# Robustness Testing of a Distributed Simulation Backplane

**Kimberly M. Fernsler**
IBM, Austin TX
kimfern@austin.ibm.com - (512) 733-5283

**Philip Koopman**
Carnegie Mellon University
koopman@cmu.edu - (412) 268-5225
http://www.ices.cmu.edu/koopman

BALLISTA

Institute for Complex Engineered Systems

DARPA

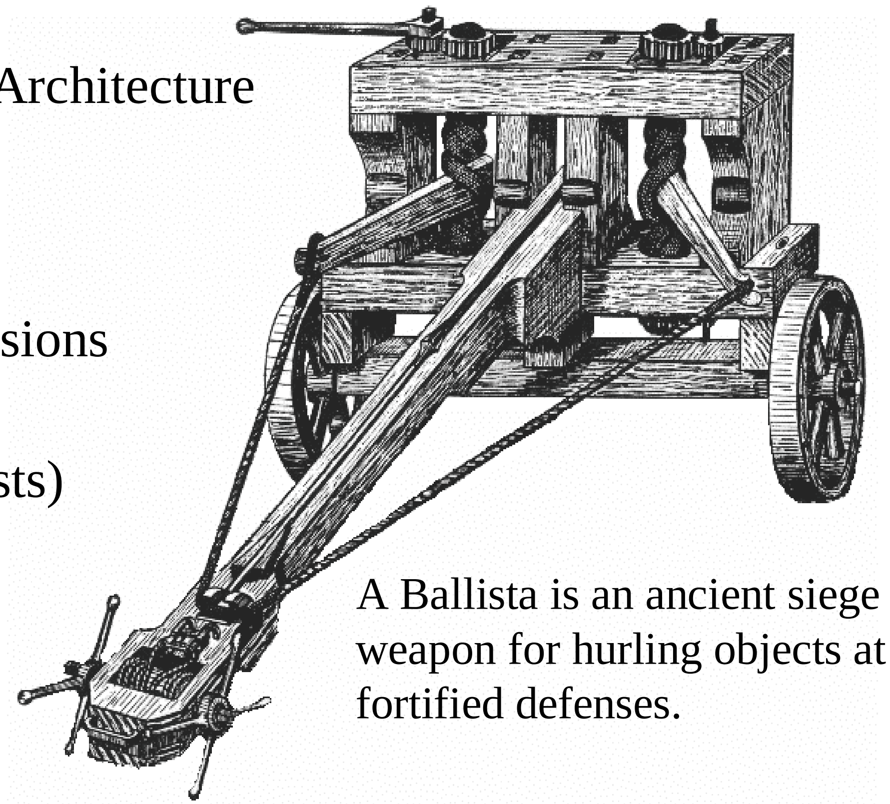
Electrical & Computer ENGINEERING

# Abstract

- **This research is built upon and extends the Ballista project.**
  - High level testing done using the API to perform fault injection
    - Send exceptional values into a system through the API
    - Requires no modification to code -- only linkable object files needed
  - Each test is a specific function call with a specific set of parameters
    - Combinations of valid and invalid parameters tried in turn
- **Yes, Ballista can be extended and it turned out to be easy!**
- **Applied Ballista to a general-purpose distributed system software used for military simulations**
  - Specifically engineered for robustness
  - They weren't perfect -- but usually they weren't too bad either
  - Ballista found the weak spots that they should concentrate on (a "profiling" tool for robustness!)
- **Porting exception handling code seems to be a problem**

# Overview: Testing the RTI

- **System Robustness**
  - Motivation
  - Ballista Automatic Robustness Testing Tool
- **Current Application:** High-Level Architecture Run-Time Infrastructure (HLA RTI)
- **Enhancements for RTI Testing**
  - Results of Ballista testing on 4 versions of HLA RTI (86 functions)
  - Data analysis of results (77,000 tests)
  - Comparison to Operating Systems
  - Segmentation faults vs. RTI Internal Error exception



A Ballista is an ancient siege weapon for hurling objects at fortified defenses.

