Noise and electronics for semiconductor detectors

A big subject but restrict to very essential information only

Some slides will be skipped and are there only to provide supplementary details for those wishing to seek further information.

Key point: Semiconductors need amplifiers since they usually do not have any built-in amplification

hence some understanding of amplifiers is required when considering how to build detector systems

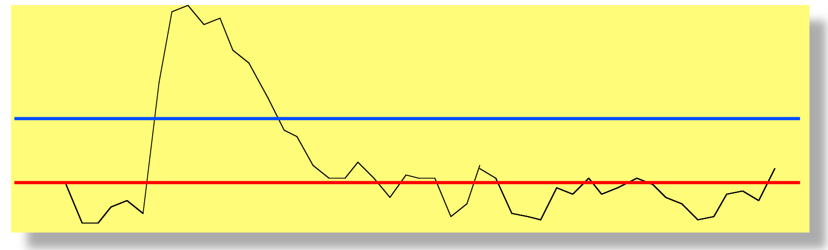
if you are prepared to accept the noise is what it is, then it may be enough for working with data from such systems just to be aware that noise is present and it probably cannot be improved, although it might be worsened!

Noise

- What is NOISE? <u>A</u> *definition:*

Any unwanted signal obscuring signal to be observed

two main origins



- EXTRINSIC NOISE examples...

pickup from external sources unwanted feedback

RF interference from system or elsewhere, power supply fluctuations

ground currents

small voltage differences => currents can couple into system

may be hard to distinguish from genuine signals *but* AVOIDABLE

Assembly & connections, especially to ground, are important

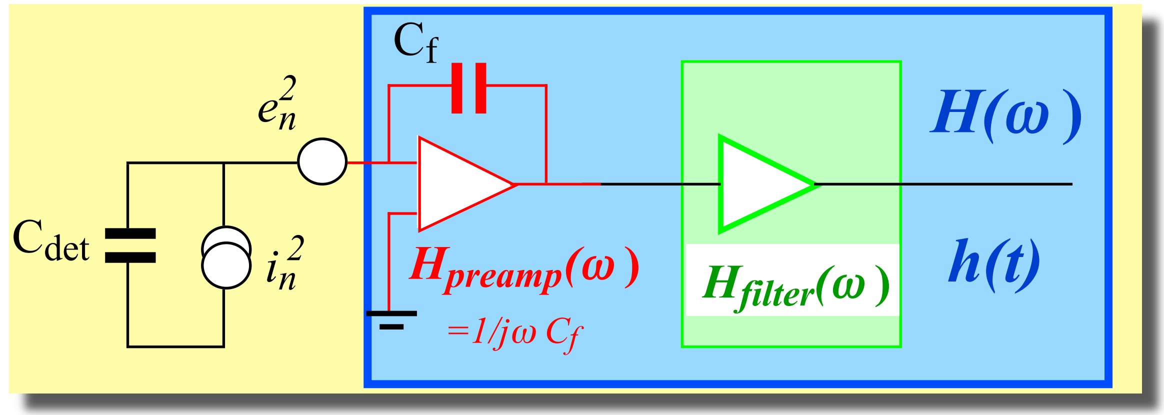
- INTRINSIC NOISE

Fundamental property of detector or amplifying electronics

Can't be eliminated but can be MINIMISED

Noise in amplifier systems

- VFE systems comprise
  - preamplifier - with noise sources
  - shaping amplifier or other filter

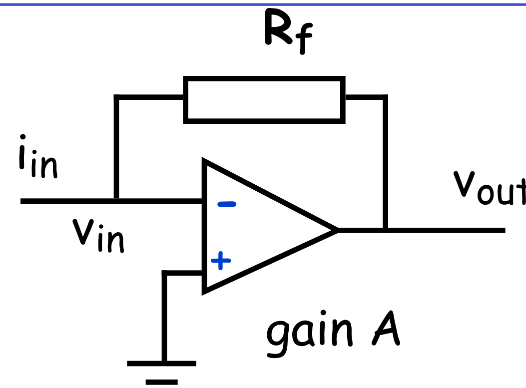


- Preamplifier usually designed with noise as an important consideration
  - preamplifier pulse shape is long duration with short, sharp peak
  - so modify it with shaper to
    - optimise signal to noise
    - generate a more practical pulse shape, avoiding pile-up
  - the first (pre-) amplifier is the most important part of the system for noise

- The system noise can be calculated once sources are understood
  - relies on Campbell's theorem and summation over bandwidth

Preamplifier types

Omit most – just be aware that different amplifier types have different noise properties and are not interchangeable

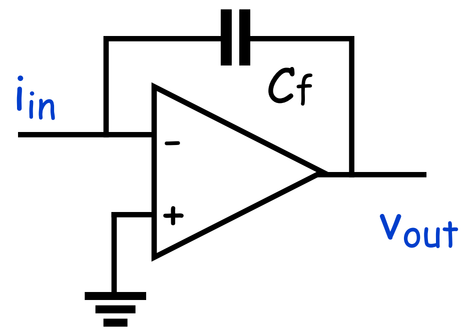


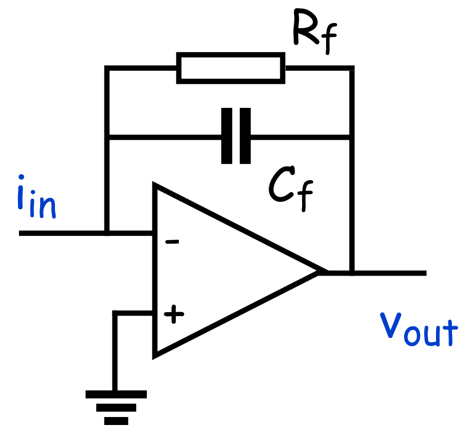
- Current sensitive - common for photodiode signals

