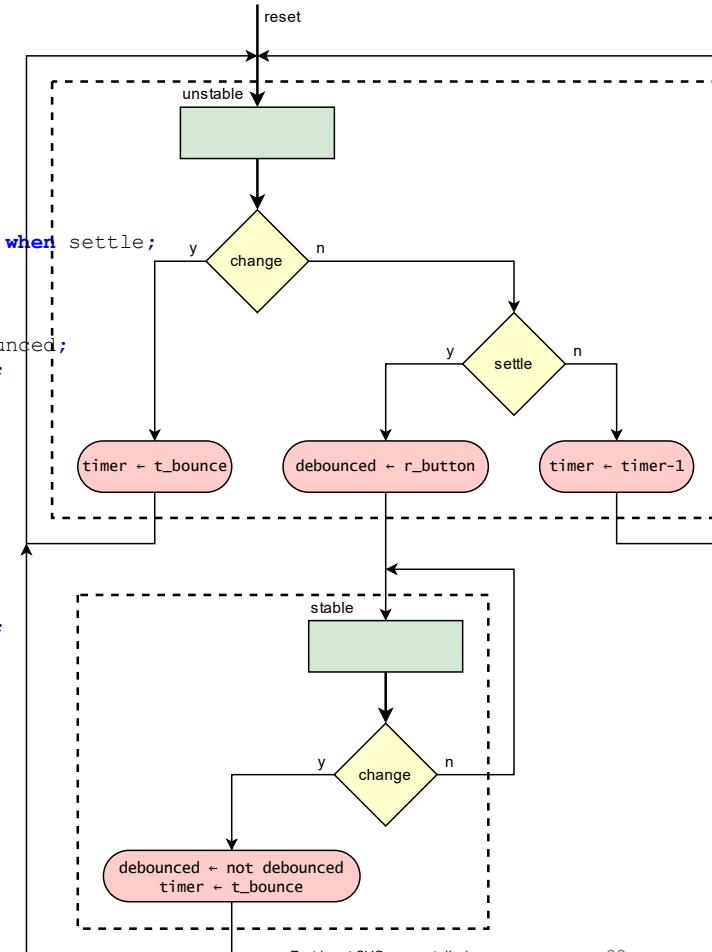
```

```

FSM_OUTPUT: process(all) is
  next_debounced <= debounced;
  next_timer <= r_timer;
  case r_state is
    when unstable =>
      if change then
        next_timer <= t_bounce;
      else
        next_timer <= r_timer-1;
        next_debounced <= r_button when settle;
      end if;
    when stable  =>
      if change then
        next_debounced <= not debounced;
        next_timer     <= t_bounce;
      end if;
    end case;
  end process;

