Multi-threaded Scheduling in CMS

Dr Christopher Jones
HSF Framework Group

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CMS's Threading Goals

Better scaling of system resources as core count increases

- Number of workflow jobs does not have to increase as core count increases
- Potential to use sites with lower available resources

More sharing between cores

- Share infrequently updated memory
  - conditions
  - I/O buffers
- Share file handles
- Share network connections

Faster processing of individual Events is NOT a goal

- CMS cares about total events/second for an entire workflow, not so much 1 job
  - A workflow processes millions of events over 10s of 1000s of jobs

Threaded Design

Run multiple transitions concurrently

- Event transitions are the most important
- Number of allowed concurrent transitions of each type set at configuration time

Within one transition run multiple modules concurrently

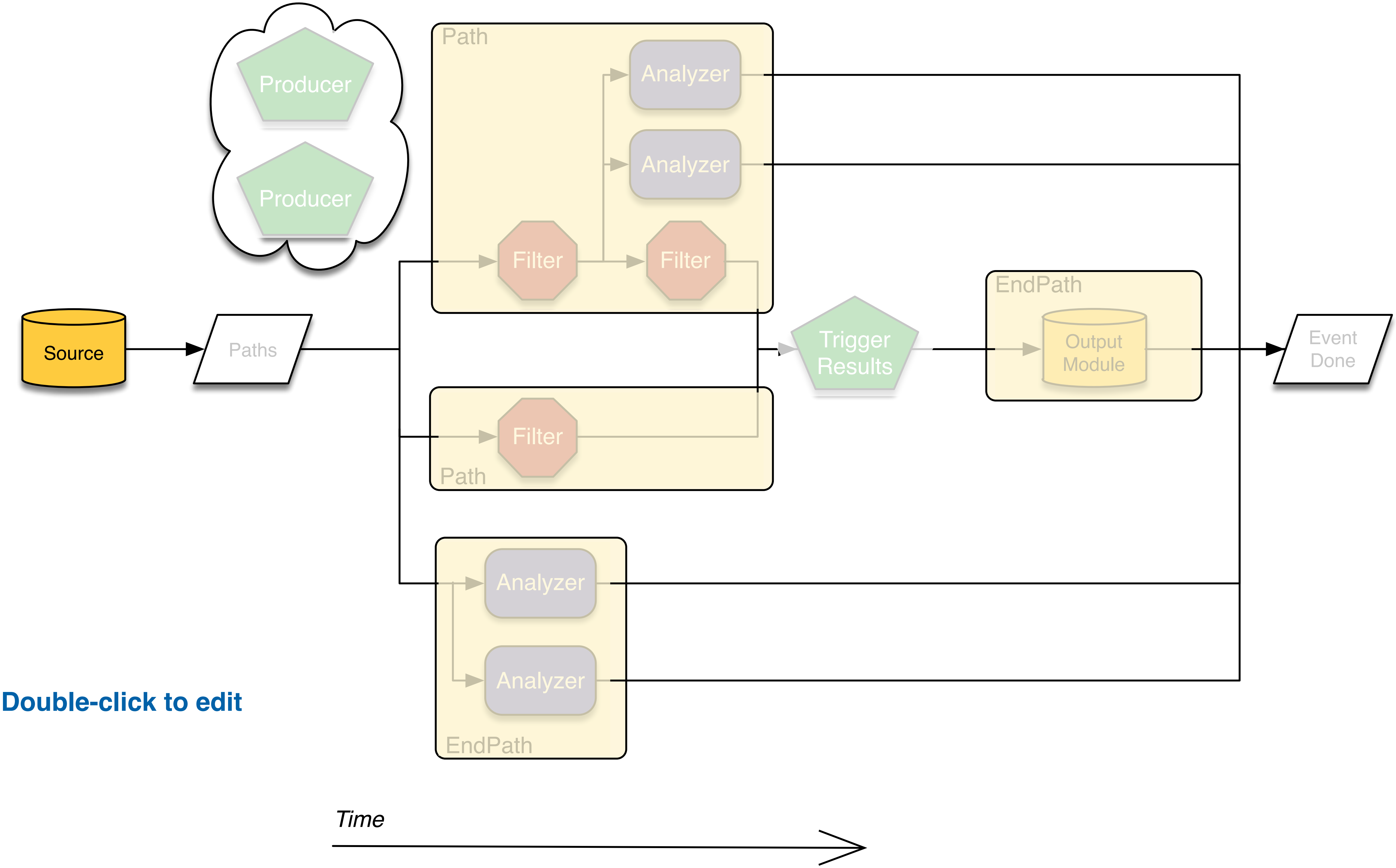
- Have to take into account module dependencies

Within one module be able to run multiple tasks concurrently

Intel’s Thread Building Blocks library used for all of the above

- Break down work into *tasks* and TBB can run them in parallel

Processing an Event



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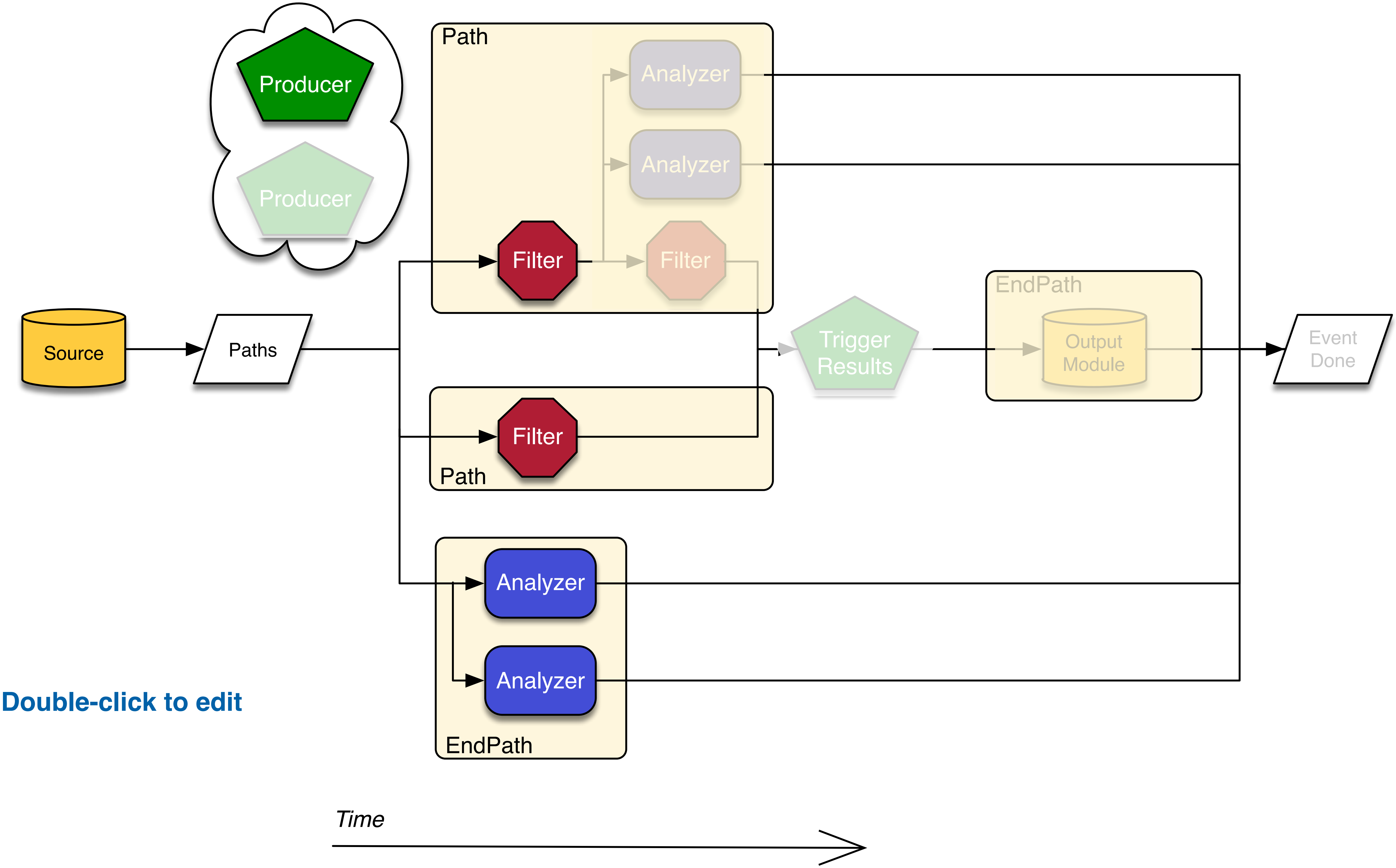

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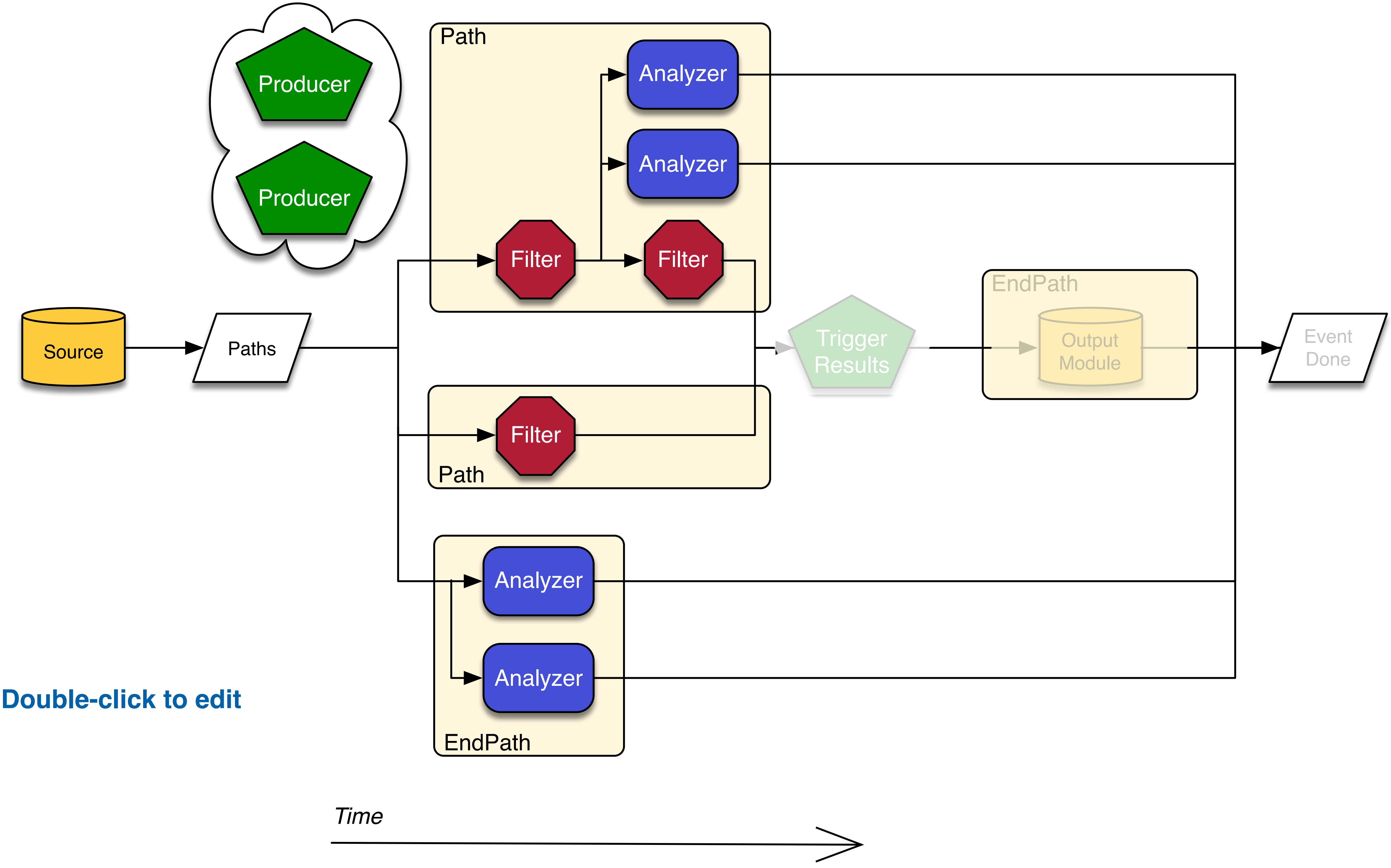

