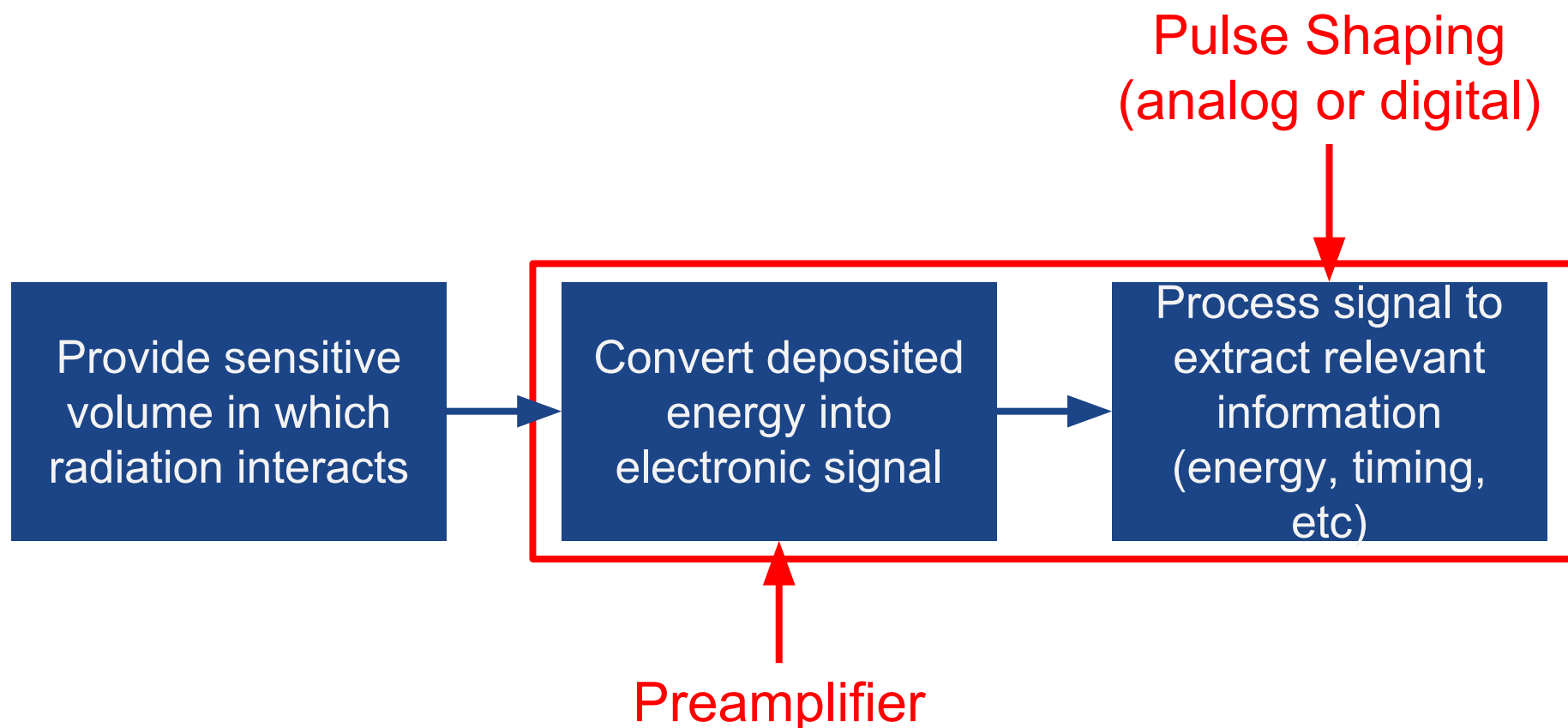


# Pulse Formation and Shaping





# Detector Signal from Single Event

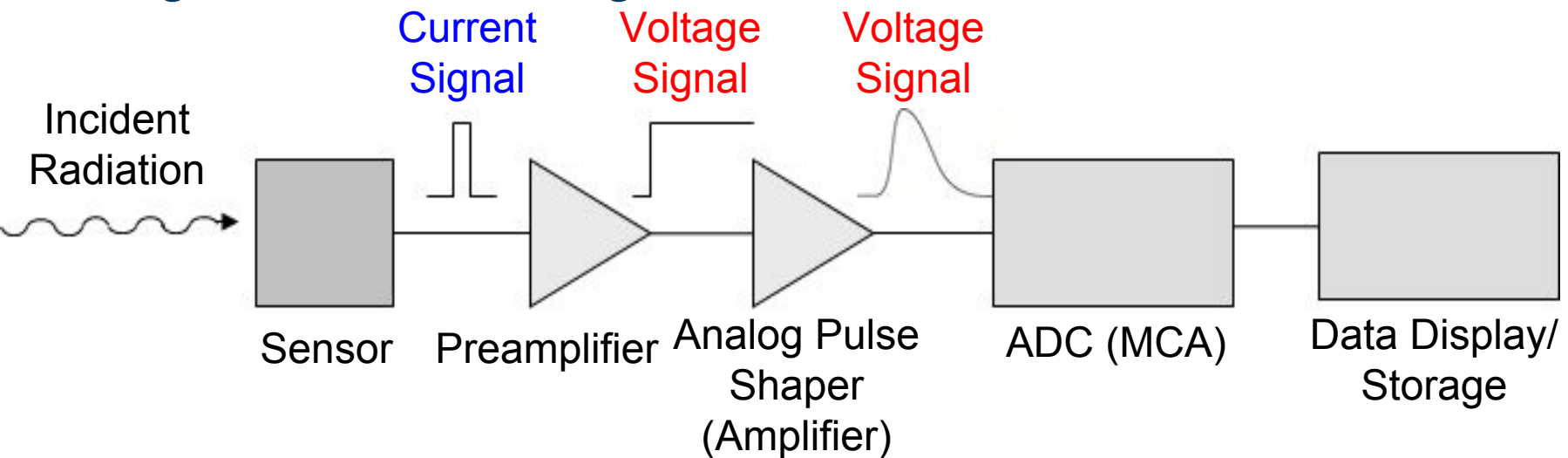
---

- Short current pulse (ns,  $\mu$ s) 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

