Exploiting the User's Knowledge of Resilience

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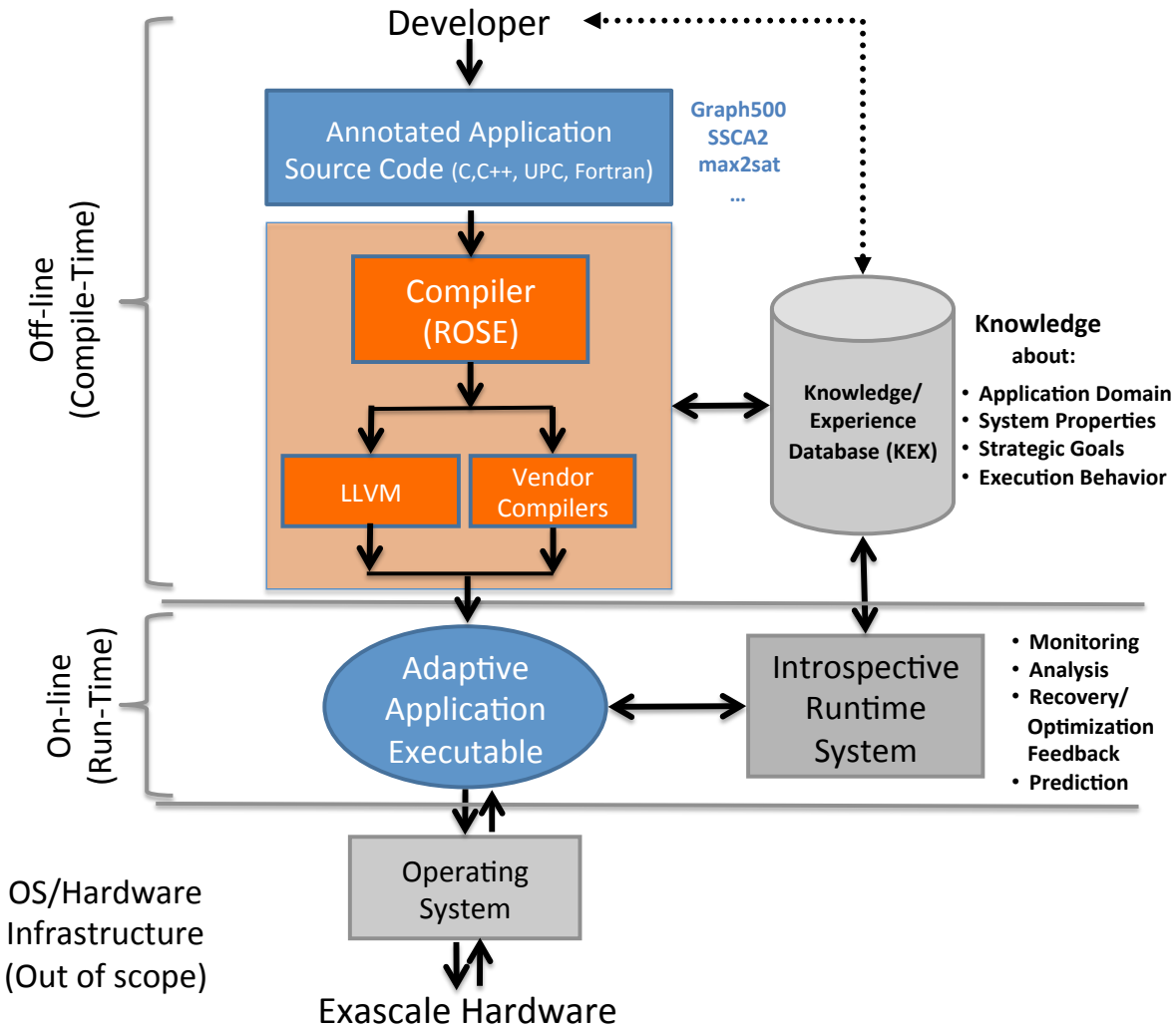
Motivation

- HPCS Random Access Benchmark explicitly tolerates a finite number of errors in both memory and arithmetic.
- Iterative solvers like Algebraic Multigrid (AMG) can hill climb over errors in intermediate state.
- Post-processing such as iterative refinement after solving a linear system can correct for small errors, as a function of condition number.
- Users can add their own fault detection and correction techniques.
- You can often roll back.

Resilient Software Architecture



RoLex: Resilience Oriented Language Extensions

- **Language extensions that allow scientific application programmers to encode their fault resilience knowledge and expectations within their application codes.**

- **Application-level error management capabilities:**
  - **Error Detection**
  - **Error Containment**
  - **Error Recovery**

  made intrinsic to application code.

- **Tightly coupled compiler infrastructure and runtime inference system**
  - **Allows programmer knowledge to be used for error management during application execution.**

RoLex: Design Objectives

- Maintain familiarity of current programming models
  - FORTRAN/C/C++ dominant choice of languages for HPC application programmers
- Concise and elegant syntax: small set of new language keywords
  - Seek to minimize the time and effort for programmers to learn and adopt RoLex
- Fair division of work between language extensions and the compiler & runtime framework
- Interoperability with other programming models/libraries
  - Message Passing Interface(MPI) as well as certain well-tuned productivity libraries such as BLAS and LAPACK
- Sensitive to performance features
  - Extensions and compiler transformations should not drastically alter code structure

RoLex Programming Model

Extensions to the C/C++ language

Type Qualifiers

- Specify how the program variables are dealt with by the runtime system when the associated variable is in error state

```
<error-management-qualifier> int array[N];
<error-management-qualifier> float matrix[M][N];
```

Directives

- Specify error management knowledge on structured blocks of computation
- In C/C++ #pragma directive species program behavior

```
#pragma <error-management-directive>
{
    /* structured blk: computation*/
}
```

Library Routines

- Extensions to existing standard library calls with error management

```
resilience_<error-management-routine>_libroutine
```

RoLex: Tolerance Extensions

Type Qualifiers

```
tolerant<precision.6f> float low_precision;
tolerant int rgb[XDIM][YDIM];
tolerant<MAX.VALUE=...> unsigned int counter;
```