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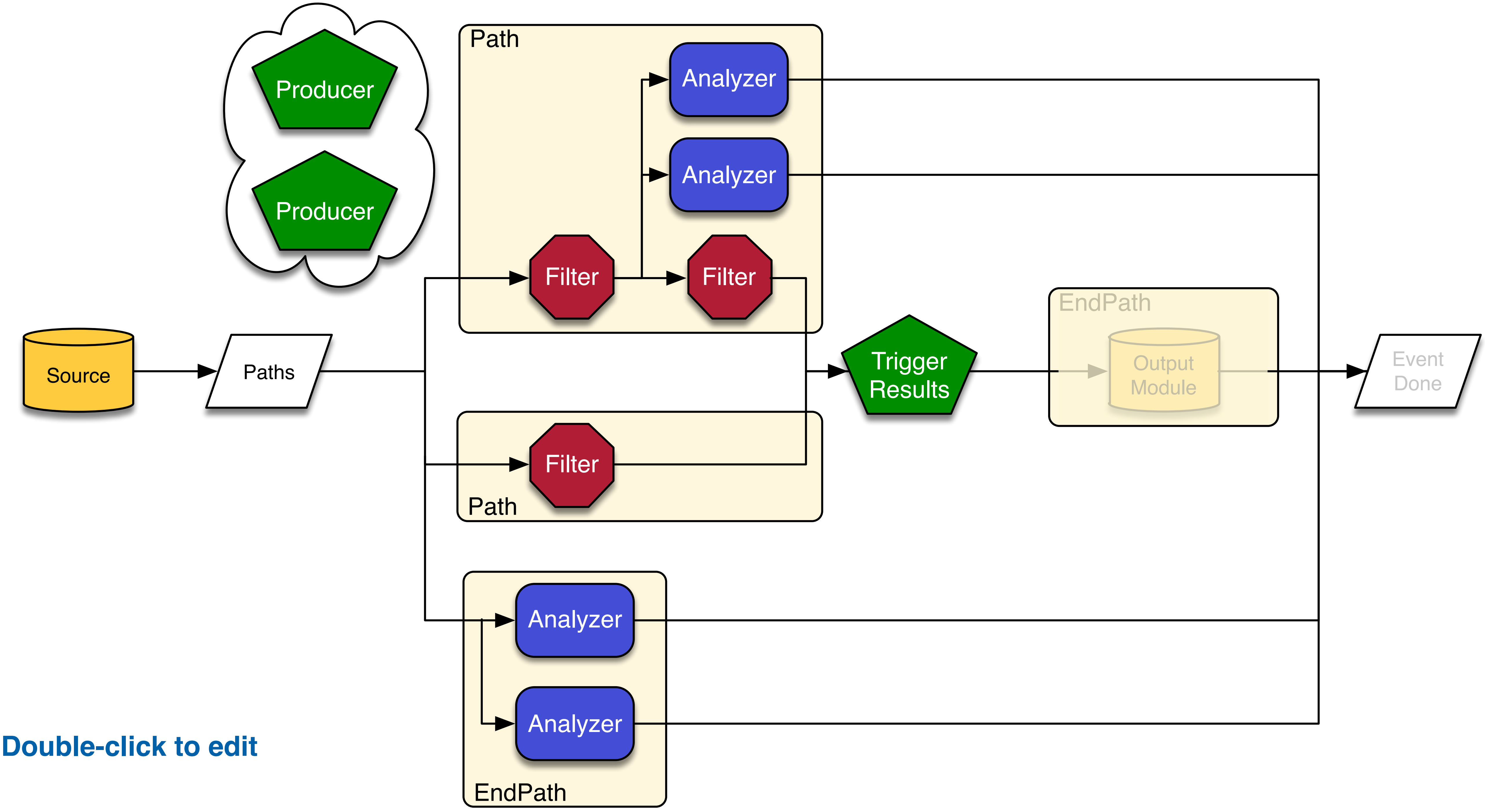

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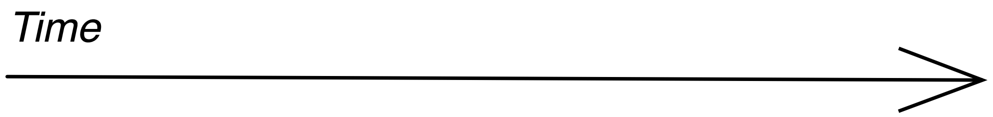

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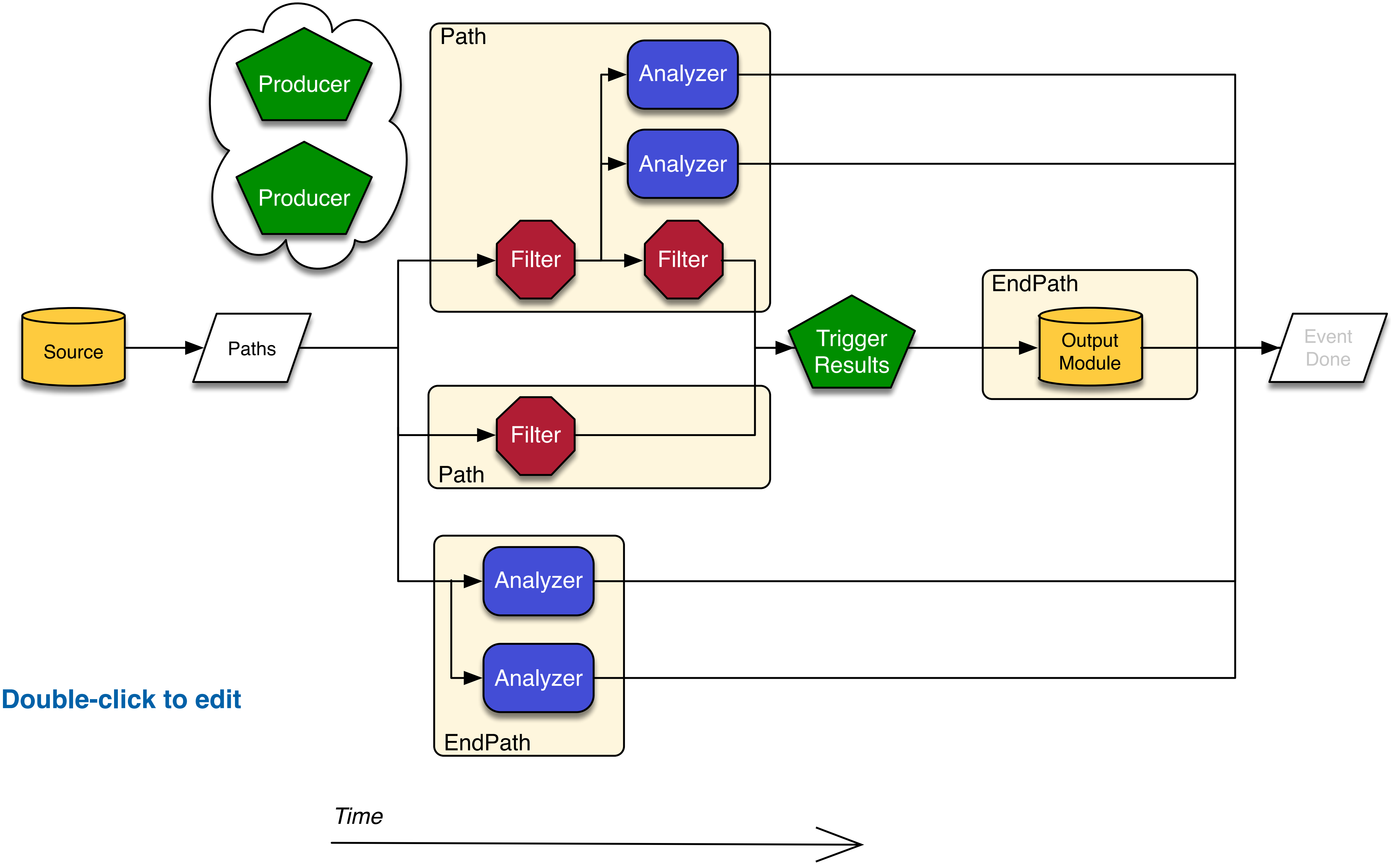

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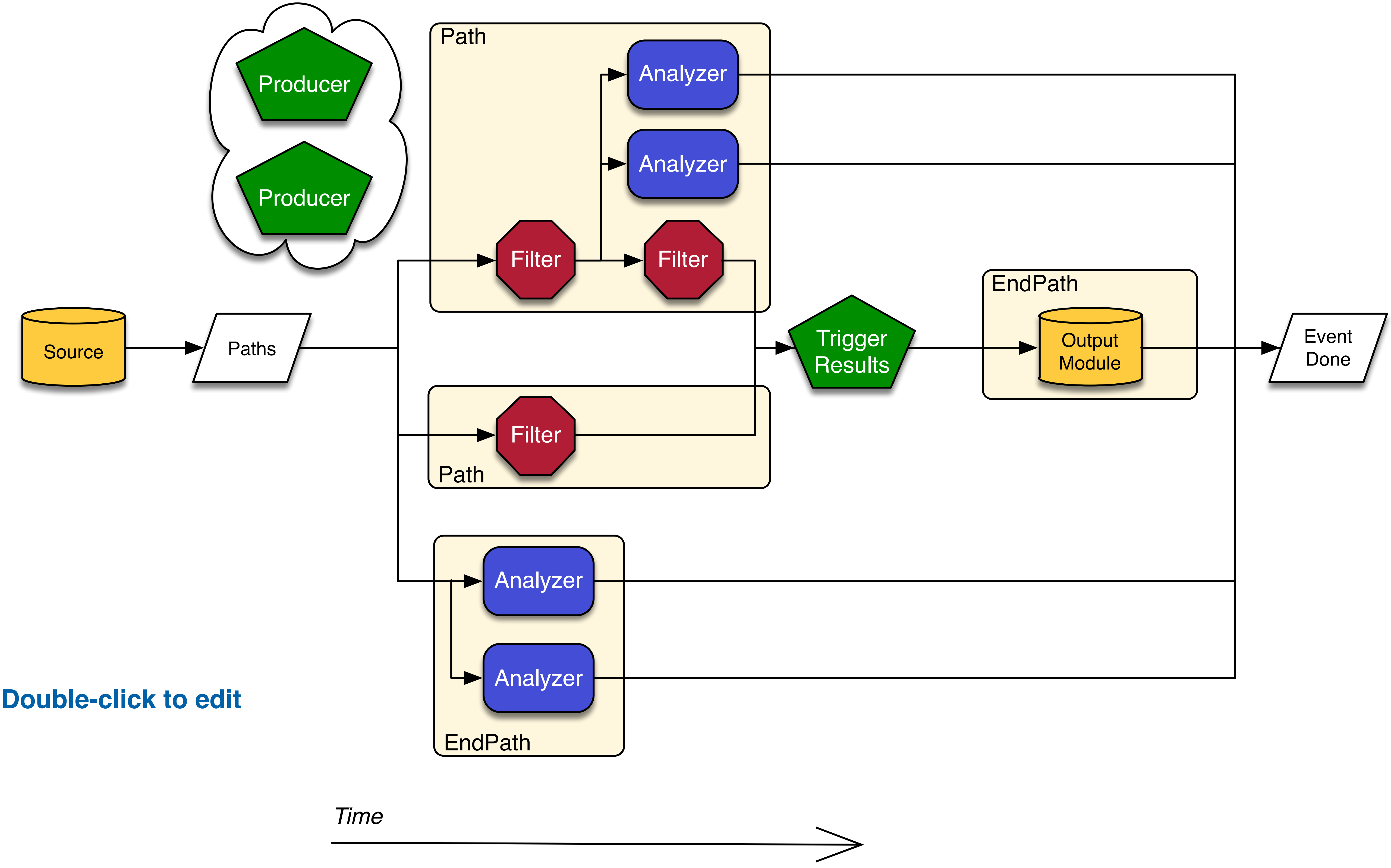

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Glossary

Paths

- Events are filtered by Paths
- Paths hold a list of Filters

Filters

- Modules after a Filter on a Path only run if the Filter passes

Producers

- Make data products used by other Modules
- Run first time their data is requested

EndPaths

- Hold modules that want to see all Events or want to see results of Paths

Modules

- Filters, Producers, Analyzers, and OutputModules are all Modules
- Modules can run concurrently

Scheduling

No process wide scheduling is done

- All decisions are done on each thread individually

Based on four items

- TBB's task scheduling
- Prefetching
- Module threading types
- Serial task queues

TBB Task Model

Pre-declare how many threads should be used

For each thread, there is a work queue

task::spawn adds a task to the queue for the thread that called spawn

tasks are pulled from the work queue in Last In First Out order

task::enqueue puts tasks on a shared queue

If a queue is empty, the thread will

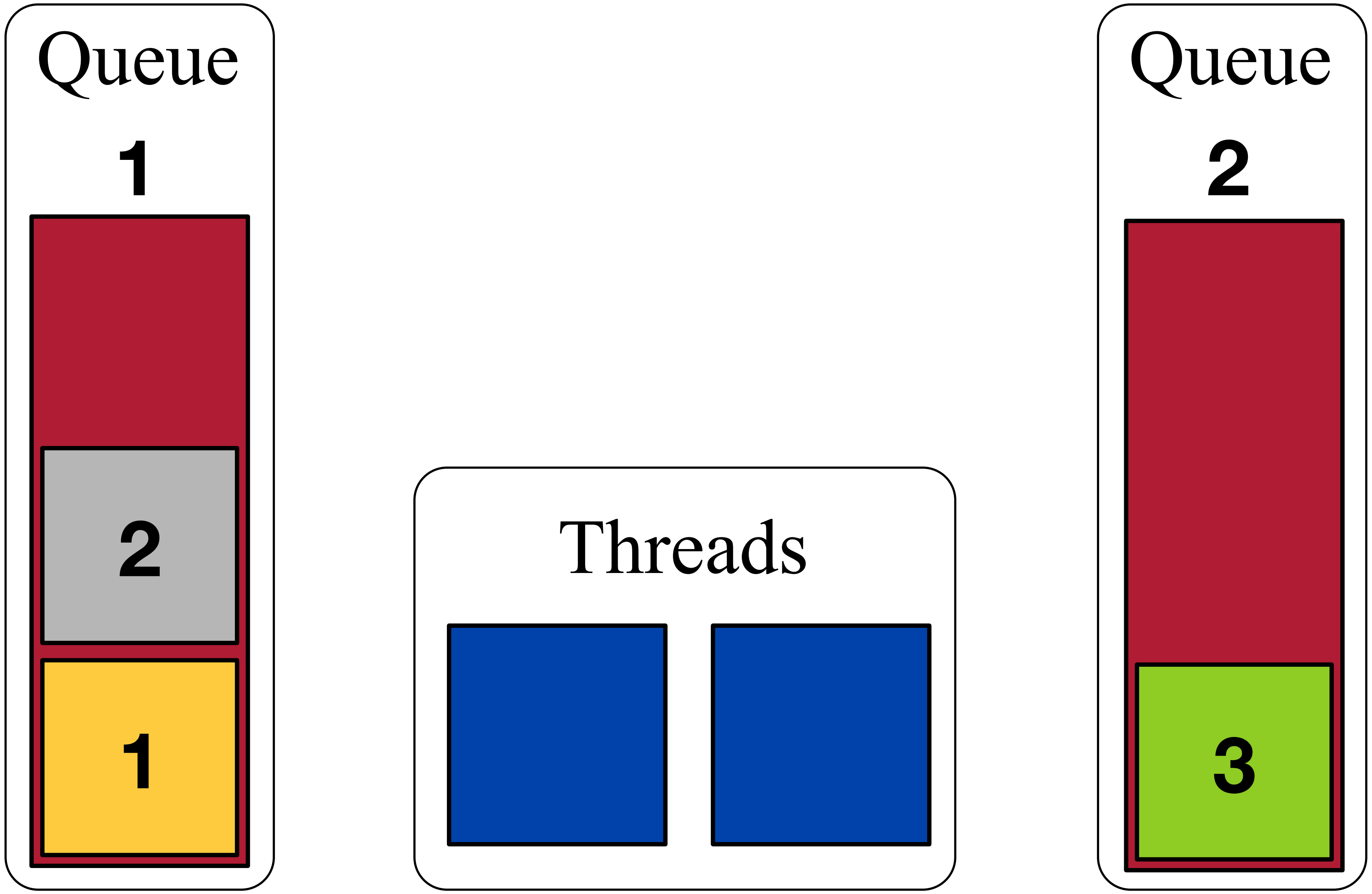
- See if a task is on the shared queue and if so take the oldest one, else
- Steal oldest task from another thread's queue

