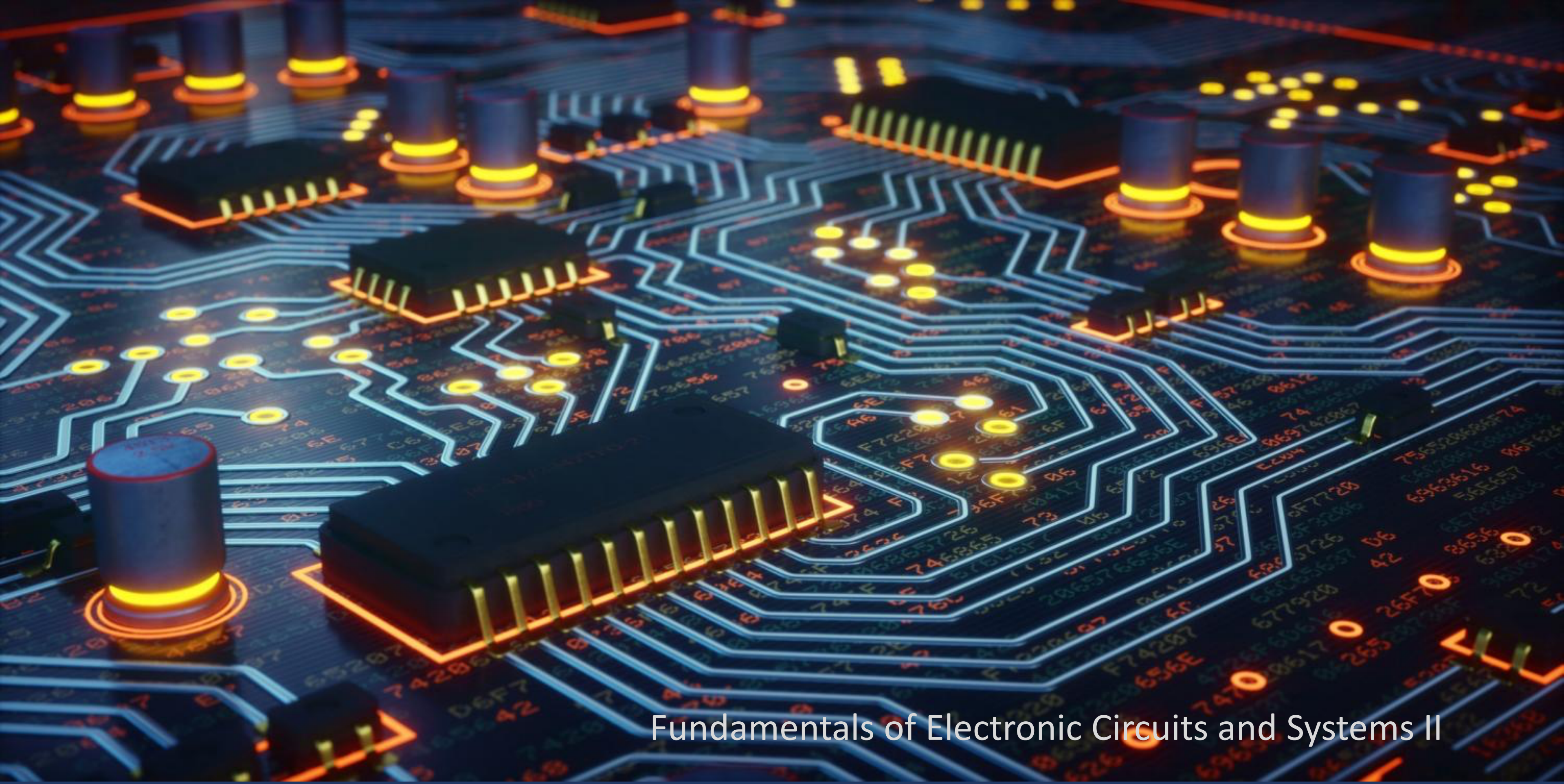


Fundamentals of Electronic Circuits and Systems II

Oscillators & Signal Generators

Milin Zhang

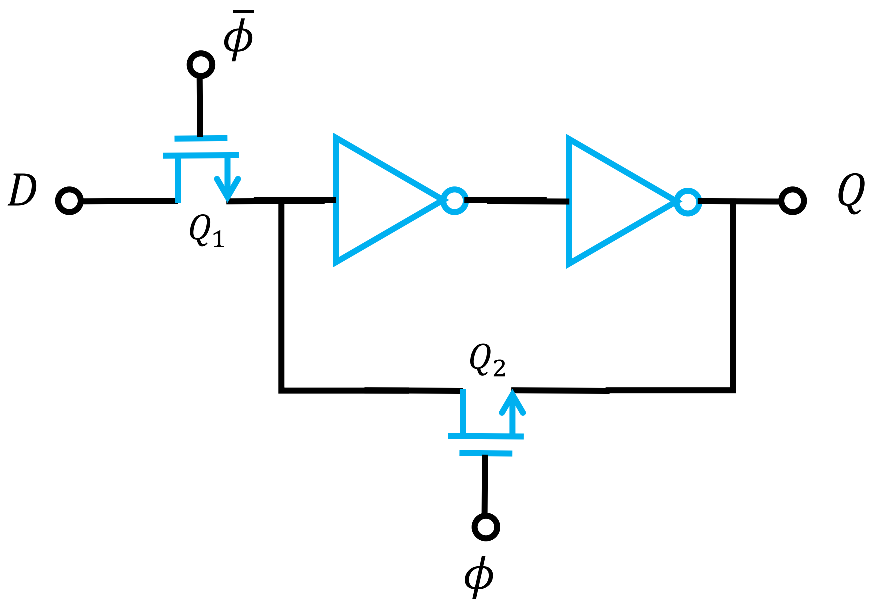
Dept of EE, Tsinghua University

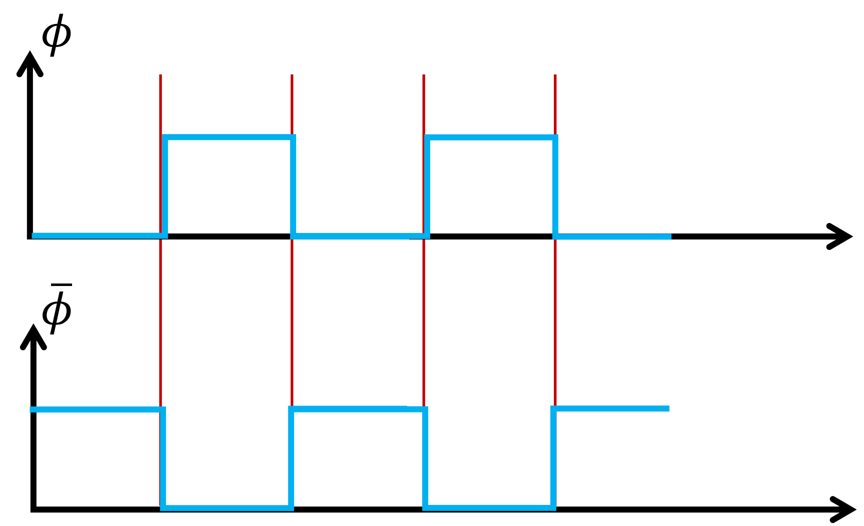
Outline

- HOW to generate an oscillation?
- Linear Oscillator
- Non-linear Oscillator

Recall: Dynamic Circuit

QUESTION: Find out the output Q with different input D. ϕ is a clock signal. The input switches between V_{dd} and GND

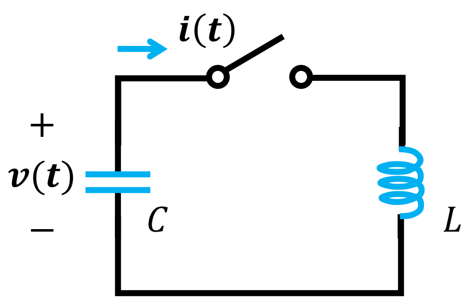


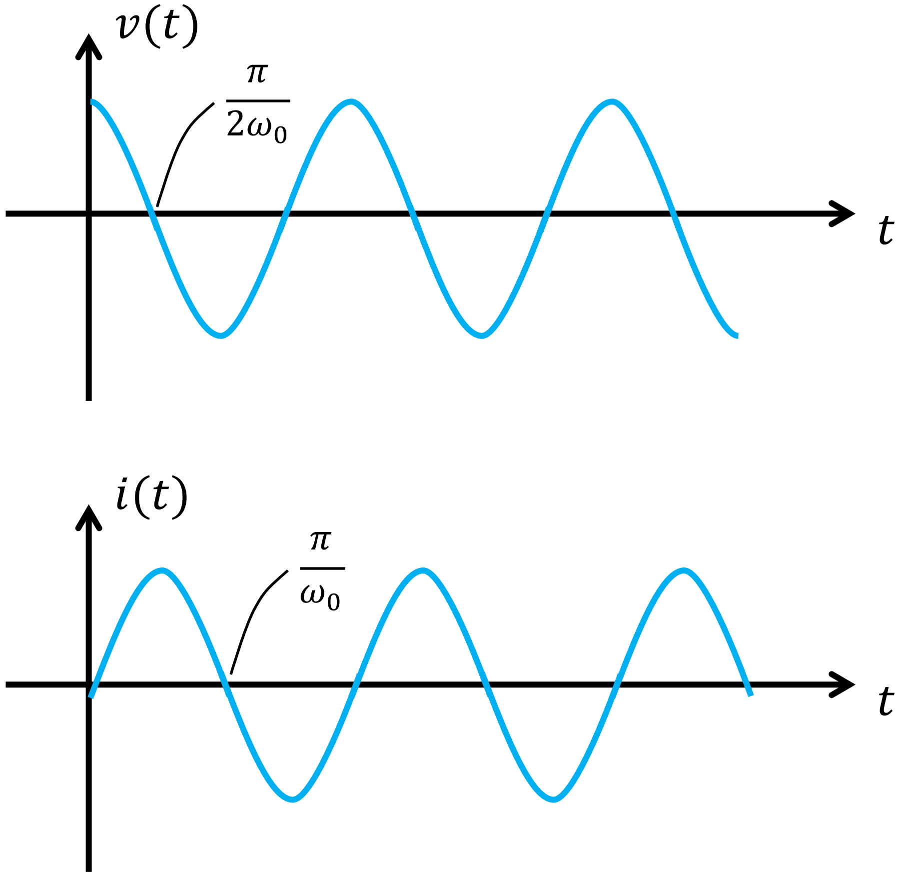


HOW to generate a CLOCK?

Recall: Source free LC circuit

QUESTION: Find how the voltage on the capacitor and the current through the inductor change after the switch is turned on.

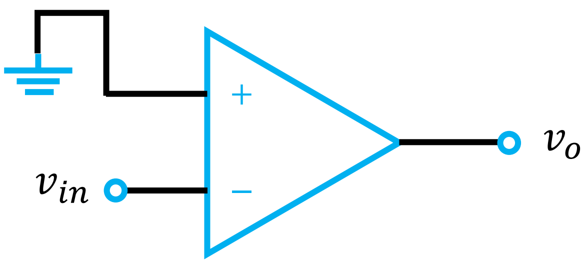


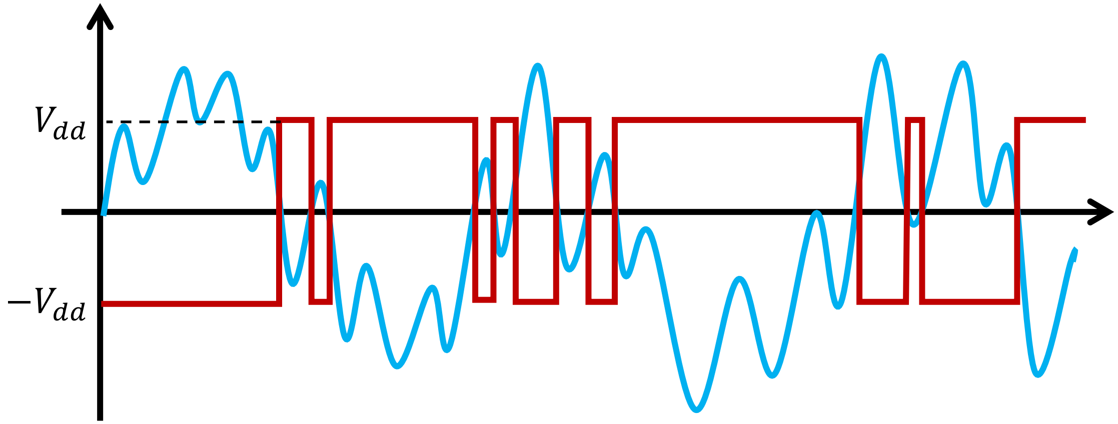


$$\begin{cases} v(t) = A\cos(\omega_0 t + \theta) \\ i(t) = \sqrt{\frac{C}{L}} A\sin(\omega_0 t + \theta) \end{cases}$$

Recall: zero-crossing detector

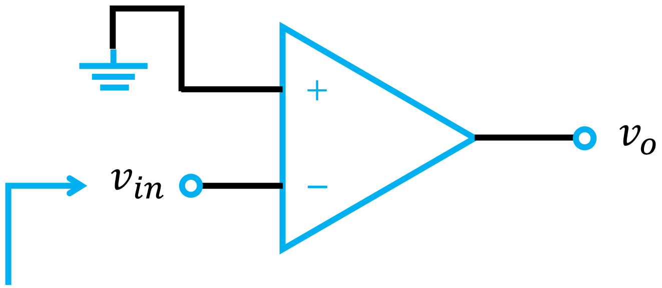
QUESTION: Find the output of the circuit. The op-amp is ideal.



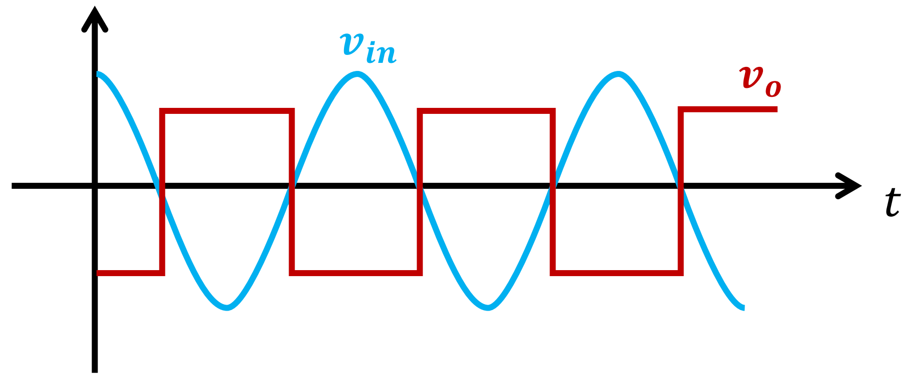


- If $v_{in} > 0$ → $v_o = -V_{dd}$
- If $v_{in} < 0$ → $v_o = V_{dd}$

How to generate a clock?



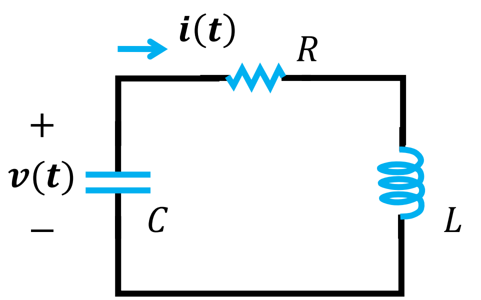
Voltage from free LC



MISSION COMPLETED?

Recall: source free RLC circuit

QUESTION: Find how the voltage on the capacitor and the current through the inductor change.



$$v_c(t) = e^{-\zeta\omega_0 t}[A_1\cos(\omega_d t) + A_2\sin(\omega_d t)]$$

Define **DAMPING FACTOR** $\alpha = \frac{R}{2L}$

Define **RESONATE FREQUENCY** $\omega_0 = \frac{1}{\sqrt{LC}}$

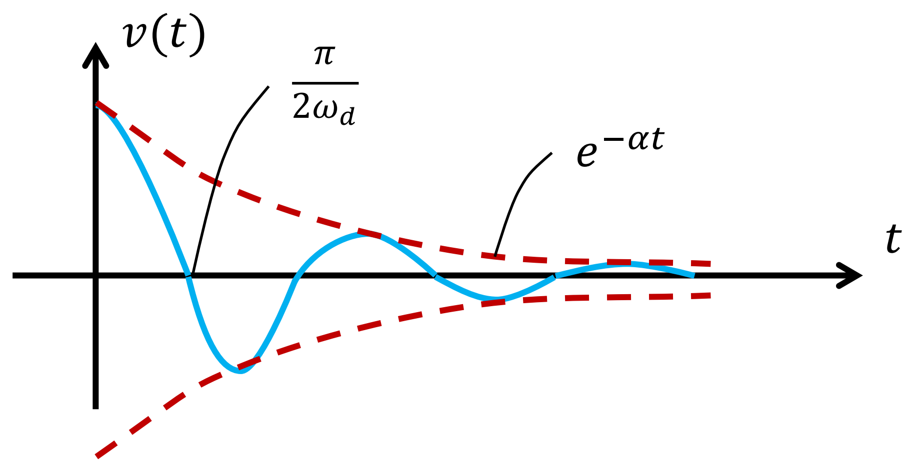
Define **DAMPING RATIO** $\zeta = \frac{\alpha}{\omega_0} = \frac{R}{2\omega_0 L}$

$$\frac{d^2v(t)}{dt^2} + \frac{R}{L}\frac{dv(t)}{dt} + \frac{1}{LC}v(t) = 0$$

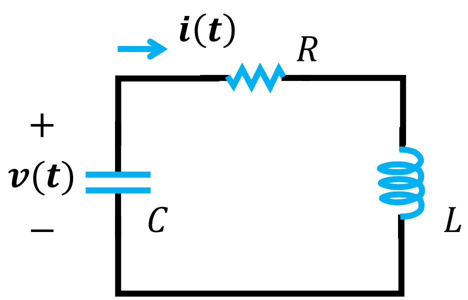
Solution: $v(t) = K_1 e^{s_1 t} + K_2 e^{s_2 t}$

