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DHARMA: Distributed asyncHronous Adaptive Resilient Management of Applications

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Programming Models and Applications Workshop
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Mission

- Assess & address fundamental challenges imposed by the need for performant, portable, scalable, fault-tolerant programming models at extreme-scale
- Two focus areas
  - Programming model analysis for next generation platforms
  - Demonstration of fault-tolerant programming model at extreme-scale

DHARMA is a fundamental Hindu concept referring to

- the order and custom which make life and a universe possible
- the behaviors appropriate to the maintenance of that order

The classical Sanskrit noun DHARMA derives from dhr

- meaning to hold, maintain, keep

Programming model analysis for next generation platforms

- Asynchronous many-task programming models are a leading new paradigm with many variants
- Goal: Address knowledge gaps
  - Comparative analysis of leading candidate solutions
  - Quantitative & qualitative tests using ASC-relevant codes
- Outcome: Guidance to code development road map for next generation platforms for ASC/ Integrated Codes

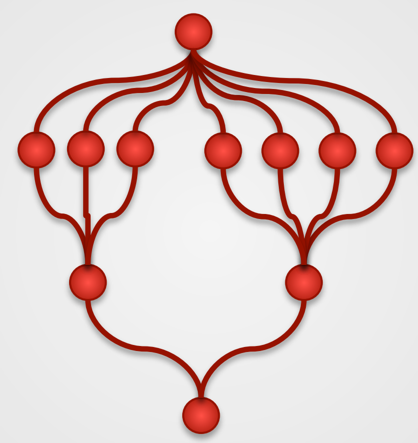
Runtimes
Uintah
Legion
HPX
Charm++
STAPL
StarPU
Swift/T

Assess
Scalability
Performance
Resilience
Interoperability with MPI

Demonstration of fault-tolerant programming model at extreme-scale

- Asynchronous many-task programming models
  - + Show promise at sustaining performance
  - + Work stealing enables load balancing
  - + Failed tasks can be re-executed
- Recovery (beyond checkpoint/restart) is challenging
  - – Distributed coherency problem
  - – Care is required to identify lost tasks due to work-stealing and asynchrony

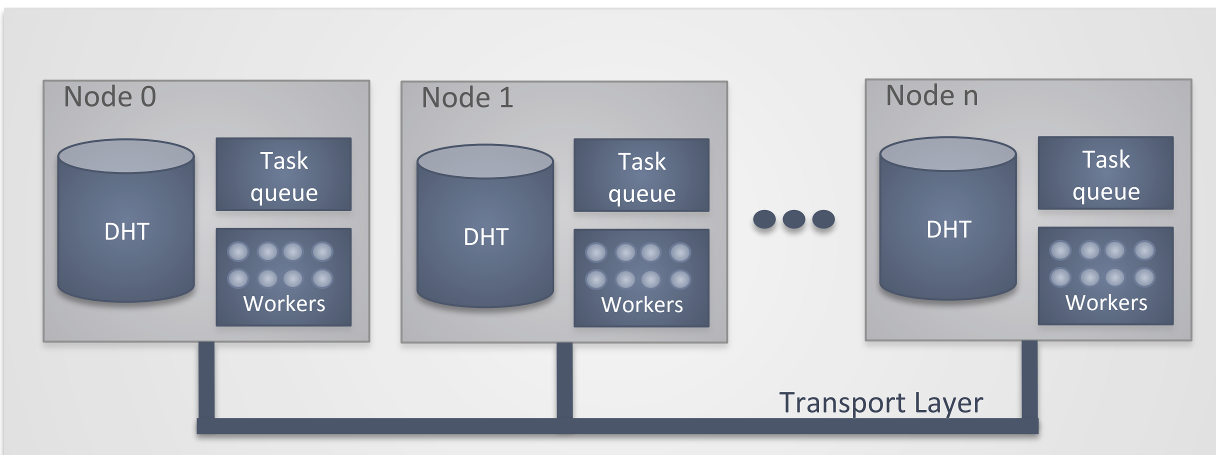
Task Graph



Nodes are tasks
Edges are data

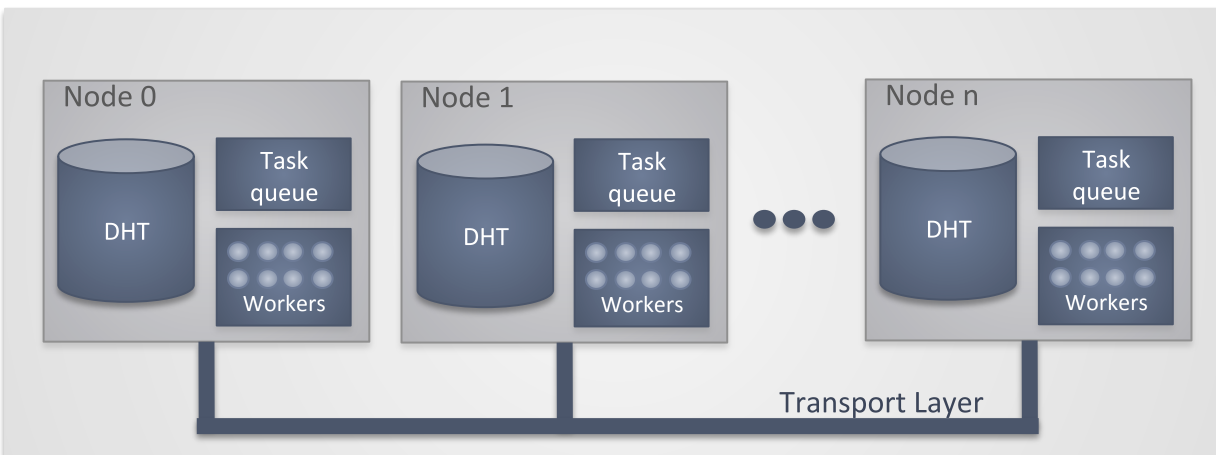
A holistic solution requires a number of fault-tolerant components

- Distributed Hash Table (DHT): Store task descriptors/data pointers
- Collection/task queue: Maintain state & work assignments
- Resilient Transport Layer
  - Fault-aware collectives: terminate cleanly with no result
  - Fault-tolerant collectives: heartbeat via overlay network to rigorously agree on which nodes are alive

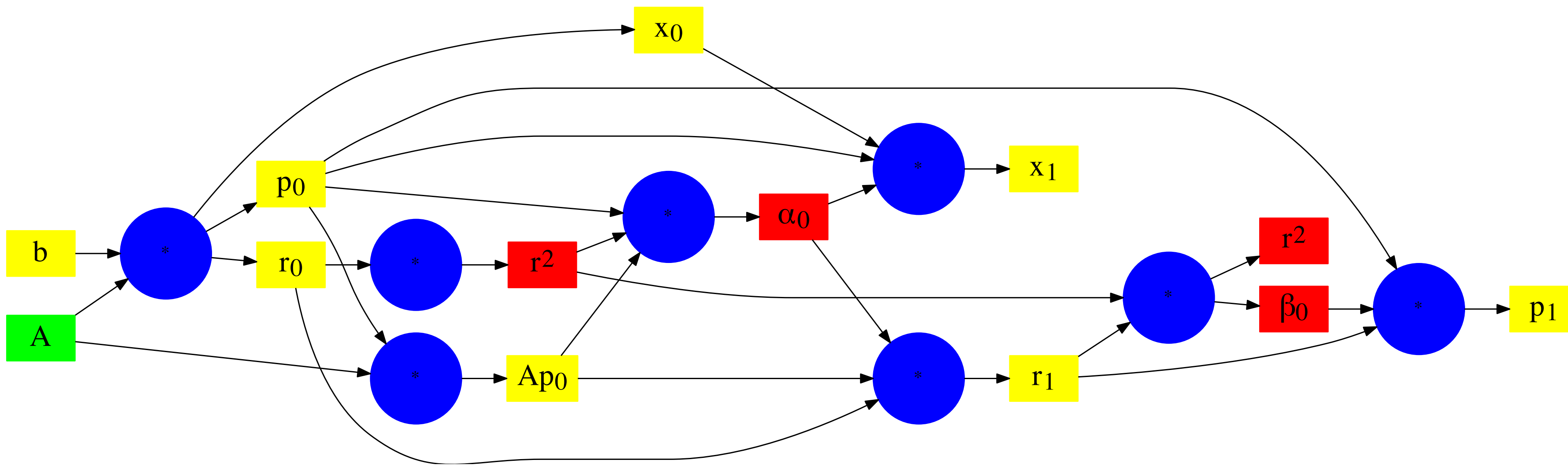


Related work

- Distributed Hash Table (DHT): Linda, Intel CnC, FOX, MATRIX
- Collection/task queue: Scioto, DAGuE, Legion, Uintah, Charm++
- Transport Layer: MPI-ULFM, FT-MPI, Hursey et. al “A log-scaling fault tolerant agreement algorithm for a fault tolerant MPI”



An example of a dense Conjugate Gradient (CG) task-graph



- Coarse-grained DAG + data parallelism
- Squares denote data (matrix/vector/scalar).
- Circles denote compute kernels.
- Data parallelism (matrix/vector) => large task parallelism.
- Each node (circle) in the coarse-grained DAG becomes a task collection.

