DAQ software

E. Pasqualucci
INFN Roma
Disclaimer

• Data acquisition is not an exact science.
• It is an alchemy of
  – Electronics
  – Computer science
  – Networking
  – Physics
  – Hacking and experience

money and manpower matter as well
Once upon a time...
Event readout

BUBBLE CHAMBER
Reading out a complex detector

- Electromagnetic Calorimetry
- Hadronic Calorimetry
- Tracking (in solenoid field)
- Beam pipe
- Muon chambers
Detector readout at the LHC

– Large number of channels ($\sim 10^7$)
– Large “event” rate
  • Bunch crossing every 25 ns
  • F. Pastore explained implications on trigger
Overview

• Aim of this lecture is
  – Give an overview of a medium-size DAQ
  – Analyze its components
  – Introduce the main concepts of DAQ software
    • As “bricks” to build larger system
  – Give more technical basis
    • For the implementation of very large systems
Basic DAQ with a real trigger

- Measure $\beta$ decay properties
- Events are asynchronous and unpredictable
- Need a **physics** trigger
- Delay compensates for the trigger latency
Dead time and trigger

What if a trigger is created when the system is busy?

Probability of time (in ms) between events for average decay rate of $f=1$kHz $\rightarrow \lambda=1$ms
Busy logic

- Busy logic avoids triggers while processing
- Which (average) DAQ rate can we achieve now?
- $\tau=1\text{ ms}$ is sufficient to run at 1kHz with a clock trigger
Data readout (a simple example)

- Modular electronics on a bus
- Data digitized by (for instance) VME modules (ADC and TDC)
- Trigger signal received by a trigger module
  - I/O register or interrupt generator
- Data read-out by a Single Board Computer (SBC)
Trigger management

• How to know that new data is available?
  – Interrupt
    • An interrupt is sent by an hardware device
    • The interrupt is
      – Transformed into a software signal
      – Caught by a data acquisition program
        » Undetermined latency is a potential problem!
        » Data readout starts
  – Polling
    • Some register in a module is continuously read out
    • Data readout happens when register “signals” new data

• In a synchronous system (the simplest one...)
  – Trigger must also set a busy
  – The reader must reset the busy after read-out completion
Real time programming

• Has to meet operational deadlines from events to system response
  – Implies taking control of typical OS tasks
    • For instance, task scheduling
  – Real time OS offer that features
• Most important feature is predictability
  – Performance is less important than predictability!
• It typically applies when requirements are
  – Reaction time to an interrupt within a certain time interval
  – Complete control of the interplay between applications
Is real-time needed?

• Can be essential in some case
  – It is critical for accelerator control or plasma control
    • Wherever event reaction times are critical
    • And possibly complex calculation is needed
• Not commonly used for data acquisition now
  – Large systems are normally asynchronous
    • Either events are buffered or de-randomized in the HW
      – Performance is usually improved by DMA readout
      – Or the main dataflow does not pass through the bus
  – In a small system dead time is normally small
• Drawbacks
  – We lose complete dead time control
    • Event reaction time and process scheduling are left to the OS
  – Increase of latency due to event buffering
    • Affects the buffer size at event building level
  – Normally not a problem in modern DAQ systems
Polling modules

- Loop reading a register containing the latched trigger

```c
while (end_loop == 0) {
    uint16_t *pointer;
    volatile uint16_t trigger;

    pointer = (uint16_t *) (base + 0x80);
    trigger = *pointer;

    if (trigger & 0x200) // look for a bit in the trigger mask
        { ... Read event ... 
        ... Remove busy ... 
    } 
    else
        sched_yield (); // if in a multi-process/thread environment
} 
```
Polling or interrupt?

• Which method is convenient?
• It depends on the event rate
  – Interrupt
    • Is expensive in terms of response time
      – Typically $O(1 \mu s)$
    • Convenient for events at low rate
      – Avoid continuous checks
      – A board can signal internal errors via interrupts
  – Polling
    • Convenient for events at high rate
      – When the probability of finding an event ready is high
    • Does not affect others if scheduler is properly released
    • Can be “calibrated” dynamically with event rate
      – If the input is de-randomized...
The simplest DAQ

- Synchronous readout:
  - The trigger is
    - Auto-vetoed (a busy is asserted by trigger itself)
    - Explicitly re-enabled after data readout
- Additional dead time is generated by the output

```c
// VME interrupt is mapped to SYSUSR1
static int event = FALSE;
const int event_available = SIGUSR1;

// Signal Handler
void sig_handler (int s)
{
    if (s == event_available)
        event = TRUE;
}

event_loop ()
{
    while (end_loop == 0) {
        if (event) {
            size += read_data (*p);
            write (fd, ptr, size);
            busy_reset ()
            event = FALSE;
        }
    }
}
```
DAQ dead time and efficiency

What if a trigger is created when the system is busy?

