

# Fundamentals of Computer Systems

Transistors, Gates, and ICs

Stephen A. Edwards

Columbia University

Summer 2017

# Semiconductor

sem-i-con-duc-tor

noun

1. A substance, such as silicon or germanium, with electrical conductivity intermediate between that of an insulator and a conductor
2. A semiconductor device

Periodic Table of the Elements

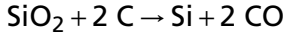
1 IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A	
H Hydrogen 1.008	He Helium 4.003											B Boron 10.811	C Carbon 12.011	N Nitrogen 14.007	O Oxygen 15.999	F Fluorine 18.998	Ne Neon 20.180	
Li Lithium 6.941	Be Beryllium 9.012											Al Aluminum 26.982	Si Silicon 28.086	P Phosphorus 30.974	S Sulfur 32.06	Cl Chlorine 35.453	Ar Argon 39.948	
Na Sodium 22.990	Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 9	10 VIII 10	11 IB 1B	12 IIB 2B	Ga Gallium 69.723	Ge Germanium 72.630	As Arsenic 74.922	Se Selenium 78.96	Br Bromine 79.904	Kr Krypton 83.80	
K Potassium 39.098	Ca Calcium 40.078	Sc Scandium 44.956	Ti Titanium 47.88	V Vanadium 50.942	Cr Chromium 51.996	Mn Manganese 54.938	Fe Iron 55.845	Co Cobalt 58.933	Ni Nickel 58.693	Cu Copper 63.546	Zn Zinc 65.38	In Indium 114.818	Sn Tin 118.710	Sb Antimony 121.757	Te Tellurium 127.6	I Iodine 126.905	Xe Xenon 131.29	
Rb Rubidium 85.468	Sr Strontium 87.62	Y Yttrium 88.906	Zr Zirconium 91.224	Nb Niobium 92.906	Mo Molybdenum 95.94	Tc Technetium 98.906	Ru Ruthenium 101.07	Rh Rhodium 101.07	Pd Palladium 106.42	Ag Silver 107.868	Cd Cadmium 112.411	Hg Mercury 200.59	Tl Thallium 204.384	Pb Lead 207.2	Bi Bismuth 208.980	Po Polonium 209	At Astatine 210	Rn Radon 222
Cs Cesium 132.905	Ba Barium 137.327	La-103 Lanthanide Series		Hf Hafnium 178.49	Ta Tantalum 180.948	W Tungsten 183.84	Re Rhenium 186.207	Os Osmium 190.23	Ir Iridium 192.22	Pt Platinum 195.08	Au Gold 196.967	Hg Mercury 200.59	Tl Thallium 204.384	Pb Lead 207.2	Bi Bismuth 208.980	Po Polonium 209	At Astatine 210	Rn Radon 222
Fr Francium 223	Ra Radium 226	Ac-103 Actinide Series		Rf Rutherfordium 261	Db Dubnium 262	Sg Seaborgium 266	Bh Bohrium 264	Hs Hassium 265	Mt Meitnerium 268	Ds Darmstadtium 271	Rg Roentgenium 272	Cn Copernicium 285	Uut Ununtrium 288	Fl Flerovium 287	Uup Ununpentium 288	Lv Livermorium 293	Uus Ununseptium 294	Uuo Ununoctium 294
		57 La Lanthanum 138.905	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.254	69 Tm Thulium 168.934	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967		
		88 Ac Actinium 227	89 Th Thorium 232.038	90 Pa Protactinium 231.036	91 U Uranium 238.029	92 Np Neptunium 237.048	93 Pu Plutonium 244.064	94 Am Americium 243.061	95 Cm Curium 247.070	96 Bk Berkelium 247.070	97 Cf Californium 251.08	98 Es Einsteinium 252.083	99 Fm Fermium 257.10	100 Md Mendelevium 258.10	101 No Nobelium 259.10	102 Lr Lawrencium 260.10		
		Alkali Metal	Alkaline Earth	Transition Metal	Semimetal	Nonmetal	Basic Metal	Halogen	Noble Gas	Lanthanide	Actinide							

