Big Data Challenges in High Energy Physics Experiments:
The ATLAS (CERN) Fast TracKer Approach

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Big Data Challenges
Big Data Challenges

• Too much data?
  • Choose the right platform
  • Get the data in the platform
  • Synchronize data processing
  • Get useful information out
  • “Foresee” the data increase and prepare for it
• **High Energy Physics** has a well known problem – how to accurately process massive quantities of data in real time

• The universe is governed by probabilistic physics
  • One measurement tells us very little
  • However carefully we set up an experiment, probabilistic physics decides what we observe
  • If we want to observe something rare, we may have to find a few occurrences (events) hidden in vast numbers of other events
The Large Hadron Collider

- World’s largest particle accelerator
- A 27km ring of accelerating structures and superconducting magnets
- Magnets temperature -271.3°C – colder than outer space!
The Large Hadron Collider

[Diagram of the Large Hadron Collider with various components and paths labeled such as ALICE, ATLAS, CMS, LHCb, SPS, and Linacs.]

Key:
- p (proton)
- ion
- neutrons
- $\bar{p}$ (antiproton)
- proton/antiproton conversion
- neutrinos
- electron

Abbreviations:
- LHC: Large Hadron Collider
- SPS: Super Proton Synchrotron
- PS: Proton Synchrotron
- AD: Antiproton Decelerator
- CTF-3: Clic Test Facility
- CNOs: Cern Neutrinos to Gran Sasso
- ISOLDE: Isotope Separator Online Device
- LEIR: Low Energy Ion Ring
- LINAC: LINear ACcelerator
- n-TOF: Neutrons Time Of Flight
The Large Hadron Collider
The ATLAS Detector

- Overall weight 7000 tones
- ~100 million electronic channels
- ~3000 km of cables
• ATLAS “sees” bunches of collisions (tens of superimposed events) every 25ns
• That is 40 million/second or about 15 trillion bunch collisions per year
• If all data would be recorded that would lead to 100000 CDs per second
• Raw analog data rate from Large Hadron Collider (LHC) detectors (event rate 40MHz)
  • About one Petabyte per second
  • This would cost about 1 trillion euros for storage

• In real time, we throw away the data not needed to make discoveries \(\rightarrow\) affordable storage
  • But the discoveries with the greatest impact are those we don’t expect
  • We really do throw away 99.9999% of LHC data before writing it to persistent storage

The ATLAS Trigger System

- **Level-1 Trigger**
  - The level-1 trigger works on a subset of information from the calorimeter and muon detectors. It requires about 2 micro-seconds to reach its decision.

- **HLT**
  - For events selected by the level-1 trigger, the information from the detector must be retained for further analysis. The data for such events are transferred to readout buffers where they remain until the HLT decision is available.

- The events arrive at HLT with a rate of 100 kHz
The real-time tracking problem

- Particle tracking (per event):
  - ~2000 charged tracks
  - ~100k strip and pixel hits
  - Up to 80 proton-proton collisions
  - Non local combinatorial problem of associating hits to a track

- Full tracking with CPUs requires order of 1 second on a x86_64 core.
- For 100kHz, 100k cores would be required along with adequate networking.
• Every 10 μs output tracks from full detector. Typical latency up to 100 ms
• Advantages: high-bandwidth connection to detector (380 fibers) & hardware optimized for specific tasks
FTK has a custom clustering algorithm, running on FPGAs.

The data are geometrically distributed to the processing units and compared to existing track patterns.

Pattern matching limited to 8 layers: 3 pixels + 5 SCTs. Hits compared at reduced resolution.

Full hits precision restored in good roads. Fits reduced to scalar products.

\[ p_i = \sum_j C_{ij} \cdot x_j + q_i \]

Good 8-layer tracks are extrapolated to additional layers, improving the fit.

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FTK consists of 9 separately produced components, with nearly 600 PCBs in the full system.
The Fast TracKer System

100 kHz Event Rate

Cluster Finding

Data Formatter

DO TF HW Proc. unit

AM Proc. unit

Core Crate
45°+10° in φ
8 η-φ towers
2 PU/tower

Second Stage Fit (4 brds)

Track Data ROB

FLIC

FTK ROBs

FTK

Raw Data ROBs
The Fast TracKer System

The FTK is a “coprocessor”. It will make tracks available to commercial computers for further processing.