Probability of time (in ms) between events for average decay rate of $f=1\text{kHz} \rightarrow \lambda=1\text{ms}$
DAQ dead time and efficiency

If $f$ is the average event rate, $\nu$ is the average DAQ rate, $\nu \tau$ is the busy time:

$$f (1 - \nu \tau) = \nu$$

$$\nu = f / (1 + f \tau) < f$$

Define $\varepsilon$ as the system efficiency:

$$\varepsilon = 1 / (1 + f \tau) < 1$$

- Due to the fluctuations introduced by the stochastic process the efficiency will always be less 100%
- Define DAQ deadtime ($d$) as the ratio between the time the system is busy and the total time. In our example $d=0.1%/Hz$
- In our specific example, $d=0.1%/Hz$, $f=1kHz \rightarrow \nu=500Hz$, $\varepsilon=50%$
• If we want to obtain $v \sim f$ ($\varepsilon \sim 100\%$) $\rightarrow f\tau << 1 \rightarrow \tau \ll 1/f$
• $f=1$ kHz, $\varepsilon=99\% \rightarrow \tau < 0.1\text{ms} \rightarrow 1/\tau > 10\text{kHz}$
• In order to cope with the input signal fluctuations, we have to over-design our DAQ system by a factor 10. This is very inconvenient!
De-randomization

- First-In First-Out
  - Buffer area organized as a queue
  - Depth: number of cells
  - Implemented in HW and SW
  - Introduces an additional latency on the data path
  - Provides a ~steady output path
Efficiency

• We can attain very high efficiency (~1) with $\tau \sim 1/f$
  – With moderate buffer size
Fragment buffering

• Why buffering?
  – Triggers are uncorrelated
  – Further de-randomization at software level
  – Create internal de-randomizers
    • Minimize dead time
    • Optimize the usage of output channels
      – Disk
      – Network
    • Avoid back-pressure due to peaks in data rate
  – Warning!
    • Avoid copies as much as possible
      – Copying memory chunks is an expensive operation
      – Only move pointers!
A simple example...

• Ring buffers emulate FIFO
  – A buffer is created in memory
    • Shared memory can be requested to the operating system
    • A “master” creates/destroys the memory and a semaphore
    • A “slave” attaches/detaches the memory
  – Packets (“events”) are
    • Written to the buffer by a writer
    • Read-out by a reader
  – Works in multi-process and multi-thread environment

• Essential point
  • Avoid multiple copies!
  • If possible, build events directly in buffer memory
The two processes/threads can run concurrently

- Header protection is enough to ensure event protection
- A library can take care of buffer management
  - A simple API is important
  - We introduced
    - Shared memories provided by OS
    - Buffer protection (semaphores or mutexes)
    - Buffer and packed headers (managed by the library)
Event buffering example

- **Data collector**

  ```c
  int cid = CircOpen (NULL, Circ_key, size));
  while (end_loop == 0) {
    if (event) {
      int maxsize = 512;
      char *ptr; uint32_t *p; uint32_t *words;
      int number = 0, size = 0;

      while ((ptr = CircReserve (cid, number, maxsize)) == (char *) -1) 
        sched_yield ();

      p = (int *) ptr;
      *p++ = crate_number; ++size;
      *p++; words = p; ++size;
      size += read_data (*p);
      *words = size;
      CircValidate (cid, number, ptr,
                   size * sizeof (uint32_t));

      ++number;

      busy_reset ();
      event = FALSE;
    }
    sched_yield ();
  }
  CircClose (cid);
  ```

- **Data writer**

  ```c
  int fd, cid;

  fd = open (pathname, O_WRONLY | O_CREAT);
  cid = CircOpen (NULL, key, 0));

  while (end_loop == 0) {
    char *ptr;

    if ((ptr = CircLocate (cid, &number, &evtsize)) > (char *) 0)
      {
      write (fd, ptr, evtsize);
      CircRelease (cid);
      }

    sched_yield ();
  }
  CircClose (cid);
  close (fd);
  ```

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By the way...

• In these examples we were
  – Polling for events in a buffer
  – Polling for buffer descriptor pointers in a queue
  – We could have used
    • Signals to communicate that events were available
    • Handlers to catch signals and start buffer readout

• If a buffer gets full
  – Because:
    • The output link throughput is too small
    • There is a large peak in data rate

⇒ The buffer gets “busy” and generates back-pressure
  ⇒ Thresholds must be set to accommodate events generated during
    busy transmission when redirecting data flow

• These concepts are very general...
Event framing

• Fragment header/trailer
• Identify fragments and characteristics
  – Useful for subsequent DAQ processes
    • Event builder and online monitoring tasks
  – Fragment origin is easily identified
    • Can help in identifying sources of problems
  – Can (should) contain a trigger ID for event building
  – Can (should) contain a status word

• Global event frame
  – Give global information on the event

• Very important in networking
  • Though you do not see that
Framing example

typedef struct
{
    u_int startOfHeaderMarker;
    u_int totalFragmentsize;
    u_int headerSize;
    u_int formatVersionNumber;
    u_int sourceIdentifier;
    u_int numberOfStatusElements;
} GenericHeader;
What can we do now....

