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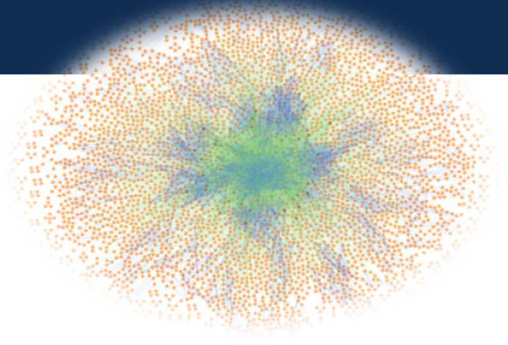

Programming Model Tradeoffs for Global vs Local Recovery: Algorithm Based Fault Tolerance

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U.S. DEPARTMENT OF ENERGY
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Outline: Talk of Two Halves

1. Programming models for scalable resilience.

2. Algorithm Based Fault Tolerance: Global vs Local recovery.

Outline

1. Programming models for scalable resilience.
2. Algorithm Based Fault Tolerance: Global vs Local recovery.

Motivations and Background

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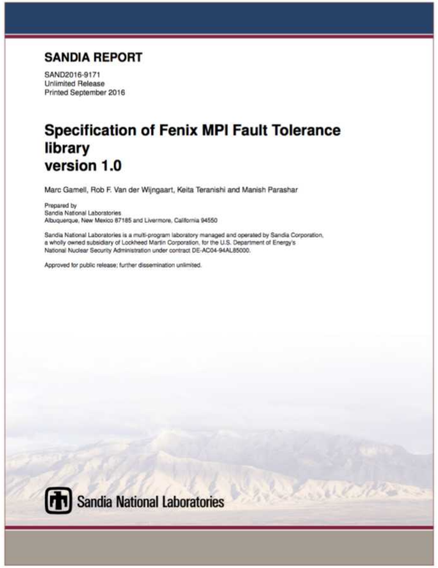
- Reliability has become a major concern of large scale computing systems
  - Complexity of hardware and software (number of components)
  - Overhead for reliability enhancement (20% penalty in power and performance)
  - Performance variability across cores, accelerators and nodes
- System level approach is expensive and C/R cannot resolve all resilience issues.
- Need better programming model support
  - Extension of Fault Tolerant MPI Proposal (Fenix)
  - On-node parallel computing
    - Asynchronous Many Task (AMT)
    - Resilience Extension of Kokkos
  - Distributed (AMT)

Fenix: Extending MPI-ULFM

- MPI-ULFM has been proposed for the fault tolerance APIs of the MPI standard (hard errors and failures)
- Survived processes continues after MPI rank failures
- New MPI functions for fixing MPI communicator
  - MPI_Comm_agree --- Sanity check (resilient collective)
  - MPI_Comm_revoke --- Invalidate MPI Communicator
  - MPI_Comm_shrink --- Fix MPI Communicator removing dead process
- User is responsible for the recovery after MPI_Comm_shrink

Fenix:

- Fault Tolerant Programming Framework for MPI Applications
  - Separation between process and data recovery
    - Allows third party software for data recovery
    - Multiple Execution Models
  - **Process recovery**
    - Extend **MPI-ULFM**
    - Process recovery through **hot spare process pool**
    - Process failure is checked at **PMPI layer** and recovery happens automatically under the cover
  - **Data recovery**
    - In-memory data redundancy
    - Multi-versioning (similar to GVR by U Chicago & ANL)


SANDIA REPORT

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Specification of Fenix MPI Fault Tolerance library version 1.0

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Fenix – Process Recovery Interface

```
void Fenix_Init (MPI_Comm comm,
                 MPI_Comm *newcomm,
                 int *role,
              int *argc, int ***argv,
              int num_spare_ranks,
              int spawn,
                MPI_Info,
              int *error);
```

If **newcomm** is NULL, Fenix tacitly replaces **comm** everywhere with resilient communicator

role:
- FENIX_ROLE_INITIAL_RANK
- FENIX_ROLE_RECOVERED_RANK
- FENIX_ROLE_SURVIVOR_RANK

spawn:
- 0:NO_SPAWN
- 1:SPAWN

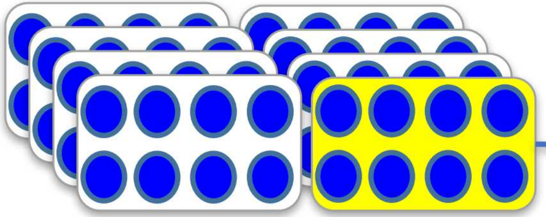
App should use **resilient communicator** (newcomm) instead of comm

Process failure triggers process recovery and long-jump to Fenix_init

```
void Fenix_Finalize ( );
```