© 2017 IUPAC Commission on Nomenclature of Inorganic Chemistry

# Sand into Silicon



Silica a.k.a.  $\text{SiO}_2$  a.k.a. Quartz

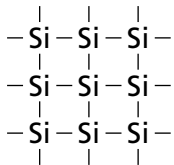


Elemental, amorphous silicon



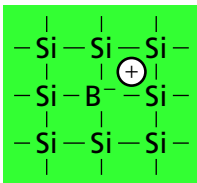
Monocrystalline  
Silicon Ingot

# Doping Silicon Makes It a Better Conductor



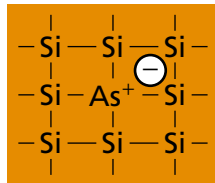
Undoped (pure)  
silicon crystal

Not a good  
conductor



p-type (doped)  
silicon:

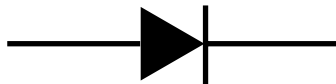
boron atom steals  
a nearby electron



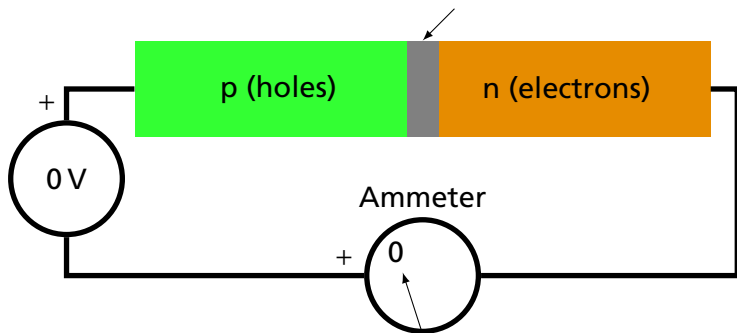
n-type (doped)  
silicon:

arsenic's extra  
electron jumps loose

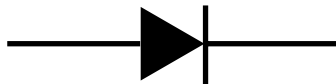
# A PN Junction aka A Diode



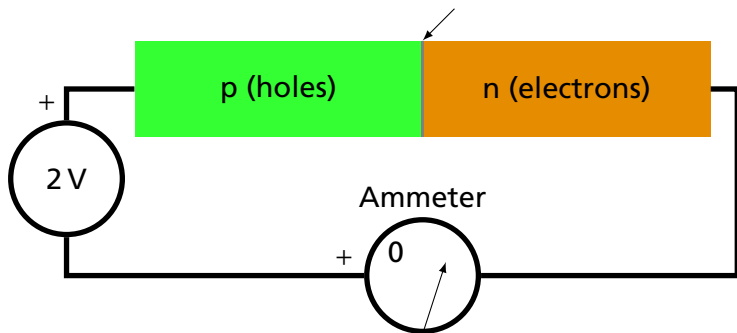
Depletion region



# A PN Junction aka A Diode

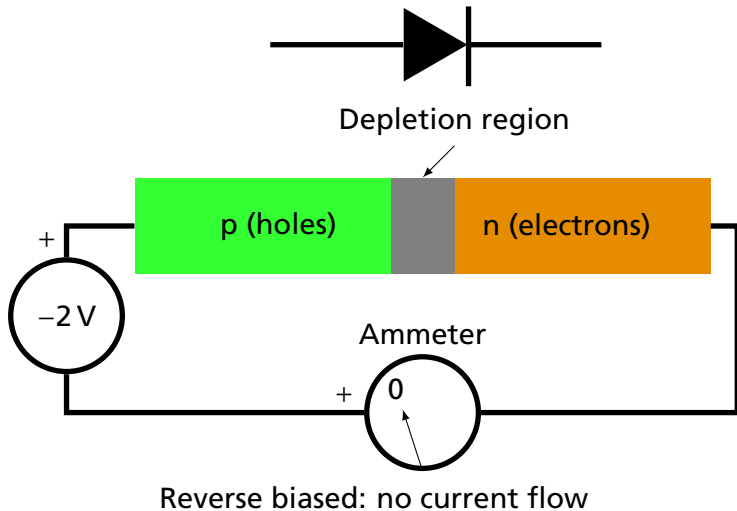


Depletion region

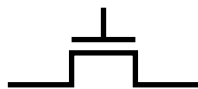


Forward biased: current flows

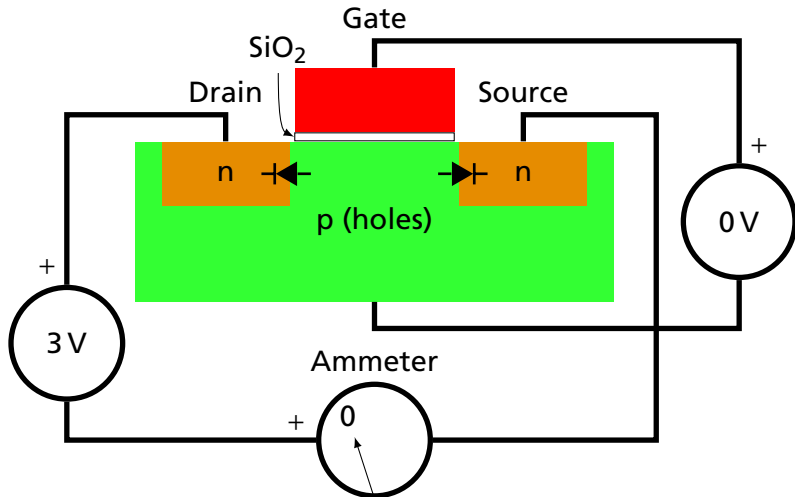
# A PN Junction aka A Diode



# An N-Channel MOS Transistor

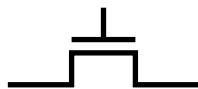


Gate at 0V: Off

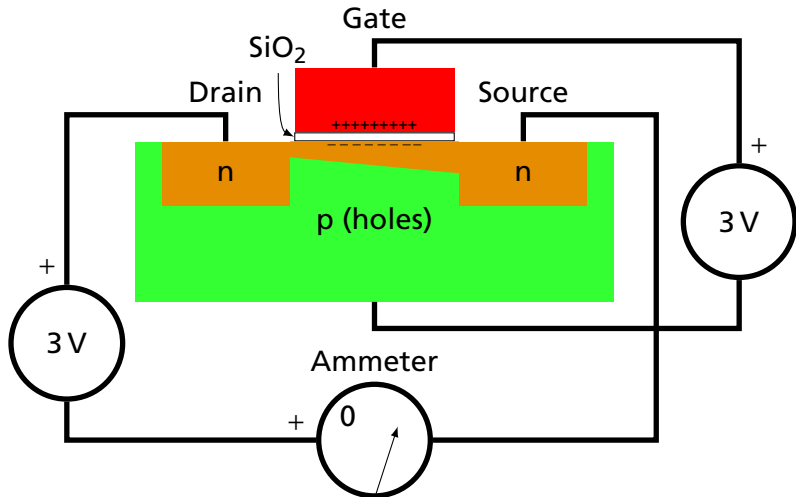




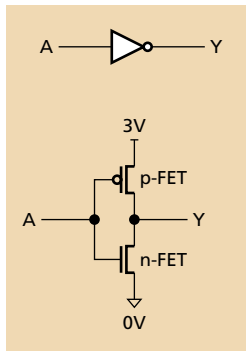
# An N-Channel MOS Transistor



Gate positive: On



# The CMOS Inverter

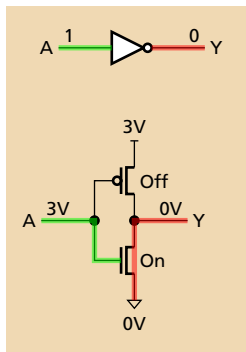


An inverter is built from two MOSFETs:

An n-FET connected to ground

A p-FET connected to the power supply

# The CMOS Inverter



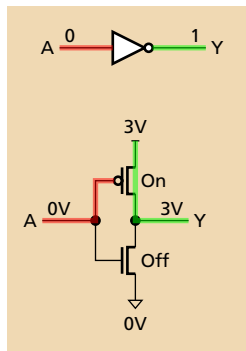
When the input is near the power supply voltage ("1"),

the p-FET is turned off;

the n-FET is turned on, connecting the output to ground ("0").

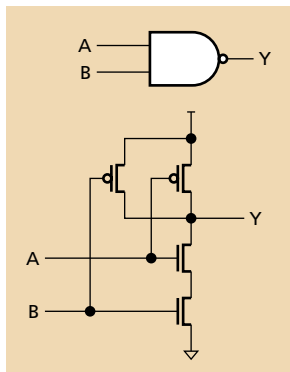
n-FETs are only good at passing 0's

# The CMOS Inverter



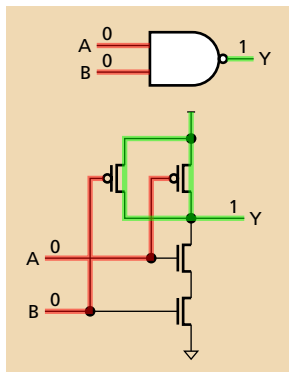
When the input is near ground ("0"), the p-FET is turned on, connecting the output to the power supply ("1"); the n-FET is turned off. p-FETs are only good at passing 1's

# The CMOS NAND Gate



Two-input NAND gate:  
two n-FETs in series;  
two p-FETs in parallel

# The CMOS NAND Gate

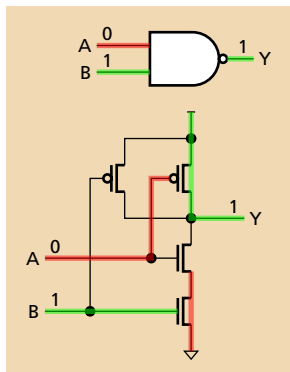


Both inputs 0:

Both p-FETs turned on

Output pulled high

# The CMOS NAND Gate



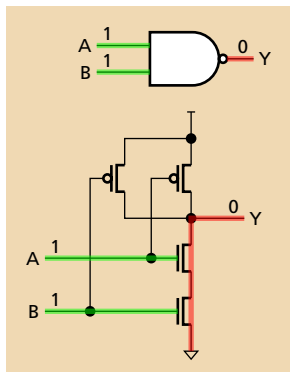
One input 1, the other 0:

One p-FET turned on

Output pulled high

One n-FET turned on, but does not control output

# The CMOS NAND Gate



Both inputs 1:

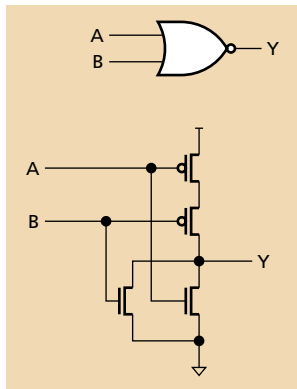
Both n-FETs turned on

Output pulled low

Both p-FETs turned off



# The CMOS NOR Gate



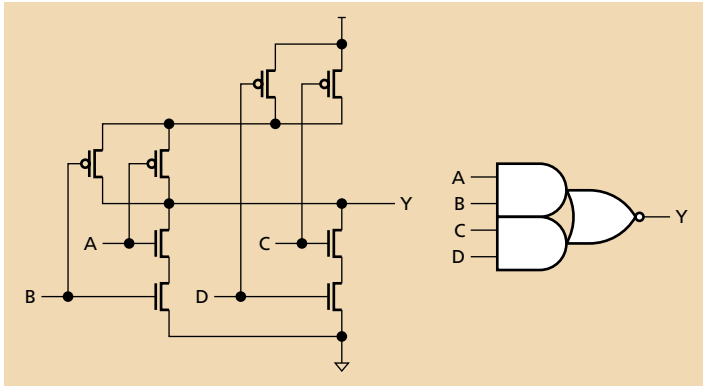
Two-input NOR gate:

two n-FETs in parallel;

