Schedule…

Date	Day	Class No.	Title	Chapters	HW Due date	Lab Due date	Exam
22 Oct	Wed	15	Transient Response 1st Order Circuits	5.3 – 5.4			
23 Oct	Thu						
24 Oct	Fri		Recitation				
25 Oct	Sat						
26 Oct	Sun						
27 Oct	Mon	16	Sinusoidal Frequency Response	6.1		LAB 5	
28 Oct	Tue						
29 Oct	Wed	17	Operational Amplifiers	8.1 – 8.2			

Good, Better, Best

<u>Elder Oaks (October 2007)</u>:

As we consider various choices, we should remember that it is not enough that something is **good**. Other choices are **better**, and still others are **best**. Even though a particular choice is more costly, its far greater value may make it the **best** choice of all.

I have never known of a man who looked back on his working life and said, "I just didn't spend enough time with my job."

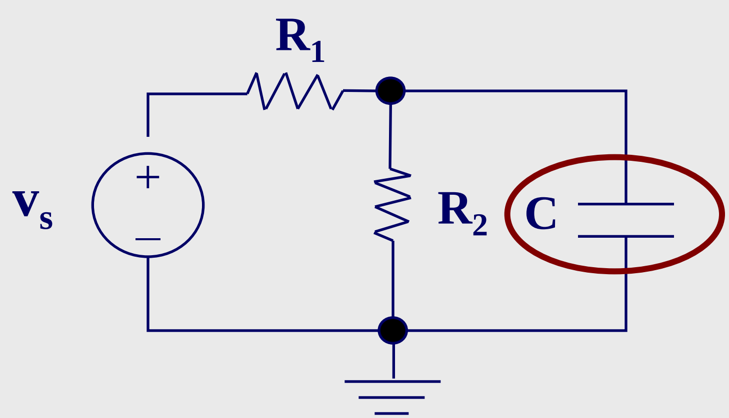
Lecture 15 – Transient Response of 1st Order Circuits

DC Steady-State

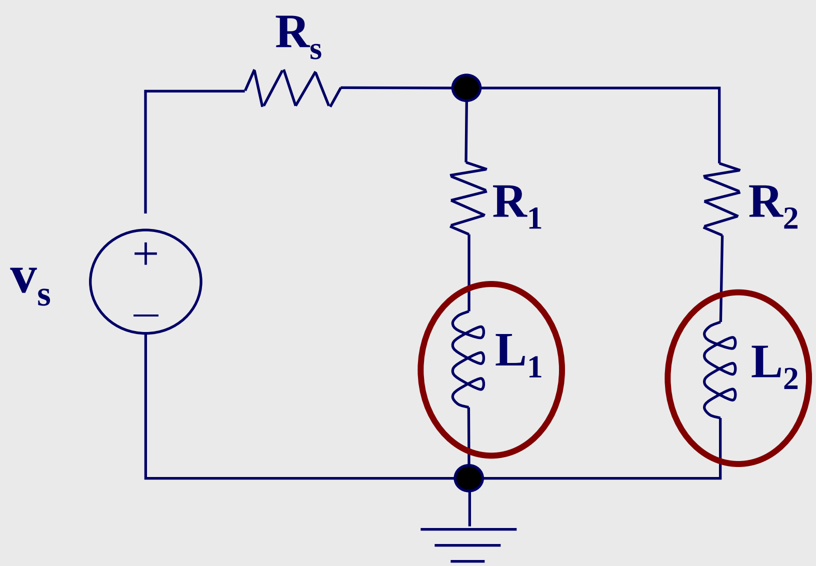
Transient Response

1st Order Circuits

Electric circuit 1st order system: any circuit containing a **single** energy storing element (either a **capacitor** or an **inductor**) and any number of **sources** and **resistors**



1st order

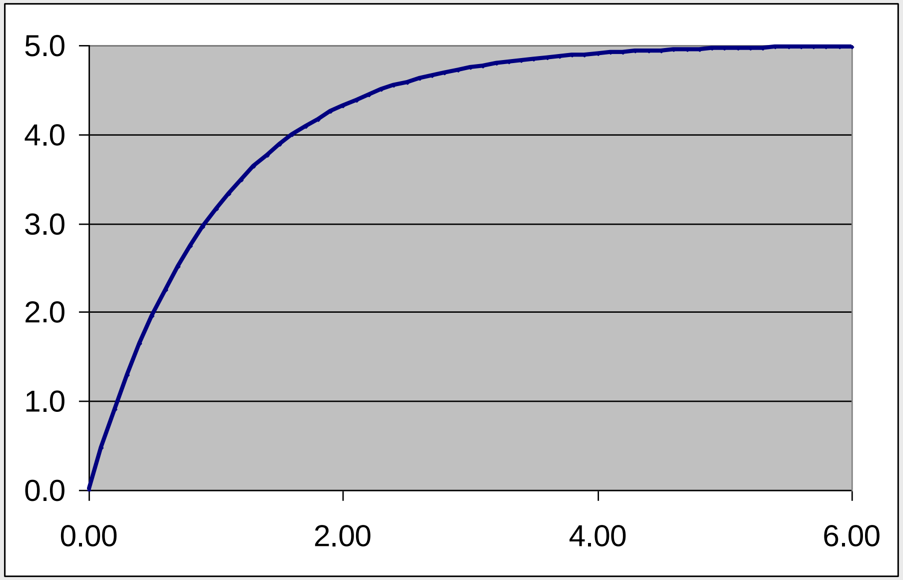


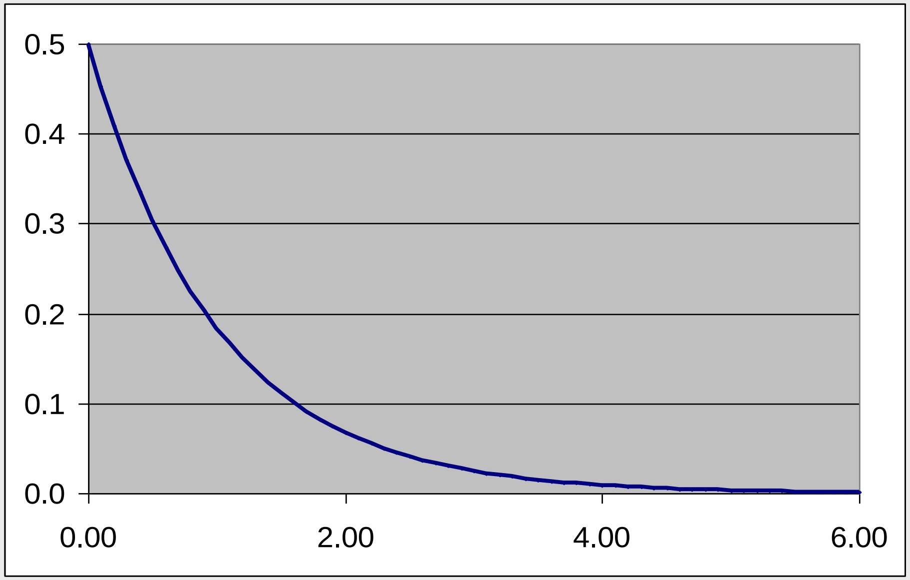
2nd order

Capacitor/Inductor Voltages/Currents

Review of capacitor/inductor currents and voltages

- exponential growth/decay





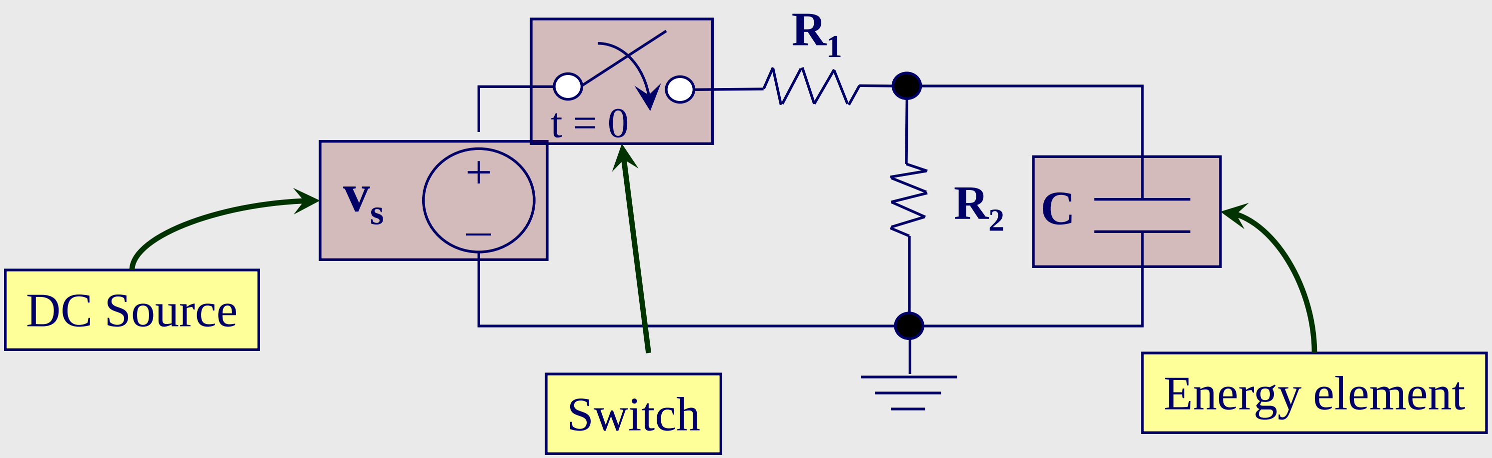
Capacitor voltage $\mathbf{v_C(t)}$
Inductor current $\boldsymbol{i_L}\mathbf{(t)}$
NB: neither can change instantaneously