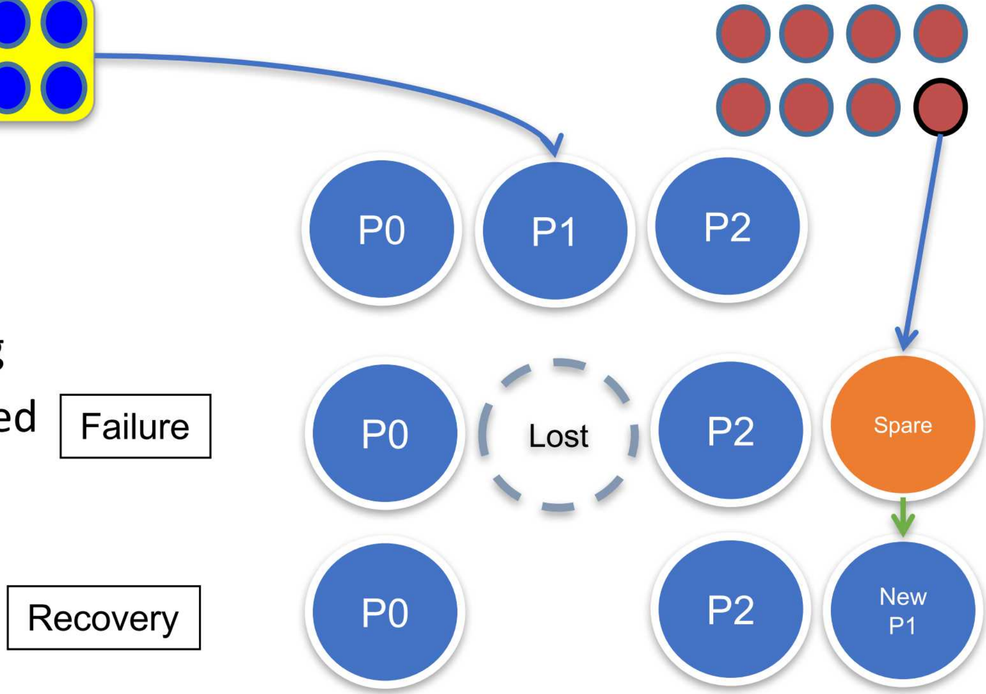
Non-Shrinking Model (with spare processes)

Compute Processes



Spare processes
(allocated at job launch)

- Fenix automatically corrects rank-ordering
- Spare ranks are ordered to fill the lost ranks



Non-Shrinking Model (Spawn)

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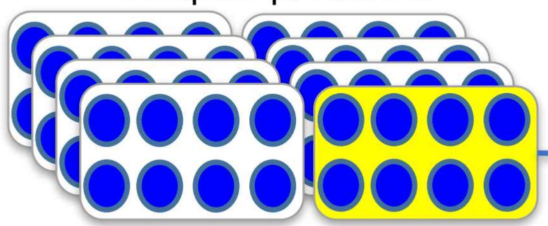
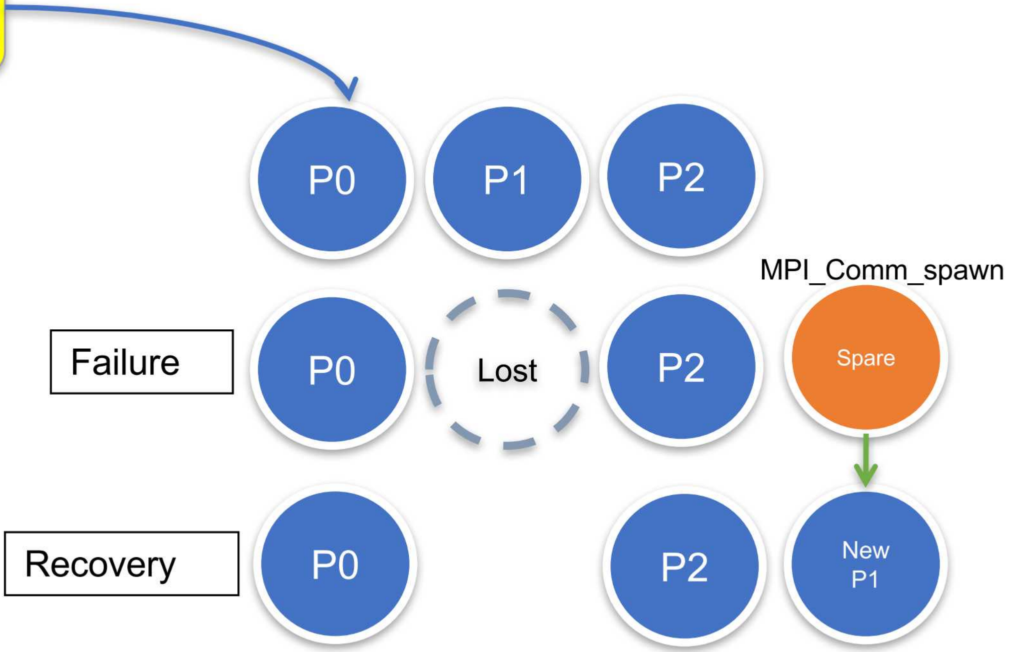
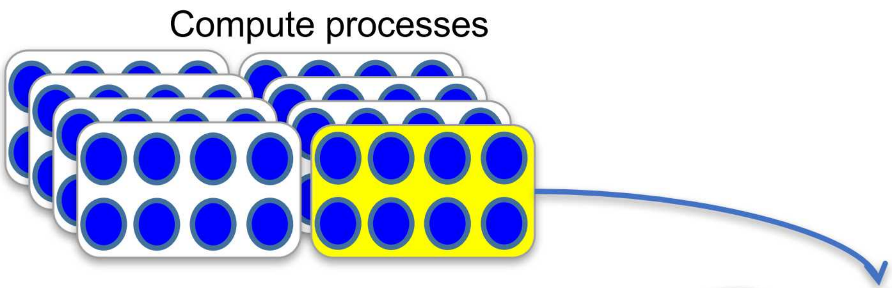