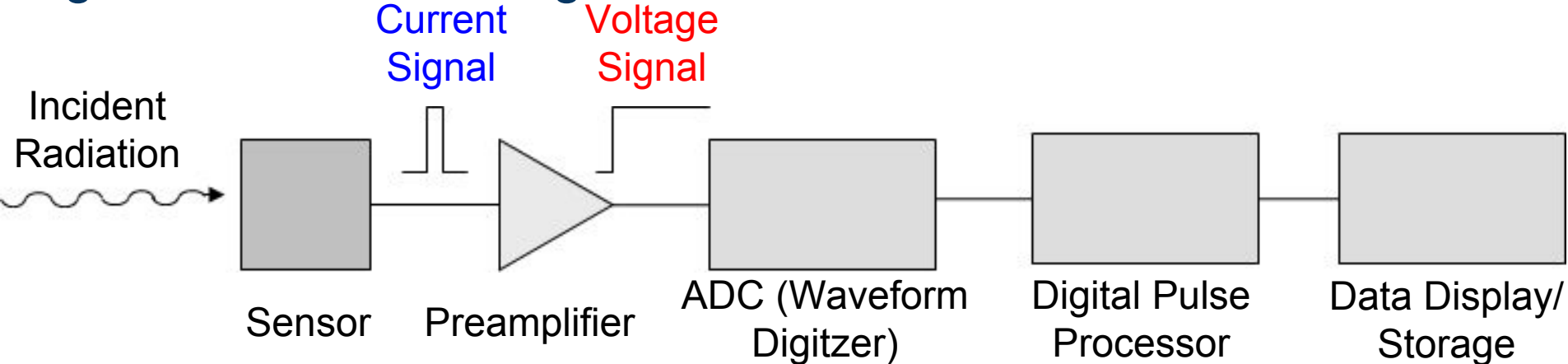


# Spectroscopy Signal Processing Chain

## Analog Pulse Processing Chain



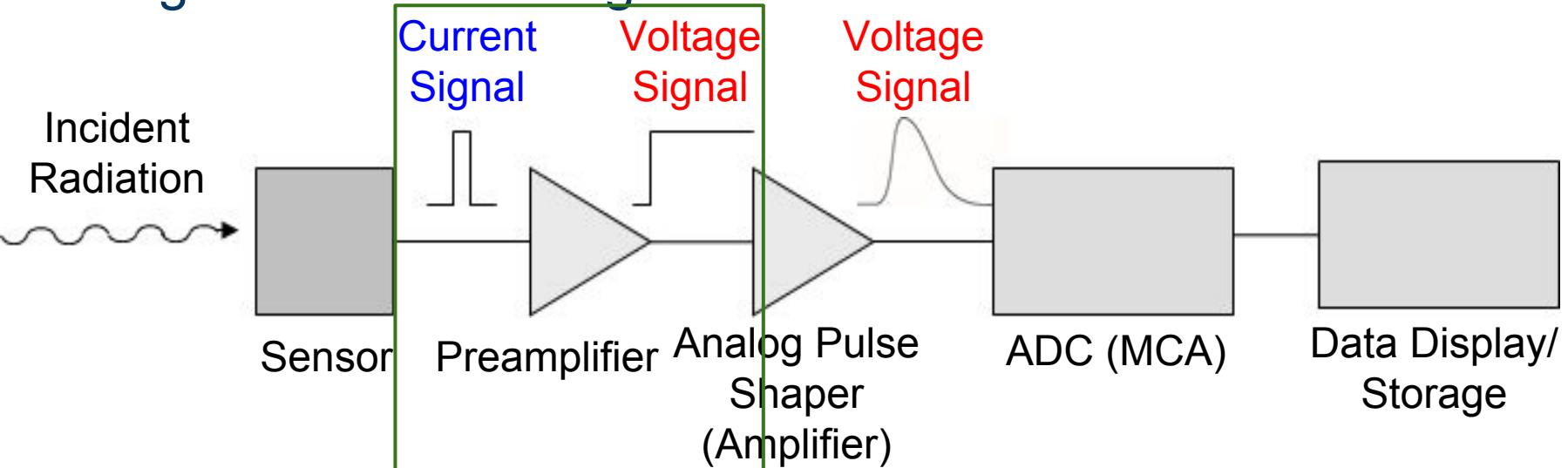
## Digital Pulse Processing Chain



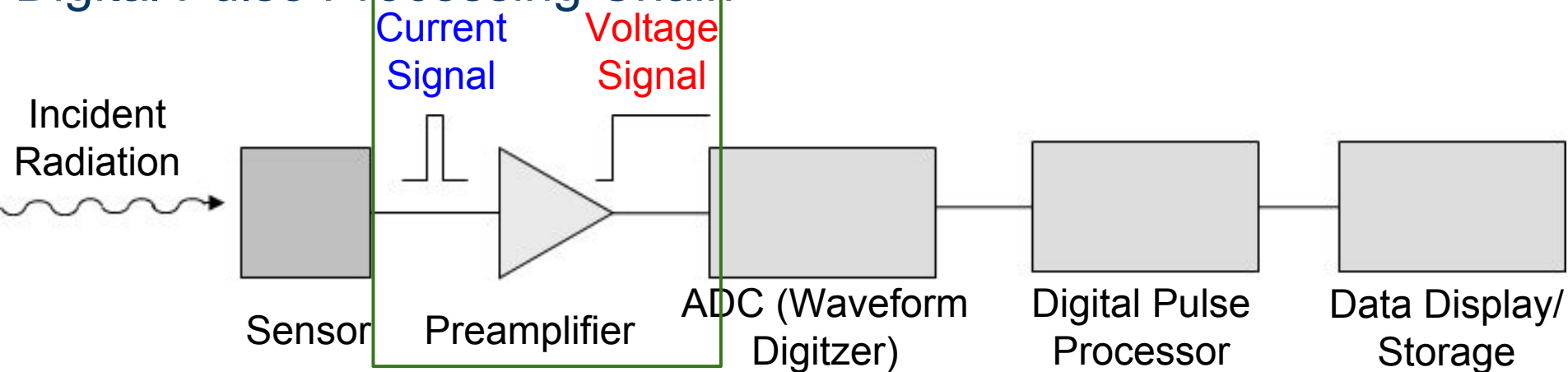


# Spectroscopy Signal Processing Chain

## Analog Pulse Processing Chain



## Digital Pulse Processing Chain



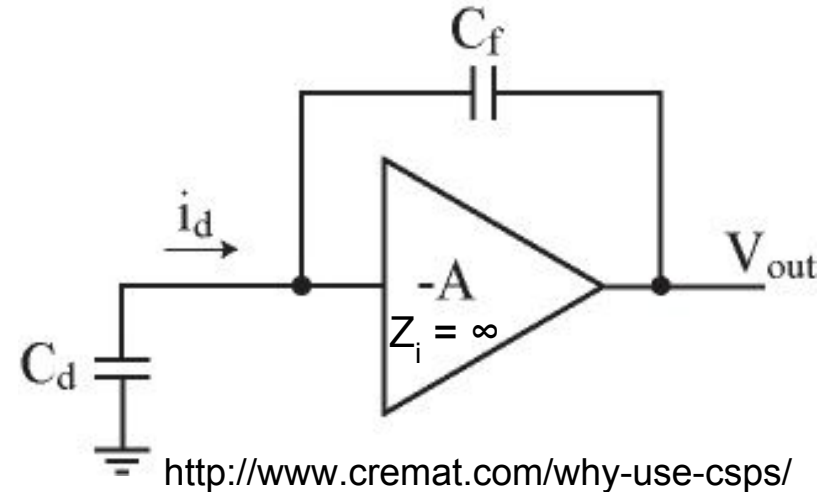


# Preamplifier Electronics

- Total charge in detector current pulse is proportional to energy deposited by interaction in detector.  
$$E \propto Q_s = \int i_s(t) dt$$
  - Need to integrate current signal: Preamplifier!
- 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)



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  $Z_i = \infty$ )

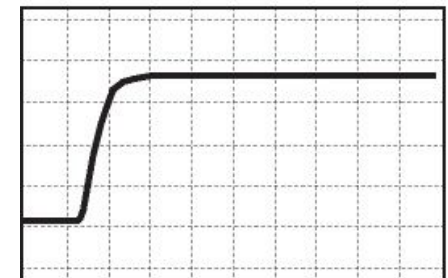
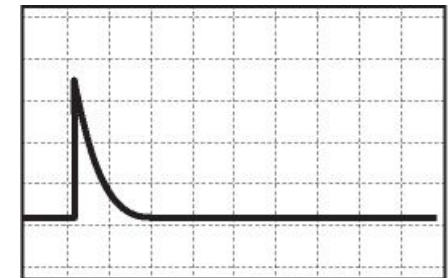
$\Rightarrow$  Effective input capacitance

From [Spieler](#)