Capacitor current $\boldsymbol{i_C}\mathbf{(t)}$
Inductor voltage $\mathbf{v_L(t)}$
NB: both can change instantaneously

Transient Response

Transient response of a circuit consists of 3 parts:

1. Steady-state response **prior** to the **switching** on/off of a **DC source**
2. Transient response – the circuit **adjusts** to the **DC source**
3. Steady-state response **following** the transient response



1. DC Steady State

1st and 3rd Step in Transient Response

DC Steady-State

DC steady-state: the **stable** voltages and currents in a circuit connected to a DC source

$$i_C(t) = C\frac{dv_C(t)}{dt} \quad \text{capacitor current}$$
$$i_C(t) \to 0 \quad \text{as } t \to \infty \quad \text{steady state current}$$

Capacitors act like **open circuits** at DC steady-state

$$v_L(t) = L\frac{di_L(t)}{dt} \quad \text{inudctor voltage}$$
$$v_L(t) \to 0 \quad \text{as } t \to \infty \quad \text{steady state voltage}$$

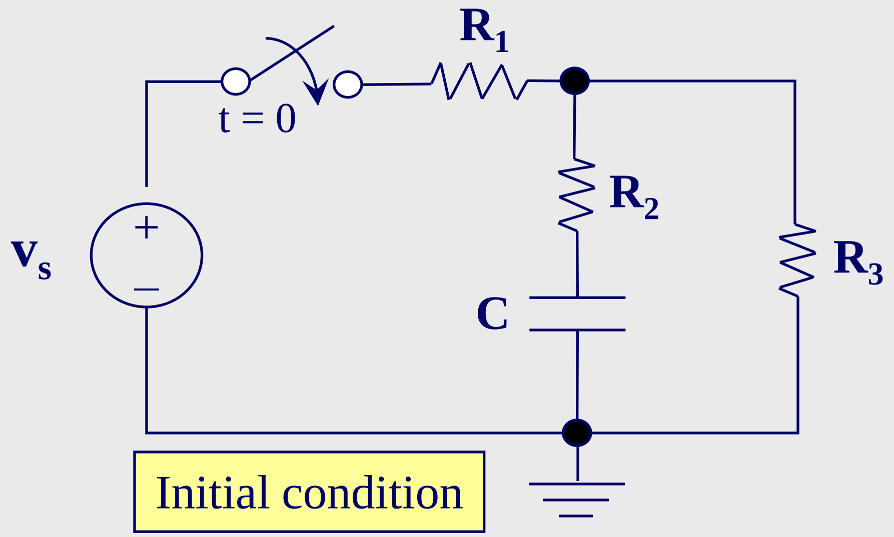
Inductors act like **short circuits** at DC steady-state

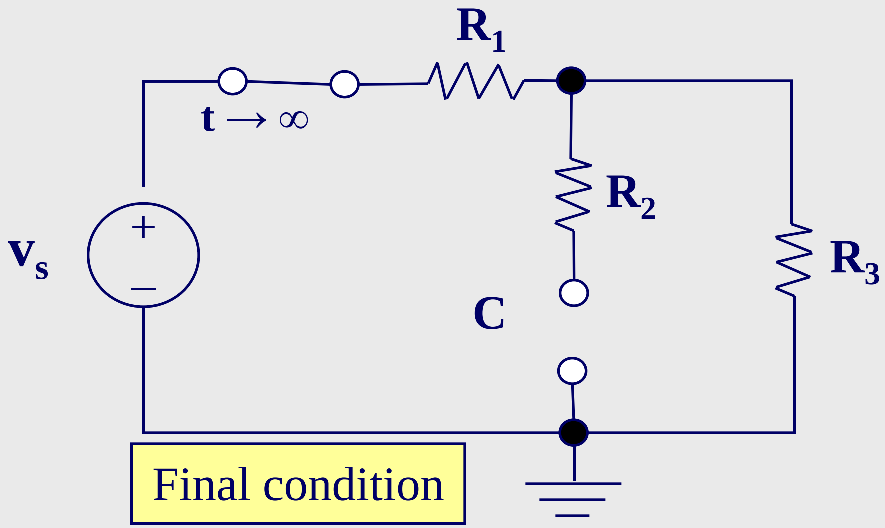
DC Steady-State

<u>Initial condition x(0)</u>: DC steady state **before** a switch is first activated

- **$x(0^-)$**: right before the switch is closed
- **$x(0^+)$**: right after the switch is closed

<u>Final condition x(∞)</u>: DC steady state a long time **after** a switch is activated

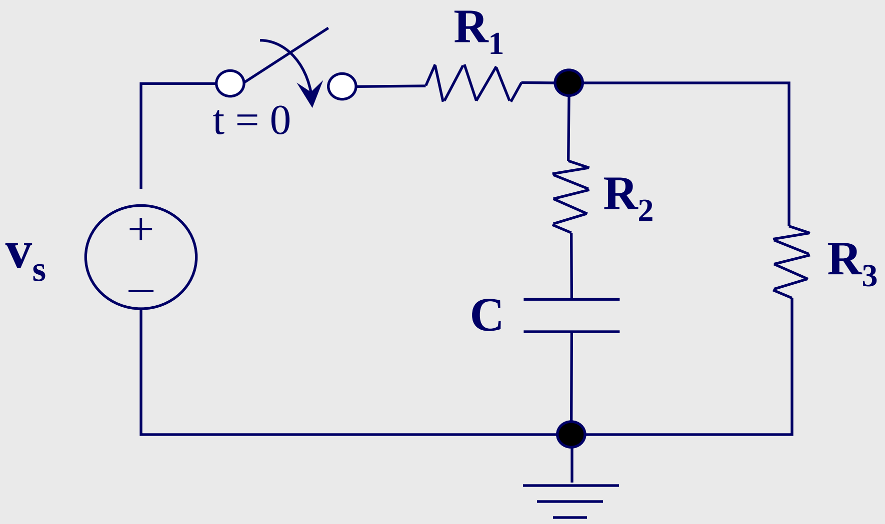




DC Steady-State

- **<u>Example1</u>**: determine the final condition capacitor voltage

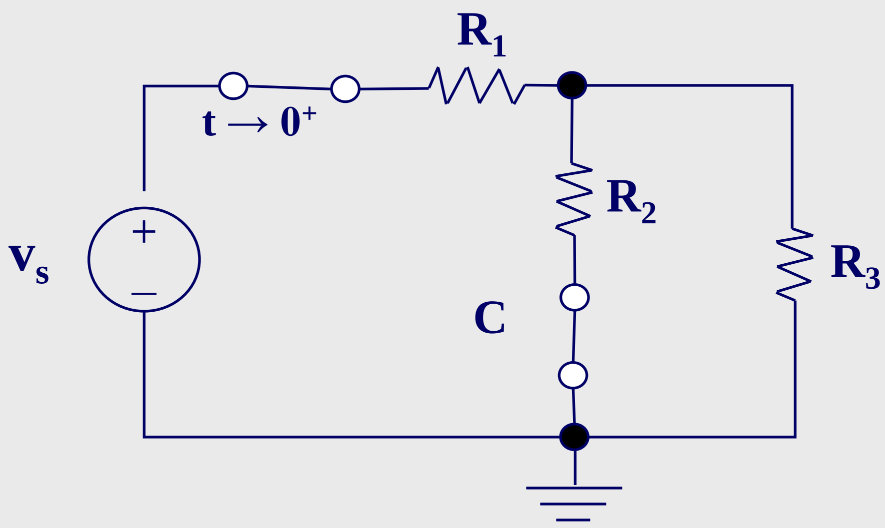
  $\mathbf{v_s}$ = 12V, $\mathbf{R_1}$ = 100Ω, $\mathbf{R_2}$ = 75Ω, $\mathbf{R_3}$ = 250Ω, **C** = 1uF