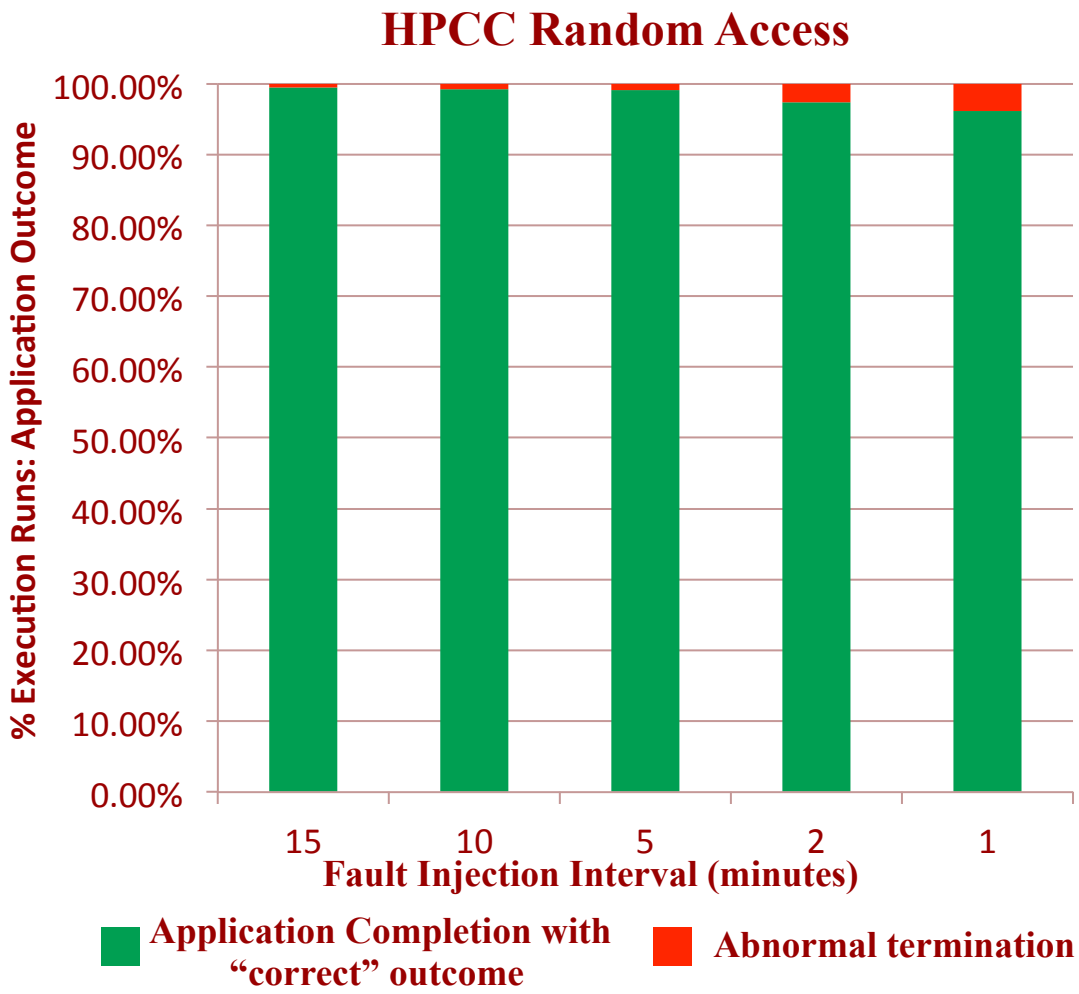
Directives

```
#pragma resilience recover-rollback share (variable_list) private(variable_list)
{ /* code block */ }
#pragma resilience recover-rollforward share(variable_list)
{ /* code block */ }
```

Library Routines

```
<type>* <var>  = (<cast>) resilience_malloc_tolerant (sizeof(<type>));

int*    array  = (int*)
                 resilience_tolerant_malloc (NUM*sizeof(int <MAX.VALUE=..>));

double* matrix = (double*)
                resilience_tolerant_malloc (NUM*sizeof(double <PRECISION=...>));
```

