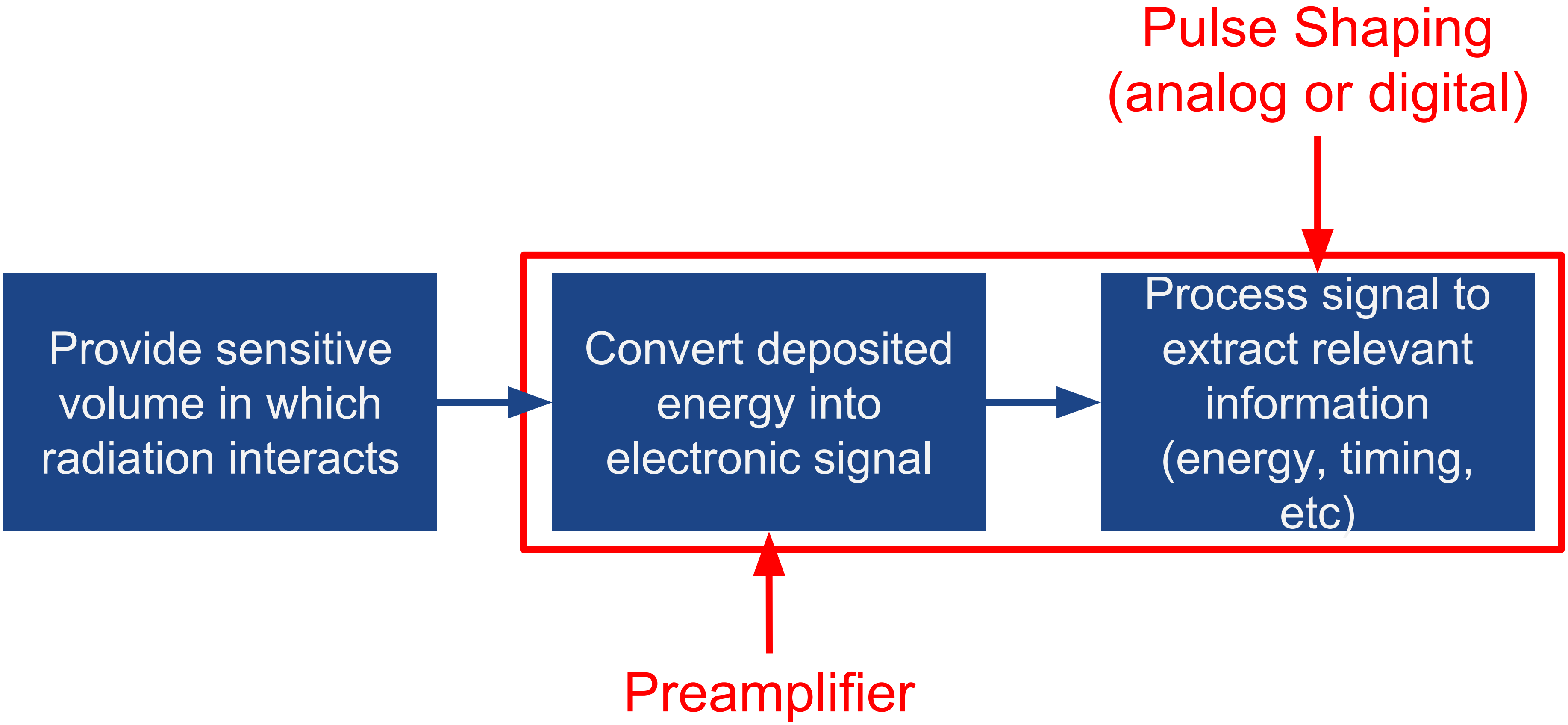
Pulse Formation and Shaping



Pulse Shaping (analog or digital)

Provide sensitive volume in which radiation interacts

Convert deposited energy into electronic signal

Process signal to extract relevant information (energy, timing, etc)

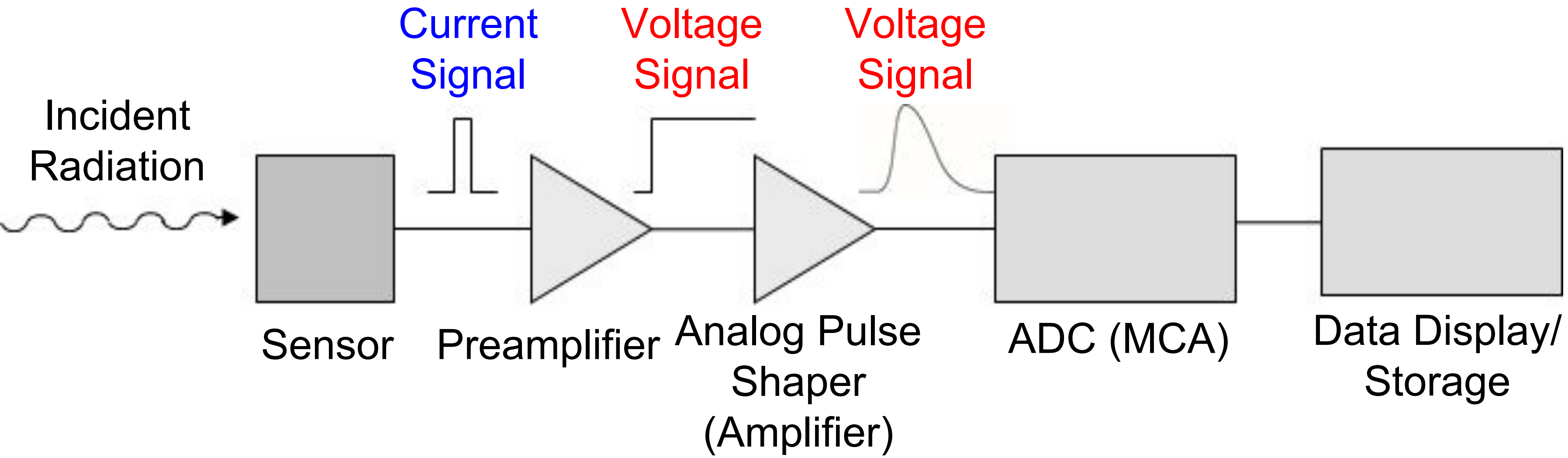
Preamplifier

Detector Signal from Single Event

- Short current pulse (ns, μs) induced on electrode by each charge-generating event in detector
- Pulse shape depends on detector material properties, charge carrier mobility, electric field, geometry (weighting field), etc.
    - May contain information about interaction position in the detector
- Total charge delivered in the current pulse contains information about energy deposition or creating interaction
- The main goal in radiation **spectroscopy** is to measure the total charge generated by each deposition event
    - There are other applications where the goals may be different, e.g. particle tracking detectors
    - Design of signal-sensing circuits dictated by application

Spectroscopy Signal Processing Chain

Analog Pulse Processing Chain


Current Signal

Voltage Signal

Voltage Signal

Incident Radiation

Sensor

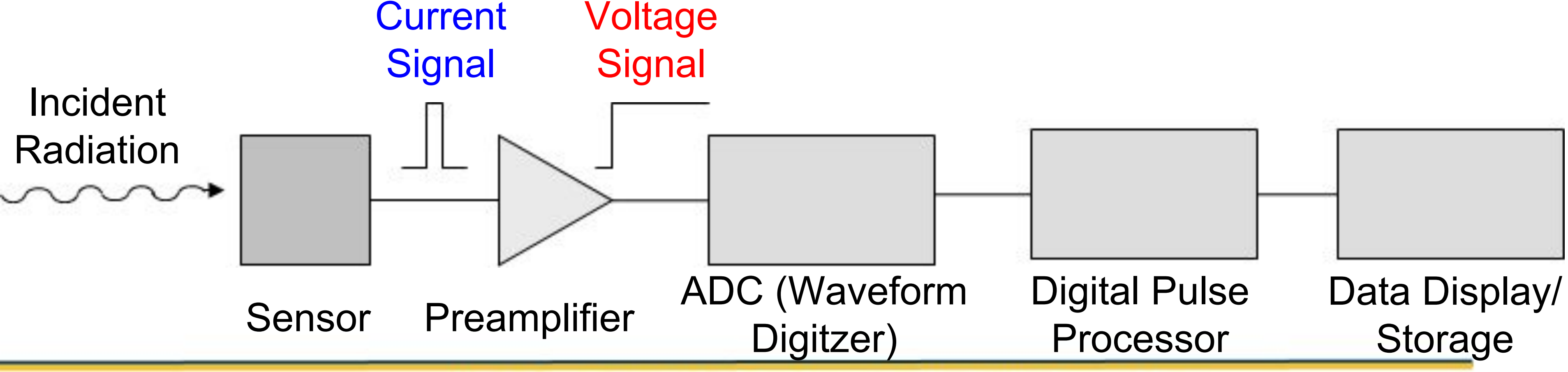
Preamplifier

Analog Pulse Shaper (Amplifier)

