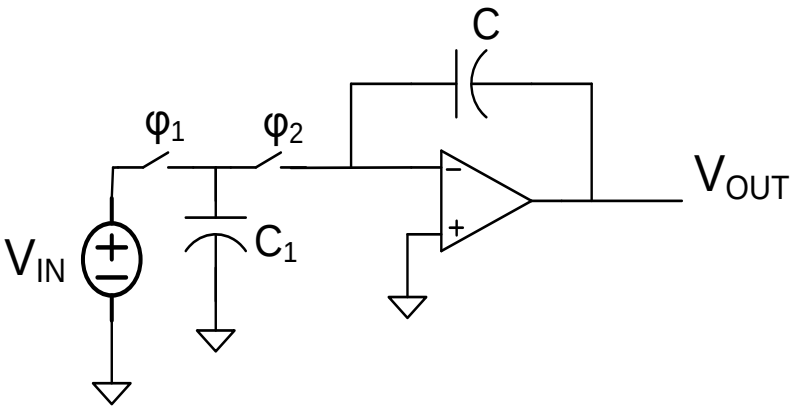
EE 508
Lecture 25

Nonideal Effects in Switched Capacitor Circuits

Op Amp Effects
Charge Injection
Alaising
Redundant Switch Removal
Matching

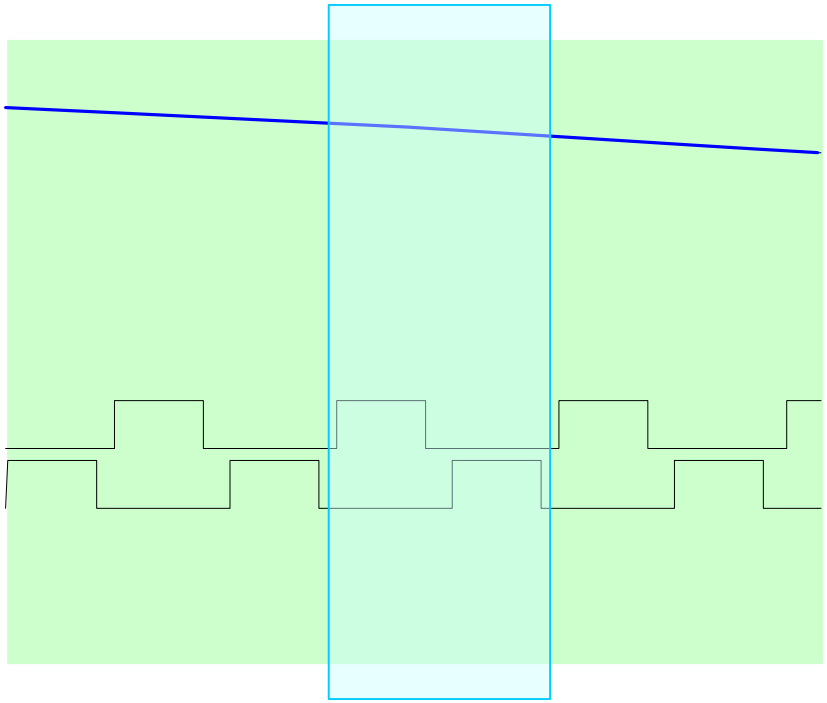
Review from Last Lecture

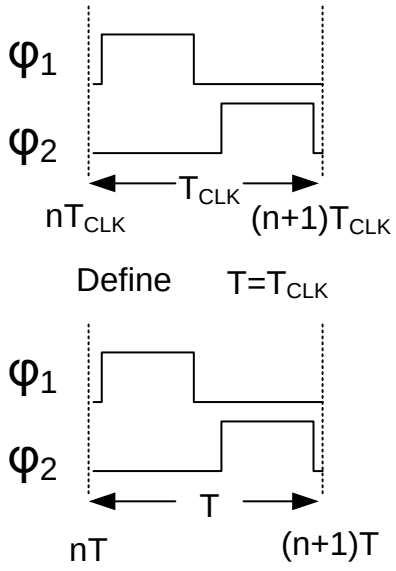
Consider the Switched-Capacitor Circuit



Assume $T_{CLK} << T_{SIG}$

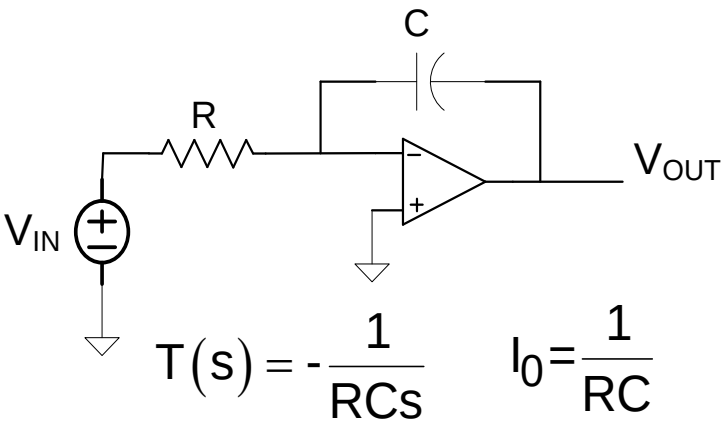
Φ_1 and Φ_2 are complimenary nonoverlapping clocks





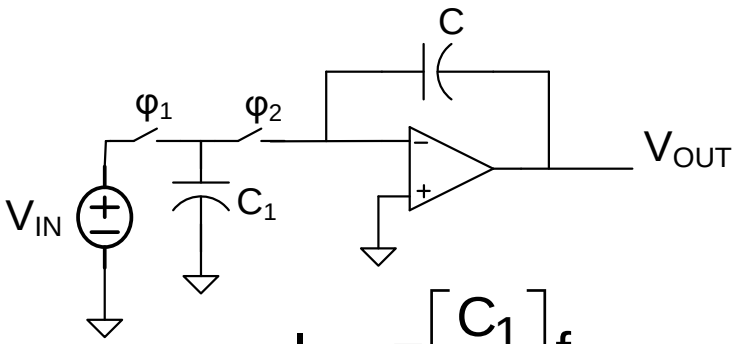
The SC integrator

Review from Last Lecture



$$T(s) = -\frac{1}{RCs} \qquad I_0 = \frac{1}{RC}$$

1. **Accuracy of R and C difficult to accurately control (often 2 or 3 orders of magnitude to variable)**
2. **Area of R and C too large in audio frequency range (2 or 3 orders of magnitude too large)**
3. **Amplifier GB limits performance**



$$I_{0eq} = \left[\frac{C_1}{C}\right] f_{CLK}$$

1. **Accuracy of cap ratio and f_{CLK} very good**
2. **Area of C1 and C not too large**
3. **Amplifier GB limits performance less**

Two of these properties were discovered independently by Gray, Broderson and Hosticka at Berkeley and by Copeland of Carelton

[1] J. T. Caves, M. A. Copeland, C. F. Rahim, and S. D. Rosenbaum, "Sampled analog filtering using switched capacitors as resistor equivalents," *IEEE J. Solid-State Circuits*, vol. SC-12, pp. 592–599, Dec. 1977.

[2] B. J. Hosticka, R. W. Brodersen, and P. R. Gray, "MOS sampled data recursive filters using switched capacitor integrators," *IEEE J. Solid-State Circuits*, vol. SC-12, pp. 600–608, Dec. 1977.

206 citations

319 citations

Updated Oct 26, 2018

Seminal source of SC concept received few citations!

But cited as a key contribution when Brodersen and Gray elected to NAE

Review from Last Lecture

Switched Capacitor Filters

The realization that a small switched capacitor was equivalent to a resistor was of little consequence

The realization that a switched capacitor was dependent upon frequency was of little consequence

The realization that RC time constants could be accurately controlled with a small amount of area in silicon was of considerable consequence

The experimental validation and the efforts to convince industry that the SC techniques offered practical solutions was the MAJOR contribution !!

