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CSCE 3304-1

27th of April 2023

CMOS Cells Propagation Delay Experiment

1 Introduction

Spice is used to design the six cells, INVx2, INVx4, NAND2x2, NAND3x2, NOR2x2, and NOR3x2, and simulate them. They were designed using a combination of pmosfets and nmosfets driving a load capacitor. The number of simulations conducted depended on the variations we had for the input transition time and the load capacitance.

The aim of this experiment is to measure the propagation delays, both rise and fall. The delay is measured by finding the difference between 50% of the input rising edge and 50% of the output edge, for instance. NgSpice has built in functions that can do the job. These commands involved measuring the time when the input voltage reached 0.9V and the time when the output voltage reached 0.9V, too. The difference in points of time was calculated to be the delay. Whether it is rising or falling, this merely depends on the edge from which we are measuring from.

2 Materials & Methods

The tools used to conduct this experiment were ngspice, PySpice, and os packages. The simulations were designed using 6 copies of a automating script, one for each cell. The script would generate all required combinations of the different spice netlist files that should be executed using ngspice. The only two language adopted were python and spice. The setup was made on different operating systems; therefore, the set-up environments and methodologies were different.

3 Simulation Infrastructure & Data Collection

3.1 Script Infrastructure

A python script was written for each cell. The main functionalities of the script were to construct a circuit using the PySpice library to give us the opportunity to change parameter values in the elements of the circuit, thus requiring six scripts. After constructing the circuit, it is dumped into a spice file appended with a control section that includes measuring the propagation delays and dumping them into a file for further analysis. The script also takes the dumped spice files and uses the 'os' package to run the simulation. The rest of the python script is merely aiming for cleaning the file and maintaining its format.

The NgSpice netlist file consists of the circuit, that has a combination of mosfets and voltage sources, pulse sources and batteries. A load capacitor is also included. A transient analysis has been conducted on the simulation with a step of 10ps for 40 ns. The pulse voltage source pulse width was set to 12ns and the period was set to 24ns for all sources across the whole simulation. The control section in the netlist is used for running the netlist and measuring the delays as explained earlier.

3.2 Data Collection Methodology

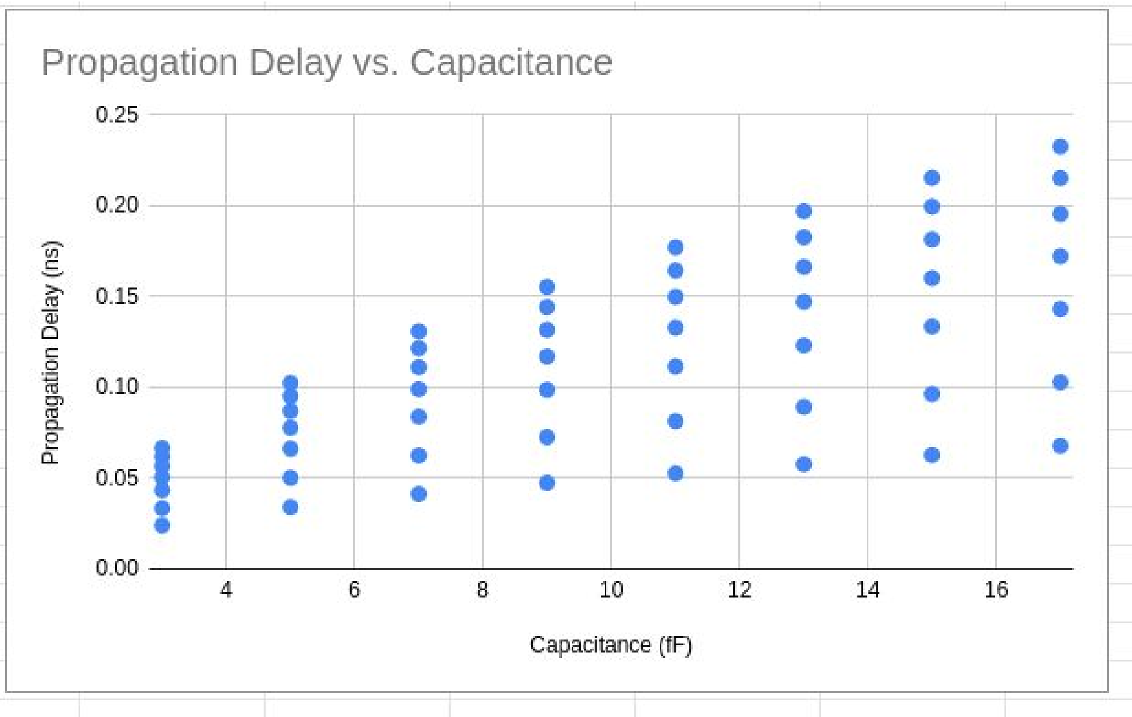
The delay values were harvested using NgSpice itself. The values were dumped in the spice netlist commands section into a text file. The whole of process of data collection involved a lot of cleaning and reformatting. Therefore, the number of text files that were generated by NgSpice were read again in python and were cleaned and extracted to a collective csv file for the overall analysis.

4 Data Collected

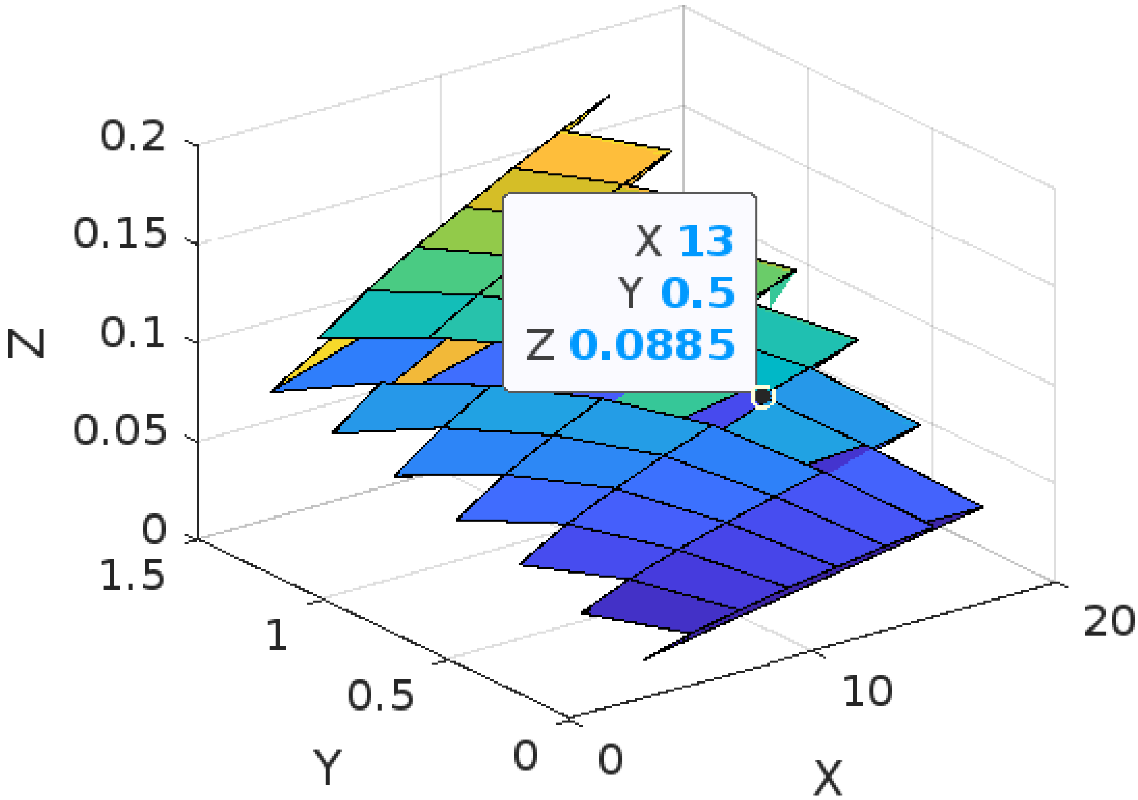
4.1 INVx2

Capacitance	Input Transition T	Rise Delay	Fall Delay	max in nanometer
3	0	2.40E-11	2.18E-11	0.02398607
5	0	3.41E-11	3.13E-11	0.03406152
7	0	4.13E-11	3.84E-11	0.04134192
9	0	4.74E-11	4.46E-11	0.04744889
11	0	5.27E-11	4.98E-11	0.05270502
13	0	5.77E-11	5.46E-11	0.05773521
15	0	6.28E-11	5.94E-11	0.06278005
17	0	6.78E-11	6.41E-11	0.06783114
3	0.25	3.35E-11	2.86E-11	0.03347996
5	0.25	5.02E-11	4.38E-11	0.05019565
7	0.25	6.25E-11	5.55E-11	0.0625079
9	0.25	7.27E-11	6.52E-11	0.07265427
11	0.25	8.14E-11	7.37E-11	0.08143041
13	0.25	8.93E-11	8.13E-11	0.08927217
15	0.25	9.64E-11	8.84E-11	0.0963522
17	0.25	1.03E-10	9.48E-11	0.1028654
3	0.5	4.34E-11	3.31E-11	0.0433817
5	0.5	6.63E-11	5.46E-11	0.06626572
7	0.5	8.39E-11	7.10E-11	0.08392852
9	0.5	9.86E-11	8.48E-11	0.09863468
11	0.5	1.12E-10	9.69E-11	0.1115259
13	0.5	1.23E-10	1.08E-10	0.1230428
15	0.5	1.33E-10	1.18E-10	0.1334909
17	0.5	1.43E-10	1.27E-10	0.1431379
3	0.75	5.06E-11	3.48E-11	0.05055198
5	0.75	7.78E-11	6.07E-11	0.07779954
7	0.75	9.90E-11	8.06E-11	0.09899141
9	0.75	1.17E-10	9.74E-11	0.1169864
11	0.75	1.33E-10	1.12E-10	0.1327958
13	0.75	1.47E-10	1.26E-10	0.1470943
15	0.75	1.60E-10	1.38E-10	0.1601169
17	0.75	1.72E-10	1.49E-10	0.1721655
3	1	5.65E-11	3.51E-11	0.05653952
5	1	8.71E-11	6.46E-11	0.08710367
7	1	1.11E-10	8.73E-11	0.1111442
9	1	1.32E-10	1.07E-10	0.1316674
11	1	1.50E-10	1.24E-10	0.1498377
13	1	1.66E-10	1.39E-10	0.1663066
15	1	1.81E-10	1.53E-10	0.1814506
17	1	1.95E-10	1.67E-10	0.1954816
3	1.25	6.18E-11	3.46E-11	0.06180175
5	1.25	9.52E-11	6.72E-11	0.09519728