- **Issues and Future Direction**
  - Extending Ballista to other application areas
  - Creating a general-purpose, scalable testing framework

# Why do we care?

- **Dozens of vendors, hundreds of users…can't afford a system crash**

# System Robustness

- **Graceful behavior in the presence of exceptional conditions**
  - Unexpected operating conditions
  - Activation of latent design defects

- **Robustness definition also includes operation in overloads**
  - Not in current research, but is set as an eventual goal
  - We conjecture overload robustness also hinges on exception handling

- **Our research goal: *improved system robustness***

# Background and Related Work

- **Ballista gets its roots from both the Software Testing and Fault-Injection communities.**

- **Predecessors include:**
  - FIAT
  - Crashme
  - FAUST
  - Fuzz
  - FERRARI
  - FTAPE
  - CMU-Crashme

- **Previous Ballista Work: Testing POSIX Operating Systems**

- **Questions left unanswered:**
  - Ballista worked on OS testing – would it work at all elsewhere?
  - How painful would it be to test Object-Oriented, C++ code with callbacks?
  - Are non-OS APIs/architectures be better suited to robust implementations?

# RTI - Some Terms

- **HLA:** a general-purpose architecture for creating distributed simulations
- **RTI:** the RTI software is the actual implementation of services to coordinate operations and data exchange during a runtime execution


- **Federation:** a set of simulations and supporting RTI that are used together to form a larger model or simulation
- **Federate:** a member of a federation; one simulation
  - Could represent one platform, like a cockpit simulator
  - Could represent an aggregate, like an entire national simulation of air traffic flow
- **Federation Execution:** a session of a federation executing together

# Ballista Scalable Test Generation

*API*

```
rtiAmb.subscribeObjectClassAttributes(
    ObjectClassHandle       theClass,
    AttributeHandleSet&   theAttributes,
    Boolean                         active)
```

*TESTING OBJECTS* / *TEST VALUES*

| RTI::Ulong TEST OBJECT | RTI::AttributeHandleSet TEST OBJECT | RTI::Boolean TEST OBJECT |
|---|---|---|
| INT_SAMPLE | AHS_VALID | BOOL_ZERO |
| INT_ZERO | AHS_NO_CREATE | BOOL_ONE |
| INT_ONE | AHS_CREATE_ONE | BOOL_TWO |
| INT_TWO | AHS_CREATE_ALOT | BOOL_THREE |
| INT_FOUR | AHS_CREATE_NEG | BOOL_FOUR |
| INT_15 | AHS_DELETE | BOOL_FIVE |
| ... | AHS_MEMB_EMPTY | BOOL_SIX |
| INT_129 | | BOOL_SEVEN |
| INT_255 | | BOOL_EIGHT |
| INT_257 | | BOOL_NINE |
| INT_2POW31 | | BOOL_TEN |
| INT2POW31_1 | | BOOL_NEG_ONE |
| INT_NEG_ONE | | |

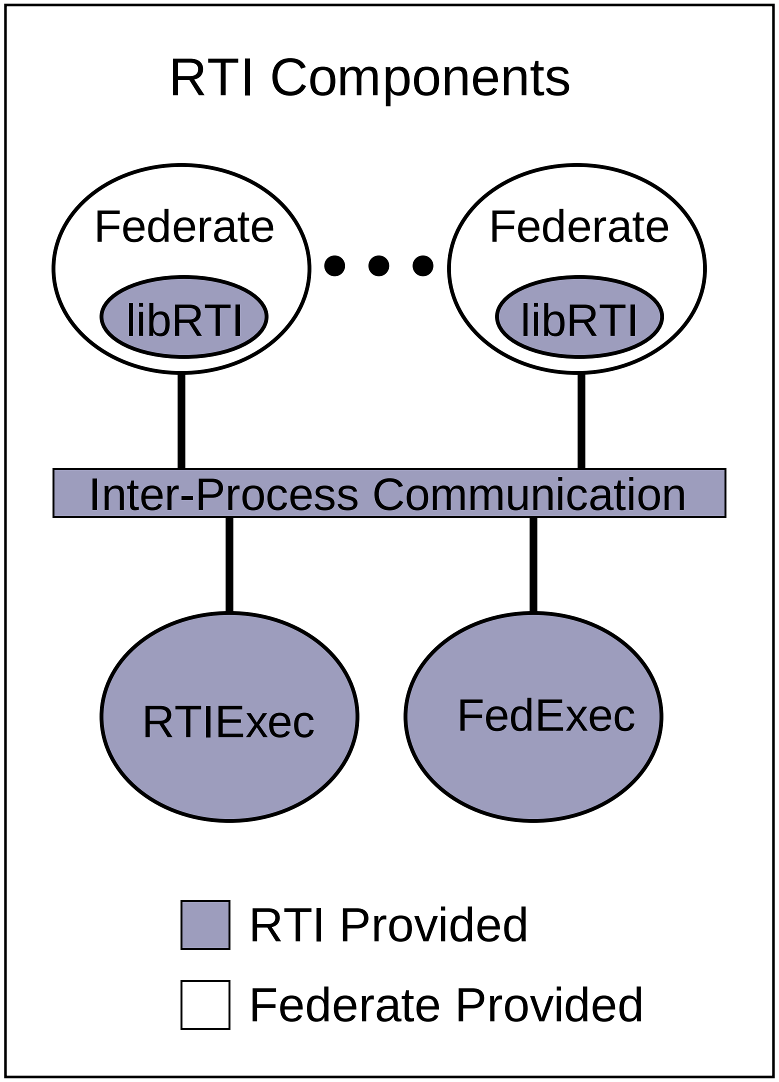
*TEST CASE*

```
rtiAmb.subscribeObjectClassAttributes(
    INT_2POW31, AHS_NO_CREATE, BOOL_ZERO)
```

