EE 508
Lecture 29

Integrator Design

- Nonideal Effects in SC Circuits
- Switched Capacitor Amplifiers
- Switched Resistor Filters
- Some other integrator structures
- Metrics for comparing integrators

Nonideal Effects in Switched Capacitor Circuits

- Parasitic Capacitances
- Charge Injection
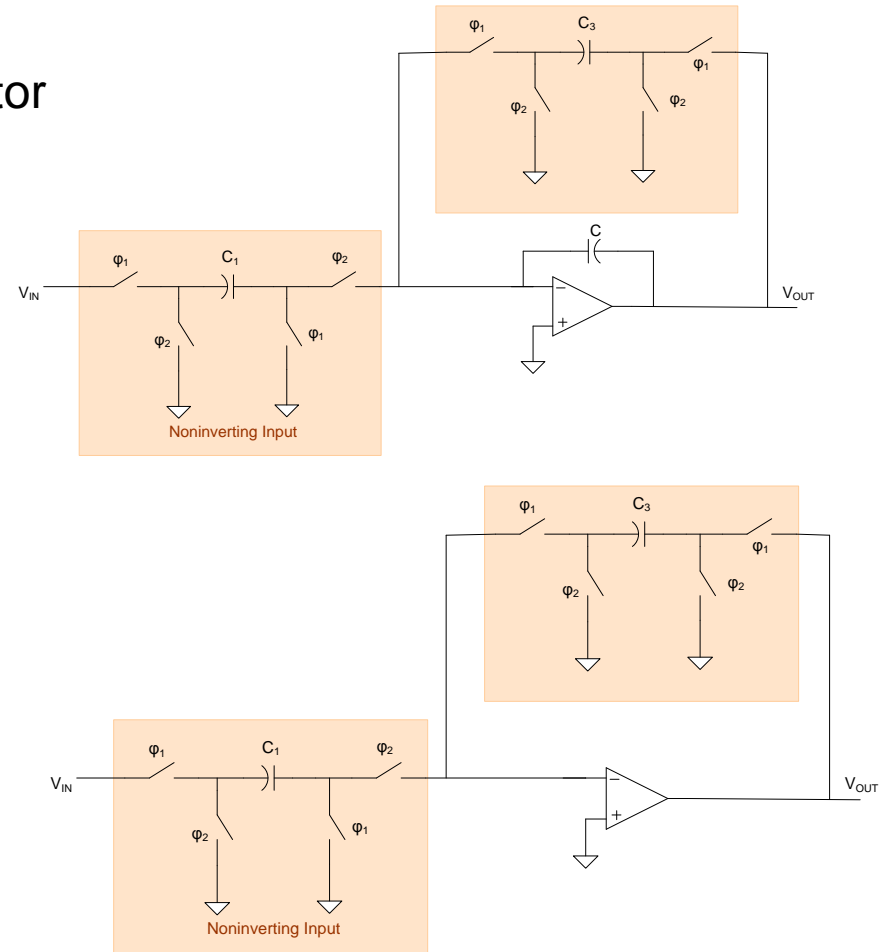- Aliasing
- Redundant Switch Removal
- Matching
- Noise

Noise

- Capacitors do not have any noise source

- Switches contribute thermal noise

- Noise due to switches looks like "capacitive" noise $\quad V_{RMS} = \sqrt{\dfrac{kT}{C}}$

Be careful with calculating noise in SC circuits !

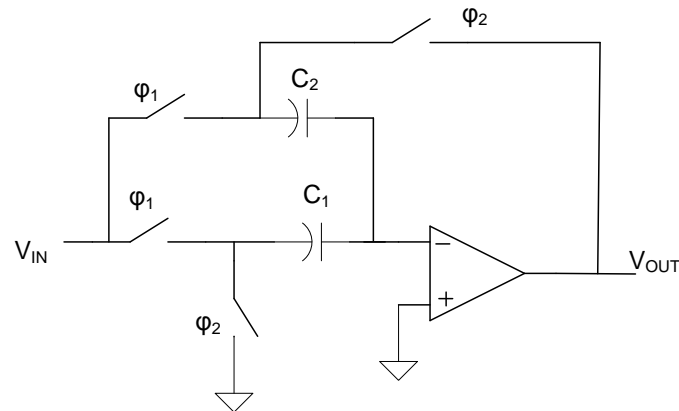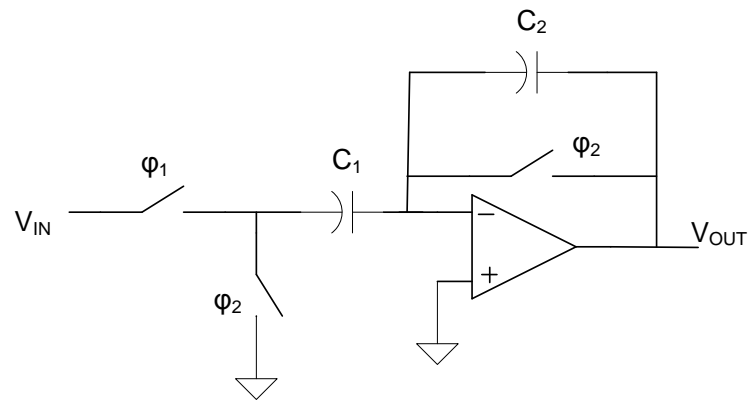# Switched Capacitor Amplifiers

Elimination of the Integration Capacitor

What happens if the integration capacitor is eliminated?

- Serves as a SC amplifier with gain of $A_V = C_1/C_2$
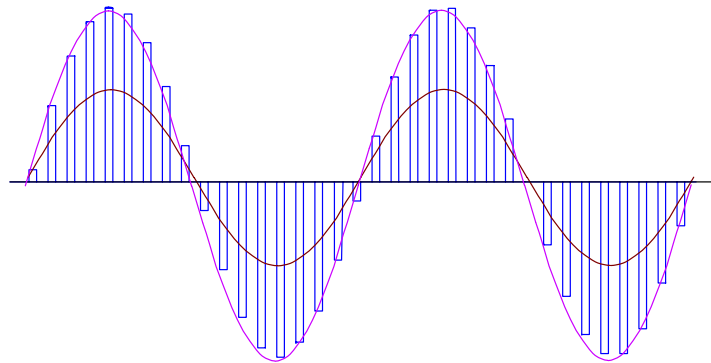- SC amplifiers and SC summing amplifiers are widely used in filter and non-filter applications
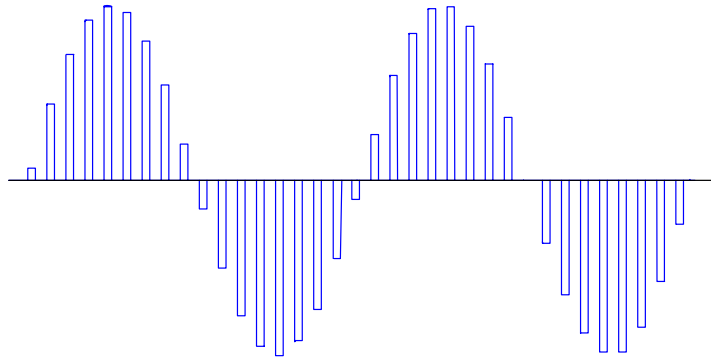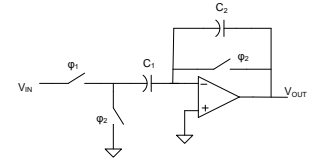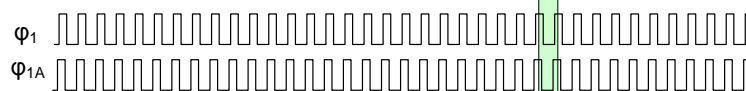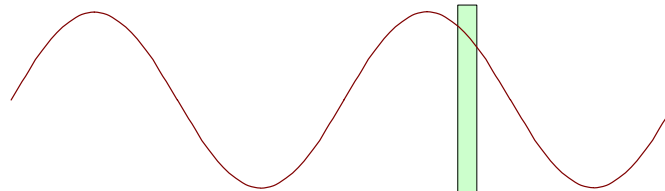
Switched Capacitor Amplifiers