Code example: Setting up runtime

```
void dharma_runtime::init()
{
 msg_api_    = new message_api(…);
 task_dht_   = new dht(…);
 mdata_dht_  = new metadata_dht(…);
 data_dht_   = new data_dht(…);
 backup_     = new nvram_backup(…);

 int max_steals  = 5;
 int eager_tasks = 100;
 queue_   = new task_queue(…, max_steals, eager_tasks);

 msg_api_->init();
}
```

Code example: Creating tasks

```
dharma_runtime* rt = new dharma_runtime;
rt->init(); //initialize the runtime
task_collection::ptr coll = new collection(rt,…, new generator(…));
rt->register_collection(coll);
.................................................
.................................................
void generator::generate_tasks()
{
 for (int i=0; i < overdecompose_; ++i){
    task::ptr t = new task(…);
    t->dependencies.push_back(new dependency(…)); //declare task deps
    append_task(t);  //adds the task to the collection
  }
}
```

Code example: Unrolling DAG

```
main
{
 dharma_runtime* rt = new dharma_runtime;
 rt->init(); //initialize the runtime
 cg_unroller starter(0,…); //start iteration 0
 starter.unroll(rt);
  ………………………………………………………………
}

void cg_unroller::unroll(dharma_runtime *rt)
{
  task_collection::ptr coll_Alpha_dp = new allreduce_collection(rt,…);
  task_collection::ptr coll_Alpha = new collection(rt,…);
  ………………………………………………………………
```

repeat

$$\alpha_k := \frac{\mathbf{r}_k^{\mathrm{T}}\mathbf{r}_k}{\mathbf{p}_k^{\mathrm{T}}\mathbf{A}\mathbf{p}_k}$$

$$\mathbf{x}_{k+1} := \mathbf{x}_k + \alpha_k \mathbf{p}_k$$

$$\mathbf{r}_{k+1} := \mathbf{r}_k - \alpha_k \mathbf{A}\mathbf{p}_k$$

if r_{k+1} is sufficiently small then exit loop

$$\beta_k := \frac{\mathbf{r}_{k+1}^{\mathrm{T}}\mathbf{r}_{k+1}}{\mathbf{r}_k^{\mathrm{T}}\mathbf{r}_k}$$

$$\mathbf{p}_{k+1} := \mathbf{r}_{k+1} + \beta_k \mathbf{p}_k$$

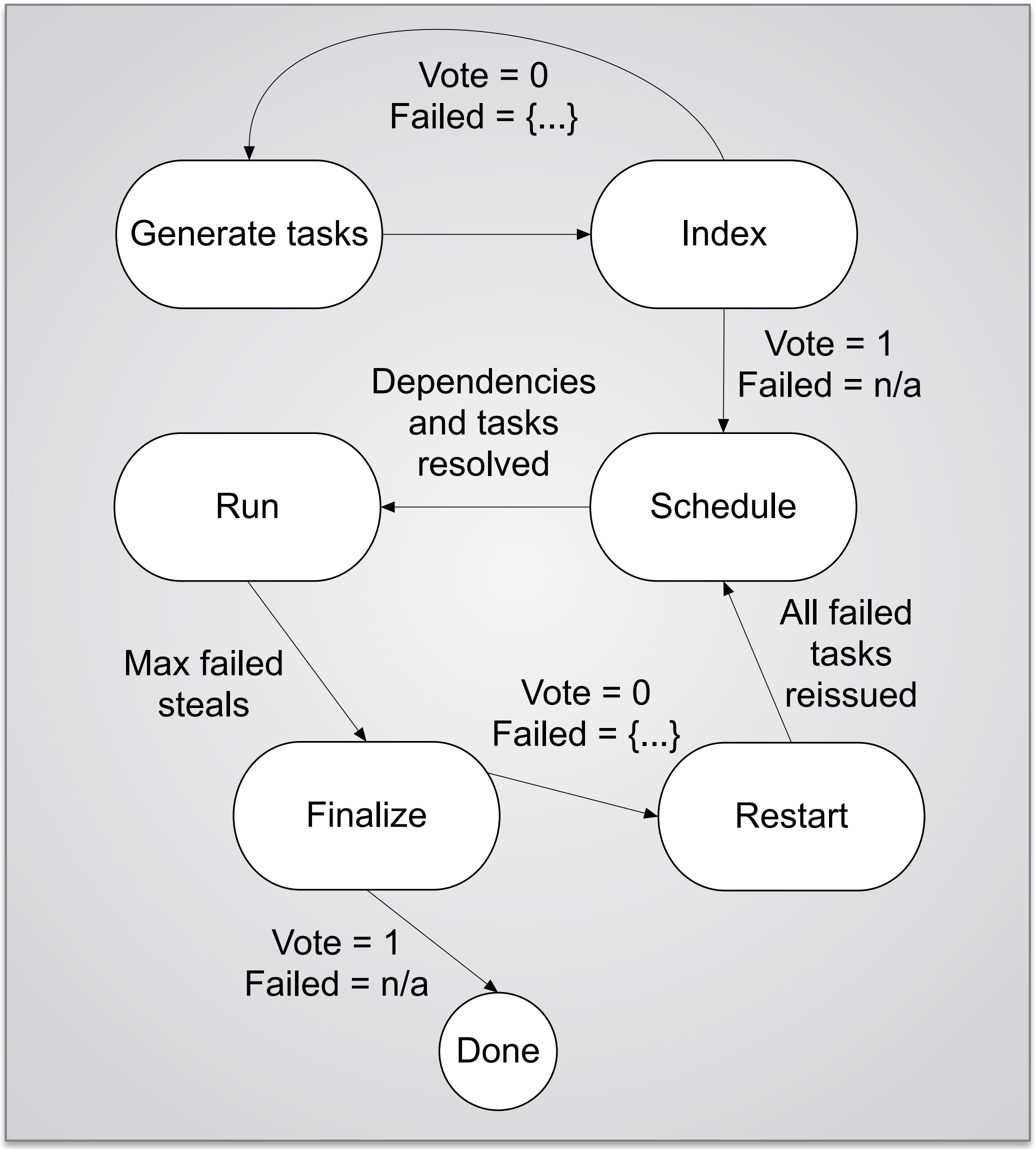
$$k := k + 1$$

end repeat

Code example: Unrolling DAG (contd…)

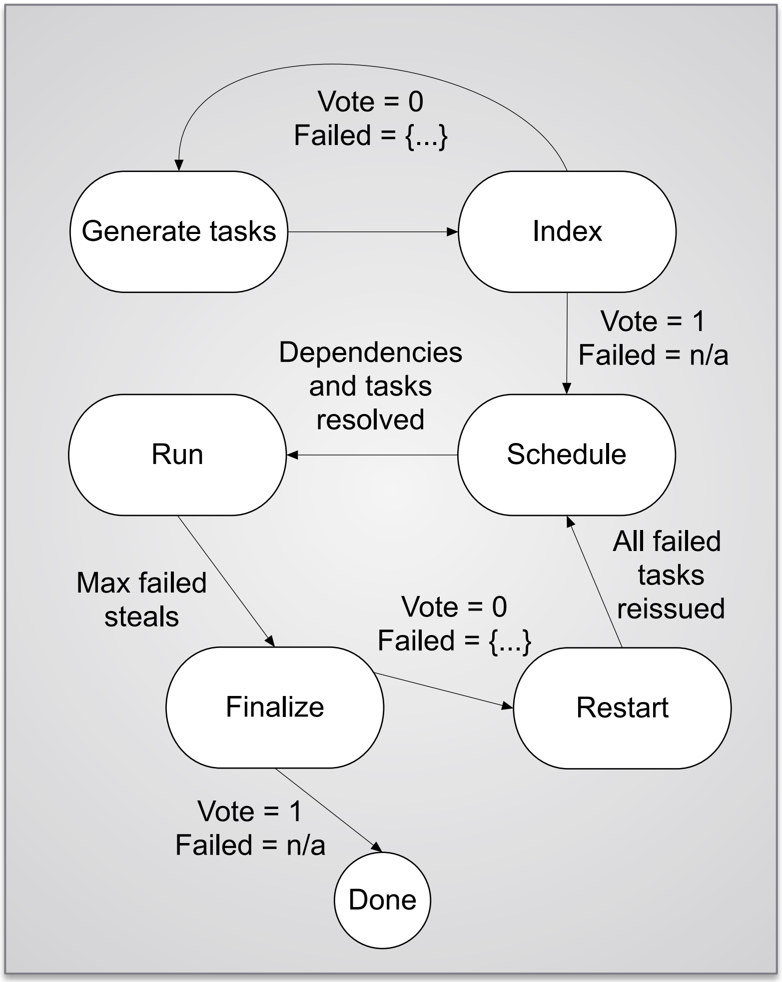
```
  ……………………………………………
  task_collection::ptr coll_p = new collection(rt,…);

  if (!end){
    coll_Beta->set_unroller(new cg_unroller(iter_+1,config_));
  }
  else {
    coll_p->set_final_collection();
  }

  rt->register_collection(coll_Alpha_dp);
  ……………………………………………
  rt->register_collection(coll_p);
}  //end cg_unroller
```