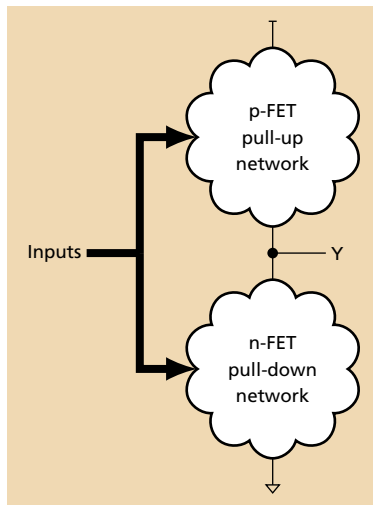
two p-FETs in series.

Not as fast as the NAND gate  
because n-FETs are faster than  
p-FETs

# A CMOS AND-OR-INVERT Gate



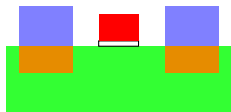
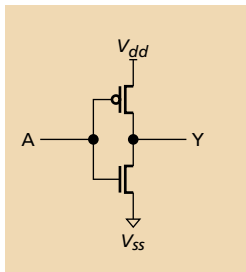
# Static CMOS Gate Structure



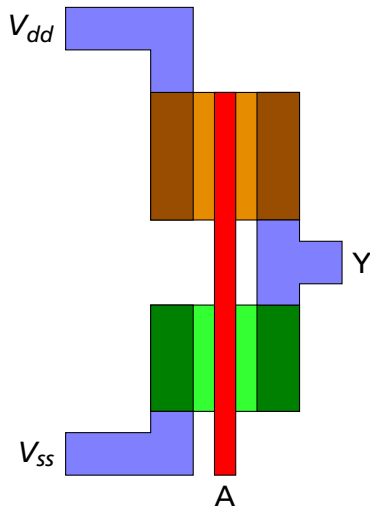
Pull-up and Pull-down networks must be complementary; exactly one should be connected for each input combination.

Series connection in one should be parallel in the other

# CMOS Inverter Layout



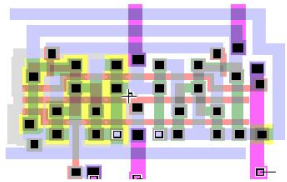
Cross Section Through  
N-channel FET



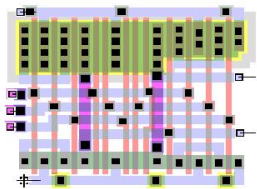
Top View

# Full Adder Layouts

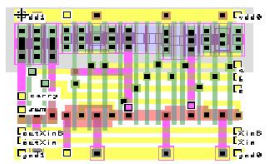
fa\_ly\_mini\_jk size: 60 · 40µm (1.2µmCMOS)



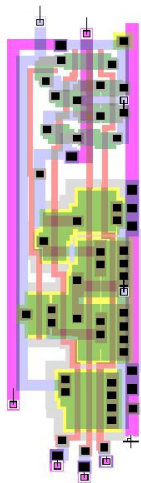
fa\_ly\_opt1 size: 63 · 50µm (1.2µmCMOS)



Fulladd L size: 37 · 26 µm (0.5µmCMOS)



fa\_ly\_itt size: 117 · 31 µm (1.2µmCMOS)



From <http://book.huihoo.com/design-of-vlsi-systems/>

# Intel 4004: The First Single-Chip Microprocessor

## Announcing a new era of integrated electronics



## A micro- programmable computer on a chip!

Intel introduces an integrated CMOS complete with a ROM for program memory, address and data registers, an accumulator and a single-chip random access memory. It's one of a family of four chips that comprise the Intel 4-bit micro-computer system - the first solution to bring you the power and flexibility of a dedicated general-purpose computer on one chip in as little as one drop of ink.