- Summing, Differencing, Inverting, and Noninverting SC Amplifiers Widely Used
- Significant reduction in switches from what we started with by eliminating C in SC integrator
- Must be stray insensitive in most applications
- Outputs valid only during one phase
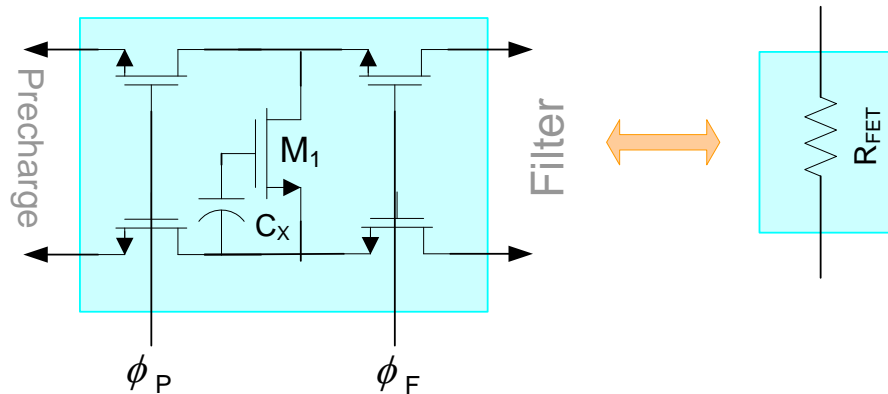
Switched Capacitor Amplifiers

Output

Input

φ_1

φ_{1A}

C_2

φ_1 C_1 φ_2

V_{IN} φ_2 V_{OUT}

Voltage Mode Integrators

- Active RC   (Feedback-based)

- MOSFET-C   (Feedback-based)

- OTA-C

- TA-C
                    Sometimes termed "current mode"

- Switched Capacitor   Will discuss later

→ Switched Resistor

- Other Structures
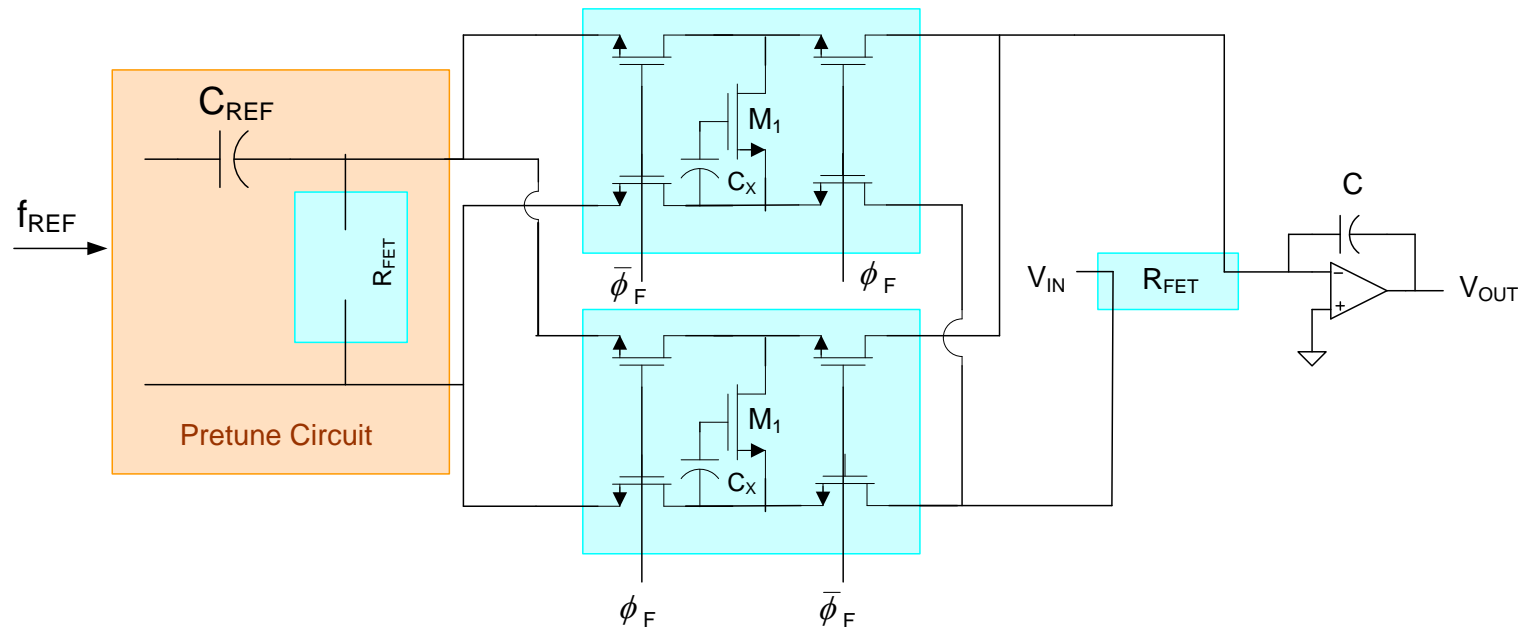
Switched-Resistor Voltage Mode Integrators