Evaluation: RoLex Tolerance Extensions

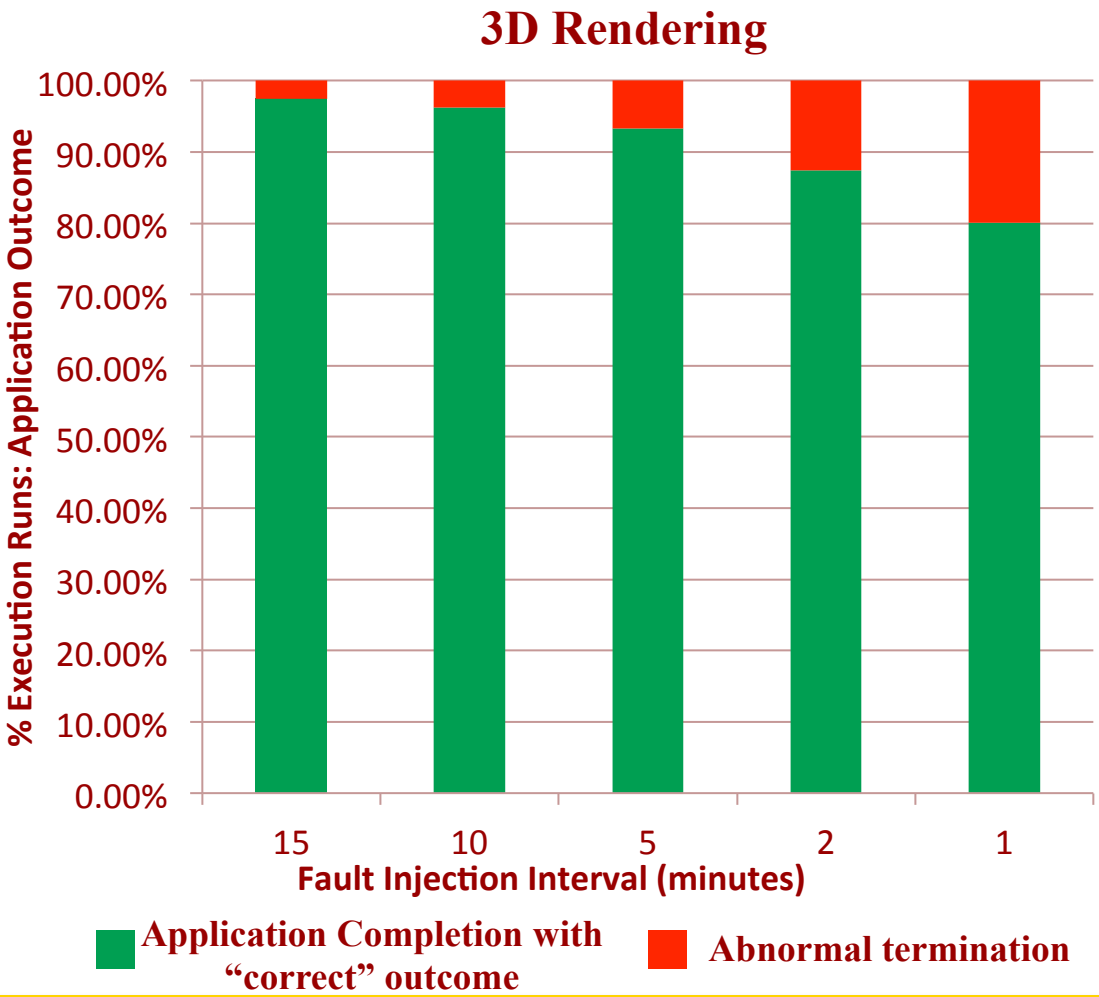


Application: Pseudo-random updates on large memory table (HPCC_Table)

RoLex: We allocate the HPCC_Table with the tolerant version of the malloc routine

Faults: Hardware uncorrectable multi-bit perturbations; raises SECDED violation to runtime system.

Evaluation: RoLex Tolerance Extensions

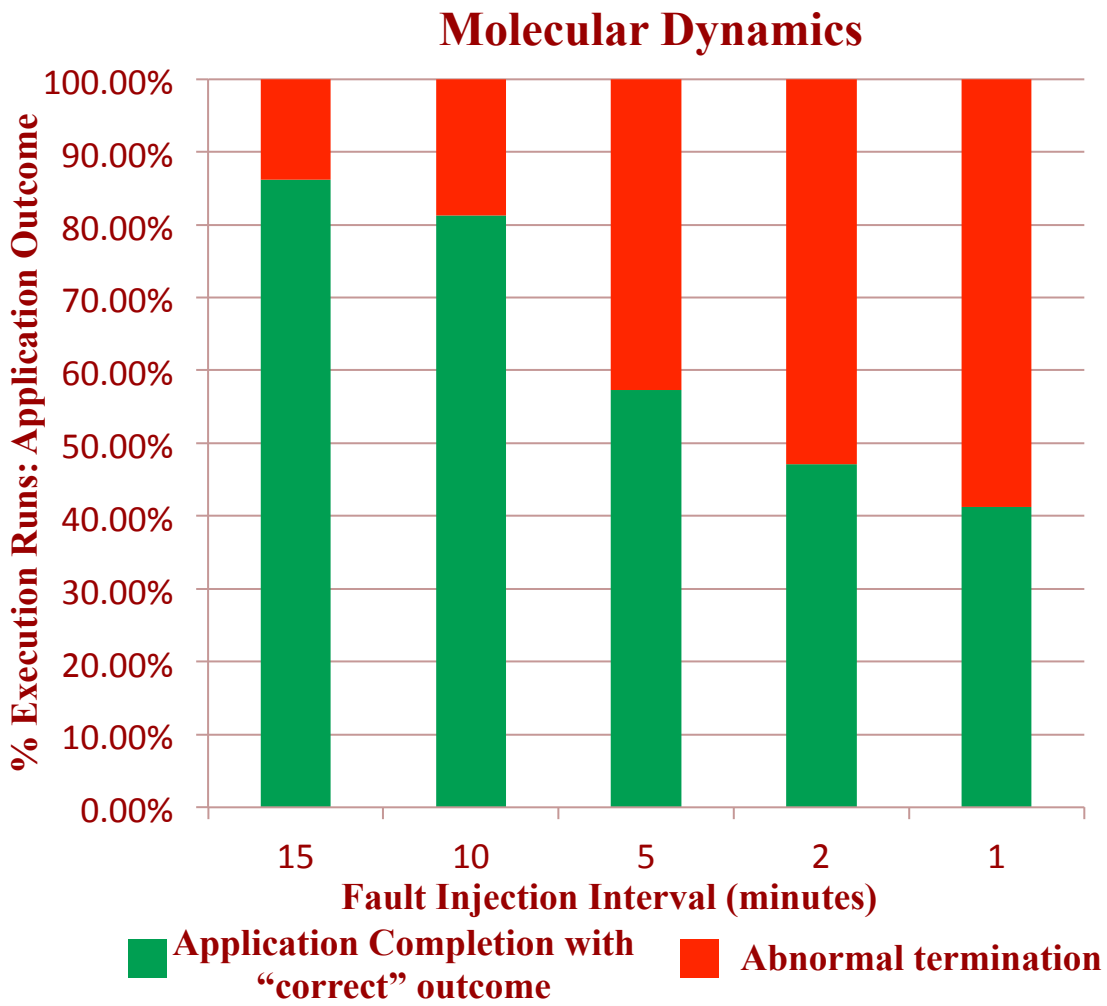


Application: Renders 3D model of a scene into a 2D screen representation. Final rendered scene written to frame buffer (declared as a 2-D array)

RoLex: We qualify frame buffer declaration tolerant type qualifier

Faults: Hardware uncorrectable multi-bit perturbations; raises SECDED violation to runtime system.

Evaluation: RoLex Tolerance Extensions



Application: MD simulation

RoLex: We qualify the Floating-point array structures for the particle position, velocity and acceleration with tolerant <PRECISION=8>

Faults: Hardware uncorrectable multi-bit perturbations; raises SECDED violation to runtime system.