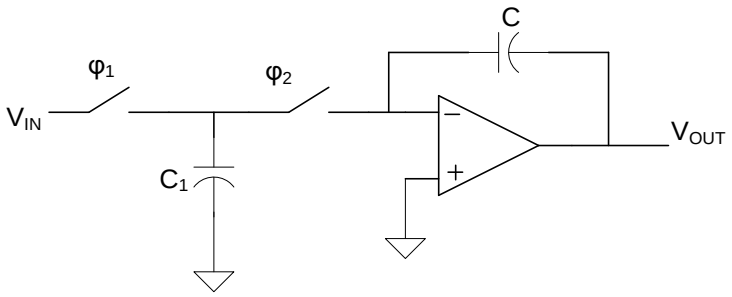
Switched-Capacitor Filter Issues

What if T_{CLK} is not much-much smaller than T_{SIG}?

Claim: The transfer function of any Switched-Capacitor Filter is a rational fraction in z with all coefficients in both the numerator and denominator determined totally by capacitor ratios

$$H(z) = \frac{\sum_{i=0}^{m} a_i z^i}{\sum_{i=0}^{n} b_i z^i}$$

Switched-Capacitor Filter Issues



Transfer function of any SC filter of form:

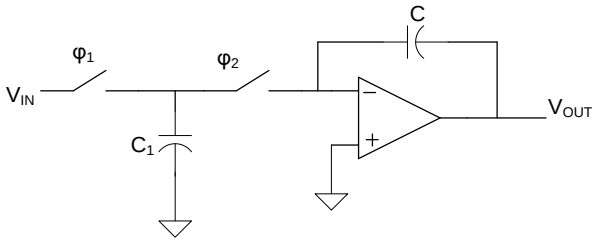
$$H(z) = \frac{\sum_{i=0}^{m} a_i z^i}{\sum_{i=0}^{n} b_i z^i}$$

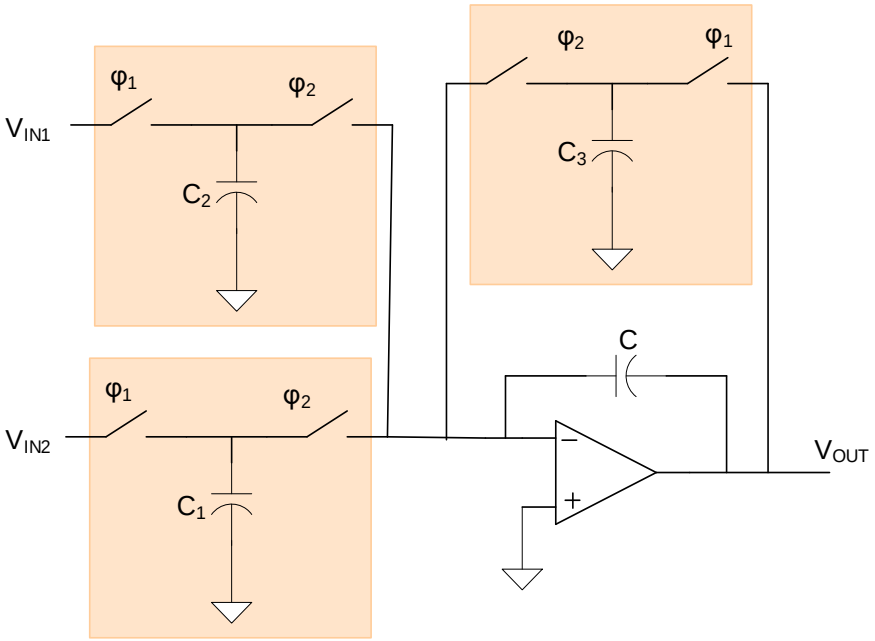
Switched-capacitor circuits have potential for good accuracy and attractive area irrespective of how T_{CLK} relates to T_{SIG}

But good layout techniques and appropriate area need to be allocated to realize this potential !

Review from Last Lecture

Switched-Capacitor Integrators

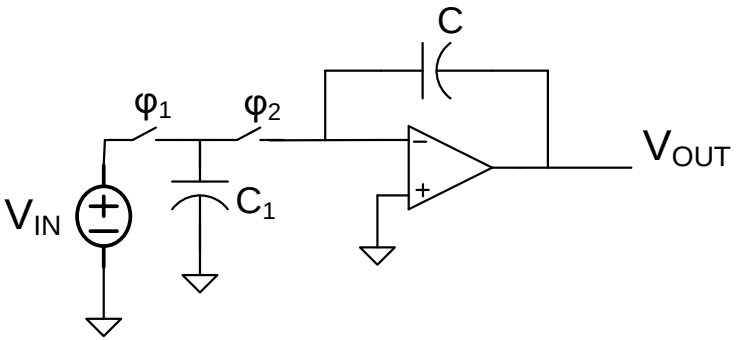




Summing Inputs and Lossy

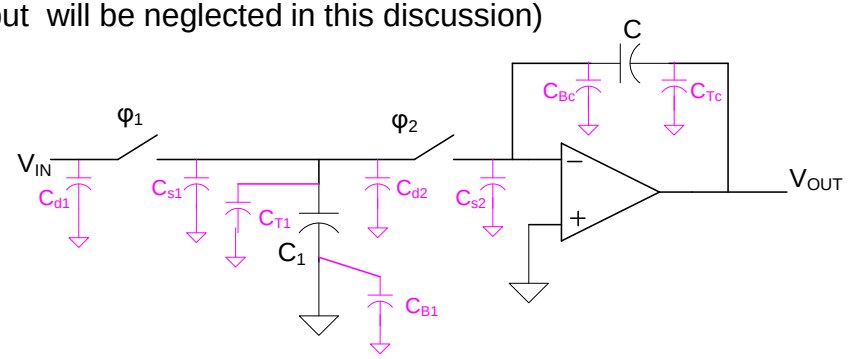
Sensitive to parasitic capacitances

The SC integrator



$$I_{0eq}=\left[\frac{C_1}{C}\right]f_{CLK}$$

Observe this circuit has considerable parasitics (gate parasitics cause offset in this circuit and some signal-dependent distortion but will be neglected in this discussion)



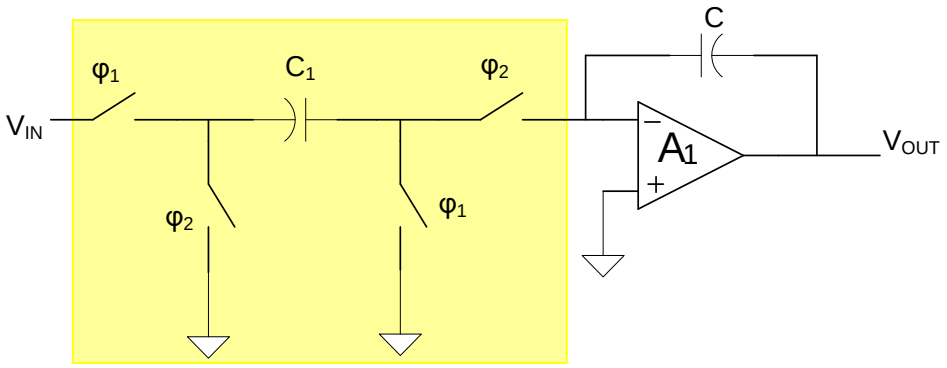
$C_{1EQ}=C_1+C_{s1}+C_{d2}+C_{T1}$

Parasitic capacitors $C_{s1}+C_{d2}+C_{T1}$ difficult to accurately match

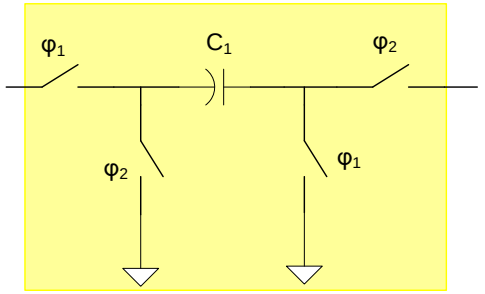
- Parasitic capacitors of THIS SC integrator limit performance
- Other SC integrators (discussed later) offer same benefits but are not affected by parasitic capacitors

