Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Multi-threaded *art*

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Outline

- *art*'s path processing
  - Consequences

- *art*'s multi-threading behavior
  - Command-line invocation
  - Guarantees and limitations
  - Kinds of modules
    - Illustrations
  - Services

- Guidance moving to multi-threaded *art* programs

Processing a data-containment level (e.g. Event)

- The order in which modules are executed for a Run, SubRun, or Event is determined by the **path declarations** in the configuration file.

```
physics: {

  producers: {
    makeHits: {...}
    makeShowers: {...}
    produceG4Steps: {...}
  }
  analyzers: {
    plotHits: {...}
  }

  hitPath: [makeHits, makeShowers]
  geomPath: [produceG4Steps]
  analyzePath: [plotHits]
}
```

Module declarations

Path declarations

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Trigger path
Trigger path
End path

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Trigger path
End path

- **The order in which *trigger paths* are executed is unspecified (single-threaded).**
- **In MT *art* trigger paths will be executed simultaneously.**
- Modules in a trigger path are executed in the order specified.
- End paths are always processed after all trigger paths.
- A module is executed once per event.

Processing a data-containment level (e.g. Event)

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Trigger path	hitPath: [makeHits, makeShowers]
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Heeding these facts is essential for successful use of *art* 3.

Consequences of *art*'s guarantees

- Modules on one trigger path may not consume products created by modules that are not on that same path.

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- The following is a configuration error (heuristically):

```
physics: {
  producers: {
    p1: { produces: ["int", ""] }
    p2: { consumes: ["int", "p1::current_process"] }
  }
  tp1: [p1]
  tp2: [p2]
}
```

Consequences of *art*'s guarantees

- Modules on one trigger path may not consume products created by modules that are not on that same path.
- The following is also a configuration error (heuristically):

```
physics: {
  producers: {
    p1: { produces: ["int", ""] }
    p2: { produces: ["int", "instanceName"] }
    readThenMake: {
      consumesMany: ["int"] // calls getMany
    }
  }
  tp1: [p1, readThenMake]
  tp2: [p2, readThenMake]
}
```

Consequences of *art*'s guarantees

- Modules on one trigger path may not consume products created by modules that are not on that same path.
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```
physics: {
    }
  }
  tp1: [p1, readThenMake]
  tp2: [p2, readThenMake]
}
```

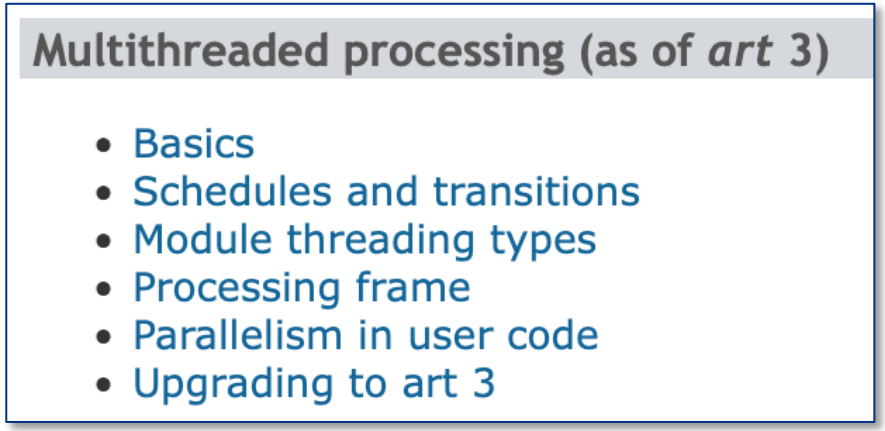
art 3 catches these errors if you use the `consumes` interface.

