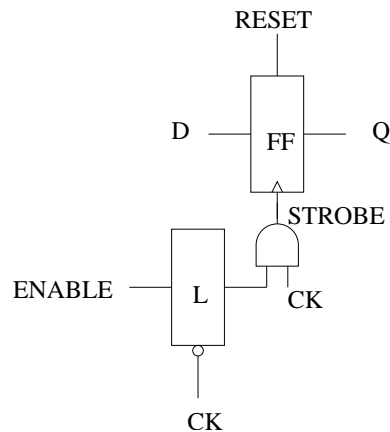

CHAPTER 3

Clock gating, pipelining and parallelizing

In this chapter you will experience some techniques for reducing power consumption by optimizing the circuit architecture. From directory `/home/repository/lowpower/ese3/` copy all the VHDL files: `cp /home/repository/lowpower/ese3/*`.

3.1 A first approach to clock gating (TL & TP)

In `ckgating.vhd` you find an implementation of the *clock gating* technique reported also in figure for sake of clarity. Notice the latch before the *and* gate. It is used to filter away glitches when the clock is high.



In the following exercise you will understand how the VHDL simulator works and how to avoid troubles both in simulation and design.

Copy and open the file `ckgbug.vhd`. Look at the signal declaration and in particular to the `std_logic_vector` type. It is an *array* of `BYTE` `std_logic`, where `BYTE` is defined as a “constant”. Signals `D1` and `D3` are defined `std_logic_vector(7 downto 0)` which means that the Most Significant Bit (MSB) is in position 7 and the Least Significant Bit (LSB) is in position 0. Differently `D2`’s MSB is in 0 and LSB is in 7.

Remember the `generate` statement used for multiple instantiations together with statement `for`. `Byte=8` instances of the flip flops, described within `fd.vhd`, are used to create first register `L1` and second register `L2`. `L1`’s input is array `D1` and its output is `D2`. `D2` is on its turn input to `L2` whose output is `D3`.

`L2` is gated (`STROBE` signal in the Port Map) while `L1` is not (`CK` signal in the Port Map). So

D2 always copies D1 (with bit positions inverted!) while D3 copies D2 only when ENABLE='1'. Suppose the reset has zeroed all values in register and try to mentally simulate what happens if input D1="01111111" and ENABLE='1'. Now simulate the VHDL code (**ckgbug.vhd**) and compare your prediction to what the simulator says.

The behavior differs from what we expected. Why? It seems that D3 directly copies D1 on the clock rising edge. This is what really happens. In fact the clock gated (STROBE) arrives at the second register a "simulation step" later than at the first register. This happens because the simulator schedules the computation of the AND output after the CLOCK assignment (causality!). As a result all things goes like the AND has an internal delay. Therefore FIRST D2 changes and copies D1, then D3 copies D2 that already changed! This is a mistake we should avoid during simulation, but it is something that could really happen, if the clock gating circuit adds too much delay such that the HOLD TIME of the FLIPFLOP is no more respected.

How can we avoid this problem? A simple solutions consists in adding a Clock-to-Output delay. For example add 0.1ps to the Q assignment in *fd.vhd*. Simulate again and see what happens. It should work now. But what if the *and* has its own delay of, for instance, 0.2ps, that is larger then the Ck-Q delay? Apply this change, and try.

Remark point

Concept of simulation step and causality

3.2 Clock gating for a complex circuit (TL & TP)

The goal is: let's consider a circuit, and understand how it works, then synthesize it and report its power consumption. Then let's try and apply clock gating where possible and synthesize it again, report the new power consumption: is the total dissipation decreasing?

The circuit you are going to analyze implements the operations sketched in figure 3.1.

