Introduction

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WHO

My name is

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I finished my Masters in 2002, and did a Ph.D on analog-to-digital converters finished in 2008.

Since that time, I've had a three axis in my work/hobby life.

I work at Nordic Semiconductor where I've been since 2008. The first 7 years I did analog design (ADCs, DC/DCs, GPIO). The next 7 years I was the Wireless Group Manager. The Wireless group made most of the analog and RF designs for Nordic's short-range products. Now I'm the IC Scientist, and focus on technical issues with our integrated circuits that occur before we go into volume production.

I work at NTNU where I did a part time postdoc from 2014 - 2017. From 2020 I've been working on and teaching Advanced Integrated Circuits

I have a hobby trying to figure out how to make a new analog circuit design paradigm. The one we have today with schematic/simulation/layout/verification/simulation is too slow

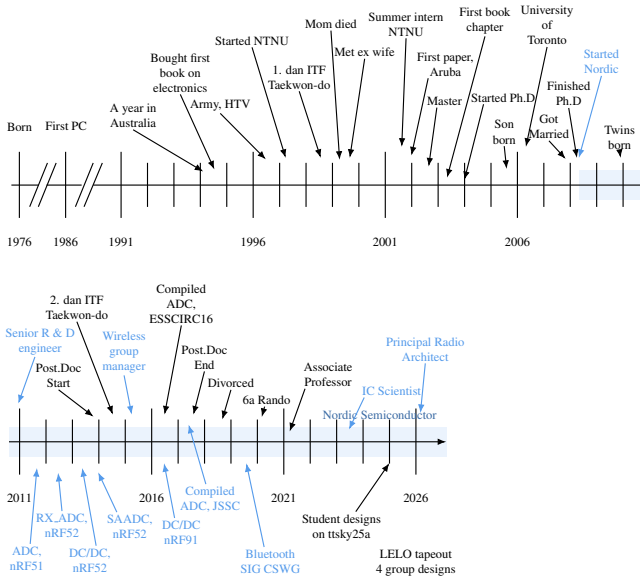

Figure 1: My life

HOW I SEE OUR ROLES

In Figure 2 you can see how I think about the research universe. There are things we know to be possible, things that actually are impossible (travel back in time, breaking thermodynamics, travel with a speed beyond light).

Between the impossible, and the possible, lies the unknown. I consider our roles as follows:

Professors: Guide students on what is impossible, possible, and hints on what might be possible

Ph.D students: Venture into the unknown and make something (more) possible

Master students: Learn all that is currently possible

Bachelor students: Learn how to make complicated into easy

Industry: Take what is possible, and/or complicated, and make it easy

Everyone in the figure pushes a border: teaching moves knowledge from complicated towards easy, research moves the border of the unknown, and industry earns its living on the innermost rings. This course lives one ring out from the centre - what is known and complicated, made learnable.

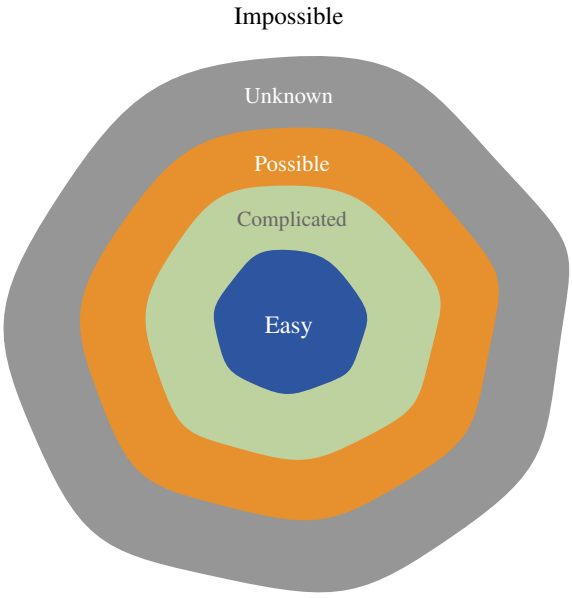

Figure 2: The research universe: Easy at the centre, then Complicated, Possible and Unknown, with the Impossible beyond the last border

I WANT YOU TO LEARN THE SKILLS NECESSARY TO MAKE YOUR OWN ICS

In 2020 the global integrated circuit market was 437.7 billion dollars! The market is expected to grow to 1136 billion in 2028. Integrated circuits enable all technologies.

I will be dead in approximately 50 years, and will retire in approximately 20 years. Everything I know will be gone (except for the small pieces I've left behind in videos or written word)

Someone must take over, and to do that, they need to know most of what I know, and hopefully a bit more.

That's where some of you come in. Some of you will find integrated circuits interesting to make, and in addition, you have the stamina, patience, and brain necessary to learn some of the hardest topics in the world.

