DAQ software

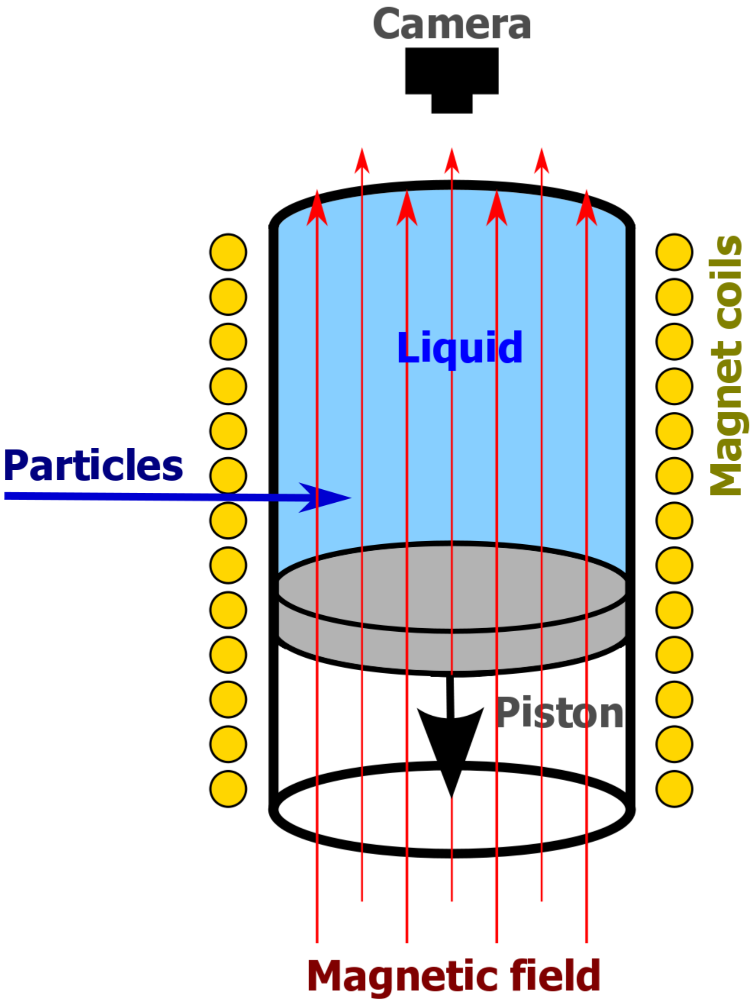
E. Pasqualucci
INFN Roma

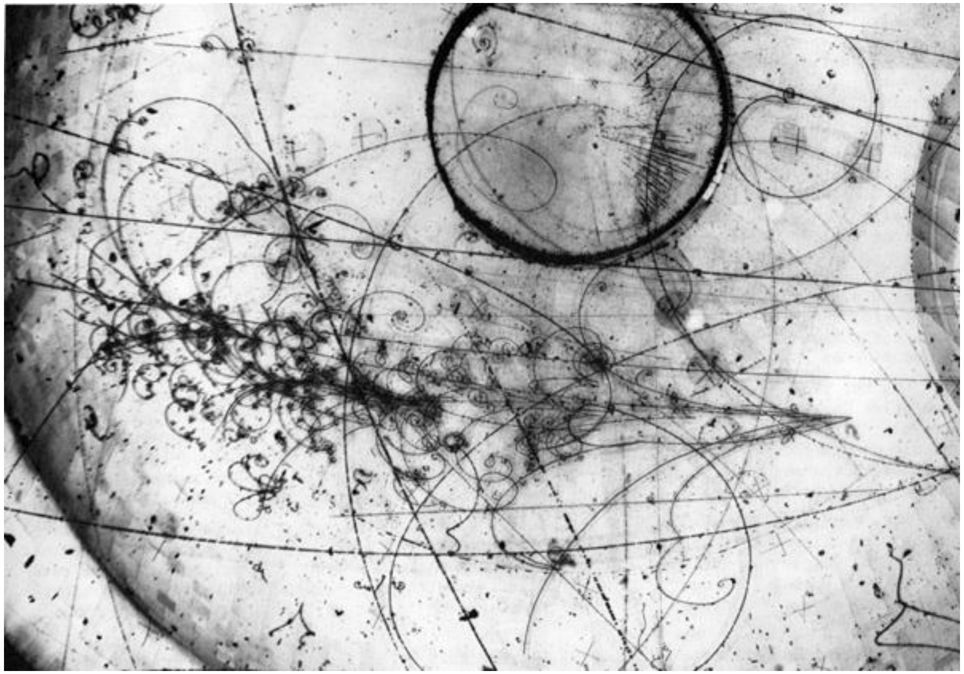
Disclaimer

- 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

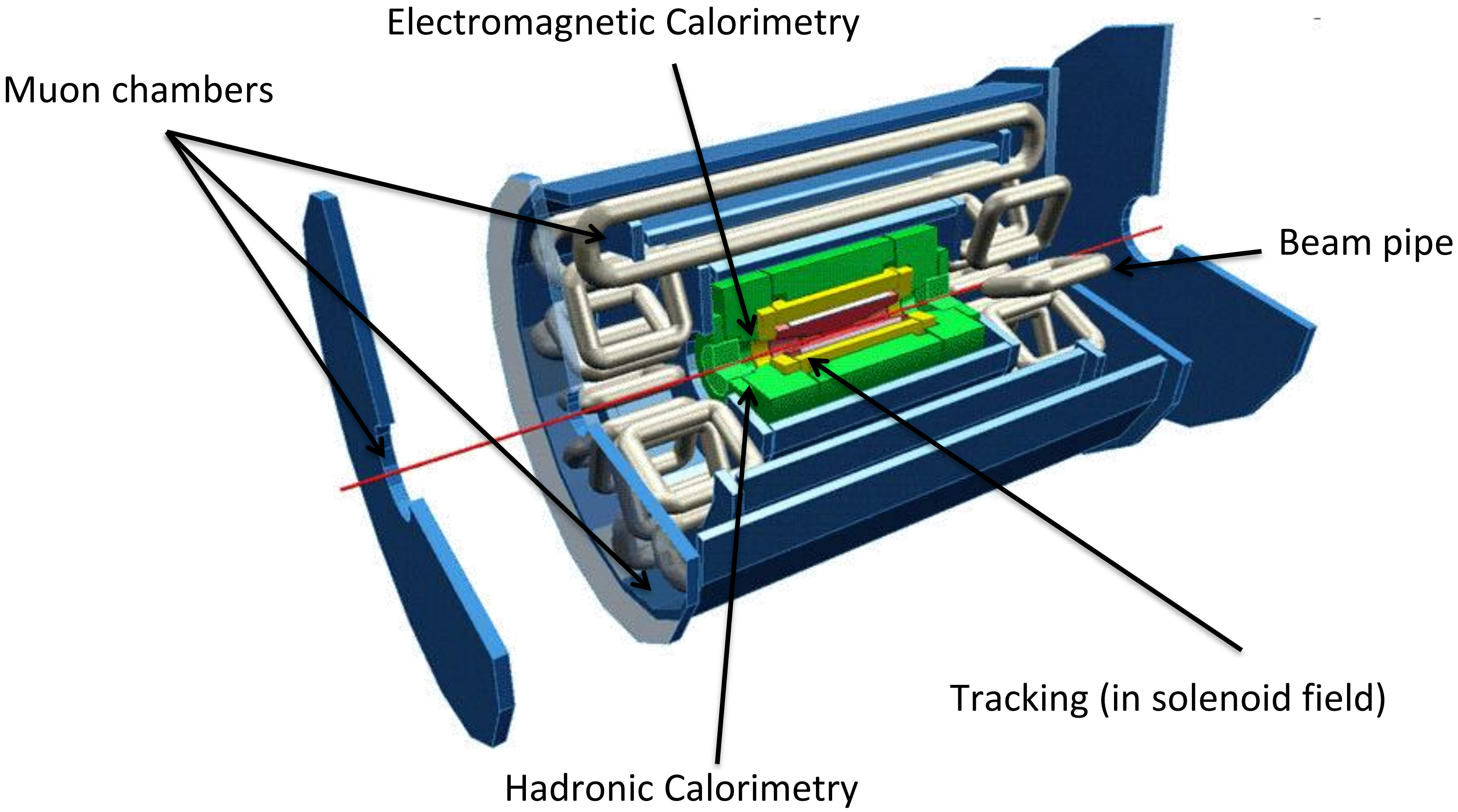
Once upon a time…





Event readout

Reading out a complex detector



Electromagnetic Calorimetry

Muon chambers

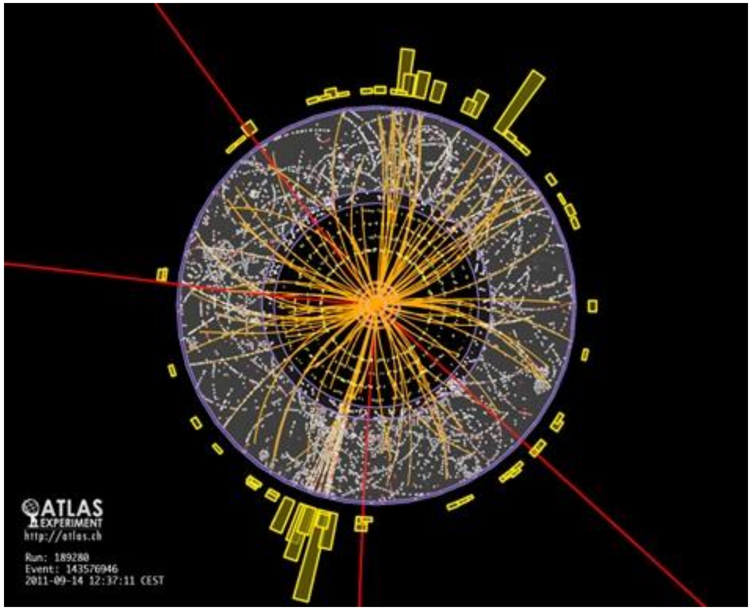
Beam pipe

Tracking (in solenoid field)

Hadronic Calorimetry

Detector readout at the LHC

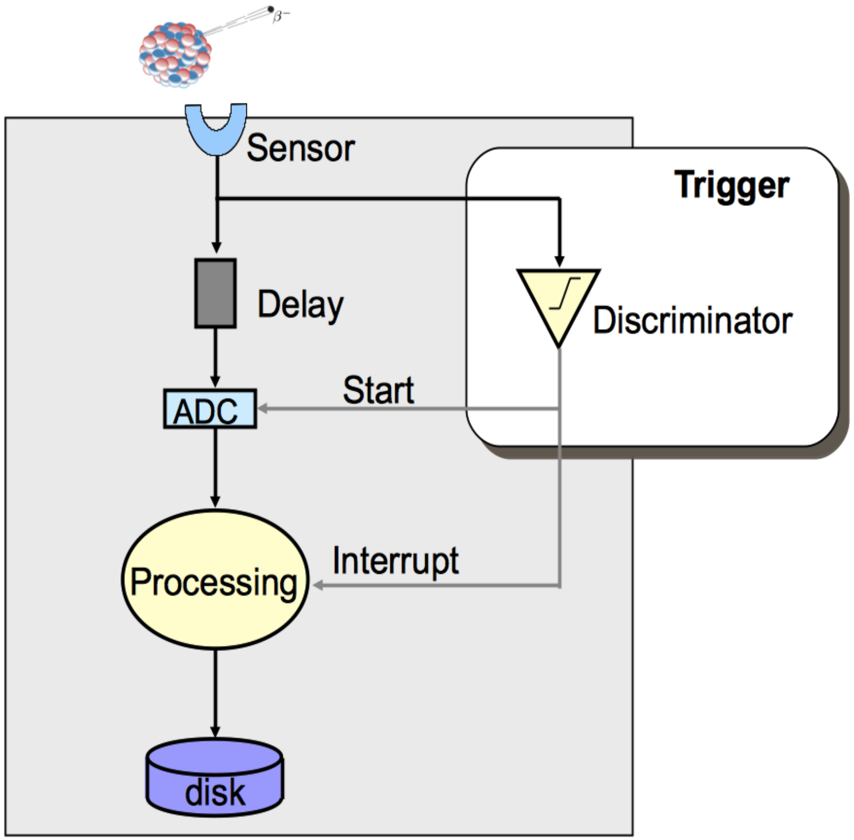
- Large number of channels (~ 10^7)
- Large "event" rate
  - Bunch crossing every 25 ns
  - F. Pastore explained implications on trigger