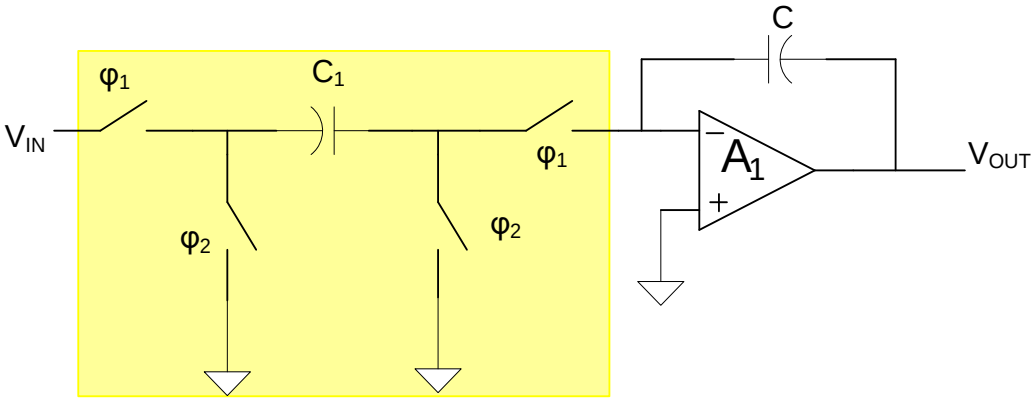
Switched-Capacitor Integrators

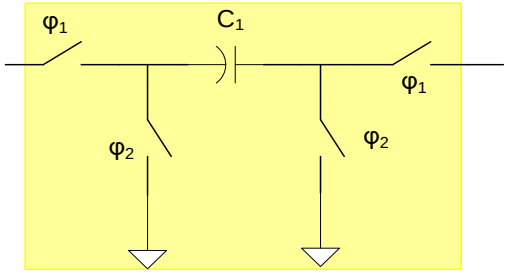
Stray-Insensitive SC Integrators



"Resistor Blocks"







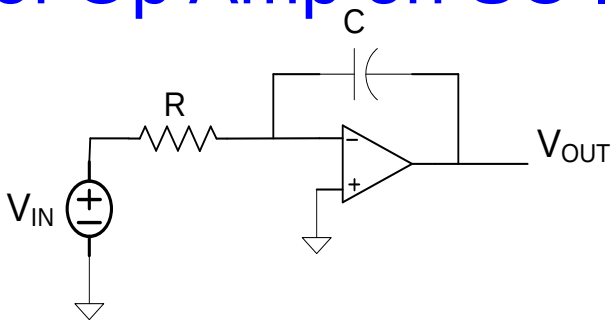
- Resistor blocks can be repeated and combined to provide summing inverting or noninverting inputs
- Resistor block can be placed in FB path to form lossy SC integrator

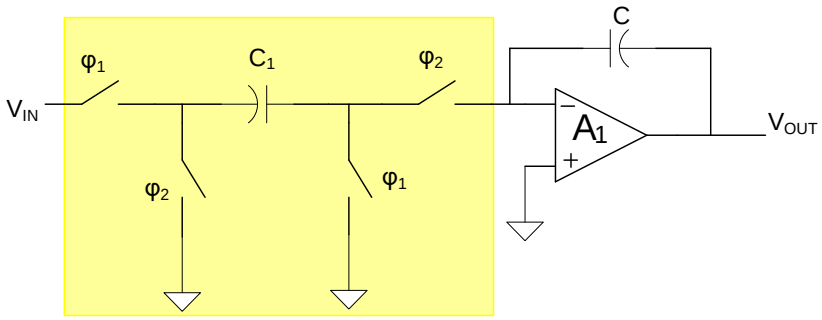
Nonideal Effects in Switched Capacitor Circuits

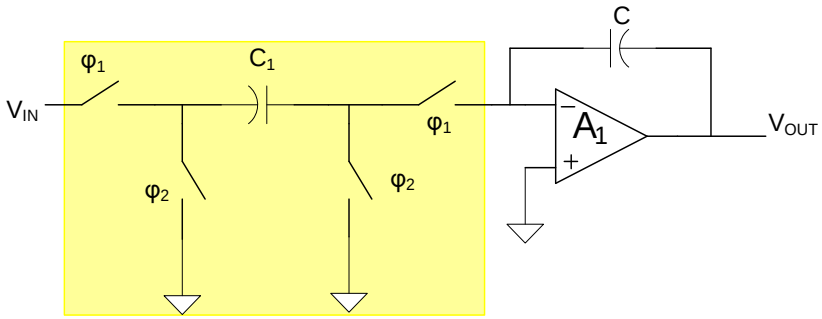
- Parasitic Capacitances
- Op Amp Affects
- Charge Injection
- Aliasing
- Redundant Switch Removal
- Matching
- Noise

Switched-Capacitor Integrators

Effects of Op Amp on SC Integrators







Can be shown that for a given band-edge, the GB requirements for the SC circuit are more relaxed than what is required for the corresponding Active RC integrator

Nonideal Effects in Switched Capacitor Circuits

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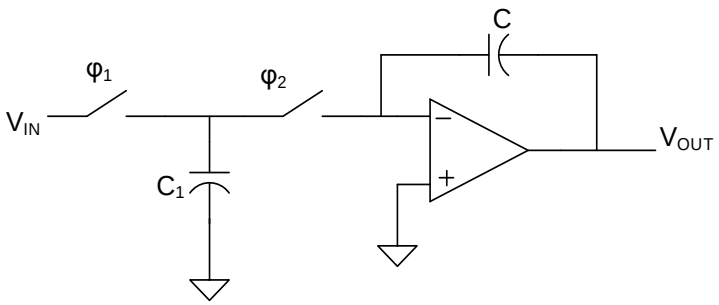
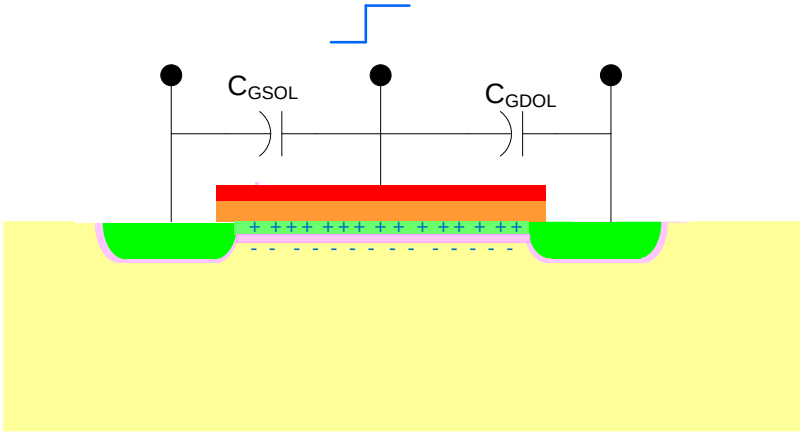
Charge Injection



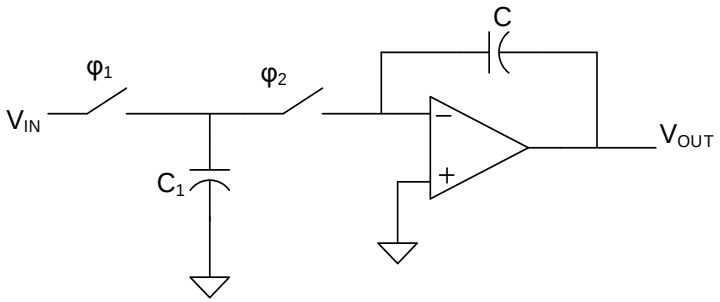


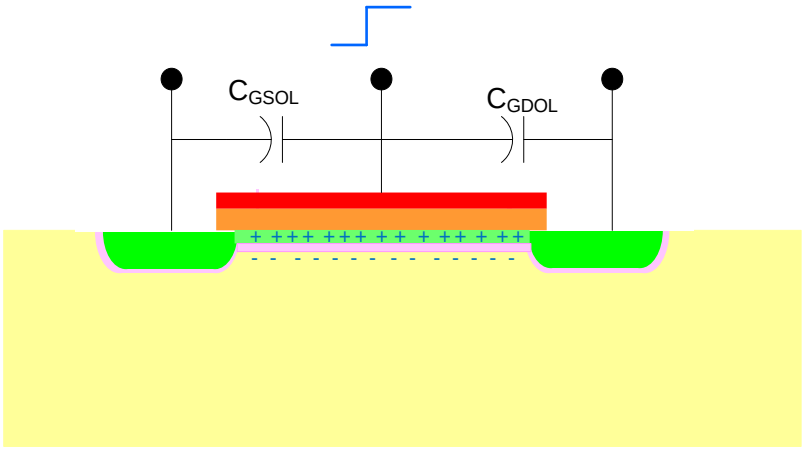
n-channel MOSFET

- Charge in OL capacitance
- Channel charge

- XPART can be used in SPICE to simulate how charge dissipates
- Distribution strongly dependent upon gate signal and S/D impedances
- XPART does not accurately model channel charge injection
- Channel charge not accurately modeled in SPICE

