Future framework directions

An LDRD approach called Meld

Kyle J. Knoepfel

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Fermilab Frameworks Workshop

Setting the stage

- Experiments use computing frameworks (like art) to process detector and simulated data for physics analysis.

- Existing computing frameworks are based on collider-physics concepts.

  Their processing constructs assume localized accelerator bunch crossings

  Events are treated as statistically independent

- DUNE, Fermilab's flagship experiment, will analyze interaction regions and data-collection time windows that sometimes overlap or vary in size.

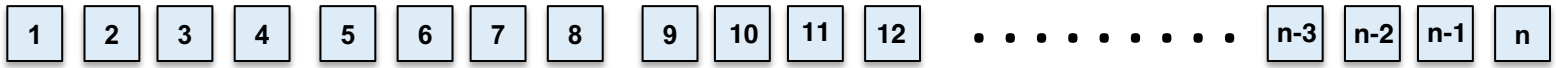
  No framework solution exists that readily supports this

  Neutrino physicists must work around current framework limitations

Processing complications (1)

- The collider physics approach to data processing

  Existing computing frameworks process data in rigid ways



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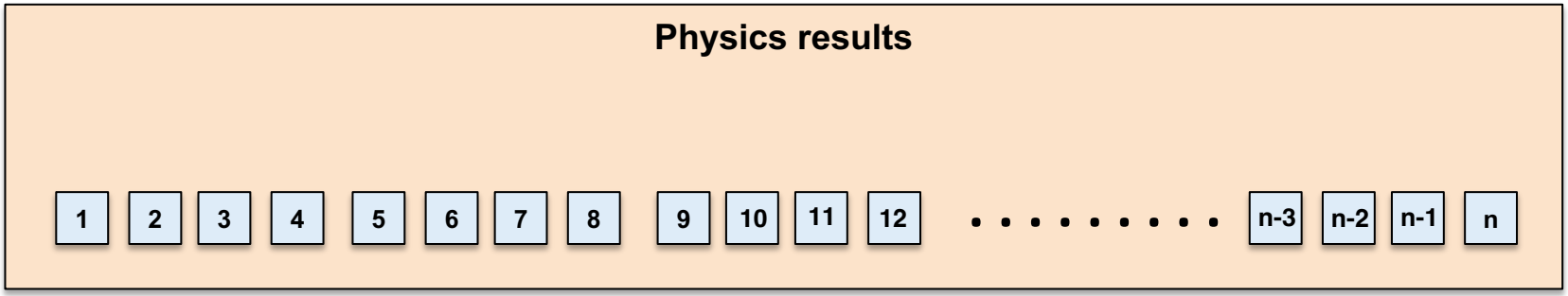

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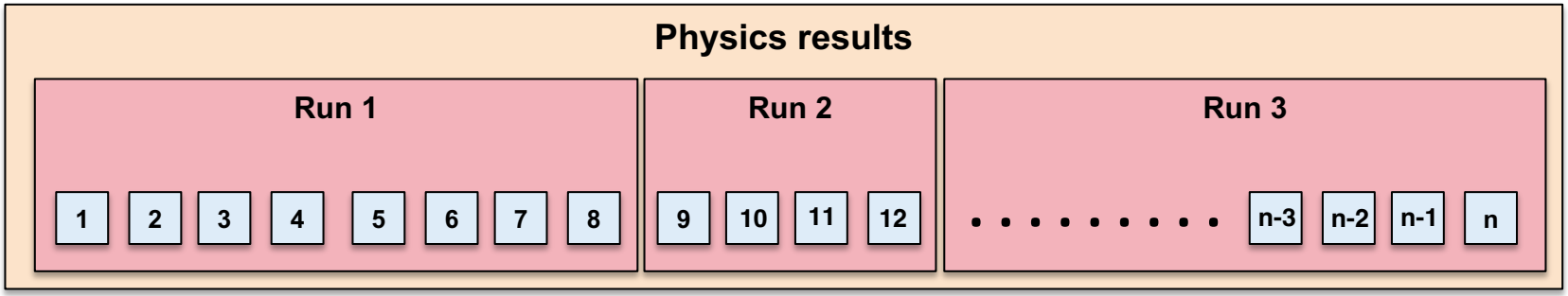

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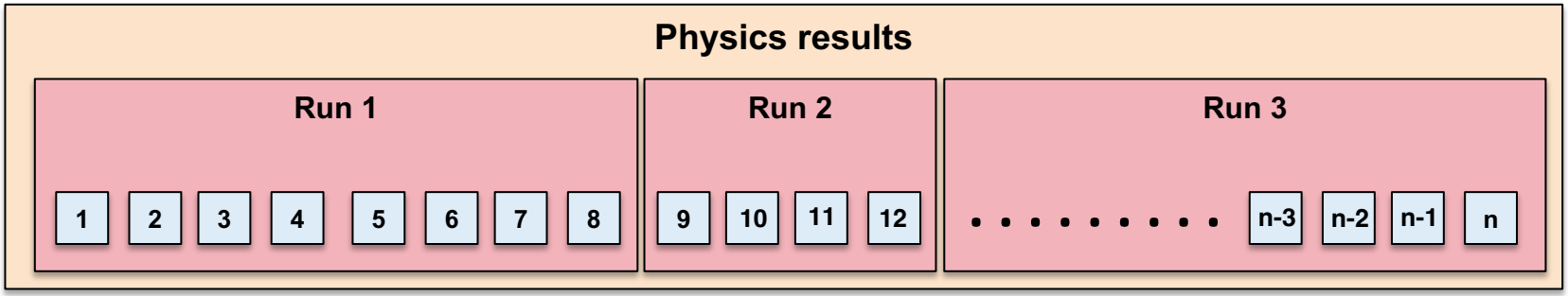

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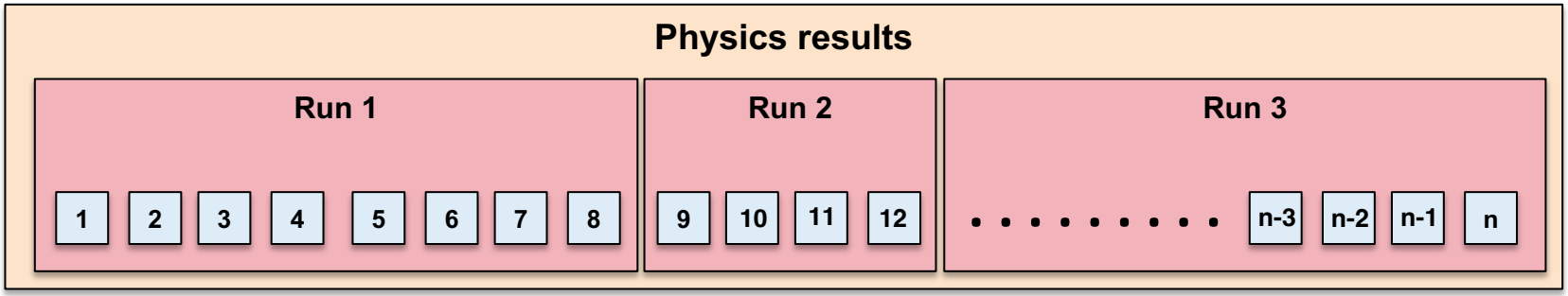

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- **This approach does not work well for DUNE.**

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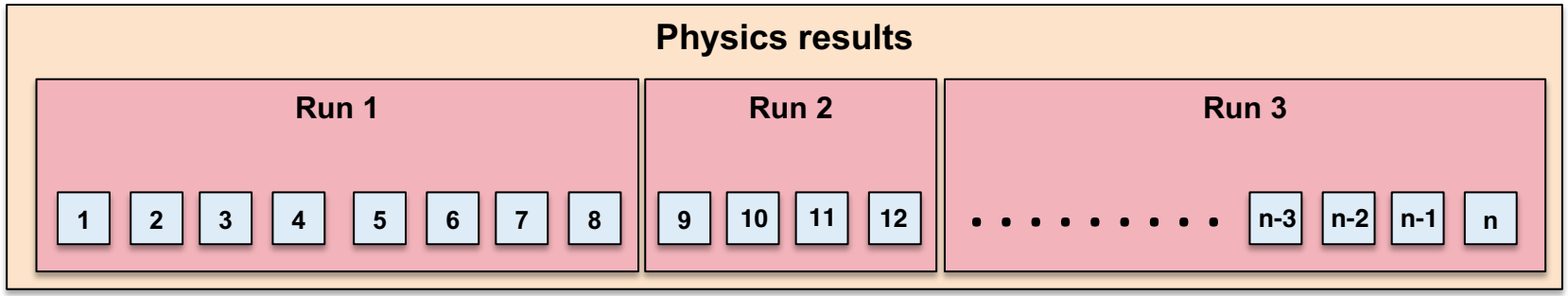
Processing complications (2)



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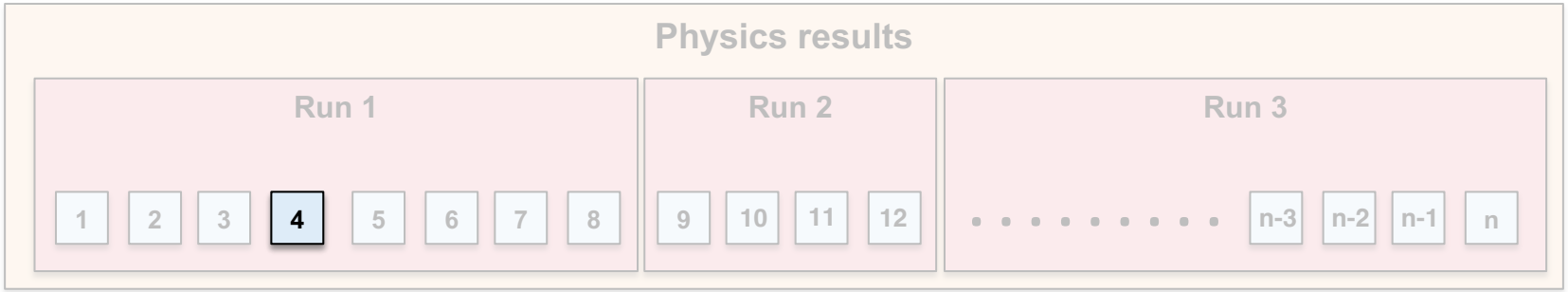

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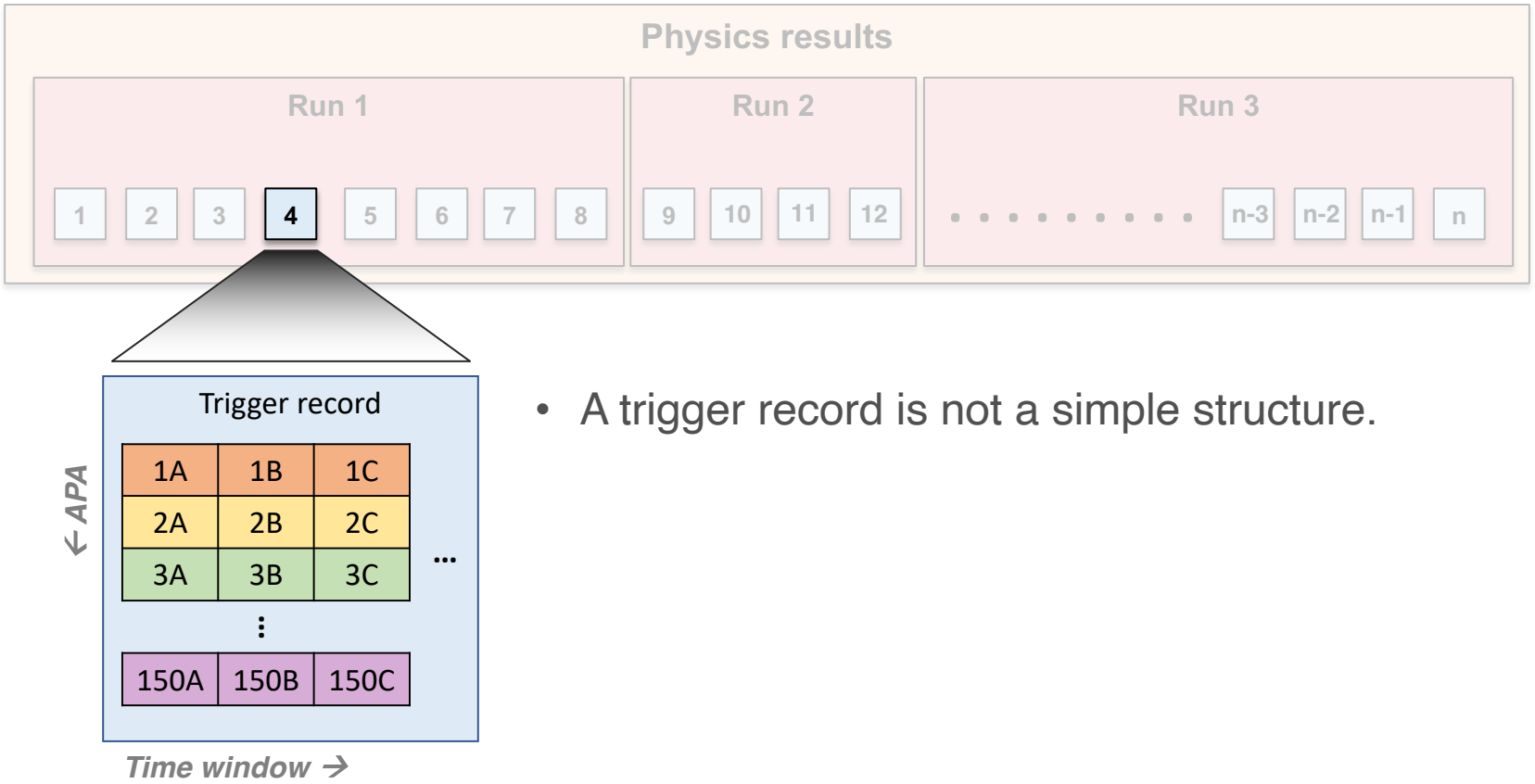

- A trigger record is not a simple structure.