DC Steady-State

- **Example1**: determine the final condition capacitor voltage

  $\mathbf{v_s} = 12V$, $\mathbf{R_1} = 100\Omega$, $\mathbf{R_2} = 75\Omega$, $\mathbf{R_3} = 250\Omega$, $\mathbf{C} = 1uF$



1. Close the switch and find **initial** conditions to the capacitor

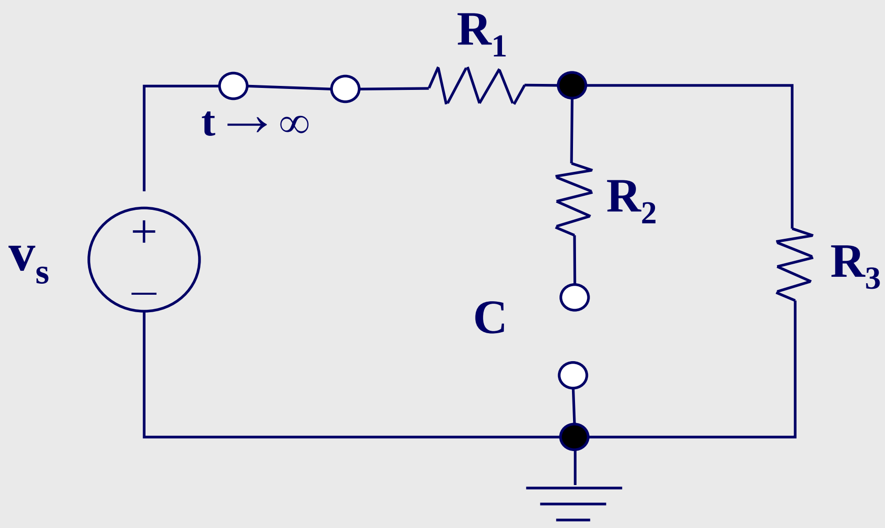
NB: **Initially (t = 0⁺)** current across the capacitor changes **instantly** but voltage cannot change instantly thus it acts as a **short circuit**

$$v_C(0^+) = v_C(0^-)$$
$$= 0V$$

DC Steady-State

- **Example1**: determine the final condition capacitor voltage

  $\mathbf{v_s}$ = 12V, $\mathbf{R_1}$ = 100Ω, $\mathbf{R_2}$ = 75Ω, $\mathbf{R_3}$ = 250Ω, **C** = 1uF



2. Close the switch and apply **finial** conditions to the capacitor

NB: since we have an open circuit no current flows through $\mathbf{R_2}$

Voltage divider :

$$v_3(\infty) = \frac{R_3}{R_1 + R_3} v_s = \frac{250}{350}(12) = 8.57V$$

$$v_C(\infty) = v_3(\infty) = 8.57V$$

DC Steady-State

Remember – capacitor voltages and inductor currents **cannot change instantaneously**

- Capacitor voltages and inductor currents don't change right before closing and right after closing a switch

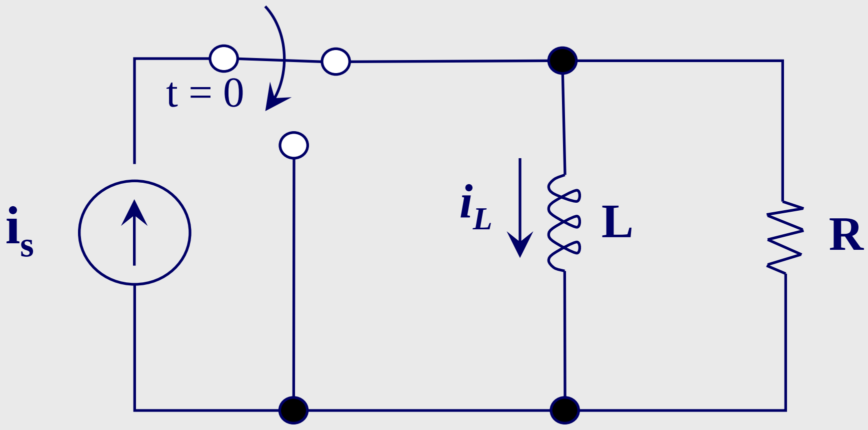
$$v_C(0^+) = v_C(0^-)$$

$$i_L(0^+) = i_L(0^-)$$

DC Steady-State

- **<u>Example2</u>**: find the initial and final current conditions at the inductor

  $\boldsymbol{i_s} = 10\text{mA}$

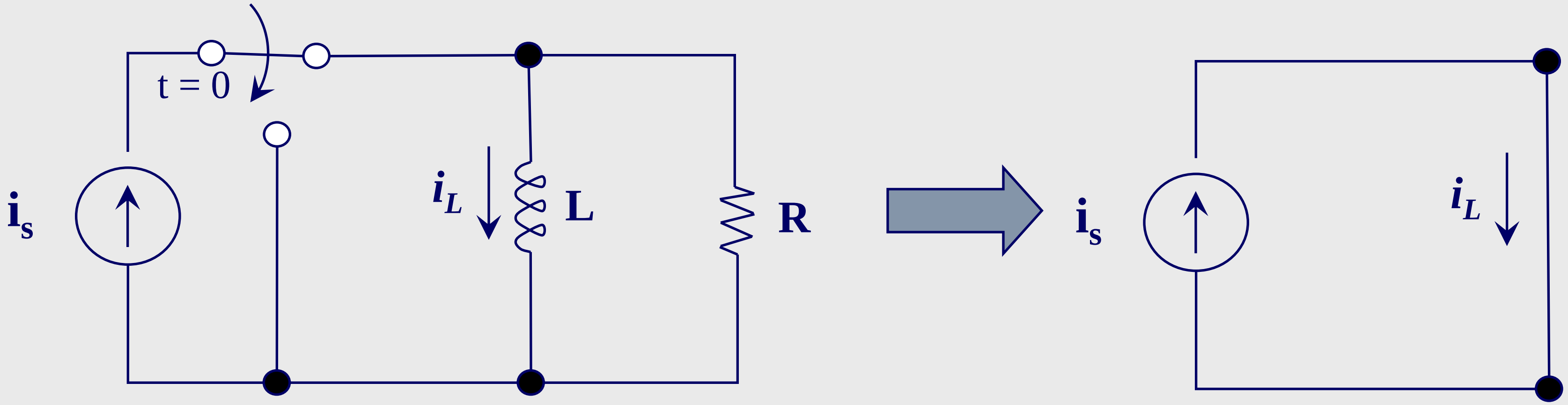


DC Steady-State

- **<u>Example2</u>**: find the initial and final current conditions at the inductor

i_s = 10mA

1. Initial conditions – assume the current across the inductor is in steady-state.



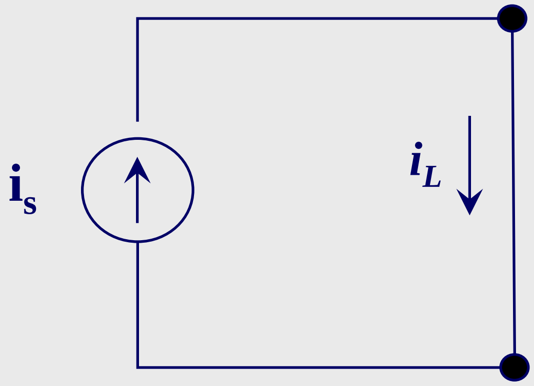
NB: in DC steady state inductors act like **short circuits**, thus no current flows through **R**