  $v_{out} \approx -i_{in}R_f$

- signals follow input current, ie fast response

  but not lowest noise





- Charge sensitive amplifier

  Ideally, simple integrator with C_f

  but need means to discharge capacitor

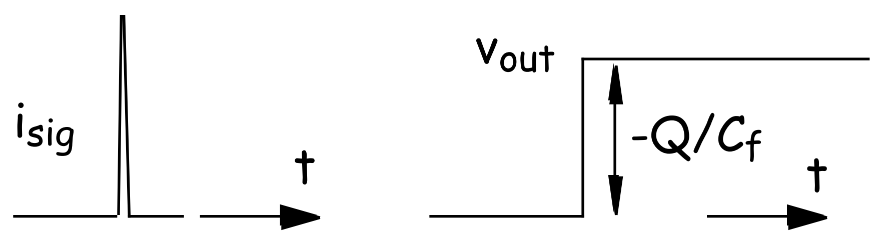
  - large R_f

- Simple integrator

  $v_{out} \approx -Q/C_f$

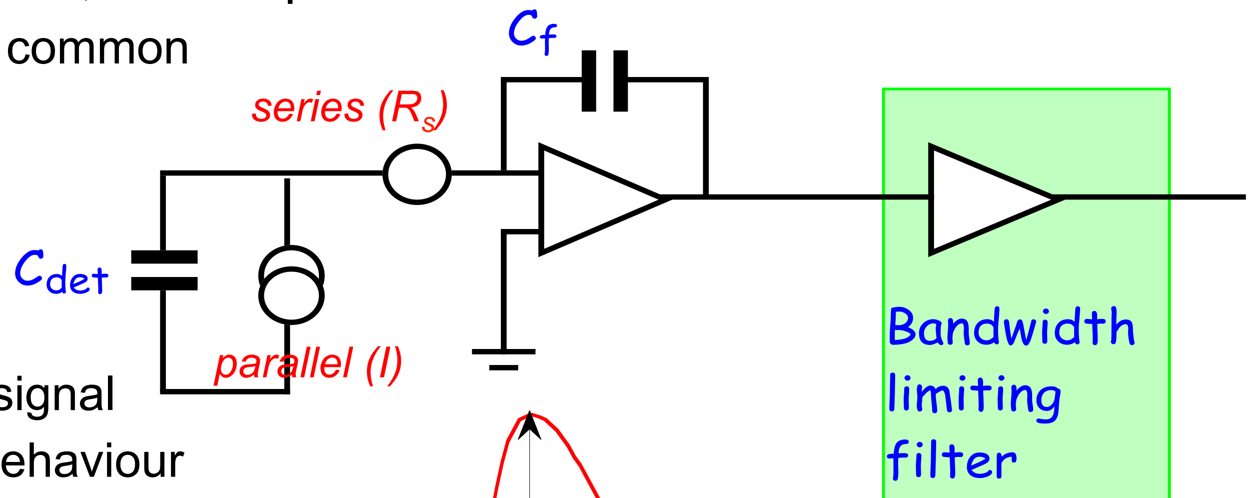
- with feedback resistor R_f

  $v_{out}(t) \approx -(Q/C_f)\exp(-t/\tau) \quad \tau = R_f C_f$

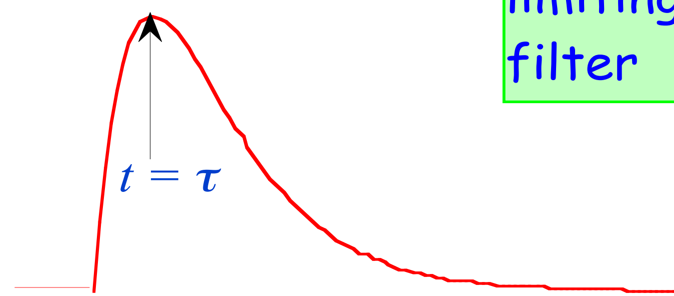


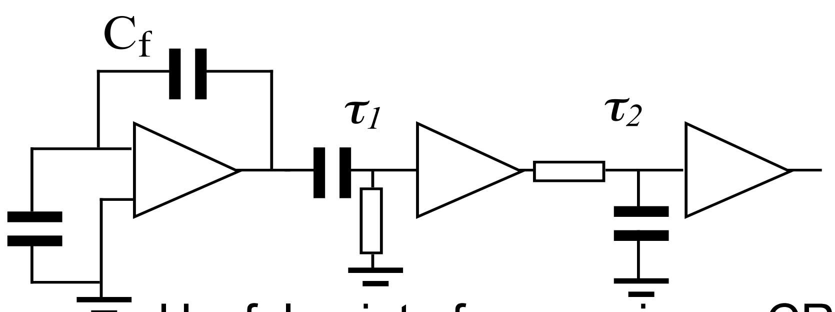
Signal processing

- If noise sources are defined, their impact can be calculated
  - **pulse shaping** is most common



  - **sampling** an amplifier signal can produce equivalent behaviour





  - Useful point of comparison: CR-RC filter

numerical result for many cases

$$ENC^2 = \frac{e^2}{8}\left(\frac{4kTR_s C_{tot}^2}{\tau} + 2eI\tau\right)$$

Some numerical values

- An approximate numerical value

$$ENC^2[e^2] \approx \left(\frac{24^2 R_s[k\Omega] C_{tot}^2[pF]}{\tau[\mu s]} + 100^2 I\tau[\mu s] \right)$$

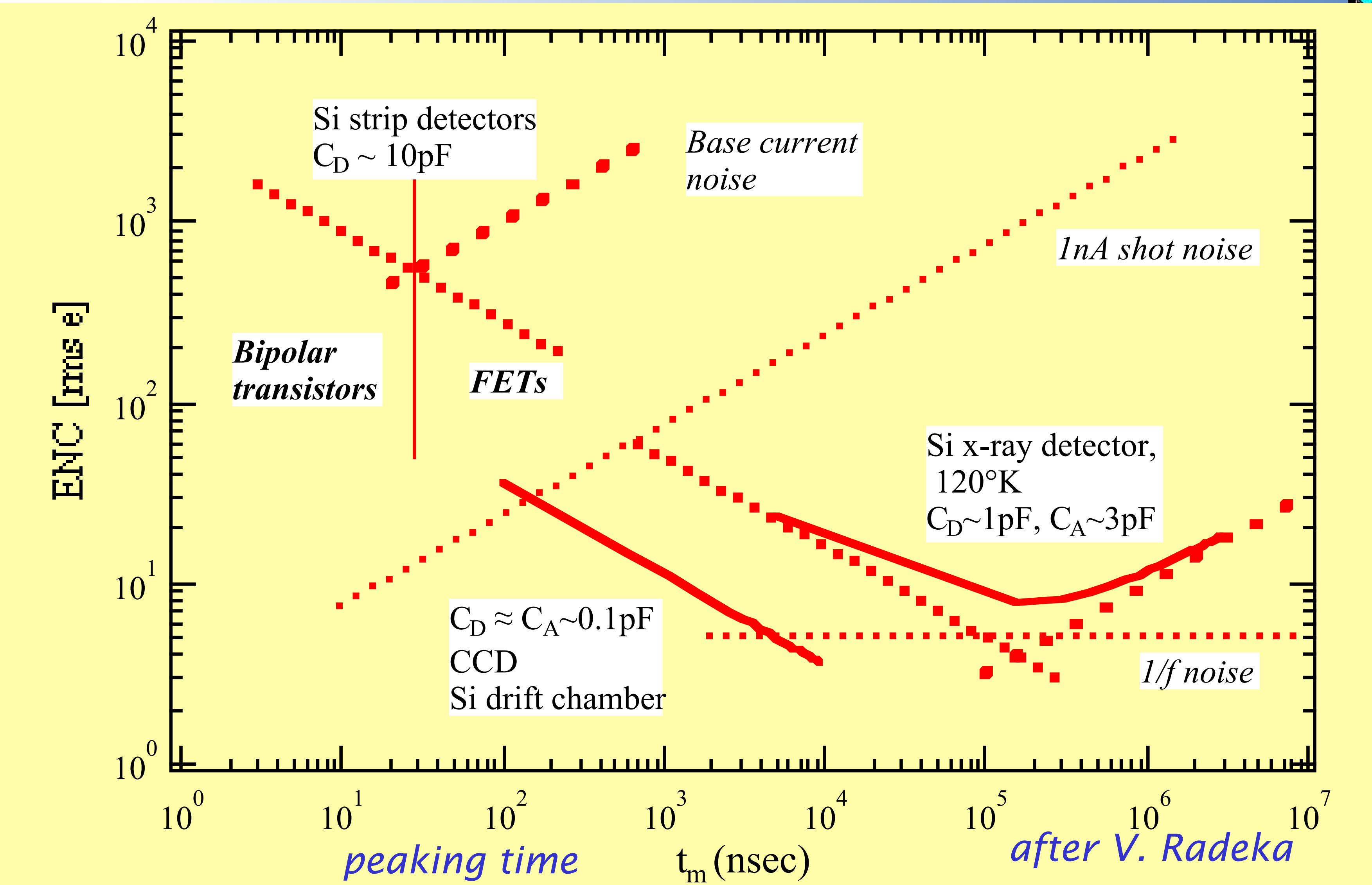
- using CR-RC filter, ignoring 1/f noise