Overview

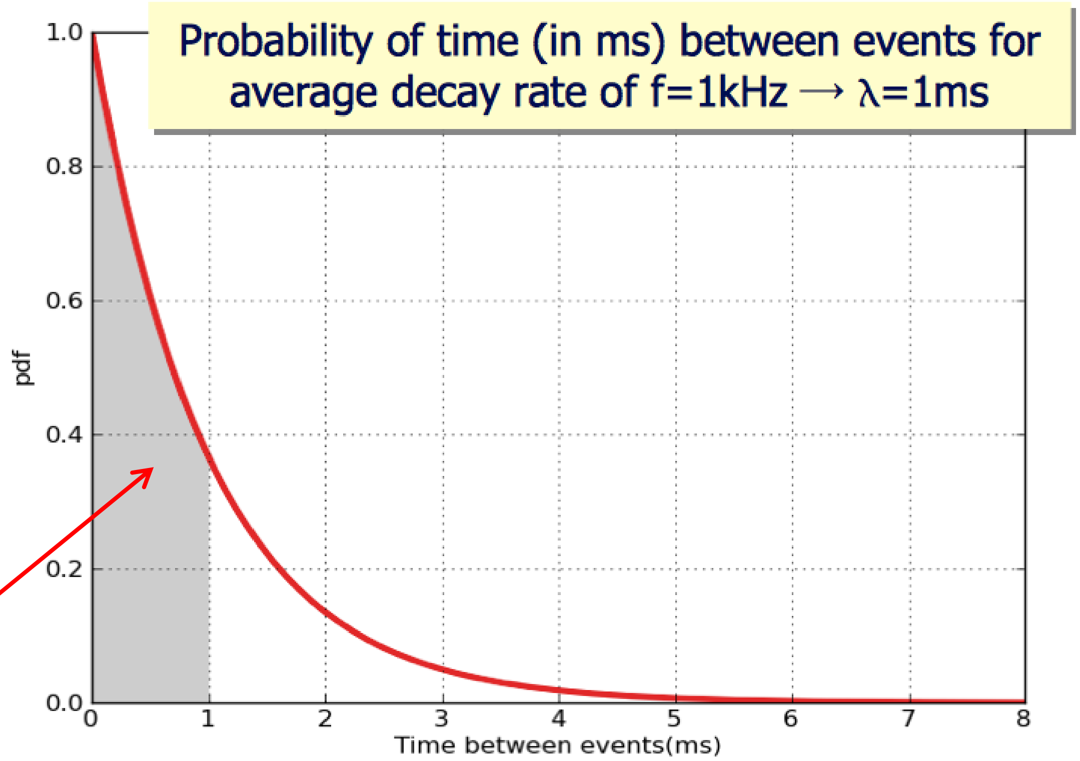
- Aim of this lecture is
  - Give an overview of a medium-size DAQ
  - Analyze its components
  - Introduce the main concepts of DAQ software
    - As “bricks” to build larger system
  - Give more technical basis
    - For the implementation of very large systems

Basic DAQ with a real trigger



- Measure β decay properties
- Events are asynchronous and unpredictable
- Need a **physics** trigger
- Delay compensates for the trigger latency

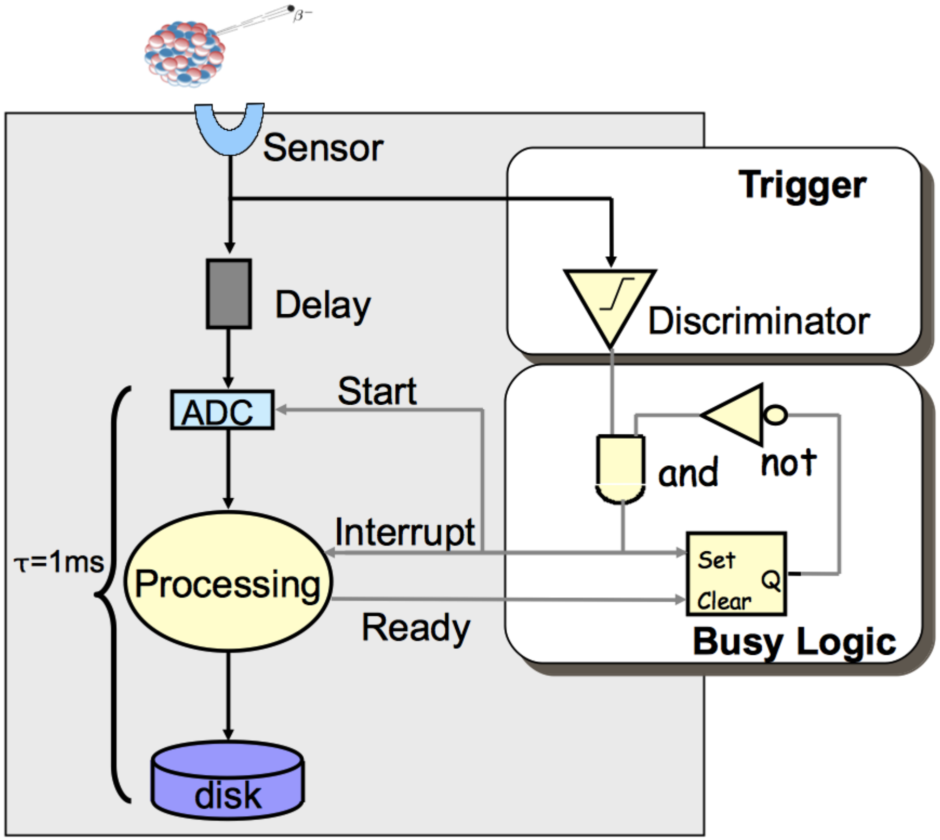
Dead time and trigger



Probability of time (in ms) between events for average decay rate of f=1kHz ⟶ λ=1ms

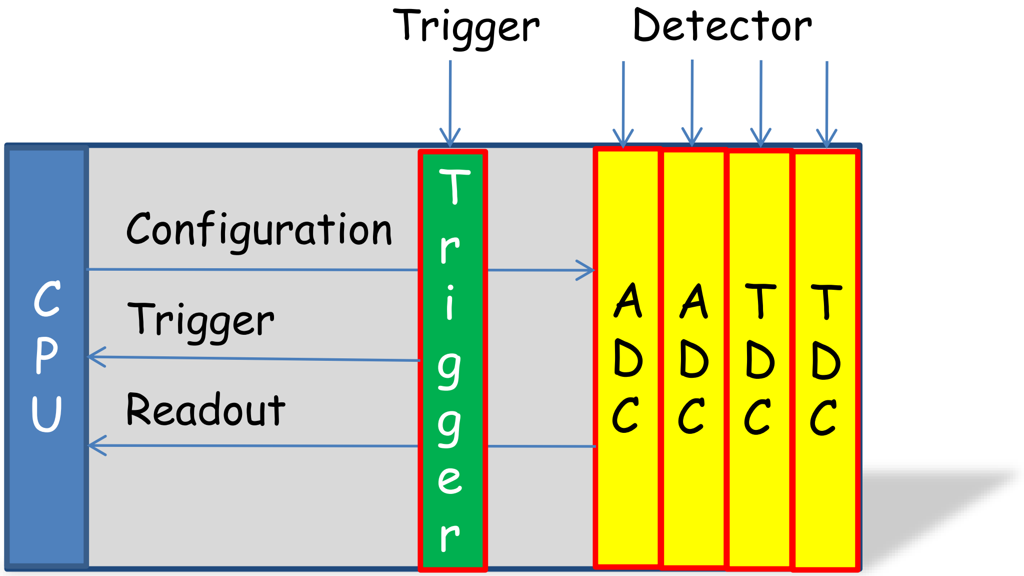
What if a trigger is created when the system is busy?

Busy logic



- Busy logic avoids triggers while processing

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 loose 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

```
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 μs))
    - 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…

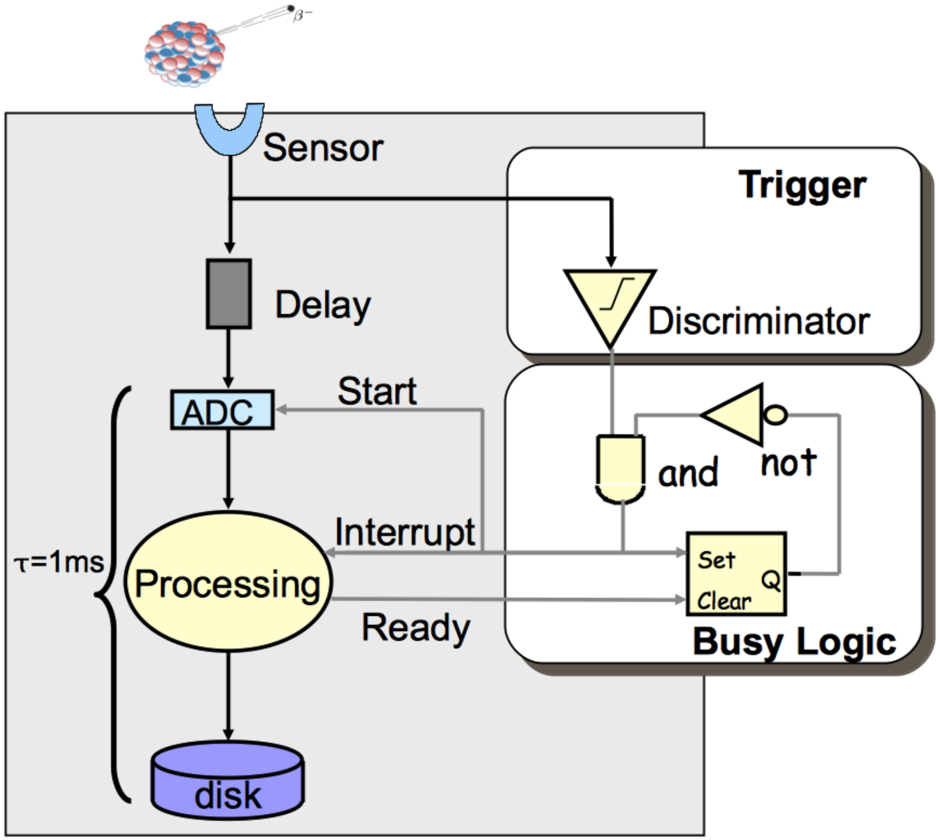
The simplest DAQ

- 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

