Mixed Signal Simulation in NGSPICE

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Digital simulation

- The order of execution of events at the same time-step does not matter
- The system is causal. Changes in the future do not affect signals in the past or the now

There are both commercial and open source tools for digital simulation. If you've never used a digital simulator, then I'd recommend you start with iverilog. I've made some examples at dicex.

Commercial

- Cadence Excelium
- Siemens Questa
- Synopsys VCS

Open Source

- iverilog/vpp
- Verilator
- SystemDotNet

Below is an example of a counter in SystemVerilog. The code can be found at counter_sv.

In the always_ff sections we code what will become our registers; combinatorial logic would go in an always_comb section.

```
module dig(
           input wire         clk,
           input wire         reset,
           output logic [4:0] b
           );

   logic                      rst = 0;

   always_ff @(posedge clk) begin
      if(reset)
        rst <= 1;
      else
        rst <= 0;
   end

   always_ff @(posedge clk) begin
      if(rst)
        b <= 0;
      else
        b <= b + 1;
   end // dig

endmodule
```

Transient analog simulation

Analog simulation is different. There is no quantized time step. How fast "things" happen in the circuit is entirely determined by the time constants, change in voltage, and change in current in the system.

It is possible to have a fixed time-step in analog simulation, for example, we say that nothing is faster than 1 fs, so we pick that as our time step. If we wanted to simulate 1 s, however, that's at least 1e15 events, and with 1 event per microsecond on a computer it's still a simulation time of 31 years. Not a viable solution for all analog circuits.

Analog circuits are also non-linear, properties of resistors, capacitors, inductors, diodes may depend on the voltage or current across, or in, the device. Solving for all the non-linear differential equations is tricky.

An analog simulation engine must parse spice netlist, and setup partial/ordinary differential equations for node matrix

The nodal matrix could look like the matrix below, i are the currents, v the voltages, and G the conductances between nodes.

$$\begin{pmatrix} G_{11} & G_{12} & \cdots & G_{1N} \\ G_{21} & G_{22} & \cdots & G_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ G_{N1} & G_{N2} & \cdots & G_{NN} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{pmatrix} = \begin{pmatrix} i_1 \\ i_2 \\ \vdots \\ i_N \end{pmatrix}$$

The simulator, and devices model the non-linear current/voltage behavior between all nodes

as such, the G's may be non-linear functions, and include the v's and i's.

Transient analysis use numerical methods to compute time evolution

The time step is adjusted automatically, often by proprietary algorithms, to trade accuracy and simulation speed.

The numerical methods can be forward/backward Euler, or the others listed below.

- Euler
- Runge-Kutta
- Crank-Nicolson
- Gear [1]

If you wish to learn more, I would recommend starting with the original paper on analog transient analysis.

SPICE (Simulation Program with Integrated Circuit Emphasis) published in 1973 by Nagel and Pederson

The original paper has spawned a multitude of commercial, free and open source simulators, some are listed below.

If you have money, then buy Cadence Spectre. If you have no money, then start with ngspice.

Commercial - Cadence Spectre - Siemens Eldo - Synopsys HSPICE

Free - Aimspice - Analog Devices LTspice - xyce

Open Source - ngspice

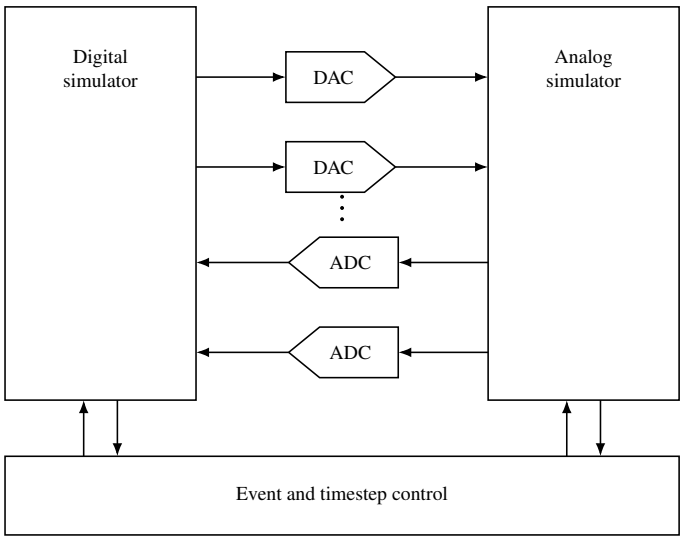

Figure 1: Mixed signal simulator, where a digital and an analog simulator exchange values through DAC and ADC connect modules under a shared event and timestep control

DEMO

Tutorial at http://analogicus.com/jnw_sv_sky130a/

Repository at https://github.com/wulffern/jnw_sv_sky130a

Assumes knowledge of Tutorial

THE CIRCUIT

In `design/JNW_SV_SKY130A/JNWSW_CM.sch` you'll find a current mirror, and a 5-bit current DAC.