A task can explicitly return a new task that is to be run next

- Guaranteed to run on the same thread

TBB Task Model

Tasks are pulled in Last In First Out order



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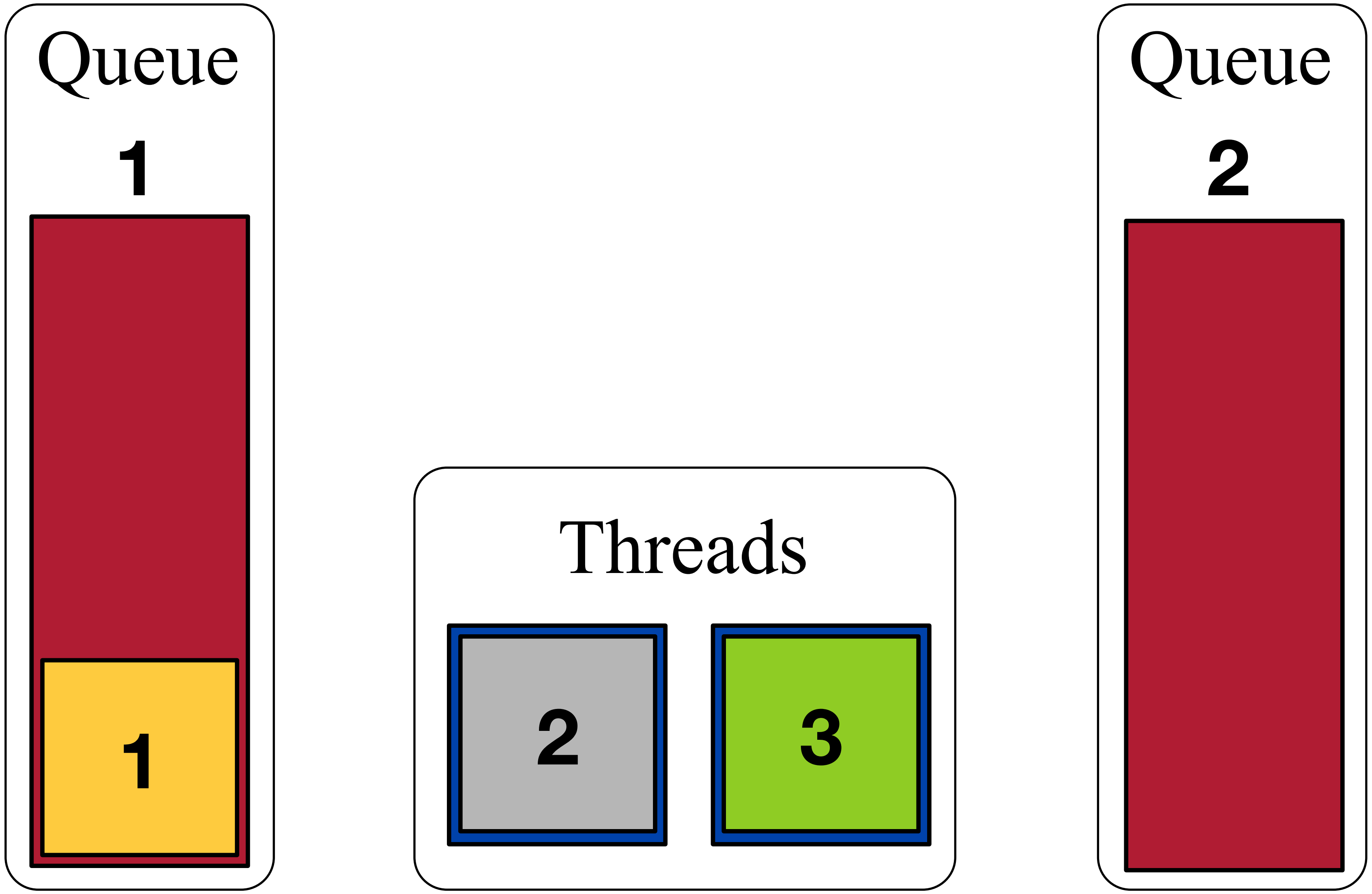
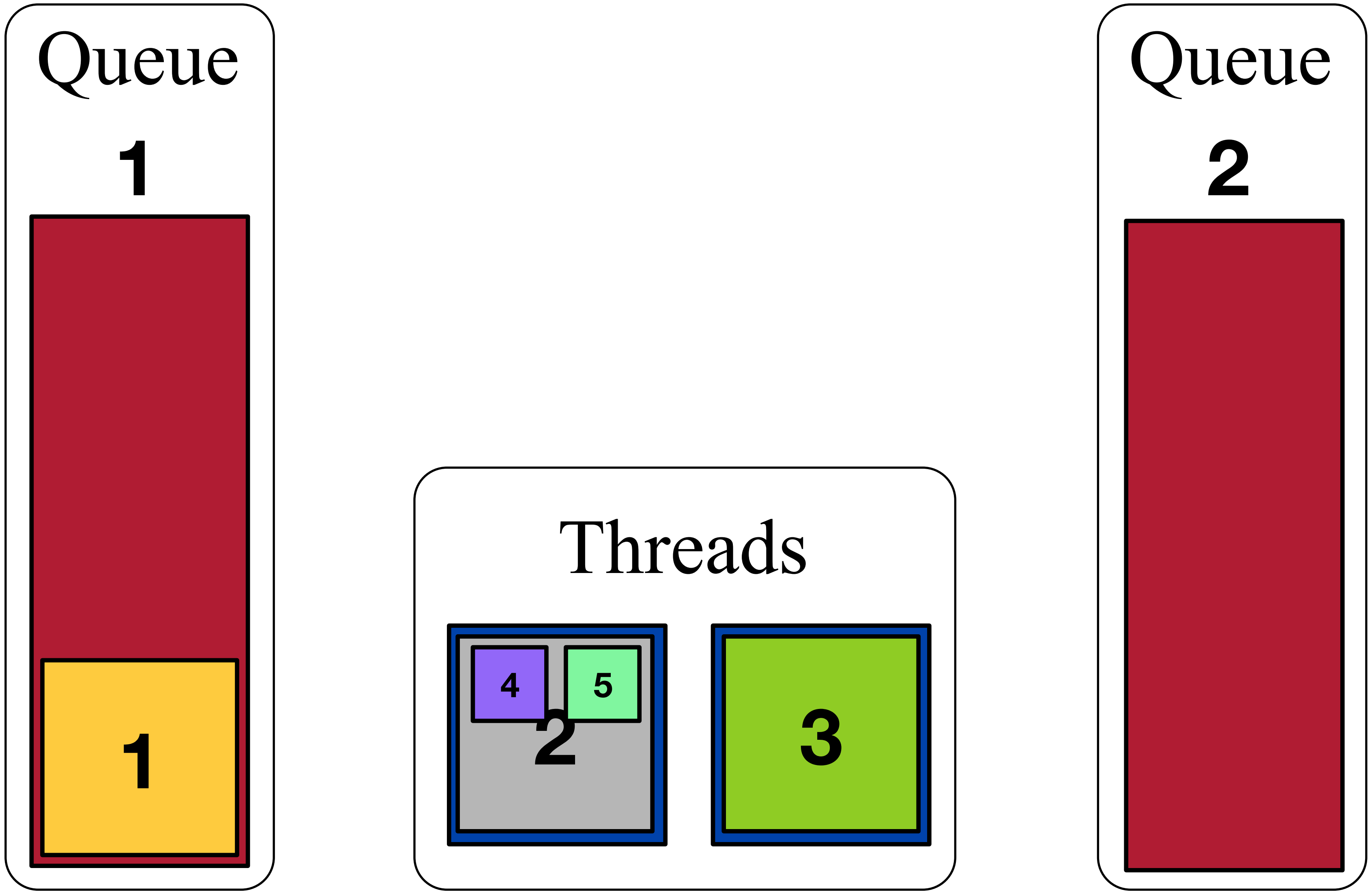


TBB Task Model

Spawned tasks go into same queue as creating task



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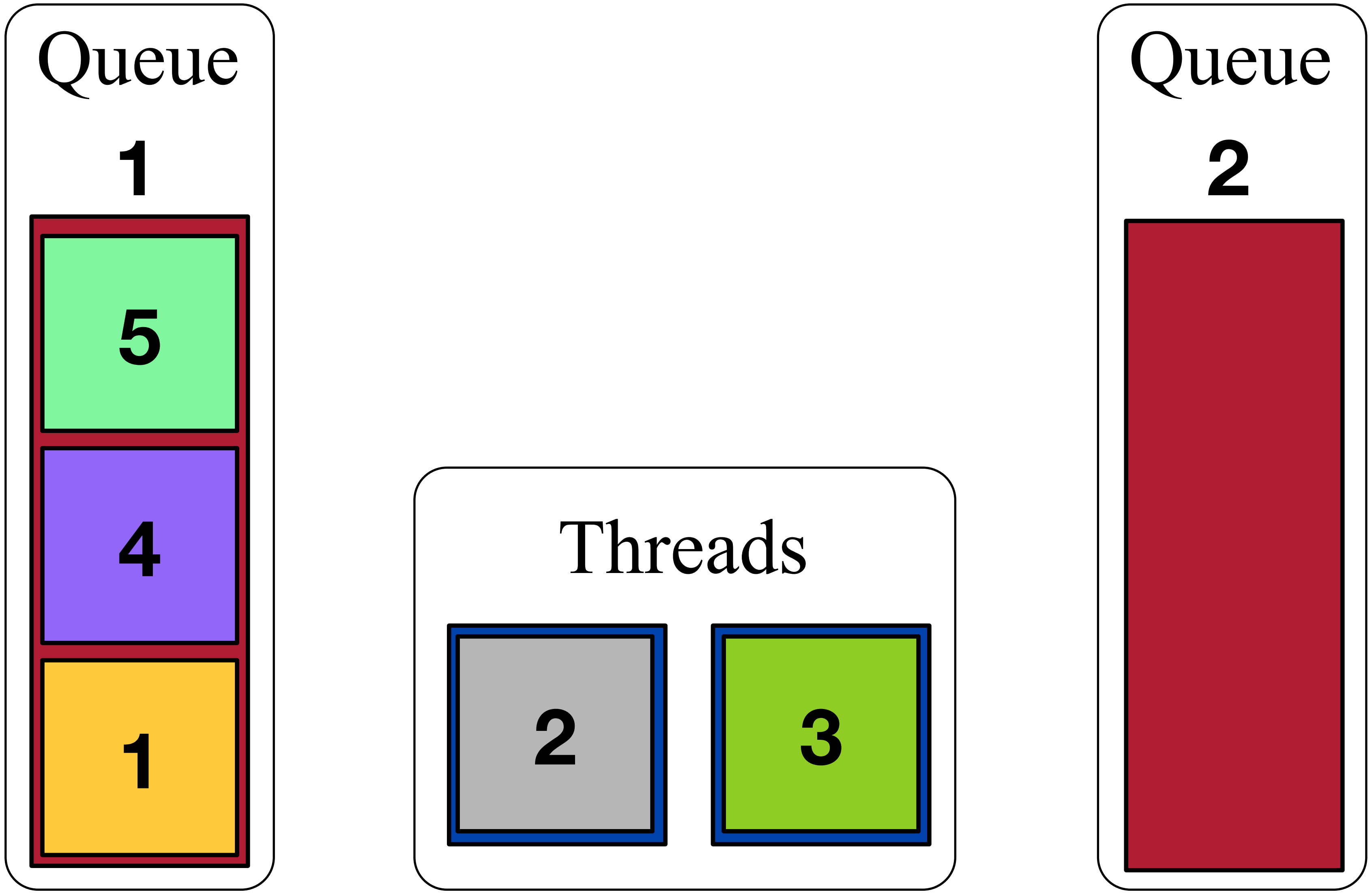

