Elements of Electronics and Circuit Analysis

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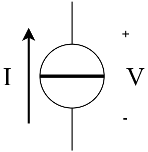
L.A.P. 1 Course

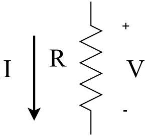
The Ohm's Law
The Kirchhoff Voltage Law (KVL)

Basic Elements of Direct Current (DC) Circuits

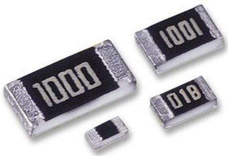
- *V*, voltage (Volt), difference of electrical potential
- *I*, current (Ampere), flow of electrons in circuit components
- *R*, resistance (Ohm), ability to “oppone” to electron flow



Voltage generator

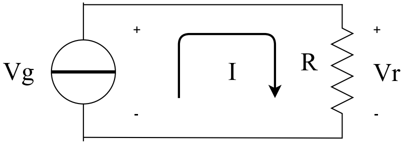


Resistor



The Ohm's Law

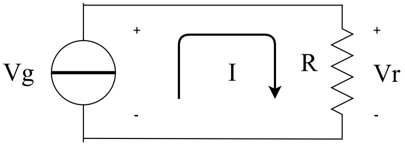
$$V = R\,I$$



$$V_g = V_r$$
$$V_r = R\,I$$

Given $V_g = 5V$ and $R = 10K\Omega$, calculate the current intensity

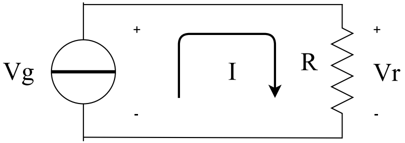
$$V = R\ I$$



$$\begin{aligned} I &= \frac{V_g}{R} = \\ &= \frac{5}{10 \cdot 10^3} = \\ &= 0.5 \cdot 10^{-3} A = \\ &= 0.5 mA \end{aligned}$$

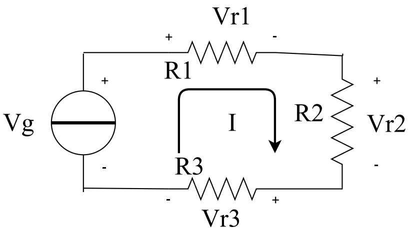
Given $V_g = 5V$, calculate the resistance to obtain a current of $3A$

$$V = R\,I$$



$$\begin{aligned} R &= \frac{V_g}{I} = \\ &= \frac{5}{3} = \\ &= 1.\overline{6}\Omega \end{aligned}$$

The algebraic sum of the voltages in a circuit **loop** is equal to 0

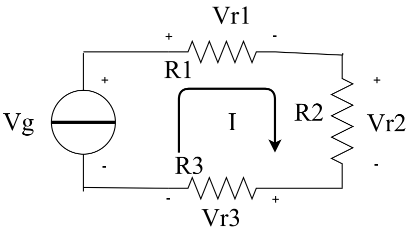


$$-V_g + V_{R1} + V_{R2} + V_{R3} = 0$$

$$V_{R1} + V_{R2} + V_{R3} = V_g$$

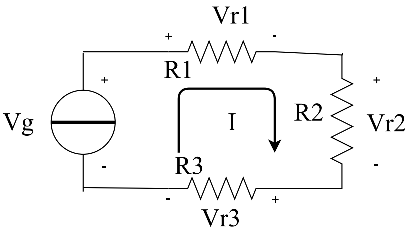
The Kirchhoff Voltage Law

Given $V_g = 5V$, $R1 = 220\Omega$, $R2 = 150\Omega$, $R3 = 18\Omega$, calculate V_{R1}, V_{R2} and V_{R3}.



$$
\begin{aligned}
V_g &= V_{R1} + V_{R2} + V_{R3} \\
V_g &= R1\ I + R2\ I + R3\ I \\
V_g &= (R1 + R2 + R3)\ I \\
I &= \frac{V_g}{R1 + R2 + R3} = \frac{5}{220 + 150 + 18} = 0.013A
\end{aligned}
$$

