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Advances in VT's Load Balancing Infrastructure and Algorithms

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What is DARMA?

A toolkit of libraries to support incremental AMT adoption in production scientific applications

Module	Name	Description
DARMA/**vt**	Virtual Transport	MPI-oriented AMT HPC runtime
DARMA/**checkpoint**	Checkpoint	Serialization & checkpointing library
DARMA/**detector**	C++ trait detection	Optional C++14 trait detection library
DARMA/**LBAF**	Load Balancing Analysis Framework	Python framework for simulating LBs and experimenting with load balancing strategies
DARMA/**checkpoint-analyzer**	Serialization Sanitizer	Clang AST frontend pass that generates serialization sanitization at runtime

DARMA Documentation: *https://darma-tasking.github.io/docs/html/index.html*

Load Balancing R&D Lifecycle

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- Application runs with VT runtime with designated *phases* and *subphases*
- VT exports LB statistics files containing object loads, communication, and mapping
- LBAF loads the statistics files, and simulates possible strategies
  - LBAF analyzes the mapping and can produce a new mapping with an experimental LB implemented in Python
  - LBAF exports a new set of mapping files
- The application can be re-run with `StatsMapLB` to follow the LBAF-generated mapping and measure the actual impact
- Process can be iterated, shortening LB development and tuning cycle

Phase Management

- A *phase* is a collective interval of time over all ranks that is typically synchronized
  - In an application, a phase may be a timestep
  - In VT parlance, a phase will often be a “collective epoch” under termination detection
  - Load balancing in VT fundamentally operates over phases
- A phase can be broken down into *subphases*
  - A subphase is typically a substructure within a phase of an application’s work that has further synchronization
  - Creates **vector** representation of workload
- We have explored the idea of further ontological structuring for the purpose enriching LB knowledge, but so far have only implemented phases and subphases

Phase Management

- Building general interface for general phase management
- Many components can naturally do things at phase boundaries
  - LB
    - Running a strategy (or several) and migrating objects accordingly
    - Outputting statistic files
  - Tracing
    - Specifying which phases traces should be enabled for which ranks
    - Specifying phase intervals for flushing traces to disk
  - Memory levels/high-water watermark for runtime/application usage
  - Diagnostics
    - Just finished developing a general diagnostic framework for performance counters/gauges of runtime behavior (e.g., messages sent/node, bytes sent/node, avg/max/min handler duration)
  - Checkpointing of system/application state
  - Termination
    - Recording state of epochs for debugging purposes

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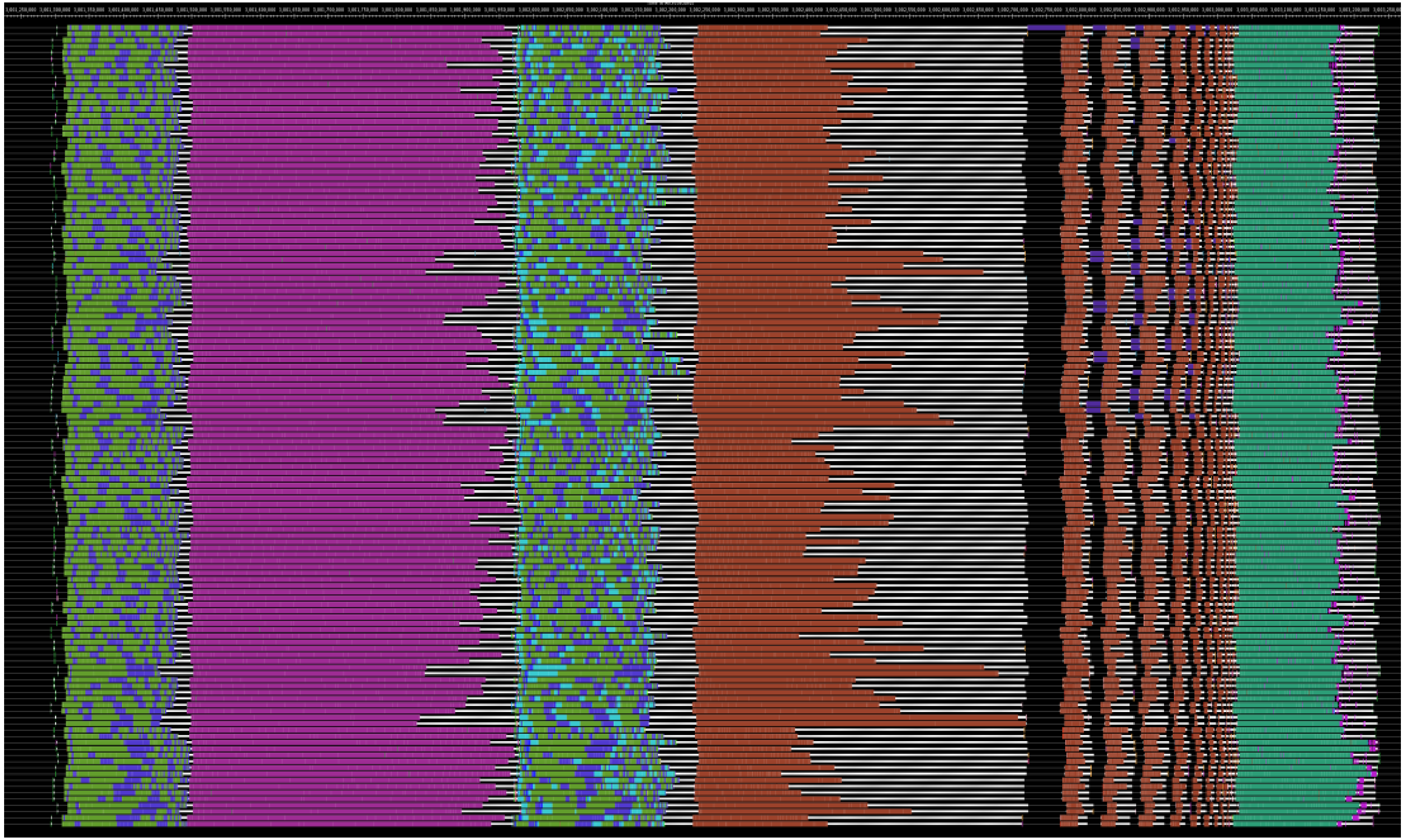
EMPIRE Load Structure – Phases, Subphases, Iterations