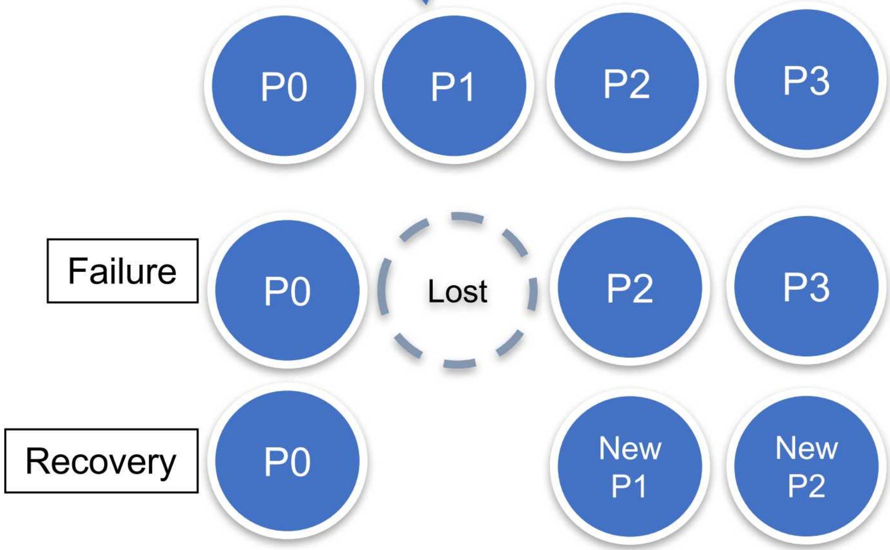
- Fenix automatically correct rank-ordering
- Spare ranks are order to fill the lost ranks
- Depends on the support of MPI_Comm_spawn



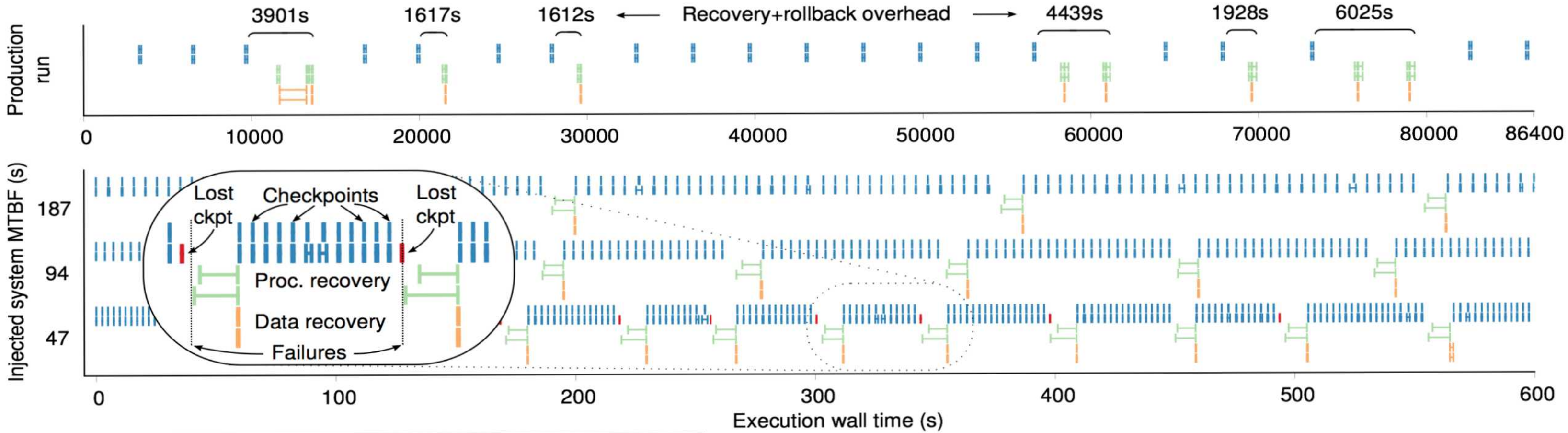
Shrink Model



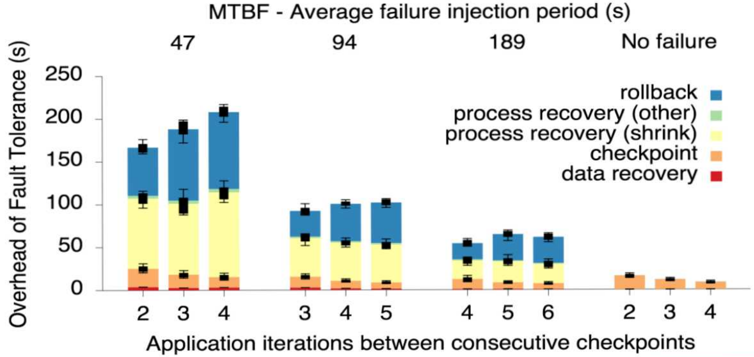
- Rank ordering after the failure is determined by MPI-ULFM.
- Fenix returns the program to the beginning.
  - User is responsible for reconstruct the state



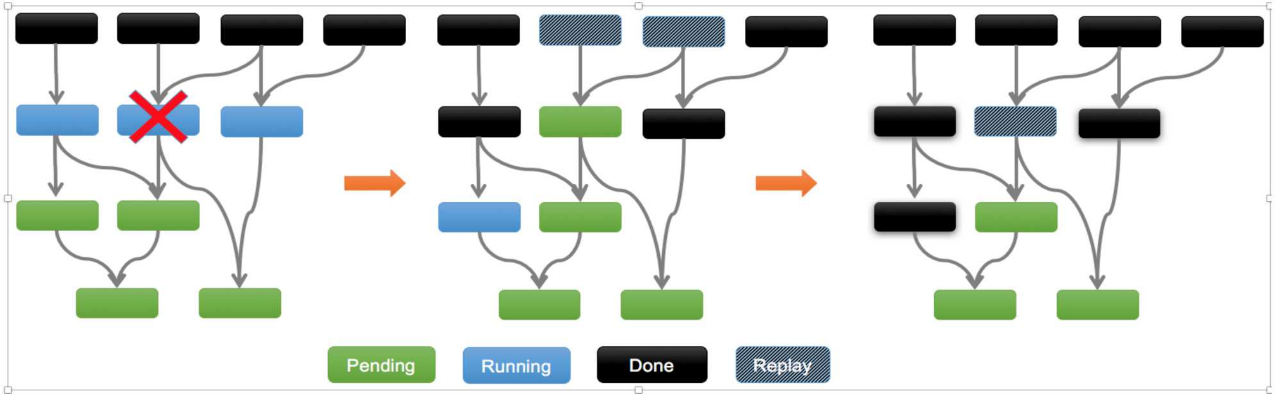
FENIX can recover from **frequent failures**