ADC (MCA)

Data Display/ Storage

Digital Pulse Processing Chain


Current Signal

Voltage Signal

Incident Radiation

Sensor

Preamplifier

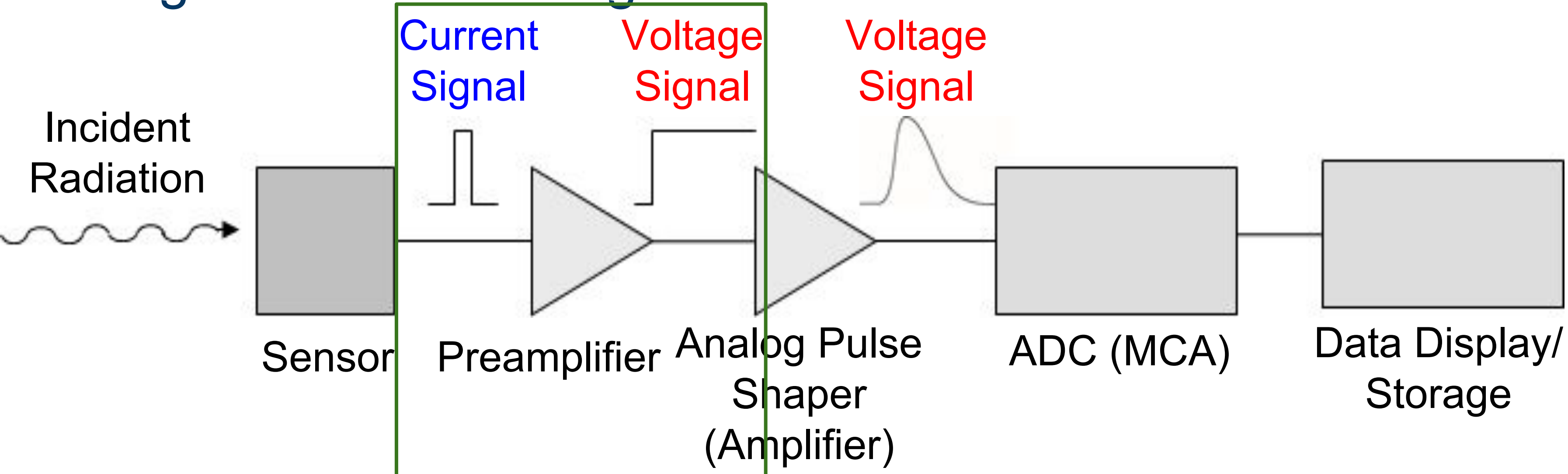
ADC (Waveform Digitzer)

Digital Pulse Processor

Data Display/ Storage

Spectroscopy Signal Processing Chain

Analog Pulse Processing Chain



Current Signal

Voltage Signal

Voltage Signal

Incident Radiation

Sensor

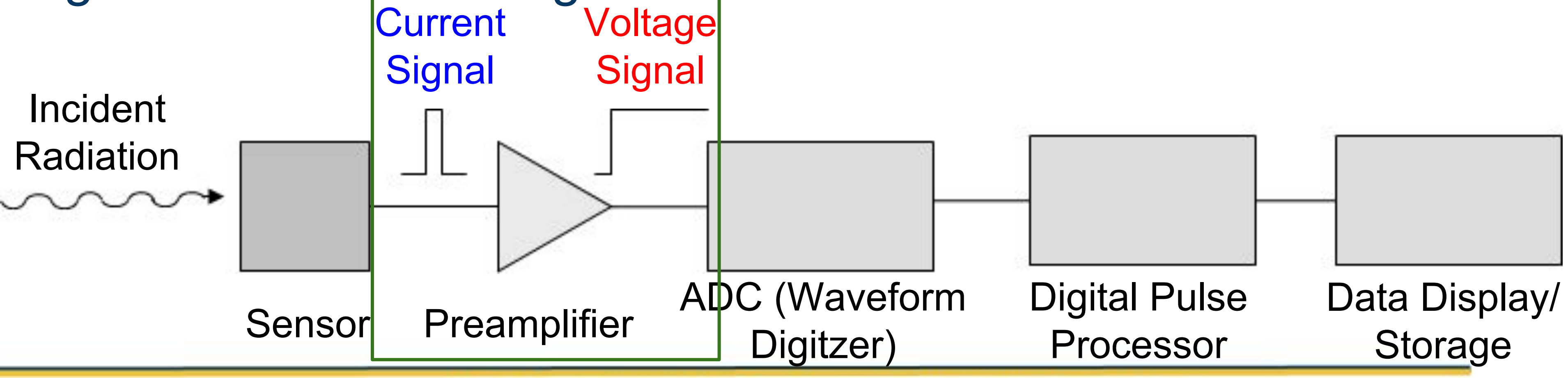
Preamplifier

Analog Pulse Shaper (Amplifier)

ADC (MCA)

Data Display/ Storage

Digital Pulse Processing Chain



Current Signal

Voltage Signal

Incident Radiation

Sensor

Preamplifier

ADC (Waveform Digitzer)

Digital Pulse Processor

Data Display/ Storage

Preamplifier Electronics

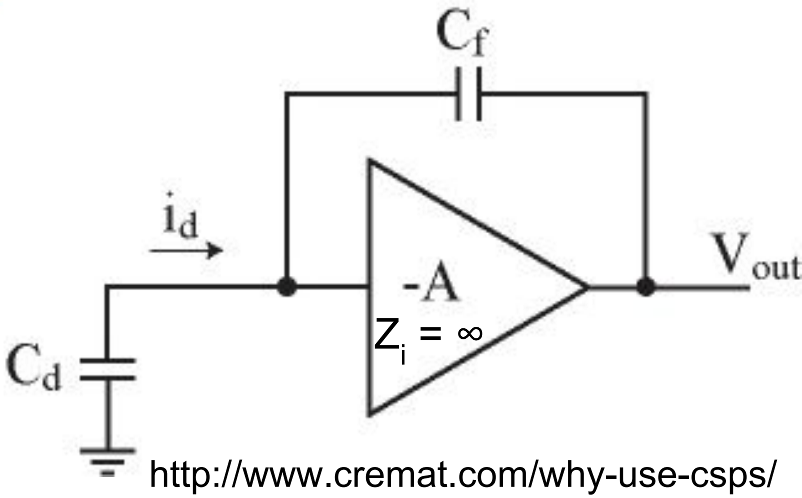
- Total charge in detector current pulse is proportional to energy deposited by interaction in detector.
  - Need to integrate current signal: Preamplifier!

$$E \propto Q_s = \int i_s(t)\, dt$$

- Desired properties for spectroscopic preamplifiers:
  - Integrate all of the signal from detector
  - High gain (CSA: V/pC)
  - Response independent of detector
  - Low noise, stable
- Further considerations based on system/application
  - Event rate, multichannel detectors, etc.
- N.B. “Preamplifier” has more to do with position in the signal chain than its role in “amplification”

Charge Sensitive Preamplifier I

- Active integrator w/ negative feedback
  - Input impedance $Z_i \rightarrow \infty$
    - No signal current through amplifier input
  - High open-loop gain (A is large)



http://www.cremat.com/why-use-csps/

Voltage difference across C_f: $v_f = (A+1)\,v_i$

$\Rightarrow$ Charge deposited on C_f: $Q_f = C_f v_f = C_f (A+1)\, v_i$

$Q_i = Q_f$ (since $Z_i = \infty$)