ie

I = 1nA τ = 1μs $ENC_p \approx$ 100e

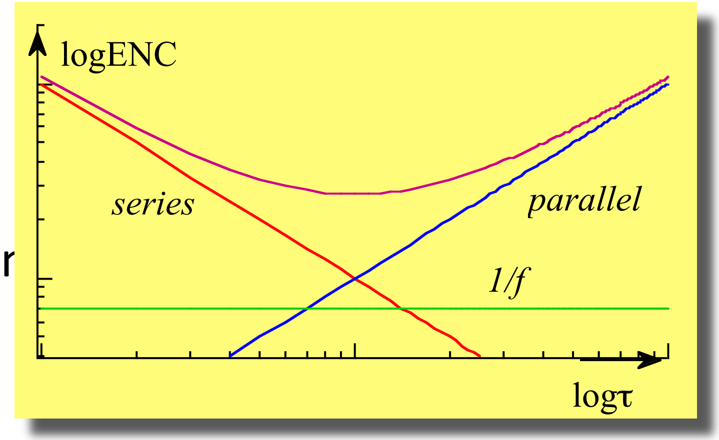
R_s = 10Ω C = 10pF τ = 1μs $ENC_s \approx$ 24e

Noise vs technology



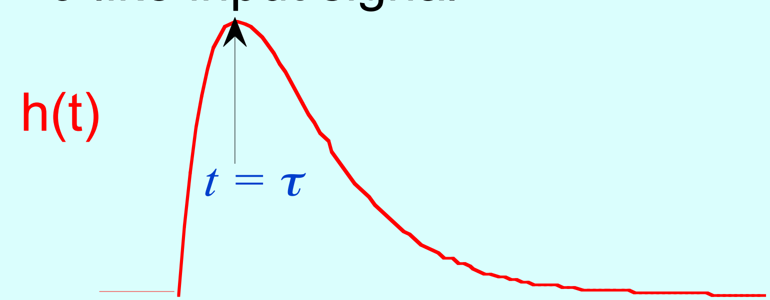
Noise calculations

- Summary of principles
  - integrate signal spectrum over bandwidth
  - integrate noise <u>in quadrature</u> over bandwidth
  - computation can be done in time or frequency domain
    but simplifications are often possible



- System noise can be computed with knowledge of impulse response and noise sources
  - $\sigma^2 \sim e_n^2 C^2 \int [h'(t)]^2\, dt + i_n^2 \int [h(t)]^2\, dt$
  - provided noise sources e_n & i_n are white
  - *properly normalise to signal of unit amplitude*

Impulse response =
output of system following fast δ-like input signal



Campbell's theorem

Omit

- Most amplifying systems designed to be linear

  $S(t) = S_1(t) + S_2(t) + S_3(t) + \ldots$

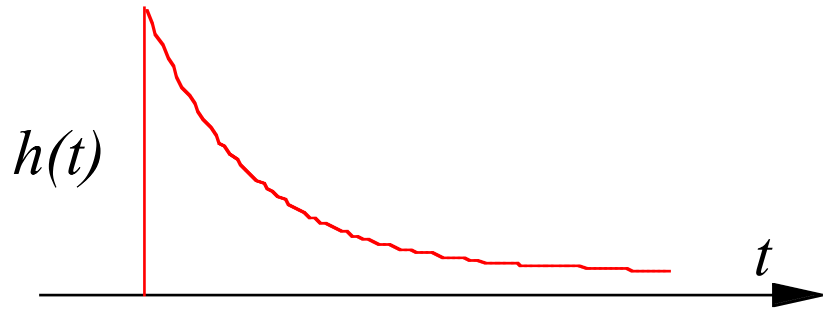
- Impulse response

  $h(t)$ = response to δ

- Transfer function

  $H(\omega) = v_{out}(\omega)/v_{in}(\omega) = \int_{-\infty}^{\infty} h(t).e^{-j\omega t}\, dt$

  ie impulse response h(t) and transfer function $H(\omega)$ are Fourier pair



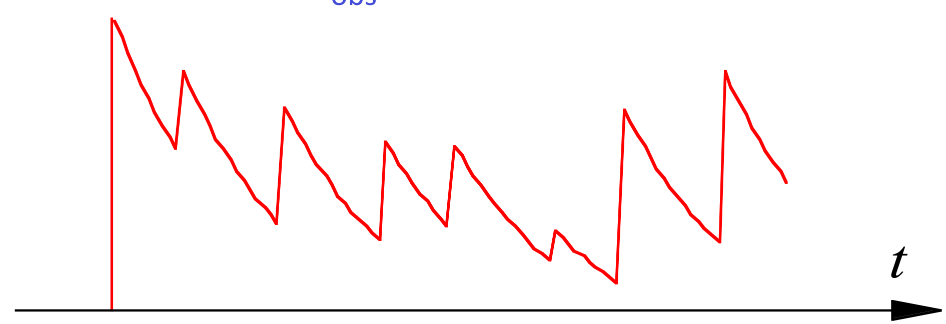
- In a linear system, if random impulses occur at rate n

  average response $\langle v \rangle = n \int_{-\infty}^{t_{obs}} h(t)dt$

  variance $\sigma^2 = n \int_{-\infty}^{t_{obs}} [h^2(t)]dt$

  so $\sigma^2 = n \int_{-\infty}^{\infty} h^2(t)\, dt = n \int_{-\infty}^{\infty} |H(\omega)|^2\, df$

i.e. sum all pulses preceding time, t_{obs}, of observation



"Rules" of low noise amplifier systems

Omit

- Combine uncorrelated noise sources in quadrature

  $e^2_{tot} = e_1^{\,2} + e_2^{\,2} + e_3^{\,2} + \ldots + i_n^{\,2} R^2 + \ldots$