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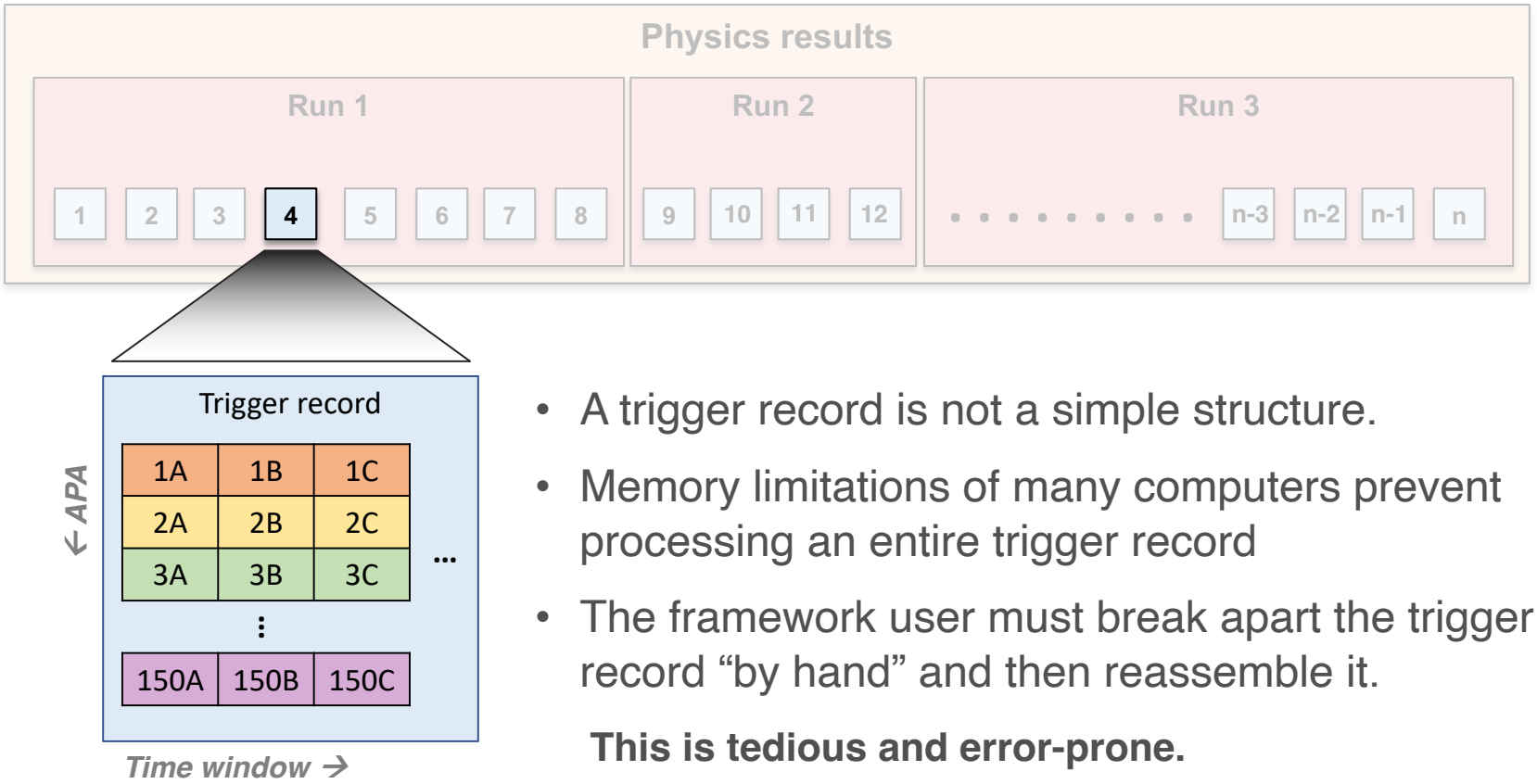

- A trigger record is not a simple structure.
- Memory limitations of many computers prevent processing an entire trigger record
- The framework user must break apart the trigger record “by hand” and then reassemble it.

This is tedious and error-prone.

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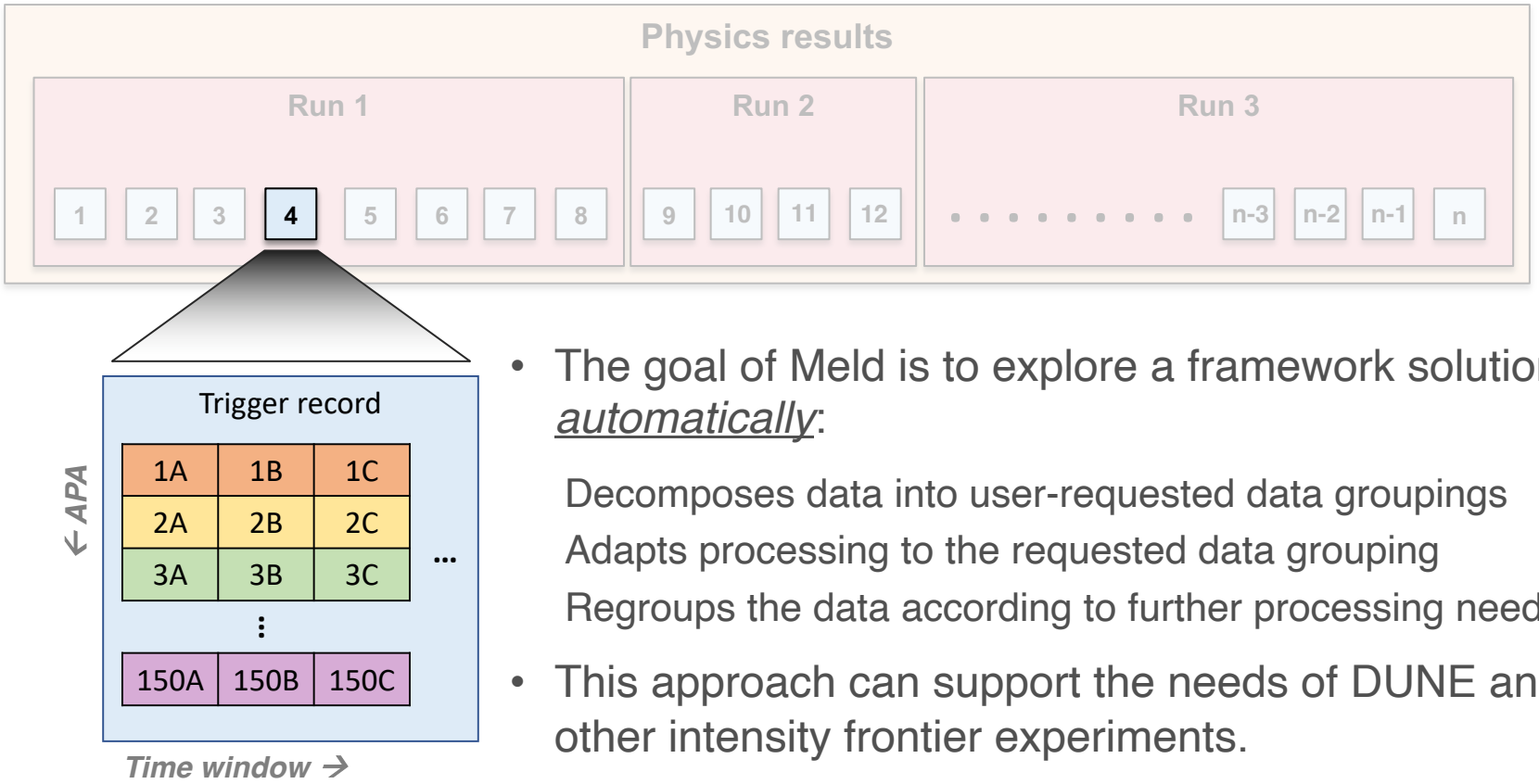

- The goal of Meld is to explore a framework solution that *automatically*:
  - Decomposes data into user-requested data groupings
  - Adapts processing to the requested data grouping
  - Regroups the data according to further processing needs.
- This approach can support the needs of DUNE and other intensity frontier experiments.

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  - Regular discussions with DUNE experts
  - Existing framework capabilities and limitations
  - Functional programming (e.g. Haskell)
  - Mathematics (set, graph, and category theory)

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Prerequisites

Support user-provided algorithms written in C++20 or newer

Design for concurrency

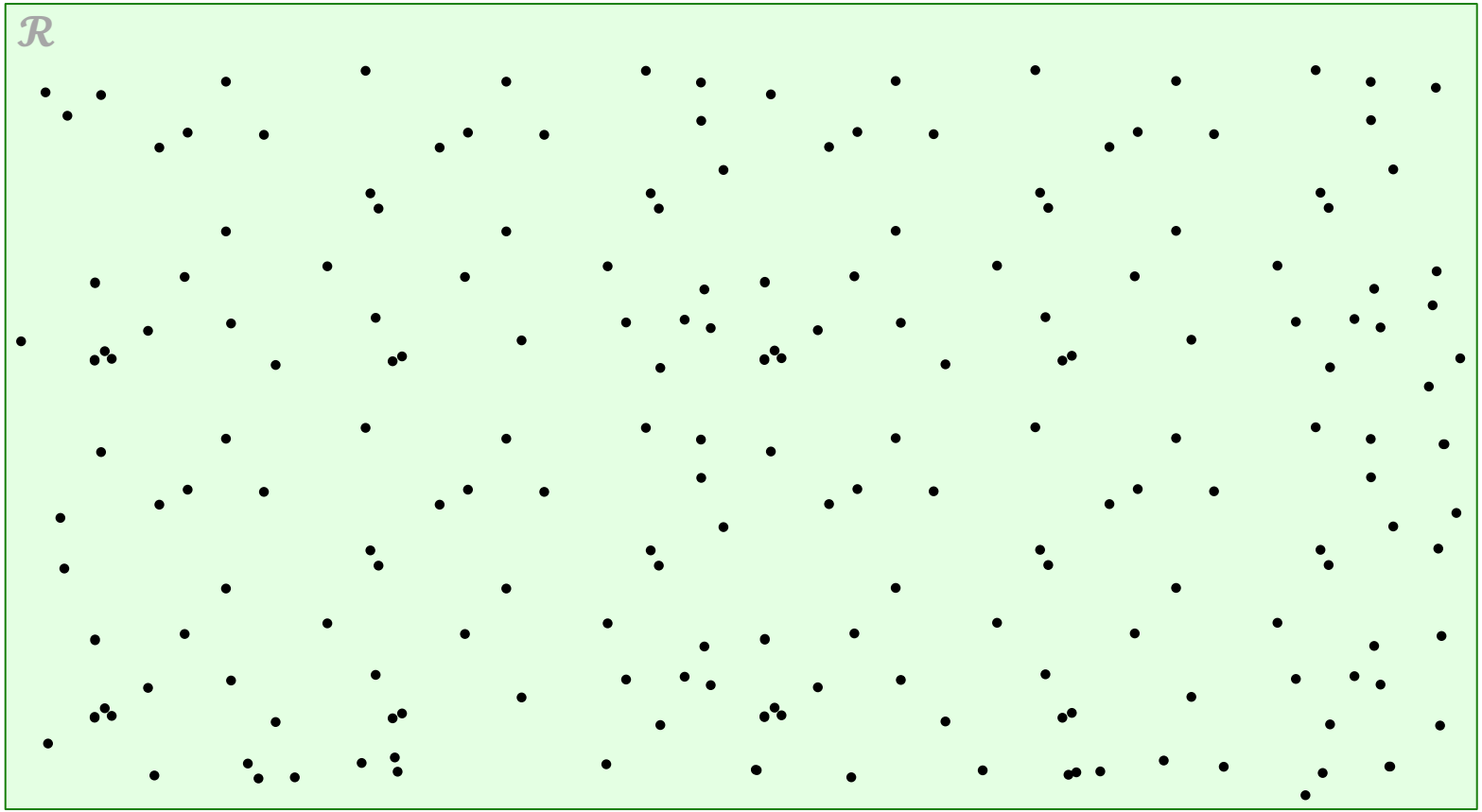
Favor community-provided software

Looking at the data

The following discussion describes a logical organization of data.

It does not imply a specific in-memory representation of data.

Looking at the data (set)



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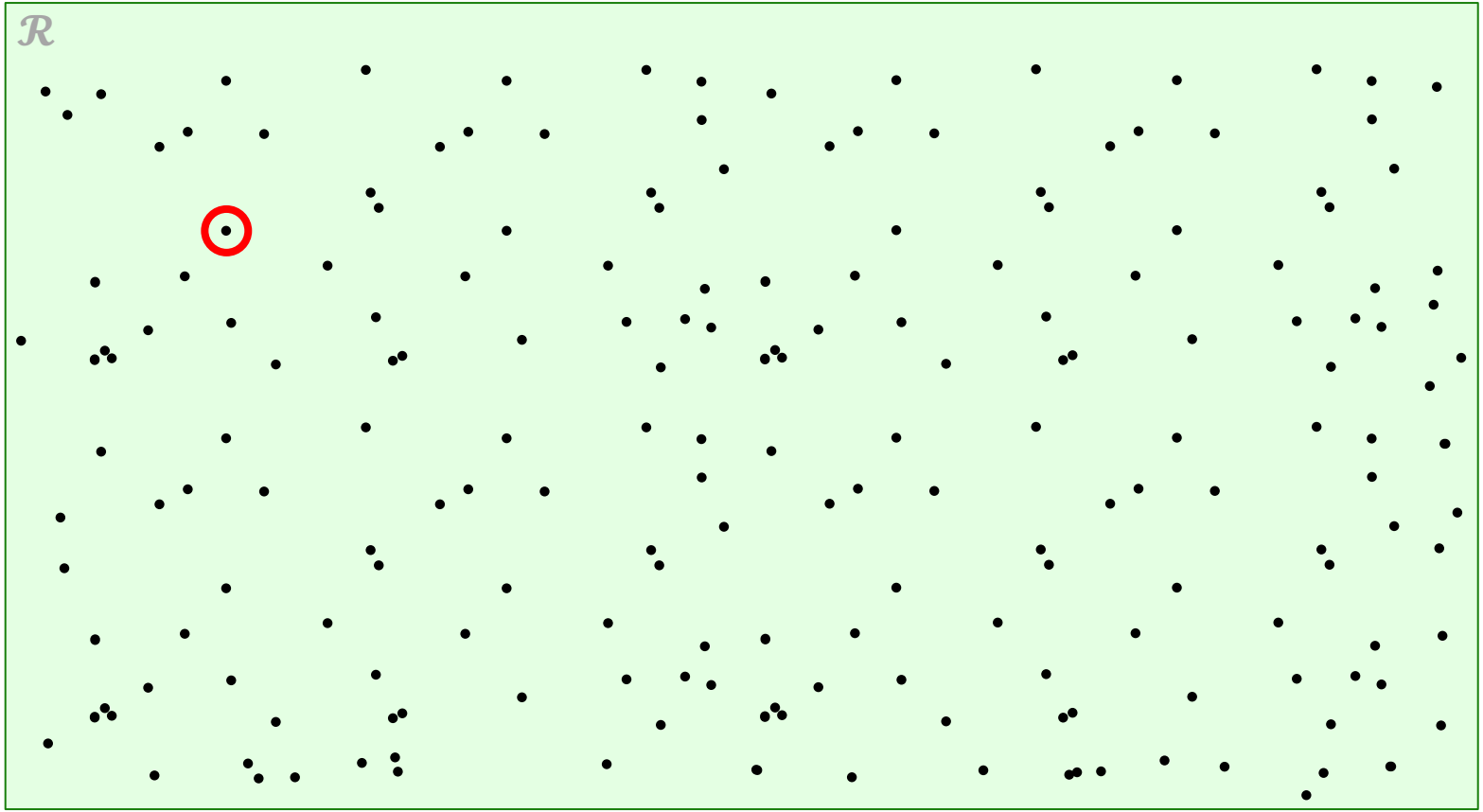
Looking at the data (products)



