Evaluating Computing Systems Using Fault-Injection and RAS Metrics and Models

Rean Griffith

Thesis Proposal

February 28th 2007

Outline

- Background (Goal, Motivation)
- Problem
- Requirements (Big Picture View)
- Hypotheses
- Solution Part I – Fault Injection via Kheiron
- Solution Part II – RAS-Models + 7U-evaluation
- Accomplishments
- Timeline
- Expected Contributions And Future Work

Goal

- A methodology for evaluating computing systems based on their reliability, availability and serviceability properties.

Why Bother?

- We understand speed (very well)
  - We use speed as our primary evaluation measure
- But…fast computers fail and so do slower ones
- Users demand that computing systems are also:
  - Reliable, Highly available and Serviceable (easy to manage, repair and recover)
- But…
  - Faster != More Reliable
  - Faster != More Available
  - Faster != More Serviceable
- How do we evaluate RAS-properties? We need other measures to draw conclusions on "better".

Wait a minute…

- Haven't we been here before?
  - 70's – Fault-tolerant Computing (FTC).
  - 80's – Dependable Systems and Networks (DSN).
  - 90's+ – Self-Managing/Autonomic Systems (AC).
- What have we learned so far?
  - FTC – Fault Avoidance, Fault Masking via Redundancy, N-Versions etc.
  - DSN – Reliability & Availability via Robustness.
  - AC – Feedback architectures, 4 sub-areas of focus (self-configuration, self-healing, self-optimizing, self-protecting)

Quick Terminology

- Reliability
  - Number or frequency of client interruptions
- Availability
  - A function of the rate of failure/maintenance events and the speed of recovery
- Serviceability
  - A function of the number of service-visits, their duration and associated costs

More Terms…

- Error
  - Deviation of system state from correct service state
- Fault
  - Hypothesized cause of an error
- Fault Model
  - Set of faults the system is expected to respond to
- Remediation
  - Process of correcting a fault (detect, diagnose, repair)
- Failure
  - Delivered service violates an environmental constraint e.g. SLA or policy

Requirements

- How do we study a system's RAS-properties?
  - Construct a representative fault-model
  - Build fault-injection tools to induce the faults in the fault-model
  - Study the impact of faults on the target system with any remediation mechanisms turned off then on
  - Evaluate the efficacy of any existing remediation mechanisms via their impact on SLAs, policies, etc.
  - Evaluate the expected impact of yet-to-be added remediation mechanisms (if possible)

Hypotheses

- Runtime adaptation is a reasonable technology for implementing efficient and flexible fault-injection tools.
- RAS-models, represented as Continuous Time Markov Chains (CTMCs), are a reasonable framework for analyzing system failures, remediation mechanisms and their impact on system operation.
- RAS-models and fault-injection experiments can be used together to model and measure the RAS-characteristics of computing systems. This combination links the details of the mechanisms to the high-level goals governing the system's operation, supporting comparisons of individual or combined mechanisms.

Spoiler…

- Part I
  - Kheiron a new framework for runtime-adaptation in a variety of applications in multiple execution environments.
  - Fault-injection tools built on top of Kheiron
- Part II
  - System analysis using RAS-models.
  - The 7-steps (our proposed 7U-evaluation) methodology linking the analysis of individual and combined mechanisms to the high-level goals governing the system's operation.

One “What” & Three “Why’s”

- What is runtime-adaptation?
- Why runtime-adaptation?
- Why build fault-tools using this technology?
- Why build our own fault tools?

Four answers…

- What is runtime-adaptation?
  - Ability to make changes to applications while they execute.
- Why runtime-adaptation?
  - Flexible, preserves availability, manages performance
- Why build fault-tools using this technology?
  - Fine-grained interaction with application internals.
- Why build our own fault tools?
  - Different fault-model/focus from robustness oriented tools like FAUMachine, Ferrari, Ftape, Doctor, Xception, FIST, MARS, Holodeck and Jaca.

Kheiron Features

- Able to make changes in running .NET, Java and Compiled C-applications.
- Low overhead.
- Transparent to both the application and the execution environments.
- No need for source-code access.
- No need for specialized versions of the execution environments.