  follows from Campbell's theorem

  consider as combinations of gaussian distributions

- First stage of amplifier dominates

  noise originates at input

  input transistor is most important - defines noise in most cases

- Noise is independent of amplifier gain or input impedance

  so noise can be referred to input

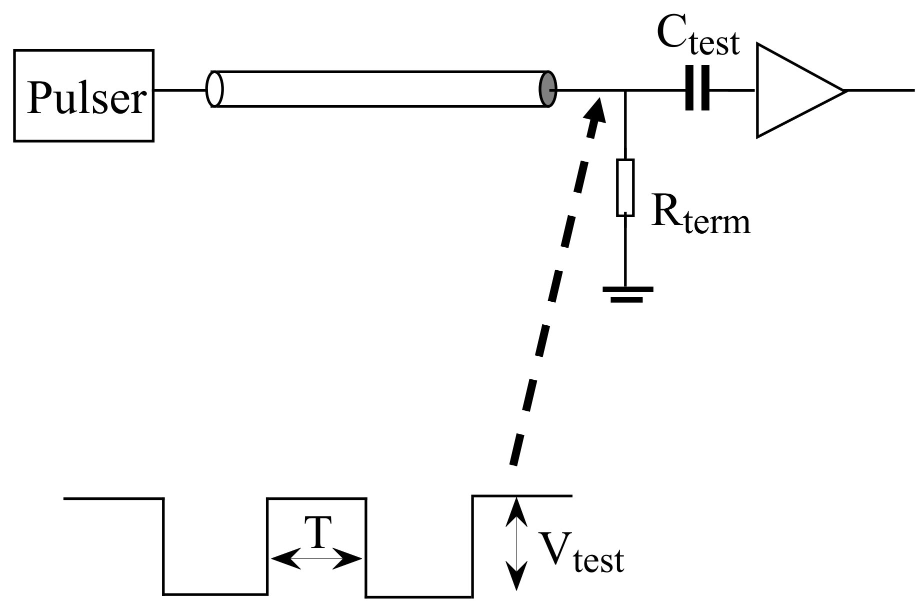
- In real systems both are approximations - but normally good ones

  so often sufficient to focus on input device

Equivalent Noise Charge

- Systems need to be calibrated:
- ENC is the signal magnitude which produces an output amplitude equal to the r.m.s. noise
  - *ideally measure in some absolute units - e, coul, keV(Si),… rather than ADC channels*
- to calibrate
  - inject charge and look at result
    - eg x-ray signal of known size
    - or electronic test pulse
      - *preferably in-situ*
  - measure V_{out} for known Q_{in}

$$Q_{test} = C_{test} V_{test} = Ne$$



Noise sources

- Thermal noise
  - Quantum-statistical phenomenon; carriers in constant thermal motion
    - macroscopic fluctuations in electrical state of system
  - Typically associated with input transistor or resistive components

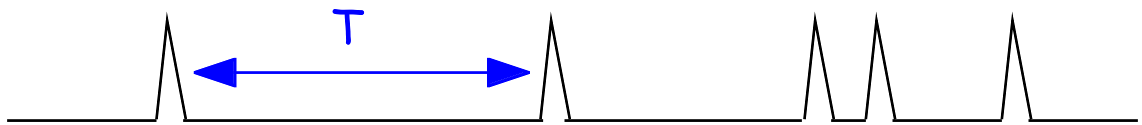
- Shot noise
  - Random fluctuations in DC current flow
  - Typically associated with sensor

- *1/f* noise
  - commonly associated with interface states in MOS electronics
  - Luckily, less important for high speed electronics

Shot noise

- Poisson fluctuations of charge carrier number

eg arrival of charges at electrode in system - induce charges on electrode



quantised in amplitude and time

- Examples

  electrons/holes crossing potential barrier in diode or transistor

  electron flow in vacuum tube

$< i_n^2 > = 2qI.\Delta f$ WHITE (NB notation e = q)

I = DC current

gaussian distribution of fluctuations in i

Thermal noise

Just note that this is needed to do calculations

- Einstein (1906) , Johnson, Nyquist (1928)

Mean voltage $\langle v \rangle = 0$

Variance $\langle v^2 \rangle = 4kT.R.\Delta f$ Δf = observing bandwidth

gaussian distribution of fluctuations in v

$\sigma(v) = \sqrt{\langle v^2 \rangle} = 1.3\ 10^{-10}\,(R.\Delta f)^{1/2}$ volts at 300K

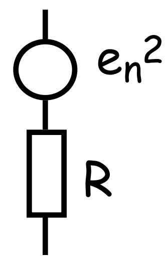
e.g. $R = 1M\Omega$ $\Delta f = 1Hz$ $\sigma(v) = 0.13\mu V$