Charge Injection

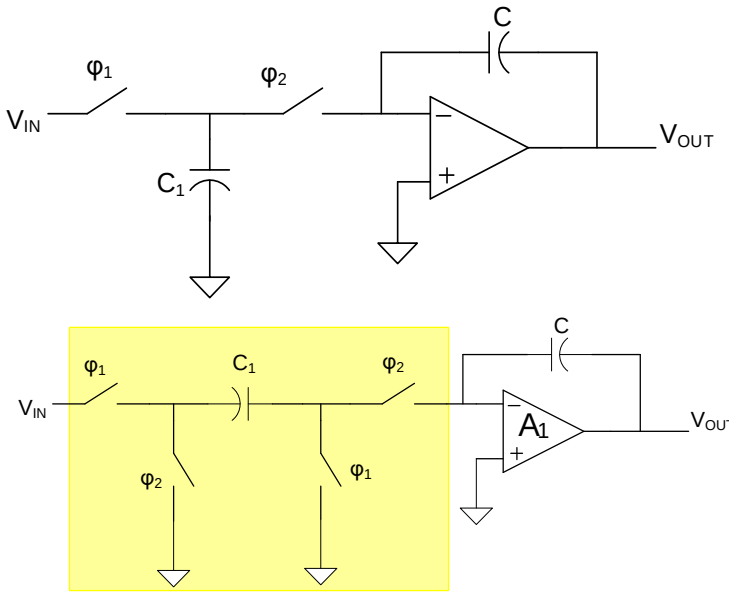


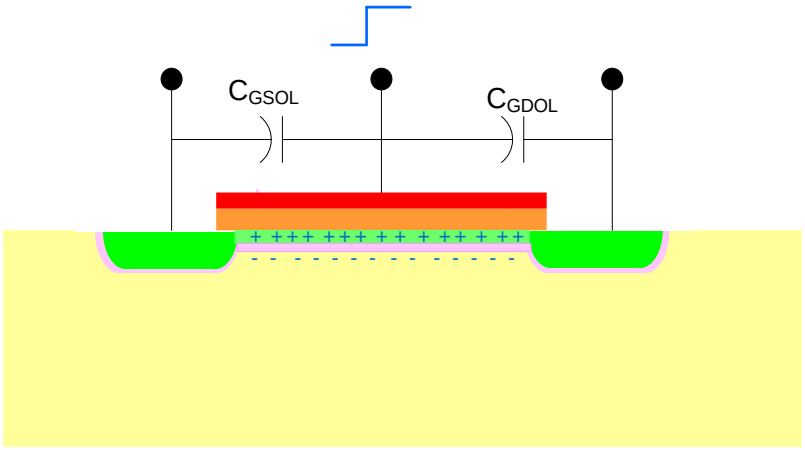


n-channel MOSFET

- If Φ_1 opens slowly, channel charge will all exit through V_{IN}
- If Φ_1 opens quickly, some charge will exit to left and some to right and split depends upon impedances seen to left and right
- Often not practical to open switches slowly
- Channel charge injection introduces errors in charge transfer and affects linearity

Charge Injection





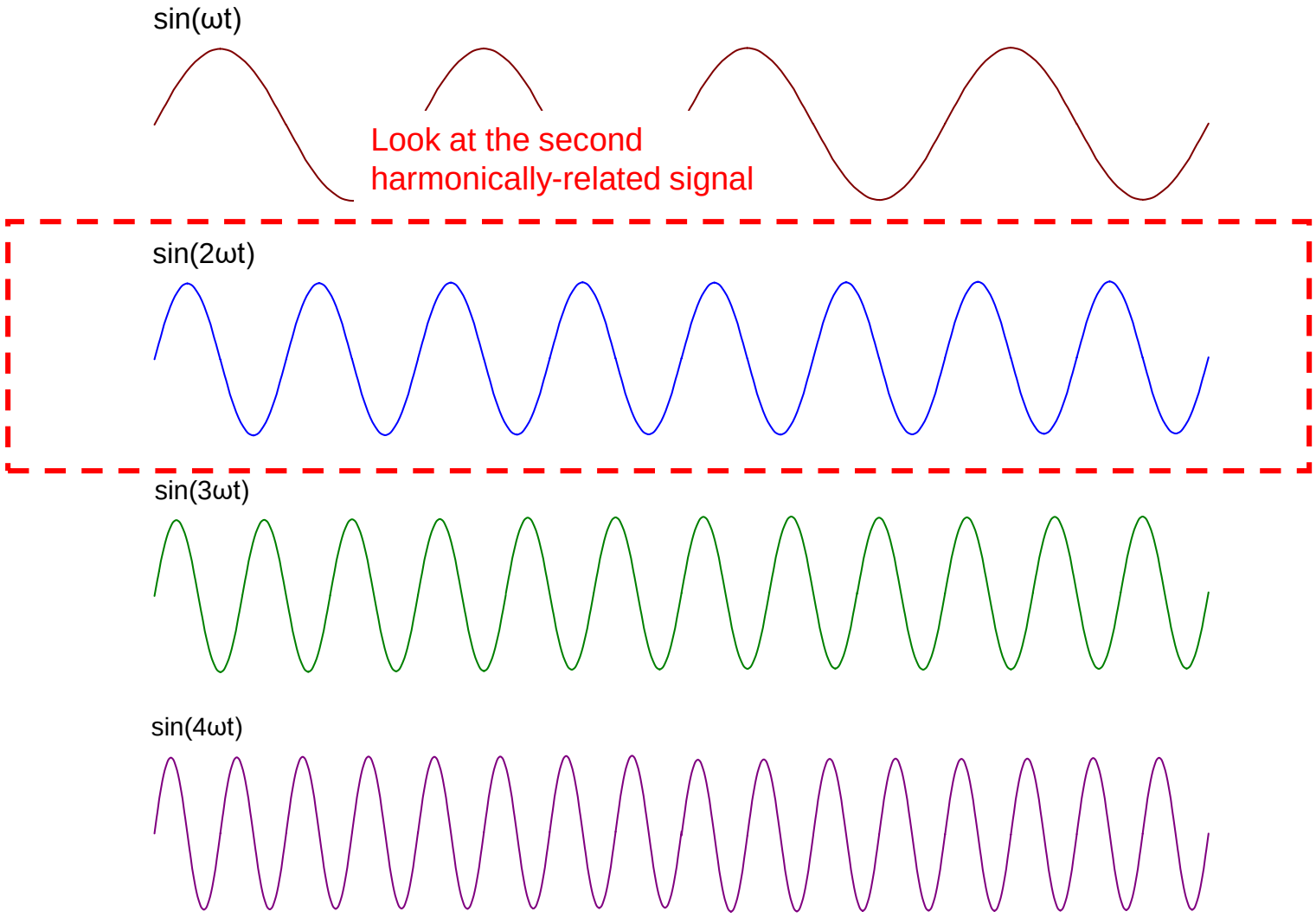
n-channel MOSFET

- Somewhat more complicated in multi-switch implementations
- There will naturally be a small amount of skew on clocks and this skew will affect charge injection
- Charge injection from some switches can be reduced or eliminated by using advanced clock (e.g. lower Φ_1 switch opens before upper Φ_1 switch)