7	1.25	1.22E-10	9.23E-11	0.1215675
9	1.25	1.44E-10	1.14E-10	0.1441883
11	1.25	1.64E-10	1.33E-10	0.1643239
13	1.25	1.83E-10	1.50E-10	0.1826295
15	1.25	2.00E-10	1.66E-10	0.1995216
17	1.25	2.15E-10	1.80E-10	0.2152305
3	1.5	6.66E-11	3.37E-11	0.06657491
5	1.5	1.02E-10	6.88E-11	0.1024344
7	1.5	1.31E-10	9.61E-11	0.1308447
9	1.5	1.55E-10	1.19E-10	0.1552874
11	1.5	1.77E-10	1.40E-10	0.1771
13	1.5	1.97E-10	1.59E-10	0.1969949
15	1.5	2.15E-10	1.76E-10	0.2153912
17	1.5	2.33E-10	1.92E-10	0.2325741



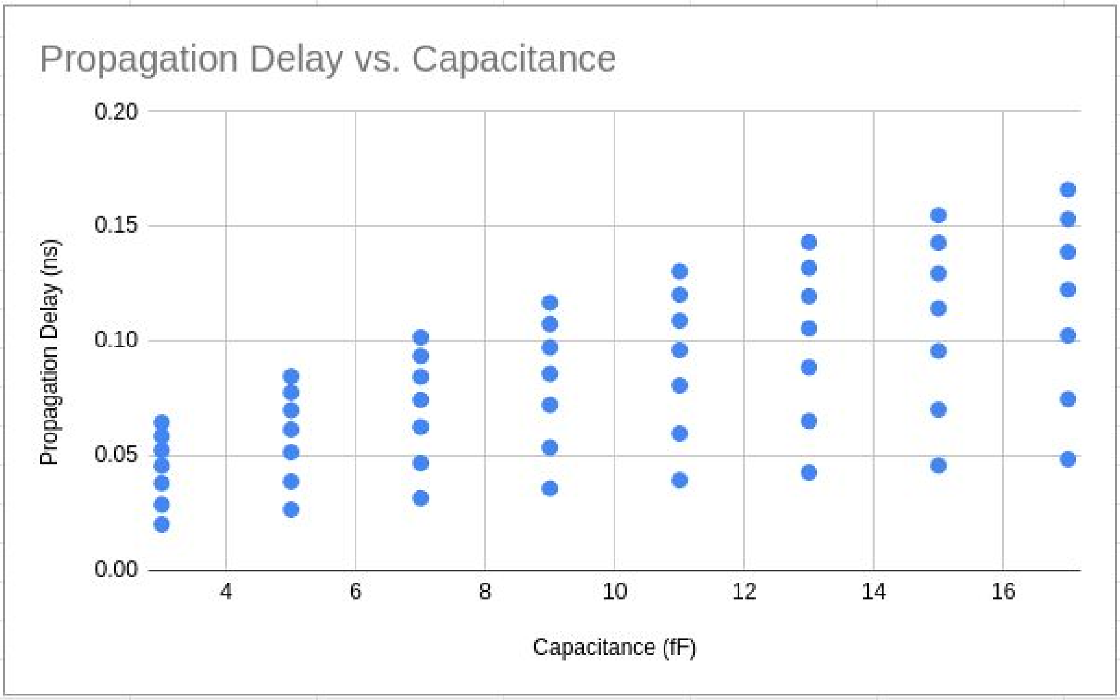
Propagation Delay vs. Capacitance
0.25
0.20
0.15
0.10
0.05
0.00
Propagation Delay (ns)
4
6
8
10
12
14
16
Capacitance (fF)

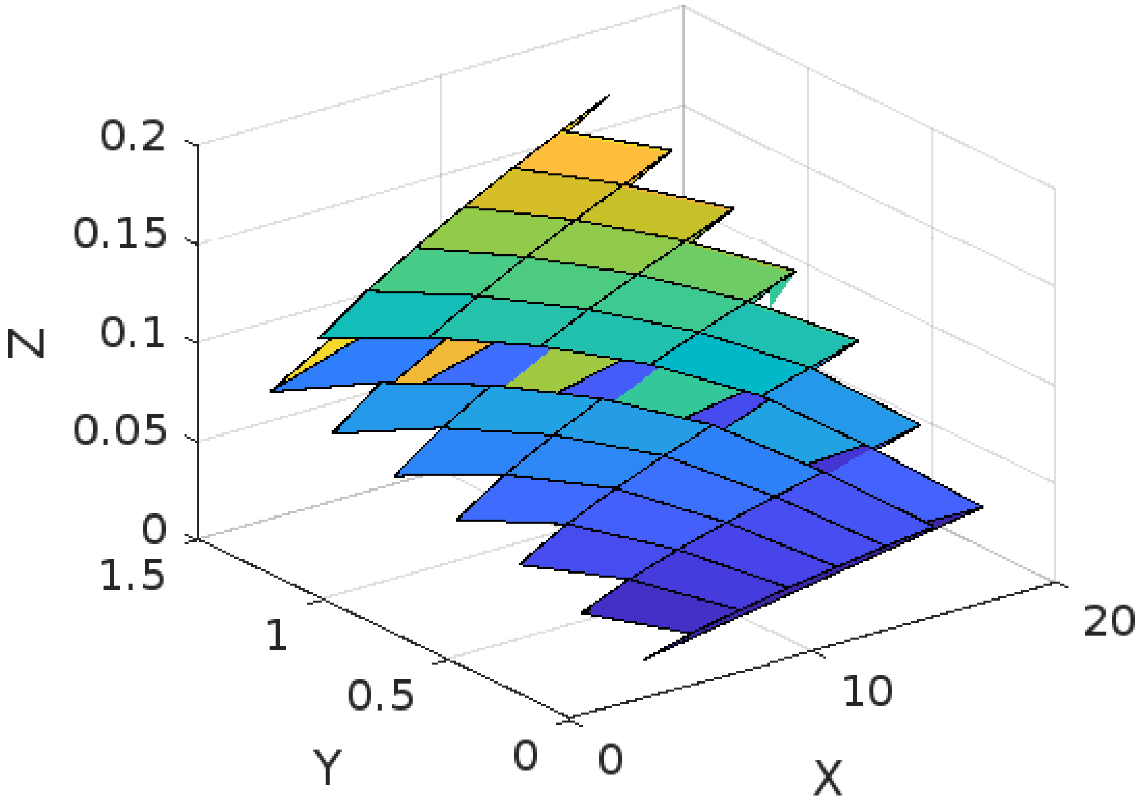


4.2 INVx4

Capacitance	Input Transition T	Rise Delay	Fall Delay	max in nanometer
3	0	2.02E-11	1.69E-11	0.02016684
5	0	2.66E-11	2.29E-11	0.02663289
7	0	3.16E-11	2.72E-11	0.03158372
9	0	3.58E-11	3.12E-11	0.0357937
11	0	3.93E-11	3.48E-11	0.03934847
13	0	4.28E-11	3.78E-11	0.04278043
15	0	4.57E-11	4.08E-11	0.0457276
17	0	4.85E-11	4.37E-11	0.04851362
3	0.25	2.87E-11	2.01E-11	0.02873158
5	0.25	3.88E-11	2.94E-11	0.03880264
7	0.25	4.68E-11	3.68E-11	0.04684639
9	0.25	5.36E-11	4.31E-11	0.05364139
11	0.25	5.98E-11	4.88E-11	0.0597516
13	0.25	6.52E-11	5.39E-11	0.06518233
15	0.25	7.02E-11	5.87E-11	0.07019997
17	0.25	7.48E-11	6.30E-11	0.07480959
3	0.5	3.81E-11	2.02E-11	0.03806951
5	0.5	5.16E-11	3.31E-11	0.05156599
7	0.5	6.26E-11	4.34E-11	0.06261836
9	0.5	7.22E-11	5.23E-11	0.07218398
11	0.5	8.07E-11	6.02E-11	0.08073233
13	0.5	8.85E-11	6.74E-11	0.0885327
15	0.5	9.58E-11	7.42E-11	0.09576532
17	0.5	1.03E-10	8.05E-11	0.1025385
3	0.75	4.57E-11	1.81E-11	0.04567383
5	0.75	6.14E-11	3.34E-11	0.06140896
7	0.75	7.44E-11	4.58E-11	0.07442391
9	0.75	8.58E-11	5.66E-11	0.08583686
11	0.75	9.61E-11	6.63E-11	0.09611779
13	0.75	1.06E-10	7.51E-11	0.105545
15	0.75	1.14E-10	8.32E-11	0.1142998
17	0.75	1.23E-10	9.09E-11	0.1225089
3	1	5.24E-11	1.49E-11	0.05242112
5	1	6.99E-11	3.23E-11	0.06990976
7	1	8.45E-11	4.64E-11	0.08451272
9	1	9.73E-11	5.87E-11	0.09731276
11	1	1.09E-10	6.97E-11	0.1089146
13	1	1.20E-10	7.98E-11	0.1196033
15	1	1.30E-10	8.91E-11	0.1295637
17	1	1.39E-10	9.79E-11	0.1389265
3	1.25	5.86E-11	1.12E-11	0.05864105
5	1.25	7.76E-11	3.02E-11	0.07761576