```
// 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;
}
```

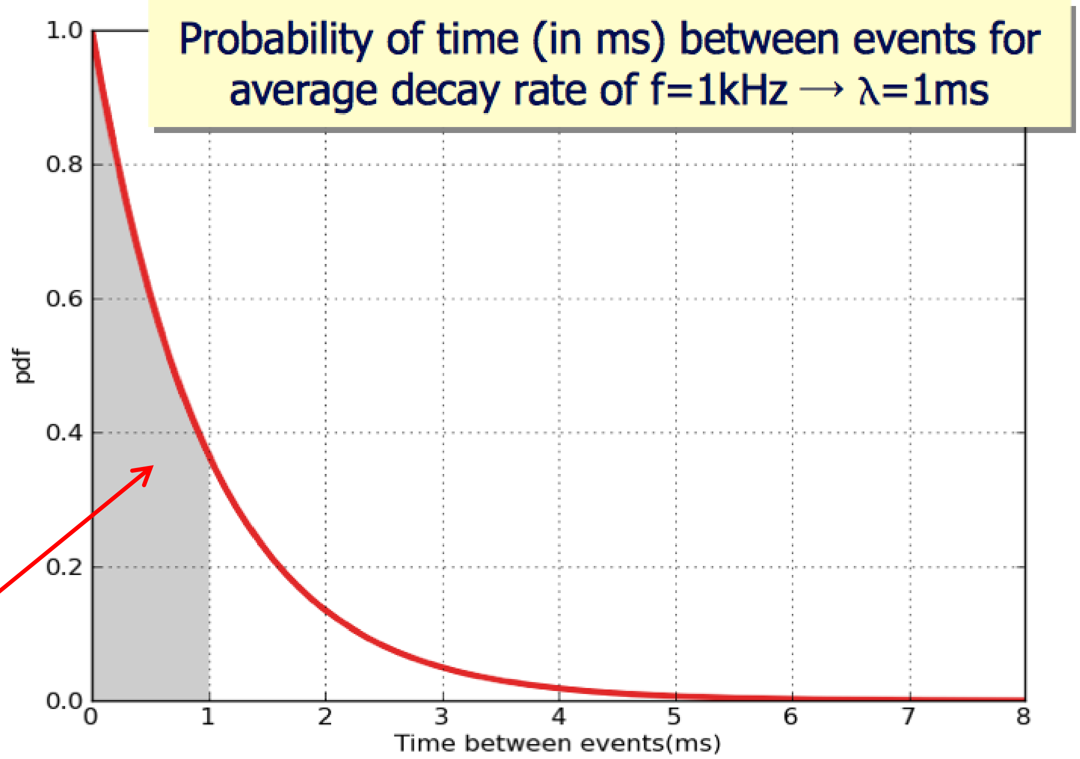
```
event_loop ()
{
  while (end_loop == 0) {
    if (event) {
      size += read_data (*p);
      write (fd, ptr, size);
      busy_reset ();
      event = FALSE;
    }
  }
}
```

Busy logic



- Busy logic avoids triggers while processing
- τ=1 ms is sufficient to run at 1kHz <u>with a clock trigger</u>
- Which (average) DAQ rate can we achieve now?

DAQ dead time and efficiency



Probability of time (in ms) between events for average decay rate of f=1kHz ⟶ λ=1ms

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

DAQ dead time and efficiency

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

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

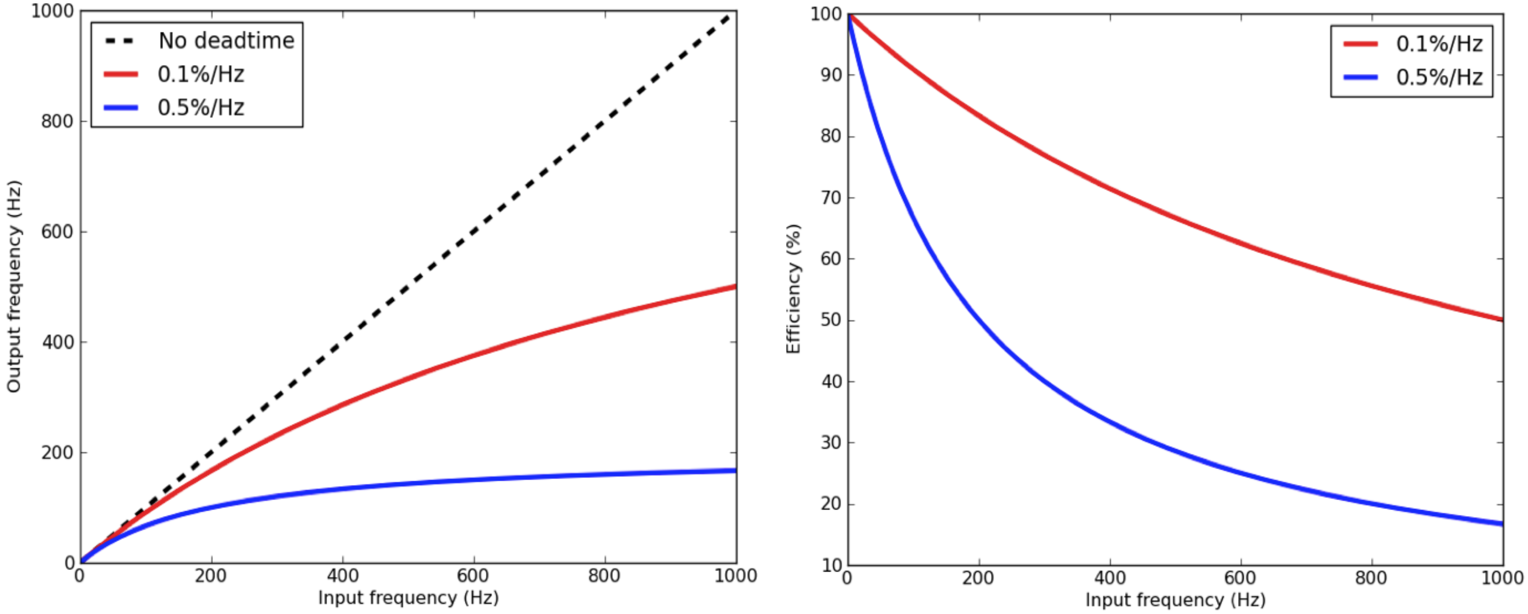
$$\nu = f / (1 + f\tau) < f$$

Define ε as the system efficiency:

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

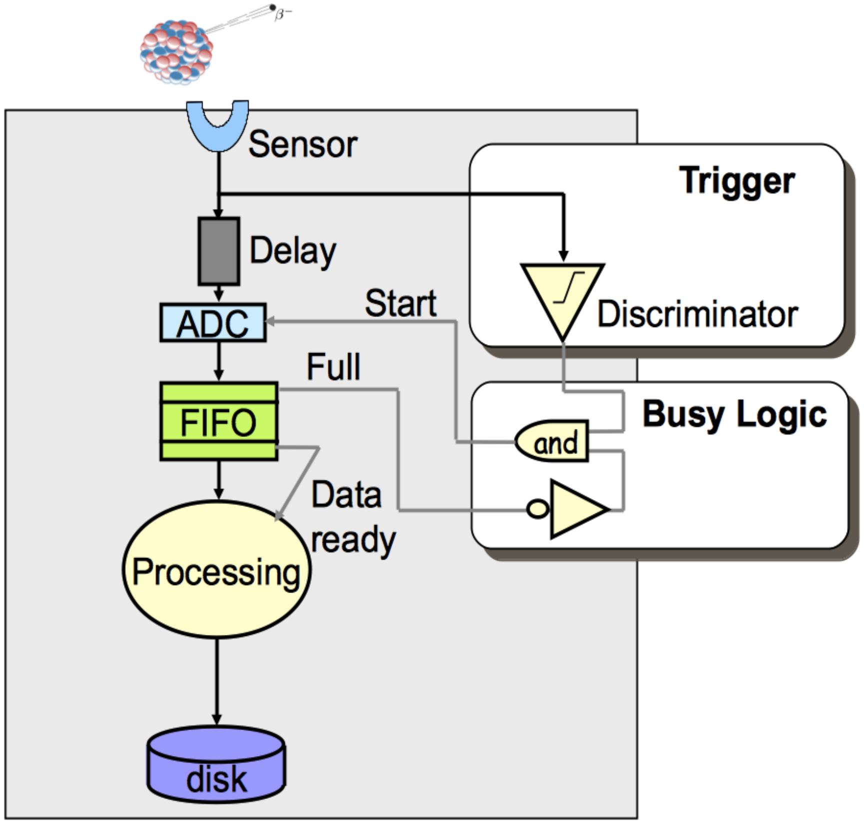
- Due to the fluctuations introduced by the stochastic process the efficiency will always be <u>less 100%</u>
- Define DAQ <u>deadtime (d) as the ratio between the time the system is busy and the total time</u>. In our example d=0.1%/Hz
- In our specific example, d=0.1%/Hz, f=1kHz → ν=500Hz, ε=50%

DAQ dead time and efficiency

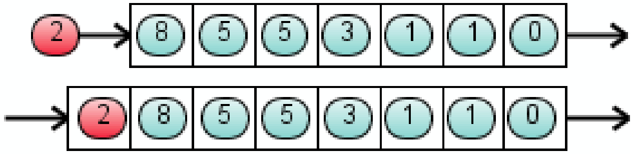


- If we want to obtain ν~f (ε~100%) → fτ<<1 → τ<<1/f
- f=1 kHz, ε=99% → τ<0.1ms → 1/τ>10kHz
- In order to cope with the input signal fluctuations, we have to over-design our DAQ system by a factor 10. <u>This is very inconvenient!</u>

De-randomization

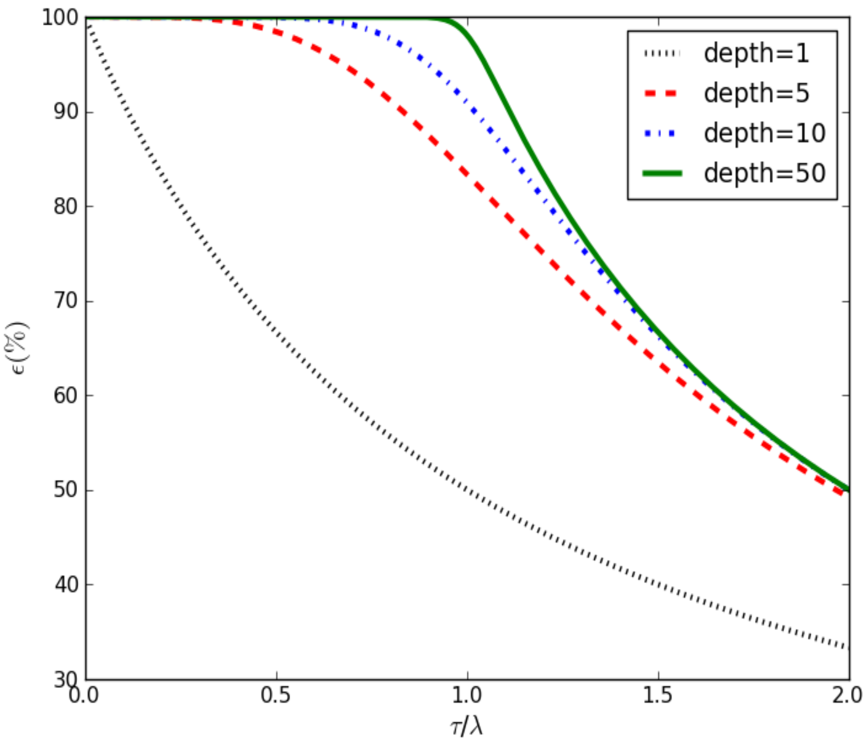


- First-In First-Out
  - Buffer area organized as a queue
  - Depth: number of cells
  - Implemented in HW and SW



  - Introduces an additional latency on the data path
  - Provides a ~steady output path

Efficiency



- We can attain very high efficiency (~1) with τ ~ 1/f
  - With moderate buffer size

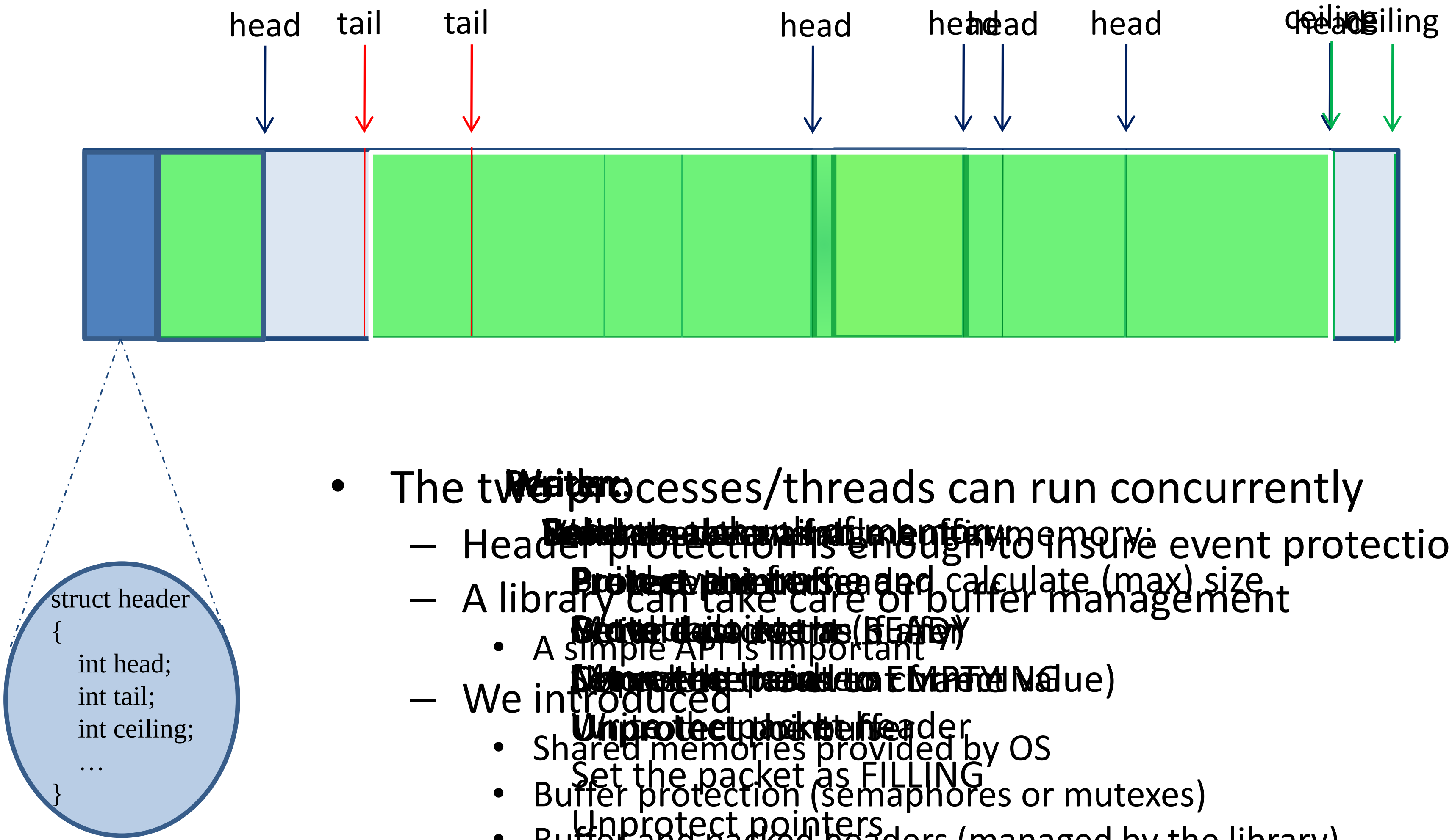
Fragment buffering

- Why buffering?
  - Triggers are uncorrelated
  - Further de-randomization at software level is needed
  - 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

Ring buffer (example from KLOE)



- The two processes/threads can run concurrently
  - Header protection is enough to insure 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)

Writer:

Reader:

Reserve a chunk of memory:

Protect pointers and calculate (max) size

Set the packet as FILLING

Unprotect pointers

Event buffering example

- Data collector