```
Module readThenMake on paths tp1, tp2 depends on
   Module p2 on path tp2
```

art's multi-threading behavior

art's multi-threading behavior

https://cdcvs.fnal.gov/redmine/projects/art/wiki#Multithreaded-processing-as-of-art-3



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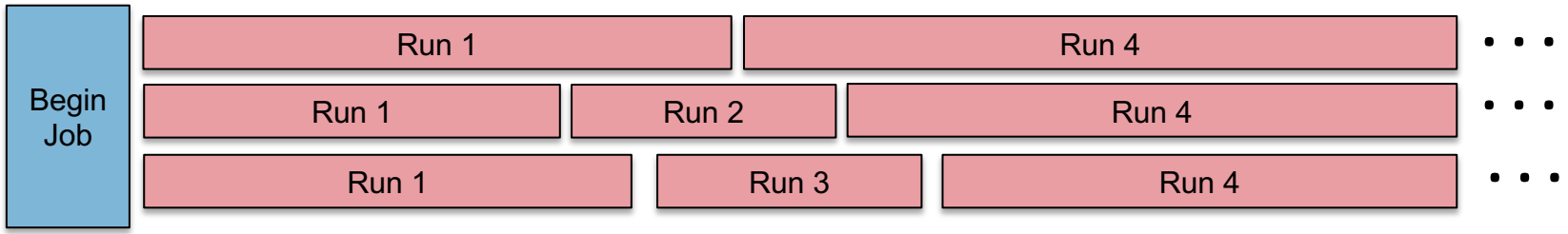
The design

- Largely based off of CMSSW's design
  - We use Intel's Threading Building Blocks (TBB)
  - Steps to be performed are factorized into *tasks*
  - You can think of a call to your module's "produce" function as performing a task
- Users specify the number of concurrent event loops (*schedule*s) and (optionally) the maximum number of threads that the process can use.
- **Each schedule processes one event at a time.**

Our goal:



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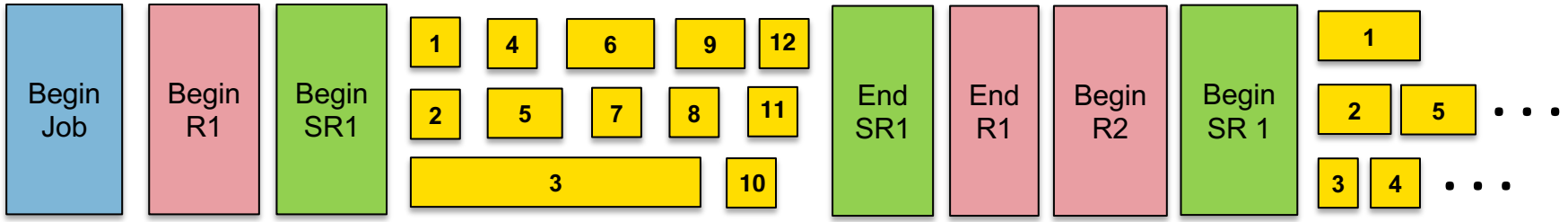
Currently implemented:



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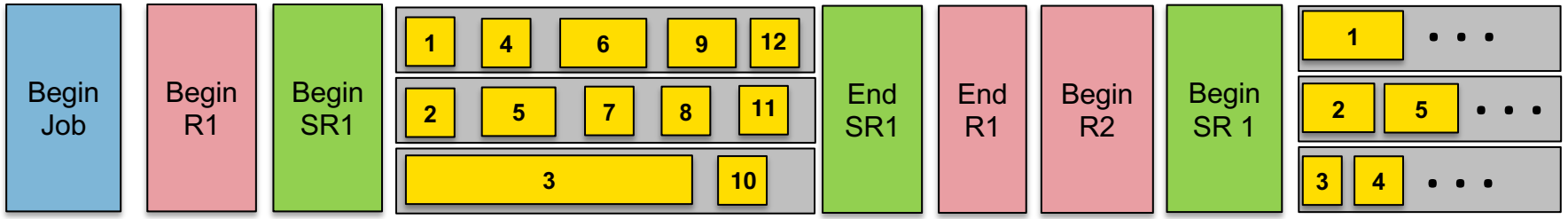

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- Users specify the number of concurrent event loops (*schedule*s) and (optionally) the maximum number of threads that the process can use.
- **Each schedule processes one event at a time.**