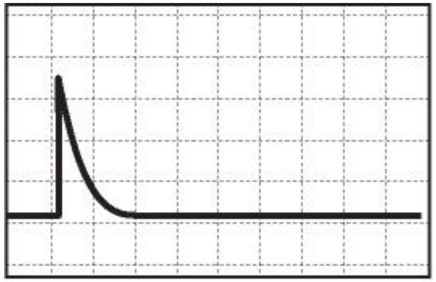
$\Rightarrow$ Effective input capacitance

$$C_i = \frac{Q_i}{v_i} = C_f (A+1)$$

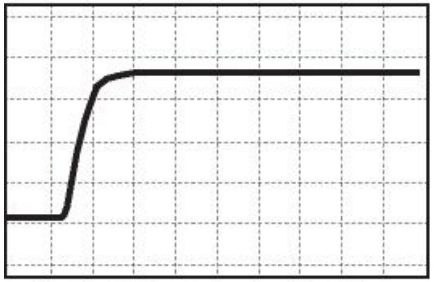
Gain

$$A_Q = \frac{dV_o}{dQ_i} = \frac{A \cdot v_i}{C_i \cdot v_i} = \frac{A}{C_i} = \frac{A}{A+1} \cdot \frac{1}{C_f} \approx \frac{1}{C_f} \quad (A >> 1)$$

From Spieler



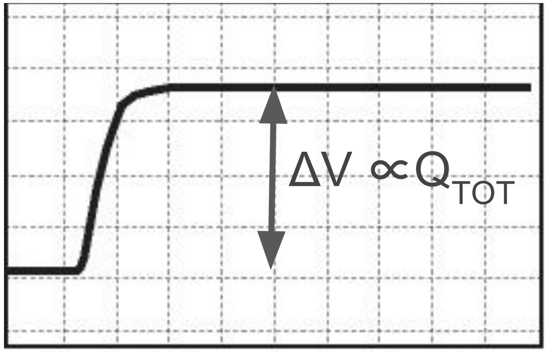
$i_d(t)$: detector current pulse: 10ns/div



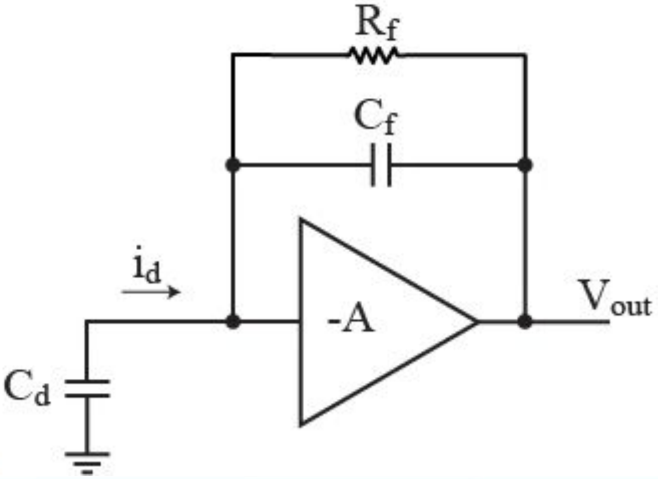
$V_{out}(t)$: CSP output pulse: 10ns/div

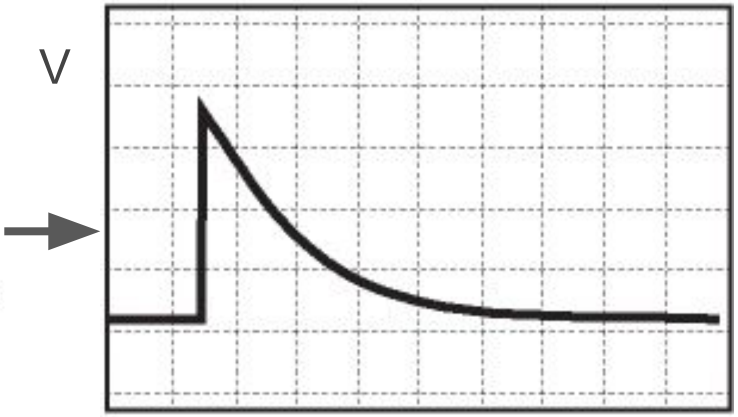
Charge Sensitive Preamplifier II

- Magnitude of voltage impulse $\propto$ total charge
- Rising edge contains additional information
    - ○ Timing
    - ○ Position sensitivity
- Resistive feedback
    - ○ Discharge back to baseline
    - ○ $\tau = R_f C_f >> t_{collection}$



$V_{out}(t)$: CSP output pulse: 10ns/div

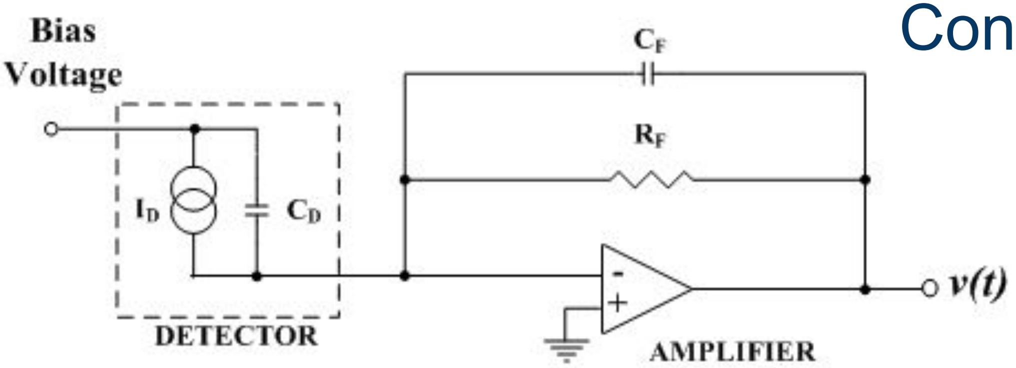




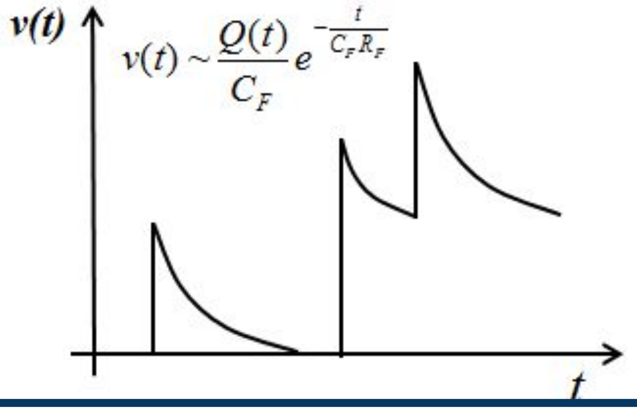
CSP output pulse: 100µs/div

Charge Reset

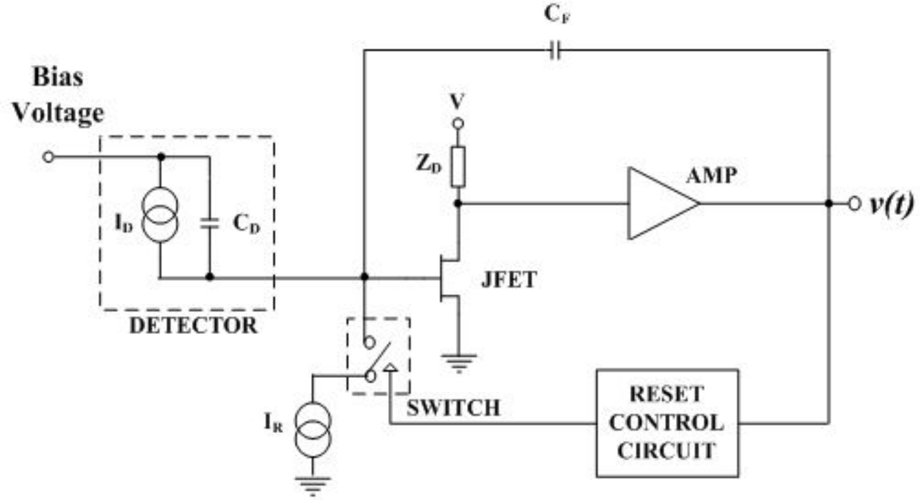
- Continuous (passive) reset may not be ideal
  - High rates can cause DC voltage to exceed supply: “lock-up”
  - Thermal noise in R_f bad for ultra-low noise applications