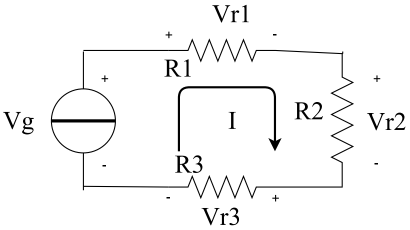
Given $V_g = 5V$, $R1 = 220\Omega$, $R2 = 150\Omega$, $R3 = 18\Omega$, calculate V_{R1}, V_{R2} and V_{R3}.



$$I = \frac{V_g}{R1 + R2 + R3} = \frac{5}{220 + 150 + 18} = 0.013A$$

$$V_{R1} = R1\ I = 220 \cdot 0.013 = 2.860\,V$$
$$V_{R2} = R2\ I = 150 \cdot 0.013 = 1.950\,V$$
$$V_{R3} = R3\ I = 18 \cdot 0.013 = 0.234\,V$$

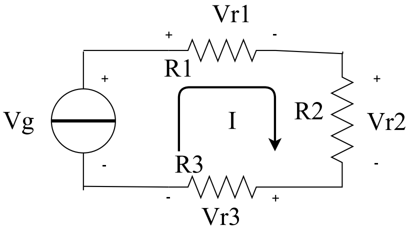
Given the circuit below, calculate e generic forumla that gives V_{R2} from V_g, $R1$, $R2$ and $R3$.



$$
\begin{aligned}
V_g &= V_{R1} + V_{R2} + V_{R3} \\
V_g &= R1\ I + R2\ I + R3\ I \\
V_g &= (R1 + R2 + R3)\ I \\
I &= \frac{V_{R2}}{R2} \\
V_g &= (R1 + R2 + R3)\frac{V_{R2}}{R2}
\end{aligned}
$$

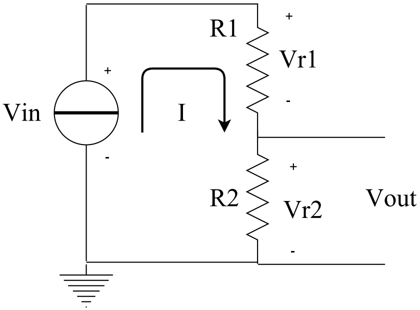
The Kirchhoff Voltage Law

Given the circuit below, calculate e generic forumla that gives V_{R2} from V_g, $R1$, $R2$ and $R3$.



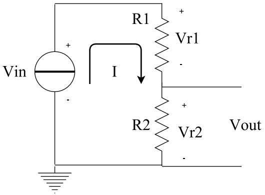
$$
\begin{aligned}
V_g &= (R1 + R2 + R3)\, I \\
I &= \frac{V_{R2}}{R2} \\
V_g &= (R1 + R2 + R3)\frac{V_{R2}}{R2} \\
V_{R2} &= \frac{R2}{R1 + R2 + R3} V_g
\end{aligned}
$$

The Voltage Divider



$$V_{out} = \frac{R2}{R1 + R2} V_{in}$$

Exercise with Voltage Divider



Determine the resistors needed to adapt a 24V sensor, to a 5V microcontroller input (use resistors in the order to Kohms)

$$V_{in} = 24$$
$$V_{out} = 5$$
$$\frac{V_{out}}{V_{in}} = 0.21 = \frac{R2}{R1 + R2}$$

Let's choose $R2 = 10\ K\Omega$

$$\frac{10}{R1 + 10} = 0.21$$
$$R1 = 37.619\ K\Omega$$

Standard Values of Resistors

- Resistors are made using some specific "standard values" of resistance
- In each order of magnitude, standard values are:

1.0	1.2	1.5	1.8
2.2	2.7	3.3	3.9
4.7	5.6	6.8	8.2

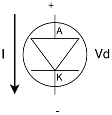
- So the value $R1 = 37.619\ K\Omega$ cannot be found in a physical component, but the nearest value must be used $\Rightarrow\ R1 = 39\ K\Omega$
- The real voltage adaptation is:

$$V_{out} = \frac{R2}{R1 + R2} V_{in} \quad = \quad \frac{10}{10 + 39} 24 = 4.9\ V$$

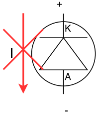
Semiconductors
Signal Diodes and Light Emitting Diodes (LEDs)

