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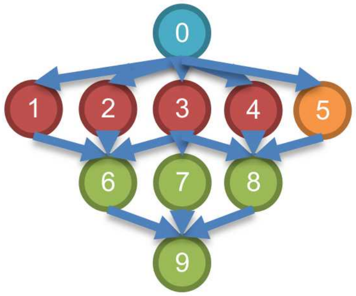

Scalable, Efficient Fault Tolerance in Asynchronous Many Task (AMT) Programming Models

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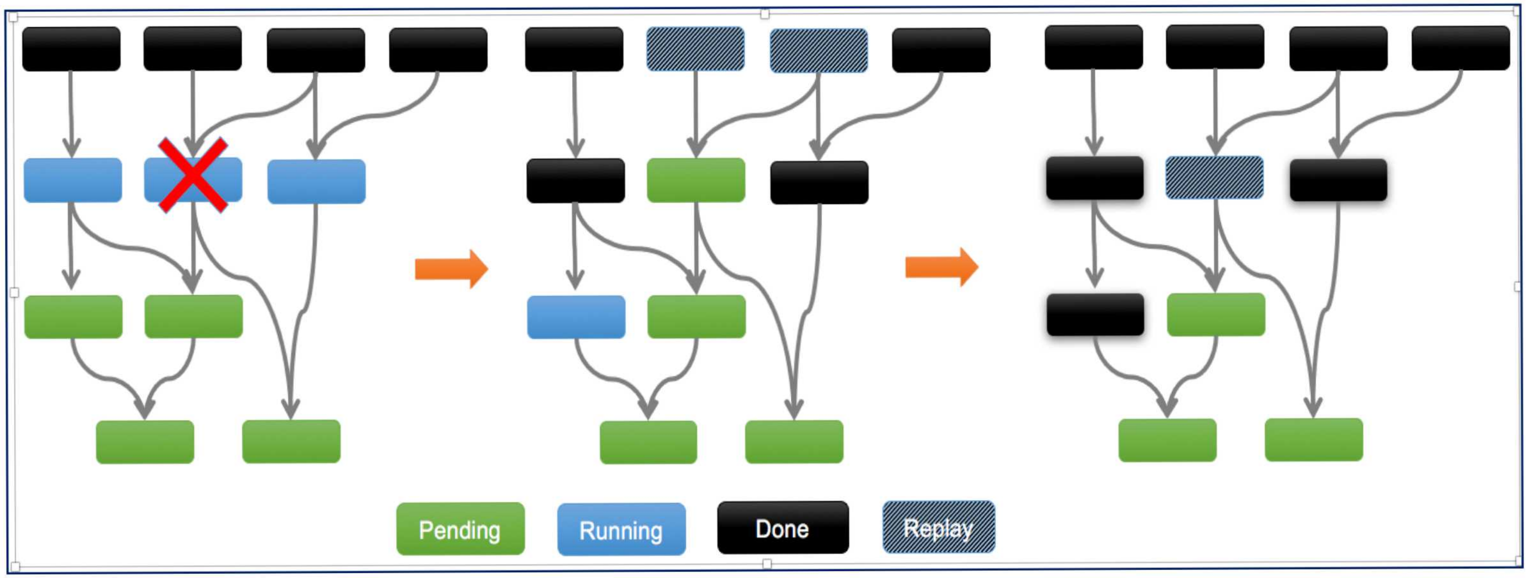
Motivations and Background



- Substantial progress in resilience and asynchronous many-task (AMT) programming models, separately.
- AMT offer:
  - More flexible and efficient failure mitigation compared to conventional (e.g. checkpoint) strategies.
  - Ability to quantify the effects of failures and benefits of various resilience strategies.
- ***Complex tradeoffs of multiple AMT resilience techniques with dynamic failure behavior*** need to be understood/documented**.**
- Need ability to extrapolate tradeoffs to extreme(exa)-scale.

Objectives

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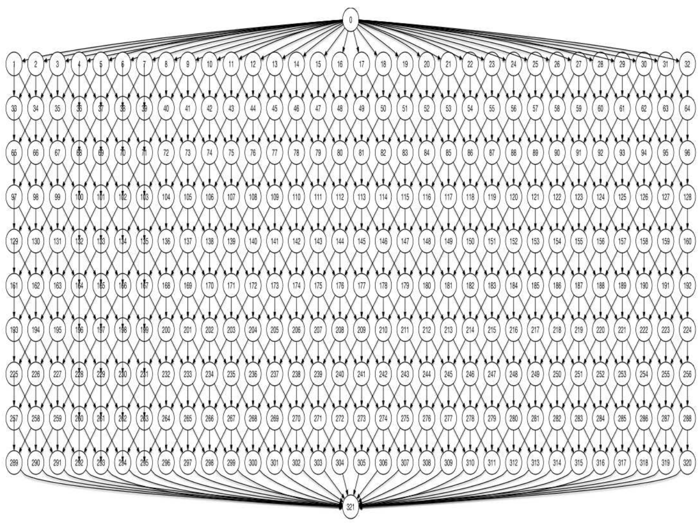
- An analysis of the scalability, performance and costs for multiple AMT resilience options.
- Prototype implementation of resilience schemes in actual asynchronous many-task programming model:
  - task replication.
  - task replay.
  - algorithm-based fault tolerance.
  - task-level checkpointing.
- An analysis of accuracy-cost tradeoffs of application-specific failure detection and mitigation schemes.
- Use representative mini-apps as basis for study.

Current Scope: On-Node AMT

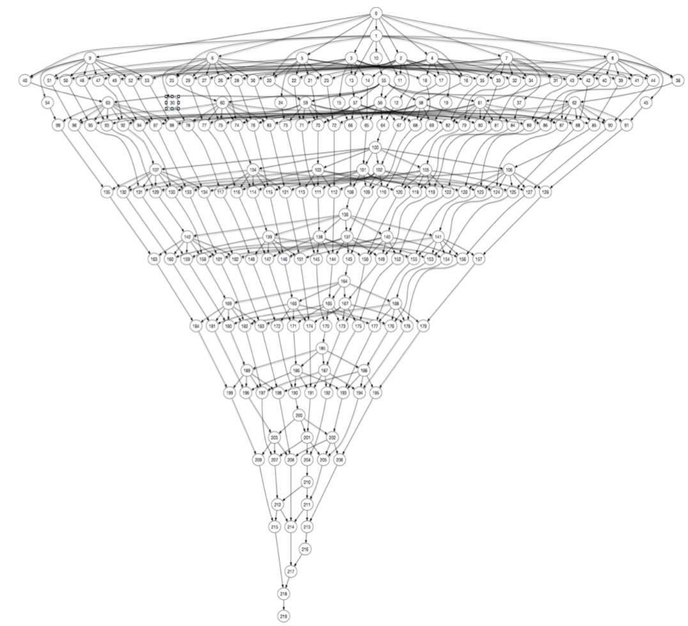
- MPI+(on-node) AMT an anticipated programming model for future complex node architecture.
- First comprehensive study with on-node AMT. Extend concepts to distributed AMT in future.
- Analyzing Failure/Error mitigation by On Node AMT is essential:
  - Hard failure of cores and accelerators, silent errors, performance degradation.
  - Failure can be manifested as task failure: non-finishing tasks, data corruption or very slow execution.
- We still need better understanding of failure-free AMT as a baseline, production-ready distributed AMT is scant.