# RTI Testing Approach

**For *every* test run, the following steps were performed:**

1. Ensure that the RTI server (RtiExec) is running
2. Create a federation:
   Registers task with the RtiExec and starts up FedExec process
3. Join the federation:
   Testing task is a federate
4. Perform “scaffolding” setup functions
5. Test the actual function
6. Free any memory allocated by the setup functions
7. Resign from the joined federation
8. Destroy the federation:
   De-register from the RtiExec
9. Shut down the RtiExec if last test or error occurred



# Enhancing Ballista for RTI - *Obstacles*

- **Exception based error reporting models**
  - Previous Ballista testing - any call which resulted in a signal being thrown was considered a robustness failure
  - The RTI throws an RTI-defined exception (rather than using the POSIX strategy of return codes).

- **RTI is a distributed system**
  - Certain amount of setup code must be executed to set the state before a test
  - In the OS testing all such "scaffolding" was incorporated into constructors and destructors for each test value instance
    - *e.g.*, creating a file for a read or write operation
  - In the RTI there were some function-specific operations required to create reasonable test starting points
  - Distinct scaffolding required to test each and every RTI function?

- **Testing object-oriented software structures**
  - Callbacks, passing objects by reference, class data types, and constructors

# Enhancing Ballista for RTI - *Solutions*

- **In general, the solutions turned out to be simpler than anticipated:**
  - <u>Exception based error reporting models</u>:
    - Included user-defined exception handling code in the general Ballista testing harness.
    - Any user-defined, “thrown” exception was considered a “pass”…
      … except for the “unknown” RTI exception, which indicated an internal RTI exception handling software defect.
  - <u>User-configurable test scaffolding code</u>:
    - Used for clean setup and shutdown of the RTI environment
    - Only 10 different scaffolding code variants sufficed for 86 functions
    - Amount of code and development effort was relatively small
  - <u>Object-oriented software structures</u>:
    - Ballista framework is flexible enough to support callbacks, passing objects by reference, class data types, and constructors – with only minor syntax changes

# Evaluating Test Results

- **The results for RTI testing fall into the following categories, loosely ranked from best to worst in terms of robustness:**