RoLex: Robustness Extensions

Type Qualifiers

```
robust (CORRECT) int* csr_matrix [ row_offsets ];
robust (DETECT)  int* graph_edge_list [N];
```

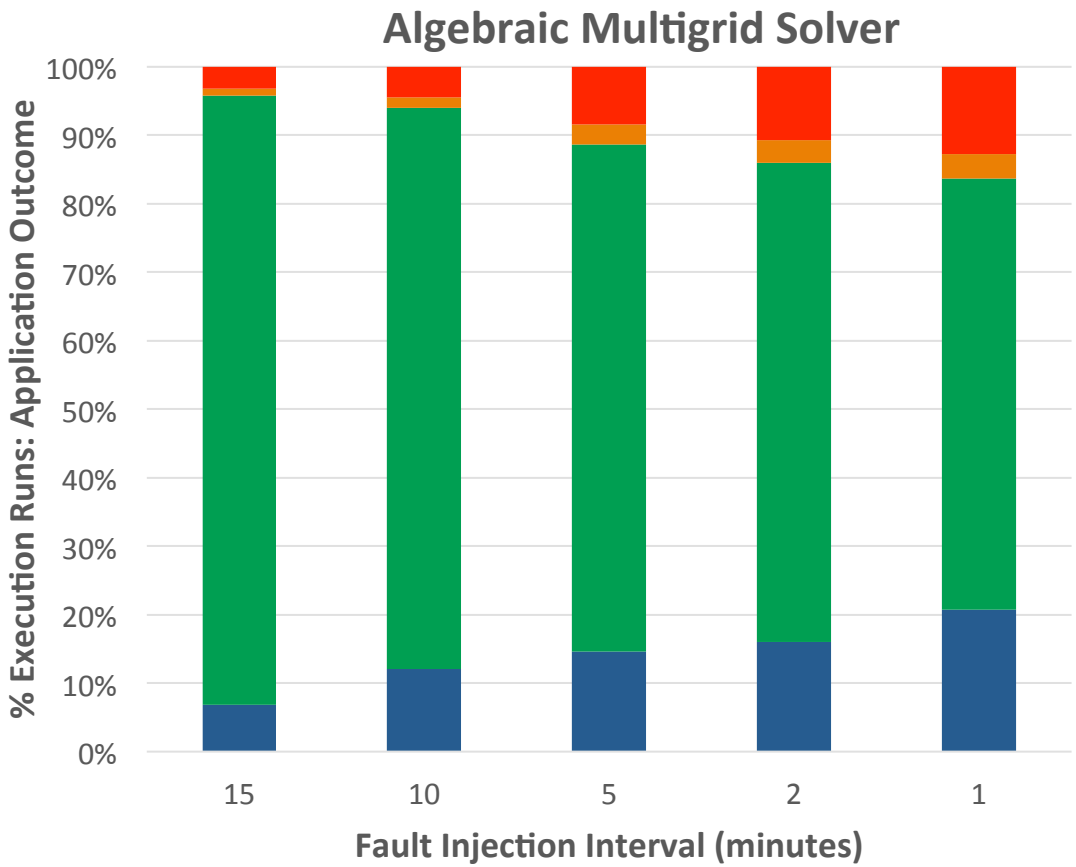
Directives

```
#pragma resilience robust detect share(variable_list) private(variable_list)
compare( variable_list)
{
  /* code block */
}
#pragma resilience robust correct share ( variable_list ) private ( variable_list ) compare
( variable_list )
{
  /* code block */
}
```

Library Routines

```
float* problem_matrix = ( float *) resilience_malloc_robust( N * sizeof ( float), STRENGTH );

resilience_validate_detect ( void * problem_matrix );
resilience_validate_correct ( void * problem_matrix );
```

Evaluation: RoLex Robustness Extensions



Application: Algebraic Multigrid Linear Solver.

RoLex: We qualify the pointer references for the matrix references using the robust qualifier; intermediate solution grids allocated with tolerant version of malloc routine.

Faults: Silent Data Corruptions; no hardware interrupt raised to the runtime system.

Silent Data Corruption Detected/Corrected through RoLex Robust Extensions

Benign Faults

Undetected Faults leading to Incorrect Outcome

Application Crash

RoLex: Amelioration Extensions

Type Qualifiers

```
heal (recovery_func()) float* matrix_A[N][N];
```

Directives

```
#pragma resilience recover-rollback reinitialize( variable_list )
{ /* code block * }
#pragma resilience recover-rollforward reinitialize( variable_list )
{ /* code block * }
#pragma resilience recover-rollback ameliorate(recovery_func())
{ /* code block */ }
#pragma resilience recover-rollforward ameliorate(recovery_func())
{ /* code block */ }
```

Library Routines

```
float * problem_matrix = (float*)
                      resilience_malloc_repairable(N * sizeof(float),checksum_func_pointer);

resilience_ameliorate_heal(void* problem_matrix);
```

Conjugate Gradients

```
// Solve a linear system with conjugate gradients

for(int k=1; k<max_iter && normr > tol; k++ ) {
  oldrtrans = rtrans;
  ddot (nrow, r, r, &rtrans, t4);
  beta = rtrans/oldrtrans;
  waxpby (nrow, 1.0, r, beta, p, p);
  normr = sqrt(rtrans);
  sparsemv(A,  p,  Ap);
  ddot(nrow,  p,  Ap, &alpha, t4);
  alpha = rtrans/alpha;
  waxpby(nrow, 1.0, x, alpha, p, x);
  waxpby(nrow, 1.0, r, -alpha, Ap, r);
  niters = k;
}
```

Sparse Matrix Structure

```
// Structure of sparse matrix A that will be protected with checksums,
// i.e., algorithm-based fault tolerance

HPC_Sparse_Matrix *A;
A->nrow = (int) nrow;
A->nnz = (int) nnz;
A->values = (double *) malloc ((nnz) * sizeof(double));
A->indices = (int *) malloc ((nnz) * sizeof(int));
A->ptr_to_rows= (int *) malloc ((nrow + 1) * sizeof(int));
```