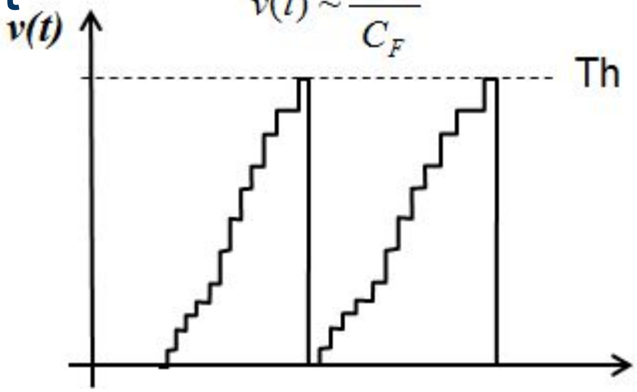
Cont. Reset



$$v(t) \sim \frac{Q(t)}{C_F} e^{-\frac{t}{C_F R_F}}$$



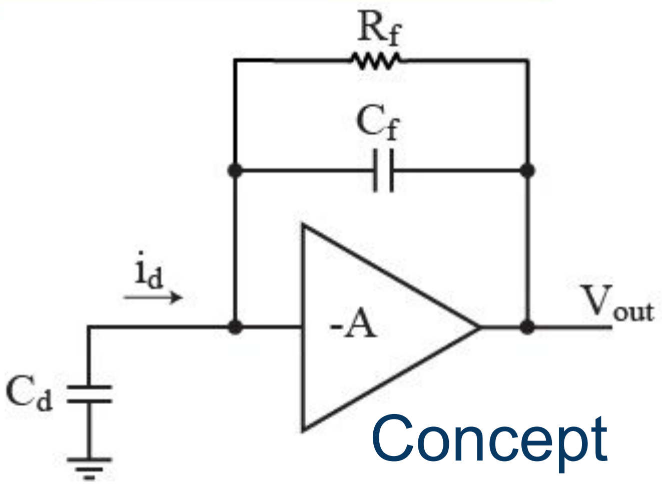
Pulsed Reset



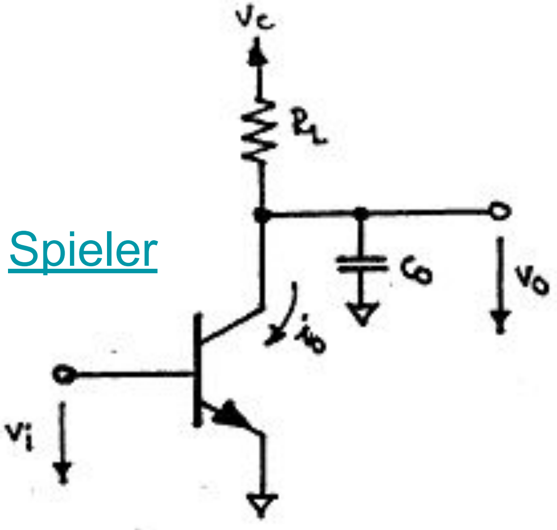
$$v(t) \sim \frac{Q(t)}{C_F}$$

Realistic Charge Sensitive Preamplifiers

- Cartoon illustrates operating principles, but assumes idealized components
    - Infinite input impedance, infinite speed
- Real CSA designs requires consideration of many more factors
    - Frequency response (impedance)
    - Timing characteristics (slew rate)
    - Matched input impedance for multichannel systems
    - Etc.
- Spieler is an excellent resource addressing these considerations



Concept

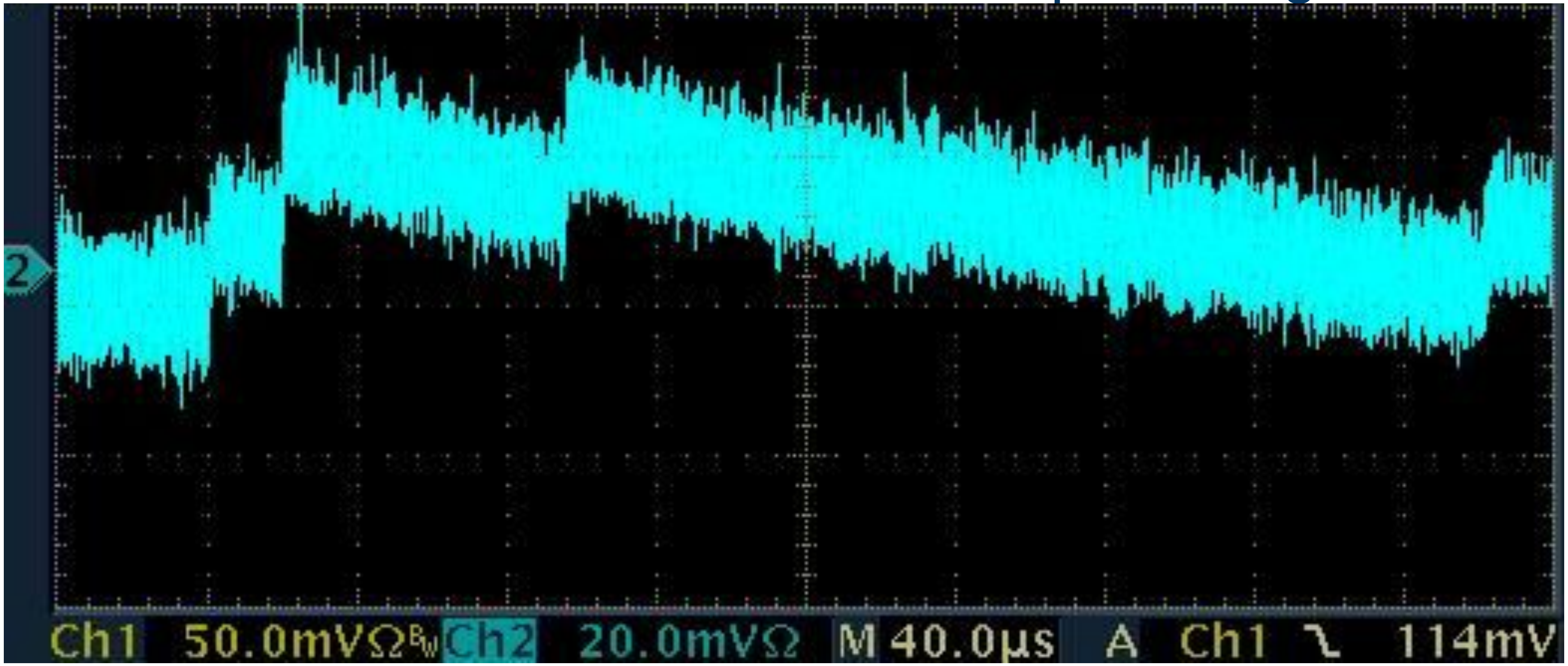


From Spieler

Implementation

Output of Preamplification Stage

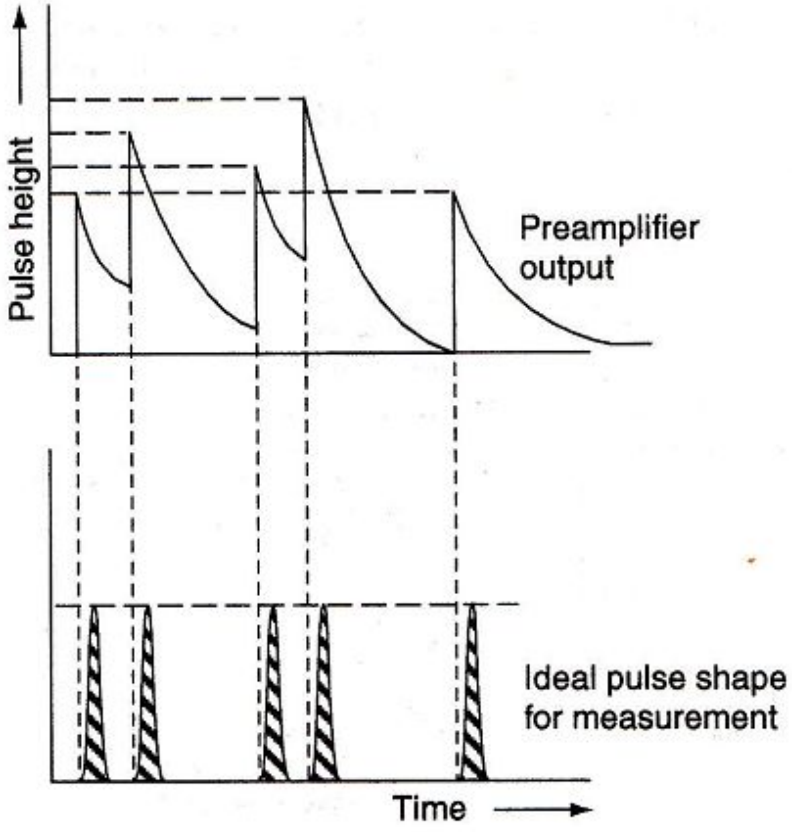
- Successfully converted detector signal to a step voltage, but…
    - Poor signal-to-noise ratio
    - Continuous reset preamps have long tails → pulse pileup
    - Tail pulse shape
- Not suitable for direct measurement of peak-height



http://www.cremat.com/why-use-csps/

Pulse Shaping I

- Spectroscopic information in magnitude of voltage step from preamplifier
  - Pulse height ∝ energy absorbed
- Maximize SNR
  - minimize noise contributions to energy resolution
- Optimum shaping depends on:
  - Noise spectrum for system
  - Requirements for pile-up free counting
- N.B. the original shape of the signal is lost!
  - Pulse shape analysis

