TRIUMF

DAQ and electronics

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GRIDS 2026

Discovery, accelerated

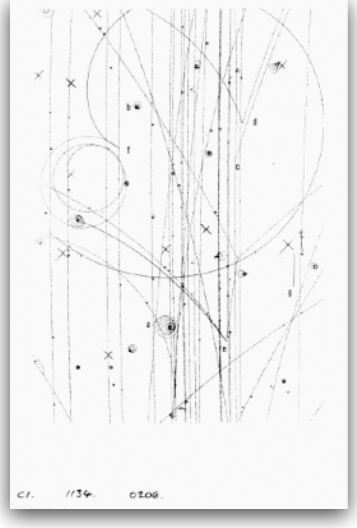
Data AcQuisition

- Convert a physical signal into data that can be analysed
- This talk will try to illuminate this black box

✳Reasonably accurate representation of my knowledge of the T2K DAQ during my PhD

DAQ in the 1960s

- "Scanner" and "computer" were job titles
- Not very scalable



DAQ now

- Almost universal approach
  - Convert physical phenomenon into **electrical signal**
  - Amplify/filter
  - Trigger
  - Simplify
  - Digitise
  - Write to disk
- The ordering can vary and some steps may be skipped

Before we dive in to the details

- Keep in mind that DAQ needs to be considered when you're designing your experiment
  - DAQ output must be sufficient for physics goals
  - Can be a large part of your budget!
- Your physics analysis and simulation also need to know about the DAQ
  - Deadtime? Pileup? Saturation? Efficiencies? Resolution? Algorithmic decisions? Rounding?
- Even if it seems simple, there are probably subtleties...

Introduction

Signal manipulation

Triggering

Wiring and crates

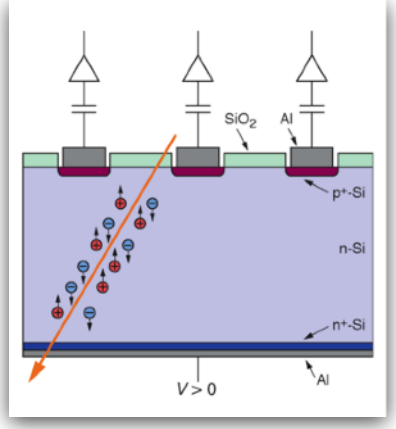
DAQ frameworks

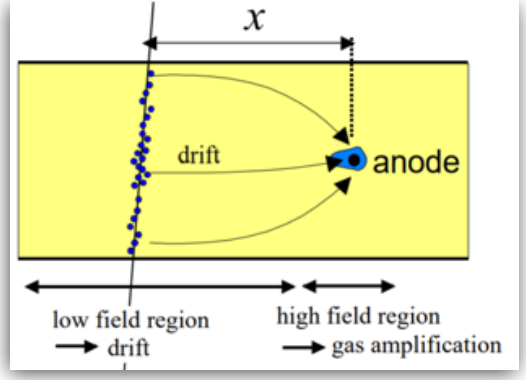
Software and firmware

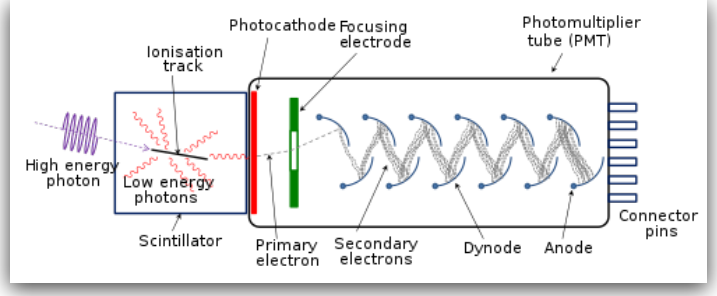
Example experiments

Electrical signals

- Electrical signals are well suited for transport, manipulation, digitisation
- Amplification within detector of 10^5 to 10^{10} typical
  - $Q_e = 1.6 \times 10^{-19}$ C; 100mV x 10ns = 10^{-9} C
- See other lectures for how detectors convert physical phenomena to electrical signals

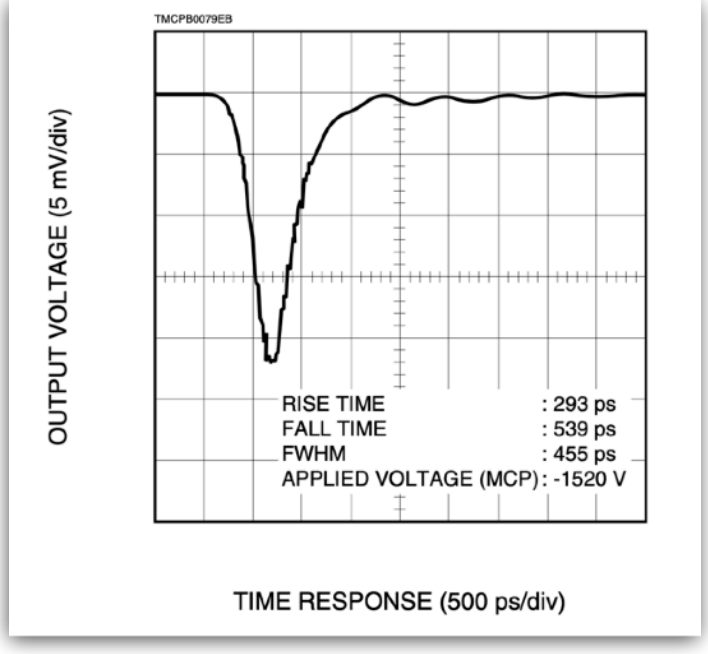






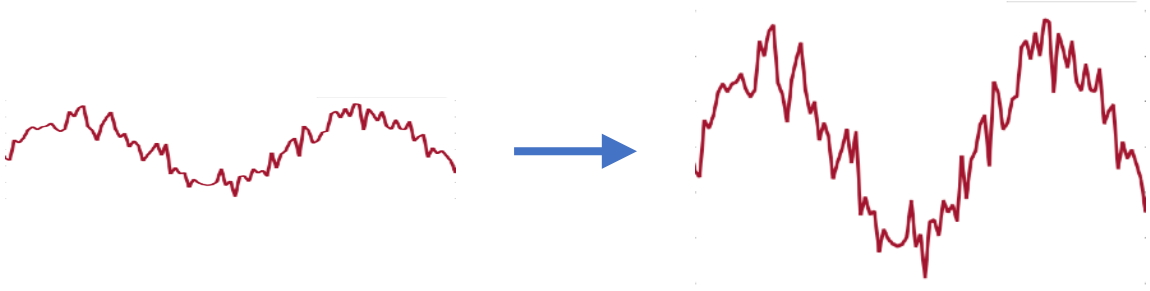
Typical detector signals

- Amplitude and time-scale vary based on device
- PMT and SiPM for a single photon ~ 100mV x 100ns
- MCP for a single ion ~ 10mV x 1ns



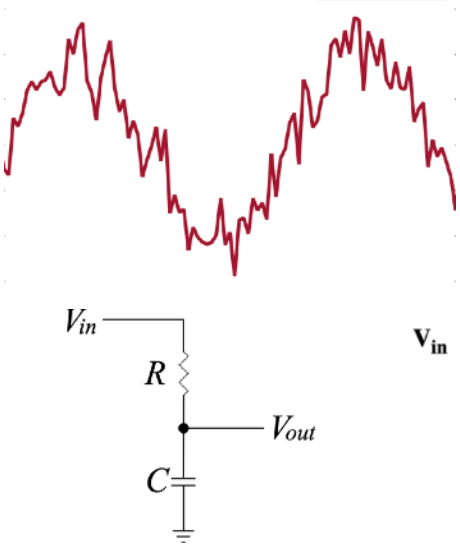
Amplification

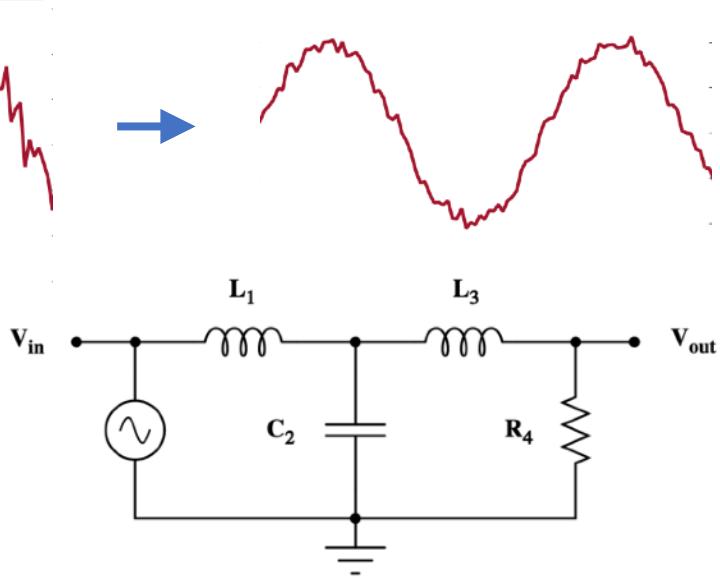
- If signal is very small, may want to amplify it further
- Reduce impact of any noise introduced after amplification (e.g. while transmitting through cables)
- Better match subsequent electronics (e.g. digitiser has a +/- 2V range)

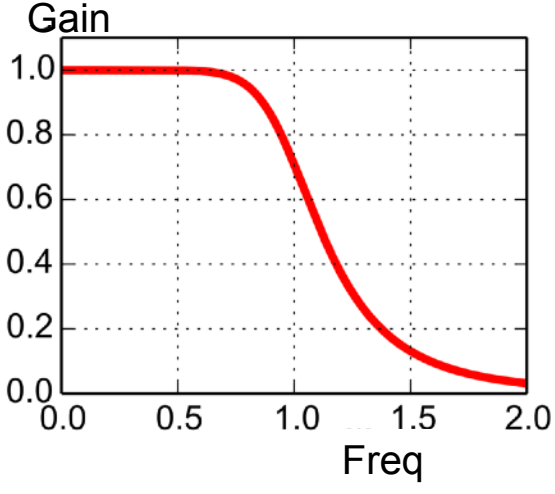


Filtering / noise reduction

- Can use a filter to reduce high-frequency noise without affecting low-frequency signal
- Can be as simple as resistor+capacitor, but "higher order" arrangements give better response