Diode

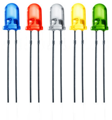
- A **diode** is an electronic component made of “semi-conductor” materials (germanium, silicon, arsenic, gallium, ...)
- It has two wires **anode** and **catode**
- If it is **directly polarized**, it causes a **voltage fall** of V_d (˜0.7V in silicon diode, ˜2.0V in LEDs) and permits current flow
- If it is **inversely polarized**, it impedes current flow
- A **LED** (Light Emitting Diode) emits visible light (of various colors) when directly polarized



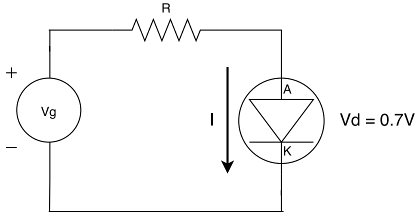
Direct Polarization



Inverse Polarization



Given $V_g = 5V$, $R = 220\Omega$, calculate the current I

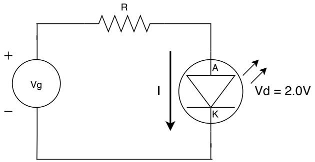


$$
\begin{aligned}
V_g &= V_R + V_d \\
5 &= V_R + 0.7 \\
V_R &= 4.3 \\
I &= \frac{V_R}{R} \\
I &= \frac{4.3}{220} = 0.02A = 20mA
\end{aligned}
$$

How to compute the limiting resistor for a LED

- LEDs have a **forward voltage** of 1.2–3.0 V
- LEDs have a **forward current** that depends on the luminosity, in general in the order of 20 mA

Given $V_g = 5V$, $I = 20\ mA$ and $V_d = 2V$, compute the limiting resistance

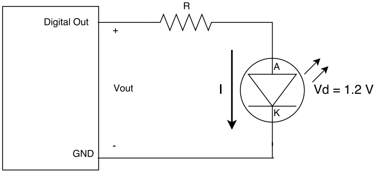


$$\begin{aligned} V_g &= V_R + V_d \\ 5 &= V_R + 2.0 \\ V_R &= 3 \\ R &= \frac{V_R}{I} = \frac{3}{0.02} = 150\Omega \end{aligned}$$

Example: how to connect a LED to a NUCLEO Board

- Digital Output generates a **voltage** of 3.3 V
- We consider a LED with a **forward voltage** of 1.2 V
- We want a current of 20 mA

- Let's compute the limiting resistor:

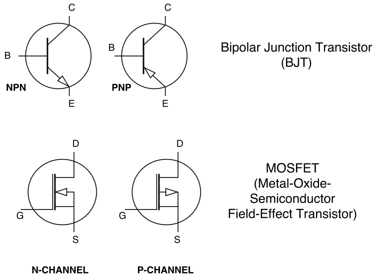


$$
\begin{aligned}
V_{out} &= V_R + V_d \\
3.3 &= V_R + 1.2 \\
V_R &= 2.1 \\
R &= \frac{V_R}{I} = \frac{2.1}{0.02} = 105\Omega
\end{aligned}
$$

Semiconductors
Transistors

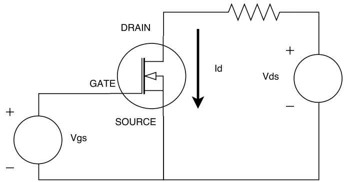
Transistor

- A **Transistor** is an electronic component made of “semi-conductor” materiales (germanium, silicon, arsenic, gallium, ...)
- It has *three wires* and acts as a **voltage/current amplifier**
- There are several types of transistors which differ in internal structure, functioning and applications:
  - **Bipolar Junction Transistor** (BJT)
  - **Junction Field-Effect Transistor** (JFET)
  - **Metal-Oxide-Semiconductor Field-Effect Transistor** (MOSFET)

