Switched Capacitor:
Sampled Data Systems

- **Basic switched capacitor theory**
- **How has Anadigm utilised this.**

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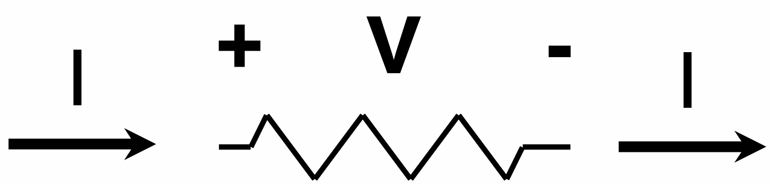
Resistor & Charge Relationship

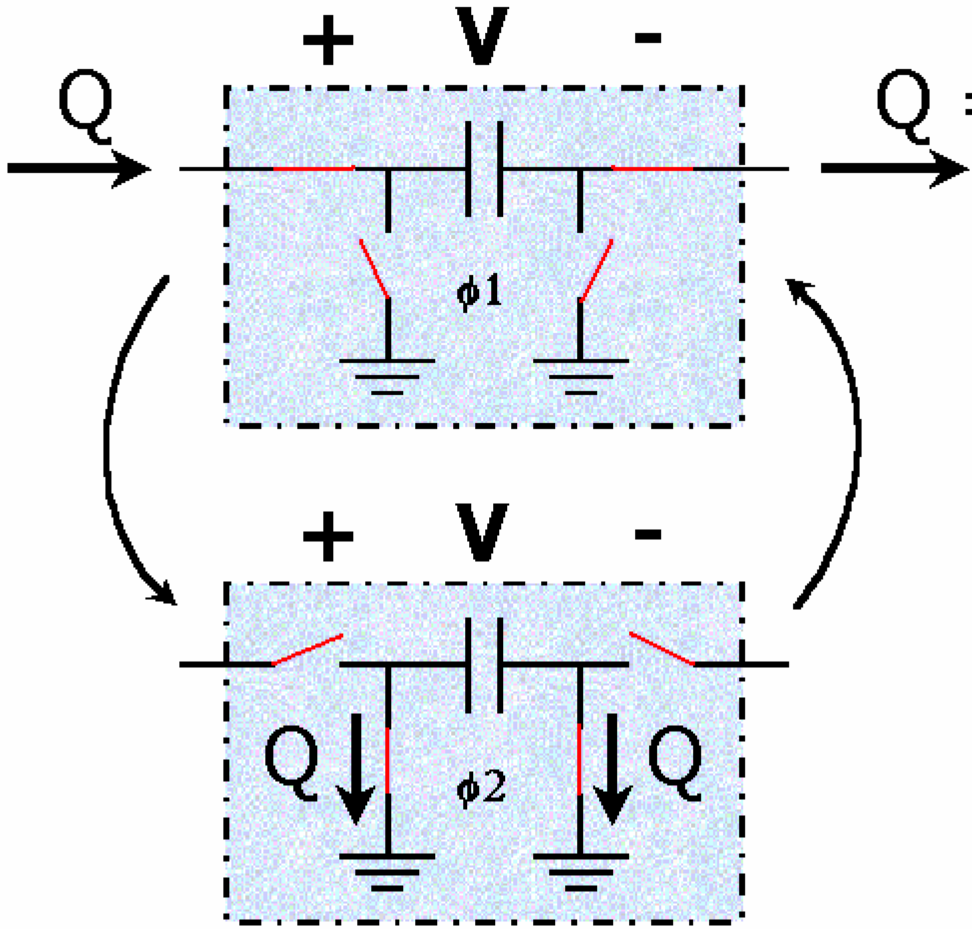


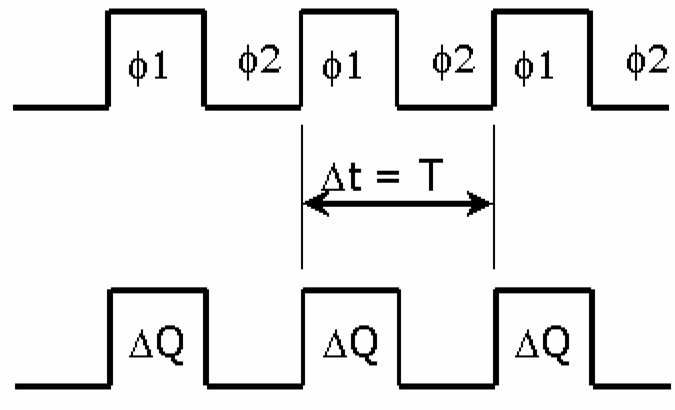
$$I = \frac{\Delta Q}{\Delta t}$$

$$R = \frac{V}{I} = \frac{V\Delta t}{\Delta Q}$$

- **Resistance is defined in terms of current (I) and voltage (V).**
- **Current is the rate of change of charge.**
- **R = V/I**

Switching Charge to a Capacitor





$$I_{AVG} = \frac{\Delta Q}{\Delta t} = \frac{C\,V}{T}$$

Switched Capacitor as a Resistor

$$R = \frac{V}{I} = \frac{\cancel{V}\,T}{C\,\cancel{V}}$$

$$\boxed{R = \frac{T}{C} = \frac{1}{fC}}$$

$$\frac{R_1}{R_2} = \frac{C_2 \cancel{T}}{\cancel{T}\,C_1} = \frac{C_2}{C_1}$$

- **Equivalent resistance**
  - Contains no "R"
  - Goes UP↑ as C goes down↓
  - Function only of "C" and clock period (T)
- **Ratios**
  - Independent of clocks
  - Depends on <u>capacitor matching</u>

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Why Switched Capacitor?

- **RC constants with only C's**
- **Area savings - much smaller for large "R"**
- **Better "resistor" values**
    - Better tolerance; typically ± 1.0%
    - Better matching - typically ± 0.1%
    - Better Linearity
    - Wider range
- **The "extras"**
    - Phase swapping
    - Frequency dependent *R*C's