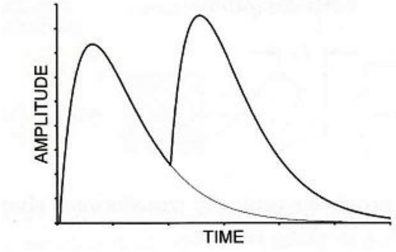


Gilmore 4.12

Pulse Shaping II

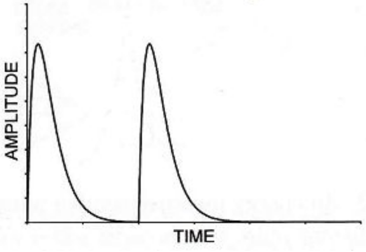
- Pulse shaping is full of trade-offs
- Example 1: SNR vs. Rate capability
  - SNR is often improved by limiting high-frequency response (LP filter)
  - This broadens the pulse, reducing rate capabilities
- Example 2: SNR vs. Peak Detect
  - Optimal pulse shape for maximizing SNR = cusp
  - Sharp peak not optimal for MCA
- “Optimum” shaping driven by application

Better HF Noise Filtering



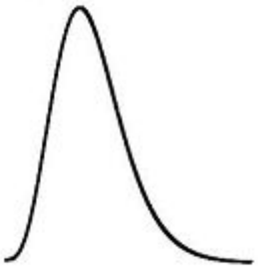
Increased Pileup

Worse HF Noise Filtering



Reduced Pulse Pileup

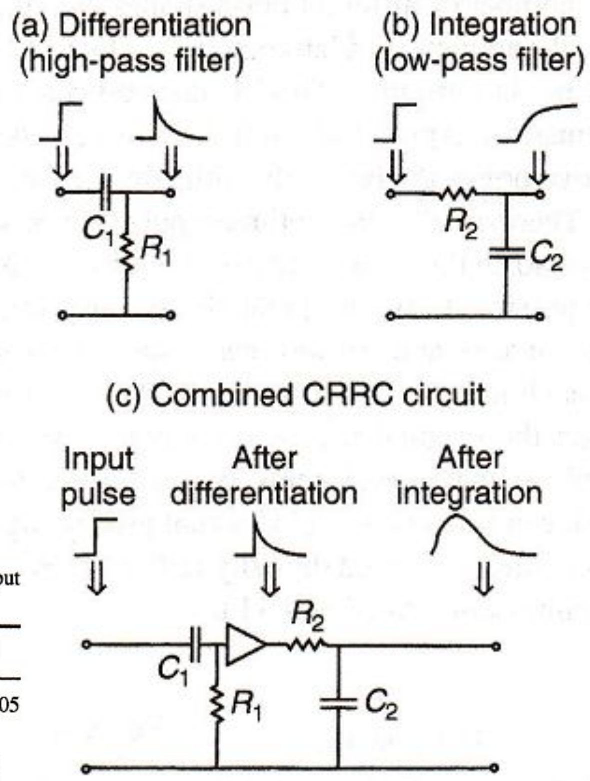
Theoretical Optimum for SNR



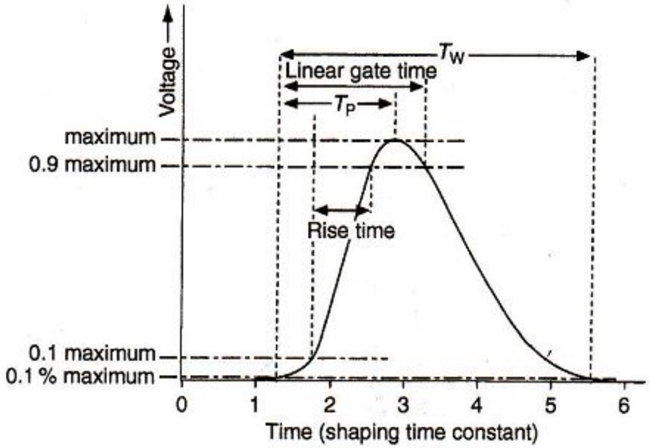
Finite peak width better for MCA

Review: Analog Signal Shaping

- Analog pulse shaper often implemented as CR-(RC)^n network
    - Unipolar, Gaussian-like (high n increases symmetry)
    - CR = differentiator (HP filt.)
    - RC = integrator (LP filt.)



Gilmore 4.13



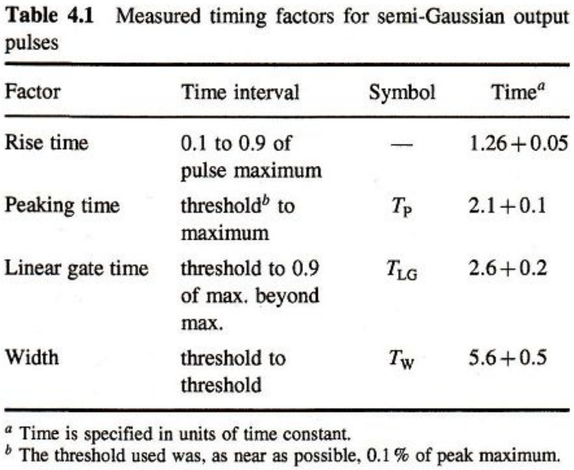


Table 4.1 Measured timing factors for semi-Gaussian output pulses

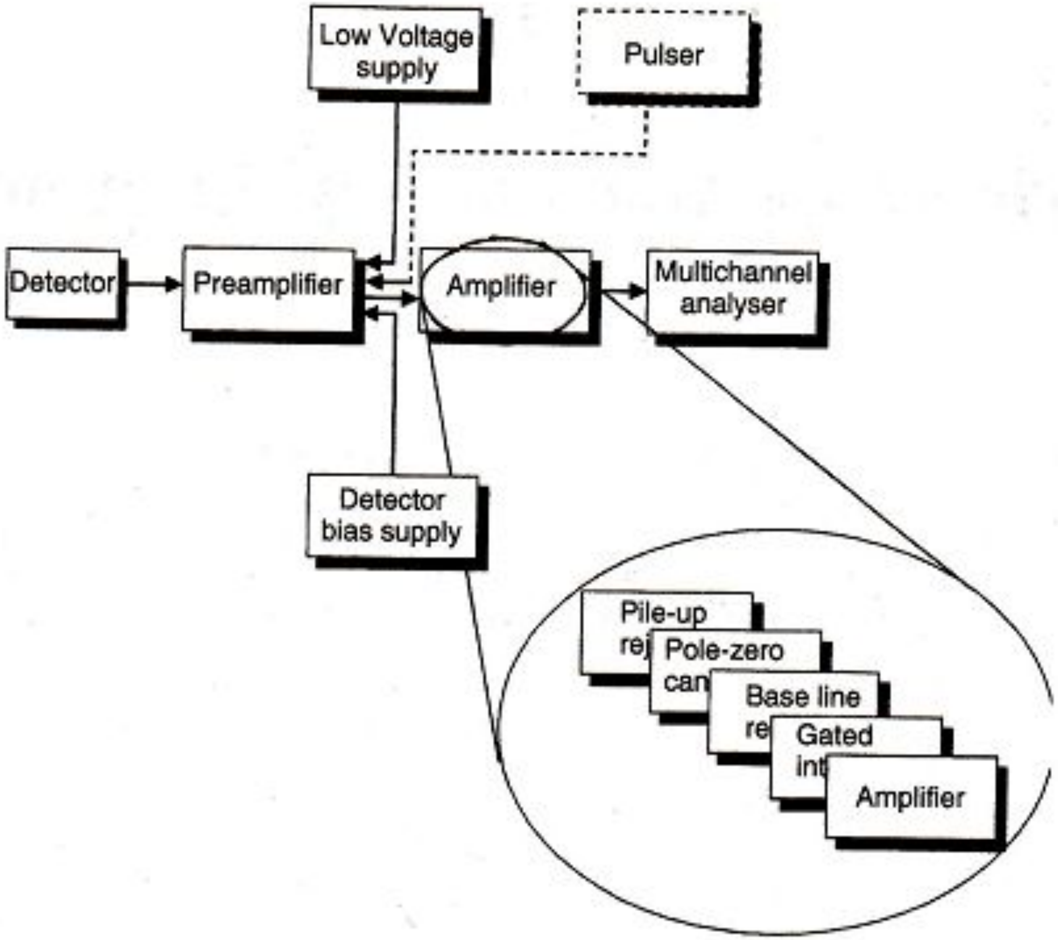
Factor	Time interval	Symbol	Time[a]
Rise time	0.1 to 0.9 of pulse maximum	—	1.26 + 0.05
Peaking time	threshold[b] to maximum	T_P	2.1 + 0.1
Linear gate time	threshold to 0.9 of max. beyond max.	T_{LG}	2.6 + 0.2
Width	threshold to threshold	T_W	5.6 + 0.5

[a] Time is specified in units of time constant.
[b] The threshold used was, as near as possible, 0.1 % of peak maximum.