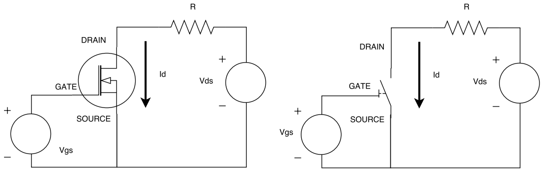


MOSFET Transistor

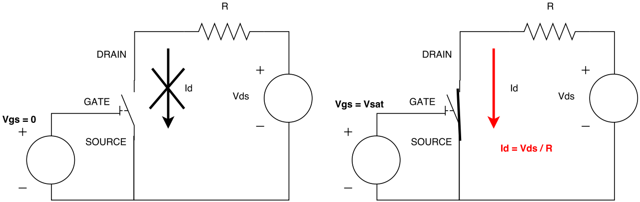
- A **MOSFET Transistor** acts as **voltage-to-current amplifier**
- It has *three wires* called **Gate**, **Source**, **Drain**
- When a certain **gate-to-source voltage** V_{GS} is applied, the **drain-to-source line starts to conduct** thus resulting in a certain current flow I_D
- The MOSFET behaviour is (basically) governed by a linear **transconductance law**: $I_D \cong G \ V_{GS}$
- G is called **transconductance** and its value (in the order of $100 - 500$) is specific of any type of MOSFET



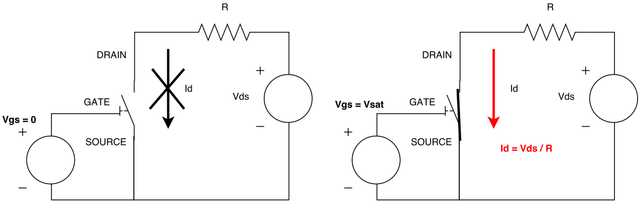
MOSFET in non-linear region



- The most interesting behaviour of MOSFET, for digital circuits, is the **non-linearity**
- The MOSFET can act as a **voltage-controlled-switch**
- When V_{GS} reaches a certain **saturation voltage** V_{SAT}, the Source and the Drain are *short-circuited*, like a classical mechanical switch



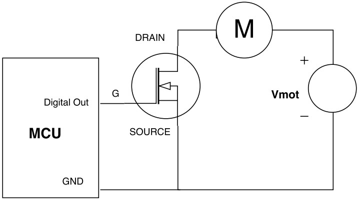
MOSFET in non-linear region



- The non-linearity is featured not only by MOSFETs but also BJTs
- The non-linearity is exploited in **all digital circuits**
- All the components of a computer/CPU/MCU are made by BJTs or MOSFETs working in the non-linear region

Example: Driving a motor from a MCU

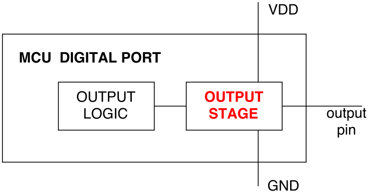
- **Power components (e.g. electric motors) cannot be directly driven by a MCU digital output**
- Small Electric Motor:
  - Working voltage of $6\ V, 12\ V, 24\ V, 48\ V$ (and even higher voltages)
  - Typical current in the order of $100\ mA - 10\ A$
- MCU digital outputs:
  - Output voltage of $5\ V$ or $3.3\ V$
  - Able to drive currents in the order of $100\ \mu A - 200\ mA$
- A MOSFET can be used as a **motor driver**: activated from a digital output, it can drive the motor connected in the **drain-source** net:



The Output Stage of a MCU Digital Port

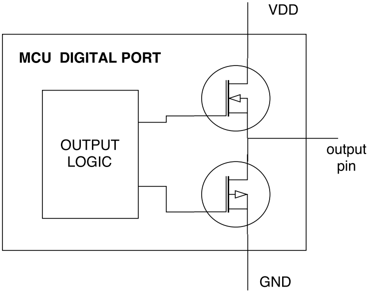
The Output Stage of MCU Digital Port

- In a MCU, the circuit of a digital output line is composed of two stages:
  1. The output logic
  2. The **output stage**, that can be configured via software



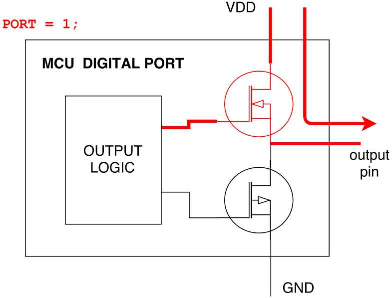
The “Push-Pull” Output Stage

- The **Push-Pull** output stage (also called **totem pole**) is made of two MOSFETs connected as in Figure, the “upper” and the “lower” one