DC Steady-State

- **Example2**: find the initial and final current conditions at the inductor

$i_s = 10\text{mA}$

1. Initial conditions – assume the current across the inductor is in steady-state.



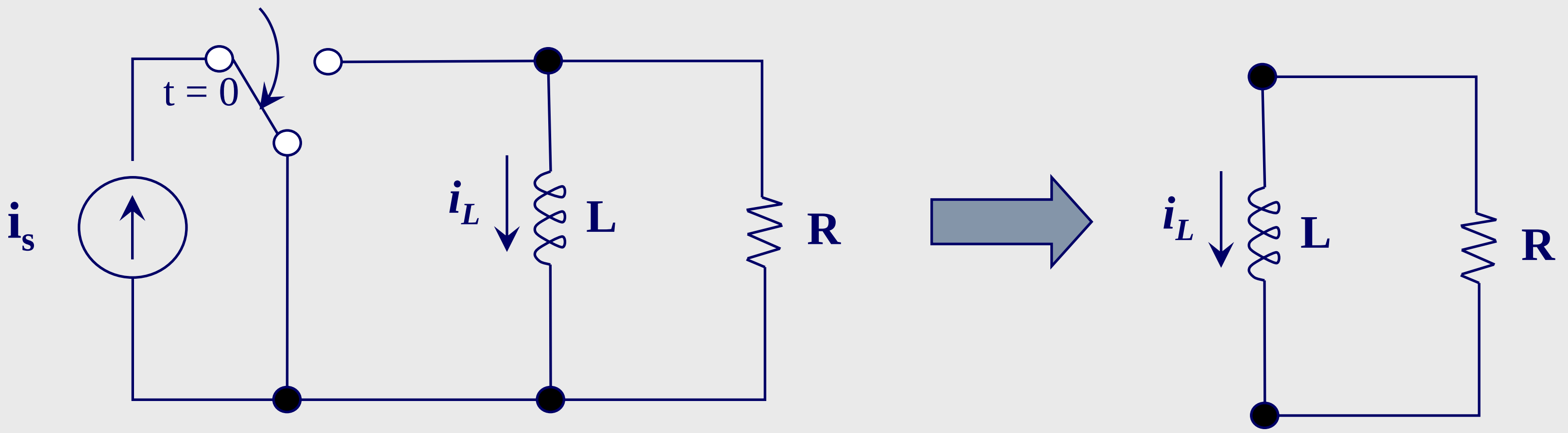
$$i_L(0^-) = i_s$$
$$= 10mA$$

DC Steady-State

- **Example2**: find the initial and final current conditions at the inductor

i_s = 10mA

1. Initial conditions – assume the current across the inductor is in steady-state.
2. Throw the switch



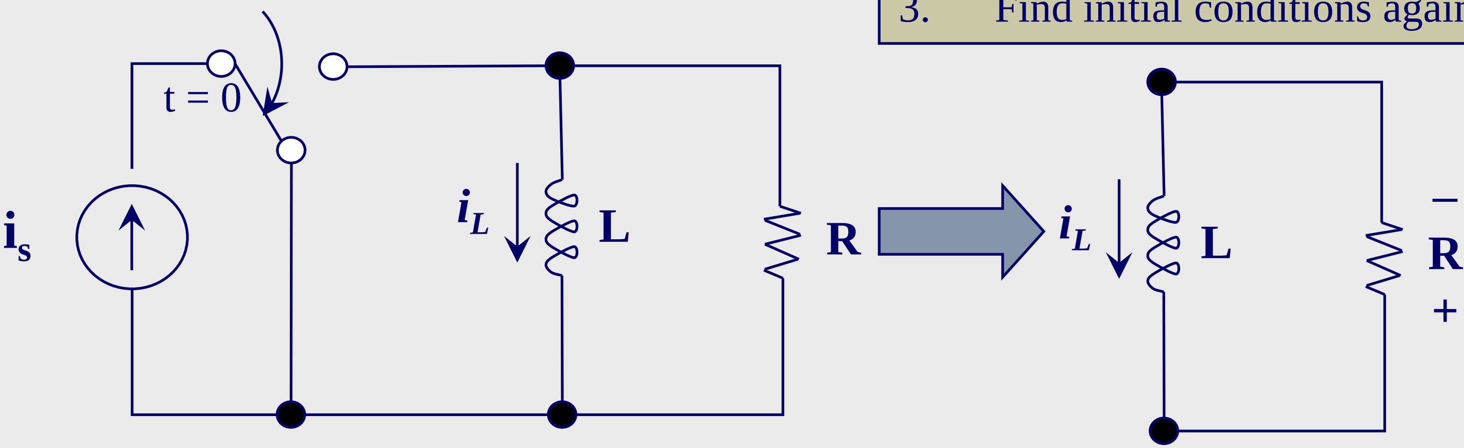
NB: inductor current cannot change instantaneously

DC Steady-State

- **<u>Example2</u>**: find the initial and final current conditions at the inductor

$\boldsymbol{i_s}$ = 10mA

1. Initial conditions – assume the current across the inductor is in steady-state.
2. Throw the switch
3. Find initial conditions again (non-steady state)



$$i_L(0^+) = i_L(0^-) = 10mA$$

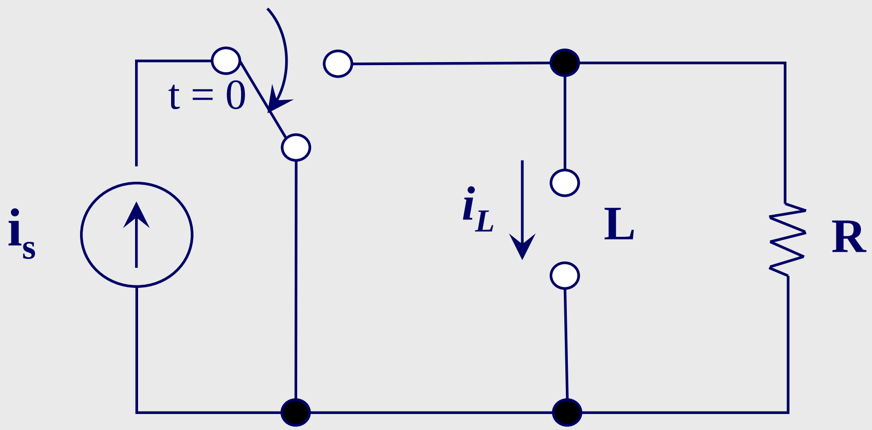
NB: polarity of **R**

NB: inductor current cannot change instantaneously

DC Steady-State

- **<u>Example2</u>**: find the initial and final current conditions at the inductor

$i_s = 10mA$



1. Initial conditions – assume the current across the inductor is in steady-state.
2. Throw the switch
3. Find initial conditions again (non-steady state)
4. Final conditions (steady-state)

$$i_L(\infty) = 0A$$

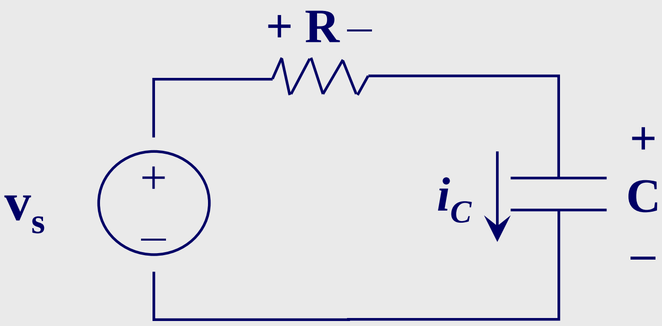
NB: since there is **no source attached** to the inductor, its current is drained by the resistor **R**

2. Adjusting to Switch

2nd Step in Transient Response

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation



$$\frac{di_C(t)}{dt} + \frac{1}{RC} i_C(t) = \frac{1}{R} \frac{dv_S(t)}{dt}$$

$$\frac{dv_C(t)}{dt} + \frac{1}{RC} v_C(t) = \frac{1}{RC} v_S(t)$$

NB: Review lecture 11 for derivation of these equations

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

$$\frac{di_C(t)}{dt} + \frac{1}{RC} i_C(t) = \frac{1}{R}\frac{dv_S(t)}{dt}$$

$$\frac{dv_C(t)}{dt} + \frac{1}{RC} v_C(t) = \frac{1}{RC} v_S(t)$$

General Solution of 1st Order Circuits

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$$\frac{dv_C(t)}{dt} + \frac{1}{RC} v_C(t) = \frac{1}{RC} v_S(t)$$

NB: Constants

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

$$\frac{di_C(t)}{dt} + \frac{1}{RC} i_C(t) = \frac{1}{R} \frac{dv_S(t)}{dt}$$

$$\frac{dv_C(t)}{dt} + \frac{1}{RC} v_C(t) = \frac{1}{RC} v_S(t)$$

NB: similarities

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

In General:

$$a_1 \frac{dx(t)}{dt} + a_0 x(t) = b_0 y(t)$$

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

In General :

$$a_1 \frac{dx(t)}{dt} + a_0 x(t) = b_0 y(t)$$

Capacitor/inductor voltage/current

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

In General :

$$a_1 \frac{dx(t)}{dt} + a_0 x(t) = b_0 y(t)$$

Forcing function
(**F** – for **DC source**)