7	1.25	9.35E-11	4.59E-11	0.09347681	
9	1.25	1.08E-10	5.94E-11	0.1075254	
11	1.25	1.20E-10	7.16E-11	0.1202127	
13	1.25	1.32E-10	8.28E-11	0.1319323	
15	1.25	1.43E-10	9.31E-11	0.1428875	
17	1.25	1.53E-10	1.03E-10	0.1532081	
3	1.5	6.45E-11	7.06E-12	0.0645439	
5	1.5	8.47E-11	2.76E-11	0.08471344	
7	1.5	1.02E-10	4.45E-11	0.1017456	
9	1.5	1.17E-10	5.92E-11	0.1167814	
11	1.5	1.30E-10	7.24E-11	0.1304627	
13	1.5	1.43E-10	8.45E-11	0.1431188	
15	1.5	1.55E-10	9.58E-11	0.15492	
17	1.5	1.66E-10	1.06E-10	0.1660604	


Propagation Delay vs. Capacitance
0.20
0.15
0.10
0.05
0.00
Propagation Delay (ns)
4
6
8
10
12
14
16
Capacitance (fF)

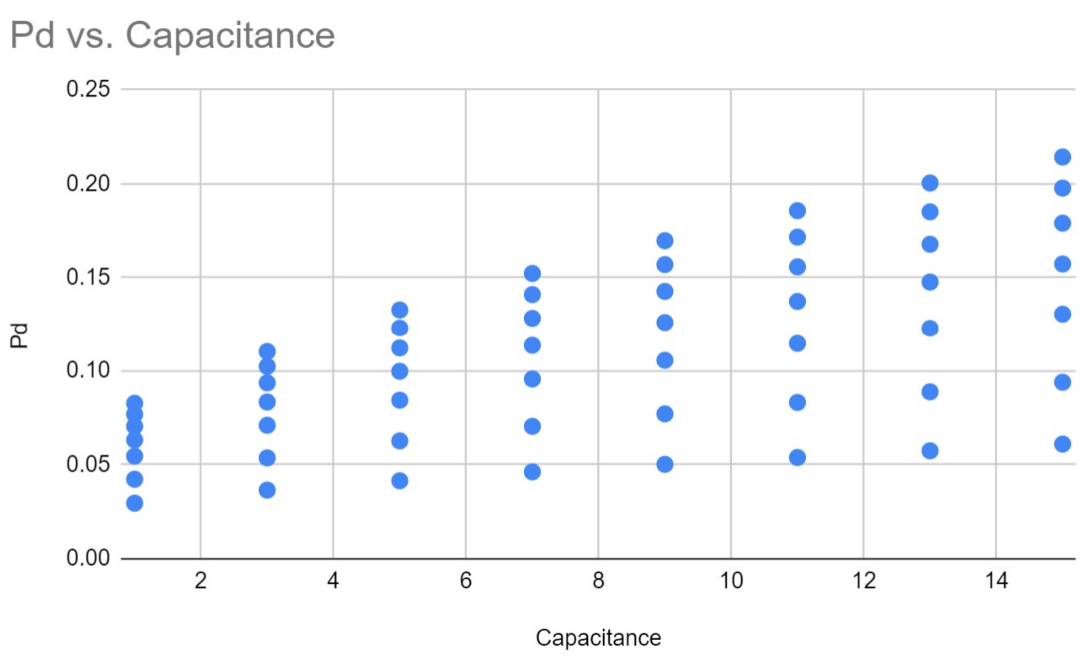


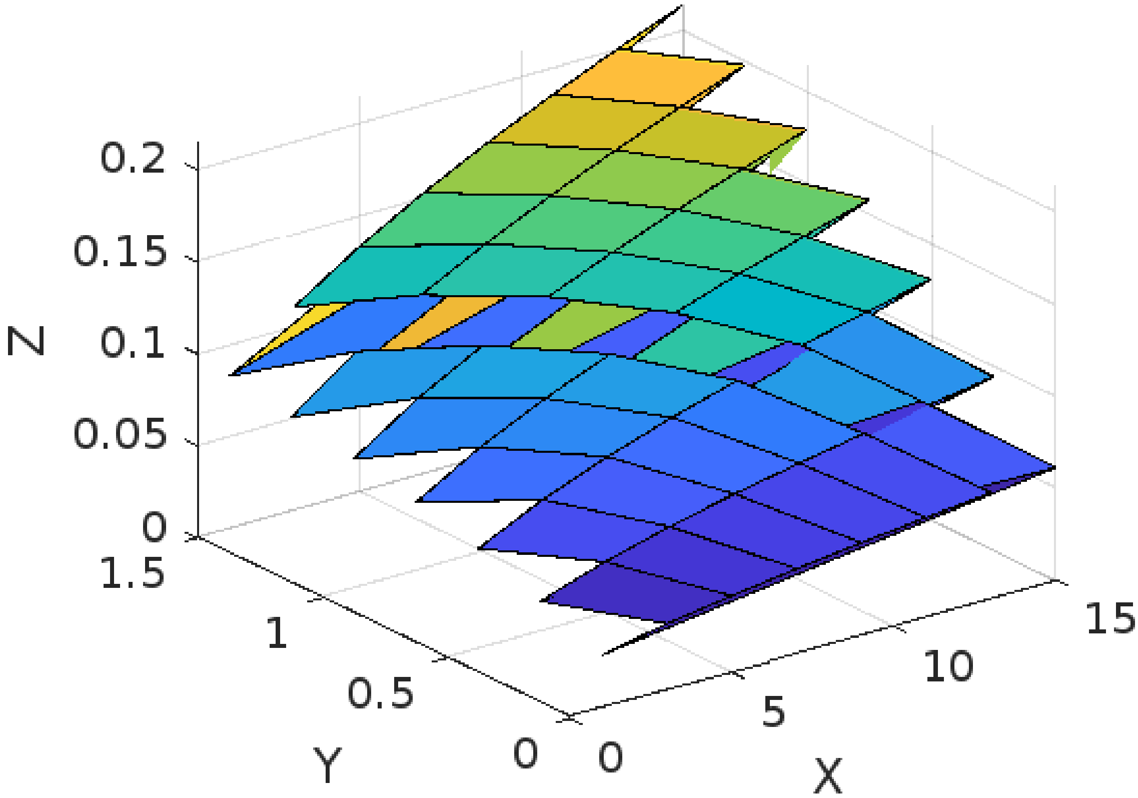
0.2
0.15
0.1
0.05
0
Z
1.5
1
0.5
0
Y
0
10
20
X

4.3 NAND2x2

Capacitance	Input Transition Time	Rise Delay	Fall Delay	nano
1	0	2.15E-11	2.96E-11	0.02961491
3	0	2.81E-11	3.65E-11	0.03654462
5	0	3.29E-11	4.15E-11	0.04152555
7	0	3.73E-11	4.63E-11	0.04626687
9	0	4.08E-11	5.03E-11	0.0503022
11	0	4.42E-11	5.39E-11	0.05392498
13	0	4.72E-11	5.75E-11	0.05749395
15	0	5.00E-11	6.11E-11	0.06106717
1	0.25	2.85E-11	4.23E-11	0.04234857
3	0.25	3.92E-11	5.37E-11	0.05369467
5	0.25	4.75E-11	6.28E-11	0.06275757
7	0.25	5.45E-11	7.05E-11	0.07051471
9	0.25	6.08E-11	7.72E-11	0.07715511
11	0.25	6.63E-11	8.32E-11	0.08324327
13	0.25	7.14E-11	8.89E-11	0.08888083
15	0.25	7.60E-11	9.40E-11	0.0939952
1	0.5	3.29E-11	5.47E-11	0.05466293
3	0.5	4.80E-11	7.11E-11	0.07108342
5	0.5	6.00E-11	8.44E-11	0.08442813
7	0.5	7.03E-11	9.57E-11	0.09572372
9	0.5	7.94E-11	1.06E-10	0.1057089
11	0.5	8.76E-11	1.15E-10	0.1147405
13	0.5	9.52E-11	1.23E-10	0.1229574
15	0.5	1.02E-10	1.31E-10	0.1306017
1	0.75	3.44E-11	6.33E-11	0.06328813
3	0.75	5.26E-11	8.35E-11	0.08347435
5	0.75	6.73E-11	9.98E-11	0.09982631
7	0.75	8.00E-11	1.14E-10	0.1137177
9	0.75	9.12E-11	1.26E-10	0.1261321
11	0.75	1.01E-10	1.37E-10	0.1374038
13	0.75	1.11E-10	1.48E-10	0.1477614
15	0.75	1.19E-10	1.57E-10	0.1573767
1	1	3.45E-11	7.05E-11	0.0705466
3	1	5.53E-11	9.37E-11	0.09366088
5	1	7.21E-11	1.12E-10	0.1122923
7	1	8.66E-11	1.28E-10	0.1283919
9	1	9.95E-11	1.43E-10	0.1427708
11	1	1.11E-10	1.56E-10	0.1558654
13	1	1.22E-10	1.68E-10	0.1678845
15	1	1.32E-10	1.79E-10	0.1791029
1	1.25	3.39E-11	7.70E-11	0.07695422
3	1.25	5.68E-11	1.02E-10	0.1024562

