Conclusions from TrackML the HEP Tracking Machine Learning Challenge

Organization
Jean-Roch Vlimant (Caltech)
Vincenzo Innocente, Andreas Salzburger (CERN)
David Rousseau, Yetkin Yilmaz (LAL-Orsay)
Paolo Calafiura, Steven Farrell, Heather Gray (LBNL)
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Laurent Basara, Cécile Germain, Isabelle Guyon, Victor Estrade (LRI-Orsay)
Edward Moyse (University of Massachusetts)
Mikhail Hushchyn, Andrey Ustyuzhanin (Yandex, HSE)
Tracking crisis

- Tracking dominates reconstruction CPU time
- At best quadratic
- HL-LHC (2025) : unmanageable
- Everything tried? → TrackML challenge
See also in outreach session talk by D. Rousseau
« TrackML : the roller coaster of organizing a HEP challenge on Kaggle and Codalab »
https://indico.cern.ch/event/577856/contributions/3423422/
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First phase: Accuracy
May – August 2018
## Leaderboard scores

Score = \( \frac{1}{N} \sum_{\text{test events}} \sum_{\text{good hits}} \text{weights} \)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Team</th>
<th>Score</th>
<th>Hits</th>
<th>Date</th>
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<tbody>
<tr>
<td>1</td>
<td>Top Quarks</td>
<td>0.92182</td>
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<td>19d</td>
</tr>
<tr>
<td>2</td>
<td>outrunner</td>
<td>0.90302</td>
<td>9</td>
<td>18d</td>
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<td>18d</td>
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<td>4</td>
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<tr>
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<td>Zidmie &amp; KhaVo</td>
<td>0.76320</td>
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<td>18d</td>
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<td>Victor Nedel'ko</td>
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<td>2mo</td>
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</table>
Optimizing score optimizes physics
Participants dendrogram

HEP

- Finnies #12
- Zidmie & KhaVo #10
- bestfitting #8
- Rei Matsuzaki #13
- Yuval & Trian #7
- DBSCAN forever #9
- demelian #4
- Sergey Gorbunov #3
- Top Quarks #1
- Komaki #6
- Edwin Steiner #5
- outrunner #2
- Andrea Lonza #11
- Victor Nedel'ko #20
- HiddenTrack #50
- Diogo #100
- Starting kit #500

correlation distance
Phase 1 winner: Top Quarks

Illustration from J-R. Vlimant

Illustration from J.S. Wind
Phase 1 #2: outrunner

- Train DNN on hit pairs
  - 27 inputs (x, y, z, cells, …)
  - 4k-2k-2k-2k-1k hidden layers
- Compute full hit adjacency matrix:
  - probability $P(i,j)$ that 2 hits match
  - Pick high probability comb
- True Deep Learning Solution
  - No track following
  - No geometric modelling
- 1 Day / event
Second phase: Throughput
Oct 2018 – March 2019
Leaderboard evolution

- **Ranking score**: 
  - 0 if time > 600 s or accuracy < 50%
  - $\sqrt{\log(1 + 600/time)} \times (\text{accuracy} - 0.5)^2$
Leaderboard evolution

27 February 2019

Computation speed (sec/event) vs Accuracy mean

- Taka
- Vicennial
- cloudkitchen
- cubus
- fastrack
Leaderboard evolution

[Graph showing the evolution of computation speed (sec/event) vs. accuracy mean over time, with data points for different teams and events labeled.]
<table>
<thead>
<tr>
<th>#</th>
<th>User</th>
<th>Entries</th>
<th>Date of Last Entry</th>
<th>score ▲</th>
<th>accuracy_mean ▲</th>
<th>accuracy_std ▲</th>
<th>computation time (sec ▲)</th>
<th>computation speed (sec/event ▲)</th>
<th>Duration ▲</th>
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<td>1.1727</td>
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<td>0.00 (14)</td>
<td>28.06 (1)</td>
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</tbody>
</table>
#1 S. Gorbunov: « fast combinatorial »

**Track Model**
- local 3-hit helix

**Track Prolongation**
- cross the next layer
- pick the best hit
- refit with the new hit

#2 FASTTrack: Graph of neighbours, cellular automata and Kalman filter

Line width indicates a cell state, color **Red**: state updated at the iteration, **Black**: no state update

[https://indico.cern.ch/event/813759/contributions/3479706/attachments/1870758/3078234/TheTrackML_workshop_talk.pdf](https://indico.cern.ch/event/813759/contributions/3479706/attachments/1870758/3078234/TheTrackML_workshop_talk.pdf)
Algorithm outline

- hits
  - sorted in voxels
  - organised in direct acyclic graphs (DAG)

Main steps
- Select promising pairs
  - 7 million / 0.99
- Extend pairs to triples
  - 12 million / 0.97
- Extend triples to tracks
  - 12 million / 0.95
- Add duplicate hits to tracks
  - 12 million / 0.96
- Assign hits to tracks
  - 90% of hits / 0.92

TrackML Workshop CERN | M. Kunze

DAGs are pre-trained on ~25 events ground truth

DAGs are used to fast navigate through voxel space

Accuracy: 0.93
Time/event: ~7 sec
Memory: 0.7 Gb

ca. 300k
97.2%

c. 500k
99.4%

c. 2 Mio.
Conclusions

• Open tracking competition organised to reach out to CS and ML communities

• Winner and runner-up HEP tracking experts…

• Retained solution will be blend from HEP expertise and new ideas

• Dataset released on CERN Open Data Portal to serve as benchmark

• Ongoing work
Contacts

- Contact: trackml.contact@gmail.com
- https://sites.google.com/site/trackmlparticle
- Twitter: @trackmllhc
- Accuracy phase @ Kaggle: https://www.kaggle.com/c/trackml-particle-identification
- Throughput phase @ Codalab: https://competitions.codalab.org/competitions/20112
  - Write-up to be finalised
- TrackML challenge Grand Finale: https://indico.cern.ch/event/813759/
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Phase 2 Mikado