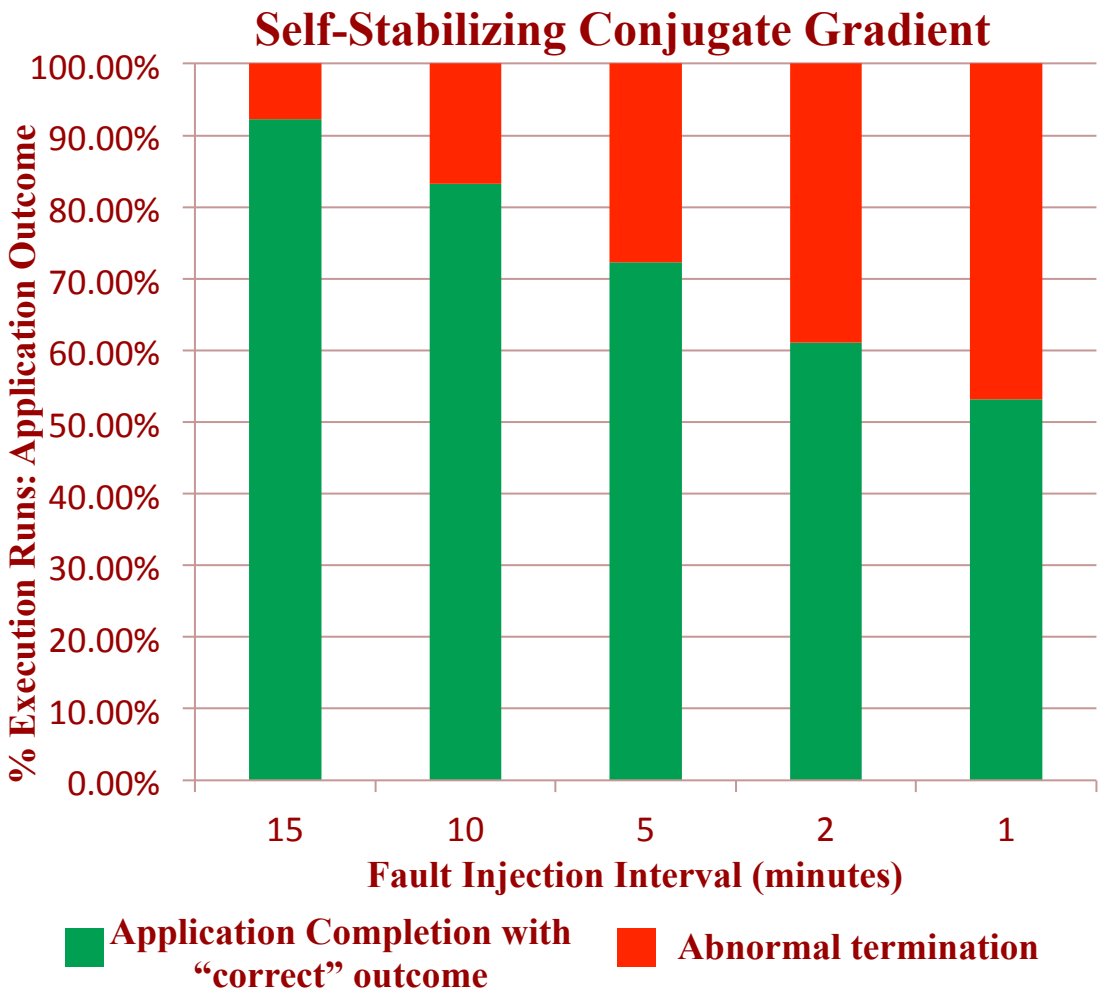
Checksum-based Fault Tolerance (Thanks Jack!)

```
// Checksum vectors for user-provided, checksum-based, repair functions.

coef_row_sum = (unit64 *) malloc (A.nrow * sizeof(double));
coef_col_sum = (uint64 *) malloc (A.nrow * sizeof(double));
ind_row_sum = (uint *) malloc (A.nrow * sizeof(int));
ind_col_sum = (uint *) malloc (A.nrow * sizeof(int));

// User-defined checksum functions

CreateChecksumD(* HPC_Sparse_Matrix, uint64* coef_row_sum, uint64* coef_col_sum);
CreateChecksumI(* HPC_Sparse_Matrix, uint * ind_row_sum, uint * ind_col_sum);
RepairChecksumD(* HPC_Sparse_Matrix, uint64* coef_row_sum, uint4* coef_col_sum);
RepairChecksumI(* HPC_Sparse_Matrix, uint * ind_row_sum, uint * ind_col_sum);
```

More Resilient, But Not Immortal, Conjugate Gradients

```
// Solve a linear system with conjugate gradients

for(int k=1; k<max_iter && normr > tol; k++ ) {
  oldrtrans = rtrans;
  ddot (nrow, r, r, &rtrans, t4);
  beta = rtrans/oldrtrans;
  waxpby (nrow, 1.0, r, beta, p, p);
  normr = sqrt(rtrans);
  sparsemv(A,  p,  Ap);
  ddot(nrow,  p,  Ap, &alpha, t4);
  alpha = rtrans/alpha;
  waxpby(nrow, 1.0, x, alpha, p, x);
  waxpby(nrow, 1.0, r, -alpha, Ap, r);
  niters = k;
}
```

Evaluation: RoLex Amelioration Extensions

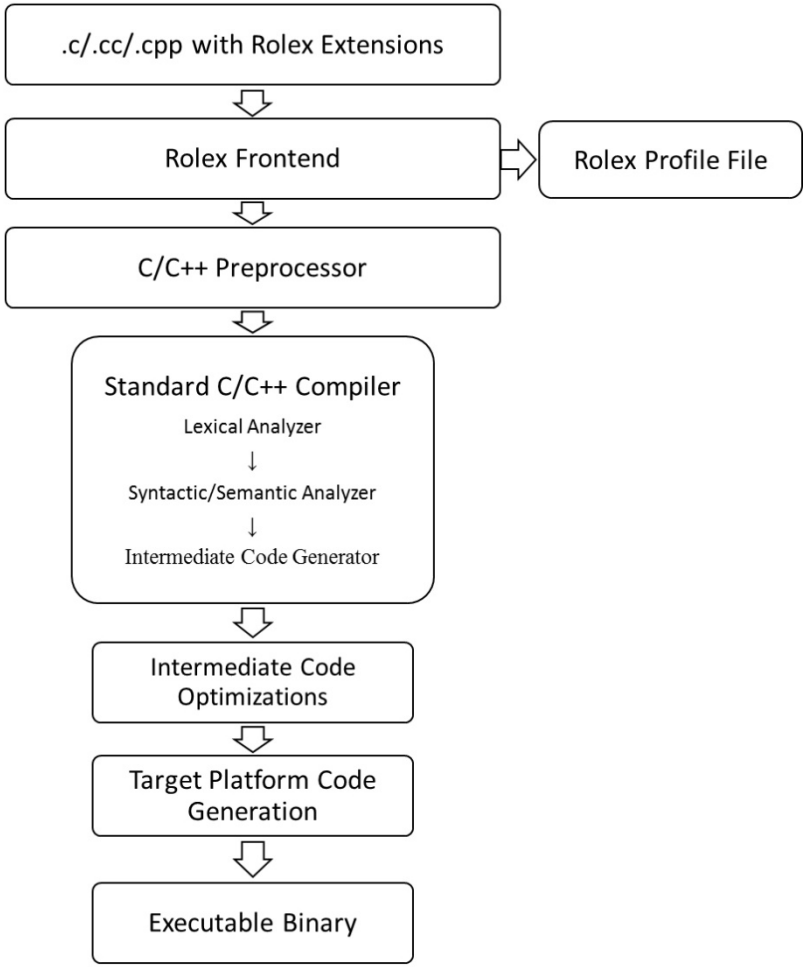


Application: Self-Stabilizing Conjugate Gradient; Contains correction step that restores numerical stability.