5	1.25	7.54E-11	1.23E-10	0.123136
7	1.25	9.15E-11	1.41E-10	0.141076
9	1.25	1.06E-10	1.57E-10	0.1570577
11	1.25	1.19E-10	1.72E-10	0.1716784
13	1.25	1.31E-10	1.85E-10	0.1851524
15	1.25	1.42E-10	1.98E-10	0.1977676
1	1.5	3.27E-11	8.28E-11	0.08277676
3	1.5	5.74E-11	1.10E-10	0.1103646
5	1.5	7.76E-11	1.33E-10	0.132857
7	1.5	9.51E-11	1.52E-10	0.1523338
9	1.5	1.11E-10	1.70E-10	0.1697743
11	1.5	1.25E-10	1.86E-10	0.1857573
13	1.5	1.38E-10	2.00E-10	0.2004839
15	1.5	1.51E-10	2.14E-10	0.2143209

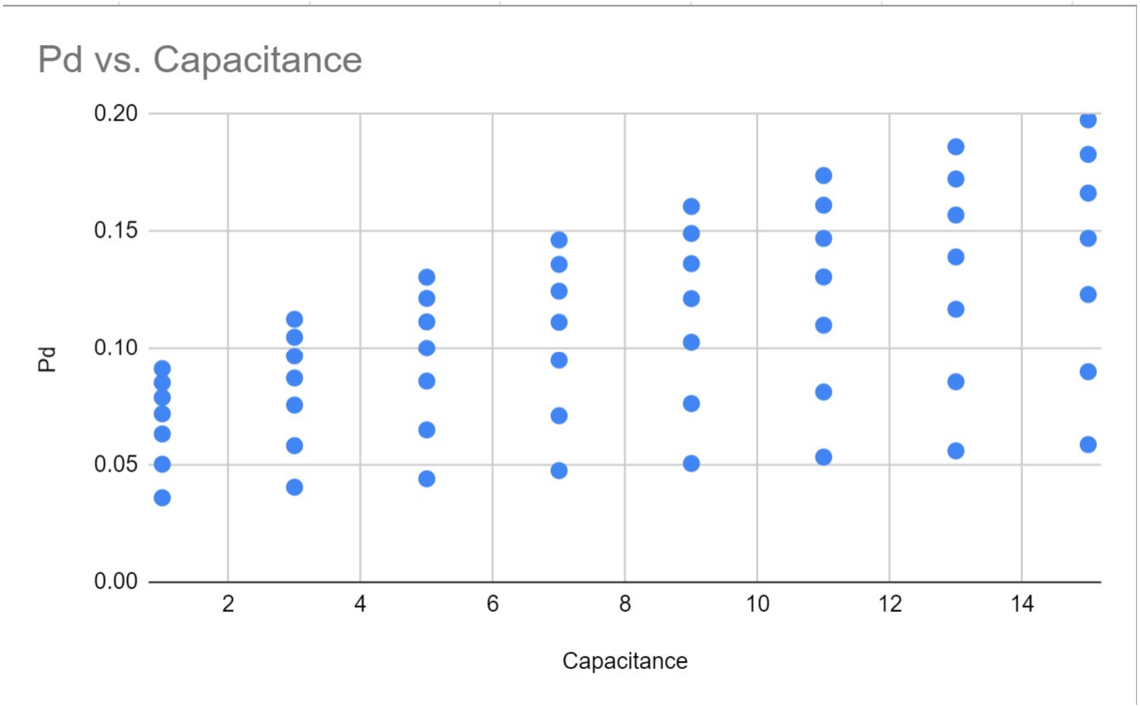

Pd vs. Capacitance
0.25
0.20
0.15
0.10
0.05
0.00
Pd
2
4
6
8
10
12
14
Capacitance



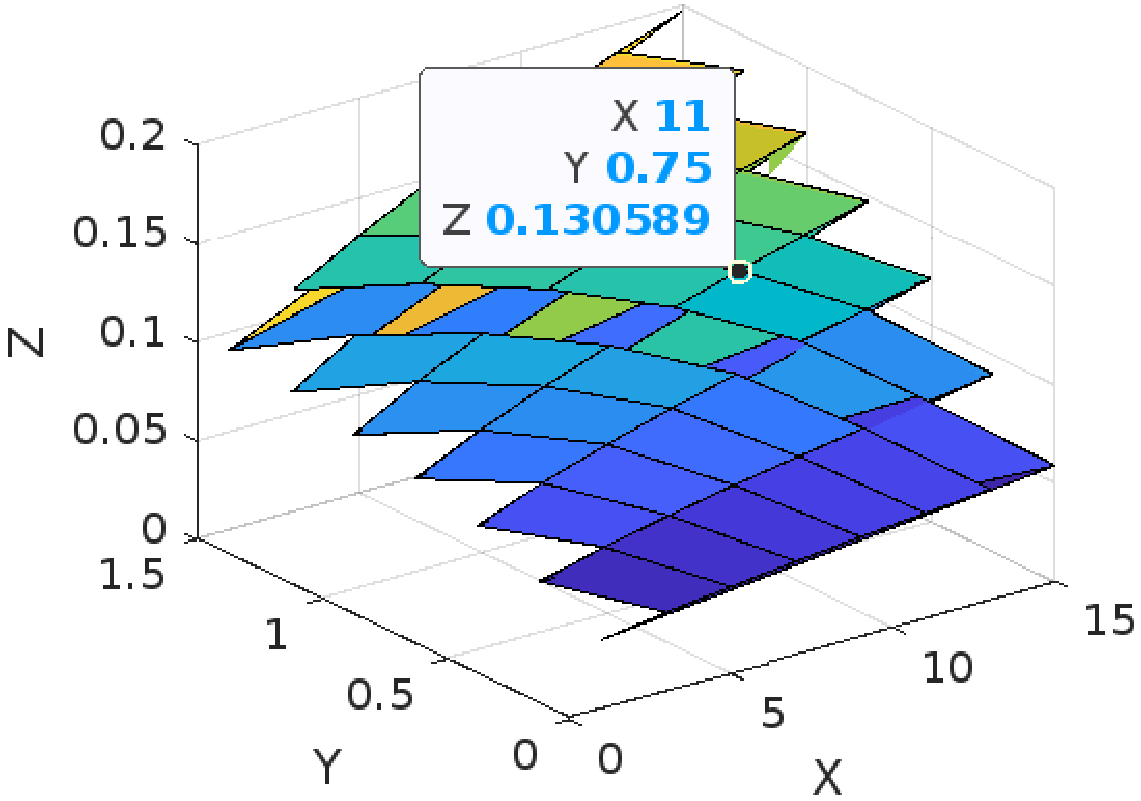
4.4 NAND3x2

Capacitance	Input Transition T	Rise Delay	Fall Delay	nano
1	0	2.23E-11	3.60E-11	0.03600899
3	0	2.73E-11	4.05E-11	0.04050193
5	0	3.08E-11	4.41E-11	0.04409555
7	0	3.42E-11	4.76E-11	0.04759343
9	0	3.72E-11	5.06E-11	0.05063919
11	0	3.98E-11	5.34E-11	0.05337411
13	0	4.22E-11	5.60E-11	0.05601492
15	0	4.45E-11	5.87E-11	0.05869955
1	0.25	2.91E-11	5.03E-11	0.05032264
3	0.25	3.67E-11	5.82E-11	0.05824558
5	0.25	4.31E-11	6.50E-11	0.06496214
7	0.25	4.86E-11	7.10E-11	0.07101314
9	0.25	5.35E-11	7.62E-11	0.07619136
11	0.25	5.79E-11	8.11E-11	0.08113473
13	0.25	6.21E-11	8.55E-11	0.08550559
15	0.25	6.58E-11	8.98E-11	0.08979872
1	0.5	3.24E-11	6.32E-11	0.06323391
3	0.5	4.35E-11	7.56E-11	0.07556869
5	0.5	5.27E-11	8.58E-11	0.08580061
7	0.5	6.06E-11	9.48E-11	0.09476998
9	0.5	6.78E-11	1.03E-10	0.1027146
11	0.5	7.44E-11	1.10E-10	0.1100017
13	0.5	8.04E-11	1.17E-10	0.1168061
15	0.5	8.61E-11	1.23E-10	0.1231005
1	0.75	3.28E-11	7.18E-11	0.07183568
3	0.75	4.62E-11	8.71E-11	0.0871244
5	0.75	5.75E-11	1.00E-10	0.1000519
7	0.75	6.73E-11	1.11E-10	0.1112417
9	0.75	7.61E-11	1.21E-10	0.1213368
11	0.75	8.42E-11	1.31E-10	0.1305886
13	0.75	9.17E-11	1.39E-10	0.1391184
15	0.75	9.87E-11	1.47E-10	0.1470481
1	1	3.18E-11	7.88E-11	0.07878016
3	1	4.72E-11	9.66E-11	0.09658552
5	1	6.01E-11	1.11E-10	0.1114134
7	1	7.13E-11	1.25E-10	0.1245306
9	1	8.15E-11	1.36E-10	0.1362658
11	1	9.08E-11	1.47E-10	0.1470243
13	1	9.95E-11	1.57E-10	0.1570155
15	1	1.08E-10	1.66E-10	0.1663732
1	1.25	3.02E-11	8.51E-11	0.0851028
3	1.25	4.71E-11	1.05E-10	0.1048441

5	1.25	6.14E-11	1.21E-10	0.1214386
7	1.25	7.39E-11	1.36E-10	0.1359528
9	1.25	8.52E-11	1.49E-10	0.1491426
11	1.25	9.56E-11	1.61E-10	0.1611999
13	1.25	1.05E-10	1.72E-10	0.1723897
15	1.25	1.14E-10	1.83E-10	0.1828896
1	1.5	2.79E-11	9.11E-11	0.09110464
3	1.5	4.64E-11	1.13E-10	0.1125275
5	1.5	6.18E-11	1.30E-10	0.1304889
7	1.5	7.54E-11	1.46E-10	0.1463679
9	1.5	8.77E-11	1.61E-10	0.1606572
11	1.5	9.90E-11	1.74E-10	0.1738713
13	1.5	1.10E-10	1.86E-10	0.1861326
15	1.5	1.19E-10	1.98E-10	0.1976221