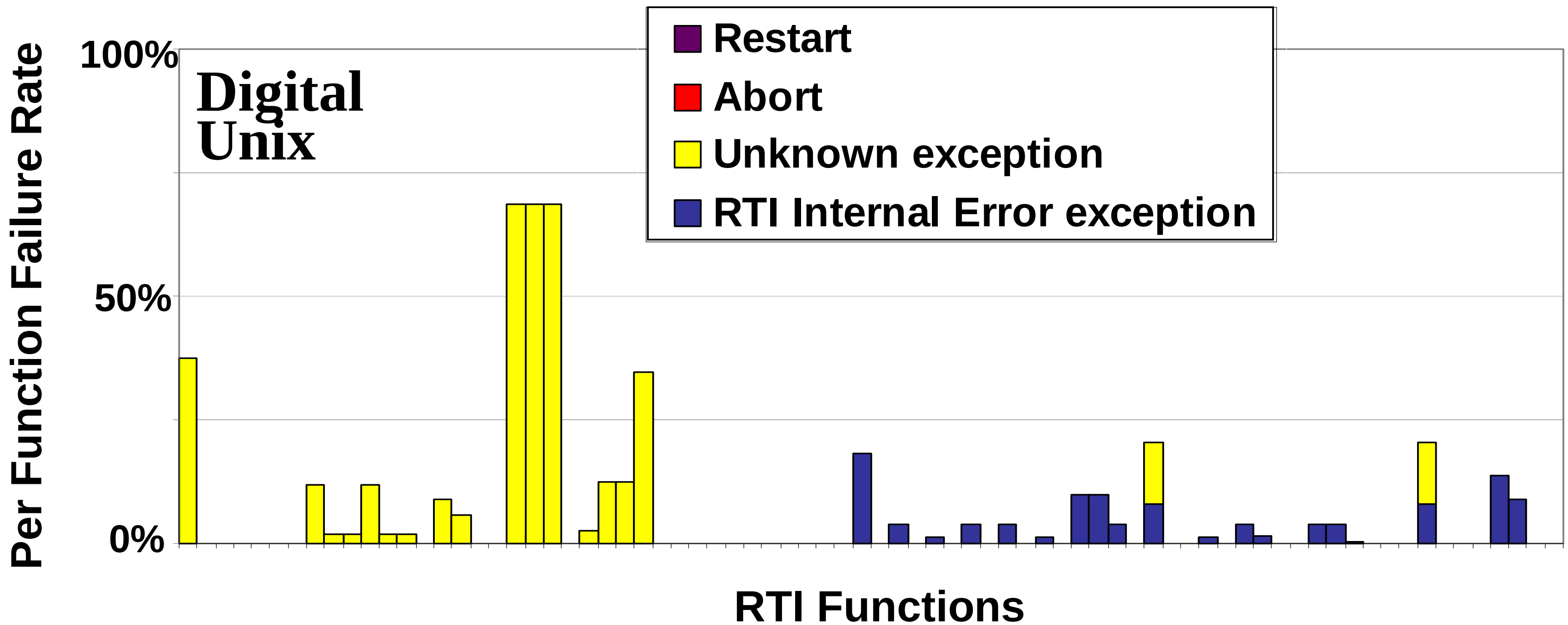
| | |
|---|---|
| **Pass** | Function call executed and returned normally, no indication of error |
| **Pass with Exception** | Valid, HLA-defined exception was thrown, indicating a gracefully caught and handled exceptional condition |
| **RTI Internal Error exception** | RTI encountered a supposedly impossible error condition, RTI managed to free memory and resign from the federation cleanly |
| **Unknown Exception** | Unknown exception was thrown & caught internally to the RTI by a catch-all condition (as opposed to a hardware signal) |
| **Abort** | Error occurred that was not caught, code exited immediately (“core dump”), no memory cleanup, required manual restart of federation |
| **Restart** | The function call did not return after an ample period of time (a “hang”) |
| **Catastrophic** | System was left in a state requiring rebooting the operating system to resume testing |