Work-flow diagram



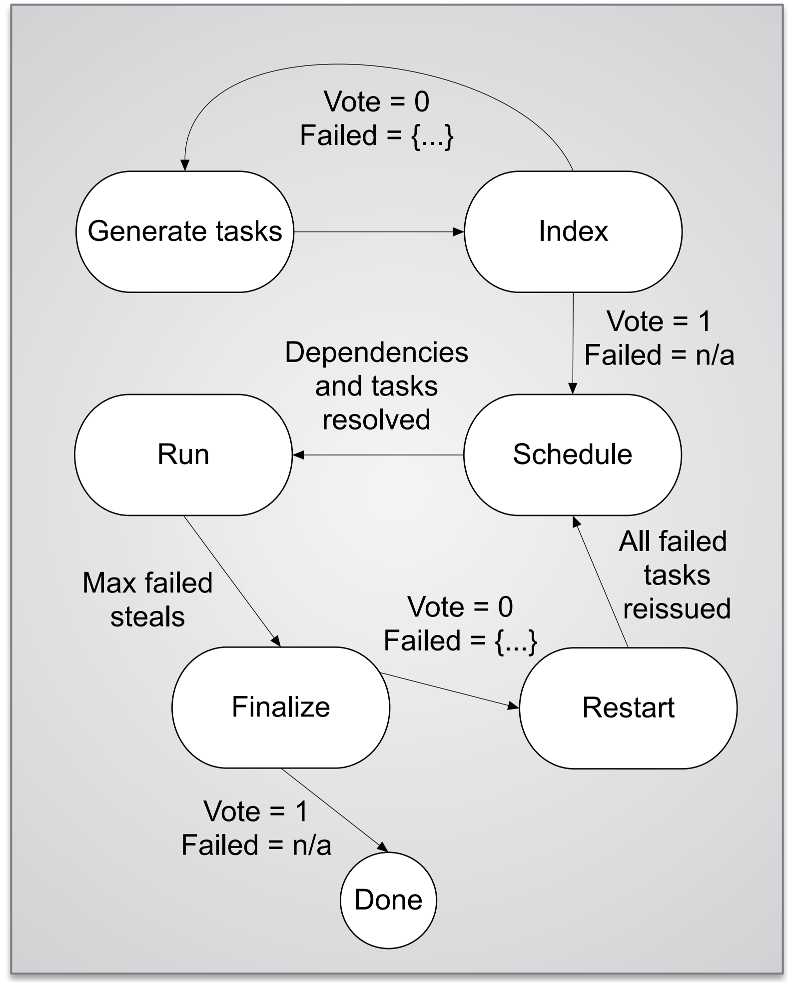
Why do you need an index phase?

- Tasks within a collection are generated locally.
- Every worker needs to *agree* on a unique label for each task i.e. tasks need to be *globally indexed*.
- The unique global index is required for:
  - scheduling a task remotely.
  - work stealing.
  - regenerating incomplete tasks due to a failure.
- This indexing is via an fault-aware **all_gather** collective.



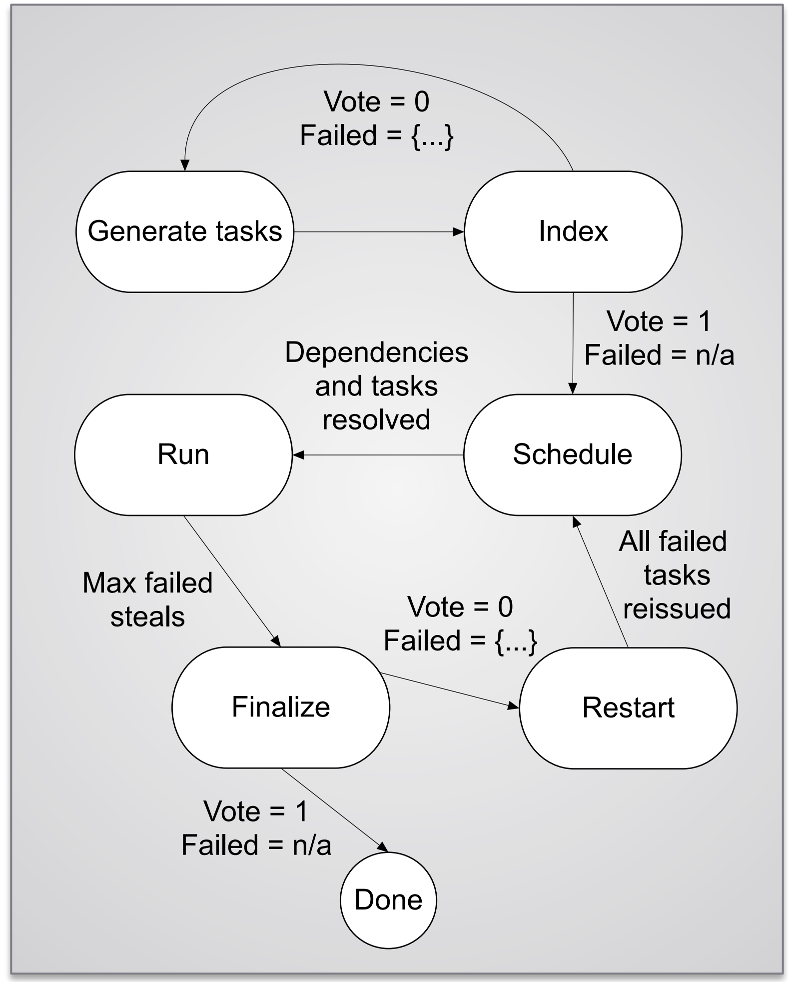
Why do you need a schedule phase?

- Each task needs to resolve its dependencies.
- The global dependency name is mapped to an actual physical location and address.
- The optimal location to run the task might be a remote node depending on:
  - data affinity (most input data resides on remote node).
  - load balancing (remote node has data backup copies and is idle).
- These decisions are made during the schedule phase.



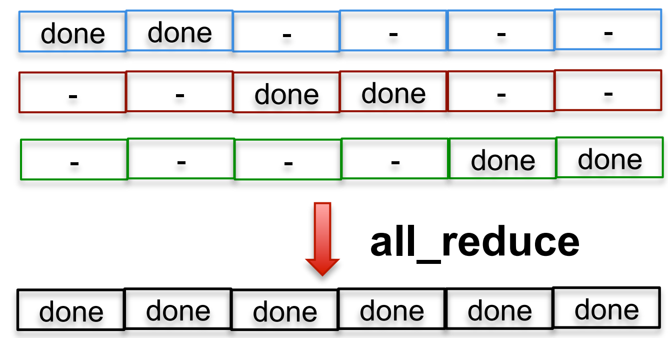
Why do you need a finalize phase?

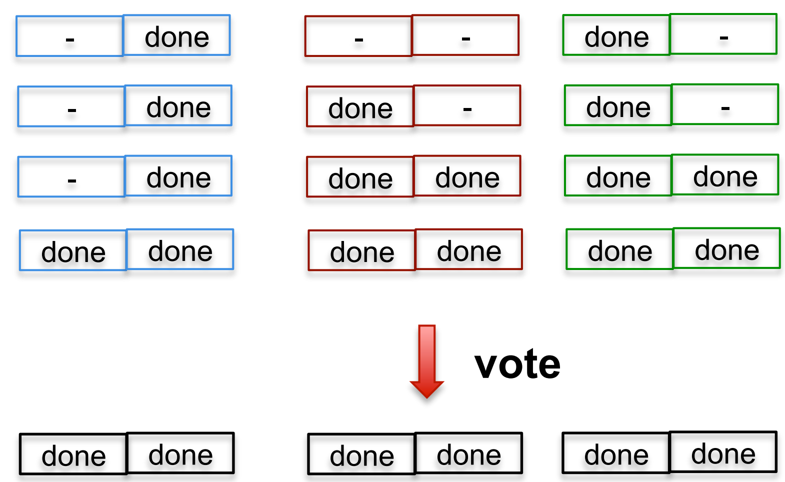
- When a worker exhausts local work:
  - it needs to determine if all work is depleted (e.g. successive steal attempts fail).
  - it needs to agree with everyone else if all work is depleted.
  - it needs to determine if any work was lost (due to failure).
- If any tasks remain incomplete due to failure, they can be detected and regenerated only in this phase.
- The finalize phase ensures that a collection is exhausted collectively by all participating workers.