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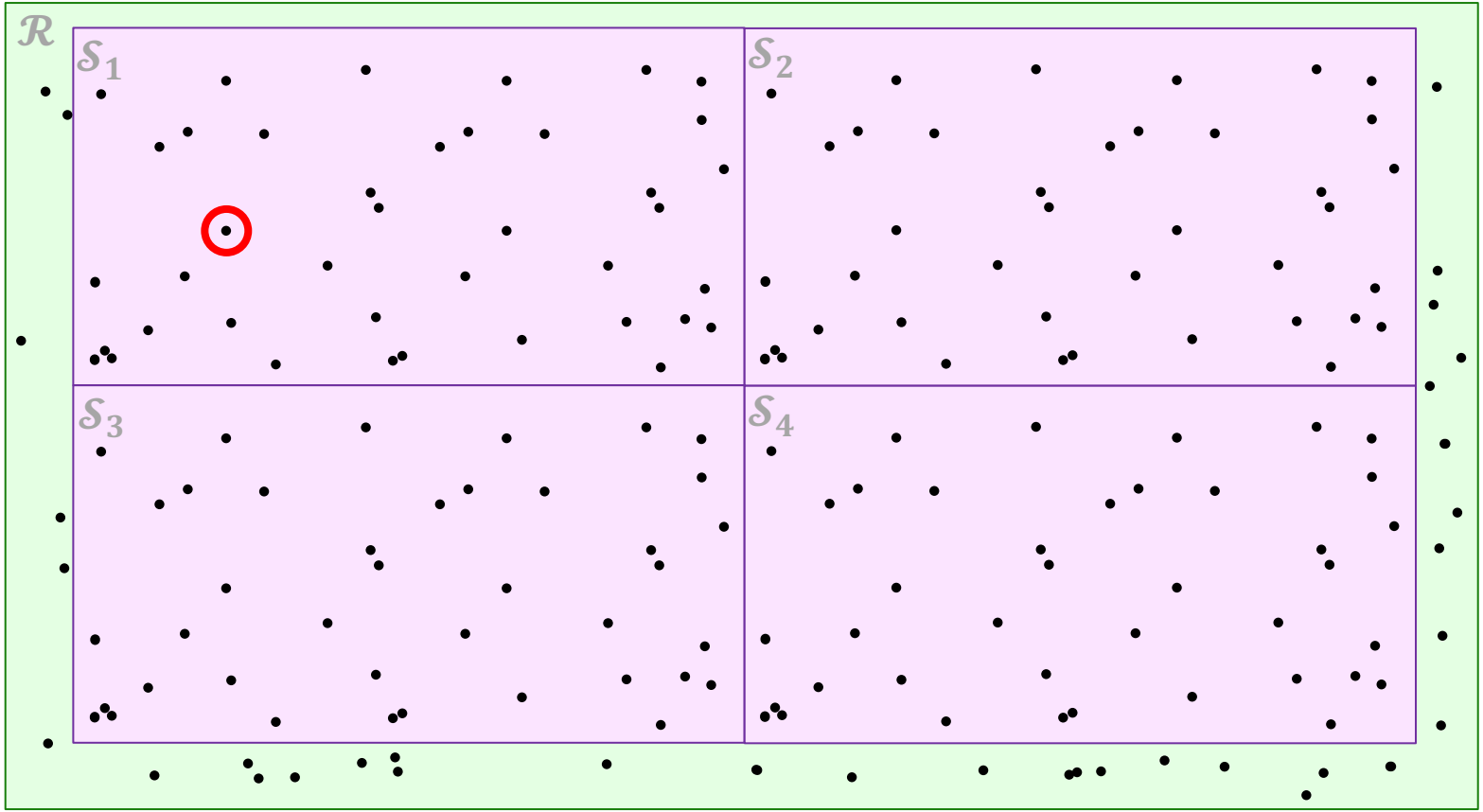

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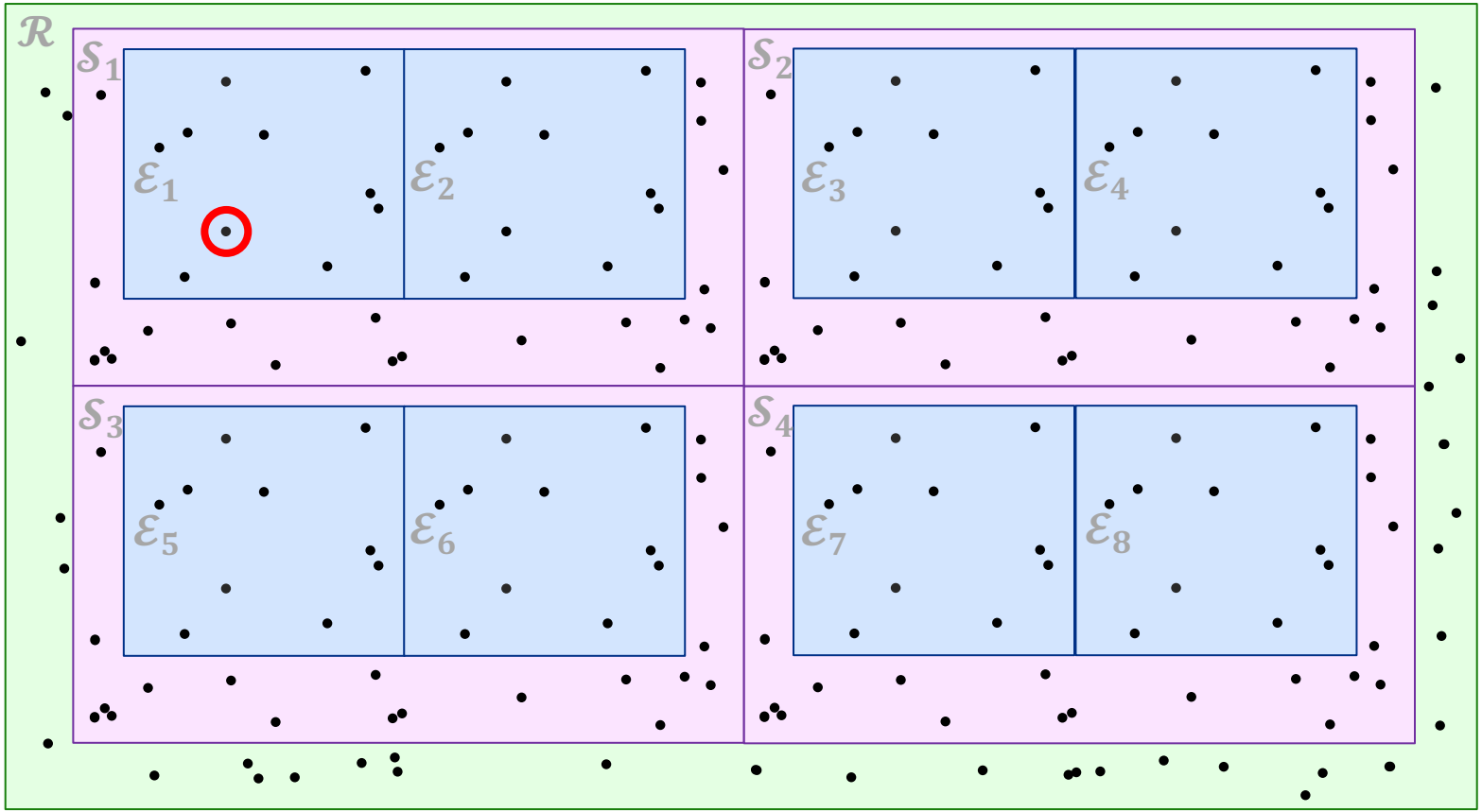

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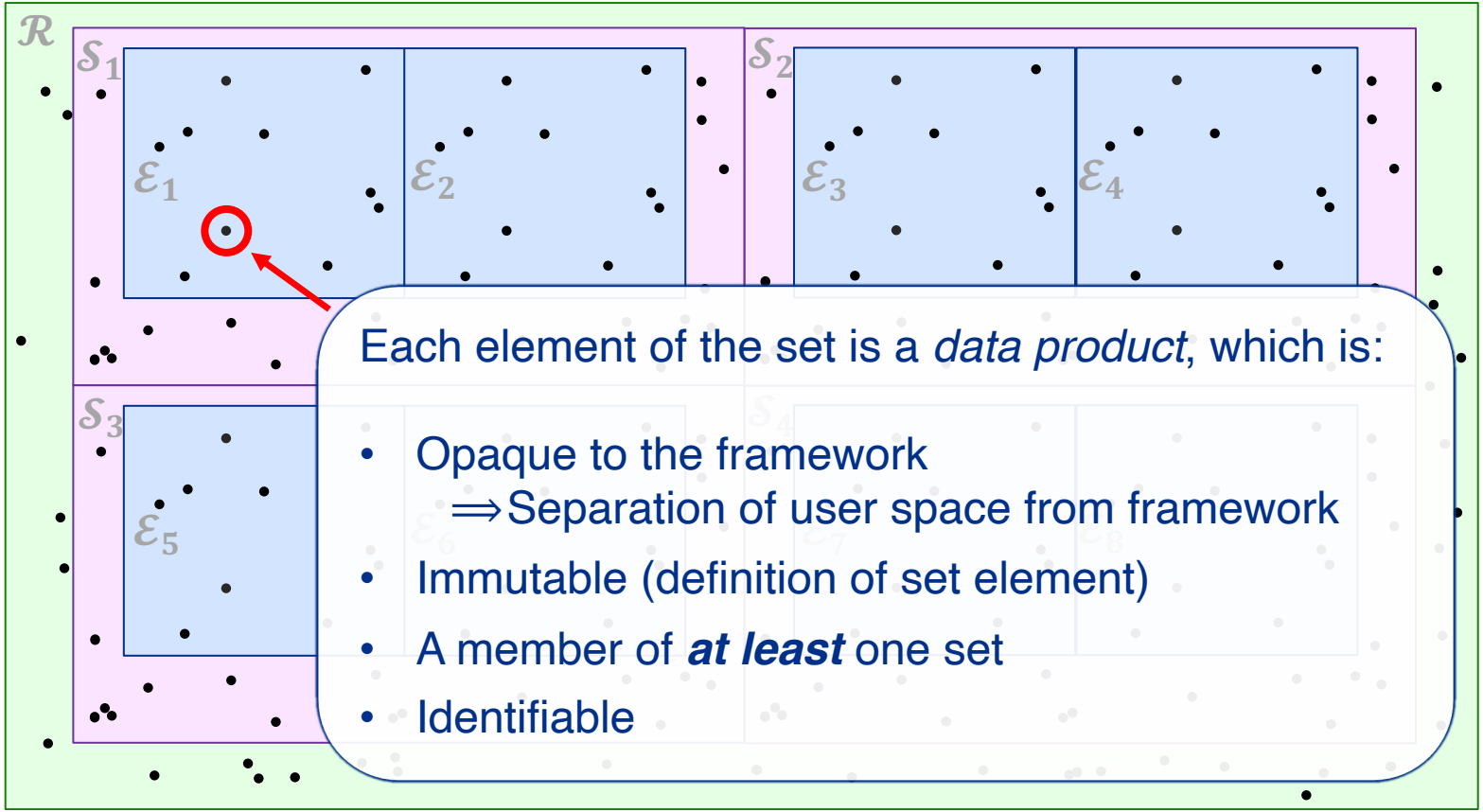

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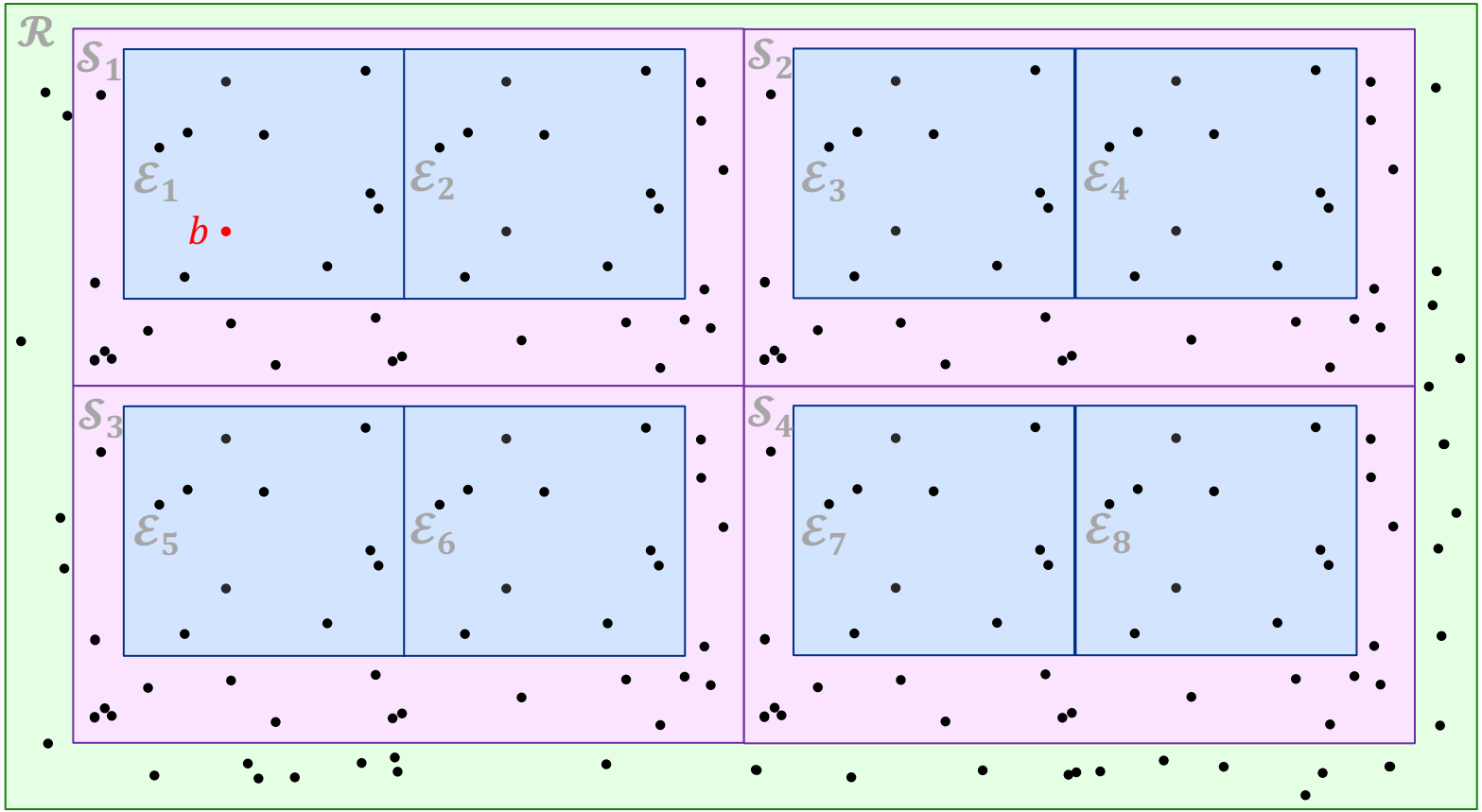

