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Detray - Heterogeneous Tracking Geometry Description and Navigation

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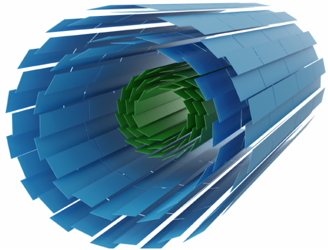
Motivation

ACTS - A Common Tracking Software

- Efficient, thread-safe `C++` implementation of track reconstruction tools.
- Detector agnostic *tracking geometry* description.
- Investigated by e.g. ATLAS, FASER, sPHENIX



Bringing Tracking Software to GPUs

- Different GPU backends, e.g. CUDA or SYCL
- Polymorphic geometry cannot be used in kernels
- Vector-of-vector data structures difficult to move to device memory system

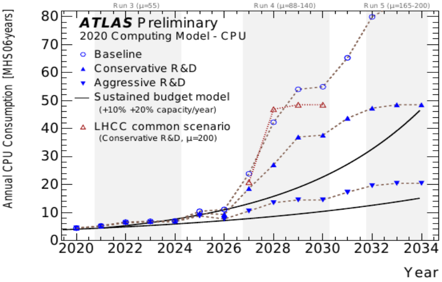
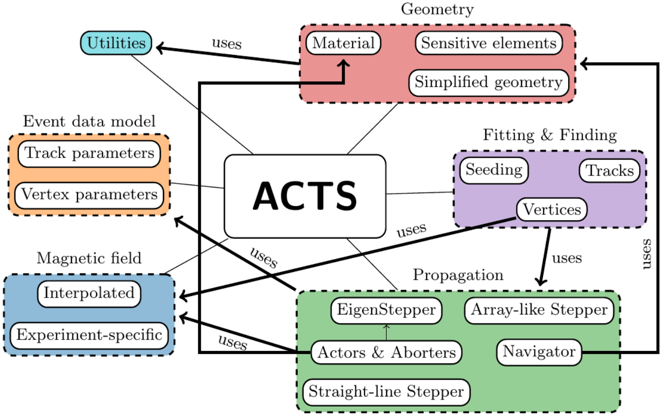


Image: sPHENIX silicon tracker in ACTS (top)

ACTS R&D Project

- **traccc:** Main GPU demonstrator: Event data model, Fitting & Finding
- **covfie:** Vector field library, used for Magnetic Field
- **detray:** Geometry, Propagation
- **vecmem:** Memory management between host and device
- **algebra-plugins:** Switch linear algebra implementation



Source: code available at https://github.com/acts-project/

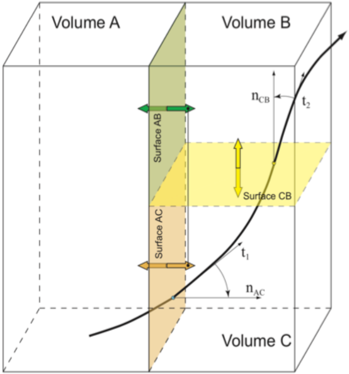
The detray Project

Tracking Geometry Building Blocks

- **Volumes** subdivide the detector into smaller navigation regions.
- **Surfaces** as core building blocks.
- A **Grid** as volume and surface finder accelerator.
- Read tracking geometry from ACTS

Design Goals

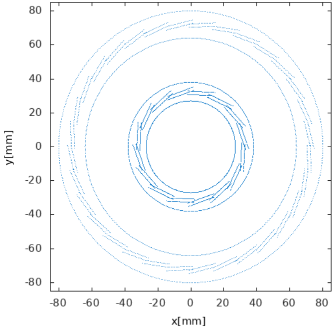
- Use classes on host (CPU) and device (GPU)
- Geometry classes without runtime polymorphism
- Flat container structure, using `vecmem` library
- Index based data linking, no pointers



resulting navigation
through the boundary portals

`detray` Detector Class

- Holds all geometry and magnetic field data
- Performs the container moves between host and device
- Provides interface to the tracking geometry data
- Testbed geometry modeled after pixel component of ACTS *generic detector*.