REGISTER_STORAGE: process(clk) is
begin
  if rising_edge(clk) then
    if reset then
      r_state   <= unstable;
      r_count  <= (others => '1');
      r_button <= '0';
      debounced <= '0';
    else
      r_state   <= next_state;
      r_count  <= next_count;
      r_button <= button;
      debounced <= next_debounced;
    end if;
  end if;
end process;

```



Text is not SVG - cannot display

IN3160 IN4160

Diagrams, Reset circuits

Yngve Hafting



Messages

Course Goals and Learning Outcome

<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

In this course you will learn about the **design of advanced digital systems**. This includes programmable logic circuits, a hardware design language and system-on-chip design (processor, memory and logic on a chip). Lab assignments provide practical experience in how real design can be made.

After completion of the course you will:

- understand important **principles for design** and testing of digital systems
- understand the relationship between behaviour and different construction criteria
- **be able to describe advanced digital systems at different levels of detail**
- be able to perform simulation and synthesis of digital systems.

Goals for this lesson:

- Be able to read, use and create -diagrams
 - Timing-/ waveform-
 - Datapath-
 - Block-
 - State-
 - ASM-,
 - ASMD
- Know the purpose of reset circuits
 - Why reset?
 - Pitfalls in reset handling

Next lesson: Microcoded FSMs

Wave diagrams

- When do we read clocked signals?
- When does assignment occur?
- Does phase matter?

Basic wave diagram layout

- Undefined values are usually hatch-patterned

- Single bit signals

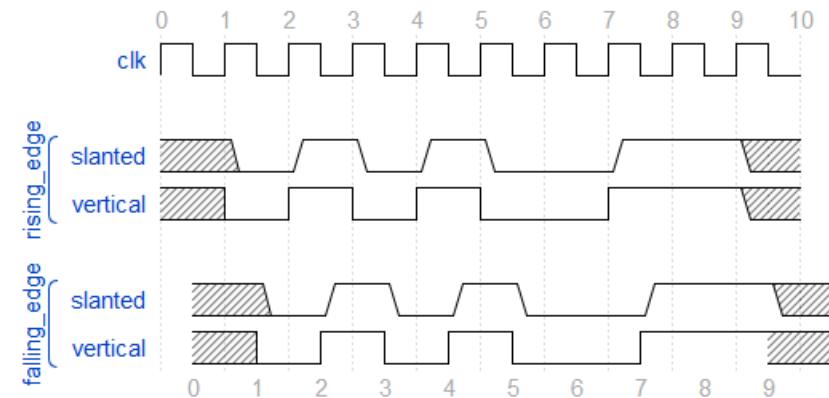
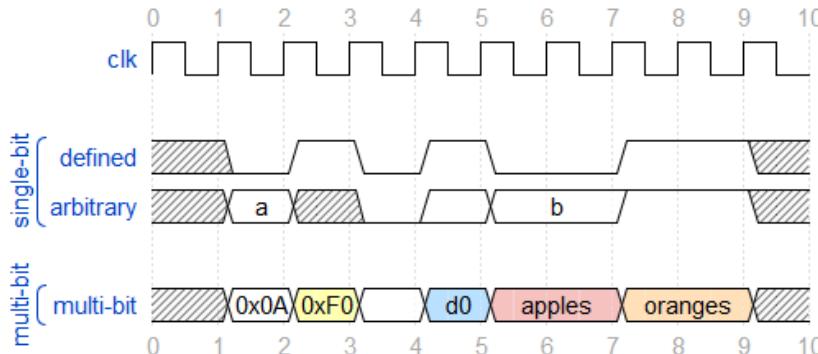
- Are usually displayed as high ('1') or low ('0')
- Defined signals of arbitrary values are usually shown as an area without hatching
 - Can be named (here a, b)

- Multi-bit is usually shown as an area

- Values or names are often used
- Multi-bit vector vs single-bit signal
 - Sometimes you must use context to understand which is which.

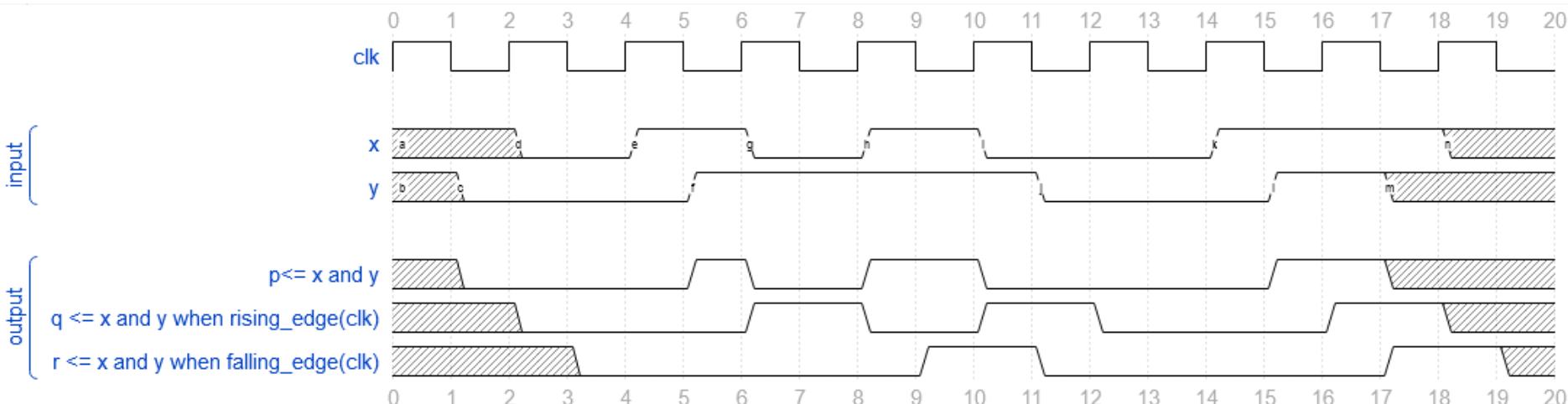
- Edges

- Both vertical and slanted edges mean the same.
 - Hand drawing mostly vertical...*
- Normally sequential logic relate to the rising_edge
- RTL-simulation of sequential logic:
 - Signals are read when edge occurs
 - Signals are assigned immediately after the edge



Basic wave diagram layout

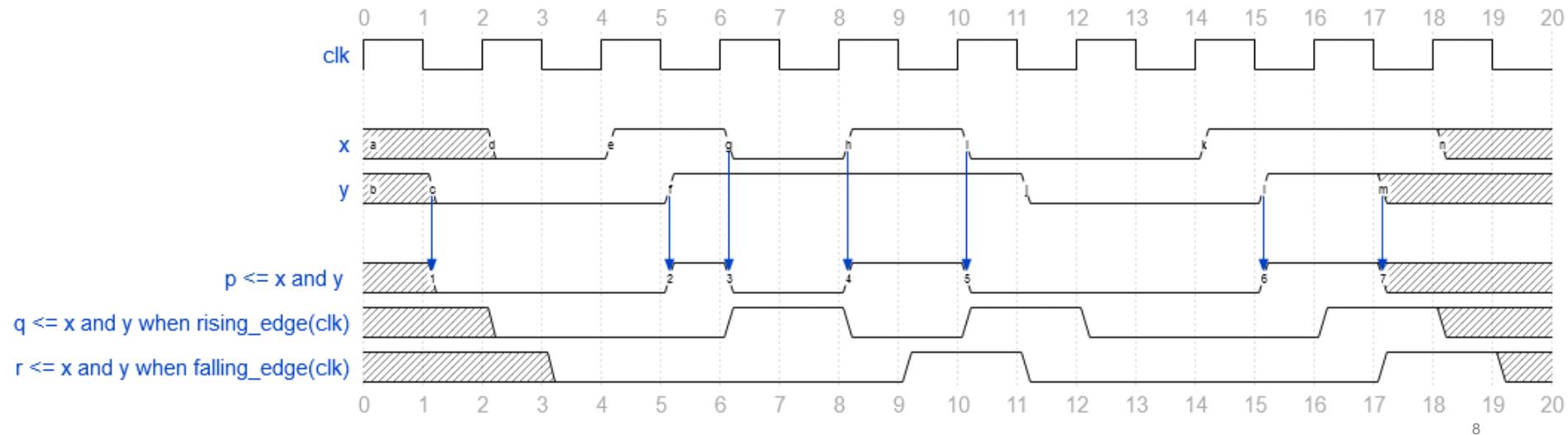
- Combinational logic (CL) responds immediately when input changes



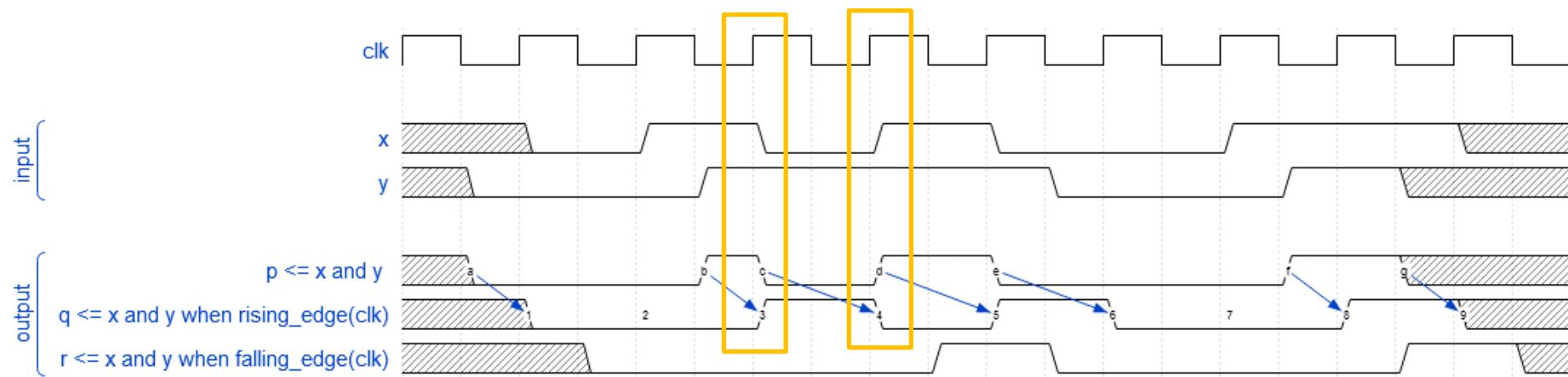
- Sequential logic (clocked circuits)
 - responds to the **input status present when the clock edge occurs**.
 - **output is changed immediately after** the clock edge occurs.
 - Unless specific timing information is given

Waveform combinational

- Combinational response is immediate in a waveform.
 - *Timing diagrams* will show gate delays
 - Clock does not matter



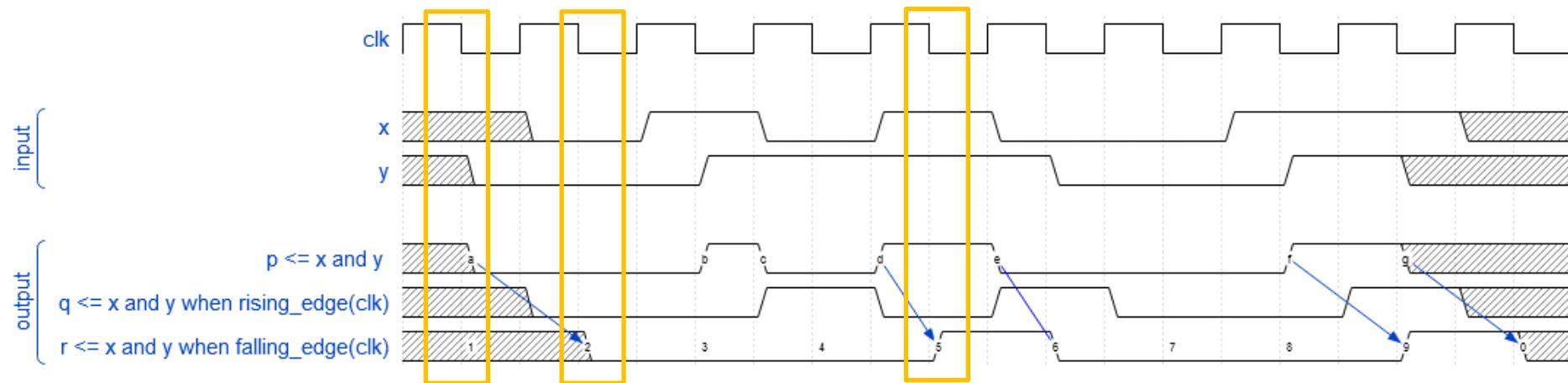
Sequential logic, `rising_edge(clk)`



– Look at what the input status **was** when the clock edge occurs.

- Here: The b-c pulse activates q for one whole clock cycle
 - even though (a **and** b) *is high for a shorter duration*
 - Only what *is present when the clock edge occurs matters*

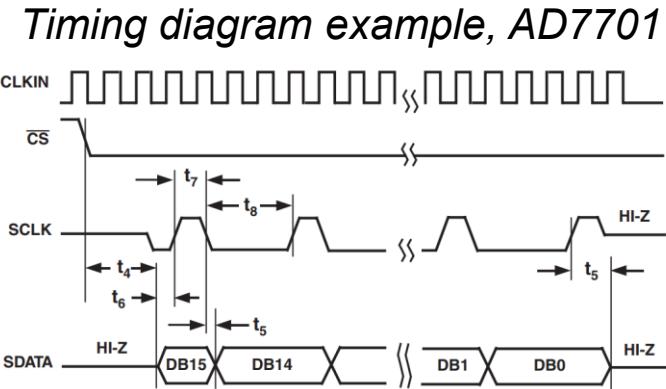
Sequential logic, falling_edge(clk)



- Here: The b-c pulse is too short to activate r
 - (a and b) is low on the next falling edge

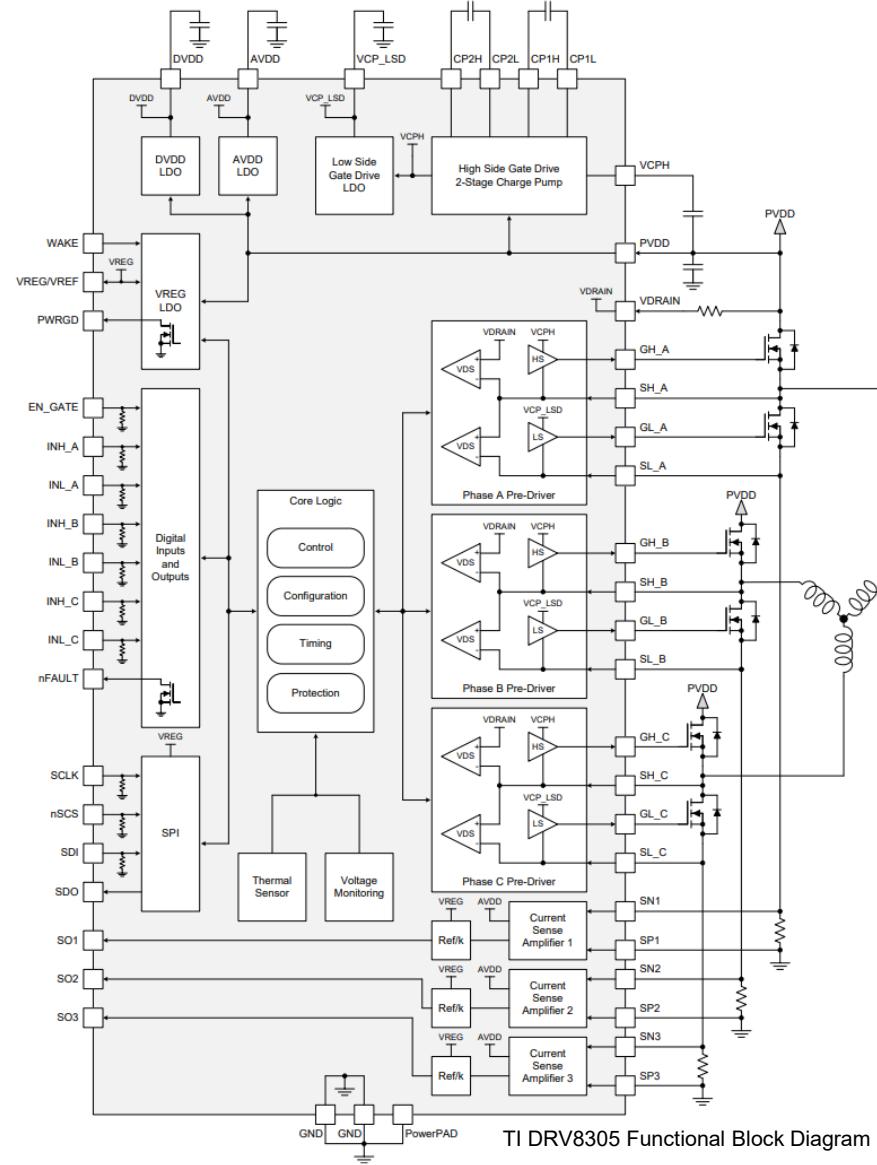
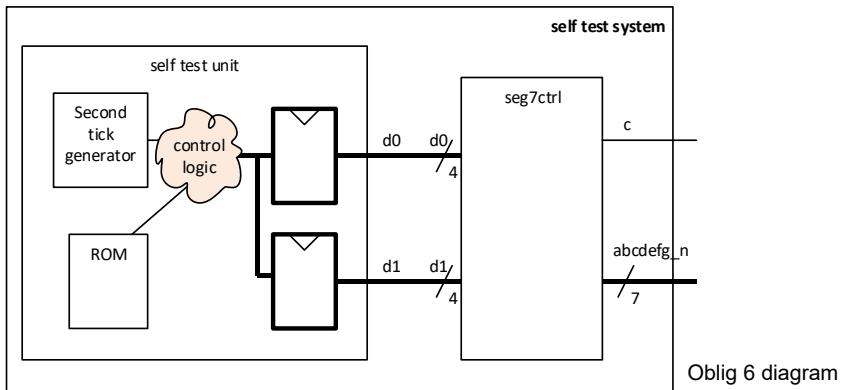
Timing diagrams

- = Waveforms with timing information for a specified circuit.
 - Typically found in a data sheets
 - Printed circuit boards (PCBs),
 - components (chips)
 - communication protocol standards
 - Can be generated with post-synthesis simulation.
 - Useful...
 - .. when considering *setup and hold timing requirements* in a system
 - selecting circuits for a PCB (Printed Circuit Board)
 - setting timing constraints for synthesis tool
 - .. when optimizing data-flow circuitry..
 - High performance ASIC design



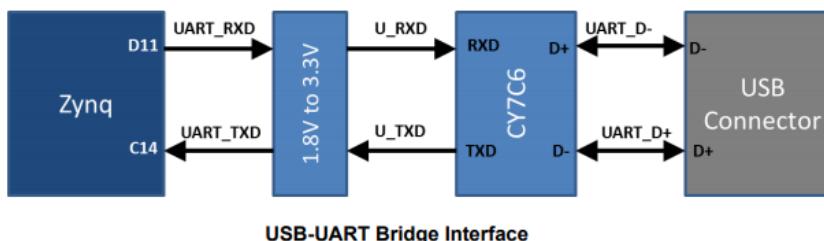
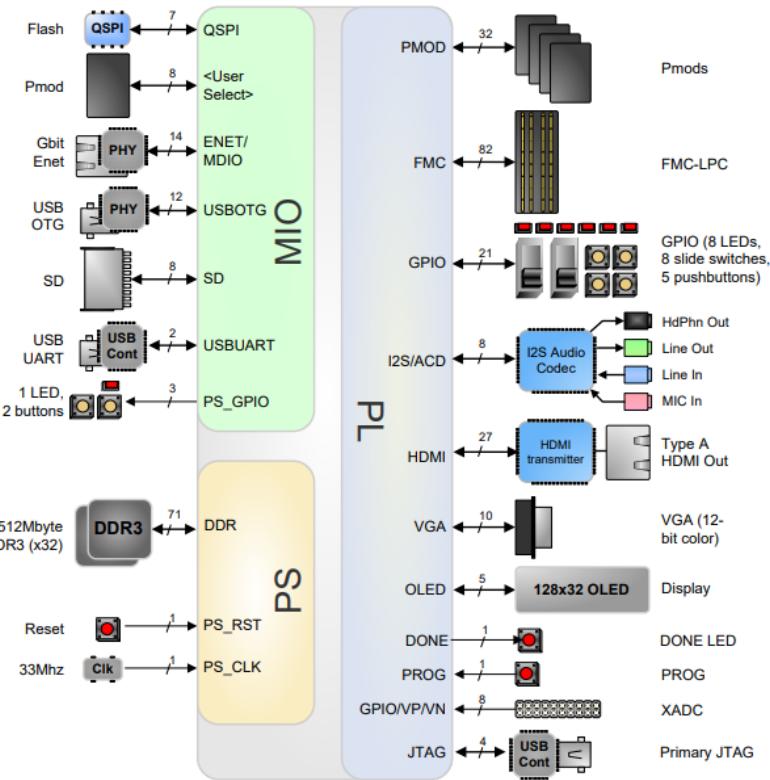
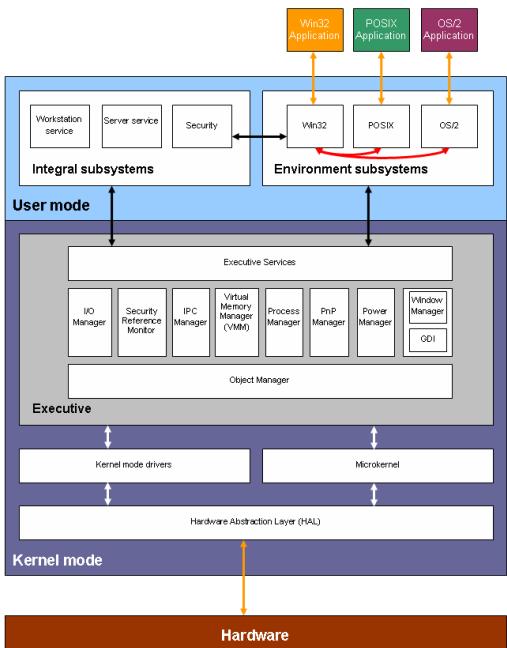
Block diagrams

- Shows how modules are connected or communicate
 - Level of detail may vary
 - May include
 - digital and analog components
- Suited for system level overview
 - Or partial overview
 - May be used for connection



Block diagrams

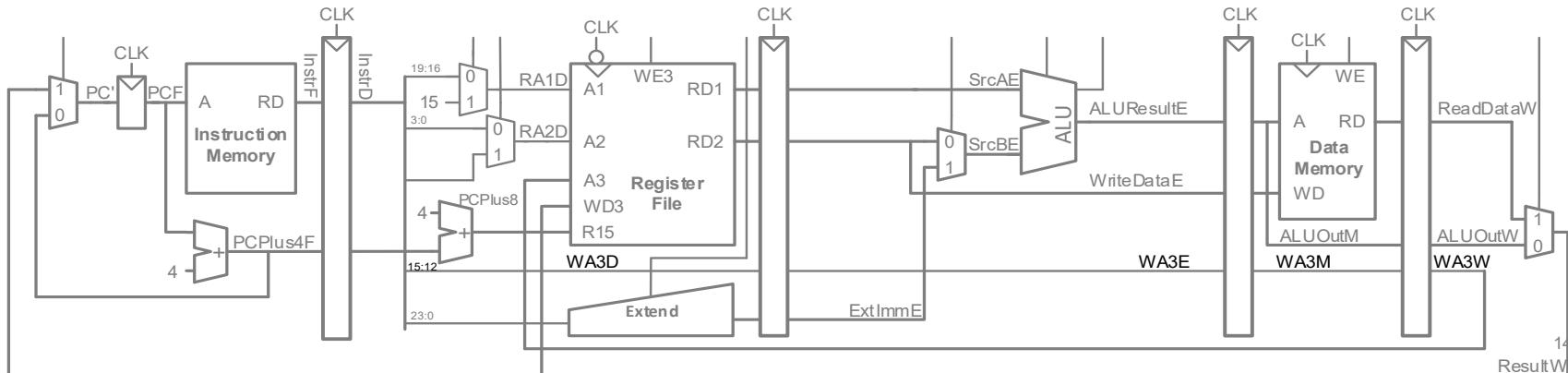
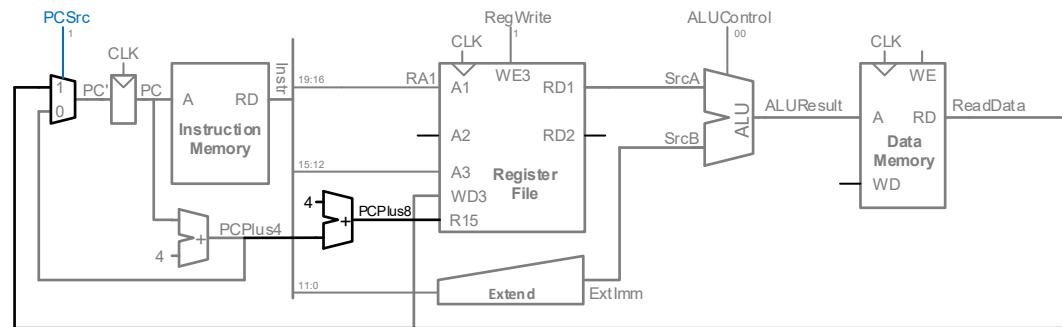
- Many variants...
 - Entire- or parts of systems
 - *HW block diagrams tend to be more detailed than those used for other purposes (SW, business, ...)*
- *Usually the first diagrams drawn in a design process*
 - Several may be added and edited later
- Almost always present in design documentation.



↖ ↑ Zedboard Users guide

Datapath Diagrams

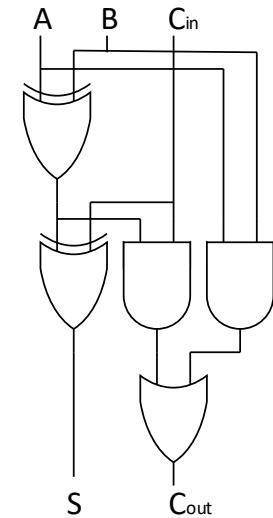
- A specialised block diagram that **show how data moves within a system or module.**
- Should normally contain
 - How data travels between modules or functional units
 - Registers (flipflops) used for storing data (not necessarily FSM -registers)
 - Bit widths for each path
- Usually direction of travel is from left to right
- Modules, such as **FSMs** will contain **registers**, however these registers **are considered control**, and *not a part of the datapath*.
 - I.e. A processor may have many states but data still moves through the pipeline one stage at a time.
 - (Thus we have non datapath modules using clk.)



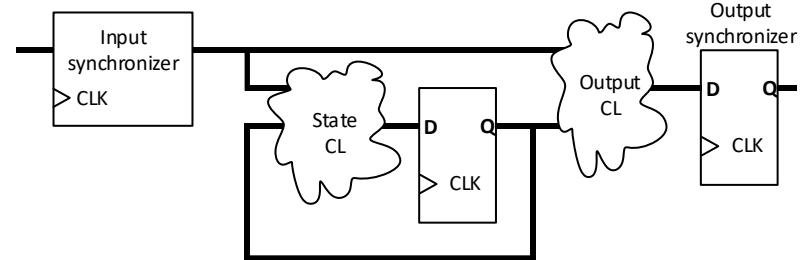
Datapath diagram \neq dataflow representation

-- Full adder:

```
S    <= A xor B xor Cin;  
Cout <= ((A xor B) and Cin) or (A and B)
```



- **Dataflow** representations are
 - Either HDL or diagrams showing gate level logic CL
 - Dataflow is low level
- Datapath diagrams *may contain* dataflow representations
 - Datapath is normally high level



Datapath diagrams

- Often used to describe parts of an architecture
- RTL logic *can* be represented using datapath diagrams
 - It is not necessarily the best representation...
 - FSMs are better described using ASM diagrams...
 - Counters..
 - LFSR..
- Drawing a datapath diagram will in some cases be a very efficient way to gain understanding..
 - => Pipelining
 - **Example:** Exam 2021, Assignment 6 (next page)-

Example: Exam 2021

Assignment 6, «Pipelining»

- The pipelined module entity is described above.
- In this assignment a module which **calculates result = a+b+c** shall be implemented.
- In order to meet timing closure at the required frequency, **pipelining shall be used**.
- All input are synchronized to the clock signal clk.
- Reset can be either synchronous or asynchronous.
- The implementation shall be synchronous to the clock signal clk.
- **All output should be driven by registers** to avoid propagating hazards.
- The computation shall use unsigned arithmetic operation on the operands a, b and c.
- *When the start signal is high the computation shall start, and the result_valid signal shall be high when valid data is present on the result signal.*
- Implement the architecture for the pipelined module.

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

entity pipelined is
port (
    clk : in std_logic;
    rst : in std_logic;
    a : in std_logic_vector(7 downto 0);
    b : in std_logic_vector(7 downto 0);
    c : in std_logic_vector(7 downto 0);
    result : out std_logic_vector(9 downto 0);
    start : in std_logic;
    result_valid : out std_logic
);
end entity pipelined;
```

- We read this as the control signal shall be pipelined along with the data
 - It is not necessary to block computation when there is no start signal.
- NOTE: It does not make sense to pipeline unless a, b, c and the control signal follows each other.
 - Ie: expect new data each clock cycle
- *Make your own datapath diagram for this task (2 min)!*

Ex2021-pipelining

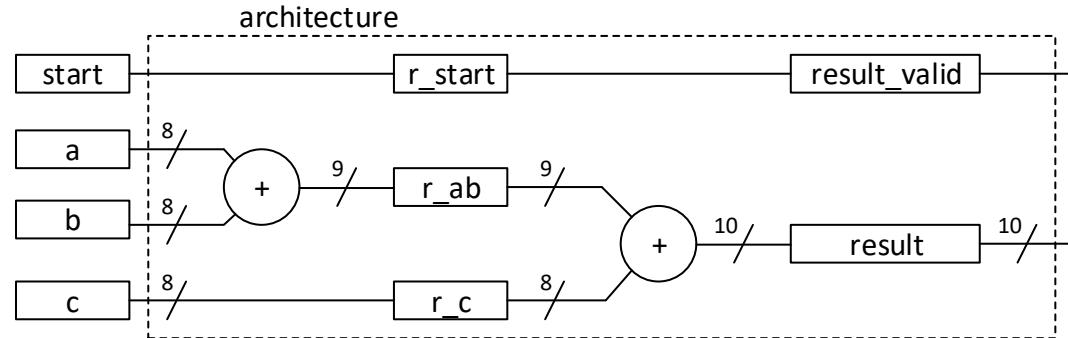
- VHDL code may come in many flavours:

```

architecture RTL of pipelined is
  signal r_start : std_logic;
  signal r_ab, next_ab : unsigned(8 downto 0);
  signal r_c : unsigned(7 downto 0);
  signal next_result : std_logic_vector(9 downto 0);
begin
  REGISTERS: process(clk) is
  begin
    if rising_edge(clk) then
      if rst then
        r_start <= '0';
        r_ab <= (others => '0');
        r_c <= (others => '0');
        result_valid <= '0';
        result <= (others => '0');
      else
        r_start <= start;
        r_ab <= next_ab;
        r_c <= c;
        result_valid <= r_start;
        result <= next_result;
      end if;
    end if;
  end process;

  next_ab <= ("0" & unsigned(a) + "0" & unsigned(b));
  next_result <= std_logic_vector("00" & r_c + "0" & r_ab);
end architecture RTL;

```



```

architecture unprocessed of pipelined is
  signal r_c : unsigned(7 downto 0);
  signal r_ab : unsigned(8 downto 0);
  signal r_start : std_logic;
  signal start : std_logic;
  signal result_valid : std_logic;
  signal result : std_logic_vector(9 downto 0);

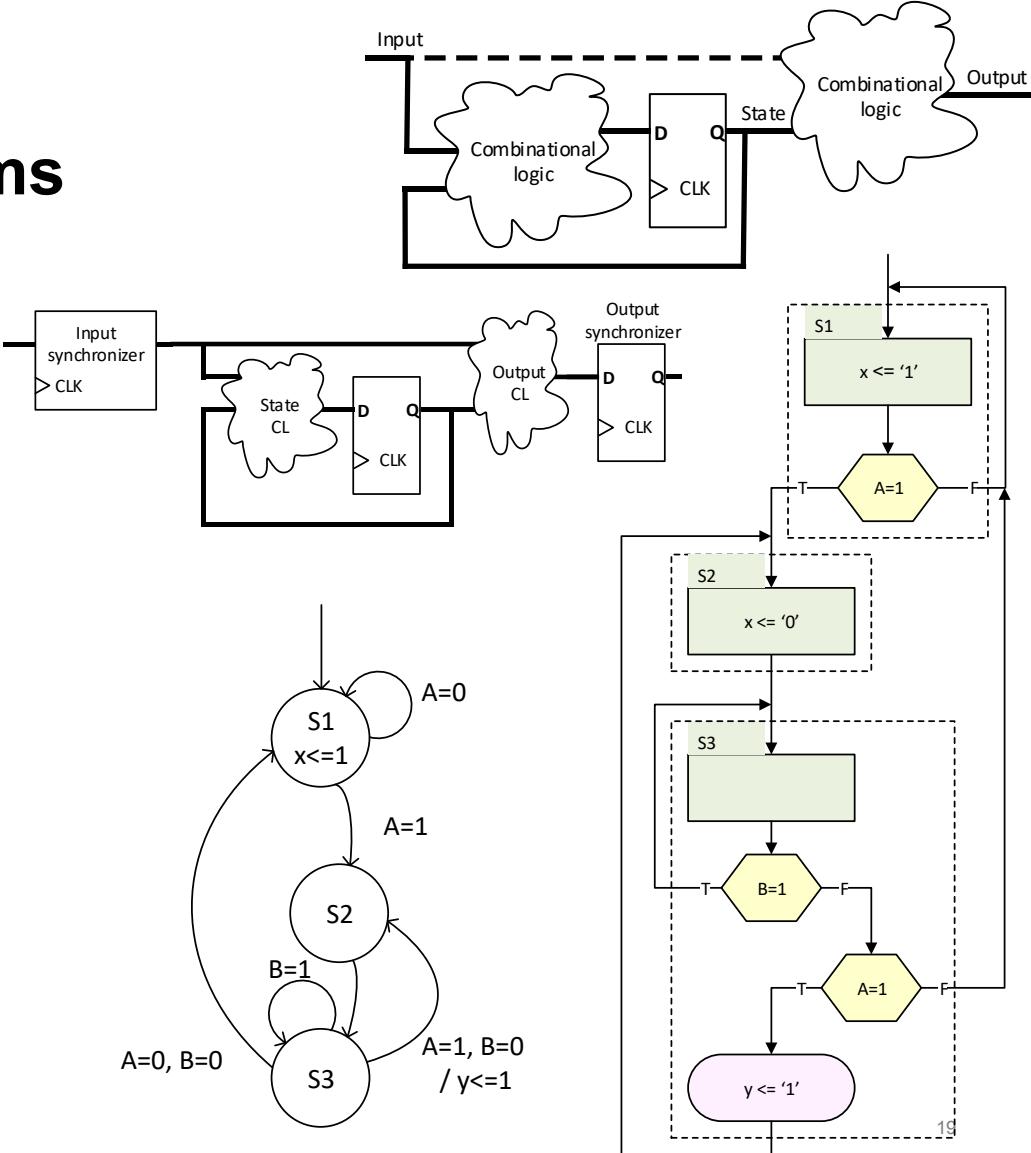
begin
  start <= '0' when rst else start when rising_edge(clk);
  result_valid <= '0' when rst else r_start when rising_edge(clk);
  ab <= (others => '0') when rst else ("0" & unsigned(a) + "0" & unsigned(b)) when rising_edge(clk);
  c <= (others => '0') when rst else (unsigned(c)) when rising_edge(clk);
  result <= (others => '0') when rst else std_logic_vector("00" & r_c + "0" & r_ab) when rising_edge(clk);
end architecture unprocessed;