- Different modules can be run in parallel on the *same* event.
- Users are allowed to use TBB's parallel facilities within their own modules.

Multi-threaded event-processing

- *art* 3 supports concurrent processing of events.
  - The number of events to process concurrently is specified by the **number of schedules**
  - The user can optionally specify the number of threads.
- The user ***opts in*** to concurrent processing.

Multi-threaded event-processing

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- The user ***opts in*** to concurrent processing.

Command	(nSch, nThr)
`art -c <config> …`	(1, 1)
`art -c <config> -j 1 …`	(1, 1)
`art -c <config> -j 4 …`	(4, 4)
`art -c <config> -j 0 …`	(nproc, nproc)
`art -c <config> --nschedules 1 --nthreads 4 …`	(1, 4)

- In a grid environment, number of threads is limited to the number of CPUs configured for the HTCondor slot (*art* adjusts the number of threads).

art 3 guarantees

- Processing of an event happens on one and only one schedule.
- For a given trigger path, modules are processed in the order specified.
- A module shared among paths will be processed only once per event.
- Product insertion into the event is thread-safe.
- Product retrieval from the event is thread-safe.
- Provenance retrieval from the event is thread-safe.
- All modules and services provided by *art* are thread-safe.
  - For `TFileService`, the user is required to specify additional serialization.

art 3 limitations—*Primum non nocere (first, to do no harm)*

- Only events within the same SubRun are processed concurrently.
- Analyzers and output modules do not run concurrently.

- Other details
  - `MixFilter` modules are legacy modules.
  - Secondary input-file reading is allowed only for 1 schedule and 1 thread.
  - `TFileService` file-switching is allowed only for 1 schedule and 1 thread.

Kinds of modules in *art* 3

- *art* guarantees that any currently-existing modules are usable in a multi-threaded execution of art.
  - No multi-threading benefits are realized with legacy modules

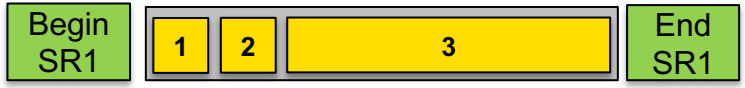
- To take advantage of *art*'s multi-threading capabilities, users will need to choose the kind of module they use:

  - **Shared module**: sees all events—calls can be serialized or asynchronous.

  - **Replicated module**: for a configured module, one copy of that module is created per schedule—each module copy sees one event at a time. Use if moving to a concurrent, shared module is not feasible.