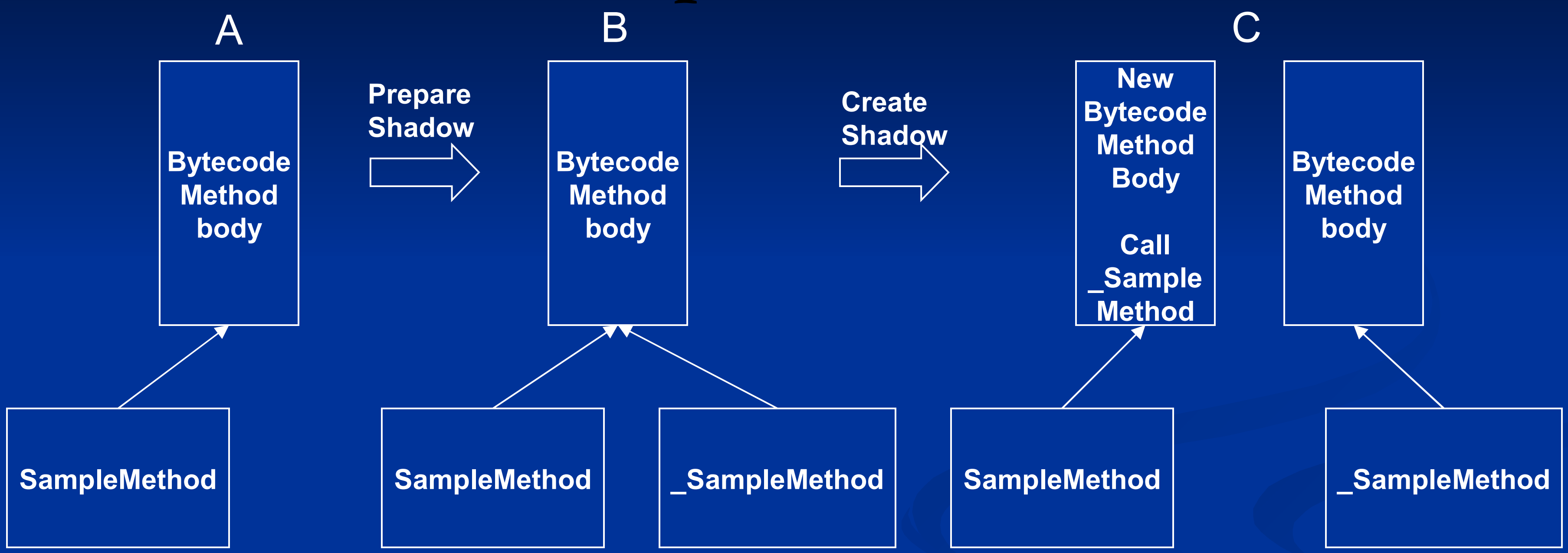
How Stuff Works

- 3 implementations of Kheiron
  - Kheiron/CLR, Kheiron/JVM and Kheiron/C
- Key observation
  - All software runs in an execution environment (EE), so use it to facilitate adapting the applications it hosts.
- Two kinds of EEs
  - Unmanaged (Processor + OS e.g. x86 + Linux)
  - Managed (CLR, JVM)
- For this to work the EE needs to provide 4 facilities…

EE-Support

EE Facilities	Unmanaged Execution Environment	Managed Execution Environment	
	ELF Binaries	JVM 5.x	CLR 1.1
Program tracing	ptrace, /proc	JVMTI callbacks + API	ICorProfilerInfo ICorProfilerCallback
Program control	Trampolines + Dyninst	Bytecode rewriting	MSIL rewriting
Execution unit metadata	.symtab, .debug sections	Classfile constant pool + bytecode	Assembly, type & method metadata + MSIL
Metadata augmentation	N/A for compiled C-programs	Custom classfile parsing & editing APIs + JVMTI RedefineClasses	IMetaDataImport, IMetaDataEmit APIs

Kheiron/CLR & Kheiron/JVM Operation

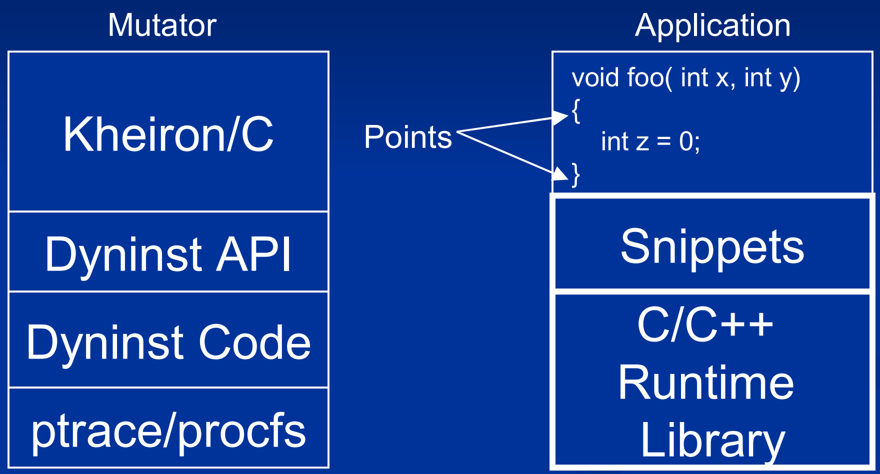


SampleMethod(args) [throws NullPointerException]
<room for prolog>
push args
call _SampleMethod(args) [throws NullPointerException]
{ try{…} catch (IOException ioe){…} } // Source view of _SampleMethod's body
<room for epilog>
return value/void