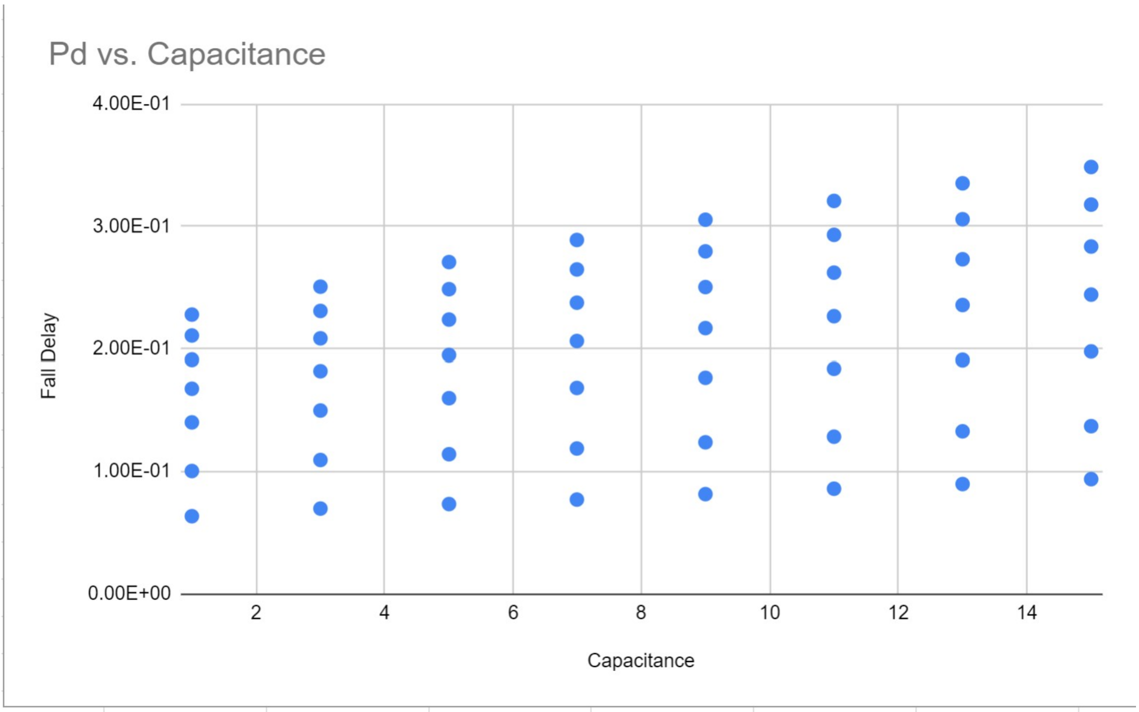
Pd vs. Capacitance
0.20
0.15
0.10
0.05
0.00
Pd
2
4
6
8
10
12
14
Capacitance

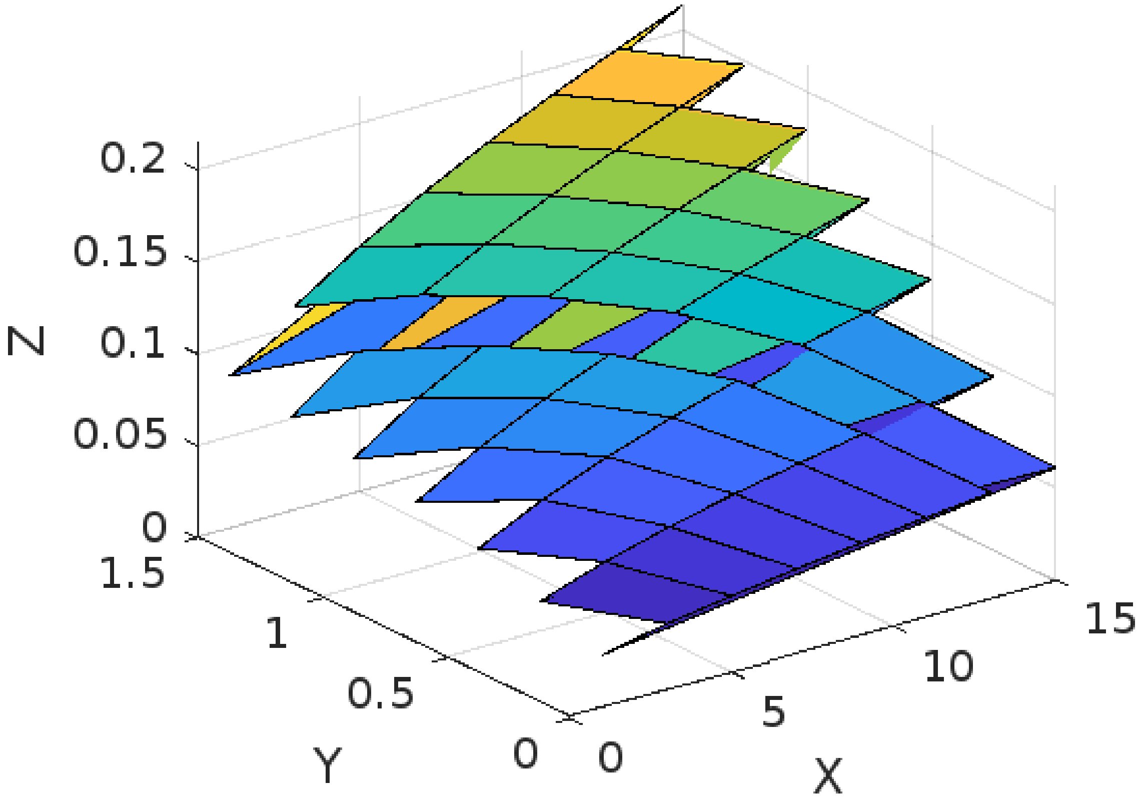


4.5 NOR2x2

capacitance	Input Trans	Rise Delay	Fall Delay	max(rise,f	max * 10^9	
1	0	4.37E-11	2.15E-11	4.37E-11	4.37E-02	
3	0	5.07E-11	2.73E-11	5.07E-11	5.07E-02	
5	0	5.62E-11	3.21E-11	5.62E-11	5.62E-02	
7	0	6.17E-11	3.60E-11	6.17E-11	6.17E-02	
9	0	6.69E-11	3.95E-11	6.69E-11	6.69E-02	
11	0	7.21E-11	4.28E-11	7.21E-11	7.21E-02	
13	0	7.72E-11	4.57E-11	7.72E-11	7.72E-02	
15	0	8.24E-11	4.84E-11	8.24E-11	8.24E-02	
1	0.25	6.59E-11	2.67E-11	6.59E-11	6.59E-02	
3	0.25	7.90E-11	3.61E-11	7.90E-11	7.90E-02	
5	0.25	8.91E-11	4.36E-11	8.91E-11	8.91E-02	
7	0.25	9.77E-11	5.02E-11	9.77E-11	9.77E-02	
9	0.25	1.05E-10	5.60E-11	1.05E-10	1.05E-01	
11	0.25	1.12E-10	6.12E-11	1.12E-10	1.12E-01	
13	0.25	1.18E-10	6.61E-11	1.18E-10	1.18E-01	
15	0.25	1.24E-10	7.06E-11	1.24E-10	1.24E-01	
1	0.5	8.94E-11	2.67E-11	8.94E-11	8.94E-02	
3	0.5	1.09E-10	4.05E-11	1.09E-10	1.09E-01	
5	0.5	1.25E-10	5.16E-11	1.25E-10	1.25E-01	
7	0.5	1.38E-10	6.11E-11	1.38E-10	1.38E-01	
9	0.5	1.50E-10	6.95E-11	1.50E-10	1.50E-01	
11	0.5	1.60E-10	7.71E-11	1.60E-10	1.60E-01	
13	0.5	1.70E-10	8.42E-11	1.70E-10	1.70E-01	
15	0.5	1.79E-10	9.07E-11	1.79E-10	1.79E-01	
1	0.75	1.08E-10	2.29E-11	1.08E-10	1.08E-01	
3	0.75	1.32E-10	4.00E-11	1.32E-10	1.32E-01	
5	0.75	1.52E-10	5.38E-11	1.52E-10	1.52E-01	
7	0.75	1.69E-10	6.56E-11	1.69E-10	1.69E-01	
9	0.75	1.84E-10	7.60E-11	1.84E-10	1.84E-01	
11	0.75	1.98E-10	8.55E-11	1.98E-10	1.98E-01	
13	0.75	2.10E-10	9.43E-11	2.10E-10	2.10E-01	
15	0.75	2.21E-10	1.02E-10	2.21E-10	2.21E-01	
1	1	1.24E-10	1.69E-11	1.24E-10	1.24E-01	
3	1	1.53E-10	3.70E-11	1.53E-10	1.53E-01	
5	1	1.76E-10	5.31E-11	1.76E-10	1.76E-01	
7	1	1.95E-10	6.68E-11	1.95E-10	1.95E-01	
9	1	2.13E-10	7.91E-11	2.13E-10	2.13E-01	
11	1	2.29E-10	9.02E-11	2.29E-10	2.29E-01	
13	1	2.43E-10	1.00E-10	2.43E-10	2.43E-01	
15	1	2.57E-10	1.10E-10	2.57E-10	2.57E-01	
1	1.25	1.40E-10	9.65E-12	1.40E-10	1.40E-01	
3	1.25	1.71E-10	3.22E-11	1.71E-10	1.71E-01	
5	1.25	1.97E-10	5.04E-11	1.97E-10	1.97E-01	
7	1.25	2.19E-10	6.60E-11	2.19E-10	2.19E-01	
9	1.25	2.39E-10	7.98E-11	2.39E-10	2.39E-01	
11	1.25	2.57E-10	9.23E-11	2.57E-10	2.57E-01	
13	1.25	2.73E-10	1.04E-10	2.73E-10	2.73E-01	