Abstract Model of AMT Program

Graph representing 1D stencil Computation



Graph representing dense Cholesky Factorization



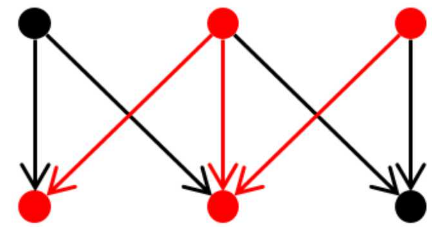
- AMT program execution can be graph and traverse it from the root.
- We started to investigate any analytical model to derive the performance and reliability.

Survey of DAG Analytical modelling

Analytical modelling intractable even for simple scientific task graphs like stencil 1D

- Conducted a survey on analytical modelling of directed acyclic graphs.
- Several papers addressed **series parallel graphs (SPG)** or their variants to derive the execution cost and reliability analytically
  - Requirements for being SPG specifically forbids an **N**-shaped subgraph. Unfortunately, even for **the simplest 1D-stencil task-DAG**, this is violated, and the N-subgraph occurs repeatedly.
  - If a graph is not SPG, the model has high complexity (#P) to compute.

Task-DAG for 1D-stencil Program



[1] R.A. Sahner, K.S. Trivedi, 1987, **IEEE Transactions on Software Engineering, vol. SE-13, no. 10, pp: 1105-1114.**
[2] J. Valdes, R.E. Tarjan, E.L. Lawler, 1982, **SIAM J. Comput., vol. 11, no. 2, pp: 298-313.**

Alternate Solution: Task-DAG Simulator

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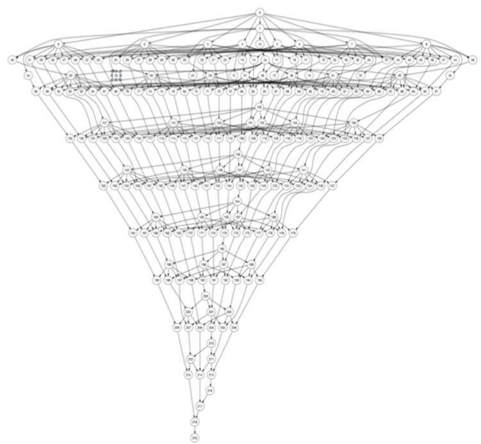
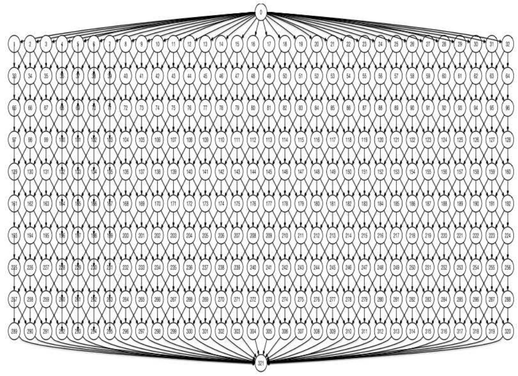
Task-DAG simulator hypothesizes the behavior of resilient AMT under numerous system and runtime situations

- Developed a tool to traverse task dags on multicore/multithreaded environment
  - 30+ Simulation Parameters including
    - # of threads
    - Scheduling
    - Task replay
    - Task replication
    - Checkpoint tasks (extra tasks inserted to take global state of data blocks)
    - Overhead for replay/replication
  - Emulate the scheduler of Habanero C++

