Electronic Instrumentation for Radiation Detection Systems

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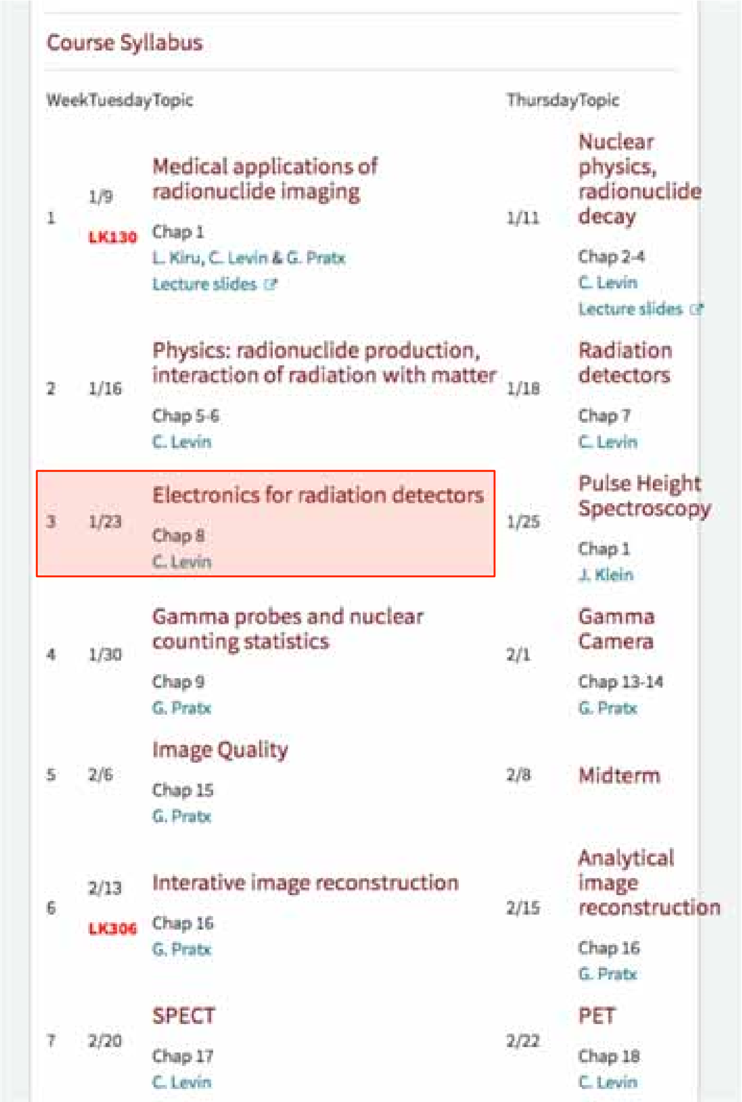
STANFORD
SCHOOL OF MEDICINE
Stanford University Medical Center

Molecular Imaging
Program at Stanford

Course Outline



Course Syllabus

Week	Tuesday	Topic	Thursday	Topic
1	1/9 LK130	Medical applications of radionuclide imaging Chap 1 L. Kiru, C. Levin & G. Pratx Lecture slides	1/11	Nuclear physics, radionuclide decay Chap 2-4 C. Levin Lecture slides
2	1/16	Physics: radionuclide production, interaction of radiation with matter Chap 5-6 C. Levin	1/18	Radiation detectors Chap 7 C. Levin
3	1/23	Electronics for radiation detectors Chap 8 C. Levin	1/25	Pulse Height Spectroscopy Chap 1 J. Klein
4	1/30	Gamma probes and nuclear counting statistics Chap 9 G. Pratx	2/1	Gamma Camera Chap 13-14 G. Pratx
5	2/6	Image Quality Chap 15 G. Pratx	2/8	Midterm
6	2/13 LK306	Interative image reconstruction Chap 16 G. Pratx	2/15	Analytical image reconstruction Chap 16 G. Pratx
7	2/20	SPECT Chap 17 C. Levin	2/22	PET Chap 18 C. Levin

Lecture Overview

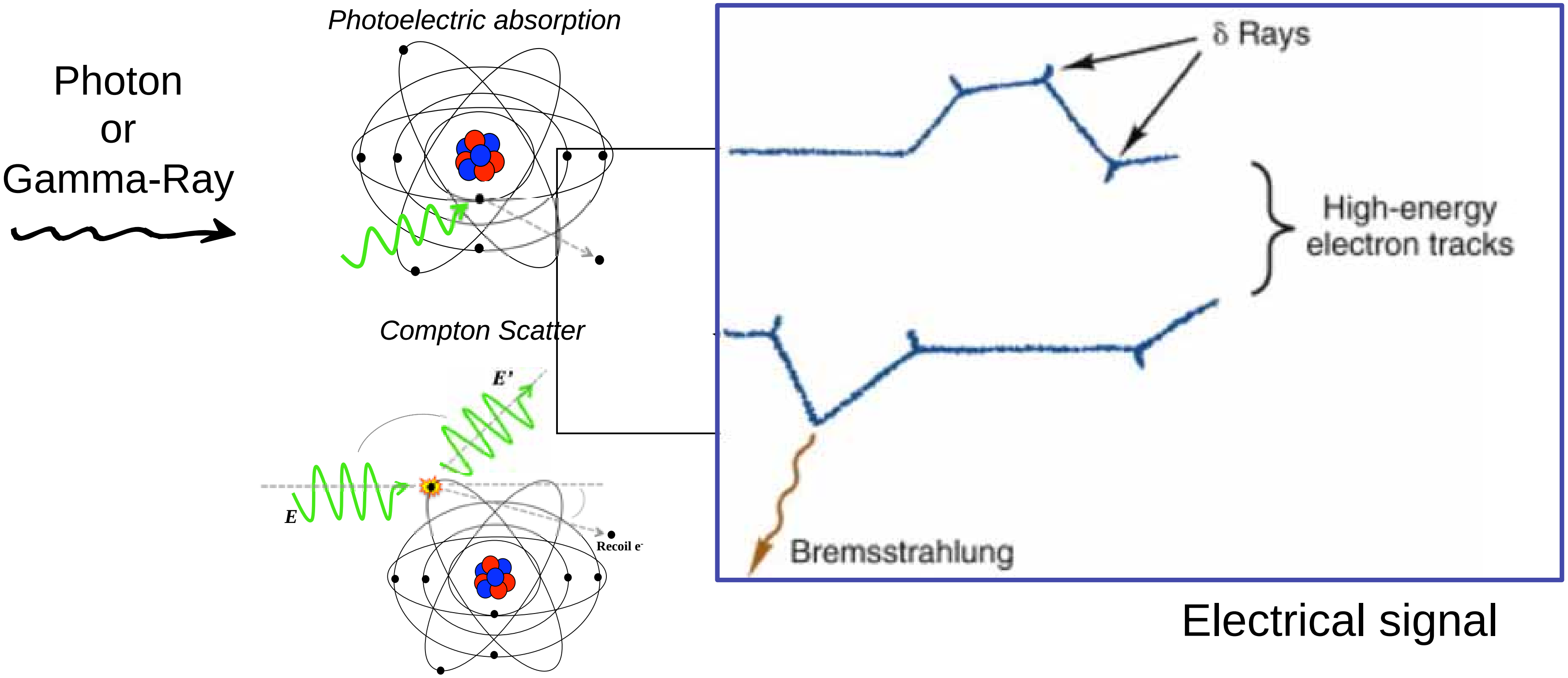
- Brief Review of Radiation Detectors
- Detector Readout Electronics
  - Preamplifiers & Amplifiers
  - Single Channel Analyzers
  - Multi Channel Analyzers
  - Time-to-Amplitude Converters
  - Digital Counters and Rate Meters
- Peripheral Components
  - High Voltage Power Supplies
  - Analog and Digital Oscilloscopes

The General Concept of Radiation Detection

Incident Radiation

Interaction with Radiation Detector

Detector response



Electrical signal

Types of Radiation Detector

Direct Radiation Detectors

Detect charge from direct Ionization of Material

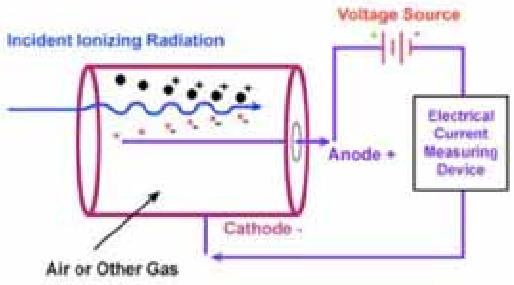
Gas Detectors

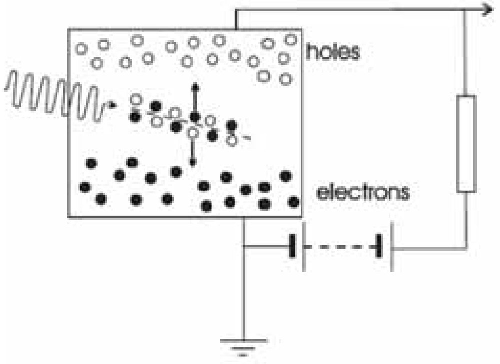
Semiconductor Detectors

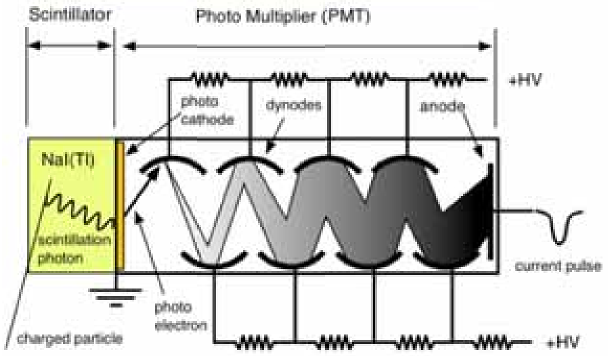
Indirect Radiation Detectors

Create charge from light from de-excitation

Scintillation Detectors

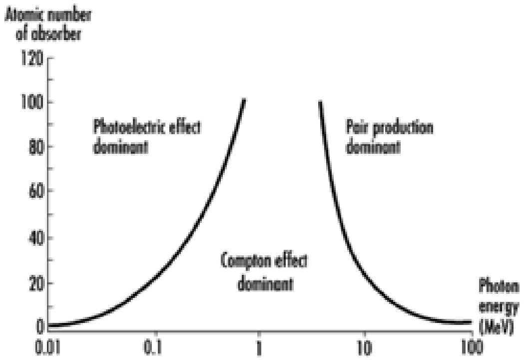






The General Concept of Radiation Detection

- Imaging in Nuclear Medicine deals with photons ~140-511 keV



Desirable Characteristics of a Radiation Detector are then:

- High Sensitivity: High electron density, i.e. Z and density
- Large Area: Can be grown or manufactured in sizes relevant for clinical molecular imaging
- Excellent Energy Resolution: Ability to distinguish between different nuclear emissions, scatter in patient
- Fast Response: Avoid dead time/incomplete charge/randoms
- Cost Effective: Proliferation dictated by affordability

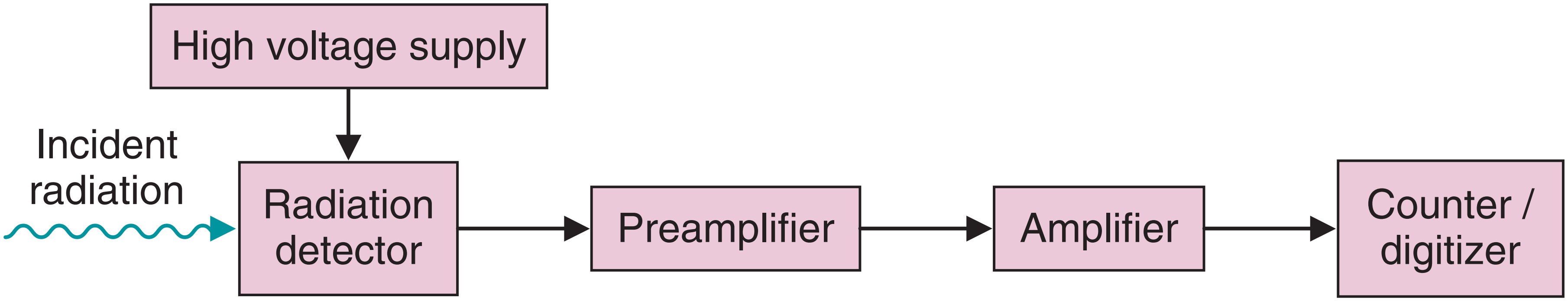
Radiation detection

- **Gas filled detectors**:
  - Low detection efficiency (low density)
  - Low conversion efficiency
- **Semiconductor detectors**:
  - Low detection efficiency (thin)
  - High conversion efficiency
  - Temperature dependent
  - Compact
- **Scintillation detectors**:
  - High detection efficiency
  - Medium conversion efficiency
  - *Some* loss of energy resolution

Conditioning Detector Signals for Application

- Detectors for Radionuclide Imaging operate in what is called "pulse mode", i.e. one pulse per detected photon.
  - Imaging in PET and SPECT are **count-starved** imaging scenarios. Pulse mode is necessary and acceptable.
- Some other applications in imaging have such a huge flux of incident radiation that they operate in current mode.
  - Ex: Computed Tomography Imaging, calibration of Intensity Modulated Radiotherapy Systems

General Signal Processing Chain for Radiation Detector:



High voltage supply

Incident radiation

Radiation detector

Preamplifier

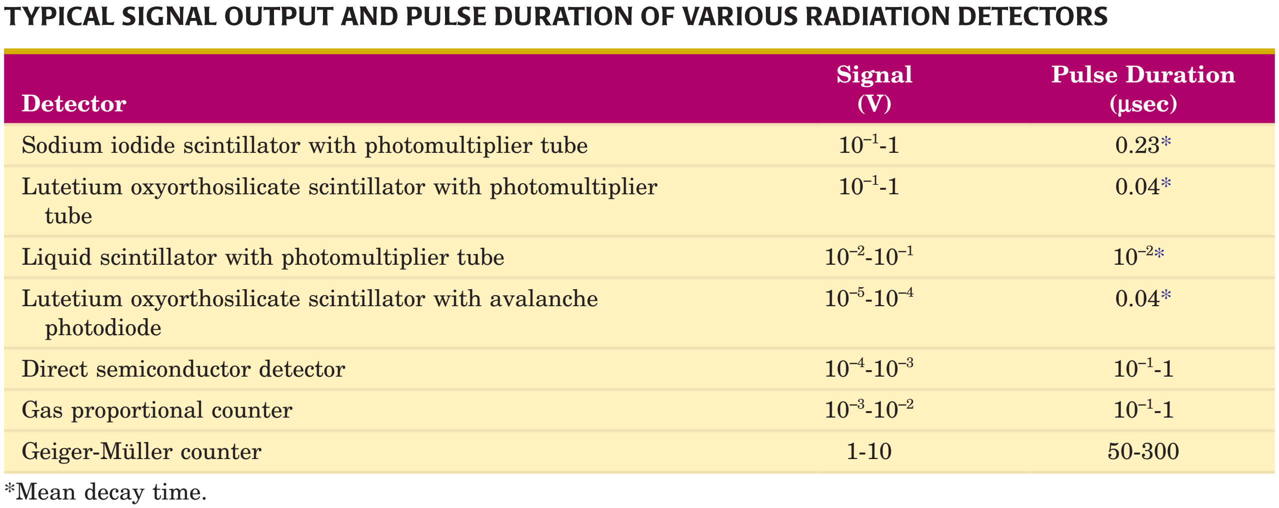
Amplifier

Counter / digitizer

Preamplifiers for Radiation Detectors:

Preamplifiers: The General Purpose

- The output signal form accumulated charge in radiation detectors is typically quite low:



TYPICAL SIGNAL OUTPUT AND PULSE DURATION OF VARIOUS RADIATION DETECTORS

Detector	Signal (V)	Pulse Duration (µsec)
Sodium iodide scintillator with photomultiplier tube	10^{-1}-1	0.23*
Lutetium oxyorthosilicate scintillator with photomultiplier tube	10^{-1}-1	0.04*
Liquid scintillator with photomultiplier tube	10^{-2}-10^{-1}	10^{-2}*
Lutetium oxyorthosilicate scintillator with avalanche photodiode	10^{-5}-10^{-4}	0.04*
Direct semiconductor detector	10^{-4}-10^{-3}	10^{-1}-1
Gas proportional counter	10^{-3}-10^{-2}	10^{-1}-1
Geiger-Müller counter	1-10	50-300

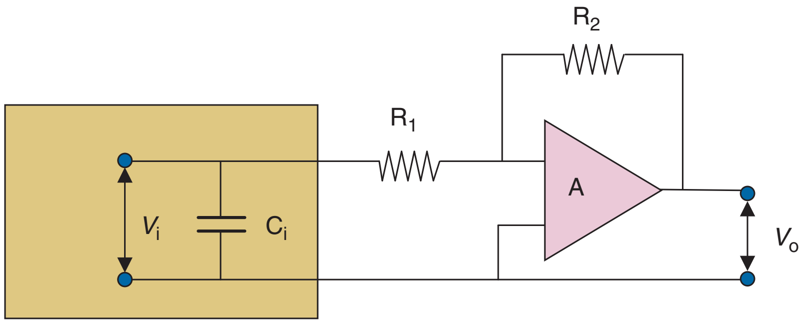
*Mean decay time.

- Three main purposes of the preamplifier (or preamp):

1. To amplify, if necessary, small signals from detectors
2. To shape signals for remaining signal processing
3. To match impedance between detector and sig. chain

Preamplifiers: Voltage and Charge Sensitive

- Two general types of preamps used for radiation detectors:
  1. Voltage Sensitive Preamp