```
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

```
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);
```

Find next event

[illegible] the buffer

Release the scheduler

Reset the busy

Release the scheduler

Close the buffer

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

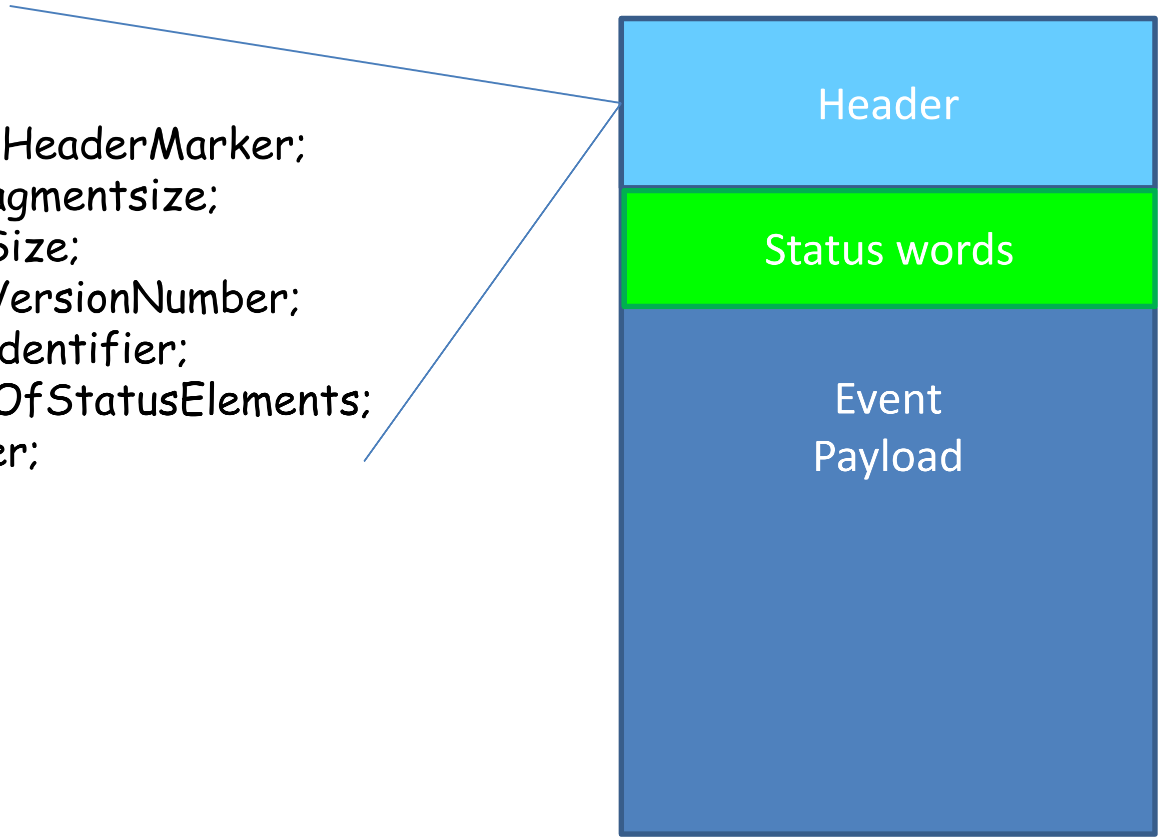
    ⇒Thresholds must be set to accommodate events generated during busy transmission when redirecting data flow
- These concepts are very general…