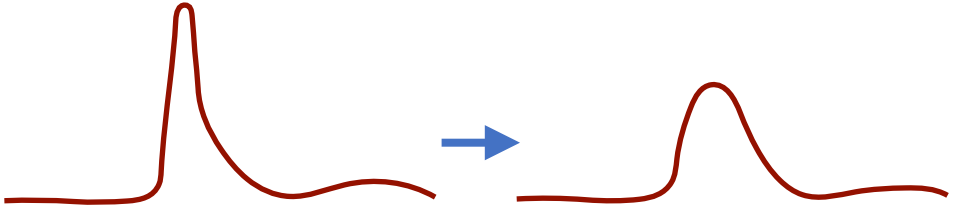


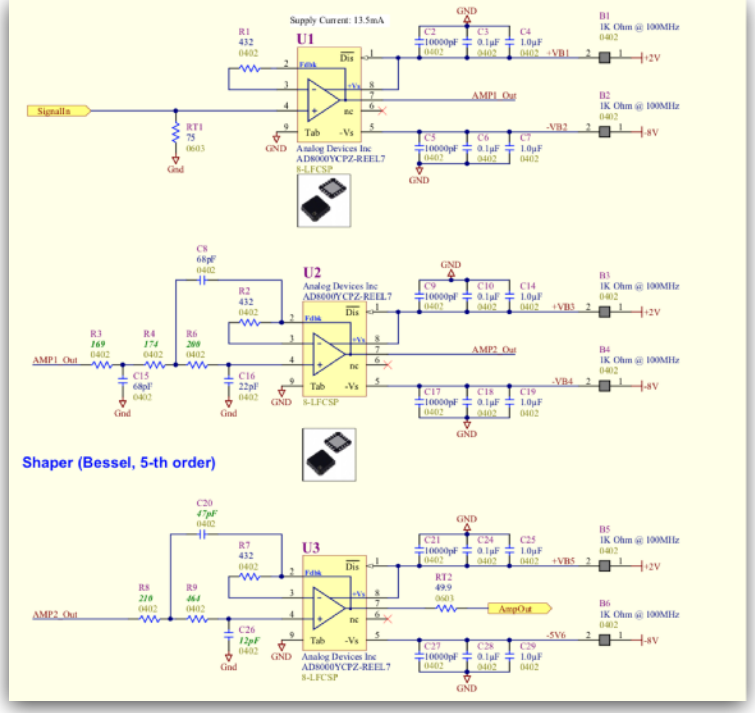




Shaping

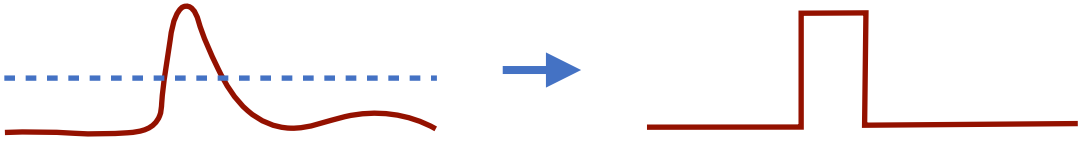
- Can stretch a fast signal to take longer
- E.g. to better match time resolution of a digitiser
  - Very fast digitisers are very expensive!
- Amplifiers+capacitors+resistors

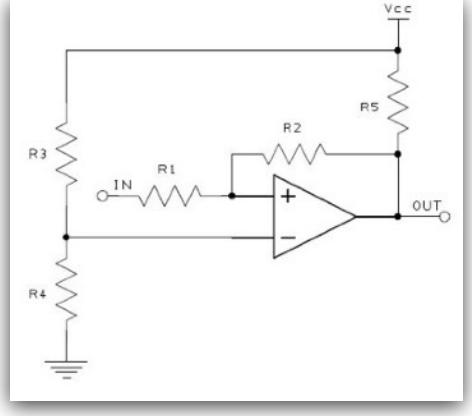




Threshold crossing - discriminators

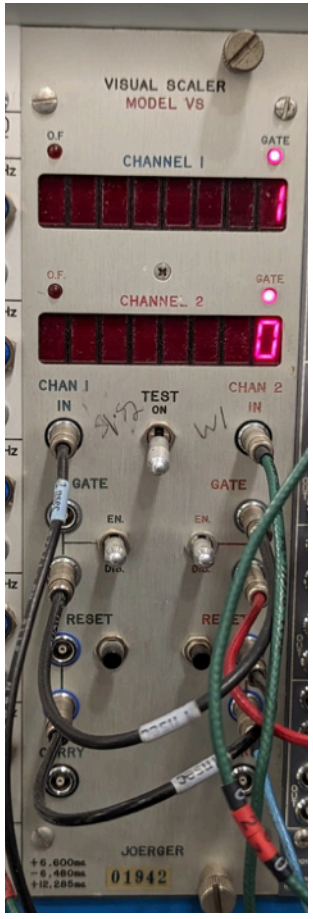
- We've looked at analog electronics so far
- Discriminators convert an analog signal to a digital (0/1)
  - Easier to process and check for coincidences etc.
  - Good for detection and timing
- Simple discriminators implemented by comparing to a set voltage





Counting pulses - scalers/MCS

- Simplest thing you can do with digital signals - count!
- Visual / blind versions available
- Multi-channel scaler (MCS) has a terribly confusing name...
  - Should really be called a histogramming scaler
  - Counts pulses in each time bin (dwell time)

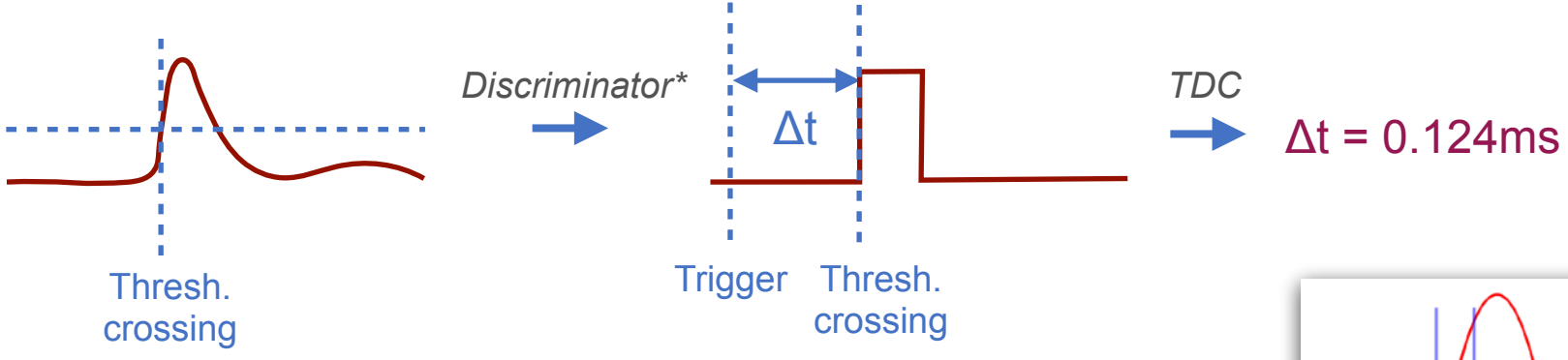


Visual scaler

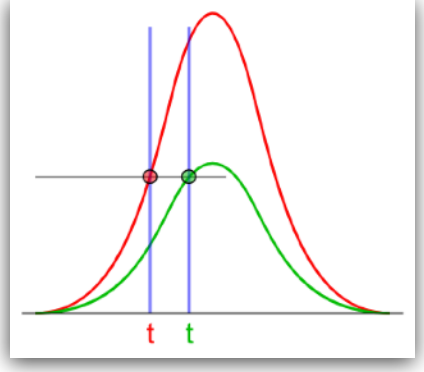
Blind MCS

Time of pulse - TDC

- Time to digital converter
- Tells you the time of a pulse relative to a trigger signal
- 3ps resolution now available commercially



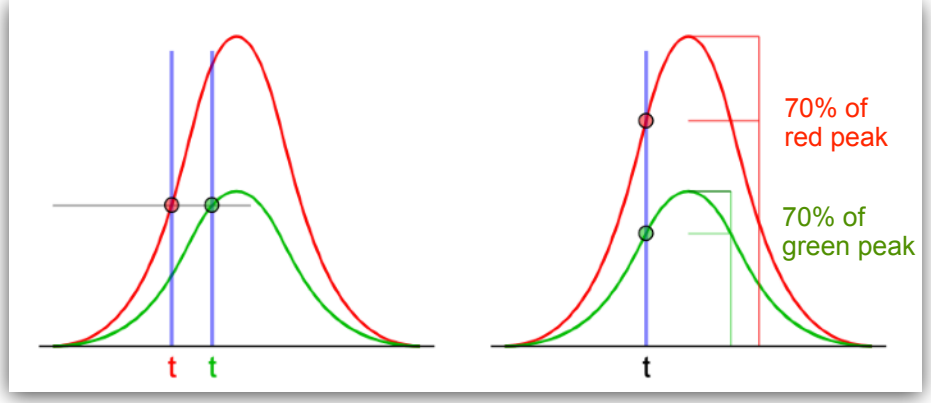
- Need to worry about time-walk effect if discriminator uses constant threshold voltage!