**Robustness Failures**

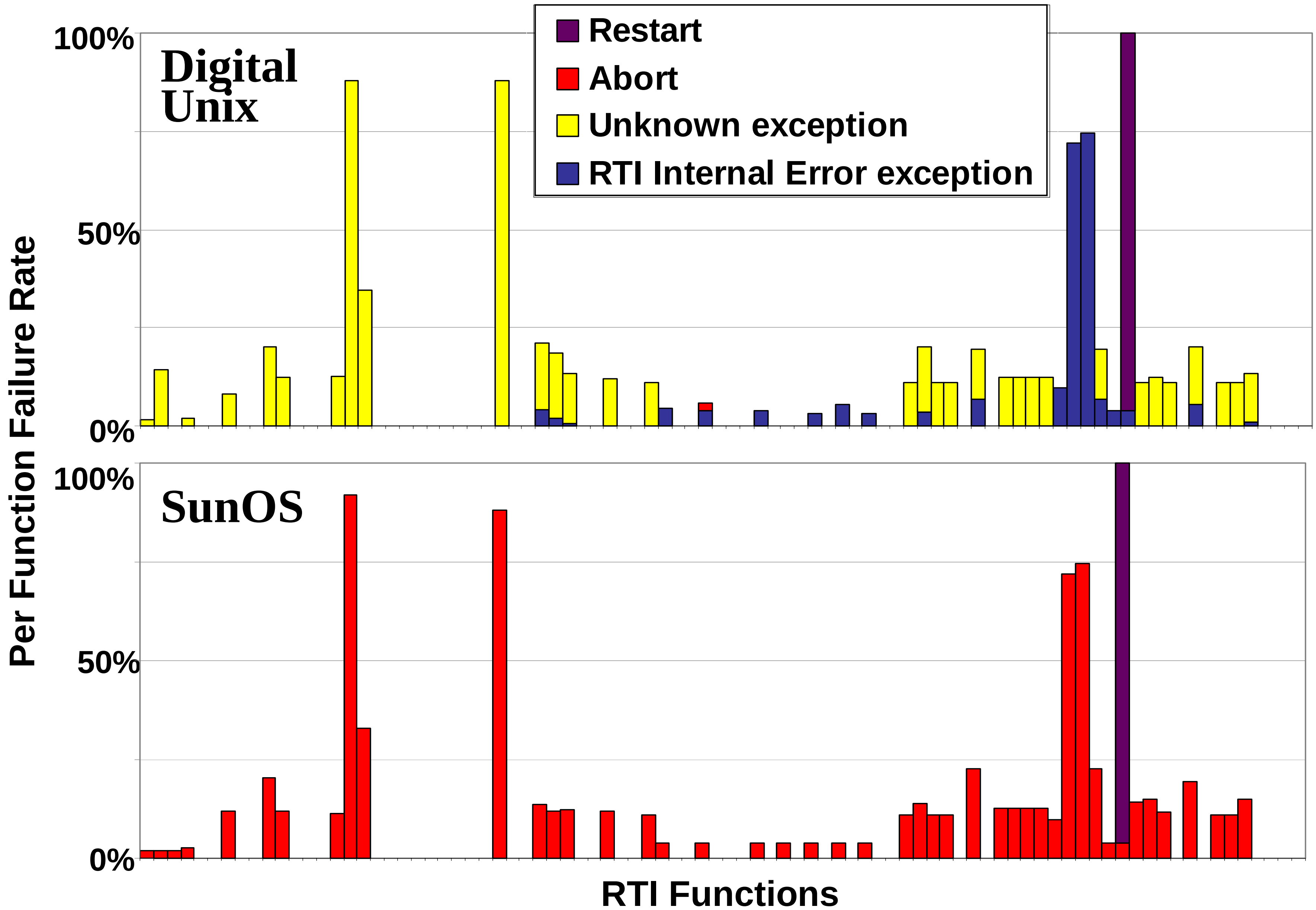
# Robustness Failures of RTI 1.0.3

- **Testing was performed on 4 different versions of the RTI**
  - RTI 1.0.3 for Digital Unix 4.0
  - RTI 1.3.5 for Digital Unix 4.0
  - RTI 1.3.5 for SunOS 5.6
  - RTI 1.3 NG for SunOS 5.6

- **Over 77,000 data points collected**
  - RTI developers' goal was **ZERO** Aborts and **ZERO** RTI Internal Errors.