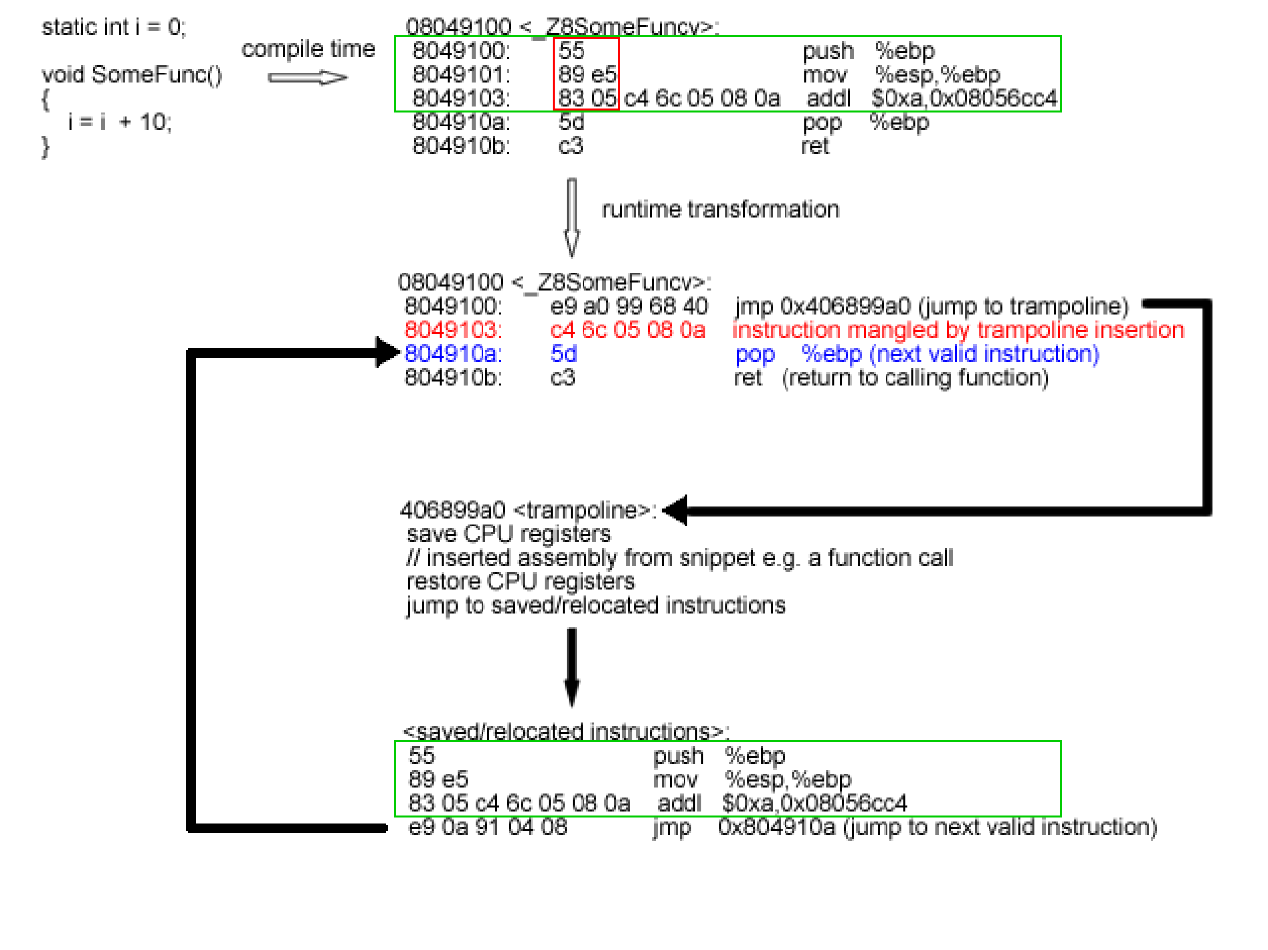
Kheiron/CLR & Kheiron/JVM Fault-Rewrite

```
public void someMethod()
{
   call StatsCop.methodEnter( "someMethod" ) // profile method enter
   call FaultManager.injectFault( "someMethod") // lookup fault to inject
   call _someMethod(); // call original implementation of someMethod
   call StatsCop.methodExit( "someMethod") // profile method exit
}
```