Finalize phase – global agreement on task status array

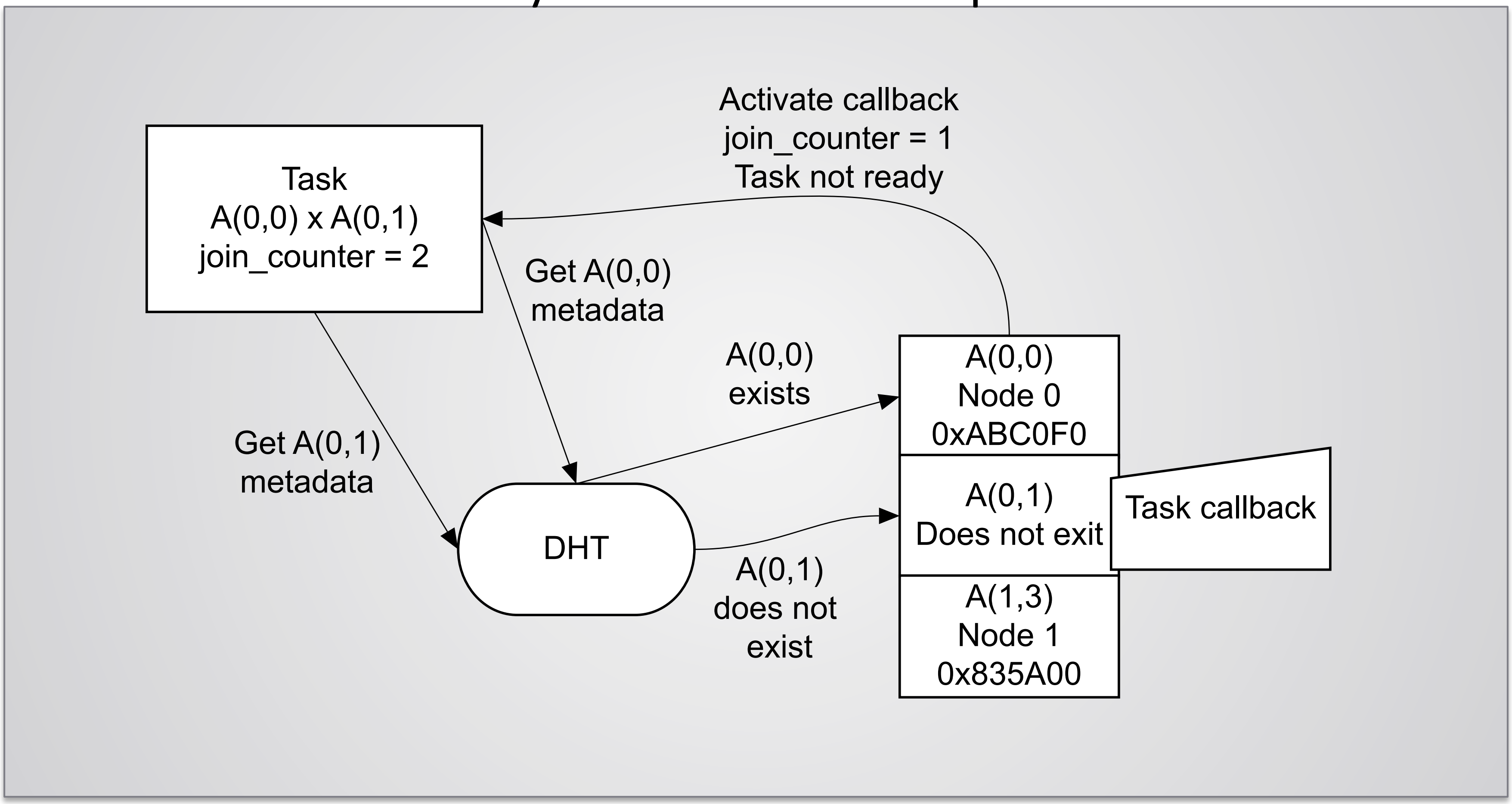
- Every node keeps task status array (bits) to confirm the global status of individual tasks.
- Naive approach:
  - each worker maintains/updates a copy of task array.
  - **all_reduce** the global (large) array.
  - not scalable (later results show).
- Alternative approach:
  - distribute the task status array.
  - completion of each task reported to designated node that is tracking its status.
  - multiple nodes can track status for a single task – redundancy.
  - when your portion of task array shows all “done” vote to finalize.

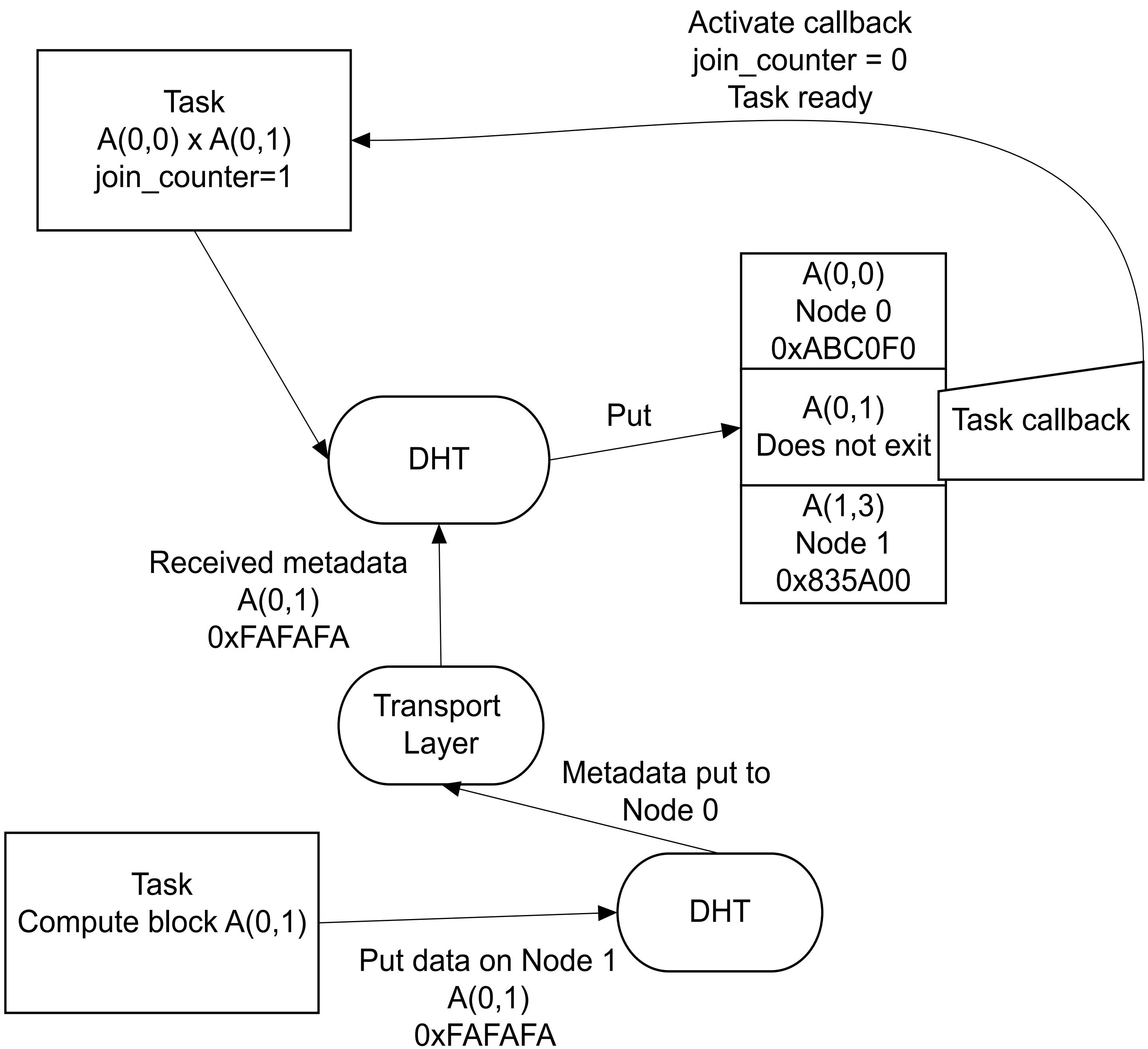




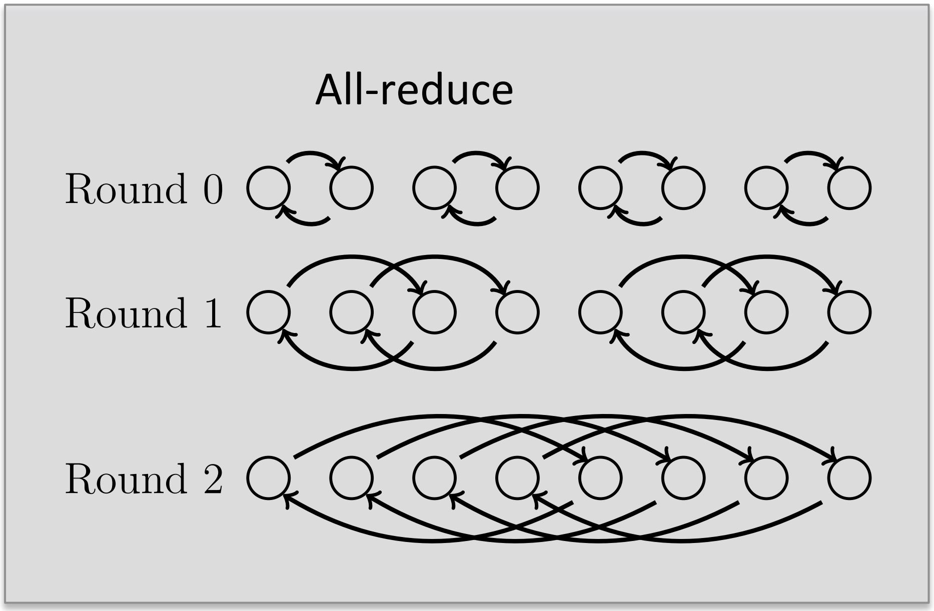
Dynamic data lookup with DHT

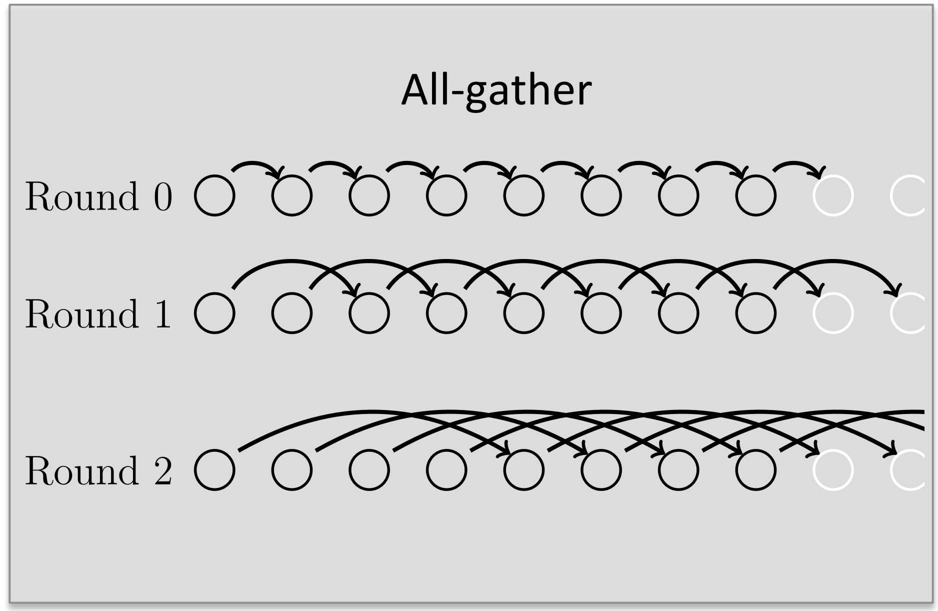
Tasks activated by callbacks when dependencies exist




