# Transistors and Logic Gates

Dov Kruger

Department of Electrical and Computer Engineering
Rutgers University

October 29, 2024

By the end of this unit you will be able to

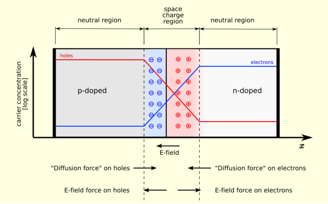
- Define basic terminology for semiconductors
- Identify different types of transistors
- Describe how CMOS gates work
- build a logic gates using transistors (but we won't)
- Use a MOSFET to turn on a power circuit
- Drive MOSFETs from your digital circuits
- Read a spec sheet for a MOSFET

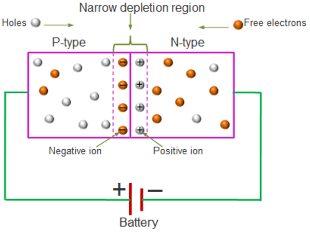
# Semiconductors

- Semiconductors: materials with electrical conductivity between conductors and insulators
- Silicon is the original, simple semiconductor
- Gallium Arsenide is more efficient for some applications
- Pure Semiconductors are poor conductors
- Doping: adding impurities to radically change conductivity
- N-type: doped with elements having extra electrons (e.g., phosphorus)
- P-type: doped with elements having fewer electrons (e.g., boron)

# Diodes and PN Junctions

- Diode: electronic component allowing current flow in one direction
- PN Junction: boundary between P-type and N-type semiconductors
- Forward bias: allows current flow (P connected to positive, N to negative)
- Reverse bias: blocks current flow (P connected to negative, N to positive)

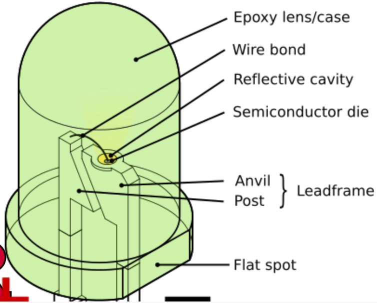



Forward bias

# Light Emitting Diodes (LEDs)

- LEDs are semiconductor devices that emit light when current flows through them
- Highly efficient: convert up to 70% of energy into light (compared to 10% for incandescent bulbs)
- Produce monochromatic light due to their atomic structure
- The material used determines the energy level of the photons emitted, hence the color
- Not made of silicon, but other semiconductor materials



# LED Materials and Colors

- Different semiconductor materials are used to produce different colors:
  - Red: Aluminum Gallium Arsenide (AlGaAs)
  - Green: Indium Gallium Nitride (InGaN)
  - Blue: Silicon Carbide (SiC) or Zinc Selenide (ZnSe)
  - White: Blue LED with yellow phosphor coating
- The choice of material is crucial for achieving the desired wavelength (color) of light
- Interesting history of blue LEDs: `https://www.youtube.com/watch?v=AF8d72mA41M`

# LED Voltage Requirements by Color

| Color | Typical Forward Voltage |
|---|---|
| Infrared | 1.2V - 1.5V |
| Red | 1.8V - 2.1V |
| Orange | 2.0V - 2.2V |
| Yellow | 2.1V - 2.4V |
| Green | 2.9V - 3.4V |
| Blue | 3.0V - 3.4V |
| White | 3.0V - 3.4V |
| Ultraviolet | 3.1V - 4.4V |

- Note: Actual voltage may vary slightly depending on specific LED model and current

# LEDs work in Reverse

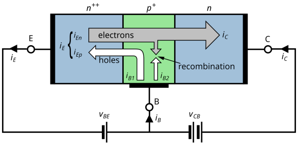
- LEDs take in electricity and efficiently turn it to light
- In reverse, they turn light into electricity
- This is how solar cells work
- Photovoltaic effect: Einstein 1905, Nobel 1922
- Solar cells are more efficient though
- Design is not symmetric
- Similar principle: Motors and generators