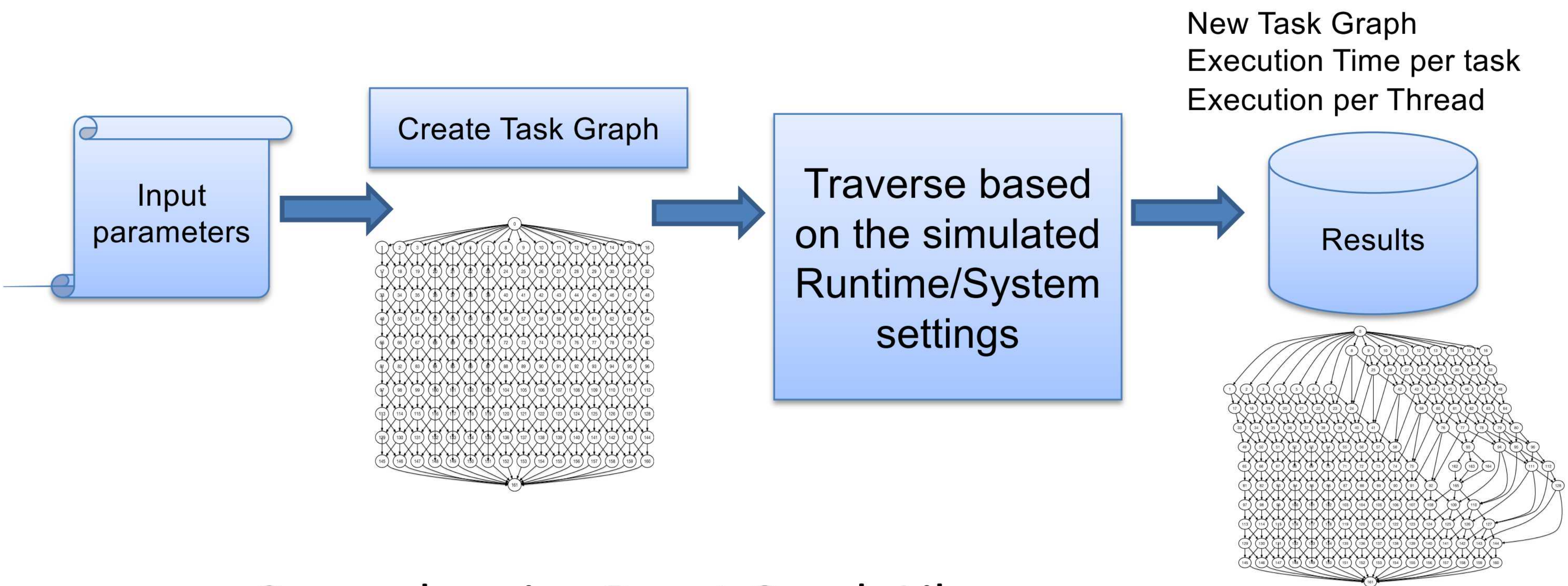
Graph representing dense Cholesky



Graph representing 1D stencil



Workflow of the Resilient-AMT Simulator

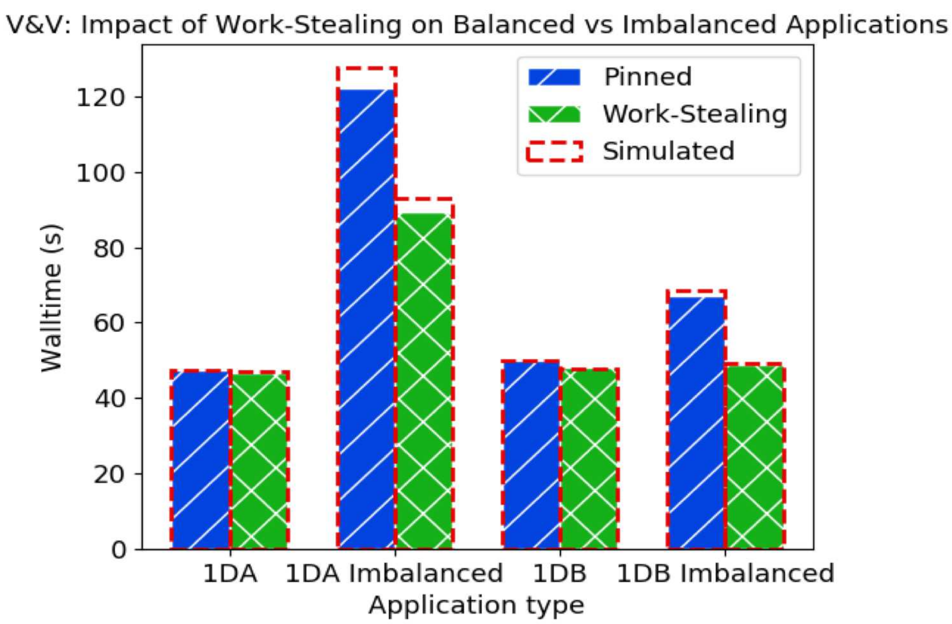


- C++ code using Boost Graph Library
- Python for visualization and organizing data

The Graph Generation Capability of the Resilient-AMT Simulator

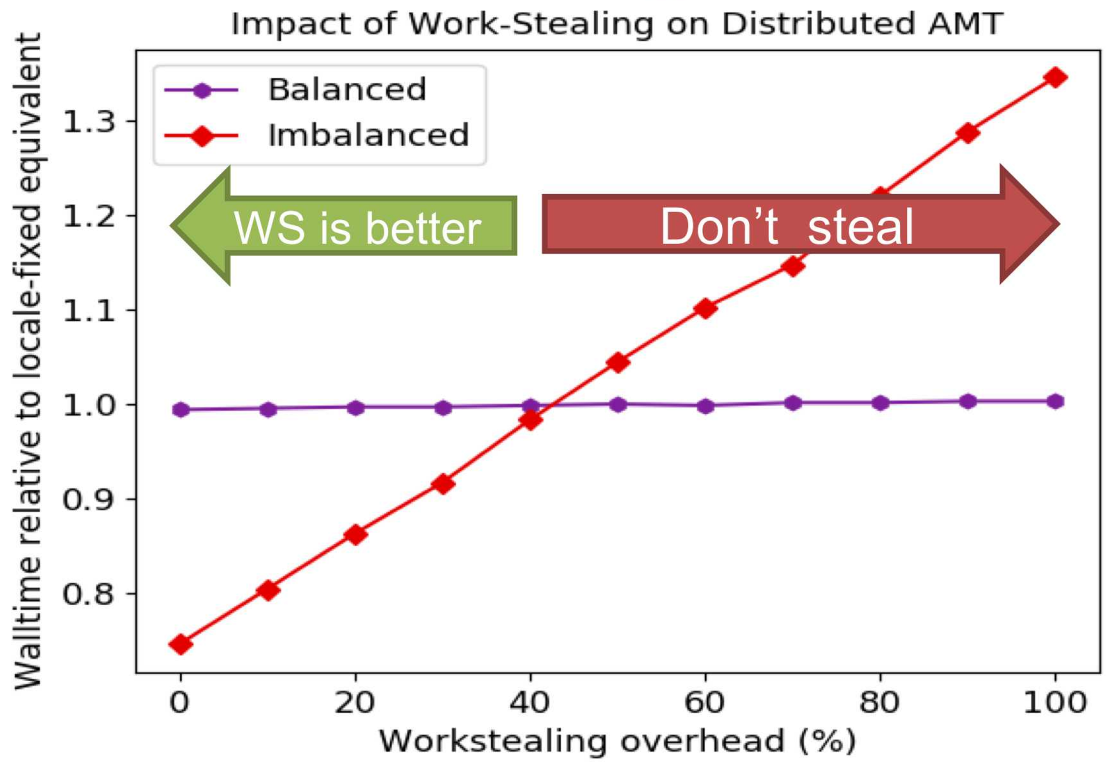
- Support generation of task graphs for:
  - 1D, 2D and 3D stencil code
  - Explicit PDE solver with unstructured mesh/arbitrary graph
  - Dense Cholesky Factorization
  - User can provide any task graphs as input files.

Simulator can predict the performance of the code in faulty situations.



- Obtain simulation parameters **just from non-resilient (no WS) executions.**
- Simulator runs the same task graph of the original program with specified resilient-AMT options.
- Accurately predicts the performance of task-replay resilience.
- Needs more rigorous performance model to simulate replications.

Simulator can explore hypothetical distributed AMT settings



- Distributed AMT settings on 8 nodes. 32 core per node.
- Overdecomposed 1D Stencil Problem
- Imbalanced Case: 10x single slow task in a single time step
- X-axis indicates the work stealing overhead relative to task execution time.