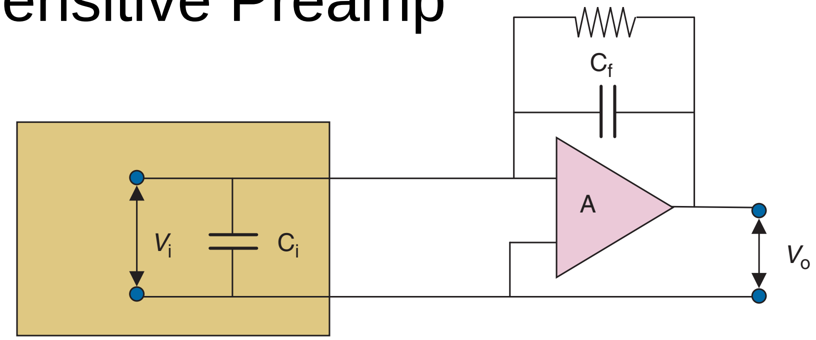


Radiation detector

$$V_i = \frac{Q}{C_i}$$

$$V_o \approx -\frac{R_2}{R_1} V_i$$

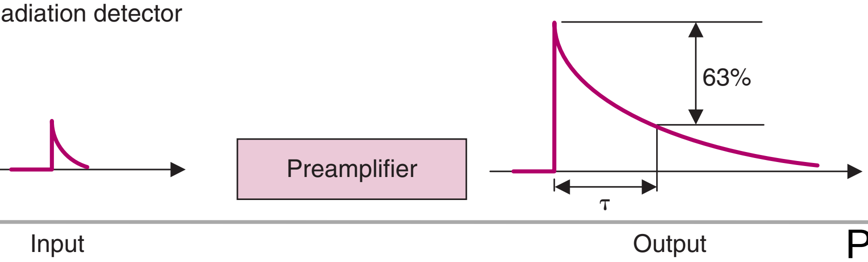
  2. Charge Sensitive Preamp



Radiation detector

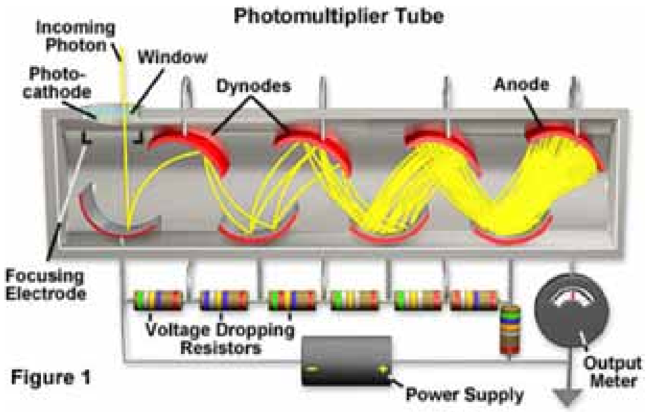
$$V_o \approx -\frac{Q}{C_f}$$

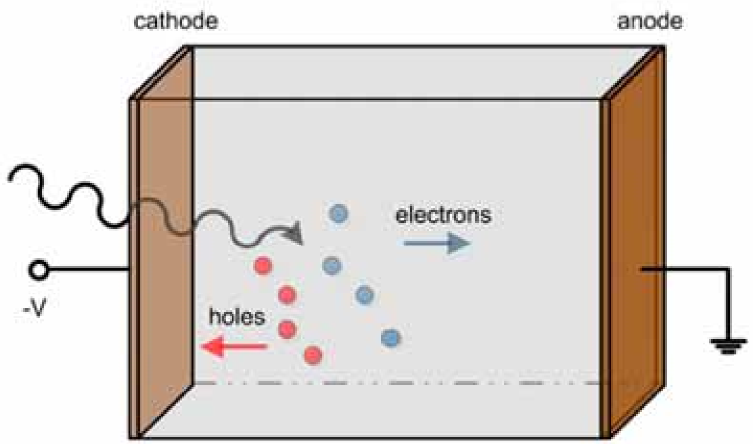
$$V = V_o e^{-t/R_f C_f}$$



Preamplifiers: Amplification

- The amplification supplied by the preamplifier depends on the detector type
  - Photomultipliers in scintillation detectors provide gain, so little amplification is necessary ~5-20x
  - In some NaI:Tl based imagers, no gain is used in the preamplifier
  - Semiconductor detectors, having smaller signals my require much more amplification ~10^3-10^4





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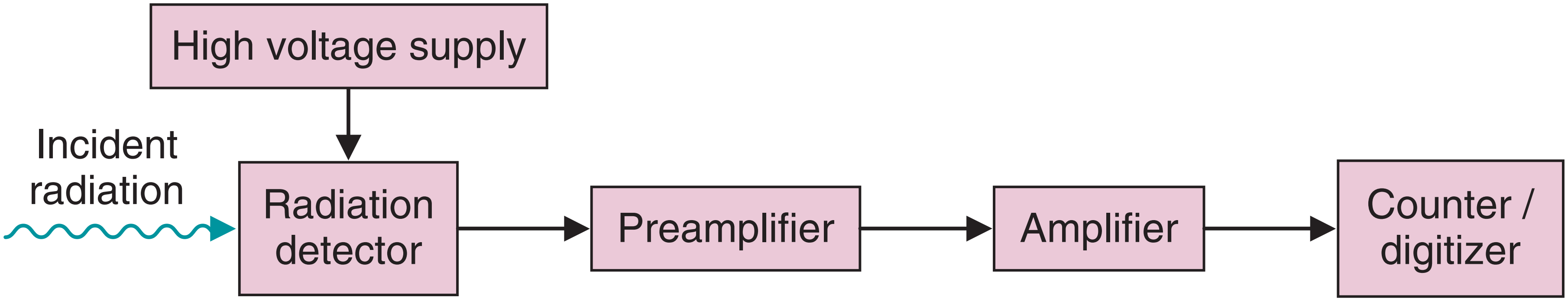
- Preamp should be linear, preserve Energy vs. Charge/Voltage
- Preamp should be placed as close to the detector output as

General Signal Processing Chain for Radiation Detector:


High voltage supply
Incident radiation
Radiation detector
Preamplifier
Amplifier
Counter / digitizer

Amplifiers for Radiation Detectors:

- Amplification and Pulse Shaping Functions
- Resistor-Capacitor Shaping
- Baseline Shift and Pulse-Pileup

Amplifiers: The General Purpose

- The output signal form the preamplifier can still be quite low for traditional electronics in signal processing chain
- Three main purposes of the preamplifier (or preamp):
  1. To amplify, the still relatively small pulses from the preamplifier
  2. To reshape the long signals from the preamplifier to minimize pulse-pileup at high count rates and improve SNR

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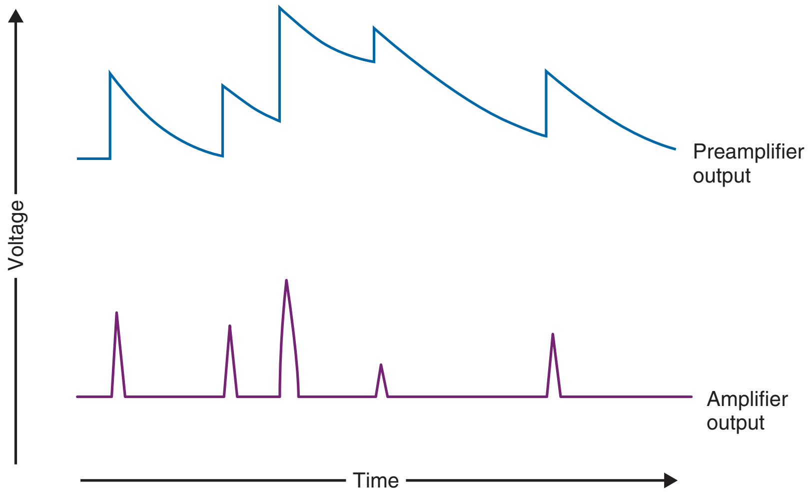
   - Preamp output typically ~500 µsec

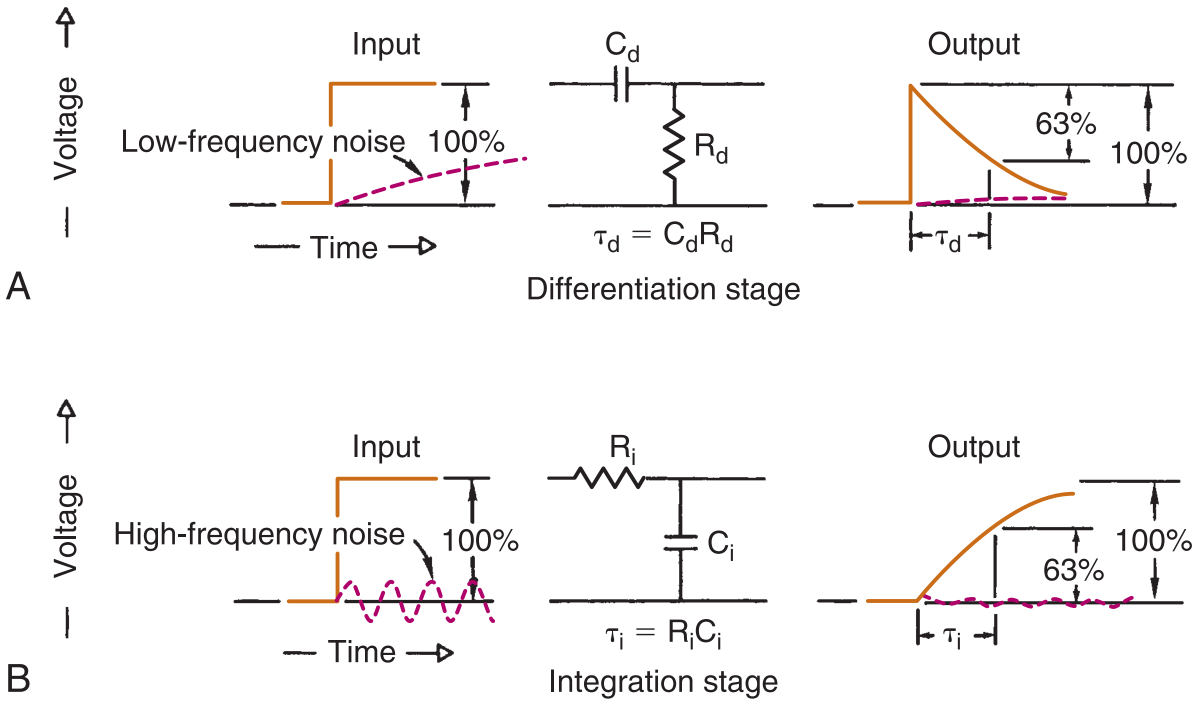
Amplifiers: The General Purpose

2. To reshape the long signals from the preamplifier to minimize pulse-pileup at high count rates and improve SNR
   - Essential function of the amplifier
   - Preamp output typically ~500 µsec
   - Pulses arriving at rates >100/sec would ride on the tail of previous pulse
   - **Inaccurate amplitude information (i.e. Energy info)**



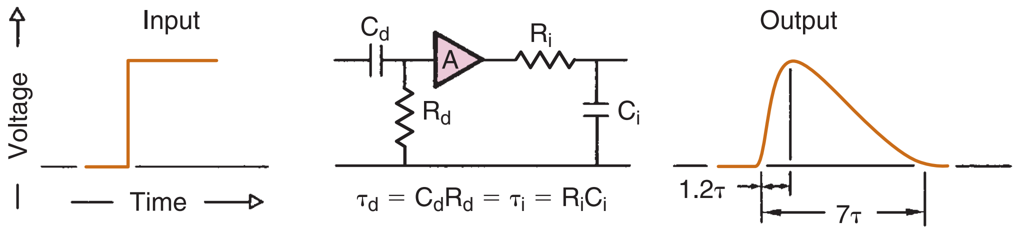
RC Shaping of Detector Signals

- The most common way to shape signal with the amplifier is RC shaping methods



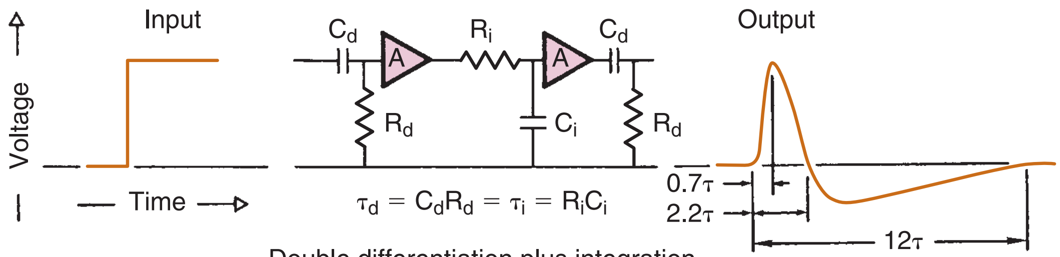
RC Shaping of Detector Signals

- In (A), the result of successive differentiation and integration shown, produces unipolar pulse. In (B), double differentiation produces bipolar pulse.