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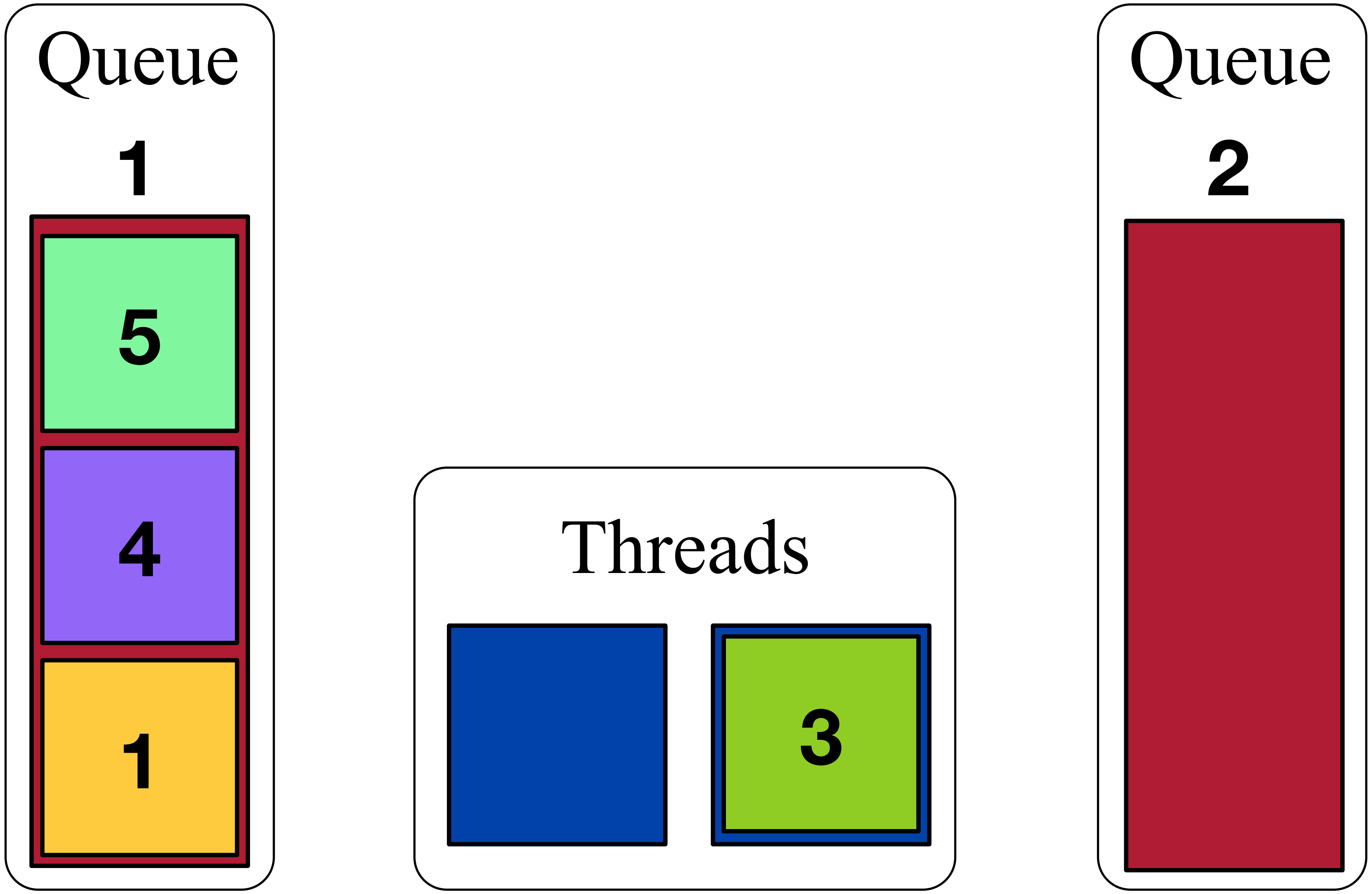

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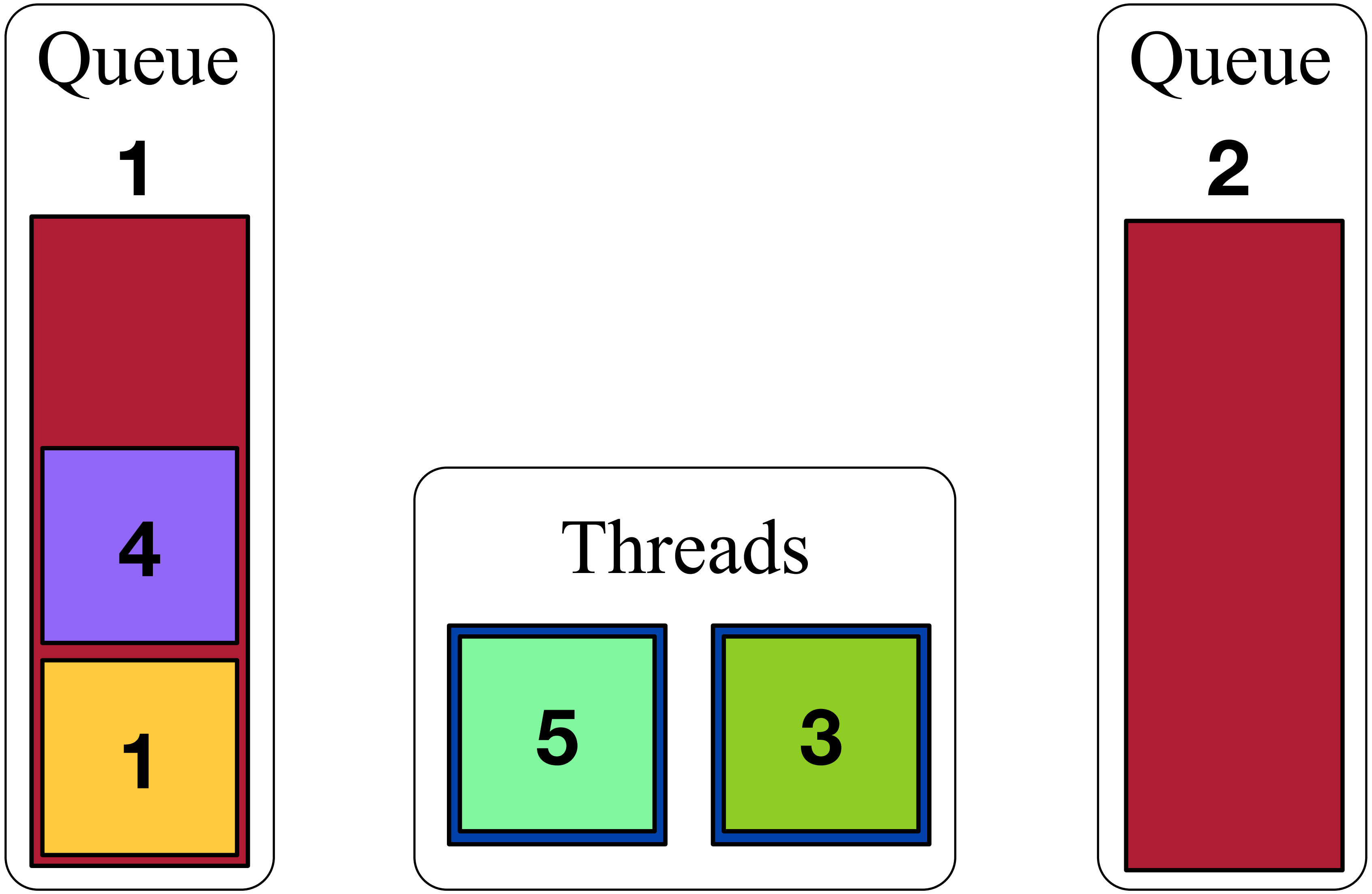

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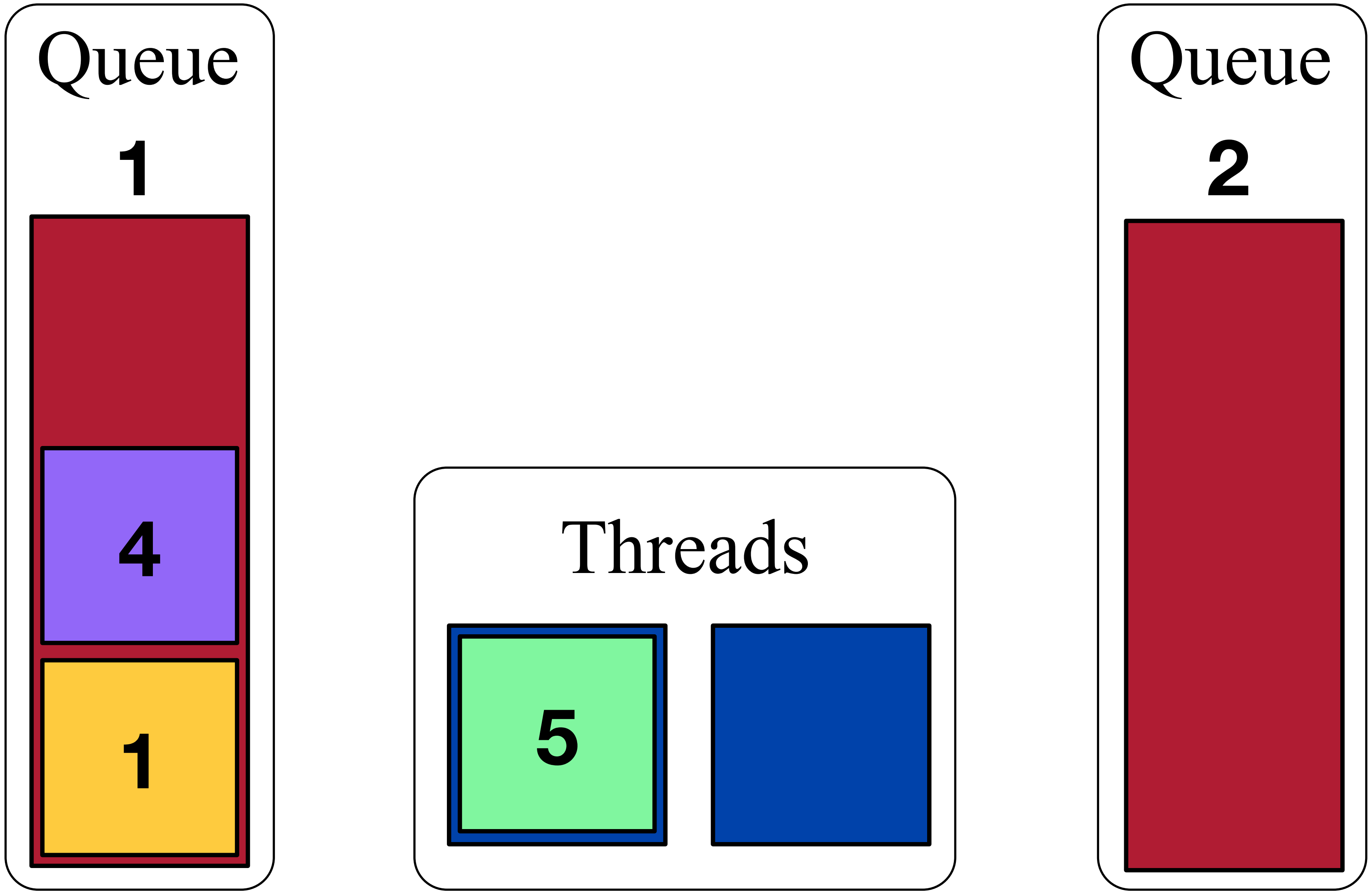
An empty thread queue steals oldest task from another queue



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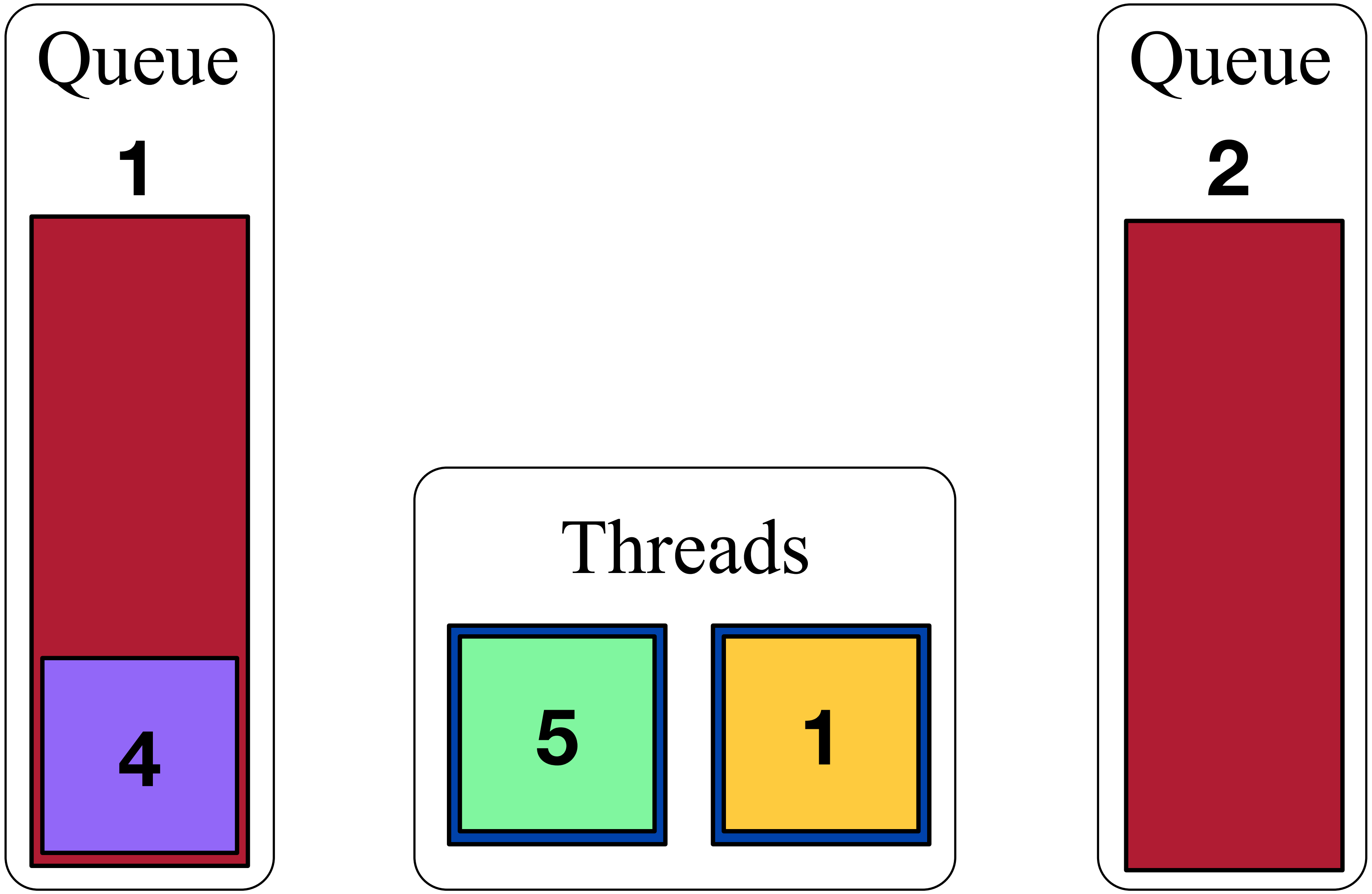
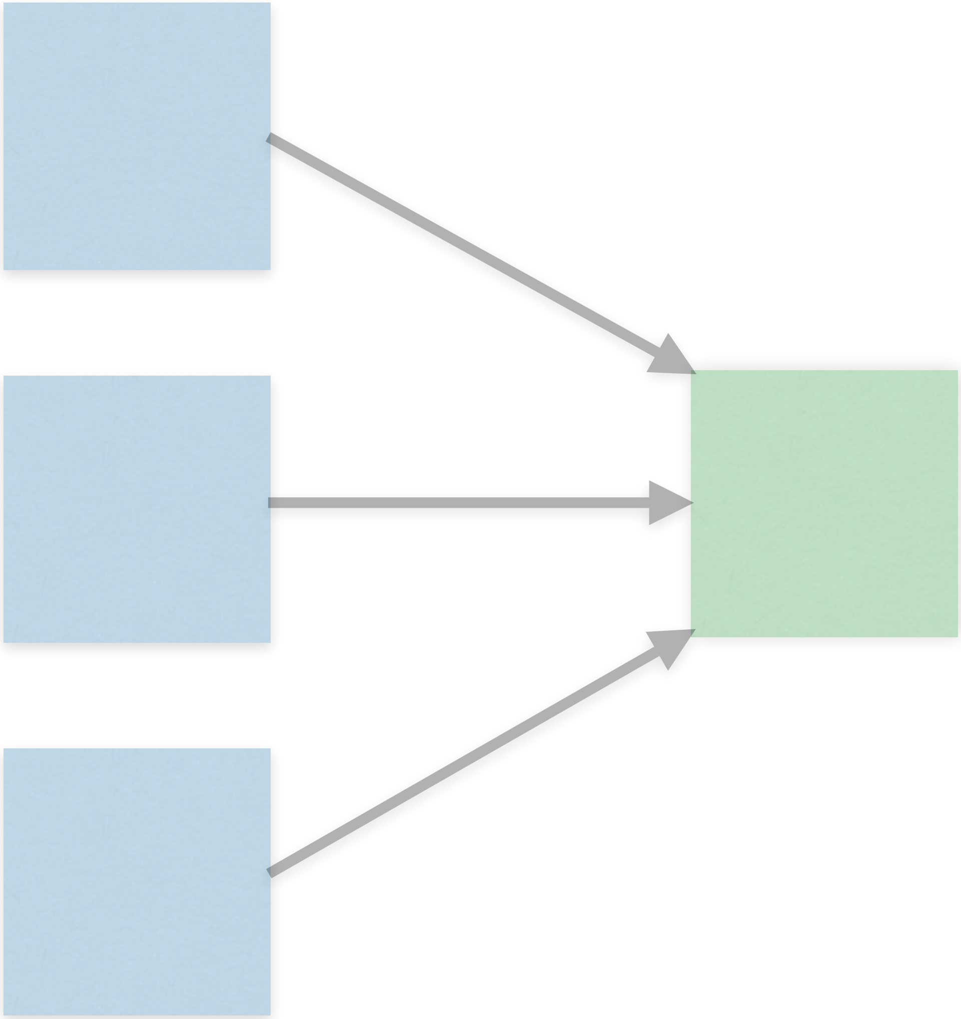