THERE WILL ALWAYS BE ANALOG CIRCUITS, BECAUSE THE REAL WORLD IS ANALOG

In this course, we'll focus on analog ICs, because the real world is analog, and all ICs must have some analog components, otherwise they won't work.

The steps to make integrated circuits are split in two. We have an analog flow, and a digital flow, as shown in Figure 3.

It's rare to find a single human that does both flows well. Usually people choose, and I think it's based on what they like and their personality.

If you like the world to be ordered, with definite answers, then it's likely that you'll find the digital flow interesting.

If you're comfortable with not knowing, and have an insatiable desire to understand how the world *really* works at a fundamental level, then it's likely that you'll find the analog flow interesting.

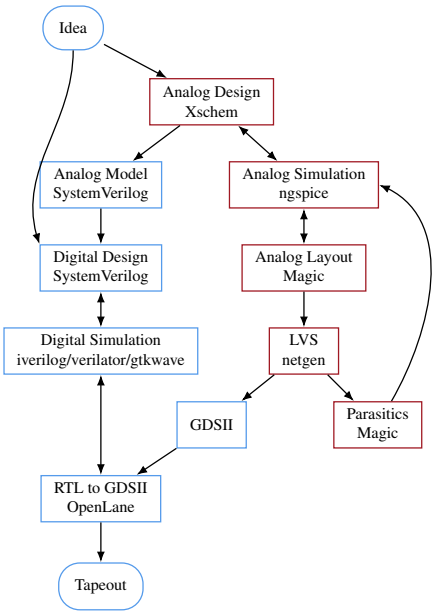

Figure 3: Analog and Digital design process

WILL YOU TAPE-OUT AN IC?

Something that would make me really happy is if someone is able to tapeout an IC in this course.

It's now possible without signing an NDA or buying expensive software licenses.

In 2020 Google and Skywater joined forces to release a 130 nm process design kit to the public. In addition, they have fueled a renaissance of open source software tools.

tinytapeout runs cheap shuttles which makes it possible for a private citizen to tape-out their own integrated circuit.

What the team needs to know to design ICs

There are a multitude of tools and skills needed to design professional ICs. It's not likely that you'll find all the skills in one human, and even if you could, one human does not have sufficient bandwidth to design ICs with all its aspects in a reasonable timeline

That is, unless we can find a way to make ICs easier.

The skills needed are

- *Project flow support*: **Confluence**, JIRA, risk management (DFMEA), failure analysis (8D)
- *Language*: **English**, **Writing English (Latex, Word, Email)**
- *Psychology*: Personalities, convincing people, presentations (Powerpoint, Deckset), **stress management (what makes your brain turn off?)**
- *DevOps*: **Linux**, build systems (CMake, make, ninja), continuous integration (bamboo, jenkins), **version control (git)**, containers (docker), container orchestration (swarm, kubernetes)
- *Programming*: Python, C, C++, Matlab *Since 1999 I've programmed in Python, Go, Visual BASIC, PHP, Ruby, Perl, C#, SKILL, Ocean, Verilog-A, C++, BASH, AWK, VHDL, SPICE, MATLAB, ASP, Java, C, SystemC, Verilog, Assembler, and probably a few I've forgotten.*
- *Firmware*: signal processing, algorithms, software architecture, security
- *Infrastructure*: **Power management**, **reset**, **bias**, **clocks**
- *Domains*: CPUs, peripherals, memories, bus systems
- *Sub-systems*: **Radio's**, **analog-to-digital converters**, **comparators**
- *Blocks*: **Analog Radio**, Digital radio baseband
- *Modules*: Transmitter, **receiver**, de-modulator, timing recovery, state machines
- *Designs*: **Opamps**, **amplifiers**, **current-mirrors**, adders, random access memory blocks, standard cells
- *Tools*: **schematic**, **layout**, **parasitic extraction**, synthesis, place-and-route, **simulation**, (System)Verilog, **netlist**
- *Physics*: transistor, pn junctions, quantum mechanics

Zen of IC design (stolen from Zen of Python)

When you learn something new, it's good to listen to someone that has done whatever it is before.

Here are some guiding principles that you'll likely forget.

- Beautiful is better than ugly.
- Explicit is better than implicit.
- Simple is better than complex.
- Complex is better than complicated.

- Readability counts (especially schematics).
- Special cases aren't special enough to break the rules.
- Although practicality beats purity.
- In the face of ambiguity, refuse the temptation to guess.
- There should be one **and preferably only one** obvious way to do it.
- Now is better than never.
- Although never is often better than *right* now.
- If the implementation is hard to explain, it's a bad idea.
- If the implementation is easy to explain, it may be a good idea.