Resilient AMT Prototype

- Resilience Extension of Habanero C++
  - AMT programming Interface by Vivek Sarkar
- Simple extension allows the user to introduce 3 major resilient proguram execution patterns
  - Task Replication Interface
  - Task Replay Interface
  - ABFT Interface

Original Task Launch

```
hclib::async_await ( lambda,
hclib_future_t *f1, ..,
hclib_future_t *f4);
```

Task Launch with Replication

```
diamond::async_await_check<N> (
lambda, hclib::promise<int> out,
hclib_future_t *f1, ..,
hclib_future_t *f4);
```

Task Launch with Replay

```
replay::async_await_check<N>(
lambda, hclib::promise<int> out,
std::function<int(void*)>
error_check_fn, void * params,
hclib_future_t *f1, .. ,
hclib_future_t *f4);
```

Habanero-C++ Overview

- Project led by Vivek Sarkar (GaTech/Rice U)
- Library-based tasking runtime and API
  - Semantically derived from X10
- Focused on: lightweight, minimal overheads; flexible synchronization; locality control; composability with other libraries;
- Simplified deployment: no custom compiler, entirely library-based, only requires C++11 compliant compiler
- Uses runtime-managed call stacks to avoid blocking
- https://github.com/habanero-rice/hclib

Habanero-C++ Overview

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HClib constructs

Description	Example
Asynchronous task creation	`async(() -> { S1; });`

Bulk task synchronization	`finish(() -> {`
	`    async(() -> { S1; async(() -> S2;); });`
	`});`

Futures and promises	`async(() -> { prom->put(42); });`
	`async(() -> { prom->get_future()->wait(); });`
	`async_await(() -> {…}, prom->get_future());`

Bulk task creation	`forall(loop, (i, j, k) -> { S3; });`
Places for locality control	`async_at(pl, () -> { S4; });`

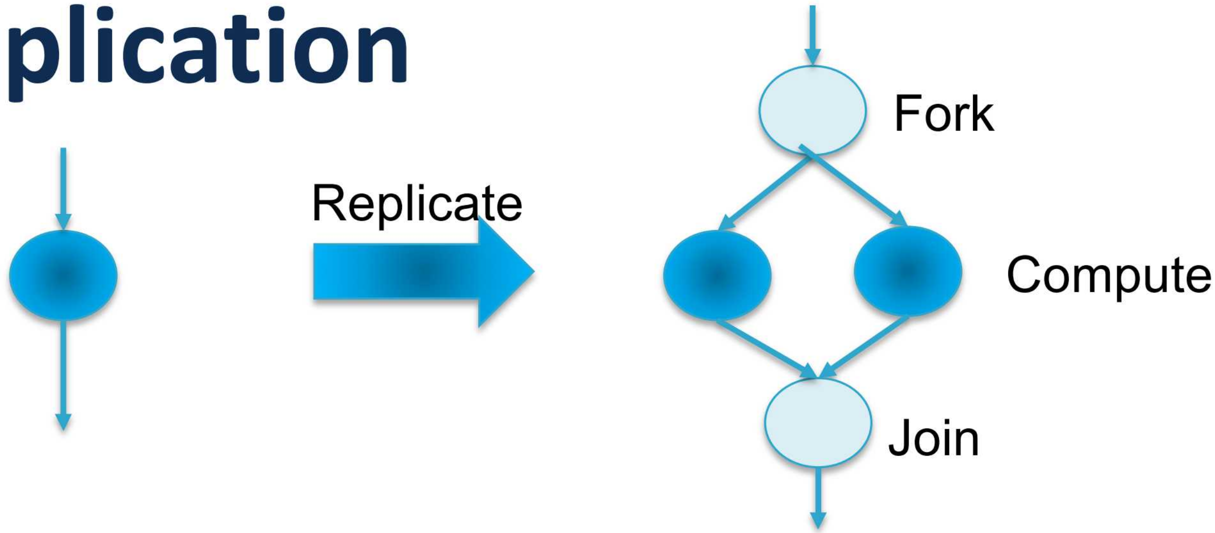
Habanero-C++ Overview

- Express data dependencies using **promises** and **futures**.
- `hclib::promise`
  - Store a value using single assignment semantics : **`promise.put(value)`**
- `hclib::future`
  - Retrieve the value stored in a promise : **`value = future.get()`**
  - Can be used as dependency for tasks
- Relation between future and promise
  - **`future = promise.get_future()`**
  - If accessed from different threads **`put()`** and **`get()`** are synchronized thus enabling a way for synchronization.

HClib extension: (1) Reference Counting

- Current implementation leaves it to user to manage dynamic allocated memory (no automatic garbage collection).
- Reference counting semantics:
  - Provide a way to perform garbage collection based on the use of future as task dependency
  - Allows transparent handling of data access by replay/replicated tasks.
- Implementation extends **`promise`** to have a reference count
  - Count set during object construction
  - Count decreased using **`release()`** method
- Extend **`async_await`** to perform automatic reference counting
  - Reference count is decreased each time a future associated with the promise is used as dependency