- Online recovery allows the usage of in-memory checkpointing, O(1s).
- Efficient recovery from high frequency node failures, as exascale compels.
- **With failures injected every 189, 94 and 47 seconds,** the total job run-time penalty is as low as **10%, 15% and 31%, respectively**.
- This can dramatically improve by optimizing ULFM shrink.



Node Level Parallel Programming Model



- Abstraction of computation and data objects allows automatic resilience support
  - Runtime scheduler orchestrates computations encapsulated by Task and parallel_for
  - Data abstractions to describe dependencies, data layout and access patterns (Read/Write/RW)
- Simple extension to the existing API provides knobs to the users to selectively apply resilience

Resilient AMT Prototype

- Resilience Extension of Habanero C++
  - AMT programming Interface by Vivek Sarkar
- Simple extension allows the user to introduce 3 major resilient program 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);
```

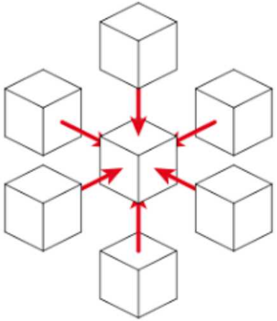
Task Launch with Replication

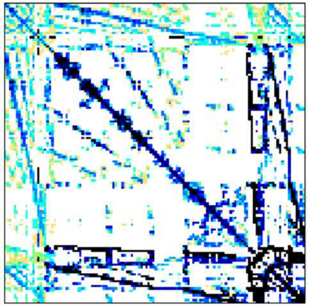
```
diamond::async_await_check<N> (
lambda, hclib::promise<int>
out, hclib_future_t *f1, ..,
hclib_future_t *f4);
```

