IN3170, spring 2025, mandatory laboratory exercise 3: gate delay driving a substantial load (deadline 28-April-2025, 10:15!)

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Abstract

In this lab we will simulate and measure a source follower, aka common drain stage. Out of the three single transistor gain stages it is the only one that can show instability. We use it here as a vehicle to derive and study frequency response.

This is the second in a series of three lab tasks that will be graded and will count 40% towards the final grade. The first lab is only be 'pass' or 'fail' and the students are required to pass this lab assignment to be admitted to the exam. The second and third labs will get a score of between 0% and 100% and will each count 20% towards the course score. The deadline in the title is a hard deadline! Do not miss it! Plan to submit well ahead of the deadline! We will use devilry.ifi.uio.no for submission of you lab report.

1 Report and Group Assignments

1.1 Requirements for the Lab Report (read carefully!)

You are required to execute the tasks and answer all the questions posed below and to submit a report on your work. The report needs to be explaining clearly what you have done, how you have done it, what the results were and what you conclude from them. A good basic rule for any scientific writing is that a document should provide sufficient detail for someone reading it to be able to replicate the results that are presented. Make sure to answer all

questions! Supply the report with drawings of the circuits (including the values of the components and parameters you used where appropriate, e.g. bias voltages/currents, component sizes etc.) and measurement setups! Show your measurements in graphs! Use labels in the schematics that you draw, such as M_1, M_2 (M is often used fro labelling CMOS transistors), $opamp_1$, I_1, V_1 etc. You should then use those labels in your text, since it is much easier to write: 'transistor M_1 in figure 1' than 'the transistor third from the top and second from the left in the righthand side circuit in figure 1'. **MANDATORY when assembling a circuit in the lab**: Include a photograph of your circuit into the report!

1.2 Graded Mandatory Group Assignments

Note that this is part of the course's exam and strict rules apply as described in the document https://www.uio.no/english/studies/examinations/compulsory-activities/mn-ifi-mandatory.html . The page explains the significance of mandatory assignments in a course and in particular group assignments. It also specifies your responsibility to not plagiarize anybody else's work and that you are required to conduct and understand your own experiments and obtain your own results, while you are still allowed and encouraged to exchange advice and experiences also between groups.

Each group must deliver a written lab report using the Devilry online submission system **before** the **hard** deadline indicated in the title. Note that you can submit multiple times and the last submission before the deadline will be graded, so it might be a good idea to plan to submit preliminary versions well before the deadline. The points given for this lab assignment will determine if the lab assignment is accepted or rejected. You will need to pass this lab assignment in order to be admitted to the exam. The next two lab assignments will be weighted as 20% of the total score of the course, i.e. your final grade.

Each task is labelled with how many points it will contribute towards the score.

2 Lab Rules

2.1 Safety

Voltages over 40 Volt can in some cases be harmful, even though it usually requires more than that. The lab equipment is thus not able to provide voltages higher than 36V. Do not use equipment other than that provided in the lab! If a part of the skin is covered with a conductive fluid or is pierced and exposed to such voltages, a current could bypass the "insulator" of the skin and run through the body. If this current passes through the heart it can cause fibrillations or even cardiac arrest. Even higher more extreme currents could also give rise to internal burns. If this happens to anybody or something else happens in the lab, seek medical help immediately: heart fibrillations can last and cause trouble

long after the incident. Also notify the person in charge of the lab.

Some electronic components can explode if they are exposed to high currents. This is important to remember when working with electrolytic capacitors. However, none of the capacitors provided in the lab are electrolytic capacitors. Never bring your own electronic components into the lab!

2.2 Conduct

Good routines are necessary to make the work in the lab effective and safe:

- Food and drinks are prohibited from every lab.
- In general everybody is responsible for keeping the lab tidy.
- Always turn off the power supply before you start adding and/or removing components.
- Use an ESD protection wrist strap when handling ICs and other sensitive components.(ESD: electrostatic discharge)
- Always clean up after using equipment and tools:
  - Turn off all equipment, except for lab computer.
  - Throw away cutoffs and vacuum clean the desk, chair, and floor if necessary.
  - Place all components you have used back to their respective places. (Do this while you work, if you have a component you don't use anymore, put it back.)
- When you leave; the desk should be clean and ready for the next group.
- Read the information posters in the lab describing what to do in case of fire or medical emergency.

