Pragma-controlled Source-to-Source Code Transformations for Robust Application Execution

Pedro C. Diniz, Chunhua Liao, Dan Quinlan and Bob Lucas

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Motivation: Trends & Projections

	2009	2012	2016	2020
System Peak Performance	2 Petaflops	20 Petaflops	~200 Petaflops	1 Exaflops
System Memory	0.3 PB	1.5 PB	~5 PB	~30 PB
System Node Count	8,000	18,000	~50,000	~100,000
Total Core Count	300,000	1,500,000	~ 50 million	~ 1 billion
Mean Time To Interrupt (MTTI)	1 day	20 hours	40 – 50 minutes	20 minutes
Power	7MW	8.2MW	~15MW	20MW

Petascale systems today already experience[1]:

- ~20 faults/hour
- 1 double-bit DRAM error every 24 hours
- Constant stream of single bit memory errors

[1] Al Geist, "What is the monster in the closet?" Talk at Workshop on Architectures I: Exascale and Beyond: Gaps in Research, Gaps in our Thinking

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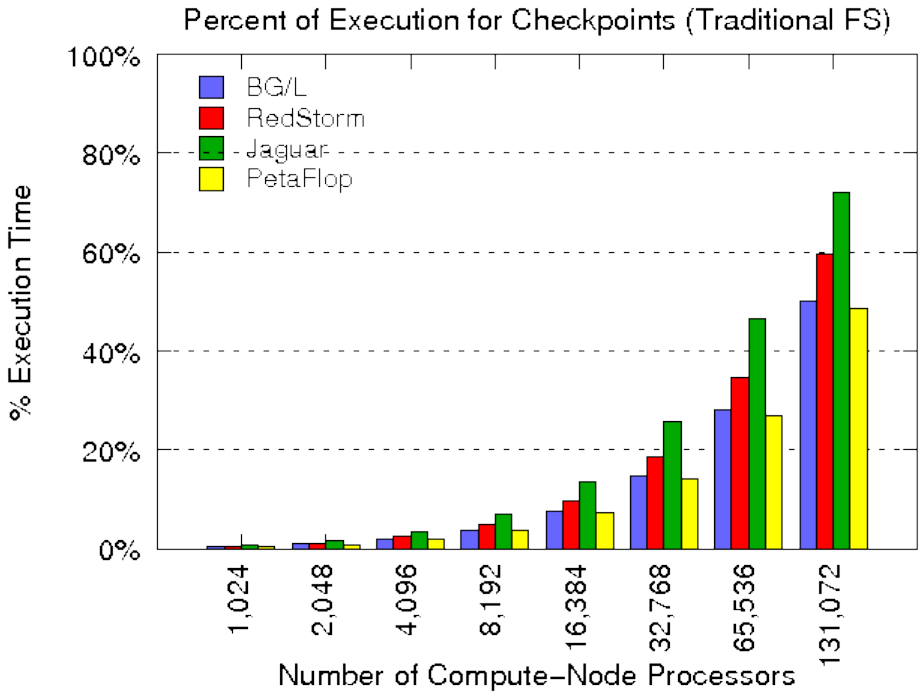
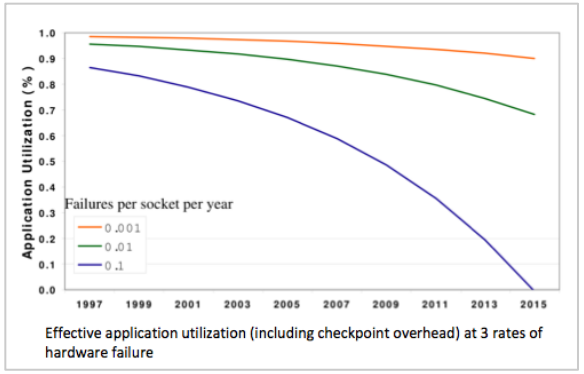
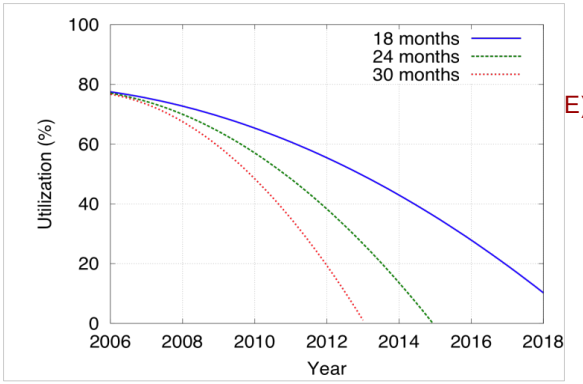
Check-Pointing and Restart



Reference:
Oldfield et al., *Modeling the Impact of Checkpoints on Next-Generation Systems*. MSST, 2007