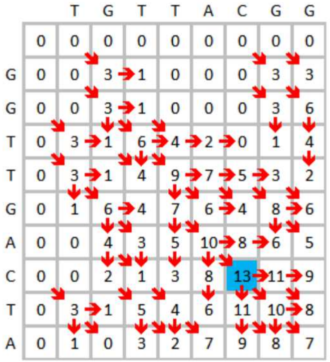
Task Launch with Replay

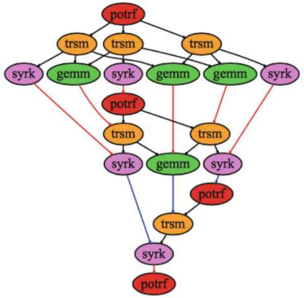
```
replay::async_await_check<N>(
lambda, hclib::promise<int>
out, std::function<int(void*)>
error_check_fn, void * params,
hclib_future_t *f1, .. ,
hclib_future_t *f4);
```

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

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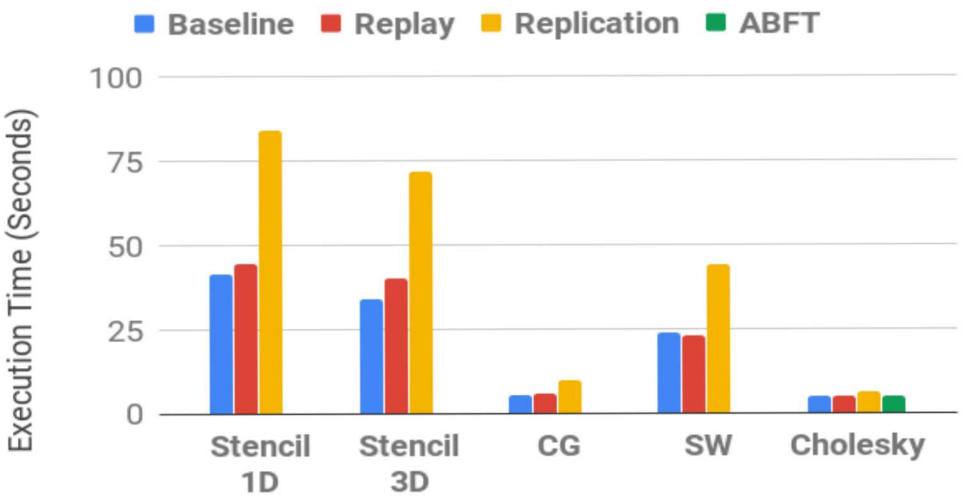
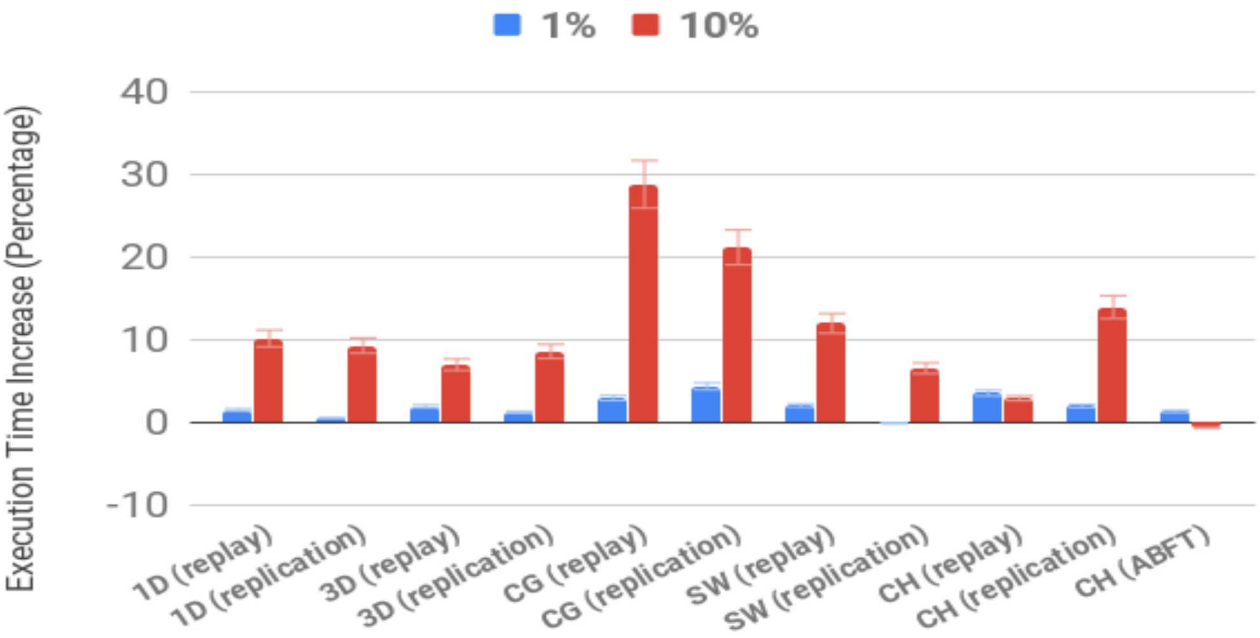
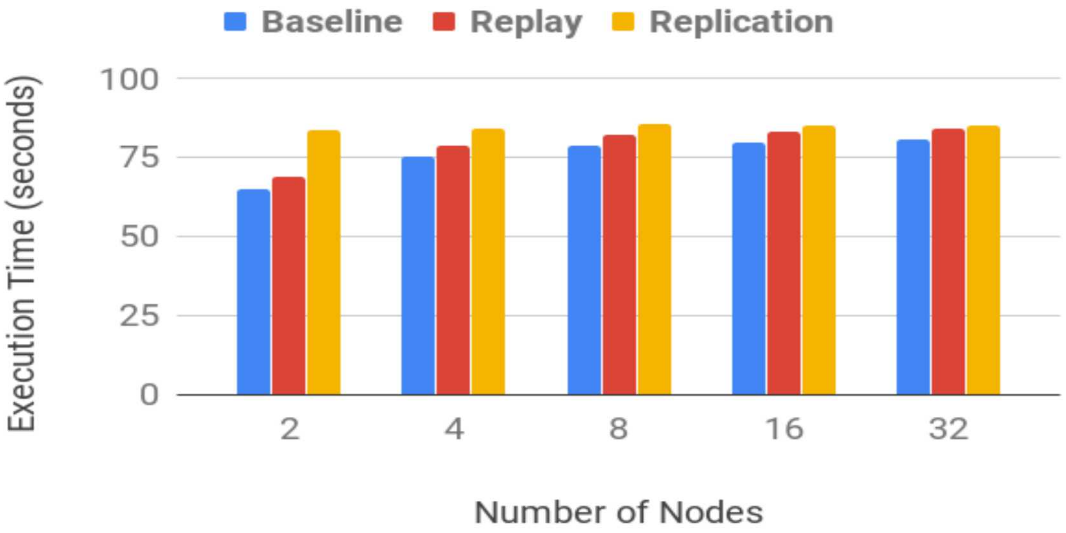


- Replication is expensive for 1D stencil, CG and SW.
- Observed some cache hits with 3D stencil
- High cache hits and critical path in task-base Cholesky suffers less replication overhead

Application delay is proportional to the # of failures

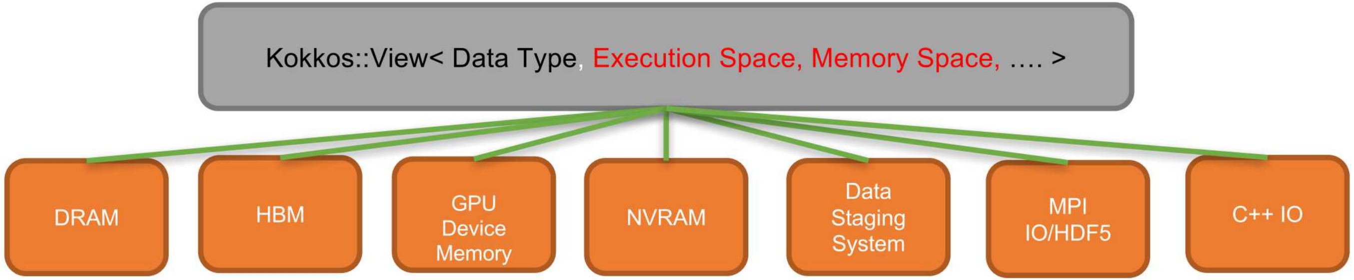


Scalability of 3D stencil code (MPI+Reslinet HCLIB)



- MPI-HCLIB implementation (1D, weak scaling, over-decomposed)
  - 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 Space** 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 Execution Space** for redundant program execution
  - **Resilient Memory Space** for checkpointing and data redundancy

Parallel Programing with Kokkos

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Serial