Typical semi-gaussian pulse resulting from CR-RC^n shaping network. Listed times normalized by shaping time constant

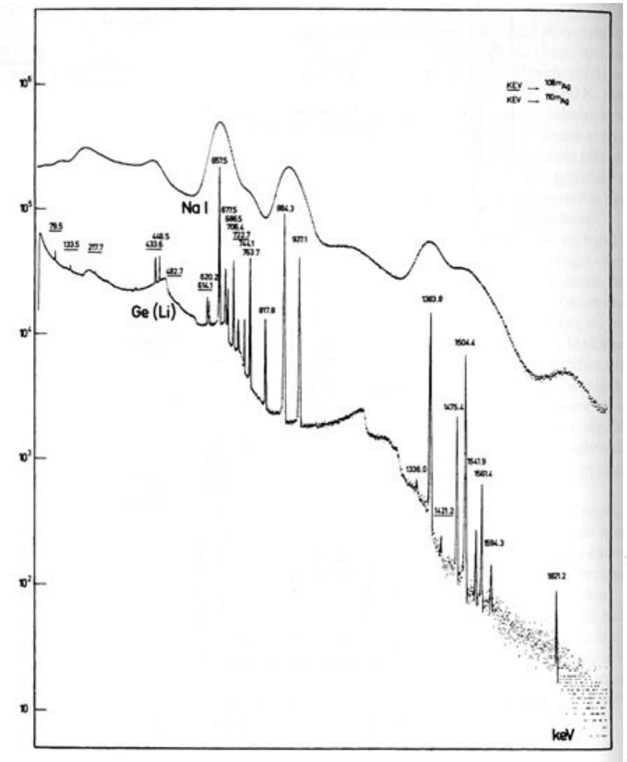
Review: Analog Signal Shaping

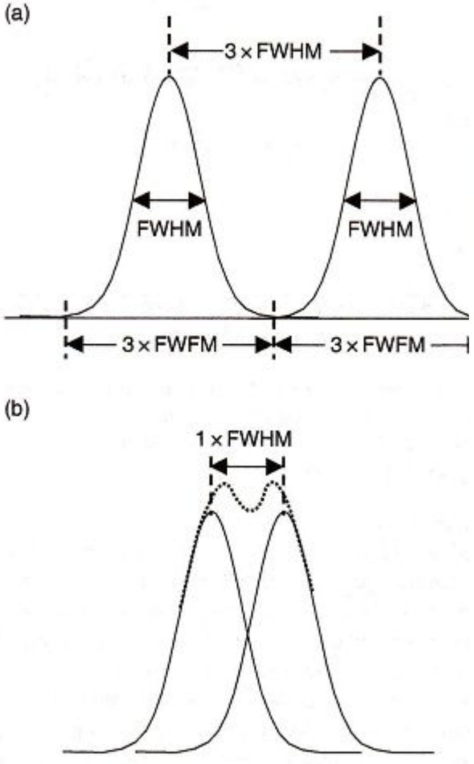
Functions of the "Spectroscopic Amplifier"



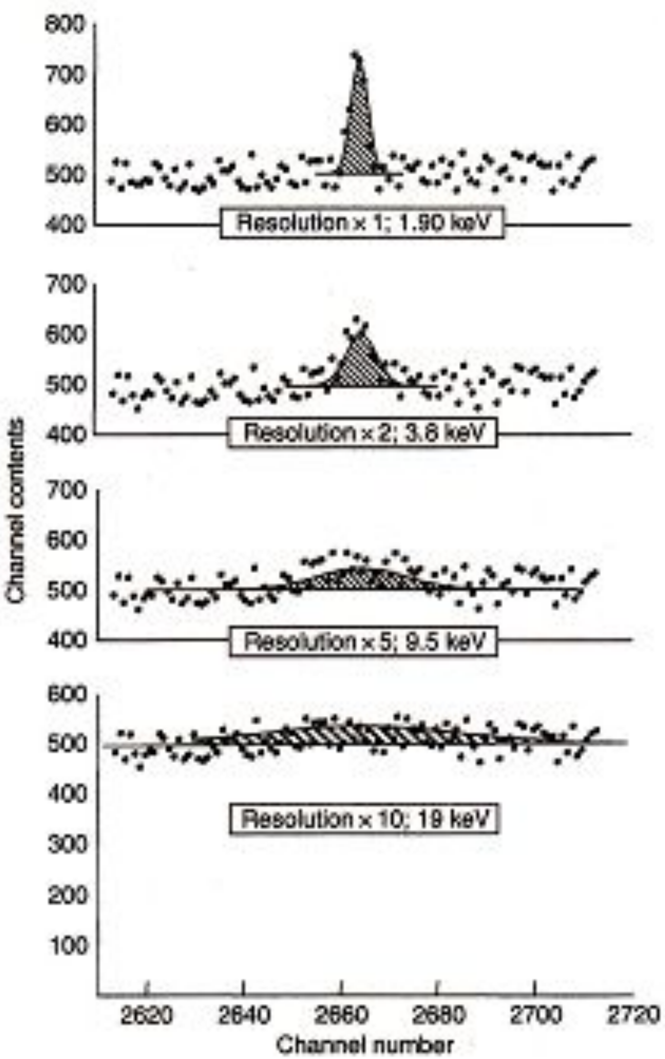
Energy Resolution

- Energy resolution is paramount for spectroscopy
  - ○ Ability to identify features
  - ○ Sensitivity