3 Task

3.1 Tools

The tools are the same as for lab 1. As an additional device, you will also us the waveform generator. Check the webpage that describes those lab devices and their MATLAB interfaces for an update!

- **Linux command line interface:** To run Cadence you'll have to start a remote session on the Linux sever nano.ifi.uio.no. The whole process is described on the web-page: https://www.uio.no/studier/emner/matnat/ifi/IN3170/v25/materiale/LabAssignmentGuides.html. In Linux you'll be working with a command line interface to start the relevant software (Cadence). The command line interface is called 'terminal' or 'xterm'. On

nano.ifi.uio.no you'll open a 'Terminal' by choosing 'Activities' from the top bar menu and then click on the 'Terminal' icon. On the lab machines there is a 'console' terminal open when you log on that you can use. Else you can also choose 'Applications' in the top bar menu and then 'System Tools' and then 'Terminal'.

When you open a terminal, your 'home directory' is the active directory by default. The active directory is the default directory where a program that is started stores any files it creates and where it is looking for files it needs first. Your 'home directory' is a directory on a file server where you can store your files and that is accessible from any Linux machine on campus. From Windows machines on Campus you access it as the disk 'm:'. It also contains a directory called 'pc' which is the directory containing your typical 'Desktop' and 'Documents' and similar Windows folders. You can, for instance, create a sub-directory in your home directory called 'IN3170' to work in with your labs, and possibly more subdirectories for individual labs to keep things organized. To make a directory use the command 'mkdir <directory_name>' and to change the active directory 'cd <directory_name>' or 'cd ..' to go 'up' to a parent directory.

- **MATLAB** is a mathematics calculation tool and script language. it is also very useful for making nice graphs, e.g. of measurement results, in a lab report.

  We will be using MATLAB in the digital exam (!!!) to express symbolic results where a variable is expressed as a function of other variables and parameters, and as the calculation tool for numeric results. So you will need some basic knowledge of Matlab syntax to be able to make simple functions and scripts. Check out some of the exercises in the compendium for examples!

  Please refer to the online html-document https://www.uio.no/studier/emner/matnat/ifi/IN3170/v25/materiale/LabAssignmentGuides.html for instruction on how to get a copy of matlab installed on your home computer. It IS also installed on nano.ifi.uio.no, as well as on the Windows computers in the course lab OJD5419, and the virtual machines 'Lab Net Workstation' from which you will control the lab instruments. Under Linux, you simply type 'matlab' in a terminal to start it.

  One useful function in MATLAB is 'help'. 'help <command_name>' will display an explanation on how to use '<command_name>'. Another help function that helps you find functions that you do not know the exact name of is 'lookfor'. Type 'help lookfor' to learn more.

- **Cadence** is an industrial SW tool for integrated circuit design. When using it for simulation, its models are much more detailed than the hand calculation models you learn about in the course. These models include a lot of secondary effects and have a lot more parameters and are able to predict with much higher accuracy how a circuit will really behave when

coming back from production. Still you'll see that the hand calculation models are a useful approximation in many cases.

We will be using the Cadence modules "Schematics Editor" and "Analog Design Environment explorer" in this course.

In order to use Cadence (and potentially other SW that runs on a Linux server at IFI/UiO) you will need the means of logging onto such a server and have a user interface to it presented on your home/UiO computer. I have made a HTML document that explains how to do that for Windows, Linux, and Mac PCs here: https://www.uio.no/studier/emner/matnat/ifi/IN3170/v25/materiale/LabAssignmentGuides.html The document also explains how to set up Cadence and how to use its tools.

- **Soldering on a PCB** You will need the skill of soldering components and cables to a printed circuit board (PCB) for this and future labs.

  There are pipes with air vents at each work place that suck in air: turn them on (green button on the desk) and suck in the fumes that occur during soldering. Small doses of those fumes are unproblematic so there is no real reason for concern, but substantial continuous exposure over a long time (e.g. if someone continuously works with PCB assembly as their job) to such fumes can be unhealthy.