Observe that if a triode-region MOS device is switched between a precharge circuit and a filter circuit (or integrator) and V_{GS} is held constant,   It will behave as a resistor while in the filter circuit

$$R_{FET} \cong \frac{L}{\mu C_{OX} W (V_{GS} - V_T)}$$
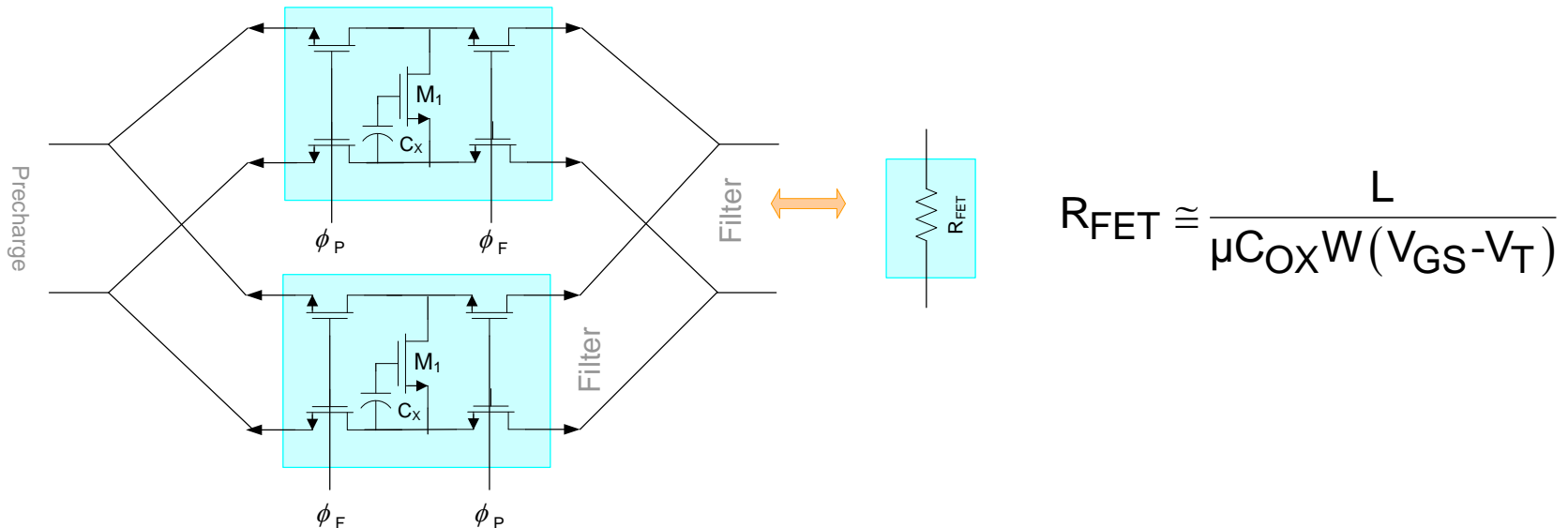
Observe that if two such circuits are switched between a precharge circuit and a filter circuit (or integrator) and V_{GS} is held constant,   It will behave as a resistor in the filter circuit at all times

Switched-Resistor Voltage Mode Integrators

Switched-resistor integrator

- Clock frequency need only be fast enough to prevent droop on C_X
- Minor overlap or non-overlap of clock plays minimal role in integrator performance
- Switched-resistors can be used for integrator resistor or to replace all resistors in any filter
- Pretune circuit can accurately establish $R_{FET}C_{REF}$ product proportional to f_{REF}
- $R_{FET}C$ product is given by accurately controlled

$$R_{FET}C = R_{FET}C\frac{C_{REF}}{C_{REF}} = [R_{FET}C_{REF}] \bullet \left[\frac{C}{C_{REF}}\right] \text{ and is thus}$$

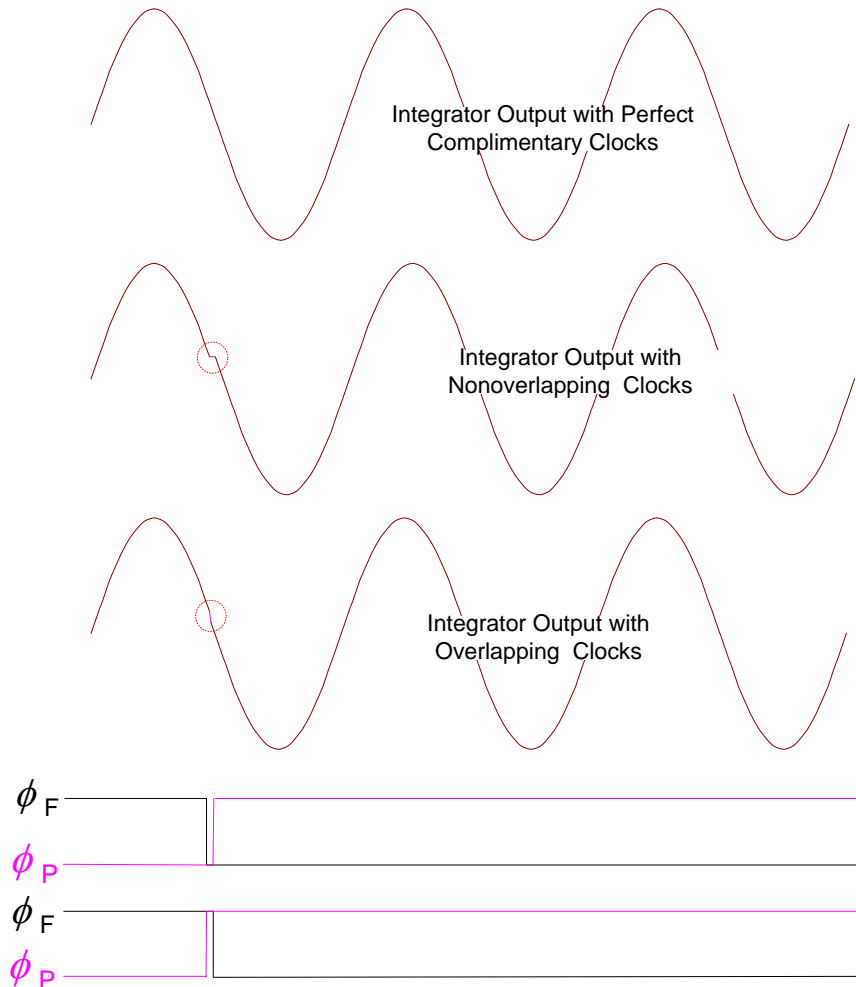# Switched-Resistor Voltage Mode Integrators
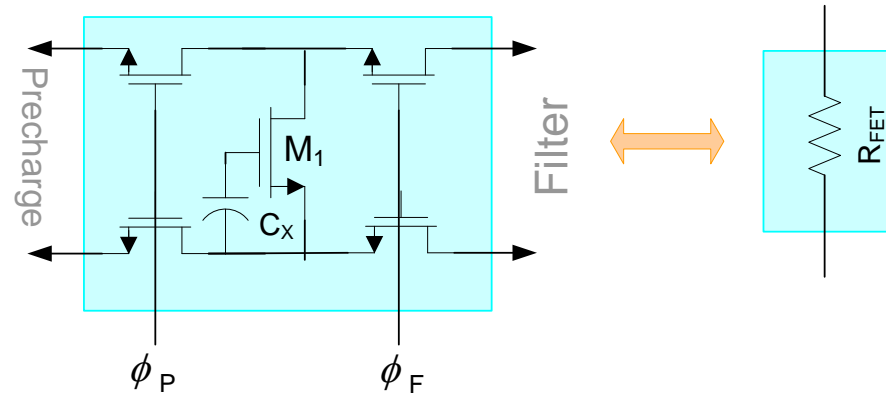
There are some modest nonlinearities in this MOSFET when operating in the triode region
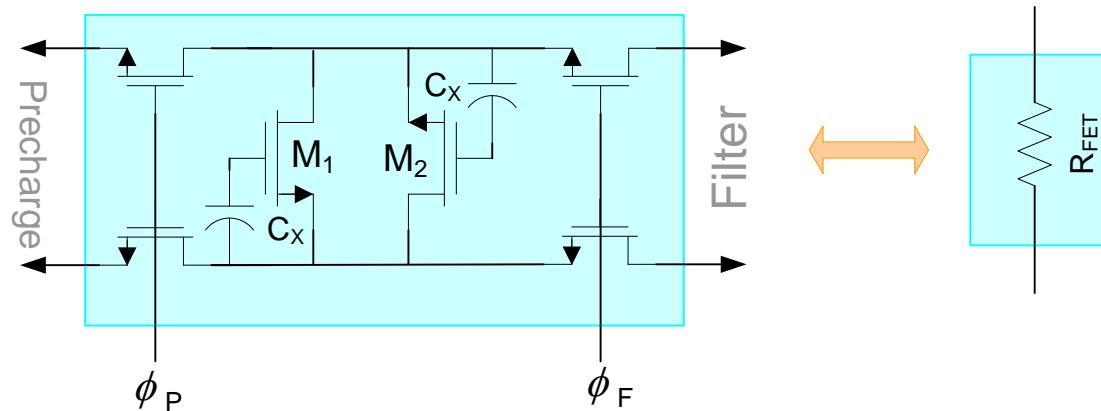
- Significant improvement in linearity by cross-coupling a pair of triode region resistors
- Perfectly cancels nonlinearities if square law model is valid for M_1 and M_2
- Only modest additional complexity in the Precharge circuit