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

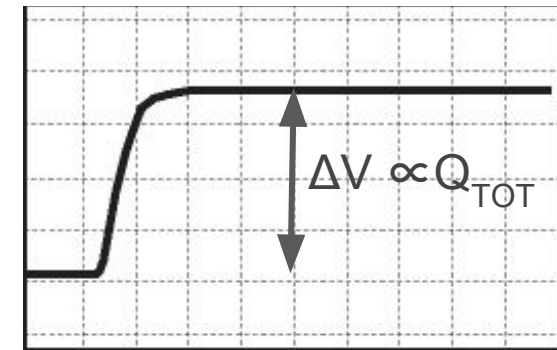
Gain

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

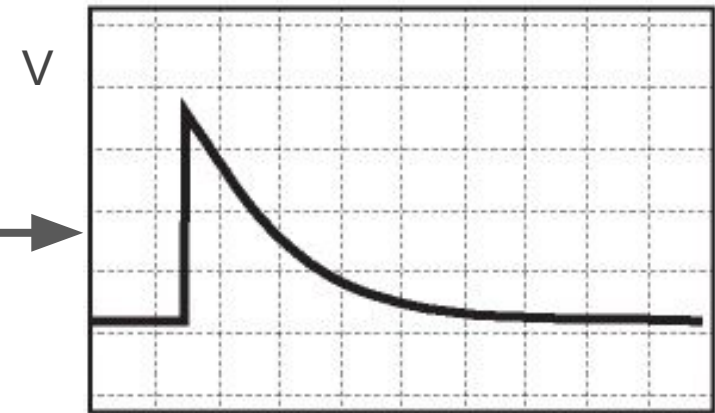
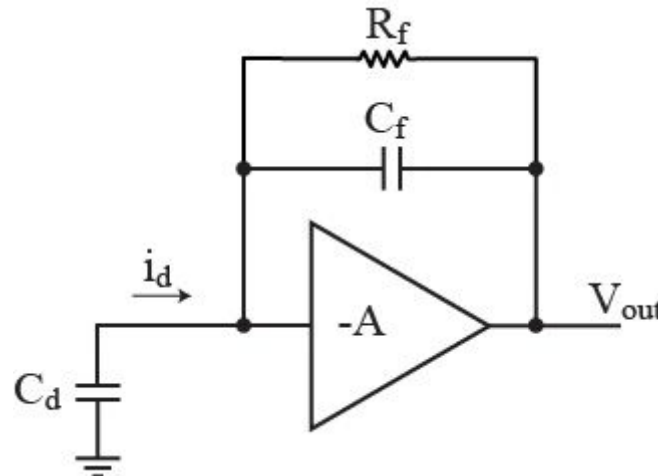


# Charge Sensitive Preamplifier II

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



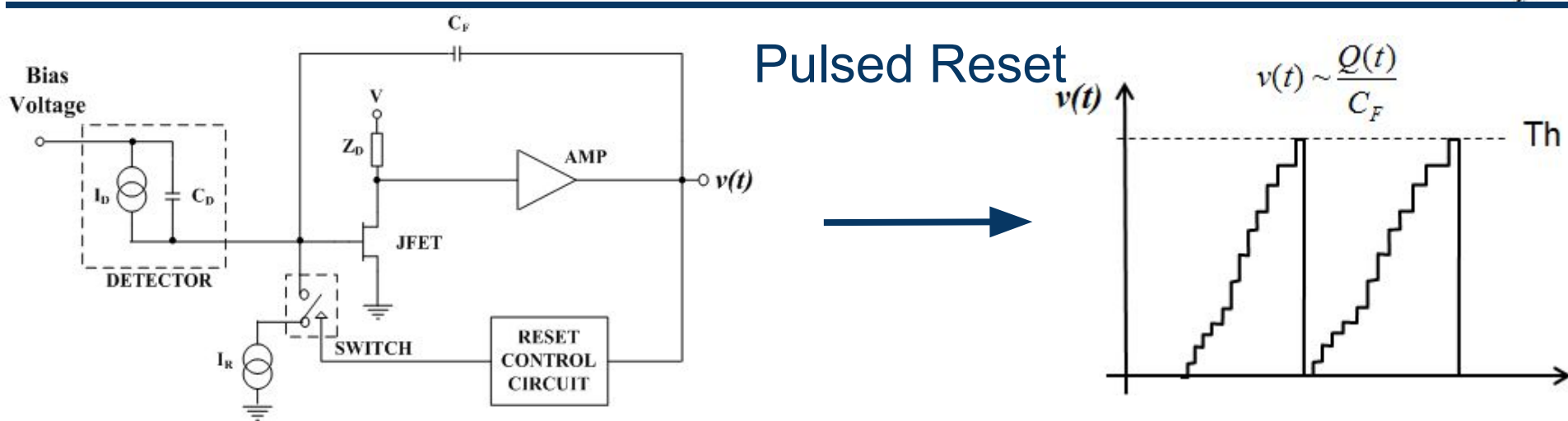
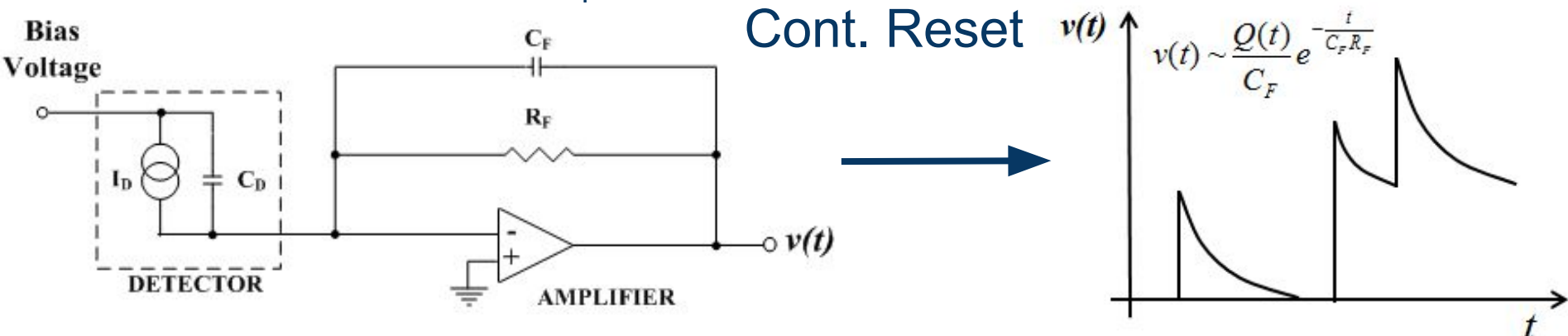
$V_{\text{out}}(t)$ : CSP output pulse: 10ns/div



CSP output pulse: 100 $\mu$ s/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

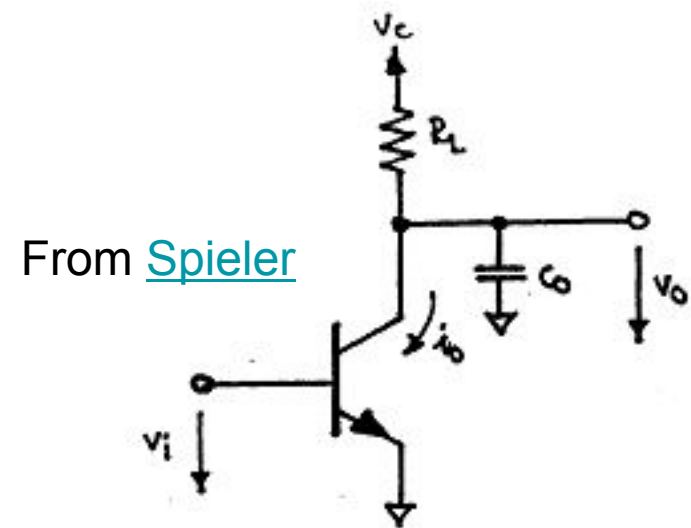
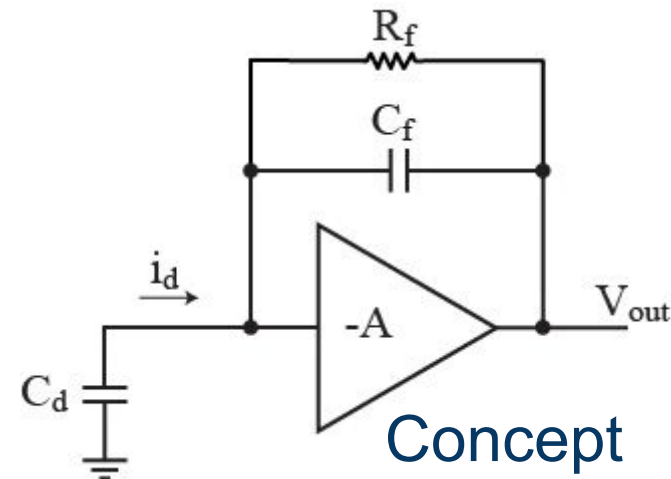