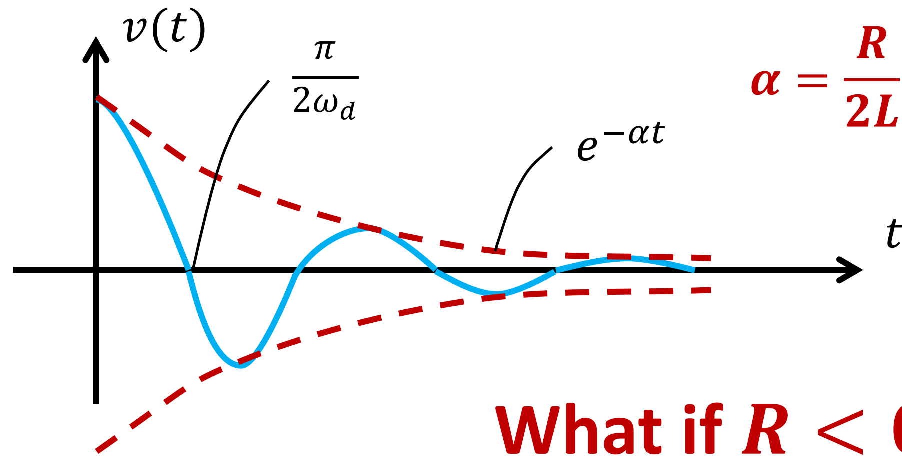
Where $\begin{cases} S_1 = -\zeta\omega_0 + \omega_0\sqrt{\zeta^2 - 1} \\ S_2 = -\zeta\omega_0 - \omega_0\sqrt{\zeta^2 - 1} \end{cases}$

and $\omega_0 = \frac{1}{\sqrt{LC}}$, $\zeta = \frac{R}{2\omega_0 L}$



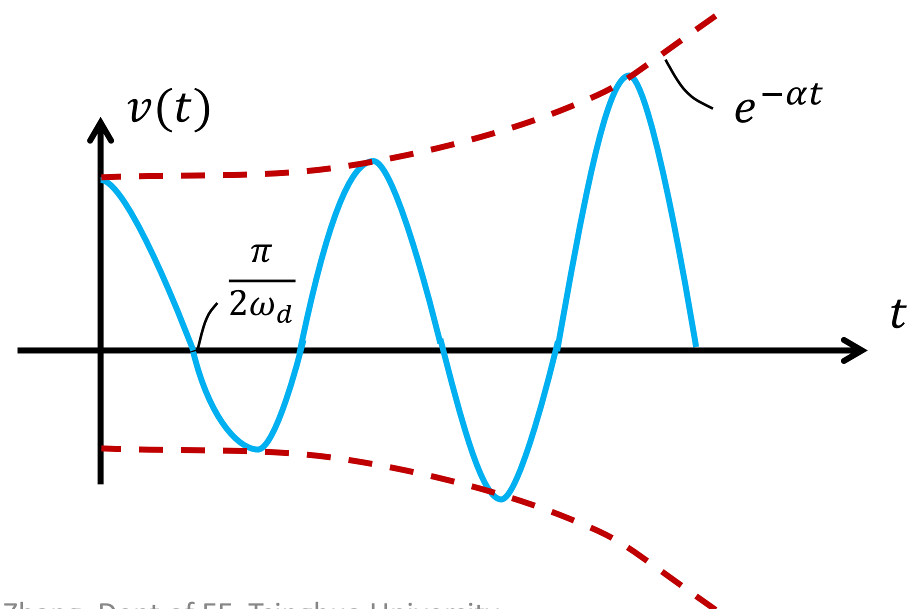
Source free RLC circuit





$$\alpha = \frac{R}{2L} > 0$$

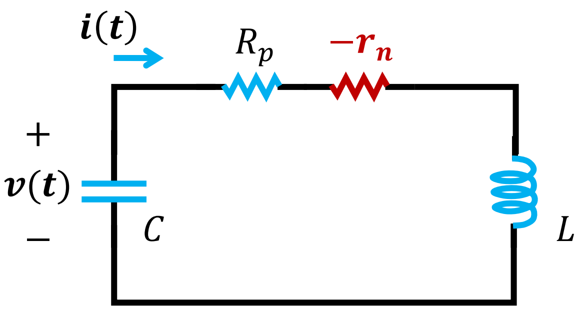
What if $R < 0$?



$$v_c(t) = K_1 e^{-\alpha t}\cos(\omega_d t + \theta_1)$$

$$\begin{cases} K_1 = \sqrt{v_{C_1}^2(0) + \left(\dfrac{\alpha C_1 v_{C_1}(0) - i_{L_1}(0)}{C_1\omega_d}\right)^2} \\ \theta_1 = tan^{-1}\left(\dfrac{\alpha C_1 v_{C_1}(0) - i_{L_1}(0)}{C_1\omega_d v_{C_1}(0)}\right) \end{cases}$$

Negative Resistance

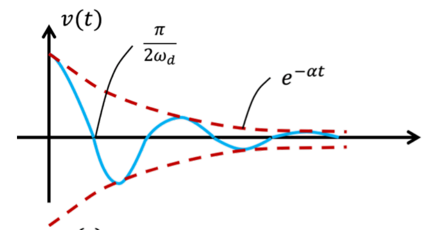


$$v_c(t) = K_1 e^{-\alpha t}\cos(\omega_d t + \theta_1)$$

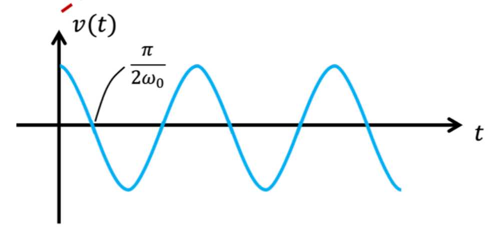
Where $\alpha = \frac{R_p - r_n}{2L}$

$$\begin{cases} K_1 = \sqrt{v_{C_1}^2(0) + \left(\frac{\alpha C_1 v_{C_1}(0) - i_{L_1}(0)}{C_1\omega_d}\right)^2} \\ \theta_1 = tan^{-1}\left(\frac{\alpha C_1 v_{C_1}(0) - i_{L_1}(0)}{C_1\omega_d v_{C_1}(0)}\right) \end{cases}$$

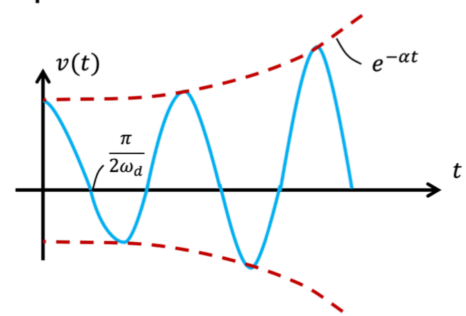
$R_p > r_n$



$R_p = r_n$

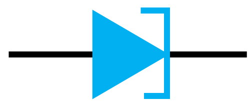


$R_p < r_n$

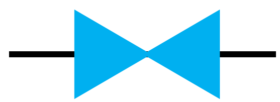


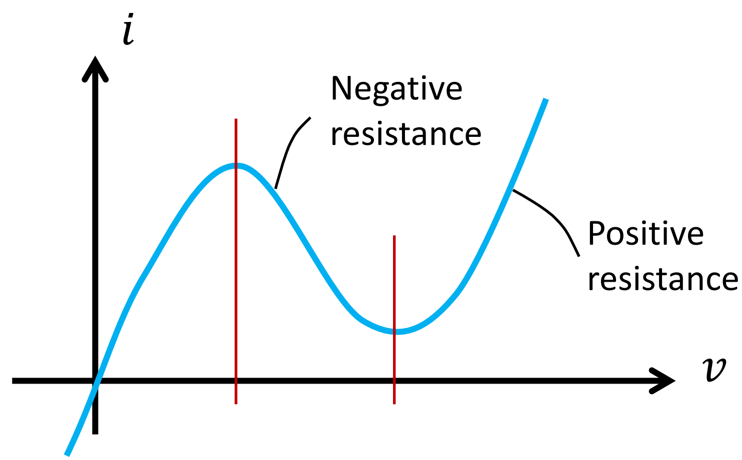
Devices with negative resistance

- Tunnel Diode

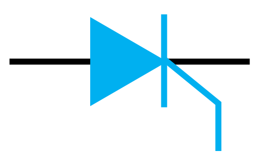


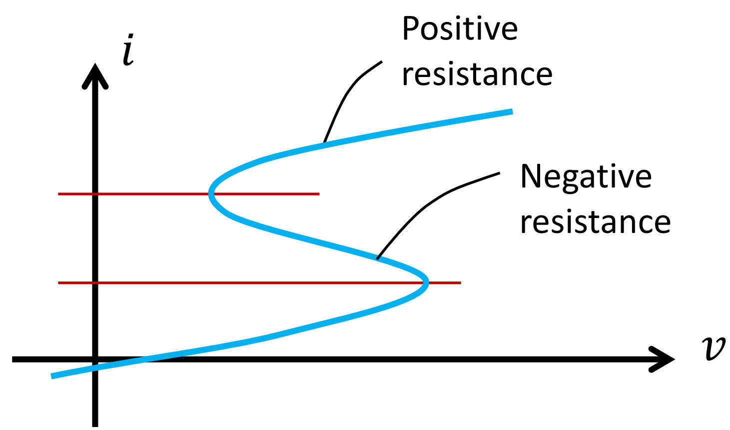
- Gunn Diode





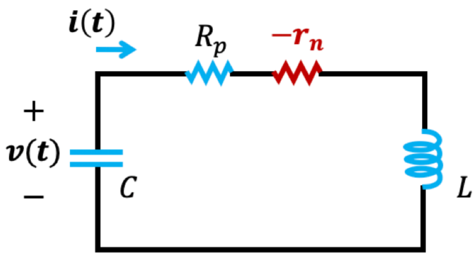
- Thyristor

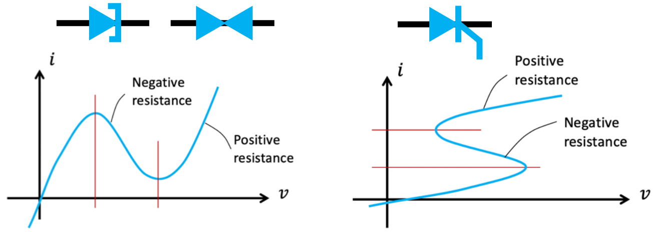




Outline

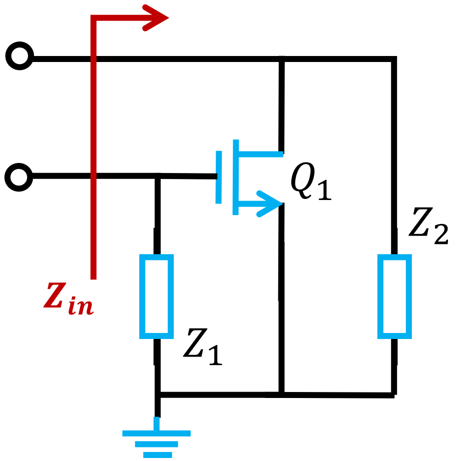
- HOW to generate an oscillation?
  - Negative resistance
  - Devices with negative resistance
  - **Circuit features negative resistance**





Example 1

QUESTION: Calculate the equivalent impedance Z_{in} of the circuit.



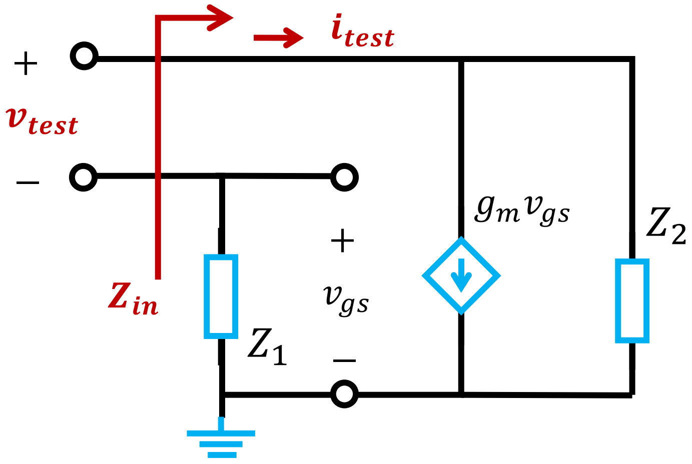
- **Step 1: perform DC analysis**

  Assume Q_1 is biased in saturation region according to DC analysis

- **Step 2: perform AC analysis**
  - **Step 2.1: replace the transistor with the small-signal model**
  - **Step 2.2: turn off DC sources**
    - SHORT all voltage sources
    - OPEN all current sources
  - **Step 2.3: Calculate small-signal model parameters**

Example 1

QUESTION: Calculate the equivalent impedance Z_{in} of the circuit.



- According to KCL

$$i_{test} = g_m v_{gs} + i_{Z_2}$$

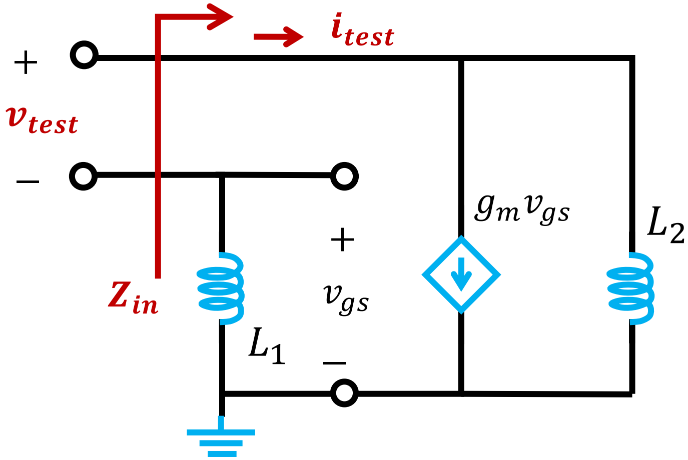
$$= g_m v_{gs} + \frac{v_{test} + v_{gs}}{Z_2}$$

$$= -g_m Z_1 i_{test} + \frac{v_{test} - Z_1 i_{test}}{Z_2}$$

$$Z_{in} = \frac{v_{test}}{i_{test}} = Z_1 + Z_2 + g_m Z_1 Z_2$$

Example 1

QUESTION: Calculate the equivalent impedance Z_{in} of the circuit.

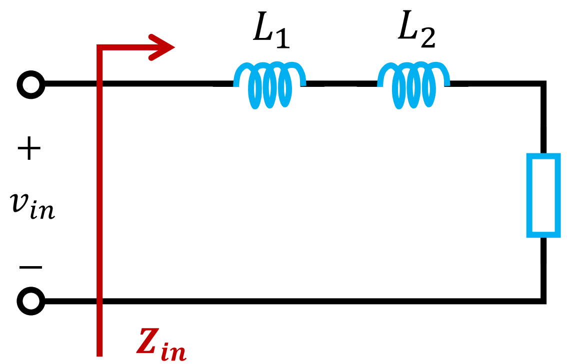


$$Z_{in} = \frac{v_{test}}{i_{test}} = Z_1 + Z_2 + g_m Z_1 Z_2$$

- If Z_1 and Z_2 are inductors

$$Z_{in} = \frac{v_{test}}{i_{test}} = Z_1 + Z_2 + g_m Z_1 Z_2$$

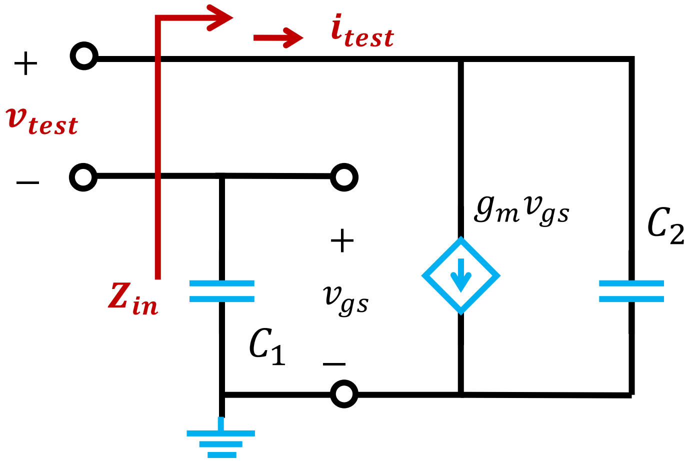
$$= j\omega L_1 + j\omega L_2 - g_m \omega^2 L_1 L_2$$



$$-r_n = -g_m \omega^2 L_1 L_2$$

Example 1

QUESTION: Calculate the equivalent impedance Z_{in} of the circuit.

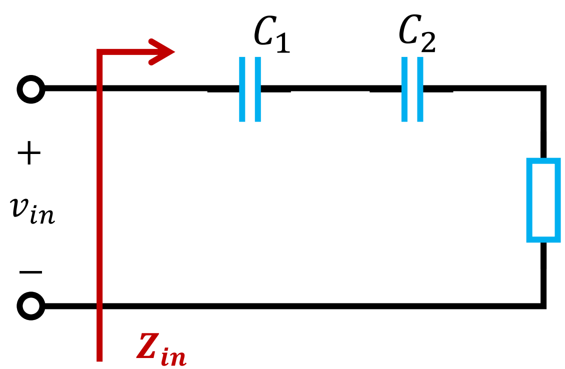


$$Z_{in} = \frac{v_{test}}{i_{test}} = Z_1 + Z_2 + g_m Z_1 Z_2$$

- If Z_1 and Z_2 are capacitors

$$Z_{in} = \frac{v_{test}}{i_{test}} = Z_1 + Z_2 + g_m Z_1 Z_2$$

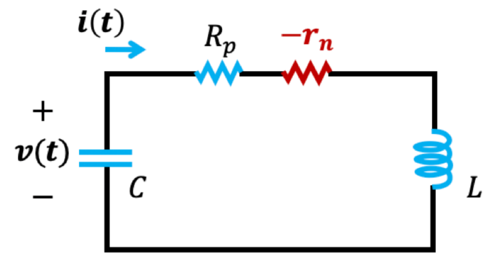
$$= \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2} - g_m \frac{1}{\omega^2 C_1 C_2}$$

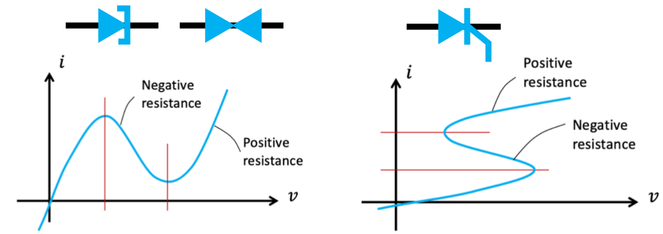


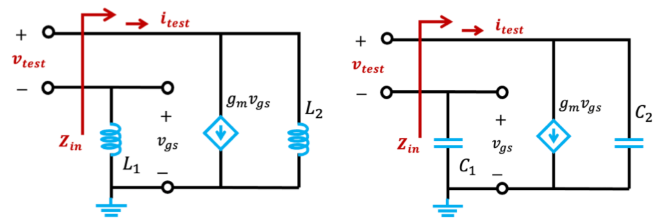
$$-r_n = -g_m \frac{1}{\omega^2 C_1 C_2}$$

Outline

- HOW to generate an oscillation?
  - Negative resistance
  - Devices with negative resistance
  - Circuit features negative resistance
- **Linear Oscillator**
  - **LC Oscillator**

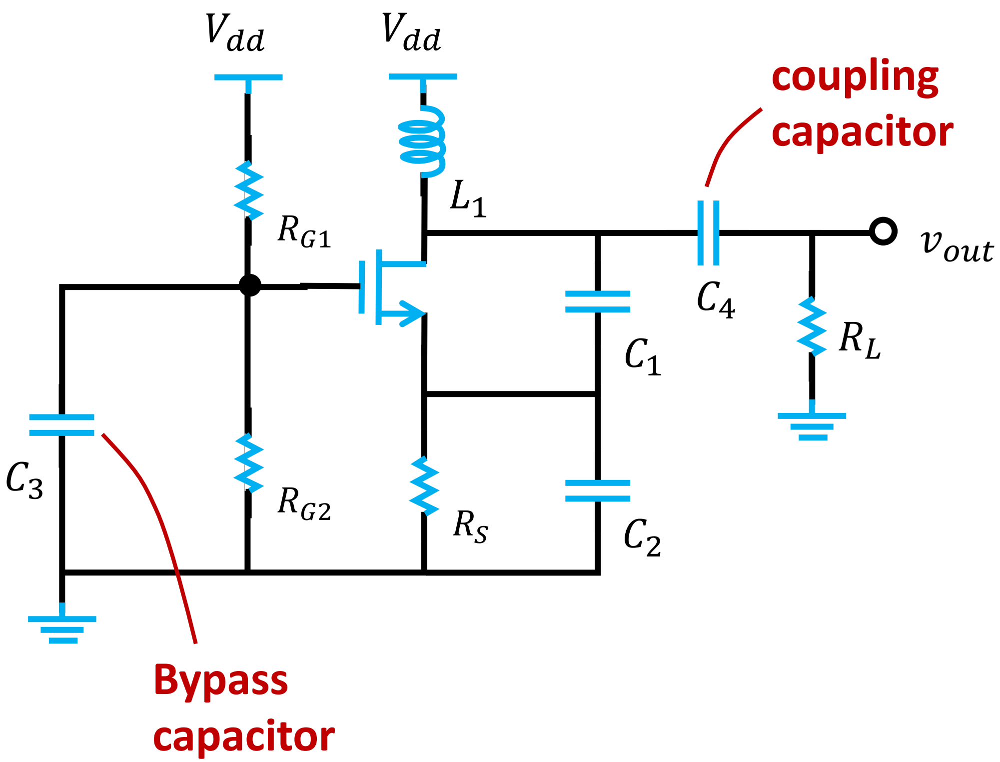






Example 2: Colpitts Oscillator

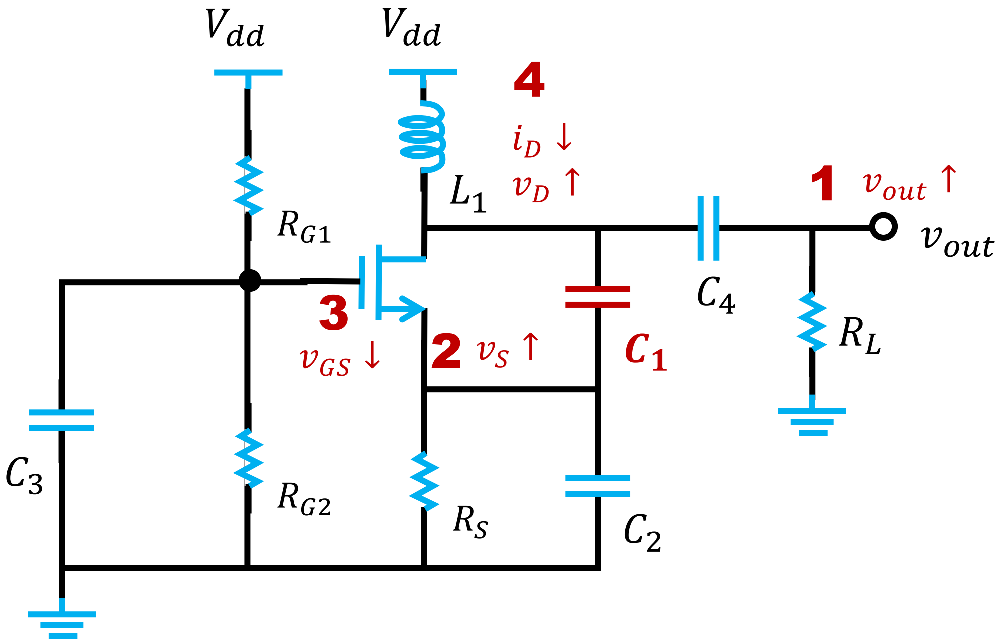
QUESTION: Find the functionality of the following circuit.