Data Prefetching

Data for modules are prefetched asynchronously

- Done when framework decides a module should be run for that Event
- Provides a large number of tasks for TBB to schedule
- Module starts after all prefetches have finished



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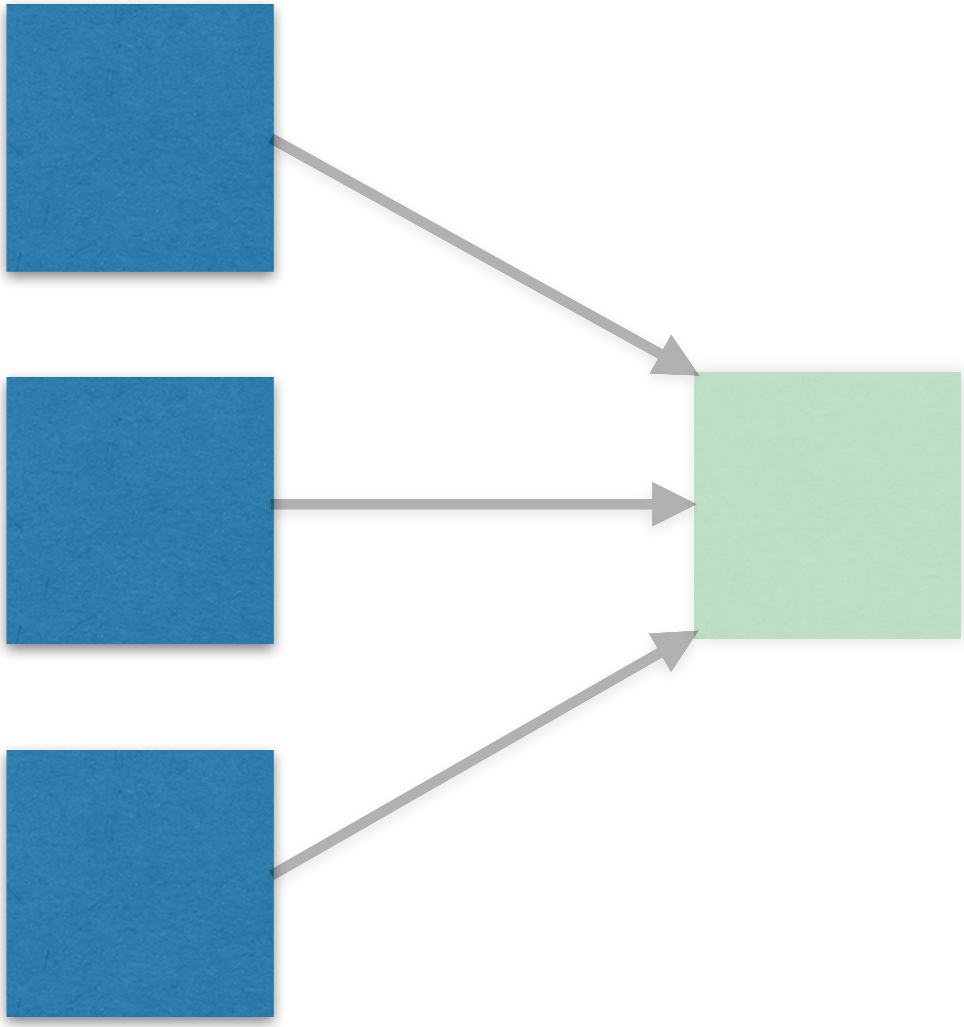

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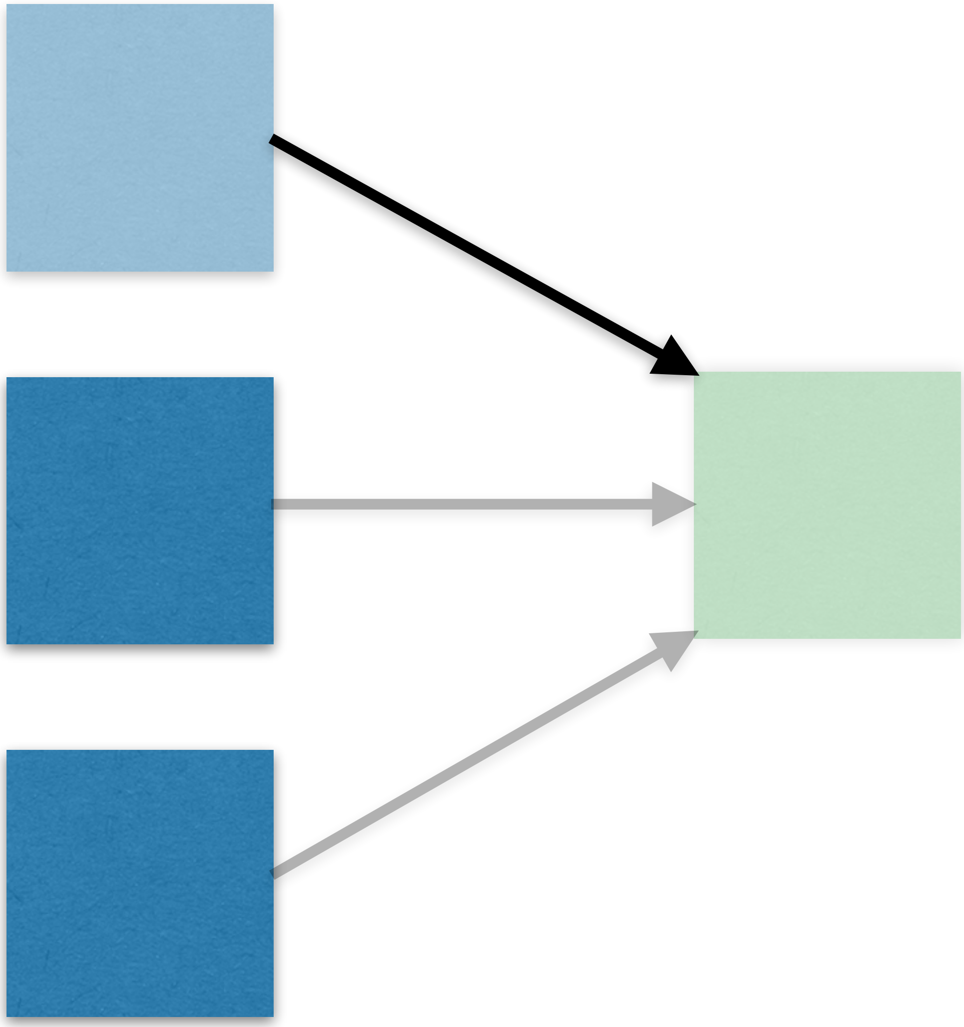

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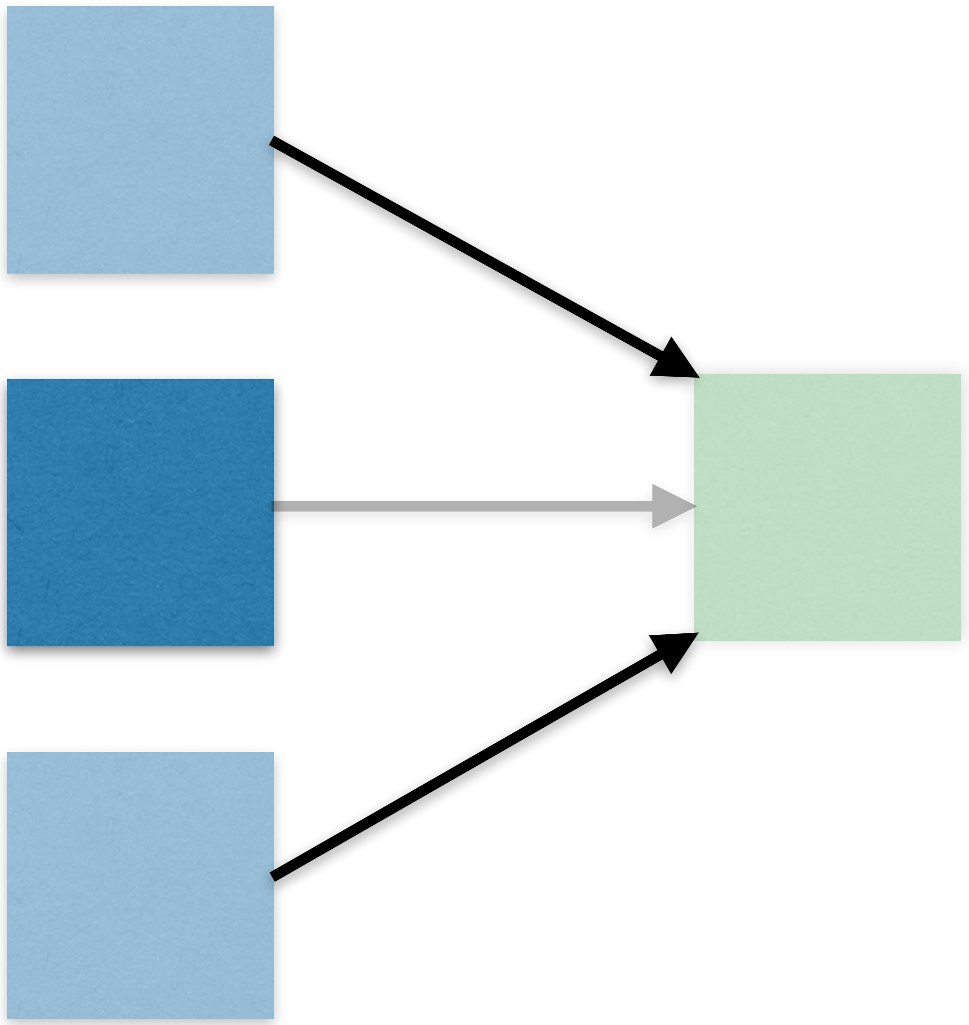