```
for (size_t i = 0; i < N; ++i)
{
  /* loop body */
}
```

OpenMP

```
#pragma omp parallel for
for (size_t i = 0; i < N; ++i)
{
  /* loop body */
}
```

Kokkos

```
parallel_for (( N, [=], (const size_t i)
{
  /* loop body */
});
```

- Provide parallel loop operations using C++ language features
- Conceptually, the usage is no more difficult than OpenMP. The annotations just go in different places.

Resilient Kokkos enables resilient data parallel computation with ease

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```
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) = ... ;

});
```

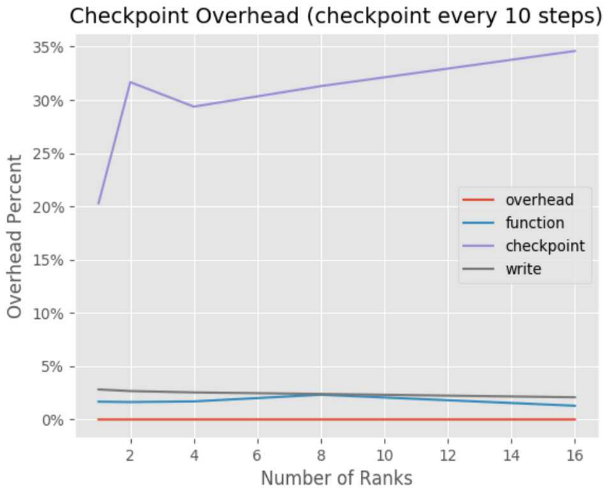
```
Kokkos::View< ... > a( "a", ... );
Kokkos::View< ... > b( "b", ... );
Kokkos::View< ... > c( "c", ... );

for ( int iter = 0; iter < 100; ++iter )
{
  // Will generate "compute_stuff/<view>.<iter>.bin" for all captured views
  Kokkos::checkpoint( "compute_stuff", iter, true, KOKKOS_LAMBDA {
    Kokkos::parallel_for( N, KOKKOS_LAMBDA( int i ) {
      // Some computation with a and b
    } );

    Kokkos::parallel_for( N, KOKKOS_LAMBDA( int i ) {
      // Some other computation with a and c
    } );
  } );
}
```

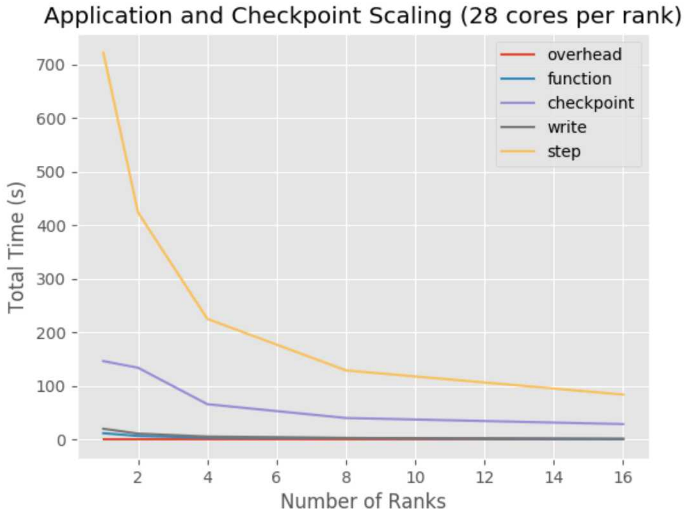
Lambda captures all Kokkos::View instances

Automatic Checkpointing

Checkpoint
"loop_1_A_B_C"

Performance of MiniMD





- Molecular Dynamics App: 32M atoms in 200x200x200 cells
- Strong scalability on 2CPUs/Node Haswell Cluster with FDR IB
- Checkpoint every 10 time steps
- Resilient Memory Space interfaced to VeloC (using the file-based checkpointing)
- **Negligible overhead for Kokkos runtime**

Outline

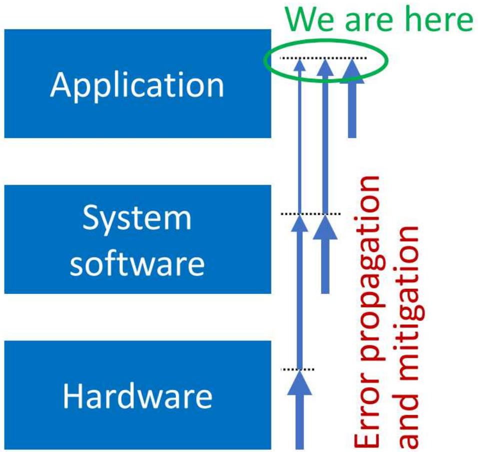
1. Programming models for scalable resilience.