- C_4 is **coupling capacitors**
- C_3 is **bypass capacitor**
- C_3 and C_4 **IDEALLY** are short circuit @DC

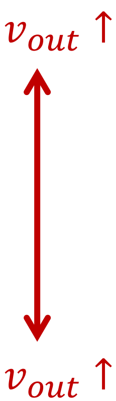
Example 2: Colpitts Oscillator

QUESTION: Find the functionality of the following circuit.



What is C_1 used for?

- If there is an increase @ v_{out}
- The voltage increase @ source
- v_{GS} decrease correspondingly
- i_D decreases, causing an decreasing of v_D



POSITIVE FEEDBACK is observed

Example 2: Colpitts Oscillator

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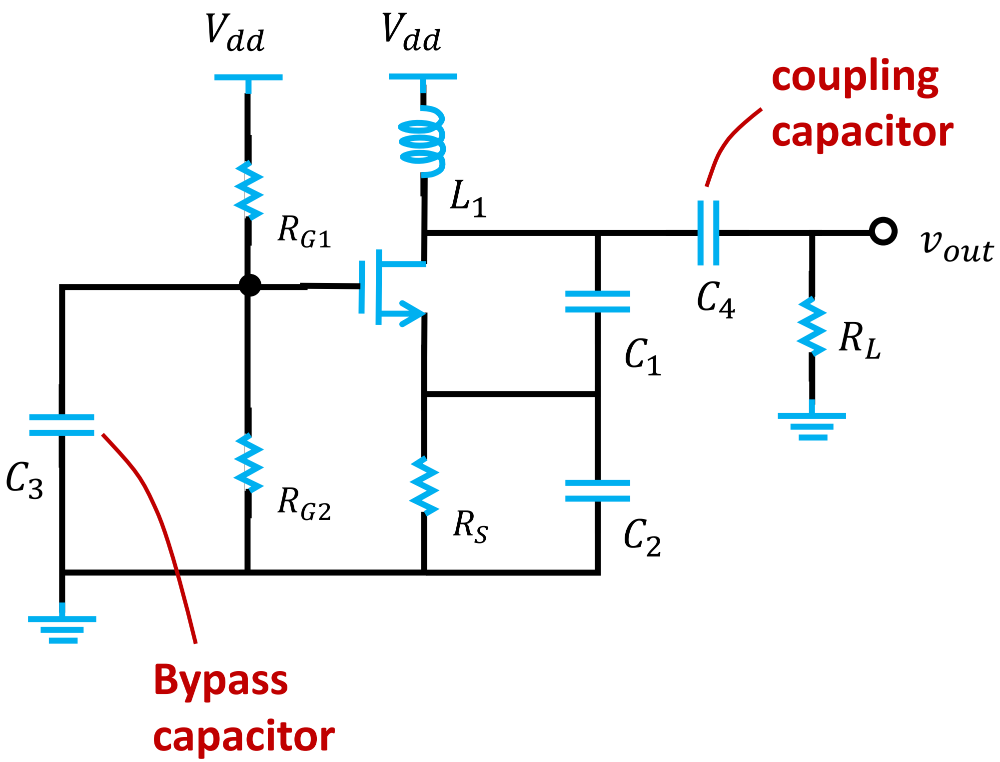

- **Step 1: perform DC analysis**
- **Step 2: perform AC analysis**
  - Step 2.1: turn off DC sources
  - Step 2.2: Calculate small-signal model parameters, g_m
  - Step 2.3: replace the transistor with the small-signal model
  - Step 2.4: Analyze the resulting circuit

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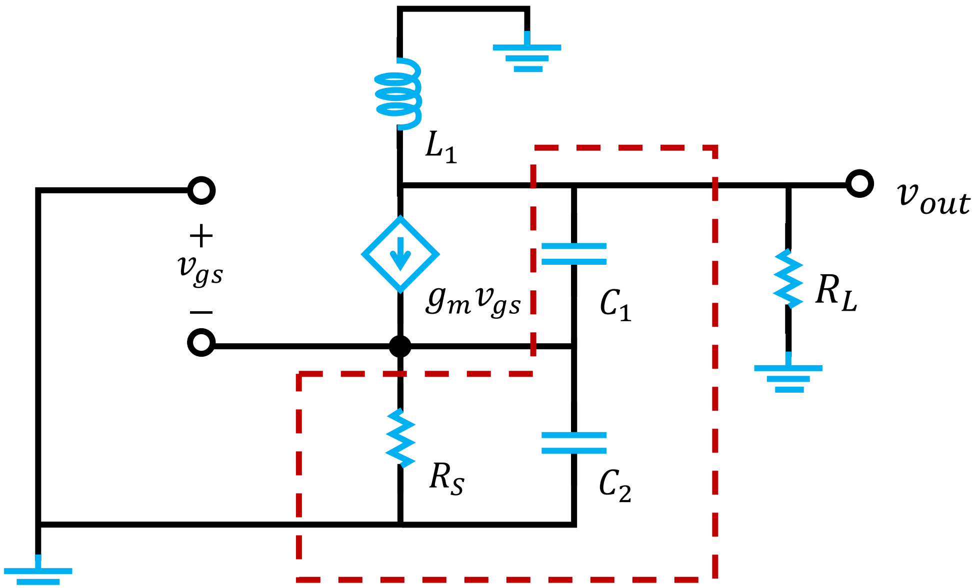
QUESTION: Find the functionality of the following circuit.

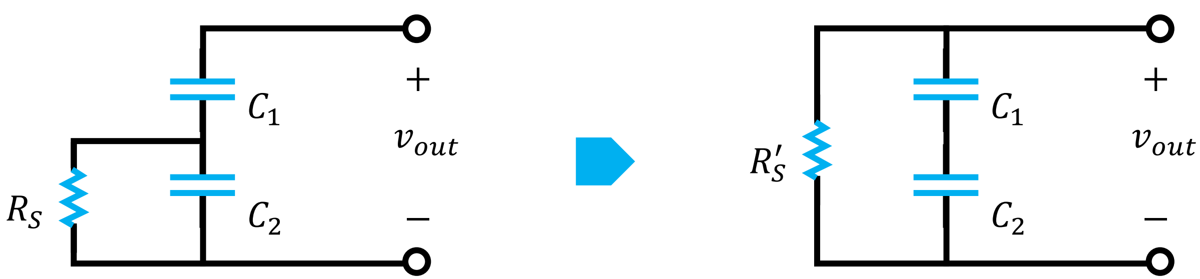


$$v_{R_S} = \frac{\frac{1}{sC_2}||R_S}{\frac{1}{sC_1}+\left(\frac{1}{sC_2}||R_S\right)} v_{out}$$

If $R_S \gg \frac{1}{sC_2}$

$$\approx \frac{\frac{1}{sC_2}}{\frac{1}{sC_1}+\frac{1}{sC_2}} v_{out} = \underbrace{\frac{C_1}{C_1+C_2}}_{p} v_{out}$$

$R_S' = \frac{R_S}{p^2}$ to keep a same power



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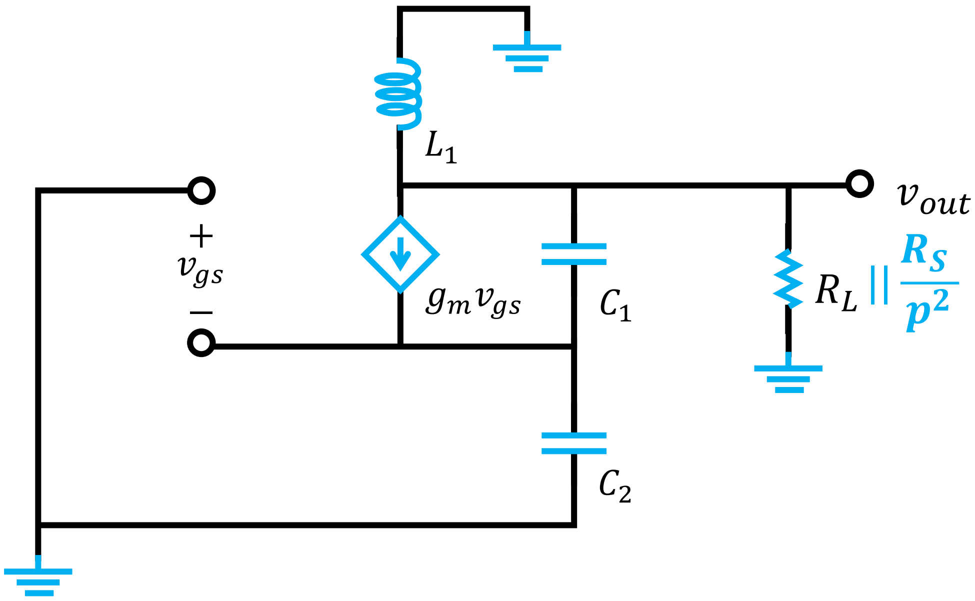
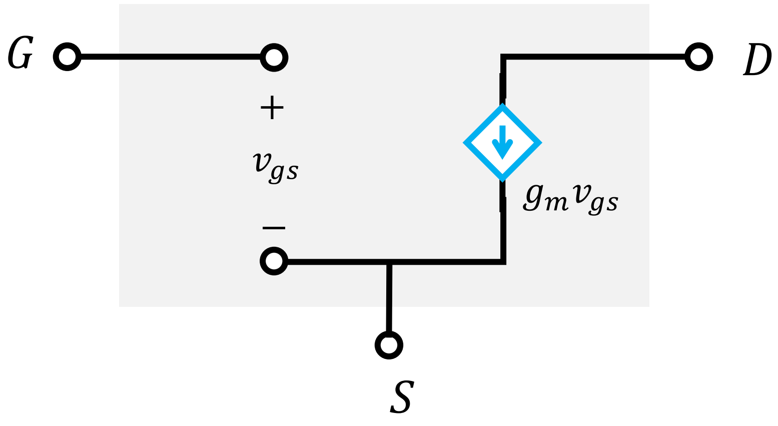
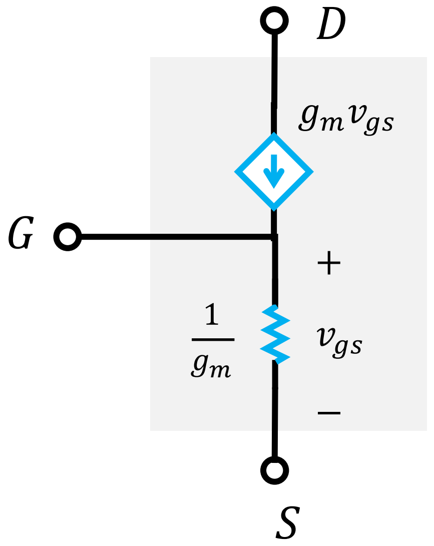


Recall: MOSFET Small-Signal Model

SIMPLIFIED HYBRID-π MODEL



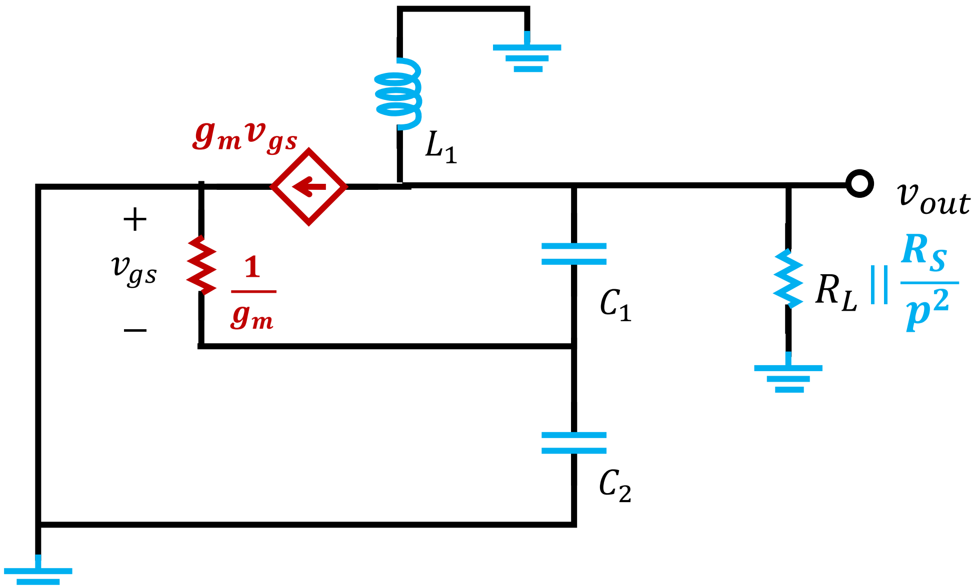
SIMPLIFIED T MODEL

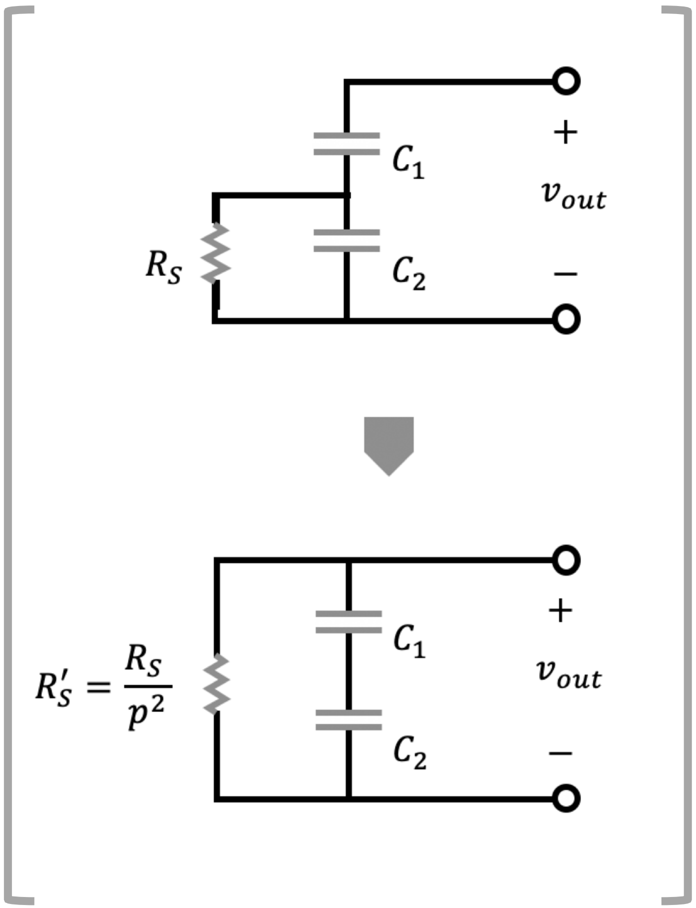


HYBRID-π MODEL and T MODEL are equivalent

Example 2: Colpitts Oscillator

QUESTION: Find the functionality of the following circuit.





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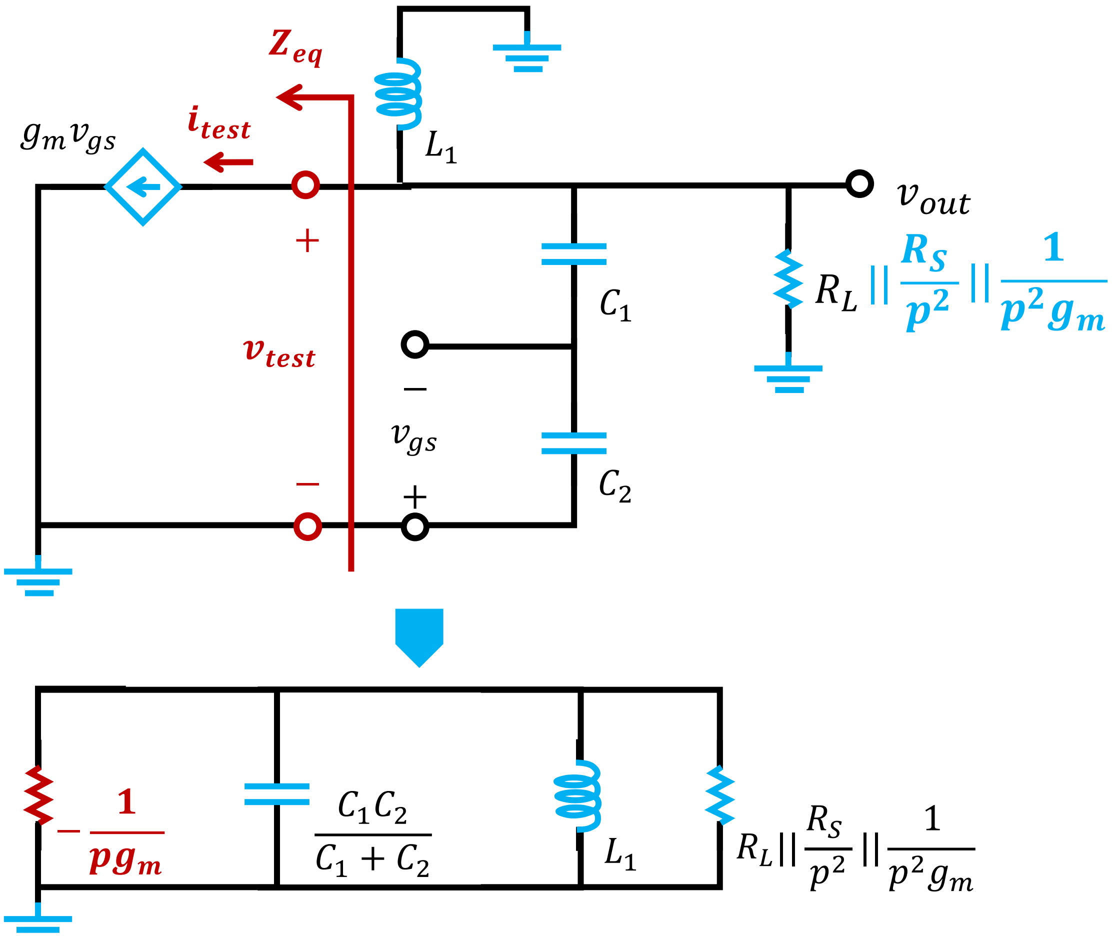