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;
```



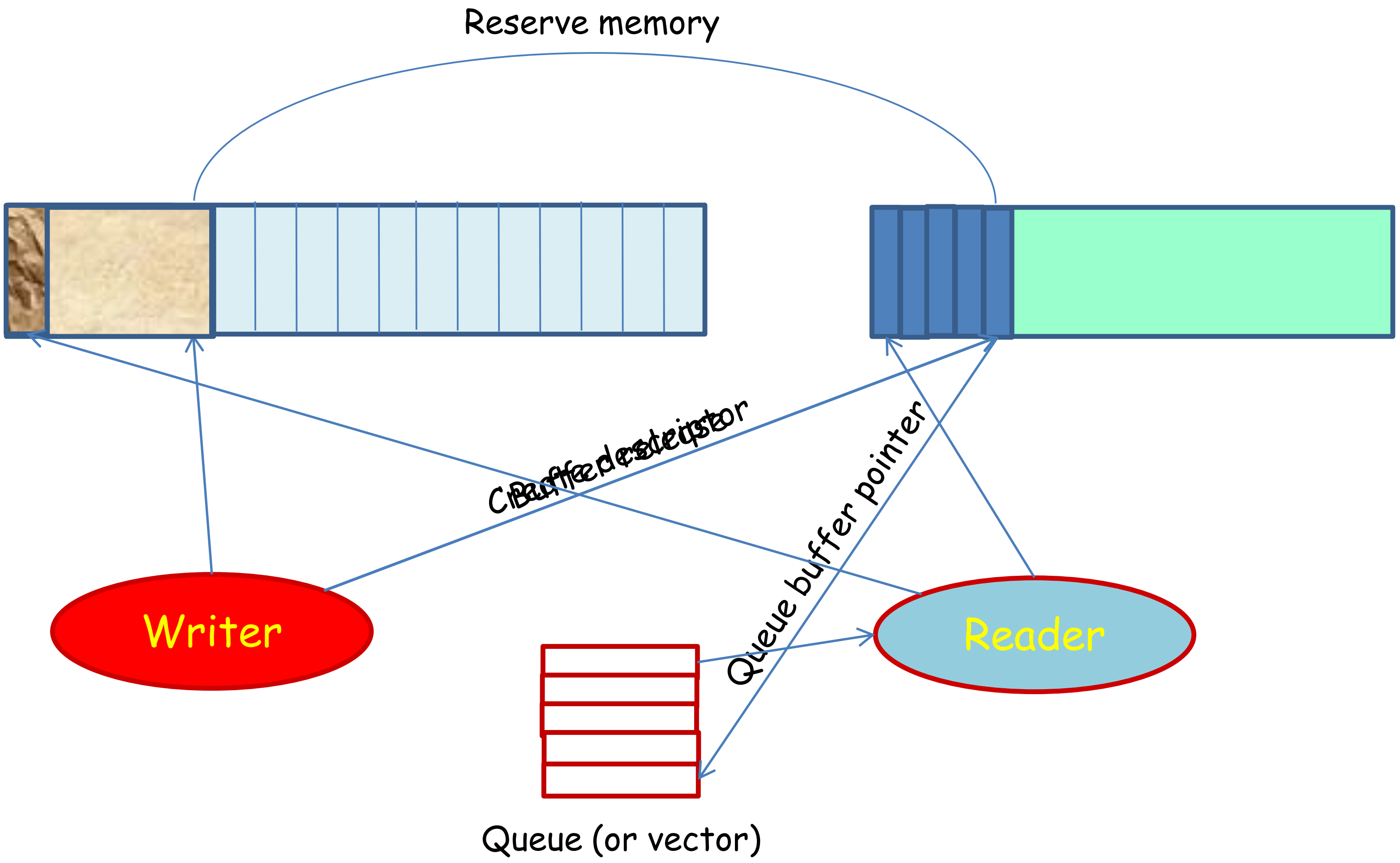
What can we do now….

- 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…

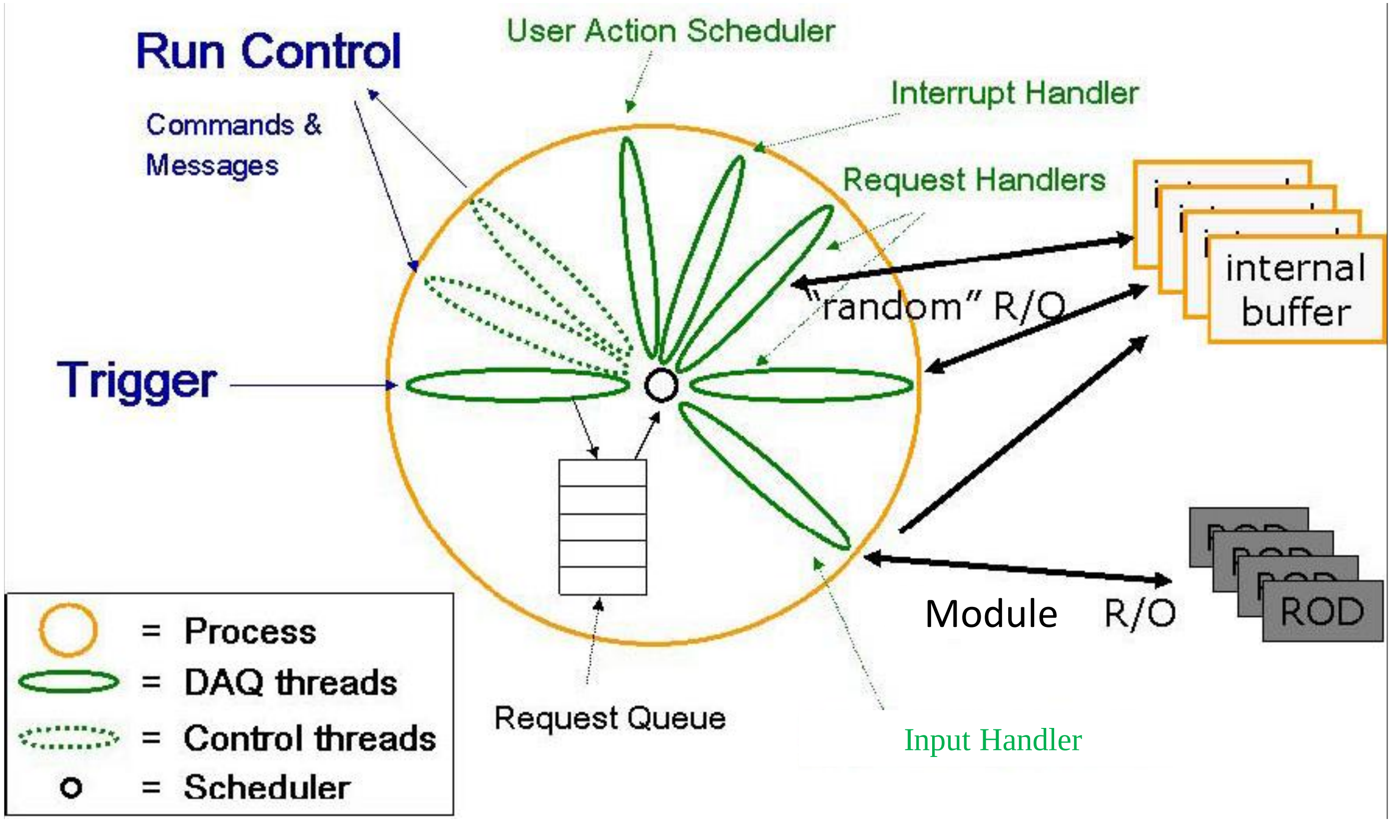
A more general buffer manager

- 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)

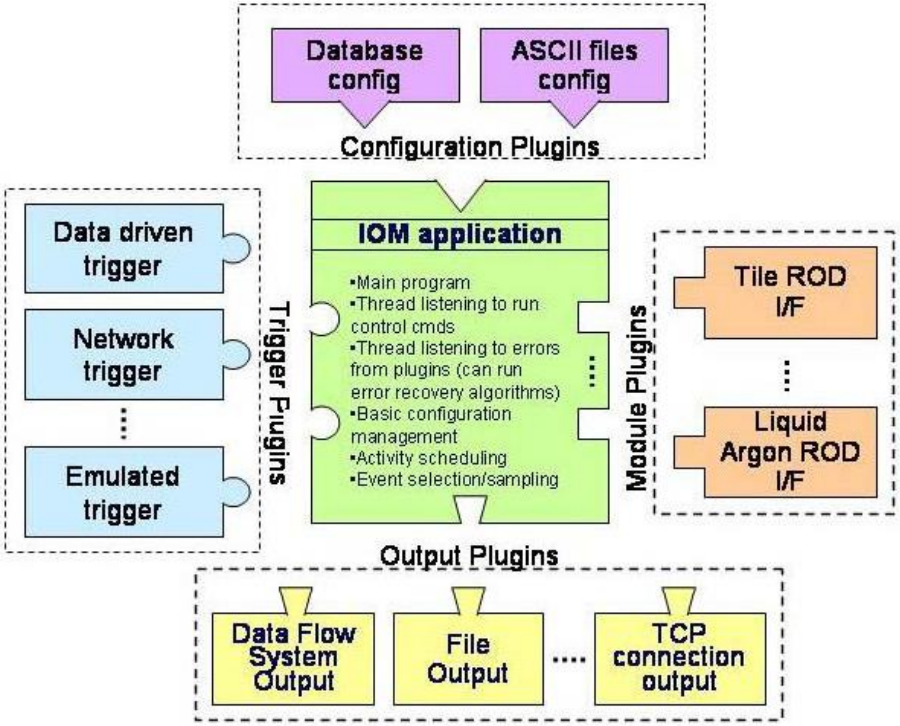


Generic readout application



Configurable applications

- Ambitious idea
  - Support all the systems with a single application
    - Through plug-in mechanism
    - Requires a configuration mechanism



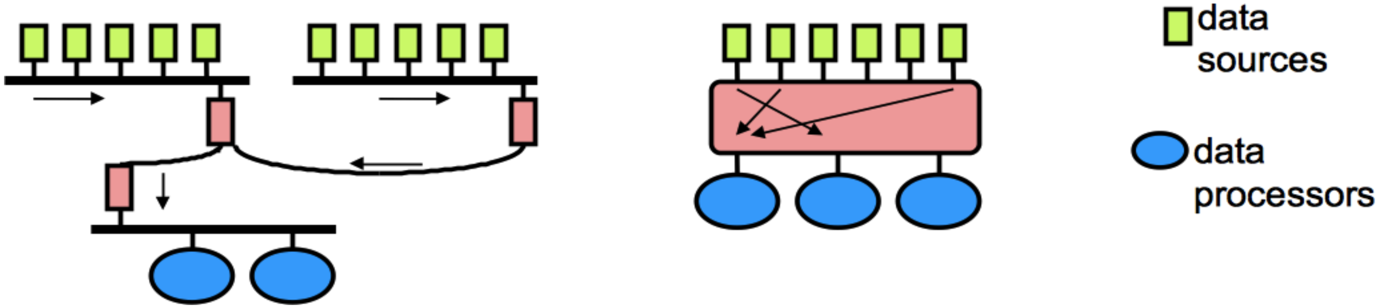
Some basic components

- 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…

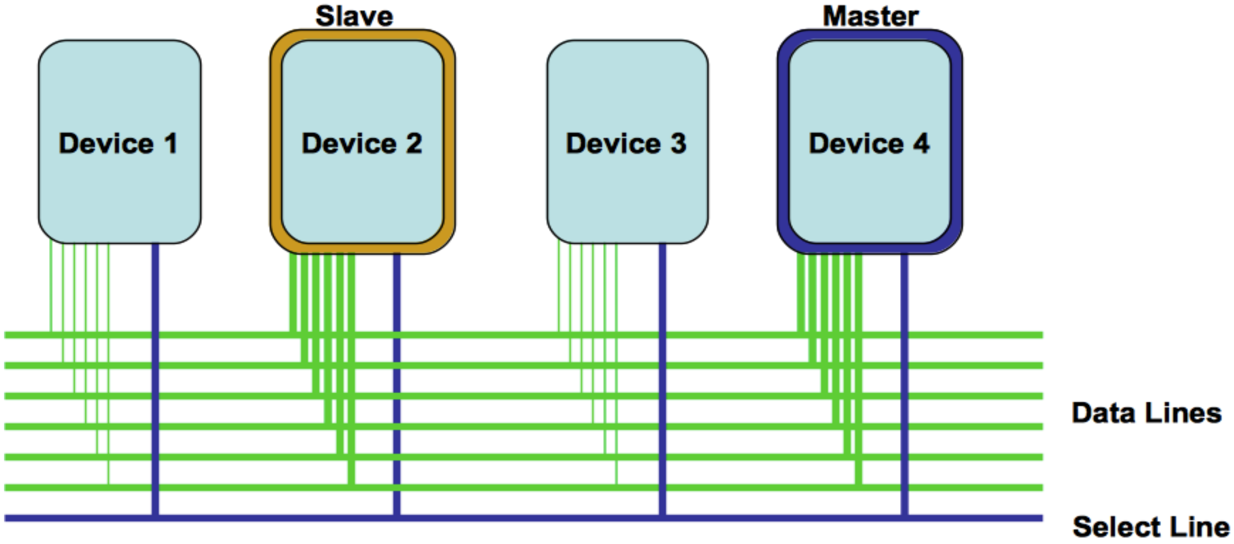
Readout topology

- 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

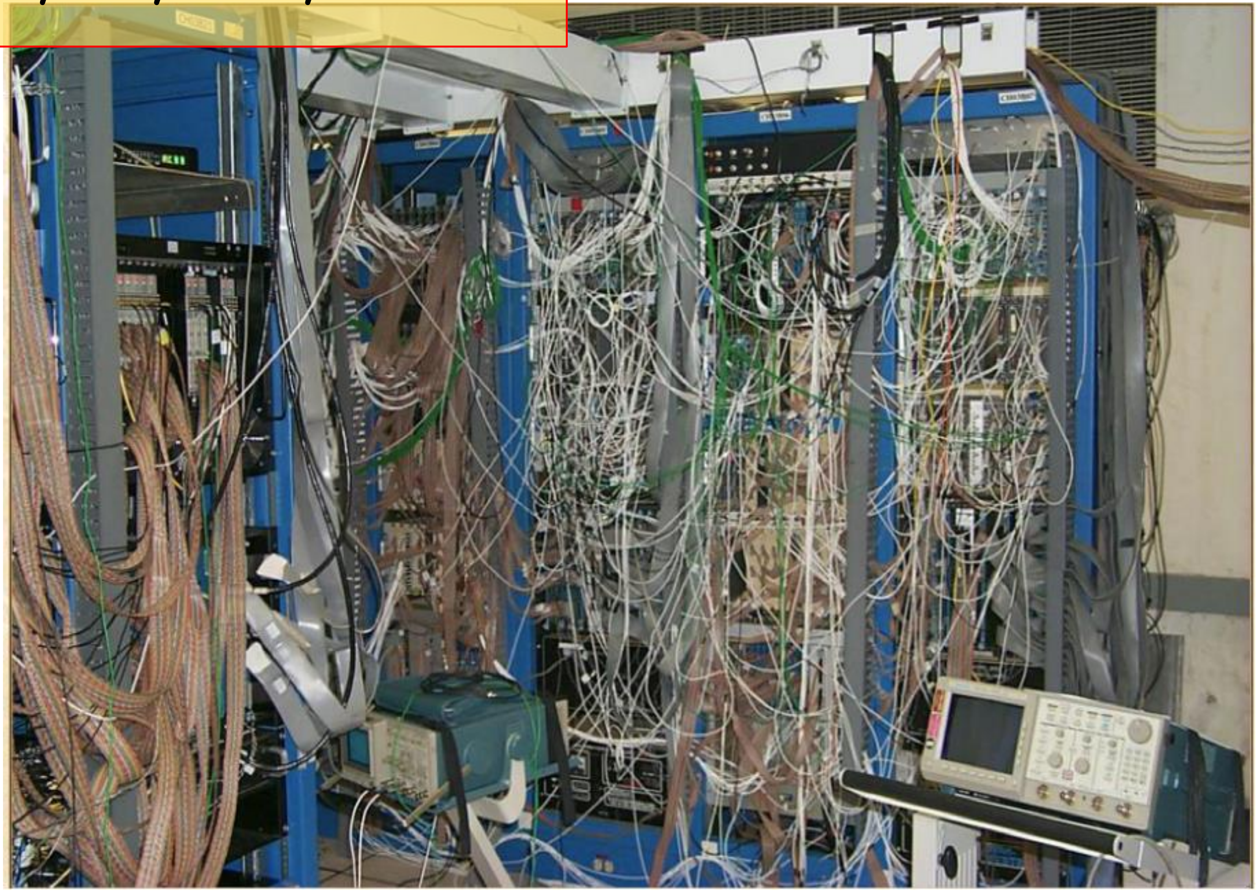
Bus facts