RoLex: We define checksum routine for matrix A and vector B which are allocated using resilience_malloc_repairable() library routine; CG iteration steps are included in the #pragma resilience roll-forward which refers to correction step function in ameliorate clause

Faults: Hardware uncorrectable multi-bit perturbations; raises SECDED violation to runtime system.

Compiler Infrastructure



Translation of RoLex:
Propagates fault resilience knowledge expressed by the programmer to the target code and execution environment through the runtime interface.

Compiler Front-end:

- Source-to-source Code Transformation: Generated program code uses only base language (C/C ++) constructs
- Parses the qualifiers and directives to generate code equipped with the error detection, containment and repair capability

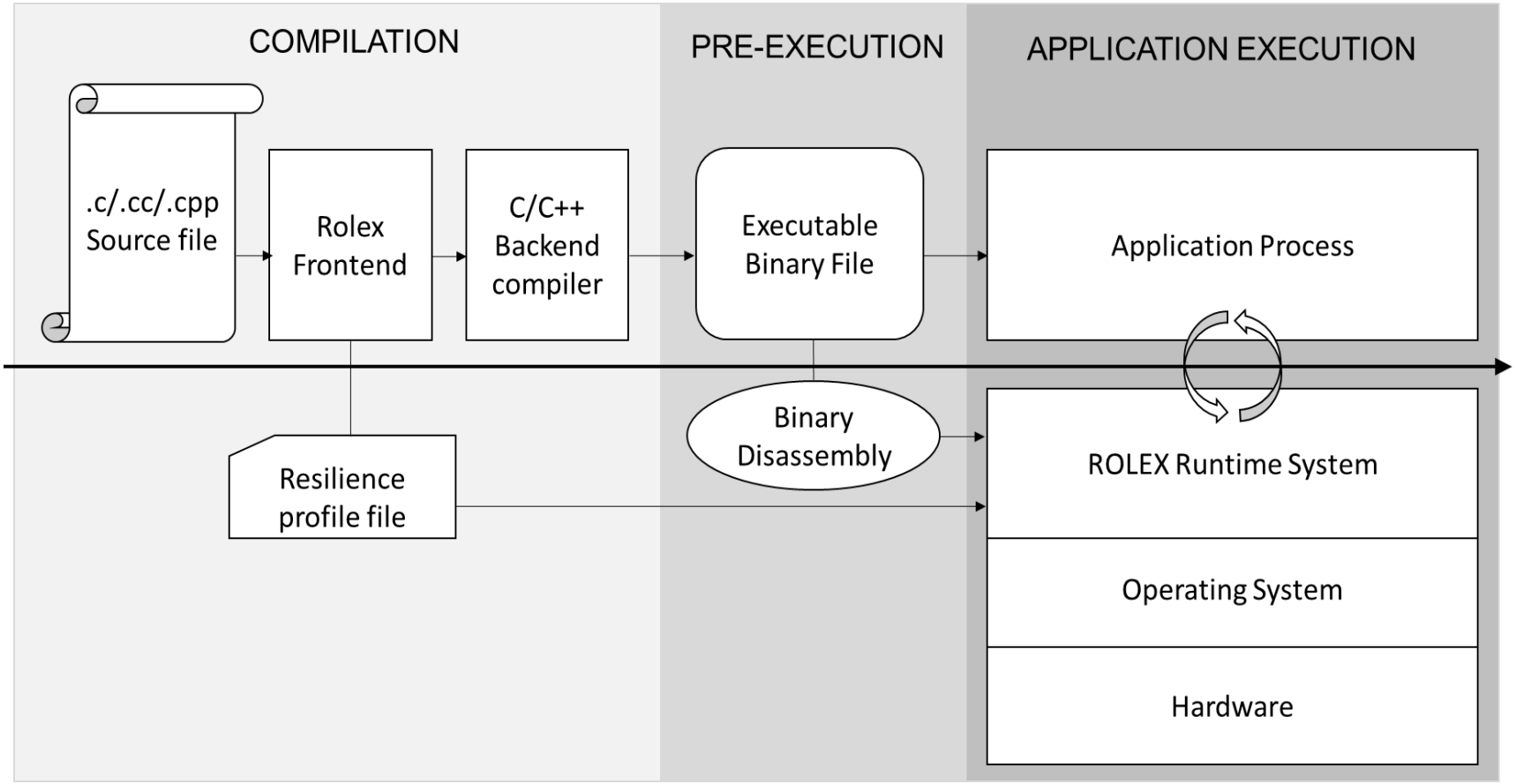
Compiler-Runtime Interface

RoLex runtime library routines (visible to compiler only)