- According to KVL

$$v_{test} = -sC_2 v_{gs} \frac{C_1 + C_2}{sC_1C_2}$$

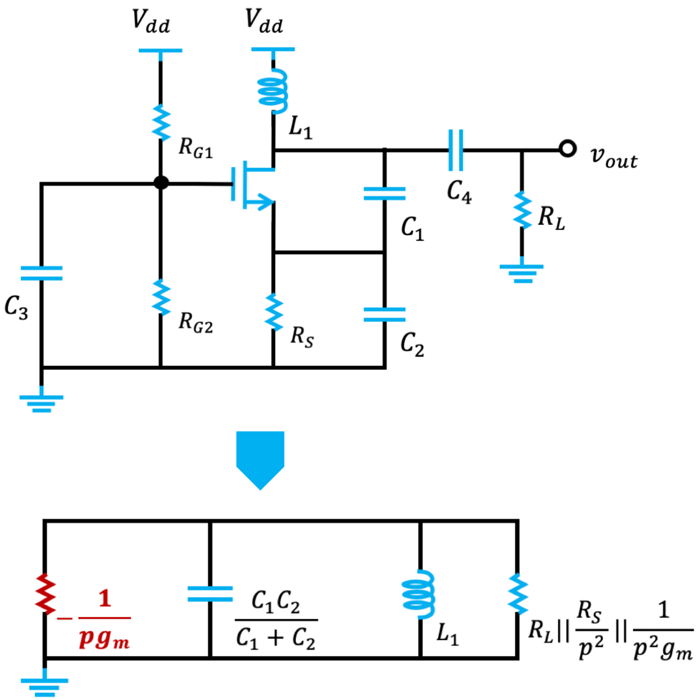
$$= -\frac{C_1 + C_2}{C_1} v_{gs}$$

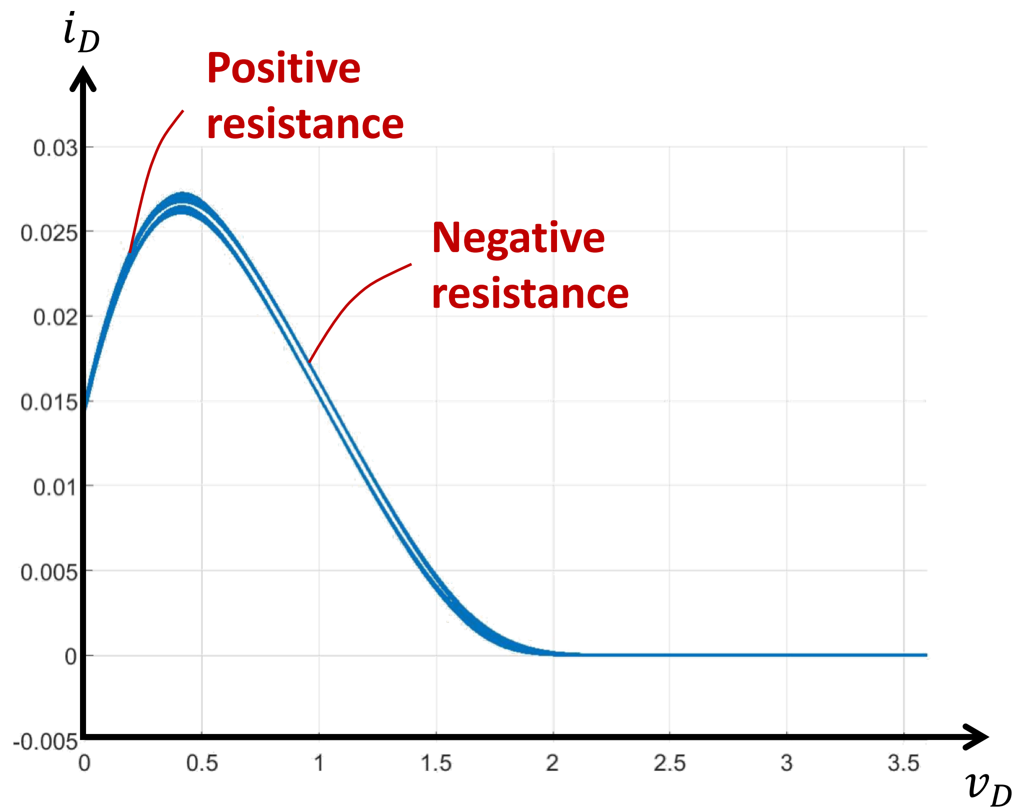
$$\frac{C_1 + C_2}{C_1} = 1/p$$

$$Z_{eq} = \frac{v_{test}}{i_{test}} = -\frac{1}{pg_m}$$

Example 2: Colpitts Oscillator

QUESTION: Find the functionality of the following circuit.





Example 2: Colpitts Oscillator

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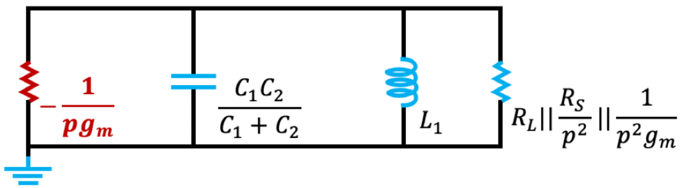
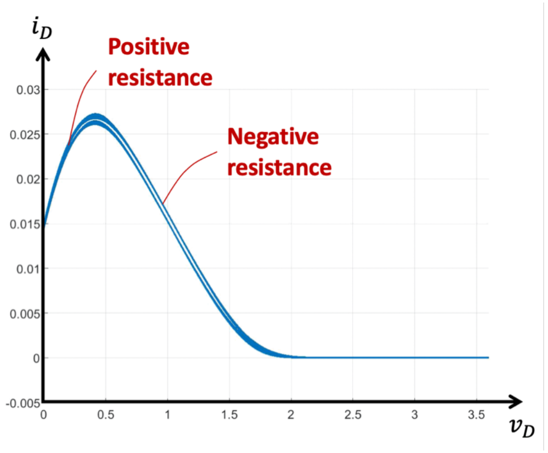




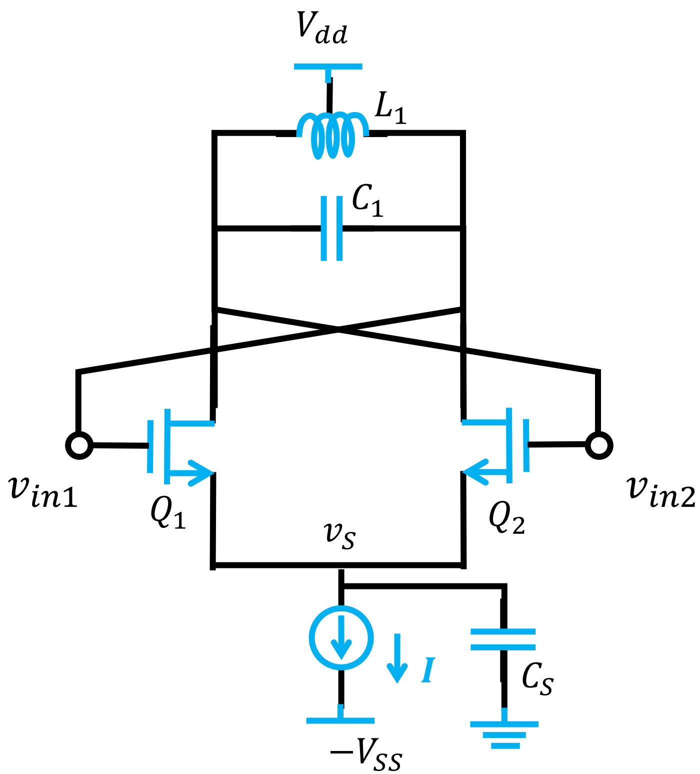
- Oscillation can be expected when

$$g_m p > p^2 g_m + \underbrace{\frac{p^2}{R_S} + \frac{1}{R_L}}_{g'_L}$$

$$\Rightarrow \quad g_m > \frac{g'_L}{p - p^2}$$

Example 3

QUESTION: Find the functionality of the following circuit. Assume Q_1 and Q_2 are matched.



- **Step 1: perform DC analysis**
- **Step 2: perform AC analysis**
  - Step 2.1: turn off DC sources
  - Step 2.2: Calculate small-signal model parameters, g_m
  - Step 2.3: replace the transistor with the small-signal model
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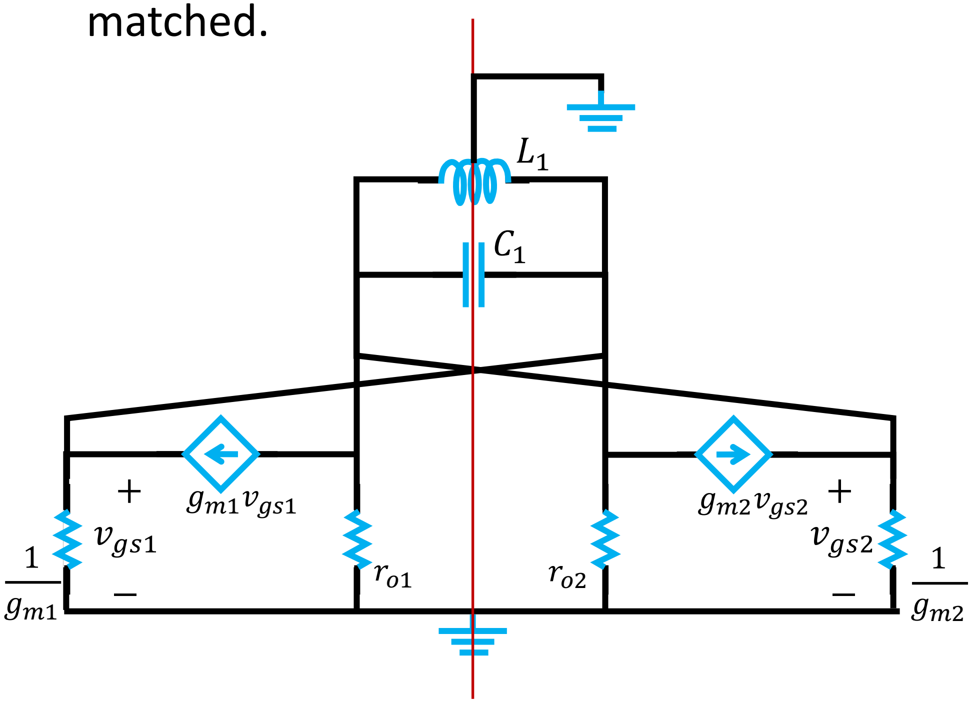
Example 3

QUESTION: Find the functionality of the following circuit. Assume Q_1 and Q_2 are matched.



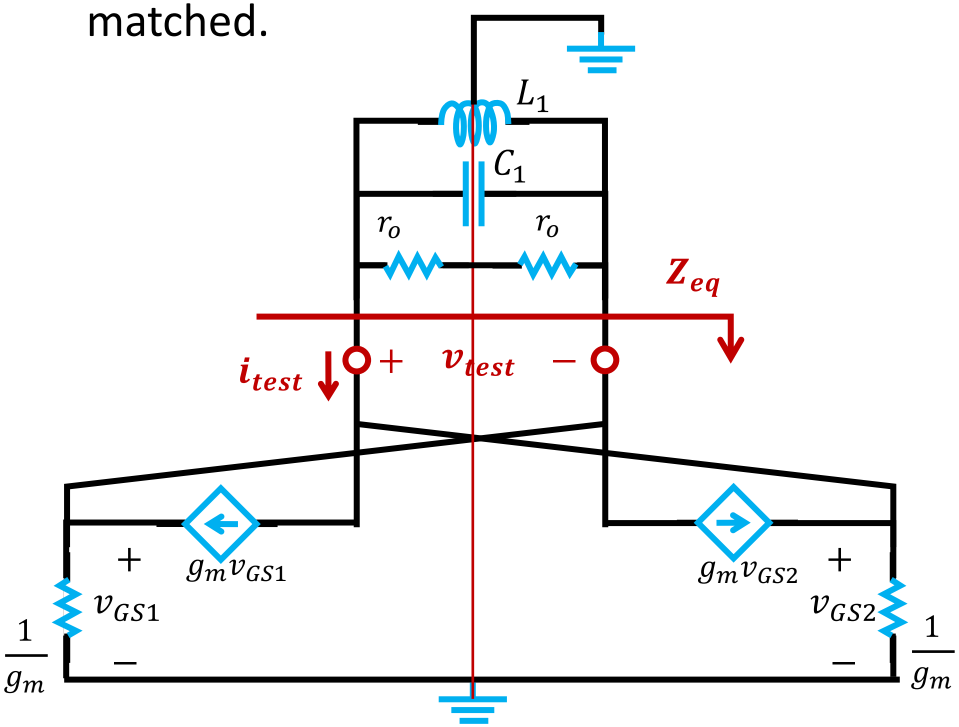
- Since Q_1 and Q_2 are matched

$$g_{m1} = g_{m2} = g_m$$

$$r_{o1} = r_{o2} = r_o$$

Example 3

QUESTION: Find the functionality of the following circuit. Assume Q_1 and Q_2 are matched.



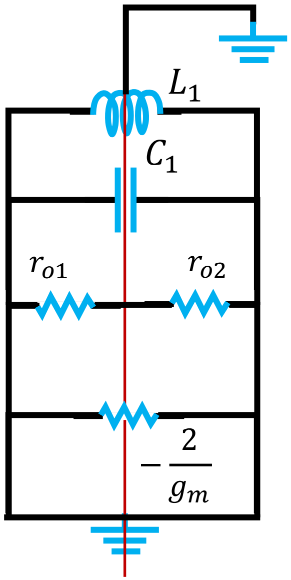
- According to KCL & resistor characteristic

$$\begin{cases} (i_{test} - g_{m1}v_{GS1} + g_{m2}v_{GS2})\dfrac{1}{g_{m2}} = v_{GS2} \\ (-i_{test} - g_{m2}v_{GS2} + g_{m1}v_{GS1})\dfrac{1}{g_{m1}} = v_{GS1} \\ v_{GS1} - v_{GS2} = v_{test} \end{cases}$$

$$Z_{eq} = \frac{v_{test}}{i_{test}} = -\frac{2}{g_m}$$

Example 3

QUESTION: Find the functionality of the following circuit. Assume Q_1 and Q_2 are matched.



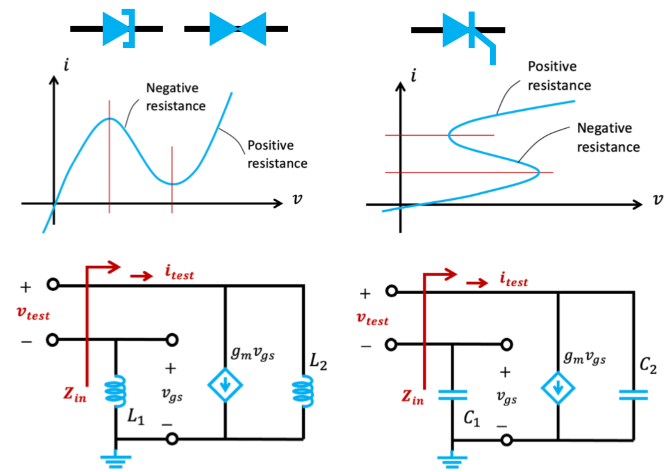
- Oscillation can be expected when

$$\frac{g_m}{2} > \frac{1}{2r_o}$$

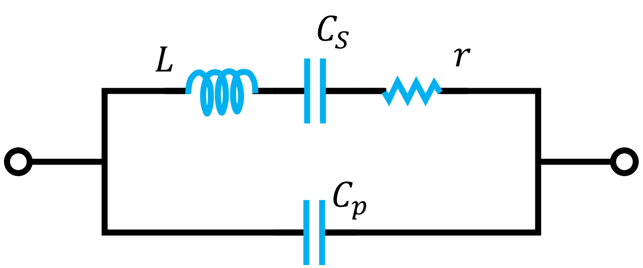
$$\Rightarrow \quad g_m > \frac{1}{r_o}$$

Outline

- HOW to generate an oscillation?
  - Negative resistance
  - Devices with negative resistance
  - Circuit features negative resistance
- Linear Oscillator
  - LC Oscillator
  - **Crystal Oscillator**

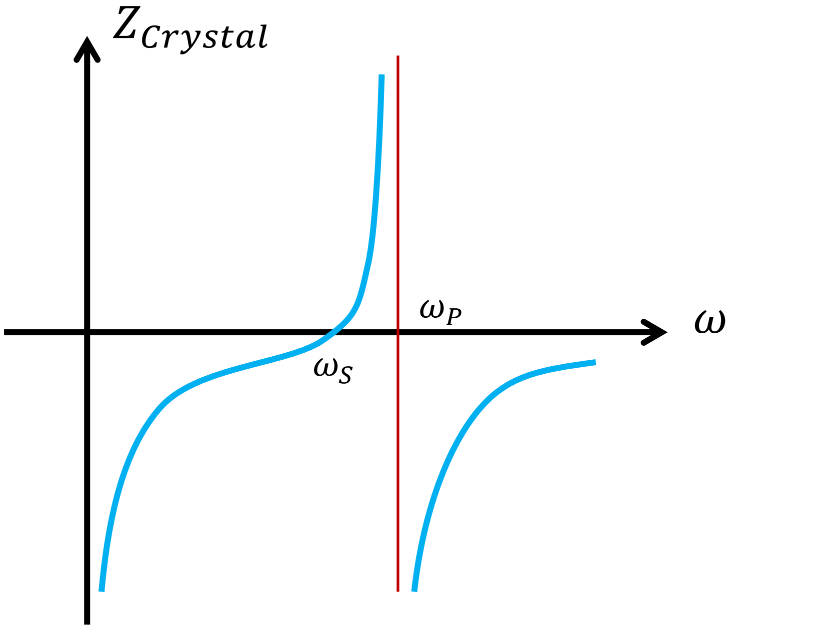


Crystal Oscillators



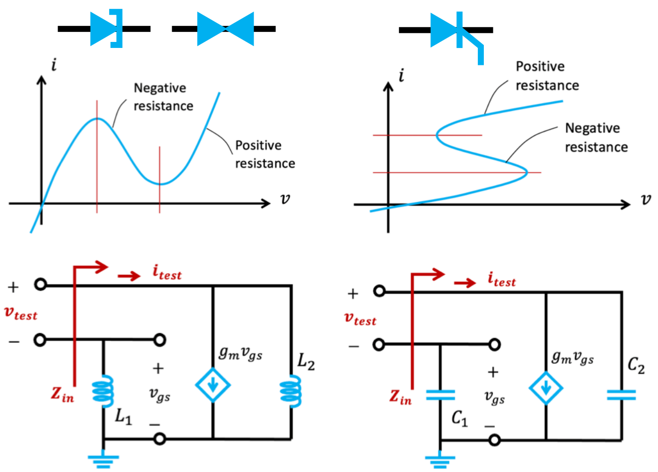
Equivalent circuit

- ☺ High frequency
- ☺ High stability
- ☹ High Q factor
- ☹ Cannot integrate on chip



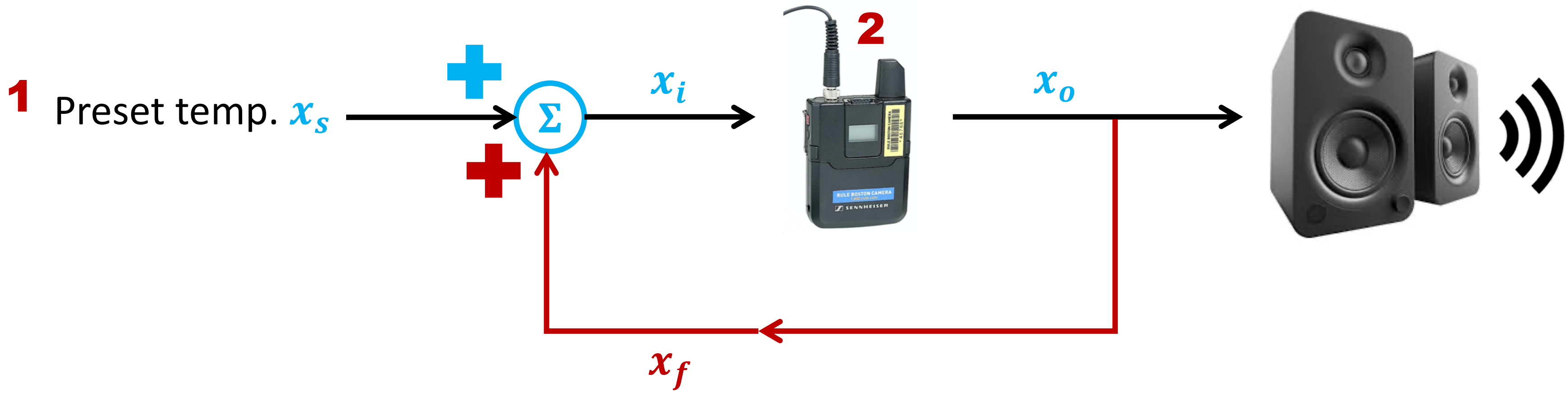
Outline

- HOW to generate an oscillation?
  - Negative resistance
  - Devices with negative resistance
  - Circuit features negative resistance