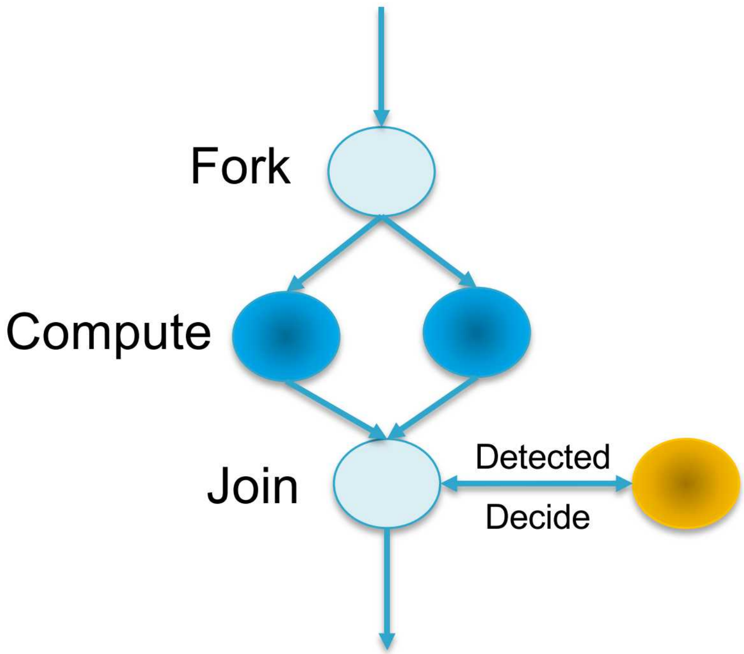
Task Replication



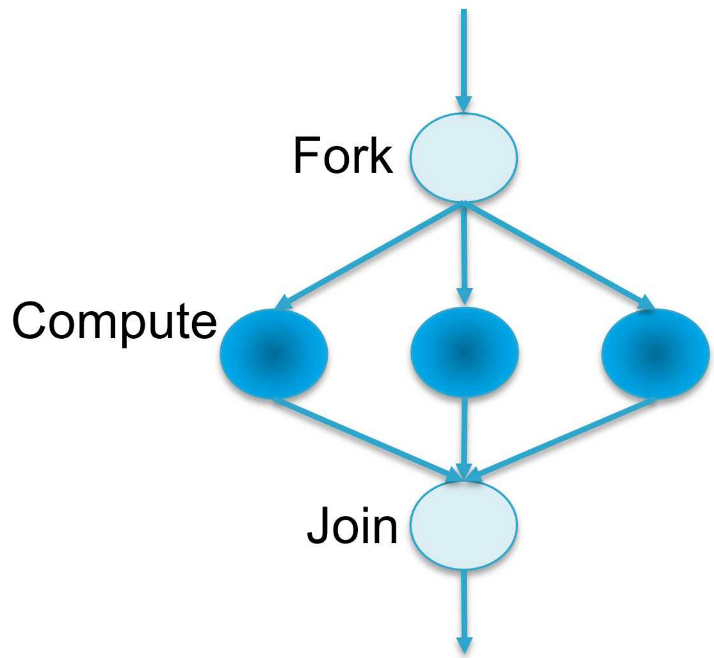
- `diamond::async_await_check<N> ( lambda, hclib::promise<int> out, hclib_future_t *f1, .., hclib_future_t *f4);`
  - Preventive failure mitigation
  - N-plicates the task and checks for equality of put operations at the end of the task
  - If error checking succeeds, actual puts are done
  - If error checking fails, puts are ignored and the error is reported using an output promise

Replication (Continued)

`diamond::async_await_check<2>(…`

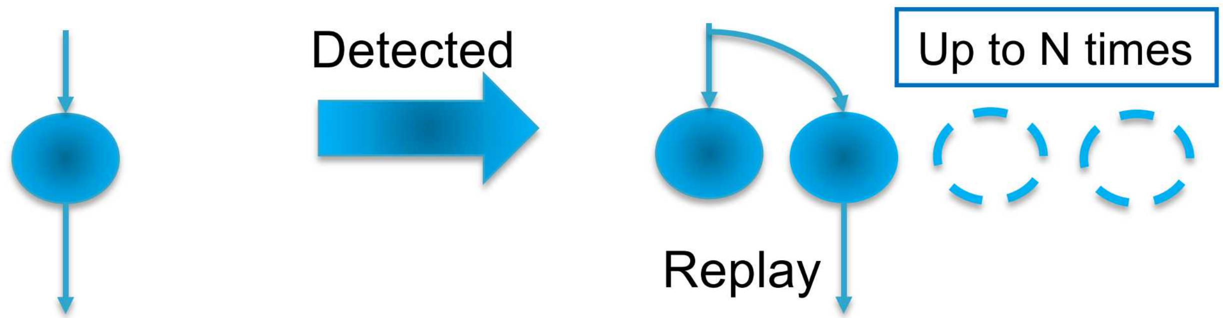


`diamond::async_await_check<3>( …`



- Duplicate (N=2) – Create two tasks and check for error in puts
  - If error checking fails, a third task is created
- Triplicate and more (N=3 ore more) – Create three tasks and check for error in puts
  - Two out of three outputs should match for success

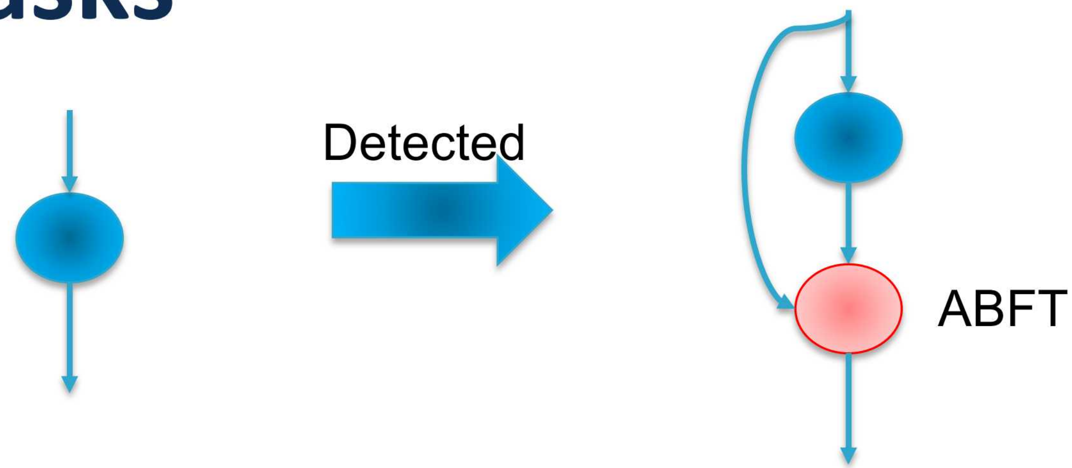
Task Replay




```
replay::async_await_check<N>( lambda,
hclib::promise<int> out, std::function<int(void*)>
error_check_fn, void * params, hclib_future_t *f1,
.. , hclib_future_t *f4);
```

- Dynamic response to failure
- Executes the task and checks for error using the error checking function
- error_check_fn(params) returns true if there is no error
- The task is executed **N** times at most if there is any error
  - If error checking fails, puts are ignored and the error is reported using an output promise

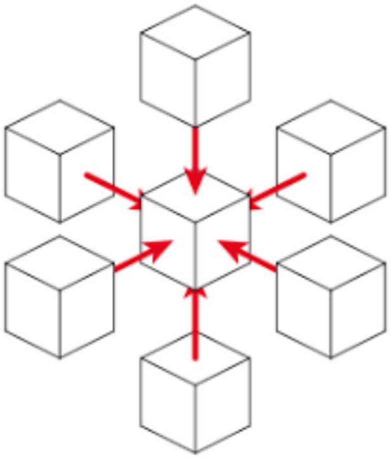
ABFT Tasks

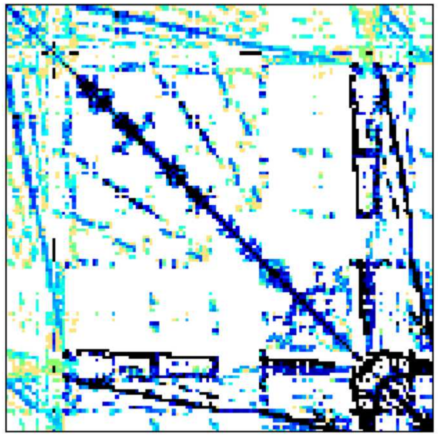


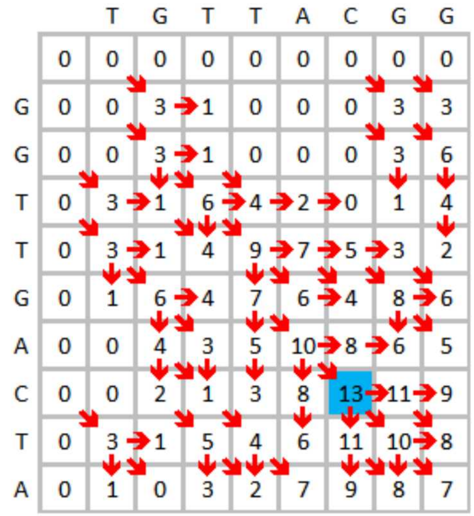

```
abft::async_await_check ( lambda, hclib::promise<int>
out, std::function<int(void*)> error_check_fn, void *
params, hclib_future_t *f1, .. , hclib_future_t *f4,
ABFT_lambda);
```