2. Algorithm Based Fault Tolerance: Global vs Local recovery.

Algorithm Based Fault Tolerance (ABFT)

- Handling hard failures is not enough for resilience.
  - An error does not always cause a crash, but leads to a “wrong” answer.
  - Physics of the problem could be leveraged to detect an error, before wide spread failure.
- Application-level detection can be a powerful complement to resilient programming models

Levels:



Example uncertainties:

How solver apps will be (re)written (programming models); prevalence of unreproducible bugs

Ability of bugs here to corrupt the app state

Rates of (initially) undetected errors; costs of mitigating in hardware (higher voltage, redundancy, shielding)

Generalizing ABFT: Physics Based Checksums

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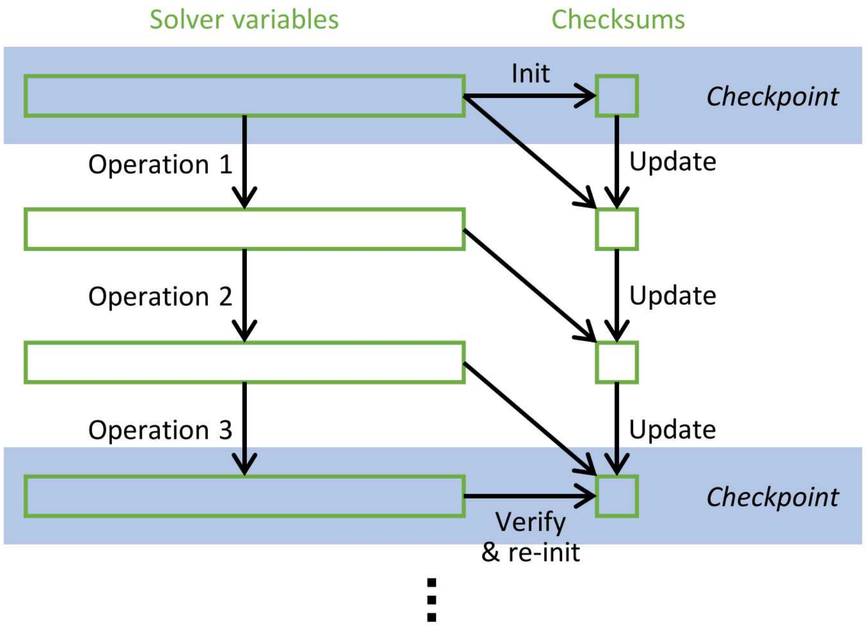
- Leverage existing work on ABFT for linear algebra, but incorporate physics.
- **Key idea:** Focus only on detection of silent errors, treat them same as hard failures.
- Enabling assumptions:
  - Failures are locally rare (component MTBFs are long, if not system MTBFs).
  - Checkpoint/restart in some form will be used/available.
  - Keep resilience overhead small.
  - Applications are solving physics equations that satisfy conservation laws.
  - Silent hardware errors and software anomalies will typically violate conservation.

Checksums for Efficient Redundancy

- Introduce a smaller side computation that remains consistent with solver state if no errors.
- Verify consistency intermittently, just before each checkpoint



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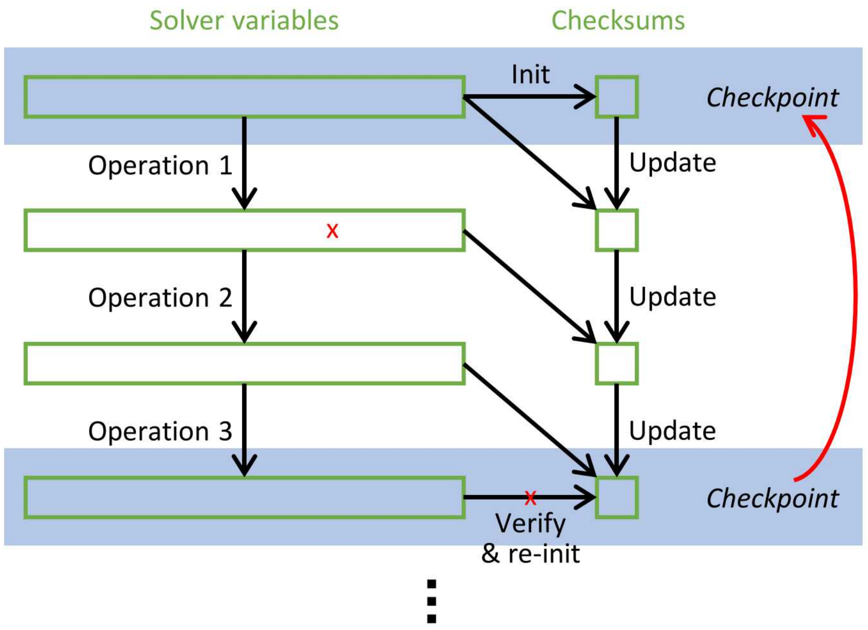


Checksums from Conservation Laws

- General local conservation law (density ρ, flux $\mathbf{J}$): $\frac{\partial \rho}{\partial t} = -\nabla \cdot \mathbf{J}$
- Conserved quantity in a region *R* (e.g., a computational subdomain): $Q(R) = \int_R dV\, \rho$
- Integrated conservation law: $\frac{dQ(R)}{dt} = -\oint_{\partial R} d\mathbf{S} \cdot \mathbf{J}$
- *Q(R)* changes only by flux through boundary, which is much faster to compute than *Q(R)* itself:
  - When discretized form of this conservation law holds, *Q(R)*, is a local physics-based checksum that can be updated efficiently and verified intermittently.
  - No global communication beyond what solver already performs; flux in each subdomain can be computed from data already being communicated between processes.