- Linear Oscillator
  - LC Oscillator
  - Crystal Oscillator
  - **Op-Amp-RC Oscillator**

Recall: Example of Positive Feedback

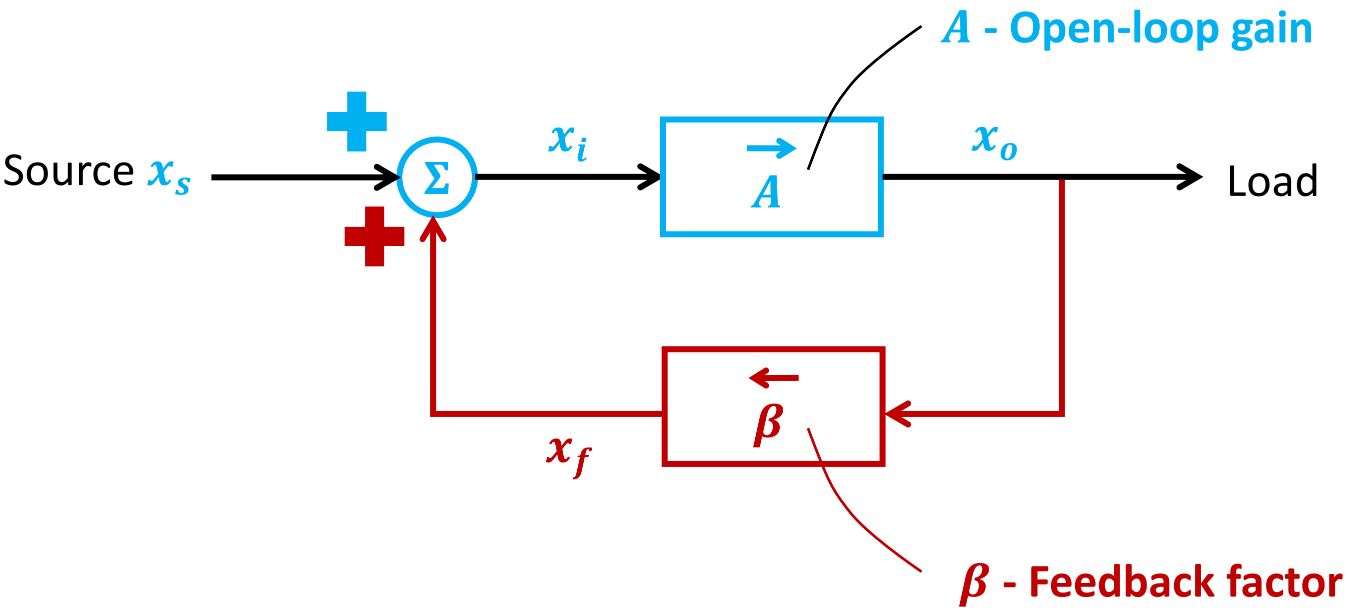


- The output x_o is related to the input x_i
- The output x_o is fed to a feedback network to generate x_f
- The input of the system turns into $x_i = x_s + x_f$

THIS IS A POSITIVE FEEDBACK

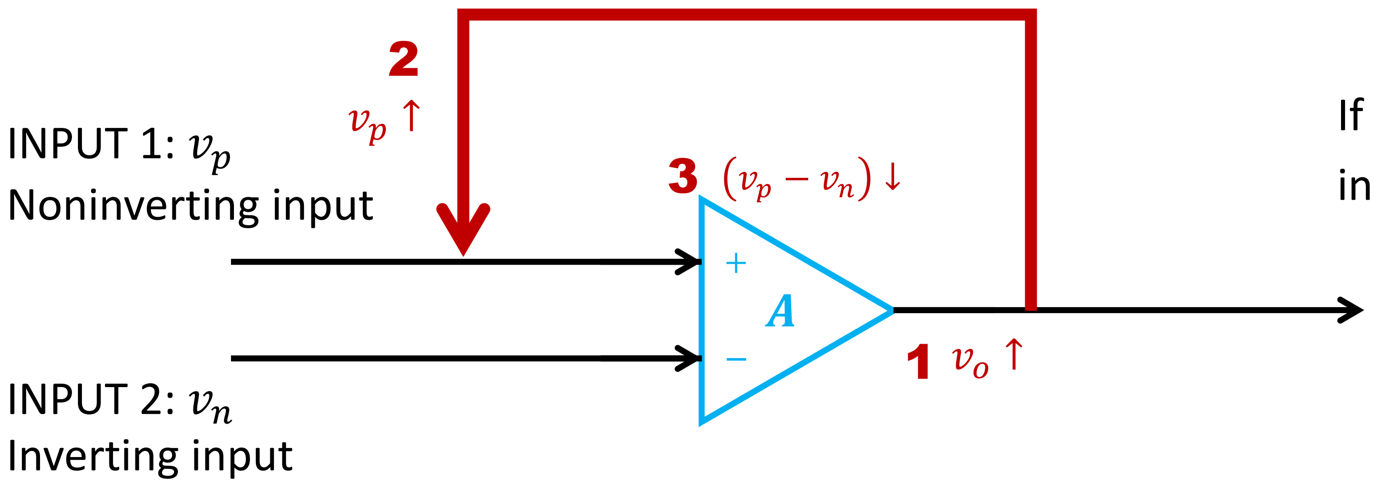
The output is fed-back to input, to INCREASE intensity of input signal

Recall: general pos. feedback structure



- The output x_o is related to the input x_i $\qquad x_o = Ax_i$
- The output is fed to a feedback network $\qquad x_f = \beta x_o$
- The input of the amplifier turns into $\qquad x_i = x_s + x_f$

Recall: Op-Amp w/ positive feedback



If the Op-Amp is biased in the linear region

OUTPUT : v_o

$v_o = A(v_p - v_n)$

How to decide if there is a positive feedback

- If there is an increase @ v_o — $v_o \uparrow$
- The inverting input v_p increases correspondingly
- If the op-amp is biased in the linear region, $v_o = A(v_p - v_n)$ increases — $v_o \uparrow$

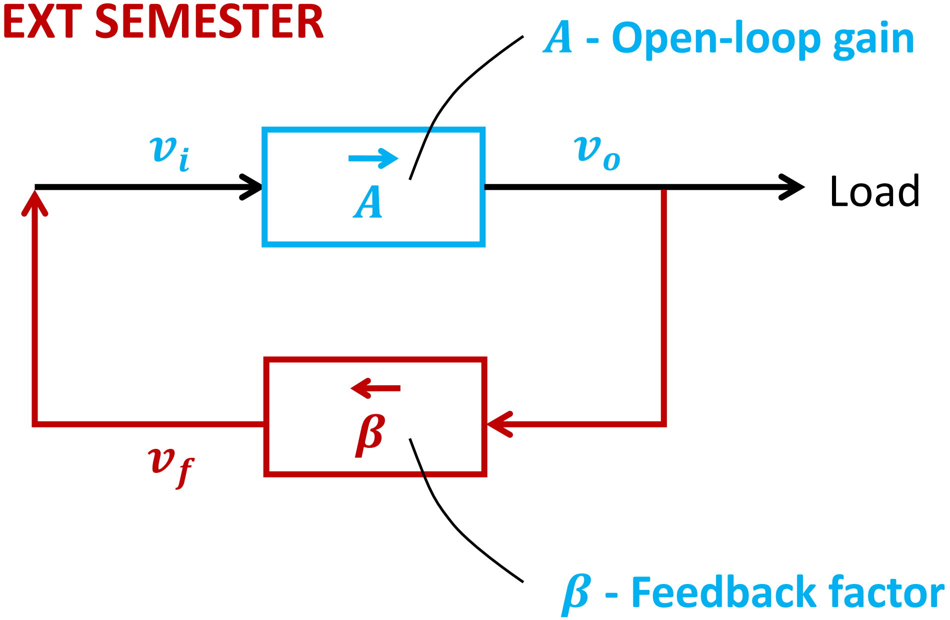
POSITIVE FEEDBACK

An unstable system "oscillates" between V_{dd} and $-V_{dd}$

Recall: positive feedback w/o input

WE WILL DISCUSS THIS NEXT SEMESTER

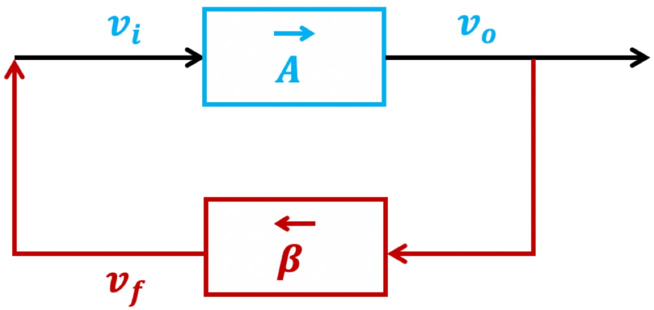
- **What if there is no input in the system?**
- **What gonna happen if there is a disturbance?**



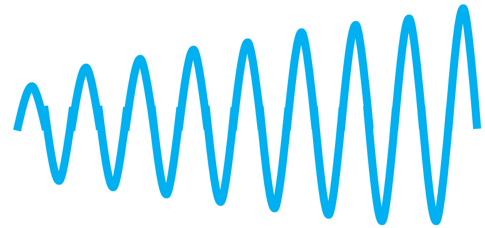
- The output x_o is related to the input x_i $\quad v_o = Av_i$
- The output is fed to a feedback network $\quad v_f = \beta v_o = A\beta v_i$

What if $A\beta > 1$ at the very beginning, but decreases to $A\beta = 1$ later?

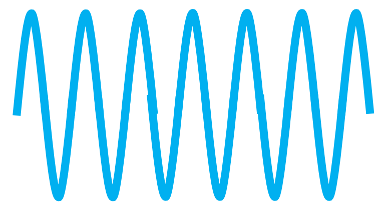
Positive feedback w/o input



A small disturb @ x_i



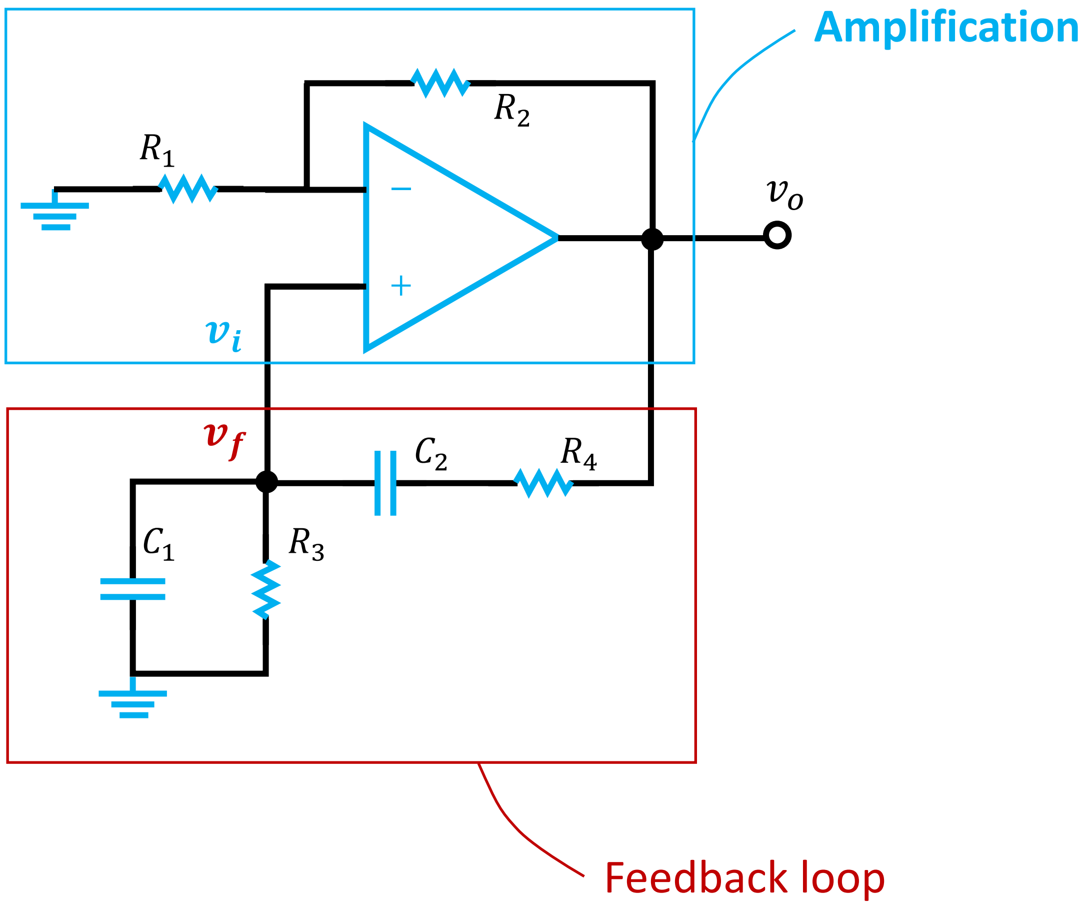
@ $A\beta > 1$
Amplitude increases

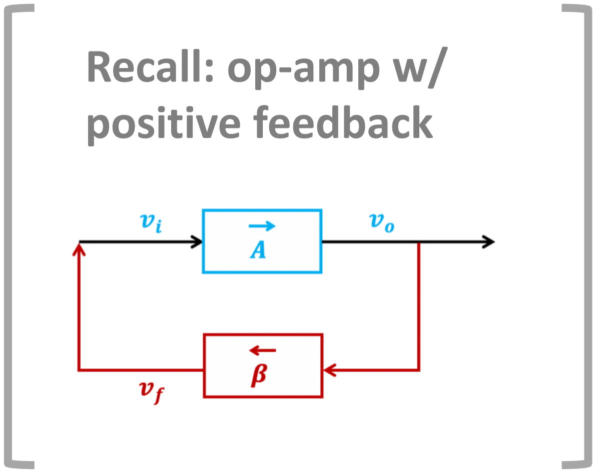


@ $A\beta = 1$
Amplitude keeps

Example 4: the Wien-Bridge Oscillator

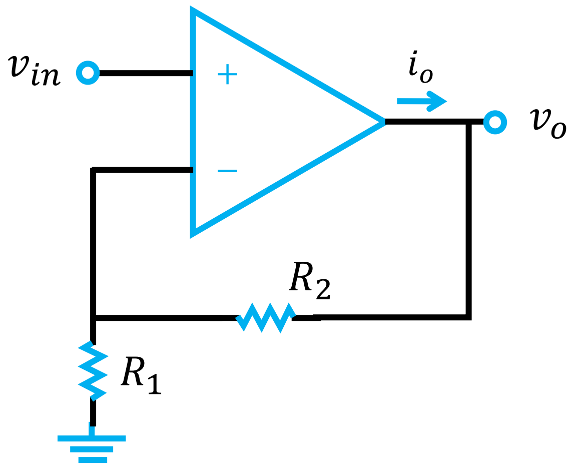
QUESTION: Find the functionality of the following circuit with $R_3 = R_4 = R$, $C_1 = C_2 = C$.





Recall: The noninverting configuration

QUESTION: Find the functionality of the following circuit with $R_3 = R_4 = R$, $C_1 = C_2 = C$.



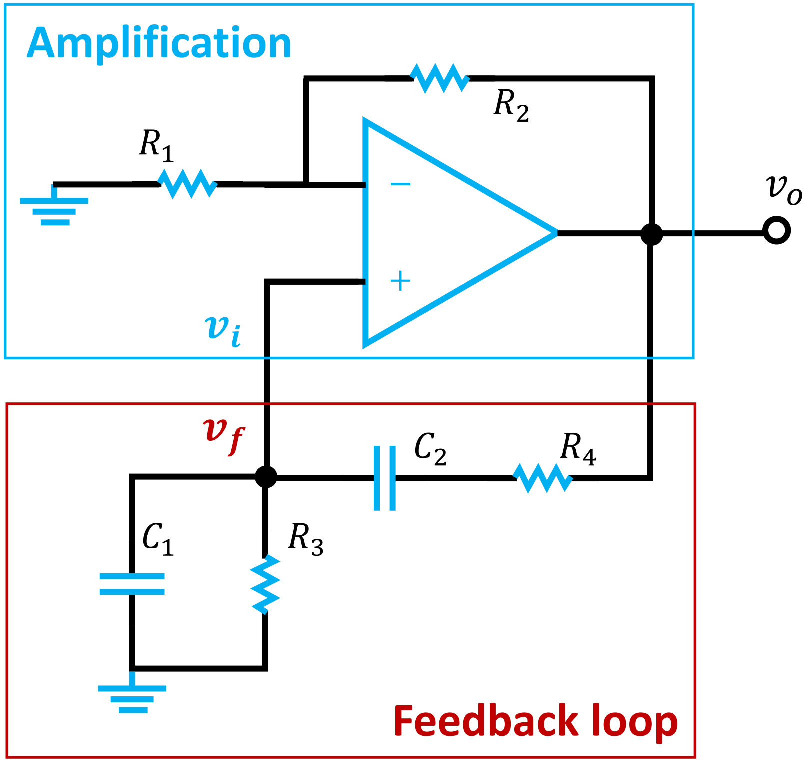
$$\begin{cases} i_{R_1} = \dfrac{v_n}{R_1} = \dfrac{v_{in}}{R_1} \\ i_{R_2} = \dfrac{v_o - v_n}{R_2} = \dfrac{v_o - v_{in}}{R_2} \\ i_{R_1} = i_{R_2} \end{cases}$$

IDEAL OP-AMP with NEGATIVE FEEDBACK enables linear region biasing

$$v_o = \frac{R_1 + R_2}{R_1} v_{in}$$

Example 4: the Wien-Bridge Oscillator

QUESTION: Find the functionality of the following circuit with $R_3 = R_4 = R$, $C_1 = C_2 = C$.