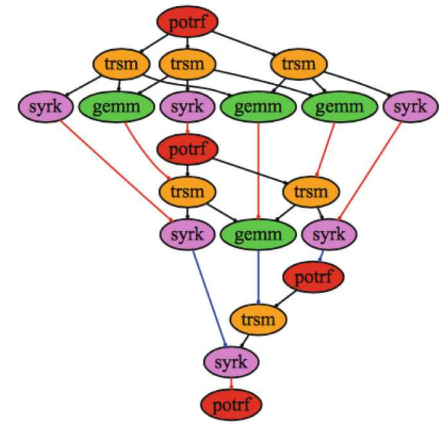
- Executes the task and checks for error using the error checking function
- error_check_fn(params) returns true if there is no error
- If there is error then **ABFT_lambda** is executed and checked for error again at its end
  - If error checking fails, puts are ignored and the error is reported using an output promise

Performance









- On 2 Haswell CPU node (16x2 cores)
- 1D and 3D stencil code
- Conjugate Gradient with crank_1 sparse matrix
- Smith-Waterman (SW) algorithms
- Task-parallel Fault-Tolerant Cholesky Factorization
  - Based on the Cao and Bosilca (IPDPS2016)
- The application data is **over-decomposed**.
  - 4 way for stencil and CG
  - 64x64 for SW and Cholesky

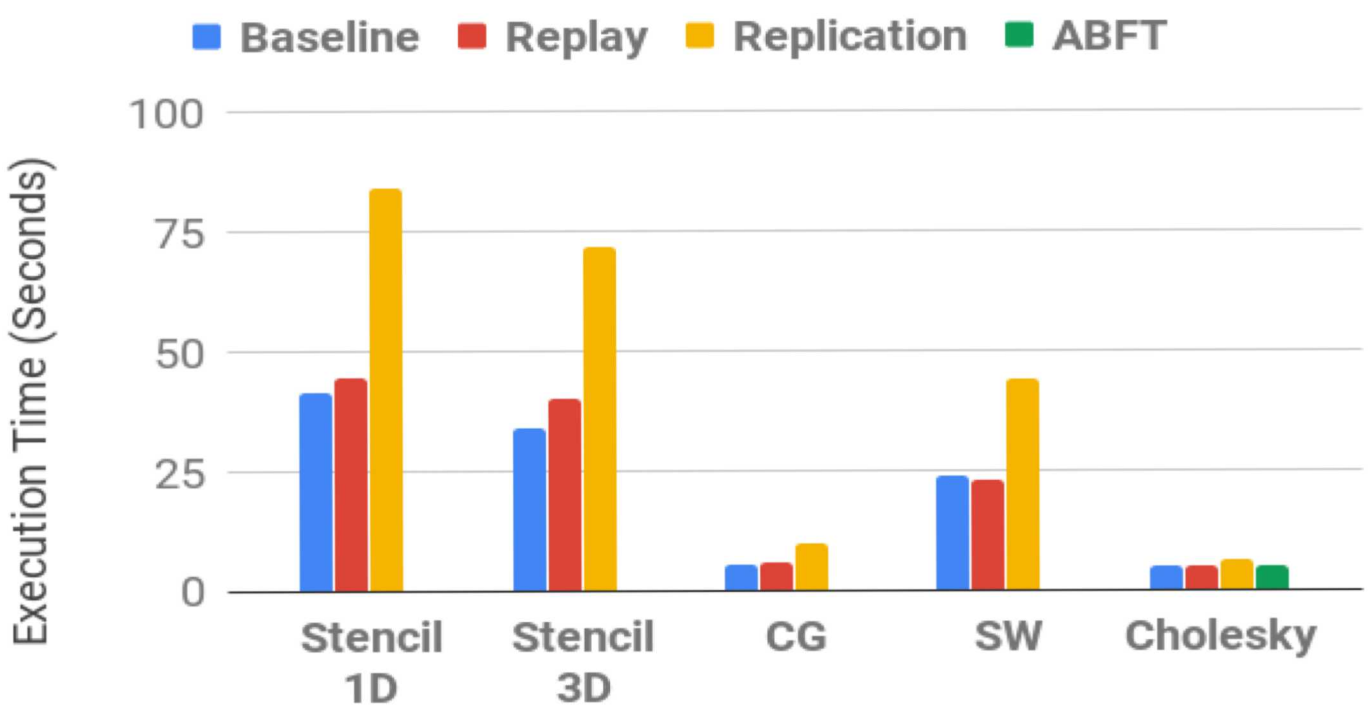
Replay and replication do not double the memory overhead

	Synthetic	Stencil 1D				
	vanilla	vanilla	Replay	Replication	Mix Replay	Mix Replication
1 worker	0.19 GB	0.67 GB	1.02 GB	0.98 GB	1.08 GB	1.05 GB
32 workers	6.19 GB	6.67 GB	7.02 GB	6.99 GB	7.08 GB	7.05 GB

- Synthetic benchmark just launch empty tasks iteratively
- Resilient 1D stencil code execute 128 tiles (16K points per tile) per iteration (**4 tasks per worker**)
- Executed 1M iterations