Effective application utilization (including checkpoint overhead) at 3 rates of hardware failure



E)

Reference:
Schroeder and Gibson, *Understanding Failures in Petascale Computers*. Journal of Physics, 2007 (assuming that the number of cores per socket grows by a factor of 2 every 18, 24 and 30 months)

Not a Scalable Approach

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Observations

- Many Algorithms are Inherently Resilient to Errors
- Programmers may have fault tolerance knowledge
- ... but no convenient mechanisms to convey this knowledge to system
  - System Layers are Inflexible
  - Programming Abstractions Very Rigid

Our Approach

Resiliency Oriented Programming Model Extensions

Evolutionary Approach: Based on current, familiar language constructs

Cross Layer Resilience

Can involve Compiler and Operating System
Introspection System to Manage State of Machine

Fault Model

Multi-bit memory errors uncorrectable by ECC schemes

Programming Extensions for Resilience

- **Previous Work**
  - Type Declarations
  - Dynamic Memory Allocation
- **This Work**
  - **#pragma** directives
  - Source-to-source Code Transformations

Programming Model Extensions

Tolerant Storage Declaration

#pragma failsafe tolerant (exp1 : exp2)

...

- Indicates:
  - Maximum number of tolerated errors (**exp1** , default: any)
  - Preferable (optional) storage assignment (**exp2** , default: none)

- Code Translation:
  - None
  - Auxiliary Storage and Resilience Map

Programming Model Extensions

Sentinel Value of Silent Data Corruption (SDC)

- **#pragma failsafe assert (predicate) error (function handler)**
  ...

- Indicates:
  - Predicate (simple, first order) to be Evaluated
  - Handler Function to be executed if Predicate Does not Hold True

Programming Model Extensions

Sentinel Value of Silent Data Corruption (SDC)

- Code Translation:

```
if(predicate(...) == 0){
    if(function handler (...) != 0){
        failsafe error++;
        FAILSAFEREPORTERROR(0,failsafe error);
         failsafe error flag = 0;
     } else {
       FAILSAFEREPORTCORRECTION(0,failsafe error);
     }
}
```

Programming Model Extensions

User-Controlled State Saving and Restoring with Retry

- **#pragma failsafe save restore (var list) retry (exp)**
  {/* code block */ }
  ...

- Indicates:
  - Set of Variables to be Saved/Restore at Each Iterations
  - Implicit Error Checking via Detected (uncorrected) Memory Error
  - Maximum Retry

Programming Model Extensions

User-Controlled State Saving and Restoring with Retry

- Code Translation (for retry = 2):

```
int fs num tries;
volatile int fs num errors ;
fs num tries = 0;
fs num errors = 0;
<code for saving data objects>
do {
  if (fs num tries != 0){
    <code for restore data objects>
  }
  fs num errors = 0;
    <original code block here>
  fs num tries++;
} while ((fs num errors != 0) && (fs num tries < 2));
if (fs num errors != 0){
  FAIL SAFE EXCEPTION ( )
}
```

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Programming Model Extensions

Redundancy-based Fault Detection and Recovery

- **#pragma failsafe dual redundancy save restore (var list1) compare (var list2) retry (exp)**
  {/* code block */ }
  ...

- Indicates:
  - Set of Variables to be Saved/Restore at Each Iteration
  - Error Checking/Correction via Matching/Voting
  - Maximum Retry