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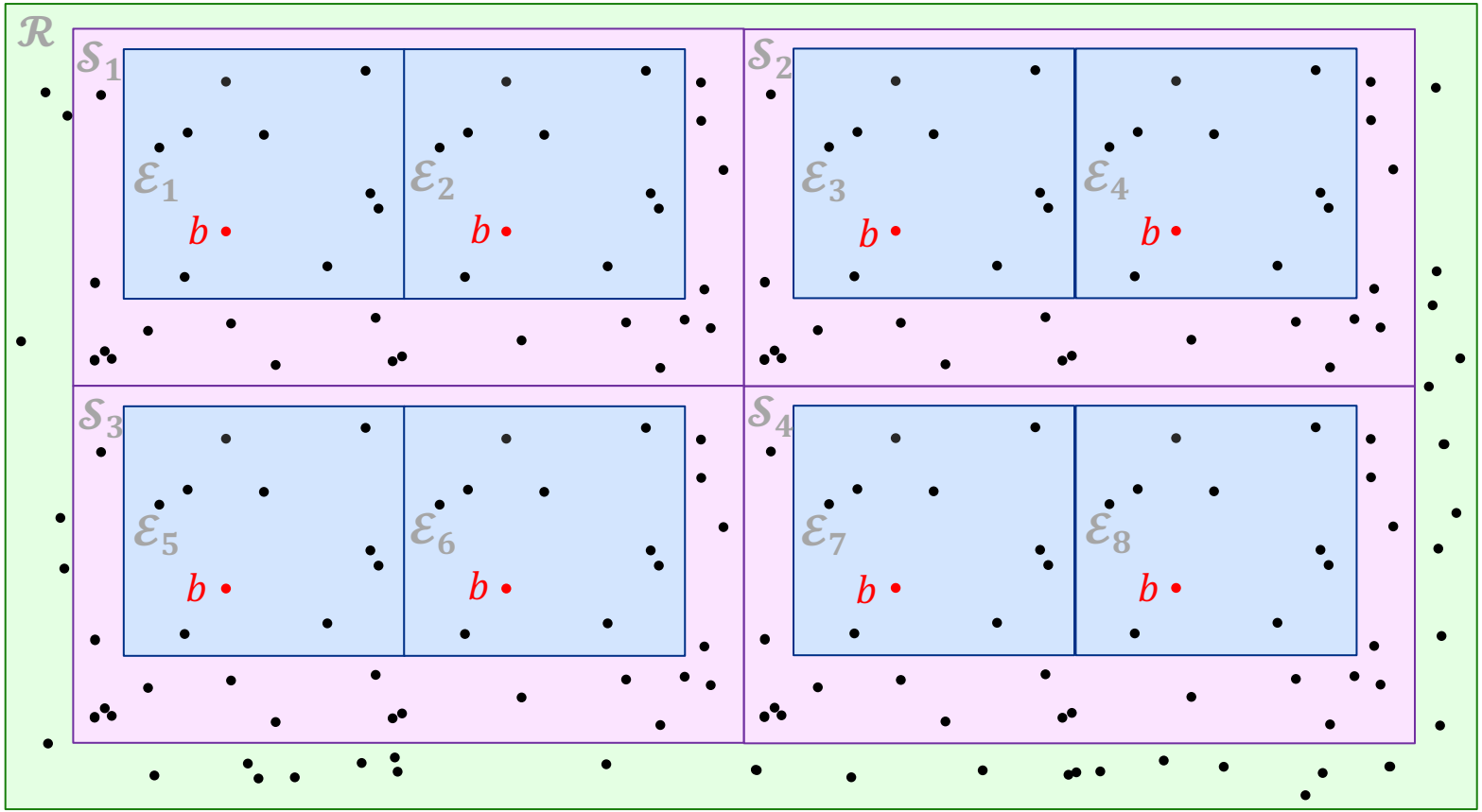

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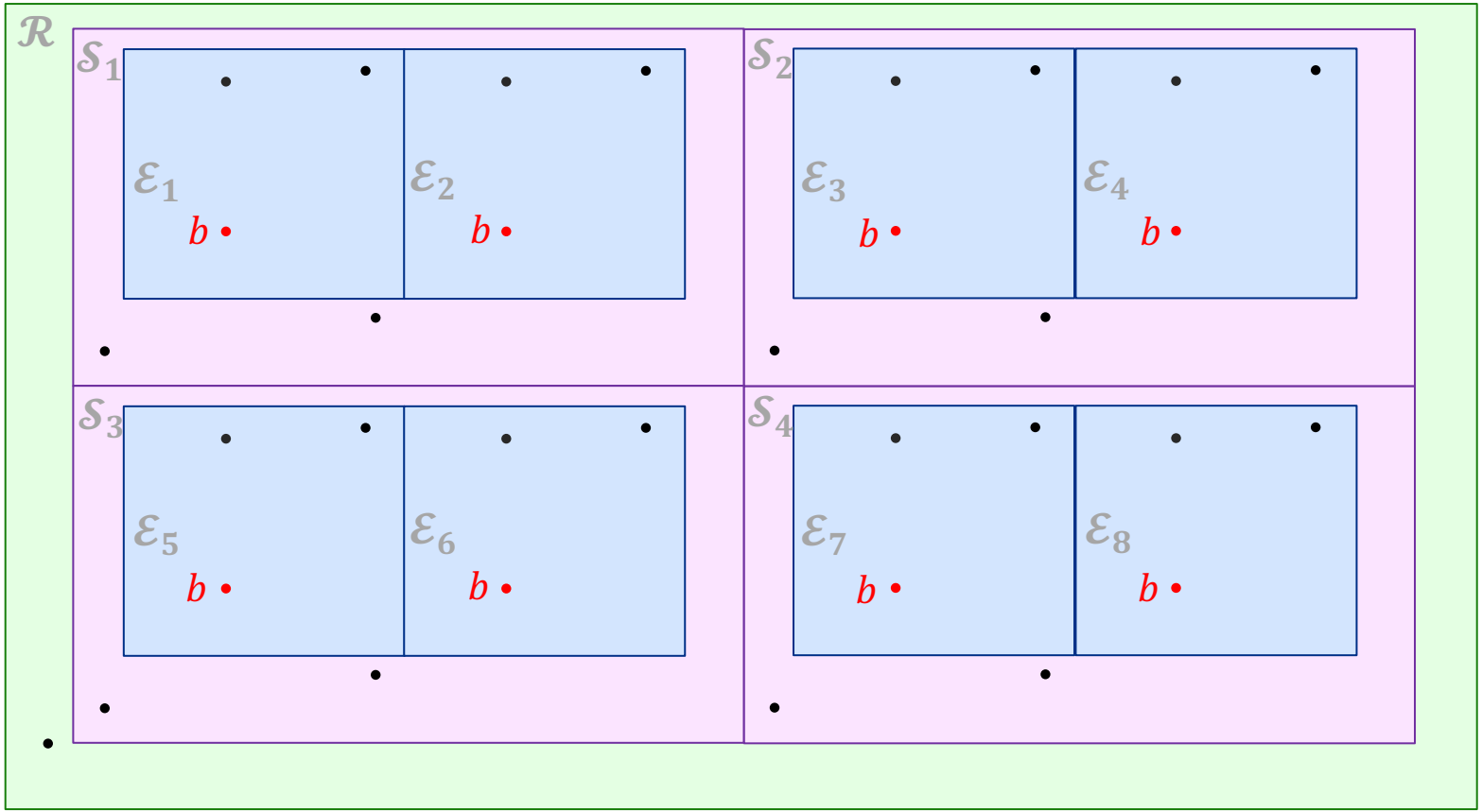

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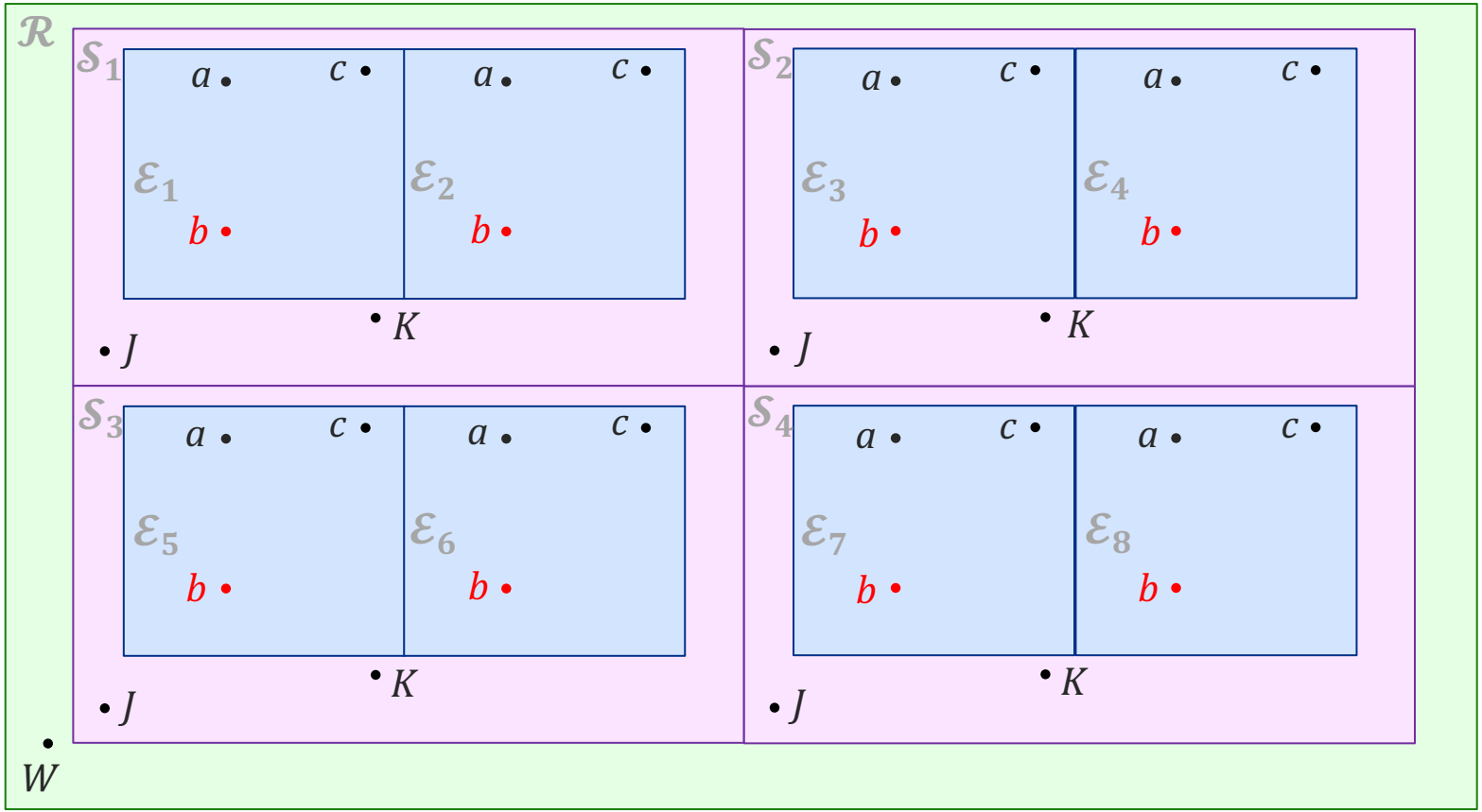

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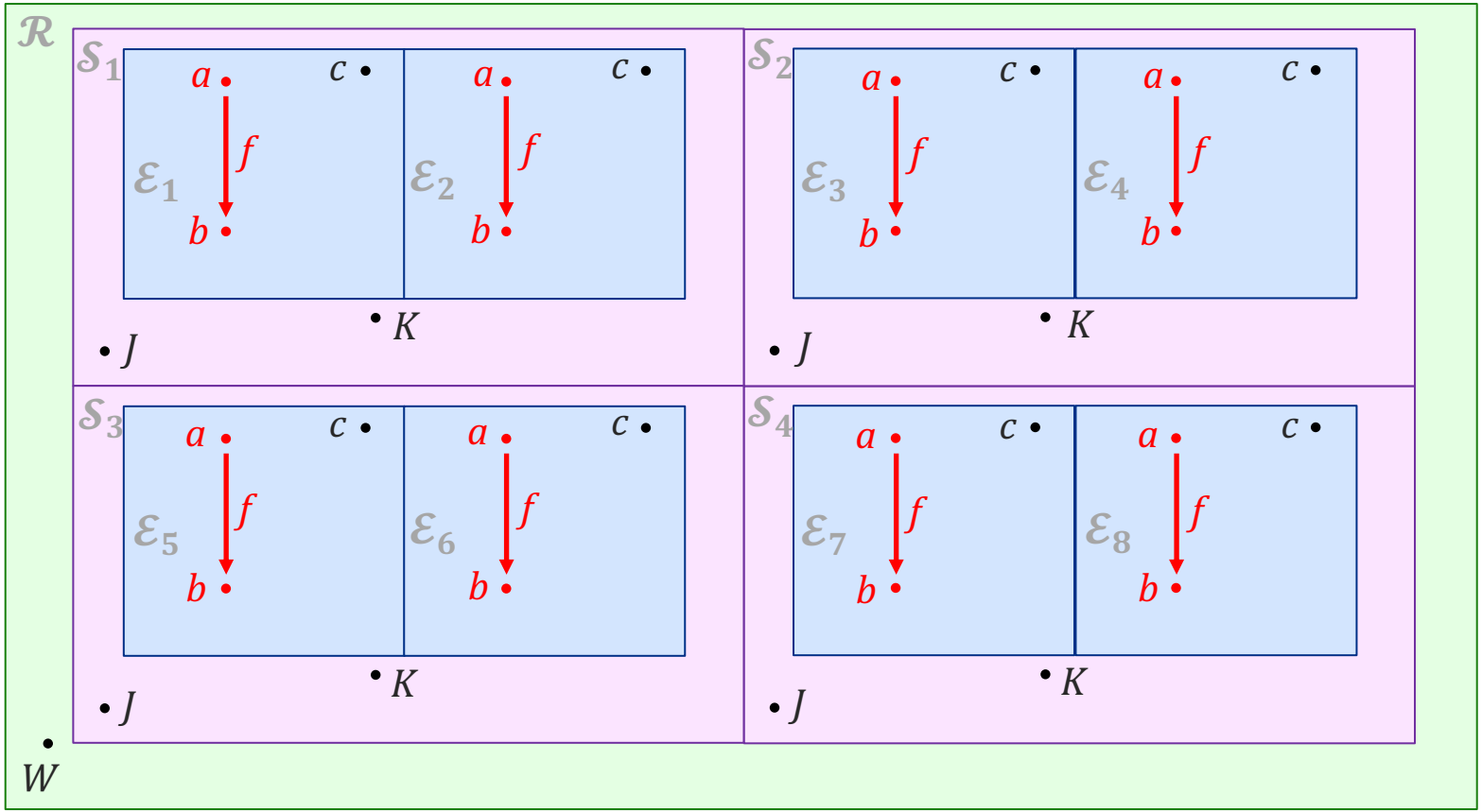