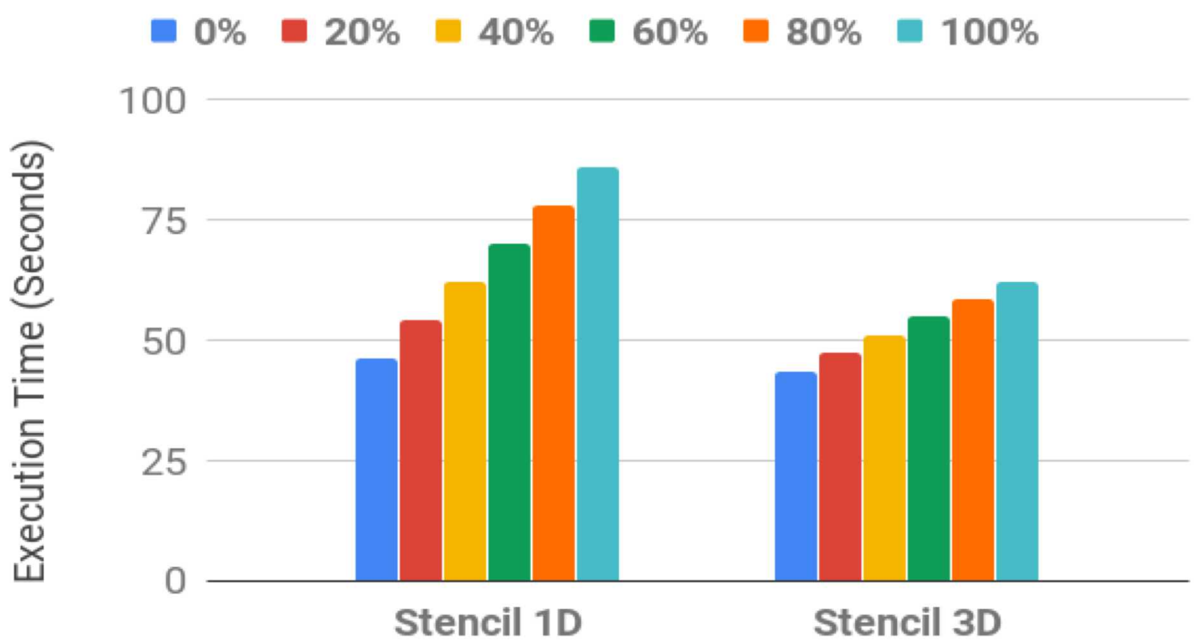
- Tested on NERSC's Cori (2 Haswell CPUs, 32 cores total, 2.3GHZ) system

Performance without faults



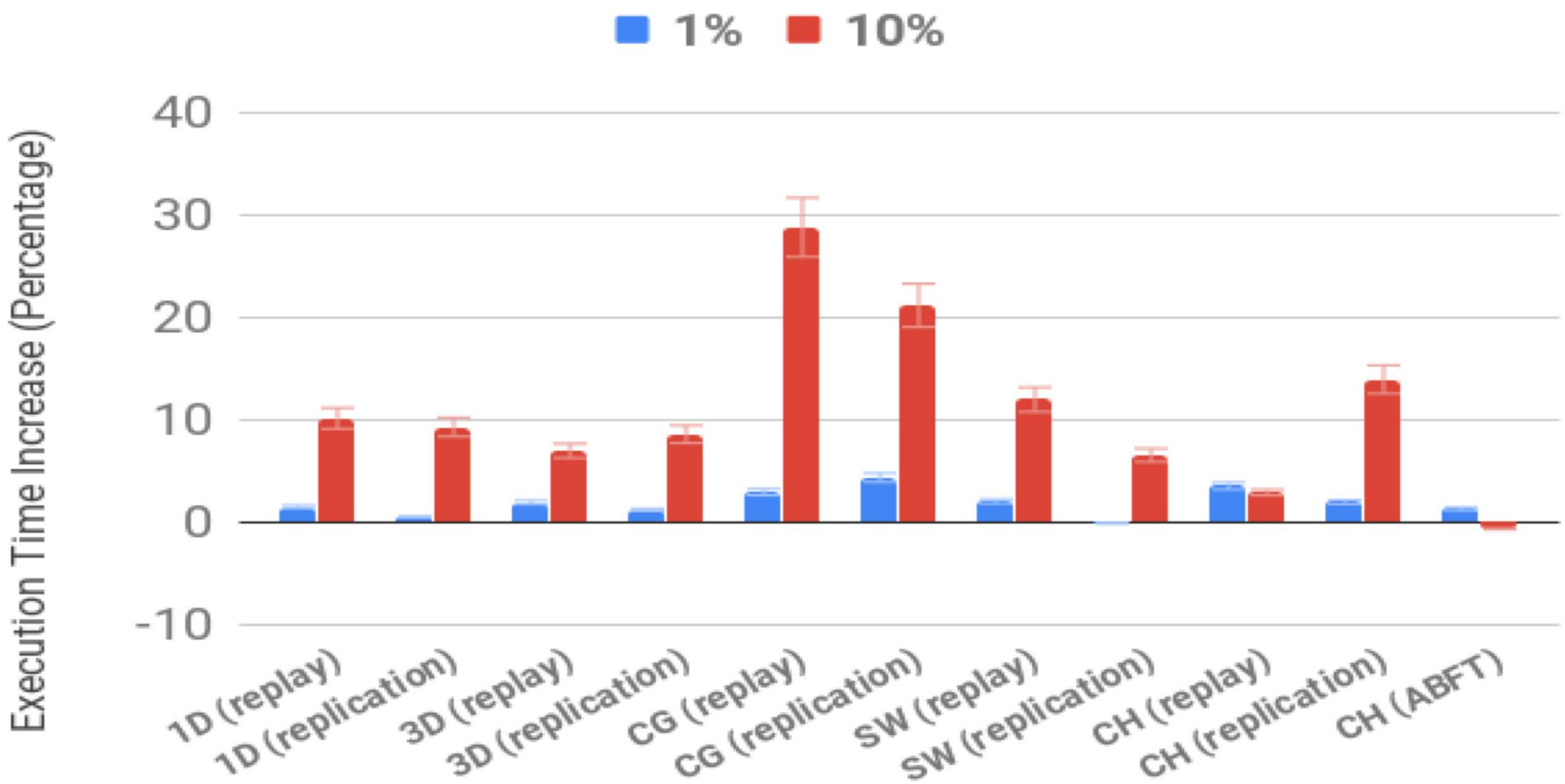
- Replication is expensive for 1D stencil, CG and SW.
- Observed some cache hits with 3D stencil
- High cache hits and critical path in task-base Cholesky suffers less replication overhead