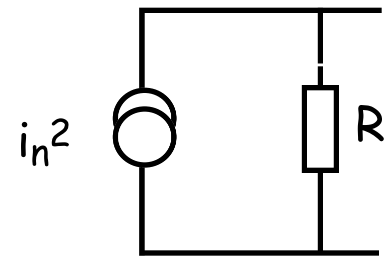
Noise power = $4kT.\Delta f$

independent of R & q independent of f - WHITE

- Circuit representations

Noise generator + noiseless resistance R





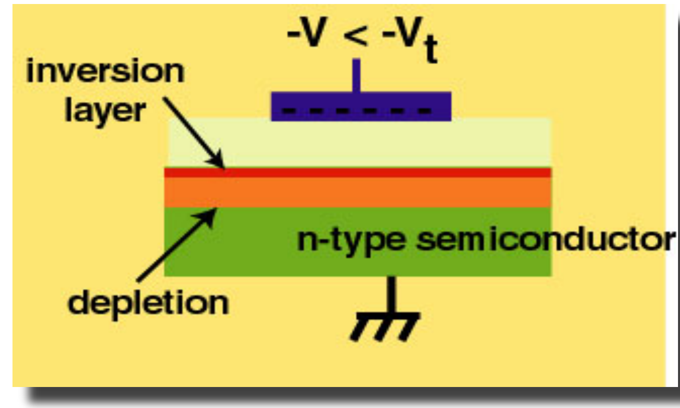
- Spectral densities

mean square noise voltage or current per unit frequency interval

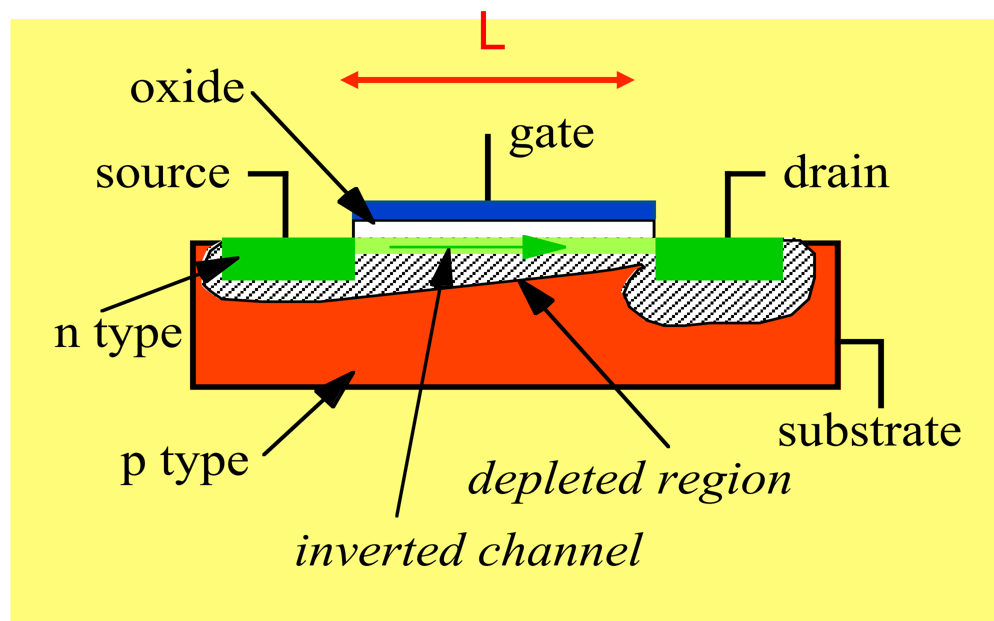
$w_V(f) = 4kTR$ (voltage) $w_I(f) = 4kT/R$ (current)

CMOS transistor

- Reminder of basic FET physics
  - bias "metal" gate to deplete substrate
  - beyond a certain threshold voltage, substrate does not deplete deeper
  - instead "inversion layer" created

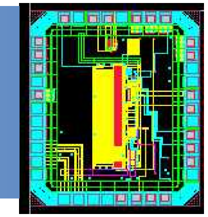


- Inversion layer
  - extremely shallow, at oxide-silicon interface
  - carriers mobile in applied field
- Transistor operation
  - Modulation of source-drain current via V_{gate}



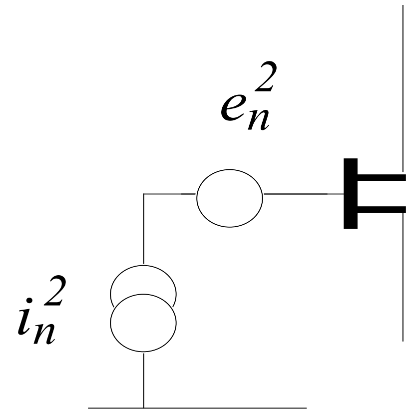
Noise in MOS circuits

Omit



- Gate shot noise is negligible *insulating gate and no current*
- Thermal noise voltage from channel
  - $$e_n^2 = 4kT\gamma(\frac{2}{3g_m})\Delta f$$

    γ = *excess noise factor ~ 1*



- Transconductance
  - $C_{ox} = \varepsilon_{ox} / t_{ox}$
  - W/L = transistor width/length

$$g_m = \sqrt{2\mu C_{ox} I_{DS}\left(\frac{W}{L}\right)}$$

C = capacitance
T = temperature
Δf = bandwidth
μ = mobility (v/E)

- *1/f* noise usually unimportant (for LHC)
- Implications
  - To achieve low noise, aim for large W/L and large (tolerable) I_{DS}
  - but $C_{amp} = C_{ox}WL$ and require capacitance matching: $C_{amp} \approx C_{det}/3$
  - Mobility is also T dependent, influencing noise and speed $\mu(T) \sim T^{-3/2}$