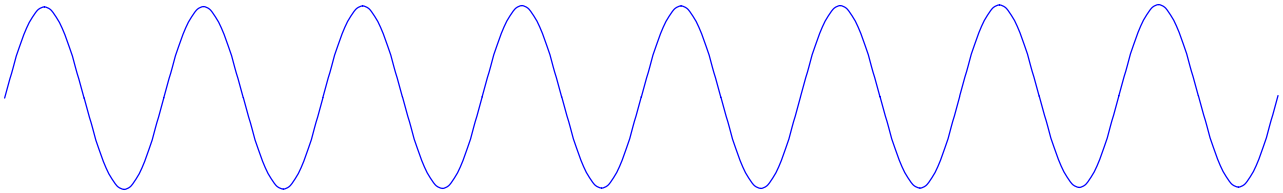
Nonideal Effects in Switched Capacitor Circuits

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

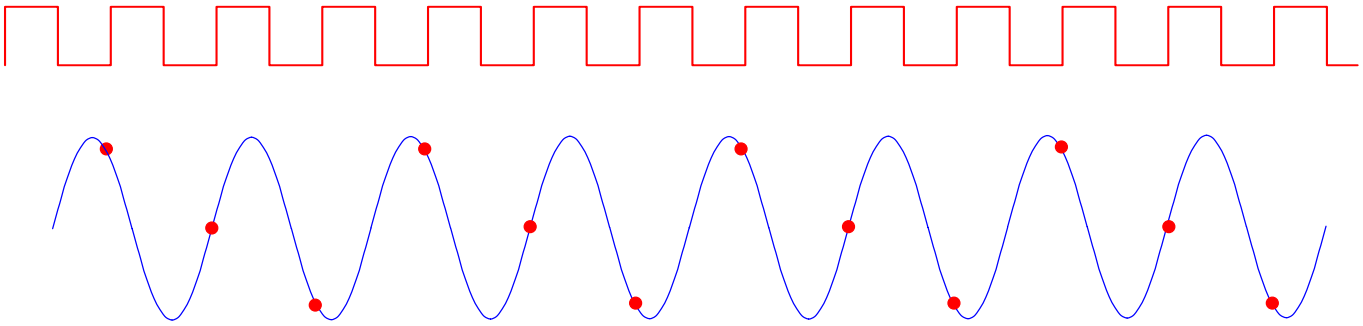
Consider a signal and harmonically-related signals



Consider a signal and harmonically-related signals

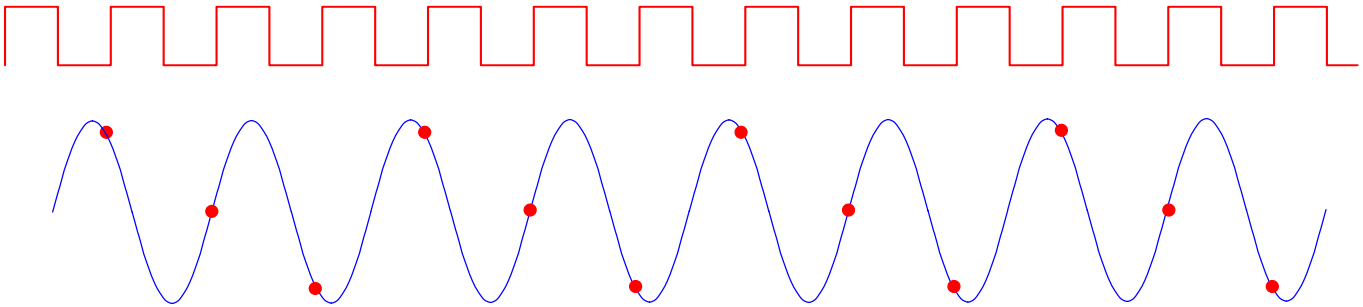


Sample with rising edges on the following clock (this could be Φ_1 for a SC filter)

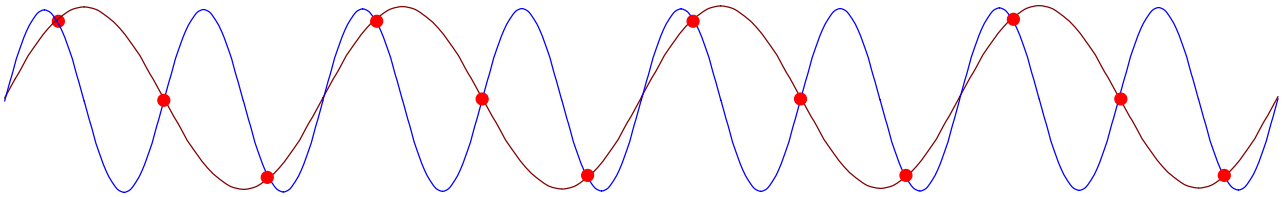


Consider a signal and harmonically-related signals

Sample with rising edges on the following clock (this could be Φ_1 for a SC filter)



Now overlay the fundamental frequency signal on this sampled waveform

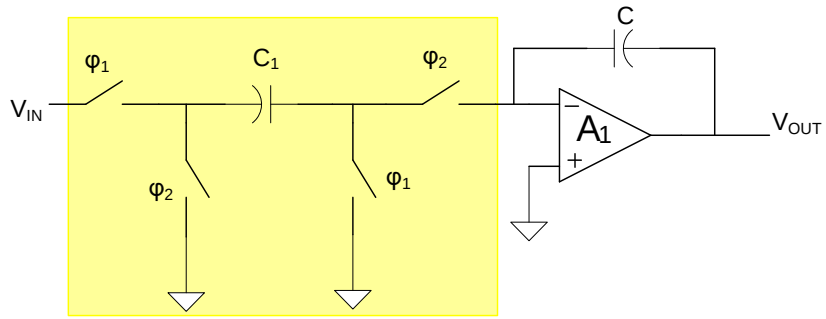


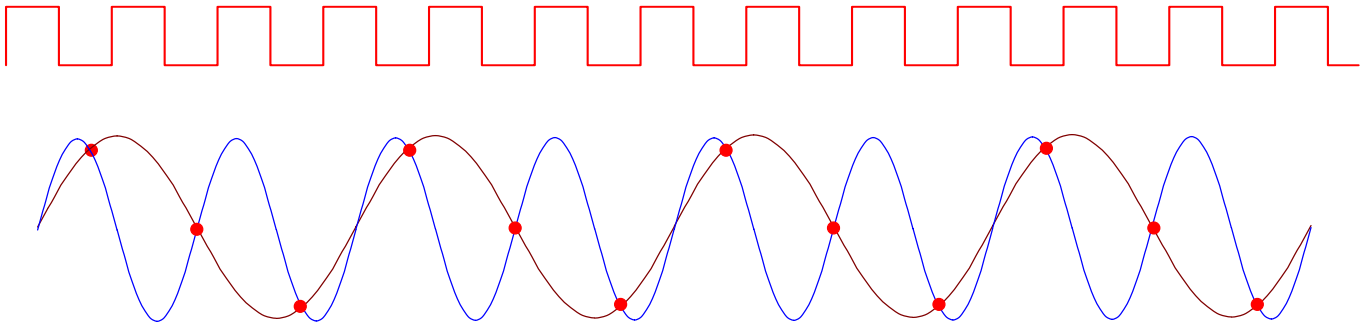
At these sample points, the samples of the two signals are indistinguishable

A similar observation will be observed if any of the other harmonically related signals are overlayed

A switched-capacitor filter can not distinguish between a fundamental and the harmonics if the ratio of the clock frequency to the signal frequency is too low