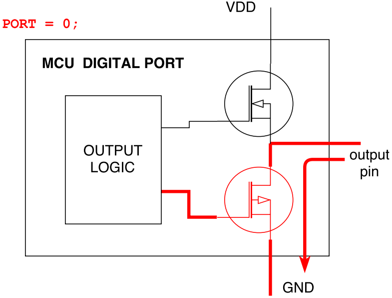
Push-Pull — Writing "1"

- When the software **writes "1"** in the output port, the output logic **activates the upper MOSFET**
- The output is thus **physically connected to VDD** (5 V or 3.3 V according to power voltage)



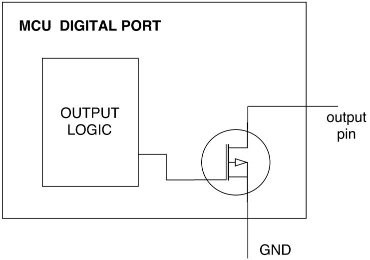
Push-Pull — Writing “0”

- When the software **writes “0”** in the output port, the output logic **activates the lower MOSFET**
- The output is thus **physically connected to ground**



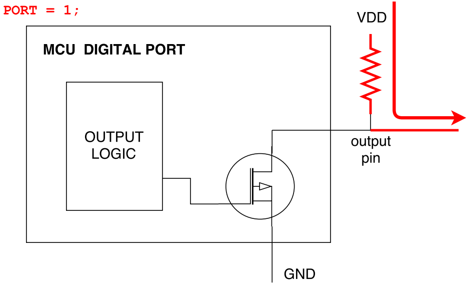
The “Open-Drain” Output Stage

- The **Open-Drain** output stage is made of only one MOSFET, the “lower” one
- Its drain of the MOSFET is connected only to the output and thus left “floating” (i.e. “open”)



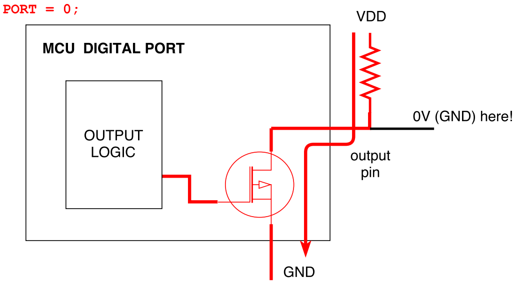
Open-Drain — Writing "1"

- When the software **writes "1"** in the output port, **nothing happens** and the drain is left **floating**
- The logic state must be maintained by an external **pull-up resistor**



Open-Drain — Writing “0”

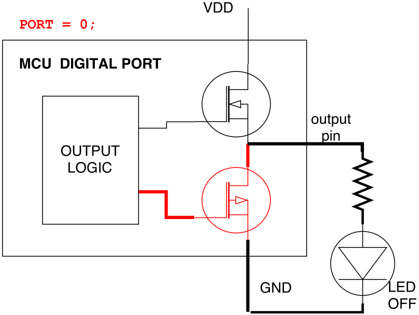
- When the software **writes “0”** in the output port, the output logic **activates the lower MOSFET**
- The output is thus **physically connected to ground**