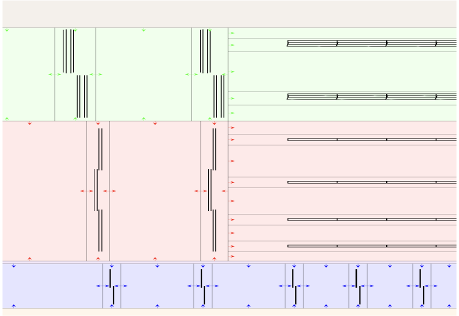
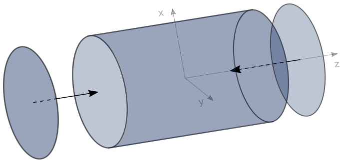
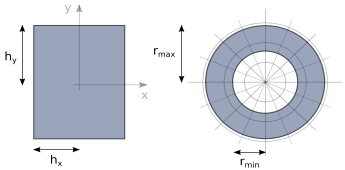


Image: The ACTS Open Data Detector implementation https://github.com/acts-project/acts/pull/1039 (right)

Geometry Description

- **Volumes**: defined by their boundary surfaces
- **Surfaces**: Placed by affine transformations and defined by boundary masks
- **Masks**: Defined by a shape type.
  Specify local coordinates and extent of surfaces.
- **Portals**: Special surfaces that tie volumes together through index links.
- **Material:** Homogeneous *slabs* or *rods* of parametrized material. Many predefined materials available.





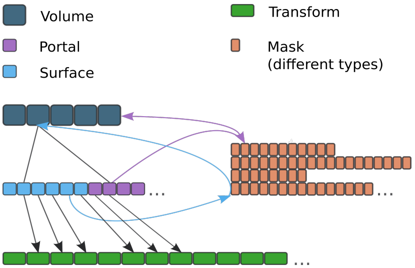
No abstract classes: Every type needs its own container. Solved by compile-time *unrolling* of tuple containers.

`detray` Container Structure

In ACTS: (For now) Jagged memory layout of volumes containing layers, containing surfaces.

Linking by Index

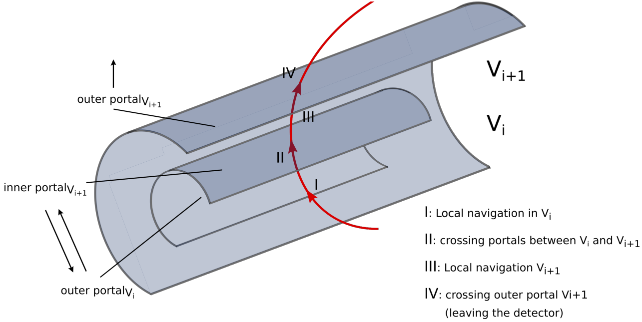
- Volume (descriptors) keep links into surface container (acceleration data structures).
- Surface (descriptors) keep indices into the transform, mask and material containers.
- Portal masks link to adjacent volume.
- Sensitive/Passive surface masks link back to mother volume.



The geometry data structures are built host-side and the memory allocation strategy is determined by *vecmem memory resources*.

Participants

- **Propagator:** runs the propagation loop: Calls stepper, navigator and the actors.
- **Navigator:** Moves between detector volumes and finds distance to next candidate surface.
- **Stepper:** Transports the track parameters and corresponding covariance matrix through magnetic field.
- **Actors/Aborters:** Extend propagation with various functionality (e.g. watch termination criteria).



Geometry Navigation

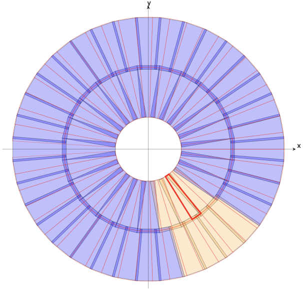
Surface Candidate Cache

- *Trust levels* determine update method:
- ***Full trust***: Track state still consistent, do nothing.
- ***High trust***: Only update the current next target surface.
- ***Fair trust***: Update all candidate surfaces and sort again.
- ***No trust***: (Re-)initialize current volume, i.e. fill cache from local neighborhood and sort.