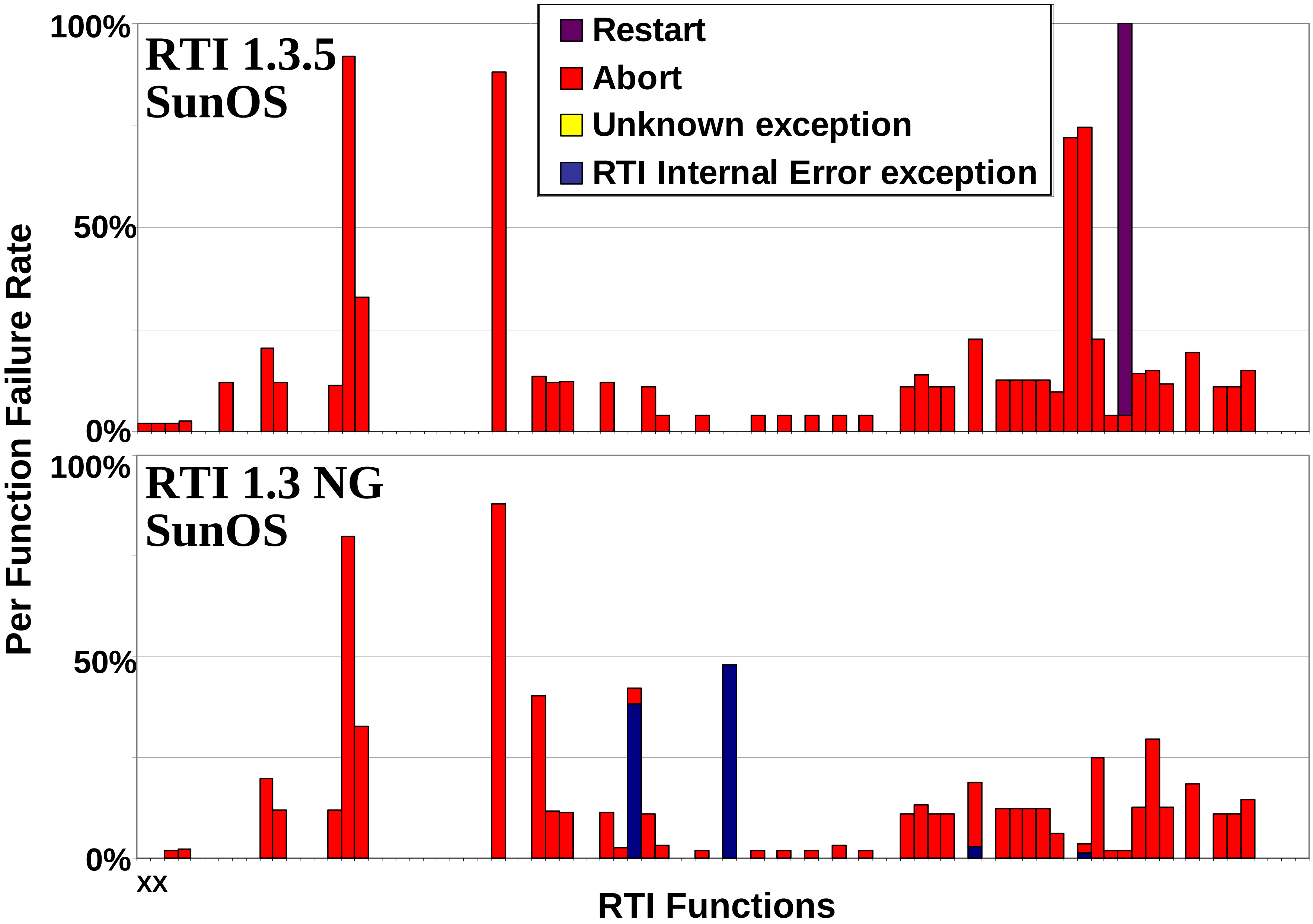
# RTI 1.3.5 Failures - Different Platforms



# HW Signal vs. RTI Internal Error

- **Robustness failure rates from both RTI 1.3.5 versions are essentially the same**
- ***BUT*, different manifestations of robustness failures:**
  - **SunOS port** - any unanticipated signal apparently leaked through and was seen as a segmentation fault
    - Code immediately aborts – no graceful shutdown
    - Could significantly disrupt the currently running federation execution
      - Other federates will not be informed properly that one federate has left
      - What will happen to the data that federate was sharing?
      - What are the consequent effects on the rest of the distributed simulation?
  - **Digital Unix port** - unanticipated signal was caught and converted to an RTI Internal Error
    - This allows recovery and cleanup; code is not aborted
- **Illustrates possible problems in porting robust applications across platforms with different exception handling support.**

# Same Platform, Different Design Teams



# Some Interesting Robustness Failures

- **Client process randomly crashing through an RTI 1.0.3 service function call, requiring machine reboot to continue testing**
- **RTI 1.3.5 Digital Unix port - one test Aborted after producing:**
  **`“Exception system exiting dues`**[sic] **`to multiple internal errors:`**
  **`exception dispatch or unwind stuck in infinite loop`**
  **`exception dispatch or unwind stuck in infinite loop”.`**
- **RTI 1.3.5 SunOS port – one Abort failure resulted in a “zombie” federate each time it occurred**
- **RTI 1.3.5 SunOS port – one Abort terminated after displaying:**
  **`“Run-time exception error; current exception: RTI internal error`**
  **`Unexpected exception thrown.”`**
  - Appears to indicate an incomplete implementation of an RTI Internal Error