Application: 1D Linear Advection Equation

- 1D linear advection equation $\frac{\partial \phi}{\partial t} + \nu \frac{\partial \phi}{\partial x} = 0$
- Consider the Lax-Wendroff stencil (with $c = \nu \Delta t / \Delta x$):

$$\phi_j^{n+1} = \tfrac{1}{2} c(c+1)\phi_{j-1}^n + (1-c^2)\phi_j^n + \tfrac{1}{2} c(c-1)\phi_{j+1}^n$$

- The discretized conserved quantity on each local subdomain is $Q(\phi) = \sum_i \phi_i$
- The conserved quantity, checksum, can be updated independently of local state:

$$Q(\phi^{n+1}) = Q(\phi^n) + \frac{c(c+1)}{2}(\phi_{-1}^n - \phi_{N-1}^n) + \frac{c(c-1)}{2}(\phi_N^n - \phi_0^n)$$

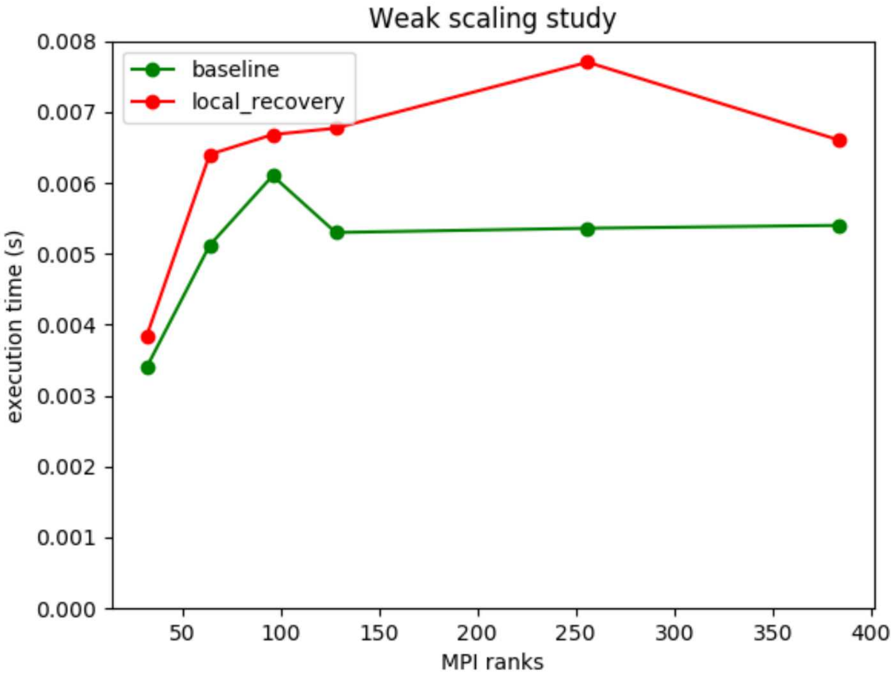
  - Checksum update requires only neighbouring (ghost) points.

Local vs Global Recovery

- The physics based checksum allow an efficient, purely local error detection mechanism.
- Upon detection, suitable resilience mechanisms can be deployed.
- Checkpoint/Rollback is most common; but global rollback recovery is a disproportionate response for a purely local detection mechanism.
- We examined “local” and “global” recovery using Fenix:
  - An MPI-based fault tolerance library for distributed resilience.
  - Primary design is for hard failure (process loss); built on top of MPI-ULFM.
  - Provides APIs for data “store”/ “restore” operations to recover from process loss.
  - Extended to provide purely local recovery (no MPI process loss, no communication for store/restore).

Results: Weak scaling study

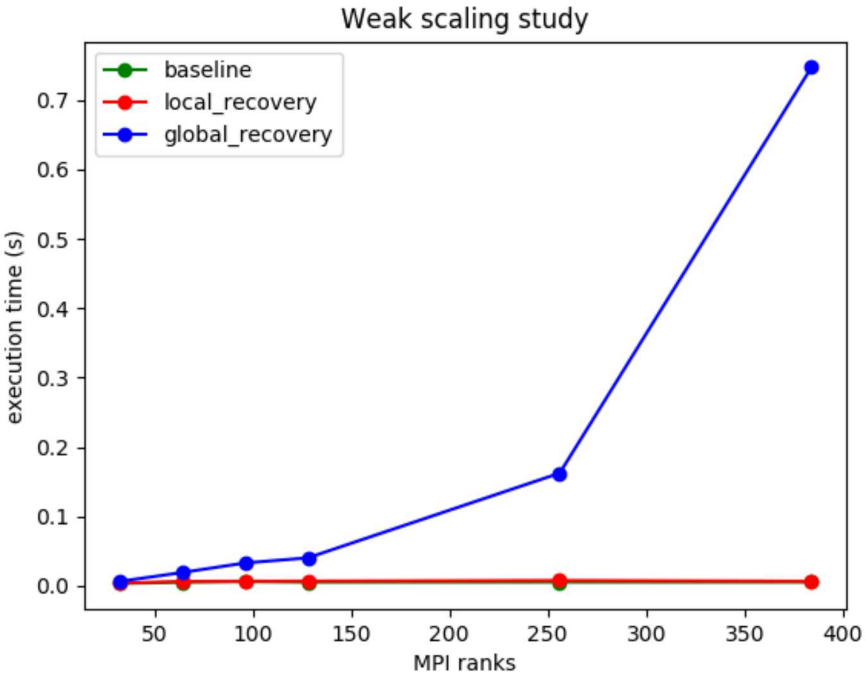
- Weak scaling study of baseline, local_recovery and global_recovery versions of 1D stencil.
- Emulated silent error rate of 0.01, 1000 grid points per rank, 1000 iterations, runs on Cori.



- Local checkpoint/restart adds marginal overhead.
- Does not disrupt weak scalability of the baseline code.
- Problem size is cache friendly.

Results: Weak scaling study

- Weak scaling study of baseline, local_recovery and global_recovery versions of 1D stencil.
- Emulated silent error rate of 0.01, 1000 grid points per rank, 1000 iterations, runs on Cori.



- Global recovery involves an global agreement (anyone fails, everyone rolls back).
- Not scalable, recovery cost scales with number of ranks.
- Cascading cost of recovery (some ranks stuck in an endless loop of restarts).