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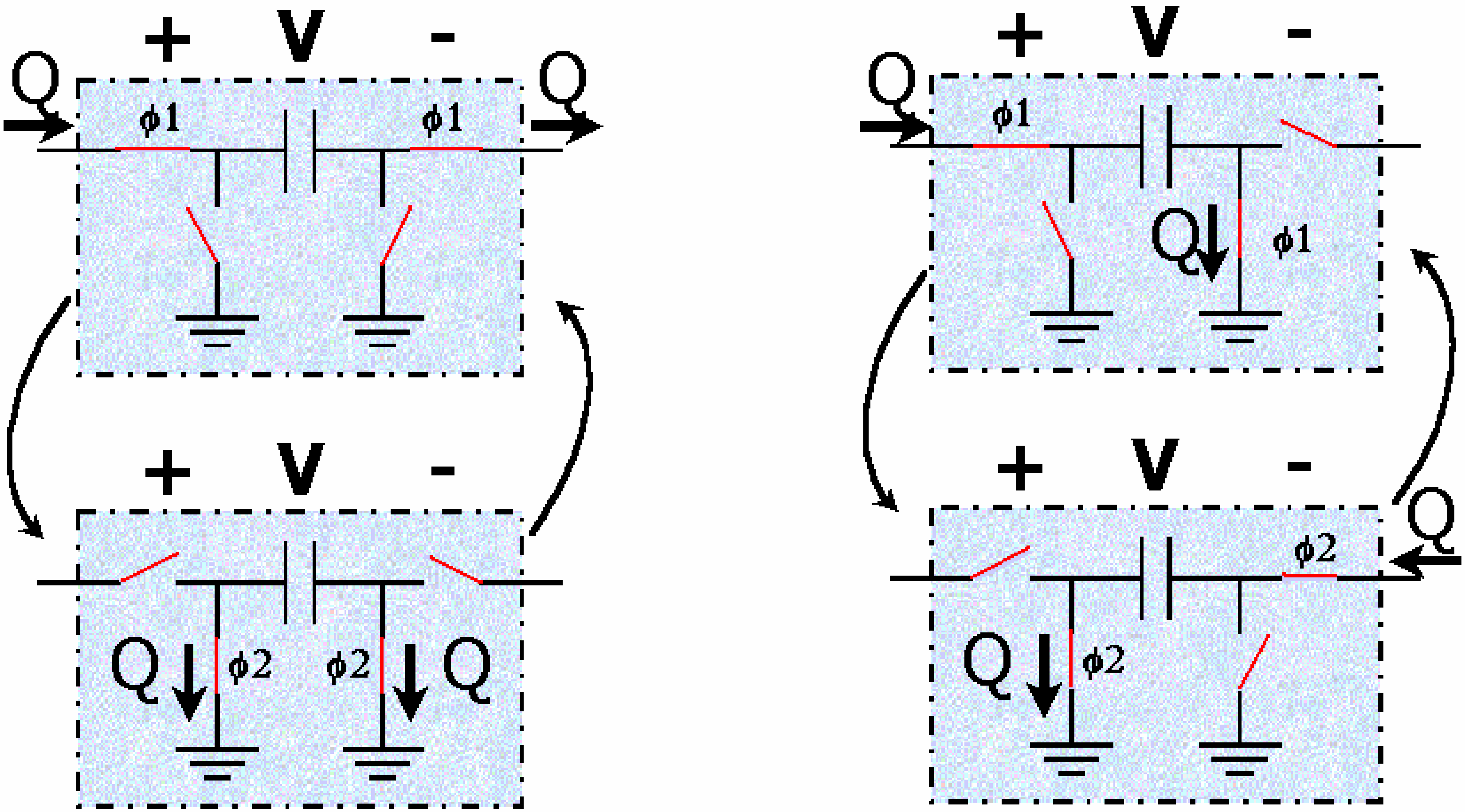
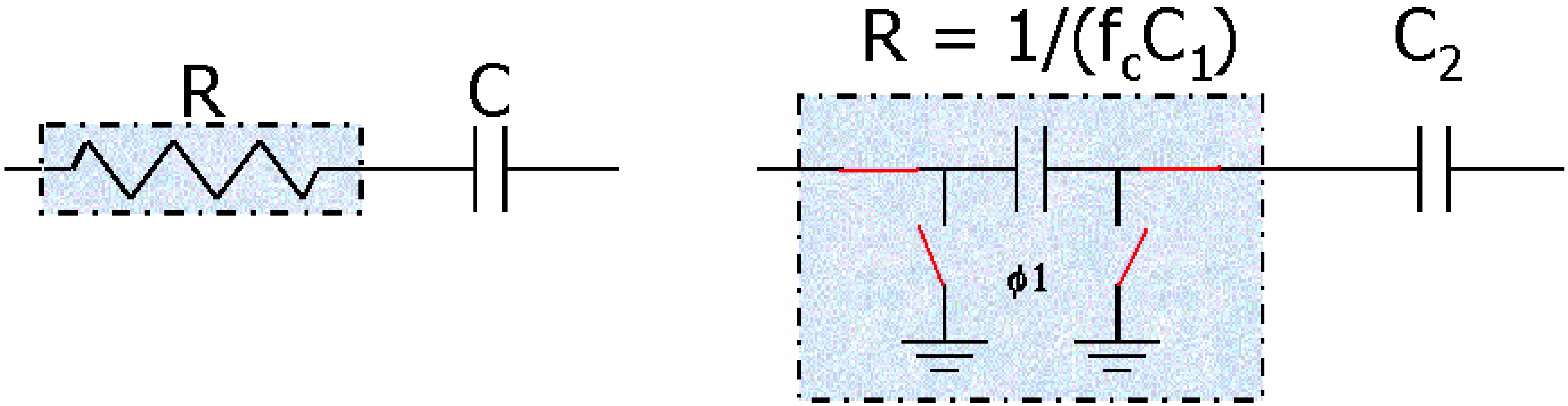
Phase Swapping