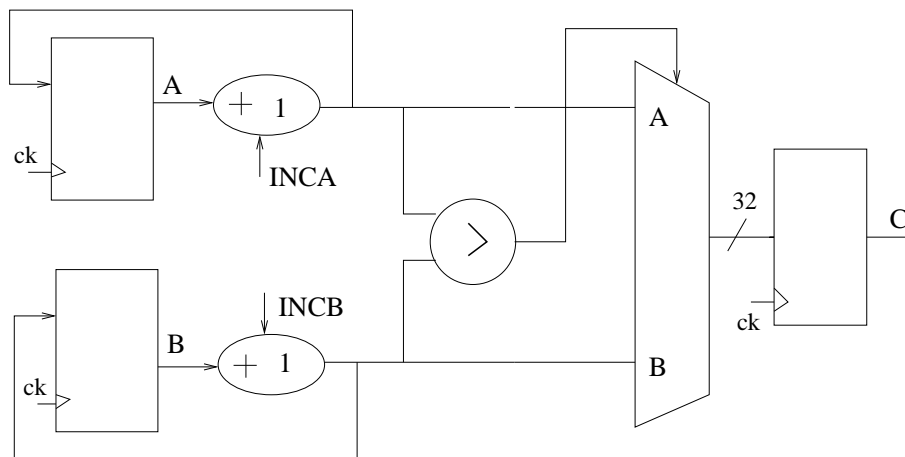


Figure 3.1:

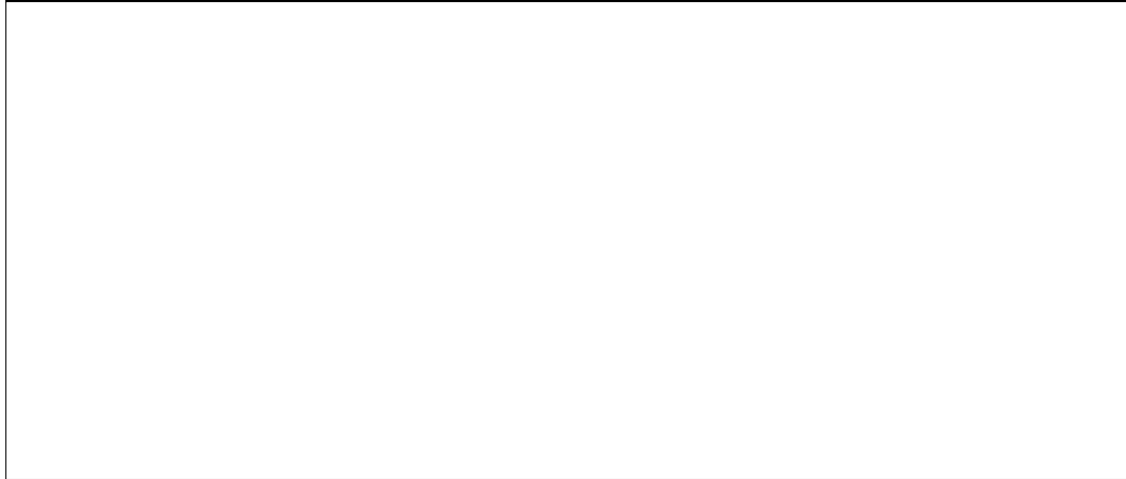
You are also provided with the VHDL, that you will find in

`/home/repository/lowpower/ese3/incomp.vhd`

In the same directory you will find the test bench *tb_incomp.vhd*. What does the circuit do? Now simulate it Are the results consistent with what you expected?

Now try to VIRTUALLY (pen and paper) apply the clock gating technique to the circuit: change the sketch in figure 3.1 to this purpose and draw it in the box below. Suggestion: use input signals INCA and INCB!

Note that you don't need to write the vhd of this part, as the given vhd is already written so that the synthesizer is capable of applying clock gating if requested.



Now you are ready to **synthesize** the circuit. Use the directives in chapter 2 to initialize the synthesizer. Remember that the synthesizer wants a subdirectory *work* as well as the simulator, and it is better if you perform simulation and synthesis in two different subdirectories (just create a subdirectory **synth** and in it a subdirectory **work**, copy in **synth** the Synopsys setup file (.synopsys_dc.setup) and the VHDL files to be synthesized and launch **design_vision**).

You should perform a first synthesis without considering clock gating. After you launched **design_vision** go to the bottom **Command Line (Log)**. Hereinafter you will be given instructions to be typed in the command line (should you insist in using menus and windows, well, it's up to you ...). If you want to become a design_compiler-pro you can also try to write directly a script using as a reference the one you saved in the last lab and the hints you will find herein.