```

- Getting to this code should be doable when having the diagram...
- Common mistakes:
 - Forgetting to put c in pipeline before calculating step 2.
 - Believing start shall be valid for 3 clock cycles...
 - Attempting SW-style loops(!)..
 - Remember we are creating circuits, not software
- Best practice: Separate CL and registers:

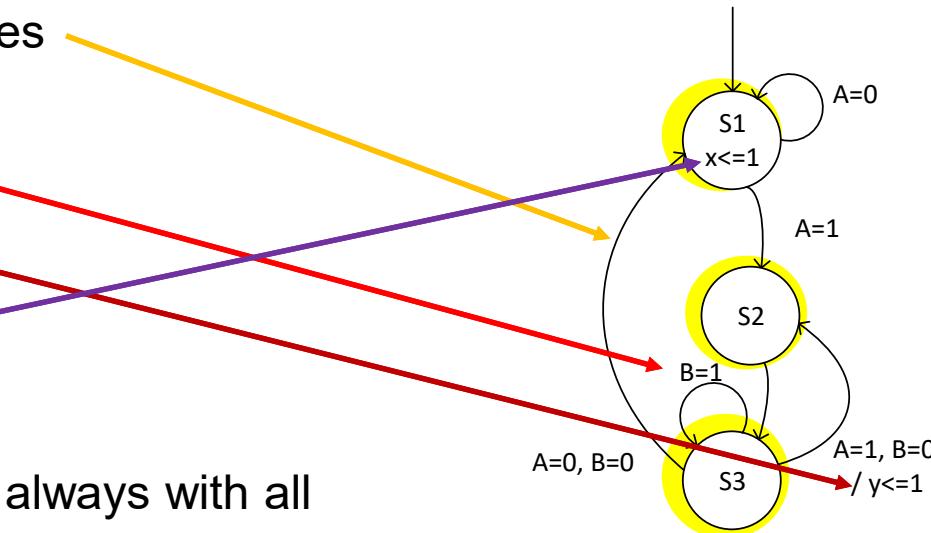
FSMs and their diagrams

- Datapath shows
 - Moore vs Mealy machine
 - Synchronizers
 - ...
- State- and ASM diagrams
 - Shows state transitions
 - conditions (and priority)
 - Output
 - Register operations (ASMD)



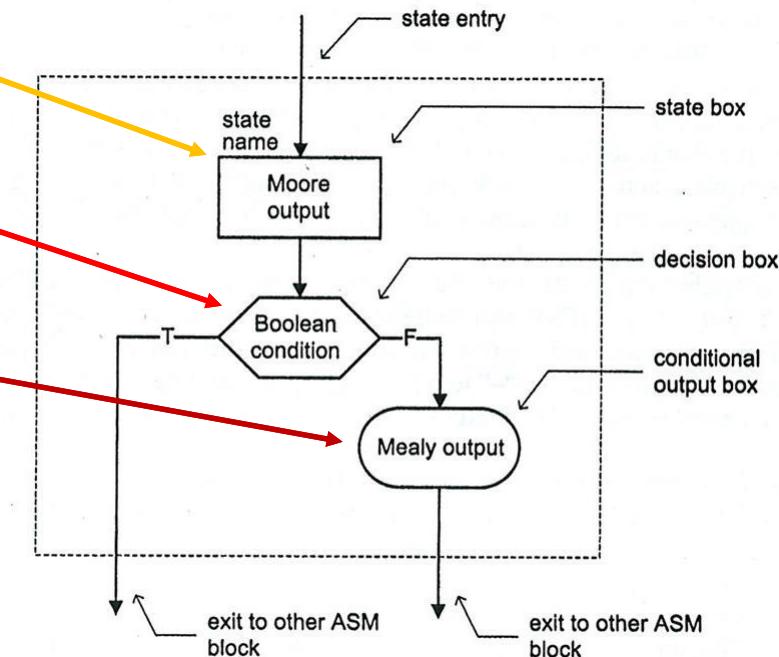
State diagram

- States
- Transitions between states
- Beside transition arc:
 - Decision parameter
 - / Mealy output
- Inside bubble:
 - Moore output
- Frequently used, but not always with all parameters.
- Note: *Default values often omitted*
 - Here: default: $x, y = 0$ (boolean false)



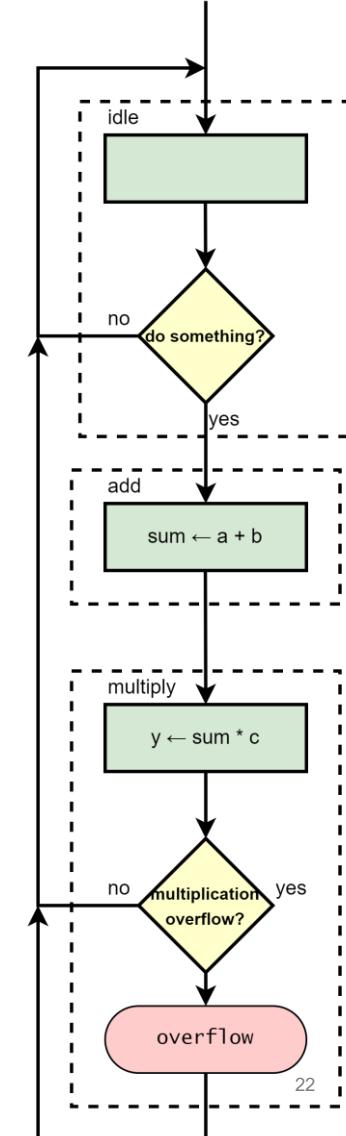
ASM (Algorithmic State Machine) block

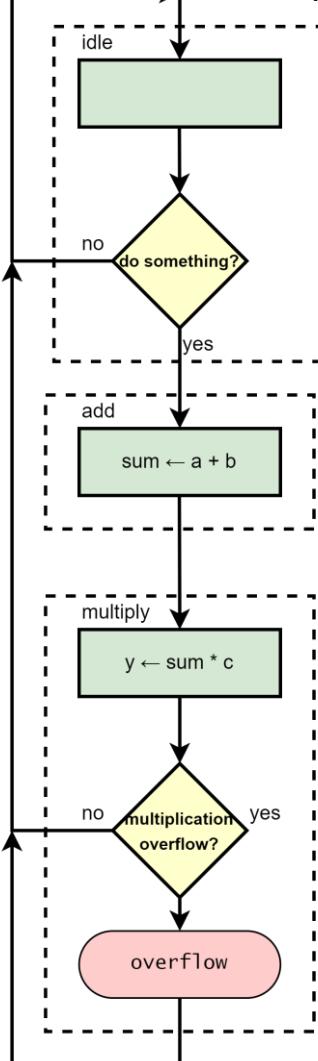
- The **state box** represents a state in the FSM,
 - State based output is shown inside (i.e. the **Moore outputs**).
- The **decision box** tests an input condition to determine the exit path of the current ASM block.
- A **conditional output box (“Mealy box”)**
 - lists conditionally asserted signals.
 - Can only be placed after an exit path of a decision box
 - (i.e. the **Mealy outputs** that depends on the state and input values).



ASM diagrams for pipelines? (From Ex23)

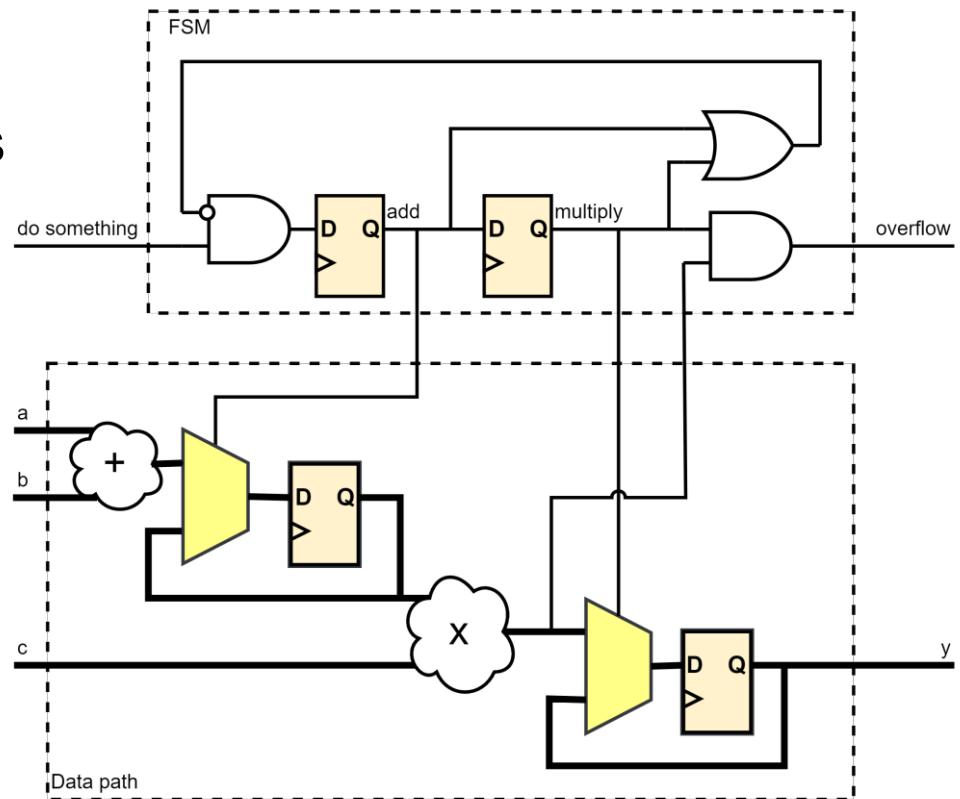
- Does the diagram describe a pipelined datapath?
 - Is the sum updated every clock cycle?
 - Is the output (y) updated every clock cycle?
 - How often *can* overflow be flagged?
- Is it possible to use ASMD for datapath pipeline?
 - How many states would there be?
- Occurs every or almost every clock cycle =>
 - Use a datapath diagram





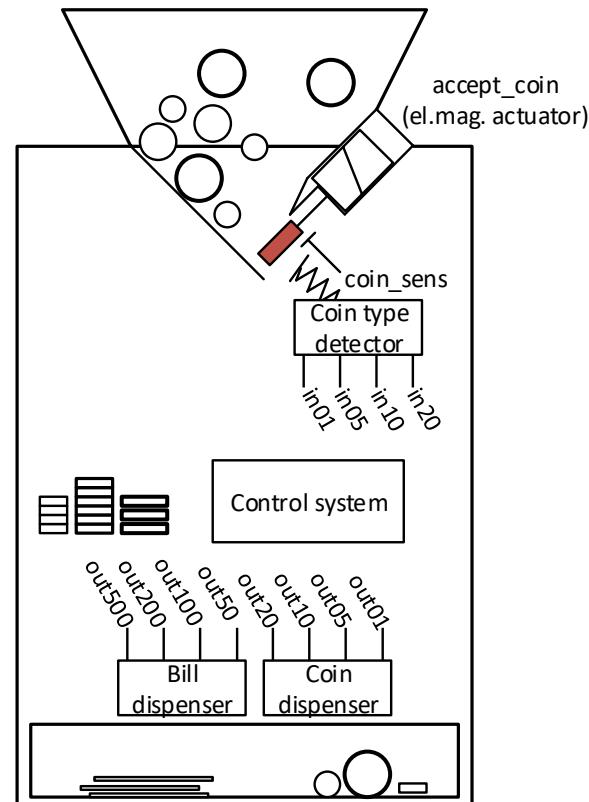
Ex 23 (continued)

- Datapath implements ASMD...
 - Other solutions are possible!
 - (*not the ex. task*)
 - Consider:
 - Which is best for
 - FSM?
 - Datapath?



Other drawings or schematics

- System sketches, drawings
 - Usually used to display a concept or an idea
 - Can be anything (*vague block diagram..?*)
- Circuit diagrams
 - Show how the current flows in a circuit
 - Netlists can be made from VHDL
 - (and then turned into circuit diagrams)



IN3160

Reset circuits

Synchronous or Asynchronous reset?