Author: Sergey Gorbunov

Based on Phase-1 algorithm
- runs iteratively in 80 passes
- & hit removal from high to low pT
- modifications with respect to Phase 1
- search branches enabled
- every pass has optimised parameters
- results in $O(10^4)$ parameters to be tuned,
  tuning done semi-automated

Accuracy: 0.944
Time/event: 0.56 sec
Memory: 0.1/0.178 Gb (1core/2 cores)
Phase 2 FASTrack
Author: Dmitry Emeliyanov

Accuracy: 0.944
Time/event: 1.11 sec → 0.8 sec
Memory: 0.6 Gb
recently down to

first runner-up to podium in Phase-1

Algorithm outline
- using measurement shapes to predict intervals of track inclination
- segment based track following network with embedded Kalman Filter
  - connection graph pre-build (&compiled) from Detector.csv file
  - run with a Cellular Automaton (CA), parallelised with OpenMP
- candidate building: graph traversal with applied simplified Kalman Filter
  - combinatorial track following for track completion
  - fast combinatorial Kalman Filter using 3rd order RK & simplified field includes clone identification & track merging

3 passes (hit removal):
- high momentum
- low momentum
- rest

TrackML, David Rousseau, IML, 16th April 2019
TrackML conclusion
Winning solution → not ML
Winning solution → not ML
Winning solution → not ML
Winning solution → not ML
Winning solution → not ML
Yuval & Trian (#7)
Hit ≡ (x,y,z)

kt\equiv 1/2R,z_0 \rightarrow \text{Hit} ≡ (\Phi,ct,st) \rightarrow \text{Hit} ≡ (\text{Track}_{ld})

Discretization indexed by uniqueTrackId

Random scanning over (kt,z_0) space. Merged by majority vote on card(TrackId)

\{ Hit_{ld},Track_{ld}, \text{card}(Track_{ld}) \} \equiv f(kt,z_0)

\{ Hit_{ld},Track_{ld} \}
Track_{ld} \equiv \text{HitSet} \rightarrow \text{Track}_{ld} \equiv \text{Track Features} \rightarrow \text{Binary classification on purity of hit set} \rightarrow \text{Track}_{ld} \equiv h(T)

Several clustering rounds. Merged on max h(T)

\{ \text{Hit}_{ld}, \text{Track}_{ld}, h(T) \}

\{ \text{Hit}_{ld}, \text{Track}_{ld} \}
$\text{Track}_{ld} \equiv \text{HitSet}$

$\text{Track}_{ld} \equiv \{(\Phi, ct, st)\}$

$\text{Track}_{ld} \equiv (k_t, z_0)$

MSE regression on $k_t, z_0$

Extend with hits by proximity of $(\Phi, ct, st)$

$\{ \text{Hit}_{ld}, \text{Track}_{ld}, (k_t, z_0), (\Phi, ct, st) \}$

$\{ \text{Hit}_{ld}, \text{Track}_{ld} \}$
Other contestants

• #7 : Yuval & Trian
  ▶ « Binned randomized Hough transform » for clustering
  ▶ ML (LightGBM) to merge tracks

• #9 : CPMP - « DBSCAN Forever »
  ▶ DBSCAN on transformed space including deviation from helix
  ▶ On each iteration clusters = new candidate tracks, merged

• #12 : The Finnies
  ▶ DBSCAN variants → 5 hit track seeding
  ▶ LSTM → estimate 10 hits
  ▶ KNN for Track fitting
Majority particle (truth)

Examined track (reconstructed)

$N_{maj}$

$N_{good}$

$N_{reco}$

Purity\_maj = \frac{N_{good}}{N_{maj}}

Purity\_reco = \frac{N_{good}}{N_{reco}}
<passing through origin>

Scattering in detector

<homogeneous magnetic field>

Energy (hence momentum) loss
LHC / HL-LHC Plan

**LHC**
- **Run 1**
  - **LS1**
    - Splice consolidation button collimators
    - RGE project
  - **Eyets**
    - Experiment beam pipes
- **Run 2**
  - **LS2**
    - Injector upgrade
    - TDIS absorber
    - 11T dipole & collimator
    - Civil Eng. P1-P5
    - ATLAS - CMS upgrade phase 1
    - ALICE - LHCb upgrade
- **Run 3**
  - **LS3**
    - HL-LHC installation
    - ATLAS - CMS upgrade phase 2

**HL-LHC**
- **Run 4 - 5...**
  - **14 TeV**
    - Energy
    - 5 to 7 x nominal luminosity

**Timeline**
- 2011 to 2012
- 2013 to 2014
- 2015 to 2016
- 2017 to 2018
- 2019 to 2020
- 2021 to 2022
- 2023 to 2026
- 2027 to 2038

**Integrated Luminosity**
- 30 fb⁻¹
- 150 fb⁻¹
- 300 fb⁻¹
- 3000 fb⁻¹

**FP7**
- Hi-Lumi

**Design Study**
- PDR Preparation
- Assess & TDR
- Main Accelerator Components
- Major Civil Works
- Technical Infrastructure

**Physics**