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

In General :

$$a_1 \frac{dx(t)}{dt} + a_0 x(t) = b_0 y(t)$$

Combinations of circuit element parameters (**Constants**)

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

In General :

$$a_1 \frac{dx(t)}{dt} + a_0 x(t) = b_0 y(t)$$

In General re - written :

$$\frac{a_1}{a_0}\frac{dx(t)}{dt} + x(t) = \frac{b_0}{a_0} F$$

Forcing Function **F**

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

In General re - written :

$$\frac{a_1}{a_0}\frac{dx(t)}{dt} + x(t) = \frac{b_0}{a_0}F$$

In General re - written :

$$\tau\frac{dx(t)}{dt} + x(t) = K_S F$$

DC gain

General Solution of 1st Order Circuits

- Expressions for voltage and current of a 1st order circuit will be a 1st order differential equation

In General re-written:

$$\frac{a_1}{a_0}\frac{dx(t)}{dt} + x(t) = \frac{b_0}{a_0}F$$

In General re-written:

$$\tau\frac{dx(t)}{dt} + x(t) = K_S F$$

Time constant

DC gain

General Solution of 1st Order Circuits

The solution to this equation (the **complete response**) consists of two parts:

- **Natural response** (**homogeneous** solution)
  - Forcing function equal to zero
- **Forced response** (**particular** solution)

$$\tau \frac{dx(t)}{dt} + x(t) = K_S F$$

General Solution of 1st Order Circuits

Natural response (homogeneous solution)

- Forcing function equal to zero

$$\tau \frac{dx_N(t)}{dt} + x_N(t) = 0$$

$$\frac{dx_N(t)}{dt} = -\frac{x_N(t)}{\tau}$$

Has known solution of the form:

$$x_N(t) = \alpha e^{-t/\tau}$$

General Solution of 1st Order Circuits

Forced response (**particular** solution)

$$\tau \frac{dx_F(t)}{dt} + x_F(t) = K_S F$$

F is constant for DC sources, thus derivative is zero

$$x_F(t) = K_S F$$

NB: This is the **DC steady-state** solution

$$x_F(t) = x(\infty) = K_S F$$

General Solution of 1st Order Circuits

Complete response (natural + forced)

$$x(t) = x_N(t) + x_F(t)$$
$$= \alpha e^{-t/\tau} + K_S F$$
$$= \alpha e^{-t/\tau} + x(\infty)$$

Solve for α by solving x(t) at t = 0

Solve for α:

$$x(0) = \alpha + x(\infty)$$
$$\alpha = x(0) - x(\infty)$$

$$x(t) = [x(0) - x(\infty)]e^{-t/\tau} + x(\infty)$$

- $x(0)$: Initial condition
- $x(\infty)$: Final condition
- τ: Time constant

General Solution of 1st Order Circuits

Complete response (natural + forced)

$$x(t) = [x(0) - x(\infty)]e^{-t/\tau} + x(\infty)$$

Transient Response — $[x(0) - x(\infty)]e^{-t/\tau}$

Steady-State Response — $x(\infty)$

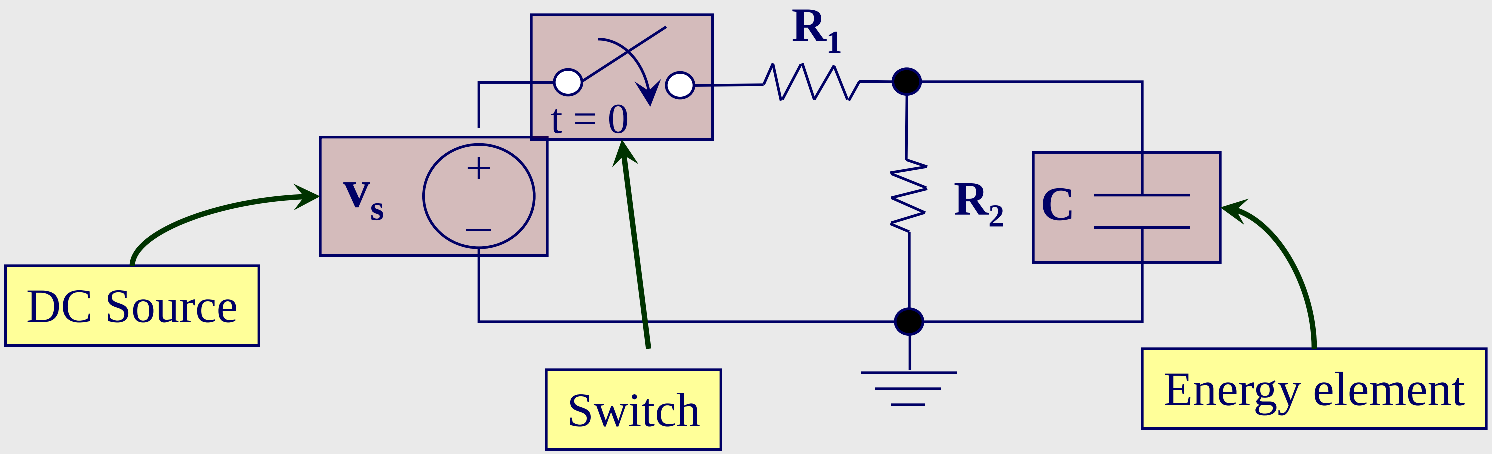
3. DC Steady-State + Transient Response

Full Transient Response

Transient Response

Transient response of a circuit consists of 3 parts:

1. Steady-state response **prior** to the **switching** on/off of a **DC source**
2. Transient response – the circuit **adjusts** to the **DC source**
3. Steady-state response **following** the transient response



Transient Response

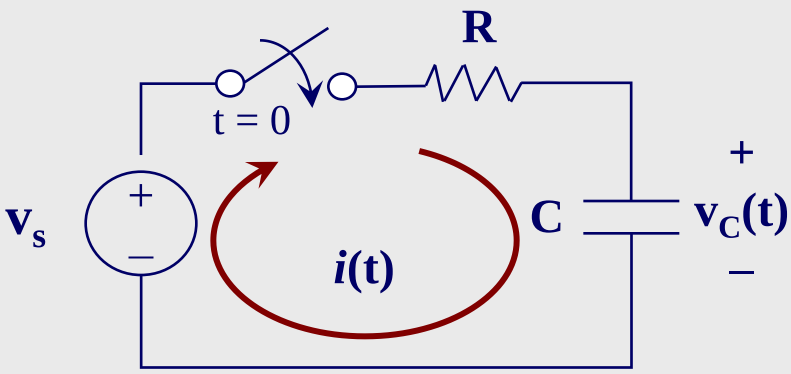
Solving 1st order transient response:

1. Solve the **DC steady-state** circuit:
   - Initial condition $\mathbf{x(0^-)}$: before switching (on/off)
   - Final condition $\mathbf{x(\infty)}$: After any transients have died out ($t \rightarrow \infty$)
2. Identify $\mathbf{x(0^+)}$**:** the circuit **initial conditions**
   - Capacitors: $\mathbf{v_C(0^+) = v_C(0^-)}$
   - Inductors: $\mathbf{i_L(0^+) = i_L(0^-)}$
3. Write **a differential equation** for the circuit at time $t = 0^+$
   - Reduce the circuit to its **Thévenin or Norton equivalent**
     - The energy storage element (capacitor or inductor) is the load
   - The differential equation will be either in terms of $\mathbf{v_C(t)}$ or $\mathbf{i_L(t)}$
   - Reduce this equation to standard form
4. Solve for the **time constant**
   - Capacitive circuits: $\boldsymbol{\tau = R_T C}$
   - Inductive circuits: $\boldsymbol{\tau = L/R_T}$
5. Write the **complete response** in the form:
   - $\mathbf{x(t) = x(\infty) + [x(0) - x(\infty)]e^{-t/\tau}}$

Transient Response

- **<u>Example3</u>**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_s}$ = 12V, $\mathbf{v_C(0^-)}$ = 5V, **R** = 1000Ω, **C** = 470uF