Intel's 4004 provides complete computing and control functions for real systems, data handling, utility functions, measuring systems, control control systems and provides control systems.

The heart of any 4004 system is a Type 4004 CPU, which contains a complete set of 45 instructions, floating point and other Type 4004 ROMs for program storage and data control plus a fully functioning program-programmed computer. To take you step with Type 4004, Intel has developed a family of Type 4004 systems to expand the computer world.

Intel's 4004 family offers you the best of both worlds. It's a complete computer system with ROM for program storage and data control plus a fully functioning program-programmed computer. To take you step with Type 4004, Intel has developed a family of Type 4004 systems to expand the computer world.

Intel's 4004 family offers you the best of both worlds. It's a complete computer system with ROM for program storage and data control plus a fully functioning program-programmed computer. To take you step with Type 4004, Intel has developed a family of Type 4004 systems to expand the computer world.

The Intel 4004 family is now in stock at Intel's Santa Clara headquarters and at our regional headquarters in Europe and Japan. In the U.S., call your local Intel representative for technical information and literature. In Europe, contact Intel at Avenue Louise 214, B-1050 Brussels, Belgium. Phone 32(2) 537-4111. In Japan, contact Intel Japan, Ltd., Parkside Plaza Bldg., 8th F., 2-2-1, Shinjuku, Shinjuku-Ku, Tokyo 102. Phone 81(3) 433-4111.

Intel Corporation now produces micro-computers, microprocessors and microperipherals at 3065 Avenida Arroyo, San Jose, Costa Rica. Phone 506(2) 226-1000.

intel  
delivers.

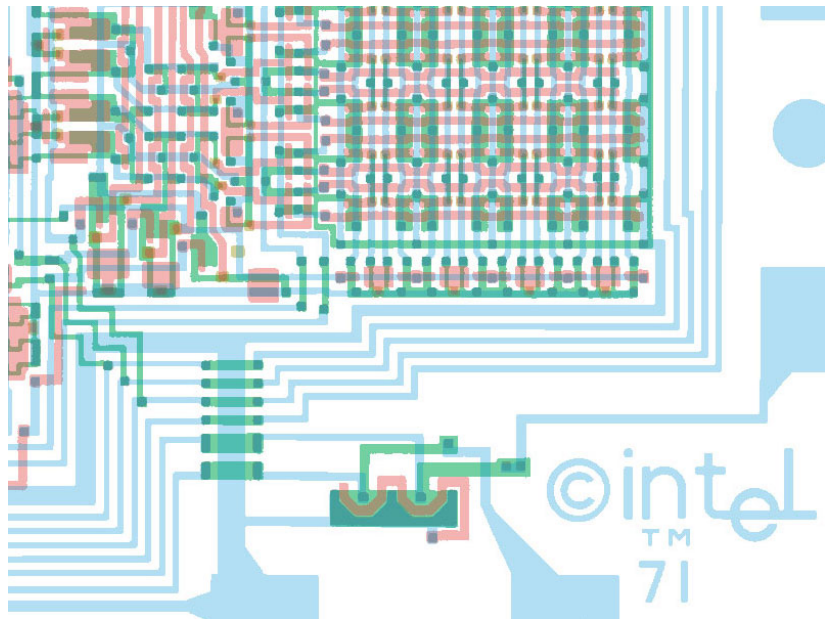
4001: 256-byte ROM + 4-bit IO port

4002: 40-byte RAM

4003: 10-bit shift register

4004: 740 kHz 4-bit CPU w/ 45 instructions (2300 transistors)

# Intel 4004 Masks



# Intel 4004 Die Photograph