# Types of Transistors

- Bipolar Junction Transistor (BJT)
- Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)
- Complementary Metal-Oxide-Semiconductor (CMOS)
- BJTs are controlled by current
- FETs are controlled by voltage

# Bipolar Junction Transistor (BJT)

- Invented in 1947: Shockley, Brattain, and Bardeen
- Three terminals: Base, Emitter, Collector
- Small current at base controls larger current
- From Emitter to Collector
- Types: NPN and PNP (NPN is more efficient)



- BJT was the first kind of transistor Invented
- Generally uses more current (less efficient) than MOSFET
- Cheaper, so still used in low-cost applications
- Electrons are more mobile than holes
- N-type materials are therefore superior to P
- NPN transistors are more efficient than PNP
- NPN symbol: 

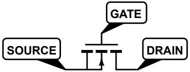
- PNP symbol: 

# Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

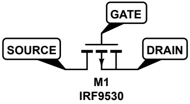
- Invented by Mohamed Atalla and Dawon Kahng in 1959
- Three terminals: Gate, Source, Drain
- Controlled by voltage to the Gate
- A dielectric on the gate prevents current
- Extremely high gate resistance
- FETs are the technology used for computers.

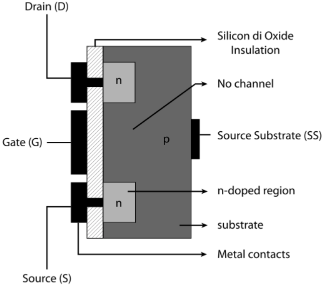
# Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

- N-channel: Turn on when $Gate = Source + V_{GS}$
- P-channel: Turn on when $Gate = Source - V_{GS}$
- N-channel symbol:



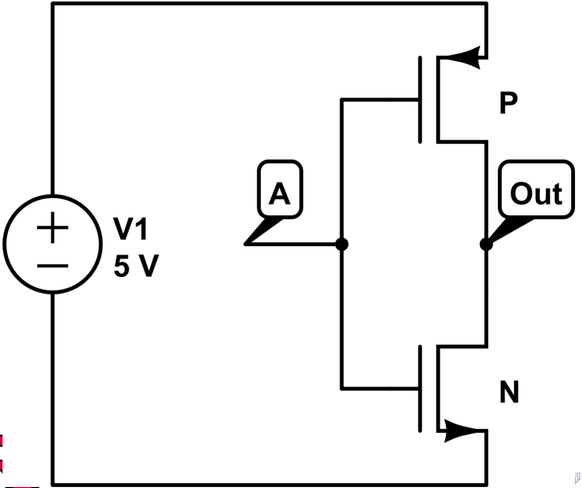

- P-channel symbol:



# Complementary Metal-Oxide-Semiconductor (CMOS)

- Combines N-channel and P-channel MOSFETs
- Used in digital logic circuits
- Low power consumption: Very high resistance on Gate



# Reading MOSFET Datasheets

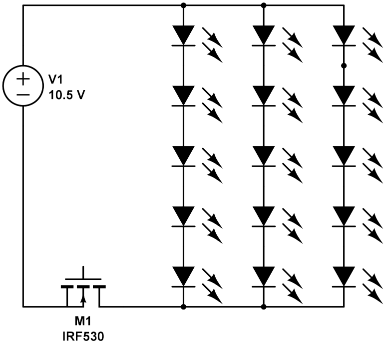
- Key parameters to look for:
  - Maximum Drain-Source Voltage ($V_{DS}$)
  - Maximum Gate-Source Voltage ($V_{GS}$)
  - Maximum Drain Current (Id)
  - Threshold Voltage ($V_{GS}(th)$)
  - On-Resistance ($RDS_{on}$)
- Always refer to the datasheet for specific characteristics and operating conditions