$R = (T/C)$

$R = -(T/C)$

The Clock as a System Reference

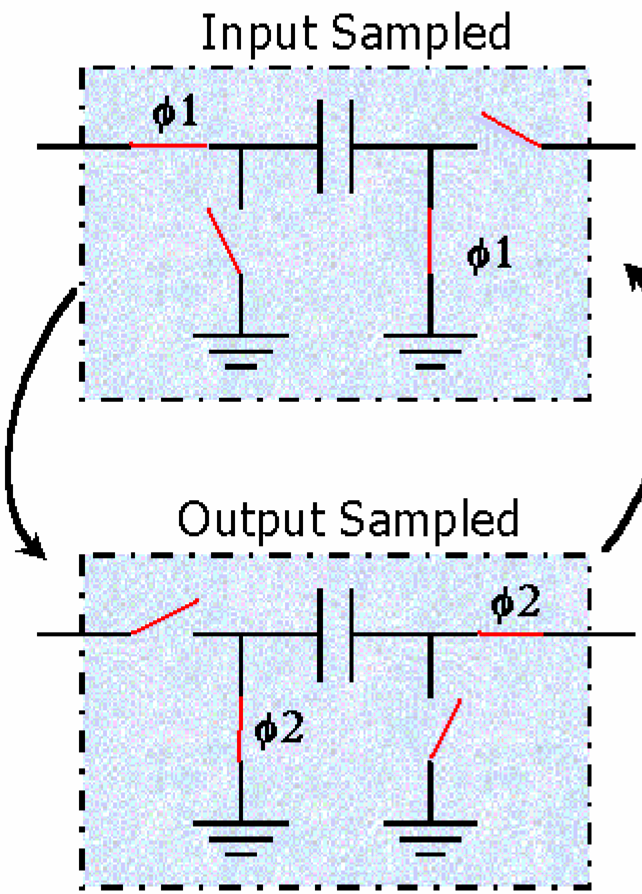


$f_0 = 1/(RC)$

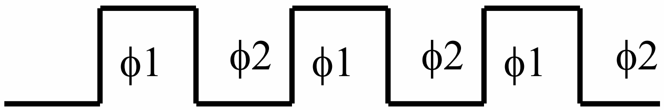
$f_0 = 1/(RC_2) = f_c(C_1/C_2)$

- **Corner frequency can be changed by changing the clock frequency**

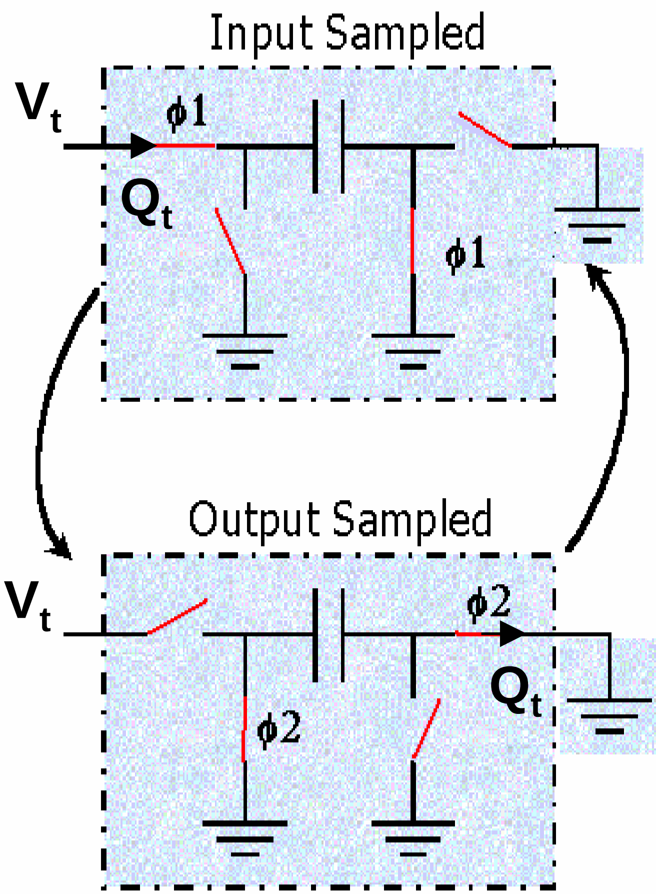
Switched Capacitor Circuits are <u>Sampled</u> Data Systems