Switched-Resistor Voltage Mode Integrators

Integrator Output with Perfect
Complimentary Clocks

Integrator Output with
Nonoverlapping Clocks

Integrator Output with
Overlapping Clocks

ϕ_F

ϕ_P

ϕ_F

ϕ_P

- Aberrations are very small, occur very infrequently, and are further filtered
- Play almost no role on performance of integrator or filter

Switched-Resistor Voltage Mode Integrators
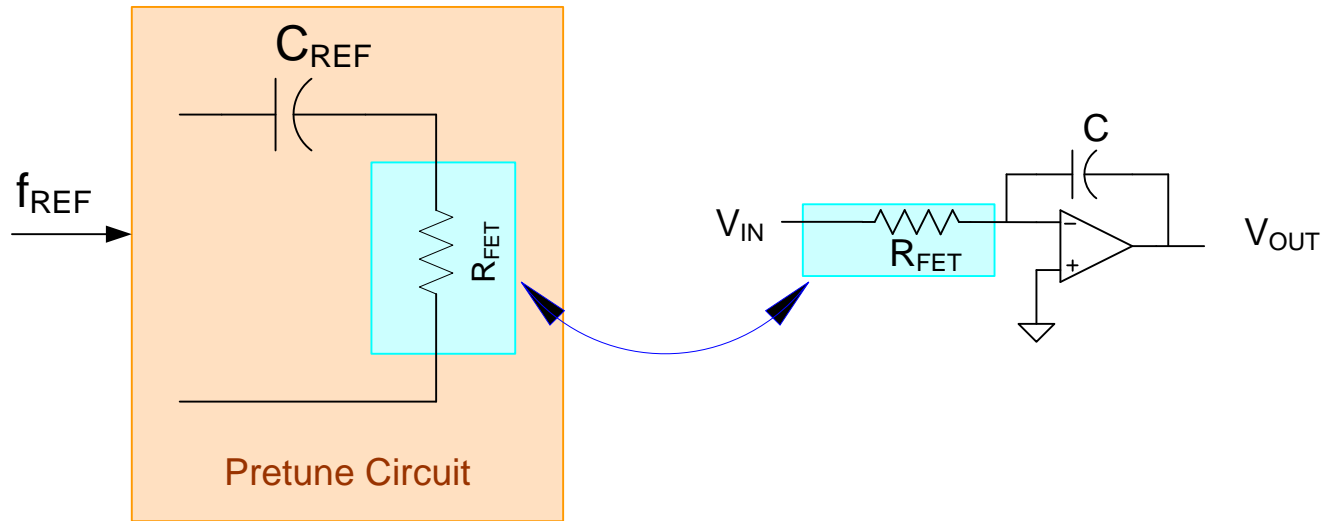
Switched-resistor integrator

- Accurate CR_{FET} products is possible
- Area reduced compared to Active RC structure because R_{FET} small
- Single pretune circuit can be used to "calibrate" large number of resistors
- Clock frequency not fast and not critical (but accuracy of f_{REF} is important)
- Since resistors are memoryless elements, no transients associated with switching
- Since filter is a feedback structure, speed limited by BW of op amp

Voltage Mode Integrators

- Active RC   (Feedback-based)
- MOSFET-C   (Feedback-based)
- OTA-C
- TA-C   Sometimes termed "current mode"
- Switched Capacitor
- Switched Resistor   Will discuss later
- Other Structures

Have introduced a basic voltage-mode integrators in each of these approaches

All of these structures have applications where they are useful

Performance of all are limited by variability or Op Amp BW

Variants of basic inverting integrator have been considered
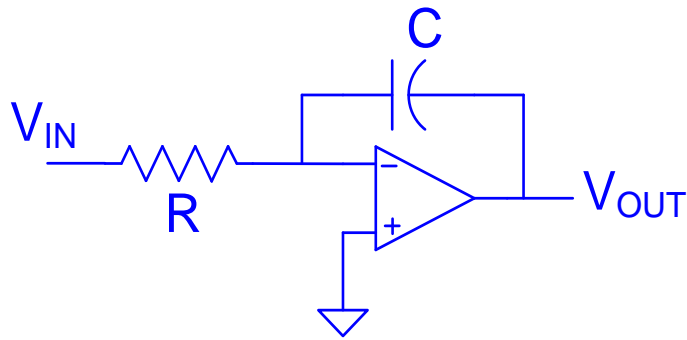
Basic Miller Integrator

- Active RC
- MOSFET-C
- OTA-C
- g_m-C
- Switched-Capacitor
- Switched-Resistor

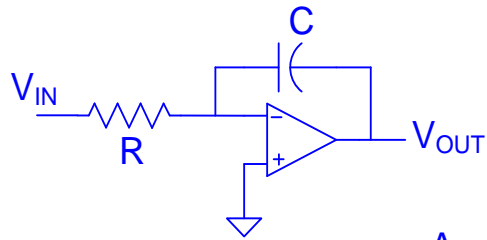**Performance of all is limited by GB of Operational Amplifiers**

How can integrator performance be improved?

- Better op amps
- Better Integrator Architectures

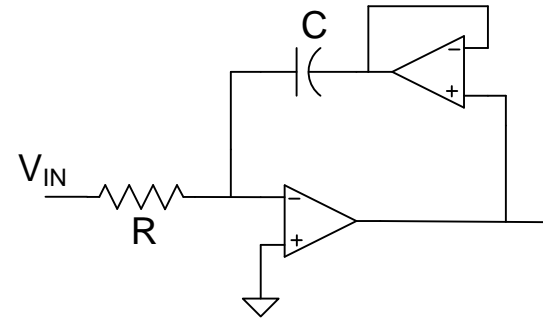How can the performance of integrator structures be compared?