What we want from the digital is to control the binary value of the current DAC.

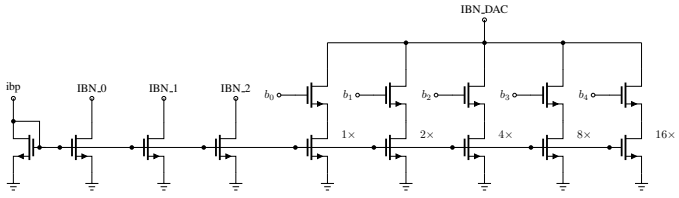

Figure 2: The JNWSW_CM schematic - a current mirror from ibp plus a 5-bit binary weighted current DAC controlled by b[4:0]

THE DIGITAL CODE

The digital code is shown below. The `clk` controls the stepping, while the `reset` sets the output `b=0`. When `reset` is off, then the `b` increments.

```
module dig(
           input wire          clk,
           input wire          reset,
           output logic [4:0] b
           );

   logic                       rst = 0;

   always_ff @(posedge clk) begin
      if(reset)
        rst <= 1;
      else
        rst <= 0;
   end

   always_ff @(posedge clk) begin
      if(rst)
        b <= 0;
      else
        b <= b + 1;
   end // dig
endmodule
```

COMPILE RTL

The first thing we need to do is to translate the verilog into a compiled object that can be used in ngspice.

```
cd sim/JNWSW_CM
ngspice vlnggen ../../rtl/dig.v
```

IMPORT OBJECT INTO SPICE FILE

I'm lazy. So I don't want to do the same thing multiple times. As such, I've written a small script to help me instanciate the verilog

```
perl ../../tech/script/gensvinst ../../rtl/dig.v dig
```

The script generates an `svinst.spi` file. The first section imports the digital compiled library

```
adut [clk
+ reset
+ ]
+ [b.4
+ b.3
+ b.2
+ b.1
+ b.0
+ ] null dut
.model dut d_cosim
+ simulation="../dig.so" delay=10p
```

Turns out that ngspice needs the digital inputs and outputs to be connected to something to calculate them (I think), so connect some resistors

```
* Inputs
Rsvi0 clk 0 1G
Rsvi1 reset 0 1G

* Outputs
Rsvi2 b.4 0 1G
Rsvi3 b.3 0 1G
Rsvi4 b.2 0 1G
Rsvi5 b.1 0 1G
Rsvi6 b.0 0 1G
```

For the busses I find it easier to read the value as a real, so translate the buses from digital `b[4:0]` to a real value `dec_b`

```
E_STATE_b dec_b 0 value={( 0
+ + 16*v(b.4)/AVDD
```

```
+ + 8*v(b.3)/AVDD
+ + 4*v(b.2)/AVDD
+ + 2*v(b.1)/AVDD
+ + 1*v(b.0)/AVDD
+)/1000}
.save v(dec_b)
```

IMPORT IN TESTBENCH

An example testbench can be seen below (`sim/JNWSW_CM/tran.spi`)

```
...

.include ../xdut.spi
.include ../svinst.spi

* Translate names
VB0 b.0 b<0> dc 0
VB1 b.1 b<1> dc 0
VB2 b.2 b<2> dc 0
VB3 b.3 b<3> dc 0
VB4 b.4 b<4> dc 0

...
```

OVERRIDE DEFAULT DIGITAL OUTPUT VOLTAGE

We can override the output dac from digital to analog to ensure that the digital signals have the right levels

```
*- Override the default digital output bridge.
pre_set auto_bridge_d_out =
     + ( ".model auto_dac dac_bridge(out_low = 0.0 out_high = 1.8)"
     +   "auto_bridge%d [ %s ] [ %s ] auto_dac" )
```

RUNNING

You can run the whole thing with

```
cd sim/JNWSW_CM/
make typical
```

SUMMARY

The one-page version of this chapter:

- SystemVerilog describes hardware as events: always_ff becomes registers, combinational logic goes in always_comb
- Event-driven simulation only computes when something changes, which is why digital simulation is fast
- Mixed-signal co-simulation bridges the two worlds: the svinst flow connects SPICE and the digital testbench

WOULD YOU LIKE TO KNOW MORE?

The IEEE 1800 standard is the authority; Sutherland's tutorials are the readable way in

The Verilator and iverilog manuals, for the two simulators used here

[1] C. Gear, "Simultaneous numerical solution of differential-algebraic equations," *IEEE Transactions on Circuit Theory*, vol. 18, no. 1, pp. 89–95, 1971, doi: 10.1109/TCT.1971.1083221.

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/.