# Realistic Charge Sensitive Preamplifiers

- 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

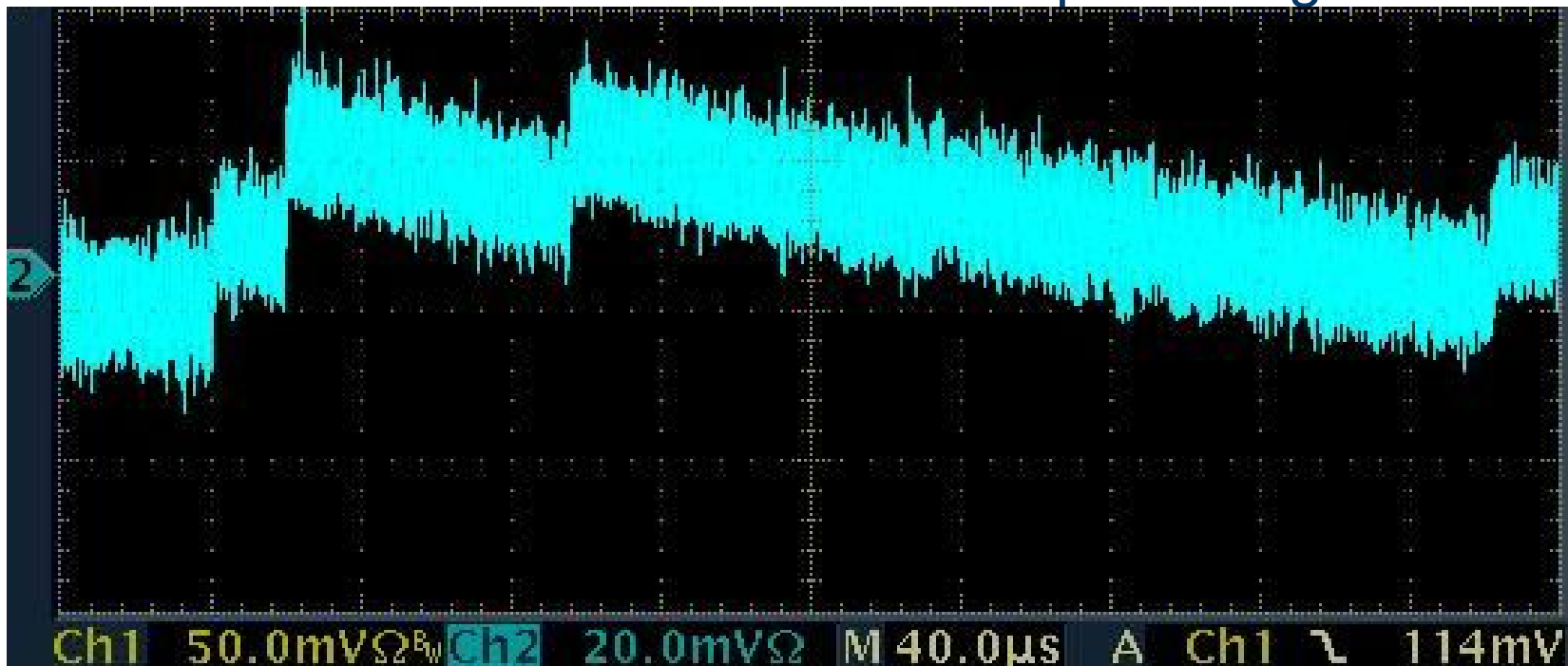


Implementation



# 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

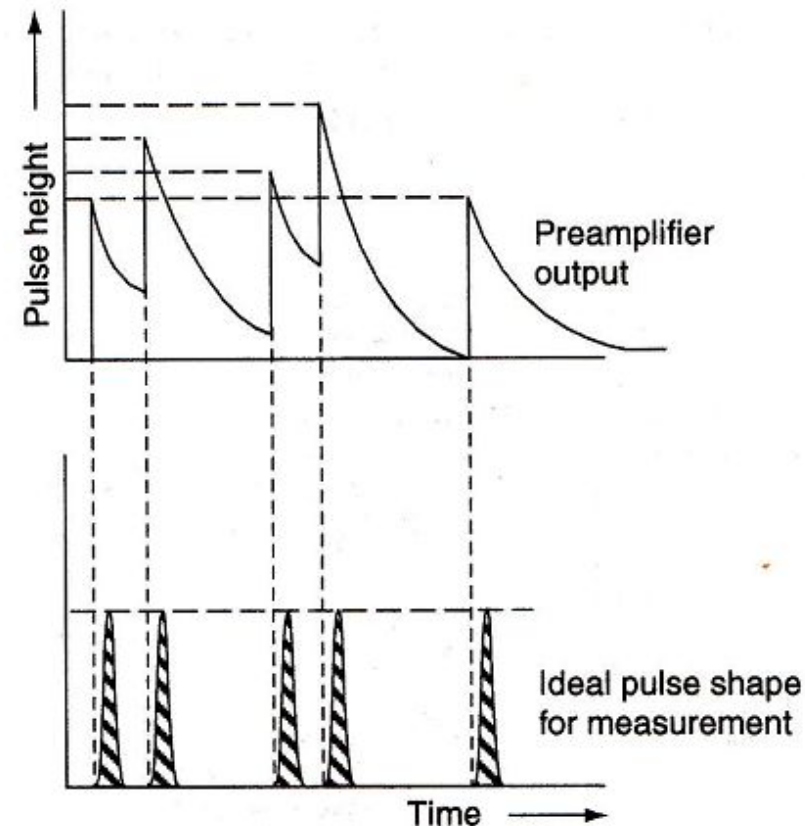


<http://www.cremat.com/why-use-csps/>



# Pulse Shaping I

- Spectroscopic information in magnitude of voltage step from preamplifier
  - Pulse height  $\propto$  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