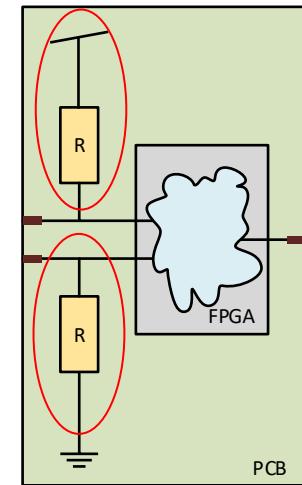
Source: Steve Kilts: Advanced FPGA Design. 2007

Outline

- Combinational logic and floating pins
- Why reset?
- Asynchronous reset
- Synchronous reset
- Reset circuits

Combinational logic and I/O pins

- No need for reset circuitry for CL
 - No values are stored in CL
 - Setting the input will give the desired output
- However... avoid floating gates
 - Floating gates may cause power surges and noise
 - All input pins should be driven
 - Even unused, unconnected inputs should be pulled high or low
 - Pull-up or pull-down on PCB or
 - FPGAs may have internal pull up/down circuitry for IO-pins.
 - » Can be a life saver... (Product/ project / etc).



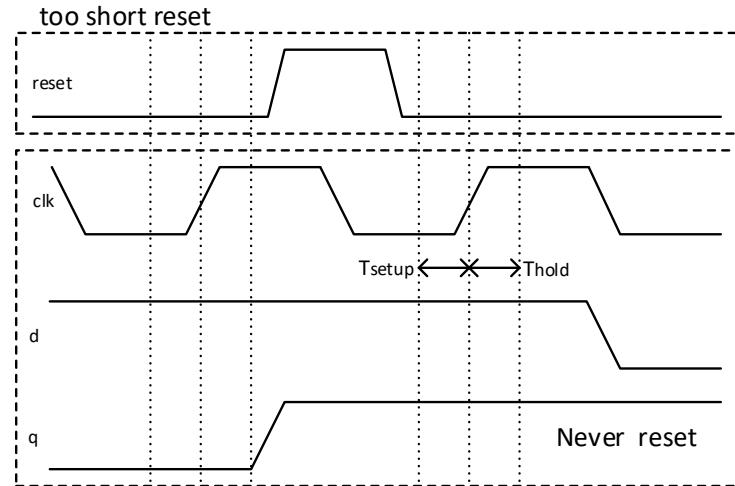
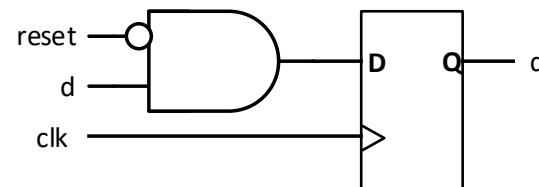
Why reset?

- Avoid unpredictable behavior during startup
 - Metastability creating unpredictable results
 - Both in our system and surrounding systems
 - Random register values may lead to undesired or illegal states
 - Lockup – states with no exit
 - undesired output can have unpleasant consequences
- To get out of illegal states
 - Unpredicted behaviour may lead to illegal states
 - Noise
 - Crosstalk / EMP
 - Radiation - both thermal and radioactive
 - Floating gates
- ... To ensure verifiable predictability ...

Synchronous reset

- Externally activated resets are per definition asynchronous
 - Synchronization is needed.
- Synchronous reset ‘and flip-flop input
 - Added logic can add to critical path
 - FPGA primitives may have this option built in.
- Reset pulses coming from faster clock domains may be missed entirely.

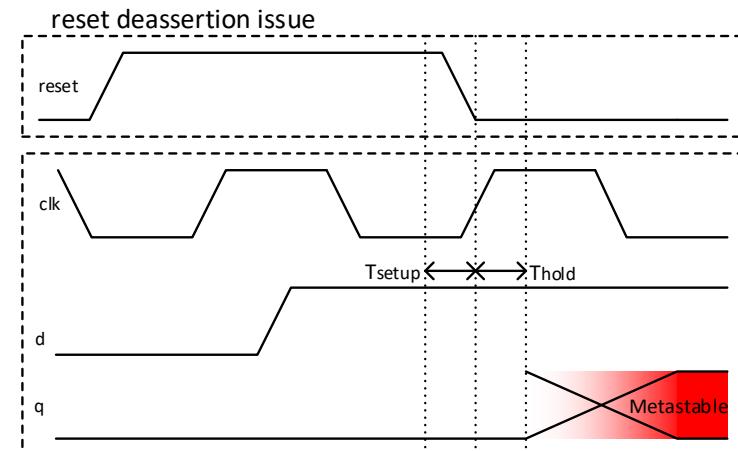
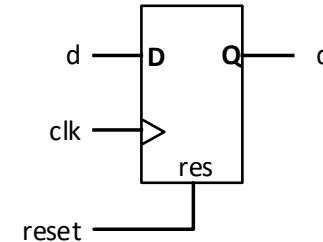
```
next_q <= '0' when reset else d;  
q <= next_q when rising_edge(clk);
```



Asynchronous reset

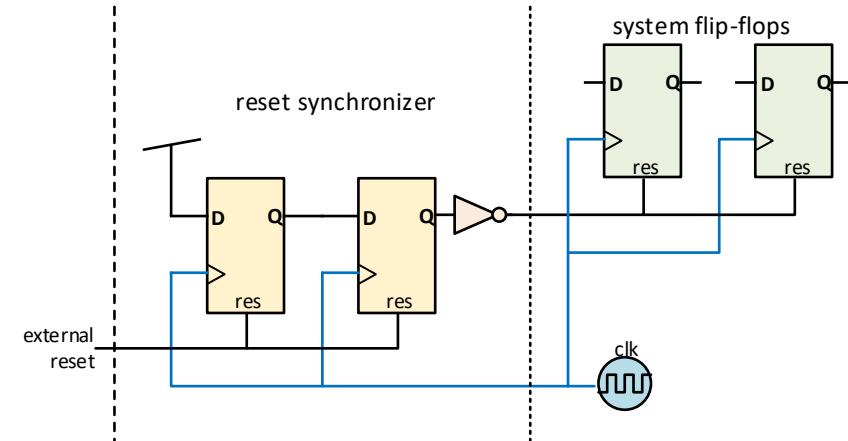
- Asynchronous assertion will always trigger
 - Reset duration must be longer than setup+hold...
- Asynchronous deassertion may cause metastability
 - Deassertion during setup/hold period

```
q <= '0' when reset else d when rising_edge(clk);
```

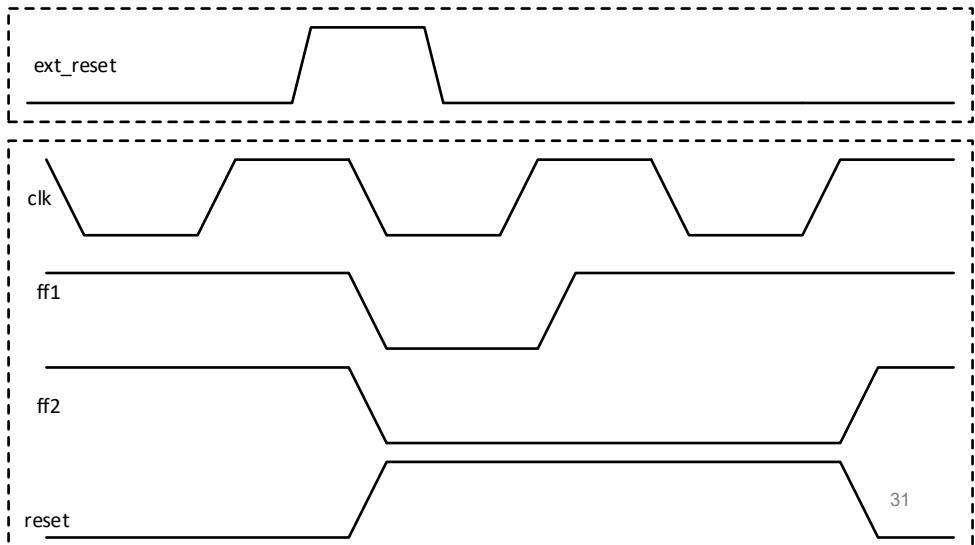


Reset circuit(s)

- Asynchronous assertion,
Synchronous deassertion
 - Short reset pulses will trigger
 - 2FF mitigates metastability
 - More in clock domain crossing lecture...
- Pitfalls?
 - Hazards => random reset
 - This circuit should not be used unless external reset is hazard-free.
- Multiple sources for reset?
 - Ensure reset pulses are long enough
 - Use Synchronous reset
 - 2FF when crossing domains



```
ff1 <= '0' when ext_reset else '1' when rising_edge(clk);
ff2 <= '0' when ext_reset else ff1 when rising_edge(clk);
reset <= not ff2;
```



Resets in IN3160

- All designs should start in a known state
 - Predefined values for all registers, no metastability.
 - We'll implemented reset functionality ensures this.
 - Can be invoked both at start and later
- The FPGAs *we use* are RAM based and
 - will always start in a predictable configuration
 - => We *can* start without using reset
 - Default state is '0' (*the FPGA's we use*)
- Not using reset at start is an exception
 - Reset functionality should always be implemented
 - There is no guarantee for (other) designs to be safe without implicit initialization
 - *If we do not have a predefined source for reset signals, use a button...*

Reset summary

- External reset is asynchronous
 - Should be synchronized to avoid causing metastability.
- It is OK to use asynchronous reset once synchronized...
 - Once synchronized, synchronous reset is perfect...
 - Some FPGA primitives prefer synch reset only.
- Reset pulse must be long enough for reset circuitry
(depends on technology / logic family, not clk frequency..)

Suggested reading

- Diagrams
 - These and earlier lecture notes.
- Reset circuits
 - Steve Kilts: Advanced FPGA Design: Architecture, Implementation and Optimization, 2007, chapter 10.
 - download from university library
Semesterside for IN3160->“Pensum/litteratur i Leganto”

IN3160 IN4160

Microcode



Yngve Hafting 2020

Source: Digital Design Using VHDL, a systems approach; Dally, Harting, Aamodt



Messages

- Next Tuesday (5.3.) Metastability and Clock domain crossing
- 8.3. + 12.3. Roar Skogstrøm (IN5200) lectures
(SoC, ILA + FPGA and ASIC design methodology)
- 15.3. No lecture.
 - A good day to embark on assignment 8?
 - Delivery date after easter...
- Guest Lecture with Inventas
 - Date: tentatively 19.3
- Oblig 8 Workshop
 - Date: tentatively 22.3

Course Goals and Learning Outcome

<https://www.uio.no/studier/emner/matnat/ifi/IN3160/index-eng.html>

In this course you will learn about the **design of advanced digital systems**. This includes programmable logic circuits, a hardware design language and system-on-chip design (processor, memory and logic on a chip). Lab assignments provide practical experience in how real design can be made.

After completion of the course you will:

- understand important **principles for design** and testing of digital systems
- understand the relationship between behaviour and different construction criteria
- **be able to describe advanced digital systems at different levels of detail**
- be able to perform simulation and synthesis of digital systems.

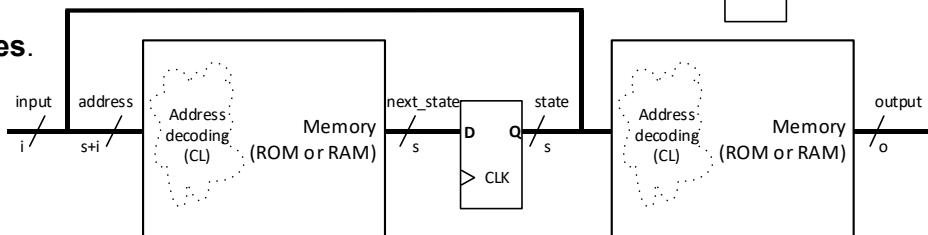
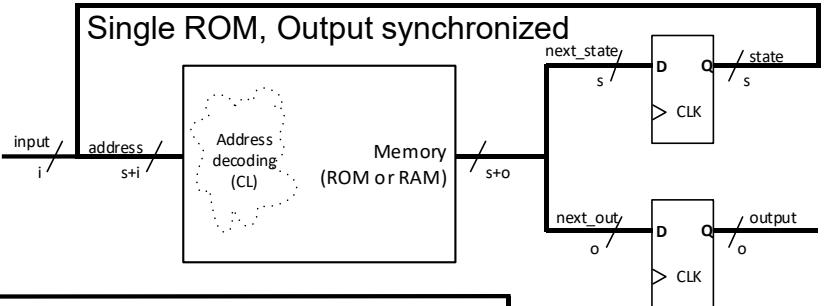
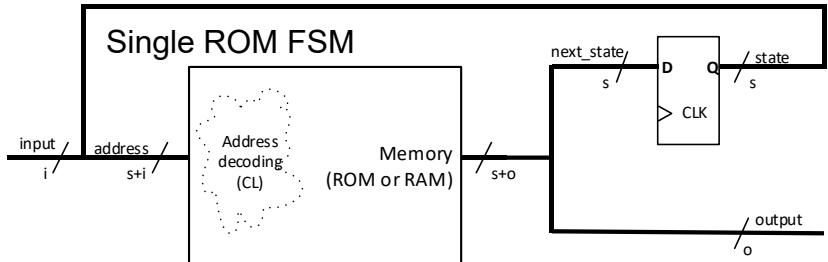
Goals for this lesson:

- Know the principles used in microcoded state-machines
- Be able to describe how microcoded state machines can lead to microprocessors

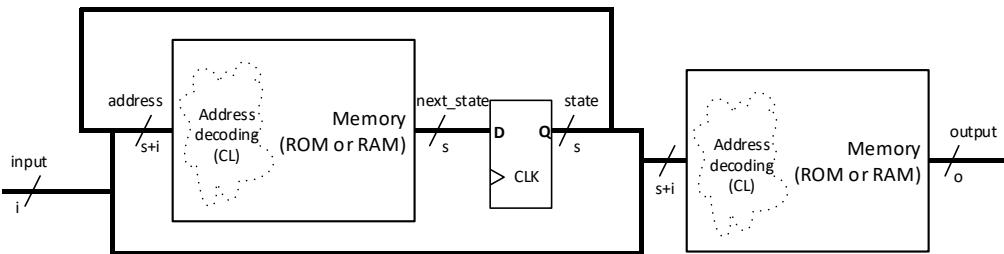
- What is microcoded FSMs
- Which variants are there
- How to implement a microcoded FSMs

Microcoded FSMs

- FSM coded using memory (asynch. mem.)**
 - Can be used for any FSM
 - Input and state decides memory output
- Single ROM solution**
 - Both Mealy and Moore possible *depending on decoding...*
 - General solution is a Mealy machine (*Moore is a special case*).
 - ROM decoding added to critical path for downstream modules.**
- Single ROM with output synchronization**
 - No hazards, but output is delayed by one clock cycle
- Dual ROM Moore machine**
 - Separate state and output decoding
 - Easier to comprehend
 - Requires the least amount of storage
 - least impact on downstream critical without synchronizers.
- Dual ROM Mealy machine**
 - Both memories has the same address decoding
 - No gains in terms of storage or critical path*



Dual ROM, Moore FSM

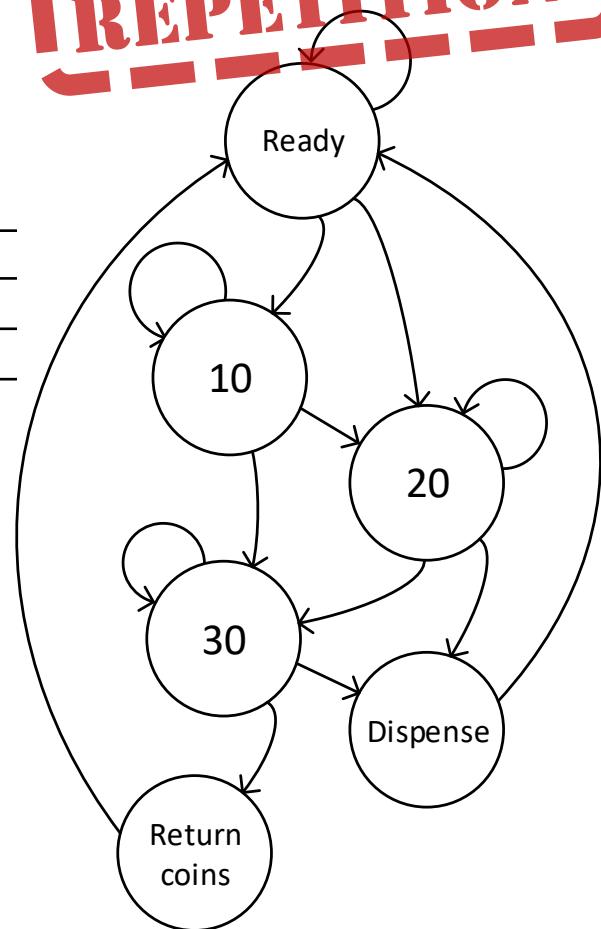
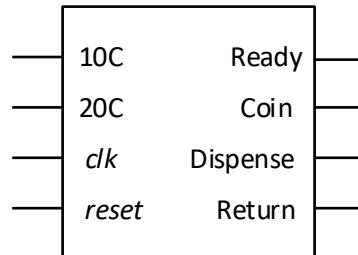


Dual ROM, Mealy FSM

REPETITION

Example: Vending machine

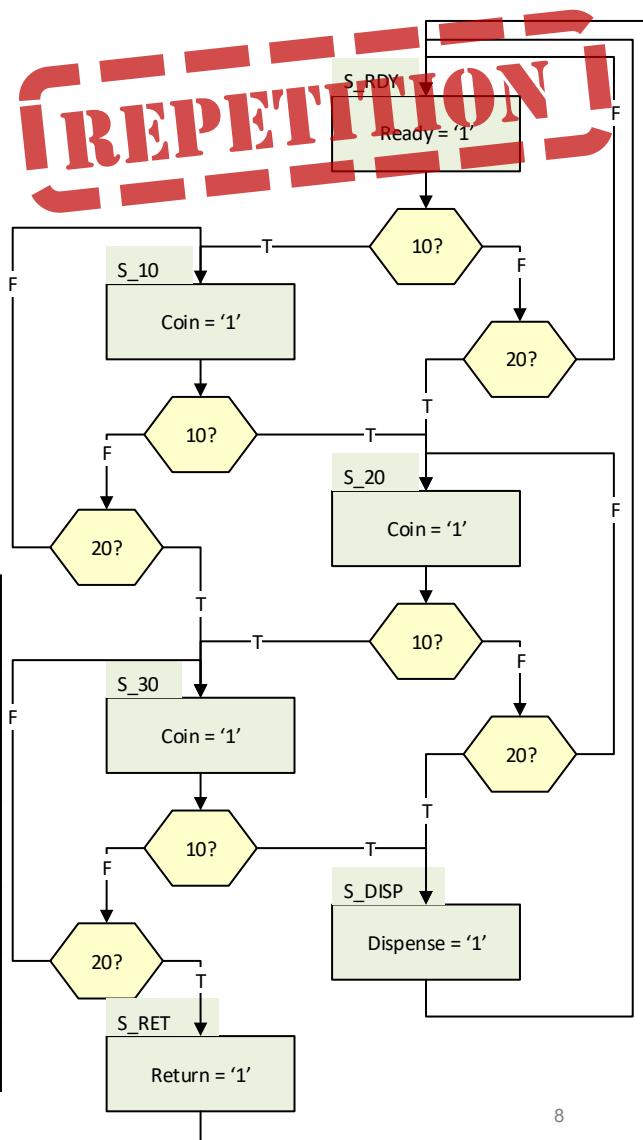
- Specification:
 - We want to design a vending machine that sells drinks for 40c.
 - The machine accepts 20c and 10c coins (all others will be rejected mechanically).
 - If 40c are inserted a drink shall be dispensed
 - If more than 40c is inserted all coins are returned
 - The machine has two lights
 - One to show that it is ready
 - One to show that further coins are needed



ASM diagram & State and output table

- If possible- simplify early.
 - Both state and output tables and ASM charts can be used to find redundancy

State	10c	20c	No coin	Ready	Coin	Dispense	Return
S_RDY	S_10	S_20	Self	1	0	0	0
S_10	S_20	S_30	Self	0	1	0	0
S_20	S_30	S_DISP	Self	0	1	0	0
S_30	S_DISP	S_RET	Self	0	1	0	0
S_DISP	S_RDY	S_RDY	S_RDY	0	0	1	0
S_RET	S_RDY	S_RDY	S_RDY	0	0	0	1



Example: Single ROM, extended State and output table

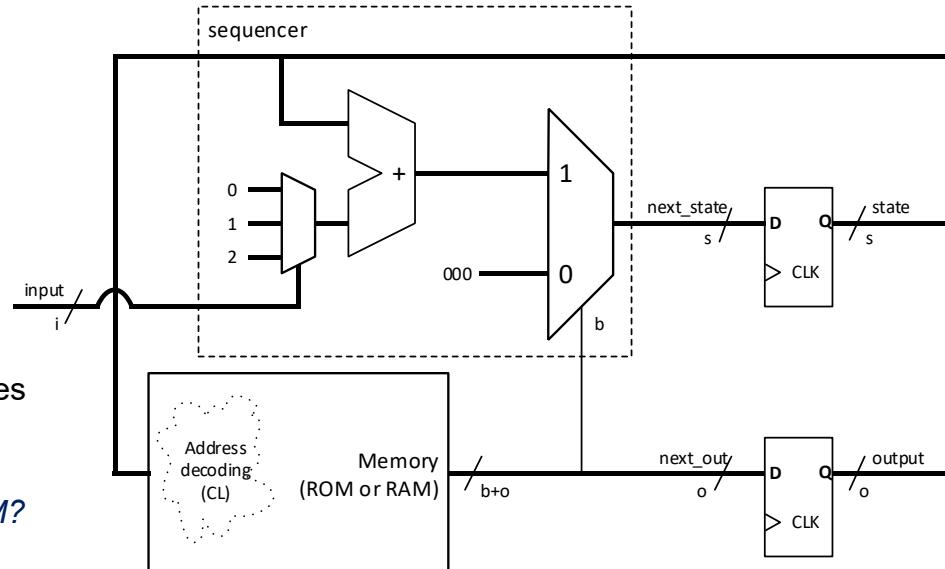
- Moore machine implementation:
 - One address for every unique combination of inputs and state
- Pro's
 - ***Can be implemented using fixed hardware***
 - ROM + a few state registers
 - Reprogrammable
- Con's
 - A lot of duplicated data in ROM
 - Output the same for all states
Here: 3x output data in legal states...
 - ***Illegal states need a plan..***
 - Here: input = "11", state = "110", "111"
=> 14 illegal states, 18 legal

Memory		State (s+i)	State	Next state			Output			
Address	Data (n_s+o)			No coin	10c	20c	Ready	Coin	Dispense	Return
000 00	000 1000	S_RDY	Self				1	0	0	0
000 01	001 1000				S_10					
000 10	010 1000					S_20				
001 00	001 0100	S_10	Self				0	1	0	0
001 01	010 0100				S_20					
001 10	011 0100					S_30				
010 00	010 0100	S_20	Self							
010 01	011 0100				S_30					
010 10	100 0100					S_DISP	0	0	1	0
011 00	011 0100	S_30	Self							
011 00	100 0100				S_DISP					
011 00	101 0100					S_RET				
100 00	000 0010	S_DISP	S_RDY				0	0	1	0
100 01	000 0010			S_RDY						
100 10	000 0010					S_RDY				
101 00	000 0001	S_RET	S_RDY				0	0	0	1
101 01	000 0001			S_RDY						
101 10	000 0001					S_RDY				

- Example resource usage:
 - 3 state registers (+ 4 output registers if synchronized.)
 - 5 bit address = 32 lines, 7 bit data => 224 bit ROM

Example: Adding a sequencer can reduce storage

- We reduce the address space from 2^{s+i} to 2^s
 - (ie. Memory has as many instructions as states)
- Here:
 - In branchable states:
Input decides if we jump 0, 1 or 2 states
 - Non branchable state => fixed next state
`next_state <= S_RDY`
 - Adding 1 branch bit and sequencing logic reduces address space from 32 to 8 and data word size from 7 to 5.
 - Can we make Mealy with this reduced size ROM?*



Memory		State	Next state			Output			
Address (s)	Data (b+o)		No coin	10c	20c	Ready	Coin	Dispense	Return
000	1 1000	S_RDY	Self	S_10	S_20	1	0	0	0
001	1 0100	S_10	Self	S_20	S_30				
010	1 0100	S_20	Self	S_30	S_DISP	0	1	0	0
011	1 0100	S_30	Self	S_DISP	S_RET				
100	0 0010	S_DISP	S_RDY			0	0	1	0
101	0 0001	S_RET	S_RDY			0	0	0	1

VHDL microcode example (1/2):

- Entity as earlier
- Read ROM from file as earlier code

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;
use STD.textio.all;