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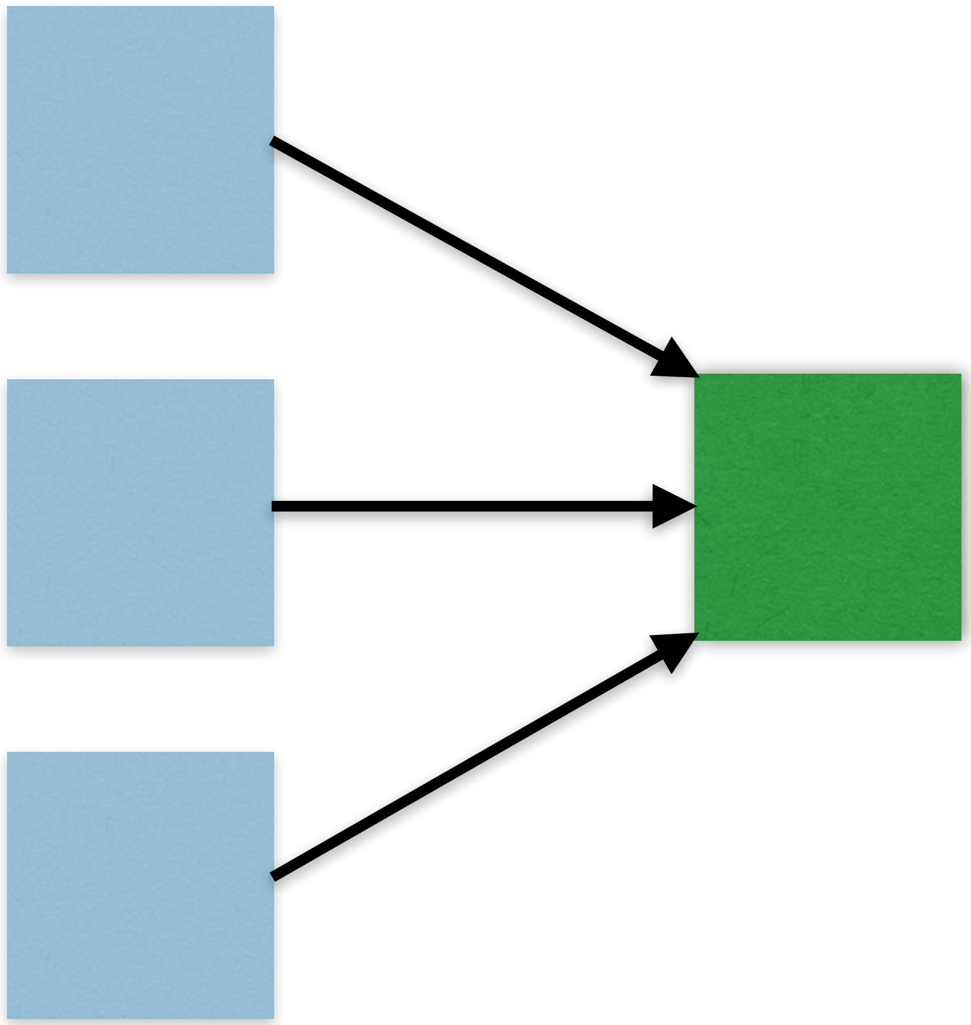


Module Threading Types

Modules are implemented based on threading types

Re-entrant

- Multiple events can simultaneously run the same instance of a module

Replicated

- Each concurrent event has its own copy of a module
- Since number of concurrent events is set at configuration the modules are made early

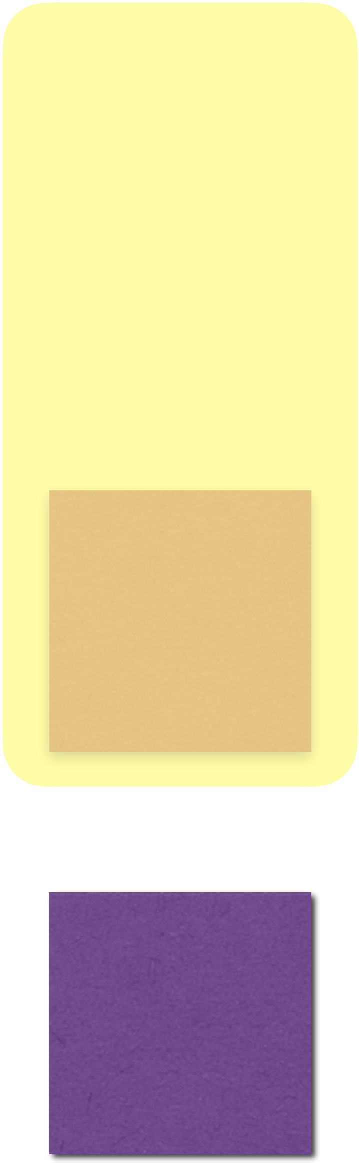
One

- Only one instance of the module
- Only one event at a time can interact with the module
- Cross event scheduling handled by a serial task queue

Serial Task Queue

A serial task queue guards a shared resource

- Modules needing the resource have their *to run* task placed in the appropriate queue
- When a task from the queue finishes, it automatically spawns the next task in the queue



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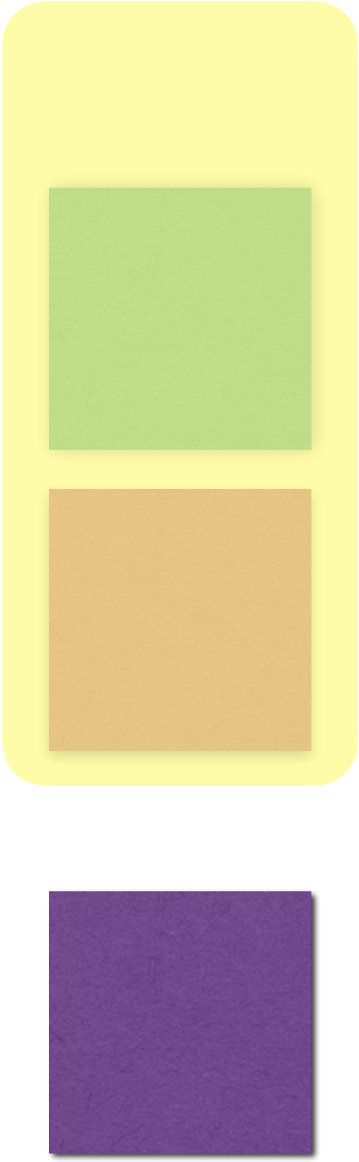

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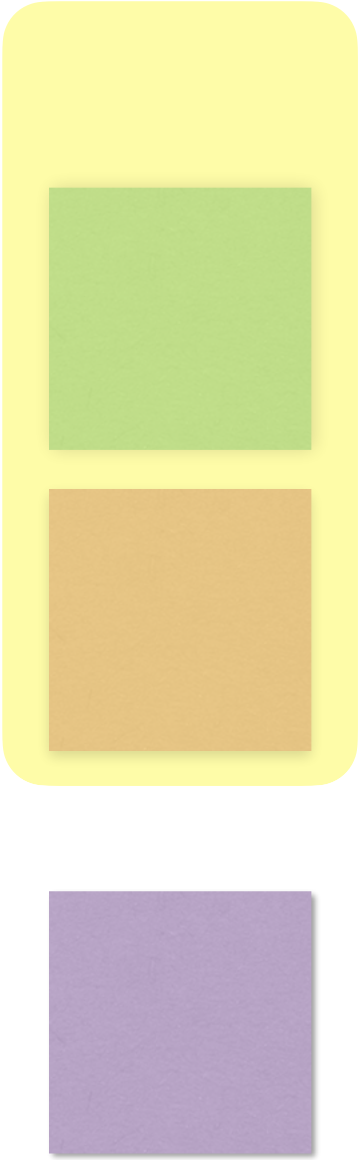

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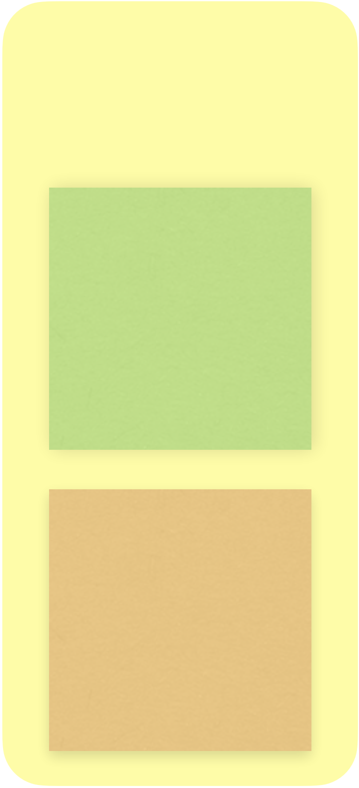

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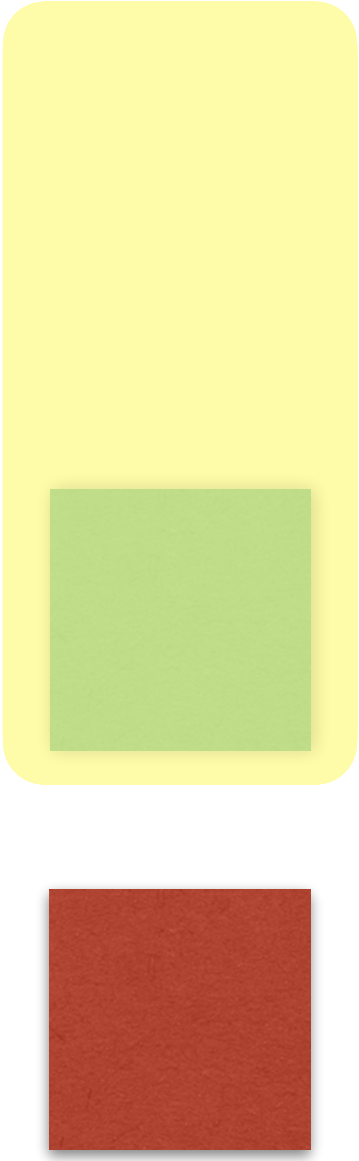


Processing Stalls

If had no shared resources, CMS's threading design scales perfectly

- If have as many threads as concurrent events
- Each thread would always have a tbb task to run for a given thread
- No cross thread communication needed

Sharing resource across concurrently running events can cause stalls

- All reads from a ROOT file must be serialized
- Writing to a ROOT output file must be serialized
  - NOTE: can write to different ROOT output files simultaneously
- *One* modules are shared across events but are not thread-safe

Mitigate stalls by having many more scheduled tasks than threads

- Running Paths/EndPaths concurrently creates many tasks
- Prefetching data products creates many tasks
- Having concurrent events creates many tasks
- Using parallel algorithms within a module can create many tasks

Example of Stall Mitigation

Simple job configuration

- 2 threads
- 2 concurrent events
- 2 *One* OutputModules (**A** and **B**) both on same EndPath

During event processing loop

- Both threads put requests to run **A** and **B** into their respective serial task queues
- The first thread to add a task to a serial task queue will have the task spawned to TBB
- A task for both **A** and **B** will be available to TBB
  - Could be for the same event or for different events depending on exact timing of calls
- Both tasks will be run
  - Either because they were spawned in different threads or one thread stole from the other
- When a tasks finish, it will run the other task waiting in the queue
- At all times both threads are busy

Stall Mitigation Performance Measurement

Machine for testing

- Westmere-EP L5640 CPU with 6 cores x 2 hyper-threads

Compared Reconstruction jobs

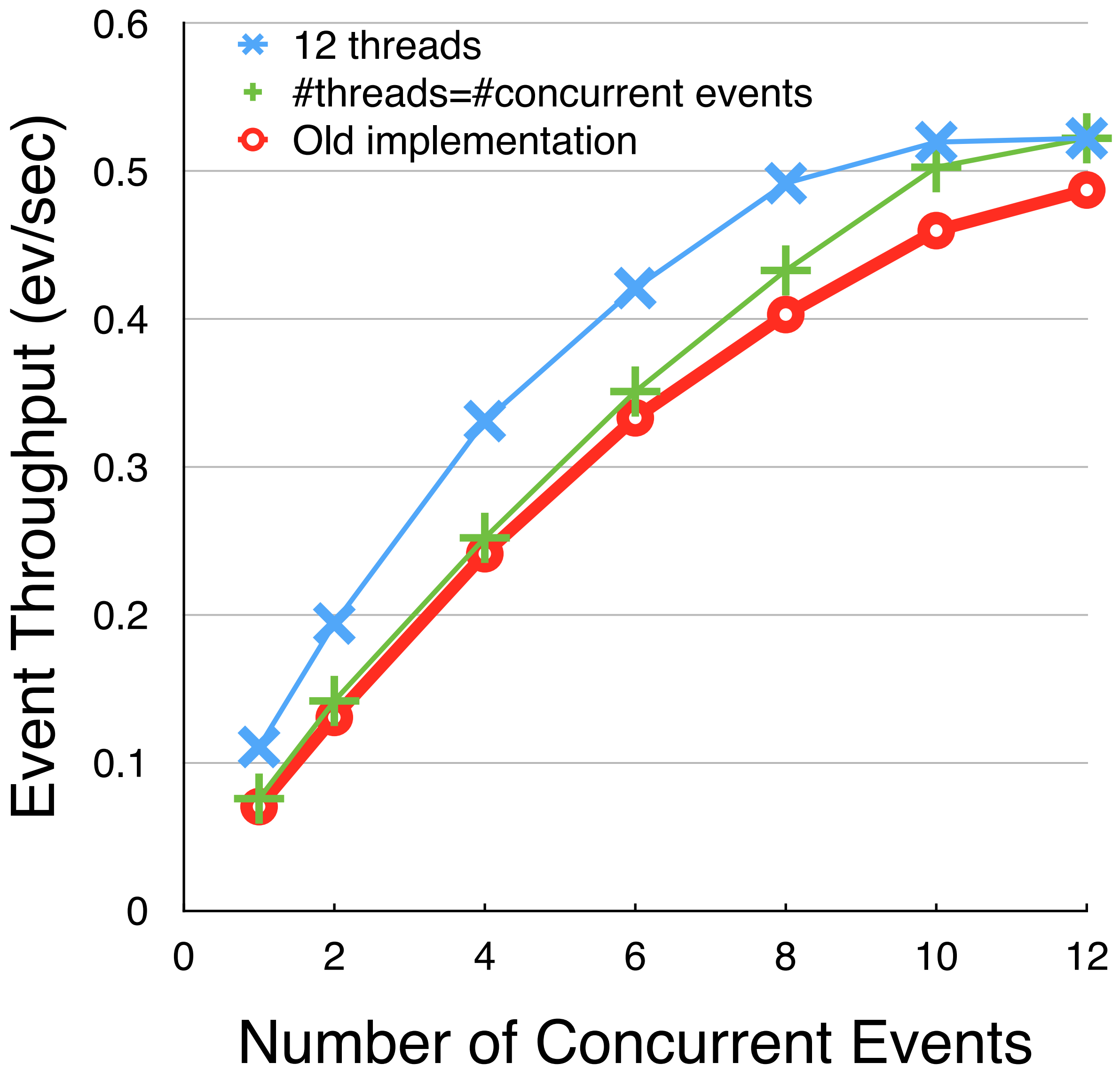
- Old *one-thread-per-event* implementation which runs modules in a fixed order
  - used mutex to guard shared resources
- Full system with number of threads == number of concurrent events
- Full system with number of threads == 12 (machines max)