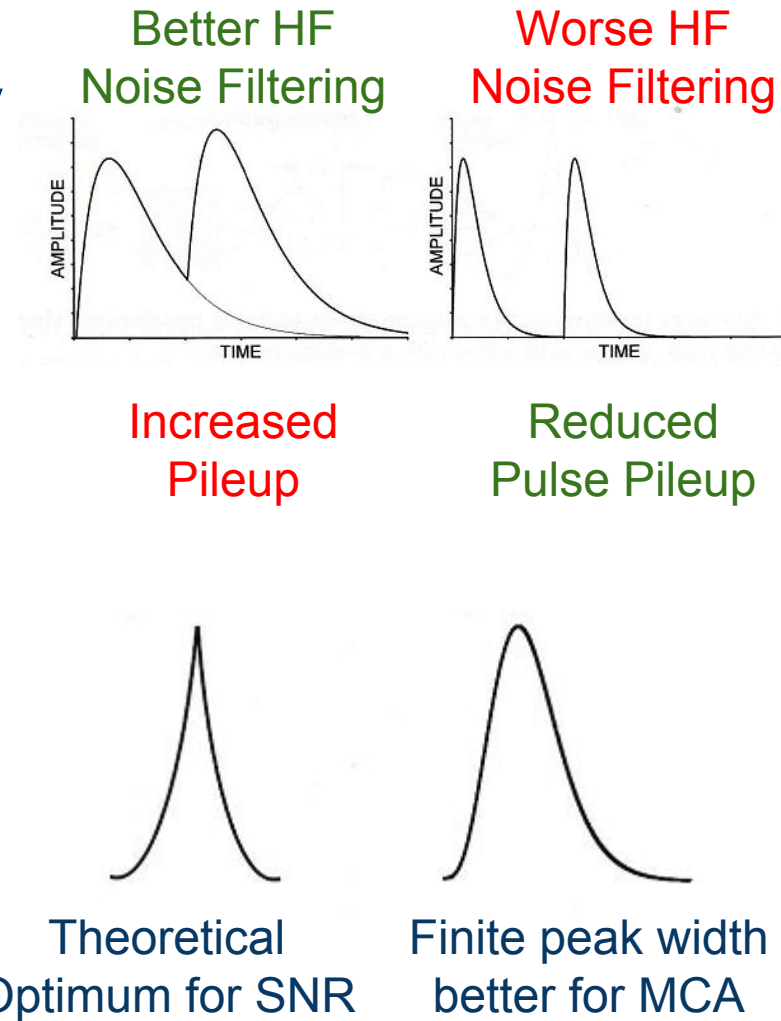


Gilmore 4.12



# Pulse Shaping II

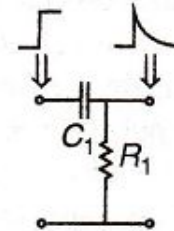
- Pulse shaping is full of trade-offs
- Example 1: SNR vs. Rate capability
  - SNR is often improved by limiting high-frequency response (LP filter)
  - This broadens the pulse, reducing rate capabilities
- Example 2: SNR vs. Peak Detect
  - Optimal pulse shape for maximizing SNR = cusp
  - Sharp peak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



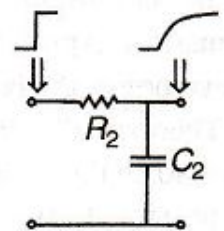
# Review: Analog Signal Shaping

- 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.)

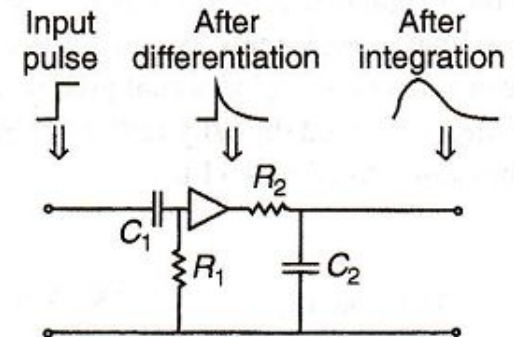
(a) Differentiation (high-pass filter)



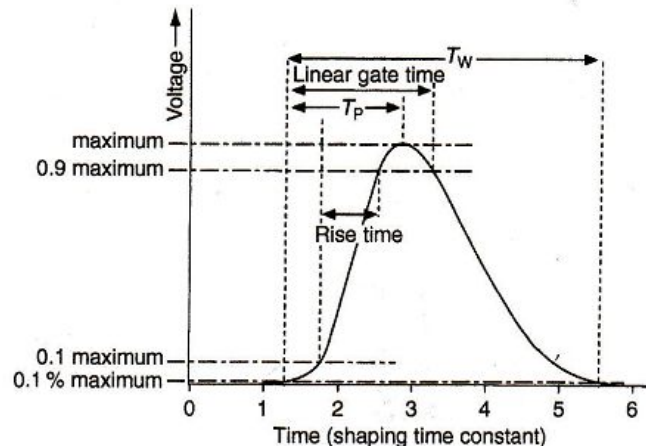
(b) Integration (low-pass filter)



(c) Combined CRRC circuit



Gilmore 4.13



**Table 4.1** Measured timing factors for semi-Gaussian output pulses

Factor	Time interval	Symbol	Time <sup>a</sup>
Rise time	0.1 to 0.9 of pulse maximum	—	$1.26 + 0.05$
Peaking time	threshold <sup>b</sup> 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	$T_w$	$5.6 + 0.5$

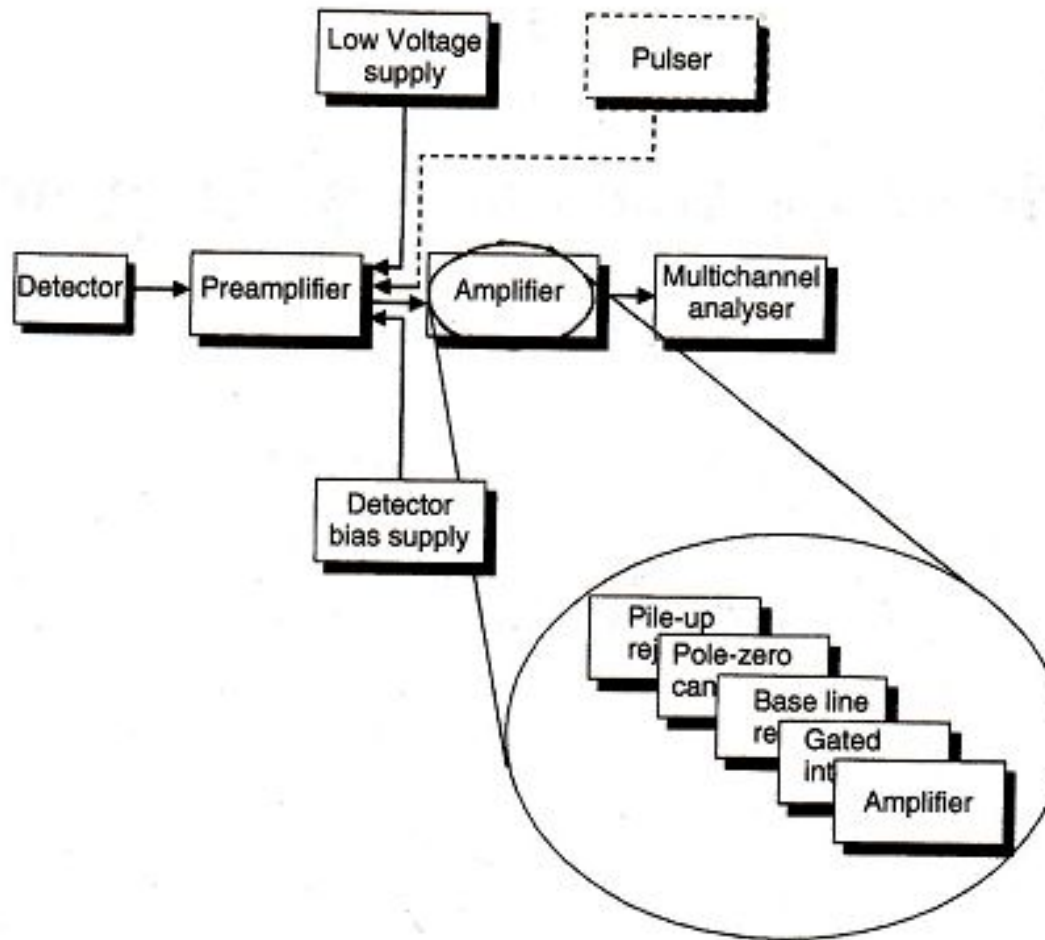
<sup>a</sup> Time is specified in units of time constant.