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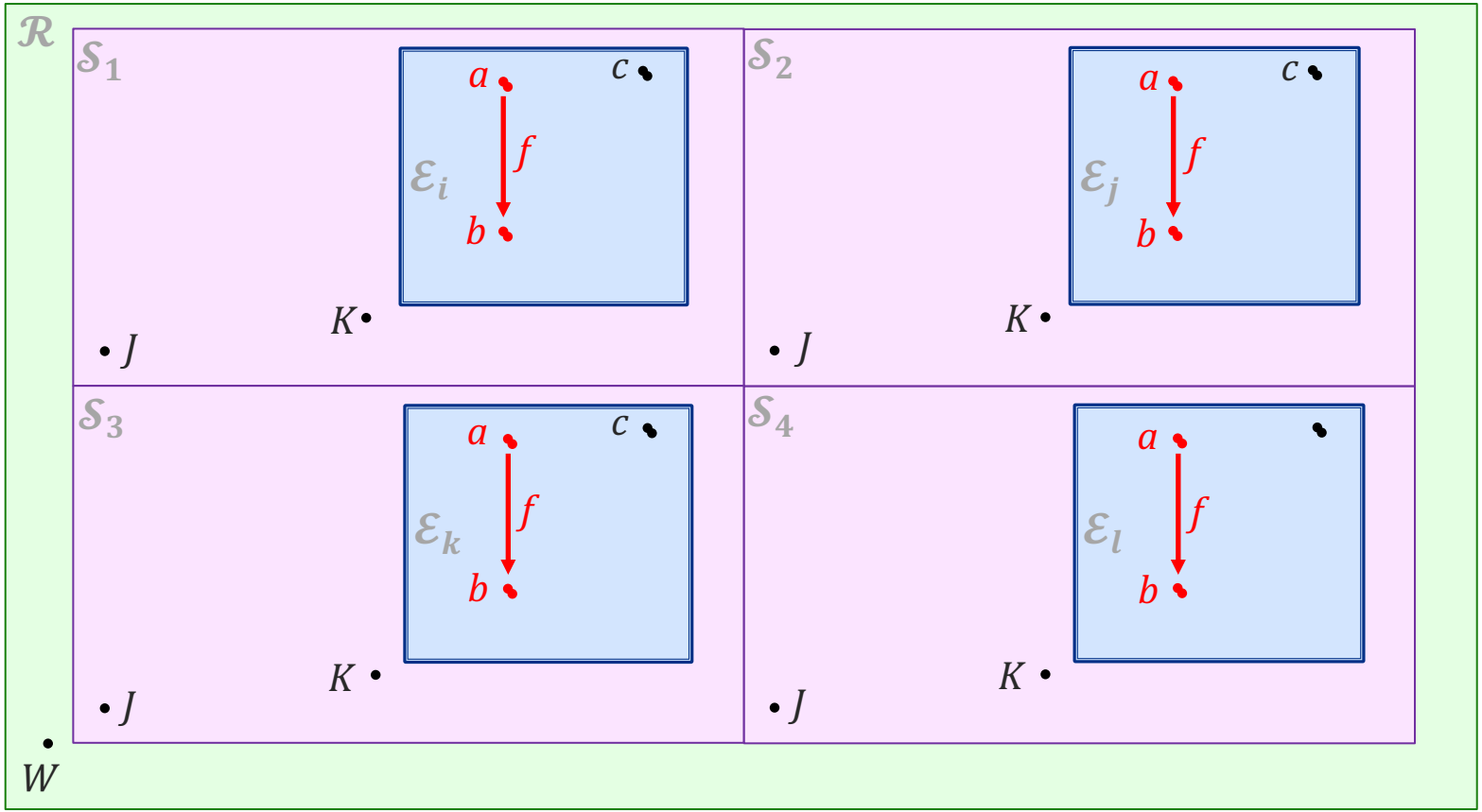
Looking at the data (product sequences)



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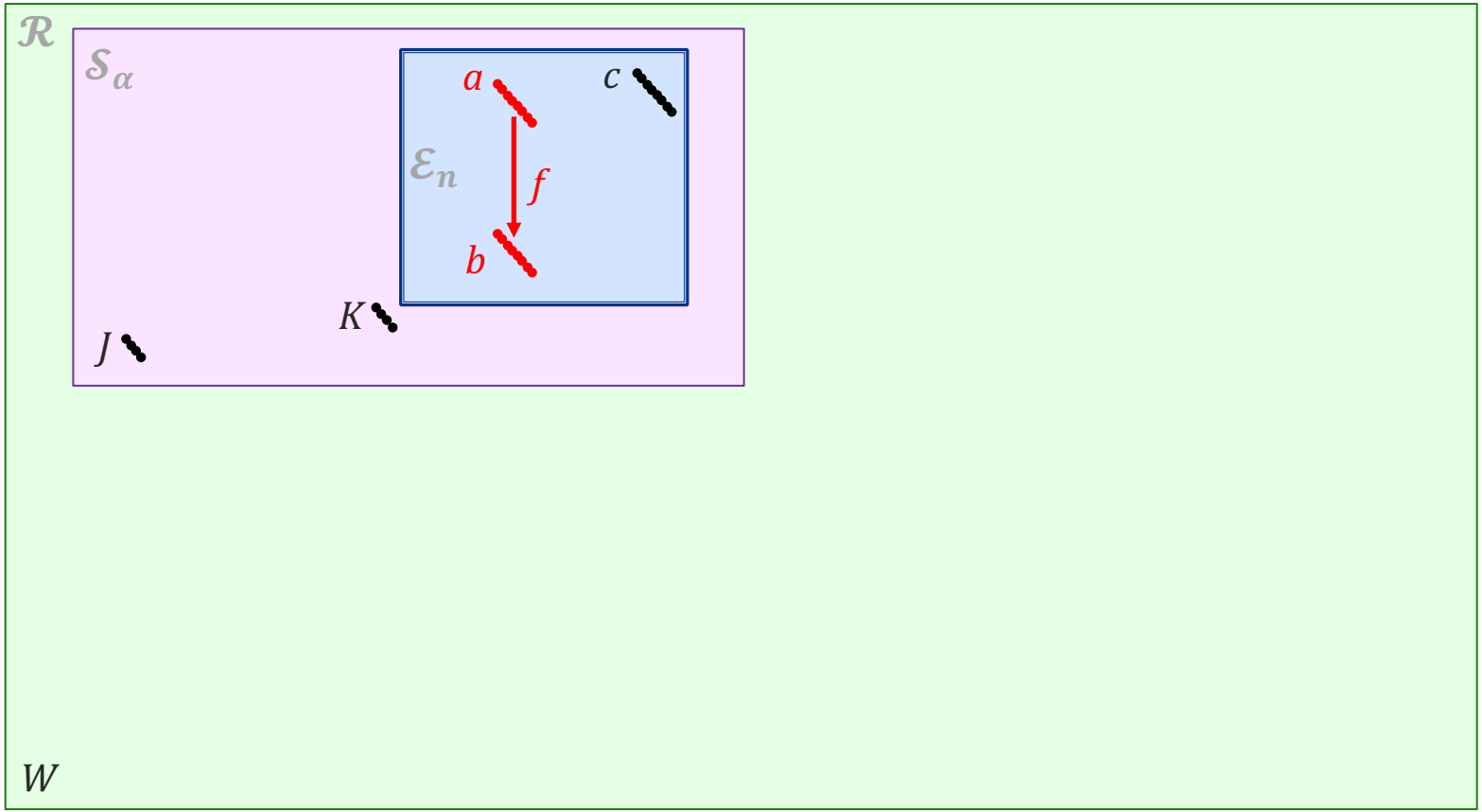

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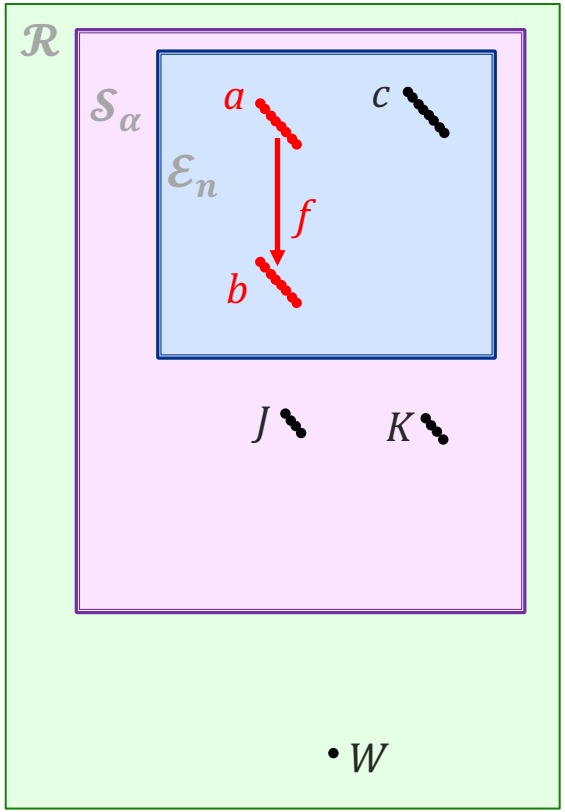

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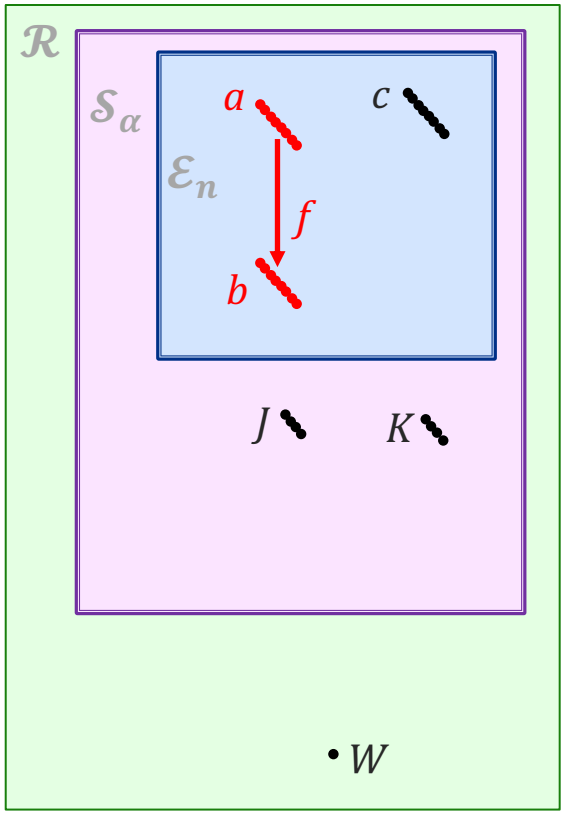

We can make the following replacement (e.g.):

$$c \quad = (c)_8$$

depicting the data products labeled c from 8 events as a sequence.

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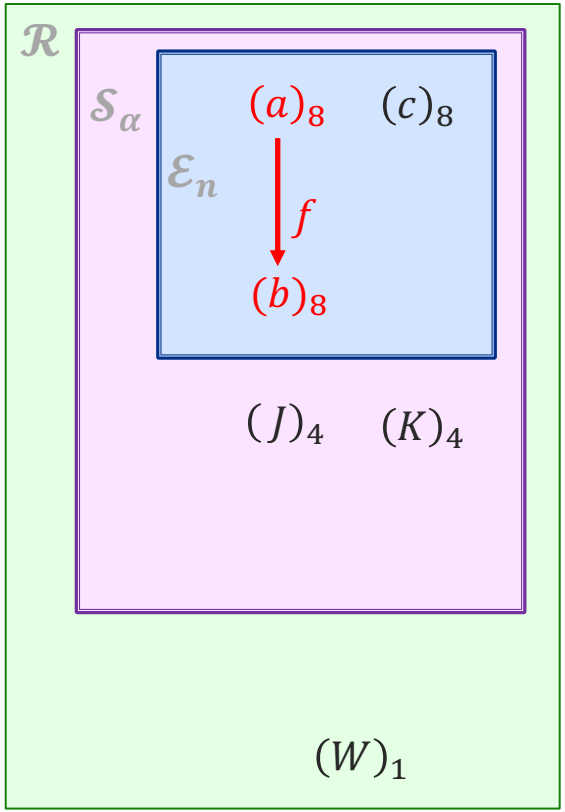

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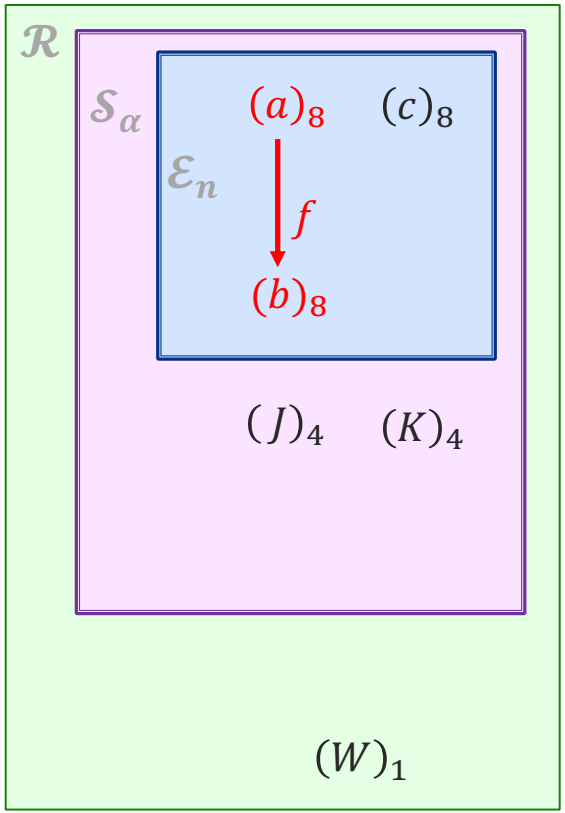