Consider a signal and harmonically-related signals

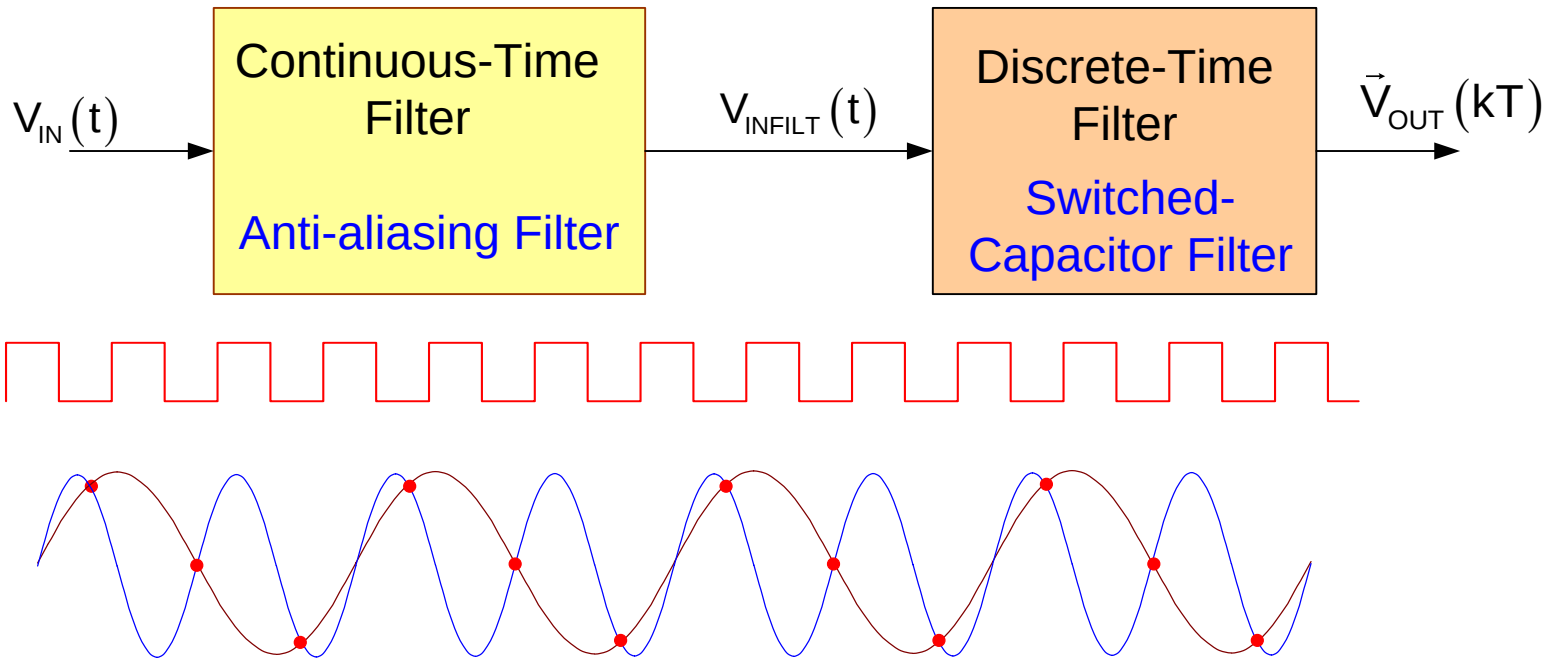




This aliases high frequency inputs (signals, noise, or even distortion) down to lower frequencies where it is indistinguishable from the lower frequency inputs 

How can this problem be resolved?

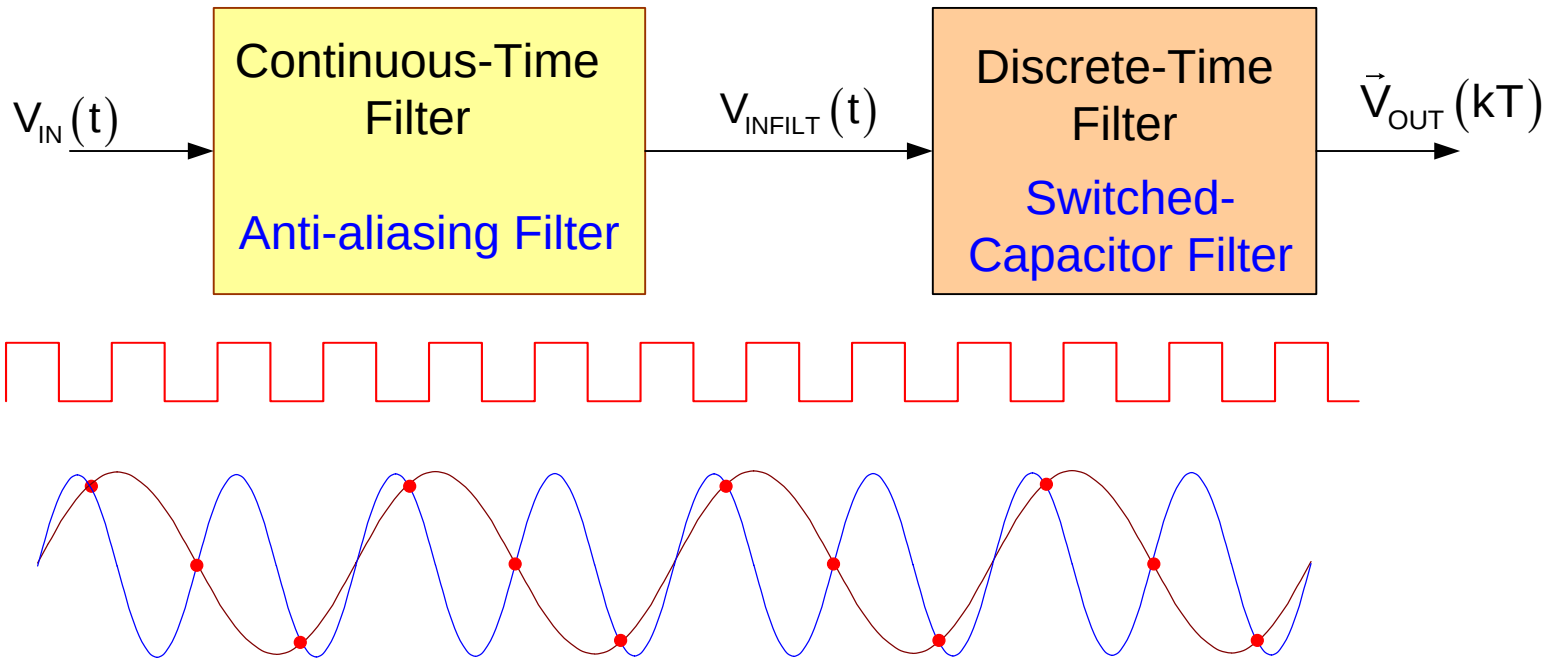
Anti-aliasing filter often required to limit frequency content at input to SC filters



Does this completely negate the benefits of the SC filter?

- Anti-aliasing filter not needed if input is already band limited
- Anti-aliasing filter often continuous-time and occasionally off-chip
- Linearity requirements of anti-aliasing filter in passband are high
- Good passband linearity can be practically attained
- Transition sharpness and accuracy typically very relaxed in the anti-aliasing filter
- Passive first-order anti-aliasing filter often adequate

Anti-aliasing filter often required to limit frequency content at input to SC filters