# Specific MOSFET Examples

- 2N7000 (Small signal MOSFET)
  - N-channel
  - Max Voltage $V_{DS} = 60V$
  - Max Current $I_D = 200mA$
  - $V_{GS}$ for max current: 10V
  - Max $V_{GS}$: 20V
  - On-Resistance $RDS_{on} = 5\Omega$
- IRF630 (Power MOSFET)
  - N-channel
  - Max Voltage $V_{DS} = 200V$
  - Max Current $I_D = 9A$
  - $V_{GS}$ for max current: 10V
  - Max $V_{GS} = 20V$
  - On-Resistance $RDS_{on} = 0.4\Omega$

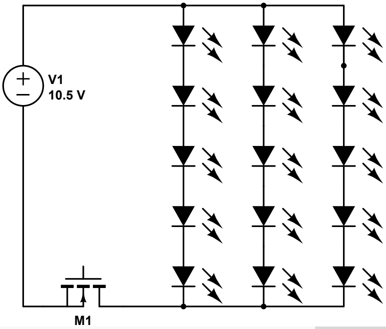
# Controlling a Bank of LEDs with an N-channel MOSFET

- Use an N-channel MOSFET to control multiple LEDs
- Connect the source to ground
- Connect the drain to the cathode of the LEDs
- Connect the anode of the LEDs to the power supply through current-limiting resistors
- Apply a voltage to the gate to turn on the MOSFET and light up the LEDs


V1
10.5 V
M1
IRF530

# Efficient Lighting with LEDs in Series

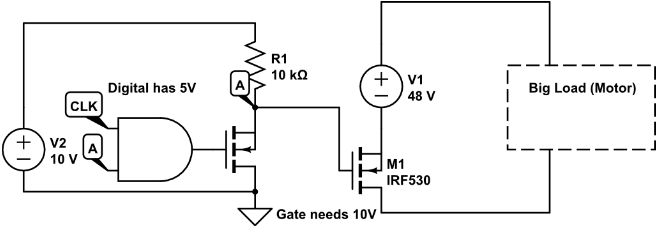
- Eliminate the resistors
- Design a circuit that uses all the voltage to light LEDs
- Example: 10.5V use 5 red LEDs in series (2.1V each)
- No need for resistors, all power is used to produce light
- Not commercially viable because highly dependent on precision voltage
- If the voltage rises, the LED lifetimes will shrink



# Level Shifting to Turn on the MOSFET

- For longest lifetime and high efficiency, MOSFET should be fully on
- Requires 10V or more, digital logic is only 5V
- Solution: Use a small secondary MOSFET and a pullup resistor for level shifting
- When the control signal is high
  - Secondary MOSFET turns on
  - Pulls the gate of the main MOSFET low
  - Main MOSFET turns off
- When the control signal is low
  - Secondary MOSFET turns off
  - Pullup resistor pulls the gate of the main MOSFET high
  - Main MOSFET turns on

# Level Shifting to Turn on the MOSFET



# Voltage Levels and P-channel MOSFETs

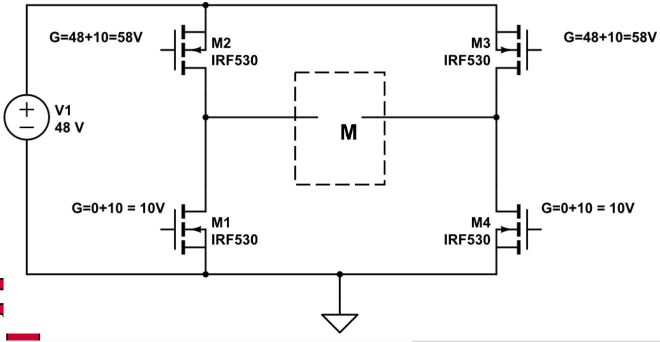
- P-channel MOSFETs are less convenient for digital circuits
- Digital circuits typically operate at 0V (low) and 5V (high)
- P-channel MOSFETs require a negative gate-source voltage to turn on
- This means the gate must be pulled below the source voltage
- In a 5V digital system, this can be challenging to achieve
- N-channel MOSFETs are preferred because they turn on with a positive gate-source voltage
- Easier to interface with standard digital logic levels