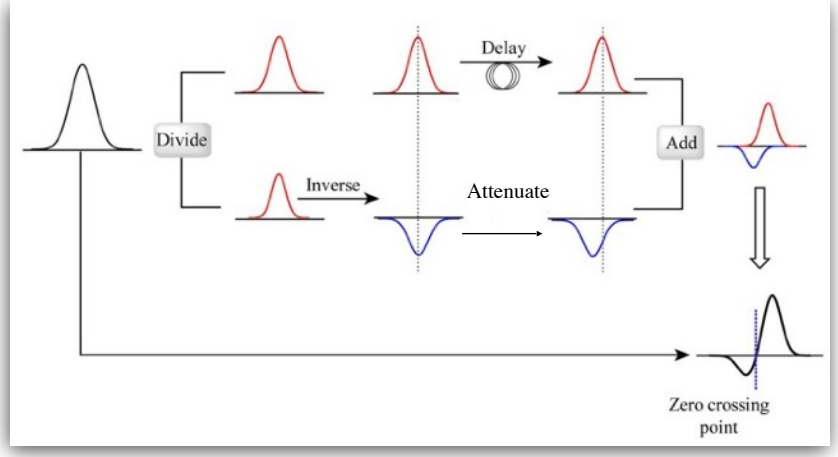


*Sometimes TDC includes its own discriminator

Constant fraction discriminator

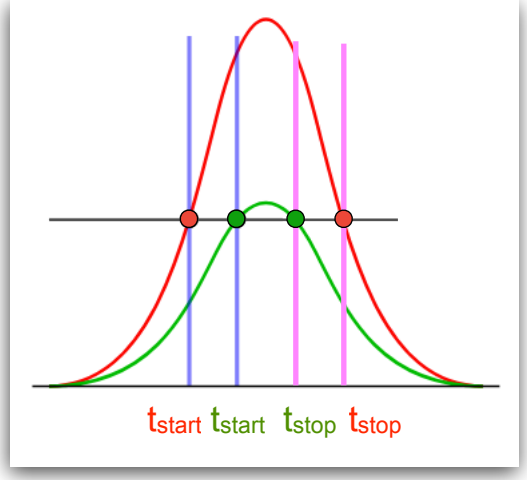
- Classic approach to dealing with time-walk correction
- Trigger at X% of pulse height, rather than fixed voltage
- Only works if signal has same rise time regardless of amplitude - e.g. scintillators





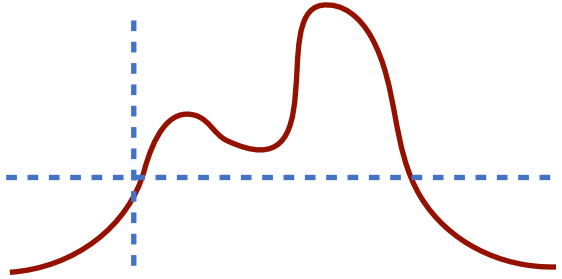
Alternative approach to time-walk

- Record start time and time-over-threshold for each pulse
  - Correlated with pulse charge / amplitude
- Do time-walk correction in software
- More flexible than CFD
  - Works even if pulse shape changes with amplitude
- You must have excellent knowledge of how your signal varies with amplitude!



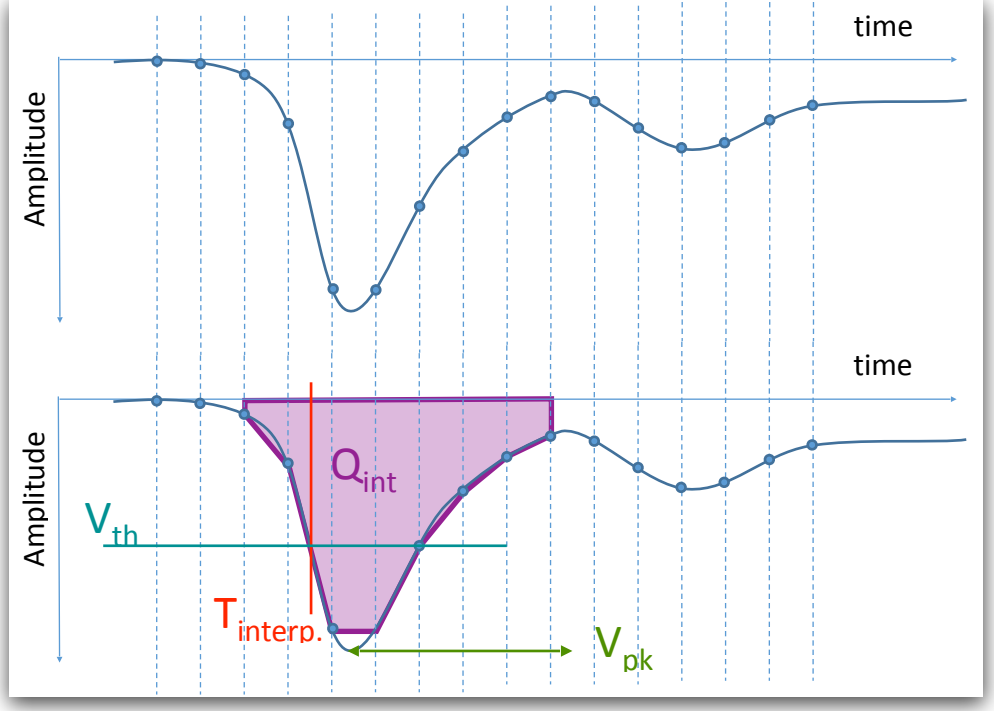
Pileup and complex waveforms

- Some experiments need to count every photon
  - E.g. dark matter experiments where signal is time distribution of ~100 photons
- Pileup of 2 photons is a problem for scaler/TDC - only get 1 count/timestamp!
- Need to either calculate the charge of the pulse (QT) or read out full waveform for offline analysis (digitiser)



ADCs / digitisers

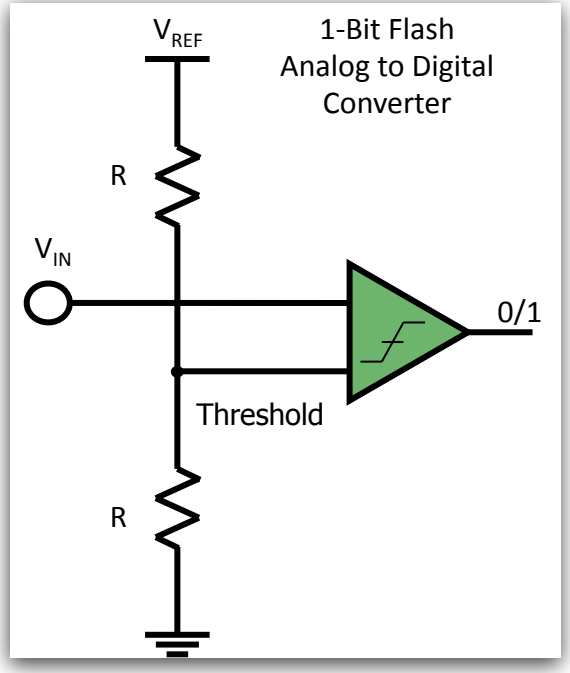
- Sample the waveform at specified sampling rate
- 10-bit resolution for 2V range: 2mV steps (4-bit: 125mV)

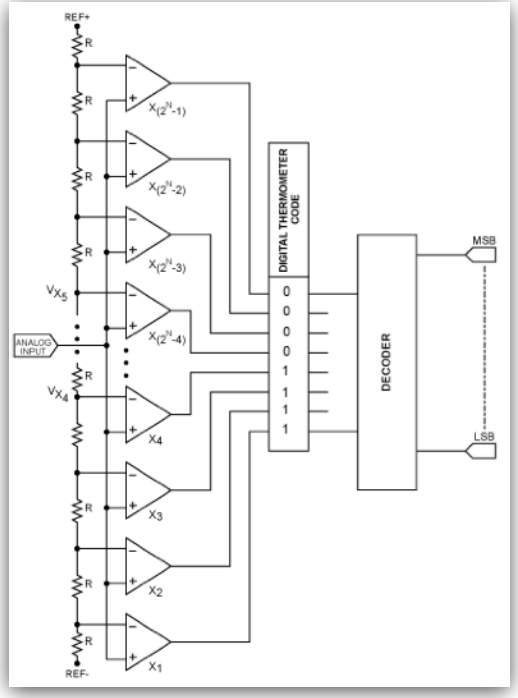


ADC Type	Resolution (bits)	Sampling rate
Dual Slope	12-20	100 sample/s
Successive approximation	8-18	10 Msample/s
Flash	4-12	10 Gsample/s
Pipeline	8-16	1 Gsample/s
Delta-sigma	8-32	1 Msample/s

Flash ADC implementation

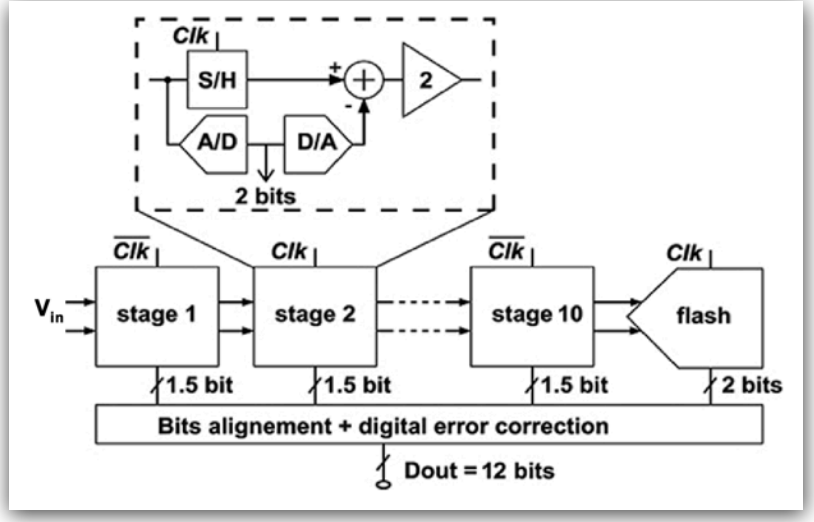
- Conceptually simple, but cost grows exponentially with resolution
- Need 2^{10} threshold comparators for 10-bit ADC!