Noise spectra

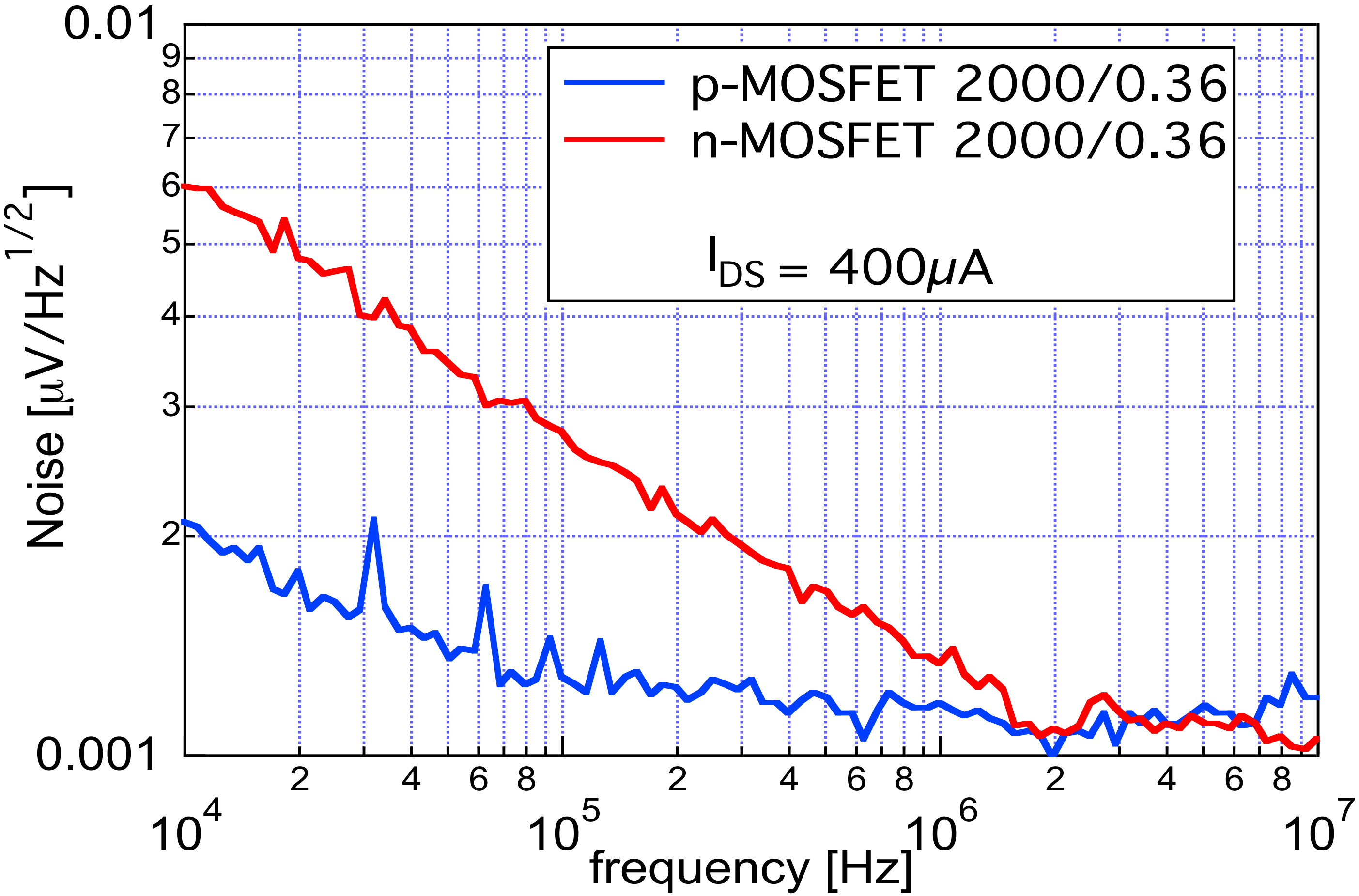
- pMOS preferred for lower 1/f noise

- 3dB bandwidth
- eg LHC

Δf_{3db} = 2.6 - 15.4MHz

  - CR-RC pulse shaping
  - τ = 25ns

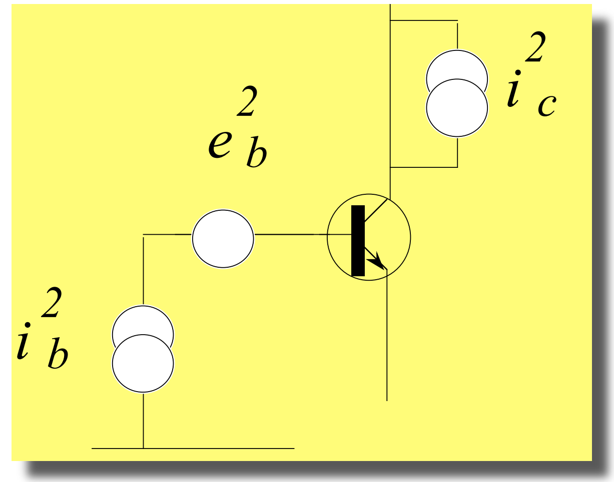
- or 1/f noise might be an issue



Bipolar transistor noise

Omit

- Basic sources are
  - Shot noise in I_C $\quad i_c^2 = 2eI_C\Delta f$
  - Shot noise in I_B $\quad i_b^2 = 2eI_B\Delta f$
  - Thermal noise in base & contacts
    - $e_b^2 = 4kT \, . \, r_{bb'} \, .\Delta f$



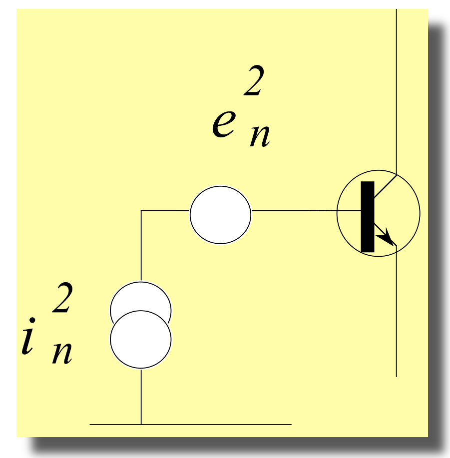
- Reconfigure so that noise sources are external

  which then shows that

  i^2_n and e^2_n are correlated,

  ie can't reduce both simultaneously

  - so achievable range of noise is limited and happens to provide best performance for high speed applications
  - however bipolar noise determined mainly by currents
    - so easy to estimate

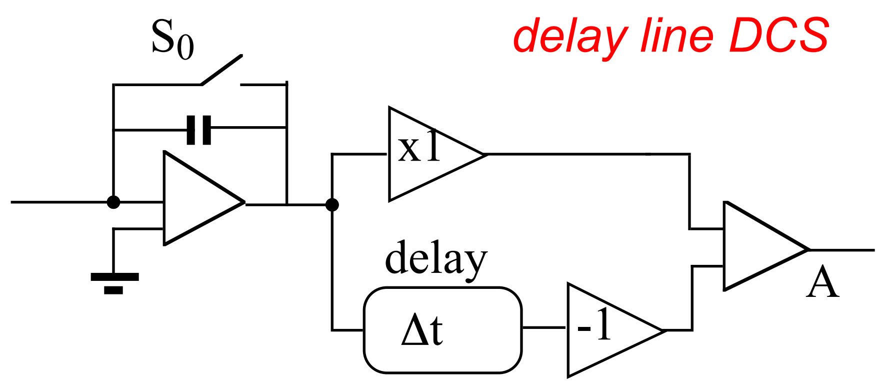


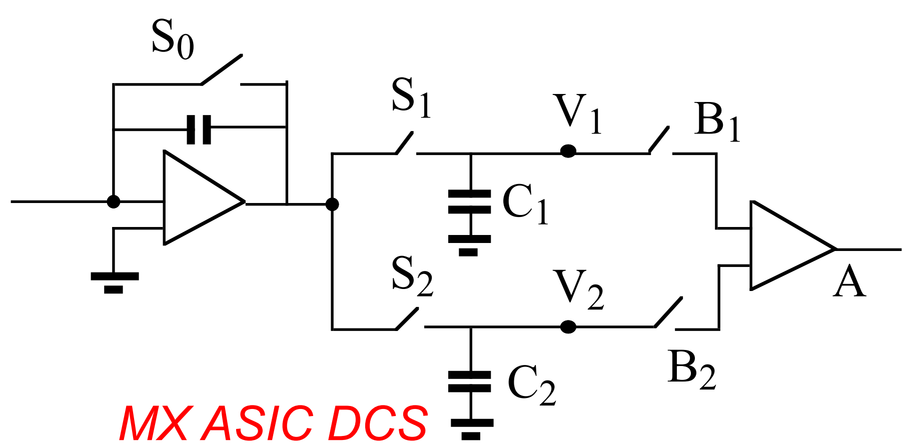
Time variant filters - sampling

- Alternative to pulse shaping
  - filters based on summation
  - easy to implement in several technologies
  - eg. typically switched capacitor filters
  - but also delay-line or digital possible
    - beware of extra noise issues

  - based on sample & hold
    - e.g. double correlated sampling

- Switched capacitor design convenient for CMOS
  - accurate capacitances (ratios)
  - MOSFET switches