Activate callback
join_counter = 0
Task ready
Task
A(0,0) x A(0,1)
join_counter=1
A(0,0)
Node 0
0xABC0F0
Put
A(0,1)
Does not exit
Task callback
DHT
A(1,3)
Node 1
0x835A00
Received metadata
A(0,1)
0xFAFAFA
Transport
Layer
Metadata put to
Node 0
Task
Compute block A(0,1)
DHT
Put data on Node 1
A(0,1)
0xFAFAFA

Fault-aware collectives





 = Send Message + Ping

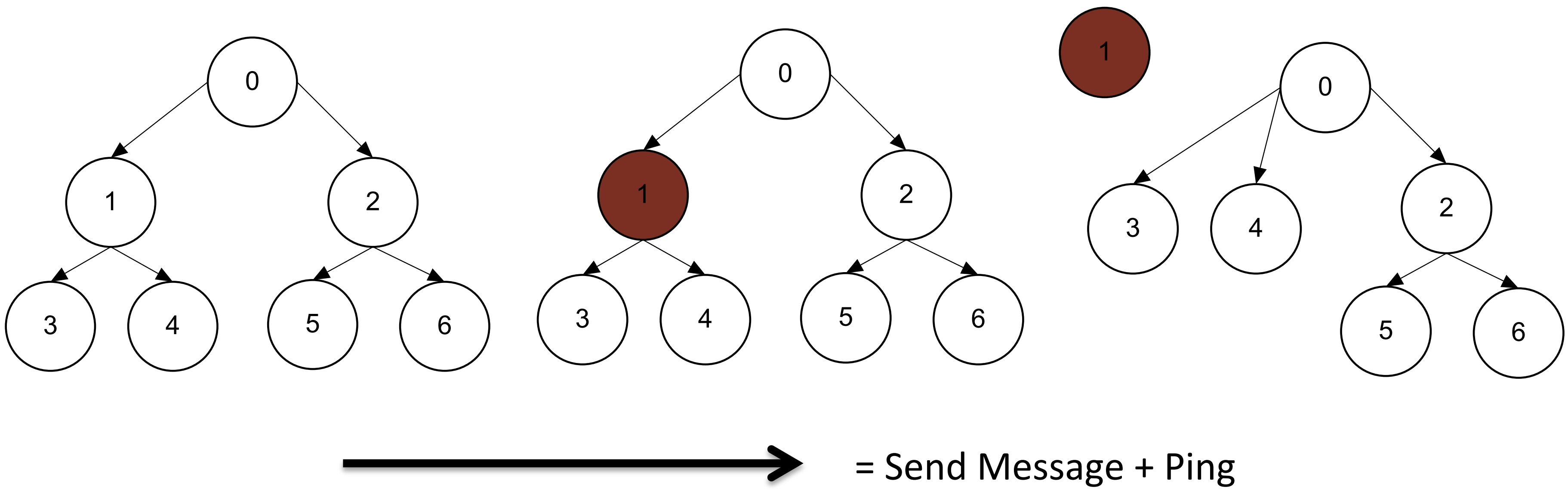
- Round partners are pinged (either timeout or RDMA NACK) to ensure alive
- If failure detected, every round of collective must still be executed (sending 0 byte fake messages)
- Only fault-aware – processes can exit with different error status, but guaranteed to finish and not deadlock waiting on dead nodes

<u>Send/recv Protocol</u>

1. Source sends RDMA header
2. Dest recvs RDMA header, executes RDMA get
3. Completion ack delivered to sender/receiver

RDMA get assumed resilient! Requires network layer support

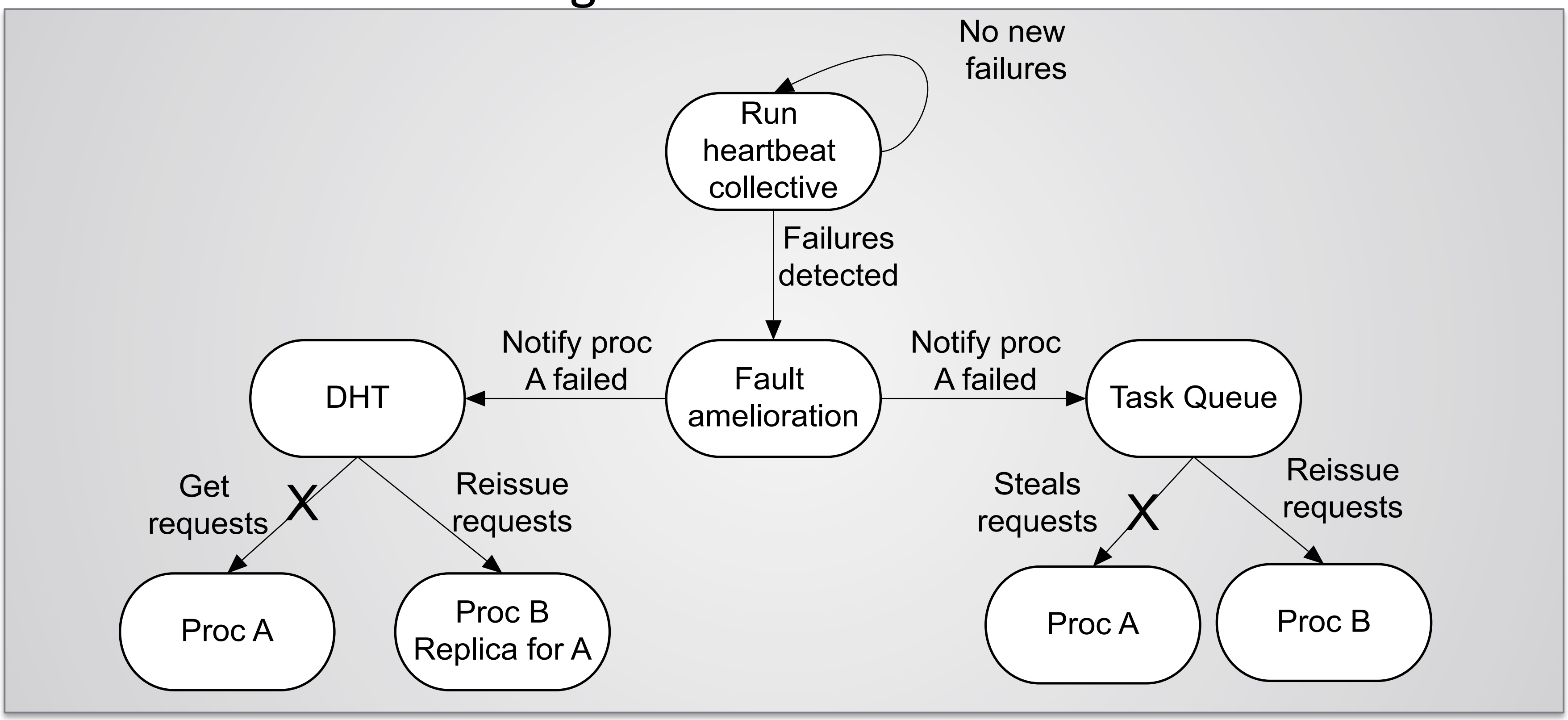
Fault-tolerant collectives: Resilient voting algorithm



- Basically same as algorithms from Hursey and Graham
- Votes passed up tree and merged on root
- Much simpler to assume root never fails – ways around it
- After failures detected, tree reconnects and votes reissued
- Can be used immediately after any fault-aware collective to vote on completion – makes any fault-aware collective fault-tolerant