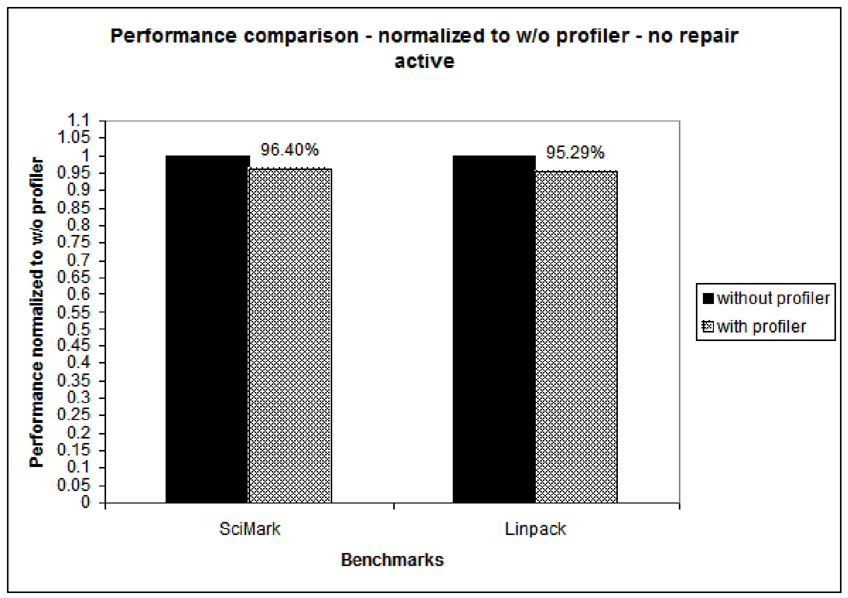
Kheiron/C Operation



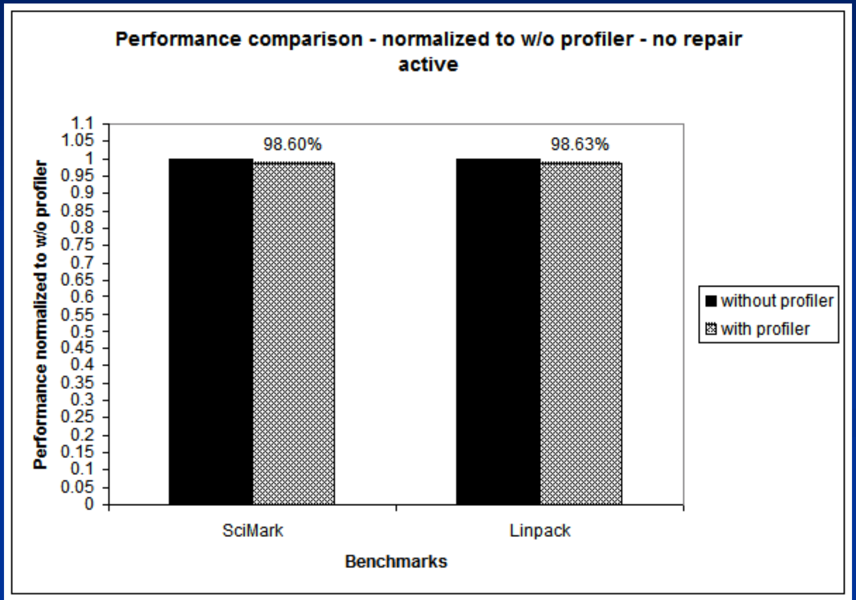
Kheiron/C – Prologue Example



Kheiron/CLR & Kheiron/JVM Feasibility

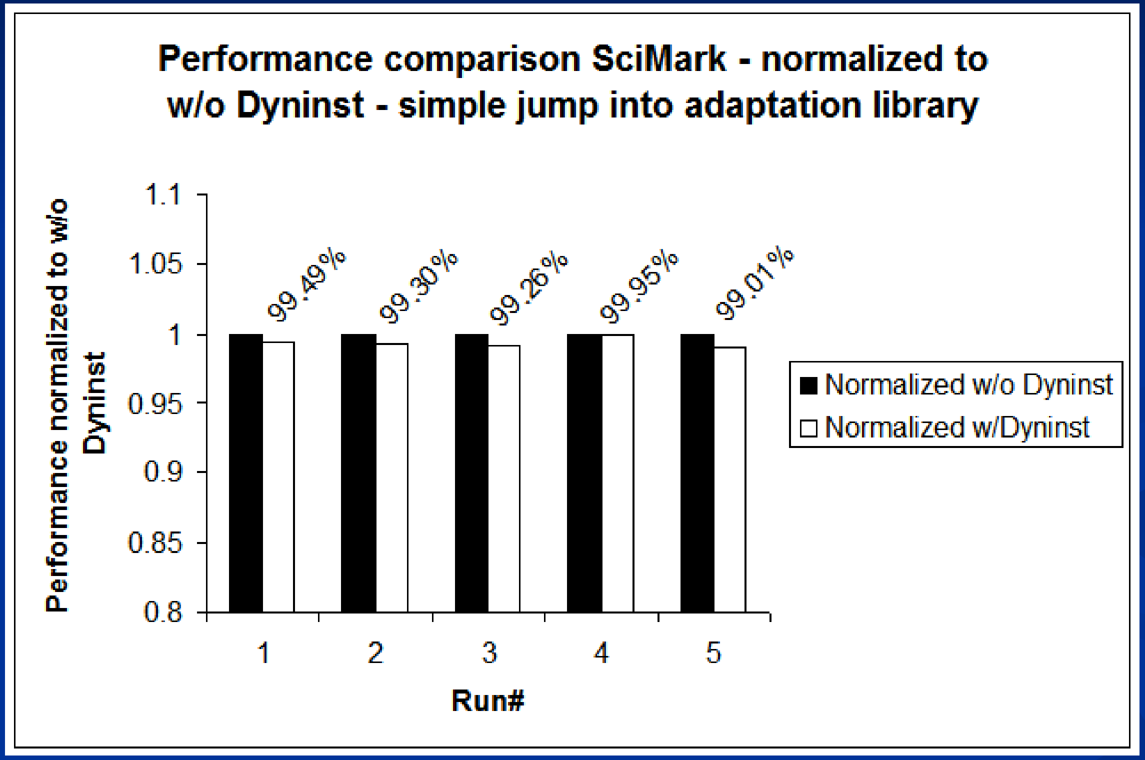


Kheiron/CLR Overheads when no adaptations active



Kheiron/JVM Overheads when no adaptations active

Kheiron/C Feasibility



Kheiron/C Overheads
when no adaptations active

Sophisticated Runtime Adaptations

- Transparent hot-swap of the job scheduler component in the Alchemi Enterprise Grid Computing System using Kheiron/CLR
  - Kheiron/CLR performs a component hot-swap without disrupting work in the grid or crashing the CLR.
- Supporting the selective emulation of compiled C-functions using Kheiron/C
  - Kheiron/C loads the STEM x86 emulator into the address space of a target program and causes selected functions to run under emulation rather than on the real processor.

Part I Summary

- Kheiron supports contemporary managed and unmanaged execution environments.
- Low-overhead (<5% performance hit).
- Transparent to both the application and the execution environment.
- Access to application internals
  - Class instances (objects) & Data structures
  - Components, Sub-systems & Methods
- Capable of sophisticated adaptations.
- Fault-injection tools built with Kheiron leverage all its capabilities.