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

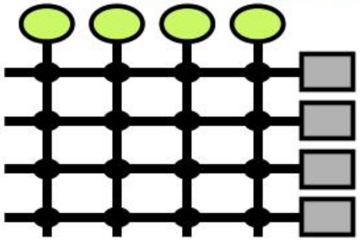
- Scalability issues ✗
  - Bus bandwidth is shared among all the devices
  - Maximum bus width is limited
  - Maximum bus frequency is inversely proportional to the bus length
  - Maximum number of devices depends on the bus length

Scalability issues…

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

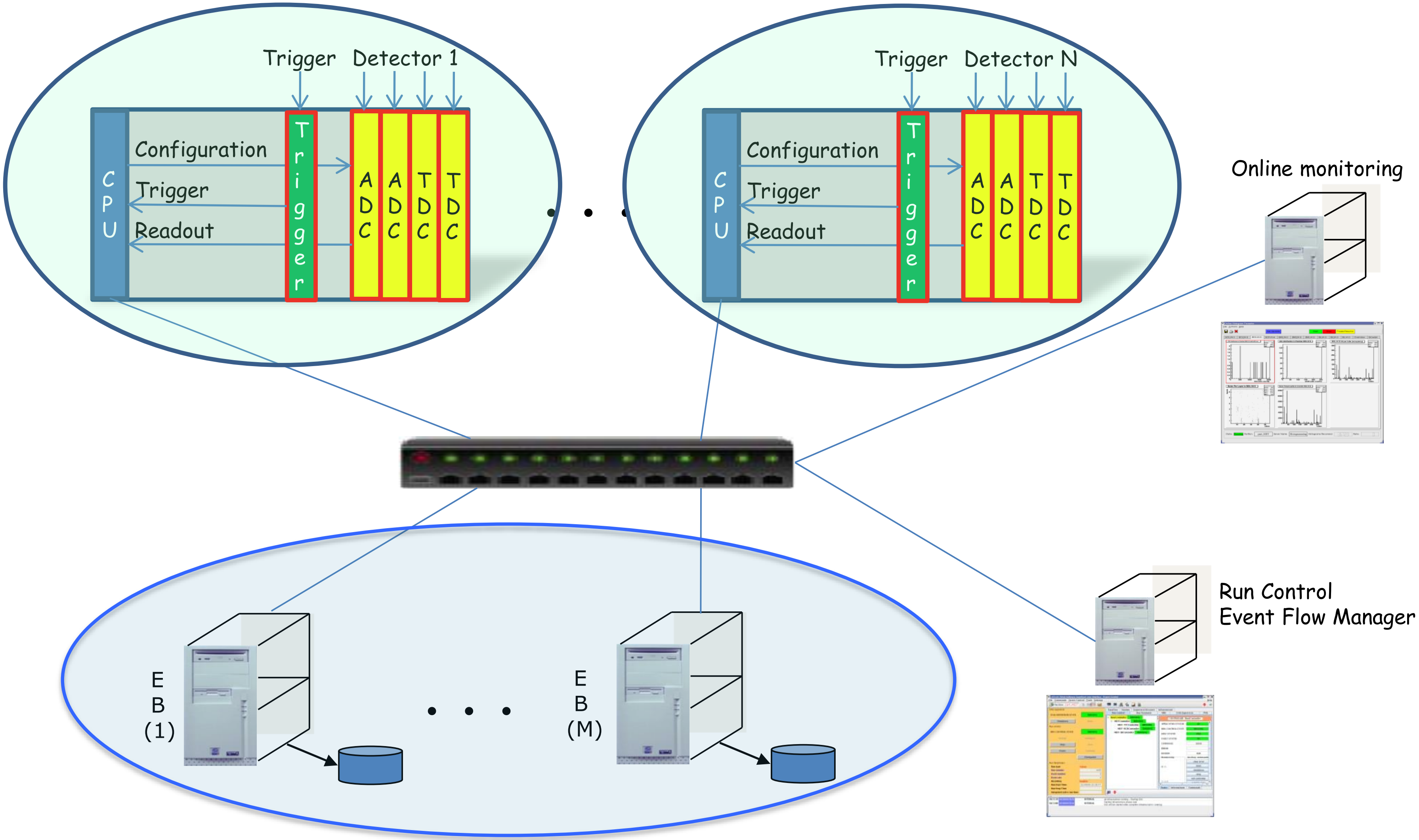


Networks



- 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?

Mixing up…



Trigger Detector 1

C P U

Configuration

Trigger

Readout

Trigger

ADC ADC TDC TDC

. . .

Trigger Detector N

C P U

Configuration

Trigger

Readout

Trigger

ADC ADC TDC TDC

Online monitoring

Run Control
Event Flow Manager

EB (1)

. . .

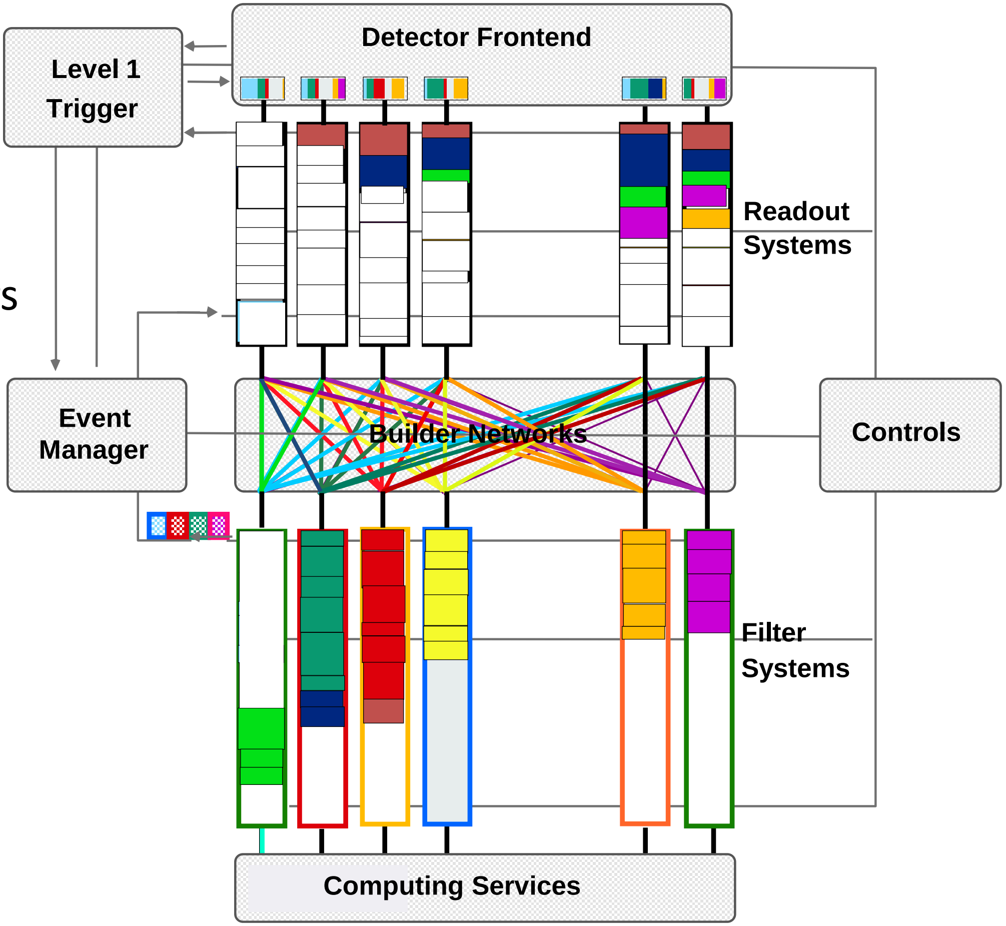
EB (M)

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