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Subphase Vector Loads

$t = \sum_{s} t_s$

Total Time

$t_s = \max_{p} w_{ps}$

Subphase Times

$=$

$\times$

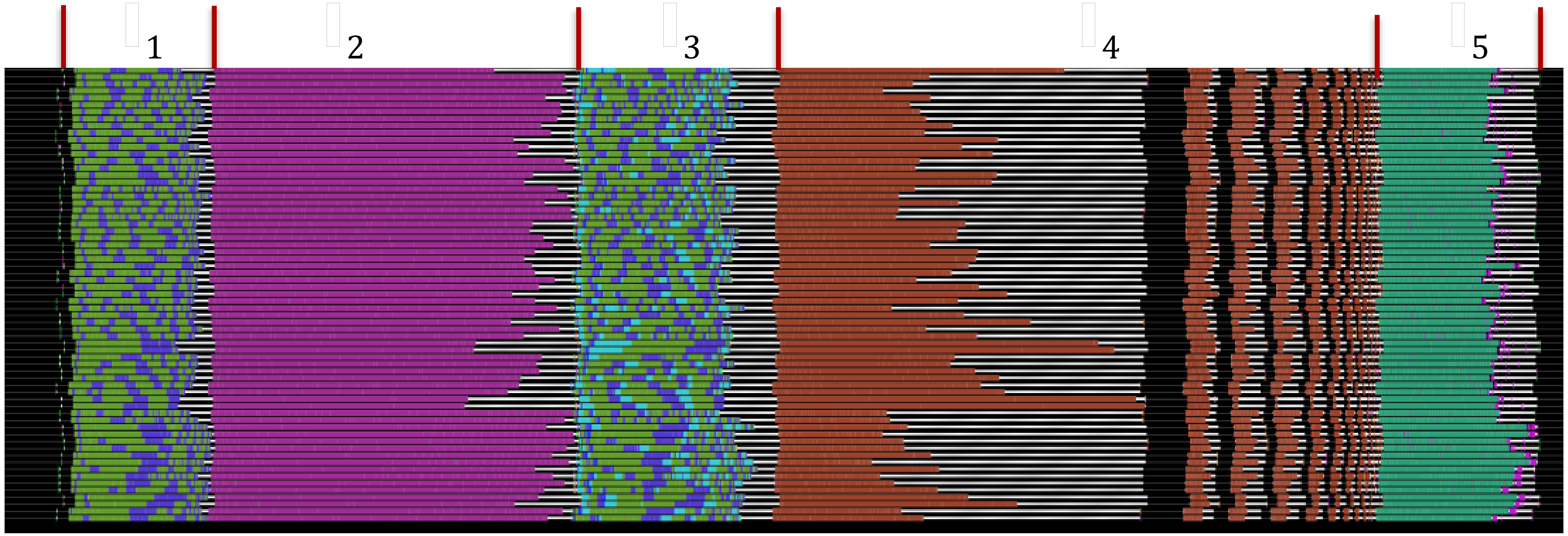
$\boldsymbol{L}\colon \mathbb{R}^{N\times S}$