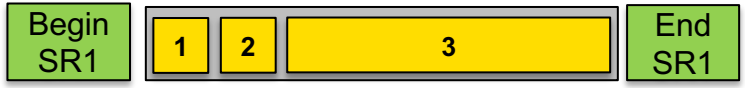
Time structure for calling modules

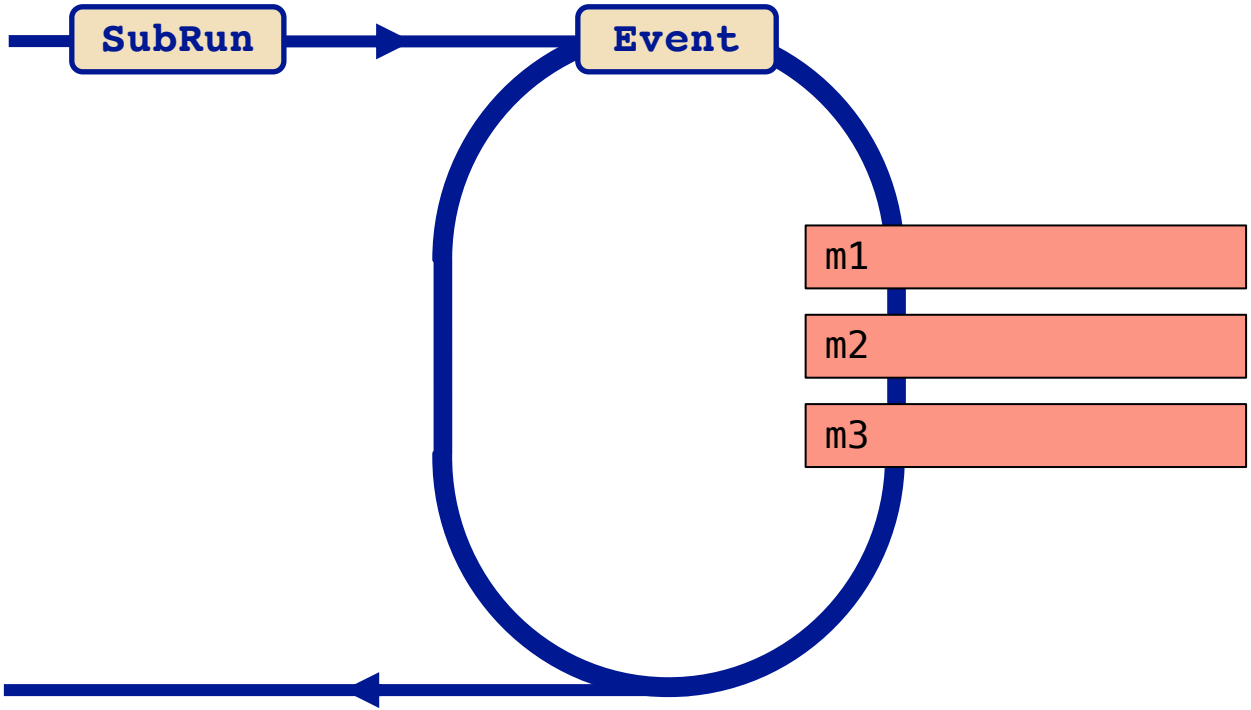
Single schedule



Time structure for calling modules

Single schedule





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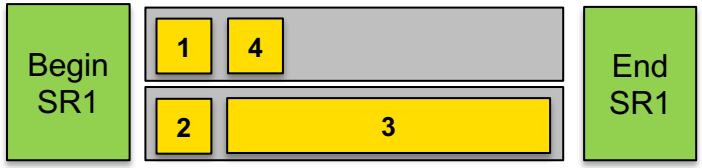
Shared modules

Modules shared across schedules

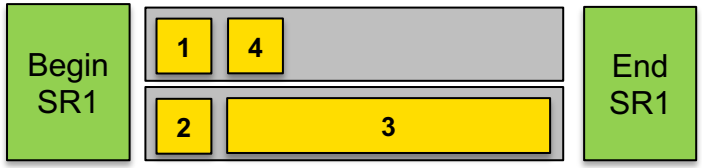
Time structure for calling modules

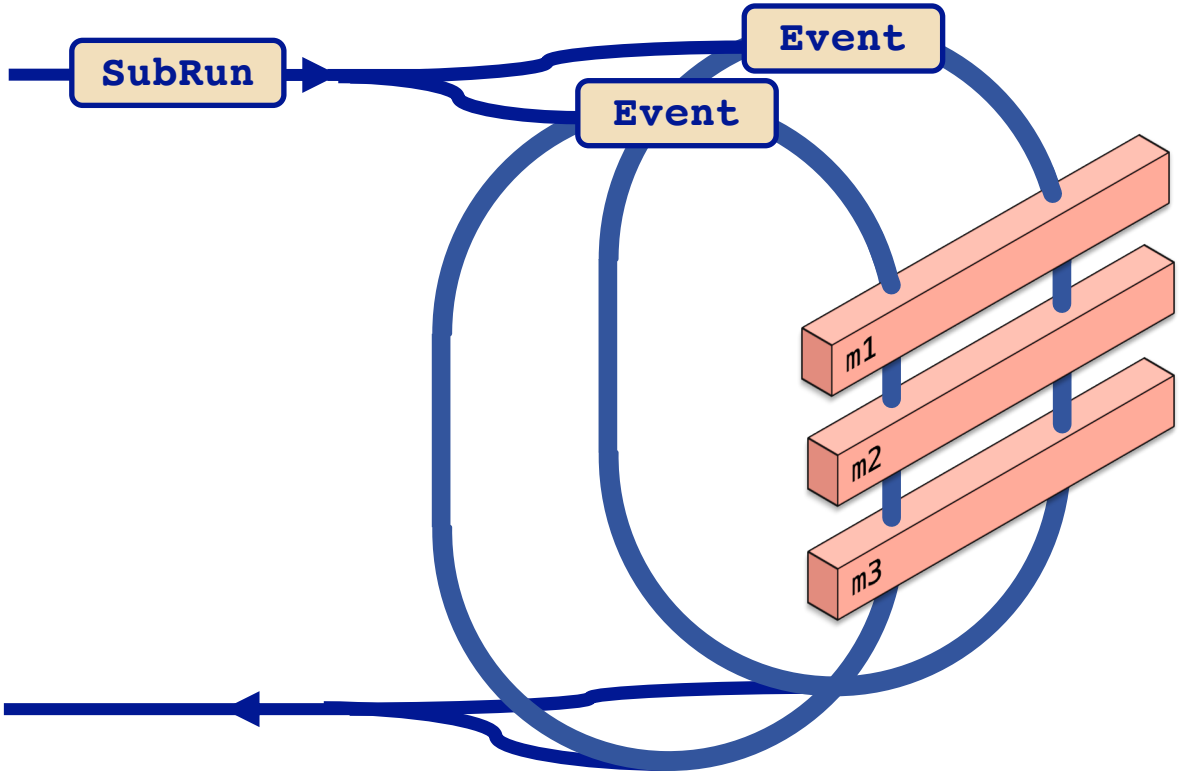
Multiple schedules



Time structure for calling modules

Multiple schedules





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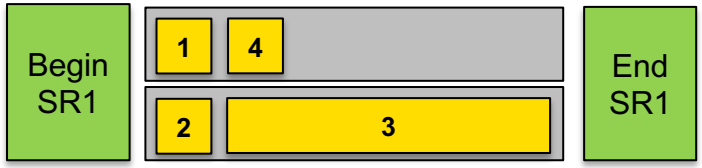
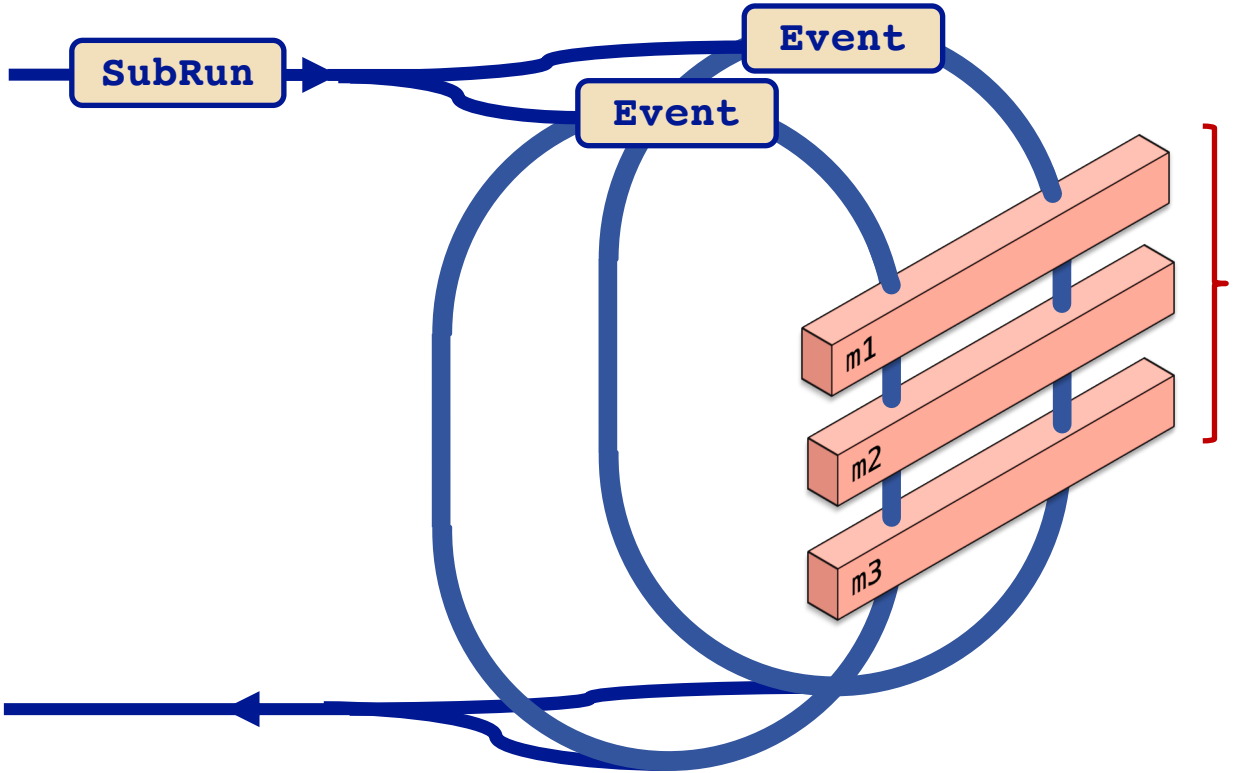
Time structure for calling modules

Multiple schedules





Data races are now possible.

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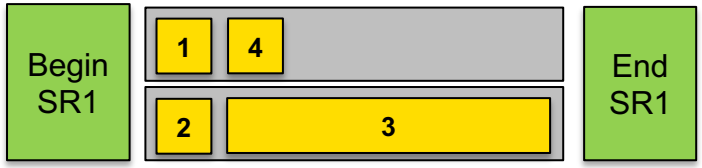
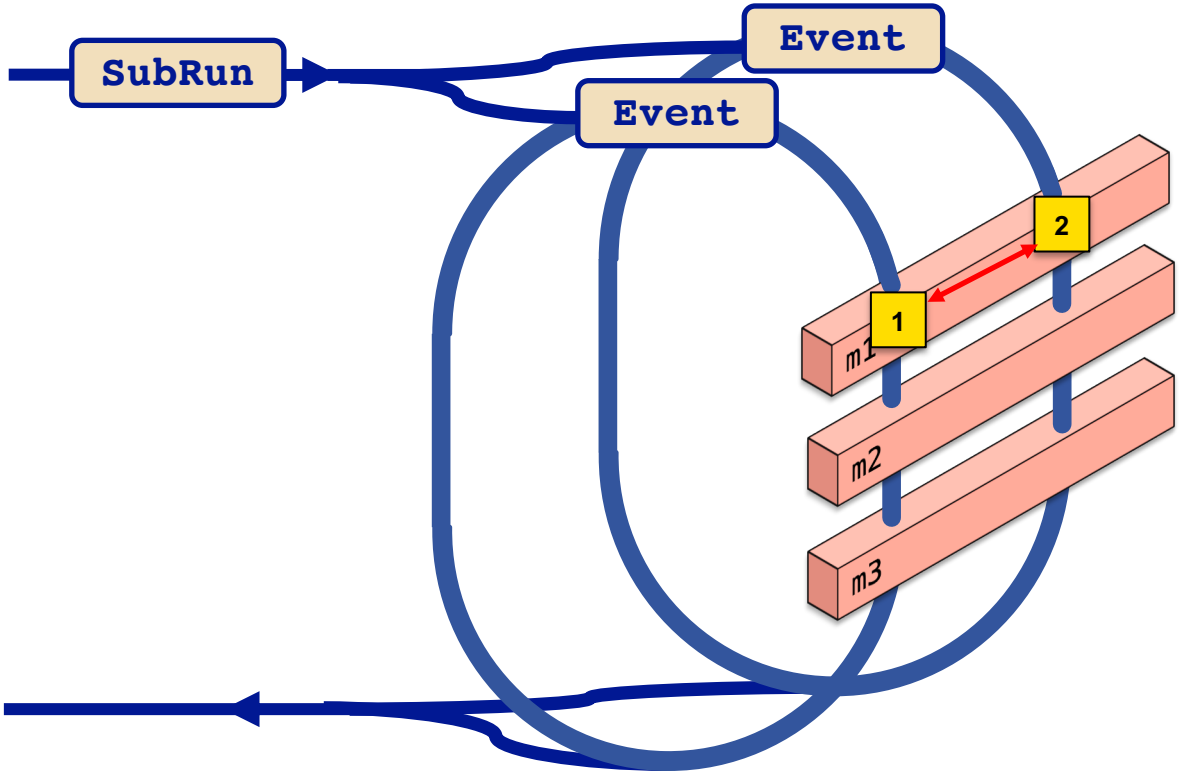
Time structure for calling modules

Multiple schedules





If the state of one of the modules is updated when simultaneously processing two events, there can be a data race.

What are some ways to handle this?

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Using a legacy module