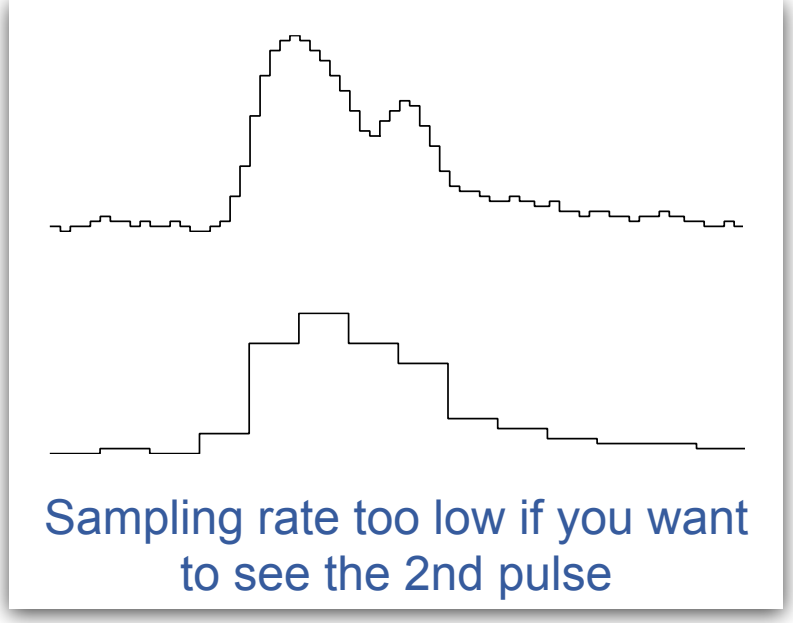
Pipeline ADC

- Use multiple few-bit flash ADCs in sequence
- Uses successive approximation. E.g.
  - Stage 1 is 1V resolution (say 2-3V)
  - Subtract 2V from signal
  - Stage 2 is 0.1V resolution (say 0.3-0.4V)
  - Final result is sum of all stages (say 2.3V)
- Much cheaper (cost grows linearly with resolution)
- But, there's a delay as voltage passes through stages
  - Might impact your trigger?



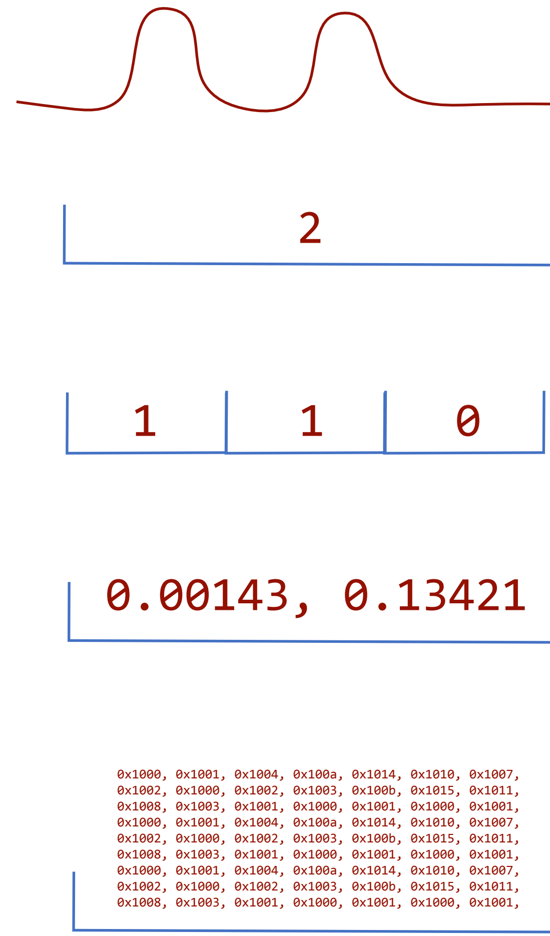
ADC considerations

- Sampling frequency
  - Need $f_{sampling} > 2 \times f_{signal}$ (Nyquist-Shannon theorem)
- Sampling delay
  - Impacts trigger logic?
- Dynamic range
  - Need to amplify signal?
- Dead time during readout
  - Only for some ADC types



Recap of possible outputs

- Discriminator + scaler
  - Number of pulses
- Discriminator + multi-channel scaler
  - Number of pulses in each time bin
- Discriminator + TDC
  - Time of each pulse (as a list)
- ADC/digitizer
  - Waveform of each pulse (at some time base and voltage resolution)



Choose based on experimental needs and budget!

Introduction

Signal manipulation

Triggering

Wiring and crates

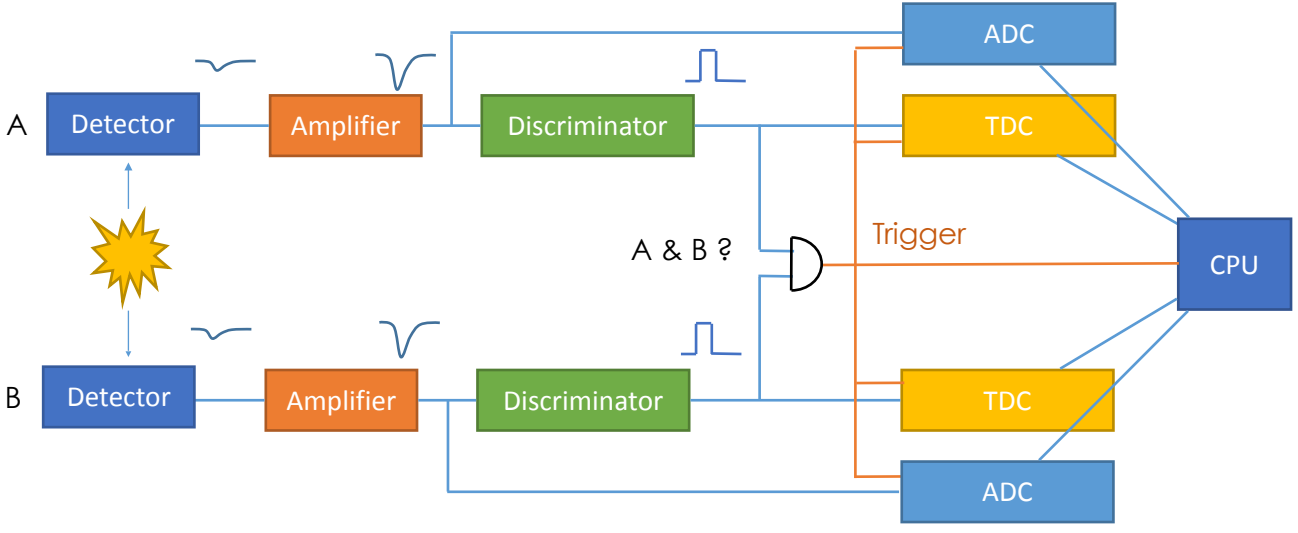
DAQ frameworks

Software and firmware

Example experiments

Event-based (internal) triggering

- Detectors produce continuous electrical signals
- Reduce data rate enormously if you only trigger data readout when something "interesting" happens
- Event-based triggering uses detector signals themselves to decide when to trigger (e.g. a coincidence between channels)



External trigger

- Trigger may be even easier if your experiment uses laser pulses / particle beam pulses
- Can work in both directions
  - DAQ tells laser/beam to pulse
  - Laser/beam tells DAQ that it has pulsed
- Either way, you can trigger your electronics using that same signal

Trigger-less DAQ

- Used in some large-scale experiments (that don't have the same resources as LHC experiments)
  - Thousands/millions of detector channels
  - Too much activity to make a coincidence trigger
- Don't use a global trigger at all
- Each channel triggers independently
  - Read out every single hit (stream is many GB/s)
  - Reconstruct events in server farm
  - Decide what data to save (few MB/s)

Why does data reduction matter?

- Data builds up quickly for experiments that run 24/7
  - 60MB/s is 2PB/yr
- Costs $$$ to store data
- Simpler data is easier and faster to process/analyse
- BUT, you have to understand your detector
  - Experiments often start off recording lots of data, then implement more aggressive reduction once they've proved that the "lost" information doesn't affect the science analysis

How much can you simplify?

- BetaNMR use multi-channel scalers, sum up the histograms in software, and only save those summed histograms
  - Written 1.5GB total since 2000

- Darkside-20k have thousands of channels and record the time/charge of each pulse
  - Write the same amount of data per second as BetaNMR write per year!

Choose based on experimental needs and budget!

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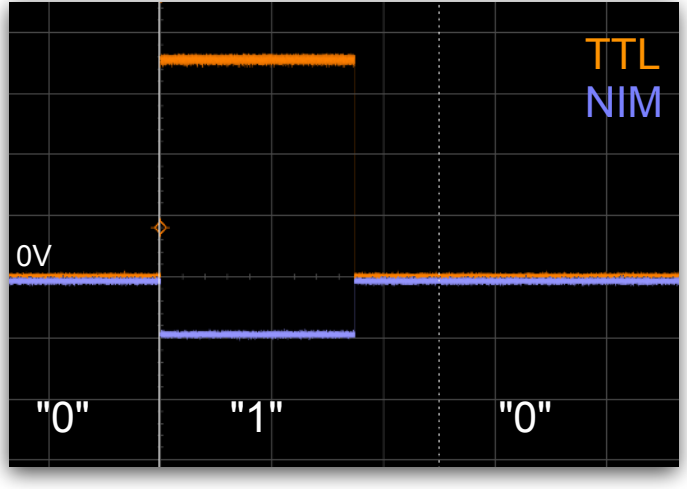
Example experiments

Digital levels

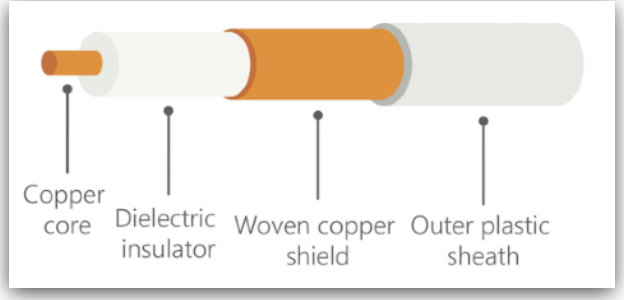
- Different standards evolved over time
  - Available technology, speed, power consumption...
  - NIM/TTL are the most common in physics
- Level translators available if you need to mix