To read the file, type in the command line:

```
analyze -format vhdl incomp.vhd
```

```
elaborate incomp -library work -architecture behavioral
```

now synthesize it by typing

```
uniquify
```

```
compile -exact_map
```

You can navigate through the synthesized schematic. Now create a clock and report the power consumption:

```
create_clock -name ck -period 5 {ck}
```

```
report_power -include_input_nets
```

The tool creates a clock of period 5 ns (nanoseconds is the default time unit and is defined in the library of logic gates used for the synthesis). Pay attention hereinafter: the report power command

uses the clock for computing the power dissipation. So you always must check the clock period you are using when comparing different report power results. The option “-include_input_nets” forces the tool to consider the input nets for power calculation as well. Without this option the tool shows a power consumption figure accounting for internal nets and cells only.

To have more detailed information on power consumption you can perform a power report on nets by typing

```
report_power -net -include_input_nets
```

you will note that for *clock*, *reset* and inputs a static probability $p(res = '1') = 0.5$ has been assigned, which is not correct. Let's understand how the rate is computed, so that we are able to change it. The toggle rate shown in the report is a floating point value which accounts for the number of transitions of a net within a clock period. It can be specified differently according to the “set_switching_activity” command (see the manual page for more information). When the power report is printed out, the toggle rate is divided by the reference clock period: For example, if toggle rate is 0.5 in a determined net with a clock period of 5, the power report prints out 0.1. In formulas, if static probability $p1 = 0.5$, this is given by $2 \cdot p1 \cdot (1 - p1) / T_{ck} = 2 \cdot 0.5 \cdot 0.5 / 5 = 0.1$. However, under the Synopsys shell it is necessary to specify the toggle rate as the number of toggles within a clock period rather than the product of two probabilities. This parameter, assigned automatically by the tool, is not correct both for the *reset* and for the *clock* signal, so correct it by typing

```
set_switching_activity -static_probability 0.5 -toggle_rate 2 -base_clock ck {ck}  
set_switching_activity -static_probability 0 -base_clock ck {rst}
```

where “-base_clock” is used to let the tool calculate toggle rate with respect to the clock named “ck”. A toggle rate of 2 for the clock means that the signal in parentheses {ck} changes twice from 0 to 1 and viceversa within a clock period. Check if the toggle rate for the clock signal is correct by running the power report for all the nets in the current design with

```
report_power -include_input_nets
```

Did something change? Finally impose a lower input probability to inputs as well

```
set_switching_activity -static_probability 0.12 -toggle_rate 0.025 -base_clock ck {INCA INCB}
```

and analyze the power report. In this case the obtained power report is for sure more accurate because it has been calculated by assuming realistic input probabilities (save it).

You can also annotate the number of gates used for this synthesis by typing:

```
report_cell
```

You are now ready to apply the clock gating technique. Luckily it will be performed for you by the synthesizer if you will give him the right directives. So reset previous results by selecting on the menu **File→Remove all Design**.

To insert clock gating logic in your RTL design and to synthesize the design with the clock gating logic, compile your netlist

```
analyze -format vhdl incomp.vhd
```

elaborate incomp -library work

uniquify

Remember that if you want to understand the meaning of a command, let's say *commandname*, you can type

man commandname

a little bit of hacking could help, now and then ...

You can synthesize now:

compile -exact_map -gate_clock

create the clock

create_clock -name ck -period 5 {ck}

and analyze the power report:

report_power -include_input_nets

As before you should change the probability of *reset*, *clock* and inputs and see how the power change

set_switching_activity -static_probability 0.5 -toggle_rate 2 -base_clock ck {ck}

set_switching_activity -static_probability 0 -base_clock ck {rst}

set_switching_activity -static_probability 0.12 -toggle_rate 0.025 -base_clock ck {INCA INCB}

Then analyze the power consumption variation with respect to the previous case

report_power -include_input_nets

and analyze the power report ¹. Did you note a power variation with respect to the previous synthesis? Report the gate number **report_cell**: is it increased or reduced?