Need metric for comparing integrator performance

Are there other integrators in the basic classes that have been considered?

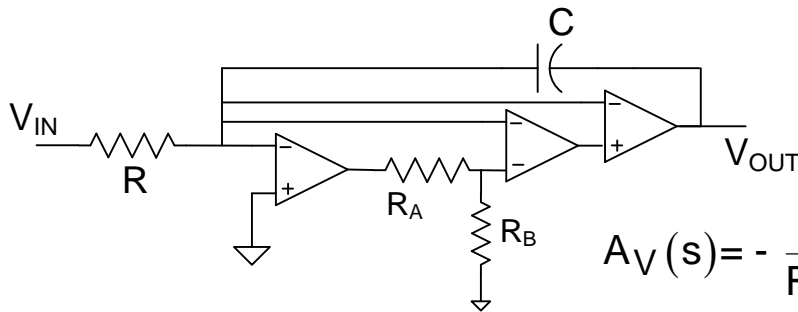$$A_V(s) = -\frac{1}{RCs}$$

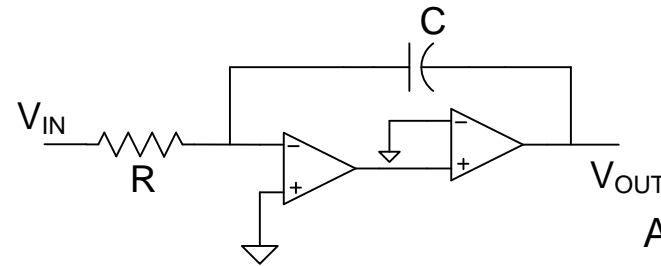Miller Inverting

$$A_V(s) = -\frac{1}{RCs}$$

High-Q Inverting
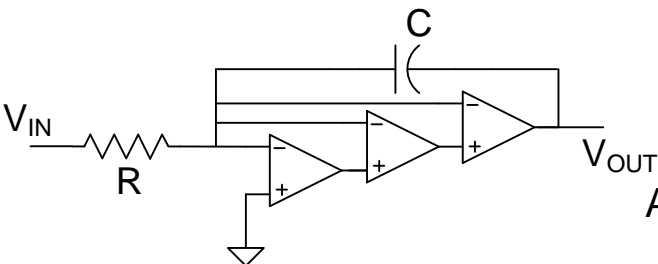
$$A_V(s) = -\frac{1}{RCs}$$

Zero Second Derivative Inverting
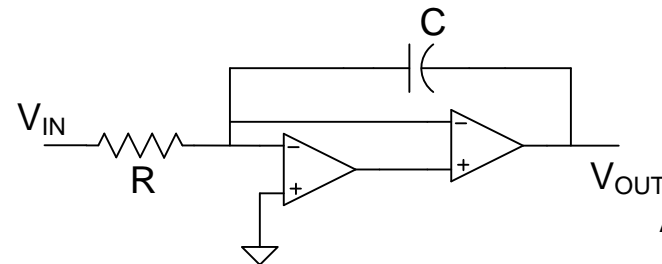
$$A_V(s) = -\frac{1}{RCs}$$

Cascaded Inverting

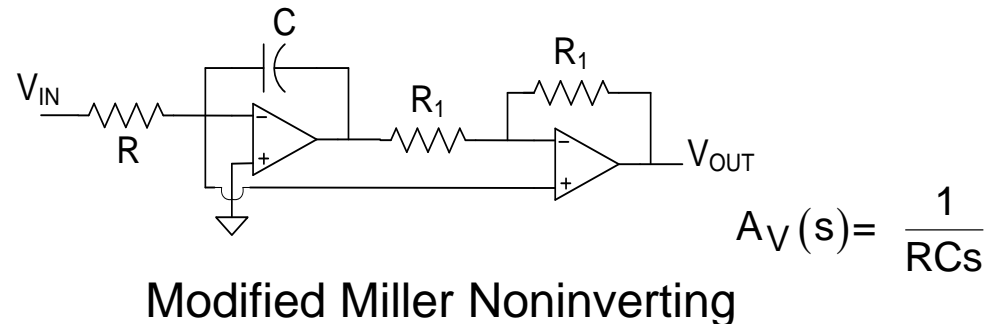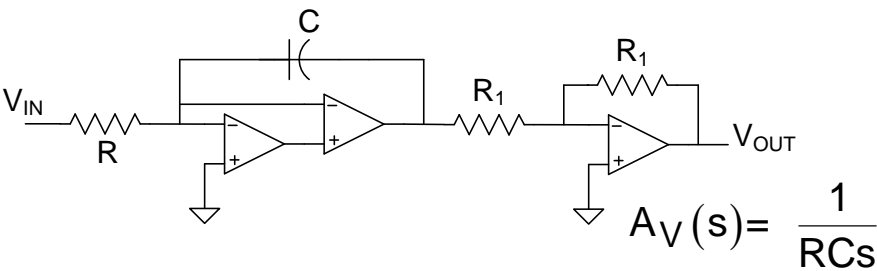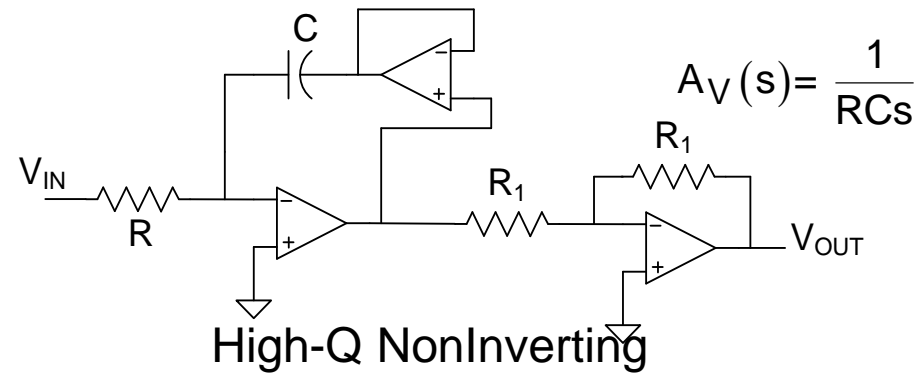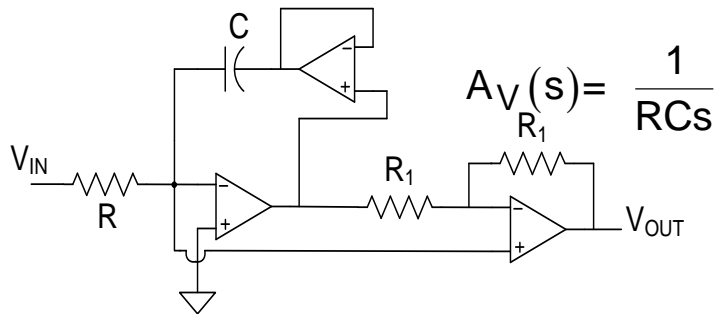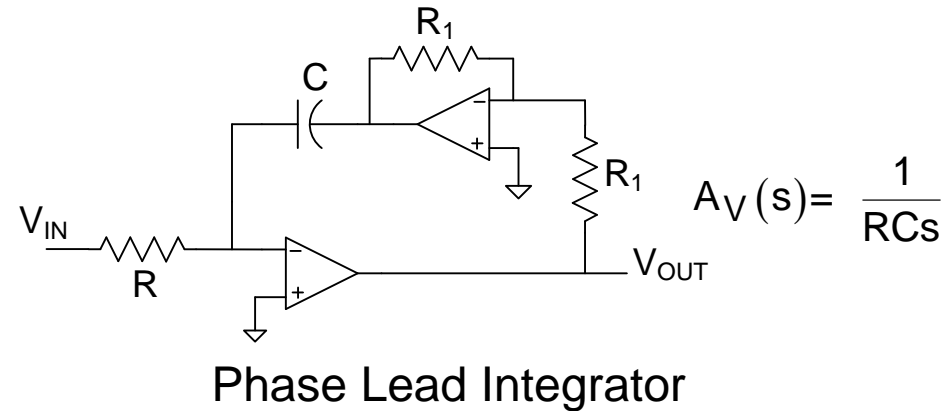$$A_V(s) = -\frac{1}{RCs}$$