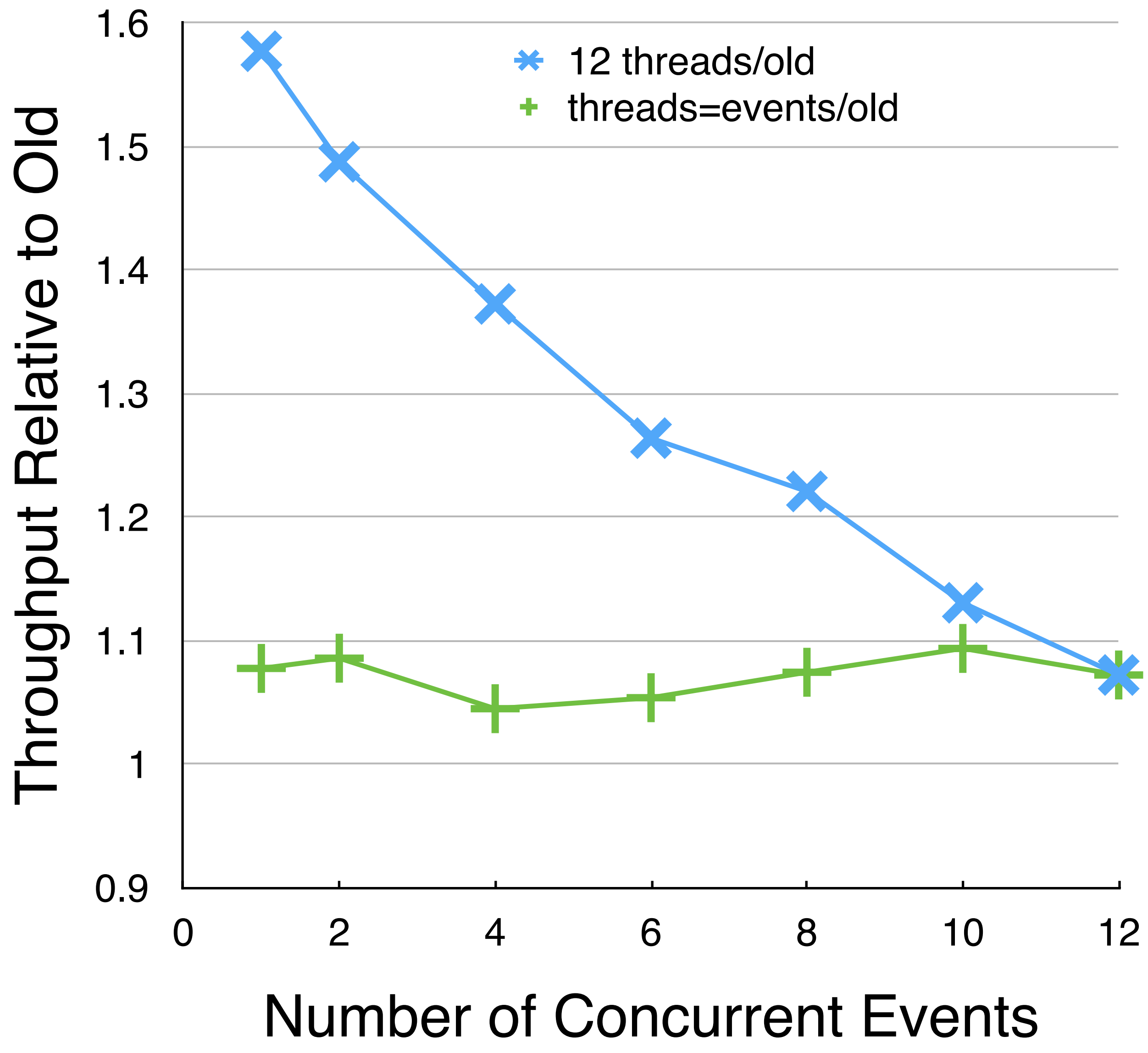
Reconstruction configuration summary

- 3 OutputModules
- 1780 other modules
- 21 Paths

NOTE: this measurement is from 2017 and CMSSW has had further improvements

Throughput Comparisons





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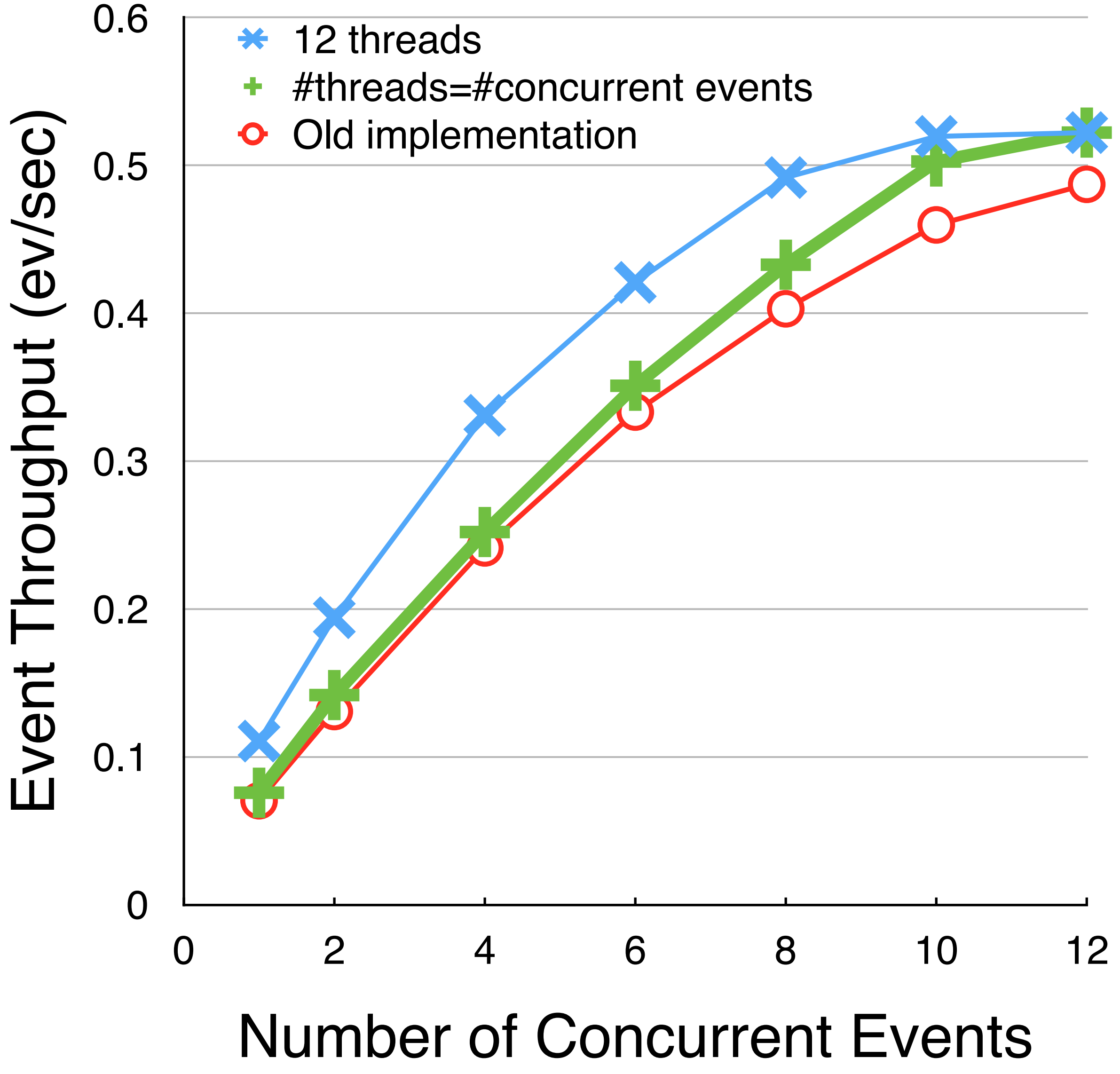