```
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);
```

```
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);
```

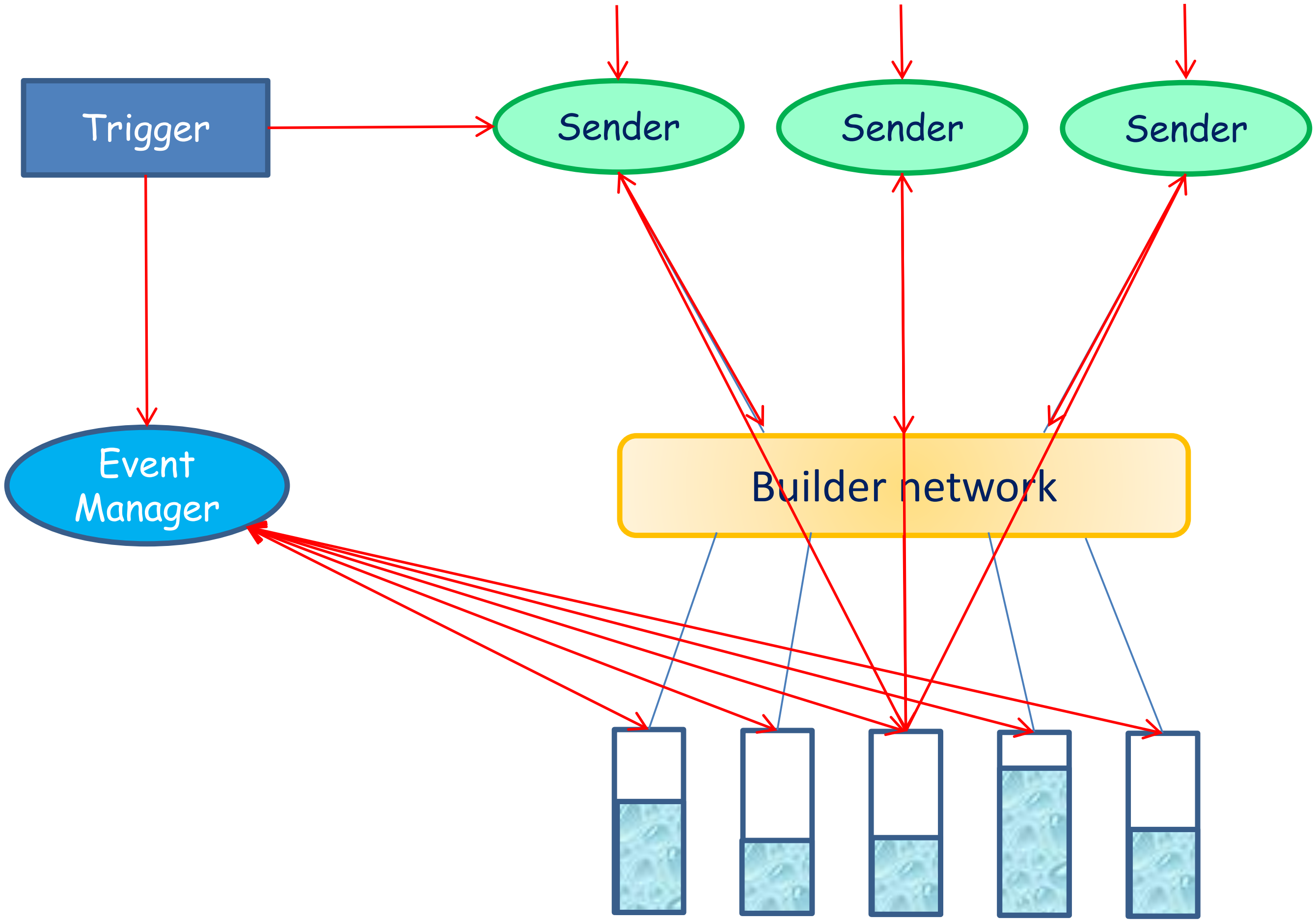
Data transmission optimization

- 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

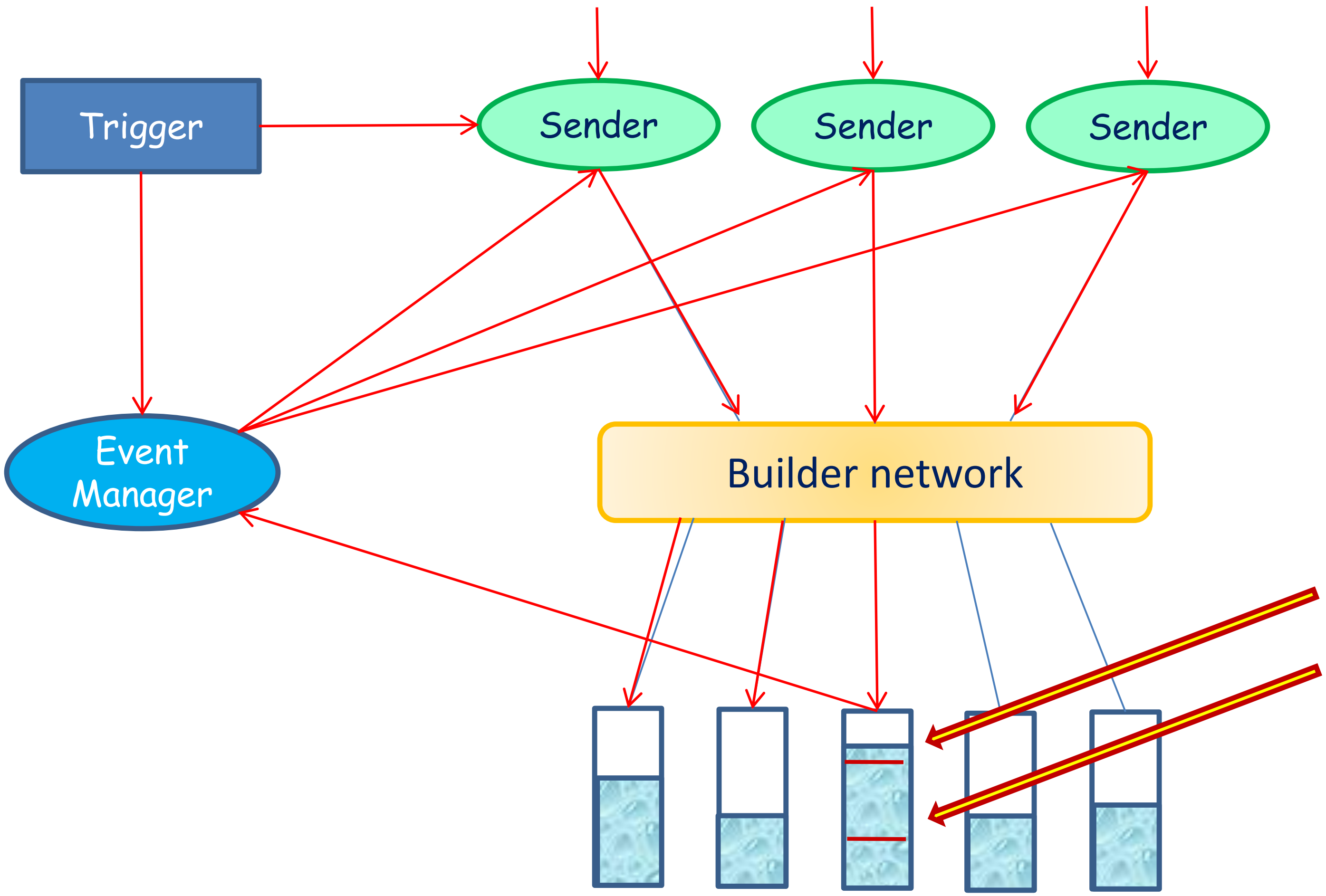
Controlling the data flow

- 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



Push example

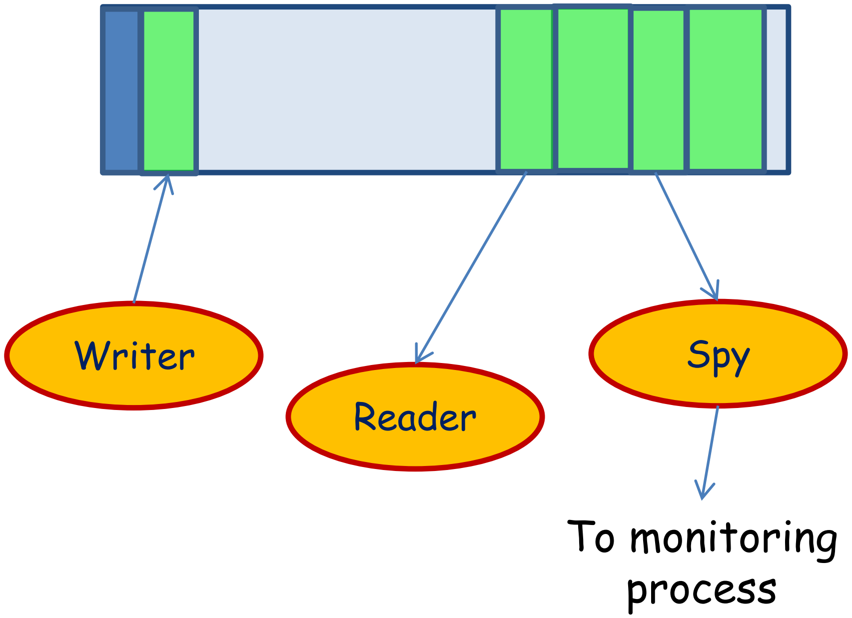


System monitoring

- 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



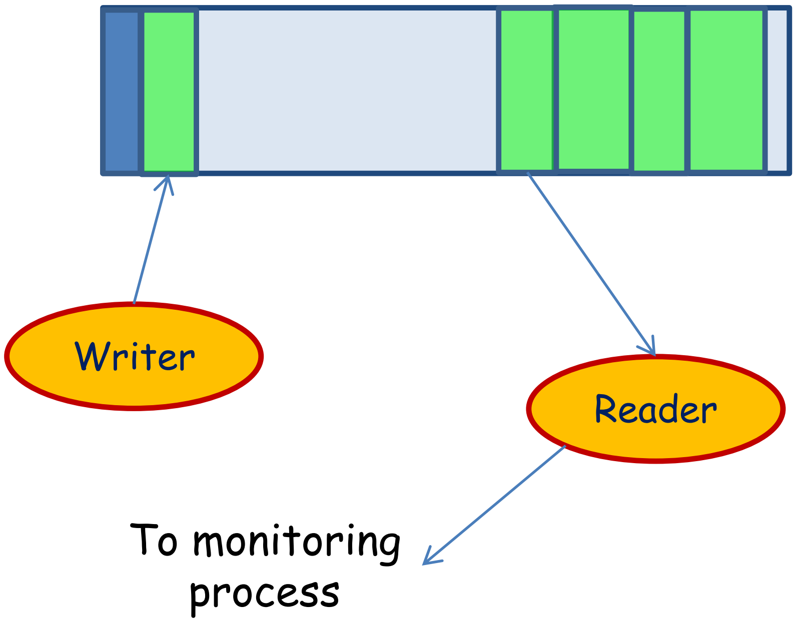
Writer

Reader

Spy

To monitoring process

- Sampling on input or output



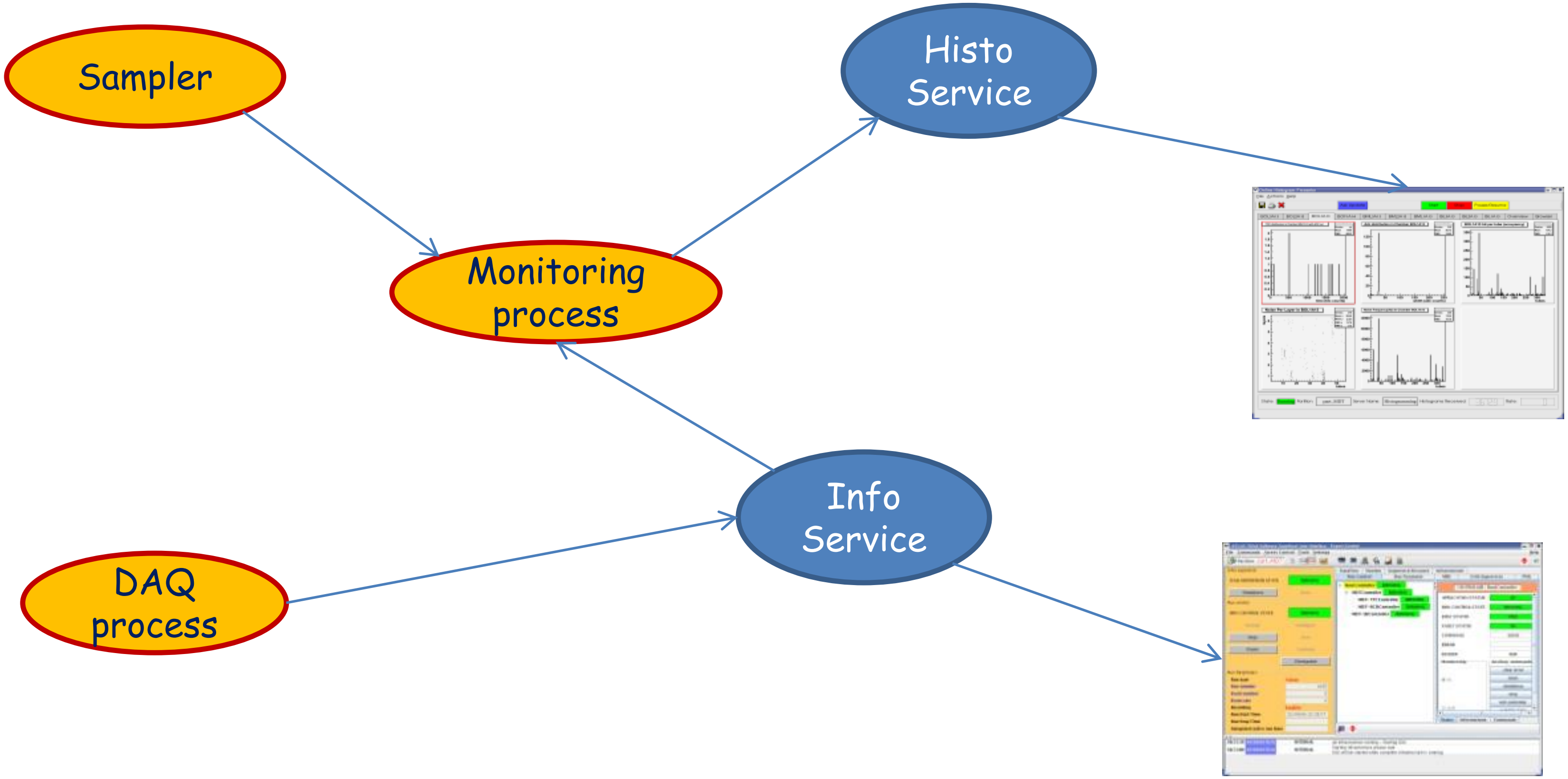
Writer

Reader

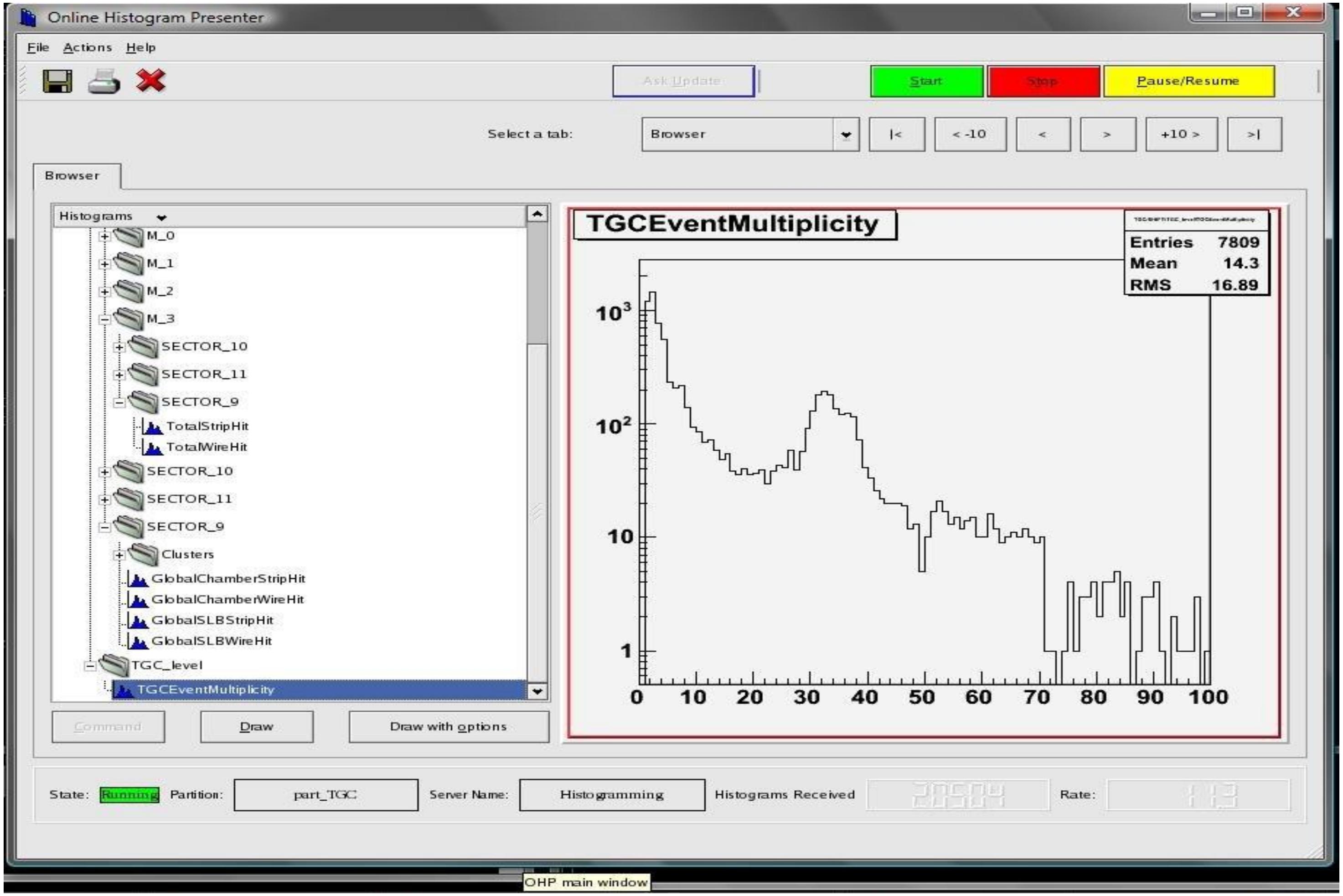
To monitoring process

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

Histogram and variable distribution



Histogram browser



Select a tab: Browser

Histograms
- M_0
- M_1
- M_2
- M_3
  - SECTOR_10
  - SECTOR_11
  - SECTOR_9
    - TotalStripHit
    - TotalWireHit
- SECTOR_10
- SECTOR_11