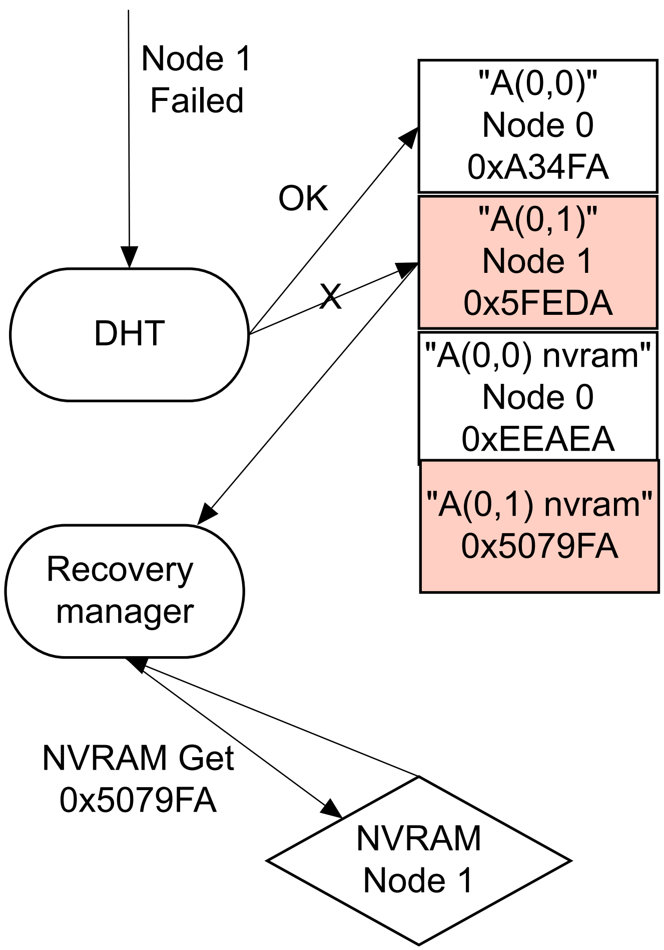
Heartbeat connects to DHT and task queue to respond to failures

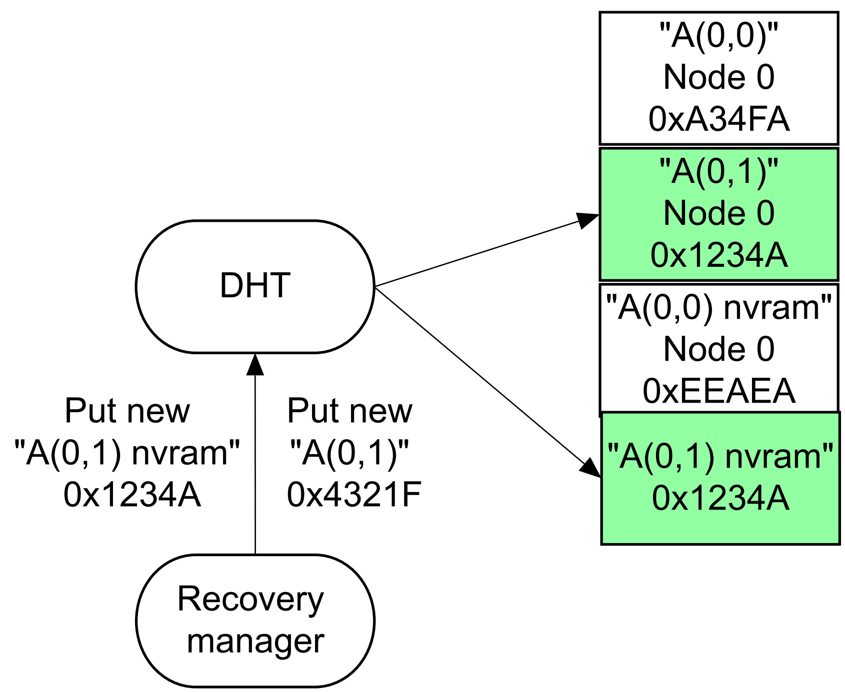
- Collectives are self-diagnosing; DHT, task queue, data backup managers need something to provide notifications of failures
- Fault-tolerant voting algorithm serves as "heartbeat" overlay network for detecting failures



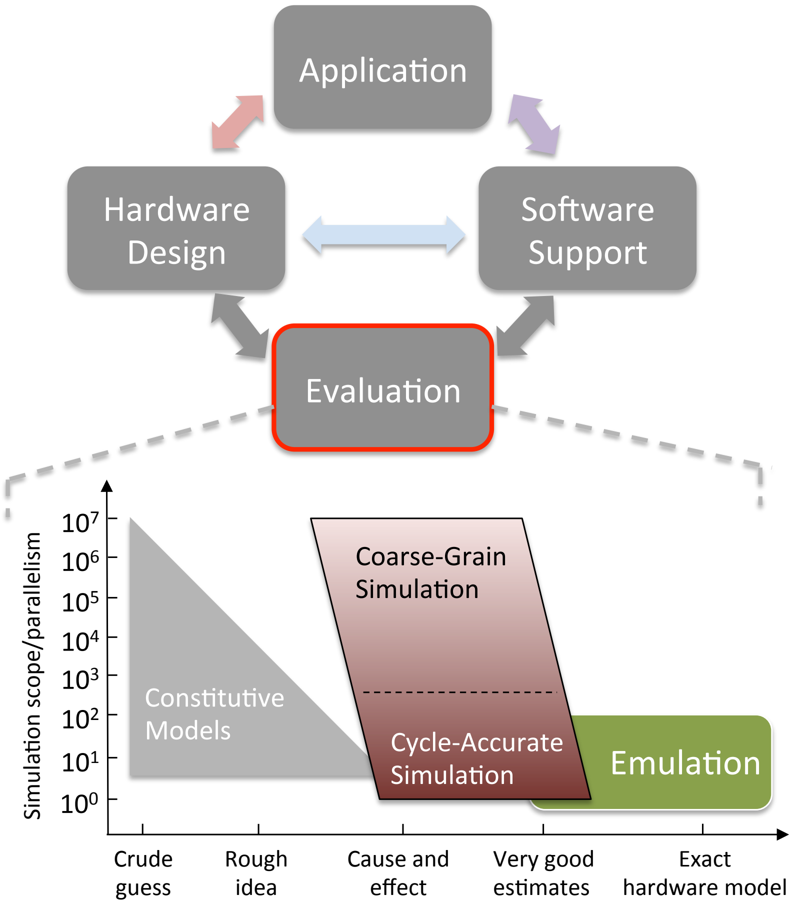
Transparent NVRAM fault tolerance with DHT

Recovery operations occur in background, no application awareness



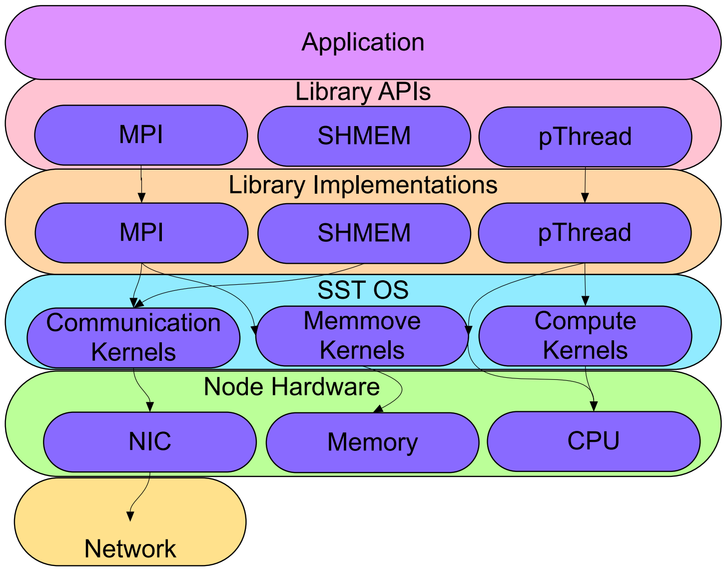


Why develop with a simulator?

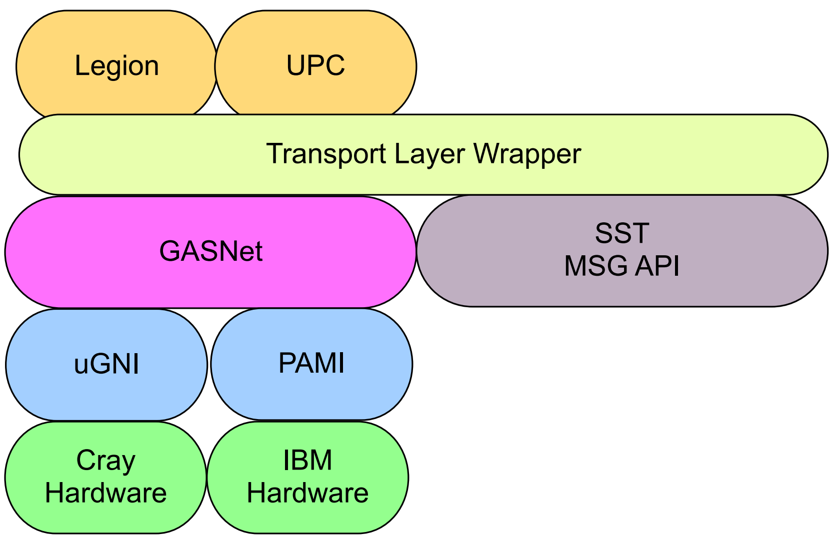


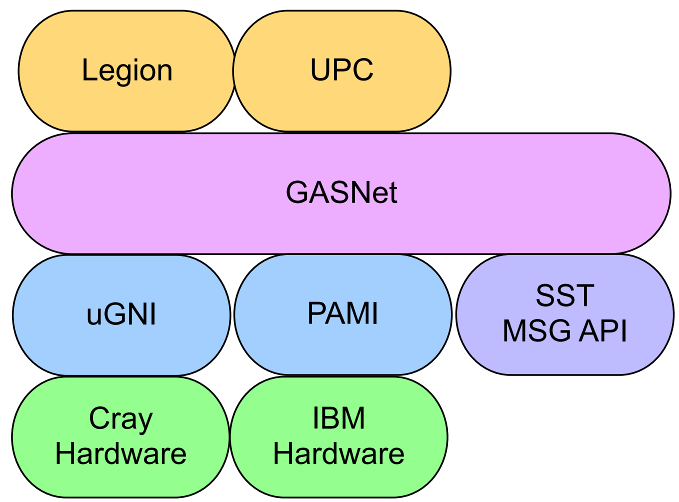
- Coarse-grained simulation explores system-level (load balancing, effects of failures)
- Think about overall structure without implementing every detail
- Rapidly iterate experiments (don't need to wait in queue)
- Co-design for speculative hardware
- Total control over when/where failures happen