<sup>b</sup> 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

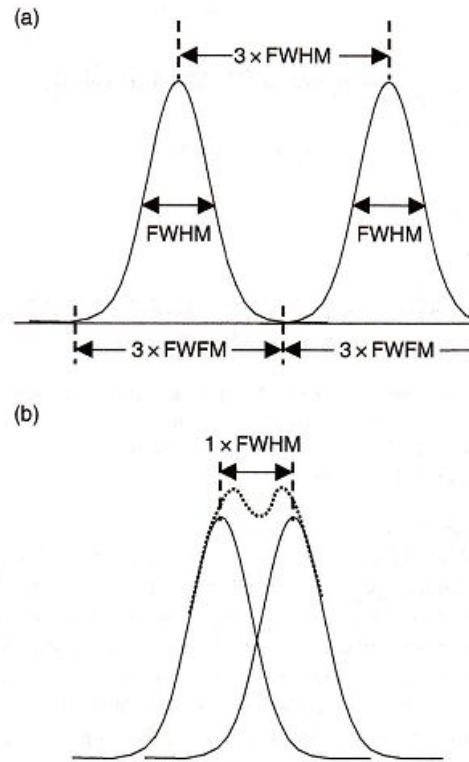
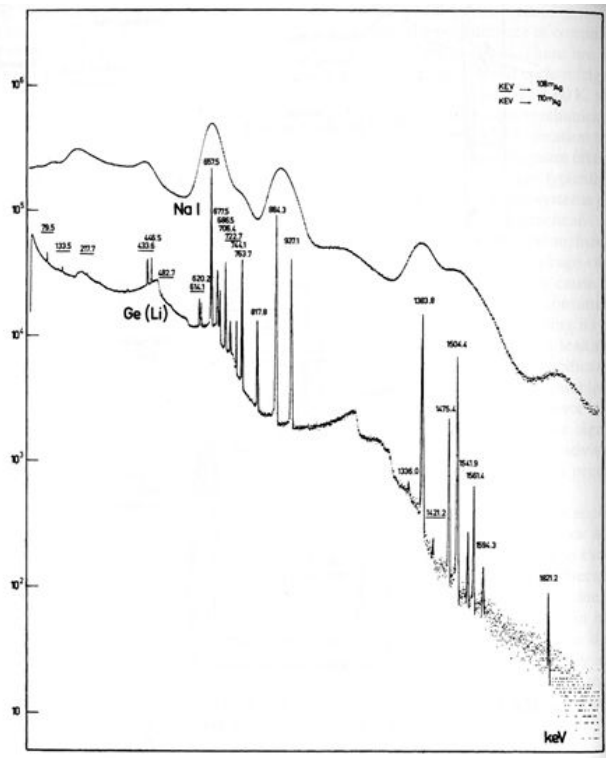
## Functions of the “Spectroscopic Amplifier”