IC design mantra

To copy an old mantra I have on learning programming (run it in a bash/zsh/cshrc terminal, or in your brain)

```
echo "Find a problem that you really want to solve,"\
     "and learn programming to solve it."\
     "There is no point in saying 'I want to learn programming',"\
     "then sit down with a book to read about programming,"\
     "and expect that you will learn programming that way."\
     "It will not happen. The only way to learn programming"\
     "is to do it, a lot." \
     |perl -pe 's/programming/analog design/ig'
```

Analog Design Process

- Define the problem, what are you trying to solve?
- Find a circuit that can solve the problem (papers, books)
- Find right transistor sizes. What transistors should be weak inversion, strong inversion, or don't care?
- Write a verification plan (ask chat). Plan to simulate everything that could go wrong.
- Check operating region of transistors (.op)
- Check key parameters (.dc, .ac, .tran)
- Check function. Exercise all inputs. Check all control signals
- Check key parameters in all corners. Check mismatch (Monte-Carlo simulation)
- Do layout, and check it's error free. Run design rule checks (DRC). Check layout versus schematic (LVS)
- Extract parasitics from layout. Resistance, capacitance, and inductance if necessary.
- On extracted parasitic netlist, check key parameters in all corners and mismatch (if possible).
- If everything works, then you're done.

On failure, go back as far as necessary

My Goal

Don't expect that I'll magically take information and put it inside your head, and you'll suddenly understand everything about making ICs.

You are the one that must teach yourself everything.

I consider my role as a guide, similar to a mountain guide. I can't carry you up the mountain, you need to walk up the mountain , but I know the safe path to take and increase the likelihood that you'll come back alive.

My guide role:

- Enable you to read the books on integrated circuits
- Enable you to read papers (latest research)
- Correct misunderstandings on the topic
- Answer any questions you have on the chapters

I'm not a mind reader, I can't see inside your head. That means, you must ask questions. Only by your questions can I start to understand what pieces of information is missing from your head, or maybe somehow correct your understanding.

At the same time, and similar to a mountain guide, you should not assume I'm always right. I'm human, and I will make mistakes. And maybe you can correct my understanding of something. All I care about is to *really* understand how the world works, so if you think my understanding is wrong, then I'll happily discuss.

Syllabus

The syllabus will be from Analog Integrated Circuit Design by Carusone, Johns and Martin [1], which everyone calls CJM, and Circuits for all seasons.

These lecture notes are a supplement to the book. I try to give some background, and how to think about electronics. It's not my goal to repeat information that you can find in the book.

Buy a hard-copy of the book if you don't have that. Don't expect to understand the book by reading the PDF.

Software

We'll use professional-grade open source software for everything: xschem for schematics, ngspice for simulation, the SKY130A PDK, Magic VLSI and netgen for layout and verification, and surfer, iverilog and verilator on the digital side. No licence server stands between you and your design.

Open source software (xschem, ngspice, sky130A PDK, Magic VLSI, netgen, surfer, iverilog, verilator)

I've made a rather detailed (at least I think so myself) tutorial on how to make a current mirror with the open source tools. You have to do that tutorial. It's Milestone 0 of the project and does count towards your final grade.

Skywater 130 nm Tutorial

I've also made some more complex examples, that can be found at the link below. There are digital logic cells, standard transistors, and few other blocks.

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Summary

The one-page version of this chapter:

- The real world is analog, so every IC carries analog circuits at its edges - there is no purely digital chip
- Making an IC splits into an analog and a digital flow, and it is rare to find one human who does both well
- Digital designers reuse each other's work; analog designers redraw - closing that gap is a theme of this course

- What you need from here: the refresher chapters, a working toolchain, and the habit of simulating everything

[1] T. C. Carusone, D. Johns, and K. Martin, *Analog integrated circuit design*. Wiley, 2011 [Online]. Available: https://books.google.no/books?id=1OIJZzLvVhcC

Carsten Wulff received the M.Sc. and Ph.D. degrees in electrical engineering from the Department of Electronics and Telecommunication, Norwegian University of Science and Technology (NTNU), in 2002 and 2008, respectively. During his Ph.D. work at NTNU, he worked on open-loop sigma-delta modulators and analog-to-digital converters in nanoscale CMOS technologies. In 2006-2007, he was a Visiting Researcher with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada. Since 2008 he's been with Nordic Semiconductor in various roles, from analog designer, to Wireless Group Manager, to currently Principle IC Scientist. From 2014-2017 he did a part time Post.Doc focusing on compiled, ultra low power, SAR ADCs in nanoscale technologies. He's also an Adjunct Associate Professor at NTNU. His present research interests includes analog and mixed-signal CMOS design, design of high-efficiency analog-to-digital converters and low-power wireless transceivers. He is the developer of Custom IC Compiler, a general purpose integrated circuit compiler, and makes the occational video on analog integrated circuits at https://www.youtube.com/@analogicus. For full CV see https://analogicus.com/markdown-cv/.