• We are now able to
  – Build a readout (set of) application(s) with
    • An input thread (process)
    • An output thread (process)
    • A de-randomizing buffer
  – Let’s elaborate a bit...
A more general buffer manager

• Same basic idea
  – Use a pre-allocated memory pool to pass “events”

• Paged memory
  – Can be used to minimize pointer arithmetic
  – Convenient if event sizes are comparable
    • At the price of some memory

• Buffer descriptors
  – Built in an on-purpose pre-allocate memory
  – Pointers to descriptors are queued

• Allows any number of input and output threads
A paged memory pool (from Atlas)
Generic readout application

Run Control

Trigger

User Action Scheduler

Interrupt Handler

Request Handlers

random" R/O

internal buffer

Module R/O

Input Handler

Request Queue

= Process

= DAQ threads

= Control threads

= Scheduler
Configurable applications

• Ambitious idea
  – Support all the systems with a single application
    • Through plug-in mechanism
    • Requires a configuration mechanism
Some basic components

• We introduced basic elements of IPC...
  – Signals and signal catching
  – Shared memories
  – Semaphores (or mutexes)
  – Message queues

• ...and some standard DAQ concepts
  – Trigger management, busy, back-pressure
  – Synchronous vs asynchronous systems
  – Polling vs interrupts
  – Real time programming
  – Event framing
  – Memory management
Scaling up...
Readout topology

• Many components are required to
  – Read out many channels
    • Readout modules/crates
  – Build events at large rate
    • Event building nodes

• How to organize interconnections?

• Two main classes
  – Bus
  – Network
Buses

- Examples: VME, PCI, SCSI, Parallel ATA, ...
- Devices are connected via a shared bus
  - Bus → group of electrical lines
  - Sharing implies arbitration
- Devices can be master or slave
- Device can be addresses (uniquely identified) on the bus
Modular electronics

• A good example are VME modules
• ADCs/TDCs are commercially available
• Modules can be configured/read out
  – Typically by a processor on a Single Board Computer
  – “Events” are built for the crate
    • Can be either directly stored or sent to another building level
Bus facts

• Simple ✓
  – Fixed number of lines (bus-width)
  – Devices have to follow well defined interfaces
  – Mechanical, electrical, communication, ...

• Scalability issues X
  – Bus bandwidth is shared among all the devices
  – Maximum bus width is limited
  – Maximum bus frequency is inversely proportional to the bus length
  – Maximum number of devices depends on the bus length
Scalability issues...

On the long term, other issues can affect the scalability of your system...
Networks

- Examples: Ethernet, Telephone, Infiniband, ...
- All devices are equal
  - Devices communicate directly with each other
  - No arbitration, simultaneous communications
- Device communicate by sending messages
- In switched network, switches move messages between sources and destinations
  - Find the right path
  - Handle “congestion” (two messages with the same destination at the same time)
    - Would you be surprised to learn that buffering is the key?
Software components

• Trigger management
• Data read-out
• Event framing and buffering
• Data transmission
• Event building and data storage
• System control and monitoring
• Data sampling and monitoring
Event building

- Large detectors
  - Sub-detectors data are collected independently
    - Readout network
    - Fast data links
  - Events assembled by event builders
    - From corresponding fragments
  - Custom devices used
    - In FEE
    - In low-level triggers
  - COTS used
    - In high-level triggers
    - In event builder network

- DAQ system
  - data flow & control
  - distributed & asynchronous
Data networks and protocols