Gilmore 6.1

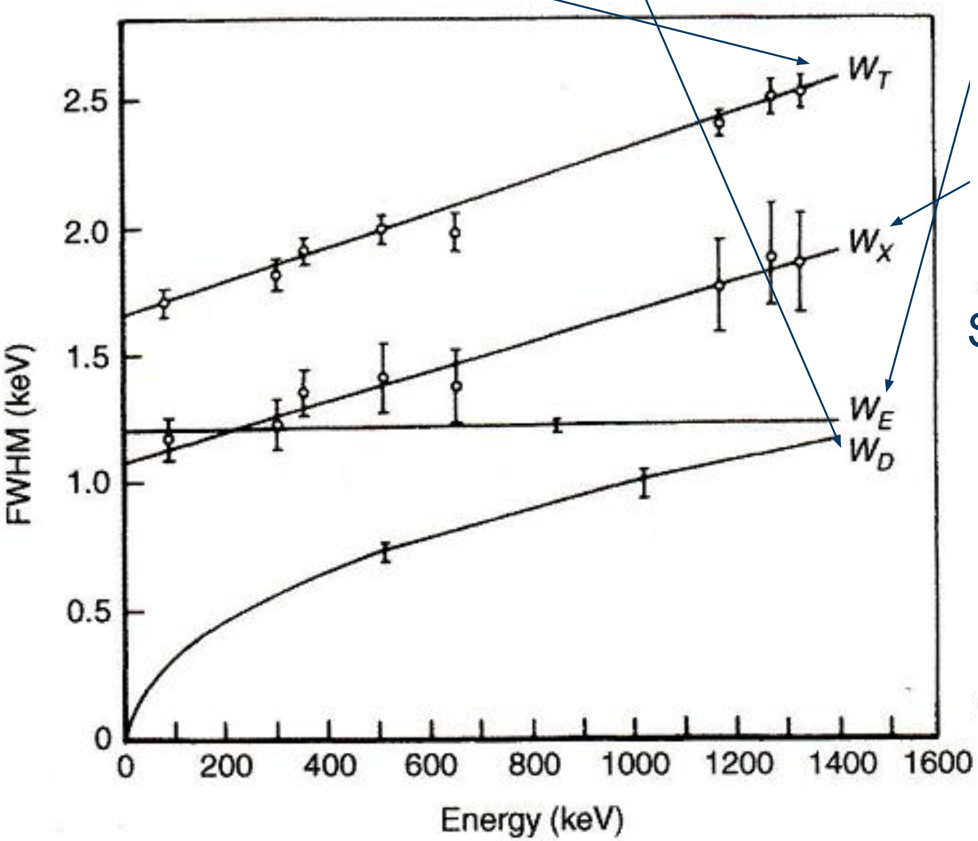


Gilmore 6.2

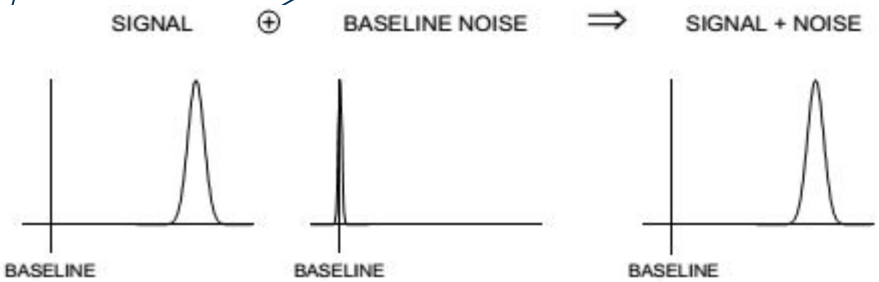
Electronic Noise & Energy Resolution

- Several sources of variability contribute to overall energy resolution

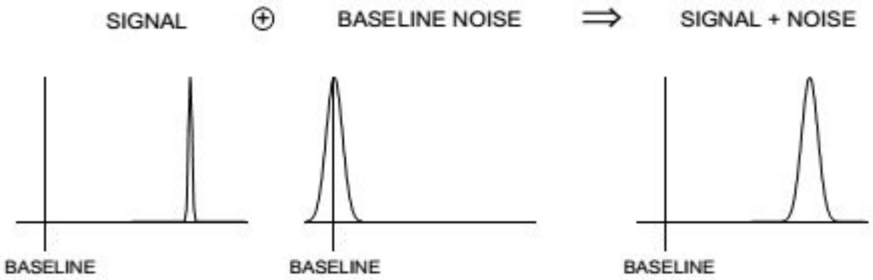
$$(\Delta E_{total})^2 = (\Delta E_{stat})^2 + (\Delta E_{electronics})^2 + (\Delta E_{charge\text{-}loss})^2$$



Knoll 12.11



Signal Variance >> Noise: e.g. Scintillator



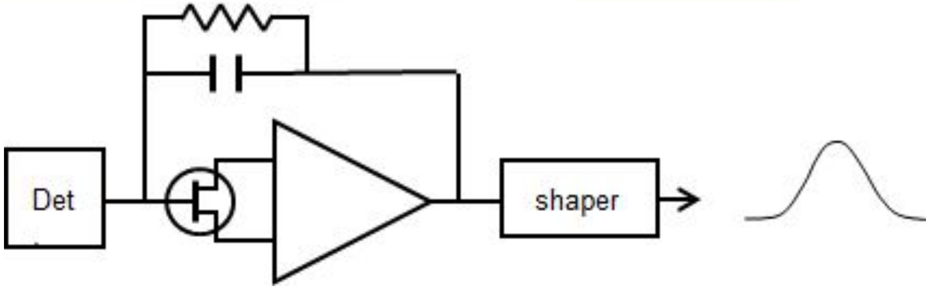
Signal Variance << Noise: e.g. HPGe

From Spieler

Sources of Electronic Noise

- Detector leakage current - shot noise
- Noise in FET - thermal effects & shot noise
- Continuous-reset preamplifier: thermal noise in feedback resistor
- Transistor-reset preamplifier: leakage current through reset element
- 1/f “flicker” noise

Noise Dependence on Shaping Time



Series (or voltage) noise

$$ENC^2 \sim (4kTR_S + e^2_{na})\, C_d^{\,2}\, 1/\tau$$

(Johnson noise associated with series resistance and the thermal noise of the FET)

Parallel (or current) noise

$$ENC^2 \sim (2qI_L + 4kT/R_f)\, \tau$$

I_L – full shot-noise leakage current

(Fluctuations in the (**surface** or **bulk**) leakage current)

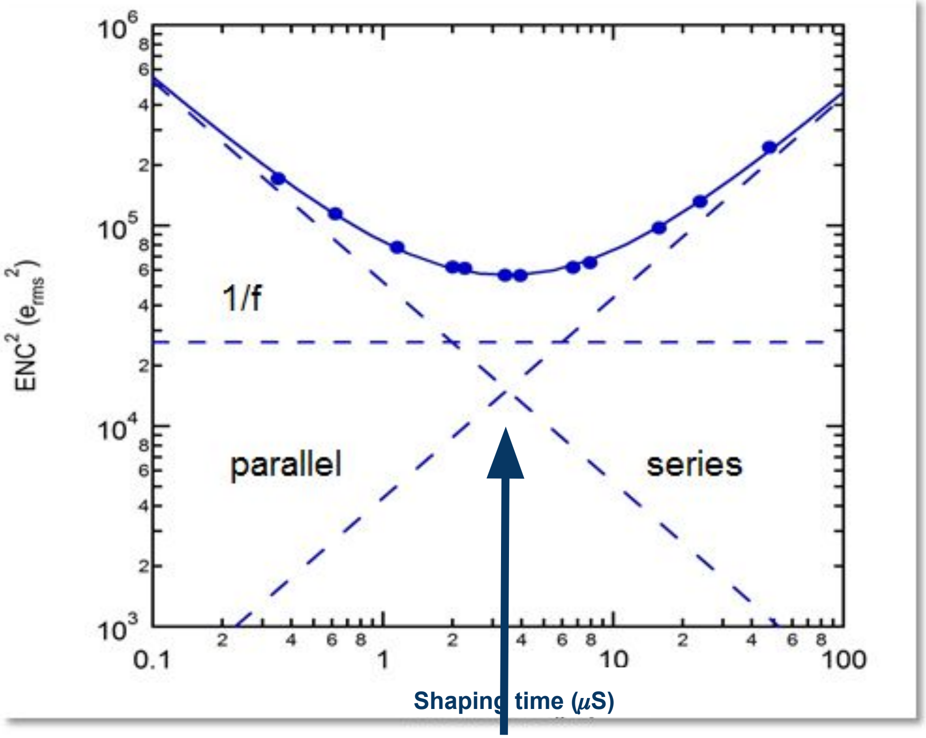
1/f noise

$$ENC^2 \sim A\, C_d^{\,2}$$

Trapping/Detrapping effects in FET, ...

(capture and release of charges in the input FET, **not** dependent on shaping time)

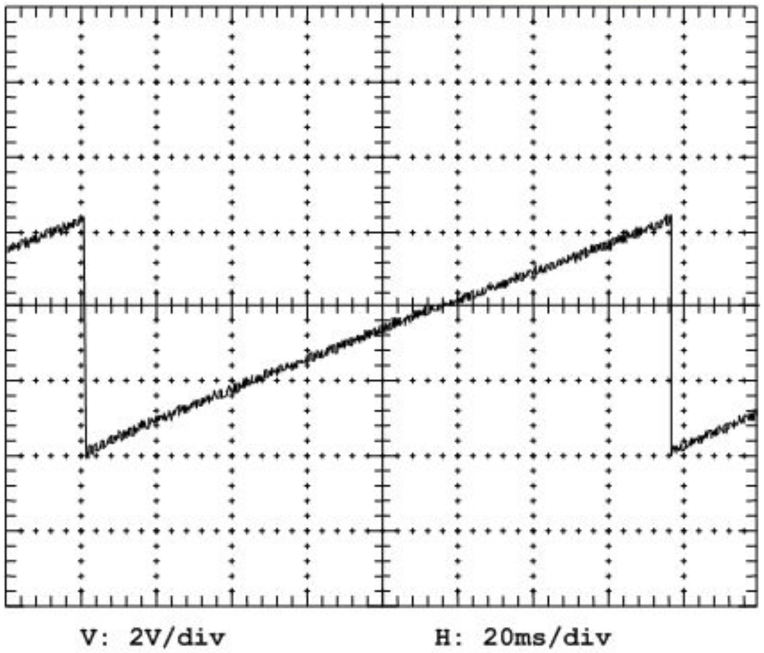
N.B. ENC: Equivalent Noise Charge [e_{RMS}]