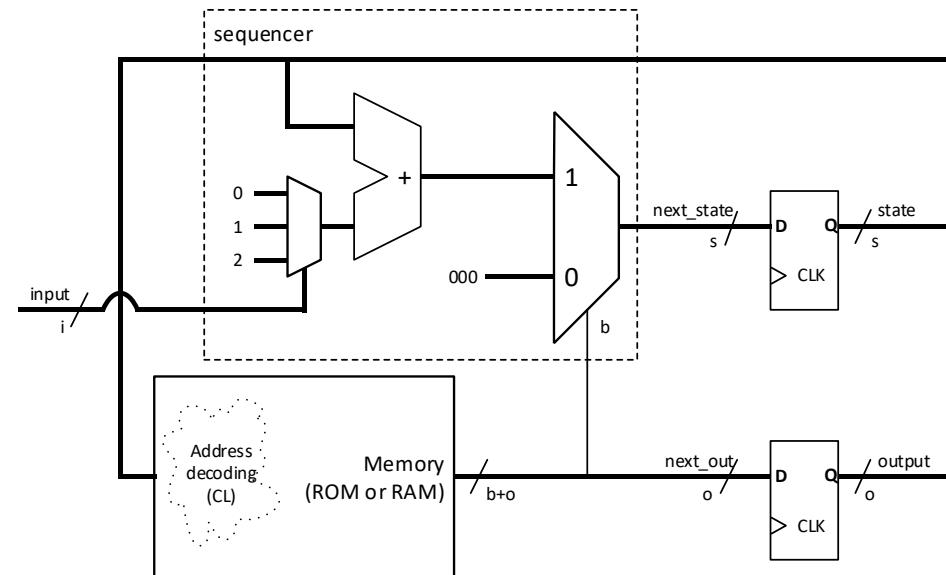
entity vending is
port(
    clk, reset, twenty, ten : in std_logic;
    ready, coin, dispense, ret : out std_logic);
end entity vending;

architecture microcode of vending is
constant data_width: natural := 5;
constant addr_width: natural := 3;
constant filename: string := "ROM_data_bits.txt";
type memory_array is array(2**addr_width-1 downto 0) of
    std_logic_vector(data_width-1 downto 0);

impure function initialize_ROM(file_name: string) return memory_array is
    file init_file: text open read_mode is file_name;
    variable current_line: line;
    variable result: memory_array;
begin
    for i in result'range loop
        readline(init_file, current_line);
        read(current_line, result(i));
    end loop;
    return result;
end function;

--initialize rom:
constant ROM_DATA: memory_array := initialize_ROM(filename);
signal address: std_logic_vector(addr_width-1 downto 0);
signal data: std_logic_vector(data_width-1 downto 0);
```

VHDL microcode example 2/2



```
--state assignment using std_logic (no "state_type"):
signal state, next_state : std_logic_vector(2 downto 0);
alias b : std_logic is data(4);
```

```
begin
  -- ROM data CL
  data <= ROM_DATA(to_integer(unsigned(address)));
  address <= state;

-- 1: register assignment:
process (clk, reset) is
begin
  if reset then
    ready      <= '0';
    coin       <= '0';
    dispense   <= '0';
    ret        <= '0';
    state     <= (others => '0');
  elsif rising_edge(clk) then
    ready      <= data(3);
    coin       <= data(2);
    dispense   <= data(1);
    ret        <= data(0);
    state     <= next_state;
  end if;
end process;

-- 2: combinational next_state logic (sequencer)
next_state <=
(others => '0') when not b else
std_logic_vector( unsigned(state) + 1) when ten else
std_logic_vector( unsigned(state) + 2) when twenty else
state;
end architecture microcode;
```

ROM (text file content)

00000
00000
00001
00010
10100
10100
10100
11000

- Address 7 is first line since we read in the ‘**range**’ order ($2^{**n}-1$ **downto** 0).
 - To have address 0 first we should read in ‘**reverse_range**’

```
for i in result'range loop
    readline(init_file, current_line);
    read(current_line, result(i));
end loop;
```

Memory	
Address (s)	Data (b+o)
000	1 1000
001	1 0100
010	1 0100
011	1 0100
100	0 0010
101	0 0001

- Why do we have two lines with 0?
- What will happen if state is set to address 7 og 6..?

Reducing delay

- Can we reduce output delay?

```

begin
    -- ROM data CL
    data <= ROM_DATA(to_integer(unsigned(address)));
    address <= state;

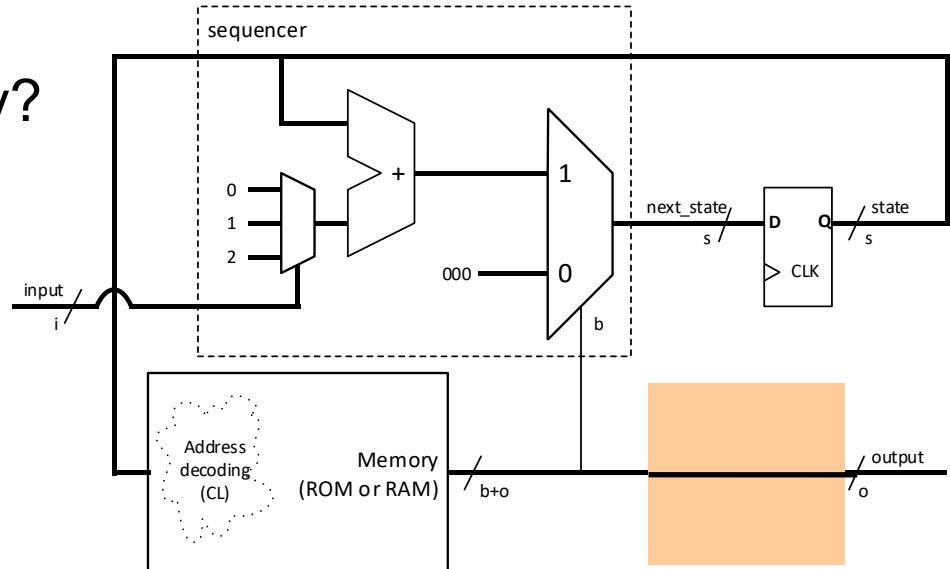
    -- output assignment based on state...
    ready      <= data(3);
    coin       <= data(2);
    dispense   <= data(1);
    ret        <= data(0);

    -- 1: sequential state assignment:
    state <= (others => '0') when reset else next_state when rising_edge(clk);

    -- 2: combinatorial next_state logic
    next_state <=
        (others => '0') when not b else
        std_logic_vector( unsigned(state) + 1) when ten else
        std_logic_vector( unsigned(state) + 2) when twenty else
        state;

end architecture microcode;

```



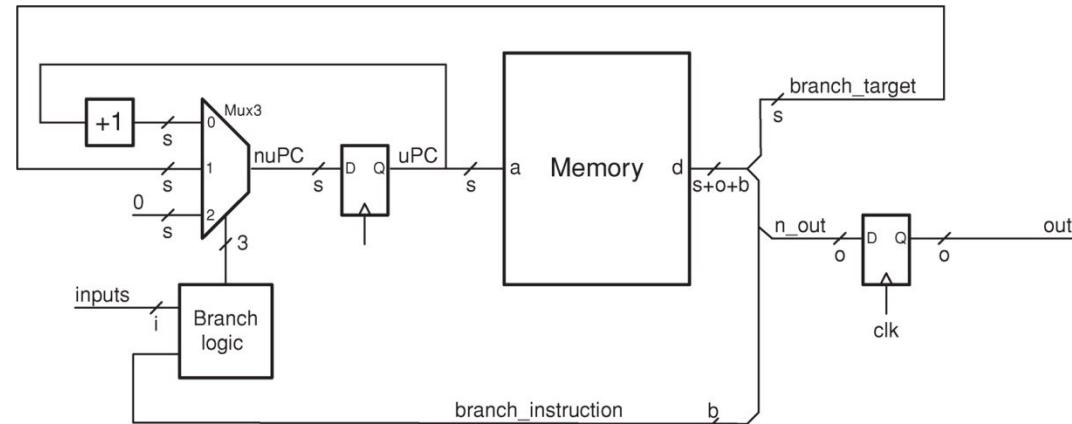
- What type of FSM is this?
- Will it work?

General Sequencer / Microsequencer

- A device that generates addresses
 - Typically a counter
 - + some logic for various types of jumping
 - Reduces the need to store subsequent addresses
 - *makes sense when there is some sort of order*
 - *Does not make sense when next state is random*
(ie next state can be anything most of the time)

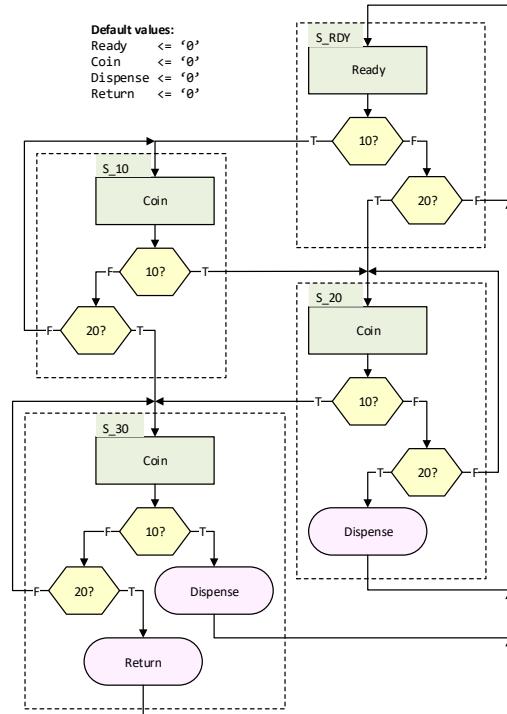
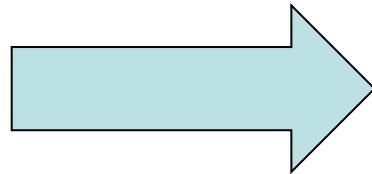
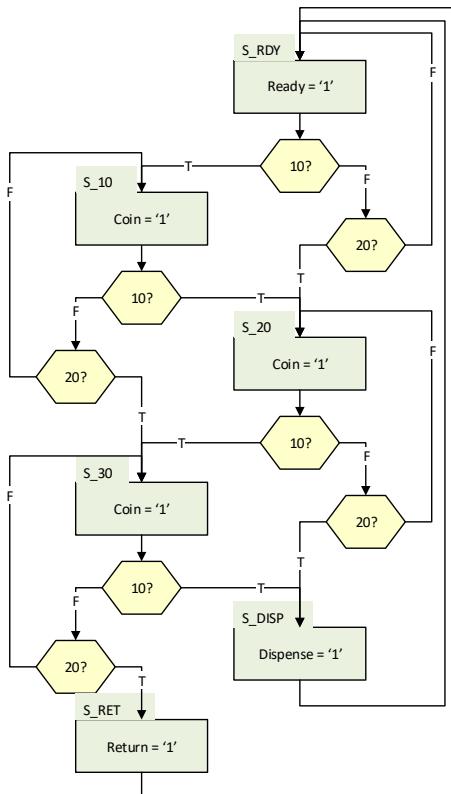
Microcoded processors

- A microcoded FSM with a sequencer can be seen as a microprocessor.
 - ROM stores instructions that are executed on each clock cycle.
 - uPC (Microprocessor Counter) is the current state.
- Branching is usually done with several bits, to enable different type of usage
- Input is the machine code we want to execute
- Processors have other functions and dedicated memory
 - ALU
 - Instruction memory
 - Data memory



Source: Digital Design Using VHDL, a systems approach; Dally, Harting, Aamodt

Going from Moore to Mealy (without sequencer)



State table conversion (*legal memory entries shown*)

Memory		State	Next state			Output			
Address (s+i)	Data (n_s+o)	State	No coin	10c	20c	Ready	Coin	Disp- ense	Re- turn
000 00	000 1000	S_RDY	Self						
000 01	001 1000			S_10		1	0	0	0
000 10	010 1000				S_20				
001 00	001 0100	S_10	Self						
001 01	010 0100			S_20					
001 10	011 0100				S_30				
010 00	010 0100	S_20	Self						
010 01	011 0100			S_30		0	1	0	0
010 10	100 0100				S_DISP				
011 00	011 0100	S_30							
011 00	100 0100			S_DISP					
011 00	101 0100				S_RET				
100 00	000 0010	S_DISP	S_RDY						
100 01	000 0010			S_RDY		0	0	1	0
100 10	000 0010				S_RDY				
101 00	000 0001	S_RET	S_RDY						
101 01	000 0001			S_RDY		0	0	0	1
101 10	000 0001				S_RDY				



Memory		State	Next state			Output			
Address (s+i)	Data (n_s+o)	State	No coin	10c	20c	Ready	Coin	Disp- ense	Re- turn
00 00	00 1000	S_RDY	Self						
00 01	01 1000			S_10					
00 10	10 1000				S_20				
01 00	01 0100	S_10	Self						
01 01	10 0100			S_20					
01 10	11 0100				S_30				
10 00	10 0100	S_20	Self				0	1	0
10 01	11 0100			S_30			0	1	0
10 10	00 0010				S_RDY	0	0	1	0
11 00	11 0100	S_30	Self				0	1	0
11 01	00 0010			S_RDY			0	0	1
11 10	00 0001				S_RDY	0	0	0	1

- Going from 224 bit ROM to
 - 4 address bits and 6 output bits => 96 bit ROM ($(2^4) * 6$)
- State should be msb in address to make comprehensible decoding
- what about unused ROM entries (illegal combinations)?: coming next slide

ROM data

- ROM data must come in correct sequence
 - here:
 - 3 legal input combinations per stored state
 - We must use multiple of 2^n (=4), otherwise we write in the wrong address
- Comments at line end = OK
 - Because we use **readline**