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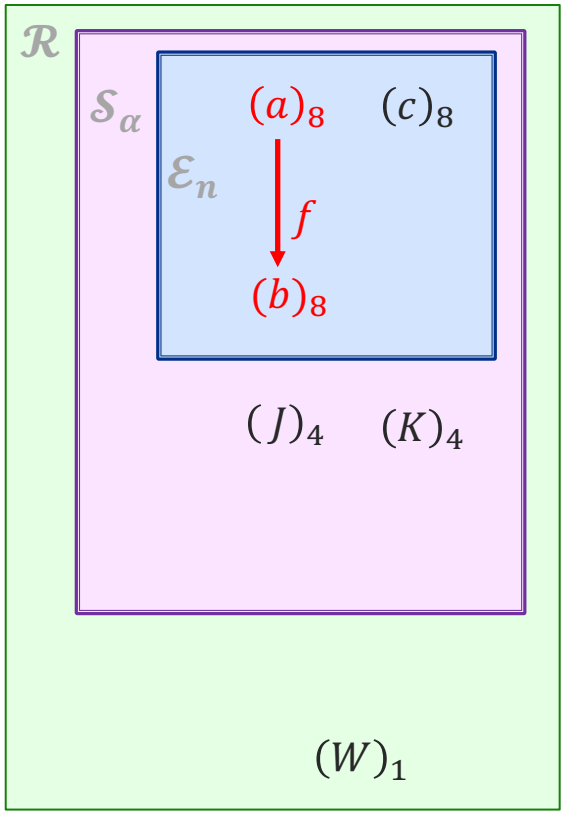

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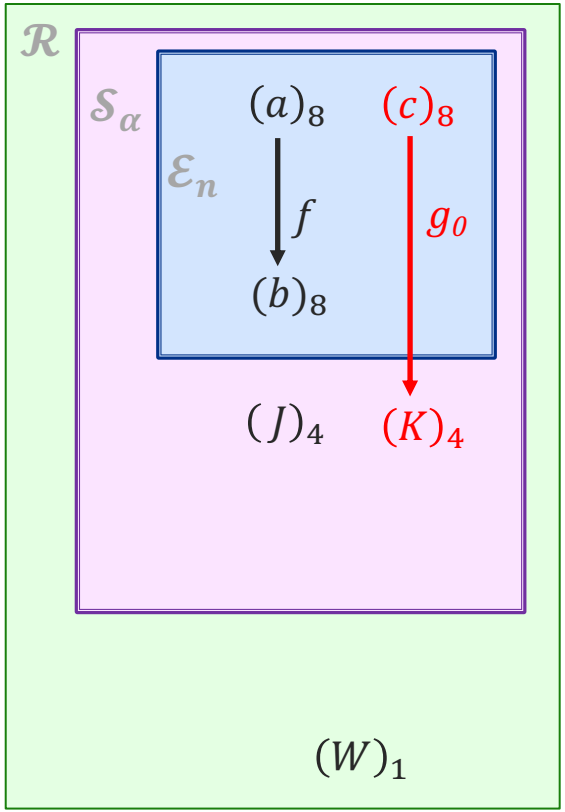

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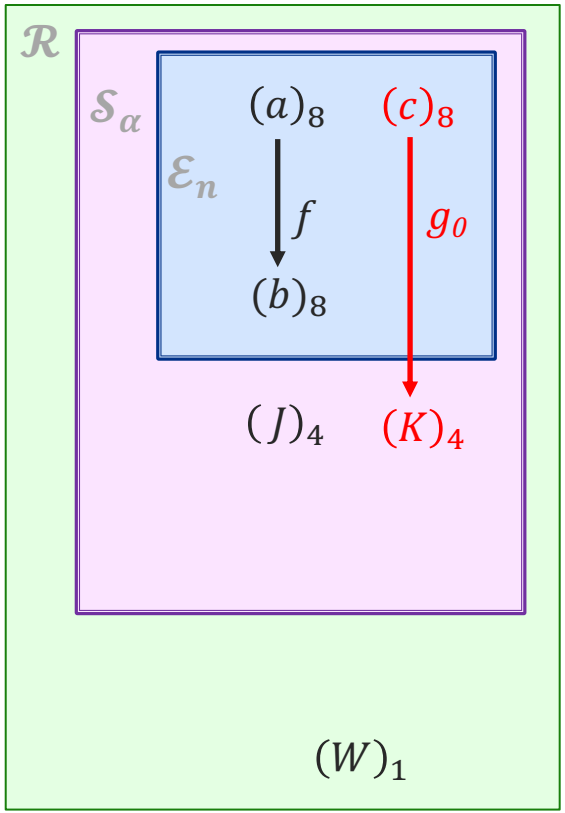

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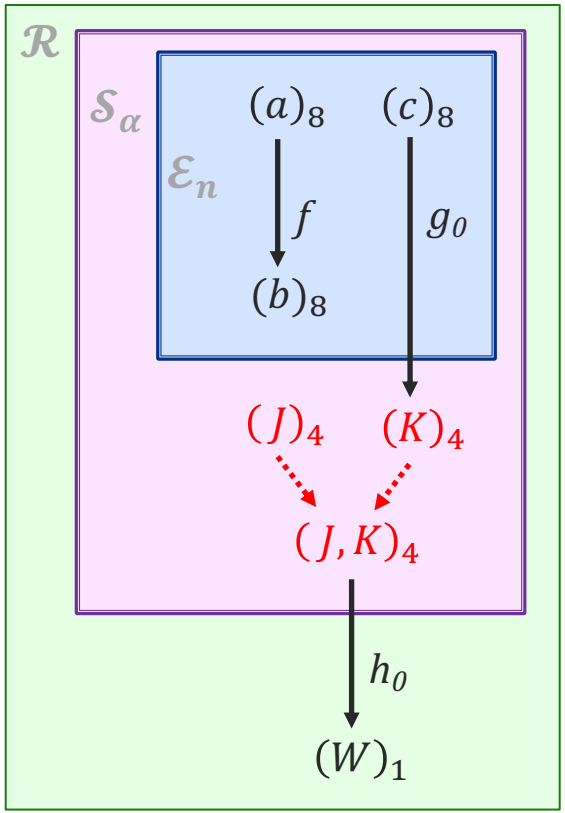

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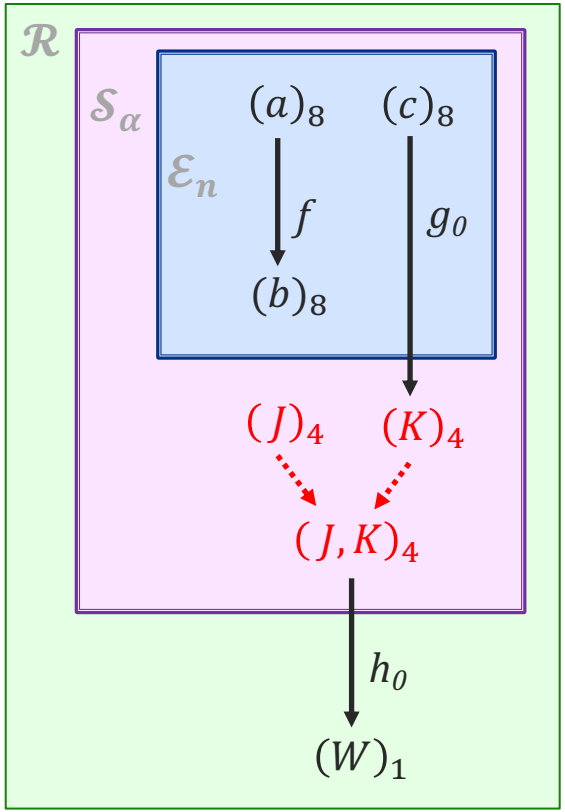

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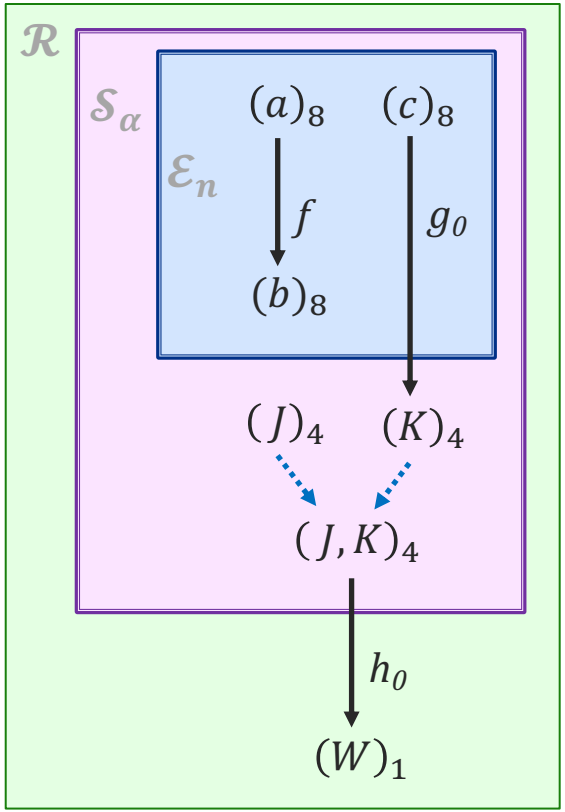

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These have to do with higher-order functions.

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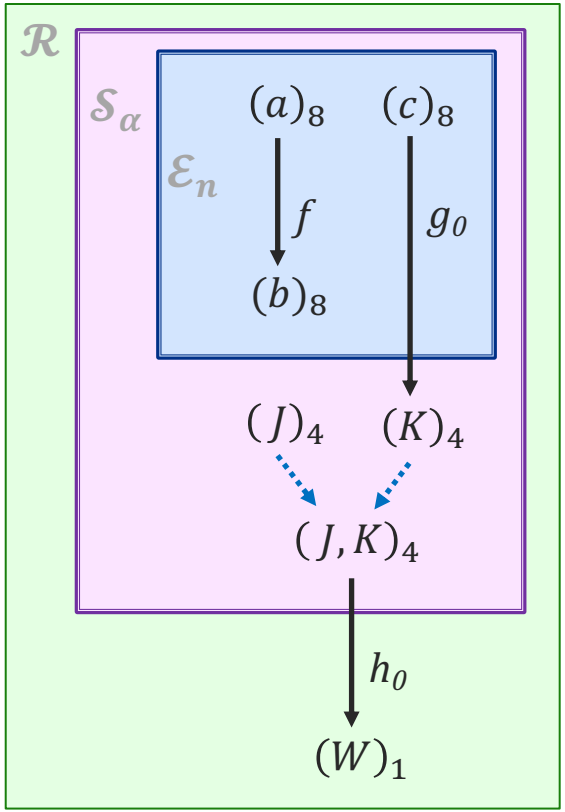
Graph of data-product sequences



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Data-centric	**Data products**	**Mappings**	*This work*

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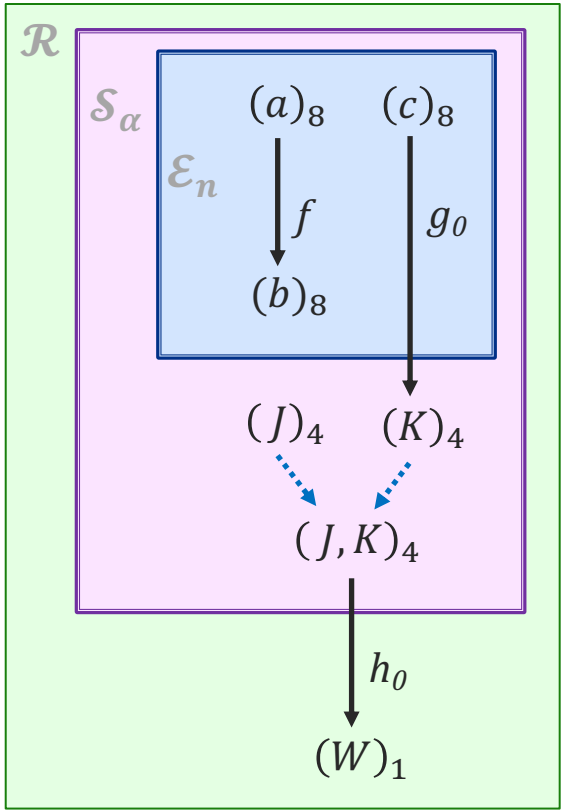

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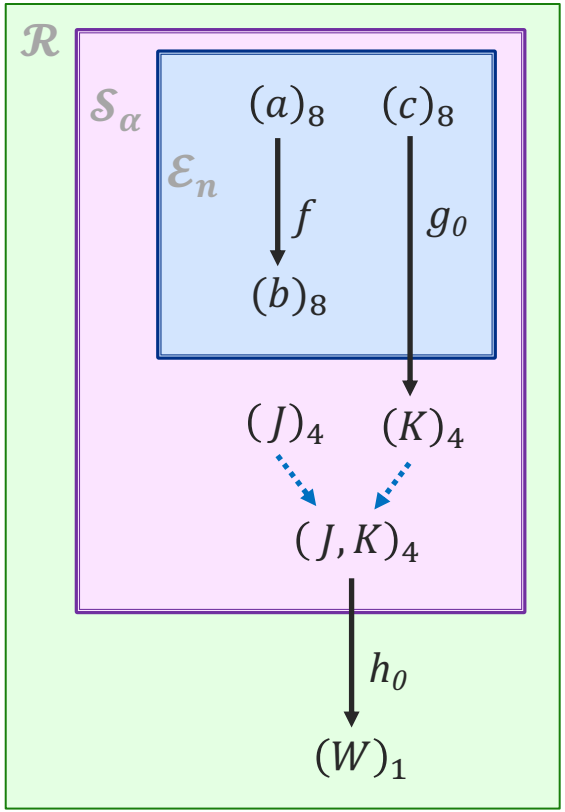

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The user specifications are the same with either view:

- Which data products to process
- The data set(s) that contain those products (event, etc.)
- Which higher-order function to use (transform, etc.)
- Which user-defined function to serve as the operation to the higher-order function.
- Allowed concurrency of each function.

The focus is just different.

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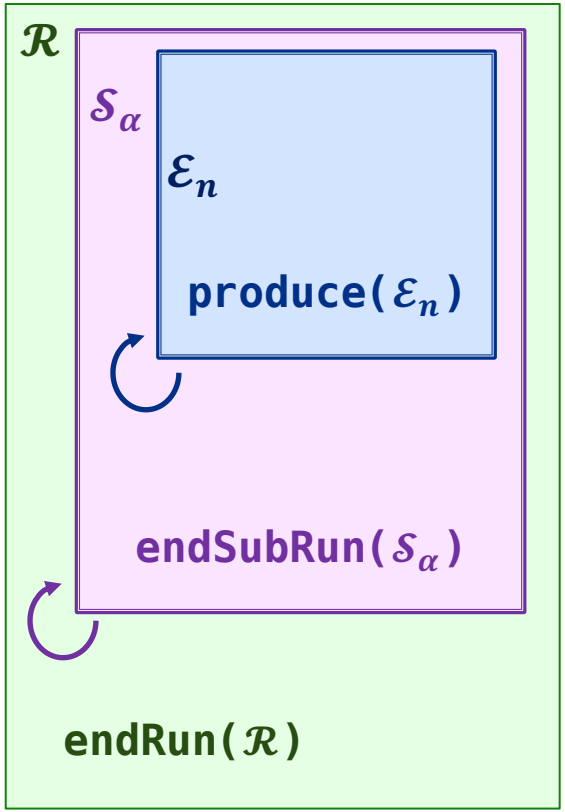
How are data products and their mappings supported now?