15	1.25	2.88E-10	1.15E-10	2.88E-10	2.88E-01	
1	1.5	1.55E-10	1.45E-12	1.55E-10	1.55E-01	
3	1.5	1.89E-10	2.64E-11	1.89E-10	1.89E-01	
5	1.5	2.17E-10	4.64E-11	2.17E-10	2.17E-01	
7	1.5	2.41E-10	6.37E-11	2.41E-10	2.41E-01	
9	1.5	2.62E-10	7.89E-11	2.62E-10	2.62E-01	
11	1.5	2.82E-10	9.28E-11	2.82E-10	2.82E-01	
13	1.5	3.00E-10	1.05E-10	3.00E-10	3.00E-01	
15	1.5	3.17E-10	1.17E-10	3.17E-10	3.17E-01	

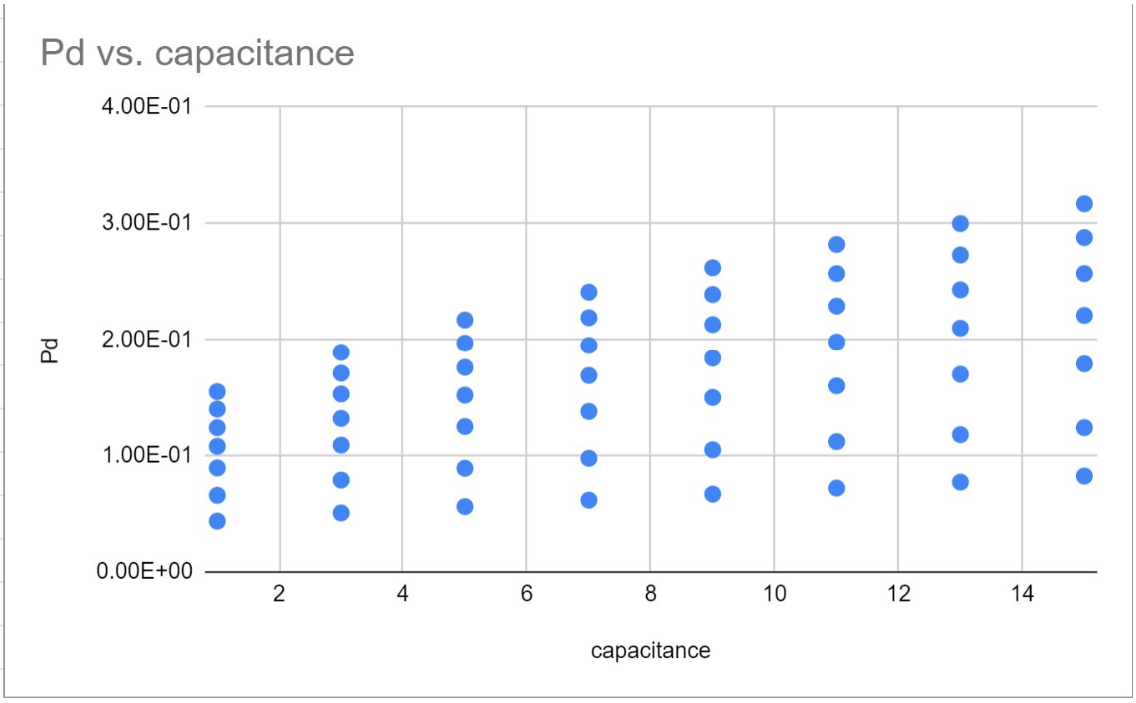

Pd vs. Capacitance
4.00E-01
3.00E-01
2.00E-01
1.00E-01
0.00E+00
Fall Delay
2
4
6
8
10
12
14
Capacitance

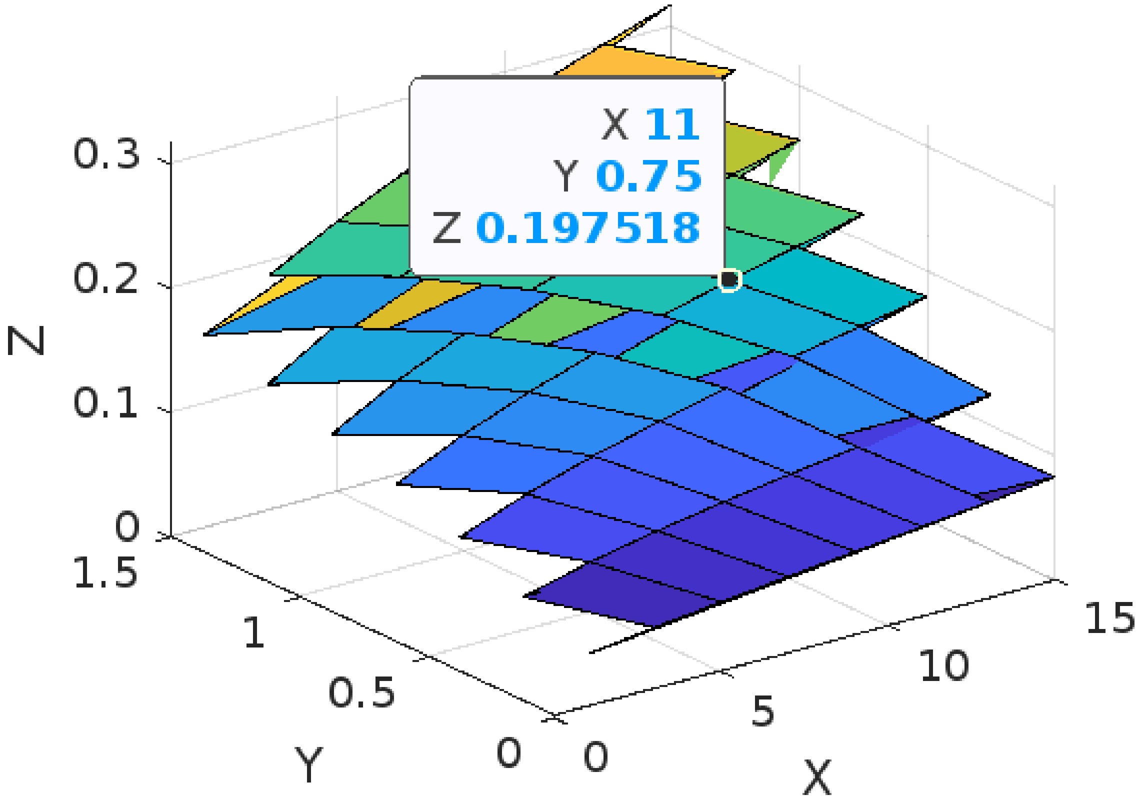


4.6 NOR3x2

Capacitan	Input Trai	Rise Dela	Fall Delay	nano
1	0	6.36E-11	2.61E-11	0.0635858
3	0	6.98E-11	2.81E-11	0.0698245
5	0	7.35E-11	3.12E-11	0.0735285
7	0	7.72E-11	3.51E-11	0.0771881
9	0	8.16E-11	3.83E-11	0.0816446
11	0	8.61E-11	4.05E-11	0.0860756
13	0	8.99E-11	4.25E-11	0.0898863
15	0	9.39E-11	4.45E-11	0.0939145
1	0.25	1.01E-10	2.90E-11	0.1005558
3	0.25	1.10E-10	3.54E-11	0.1095778
5	0.25	1.14E-10	4.21E-11	0.1142967
7	0.25	1.19E-10	4.67E-11	0.1189739
9	0.25	1.24E-10	5.10E-11	0.1240399
11	0.25	1.29E-10	5.53E-11	0.1286315
13	0.25	1.33E-10	5.95E-11	0.1330468
15	0.25	1.37E-10	6.31E-11	0.1372404
1	0.5	1.40E-10	2.84E-11	0.1403353
3	0.5	1.50E-10	3.88E-11	0.150036
5	0.5	1.60E-10	4.69E-11	0.1601148
7	0.5	1.68E-10	5.46E-11	0.1684915
9	0.5	1.77E-10	6.10E-11	0.1767768
11	0.5	1.84E-10	6.70E-11	0.1841409
13	0.5	1.91E-10	7.28E-11	0.1910387
15	0.5	1.98E-10	7.82E-11	0.1978283
1	0.75	1.68E-10	2.38E-11	0.1678306
3	0.75	1.82E-10	3.64E-11	0.1821438
5	0.75	1.95E-10	4.70E-11	0.1949392
7	0.75	2.06E-10	5.61E-11	0.2063296
9	0.75	2.17E-10	6.44E-11	0.2168811
11	0.75	2.27E-10	7.22E-11	0.2266244
13	0.75	2.36E-10	7.90E-11	0.2357588
15	0.75	2.44E-10	8.56E-11	0.2442721
1	1	1.91E-10	1.66E-11	0.1913017
3	1	2.09E-10	3.15E-11	0.2085217
5	1	2.24E-10	4.40E-11	0.2238589
7	1	2.38E-10	5.46E-11	0.2376575
9	1	2.50E-10	6.46E-11	0.2504391
11	1	2.62E-10	7.33E-11	0.2622249
13	1	2.73E-10	8.16E-11	0.2731759
15	1	2.84E-10	8.93E-11	0.2835973
1	1.25	2.11E-10	8.10E-12	0.2108425
3	1.25	2.31E-10	2.49E-11	0.2309152
5	1.25	2.49E-10	3.90E-11	0.2487276

7	1.25	2.65E-10	5.11E-11	0.2648541
9	1.25	2.80E-10	6.23E-11	0.2796394
11	1.25	2.93E-10	7.22E-11	0.2931582
13	1.25	3.06E-10	8.17E-11	0.3059107
15	1.25	3.18E-10	9.02E-11	0.3179022
1	1.5	2.28E-10	-1.43E-12	0.2279237
3	1.5	2.51E-10	1.72E-11	0.2507488
5	1.5	2.71E-10	3.26E-11	0.2708647
7	1.5	2.89E-10	4.61E-11	0.2889676
9	1.5	3.06E-10	5.84E-11	0.3055288
11	1.5	3.21E-10	6.94E-11	0.3209058
13	1.5	3.35E-10	7.98E-11	0.3353102
15	1.5	3.49E-10	8.94E-11	0.3486471