Object **L**oads

$\boldsymbol{A}\colon \mathbb{B}^{P\times N}$

Object **A**ssignments

$\forall_{n} \left[\sum_{p} a_{pn} = 1 \right]$



Objective Function:

$\min_{A} t$

Subphase Vector Loads

- From 0-1 optimization to smaller Integer Program optimization

$\boldsymbol{A}\colon \mathbb{B}^{P \times N}$ $\qquad = 1 \Leftrightarrow \quad =$ $\qquad \vec{\boldsymbol{M}}\colon \mathbb{N}^{N}$

Object **<u>A</u>**ssignments

Object **<u>M</u>**appings

- Replace $t_s = \max_p w_{ps}$ with $\forall_p \left[t_s \geq w_{ps}\right]$ to (partially) linearize

- Plug this in to standard solvers
  - Possibly MPI-based for live use!

Load Modeling

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- When a selected strategy runs after a phase completes, it has access to data from the application's execution
- *Load models* provide a novel mechanism for manipulating how the load balancer observes instrumented data from phases and subphases, past and future
  - The most basic, naïve model would read raw instrumented data and assume it persists to the next phase/subphase to perform task assignment calculations for the subsequent phase
  - Explicit embodiment of “principle of persistence”
  - Offers configuration, alternatives
  - Composable functions, easy extension
- Can also map vector of per-subphase data to scalars for current strategies

Load Modeling

```
struct PhaseOffset {
  int phases;
  static constexpr unsigned int NEXT_PHASE = 0;
  unsigned int subphase;
  static constexpr unsigned int WHOLE_PHASE = ~0u;
};

class LoadModel {
  virtual TimeType getWork(
    ElementIDType object,
    PhaseOffset when
  ) = 0;
  // ...
};
```

Default:

NaivePersistence . Norm(1) . RawData

Load Model	Description	Reference
Utilities		
LoadModel	Pure virtual interface class, which the following implement	`vt::vrt::collection::balance::LoadModel`
ComposedModel	A convenience class for most implementations to inherit from, that passes unmodified calls through to an underlying model instance	`vt::vrt::collection::balance::ComposedModel`
RawData	Returns historical data only, from the measured times	`vt::vrt::collection::balance::RawData`
Transformers	Transforms the values computed by the composed model(s), agnostic to whether a query refers to a past or future phase	
Norm	When asked for a `WHOLE_PHASE` value, computes a specified l-norm over all subphases	`vt::vrt::collection::balance::Norm`
SelectSubphases	Filters and remaps the subphases with data present in the underlying model	`vt::vrt::collection::balance::SelectSubphases`
CommOverhead	Adds a specified amount of imputed 'system overhead' time to each object's work based on the number of messages received	`vt::vrt::collection::balance::CommOverhead`
PerCollection	Maintains a set of load models associated with different collection instances, and passes queries for an object through to the model corresponding to its collection	`vt::vrt::collection::balance::PerCollection`
Predictors	Computes values for future phase queries, and passes through past phase queries	
NaivePersistence	Passes through historical queries, and maps all future queries to the most recent past phase	`vt::vrt::collection::balance::NaivePersistence`
PersistenceMedianLastN	Similar to NaivePersistence, except that it predicts based on a median over the N most recent phases	`vt::vrt::collection::balance::PersistenceMedianLastN`
LinearModel	Computes a linear regression over on object's loads from a number of recent phases	`vt::vrt::collection::balance::LinearModel`
MultiplePhases	Computes values for future phases based on sums of the underlying model's predictions for N corresponding future phases	`vt::vrt::collection::balance::MultiplePhases`

Load Balancing Strategies

Load Balancer	Type	Description	Reference
RotateLB	Testing	Rotate objects in a ring	`vt::vrt::collection::lb::RotateLB`
RandomLB	Testing	Randomly migrate object with seed	`vt::vrt::collection::lb::RandomLB`
GreedyLB	Centralized	Gather to central node apply min/max heap	`vt::vrt::collection::lb::GreedyLB`
GossipLB	Distributed	Gossip-based protocol for fully distributed LB	`vt::vrt::collection::lb::GossipLB`
HierarchicalLB	Hierarchical	Build tree to move objects nodes	`vt::vrt::collection::lb::HierarchicalLB`
ZoltanLB	Hyper-graph Partitioner	Run Zoltan in hyper-graph mode to LB	`vt::vrt::collection::lb::ZoltanLB`
StatsMapLB	User-specified	Read file to determine mapping	`vt::vrt::collection::lb::StatsMapLB`

Conclusions and Future Work

- Increase expressiveness of load data
- Shorten LB development and tuning cycles
- Improve abstractions in real implementations
- Formalize time-vector balancing challenge
  - Can actually try out dedicated solvers and general heuristics