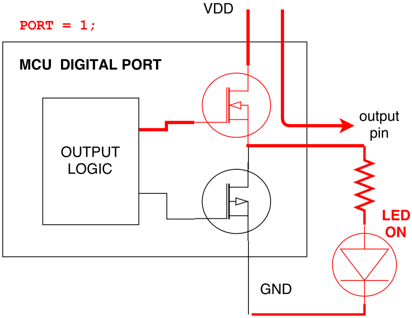


Connecting a LED to a MCU Digital Port

LED connected from output to ground

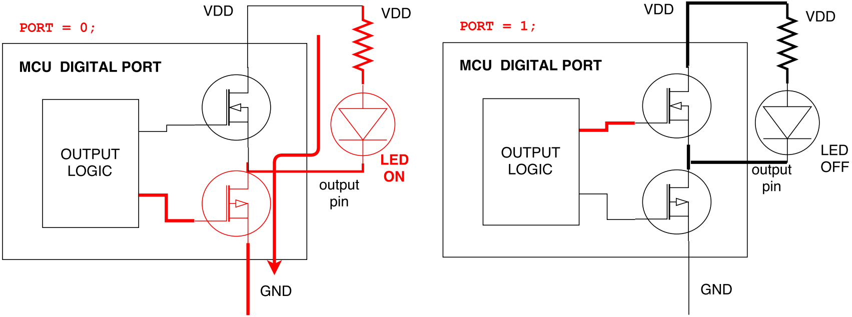
- When the LED is connected from output to ground
  - Writing **"0"** in the output port means to **turn off the LED**
  - Writing **"1"** in the output port means to **turn on the LED**





LED connected from output to VDD

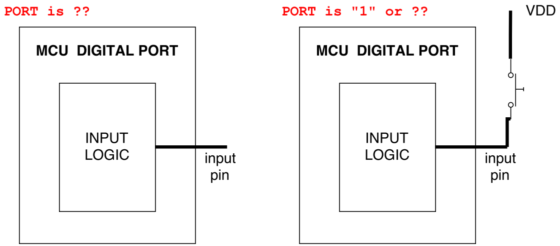
- When the LED is connected from output to VDD
  - Writing **“0”** in the output port means to **turn on the LED**
  - Writing **“1”** in the output port means to **turn off the LED**



Digital Inputs and Pushbuttons

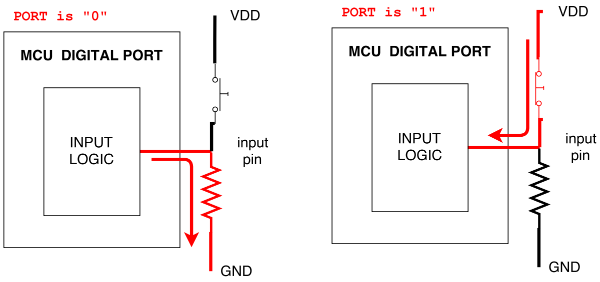
Digital Inputs

- A **digital input** of a MCU, when used, cannot be left **open/floating**
- Even if (apparently) no current flows, a floating input can “capture” everything from the environment (it is like an “antenna”)
- If a pushbutton is connected as in figure:
  - Software reads “1” when the button is pressed
  - but if the button is not pressed, the value could be either “0” or “1”
  - We must **force a state** when the button is **not** pressed



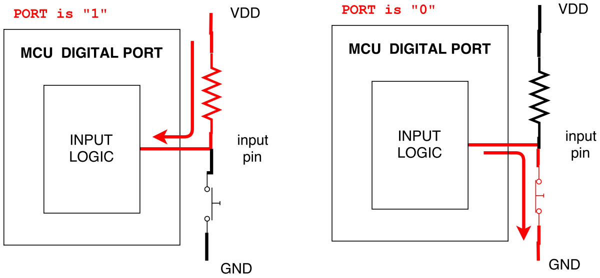
Digital Inputs wih “Pull-Down” configuration

- A resistor is connected through the input and the ground
- The pushbutton is connected through the input and the VDD
    - When the pushbutton is **not pressed**, the resistor “pulls down” the input, so the software reads “0”
    - When the pushbutton is **pressed**, the pin is directly connected to positive voltage (VDD), so the software reads “1”



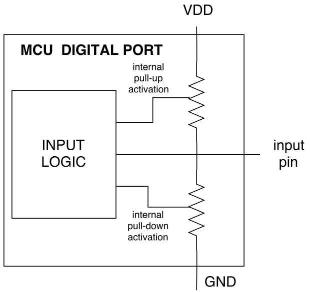
Digital Inputs with “Pull-Up” configuration

- A resistor is connected through the input and VDD
- The pushbutton is connected through the input and the ground
    - When the pushbutton is **not pressed**, the resistor “pulls up” the input, so the software reads “1”
    - When the pushbutton is **pressed**, the pin is directly connected to ground, so the software reads “0”