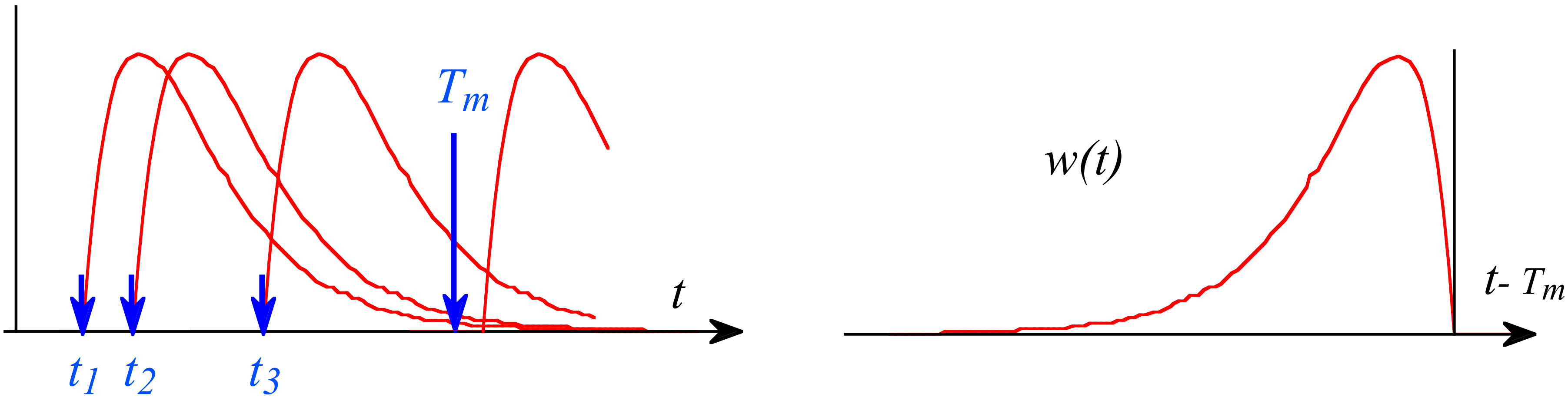




Weighting function

Omit

- How to calculate noise of time variant systems?
  - What output is produced at T_m by impulse at time t?
  - consider all t - defines weighting function



- Time invariant filter *w(t)* is mirror image of *h(t)*

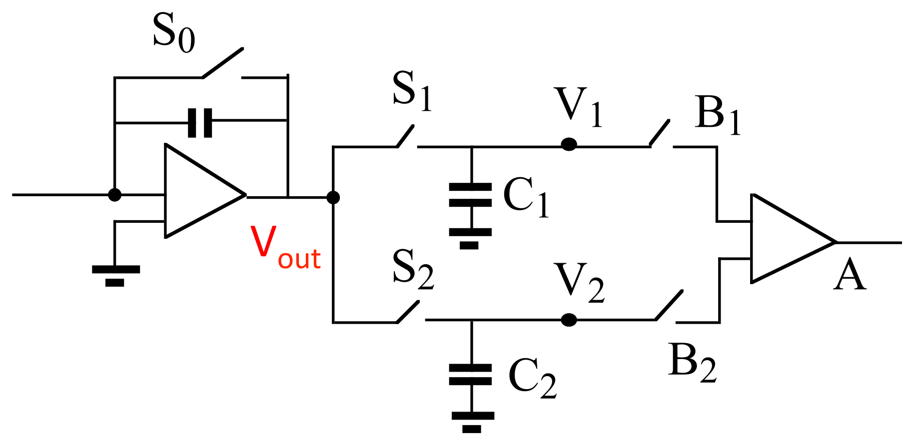
- Noise calculation $ENC^2 = e_n^2 C^2 \int [w'(t)]^2 dt + i_n^2 \int [w(t)]^2 dt$

Double correlated sampling

- Sample & hold method

initially switches S_0 B_1 B_2 open, S_1 S_2 closed

switch S_0 is Reset



V_{out} = output from charge sensitive preamplifier

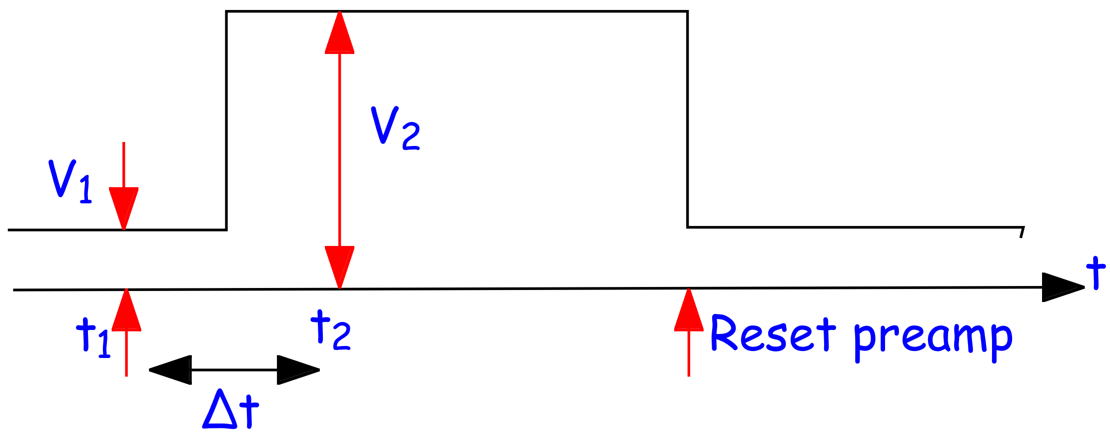
open S_1 : preserves V_{out} on C_1

after time Δt open S_2 : preserves V_{out} on C_2

then, close B_1 and B_2:

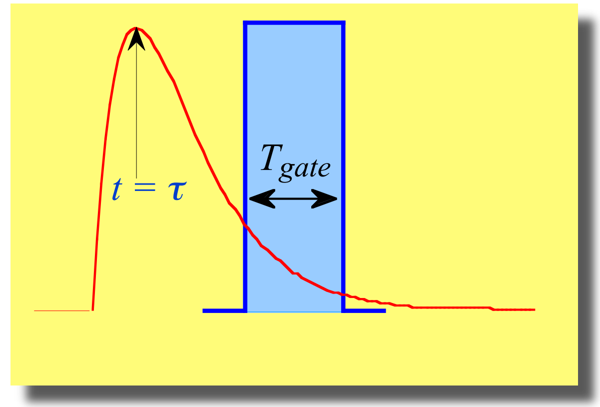
output $A = V_1 - V_2$

reset preamp later

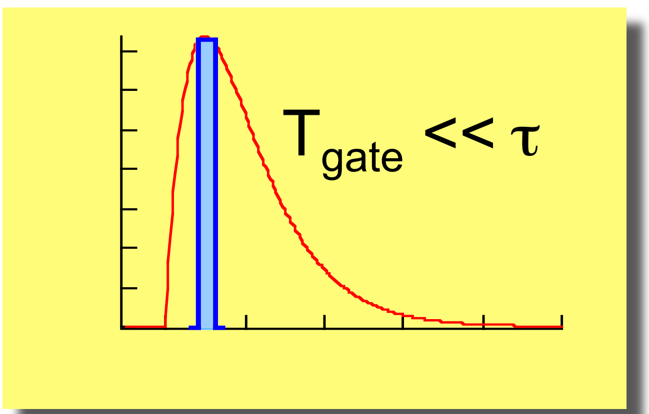


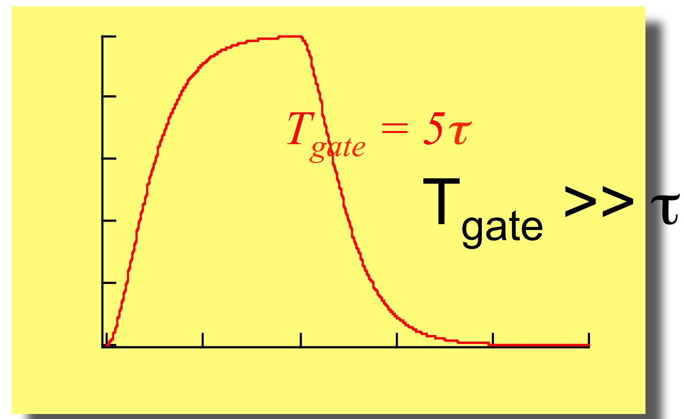
- need to know when signal will arrive!