- For the amplification system, the gain

$$A = \frac{v_o}{v_i} = \frac{R_2 + R_1}{R_1}$$

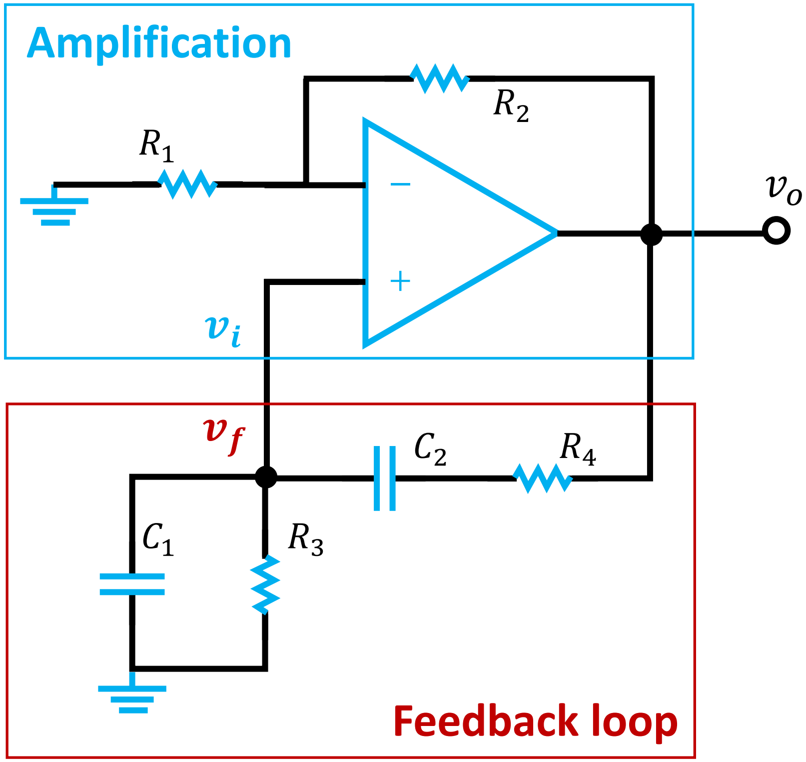
- For the feedback loop

$$\beta = \frac{v_f}{v_o} = \frac{R_3 || \frac{1}{sC_1}}{R_4 + \frac{1}{sC_2} + R_3 || \frac{1}{sC_1}}$$

$$= \frac{1}{3 + sRC + \frac{1}{sRC}}$$

Example 4: the Wien-Bridge Oscillator

QUESTION: Find the functionality of the following circuit with $R_3 = R_4 = R$, $C_1 = C_2 = C$.



$$\begin{cases} A = \frac{v_o}{v_i} = \frac{R_2 + R_1}{R_1} \\ \beta = \frac{1}{3 + sRC + \frac{1}{sRC}} \end{cases}$$

- The transfer function

$$H(s) = A\beta = \frac{1 + \frac{R_2}{R_1}}{3 + sRC + \frac{1}{sRC}}$$

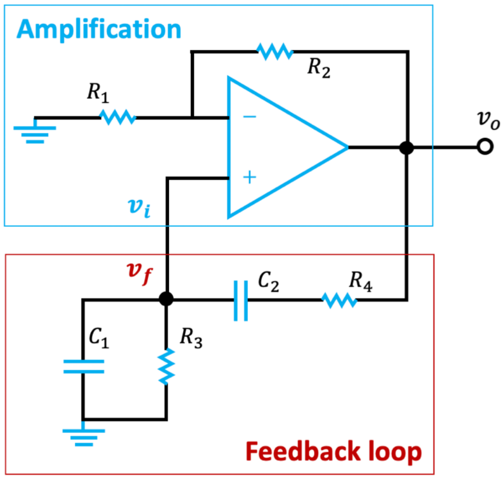
- $H(s)$ is a real number, when

$$sRC + \frac{1}{sRC} = 0 \quad \Rightarrow \quad \omega_0 = \frac{1}{RC}$$

The oscillation frequency ω_0 is "determined" by the feedback loop

Example 4: the Wien-Bridge Oscillator

QUESTION: Find the functionality of the following circuit with $R_3 = R_4 = R$, $C_1 = C_2 = C$.



$$\begin{cases} A = \frac{v_o}{v_i} = \frac{R_2 + R_1}{R_1} \\ \beta = \frac{1}{3 + sRC + \frac{1}{sRC}} \\ H(s) = A\beta \text{ is real @ } \omega_0 = \frac{1}{RC} \end{cases}$$

- $A\beta = 1$ when $\frac{R_2}{R_1} = 2$

Positive feedback is observed

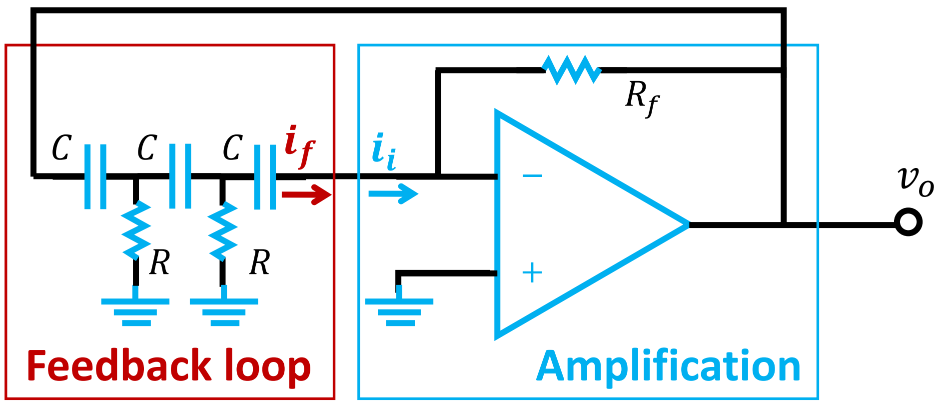
- Oscillation is triggered when $\frac{R_2}{R_1} > 2$

- The gain with feedback can be calculated as

$$A_f = \frac{A}{1 - A\beta} = \frac{A}{1 - \frac{1}{3}A} \quad @\omega = \omega_0$$

Example 5: the Phase-Shift Oscillator

QUESTION: Find the functionality of the following



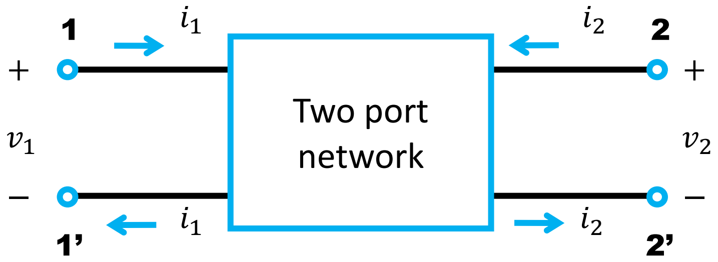
- For the amplification system, the gain

$$A = \frac{v_o}{i_i} = -R_f$$

- For the feedback loop

$$\beta = \frac{i_f}{v_o}$$

Recall: T parameters



- v_1, i_1 are dependent
- v_2, i_2 are independent

→ T **parameters**

$$\begin{cases} v_1 = Av_2 - Bi_2 \\ i_1 = Cv_2 - Di_2 \end{cases}$$

or

$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} v_2 \\ -i_2 \end{bmatrix}$$

$A = \frac{v_1}{v_2}$ when $i_2 = 0$

$B = -\frac{v_1}{i_2}$ when $v_2 = 0$

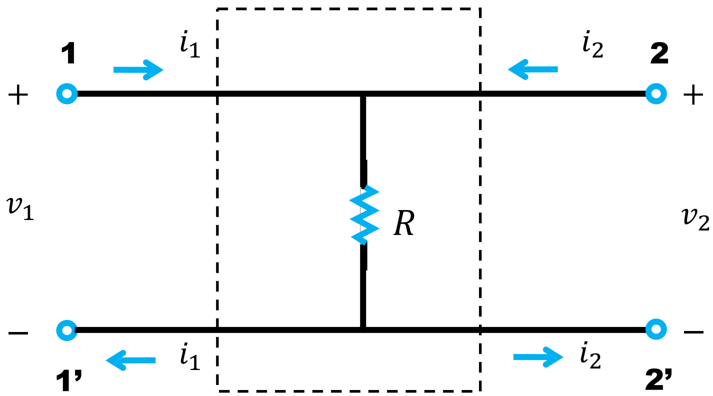
$C = \frac{i_1}{v_2}$ when $i_2 = 0$

$D = -\frac{i_1}{i_2}$ when $v_2 = 0$

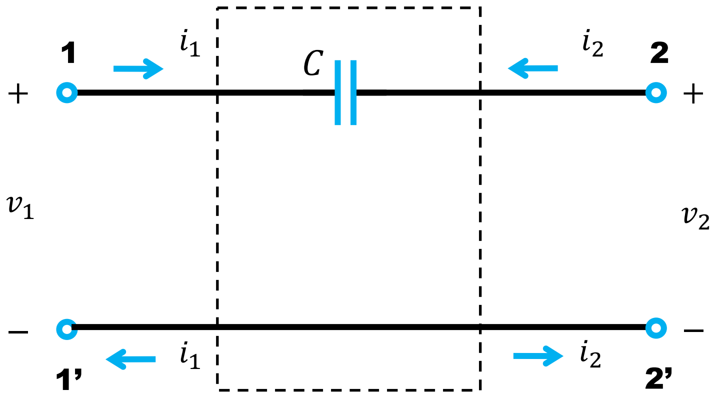
T Parameters are also called as $ABCD$ parameters

Recall: T parameters

QUESTION: find the T parameters of the circuit below



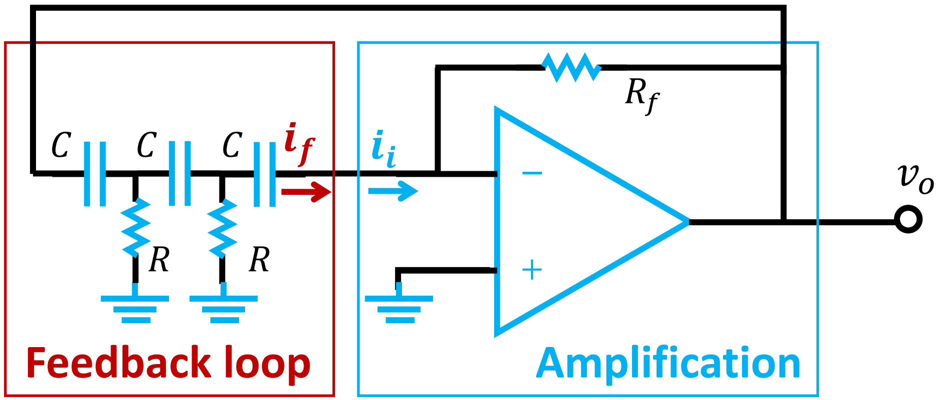
$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{R} & 1 \end{bmatrix} \begin{bmatrix} v_2 \\ -i_2 \end{bmatrix}$$



$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{sC} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_2 \\ -i_2 \end{bmatrix}$$

Example 5: the Phase-Shift Oscillator

QUESTION: Find the functionality of the following



- For the amplification system, the gain

$$A = \frac{v_o}{i_i} = -R_f$$

- For the feedback loop $\beta = \frac{i_f}{v_o}$

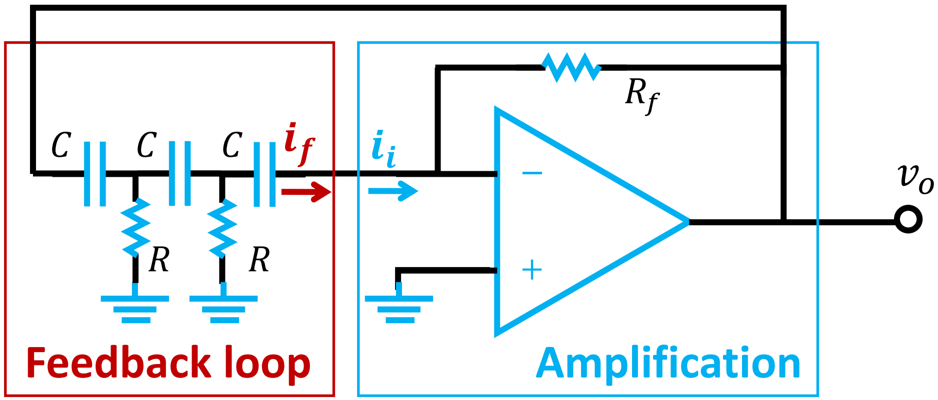
$$\begin{bmatrix} v_o \\ i_o \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{sC} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{R} & 1 \end{bmatrix} \begin{bmatrix} 1 & \frac{1}{sC} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{R} & 1 \end{bmatrix} \begin{bmatrix} 1 & \frac{1}{sC} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_f \\ i_f \end{bmatrix}$$

$$= \begin{bmatrix} * & \left[\left(\frac{1}{sRC}\right)^2 + \frac{4}{sRC} + 3\right]\frac{1}{sC} \\ * & * \end{bmatrix} \begin{bmatrix} v_f \\ i_f \end{bmatrix}$$

$$\boldsymbol{\beta = \frac{i_f}{v_o} = \frac{sC}{\left(\frac{1}{sRC}\right)^2 + \frac{4}{sRC} + 3}}$$

Example 5: the Phase-Shift Oscillator

QUESTION: Find the functionality of the following



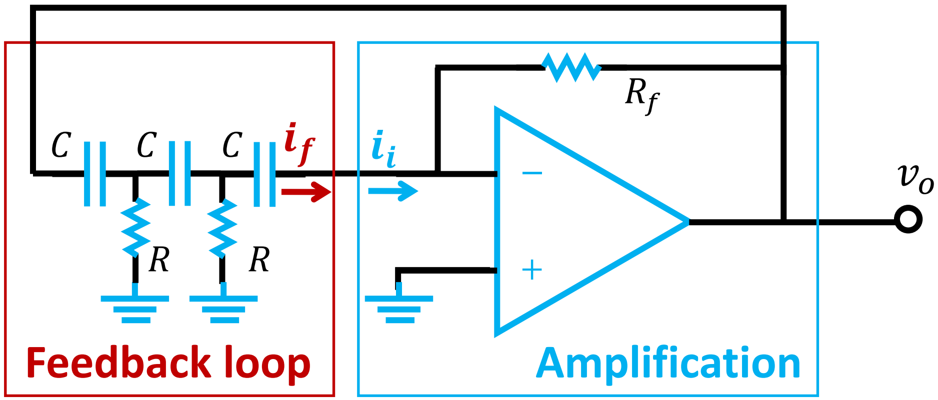
$$\begin{cases} A = \dfrac{v_o}{i_i} = -R_f \\ \beta = \dfrac{i_f}{v_o} = \dfrac{sC}{\left(\dfrac{1}{sRC}\right)^2 + \dfrac{4}{sRC} + 3} \end{cases}$$

- The transfer function $H(s) = A\beta = -\dfrac{sR_fC}{\left(\dfrac{1}{sRC}\right)^2 + \dfrac{4}{sRC} + 3} = |H(j\omega)|e^{j\varphi(\omega)}$

where
$$\begin{cases} |H(j\omega)| = \dfrac{R_f(\omega RC)^3}{R\sqrt{1 + 10(\omega RC)^2 + 9(\omega RC)^4}} \\ \varphi(\omega) = \dfrac{\pi}{2} - arctan\dfrac{4\omega Rc}{1 - 3\omega^2R^2C^2} \end{cases}$$

Example 5: the Phase-Shift Oscillator

QUESTION: Find the functionality of the following



$$\begin{cases} A = \frac{v_o}{i_i} = -R_f \\ \beta = \frac{i_f}{v_o} = \dfrac{sC}{\left(\frac{1}{sRC}\right)^2 + \frac{4}{sRC} + 3} \\ H(s) = A|\beta(j\omega)|e^{j\varphi(\omega)} \end{cases}$$

- Positive feedback is observed when $\begin{cases} H(s) \text{ is a real number} \\ H(s) > 1 \end{cases}$ ➡ $\boldsymbol{\omega_0 = \frac{1}{\sqrt{3}RC}}$

The oscillation frequency ω_0 is "determined" by the feedback loop

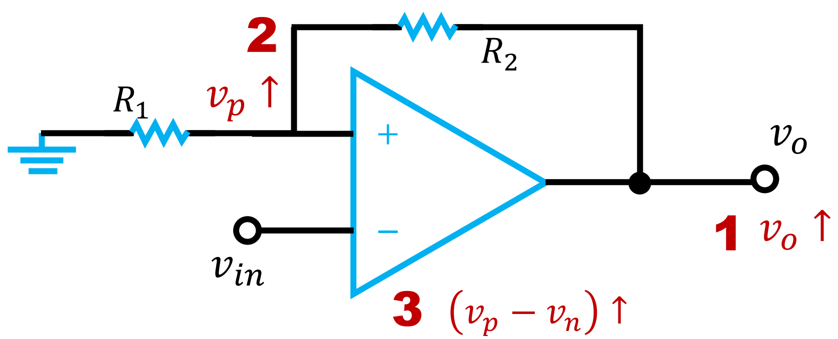
- Oscillation is triggered when $A\beta(j\omega_0) > 1$ ➡ $\boldsymbol{\frac{R_f}{12R} > 1}$

Outline

- HOW to generate an oscillation?
  - Negative resistance
  - Devices with negative resistance
  - Circuit features negative resistance
- Linear Oscillator
  - LC Oscillator
  - Crystal Oscillator
  - Op-Amp-RC Oscillator
- **Non-linear Oscillator**
  - **Bistable Circuit**

Example 6: Schmitt Trigger

QUESTION: Find the functionality of the following circuit.



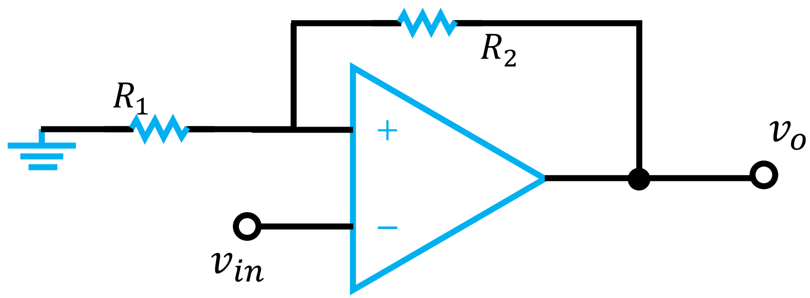
- If there is an increase @ v_o — $v_o \uparrow$
- The noninverting input v_p increases correspondingly
- If the op-amp is biased in the linear region, $v_o = A(v_p - v_n)$ increases — $v_o \uparrow$

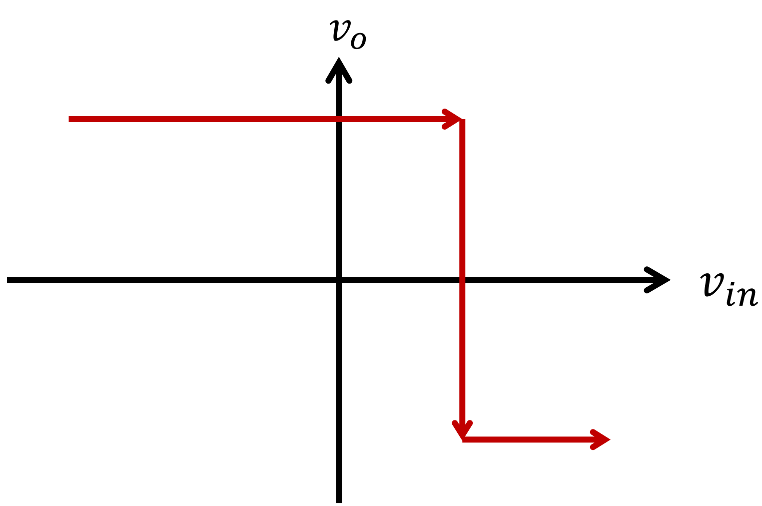
THIS IS A POSITIVE FEEDBACK

The op-amp biased @ saturation region

Example 6: Schmitt Trigger

QUESTION: Find the functionality of the following circuit.





- If v_{in} is very small
- The op-amp is biased in positive saturation region, $v_o = V_{sat}$
- According to KVL

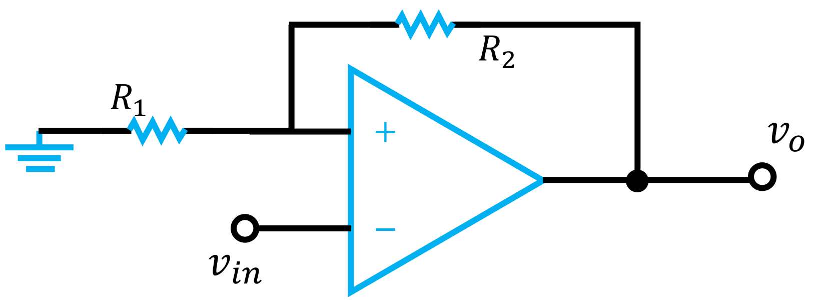
$$v_+ = \frac{R_1}{R_1 + R_2} V_{sat}$$

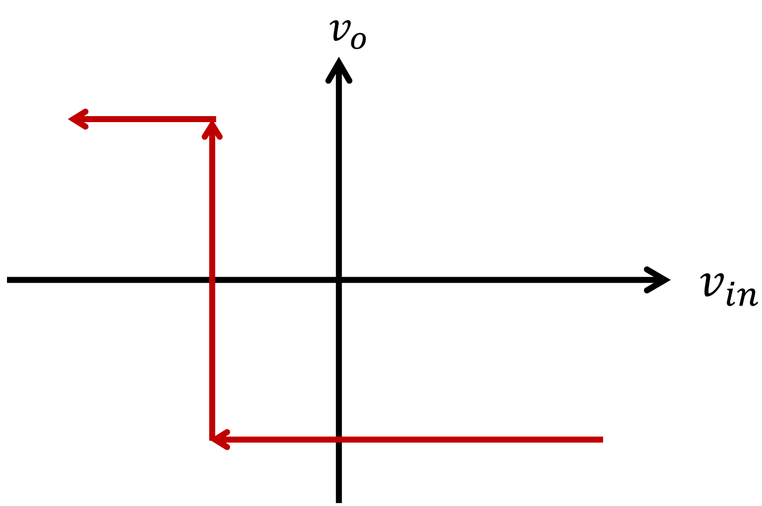
- When $v_{in} > v_+$, the op-amp flips into the negative saturation region, $v_o = -V_{sat}$
- According to KVL

$$v_+ = -\frac{R_1}{R_1 + R_2} V_{sat}$$

Example 6: Schmitt Trigger

QUESTION: Find the functionality of the following circuit.