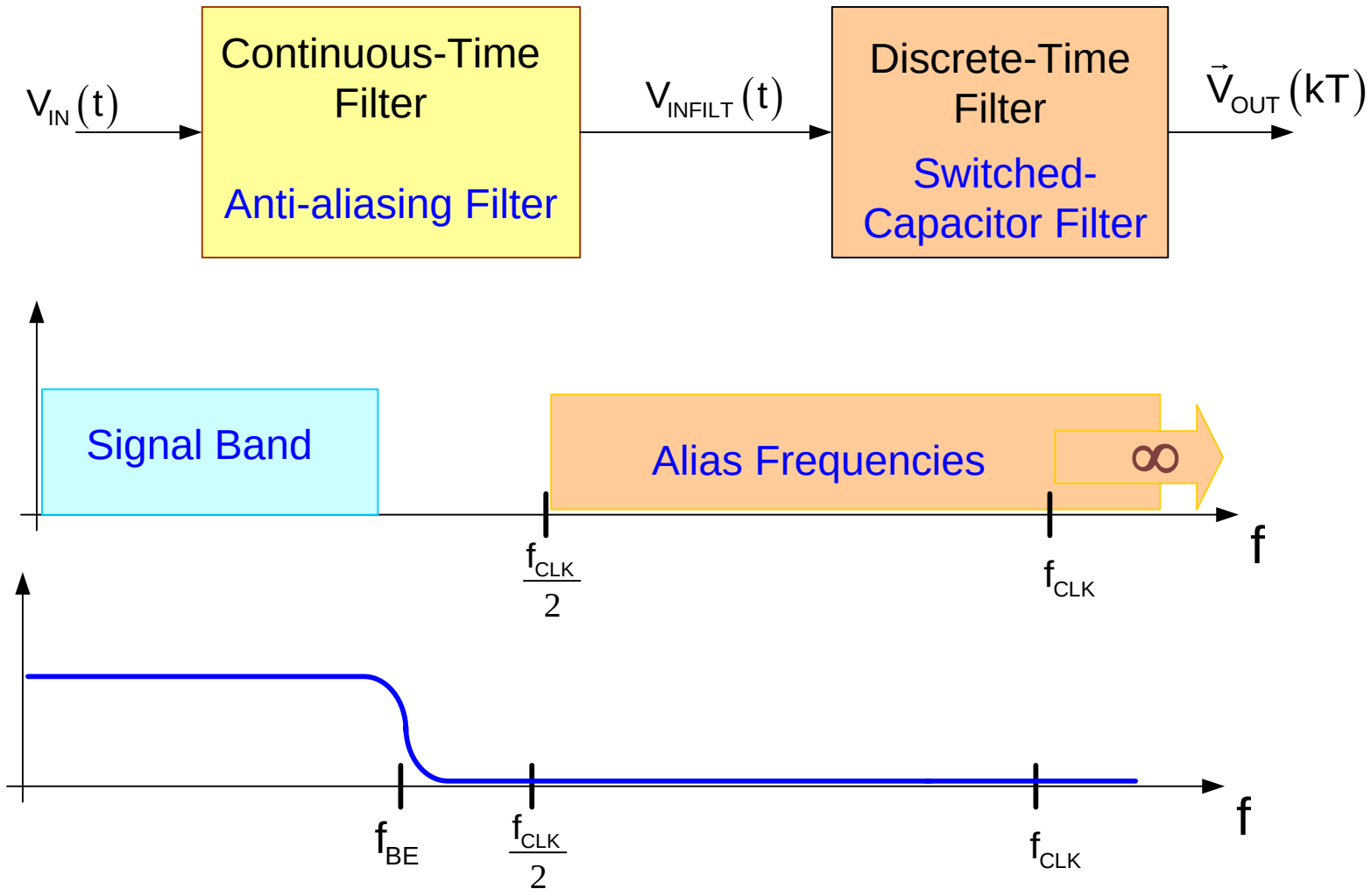
What are the band-edge requirements for the anti-aliasing filter?

Band edge of filter should limit all signals (and noise) at frequencies that are not wanted

What are SC clock requirements?

f_{CLK} must be at least twice the frequency of the signals that are to be passed by the SC filter

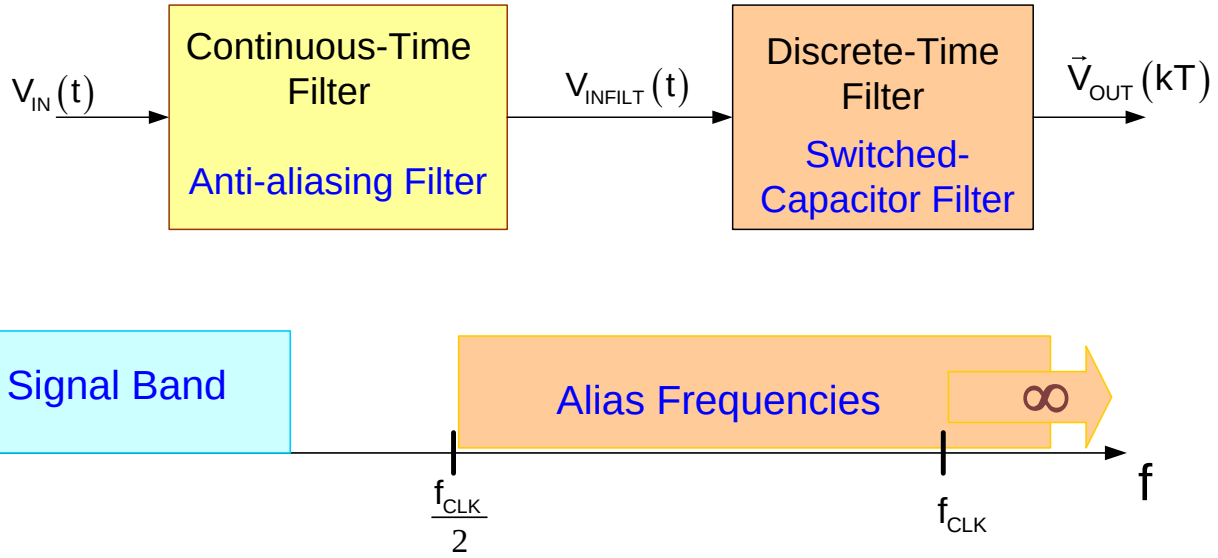
Anti-aliasing filter often required to limit frequency content at input to SC filters

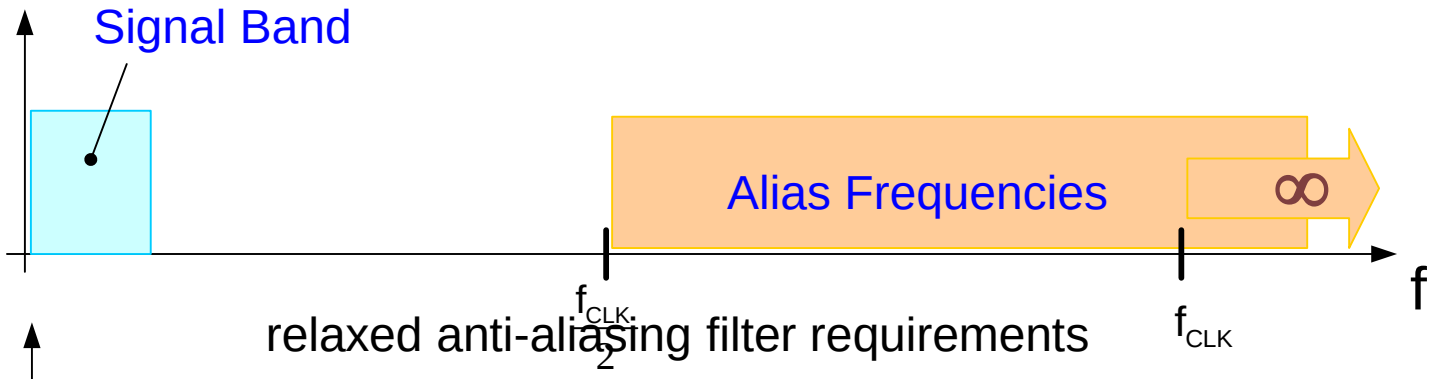


Antialiasing Filter

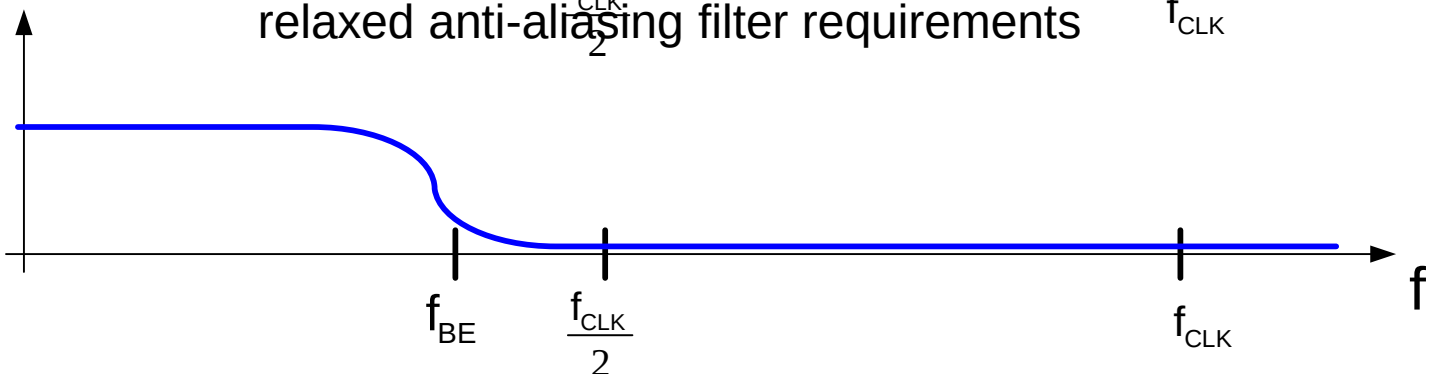
Must only attenuate at frequencies where energy is above an unacceptable level in the alias band