CR-RC pulse + integrating ADC



- Example of time-variant filter..
- Convolution of pulse shape with gate
  - $w(t) = h(t) * g_{gate}(t)$
  - *(ignoring t reflection)*
  - examples





similar to peak sensing ADC
gated at peak!

new, wider weighting function
recompute noise integrals

ADC may change filtering and **increase** or **decrease** noise

Digitisation noise

- Eventually need to convert signal to a number

  quantisation (rounding) of number = noise source

  the more precise the digitisation, the smaller the noise

- After digitisation all that is known is that

  signal was between $-\Delta/2$ and $\Delta/2$

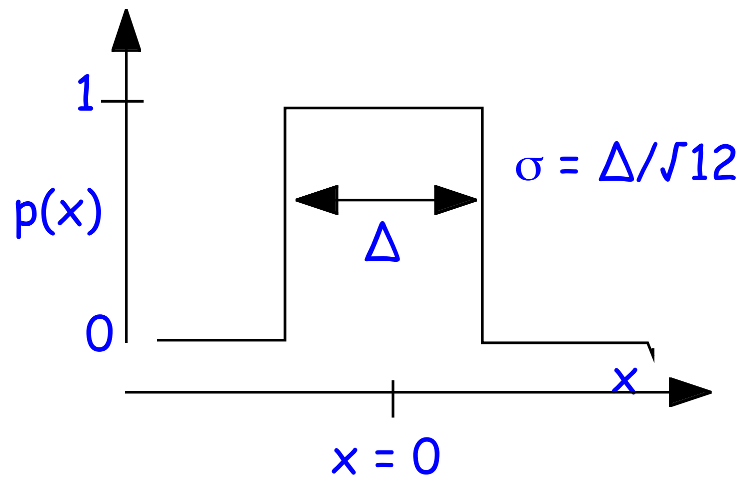
  $\langle x \rangle = \int x.p(x).dx / \int p(x).dx$

  $\sigma^2 = \langle x^2 \rangle = \int x^2.p(x).dx / \int p(x).dx$

  $\int p(x).dx \quad = \int_{-\Delta/2}^{\Delta/2} dx = [x]_{-\Delta/2}^{\Delta/2} = \Delta$

  $\int x^2.p(x).dx \quad = \int_{-\Delta/2}^{\Delta/2} x^2.dx = [x^3/3]_{-\Delta/2}^{\Delta/2} = 2\Delta^3/24$

  so $\sigma^2 = \Delta^2/12$



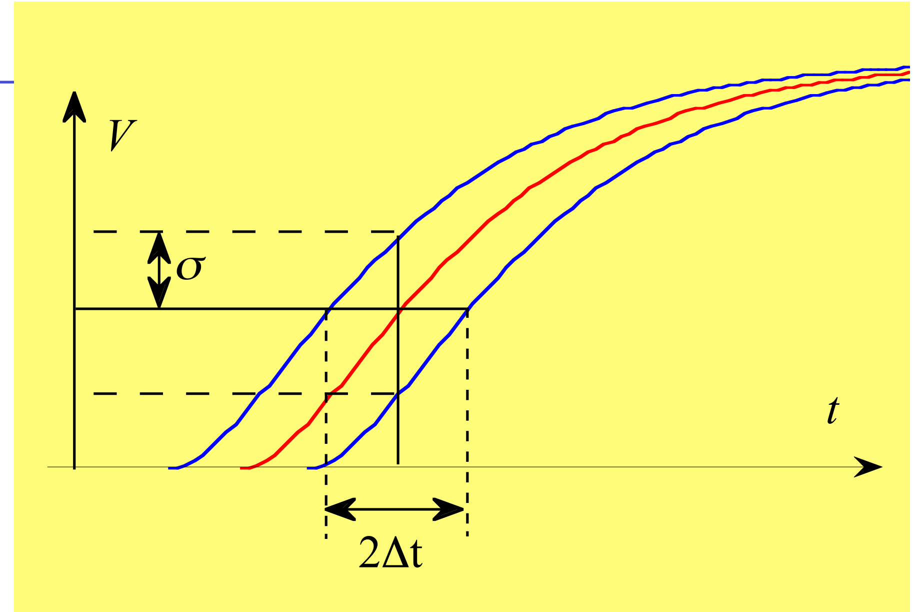
- ie statistical noise which is proportional to digitisation unit

Time measurements and noise

- When did signal cross threshold ?

  noise causes "jitter"

  $\Delta t = \sigma_{noise}/(dV/dt)$



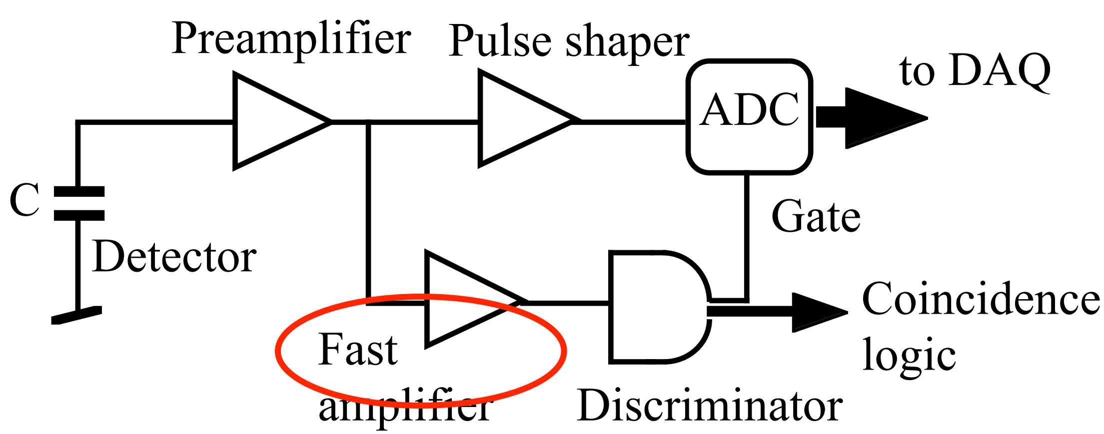
- compromise between

  bandwidth (increased dV/dt)

  noise (decreased bandwidth)

- limits systems where preamplifier pulse used to generate trigger

  eg x-ray detection



- typical preamp response

  $V = V_{max}(1-e^{-t/\tau_{rise}})$

  so $\Delta t \approx \sigma_{noise}\tau_{rise}/ V_{max}$ $t << \tau$