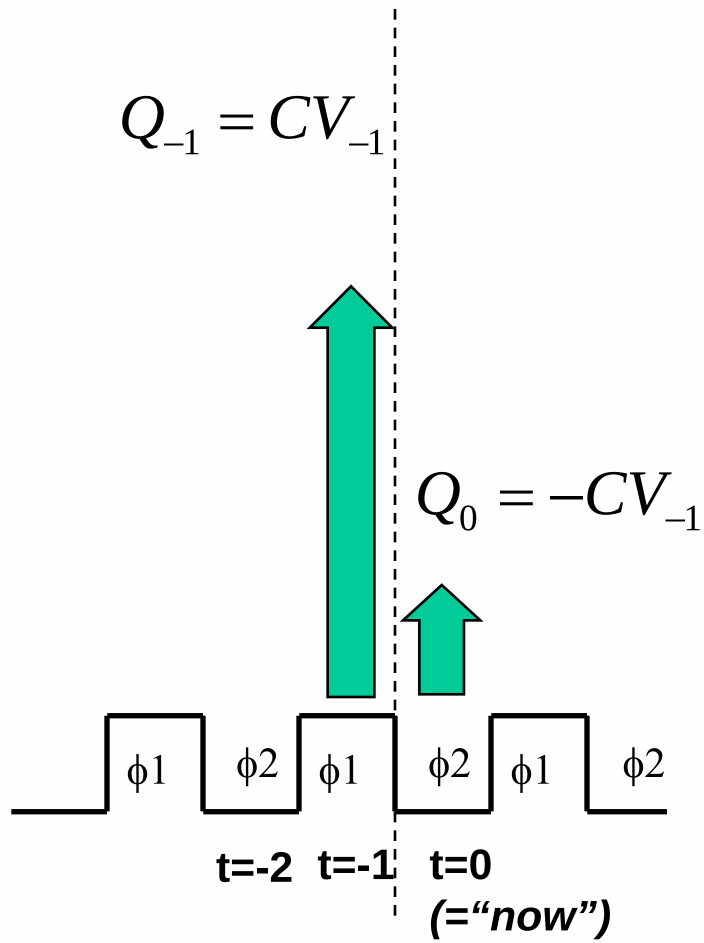


- Inputs and outputs may be valid only on certain phases
- Subject to sampled data system constraints