Programming Model Extensions

Redundancy-based Fault Detection and Recovery

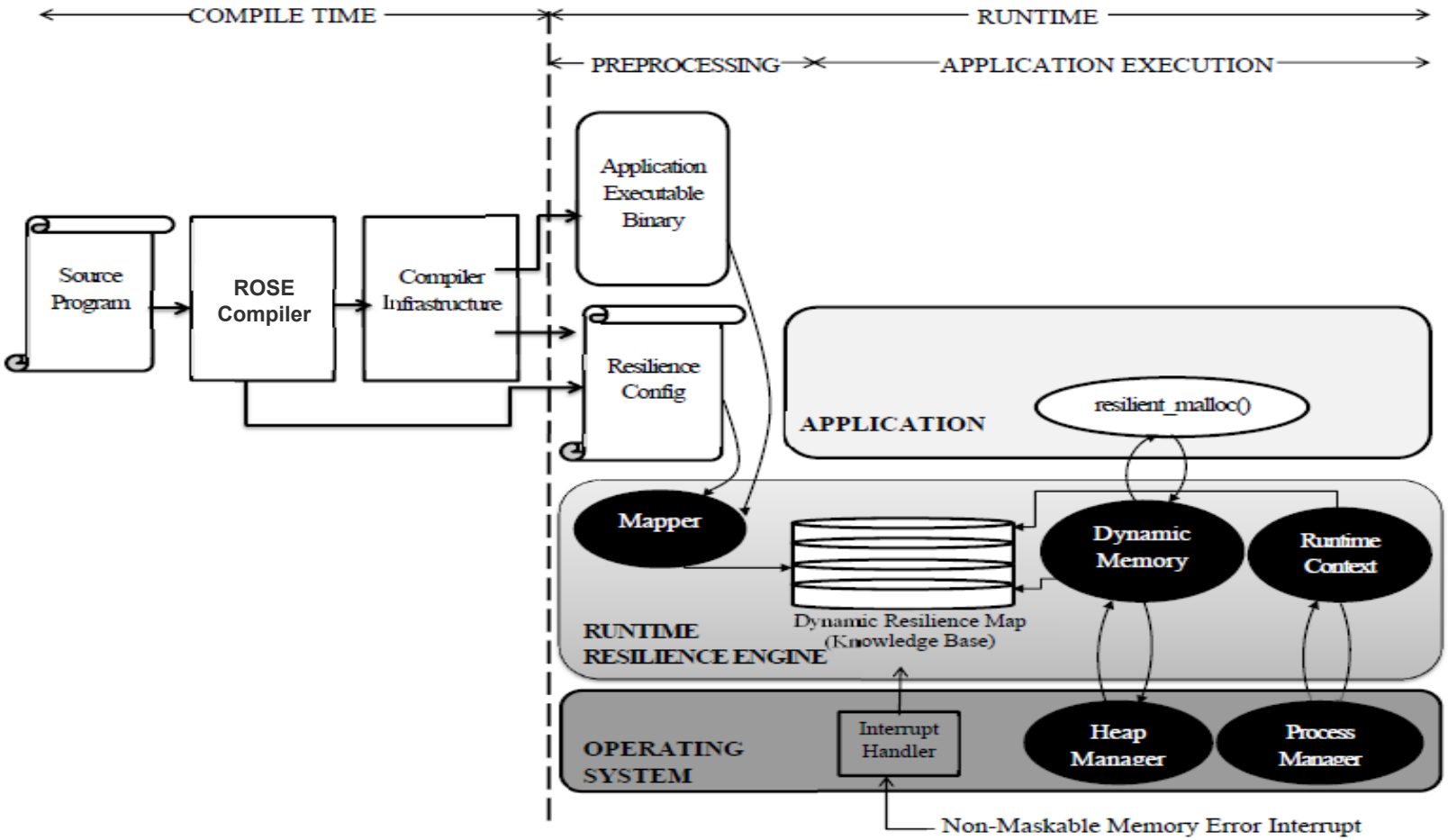
- Code Translation (for retry = 2):

```
int fs num tries ;
volatile int fs num errors ;
< declaration of duplicated of variables in var list2>
...
fs num tries = 0; fs num errors = 0;
<code for saving data in var list1> do
if (fs num tries != 0){
<code for restore data in var list1>
}
fs num errors = 0;
#omp parallel num threads(2)
{
<original code relabeling variables in var list2> }
<compare variables in var list2 for each thread>
if (mismatch( var list2 )) fs num errors++;
fs num tries++;
} while ((fs num errors != 0) && (fs num tries < 2));
if(fs num errors != 0){ FAIL SAFE EXCEPTION ( ) ;
}
```

Preliminary Results : CG kernel

- Simple Iterative Algorithm for Solving Ax = b (40 x 32)
- Main Matrix A is 4 MB and various vectors 0.23 MB
- Error Amelioration
  - in A, fixed using checksum (ABFT)
  - in vectors x, b and others, fixed by reloading saved state
- Errors
  - Restart of the previous iteration using saved state
  - Use of **#pragma save_restore directive** with **retry (2)**
- Total of 21 iterations (0.5 secs/iteration on Desktop)

System Workflow



Preliminary Results : CG kernel

- Methodology:
  - Force Memory Errors in Address Space
  - Restart iteration based on which data structure afflicted
  - Maximum Restart set to 2; additional storage for vectors

Error Internal (secs)	Checksum Recovery	Iteration Restart Recovery	Algorithm Iterations	Execution Time (secs)	Execution Overhead
2	12	1	34	23.761	122.5%
4	5	1	27	20.537	92.3%
5	4	1	26	18.569	73.9%
10	1	1	23	15.368	4.5%
20	1	0	22	11.310	0.6%

Table 1. Execution times vs. injected memory rates for CG simple solver.

  - All “Injected” Errors were Corrected
  - Majority of Errors in A, checksum Correction
  - Overhead not Excessive

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Summary

- Approach highlights the benefits of programmer interfaces to express fault tolerance knowledge to the lower levels of system abstraction

Future Directions and Ongoing Work

- Richer set of opportunities for cross-layer resilience
- Interface to Indicating “dead regions” for data

Acknowledgment

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