# N-channel MOSFETs are Preferred

- N-channel MOSFETs are preferred because resistance is lower
- Easier to interface with standard digital logic levels
- P-channel MOSFETs require a negative gate-source voltage to turn on
- This can be challenging to achieve in a 5V digital system
- N-channel MOSFETs turn on with a positive gate-source voltage
- Easier to drive with standard digital logic levels
- N-channel MOSFETs are more common and easier to use in digital circuits

# H-Bridge Controller with 4 N-Channel MOSFETs

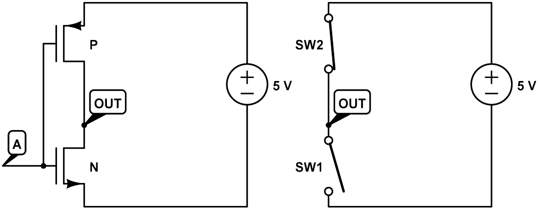
- H-Bridge with 4 N-channel MOSFETs for motor control
- Lower N-channel MOSFETs driven directly by Arduino (5V)
- Upper N-channel MOSFETs require $48 + 10 = 58V$ to fully turn on
- Full on state requires 10V for lower MOSFETs and 58V for upper MOSFETs
- Typical solution: Buy an H-Bridge driver
- Full H-bridge on a chip: L298N (low power)



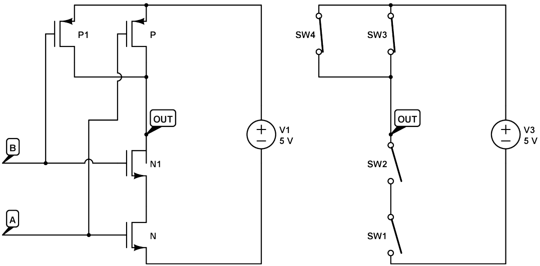
# How is Logic Implemented?

- CMOS is the dominant logic technology today
- Complementary Metal Oxide Semiconductor
- CMOS is a type of MOSFET
- First CMOS IC: 4-bit binary multiplier, 1964
- Preferred for digital logic due to
  - Low power consumption
  - High speed
  - Ability to integrate many transistors on a single chip

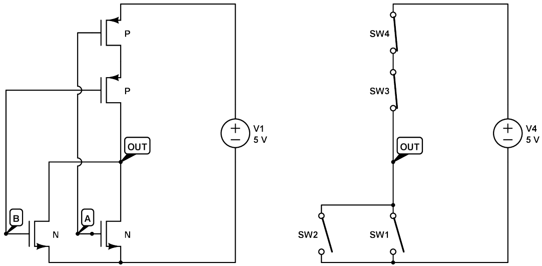
# Switch Equivalents of Transistors: NOT



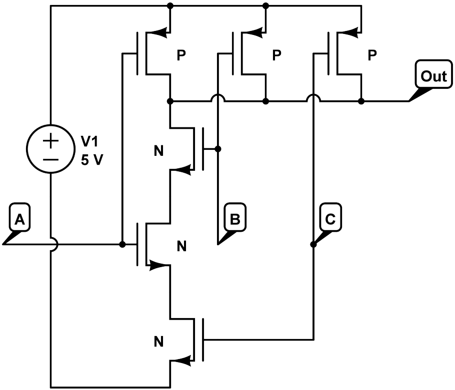
# Switch Equivalents of Transistors: NAND



# Switch Equivalents of Transistors: NOR



# CMOS 3-Input NAND Implementation



- Switching a transistor on and off takes a finite time
- 74LS gate delays are 10ns
- 4000 CMOS delays are 1ns
- Modern Computers clock cycles of 3GHz
- In that time, hundreds of gate delays must happen
- Details are proprietary. Hard to find out how fast
- Assume 300 gate delays per clock cycle: $333ps/300 = 1.11ps$
- Chatgpt claims 10-20ns