- Data transmission
  - Fragments need to be sent to the event builders
    - One or more...
  - Usually done via switched networks
- User-level protocols
  - Provide an abstract layer for data transmission
    - ... so you can ignore the hardware you are using ...
    - ... and the optimizations made in the OS (well, that’s not always true) ...
- Most commonly used
  - TCP/IP suite
    - UDP (User Datagram Protocol)
      - Connection-less
    - TCP (Transmission Control Protocol)
      - Connection-based protocol
      - Implements acknowledgment and re-transmission
TCP client/server example

```c
struct sockaddr_in sinhim;
sinhim.sin_family = AF_INET;
sinhim.sin_addr.s_addr = inet_addr(this_host);
sinhim.sin_port = htons(port);

if (fd = socket (AF_INET, SOCK_STREAM, 0) < 0) {
    // Error !
}
if (connect (fd, (struct sockaddr *)&sinhim,
            sizeof (sinhim)) < 0) {
    // Error !
}

while (running) {
    memcpy ((char *) &wait, (char *) &timeout,
            sizeof (struct timeval));
    if ((nsel = select (nfds, 0, &wfds,
                        0, &wait)) < 0)
        { ; // Error ! }
    else if (nsel) {
        if (((BIT_ISSET (destination, wfds)))
            count = write (destination, buf, buflen);
            // test count...
            // > 0 (has everything been sent ?)
            // == 0 (error)
            // < 0 we had an interrupt or
            // peer closed connection
        }
    }
}

close (fd);
```

```c
struct sockaddr_in sinme;
sinme.sin_family = AF_INET;
sinme.sin_addr.s_addr = INADDR_ANY;
sinme.sin_port = htons(ask_var->port);

fd = socket (AF_INET, SOCK_STREAM, 0);
bind (fd0, (struct sockaddr *) &sinme,
     sizeof(sinme));
listen (fd0, 5);

while (n < ns) { // we expect ns connections
    int val = sizeof(this->sinhim);
    if ((fd = accept (fd0,
                      (struct sockaddr *) &sinhim, &val)) >0) {
        FD_SET (fd, &fds);
        ++ns;
    }
}

while (running) {
    if ((nsel = select( nfds, (fd_set *) &fds,
                      0, 0, &wait)) []
        count = read (fd, buf_ptr, buflen);
        if (count == 0) { close (fd);
            // set FD bit to 0
        }
    }
}

close (fd0);
```
Data transmission optimization

• When you “send” data it is copied to a system buffer
  – Data is sent in fixed-size chunks
• At system level
  – Each endpoint has a buffer to store data that is transmitted over the network
  – TCP stops to send data when available buffer size is 0
    • Back-pressure
  – With UDP we get data loss
  – If buffer space is too small:
    • Increase system buffer (in general possible up to 8 MB)
  – Too large buffers can lead to performance problems
Controlling the data flow

• Throughput optimization
• Avoid dead-time due to back-pressure
  – By avoiding fixed sequences of data destinations
  – Requires knowledge of the EB input buffer state
• EB architectures
  – Push
    • Events are sent as soon as data are available to the sender
      – The sender knows where to send data
      – The simplest algorithm for distribution is the round-robin
  – Pull
    • Events are required by a given destination processes
      – Needs an event manager
        » Though in principle we could build a pull system without manager
Pull example

Event Manager

Trigger

Sender

Builder network

Sender

Sender
Push example
System monitoring

• Two main aspects
  – System operational monitoring
    • Sharing variables through the system
  – Data monitoring
    • Sampling data for monitoring processes
    • Sharing histogram through the system
    • Histogram browsing
Event sampling examples

- Spying from buffers

- Sampling on input or output

Sampling is always on the “best effort” basis and cannot affect data taking

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Histogram and variable distribution
Histogram browser

![Histogram browser](image)
Controlling the system

• Each DAQ component must have
  – A set of well defined states
  – A set of rules to pass from one state to another
    $\Rightarrow$ Finite State Machine

• A central process controls the system
  – Run control
    • Implements the state machine
    • Triggers state changes and takes track of components’ states
      – Trees of controllers can be used to improve scalability

• A GUI interfaces the user to the Run control
  – ...and various system services...
GUI example

• From Atlas
Finite State Machines

• Models of the behaviors of a system or a complex object, with a limited number of defined conditions or modes

• Finite state machines consist of 4 main elements:
  – States which define behavior and may produce actions
  – State transitions which are movements from one state to another
  – Rules or conditions which must be met to allow a state transition
  – Input events which are either externally or internally generated, which may possibly trigger rules and lead to state transitions
Propagating transitions

- Each component or sub-system is modeled as a FSM
  - The state transition of a component is completed only if all its sub-components completed their own transition
  - State transitions are triggered by commands sent through a *message system*
FSM implementation

• State concept maps on object state concept
  – OO programming is convenient to implement FSM
  – Though you can leave without OO...

• State transition
  – Usually implemented as callbacks
    • In response to messages

• Remember:
  – Each state MUST be well-defined
  – Variables defining the state must have the same values
    • Independently of the state transition
Message system

• Networked IPC
• I will not describe it
• Many possible implementations
  – From simple TCP packets...
  – ... through (rather exotic) SNMP ...
    • (that’s the way many printers are configured...)
    • Very convenient for “economic” implementation
      – Used in the KLOE experiment
  – ... to Object Request Browsers (ORB)
    • Used f.i. by ATLAS
A final remark

• There is no absolute truth
  – Different systems require different optimizations
  – Different requirements imply different design

• System parameters must drive the DAQ design
  – Examples:
    • An EB may use dynamic buffering
      – Though it is expensive
      – If bandwidth is limited by network throughput
    • React to signals or poll
      – Depends on expected event rate
    • Event framing is important
      – But must no be exaggerated
Thanks for your attention!