Zero Second Derivative Inverting

$$A_V(s) = -\frac{1}{RCs}$$

Zero Sensitivity Inverting

Are there other integrators in the basic classes that have been considered?

Miller Noninverting $\quad A_V(s) = \dfrac{1}{RCs}$

Phase Lead Integrator $\quad A_V(s) = \dfrac{1}{RCs}$

Modified High-Q Noninverting $\quad A_V(s) = \dfrac{1}{RCs}$

High-Q NonInverting $\quad A_V(s) = \dfrac{1}{RCs}$

Zero Sensitivity Noninverting $\quad A_V(s) = \dfrac{1}{RCs}$

Modified Miller Noninverting $\quad A_V(s) = \dfrac{1}{RCs}$

Are there other integrators in the basic classes that have been considered?

Miller Noninverting $A_V(s) = \dfrac{1}{RCs}$
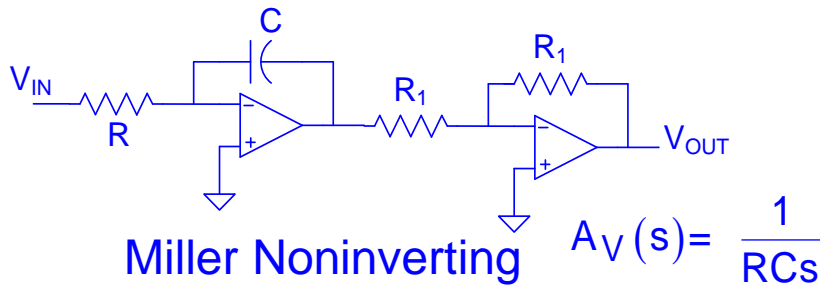
Balanced Time Constant Noninverting

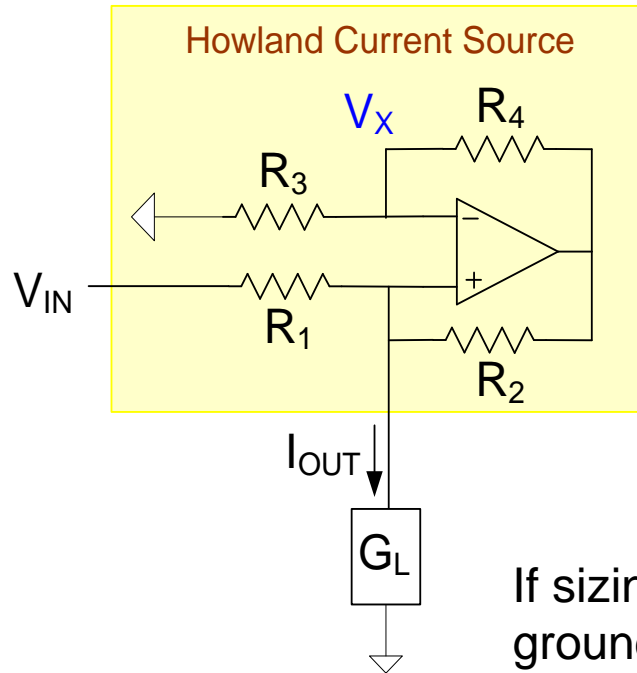$A_V(s) = \dfrac{1}{RCs}$

Zero Sensitivity Noninverting
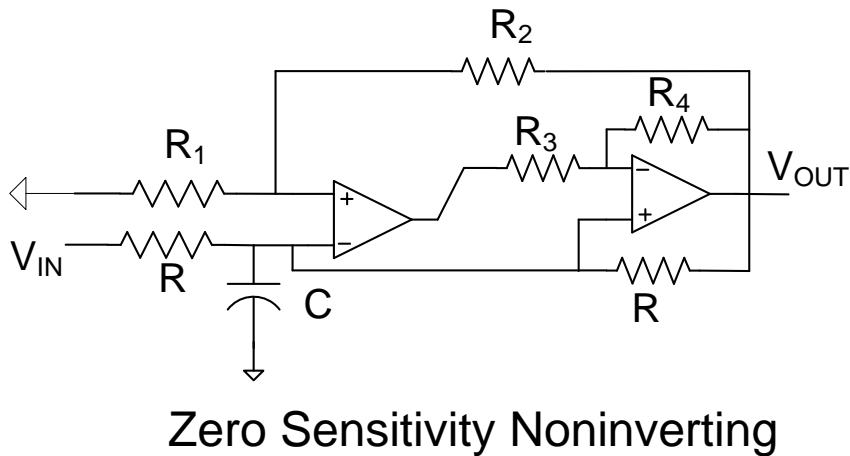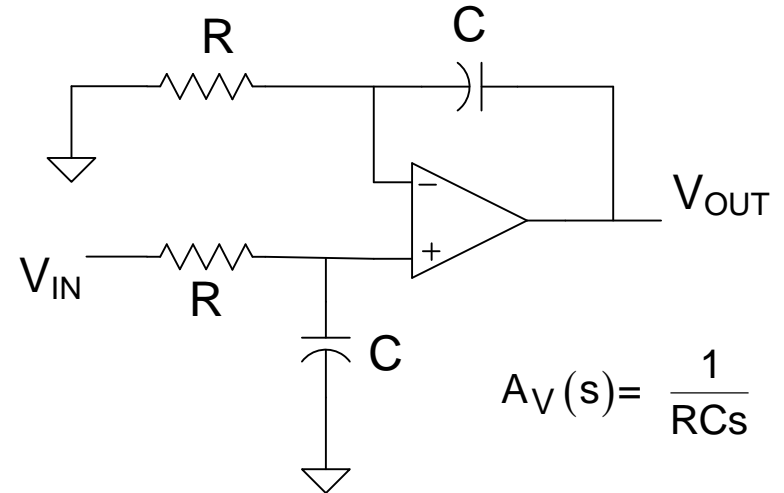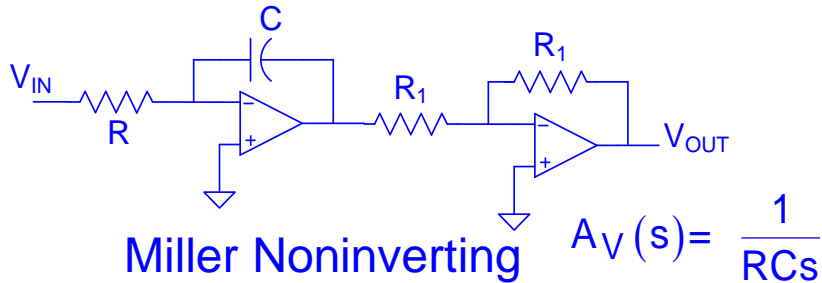
$A_V(s) = \dfrac{2}{RCs}$