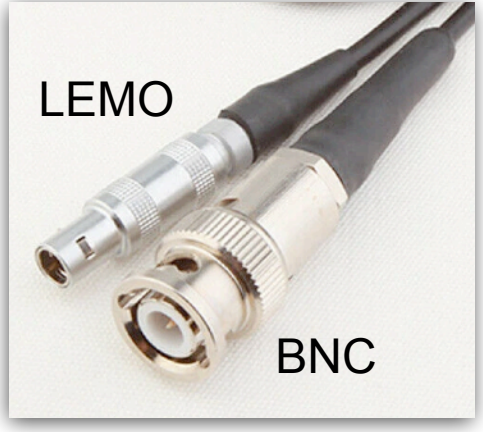
Standard	Digital 0	Digital 1
NIM	0 V	-0.8 to -1 V
TTL	0 to +0.7 V	+1.5 to +5 V
ECL	-1.75 V	-0.9 V



Cables and connectors

- Most signals transmitted using coaxial cables
- Different connector options
  - SHV is for safe high voltage connections
  - LEMO 00 is very often used in physics
    - Latches into the receiver
    - Pull the outer housing, not the cable!
  - BNC also common
    - Larger but cheaper

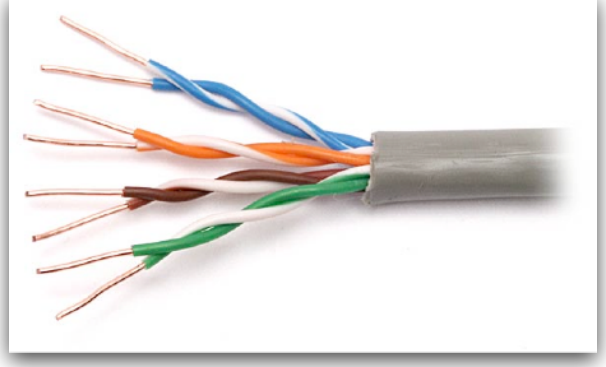


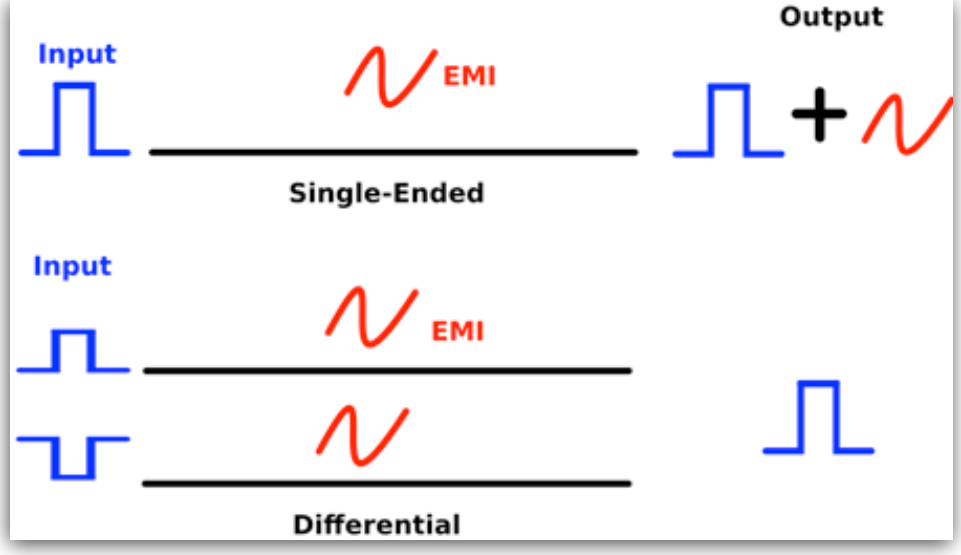


Description	Price
LEMO 00 - LEMO 00 Single Probe Transducer Cable, 4 foot length	$85.00

LVDS

- Low voltage *differential* signalling
- Instead of sending +2V, send (A) +1V and (B) -1V
  - Receiver does (A-B) to get +2V
  - But any "pickup noise" is cancelled out!
- Usually implemented in a "twisted pair" cable



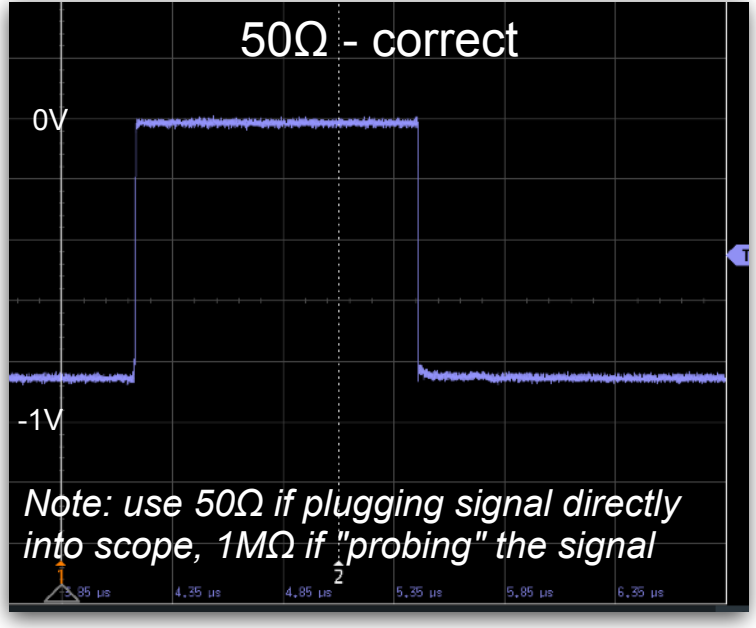


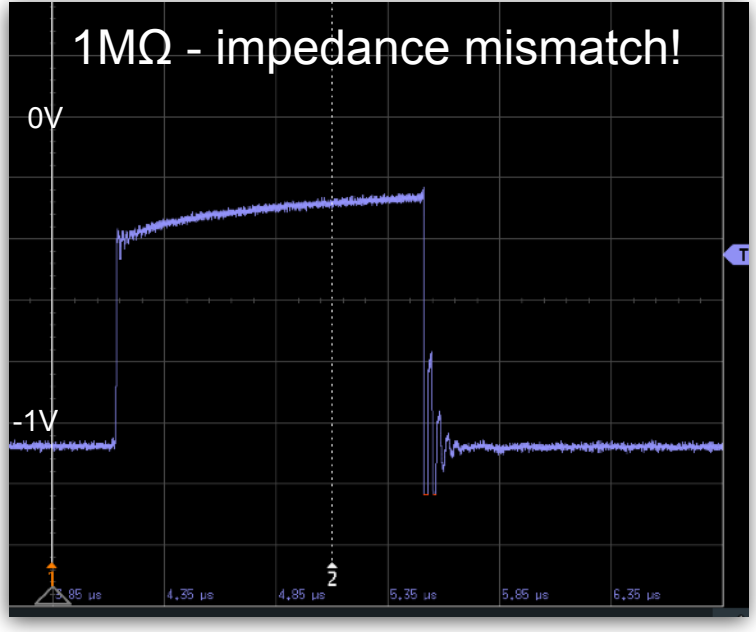
Impedance matching and reflections

- Impedance (Z) is the complex version of resistance
  - Z = R + jX; R is resistance (DC); X is reactance (AC)
  - Ideally resistors are pure-R, capacitors are pure-X
  - Reactance varies with frequency of signal
- If there's a mismatch between source/cable/receiver, can get reflections in the signal
- Almost all devices/connectors you'll use are 50Ω
  - Beware - RF systems often use 75Ω

But I don't design electronics or deal with RF...

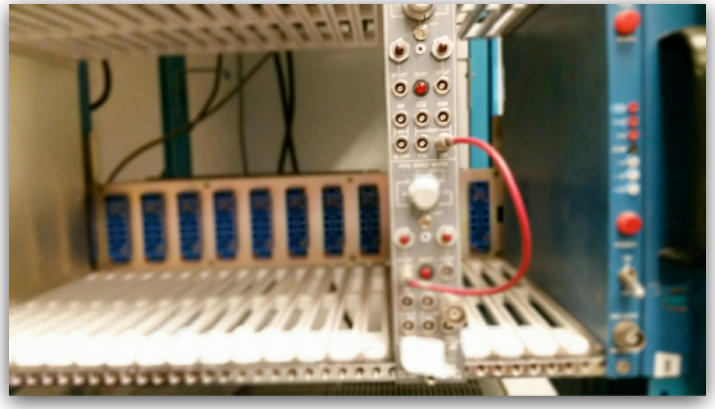
- The impedance mismatches you're likely to see are:
  - Oscilloscope being in 1MΩ termination instead of 50Ω
  - Forgetting to terminate daisy-chains

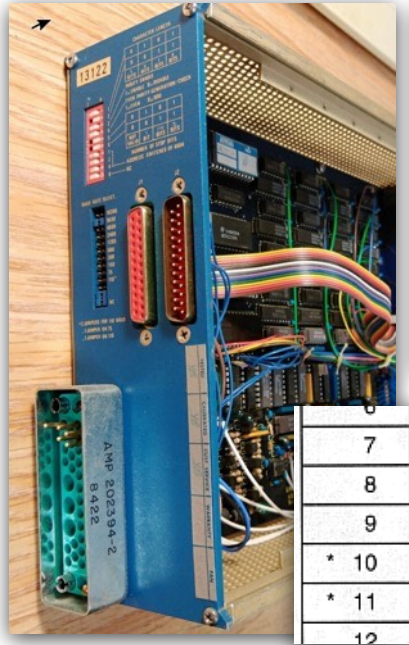


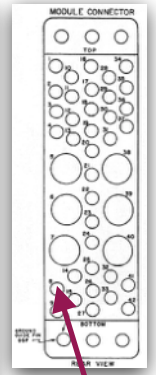


NIM crates

- Very simple (and old) standard
- Provides power to NIM modules through a standardised connector
  - One of the power pins is 200V!!
- Many modules available
  - Amplifier, discriminator, fan-out, coincidence, scaler, ...
- Not used much outside physics







7	
8	+200 V D.C.
9	SPARE
* 10	+6 V
* 11	-6 V
12	RESERVED

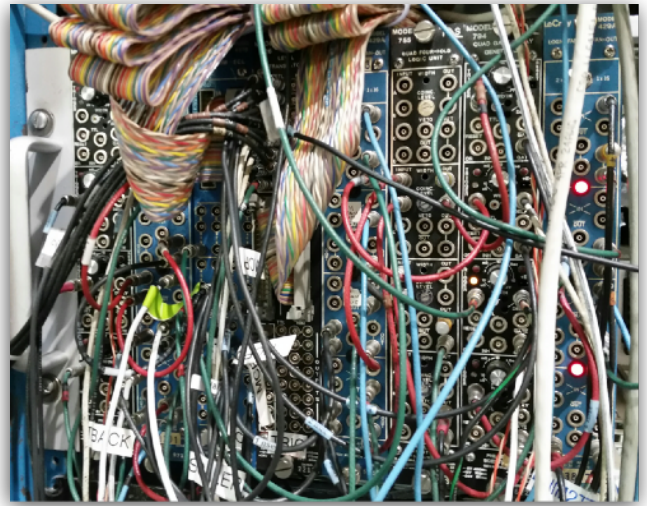
"NIM" has two meanings - crate and voltage levels!