Transient Response

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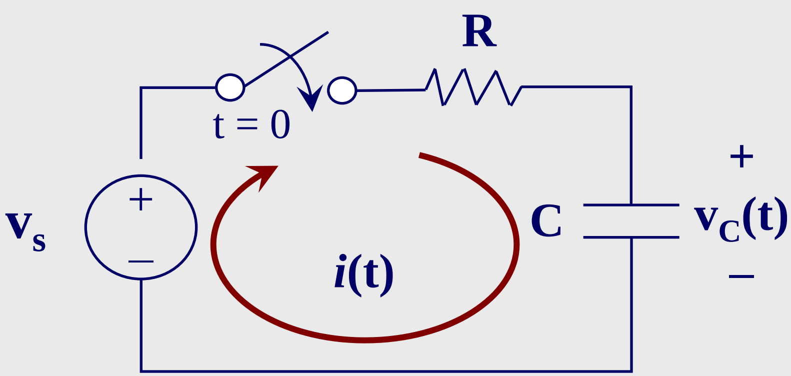


1. DC steady-state
   a) Initial condition: $\mathbf{v_C(0)}$
   b) Final condition: $\mathbf{v_C(\infty)}$

$$v_C(t<0) = v_C(0^-) = 5V$$

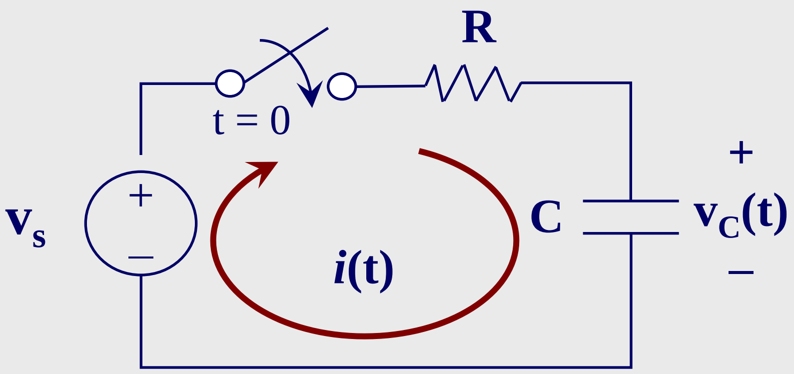
$$v_C(\infty) = v_S = 12V$$

NB: as t → ∞ the capacitor acts like an open circuit thus $\mathbf{v_C}(\infty) = \mathbf{v_S}$

Transient Response

- **Example3**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_s}$ = 12V, $\mathbf{v_C(0^-)}$ = 5V, **R** = 1000Ω, **C** = 470uF



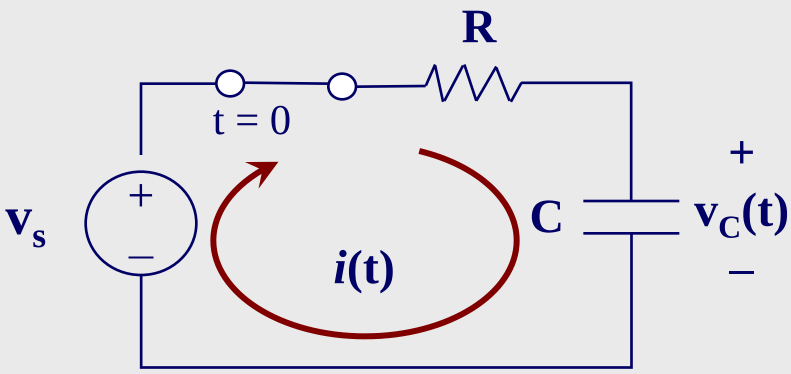
2. Circuit initial conditions: $\mathbf{v_C(0^+)}$

$$v_C(0^+) = v_C(0^-)$$
$$= 5V$$

Transient Response

- **Example3**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_s}$ = 12V, $\mathbf{v_C(0^-)}$ = 5V, **R** = 1000Ω, **C** = 470uF



3. Write differential equation (already in Thévenin equivalent) at t = 0

$$\text{KVL}:$$

$$-v_S + v_R(t) + v_C(t) = 0$$

$$i_C(t)R + v_C(t) = v_S$$

$$RC\frac{dv_C(t)}{dt} + v_C(t) = v_S$$

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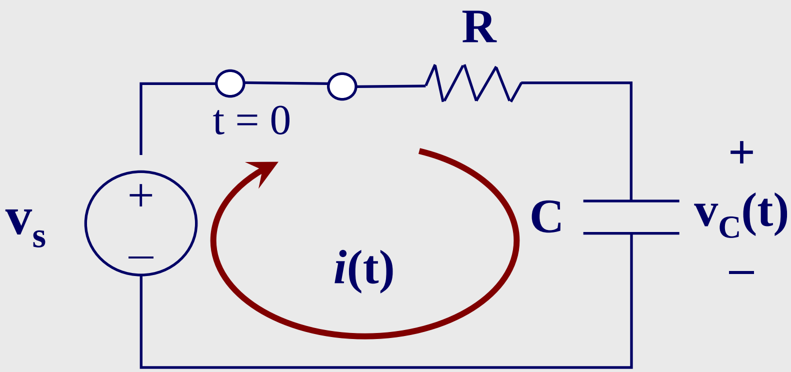
Transient Response

- **<u>Example3</u>**: find **v_c(t)** for all t

  v_s = 12V, **$v_C(0^-)$** = 5V, **R** = 1000Ω, **C** = 470uF



3. Write differential equation (already in Thévenin equivalent) at t = 0

NB: solution is of the form:

$$\tau \frac{dx(t)}{dt} + x(t) = K_S F$$

$$\text{KVL}:$$

$$-v_S + v_R(t) + v_C(t) = 0$$

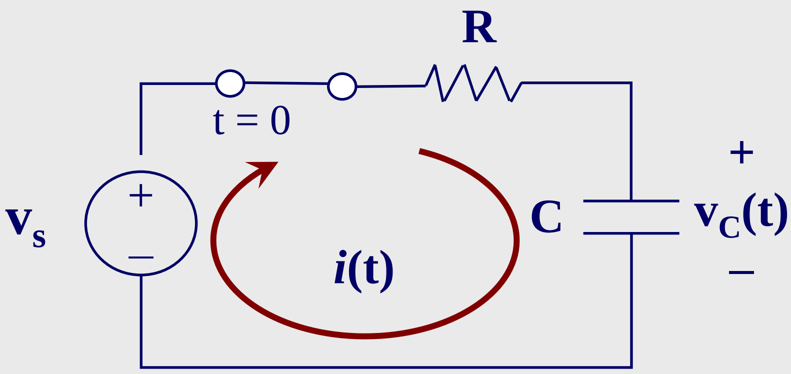
$$i_C(t)R + v_C(t) = v_S$$

$$RC\frac{dv_C(t)}{dt} + v_C(t) = v_S$$

Transient Response

- **Example3**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_s}$ = 12V, $\mathbf{v_C(0^-)}$ = 5V, **R** = 1000Ω, **C** = 470uF



4. Find the time constant **τ**

$$\tau = RC$$
$$= (1000)(470 \times 10^{-6})$$
$$= 0.47$$

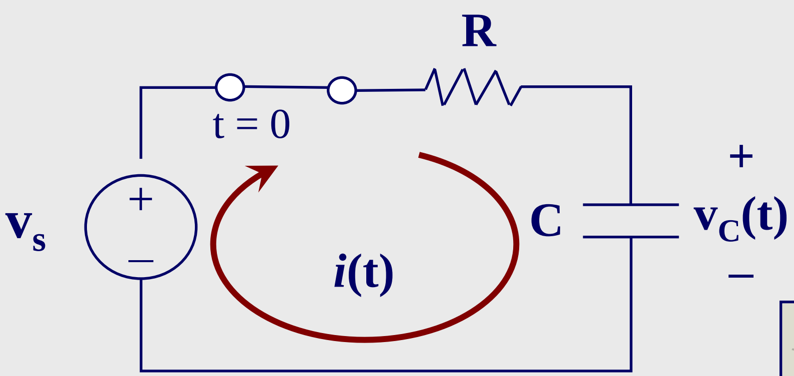
$$K_S = 1$$

$$F = v_S$$
$$= 12$$

Transient Response

- **Example3**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_s}$ = 12V, $\mathbf{v_C(0^-)}$ = 5V, **R** = 1000Ω, **C** = 470uF