Now it should be instructive to understand what's happened in this last operation: try to navigate the schematic and find a clock gating element. Is something similar to what you expected?

Remark point

How to apply clock gating, how to annotate activity.

3.2.1 Some more clock gating? (TL & TP)

Now a question: are we sure that we applied clock gating wherever possible? The VHDL you synthesized imposing the clock gating style helps in inserting the clock gating elements for sure the two initial registers, but the register to the output pin is not gated: why? Something could be inserted in the original VHDL to help the synthesizer...

Once you have changed the VHDL code synthesize it as before without clock gating and report the power consumption (three steps: no probability change, change the reset, change the input). Check the number of gates as well.

Finally perform again the clock gating synthesis as before, analyze the power consumption (three steps) and the number of gates. Navigate the schematic and check where other clock gating block has been inserted.

¹If you're getting bored check the history window or type **history** in the command window: in both cases a list of the last commands you typed is displayed and a sequential number is associated to them, let's say *nb*. If you type in the command window **!nb** the associated instruction is automatically executed...

Remark point

How to force the clock gating using VHDL.

3.2.2 An automatic way to annotate activities (TL & TP)

In the previous exercise you have seen that a wrong activity annotation can lead to wrong results in the power estimation. It is strictly necessary to put a reasonable activity on the nodes, also in the cases that circuits are very complex. In such cases it is not practical to annotate the activity of each node with the command “set_switching_activity” and it is necessary to make the annotation process automatic by using standard files called SAIF files.

Let's consider the overall annotation process in figure 3.2: The process is inclusive of two parts, one in the VHDL simulator and another in the design compiler (Synopsys synthesizer). First (1), after having analyzed, elaborated and compiled the design, the synthesizer can generate a forward annotation SDF file which accounts for the names of the netlists on the design. The SDF or Standard Delay Format file contains the delays of your circuit.

Once the VHDL simulator has read the SDF file, after having run simulation (2), it generates a VCD (Value Changed Dump) file by writing the activities in each node². Finally, the VCD file should be converted into a backward SAIF file (3). The synthesizer can read the backward annotation file and update the properties of the nodes (4) with the activities calculated from the VHDL testbench.

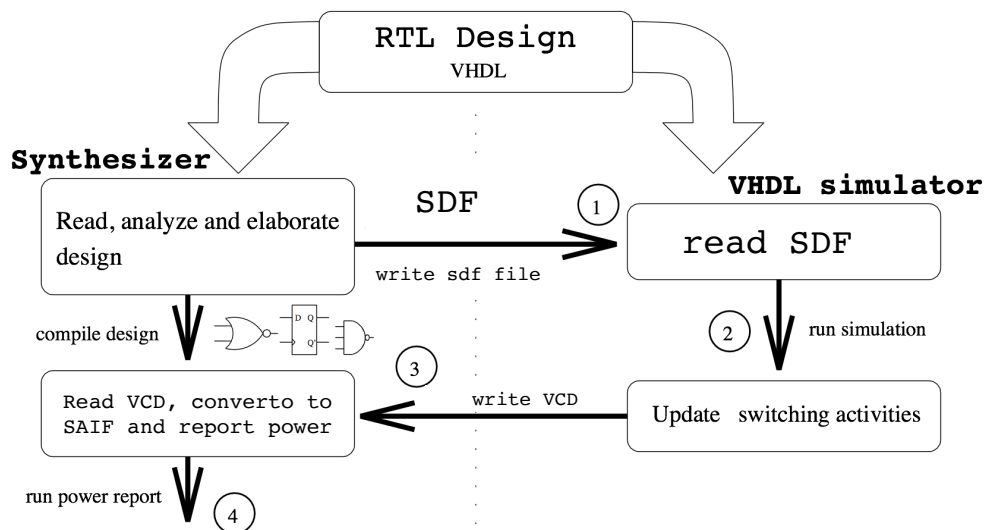


Figure 3.2:

We will now see how to realize this back-annotation process. Considering that you will use both Modelsim and Synopsys, for convenience create a new folder in your `ese3` directory called `saiftest`. Inside this directory create two folders called `modelsim` and `synth`. By using two different command shells you will run both Modelsim and Synopsys inside `modelsim` and `synth`, respectively. Don't forget to copy the `.synopsys_dc_setup` file in `synth`. Copy the source VHDL files `inccomp.vhd` and `tb_inccomp.v` inside `saiftest`.