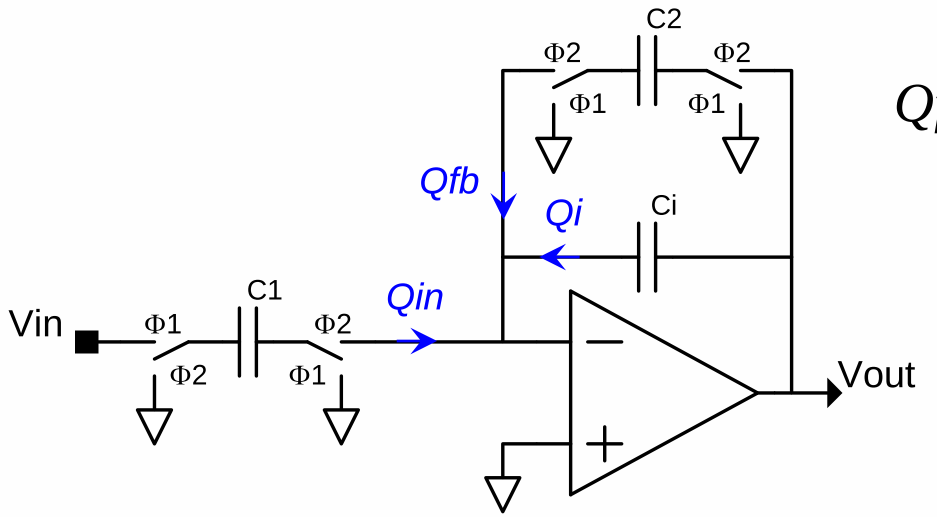


Expression of Sampled Data Function





Sampled Data Example…



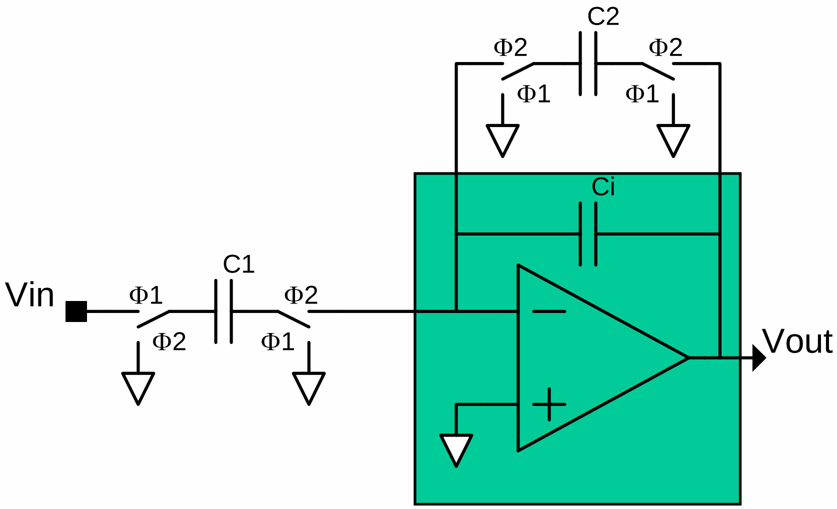
$$Qfb_0 = C2 \cdot Vout_0$$

$$Qi_0 = Ci \cdot (Vout_0 - Vout_{-1})$$

$$Qin_0 = -C1 \cdot Vin_{-1}$$

$$\boxed{-C1 \cdot Vin_{-1} + C2 \cdot Vout_0 + Ci \cdot (Vout_0 - Vout_{-1}) = 0}$$

…And we get : AnadigmDesigner Simulator Equation!



All SC functions are about ***ratios*** of capacitors. Normalise all caps connected to an integrator stage to the integrator cap (=C_2 here). So:

$$nC_i = 1 \qquad nC_1 = \frac{C_1}{C_i} \qquad nC_2 = \frac{C_2}{C_i}$$

On $\phi 2$: $$Vout_0 = \frac{1}{(1 + nC_2)} \cdot (Vout_{-1} + nC_1 Vin_{-1})$$

On $\phi 1$: $$Vout_0 = Vout_{-1}$$

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Performance: Programming Boundaries

- **Op-amp dynamics**
  - Gain-bandwidth product
  - Op-amp slew rate
  - Loading limits
- **Input offset**
- **Limit on filter order**
- **Capacitance spread**