A

Differentiation plus integration



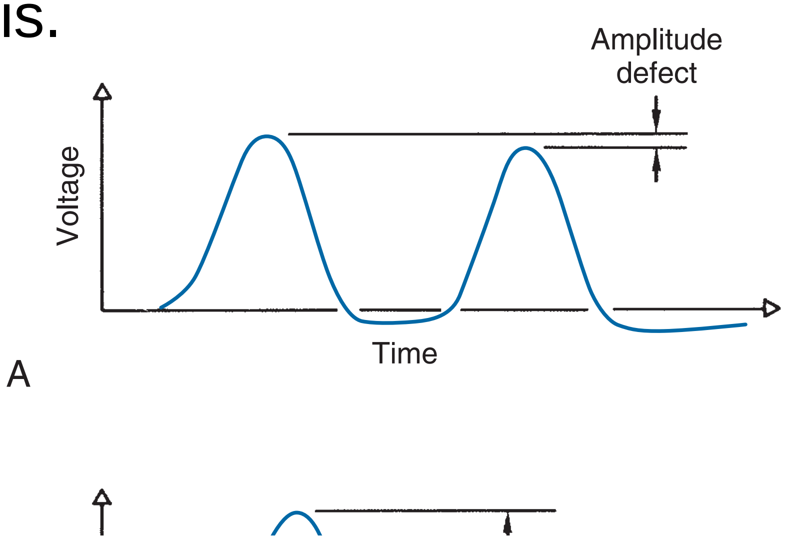
B

Double differentiation plus integration

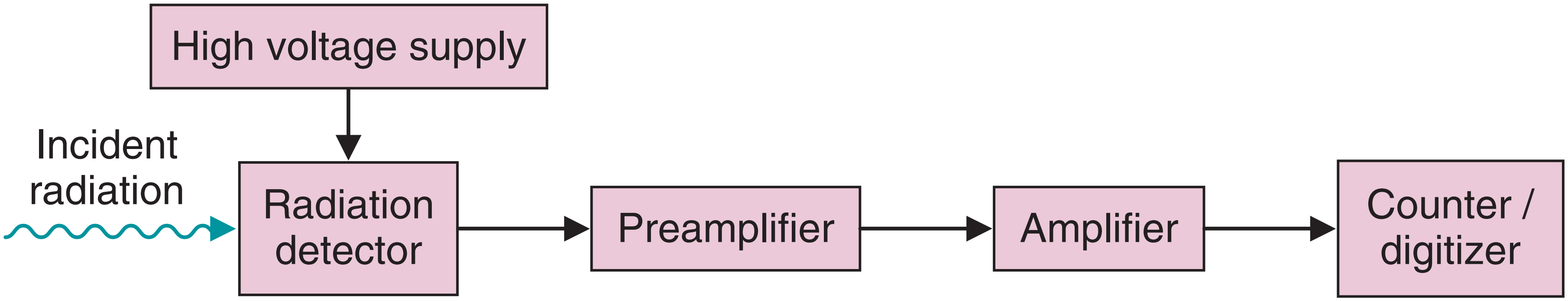
- Unipolar pulses preferred for best energy resolution, bipolar pulses preferred for high count rate applications

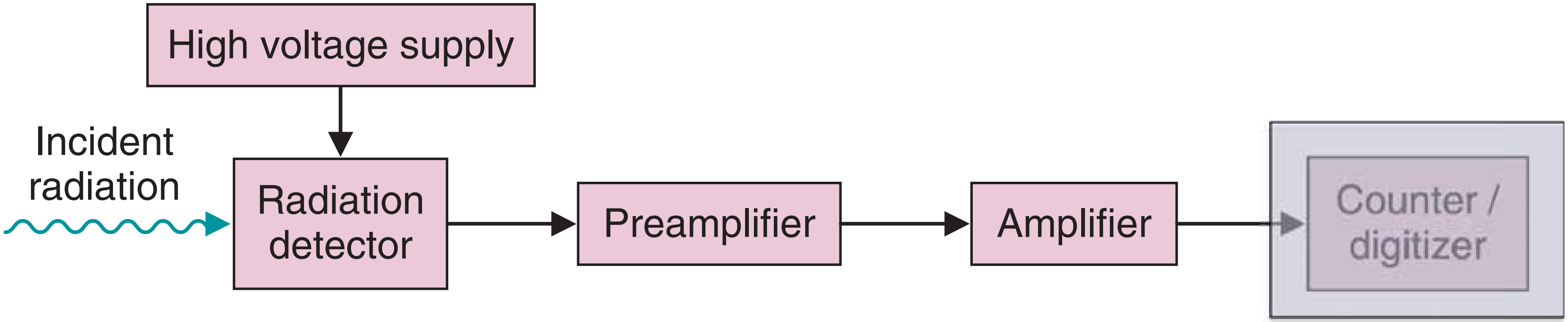
Baseline Shifts and Pulse Pile-up

- In (A), an example of amplitude defect shown due to baseline shifts. Event riding on negative portion of unipolar pulse appears less energy than actually is.
- Corrected with pole-zero cancelling circuits.
- In (B), the effect of pulse-pileup is shown.
- Situations avoided with low RC time constants, reducing SNR and energy resolution



General Signal Processing Chain for Radiation Detector:





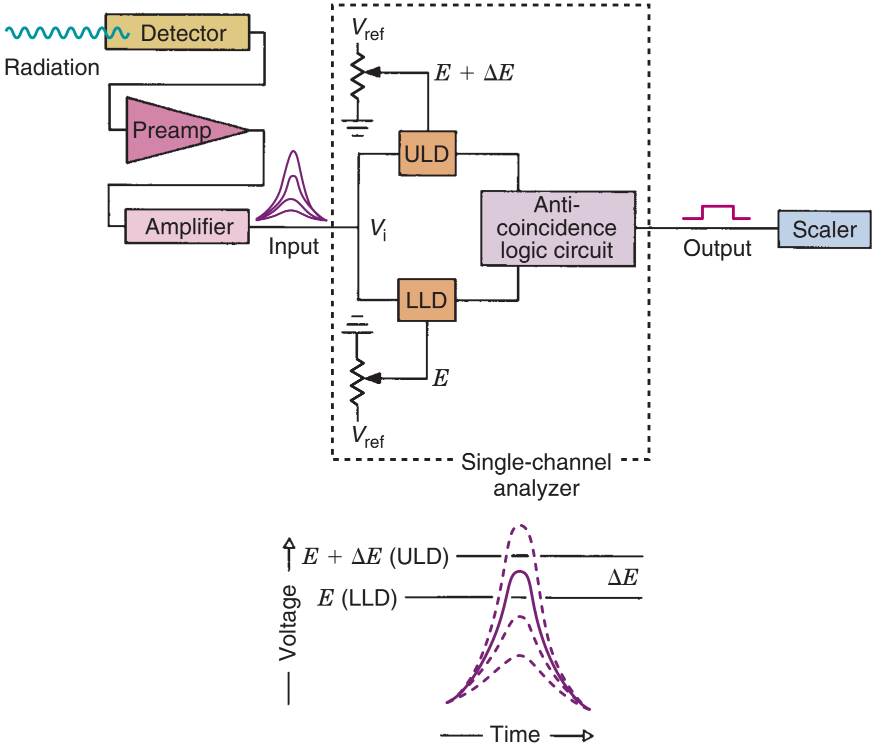
Pulse Height Analyzers

- Single Channel Analyzers
- Multi-Channel Analyzers

Pulse Height Analyzers: Basic Functions

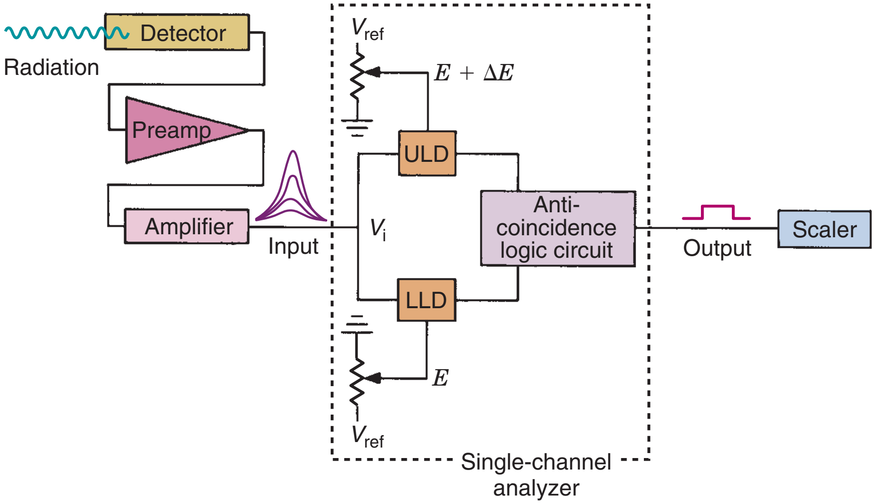
- For energy sensitive detectors (ex. NaI:Tl), examining amplitude of amplifier pulses provides information on energy deposited in the detector
- A devices for this task is called a pulse height analyzer (PHA).
- A PHA examines pulse height to determine if it lies within a particular range or “channel”:
  - Single channel analyzer
  - Multi channel analyzer