- If v_{in} is very large
- The op-amp is biased in negative saturation region, $v_o = -V_{sat}$
- According to KVL

$$v_+ = -\frac{R_1}{R_1 + R_2} V_{sat}$$

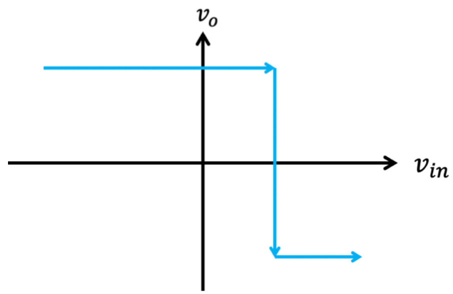
- When $v_{in} < v_+$, the op-amp flips into the positive saturation region, $v_o = V_{sat}$
- According to KVL

$$v_+ = \frac{R_1}{R_1 + R_2} V_{sat}$$

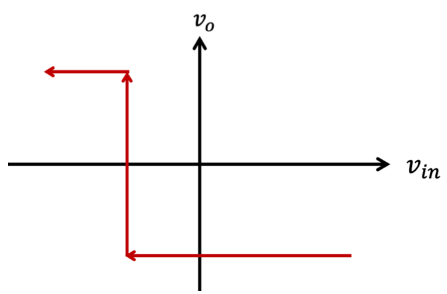
Example 6: Schmitt Trigger

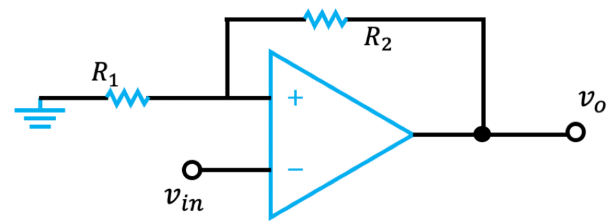
QUESTION: Find the functionality of the following circuit.

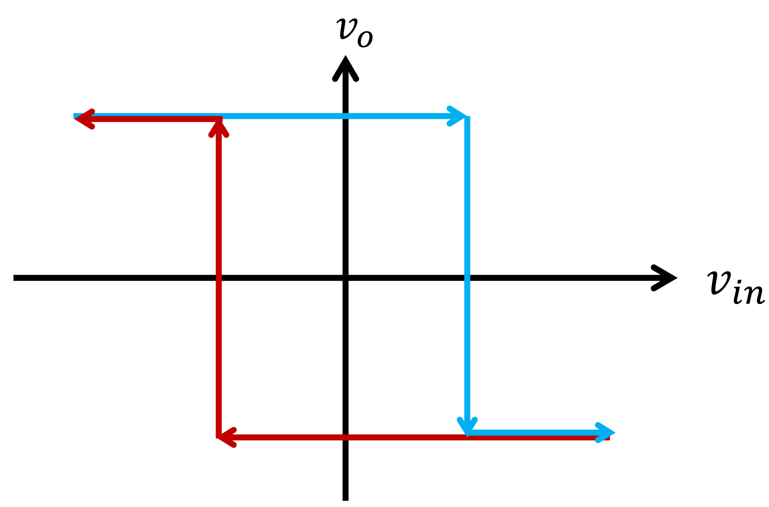
v_{in} increases from a small value



v_{in} decreases from a large value

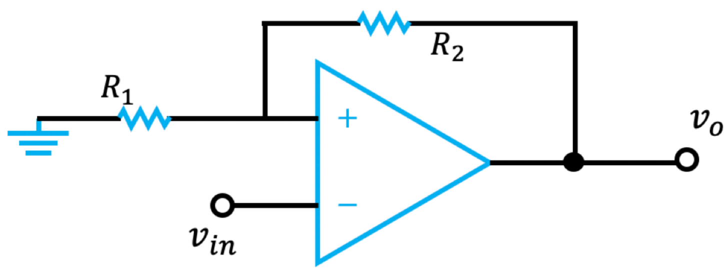


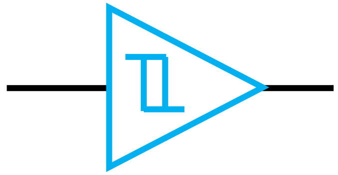


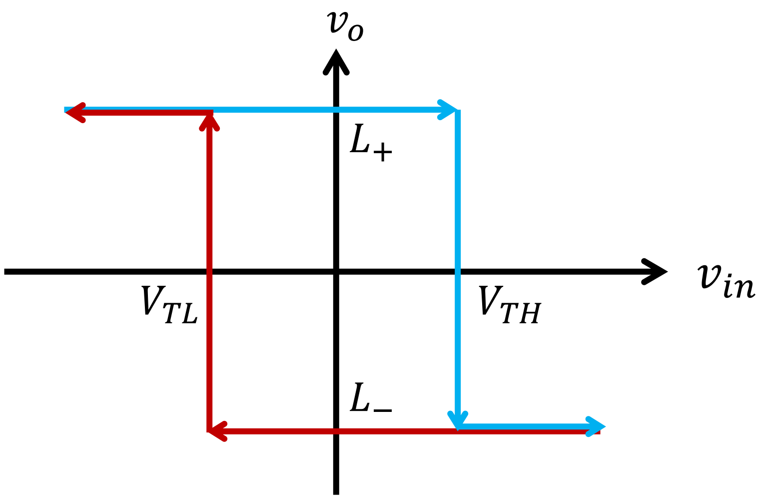


Example 6: Schmitt Trigger

QUESTION: Find the functionality of the following circuit.



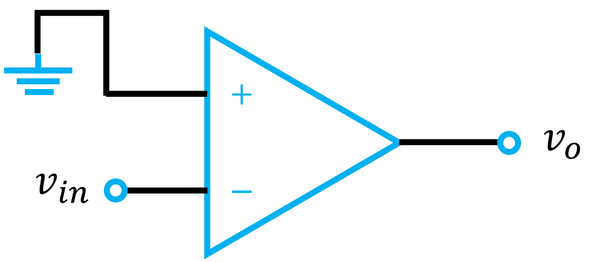


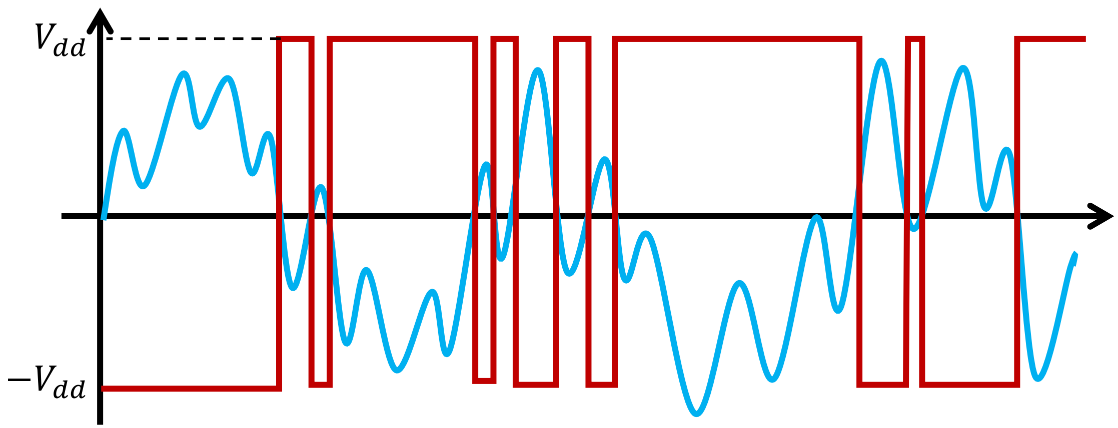


- Two possible levels: L_+, L_-
- Two thresholds: V_{TH}, V_{TL}

Recall: zero-crossing detector

QUESTION: Find the output of the circuit. The op-amp is ideal.

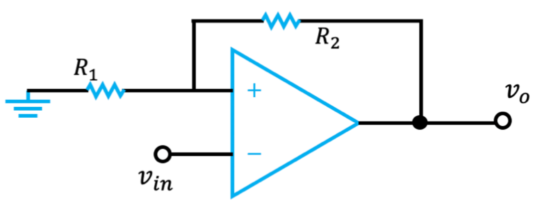


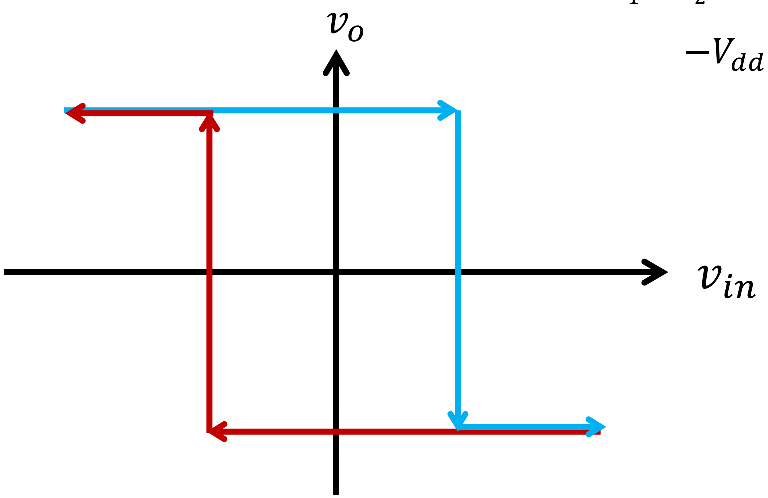


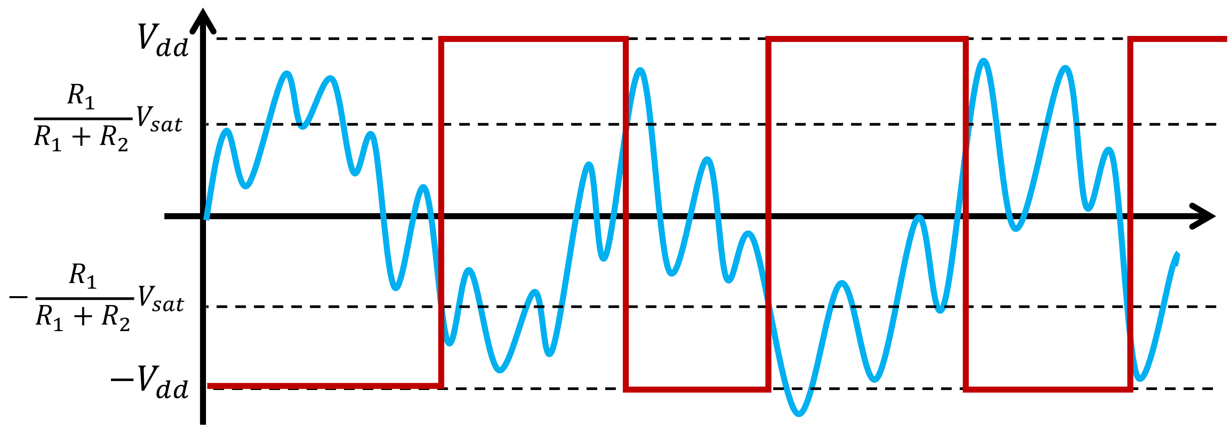
- If $v_{in} > 0$ → $v_o = -V_{dd}$
- If $v_{in} < 0$ → $v_o = V_{dd}$

Example 6: Schmitt Trigger

QUESTION: Find the output of the circuit. The op-amp is ideal.



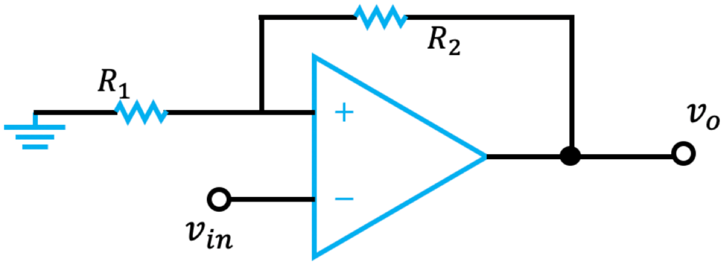


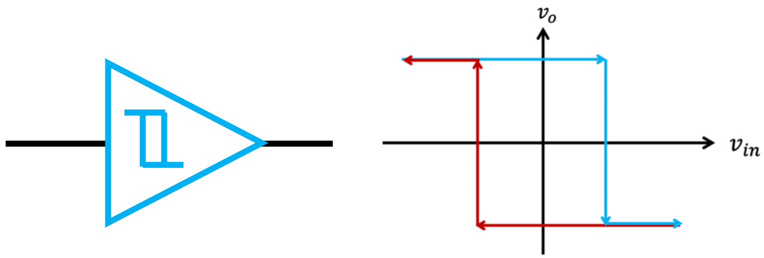


A better tolerance to noise

Outline

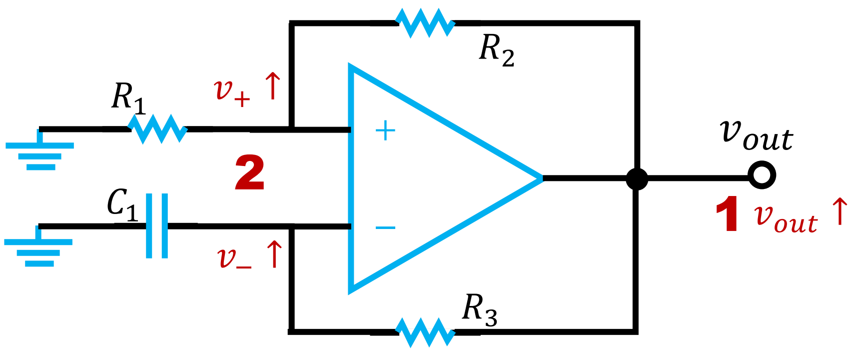
- HOW to generate an oscillation?
  - Negative resistance
  - Devices with negative resistance
  - Circuit features negative resistance
- Linear Oscillator
  - LC Oscillator
  - Crystal Oscillator
  - Op-Amp-RC Oscillator
- Non-linear Oscillator
  - Bistable Circuit
  - **Astable Multibibrators**





Example 7

QUESTION: Find the functionality of the following circuit.



What are R_2 and R_3 used for?

- If there is an increase @ v_{out}
- The input voltages v_+ and v_- increase

- If $\Delta v_+ > \Delta v_-$

$v_{out} \uparrow$ causing an increasing of v_{out}

POSITIVE FEEDBACK is observed

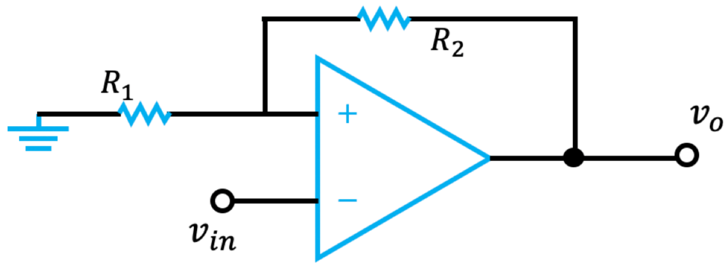
- If $\Delta v_+ < \Delta v_-$

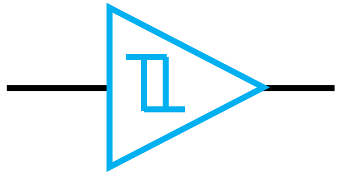
$v_{out} \uparrow$ causing an decreasing of v_{out}

NEGATIVE FEEDBACK is observed

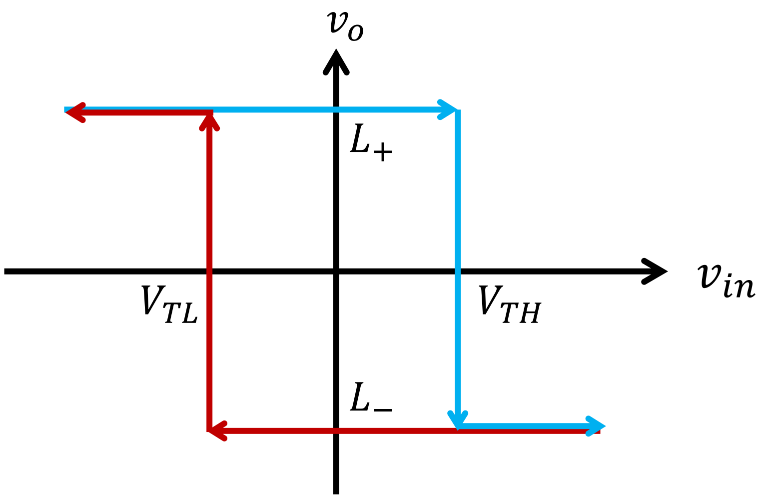
Recall: Schmitt Trigger

QUESTION: Find the functionality of the following circuit.





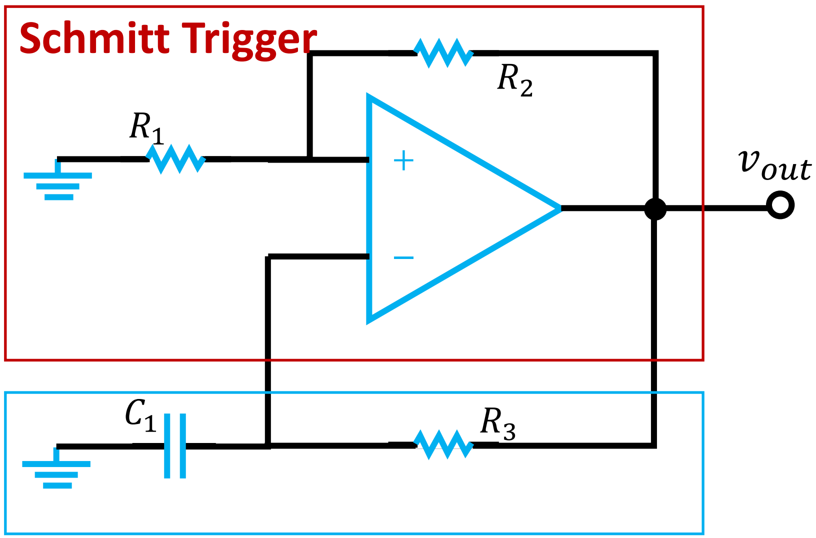
Schmitt Trigger

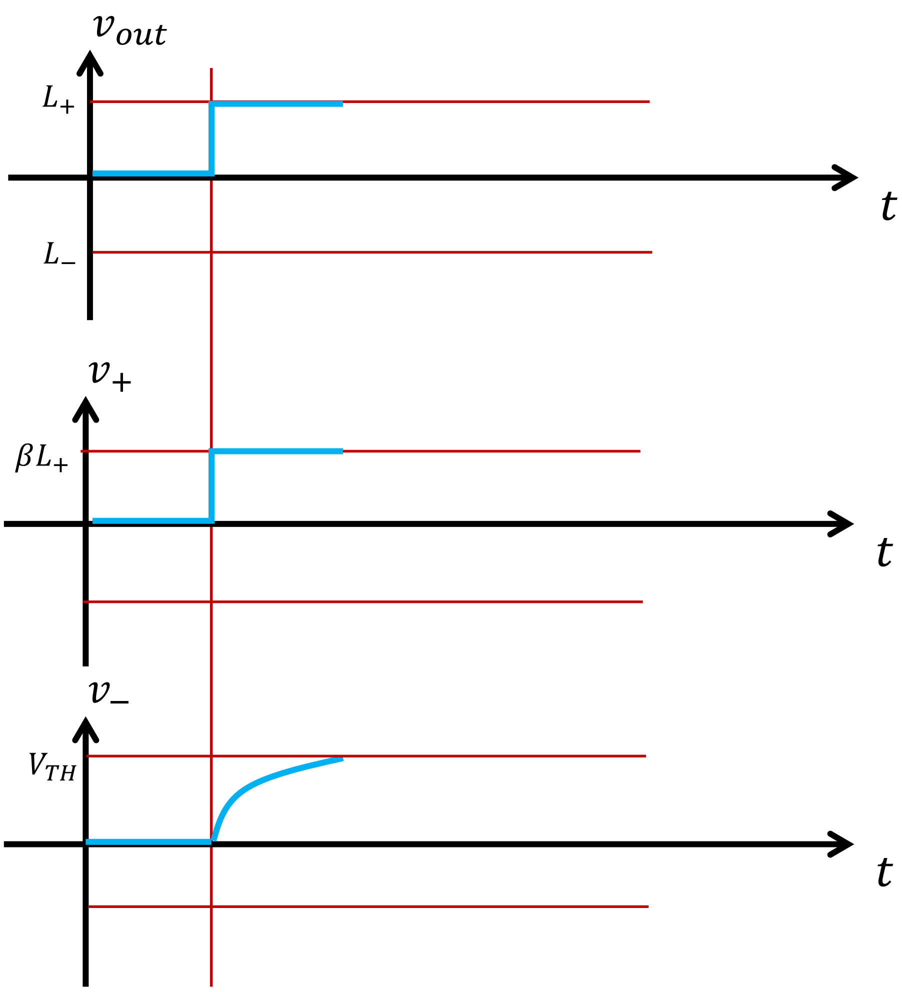


- Two possible levels: L_+, L_-
- Two thresholds: V_{TH}, V_{TL}

Example 7

QUESTION: Find the functionality of the following circuit.