Anti-aliasing filter often required to limit frequency content at input to SC filters

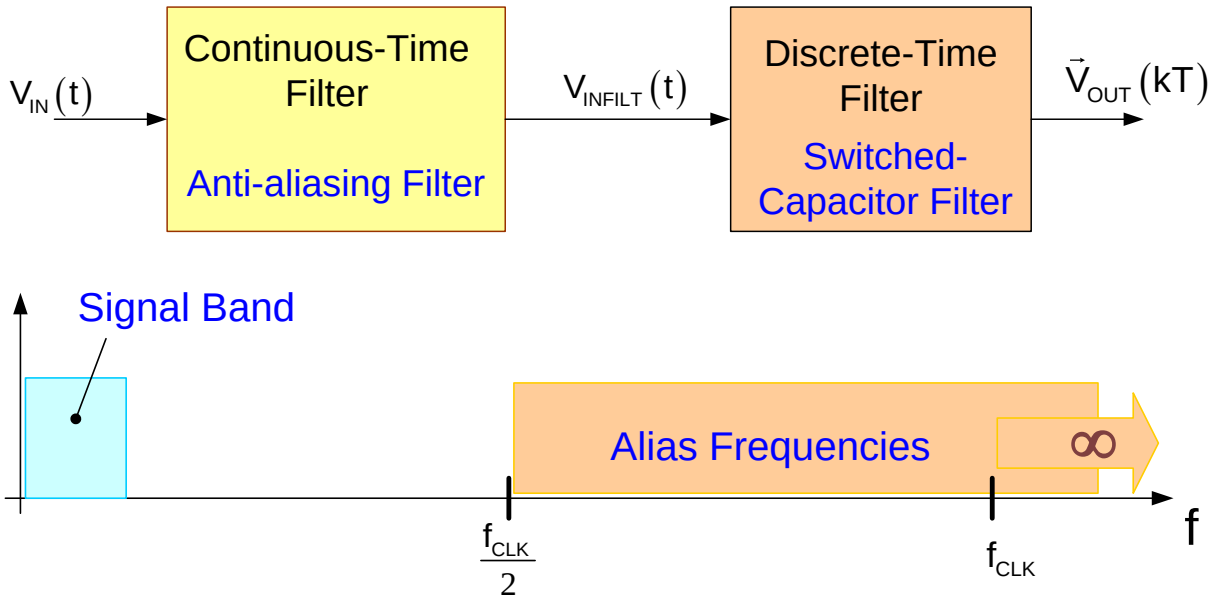




relaxed anti-aliasing filter requirements



Anti-aliasing filter often required to limit frequency content at input to SC filters



Why not just make the clock frequency >> signal band edge ?

Recall in the continuous-time RC-SC counterparts

$$f_{POLES} \cong \frac{1}{RC} \cong f_{CLK} \frac{C_1}{C}$$

Since f_{POLES} will be in the signal band (that is why we are building a filter) large f_{CLK} will require large capacitor ratios if $f_{CLK} >> f_{POLES}$

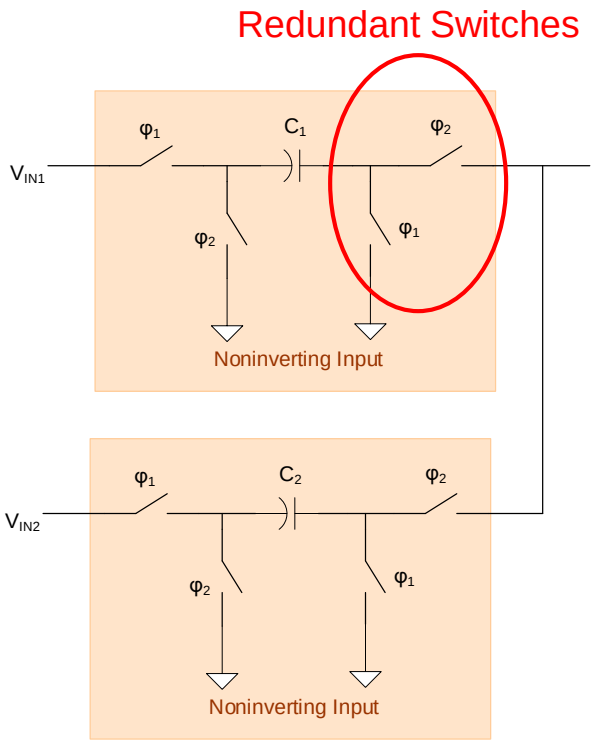
- Large capacitor ratios not attractive on silicon (area and matching issues)
- High f_{CLK} creates need for high GB in the op amps (area,power, and noise increase)

Often f_{CLK}/f_{POLES} in the 10:1 range proves useful (20:1 to 5:1 typical)

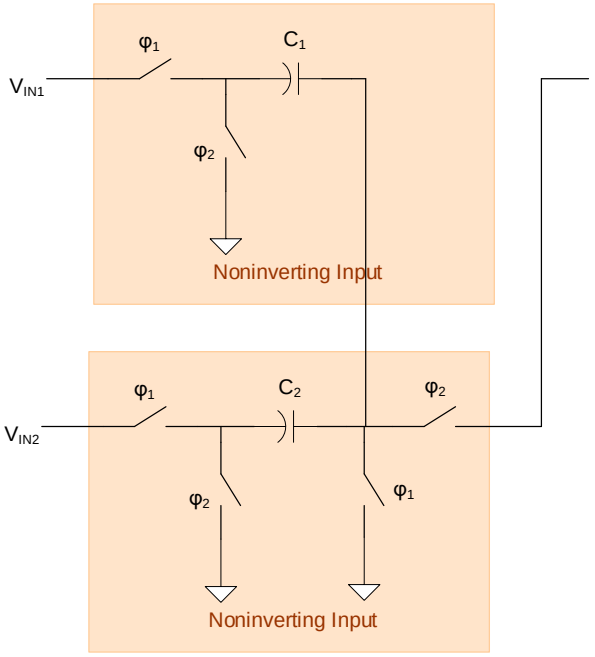
Nonideal Effects in Switched Capacitor Circuits

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

Elimination of Redundant Switches



Switched-Capacitor Input with Redundant Switches



Switched-Capacitor Input with Redundant Switches Removed

Although developed from the concept of SC-resistor equivalence, SC circuits often have no Resistor-Capacitor equivalents

Nonideal Effects in Switched Capacitor Circuits

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

Matching

- Matching is a statistical concept and directly relates to yield
- With good layout, matching to 0.01% or better can be achieved
- Common-centroid widely used to eliminate gradient effects
- Pelgrom parameter useful for analytically predicting yield with common-centroid layouts
- Area affects local variations
- Little in the literature or in PDKs to predict matching without gradient cancellation
- Must match all contacts and interconnects to get good matching
- Neighbor effects are important

Stay Safe and Stay Healthy !

End of Lecture 25