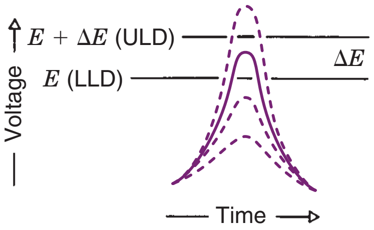
Single Channel Analyzers (SCAs)



- Output is identical square pulses, no longer containing energy information, already extracted by SCA
- These output pulses are used to drive counters, rate meters, or other circuits

Single Channel Analyzers (SCAs)

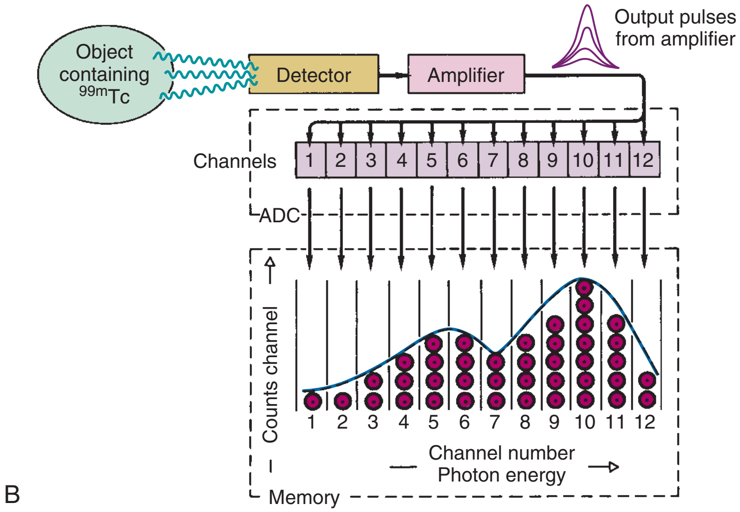




- A second type of SCA, where there is no upper level discriminator, that includes all events above one lower threshold is simply called a discriminator

Multi Channel Analyzers (MCAs)

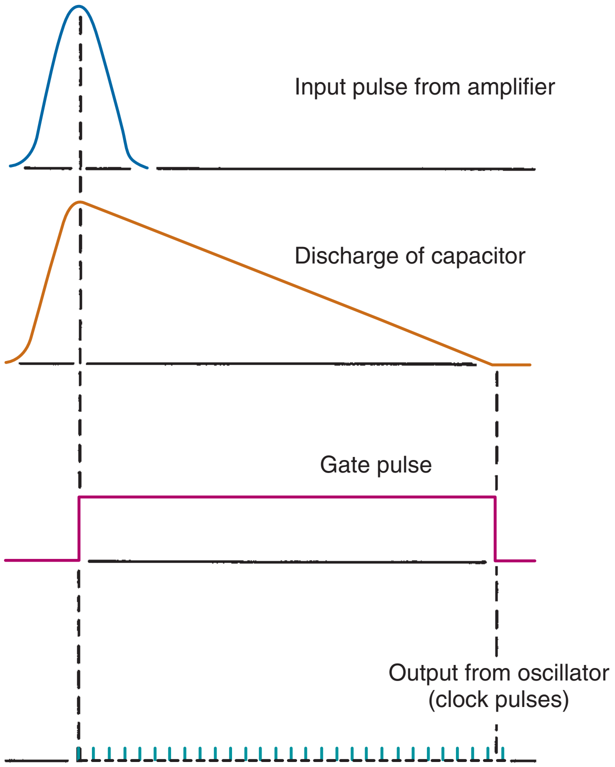
- Some applications require simultaneous recording of information in multiple energy windows
- Some SCAs have 2-3 windows, but a practical solution is Multi Channel Analzyers that use ADCs to sort Energy info



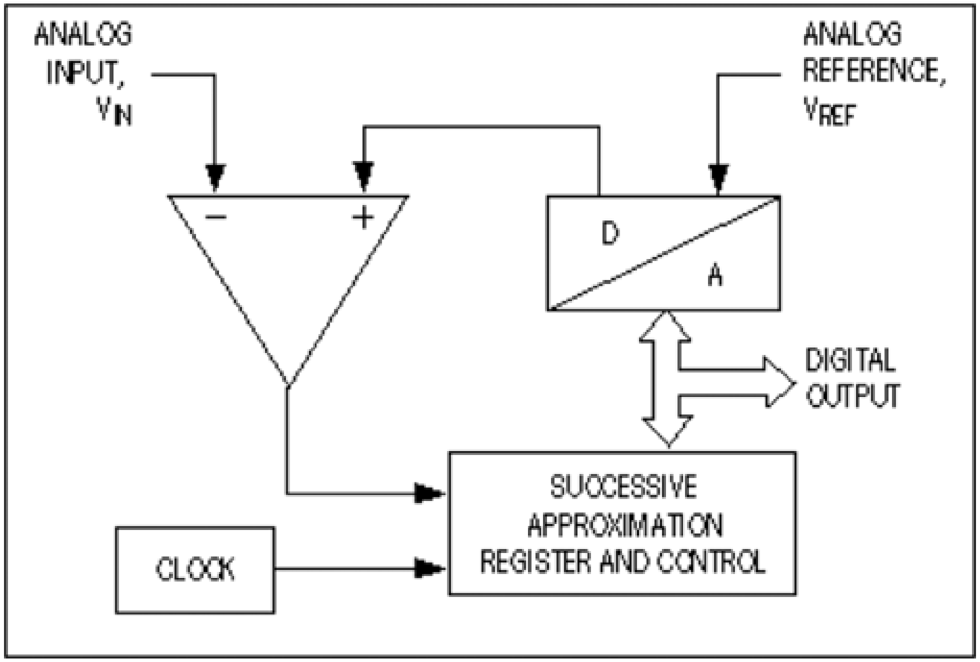
Analog to Digital Conversion Methods (ADC)

- The ADC is the heart of the MCA, and two general types are used in radionuclide imaging applications:

Wilkinson (or Ramp) Converter

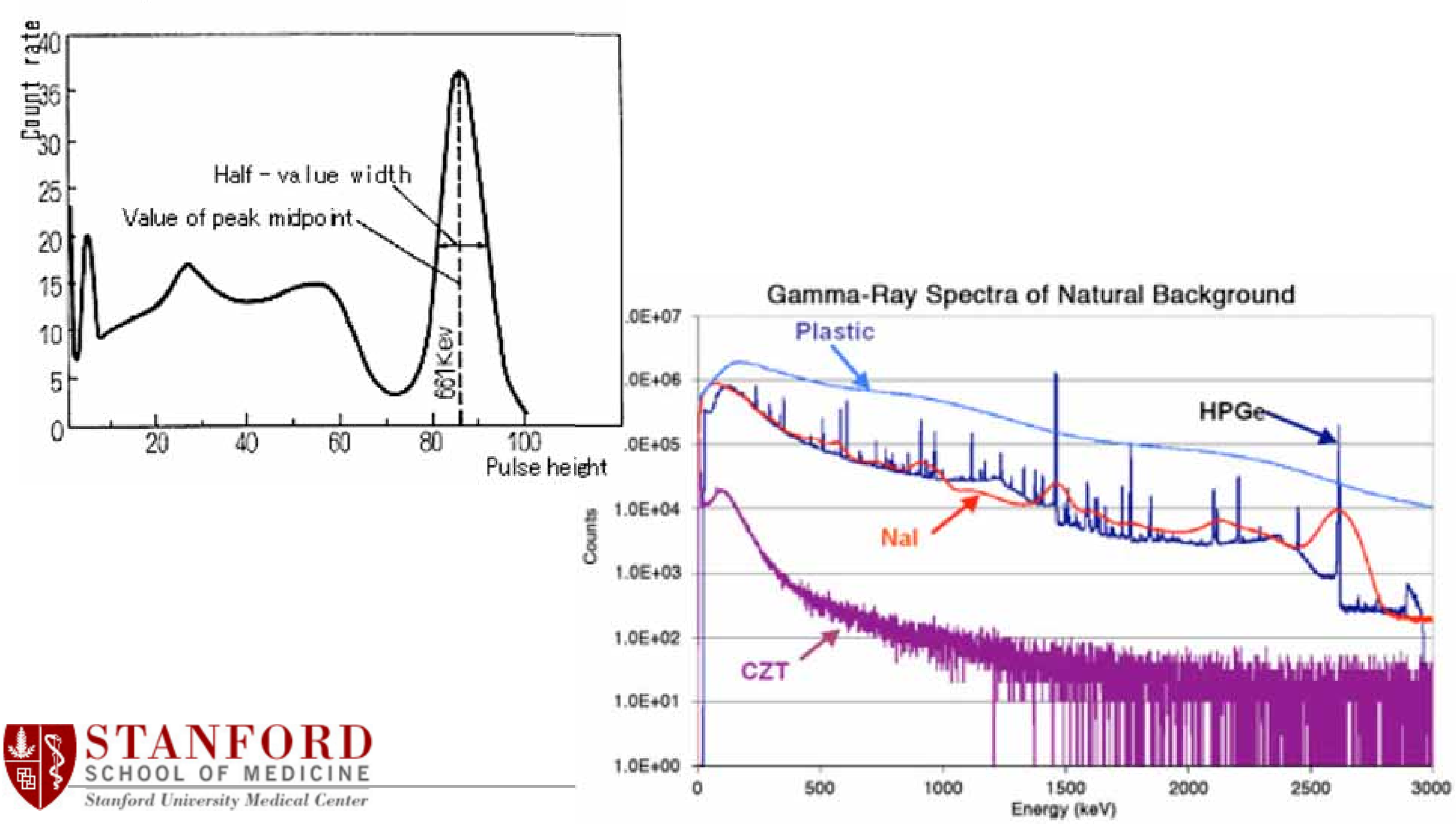


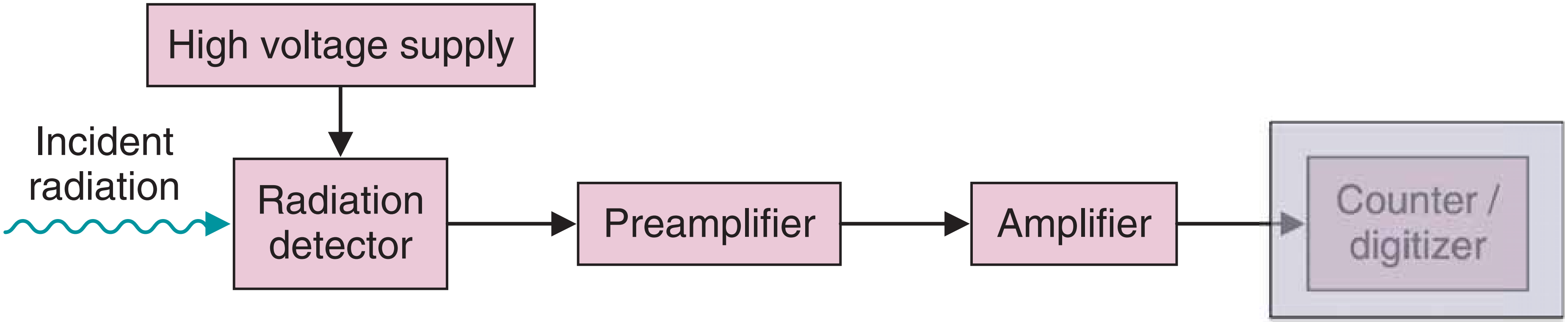
Successive Approximations Converter



MCA in Application: Spectroscopy

- The application of MCA provides powerful spectroscopic capabilities




High voltage supply

Incident radiation

Radiation detector

Preamplifier

Amplifier

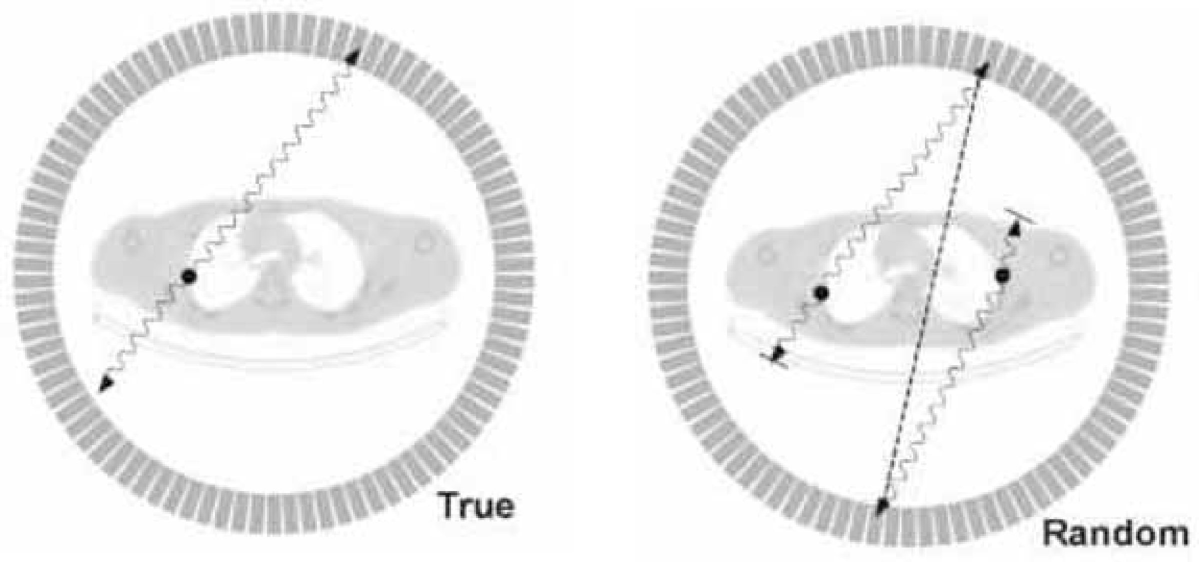
Counter / digitizer

Time-to-Amplitude Converters (TACs):

- Convert time difference between two pulses to a proportional Voltage

Time-Pickoff in Radionuclide Imaging

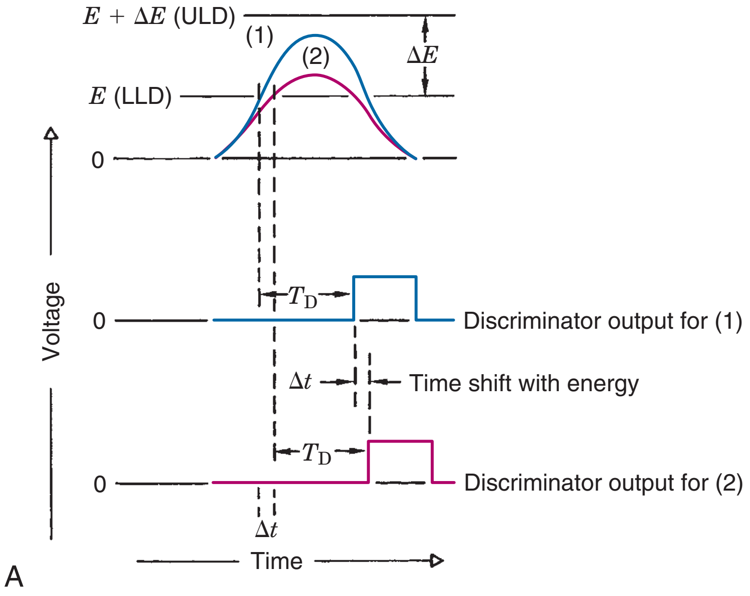
- Applications in radionuclide imaging require knowledge on the time of arrival of tracer-specific emissions at the detector
  - Ex: PET coincidence annihilation photons to discriminate real events from randoms.



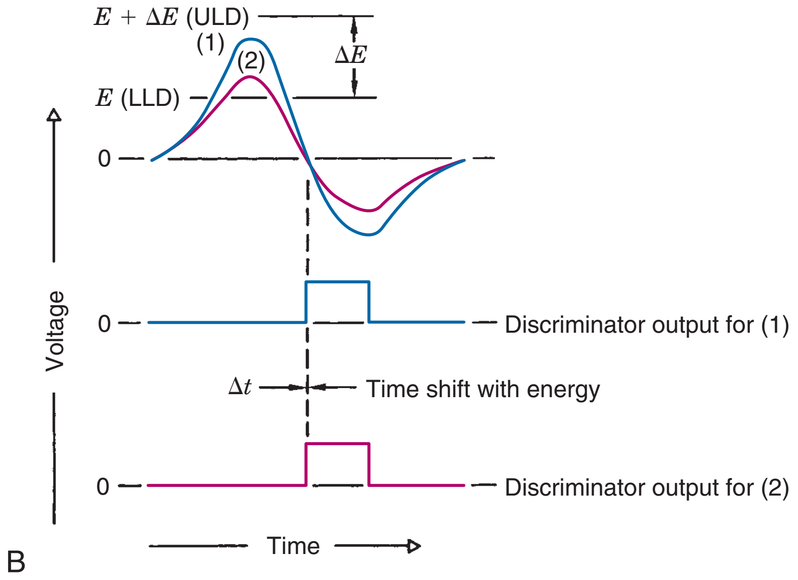
Timing Methods: Time of Interaction Estimation

- Timing Methods: Leading Edge and Crossover Timing

Leading Edge, Most Simplistic



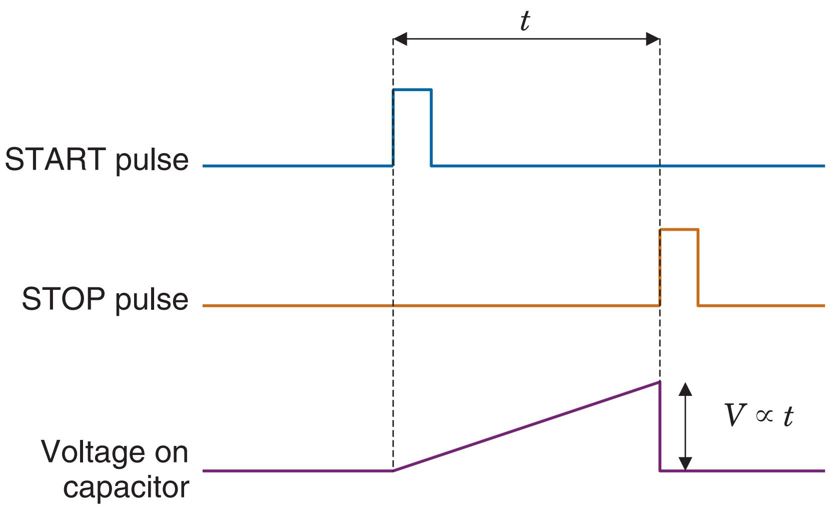
Zero-crossing Time Pickoff



- Other fast timing methods include peak detection and constant fraction discrimination