  When soldering any kind of conductor to a PCB pad you want to establish an electric contact between that conductor and the pad on the PCB surface. To make a proper contact you need to heat BOTH the pad AND the conductor, so try to touch BOTH with the soldering iron. The solder tin only need to touch one of those two and will melt automatically if that surface becomes hot enough. So I usually hold the soldering iron to the conductor and try to place the tip on the pad on the PCB, while I hold the solder to the conductor from the opposite side. Then the solder will liquefy automatically as the conductor and pad become hot enough and the connection between those two is thus guaranteed to be good. If the pad becomes hot enough as well you will notice the liquid solder 'flowing out' onto the pad. In contrast, if you do not heat the pad enough the solder may look like it touches the pad as a bobble 'tucking in' at the contact point instead of flowing out. It may still touch and may establish a finicky contact, but it is not solidly 'glued' to the pad, may be unreliable and can get loose.

  You'll find some good video on this on Youtube, for example: https://www.youtube.com/watch?v=vAx89WhpZ3k

- **Hex-inverter IC, 74HCT14:** find a datasheet here: https://www.uio.no/studier/emner/matnat/ifi/IN3170/v25/materiale/cd74hc14.pdf. There will be generic PCBs in the lab for you to solder these on and to connect the inverters according to your circuit design. Remember to always connect the power supply rails of each IC!

- **Lab instruments** will be used to measure and characterise some experimental circuits in the lab. You can control them locally manually for single measurements and to set up the right instrument parameters or remotely via MATLAB functions, also to execute series of automated measurements and to write results into MATLAB readable files for making illustrations. Check out this HTML page for a list and descriptions of the MATLAB functions: https://www.uio.no/studier/emner/matnat/ifi/IN3170/v25/materiale/LabAssignmentGuides.html

  The four instruments are:

  Oscilloscope: This instrument is for recording voltage traces over time. Note that scope probes also have some input impedance (capacitance and resistance) that might influence the node that you measure! Use the identifier "mdo" in LabInst_GetHandle.

  DC power supply: This instrument provides multiple programmable stable voltage outputs on corresponding output channels. Use the identifier "gpp" in LabInst_GetHandle.

  Multi-meter: This instrument measures a number of electrical units, typically a voltage or a current. Note that you may connect different input ports to measure either voltage or current! Use the identifier "gdm" in LabInst_GetHandle.

  Function generator: This instrument produces voltage traces over time. Typically from a selection of standard waveforms, such as sine waves or square waves. Use the identifier "gfm" in LabInst_GetHandle.

  There are extensive user manuals to be found here (if you want to investigate advanced features): https://www.uio.no/studier/emner/matnat/ifi/IN3170/v25/materiale/Lab%20Instrument%20Documentation/

3.2 Tasks

Task 1 (8p) :

In short:

simulate a cascade of inverters to minimize the total delay when driving a substantial capacitive load. A typical situation when driving an off-chip signal from a CMOS chip. Show the gate delay before and after optimization in a transient (!) simulation. Note that the first element in the cascade needs to be a minimum size inverter, i.e. we shall not exploit the infinite output conductance of the 'vpulse' simulation signal source to get an advantage.

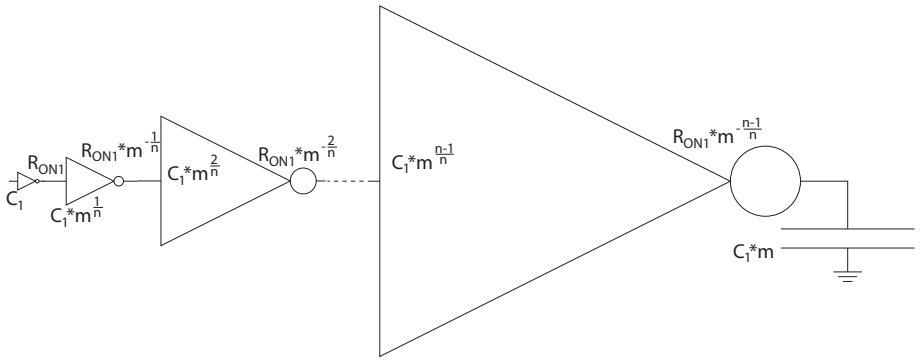


Figure 1: Reprint of the figure 7.8 from the compendium and subject of this lab exercise.