RODs → Data Formatter → Cluster Finding → Second Stage Fit (4 brds) → Track Data ROB → FLIC → FTK ROBs

100 kHz Event Rate

Raw Data ROBs
The Fast TracKer System

Cluster finding / tower definition

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HLT Processing

FTK
The Fast TracKer System

Cluster finding / tower definition

128 Processing Units execute Pattern Matching and the 1st stage track fitting

Cluster Finding

Data Formatter

100 kHz Event Rate

RODs

Second Stage Fit (4 brs)

FLIC

Track Data ROB

Raw Data ROBs

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19
AM find track candidates with enough Si hits

$O(10^9)$ patterns for FTK

Patterns simultaneously see the silicon hits leaving the detector at full speed.

Pattern recognition is complete as soon as all data is received! $\rightarrow$ low latency

Based on the Associative Memory chip (content-addressable memory) initially developed for the CDF Silicon Vertex Trigger (SVT). [L. Ristori, M. Dell’Orso NIM A 278, 436 (1989)]
AM working principle

One flip-flop per layer stores the match results.

Flexible input: position, time, objects (e, μ, γ)

Pattern matching is completed as soon as all hits are loaded. Data arriving at different times is compared in parallel with all patterns. Unique to AM chip: look for correlation of data received at different times.
Solving the PM problem in 2 steps

- Find low resolution track candidates called “roads”. Solve most of the pattern recognition.
- Then fit tracks inside roads at full resolution.
- Thanks to 1st step it is much easier.
- Close to offline quality.
The Fast TracKer System

Cluster finding/tower definition

128 Processing Units execute Pattern Matching and the 1st stage track fitting

2nd stage track fitting

Proc. HW unit

Second Stage Fit (4 brs)

FLIC

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Track Fitting – Hit Combinations

Best fit is selected, others are discarded

Road

Visualization of the possible hit combinations on an example Road

layer 1
» 2
» 3
» 4
» 5
» 6

SuperStrip

$x^2 = 0$ best fit

$x^2$ large, worst fit
The Fast TracKer System

Cluster finding / tower definition

128 Processing Units execute Pattern Matching and the 1st stage track fitting

Sends the tracks to downstream commercial computers

Data Formatter

2nd stage track fitting

Raw Data ROBs

RODs

100 kHz Event Rate

Proc. HW unit

Second Stage Fit (1 DR3)

FLIC
Multiuse/multipurpose system?

- We have developed a powerful pattern matching system
- We have the AM chip that is a general processing element for “data correlation searches”
- What else can we use it for?
Image reconstruction

• Cognitive image processing
• Fast pattern matching mimicking the operation of the human brain

• AM like algorithm used to identify salient features of the images.
• M. M. Del Viva, G. Punzi, D. Benedetti
  DOI: 10.1371/journal.pone.0069154
Biomedical Applications

• Can be used for:
  • 3D Image Processing for MRI/PET scans
  • Cancer research
  • DNA/protein alignment

• We are currently conducting studies...
The Fast TracKer System
“Mini FTK” for image processing
“Big Data” problem in High Energy Physics - how to accurately process massive quantities of data in real time → high performance application specific hardware

The ATLAS Fast TracKer is a very fast and efficient system that provides track candidates to the next processing level

It is based on a multipurpose/multiuse pattern matching processing unit

Currently investigating various interdisciplinary fields for new applications...
What are we looking for?
The discovery of the Higgs Boson

- July 4th 2012 – Announcement of the discovery of a Higgs boson from the ATLAS and CMS collaborations
A Higgs Event
Thank you...
Indicative References:


Track fitting – high quality helix parameters and $\chi^2$

- Over a narrow region in the detector, equations linear in the local silicon hit coordinates give resolution nearly as good as a time-consuming helical fit.

\[ p_i = \sum_{j=1}^{14} a_{ij} x_j + b_i \]

- $p_i$'s are the helix parameters and $\chi^2$ components.
- $x_j$'s are the hit coordinates in the silicon layers.
- $a_{ij}$ & $b_i$ are prestored constants determined from full simulation or real data tracks.
  - The range of the linear fit is a “sector” which consists of a single silicon module in each detector layer.
- This is VERY fast in FPGA DSPs.