Pd vs. capacitance
4.00E-01
3.00E-01
2.00E-01
1.00E-01
0.00E+00
Pd
2
4
6
8
10
12
14
capacitance



5 Extracted Linear Delay Models

5.1 INVx2

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.957728506							
R Square	0.917243892							
Adjusted R Square	0.91412102							
Standard Error	0.015950473							
Observations	56							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	0.149454079	0.074727039	293.7181	2.0975E-29			
Residual	53	0.013484132	0.000254418					
Total	55	0.162938211						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*Upper 95.0%*
Intercept	-0.022127527	0.006033196	-3.667629275	0.000568	-0.034228586	-0.01003	-0.03423	-0.010026468
Capacitance	0.007884455	0.000465125	16.95125249	4.68E-23	0.006951532	0.008817	0.006952	0.008817378
Input Transition Time	0.073847559	0.004262943	17.32313916	1.76E-23	0.065297177	0.082398	0.065297	0.08239794

```
k2 = 0.007884455 ns/fF

k1 = 0.073847559 ns

k3 = -0.022127527 ns

pd = 0.073847559 * InputTrans + 0.007884455 * LoadCap + (-0.022127527)
```

5.2 INVx4

SUMMARY OUTPUT									
Regression Statistics									
Multiple R	0.968731987								
R Square	0.938441662								
Adjusted R Square	0.936118706								
Standard Error	0.009490514								
Observations	56								
ANOVA									
	df	*SS*	*MS*	*F*	*Significance F*				
Regression	2	0.072773919	0.03638696	403.9859554	8.24333E-33				
Residual	53	0.004773703	9.00699E-05						
Total	55	0.077547622							
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*lpper 95.0%*	
Intercept	-0.008230489	0.003589745	-2.292777944	0.025857942	-0.015430606	-0.00103	-0.01543	-0.00103	
Capacitance	0.004993812	0.000276749	18.04455345	2.75784E-24	0.004438724	0.005549	0.004439	0.005549	
Input Transition Time	0.055707553	0.002536447	21.96283228	2.7771E-28	0.050620085	0.060795	0.05062	0.060795	

```
k2 = 0.004993812 ns/fF

k1 = 0.055707553 ns

k3 = -0.008230489 ns

pd = 0.055707553 * InputTrans + 0.004993812 * LoadCap + (-0.008230489)
```

5.3 NAND2x2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9628399783
R Square	0.9270608238
Adjusted R Square	0.9243084021
Standard Error	0.01320894938
Observations	56

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.1175329	0.0587664	336.81641	0
Residual	53	0.0092472	0.0001744		
Total	55	0.1267802			

	Coefficients	tandard Err	t Stat	P-value	Lower 95%	Upper 95%	ower 95.0%	Jpper 95.0%
Intercept	0.005820771533	0.0044295	1.3140687	0.1944823	-0.003063838887	0.0147053	-0.0030638	0.0147053
Capacitance	0.006133679702	0.0003851	15.924158	0	0.005361104883	0.0069062	0.0053611	0.0069062
Input Transition Ti	0.07235304804	0.0035302	20.495219	0	0.06527228286	0.0794338	0.0652722	0.0794338

```
k2 = 0.006133679702 ns/fF

k1 = 0.07235304804 ns

k3 = 0.005820771533 ns

pd = 0.07235304804 * InputTrans + 0.006133679702 * LoadCap + 0.005820771533
```

5.4 NAND3x2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9641715897
R Square	0.9296268545
Adjusted R Square	0.9269712641
Standard Error	0.01141539996
Observations	56

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.0912346	0.0456173	350.06409	0
Residual	53	0.0069065	0.0001303		
Total	55	0.0981411			

	Coefficients	tandard Err	t Stat	P-value	Lower 95%	Upper 95%	ower 95.0%	Jpper 95.0%
Intercept	0.01713628295	0.0038281	4.4764250	0.0000406	0.009458050682	0.0248145	0.0094580	0.0248145
Capacitance	0.004910063537	0.0003328	14.750258	0	0.004242391166	0.0055777	0.0042423	0.0055777
Input Transition Time	0.06701961071	0.0030508	21.967204	0	0.06090029235	0.0731389	0.0609002	0.0731389

```
k2 = 0.004910063537 ns/fF

k1 = 0.06701961071 ns

k3 = 0.01713628295 ns

pd = 0.06701961071 * InputTrans + 0.004910063537 * LoadCap + 0.01713628295
```

5.5 NOR2x2

SUMMARY OUTPUT

Regression Statistics	
Multiple F	0.9747398
R Square	0.9501178
Adjusted I	0.9482354
Standard I	0.0164060
Observati	56

ANOVA

	df	SS	MS	F	gnificance F
Regressio	2	0.2717175	0.1358587	504.75166	0
Residual	53	0.0142654	0.0002691		
Total	55	0.2859830			

	Coefficient	andard Err	t Stat	P-value	Lower 95%	Upper 95%	ower 95.0%	pper 95.0%
Intercept	0.0125367	0.0055017	2.2786935	0.0267414	0.0015016	0.0235718	0.0015016	0.0235718
capacitan	0.0074182	0.0004784	15.506112	0	0.0064587	0.0083778	0.0064587	0.0083778
Input Trai	0.1215968	0.0043847	27.731999	0	0.1128021	0.1303914	0.1128021	0.1303914

```
k2 = 0.00741829737244898 ns/fF

k1 = 0.121596801071429 ns

k3 = 0.0125367 ns

pd = 0.1215968 * InputTrans + 0.00742 * LoadCap + 0.0125367
```

5.6 NOR3x2

SUMMARY OUTPUT

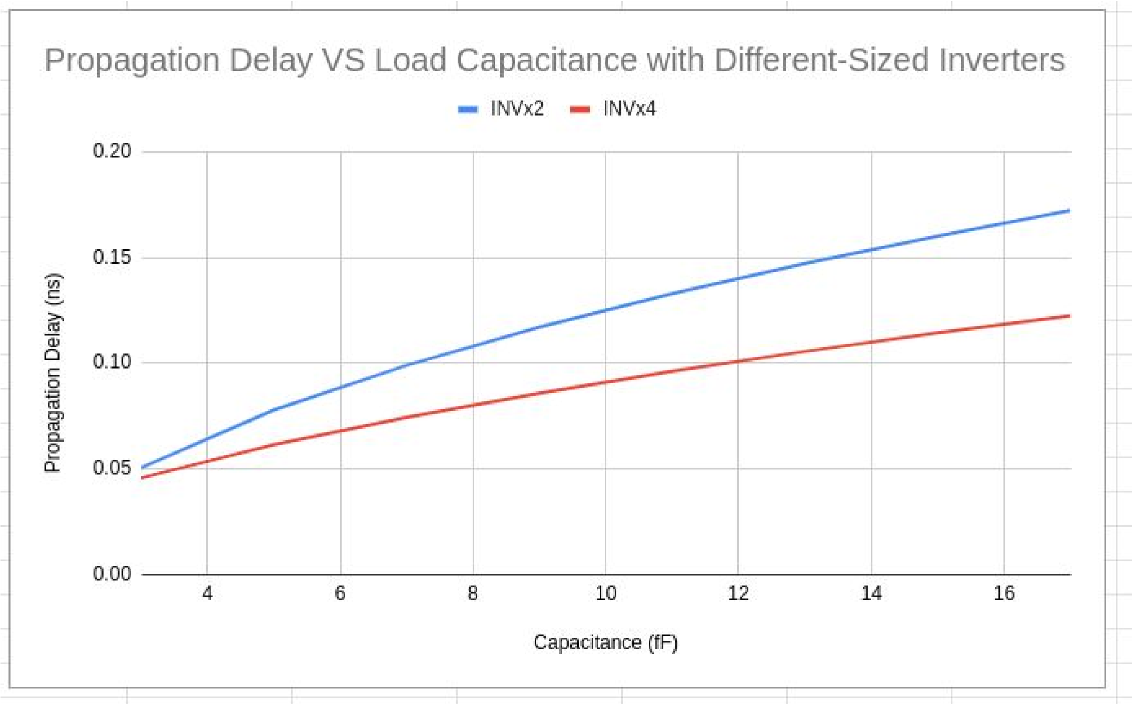
Regression Statistics	
Multiple R	0.9835690416
R Square	0.9674080595
Adjusted R Square	0.966178175
Standard Error	0.01433780856
Observations	56