```
class HistMaker : public art::EDProducer {
public:
  explicit HistMaker(Parameters const& p) : EDProducer{p}
  {}

  void produce(Event& e) override {} // Called serially wrt. all
                                     // serialized modules
};
```

- Legacy modules imply maximum serialization.
  - Legacy modules cannot be run in parallel with any other legacy modules or any serialized shared modules.
- With *art* 3, any new modules should not be legacy modules.
- The better solution is to use a `SharedModule`, which can be serialized only wrt itself.

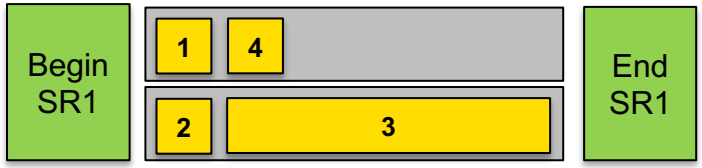
Use a shared module

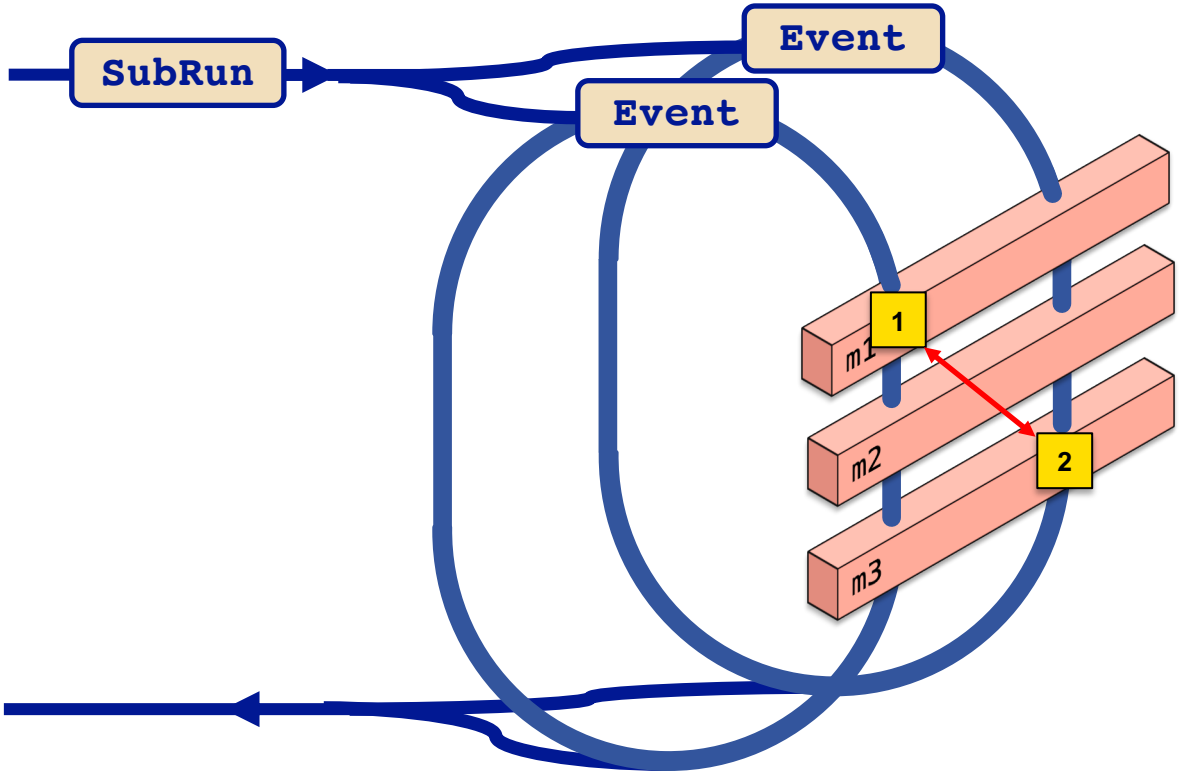
```
class HistMaker : public art::SharedProducer {
public:
  explicit HistMaker(Parameters const& p,
                     ProcessingFrame const&) : SharedProducer{p}
  {
    serialize<InEvent>(); // Declaration to process
                          // one event at a time.
  }