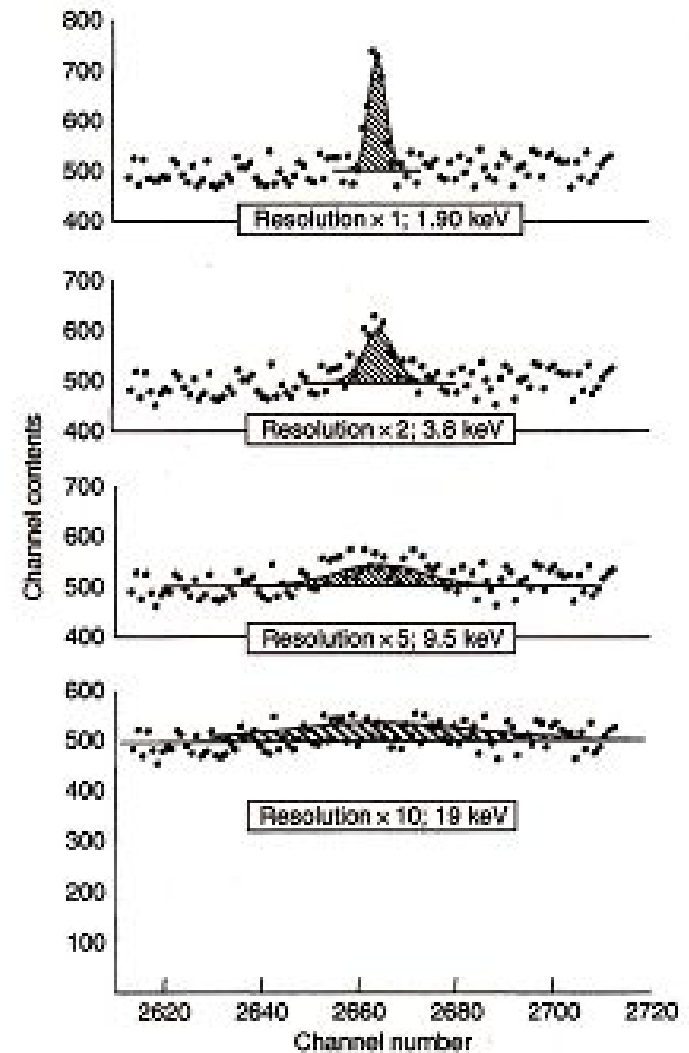


# Energy Resolution

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



Gilmore 6.1

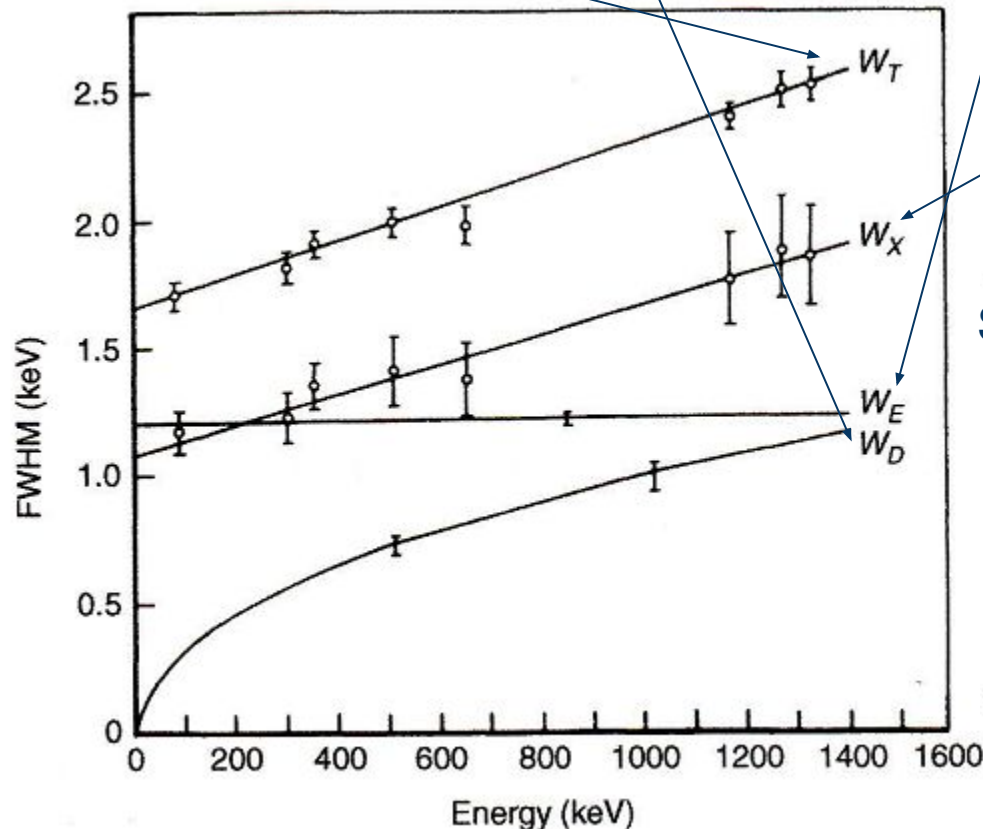


Gilmore 6.2

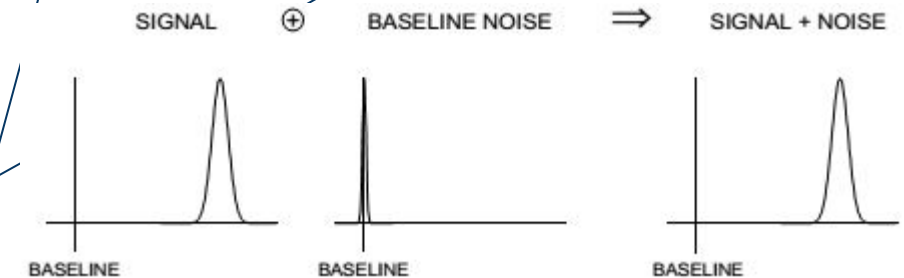
# Electronic Noise & Energy Resolution

- Several sources of variability contribute to overall energy resolution

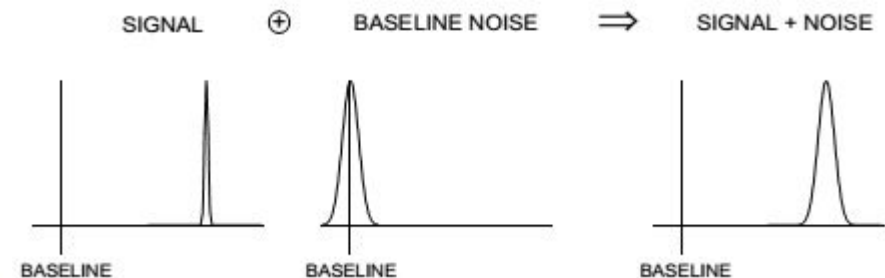
$$(\Delta E_{\text{total}})^2 = (\Delta E_{\text{stat}})^2 + (\Delta E_{\text{electronics}})^2 + (\Delta E_{\text{charge-loss}})^2$$



Knoll 12.11



Signal Variance  $\gg$  Noise: e.g. Scintillator



Signal Variance  $\ll$  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

$$ENC^2 \sim (4kTR_S + e_{na}^2) C_d^2 1/T$$

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

## Parallel (or current) noise

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

$I_L$  – full shot-noise leakage current

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

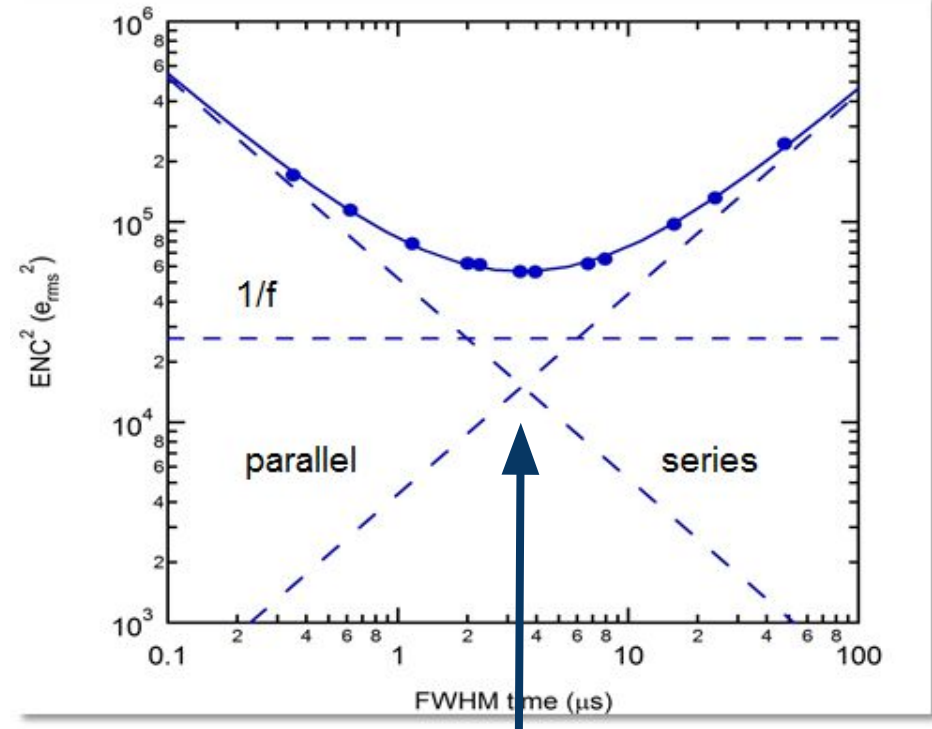
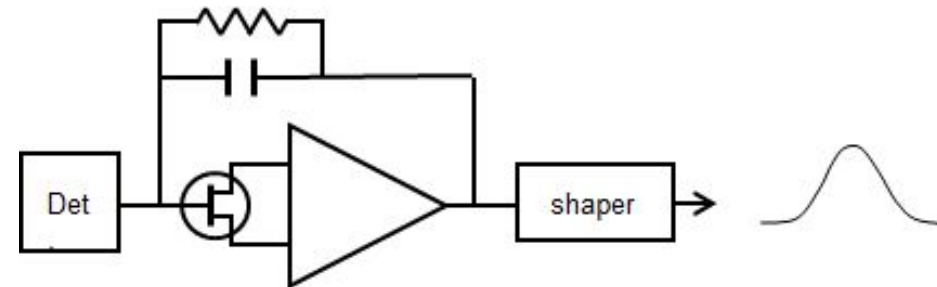
## 1/f noise

$$ENC^2 \sim A C_d^2$$

Trapping/Detrapping effects in FET, ...

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

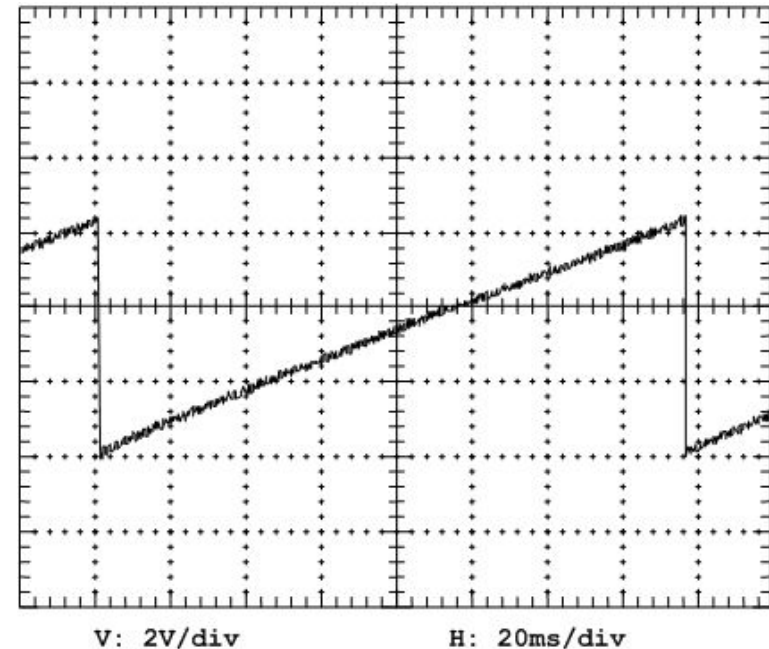
**N.B.** ENC: Equivalent Noise Charge [ $e_{RMS}$ ]