```
001000 S_RDY
011000 S_RDY -> S_10
101000 S_RDY -> S_20
000000 illegal state, no output, next state S_RDY
010100 S_10 -> S_10
100100 S_10 -> S_20
110100 S_10 -> S_30
000000 illegal state, no output, next state S_RDY
100100 S_20 -> S_20
110100 S_20 -> S_30
000010 S_20 -> S_RDY & dispense
000000 illegal state, no output, next state S_RDY
110100 S_30 -> S_30
000010 S_30 -> S_RDY & dispense
000001 S_30 -> S_RDY & return
000000 illegal state, no output, next state S_RDY
```

VHDL microcoded mealy machine

- ROM size changed
 - 4 bit address gives 16 entries
- Reading in **reverse' range**

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;
use IEEE.numeric_std.all;
use STD.textio.all;

entity vending is
port(
    clk, reset, twenty, ten : in std_logic;
    ready, coin, dispense, ret : out std_logic);
end entity vending;

architecture microcode_mealy of vending is
constant data_width: natural := 6;
constant addr_width: natural := 4;
constant filename: string := "ROM_mealy_data_bits.txt";
type memory_array is array(2**addr_width-1 downto 0) of
std_logic_vector(data_width-1 downto 0);

impure function initialize_ROM(file_name: string) return memory_array is
file init_file: text open read_mode is file_name;
variable current_line: line;
variable result: memory_array;
begin
for i in result'reverse_range loop
    readline(init_file, current_line);
    read(current_line, result(i));
end loop;
return result;
end function;
```

VHDL microcoded mealy machine

- State only 2 bits
- Address:
 - State is MSB in address (necessary)
 - Input gives rest of address

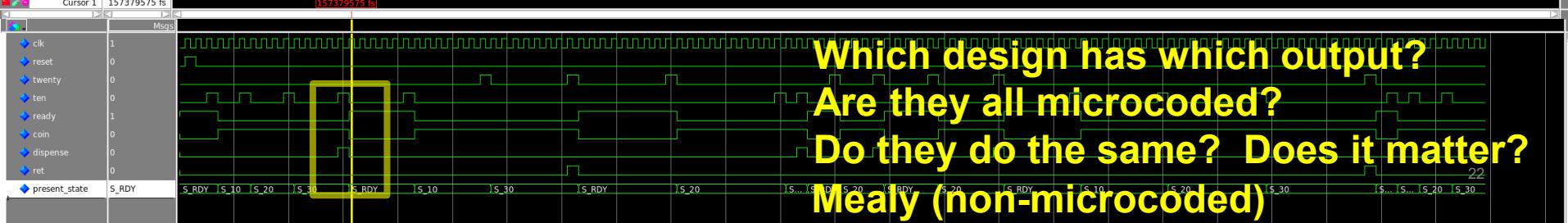
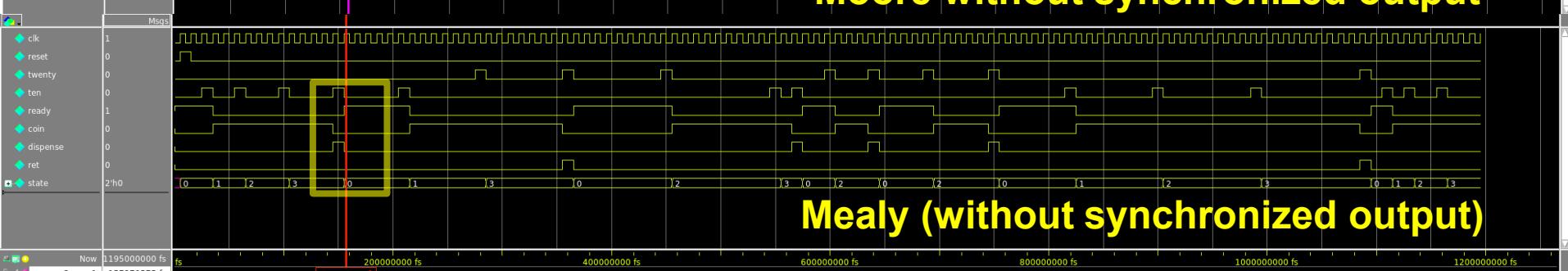
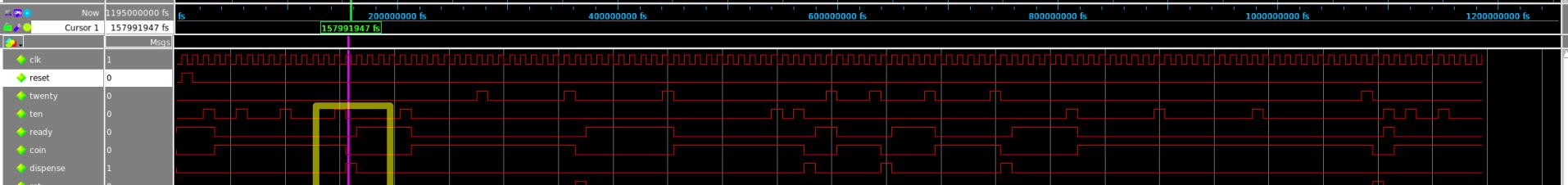
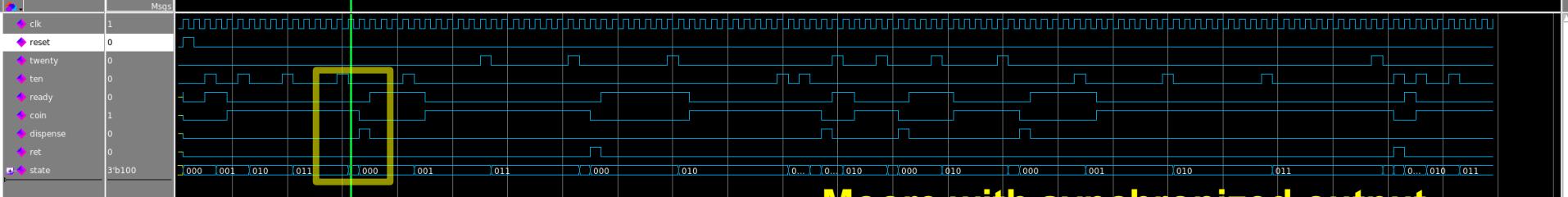
```
--initialize rom:
constant ROM_DATA: memory_array := initialize_ROM(filename);
signal address: std_logic_vector(addr_width-1 downto 0);
signal data:     std_logic_vector(data_width-1 downto 0);

-- state register declaration
signal state : std_logic_vector(1 downto 0);
begin
  -- ROM data CL
  data <= ROM_DATA(to_integer(unsigned(address)));
  address <= state & twenty & ten ; -- state is MSB

  -- output assignment based on state...
  ready    <= data(3);
  coin     <= data(2);
  dispense <= data(1);
  ret      <= data(0);

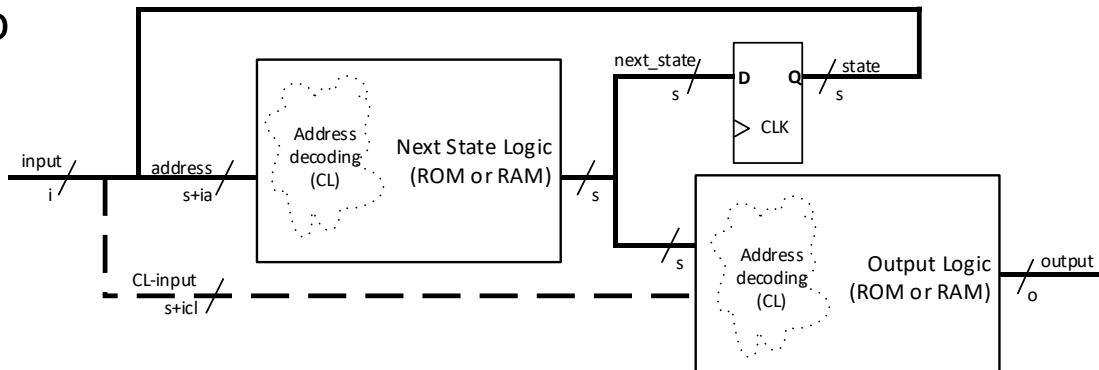
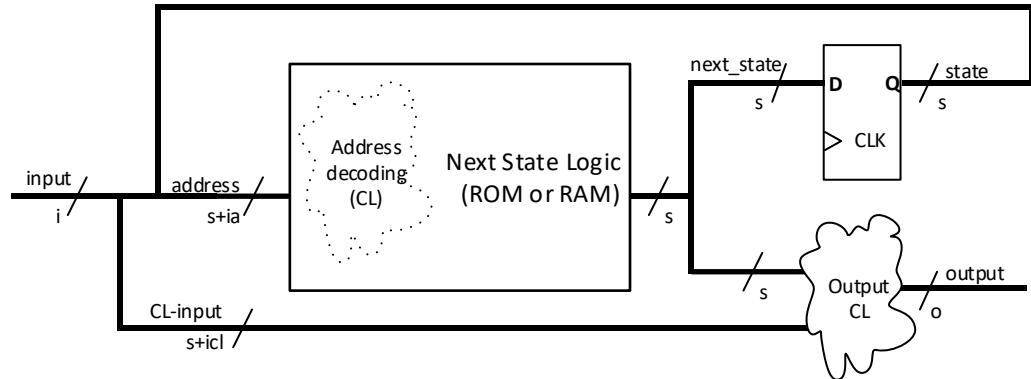
  -- sequential state assignment:
  state <= (others => '0') when reset else data(5 downto 4) when rising_edge(clk);

end architecture microcode_mealy;
```



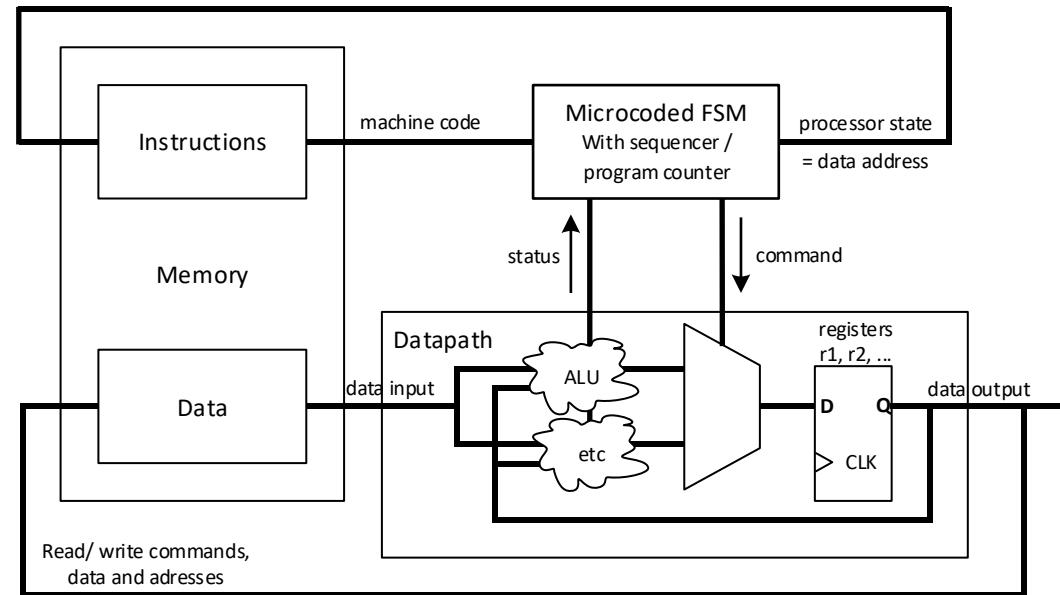
Microcode considerations..

- ROM size can be reduced by
 - Separating output CL
 - CL can be a separate ROM
 - Separate state CL and output CL
 - What does the synthesizer do with our FSMs?
 - Breaks it up into LUTs and flipflops
 - LUT = small ROM..



Microprocessors

- Microcoded state machines can and has been used to create processors.
 - Early x86 processors were entirely microcoded (8088, 8086, 80286, 80386).
 - Microcoded processors *can be* patchable..
 - => BIOS upgradeable, etc.
- ROM content dictates instruction set (machine code)
- Modern processors are normally not (fully) microcoded
 - Optimization and move towards RISC dictates hardwired circuitry for speed and power
 - Method can still be used –
 - for complex instructions, variable length instructions
 - To ensure updates can be implemented after shipping..
 - *One could argue this is what we actually when using LUT based FPGAs*



Summary of microcoded state machines

- All FSMs *can* be implemented using 1 ROM + state registers
 - The general solution suggests a mealy machine,
 - We get Moore having *the same output regardless of input* in each state
- Using 2 ROMs (separate state and output decoding)
 - May reduce memory usage
 - when none or only some input are used to determine output
- Sequencers, Branching- and Output logic
 - may reduce ROM size
 - adds structure outside the state ROM.
 - This is one way of implementing processors and instruction sets.
- Consider using microcode when...
 - *the state machine is (best) defined by a (large) table*
 - when changes to the state table likely will happen at some point in the future.

Suggested reading

- D&H 18
 - 18 p398-427

Next lesson

- Clock Domain Crossing “CDC”