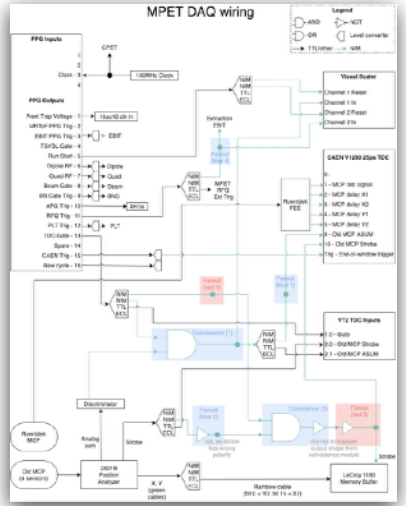
Backplane-based crates

- Backplane allows boards to talk to each other
  - Often put a single-board computer in the crate to read out data from all boards
- VME (1981)
  - Still used in physics, military, railroads...
  - Max ~ 1Gb/s through backplane (generally less)
  - Some boards now only use backplane for power - read data out via ethernet
- uTCA (2003)
  - Developed by telecommunications industry
  - Higher data rate through backplane (100Gb/s)

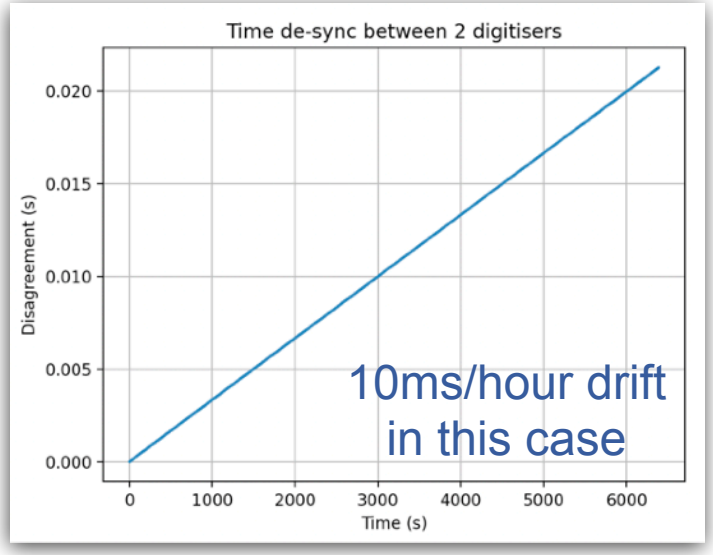
Wiring top tips

- Can be time-consuming to trace the logic
  - Make a diagram and label your cables
  - drawio.com is a great tool
- Labs have lots of modules lying around that are OLD!
  - Assume every connection is bad until checked...





A quick word about clocks



- Many devices have on-board clocks
- These are generally quite inaccurate and *will* drift
  - Bad if you need to correlate data from multiple boards
- If you have multiple devices, use one as the master and distribute that clock signal to others
- If you need true and stable, use a Rb clock or similar
- If you need the true "real world" time (e.g. for supernova search) use GPS

Introduction

Signal manipulation

Triggering

Wiring and crates

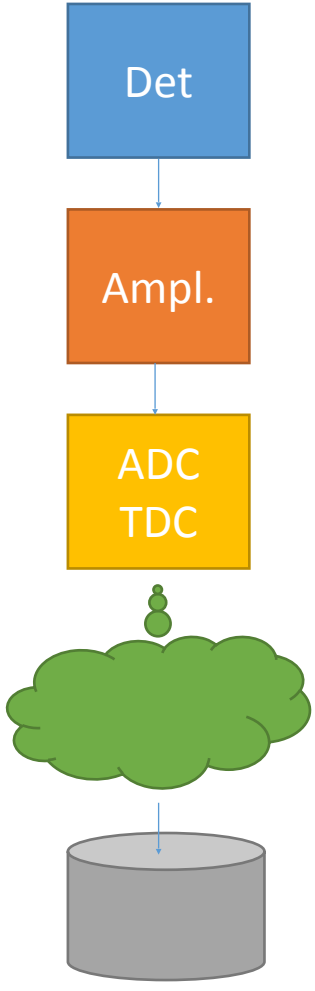
DAQ frameworks

Software and firmware

Example experiments

Final piece of the puzzle

- Need to read data from digitisers, TDCs etc and store on disk for final physics analysis
- Often want to combine data from multiple detectors into a single "event"
- Generally acquire data in "runs" with specific experimental conditions
  - E.g. PMT voltages, calibration source location, beam energy, ...
- Several frameworks available to help

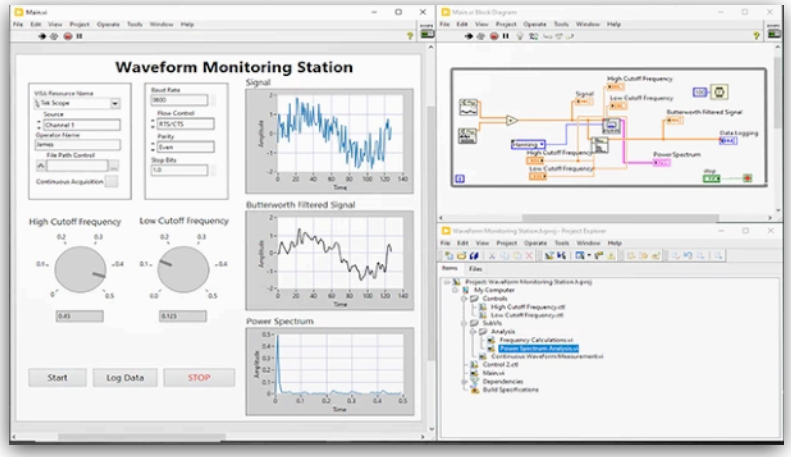


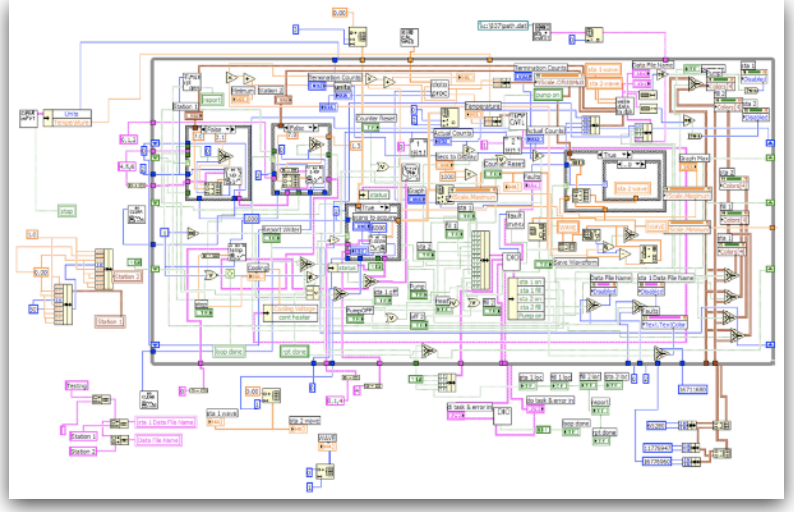
What we want from a DAQ framework

- Read data from many types of hardware
- Configure devices and store the configuration
  - Including "slow control" of voltages,
- Collect data from many devices into a single "event"
  - Multiple programs, possibly on multiple computers
- Stable - will it still work in 10 years?
- Efficient and performant - GB/s input?
- Nice to have - alarms, event displays, web interface, ...

LabView

- "Low code" proprietary system by National Instruments
- All NI devices will come with a LabView driver
- Simple to setup tabletop experiments
- Does not scale well for experiments that need high speed, complex logic, many devices, or use Linux





Other DAQ frameworks

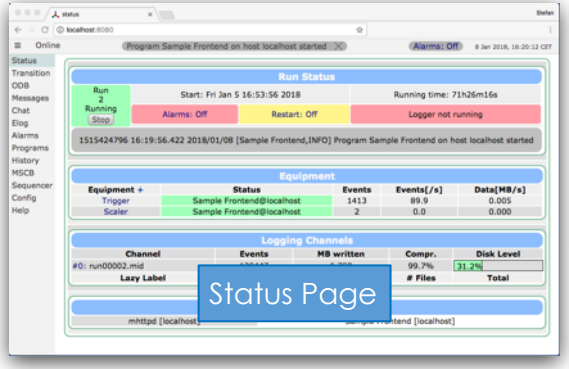
- Many labs have developed their own systems

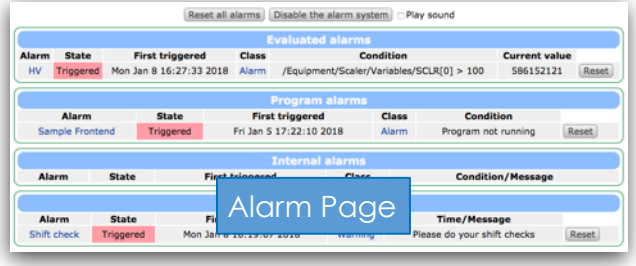
Framework	Developed by	Written in	Used by
ORCA	North Carolina	Objective-C (MacOS only)	Katrin, Majorana, SNO+, ...
artdaq	Fermilab	C++	Lariat, mu2e, SBND, ...
CODA	Jefferson	Java (plus need special VME hardware)	JLab
MIDAS NewGen	Rutherford	Tcl	Rutherford
MIDAS	PSI/TRIUMF	C++ and python	mu3e, T2K, Alpha-G, MEG, Darkside, ...