⇒ Stepper/actors can lower trust level to trigger navigation update.

Local Navigation in a Volume

- Accelerator data structures provide surface neighbourhood lookups.
- Navigate local neighborhood, before reassuming inter-volume navigation.
- In principle: Any kind of accelerator data structure possible.



Propagation Loop

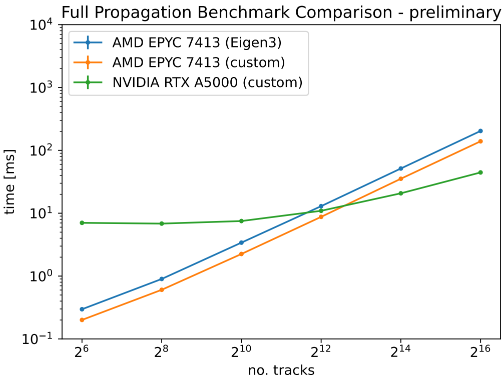
```
// initialize the propagation
navigator.init(propagation);

run_actors(propagation._actor_states,
           propagation);

// run while propagation has hearbeat
while (propagation.heartbeat) {

  stepper.step(propagation);

  navigator.update(propagation);

  run_actors(propagation.actor_states,
             propagation);

  navigator.update(propagation);
}
```

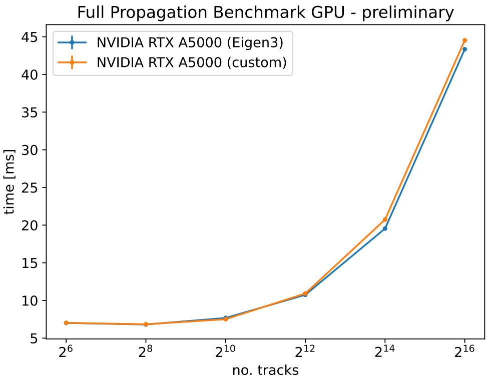
Actor Mechanism

- E.g. *aborters, material interactor, random scatterer* . . .
- Can be plugged in at compile time.
- Perform various tasks in every step
- Possible to *observe* other actors ⇒ call tree

⇒ Schedules one track per thread, currently.

Preliminary Benchmarks



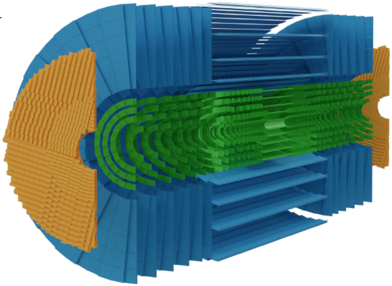


Source: tag v0.29.0 (https://github.com/acts-project/detray)

Summary and Outlook

Status

- Testbed geometry modelled after ACTS generic detector's pixel detector
- Uses COVFIE library for inhomogeneous B-field description (WIP)
- Adaptive Runge-Kutta-Nyström algorithm for field integration
- Transport of track parametrization and covariance through (in-)homogeneous B-field
- Simple material description with material interactions



Major on-going Developments

- Integration of navigation accelerator data structures (grid collections are available on device, but not yet used)
- Read existing tracking geometry implementations from ACTS (e.g. ATLAS ITk)

Acknowledgements

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References

[1] M. Aleksa *et al.*, "Strategic R&D Programme on Technologies for Future Experiments," CERN, Geneva, Tech. Rep., Dec. 2018, CERN-OPEN-2018-006. [Online]. Available: https://cds.cern.ch/record/2649646.

[2] *CUDA C++ Programming Guide*, Oct. 2022. [Online]. Available: https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html (visited on 10/24/2022).

[3] J. Nickolls *et al.*, "Scalable Parallel Programming with CUDA: Is CUDA the Parallel Programming Model That Application Developers Have Been Waiting For?" *Queue*, vol. 6, no. 2, pp. 40–53, Mar. 2008. DOI: 10.1145/1365490.1365500. [Online]. Available: https://doi.org/10.1145/1365490.1365500.