During the simulation you are going to perform, the inclusion of the technological library can be specified with the command `vsim` by adding the additional library among the command parameters. However, to make the execution of this laboratory session easier, part of the commands will be executed

²In this case the concept of node corresponds to the concept of “signal” in the VHDL/Verilog language, thus variables are not mapped as nets and not annotated

by using two scripts called `forward.do` and `backward.do`. Copy the file `forward.do` from `/home-/repository/lowpower/ese3/do/forward.do` in `saiftest/modelsim` and the file `backward.do` from the same location in `saiftest/synth`. Now you have a folder called `saiftest` including the VHDL/Verilog files and two folders called `modelsim` and `synth` which include one script each. Hopefully now you are ready to start.

For this example let's refer to the `incomp` entity included in the file `incomp.vhd`. Run `synopsys`³ and after having analyzed and elaborated `incomp.vhd` type

```
compile -exact_map
write -hierarchy -format ddc -output incomp.ddc
```

The last command is required to save your design with the constraints you specified for implementing your design.

Now save the verilog netlist associated to your design and the SDF file using the following commands:

```
ungroup -all -flatten
change_names -hierarchy -rules verilog
write_sdf ../incomp.sdf
write -f verilog -hierarchy -output ../incomp_netlist.v
```

Now, close Synopsys and run Modelsim from another shell working in the `modelsim` directory (remember the `vlib work` command). After the design compilation (that is the two files `incomp_netlist.v` and `tb_incomp.v`), run the script `forward.do`. It reads the technological library and SDF file. It simulates the verilog testbench and writes the VCD file (named `incomp.vcd`) where the values will be annotated. Open the file and check what's inside the script: This could be useful to understand how you can adapt it to other designs.

Now before going back to Synopsys, the VCD file should be converted into a SAIF file (Standard Activity Interchange Format). This can be done going into the shell where you run Synopsys. Within that shell type:

```
vcd2saif -64 -input ../incomp.vcd -output ../backward.saif
```

Now you can run again Synopsys. Load your previously saved design typing:

```
read_ddc incomp.ddc
```

Now run the script `backward.do`. It reads the backannotated file and updates nets information. Check what's inside the script and the power consumption of the design (with the command `report_power -include_input_nets -net`). The activities should be annotated from the Modelsim simulation.

Note: This automatic process is inherently based on the Verilog testbench, thus on the generation of an at most “complete” set of inputs to the design. Whether simulation conditions in the VHDL testbench are not “realistic”, the power consumption figure of merit can be completely wrong.

Remark point

How to annotate activity automatically by using SAIF mechanism.

³Don't forget to set the environmental variables with `setsynopsys` or `setmentor` before running `design_vision` or `vsim`!

3.3 Pipelining and parallelizing (TL Homework, TP optional but STRONGLY suggested)

Now we will see how to greatly reduce the power dissipation by exploiting the parallelization and/or pipelining of computation that allow reducing the power supply voltage and so save energy.

Let's consider again the previous datapath in figure 3.1. Suppose that all blocks have been characterized at 1 V, f=5 MHz in terms of delay, power and area as in the following table:

cell type	delay (ns)	power (μW @1 V, 5 MHz)	area (μm^2)
REGISTER	2.0 (ck→Q)	0.6	319.0
INCREMENT	40.0	2.55	256.0
COMPARATOR	84.0	2.16	161.0
MUX	14.0	1.67	117.0

Suppose also that delays follow this law with V_{dd}

$$T(V_{dd}) = k \frac{1}{1 - \frac{V_t}{V_{dd}}} = k \frac{1}{1 - \frac{V_t}{V_{dd_{NOM}}} \frac{V_{dd_{NOM}}}{V_{dd}}}$$

where k is a constant and V_t is the threshold voltage of CMOS transistors (supposed symmetric for NMOS and PMOS transistors). Normally the modern devices are designed to work at $V_{dd_{NOM}} = 4V_t$. Therefore if we introduce the normalized potential $u = V_{dd}/V_{dd_{NOM}}$ and use threshold voltage as 0.25 times the nominal V_{dd} , we can express delays as follows

$$T(u) = T(V_{dd} = V_{dd_{NOM}}) \cdot \frac{0.75u}{u - 0.25}$$

In an analogous way, the power can be expressed as

$$P(u) = P_{NOM} \cdot u^2$$

In the following figure normalized delay and power are reported.