  // Called serially wrt. itself
  void produce(Event&, ProcessingFrame const&) override;
};
```

- But there can be other data race problems.

Time structure for calling modules

Multiple schedules





If two modules are processing different events at the same time, but they are using a common resource, there can be a data race.

How do we avoid such a data race?

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Serialized module due to shared resource

Serialized module due to shared resource

```
class Fitter : public art::SharedProducer {
public:
  explicit Fitter(Parameters const& p,
                  ProcessingFrame const& frame) : SharedProducer{p
    consumes<TCollection>(); // declare the common resource
  }

  // Called serially wrt. other modules that use TCollection
  void produce(Event& e) override;
};
```

Suppose you want to call **`TCollection::(Set|Get)CurrentCollection`**

First step: please don't. This is only illustrating a thread-unsafe interface.

Serialized module due to shared resource

```
class Fitter : public art::SharedProducer {
public:
  explicit Fitter(Parameters const& p,
                  ProcessingFrame const& frame) : SharedProducer{p}
  {
    serialize<InEvent>("TCollection"); // Declare the common resource
  }

  // Called serially wrt. other modules that use TCollection
  void produce(Event& e) override;
};
```

If you can guarantee no data races…

```
class HitMaker : public art::SharedProducer {
public:
  explicit HitMaker(Parameters const& p ,
                    ProcessingFrame const&) : SharedProducer{p}
  {
    async<InEvent>();
  }

  void produce(Event&) override; // Called asynchronously
};
```

Replicated modules

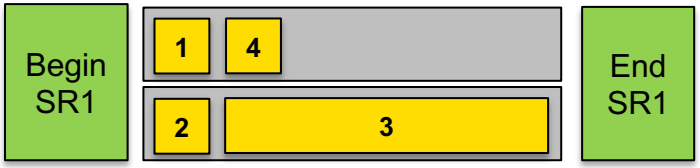
One module per schedule

Replicated modules

One module per schedule

- Sometimes the easiest way to gain multi-threading benefits is to replicate modules across schedules—avoids data races from sharing a module.

Time structure for calling modules
Multiple schedules



Time structure for calling modules

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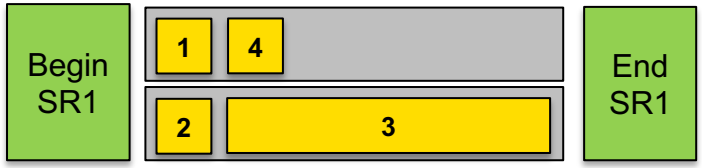

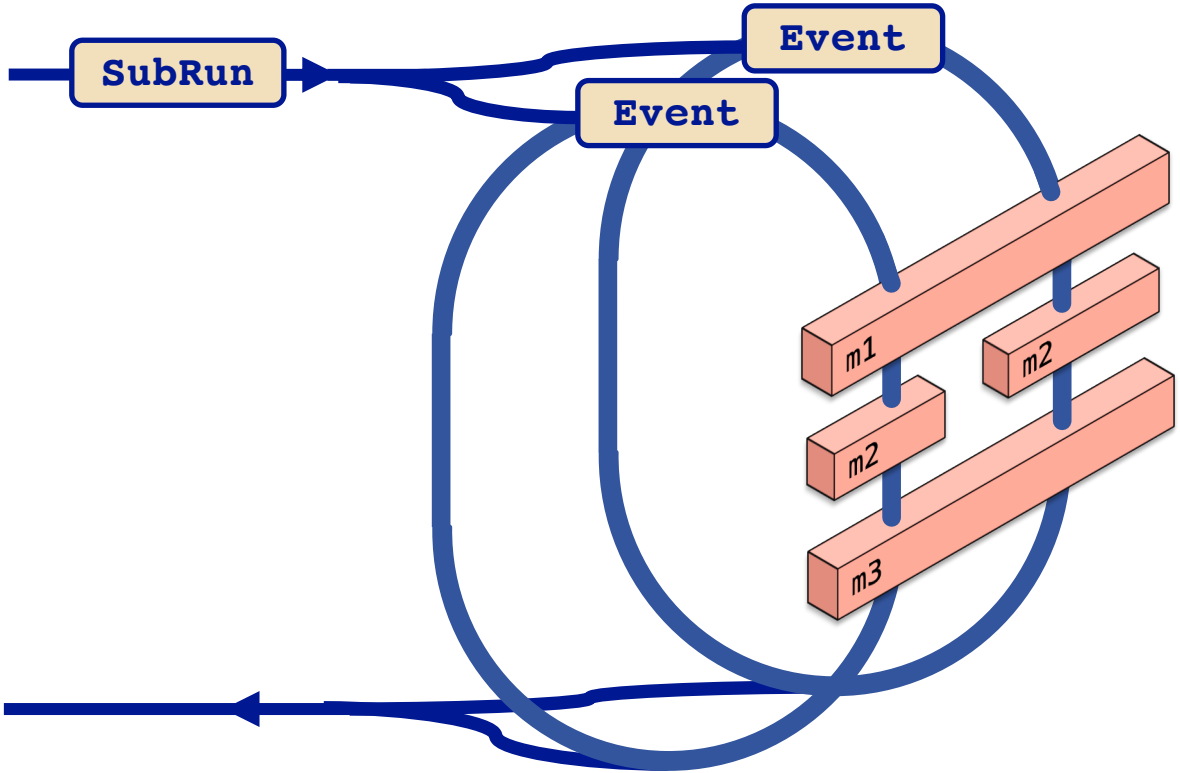

Multiple copies of configured module **`m2`** avoids data-races wrt. **`m2`** data members.

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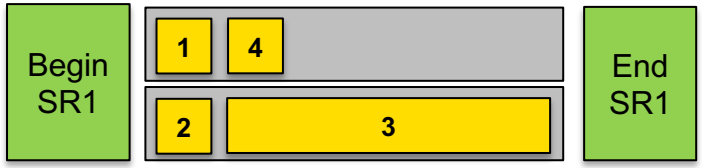
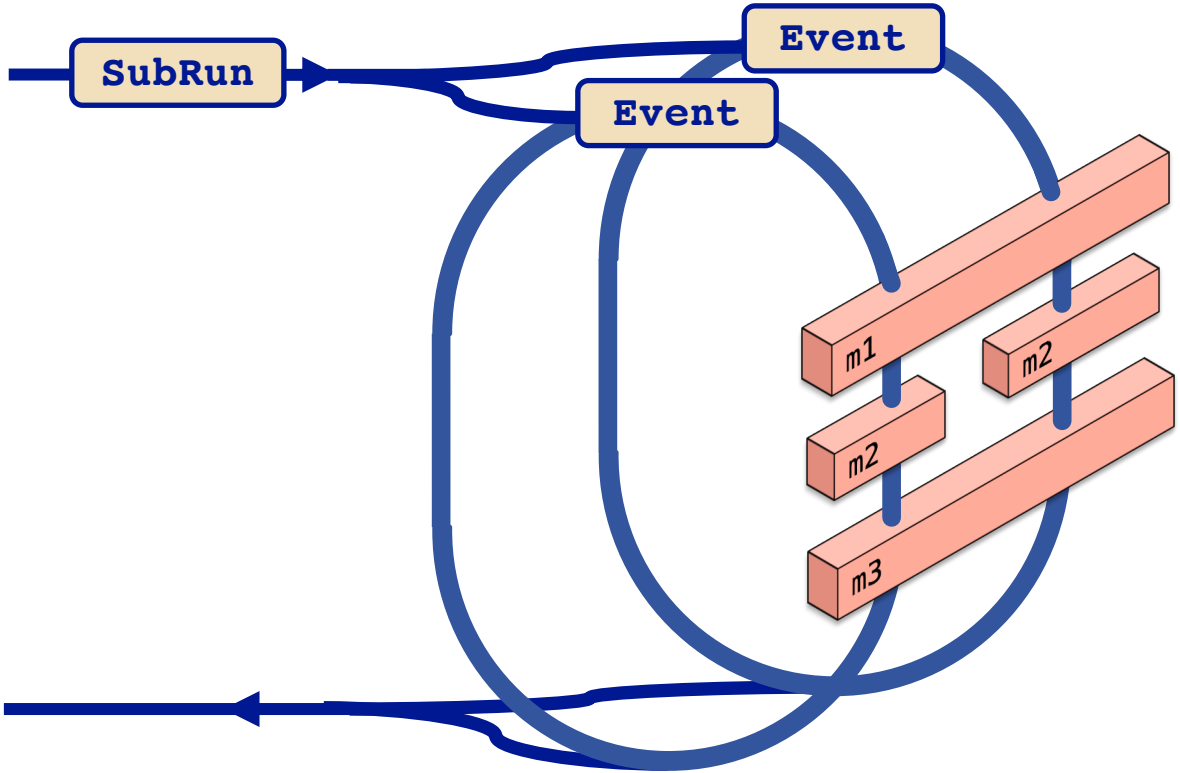
Time structure for calling modules

Multiple schedules





Multiple copies of configured module **`m2`** avoids data-races wrt. **`m2`** data members.

Consequence: each module copy does not see all events.

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Replicated producer