Mixing replication and replay

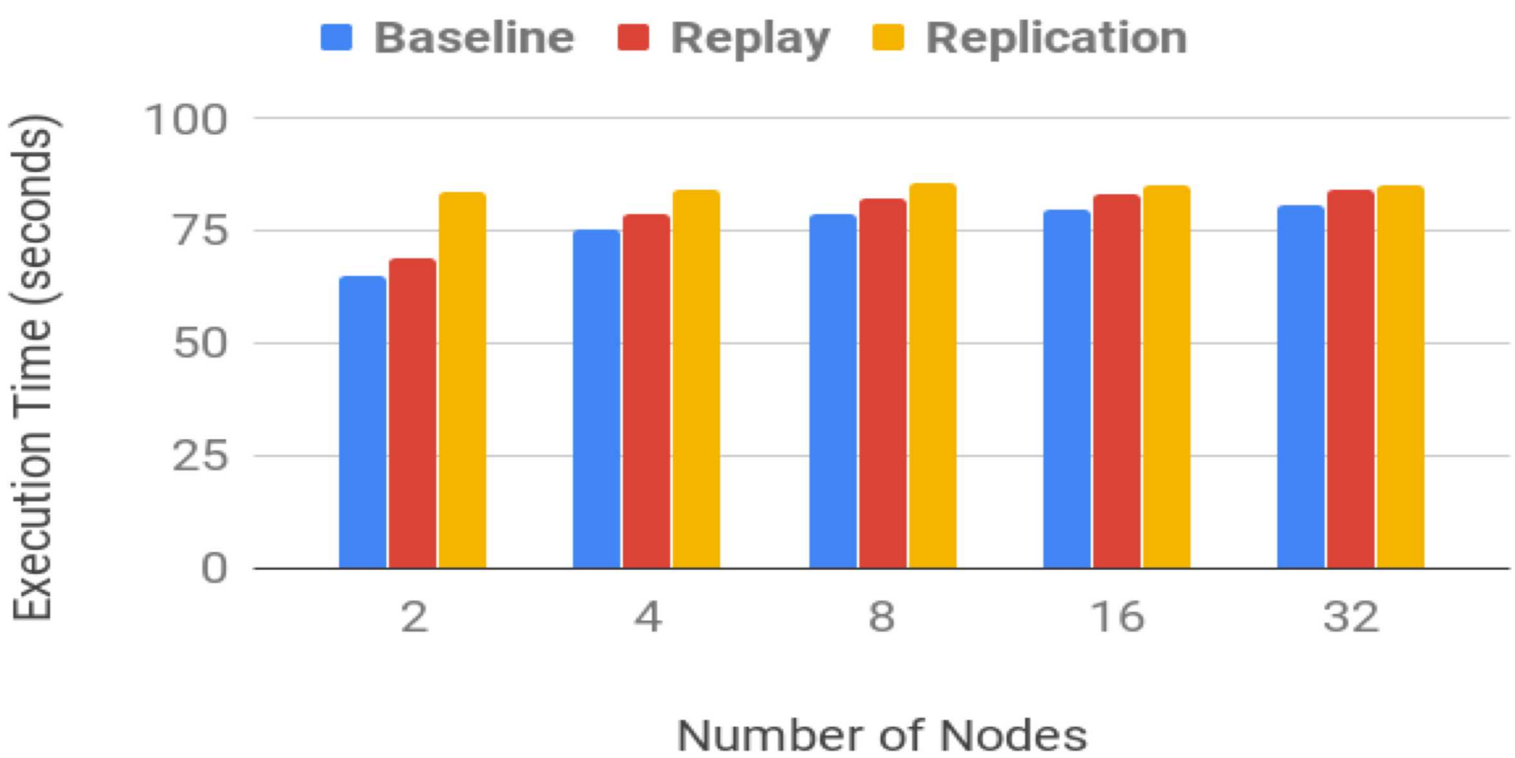


- Replication doubles the execution time of 1D case.
- We observed many L3 cache hits in the 3D case.
  - Less overhead for replication

Application delay is proportional to the # of failures

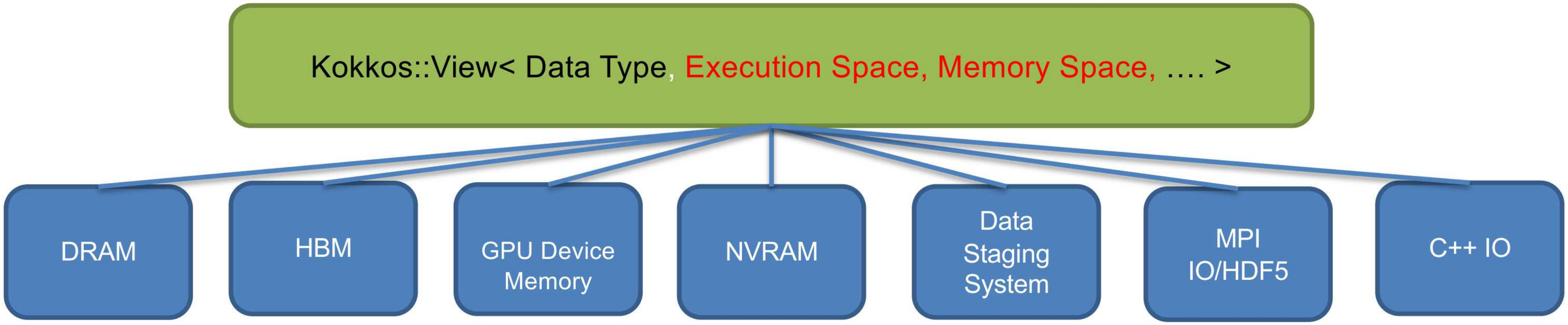


Scalability of 3D stencil code (MPI+Reslinet HCLIB)



- MPI-HCLIB implementation (1D, Weak scaling, over-decomposed)
  - No failure
  - MPI (2-sided) calls are running on special worker (thread-funnel).
  - Preliminary results indicate replication overhead are masked by MPI overhead

Ongoing Work: Resilient Kokkos



- Kokkos provides abstraction of data and (on-node) parallel program execution
  - Kokkos::View provides an array with a variety of tunable parameters through template
  - Execution and Memory Space to provide performance portability over multiple node architecture
  - Exploit C++ Lambda to support parallel program execution
- Kokkos' abstraction to enable resilient parallel computation!

Resilient Kokkos enables resilient data parallel computation

```
Kokkos::View<double *, ..., ResilientSpace> A(1000);
parallel_for( RangePolicy<>(0, 100 ), KOKKOS_LAMBDA (
const int i)
{
  A(i) = ... ;
});
```

Replication

```
parallel_for( RangePolicy<>(0, 100 ), KOKKOS_LAMBDA ( const int
i)

{
  A(i) = ... ;

});
```

```
Kokkos::View<double *, ..., ResilientSpace> A(1000);

parallel_for( "loop_1", RangePolicy<>(0, 100 ),
KOKKOS_LAMBDA ( const int i)

{
  A(i) = ... ;

});
```

Automatic Checkpointing

Checkpoint
"loop_1,A"

Conclusion

- Discussed Resilient Programming Models for:
  - Asynchronous Many Task Programming Model
    - Analytical model
    - Simulator based study
    - Resilience is embedded to the programming model itself.
    - Simple extension of tasking API to enable resilient computation patterns
  - Kokkos
    - Extend **Memory and Execution Space** concept to enable reslience in application data and computation

Q&A