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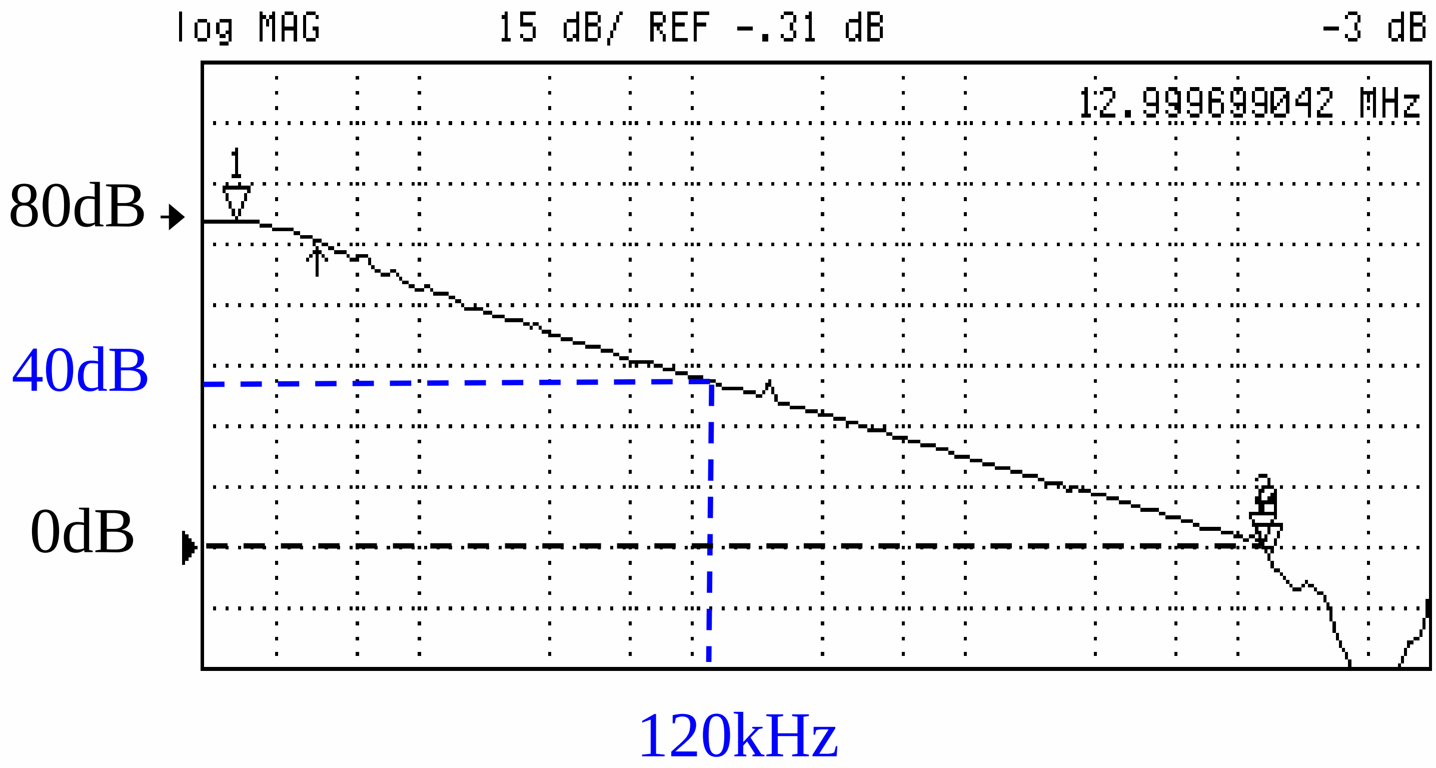
Opamp Gain Bandwidth Product



- **There is a natural trade-off between bandwidth and gain**
- **This knowledge is built into the IPmodules**

Op-amp Slew Rate

- **Defines speed at which large transitions in output voltage are made.**
- **The op-amp is no longer operating in small-signal mode (the 'virtual ground' is destroyed temporarily)**
- **This is *separate to* GB product**
- **It arises from internal features of the op-amp, and is not a feature of capacitive loading**
    - Note: excess capacitive load causes op-amp instability (ringing)
    - Anadigm op-amp's are designed to drive 100pF load at unity gain
        - About 6 or 7 full-size input caps