- SECTOR_9
  - Clusters
  - GlobalChamberStripHit
  - GlobalChamberWireHit
  - GlobalSLBStripHit
  - GlobalSLBWireHit
- TGC_level
  - TGCEventMultiplicity

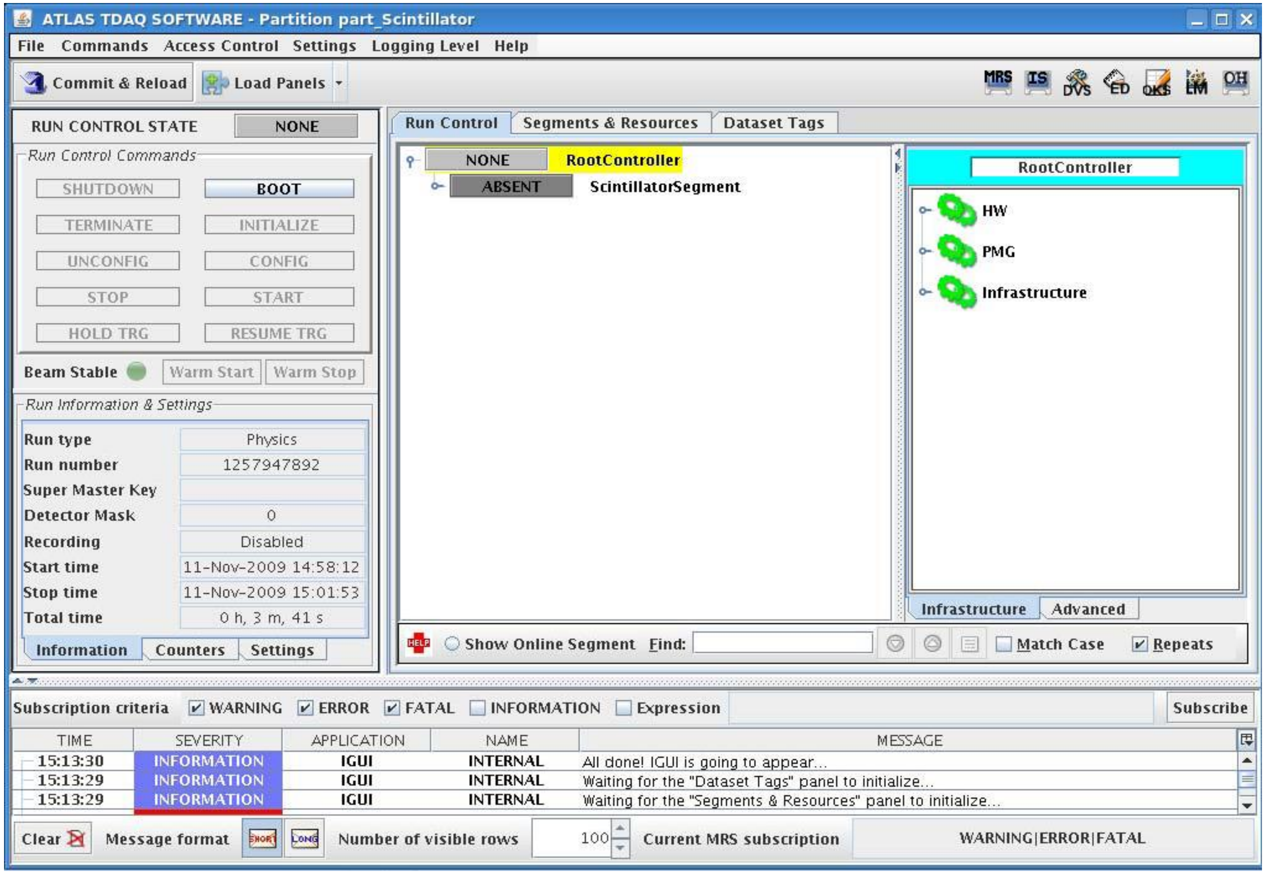
State: Running Partition: part_TGC Server Name: Histogramming Histograms Received 20584 Rate:

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
  - ⇒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

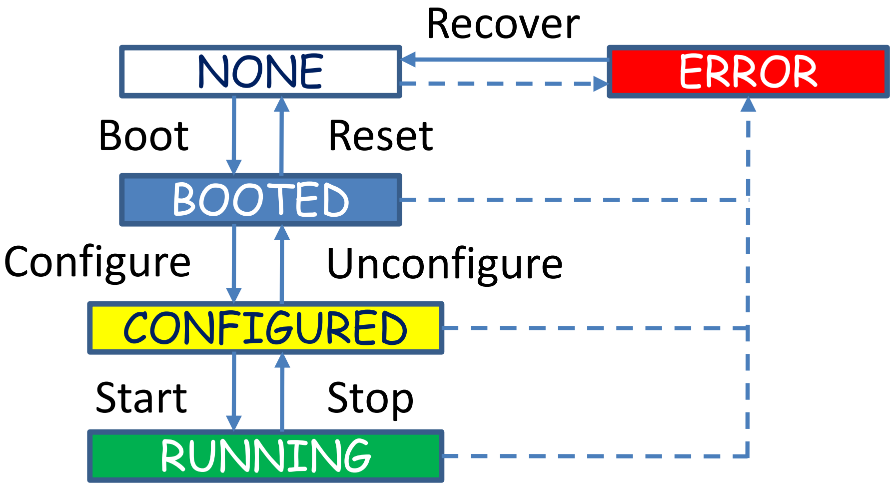


Run type	Physics
Run number	1257947892
Super Master Key	
Detector Mask	0
Recording	Disabled
Start time	11-Nov-2009 14:58:12
Stop time	11-Nov-2009 15:01:53
Total time	0 h, 3 m, 41 s

TIME	SEVERITY	APPLICATION	NAME	MESSAGE
15:13:30	INFORMATION	IGUI	INTERNAL	All done! IGUI is going to appear...
15:13:29	INFORMATION	IGUI	INTERNAL	Waiting for the "Dataset Tags" panel to initialize...
15:13:29	INFORMATION	IGUI	INTERNAL	Waiting for the "Segments & Resources" panel to initialize...

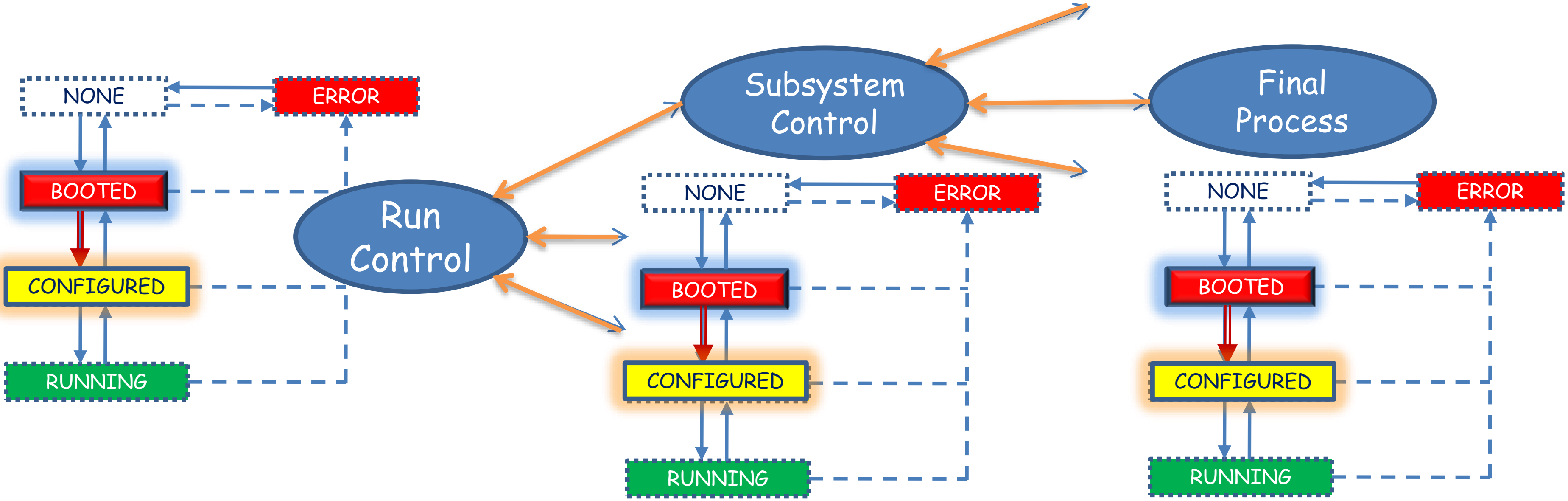
Finite State Machines

- 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!