Time-to-Amplitude Converters: Function

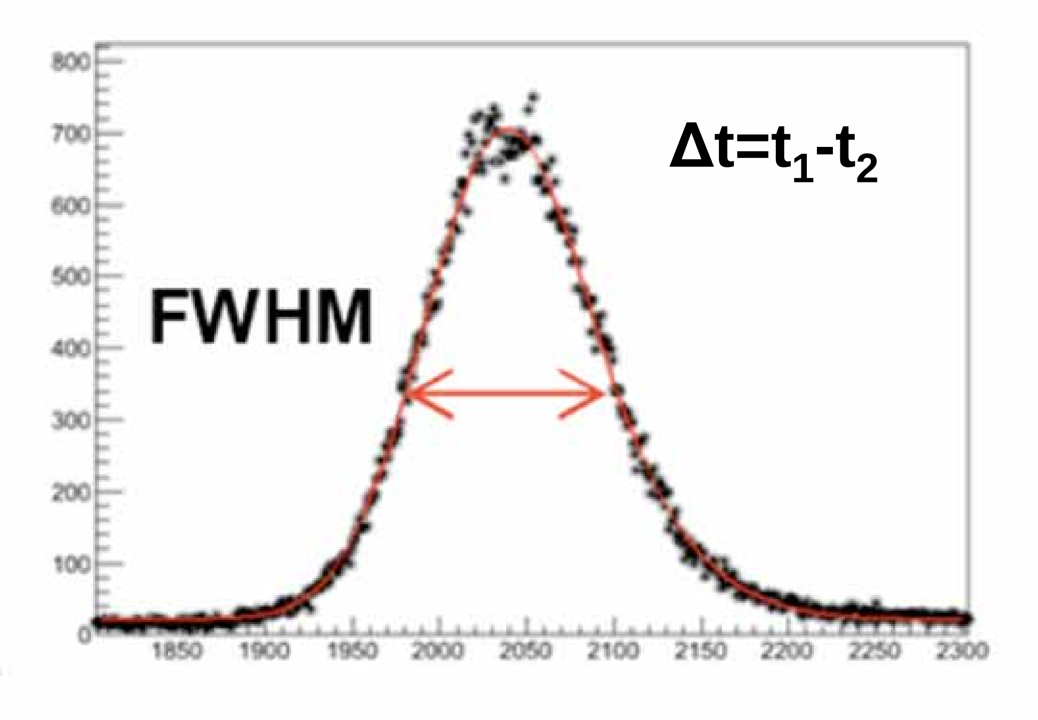
- Typically SCA selects events within a certain energy range, producing logic pulse for first event passed to module inside energy window
- Module drives a constant current source to charge a capacitor
- Second event into module within energy window terminates charging of capacitor
- Current source linear, therefore, Voltage at capacitor also linear with time between START and STOP

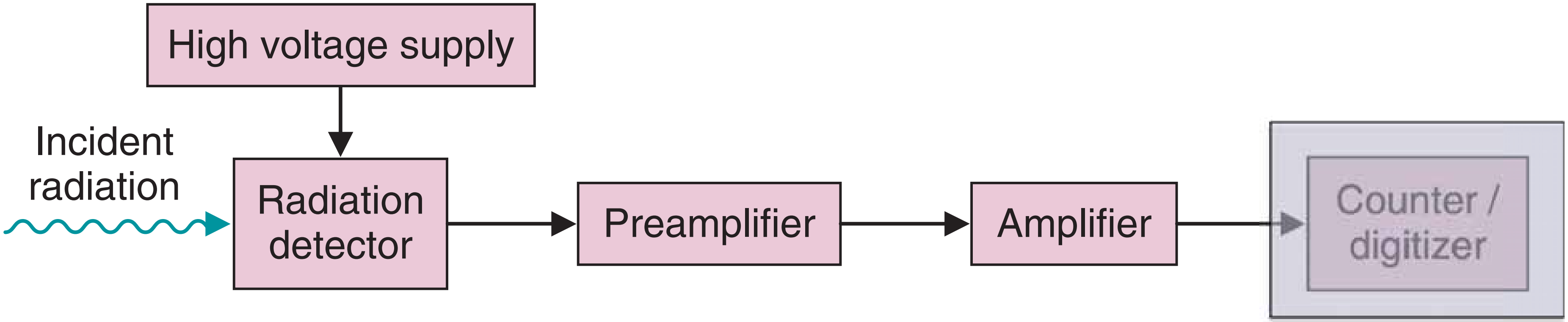


Time-to-Amplitude Converters: Function

- Output of the module is a logic pulse with amplitude proportional to time between the two events
- This can be viewed with a MCA, calibrated for time
- Can also be used to form a coincidence window for counting
- These modules not really used in imaging systems, more so for research applications

MCA Time Difference Spectrum:





Incident radiation

High voltage supply

Radiation detector

Preamplifier

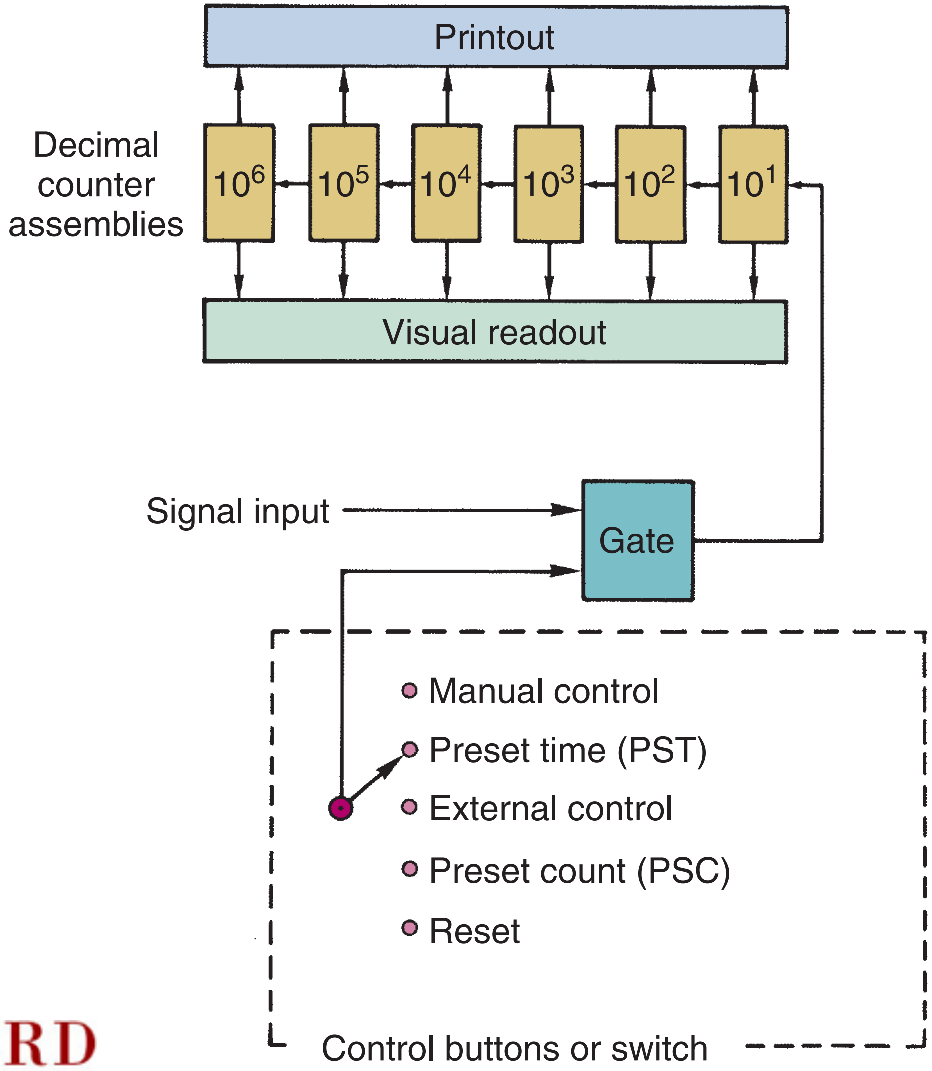
Amplifier

Counter / digitizer

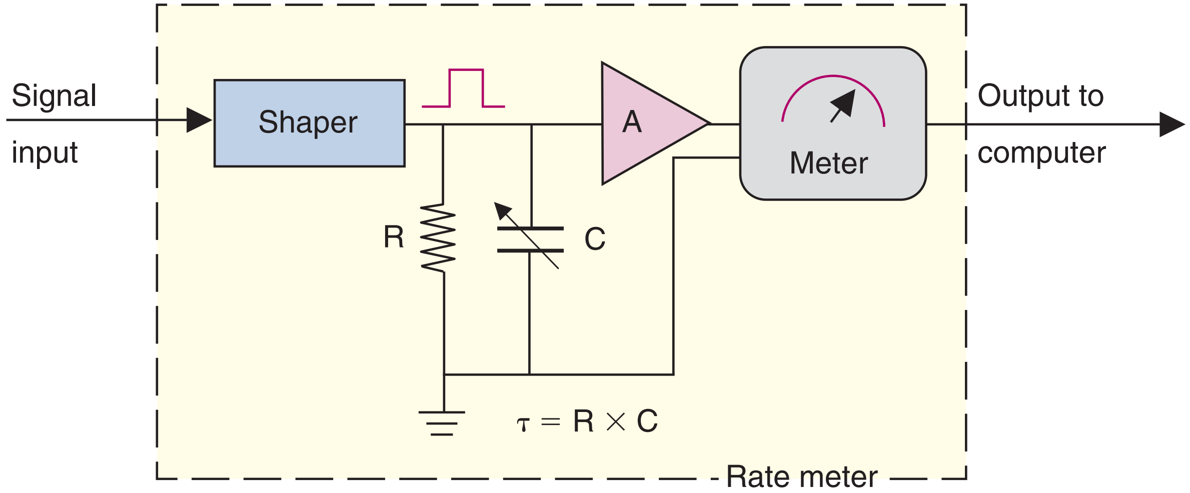
Digital Counters and Rate Meters:

- Scalers, Timers, and Counters
- Analog Rate Meters

Scaler-Timer



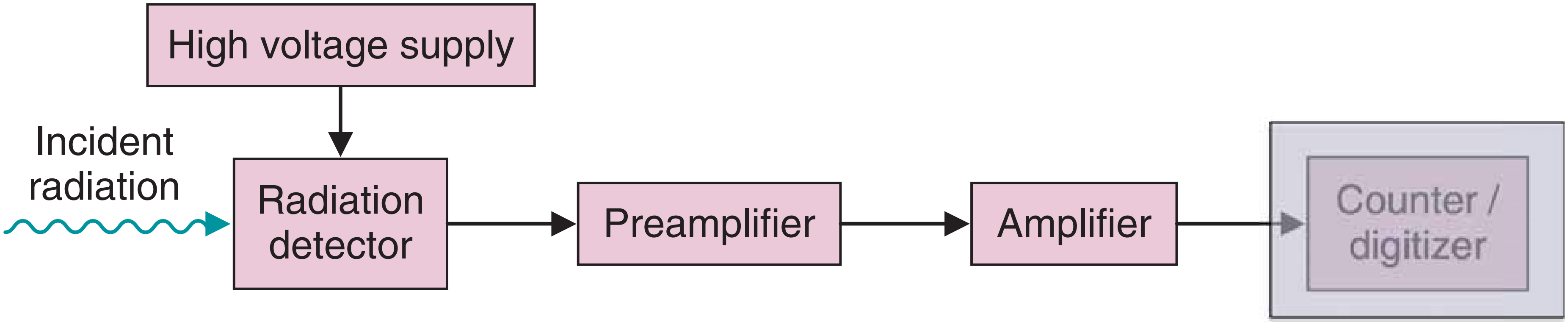
Analog Rate Meter



$$I = \bar{n}Q$$

$$V = \bar{n}QR$$

$$V_o = k\bar{n}QR$$



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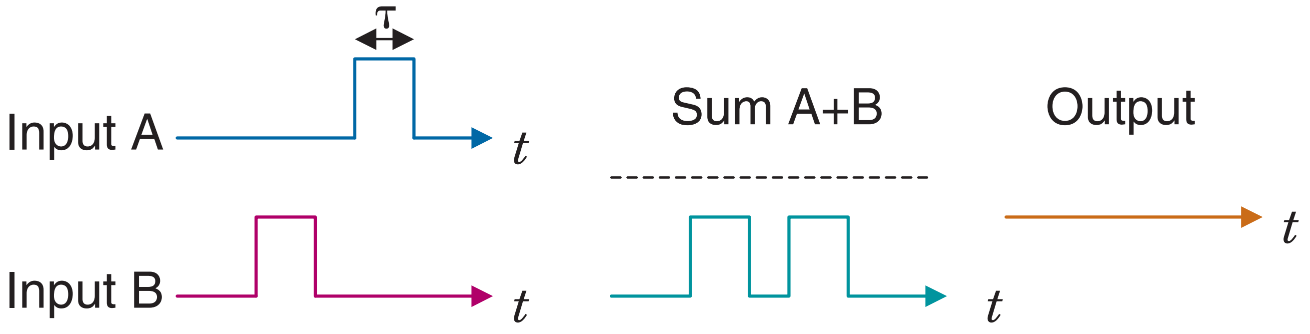
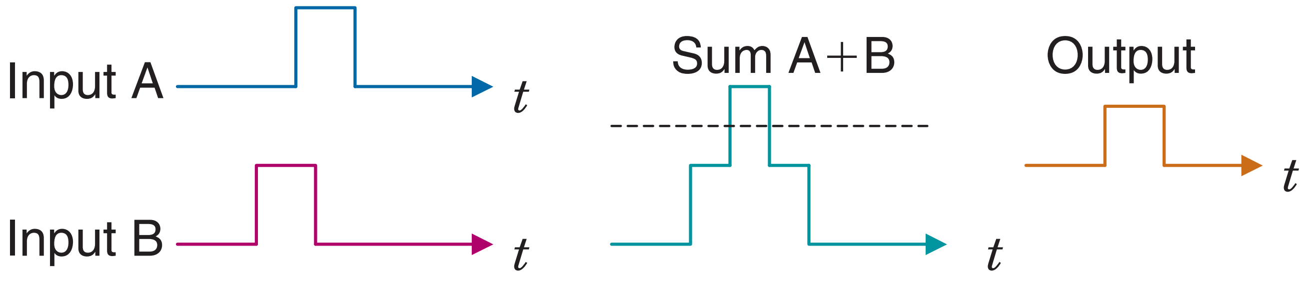
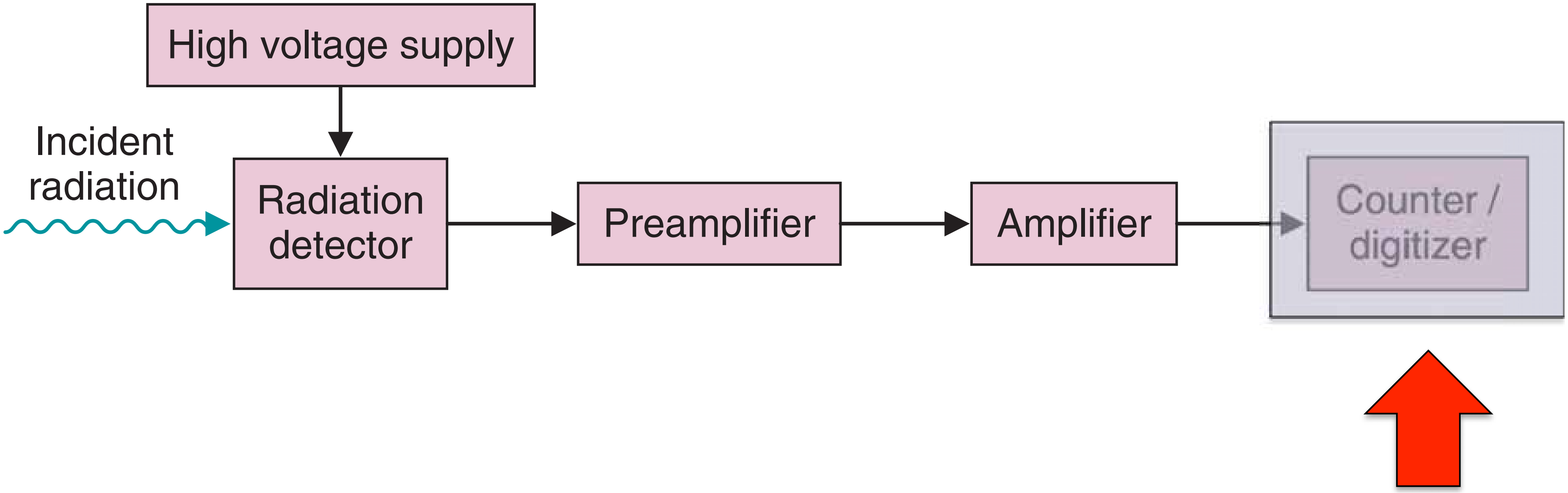
Coincidence Units:

Coincidence Untis







High voltage supply

Incident radiation

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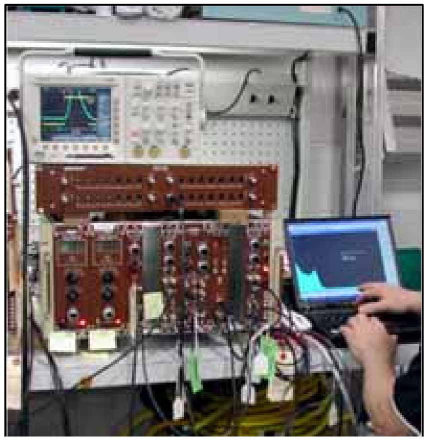
Peripheral Components for Radiation Detectors:

- High Voltage Power Supplies
- Analog and Digital Oscilloscopes

Power Supplies and Integrated Electronics Platforms

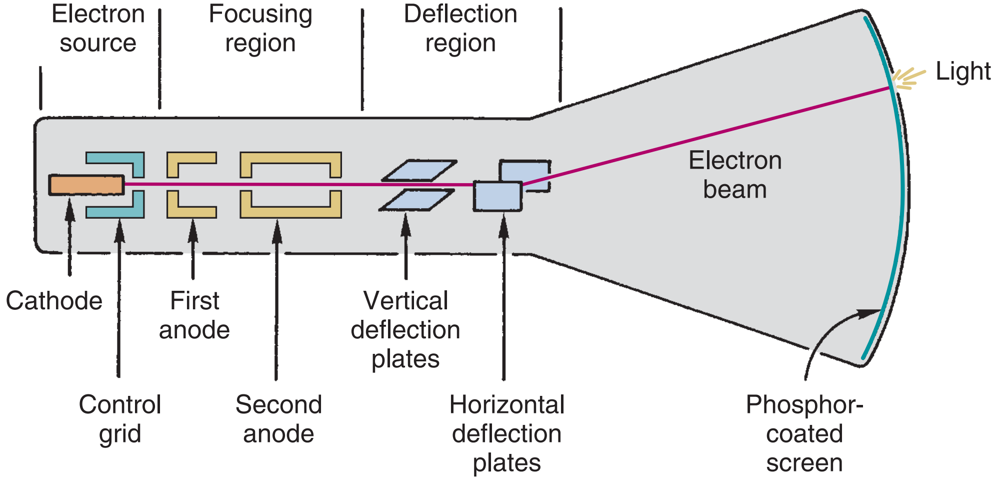
- Keep in mind that a single detector requires hundreds or thousands of volts
- General research applications for traditional radiation detection problems have well-defined needs.
- Nuclear Instrumentation Measurement (NIM) Electronics Bin



- Other mixed analog/digital standardized platforms have emerged
  - CAMAC
  - VME

Analog and Digital Oscilloscopes

- Analog Oscilloscopes – Cathode Ray Tube:



- Digital Oscilloscopes – Fast ADCs + Digital Algorithms

Summary: Electronics for Radiation Detectors

- Charge generated in radiation detectors from interaction of photons in radionuclide imaging is typically quite low
- Preamplifiers amplify and preserve information from detectors
- Amplifiers mostly shape signals and provide additional amplification if necessary for remainder of signal processing chain
- With a clean, linear signal from amplifiers, the signal can be processed to extract or infer information about the radiation that interacted in the detector:
  - SCA – Is signal within a defined energy window?
  - MCA – Statistically visualize events in detector.
  - Counters – How many events? How fast? (Activity)
  - TACs – What was the time difference between multiple events? (Coincidence Processing)