With art, users do not transparently interact with data products. They instead:

- Implement functions based on datasets (e.g. event)
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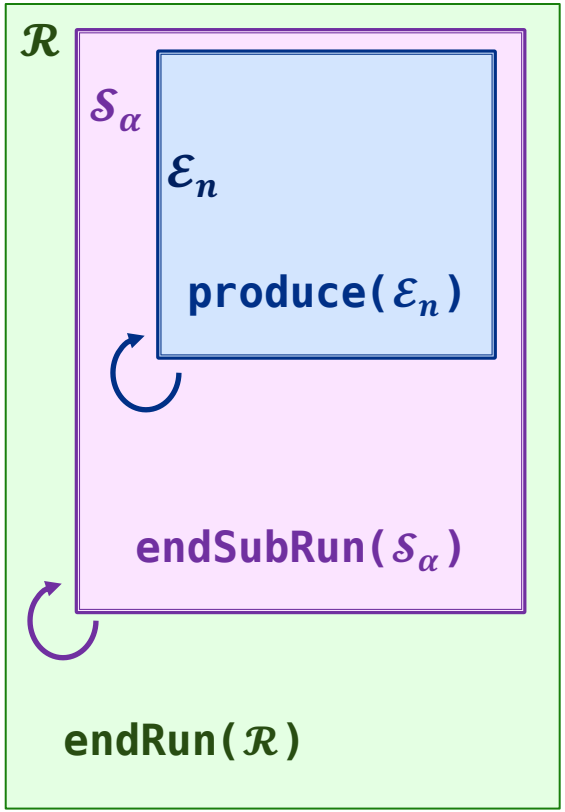

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- Technical limitations of C++ whenever the framework was designed.

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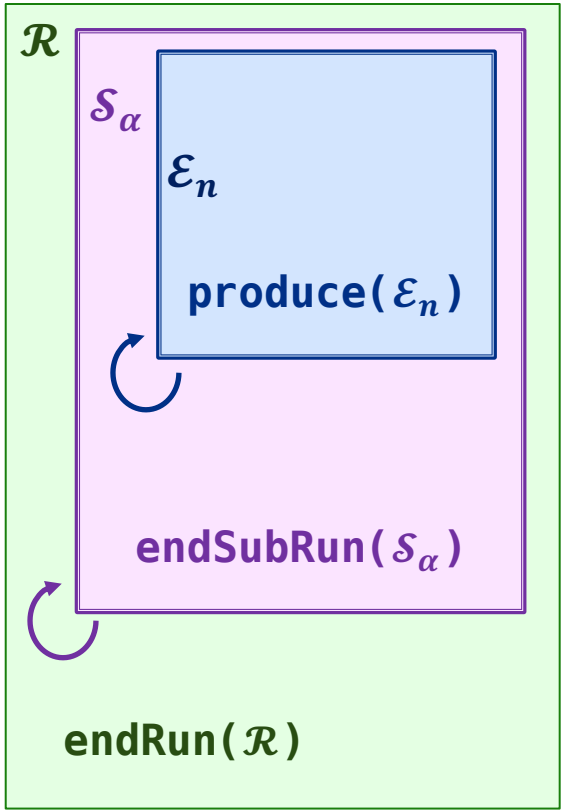

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Results in a lot of software mechanics...

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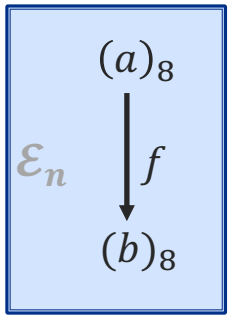
Example: Simple transform

- Create tracks from hits for each event.



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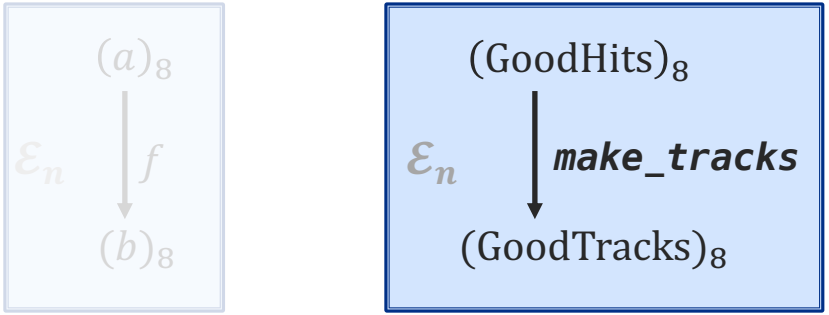


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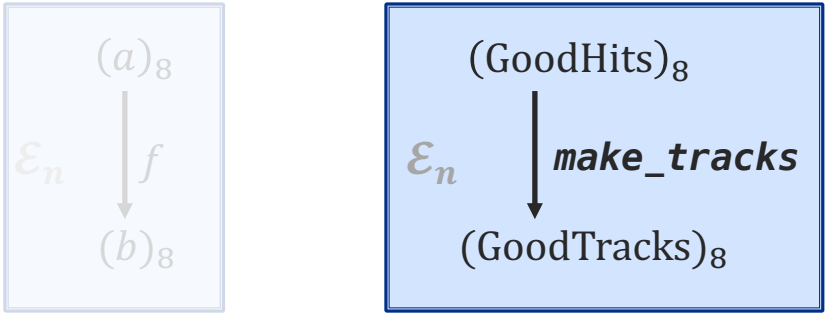


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Tracks make_tracks(Hits const& hits) { ... }
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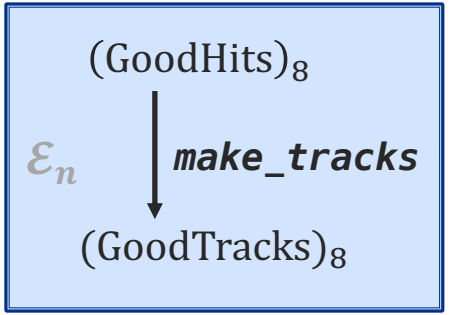
art

```
#include "art/Framework/Core/SharedProducer.h"
#include "art/Framework/Principal/Event.h"

namespace {
  Tracks make_tracks(Hits const& hits) { ... }
}

namespace expt {
  class TrackMaker : public art::SharedProducer {
  public:
    TrackMaker(fhicl::ParameterSet const&) :
    {
      consumes<Hits, art::InEvent>("GoodHits");
      produces<Tracks, art::InEvent>("GoodTracks");

      async<art::InEvent>();
    }

    void produce(art::Event& e,
                 art::ProcessingFrame const&) override
    {
      auto const& hits = e.getProduct<Hits>("GoodHits");
      auto tracks = make_tracks(hits);
      e.put(std::make_unique<Tracks>(std::move(tracks)),
            "GoodTracks");
    }
  };
}

DEFINE_ART_MODULE(expt::TrackMaker)
```


Fermilab

Example: Simple transform

- Create tracks from hits for each event.




```
Tracks make_tracks(Hits const& hits) { ... }
```

This is just a transform? 😬

art

```
#include "art/Framework/Core/SharedProducer.h"
#include "art/Framework/Principal/Event.h"

namespace {
  Tracks make_tracks(Hits const& hits) { ... }
}

namespace expt {
  class TrackMaker : public art::SharedProducer {
  public:
    TrackMaker(fhicl::ParameterSet const&) :
    {
      consumes<Hits, art::InEvent>("GoodHits");
      produces<Tracks, art::InEvent>("GoodTracks");

      async<art::InEvent>();
    }

    void produce(art::Event& e,
                 art::ProcessingFrame const&) override
    {
      auto const& hits = e.getProduct<Hits>("GoodHits");
      auto tracks = make_tracks(hits);
      e.put(std::make_unique<Tracks>(std::move(tracks)),
            "GoodTracks");
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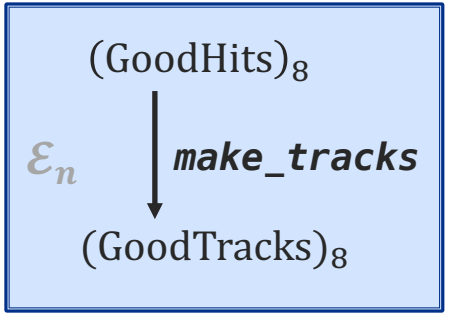


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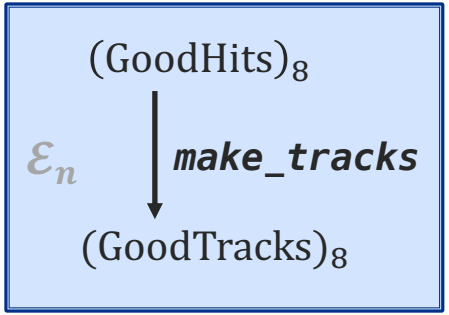
Fermilab

Example: Simple transform

art

- Create tracks from hits for each event.

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This is just a transform? 😬
Nobody wants this.

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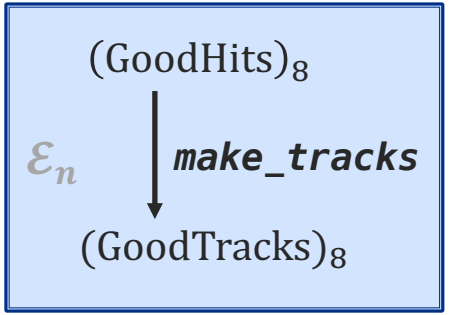


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Meld

```
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DEFINE_MODULE(m, config) {
  m.with(make_tracks)
   .transform("GoodHits").in_each("Event")
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```

A better way…

Fermilab

Example: Simple transform

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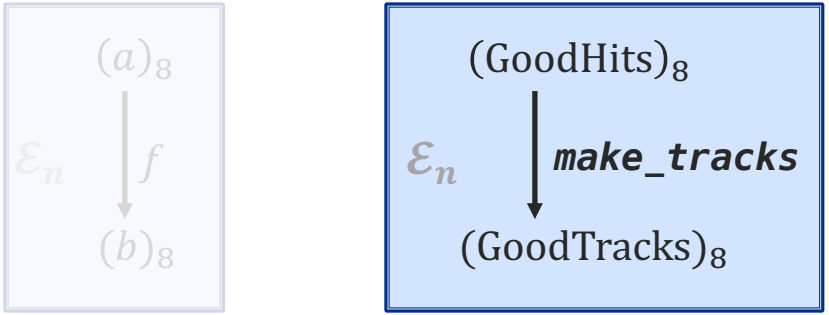


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- Minimal boilerplate.

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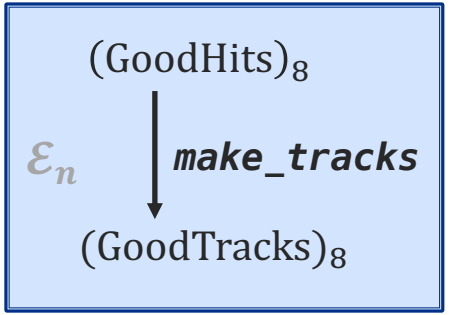


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- Minimal boilerplate.
- `Event` is now a label.

Fermilab

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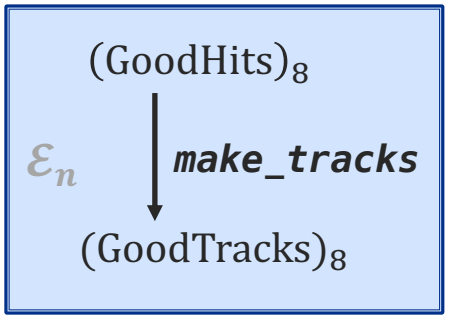


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A better way…

Meld

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   .transform("GoodHits").in_each("Event")
   .to("GoodTracks")
   .using_concurrency(unlimited);
}
```
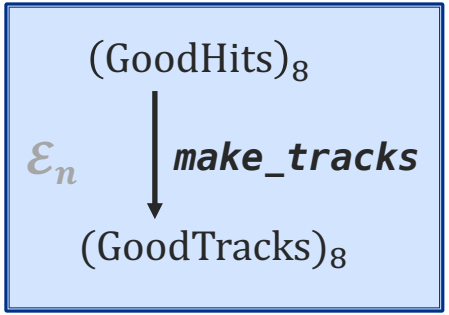

- Minimal boilerplate.
- `Event` is now a label.
- Higher-order function is now explicit.

Fermilab

Example: Simple transform

- Create tracks from hits for each event.

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  m.with(make_tracks)
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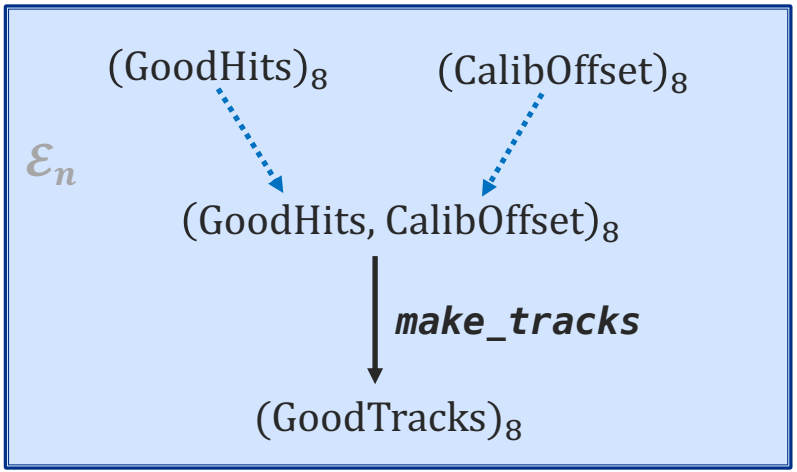
   .to("GoodTracks")
   .using_concurrency(unlimited);
}
```

"That's a nice, clean, toy problem. I'd like to see what reality looks like."
—A member of the ATLAS experiment

Example: Transform with two arguments

- Create calibrated tracks from hits for each event.