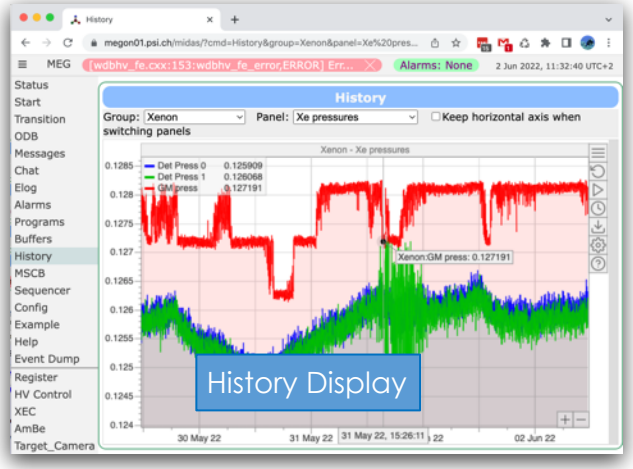
MIDAS

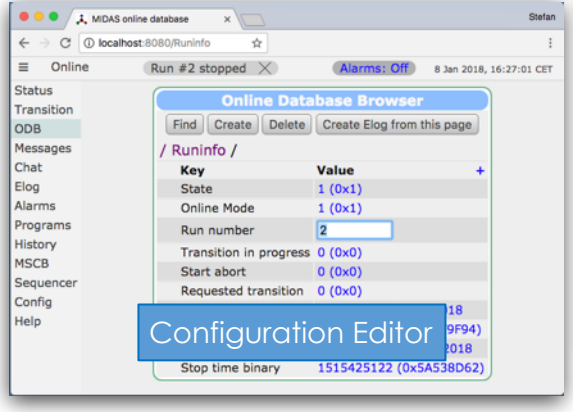
- Maximum Integrated Data Acquisition System
- Very customisable
  - Can implement data readout in C++ or python
  - Webpages in javascript
- Free (GPL)
- Good for 1-50 computers and ~ 1GB/s data rate

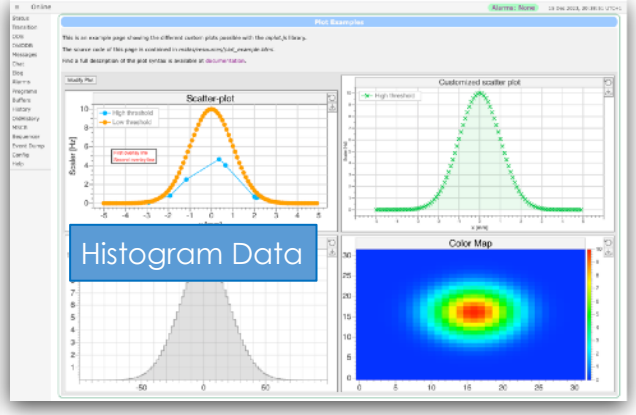
MIDAS webpages

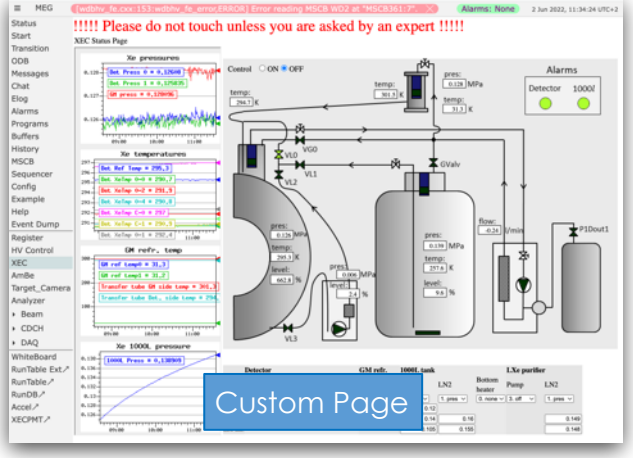












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Software

- Any non-trivial experiment requires custom DAQ software
  - Data readout, event building, realtime analysis, ...
- Language depends on your DAQ framework
- May need to write low-level code to talk to devices
  - C functions, register maps, sockets, memory buffers
  - Some vendors provide higher-level libraries

Software - Python

- Easy to learn with rich ecosystem of libraries in PyPI
  - E.g. python-vxi11 for talking to many DAQ devices
- Slower to execute compared to C/C++
  - Can (carefully) call C code/libraries from Python
- Added python support to midas a few years ago
  - Very popular, especially for low-data-rate applications
  - Correct usage of numpy can make code much faster

Software - C/C++

- Compile your software, then run it
  - Compiler is your friend, not your enemy
  - Try to fix all warnings/errors
- You need to know a little more about memory, pointers
  - "New" smart pointers make memory usage safer
  - std::shared_ptr etc.
- Modern C++ has many features
  - Keep it simple

Software - development tips

- Write code that is readable!
  - Make your life as easy as possible when you need to debug/extend
- Try to separate layers of complexity
  - Don't obscure the high-level algorithm with low-level implementation details
- Give your functions sensible names
  - The principle of least surprise
- Document the *why* not the *what*

Software - outsourcing to AI

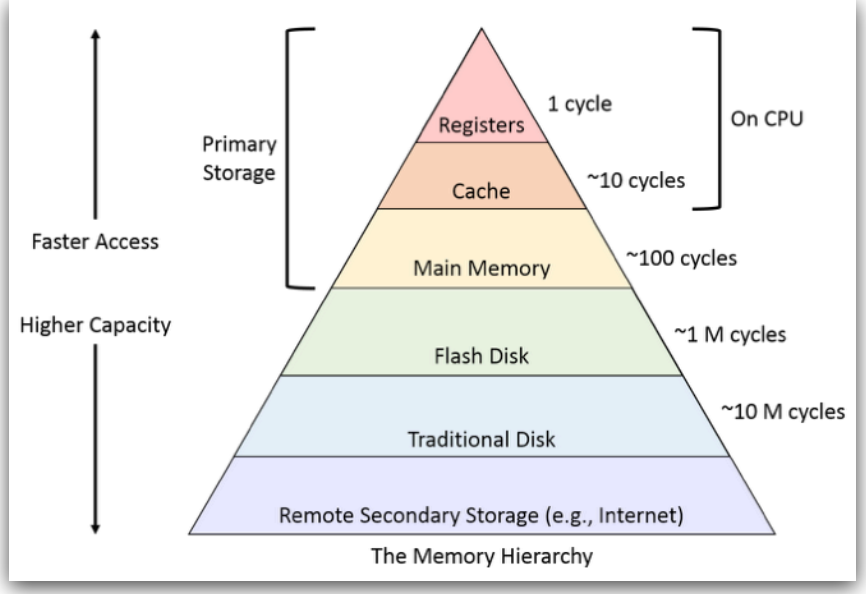
- ChatGPT / CoPilot / Claude / Cursor can generate code
- *May* generate working code quickly
- It can be excellent for smaller tasks
  - E.g. how to add a label to a plot in matplotlib / ROOT
- I think it's a long-term risk for bigger tasks
  - Sometimes it's wrong, or does the right thing in a weird way
  - Harder to maintain/explain/standardise AI-gen code
  - Normally at least 1 person understands the codebase (the original author) - now it may be 0?
- Ask me to rant about "vibe coding" when we're at the pub...

Software - testing

- Test any code you write!
  - Just because your code compiles doesn't mean it's correct...
  - Ensure you don't introduce "regressions" as code evolves
- Strongly consider testing frameworks
  - unittest module for Python
  - Catch2/GoogleTest for C++
  - May want to write a dummy/mock device so you can run tests without talking to real hardware devices
- I structure my code so I can test ~99% of it on my laptop

Software - getting faster

- You can (almost) always make your code faster
  - Use a more efficient algorithm
  - Use a compiled language
  - Buy more/faster computers
  - Optimise your in-memory data layout/usage
  - Use a GPU (for very parallel problems)
  - Write firmware



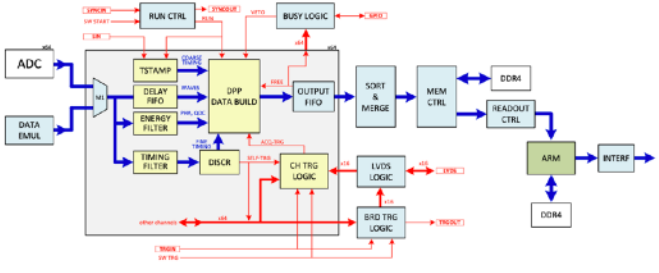
Stand-up Maths on YouTube: Someone improved my code by 40,832,277,770%

Software vs firmware

- Software runs on a general purpose PC
  - You don't have tight control over what happens when
  - You can try to declare yourself as a "high priority" program, but the OS still decides how much CPU time each program can have
- Firmware runs on dedicated hardware
  - Your code defines what should happen every single clock cycle (multiple instructions possible)
  - You know *precisely* what will happen 100 million times per second (for 100MHz clock)

Firmware development

- Hardware design languages - VHDL/SystemVerilog
- Writing firmware code takes a LOT longer than software
- Generally an engineer-level position
- BUT companies are starting to offer "open firmware" solutions, e.g. CAEN OpenFPGA
  - CAEN write most of the firmware, but allow you to implement some custom logic
  - They provide a development kit to make your work easier