If $R_1 = R_2$ and $R_3 = R_4$

(note this has a grounded integrating capacitor!)

De Boo Integrator
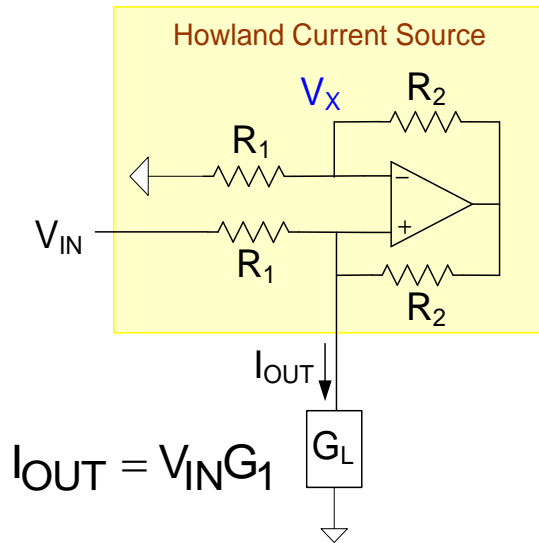
Consider the Howland Current Source

$$I_{OUT} = V_{IN}G_1 + \left[V_X \left(\frac{G_2 G_3}{G_4} - G_1 \right) \right]$$

If resistors sized so that $\quad G_1 = \dfrac{G_2 G_3}{G_4}$
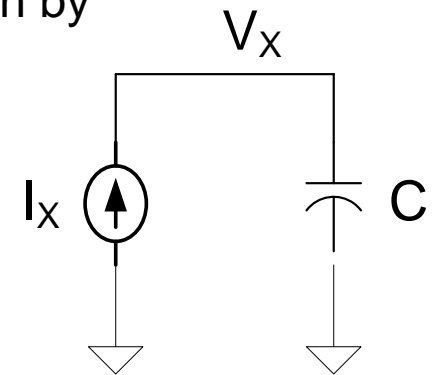
$$I_{OUT} = V_{IN}G_1$$

If sizing constraints are satisfied, behaves as a grounded constant-current source

DeBoo Integrator

Howland Current Source

V_X R_2

R_1

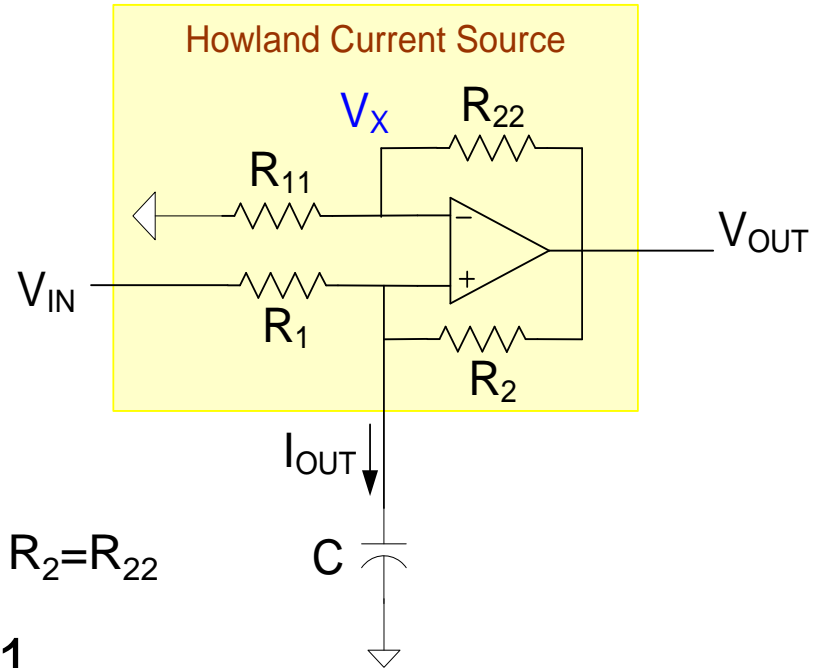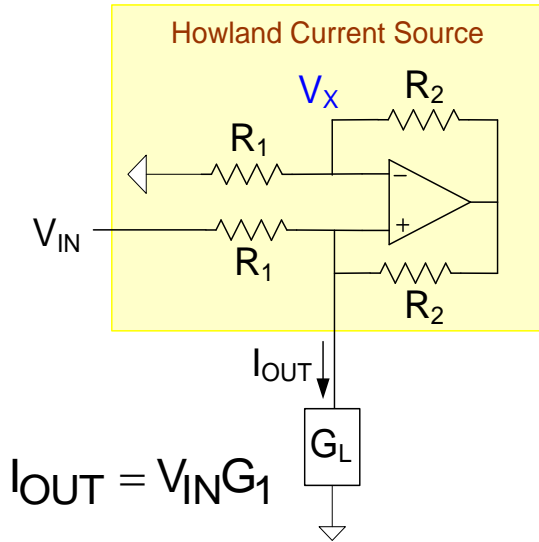V_{IN} R_1

R_2

I_{OUT}

$I_{OUT} = V_{IN}G_1$ G_L

Observe that if a current source drives a grounded capacitor, then the nodal voltage on the capacitor is given by

$$V_X = I_X \frac{1}{sC}$$

V_X

I_X C

Thus, if we could make I_X proportional to V_{IN}, the voltage on the capacitor would be a weighted Integral of V_{IN}