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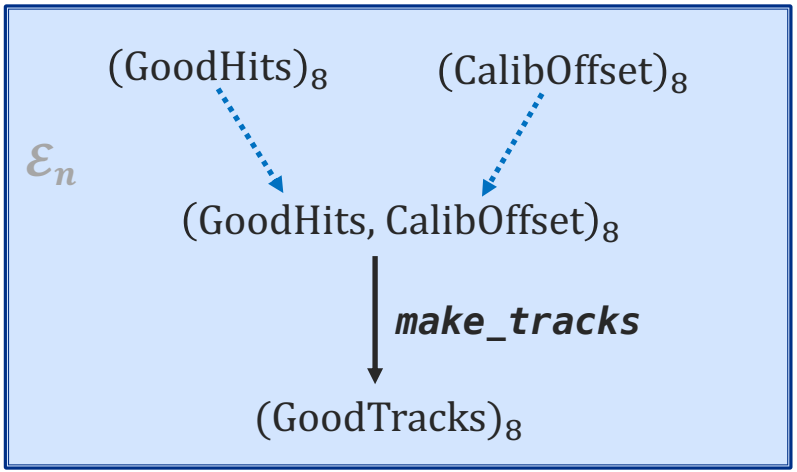
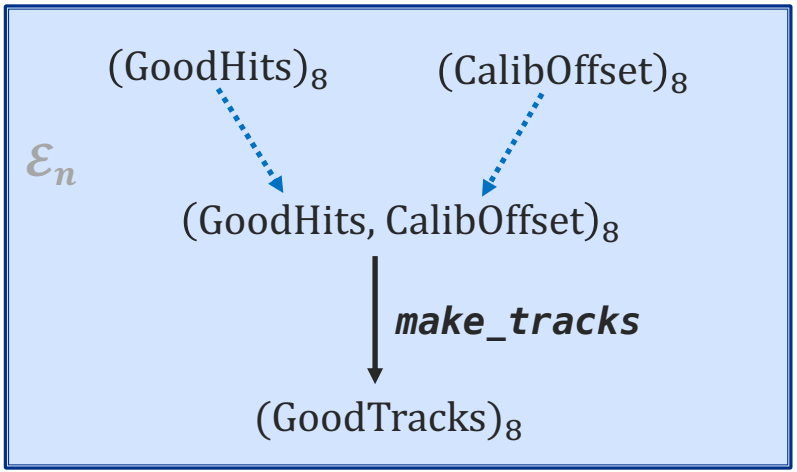



```
Tracks make_tracks(Hits const& hits,
                   ScalarOffset const& offset)
{ ... }
```


Fermilab

Example: Transform with two arguments

- Create calibrated tracks from hits for each event.




```
Tracks make_tracks(Hits const& hits,
                   ScalarOffset const& offset)
{ ... }
```

```
#include "meld/module.hpp"

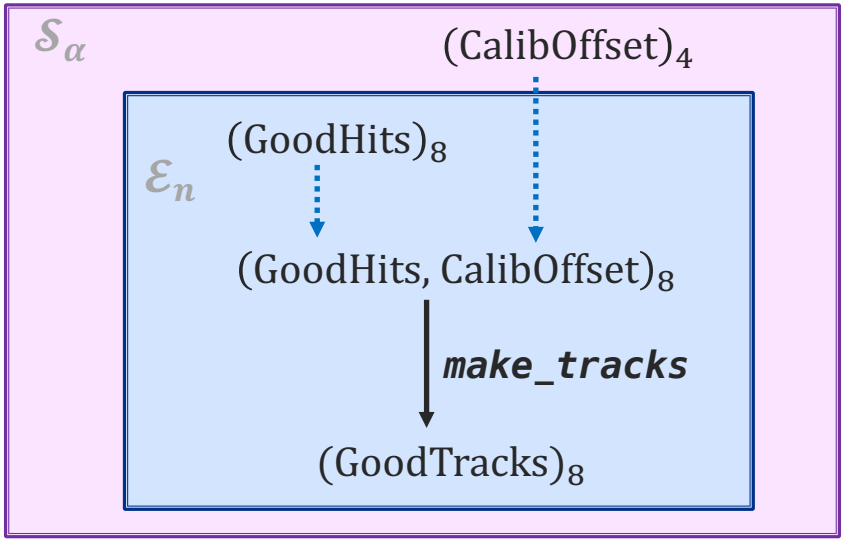
namespace {
  Tracks make_tracks(Hits const& hits,
                     ScalarOffset const& offset)
  { ... }
}

DEFINE_MODULE(m, config) {
  m.with(make_tracks)
   .transform("GoodHits"_p.in_each("Event"),
              "CalibOffset"_p.in_each("Event"))
   .to("GoodTracks")
   .using_concurrency(unlimited);
}
```


Fermilab

Example: Transform with two arguments (different domains)

- Create calibrated tracks from hits for each event.




```
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                   ScalarOffset const& offset)
{ ... }
```

```
#include "meld/module.hpp"

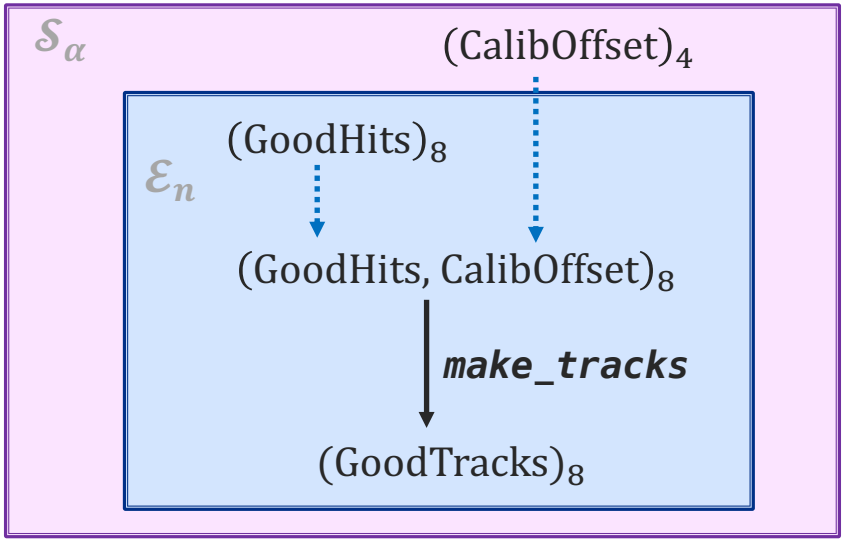
namespace {
  Tracks make_tracks(Hits const& hits,
                     ScalarOffset const& offset)
  { ... }
}

DEFINE_MODULE(m, config) {
  m.with(make_tracks)
   .transform("GoodHits"_p.in_each("Event"),
              "CalibOffset"_p.in_each("SubRun"))
   .to("GoodTracks")
   .using_concurrency(unlimited);
}
```


Fermilab

Example: Transform with two arguments (different domains)

- Create calibrated tracks from hits for each event.




```
Tracks make_tracks(Hits const& hits,
                   ScalarOffset const& offset)
{ ... }
```

```
#include "meld/module.hpp"

namespace {
  Tracks make_tracks(Hits const& hits,
                     ScalarOffset const& offset)
  { ... }
}

DEFINE_MODULE(m, config) {
  m.with(make_tracks)
   .transform(config.get<input_tag>("HitsProduct"),
              config.get<input_Tag>("OffsetProduct"))
   .to(config.get<input_tag>("TracksProduct"))
   .using_concurrency(
      config.get<unsigned int>("Concurrency"));
}
```

```
# Configuration for the above user-registered function
{
  HitsProduct: { name: "GoodHits" domain: "Event"}
  OffsetProduct: { name: "CalibOffset" domain: "SubRun"}
  TracksProduct: "GoodTracks"
  Concurrency: 4
}
```


Fermilab

Meld implementation

- https://github.com/knoepfel/meld (not even alpha release)
- Implemented using oneTBB's flow graph 

Supported construct	User function	
Transform (Map)	$f(\boldsymbol{a}) \rightarrow \boldsymbol{b}$	*Standard data-processing idioms*
Filter	$f(\boldsymbol{a}) \rightarrow \text{Boolean}$	
Monitor	$f(\boldsymbol{a}) \rightarrow \text{Void}$	
Reduction (Fold)	$f_c(\boldsymbol{a}) \rightarrow \boldsymbol{c}$	*For splitting and then combining events*
Splitter (Unfold)	$f_n(\boldsymbol{a}) \rightarrow (\boldsymbol{d})_n$	
Zip	—	*For combining arguments to user functions*
Sliding window	—	*To do:* ***For sliding over adjacent events***

Sample hierarchies tested by Meld

```
[info] Number of worker threads: 12
[info] Processed levels:

  job
   │
   └ run: 1
      │
      └ subrun: 2
         │
         └ event: 10

[info] CPU efficiency: 259.55%
[info] Max. RSS: 6.205 MB
```

art-based hierarchy

Performance numbers are preliminary

Sample hierarchies tested by Meld

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[info] Number of worker threads: 12
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art-based hierarc

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[info] Number of worker threads: 12
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Non-trivial hierarchy

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[info] Number of worker threads: 12
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```

Non-trivial hierarchy

```
[info] Number of worker threads: 12
[info] Processed levels:

  job
   │
   └ event: 100000

[info] CPU efficiency: 882.50%
[info] Max. RSS: 16.527 MB
```

Flat hierarchy

But I have all this art code…

- There are a few million lines of art-aware code out there.
- Is it possible for meld to be backwards compatible?
- Conceptually not difficult.

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```
#include "art/Framework/Core/EDProducer.h"

namespace expt {
  class MyProducer : public art::EDProducer {
  public:
    MyProducer(fhicl::ParameterSet const& pset);
    void beginRun(art::Run& r) override;
    void beginSubRun(art::SubRun& sr) override;
    void produce(art::Event&) override;
    void endSubRun(art::SubRun& sr) override;
    void endRun(art::Run& r) override;
  };

  // Implementation ...
}

DEFINE_ART_MODULE(expt::MyProducer)
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    void beginSubRun(art::SubRun& sr) override;
    void produce(art::Event&) override;
    void endSubRun(art::SubRun& sr) override;
    void endRun(art::Run& r) override;
  };

  // Implementation ...
}

DEFINE_ART_MODULE(expt::MyProducer)
```

Can expand to

```
DEFINE_MODULE(m, pset)
{
  auto bound_obj = m.make<expt::MyProducer>(pset);
  bound_obj.with_legacy(&expt::MyProducer::beginRun)
           .process<Run>();
  bound_obj.with_legacy(&expt::MyProducer::beginSubRun)
           .process<SubRun>().following<SubRun>();
  bound_obj.with_legacy(&expt::MyProducer::produce)
           .reduce<Event>().to<SubRun>();
  bound_obj.with_legacy(&expt::MyProducer::endSubRun)
           .reduce<SubRun>().to<Run>();
  bound_obj.with_legacy(&expt::MyProducer::beginRun)
           .reduce<Run>();
}
```

Summary

> ***"Ways change, Stil."*** —Paul from *Dune* by Frank Herbert

- Supporting DUNE's framework needs suggests rethinking framework concepts.

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- Meld seeks to address these needs by considering a framework job as a

(1) graph of data products *connected by*
(2) user-provided operations *of*
(3) higher-order functions.

- Preliminary work indicates this is a productive avenue to pursue.
- Conceptually possible to be backwards compatible with existing art modules.

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- Preliminary work indicates this is a productive avenue to pursue.
- Conceptually possible to be backwards compatible with existing art modules.

Thank you for your time and attention.

Backup slides

Accessing provenance information

```
#include "meld/module.hpp"

namespace {
-  Tracks make_tracks(Hits const& hits) { ... }
+  Tracks make_tracks(meld::handle<Hits> hits) { ... }
}

DEFINE_MODULE(m, config) {
  m.with(make_tracks)
   .transform("GoodHits").in_each("Event")
   .to("GoodTracks")
   .using_concurrency(unlimited);
}
```

Class example using lambda expression

```
#include "meld/module.hpp"

DEFINE_MODULE(m, config)
{
  auto threshold = config.get<unsigned int>("threshold");
  m.with([threshold](Hits const& hits) { return hits.size() > threshold; })
   .filter("GoodHits").in_each("Event")
   .using_concurrency(unlimited);
}
```

Class example registering two member functions

```
#include "meld/module.hpp"

class Selector {
public:
  Selector(unsigned int n) : threshold{n} {}
  bool gt(Hits const& hits) const { return hits.size() > threshold; }
  bool le(Hits const& hits) const { return !gt(hits); }

private:
  unsigned int threshold;
};

DEFINE_MODULE(m, config)
{
  auto threshold = config.get<unsigned int>("threshold");
  auto bound_m = m.make<Selector>(threshold);
  bound_m.with(&Selector::gt).filter("GoodHits").in_each("Event");
  bound_m.with(&Selector::le).filter("GoodHits").in_each("Event");
}
```

Reduction example

```
class MyAccumulator : public art::EDProducer {
public:
  MyAccumulator(ParameterSet const&)
  {
    produces<int, art::InSubRun>("sum");
  }

  void produce(art::Event&) override
  {
    ++counter_;
  }

  void endSubRun(art::SubRun& sr) override
  {
    sr.put(std::make_unique<int>(counter_), "sum");
    counter_ = 0;
  }

private:
  int counter_ = 0;
};

DEFINE_ART_MODULE(MyAccumulator)
```

```
void accumulate(int& counter,
                meld::level_id const&)
{
  ++counter;
}


DEFINE_MODULE(m) {
  m.with(accumulate, 0).for_each("SubRun")
   .reduce("id").in_each("Event")
   .to("sum");
}
```

Higher-order functions

- We are interested in the mappings of the form:

$$\left\{(\boldsymbol{a})_n \xrightarrow{f} (\boldsymbol{b})_m\right\} \in \mathcal{D}$$

- Each object $\boldsymbol{a}$ corresponds to a tuple of arguments passed to f.
- The signature of f and the value $f(\boldsymbol{a})$, depends on the higher-order function.
- The above mapping happens within a domain $\mathcal{D}$ (e.g. job, run, event).
- Each object $\boldsymbol{a}$ is an element of a subset of the domain $\mathcal{D}$.

Supported higher-order functions

Meld term	CS term	Mathematical description		Domain
Transform	Map	$(\boldsymbol{a})_n \xrightarrow{f} (\boldsymbol{b})_n$	where $f(\boldsymbol{a}) \to \boldsymbol{b}$	Same as $(\boldsymbol{a})_n$
Filter	Filter	$(\boldsymbol{a})_n \xrightarrow{f} (\boldsymbol{a})_m$ where $m \leq n$	where $f(\boldsymbol{a}) \to \mathrm{Boolean}$	Same as $(\boldsymbol{a})_n$
Monitor	—	$(\boldsymbol{a})_n \xrightarrow{f} (\ )_0$	where $f(\boldsymbol{a}) \to \mathrm{Void}$	Same as $(\boldsymbol{a})_n$
Reduction	Fold	$(\boldsymbol{a})_n \xrightarrow{f_c} (\boldsymbol{c})_1$	where $f_c(\boldsymbol{a}) \to \boldsymbol{c}$	**Above** $(\boldsymbol{a})_n$
Splitter	Unfold	$(\boldsymbol{a})_1 \xrightarrow{f_n} (\boldsymbol{d})_m$	where $f_n(\boldsymbol{a}) \to (\boldsymbol{d})_n$	**Below** $(\boldsymbol{a})_n$
Zip	Zip	$\left((a)_n, (b)_n\right) \to (a, b)_n$		More nested domain