Digital Inputs with interla “Pull-Up”/”Pull-Down”

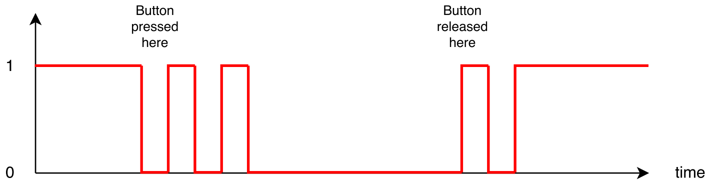
- Pull-up/pull-down resistors are not necessary when the digital port provides them “internally”
- In the STM32, each port pin can be configured to activate an **internal pull-up or pull-down resistor**
- Configuration is made per-pin through a proper special function register



Switch and Pushbutton bouncing effect

The Bouncing Effect

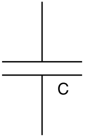
- Switches and pushbutton contain **springs** so, from the mechanical point of view, they are oscillating systems
- In a digital circuit, these systems provoke a “bouncing effect”: the signal “bounces” between “0” and “1” when the button is pressed or relased
- Bouncing can be read by the software (that is very fast) thus causing malfunctioning of the system
- Bouncing can be removed by using **capacitors**

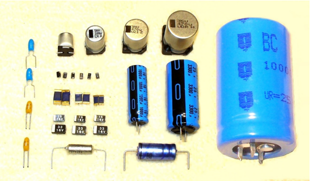


Capacitors

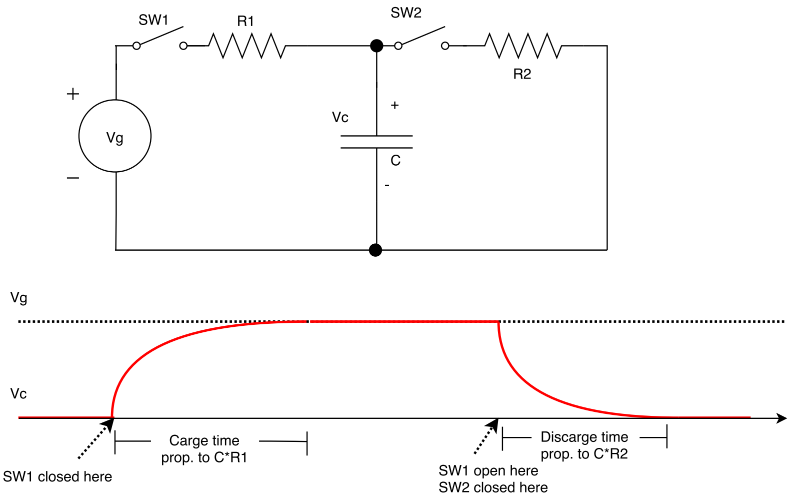
Capacitors

- A **capacitor** is a circuit element able to **gather/store electric charge**
- It is composed of two **plates** separated by a **dielectric** (insulator)
- The electric energy is stored in plates and depends on the size and material of plates and insulator
- The **capacity** (ability to store electric energy) is measured in **Farad** ($\mu F, nF, pF$)



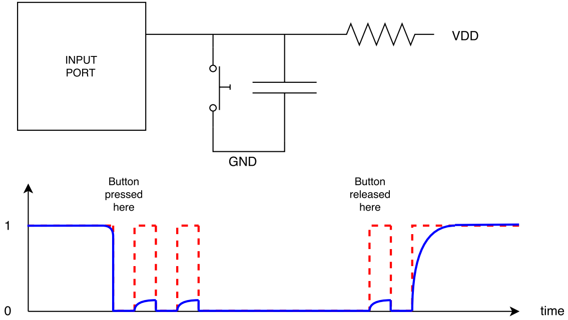


Dynamics of a capacitor



Debouncing Circuit with Capacitor

- A **Debounce capacitor** is placed in parallel of push-buttons or switches
- The result is removing the “bouncing effect” of the mechanical parts
- During bouncing, when the pushbutton is “off”, the capacitor is charged through the resistance, so the voltage increases but it does not reach a value enough to make the port read as “1”



Elements of Electronics and Circuit Analysis

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L.A.P. 1 Course