[4] N. Bell *et al.*, "Thrust: A productivity-oriented library for cuda," in *GPU Computing Gems Jade Edition*, ser. Applications of GPU Computing Series, Boston: Morgan Kaufmann, 2012, pp. 359–371. DOI: https://doi.org/10.1016/B978-0-12-385963-1.00026-5.

[5] J. Myrheim *et al.*, "A fast runge-kutta method for fitting tracks in a magnetic field," *Nucl. Instrum. Methods*, vol. 160, no. 1, pp. 43–48, 1979. DOI: https://doi.org/10.1016/0029-554X(79)90163-0.

[6] L. Bugge and J. Myrheim, "Tracking and track fitting," *Nuclear Instruments and Methods*, vol. 179, no. 2, pp. 365–381, 1981, ISSN: 0029-554X. DOI: https://doi.org/10.1016/0029-554X(81)90063-X.

[7] E. Lund, L. Bugge, I. Gavrilenko, *et al.*, "Track parameter propagation through the application of a new adaptive runge-kutta-nyström method in the atlas experiment," *Journal of Instrumentation*, vol. 4, no. 04, P04001, Apr. 2009. DOI: 10.1088/1748-0221/4/04/P04001.

[8] C. Allaire *et al.*, *OpenDataDetector*, gitlab, version v1, 2021. DOI: 10.5281/zenodo.4674402. [Online]. Available: https://gitlab.cern.ch/acts/OpenDataDetector/.

Backup

Heterogeneous Computing Model

Implementation in `detray`

- Goal: outsource many-track propagation to device.
- Need to handle host-device memory transfers.
- Core classes templated on `STL` vs. vecmem containers.
- The geometry data structures are built host side and memory allocation strategy is determined by *vecmem memory resources*.

```
#include <vecmem/containers/vector.hpp>

// Transform store using managed memory
vecmem::cuda::managed_memory_resource mng_mr;

// Build with host vector type
transform_store<vecmem::vector> store(mng_mr);

// Get store view object
auto sv = detray::get_data(store);

// Run the kernel
test_kernel<<<block_dim, thread_dim>>>(sv);
```

```
#include <vecmem/containers/device_vector.hpp>

// Kernel-side construction
__global__ void test_kernel(store_view sv) {
  // Build with device vector type
  transform_store<vecmem::device_vector> store(sv);

  // Do something
}
```

Parameter and Error Propagation

Track state parametrization: global $(x, y, z, t, v_x, v_y, v_z, q/p)$, local $(\mathrm{loc}_0, \mathrm{loc}_1, \varphi, \theta, q/p, t)$

Field Integration

- No track solution in closed form inhomogeneous magnetic field.
- Numeric Integration: Runge-Kutta-Nyström algorithm (4-th order).
- Takes distance to next target surface and adjusts step-size according to integration error.
- Magnetic field map interpolation to get field vectors at arbitrary positions (covfie library).

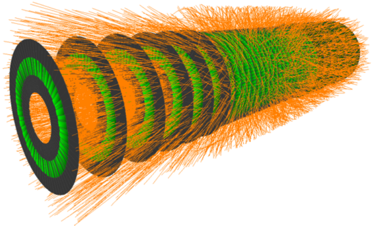
Covariance Transport and Material Interaction

- Do covariance transport: Transform initial covariance estimate with coordinate transform/RK-transport Jacobians.
- Called at every material surface to add material effects to covariance.
- Takes energy loss effects and multiple scattering into account.

$\Rightarrow$ Both implemented as actors.

Kaggle TrackML challenge

- Generic Tracking Detector design
- Reduced physics list in fastsim
- But: afterwards dataset was used for further tracking R&D



⇒ Provide simplified generic, but more realistic dataset!

Next level: The Open Data Detector [8]

- More realistic detector description
- 4 layer Pixel detector
- Short- and Long-Strip detector
- Detector mounting, cables, cooling . . .

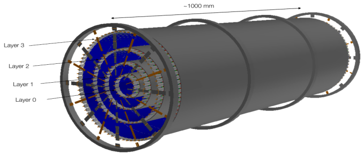


Image: (top) https://sites.google.com/site/trackmlparticle/