```
class Accumulator : public art::ReplicatedProducer {
public:
  explicit Accumulator(Parameters const& p,
                       ProcessingFrame const& frame)
    : ReplicatedProducer{p, frame}
  {}

  // Each module copy sees one event at a time
  void produce(Event&, ProcessingFrame const&) override;
};
```

- Do not use a replicated producer is you need to use a shared resource.
- For *art* 3.0, replicated modules cannot produce Run and SubRun data products.

What is the `ProcessingFrame` type?

> *"O `art::ServiceHandle<T>{}`, thou time is short."*
> *- Anonymous*

- Until now, users have been able to create `ServiceHandles` from anywhere; this pattern is changing.
- The recommended pattern is for *art* users to create service handles from the passed-in `ProcessingFrame` object.

```
void HitMaker::beginRun(Run&, ProcessingFrame const& frame)
{
  auto h1 = frame.serviceHandle<Calib>();       // => ServiceHandle<Calib>
  auto h2 = frame.serviceHandle<Calib const>(); // => ServiceHandle<Calib const>
}
```

- This will eventually allow for replicated services, akin to replicated modules.

Services

- Services are globally shared objects (across schedules and threads).
  - They can be accessed from anywhere through a ServiceHandle.
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- In order to use a service in an art job, with more than one schedule/thread enabled, the service must be GLOBAL (SHARED, for art 3.03).
- LEGACY services are supported only in single-schedule/single-threaded mode.

```
---- Configuration BEGIN
  The service 'MyService' is a legacy service,
  which can be used with only one schedule and one thread.
  This job uses 2 schedules and 2 threads.
  Please reconfigure your job to use only one schedule/thread.
---- Configuration END
```

ROOT and MT

- ROOT's thread-safety flag **has** been enabled by *art*.
  - Allows (e.g.) multiple ROOT files to be opened in parallel.
- ROOT's implicit MT flag **has not** been enabled by *art.*
- All interactions *art* has with ROOT are serialized.
  - Input-file reading
  - Output-file writing
  - To use `TFileService`, you must use a shared module that calls the appropriate `serialize` function.

Guidance moving to *art* 3

- **Solve workflow issues first.**
  - You might have thread-safe modules and services.
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Recompile/rerun jobs with 1 schedule/1 thread (default)

Add consumes statements to modules (use –M program option for help)

Recompile/rerun jobs with 1 schedule/1 thread and use `--errorOnMissingConsumes`

Recompile/rerun jobs with more than 1 schedule/1 thread

Guidance moving to *art* 3

- **Solve workflow issues first.**
  - You might have thread-safe modules and services.
  - If you're relying on illegal path configurations, you'll run into product dependency errors.
- **Determine what kind of module you need.**
  - Producer, filter, or analyzer?
  - Do you need to create (Sub)Run products?
  - Do you need to see every event?
  - Do you need to call an external library that is not thread-safe?
  - Do you have mutable data members for which operations are not thread-safe?

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- We can provide guidance in dealing with such issues.
- **Contact us**.