ANOVA

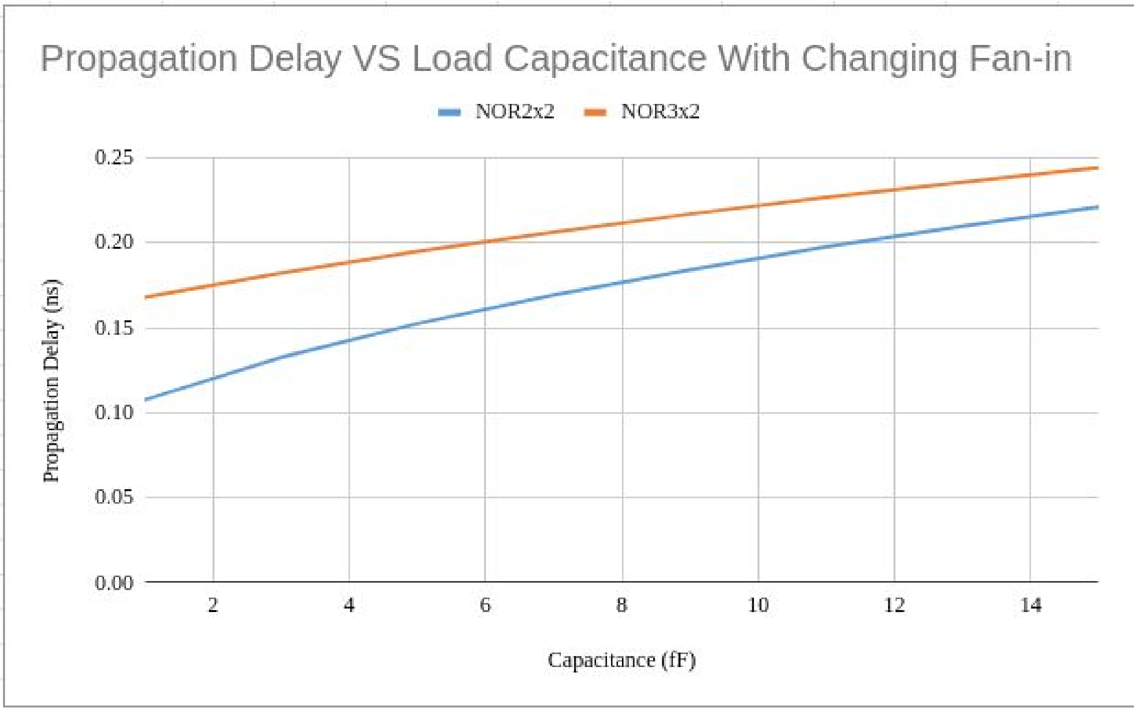
	df	SS	MS	F	Significance F
Regression	2	0.323400(	0.161700:	786.5844	0
Residual	53	0.010895:	0.000205!		
Total	55	0.334296(			

	Coefficients	andard Err	t Stat	P-value	Lower 95%	Upper 95%	ower 95.0%	pper 95.0%
Intercept	0.04766146294	0.004808:	9.912664(	0	0.03801755868	0.057305:	0.038017!	0.057305:
Capacitance	0.005253200391	0.000418(	12.56448!	0	0.00441460002	0.006091!	0.004414(	0.006091!
Input Transition Time	0.1441595429	0.003831!	37.62050(	0	0.1364736435	0.151845	0.136473(	0.151845

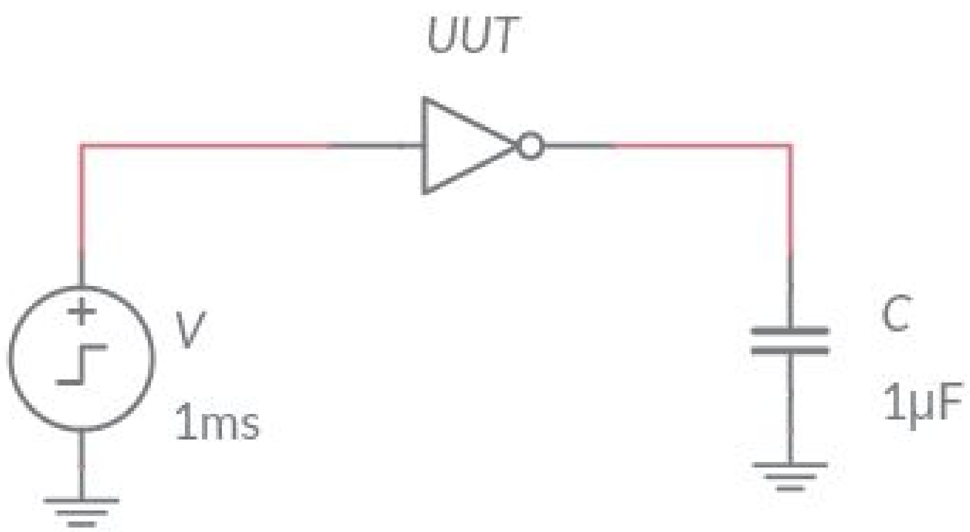
```
k1 = 0.144159542857143 ns

k2 = 0.00525320039115647 ns/fF

k3 = 0.04766146294 ns

pd = 0.14416 * InputTrans + 0.00525 * LoadCap + 0.04766146294
```

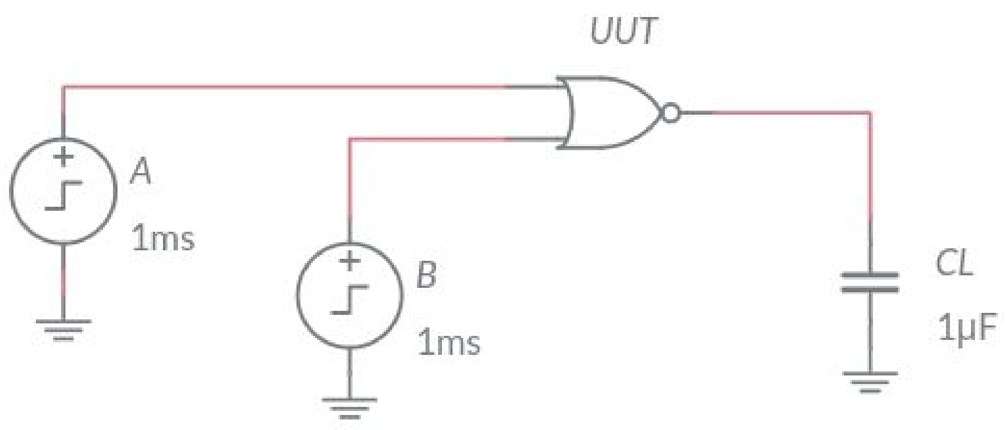


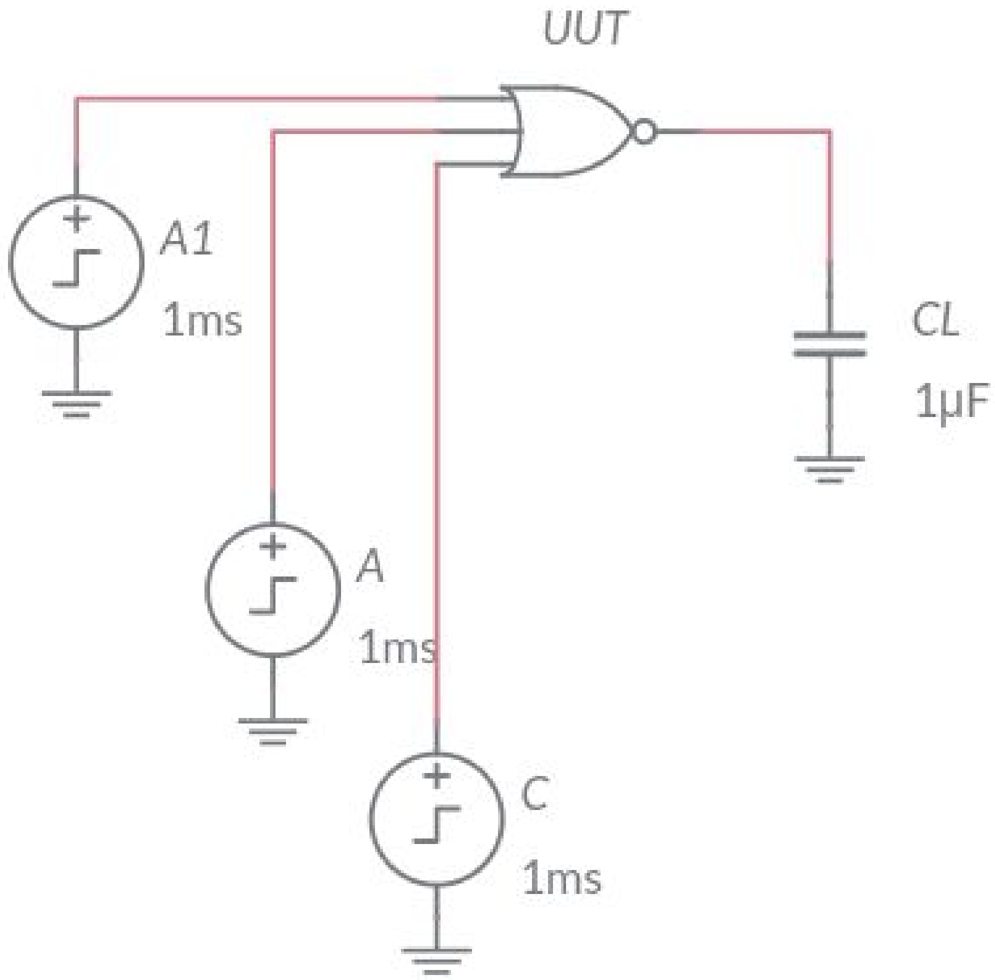
Both graphs were generated with the input transition time kept constant at 0.75 ns.



The following are figures demonstrating the cells that were tested:


UUT
V
1ms
C
1µF


UUT
A
1ms
B
1ms
CL
1µF



6 Conclusion

Overall, after the analysis of the outcome of the six cells, it was noticed that the propagation delay is influenced by four different factors:

1. **Load Capacitance:** As the load capacitance increases, the propagation delay increases since the capacitor require more time to get charged or discharged.

2. **Input Transition Time:** As the input transition time increases, the switching time of

the input increases; this delay is then reflected later as an increase of the propagation delay.

3. **Cell Size:** After comparing the two inverter cells, as the width of the transistor increases, the resistance decreases, which means that the propagation delay decreases. This assures the concept of having the propagation delay proportional to the resistance and the internal parasitic capacitance.

4. **Fan-in of NAND & NOR Gates:** Having a greater fan-in for a cell means that there are more transistors in series in both NAND and NOR gates. This, in turn, increases the resistance. Furthermore, we have more transistors connected in parallel in the 3-input cell compared to the 2-input cell, which results in having a greater internal parasitic capacitance. Therefore, it is expected to have a greater propagation delay when the fan-in = 3 than when fan-in = 2 due to the aforementioned relationship (delay is proportional to resistance and internal capacitance).