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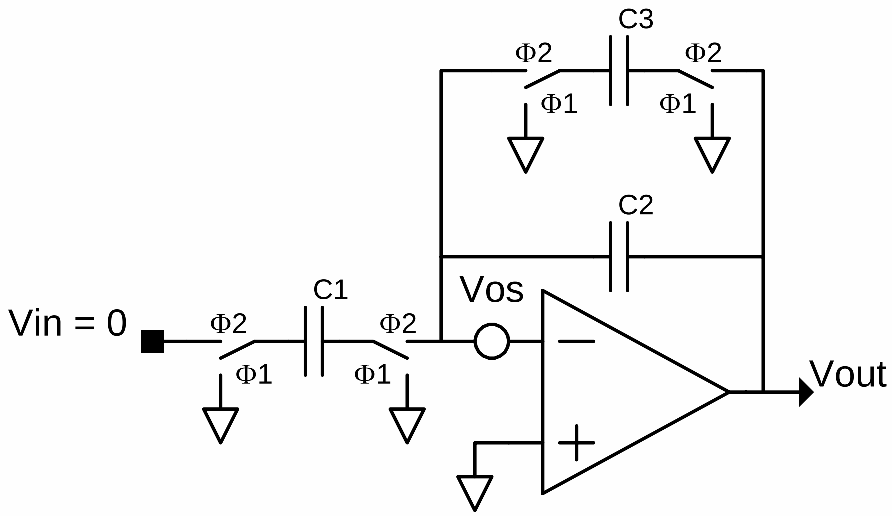
Input Offset



$$V_{out} = V_{os} \cdot \frac{(C_1 + C_3)}{C_3}$$

- **Anadigm 3.3volt products have an internal offset "nulling" circuit**

this reduces the effective offset from a few mil-volts to less than 250 micro-volts.

- **5 volt products do not have this feature**

Filter Order

- **In theory, very large filters can be constructed with Anadigm's dpASP and FPAA products, 8 poles with each device and multiple devices can be used.**
- **All the previous effects are *cumulative* and will put a practical limit on filters that can be built.**
- **A rule of thumb, a maximum order of about 10-12 can be realised without special consideration of the second order effects mentioned previously (e.g. C-message telecoms filter)**
  - Higher order filters with poles in their transfer function (IIR filters) are not often called for anyway.

Capacitance Spread

- **The ratio of C_{max} to C_{min} in a given Switched Capacitor stage**
- **Limits CAM parameter ranges**
  - Lowest filter cut-off frequency
  - Minimum and maximum gain settings
  - Maximum length of integrator time-constant

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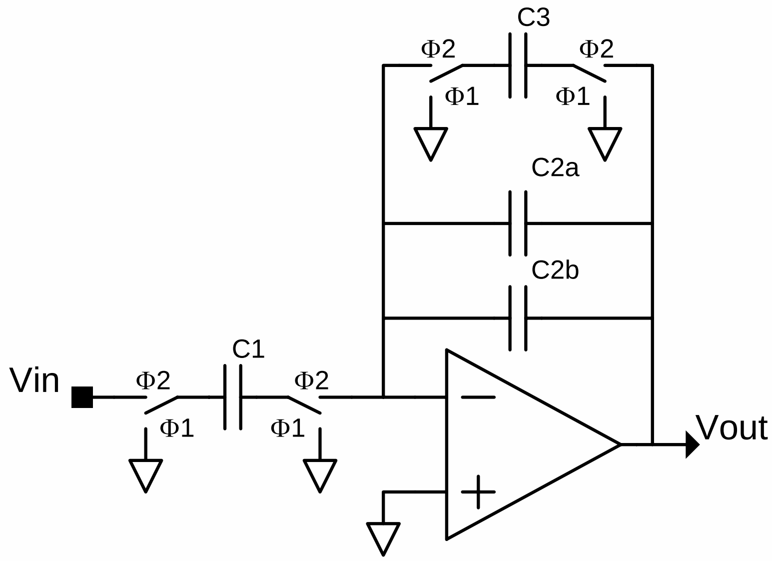
Extending Capacitance Spread



Uses parallel combinations of available capacitors
Many of Anadigm's CAM use this technique.