**“Noise Corner” = Optimum SNR**

# Leakage Current

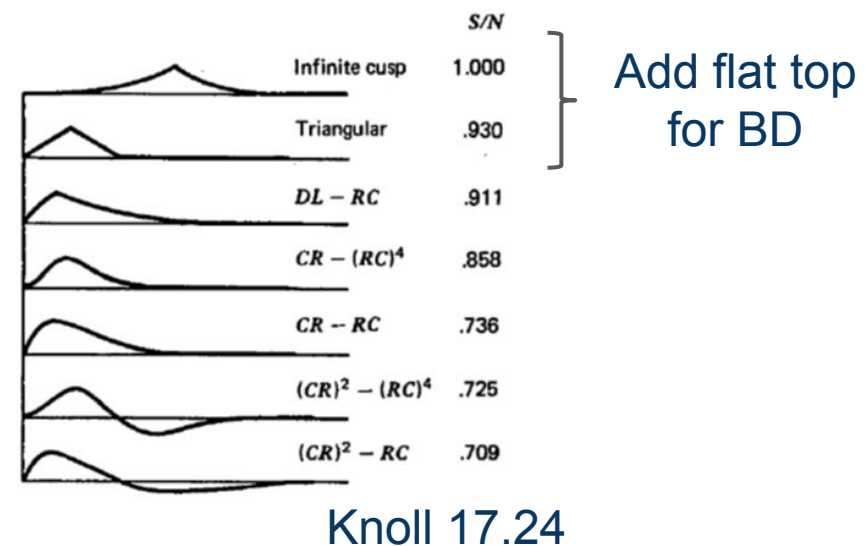
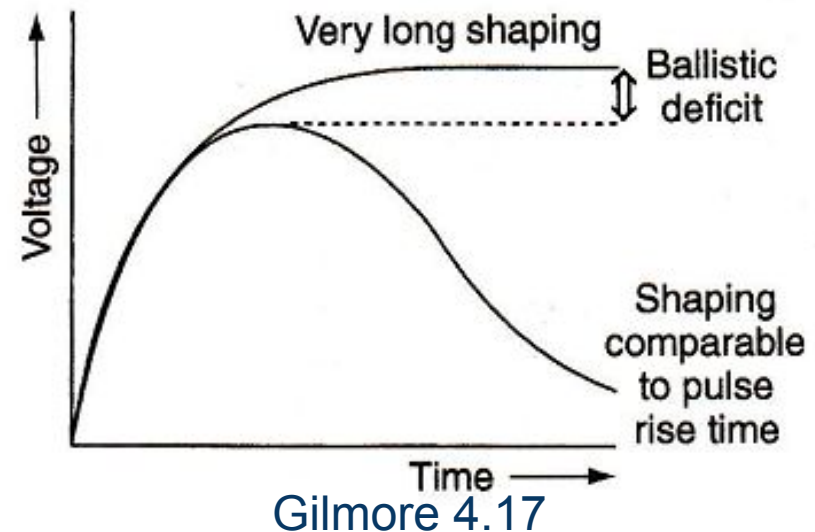
- Source of charge seen at preamplifier output
  - $\therefore$  sometimes referred to as “step” noise
- Bulk leakage current
  - Thermal excitation of charge carriers across bandgap
    - $\propto T^{3/2} \exp(-E_g/(2kT))$
- Surface leakage
  - Channeling/contamination on surf.
  - Mitigate with clean 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  $\rightarrow$  ballistic deficit
  - Charge collection / pulse shape variability
- Can be avoided with trapezoidal shapers
  - Introduce “flat-top” w/ duration  $\geq$  maximum charge collection time



# 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

$r dt$  – probability of event occurrence in time interval  $dt$

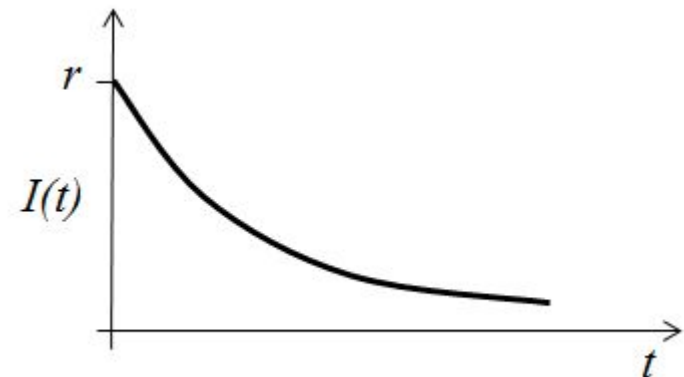
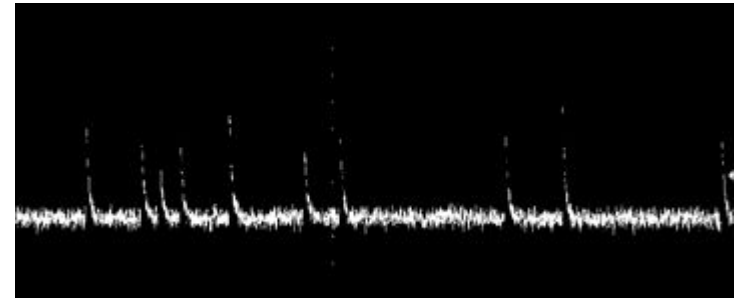
$$P(0) = \frac{(rt)^0 e^{-rt}}{0!} \quad \text{probability of no event in time interval } 0 \text{ to } t$$

$I(t)dt$  - probability of next event occurrence after delay

of  $t$  relative to previous event:

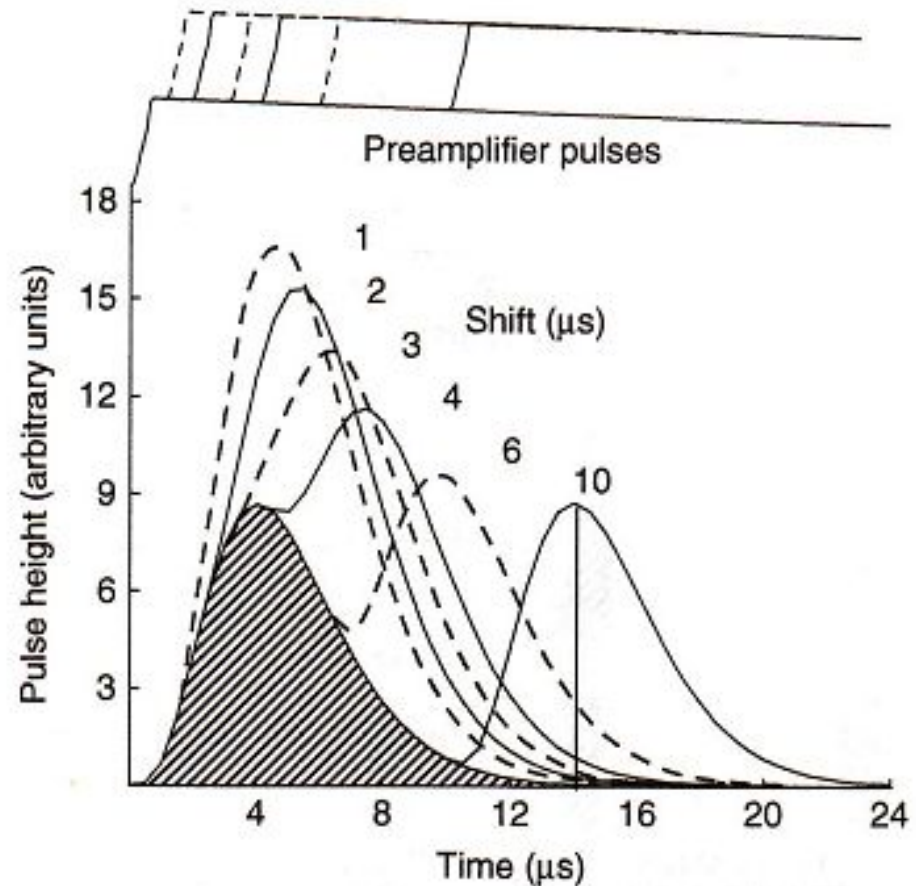
$$I(t) = r e^{-rt}$$

$I(t)$  - 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<sup>4</sup> shaping network with  $T_{\text{shape}} = 1 \mu\text{s}$  (Gilmore 4.22)