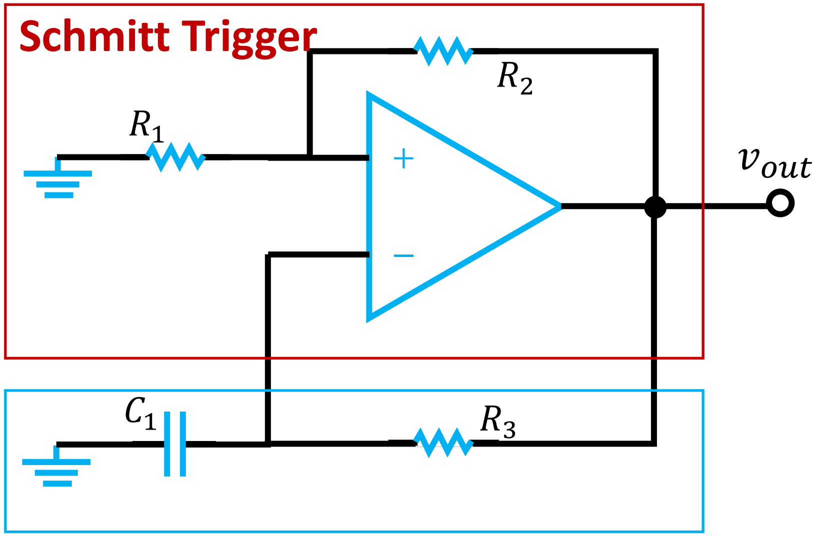
- Assume v_{out} flipped to L_+ due to unexpected disturb
- According to KVL

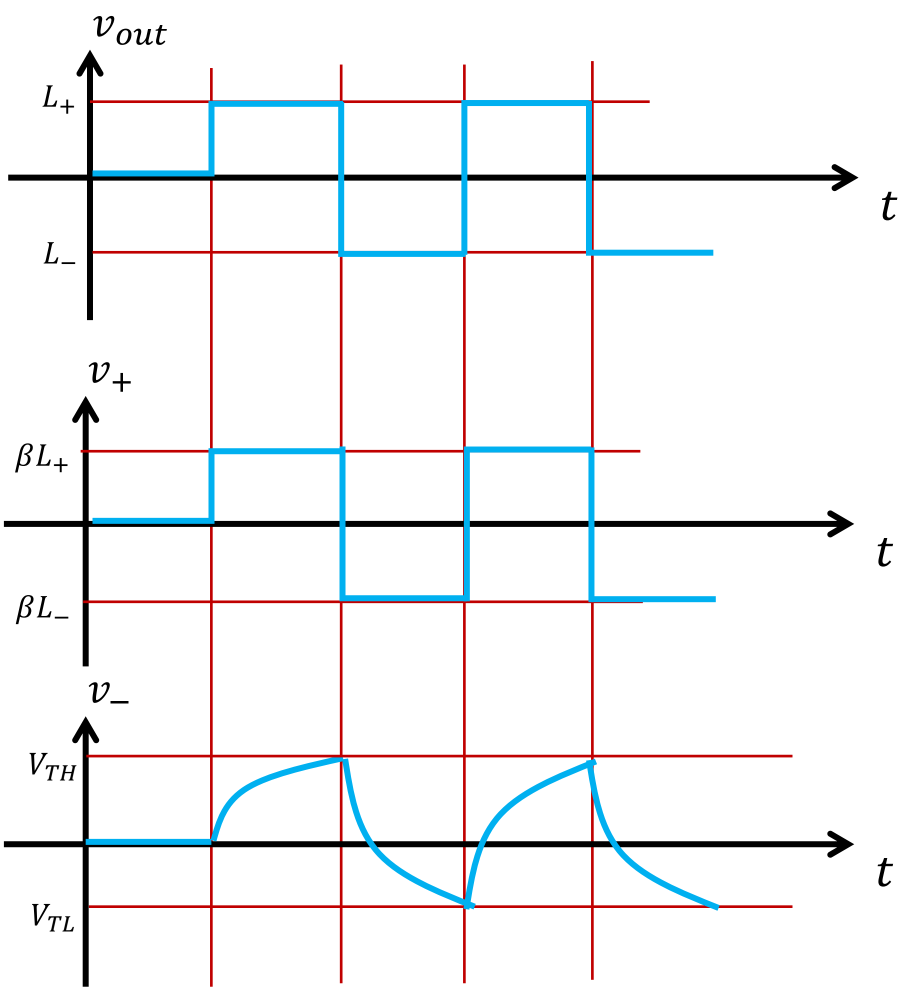
$$v_+ = \frac{R_1}{R_1 + R_2} L_+ = \beta L_+$$

- C_1 is charged to V_{TH}

Example 7

QUESTION: Find the functionality of the following circuit.





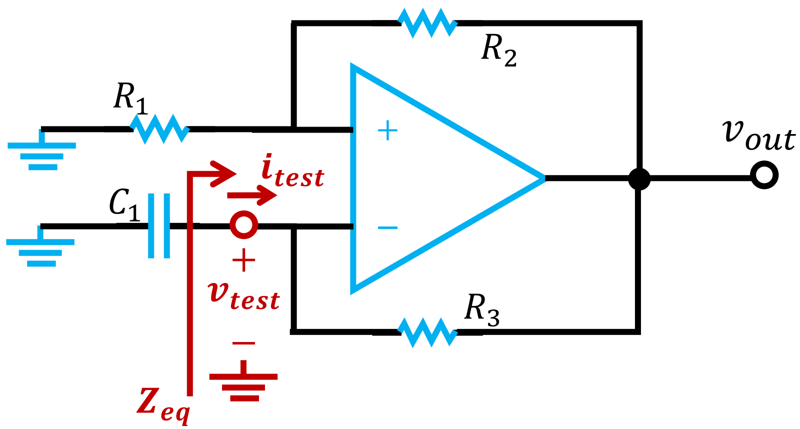
- v_{out} flipped to L_- due to the increasing of the v_-
- According to KVL

$$v_+ = \frac{R_1}{R_1 + R_2} L_- = \beta L_-$$

- C_1 is discharged to V_{TL}

Example 7

QUESTION: Find the functionality of the following circuit.



- If the op-amp is biased in **linear region**

  Approximately $v_+ = v_-$

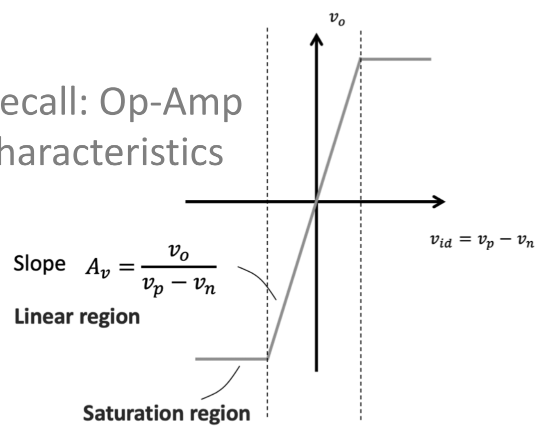
- According to KVL

$$v_+ = v_- = \frac{R_1}{R_1 + R_2} v_{out}$$

$$i_{test} = \frac{v_{test} - v_{out}}{R_3}$$

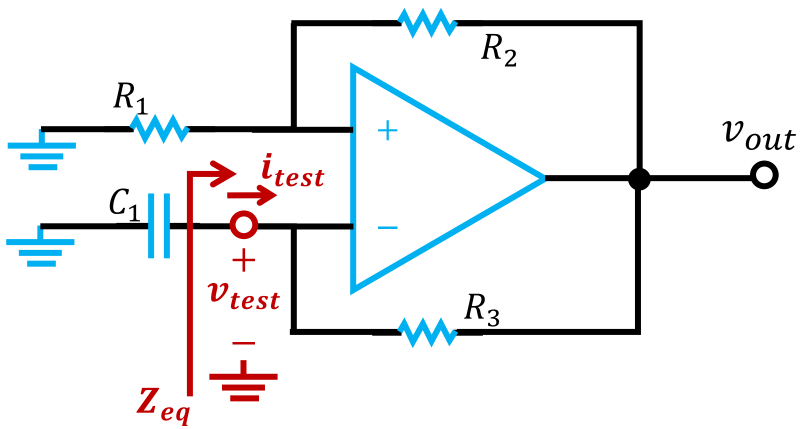
$$Z_{eq} = \frac{v_{test}}{i_{test}} = \frac{v_-}{i_{test}} = -\frac{R_1}{R_2} R_3$$

Recall: Op-Amp characteristics



Example 7

QUESTION: Find the functionality of the following circuit.



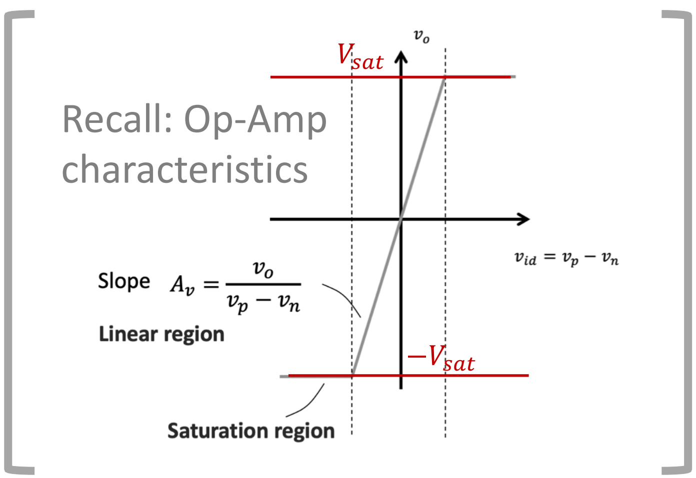
- If the op-amp is biased in **saturation region**
- If $v_{out} = -V_{sat} \quad (v_+ \ll v_-)$
- According to KVL

$$i_{test} = \frac{v_{test} - v_{out}}{R_3} = \frac{v_{test} + V_{sat}}{R_3}$$

$$Z_{eq} = \frac{v_{test}}{i_{test}} = R_3 \frac{1}{1 + \frac{V_{sat}}{v_{test}}}$$

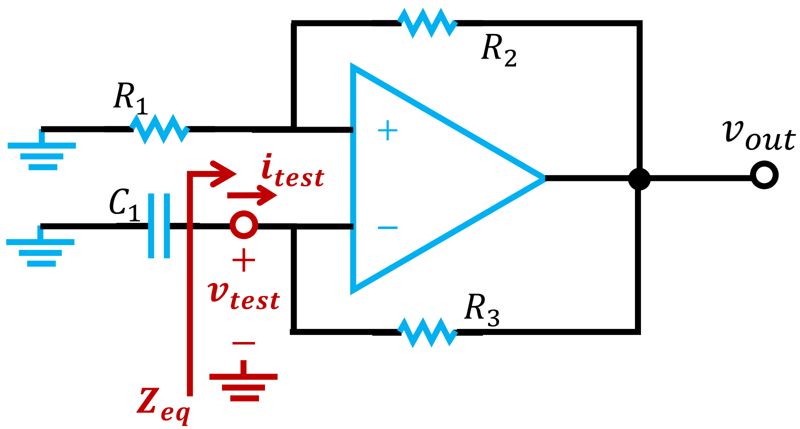
- To keep $v_{out} = -V_{sat}$

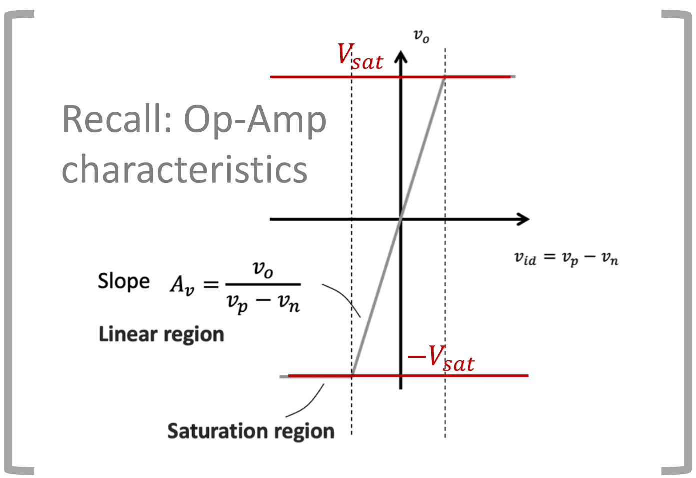
$$v_- > v_+ = -\frac{R_1}{R_1 + R_2} V_{sat}$$



Example 7

QUESTION: Find the functionality of the following circuit.





- If the op-amp is biased in **saturation region**
- If $v_{out} = V_{sat}$
- According to KVL

$$i_{test} = \frac{v_{test} - v_{out}}{R_3} = \frac{v_{test} - V_{sat}}{R_3} < 0$$

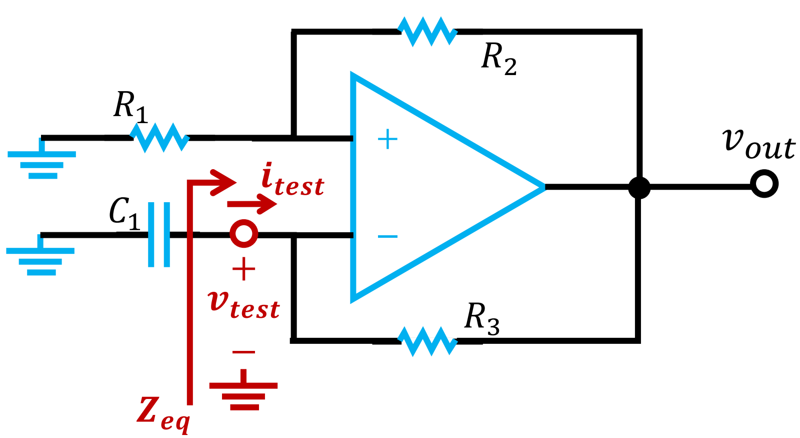
$$Z_{eq} = \frac{v_{test}}{i_{test}} = R_3 \frac{1}{1 - \frac{V_{sat}}{v_{test}}}$$

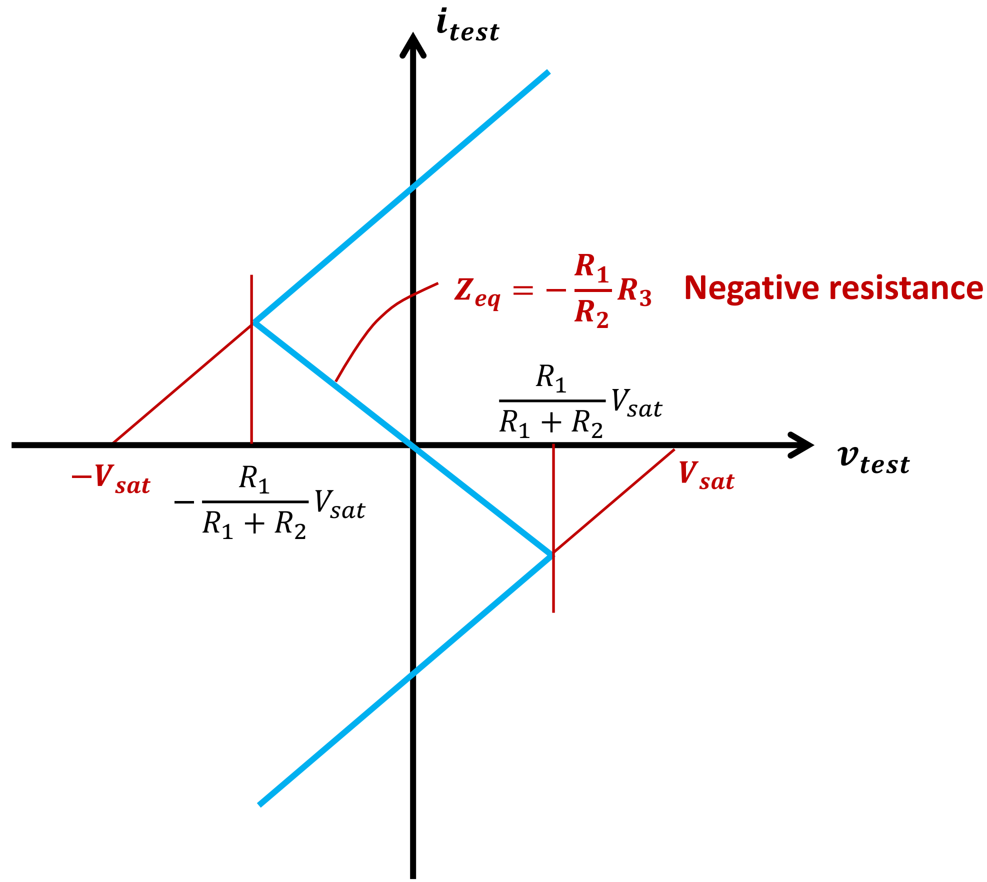
- To keep $v_{out} = V_{sat}$

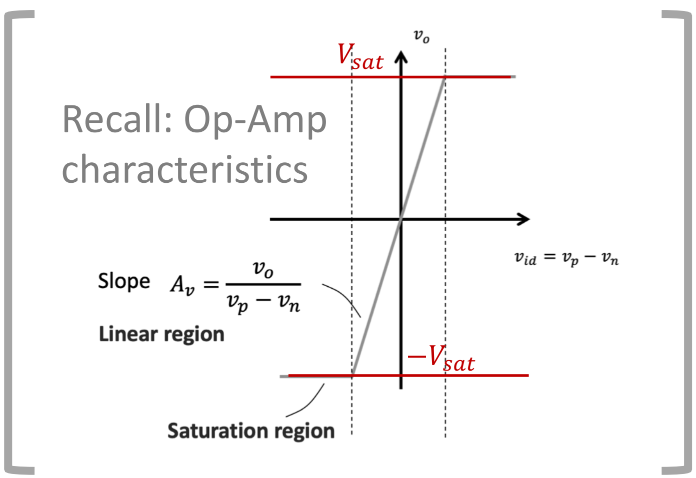
$$v_- < v_+ = \frac{R_1}{R_1 + R_2} V_{sat}$$

Example 7

QUESTION: Find the functionality of the following circuit.







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Reading tasks & learning goals

- Reading tasks
  - Microelectronic Circuits, 6th edition
    - Chapter 17.1 – 17.6
- Learning goals
  - Well understand the concept of **negative resistance**
  - Well understand how to calculate the specification of a **linear oscillation circuit**
  - Well understand how to analyze a circuit consisting of **op-amp with positive feedback**
  - Well understand how to calculate the specification of a **non-linear oscillation circuit**