More exhaustive:
It is a common issue when using integrated circuits that the ultimately need to connect to the macroscopic world and drive external signals on a PCB. Already the connection pads on the ASIC itself are big metal plates where micro-wires shall be attached an they alone do usually have a capacitance to Gnd of around 10pF, i.e. much more than a typical node between on-chip components. All of this is explained in section 7.3 in the compendium, including a considerable improvement when using a cascade inverters (i.e. a number of consecutive inverters) with steadily increasing $\frac{W}{L}$-ratios. Check out the theory for an optimal solution in section 7.3!

Let us assume that a digital signal needs to drive an off chip load, including the pad, micro-wires, the IC package connectors, wire traces on the PCB and finally input capacitance of a receiving electronic circuits, e.g. a FPGA, of 50pF. Let us furthermore assume the initial source of the signal is an inverter consisting of a nFET with $W = 200$nm and $L = 60$nm and the pFET being 2.5 times wider, with the same length.

First, deduce the input capacitance of that inverter with an appropriate experiment/simulation. Report that input capacitance and document the deduction!

Then report the gate propagation delay, if that inverter alone were directly connected to a 50pF capacitance. Generic circuit elements, like resistors and capacitors, are found in library 'analogLib' together with ideal signal sources. In this case the 'vpulse' will be appropriate to generate an square wave input signal. Make the transition fast, i.e. 1ps, and make the cycle long enough for the output of the inverter to settle close to the supply voltages before the next transition. Report and document both propagation delays t_{pHL} and t_{pLH}, as well as their average t_p.

Then apply the optimisation as described in section 7.3 and shown in figure 1. Use the appropriate number of gates and ratio between the widths of

consecutive gates to achieve a theoretical maximal reduction of the total delay through the cascade. Note: It does not matter whether the final output is inverted or not inverted compared to the 'vpulse' input.

Task 2 (8p) :

In short:

Using the Schmitt trigger inverters on IC 74HCT14, improve on the gate delay when using but a single inverter driving a substantial load of (1μF). NOTE: the first element needs to be a single inverter! That is to prevent exploiting that the waveform generator has a low output impedance, i.e. is pretty strong when it comes to driving capacitive loads.

More exhaustive:

Connect the output a single inverter from IC 74HCT14 to a 1uF capacitor to Gnd and the input to a channel from the mfg waveform generator. Use 5V Vdd in general, like in the previous lab. Set the waveform generator to produce a square wave. Observe the output on the oscilloscope. Make the frequency slow enough that the output signal from the inverter manages to settle before the next input transition. You can configure the waveform generator manually for this. Report and document the HL, LH and average propagation delay of the input signal to the output. You might want to look at the HL and LH transition separately by adjusting the trigger condition on the oscilloscope. Thus you can devote the entire recording length of the oscilloscope on the settling time after either the HL or LH input transition. This way, you can also simply use a very low frequency for the waveform generator.

Now, we do not have knowledge of, nor can we manipulate the $\frac{W}{L}$-ratio of these inverters. So how can we get a circuit that behaves the same like, say, one of these inverters but with double the $\frac{W}{L}$-ratio?

If you figure that out, try to make a circuit that behaves like a cascade of transistors with consecutively increasing $\frac{W}{L}$-ratios (where the first element still needs to be a single inverter!) and try to improve the total delay from the square wave input. We will not be able to choose the optimal ratio of increasing $\frac{W}{L}$-ratio per stage, nor the optimal number of stages, but will need to be pragmatic. Actually just one or two more stages, may do the job. All that I would like you strive for is a noticeable improvement of the total propagation delay. In case that does proof to be difficult, I want you to document your attempts and results anyway. And of course also if you succeed: report and document your results thoroughly.

Note: in case you'd like to observe some intermediate nodes in the cascade, please be aware that a connected scope probe introduce 15pF to that node! So your observation will influence the result. Good to remember in other contexts too.