Using the previous delay and power table, compute the allowed clock frequency and related power dissipation (suggestion: setup and hold time of registers is assumed negligible, power have to be recomputed at the new frequency of operation):

original solution	
delay (critical path)	ns
allowed clock frequency	MHz
power	μW
area	μm^2

Suppose now you want to utilize some parallelization in order to reduce the power dissipation at the same throughput (i.e. same frequency). You are allowed to duplicate the datapath, then almost doubling the switched capacitance, **but** you can work at half the clock frequency. Can you draw the new circuit?

Compute the new voltage supply, power dissipation and area, including the overhead of the output multiplexer you should have added.

parallel solution	
delay (critical path)	ns
allowed clock frequency	MHz
power	μW
area	μm^2

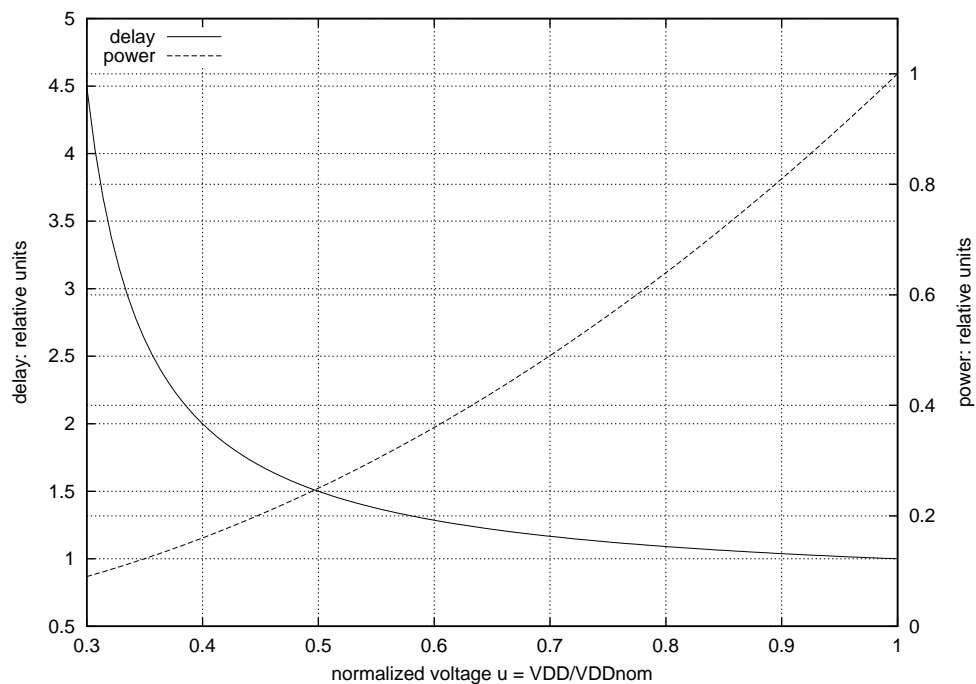


Figure 3.3:

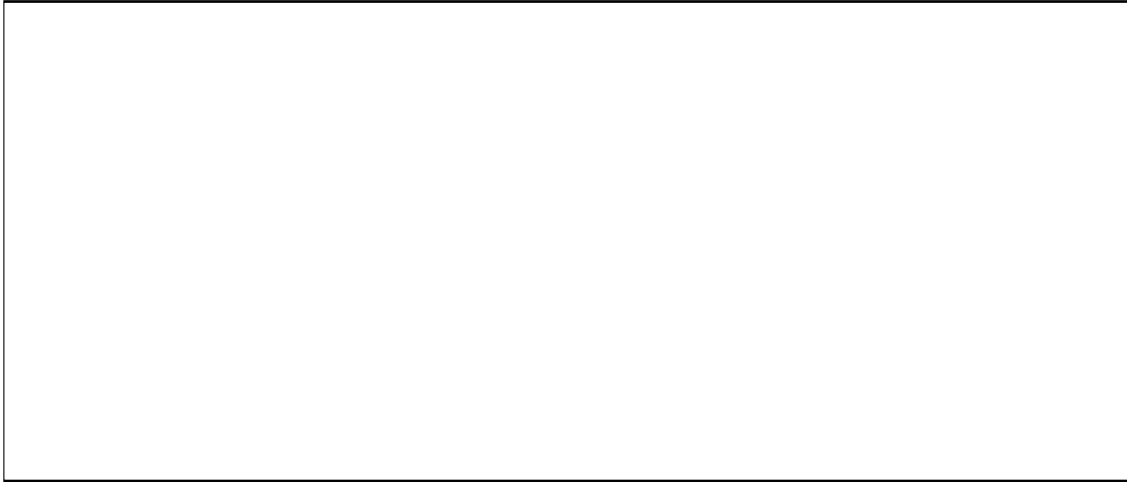


Suppose now you want to employ pipelining, choose where to insert pipeline registers. Draw again the circuit.

Then compute the new supply, power and area figures taking also into account the overhead of new pipeline registers.

pipelined solution	
delay (critical path)	ns
allowed clock frequency	MHz
power	μW
area	μm^2

Try now to use combinations of both techniques, finer grain pipelines (new registers), and more



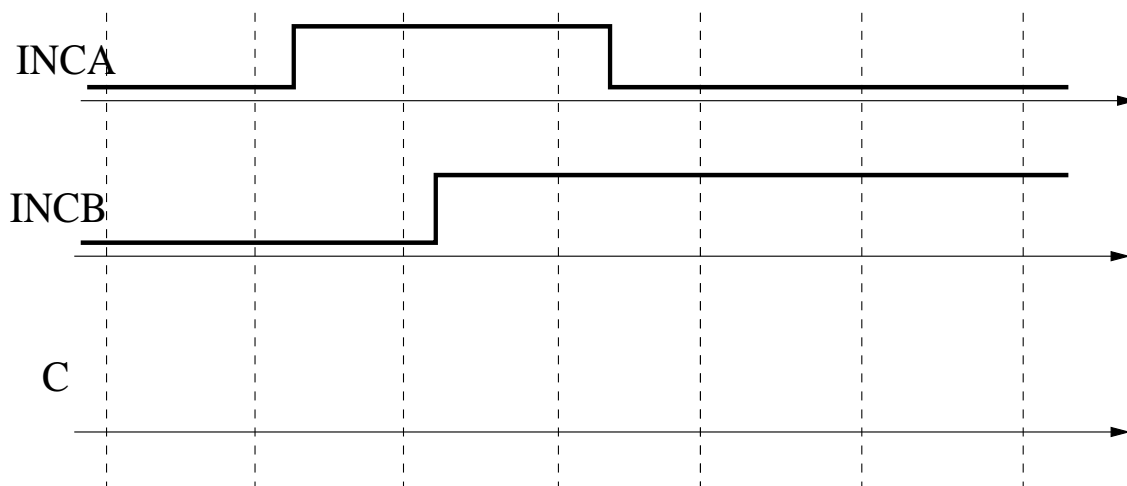
parallelization degrees (e.g. triplication) and discuss advantages and drawbacks of these solutions and of the previous ones and compare them trying to carry out your own conclusions.

Remark point

How to modify an architecture accounting for parallel and pipelined low-power techniques, how to compute the power advantages.

3.3.1 Are you sure it was correct?

Look at the waveform in figure 3.3.1. Use such signals for finding the output C in the case of the original architecture. Then consider the parallel architecture and find the output C. Are the results coherent?



Remark point

Applying parallelizing and pipeline so that data coherence is assured.