"Noise Corner" = Optimum SNR

Leakage Current

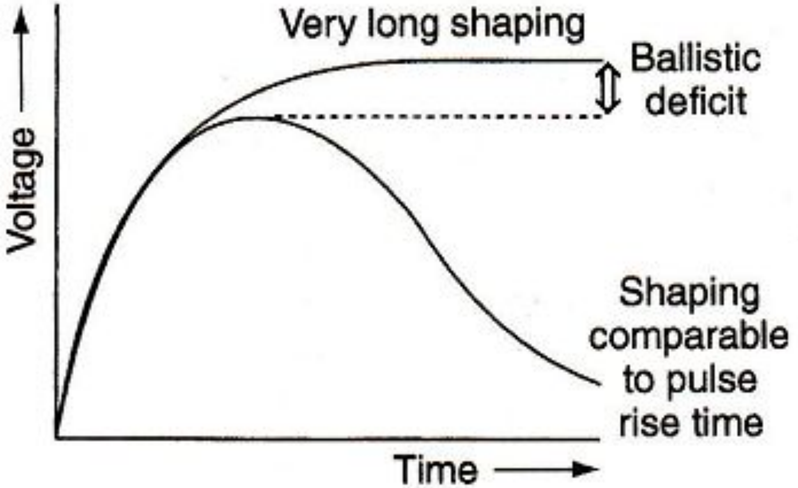
- Source of charge seen at preamplifier output
  - ∴ sometimes referred to as “step” noise
- Bulk leakage current
  - Thermal excitation of charge carriers across bandgap
    - $\propto T^{3/2}\exp(-E_g/(2kT))$
- Surface leakage
  - Channeling/contamination on surf.
  - Mitigate with clean processing, guard rings
- Short shaping times to mitigate effect on energy resolution



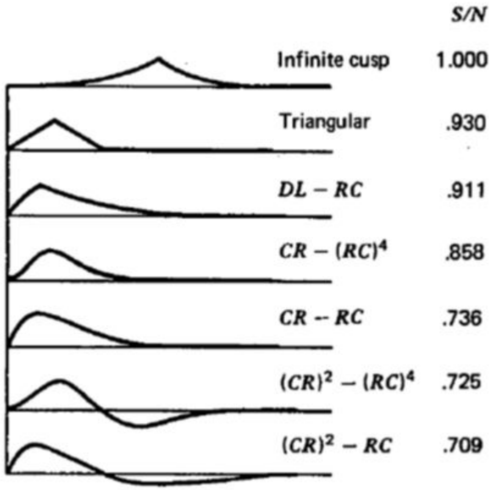
Leakage current seen on output of transistor-reset preamplifier

Ballistic Deficit

- Short shaping time desirable in many circumstances
    - Reduce pileup
    - Minimize parallel noise contributions
- Shaping time on order of pulse rise time → ballistic deficit
    - Charge collection / pulse shape variability
- Can be avoided with trapezoidal shapers
    - Introduce “flat-top” w/ duration>= maximum charge collection time



Gilmore 4.17

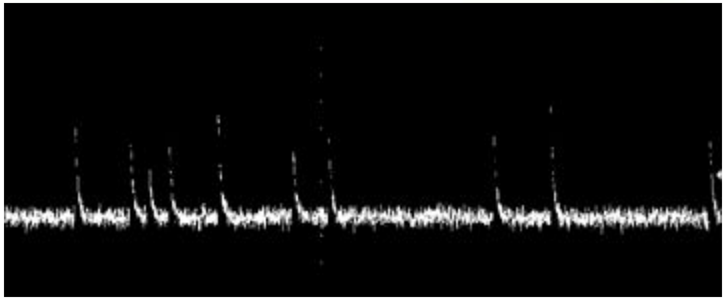


Add flat top for BD

Knoll 17.24

Pulse Pile-up I

- Consequence of random nature of radioactive decay
  - Poisson random process



$$P(x) = \frac{(\bar{x})^x e^{-\bar{x}}}{x!}$$

r – average rate of detector event occurrence

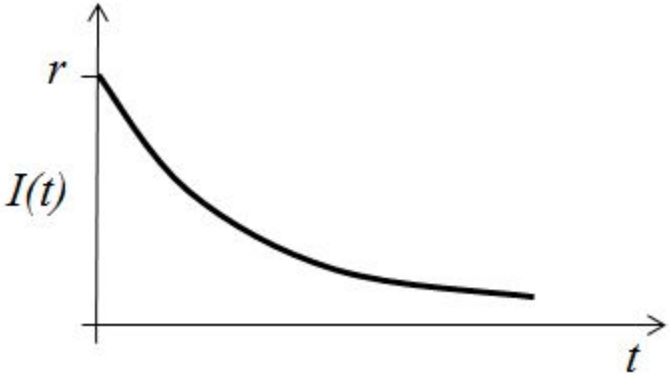
rdt – probability of event occurrence in time interval dt

$$P(0) = \frac{(rt)^0 e^{-rt}}{0!}$$

probability of no event in time interval ***0*** to ***t***

I(t)dt - probability of next event occurrence after delay of ***t*** relative to previous event:

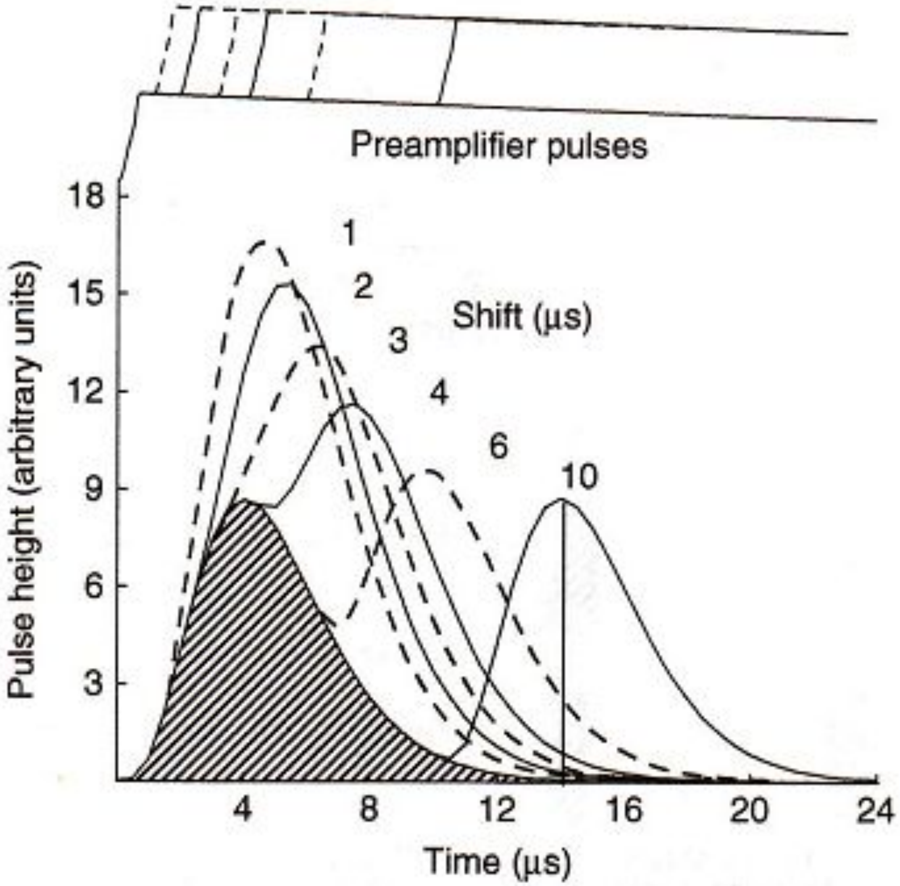
$$\boxed{I(t) = re^{-rt}}$$



I(t) - distribution function of time intervals between adjacent random events

Pulse Pile-up II

- Analog shapers often include “pile-up rejection” circuits
- Information from pile-up pulses is often recoverable
- Digital domain
    - Adaptive filtering
        - Signal shape depends on rate
    - Pile-up flagging
        - Record pile-up events for subsequent processing



Pulse Pileup from CR-RC^4 shaping network with T_{shape} = 1μs (Gilmore 4.22)