SST Macroscale stack diagram



- SST is an on-line simulator
- Compile applications directly into SST libraries to simulate MPI/ pthreads/etc
- SST can link into runtime systems at two different levels: directly or indirectly as GASNet backend
- Illustrated for existing runtime systems like Legion and UPC





Compile-and-go simulation

```
int USER_MAIN(int argc, char **argv)
{
 MPI_Init(&argc, &argv);

 ...

 for (int iter=0; iter < niter; ++iter){
   MPI_Isend(left_block, nelems_left_block, MPI_DOUBLE,
       row_send_partner, row_tag, MPI_COMM_WORLD, &reqs[0]);
   MPI_Isend(right_block, nelems_right_block, MPI_DOUBLE,
       col_send_partner, col_tag, MPI_COMM_WORLD, &reqs[1]);
   MPI_Irecv(next_left_block, nelems_left_block, MPI_DOUBLE,
       row_recv_partner, row_tag, MPI_COMM_WORLD, &reqs[2]);
   MPI_Irecv(next_right_block, nelems_right_block, MPI_DOUBLE,
       col_recv_partner, col_tag, MPI_COMM_WORLD, &reqs[3]);

   do_dgemm('T', 'T', nrows, ncols, nlink, 1.0, left_block, nrows,
      right_block, ncols, 0, product_block, nrows);
  }

  ...

  MPI_Finalize();
}
```

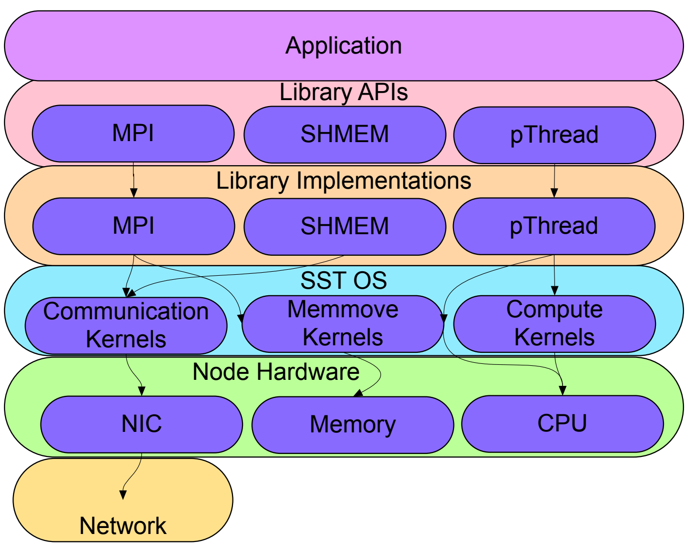
Linkage intercepts main and spawns user-space thread to simulate process

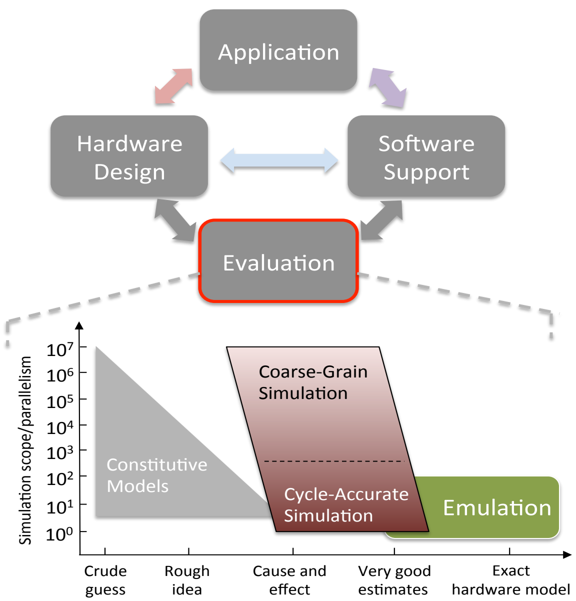
Linkage intercepts MPI calls and simulates send/recv time via congestion models

Linkage intercepts BLAS calls and estimates compute time without actually performing work

What are you giving up (or not) with simulation?

- NOT emulation – coarse-grained simulation
- No real computation, tasks just simulate time passing
- Coarse-grained network models (approximate treatment of congestion)
- Full runtime is executing – tasks are not actually run, but all task/data management is executing for real





We have implemented the DHARMA runtime system in SST

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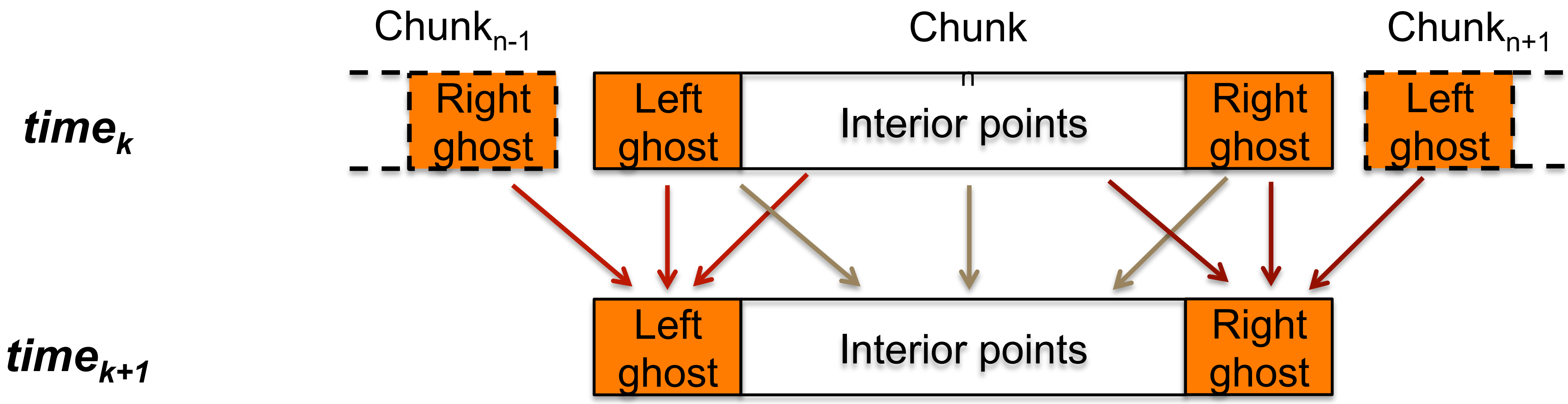
- Coarse-grained simulation allows for system-level exploration
- Skeletonized mini-apps of explicit and implicit solver

Runtime studies	Algorithmic studies
Scalability with no faults (strong and weak)	Task-granularity and decomposition
Performance in the presence of faults	Classification of performance according to compute/ communication ratios
Node degradation tests	Algorithmic tradeoffs
Comparison against baseline MPI skeleton	Matrix assembly variants made possible by shift to many-task model

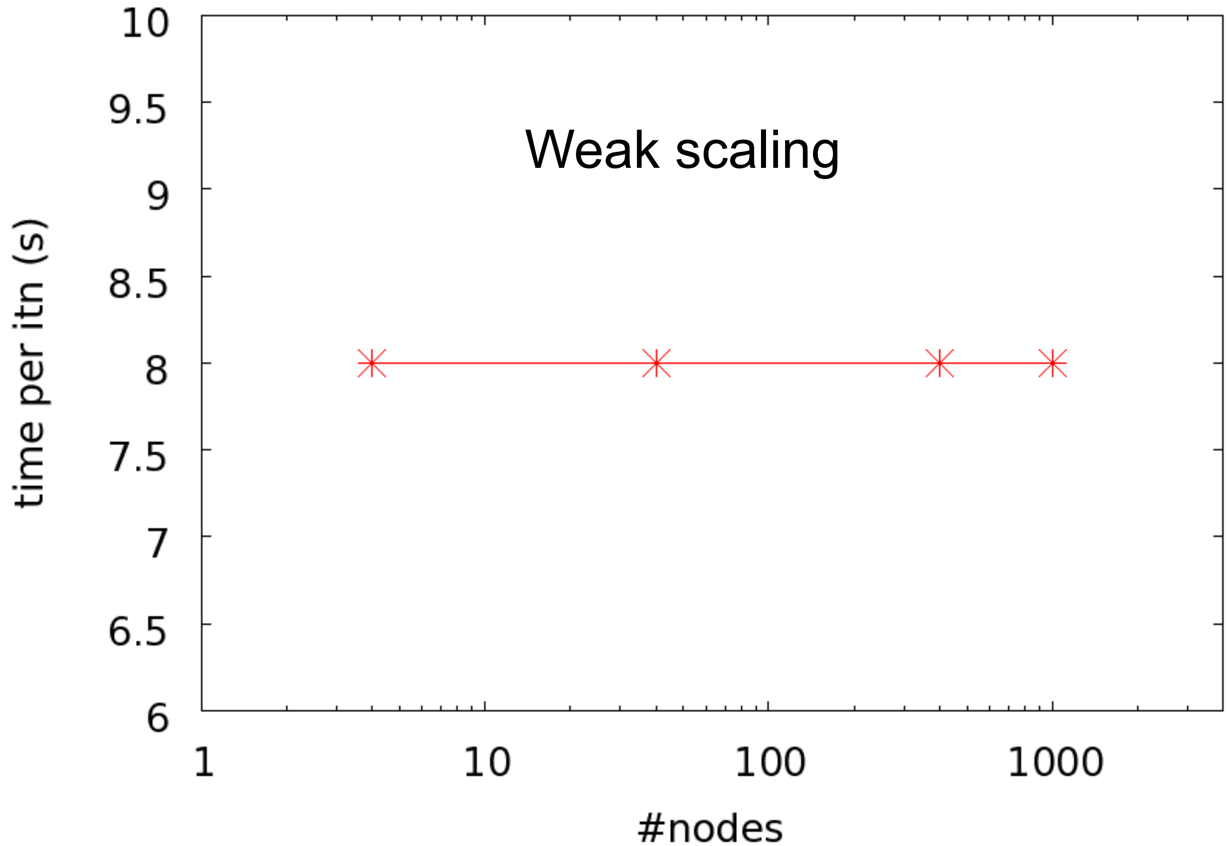
- Demonstration of full-scale implementation of run-time and associated mini-apps on capability-class system next year