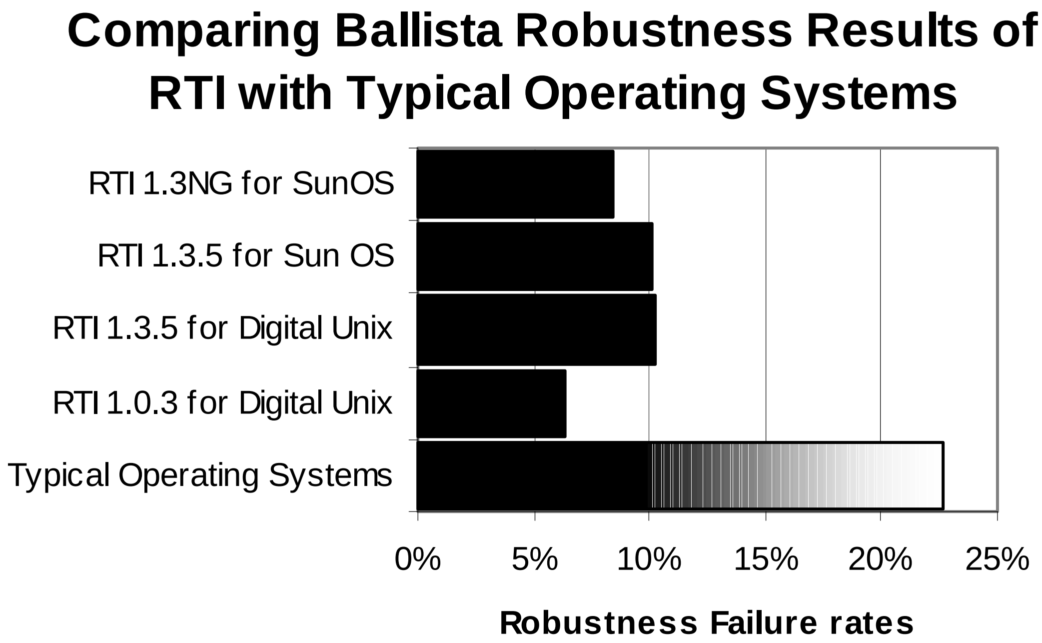
# Normalized Failure Rates

- **Directly measured robustness failure rates:**
  - RTI 1.0.3 for Digital Unix: 6.41%
  - RTI 1.3.5 for Digital Unix: 10.20%
  - RTI 1.3.5 for SunOS: 10.05%
  - RTI 1.3 NG for SunOS: 8.44%

  - Computed by:
    - Determining the proportion of robustness failures across tests for each function within each system being tested
    - Producing a uniformly weighted average across all the functions

- **Operational Profiling**
  - Test with a specific simulation program running
  - Weightings would be used to reflect the dynamic frequency of calling each function to give an exposure metric that is potentially more accurate
  - Common-sense check on these results shows that functions with high robustness failure rates do in fact include commonly used features

# Comparison to OS Results




- **RTI is more robust than POSIX operating systems**
  - RTI robustness = 6.4% - 10.2%
  - POSIX OS robustness = 10.0% - 22.7%
- **This was expected – RTI was designed specifically to be robust**
  - Fewer Catastrophic and Restart Failures as well
- **Newer software version does not necessarily indicate increased robustness (as seen with OS results)**

# Future Work

- **Working to make Ballista part of the standard verification suite for RTI development**
- **Explore issues of concurrent testing to find potentially more subtle bugs related to timing and resource sharing**
- **Pattern analysis software for better test selection & result analysis**
- **Generalized testing now available as WWW testing service**
  - http://www.ices.cmu.edu/ballista

# Conclusions

- **Ballista robustness testing approach**
  - Scalable, portable, reproducible
  - Demonstrated to find exception handling problems in software specifically written to be highly robust
- **Testing the RTI led to scalable extensions of the Ballista architecture**
  - Exception-based error reporting models
  - Object-oriented software structures (callbacks, pass by reference, constructors)
  - Operating in a state-rich, distributed system environment

  \- *All were easily integrated into the existing Ballista framework!*
- **As expected, RTI is much more robust than POSIX operating systems. BUT several weak spots found:**
  - Non-robust testing responses included exception handling errors, hardware segmentation violations, "unknown" exceptions, and task hangs.
  - Difficulties in providing comparable exception handling coverage across platforms
  - Results illustrate common robustness failures that programmers can overlook