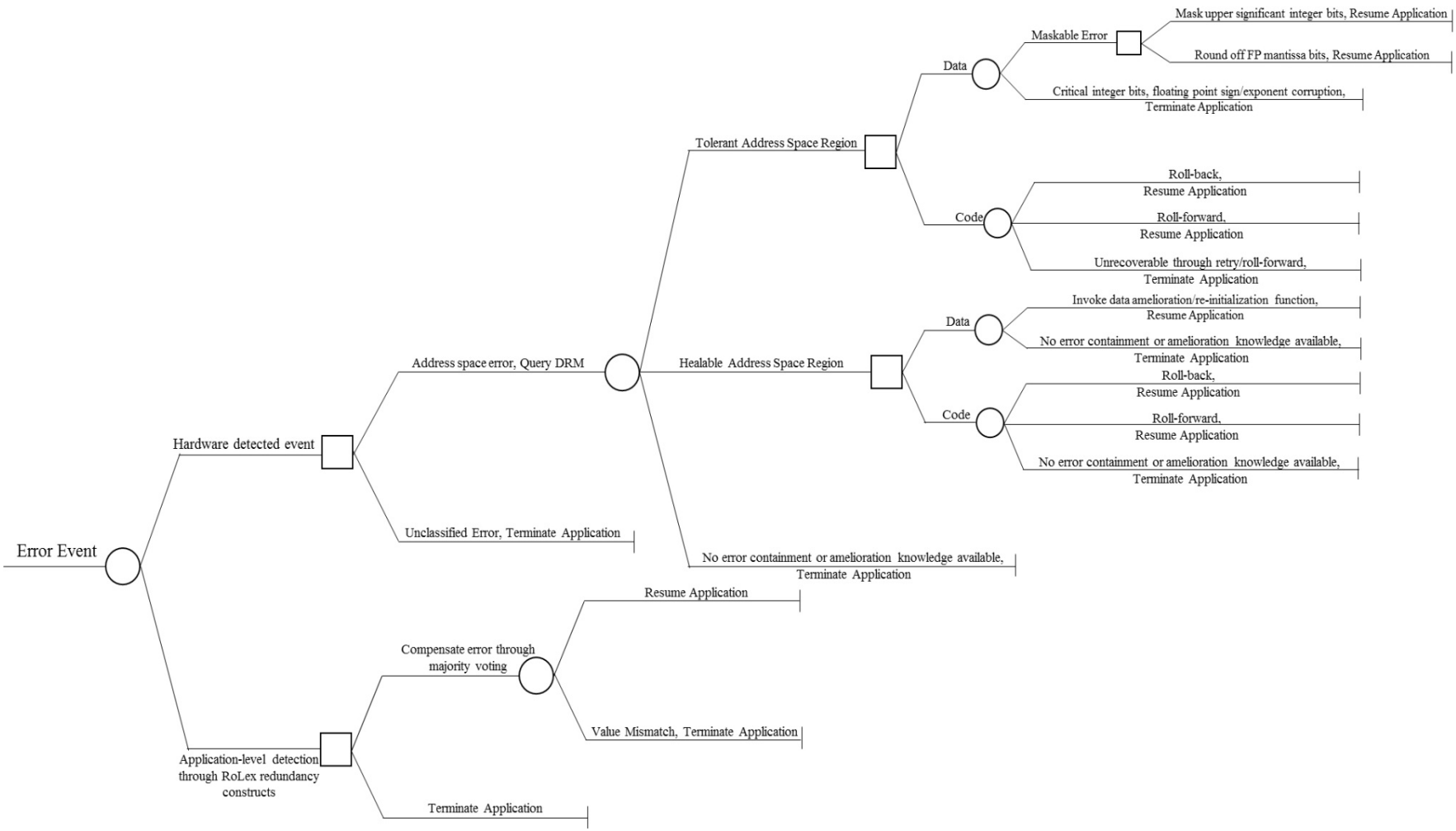
- Inserted by front end compiler into source code

`__rolex_initialize()`	:	runtime initialization
`__rolex_finalize()`	:	runtime termination
`__rolex_preserve_env()`	:	save program environment
`__rolex_restore_env()`	:	restore program environment
`__rolex_jmp_fwd()`	:	move execution forward to set point
`__rolex_rollback_fwd()`	:	move execution forward to set point
`__rolex_chkpoint()`	:	save specified variable state
`__rolex_restore_chkpoint()`	:	restore previously saved variable state

RoLex based Execution Model: Workflow

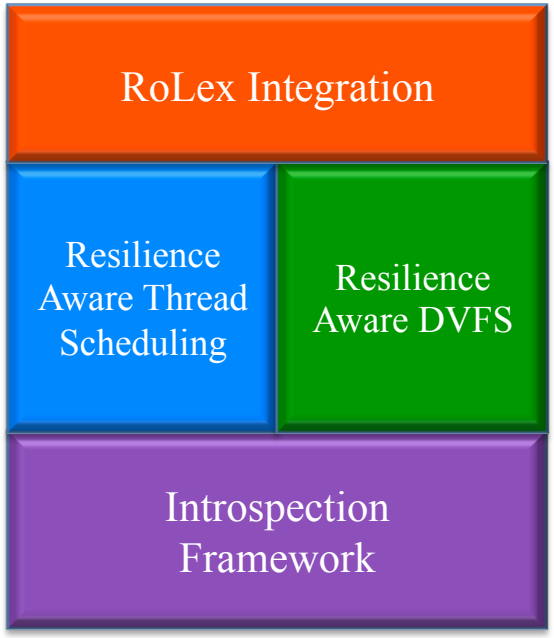


Runtime Inference System



Introspection based Runtime System: Components

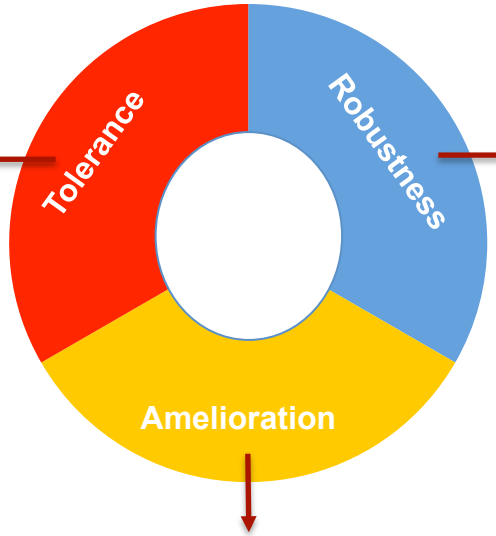
- Introspection Framework
- Resilience driven Resource Management Strategies:
  - Resilience Aware Thread Scheduling
  - Resilience Aware DVFS
- RoLex Integration