Explicit 1D-PDE problem



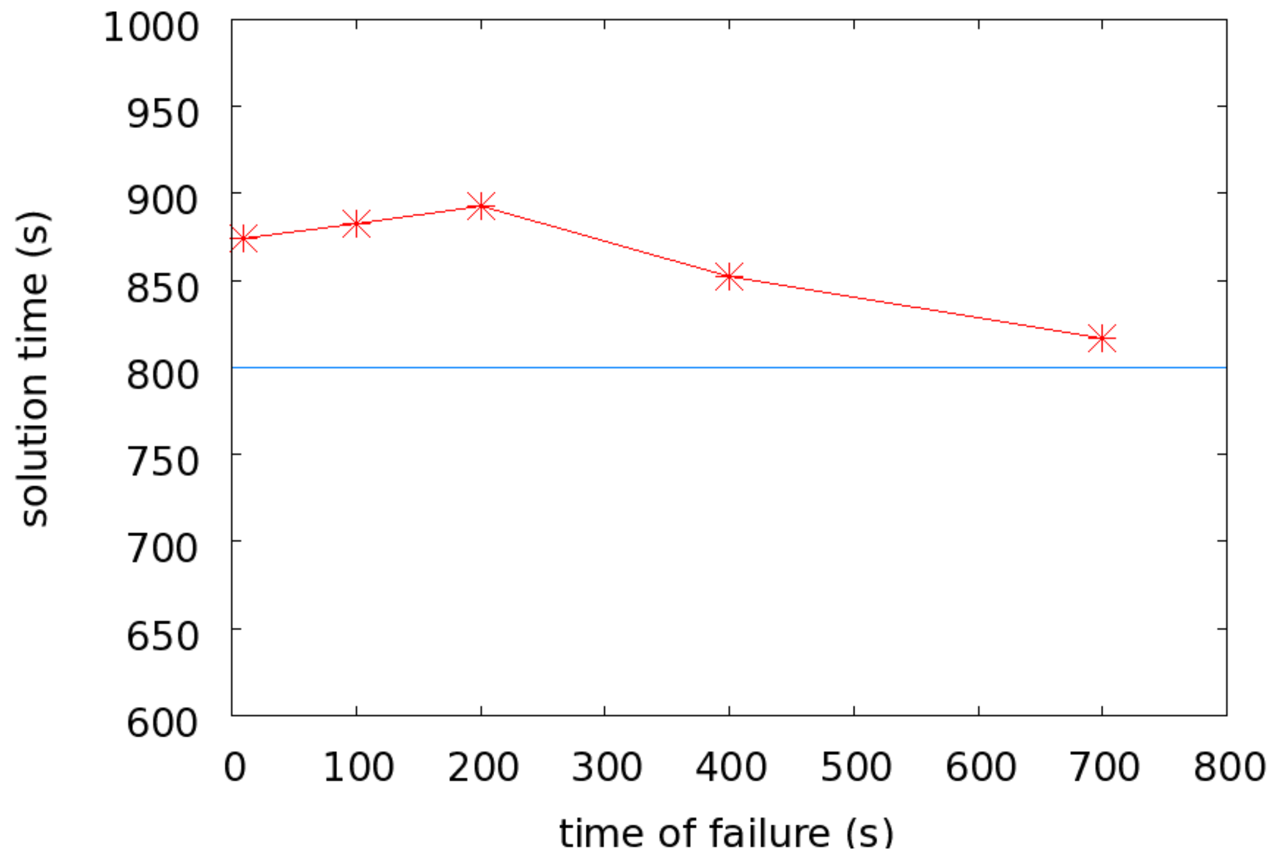
- Two tasks for each chunk: one for interior points, another for ghost points.
- Compute times based on typical S3D cost.

Baseline – no failures



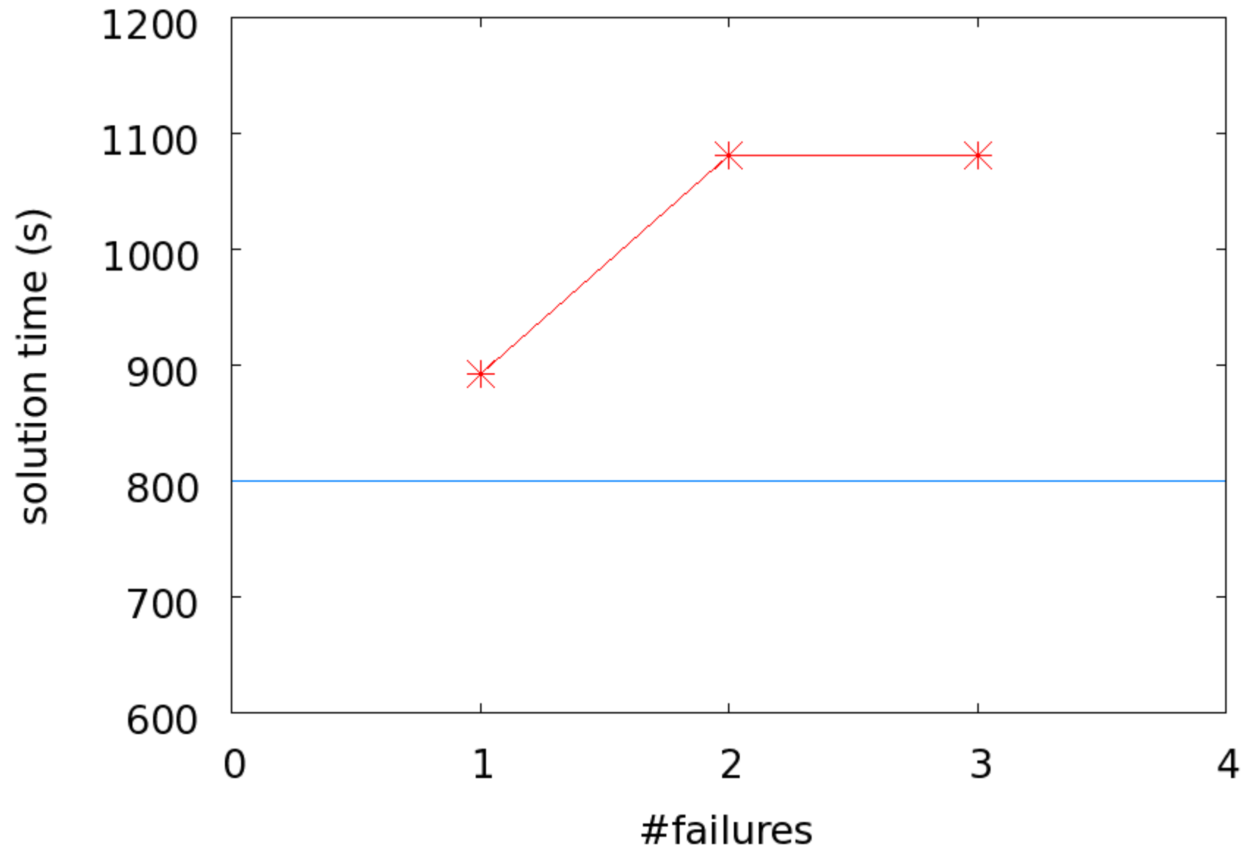
- Specs: 10 chunks per node, n_{int} = 8000, n_{gh} = 4, #itns = 2-100
- SST simulation shows perfect weak scaling of the problem with *dharma* runtime.

Impact of 1 failure



- Tests with just 1 node failure at various instants (#nodes=400)
- The time to solution non-monotonic with failure induction time.
- Early fault – more time to absorb. Late fault – less overhead.

Impact of multiple failures



- Tests with multiple failures (#nodes=400, #itns=100).
- 1st failure at 200s, 2nd at 400s and 3rd at 700s.
- Overhead not proportional to number of failures.

Summary

- DHARMA aims at tackling challenge of resilience in dynamic, adaptive, task-DAG world
- Distributed consistency problem at heart of runtime
- Many places to optimize
- Can we use application knowledge to structure runtime and make resilience strategy both as EFFICIENT and TRANSPARENT as possible?
- What's the burden to the programmer?