De Boo Integrator

Howland Current Source

V_X R_2

R_1

V_{IN}

R_1

R_2

I_{OUT}

G_L

$I_{OUT} = V_{IN}G_1$

Howland Current Source

V_X R_{22}

R_{11}

V_{IN}
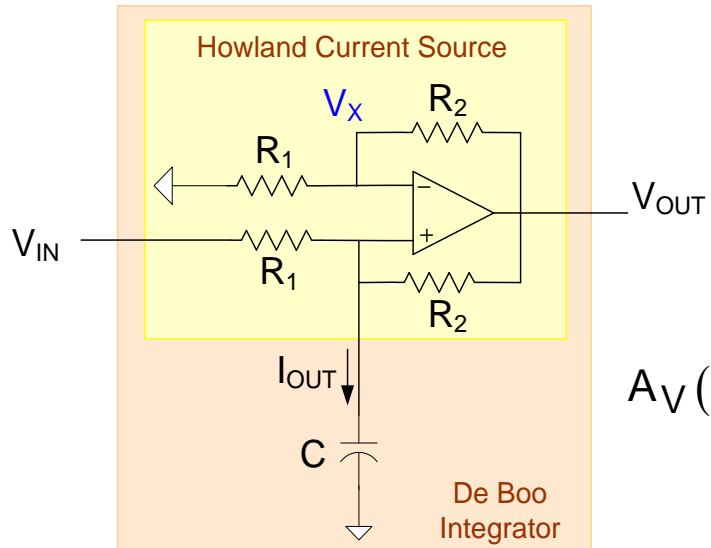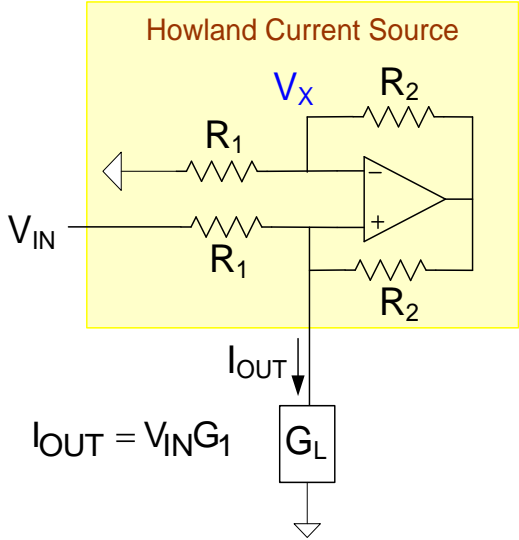
R_1

R_2

V_{OUT}

I_{OUT}

C

If $R_1 = R_{11}$ and $R_2 = R_{22}$

$$V_X = \frac{V_{IN}}{R_1}\frac{1}{sC}$$

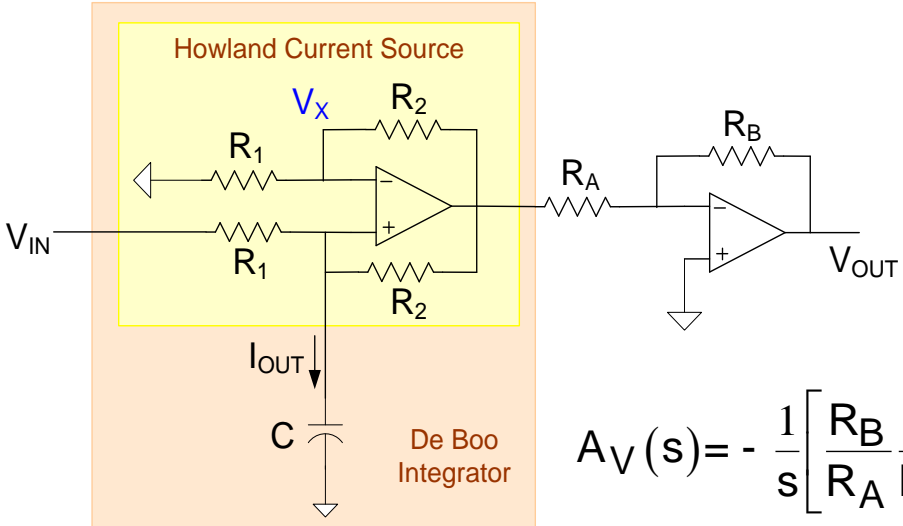$$V_{OUT} = V_X\left(1 + \frac{R_{22}}{R_{11}}\right) = \frac{V_{IN}}{R_1}\frac{1}{sC}\left(1 + \frac{R_{22}}{R_{11}}\right)$$

$$A_V(s) = \frac{1}{s}\left[\frac{1}{R_1C}\left(1 + \frac{R_{22}}{R_{11}}\right)\right]$$

De Boo Integrator

$$A_V(s) = \frac{1}{s}\left[\frac{1}{R_1 C}\left(1 + \frac{R_{22}}{R_{11}}\right)\right]$$

$$I_{OUT} = V_{IN} G_1$$

$$A_V(s) = -\frac{1}{s}\left[\frac{R_B}{R_A}\frac{1}{R_1 C}\left(1 + \frac{R_{22}}{R_{11}}\right)\right]$$

Many different integrator architectures that ideally provide the same gain

Similar observations can be made for other classes of integrators
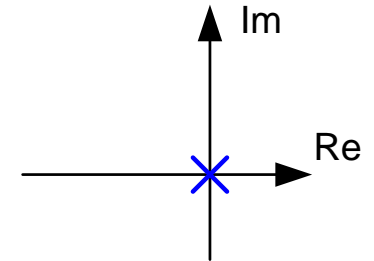
How can the performance of an integrator be characterized and how can integrators be compared?

How can the performance of an integrator be characterized and how can integrators be compared?

Consider Ideal Integrator Gain Function

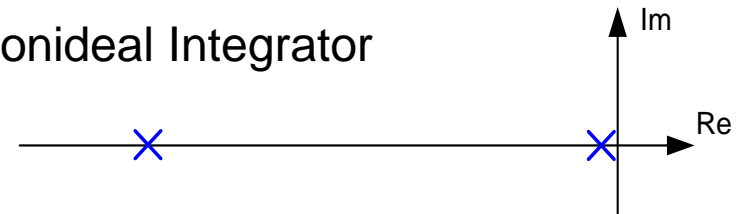$$A_V(s) = \frac{I_0}{s} \qquad A_V(j\omega) = \frac{I_0}{j\omega}$$

Ideal Integrator

Consider a nonideal integrator Gain Function

$$A_V(s) = \frac{\alpha I_{01}}{s+\alpha} A_{OO}(s)$$

Nonideal Integrator

Key characteristics of an ideal integrator:

- Magnitude of the gain at $I_0 = 1$
- Phase of integrator always 90°
- Gain decreases with $1/\omega$

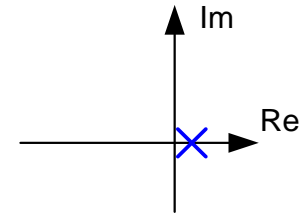Are any of these properties more critical than others?

In many applications:

Key property of ideal integrator is a phase shift of 90° at frequencies around I_0!

How can the performance of an integrator be characterized and how can integrators be compared?

Is stability of an integrator of concern?

Ideal Integrator

- Ideal integrator is not stable
- Integrator function is inherently ill-conditioned
- Integrator is almost never used open-loop
- Stability of integrator not of concern, stability of filter using integrator is of concern
- Some integrators may cause unstable filters, others may result in stable filters
- Instability in filter because desired poles move in RHP is of little concern since the filter performance would be unacceptable long before the stability became an issue
- Instability in filter due to parasitic poles is of concern but not a problem in most circuits

End of Lecture 29