Yellow boxes are bits you can customise

Introduction

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Reminder of our building blocks

Signal manipulation
Amplifier
Noise filter
Stretching
Summation

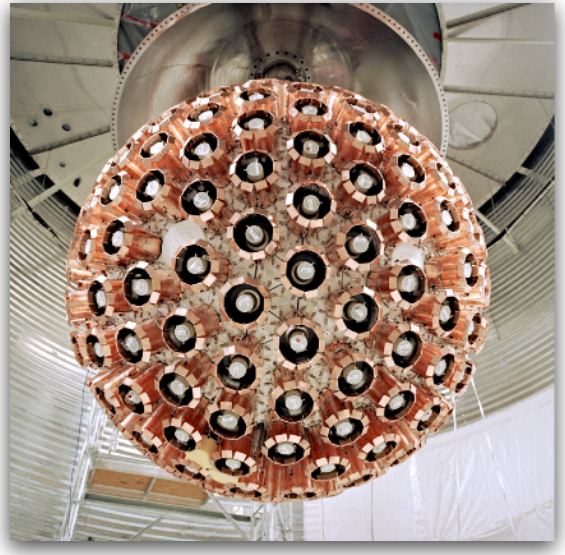
Digitisation
Discriminator
Scaler/MCS
TDC
Digitiser/ADC

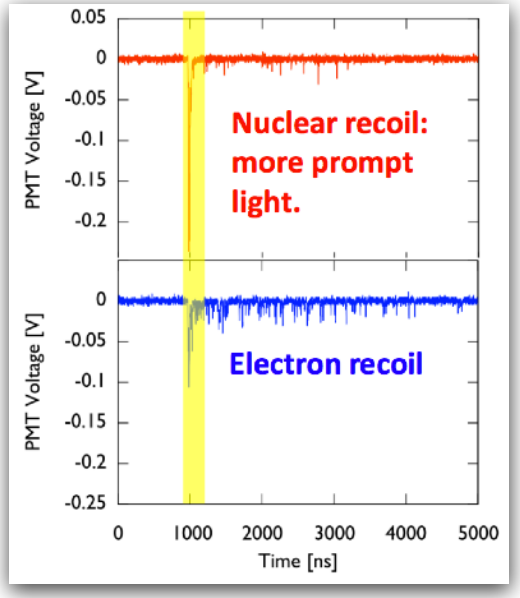
Digital logic
Coincidence (AND)
Fan-in (OR)
Inverter (NOT)

Custom code
Firmware
Software

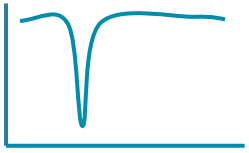
Example 1 - DEAP-3600

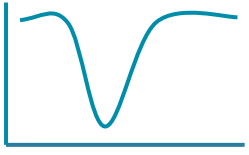
- Dark matter search - 255 PMTs in LAr
- High background rate (kHz)
- Distinguish signal/background using energy and time distribution of photons
  - Need to record detailed info for signal-like events
- Runs 24/7 for many years
  - Need to suppress background
  - Trigger needs custom firmware

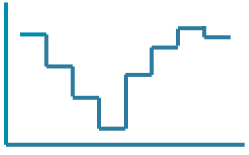




Example 1 - DEAP-3600







255 LAr PMTs

22 signal conditioning boards (slow down the fast PMT pulses)

SUM

Trigger signals

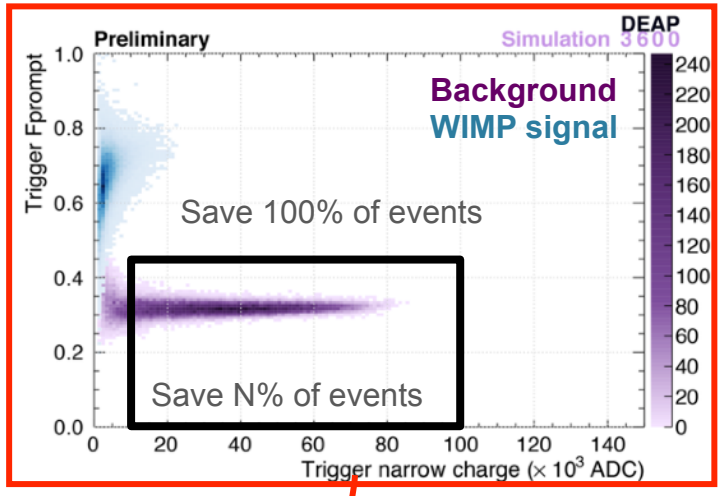
Trigger (DTM)

32 250MHz digitizers

4 62.5MHz digitizers

4 readout PCs

Event builder PC



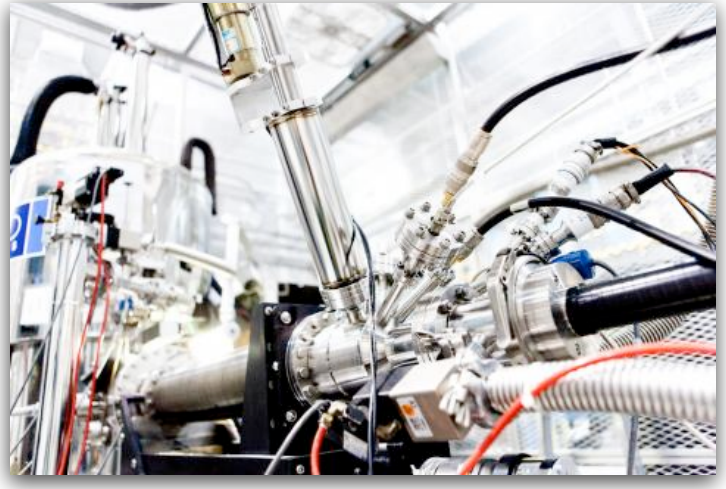
Custom hardware

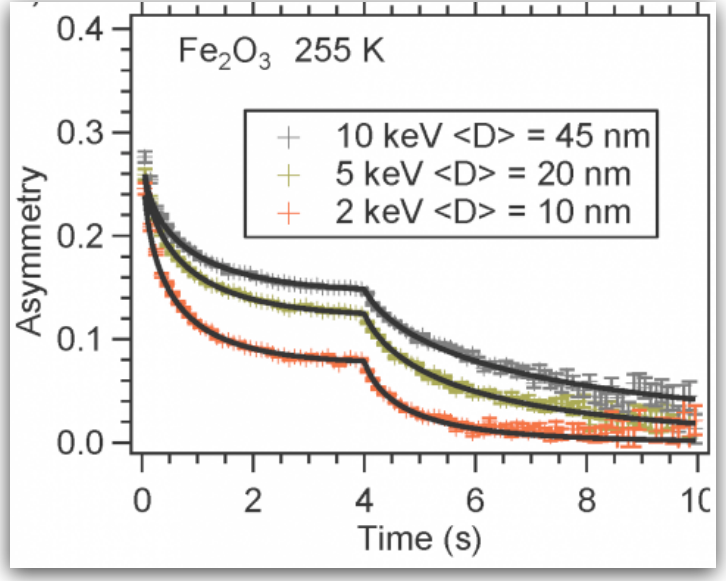
Commercial hardware

Custom software/ firmware

Example 2 - BNMR

- Beamline experiment for condensed matter and material science
- Inject ions, count beta decays as a function of time
- Complex timing schemes for ion beam, RF, lasers
  - Different for each experiment and sample





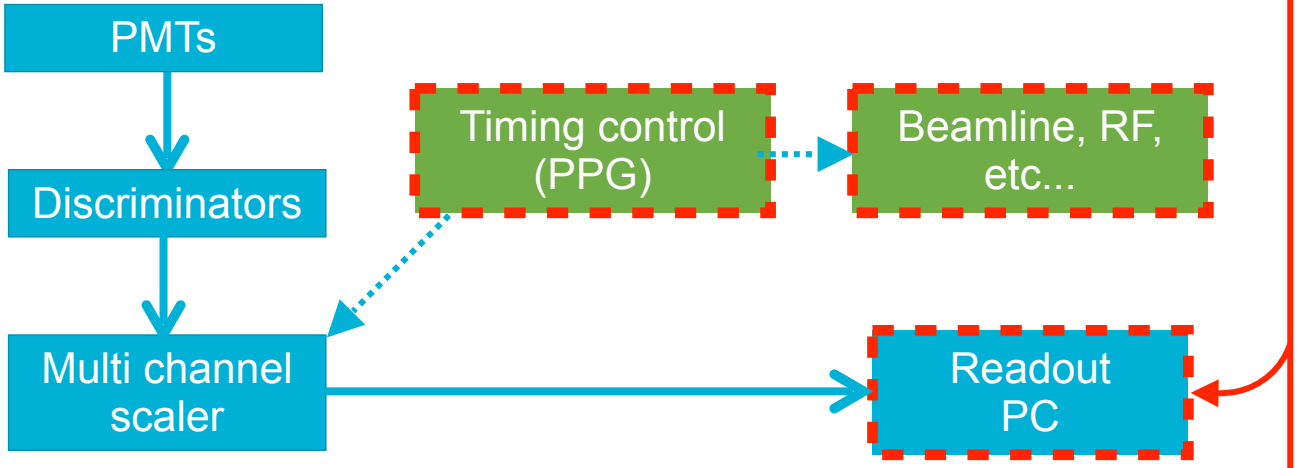
Example 2 - BNMR

- Hardware is relatively simple
- Complexity is in the software
- Good user interfaces can greatly improve efficiency

Custom hardware

Commercial hardware

Custom software/ firmware



Conclusion

- DAQ links the hardware and data analysis
  - Tools for operating and validating the experiment
  - Knowledge of DAQ needed for proper data analysis
- Many decisions to make based on physics needs/budget
  - Important to consider this early in design process
- Lots of DAQ frameworks, but I recommend midas
- DAQ software spans low-level device communication through high-level user interfaces
- Test your code - your analysis depends on it!