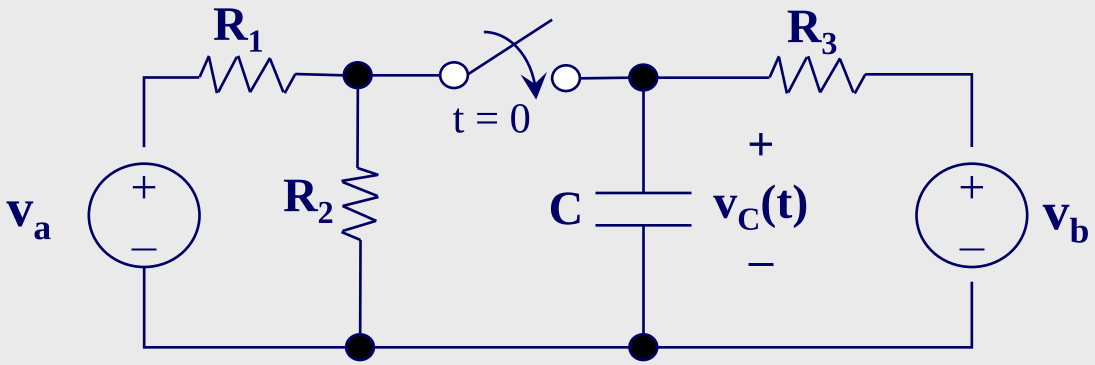
5. Write the complete response
   $\mathbf{x(t) = x(\infty) + [x(0) - x(\infty)]e^{-t/\tau}}$

$$v_C(t) = v_C(\infty) + [v_C(0) - v_C(\infty)]e^{-t/\tau}$$
$$= 12 + (5 - 12)e^{-t/0.47}$$
$$= 12 - 7e^{-t/0.47}$$

Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

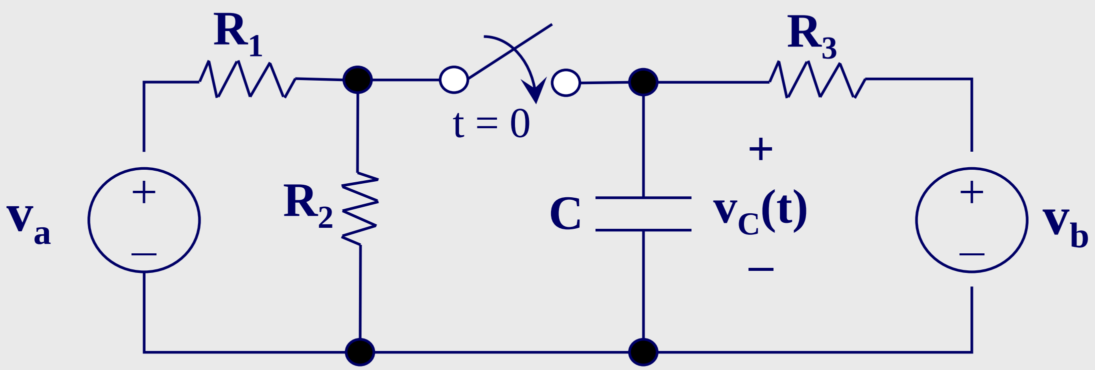
  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF



Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF



1. DC steady-state
   a) Initial condition: $\mathbf{v_C(0)}$
   b) Final condition: $\mathbf{v_C(\infty)}$

For t < 0 the capacitor has been charged by $\mathbf{v_b}$ thus $\mathbf{v_C(0^-) = v_b}$

$$v_C(0^-) = v_b$$
$$= 5V$$

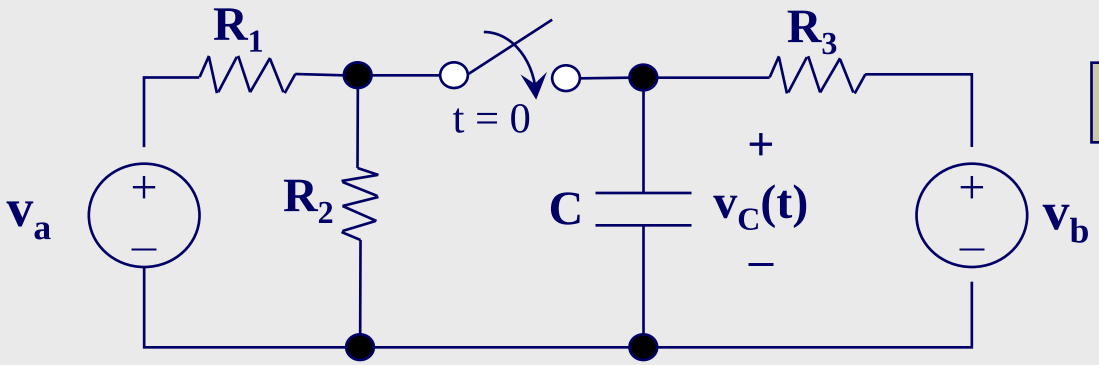
For t → ∞ $\mathbf{v_c(\infty)}$ is not so easily determined – it will be equal to $\mathbf{v_T}$ (the open circuited Thévenin equivalent)

$$v_C(\infty) = v_T$$

Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF



2. Circuit initial conditions: $\mathbf{v_C(0^+)}$

$$v_C(0^+) = v_C(0^-) = 5V$$

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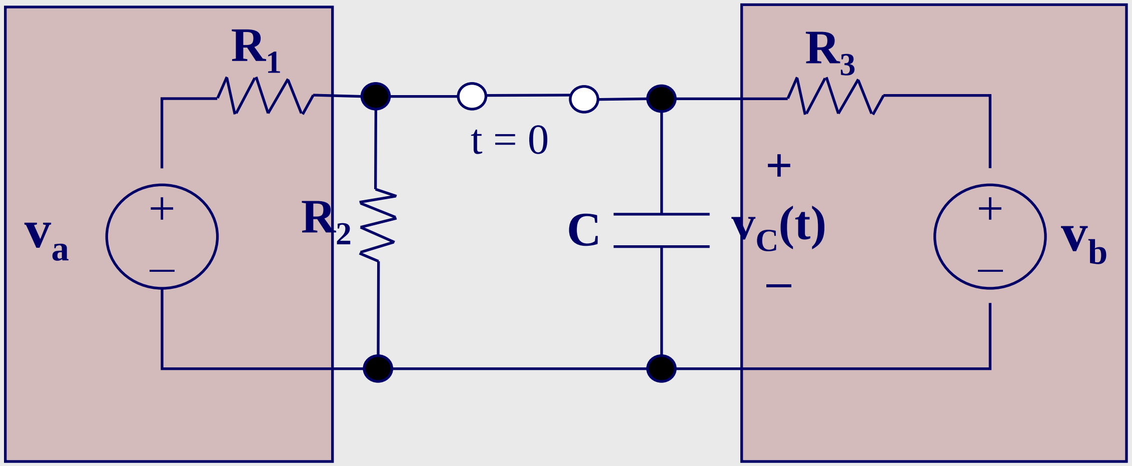
Transient Response

- **<u>Example4</u>**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF

3. Write differential equation at t = 0
   a) Find Thévenin equivalent



$$i_a = \frac{v_a}{R_1} = \frac{12}{10} = 1.2\ A$$

$$i_b = \frac{v_b}{R_3} = \frac{5}{10} = 0.5\ A$$

Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF

3. Write differential equation at t = 0
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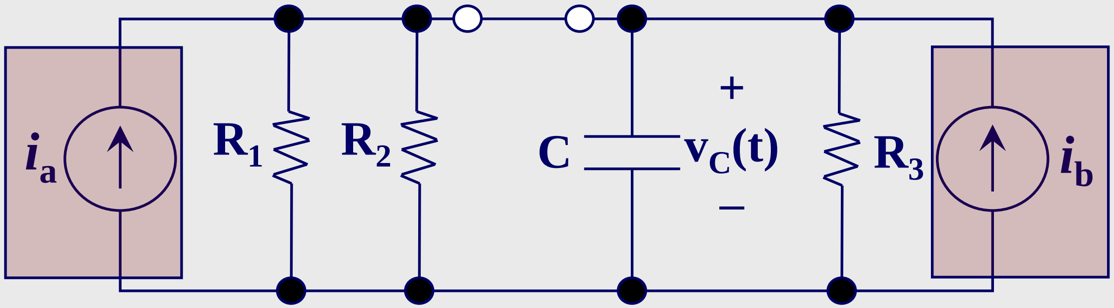
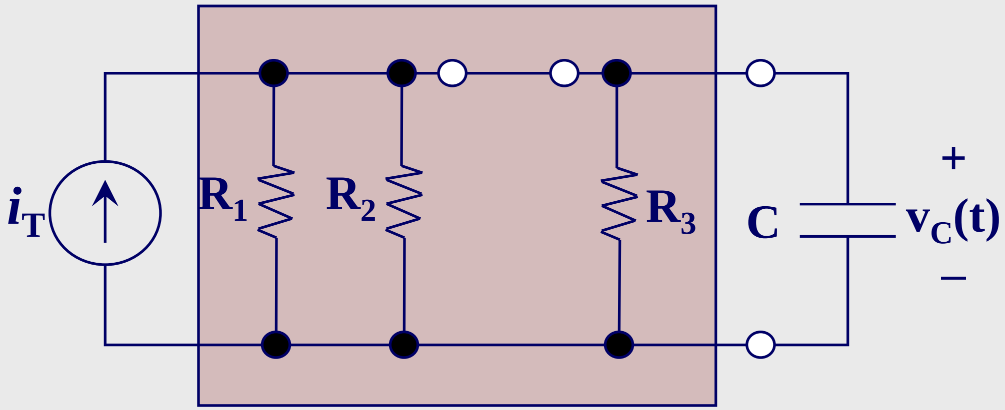