Integration with RoLex Features: Resilience Aware Thread Assignment

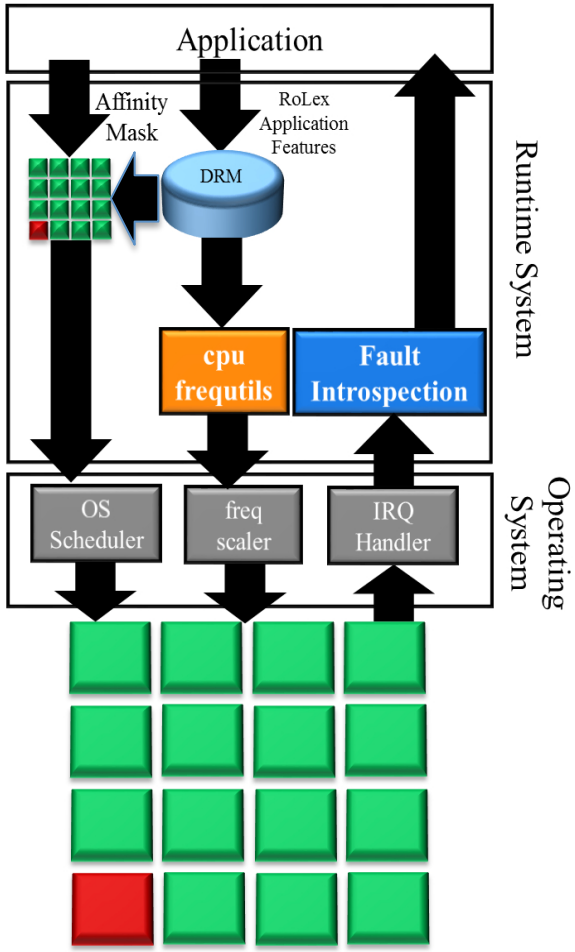
- Policies for realignment of thread affinities based on fault resilience features of the application phase

Resists reconfiguration: allows tolerant computation to persist on vulnerable core



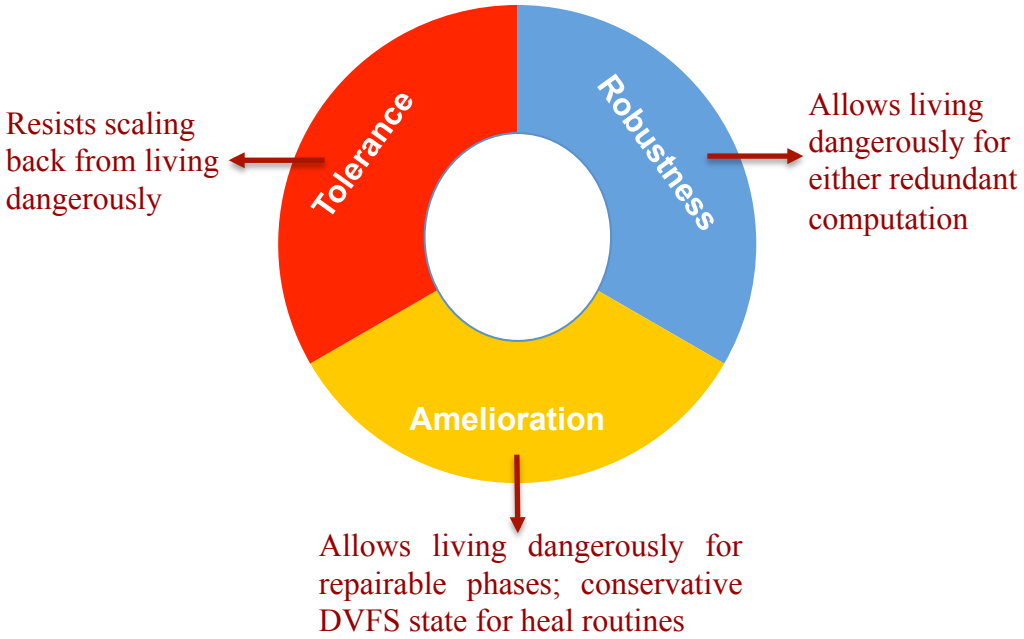
Allows modification of thread affinity mask depending on assignment of redundant computation

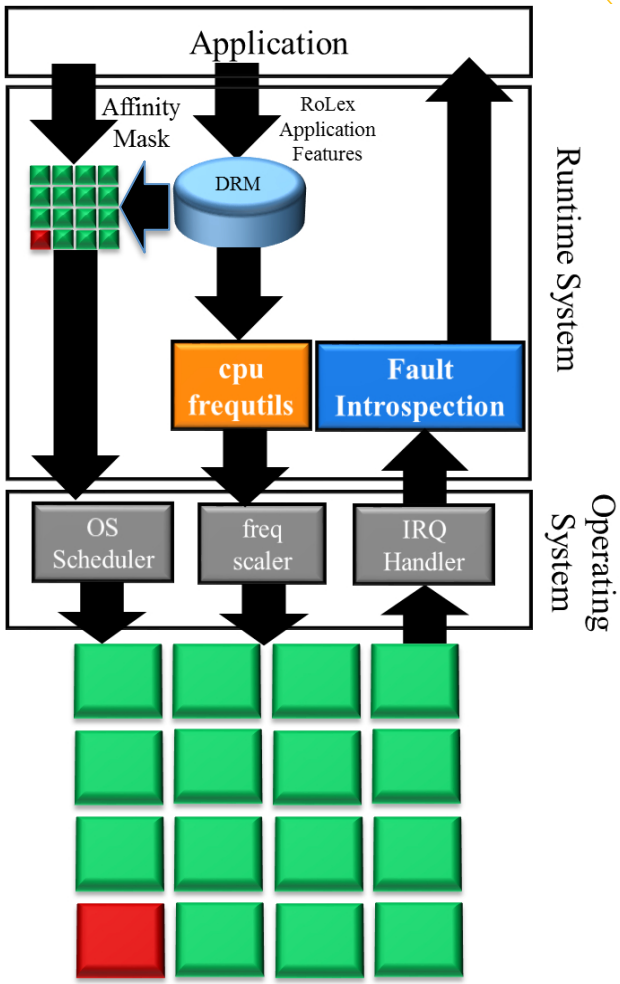
Resists thread migration until repair/heal routines are required to be invoked.



Integration with RoLex Features: Resilience Aware DVFS

- Policies for living dangerously/risk averse DVFS modes based on fault resilience features of the application phase





Summary

- **Created a assertion language**
  Allows users to communicate knowledge about their requirements with respect to resilience

- **Created an Introspection Framework for Resilience**
  Exploits user's guidance to make run time decisions on how to respond to faults

- **Leverage this automate a variety of resilience mechanisms**
  Turn redundant threads on/off based on fault rate
  Migrate threads away from flaky nodes
  Aggressively adjust frequency independent of voltage