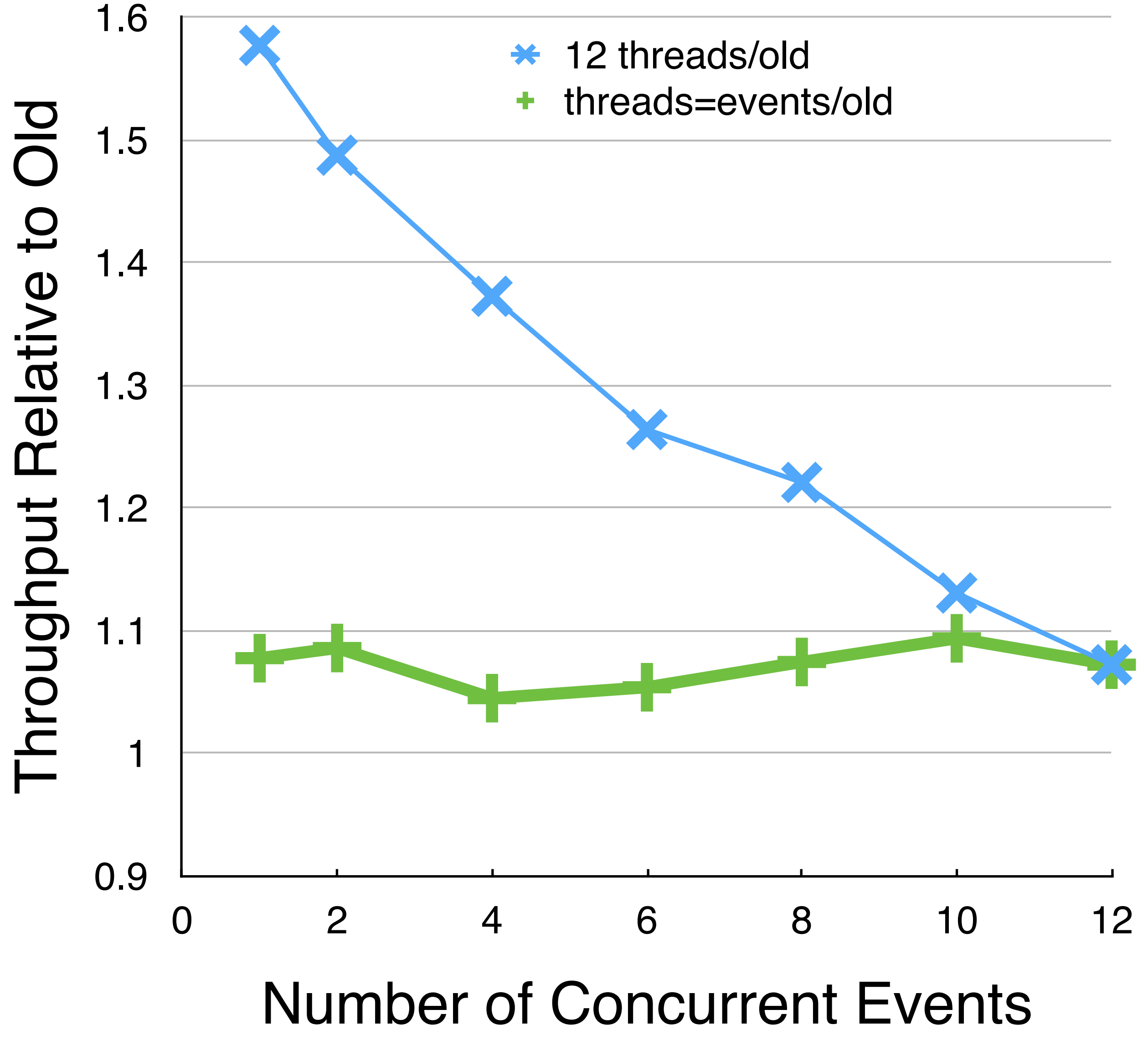

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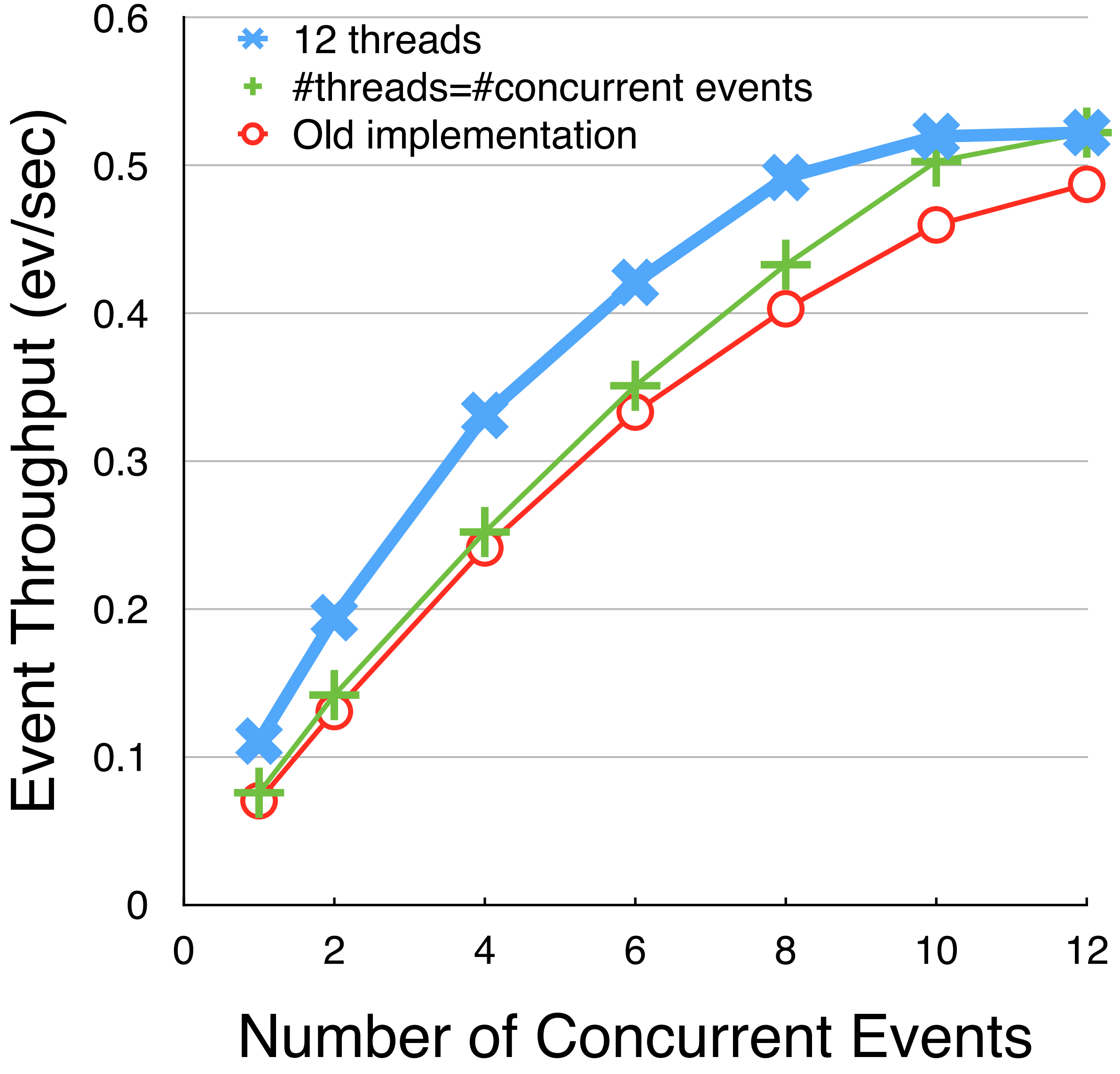
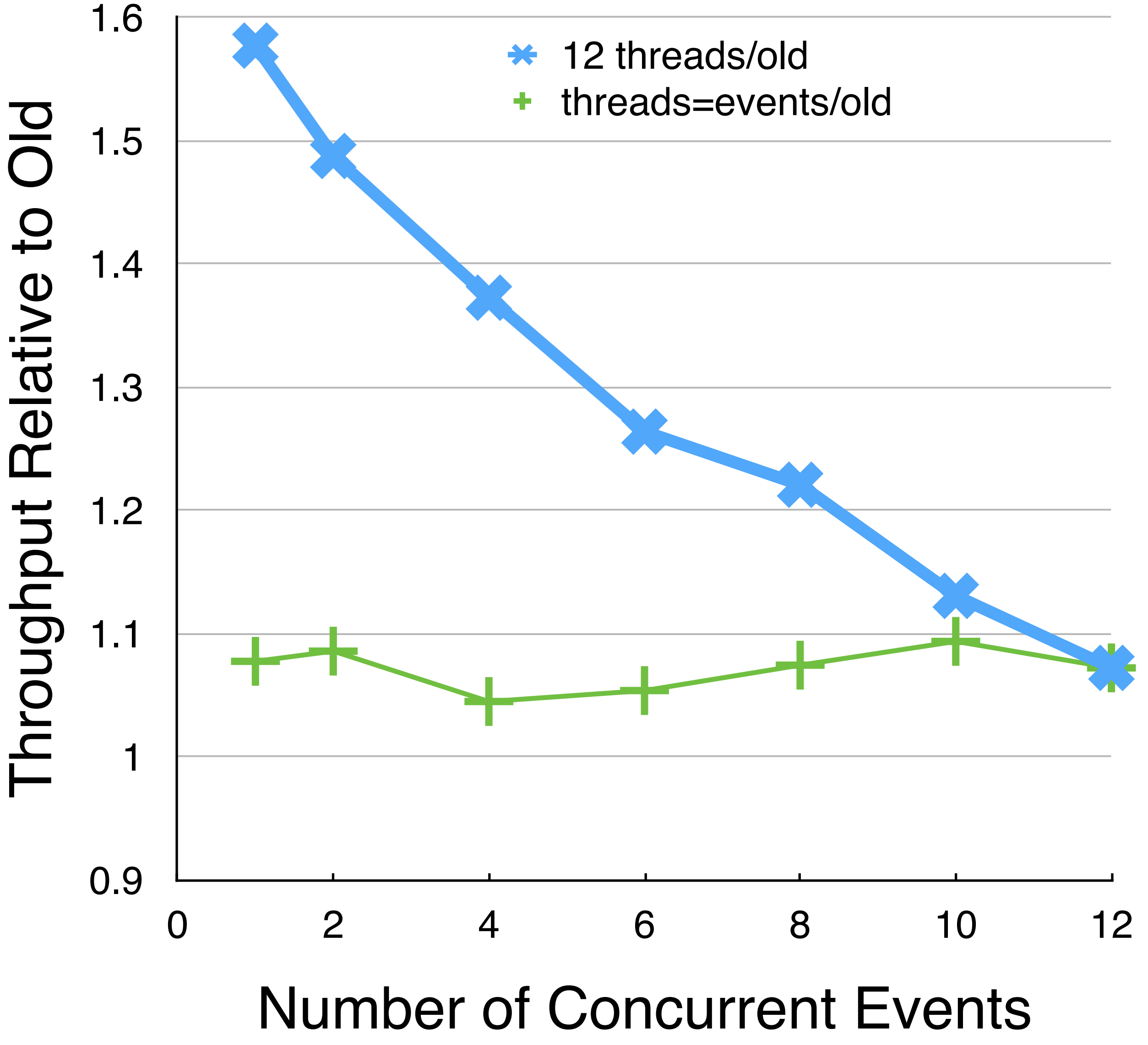




Stall Mitigation Findings

Stalls were solely caused by just one of the OutputModules

- The one which takes longest per event

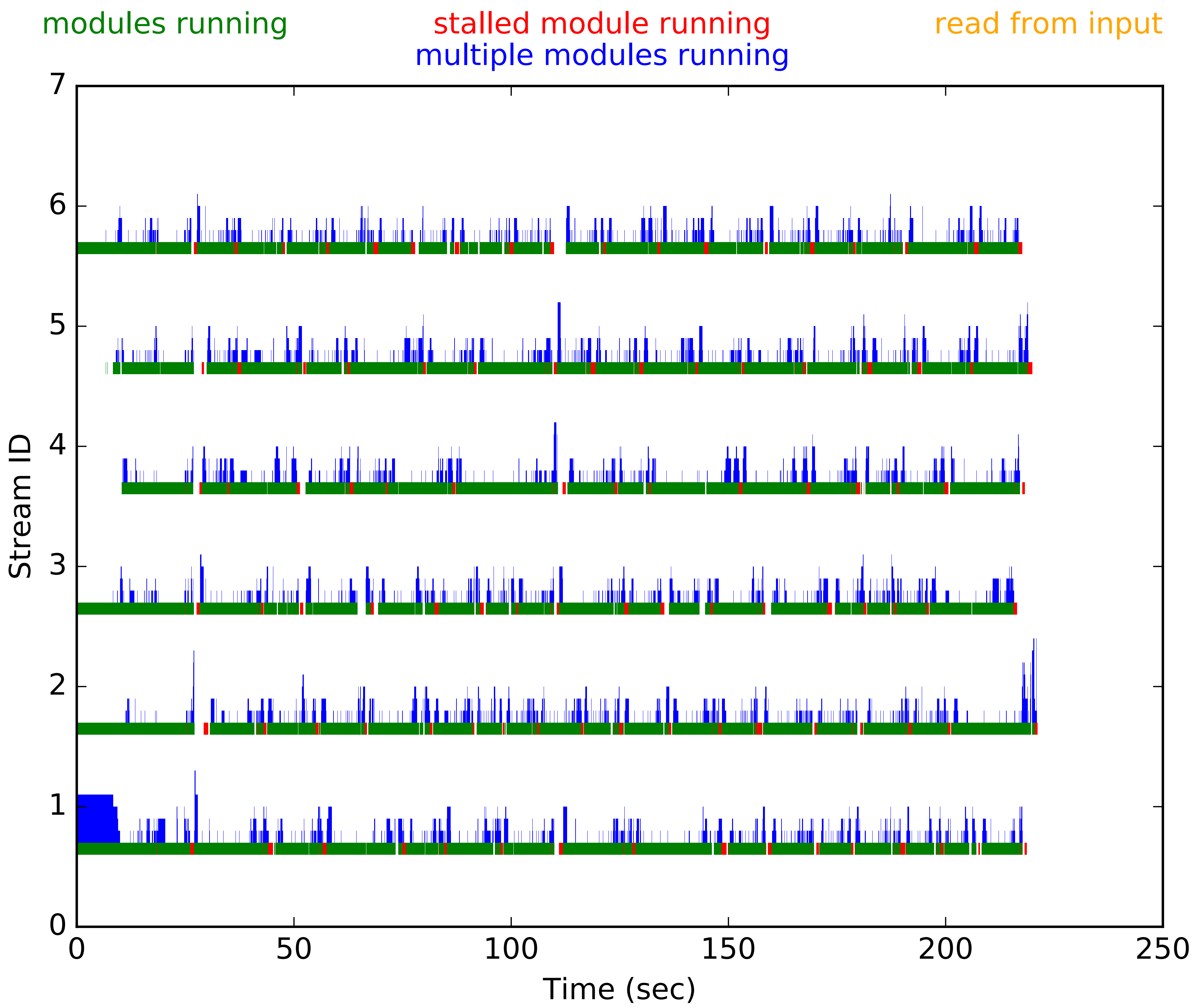
Full system's scheduling allows stall mitigation

- Framework can re-order the run order of the OutputModules
- Many tasks available per thread allows threads to stay busy

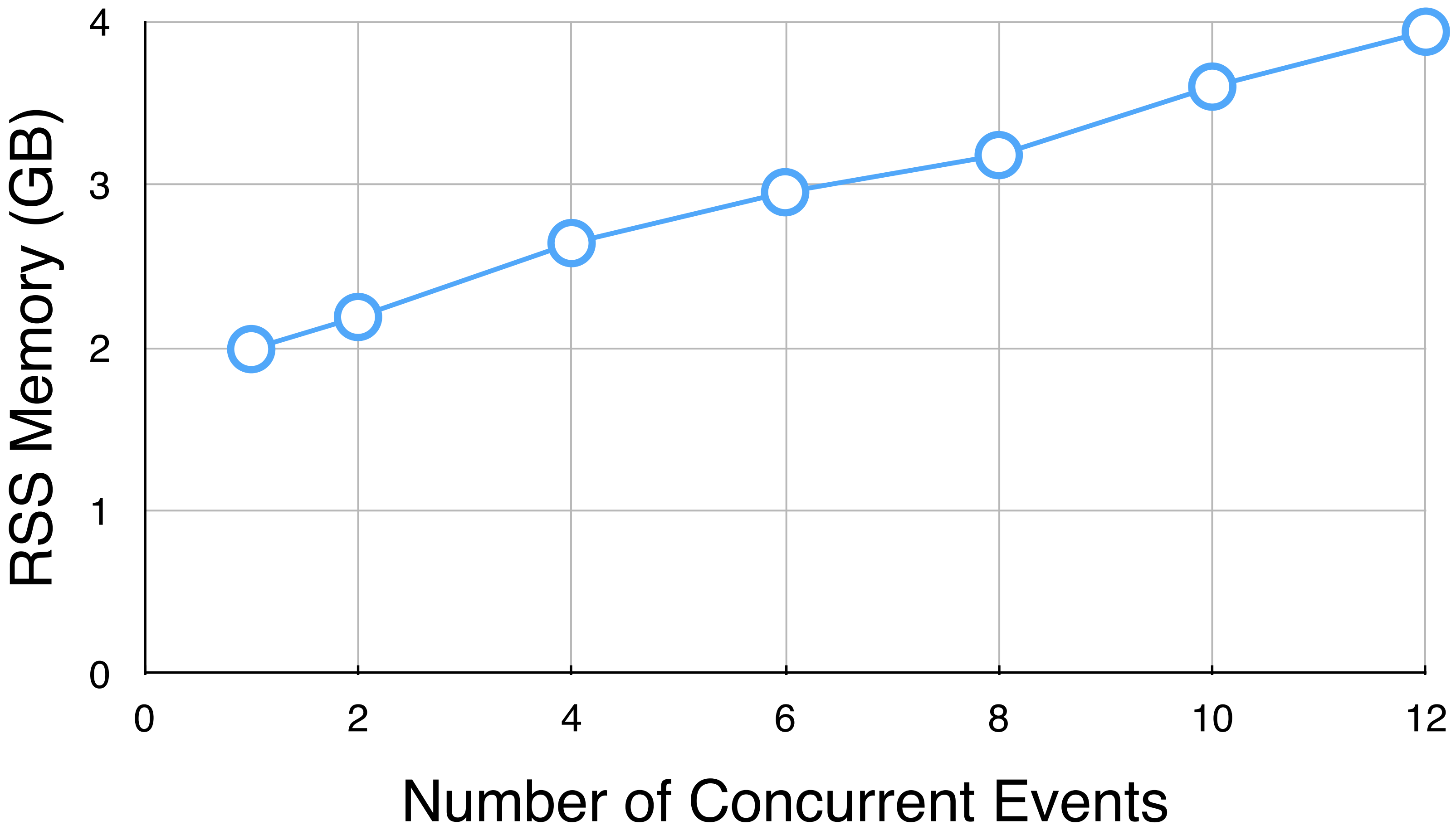
Additional threads increase throughput

- CMS has limited concurrency within an Event
  - about 1.6 threads per event is the maximum concurrency
- limited because of module dependencies and module run time

Reconstruction with 8 threads and 6 Concurrent Events



Memory Utilization



High initial memory

- ~2 GB

Memory grows slowly w.r.t number of concurrent events

- ~150 MB/event

Conclusions

CMS is happy with the threaded framework

- Have used in production since beginning of LHC Run 2 (2015)
- Used for all production workflows
  - online high level trigger farm, event generation, Geant simulation, and reconstruction
- Typically use 8 threads per job
  - Number of concurrent events == number of threads
  - This limit is primarily set by the grid site's batch slot configuration

The scheduling mechanism

- Has very little overhead even when only using very fast running modules
  - Using longer running modules the overhead is negligible
- Scales very well with number of threads
  - Only limited by the number of serial tasks queues in the job
  - The serial task queue around the Source is the ultimate limit at the moment