$$i_T = i_1 + i_2$$
$$= 1.2 + 0.5$$
$$= 1.7\ A$$

Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF



3. Write differential equation at t = 0
   a) Find Thévenin equivalent

$$i_T = 1.7\ A$$

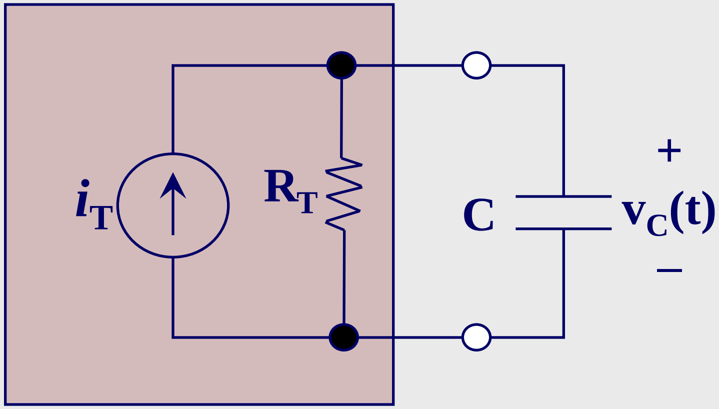
$$\begin{aligned} R_T &= R_1 \parallel R_2 \parallel R_3 \\ &= \frac{R_1R_2R_3}{R_1R_2 + R_1R_3 + R_2R_3} \\ &= \frac{(10)(5)(10)}{(10)(5)+(10)(10)+(5)(10)} \\ &= \frac{500}{200} \\ &= 2.5\Omega \end{aligned}$$

Transient Response

- **<u>Example4</u>**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF

3. Write differential equation at t = 0
   a) Find Thévenin equivalent



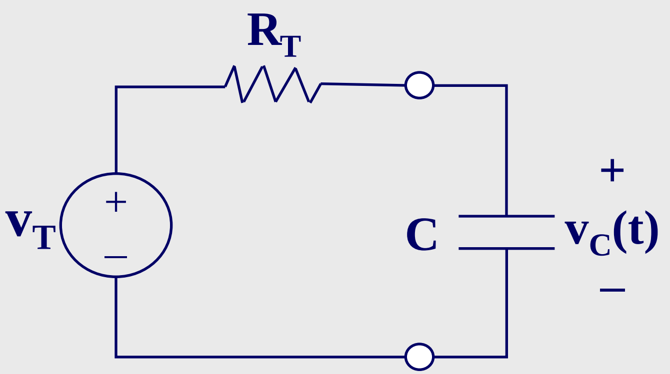
$$v_T = i_T R_T$$
$$= (1.7)(2.5)$$
$$= 4.25\ V$$

$$i_T = 1.7\ A$$
$$R_T = 2.5\Omega$$

Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF



3. Write differential equation at t = 0
   a) Find Thévenin equivalent
   b) Reduce equation to standard form

$$v_T = 4.25\,V$$
$$R_T = 2.5\Omega$$

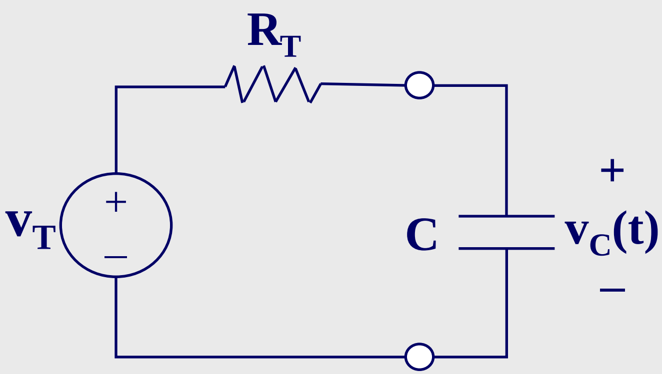
KVL:

$$-v_T + v_{RT}(t) + v_C(t) = 0$$
$$i_C(t)R_T + v_C(t) = v_T$$
$$CR_T\frac{dv_C(t)}{dt} + v_C(t) = v_T$$

Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF



4. Find the time constant **τ**

$$\tau = R_T C = (2.5)(10^{-6}) = 2.5\times10^{-6}$$

$$v_T = 4.25\,V$$
$$R_T = 2.5\Omega$$

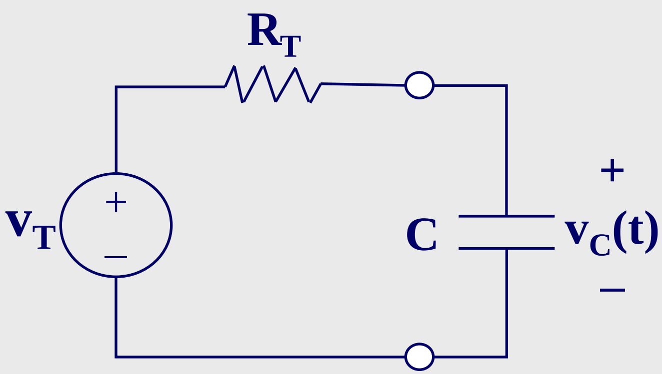
$$K_S = 1$$

$$F = v_T = 4.25$$

Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF



5. Write the complete response
   $\mathbf{x(t) = x(\infty) + [x(0) - x(\infty)]e^{-t/\tau}}$

$$v_C(t) = v_C(\infty) + \left[v_C(0) - v_C(\infty)\right] e^{-t/\tau}$$

$$= 4.25 + (5 - 4.25)e^{-t/2.5\times10^{-6}}$$

$$= 4.25 + 0.75e^{-t/2.5\times10^{-6}}$$

$$v_T = 1.75\,V$$

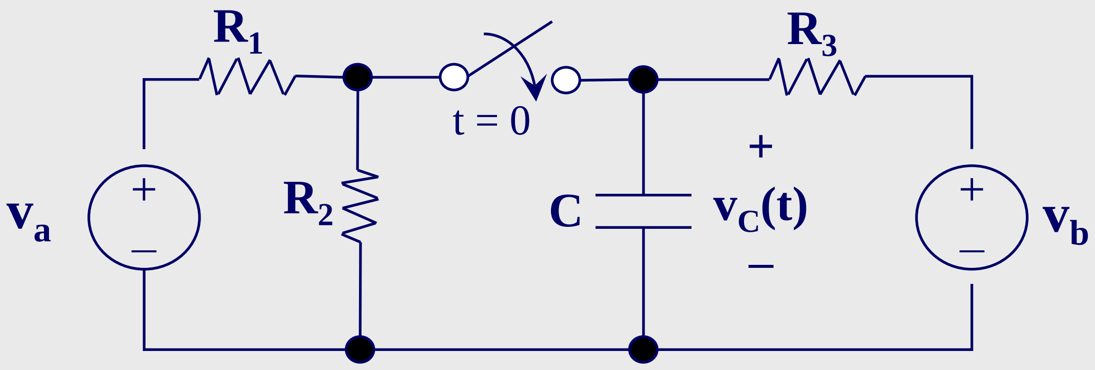
$$R_T = 2.5\Omega$$

Transient Response

- **Example4**: find $\mathbf{v_c(t)}$ for all t

  $\mathbf{v_a}$ = 12V, $\mathbf{v_b}$ = 5V, $\mathbf{R_1}$ = 10Ω, $\mathbf{R_2}$ = 5Ω, $\mathbf{R_3}$ = 10Ω, **C** = 1uF

5. Write the complete response
   $\mathbf{x(t) = x(\infty) + [x(0) - x(\infty)]e^{-t/\tau}}$



$$v_C(t) = 4.25 + 0.75e^{-t/2.5\times10^{-6}}$$