Outline

- ~~Background (Goal, Motivation)~~
- ~~Problem~~
- ~~Requirements (Big Picture View)~~
- ~~Hypotheses~~
- ~~Solution Part I – Fault Injection via Kheiron~~
- Solution Part II – RAS-Models + 7U-evaluation
- Accomplishments
- Timeline
- Expected Contributions And Future Work

Target System for RAS-study

- N-Tier web application
  - TPC-W web-application & Remote Browser Emulators
  - Resin 3.0.22 application server & web server (running Sun Hotspot JVM 1.5)
  - MySQL 5.0.27
  - Linux 2.4.18 kernel
- Fault model
  - Device driver faults injected using SWIFI device driver fault-injection tools
  - Memory-leaks injected using Kheiron/JVM-based tool

Expected Fault-Model Coverage

Fault Category	Target	Remediation
Memory Leak	Web-application server/Web-application classes	System reboot (reactive) Application-server restart (reactive) Application-server restart (preventative) – To Be Added
28 possible device driver faults	Operating system kernel	System reboot (reactive) Nooks driver recovery (reactive)

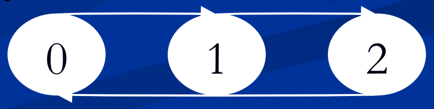
Analytical Tools

- RAS-models (Continuous Time Markov Chains)
  - Based on Reliability Theory.
  - Capable of analyzing individual or combined RAS-enhancing mechanisms.
  - Able to reason about perfect and imperfect mechanisms.
  - Able to reason about yet-to-be-added mechanisms.
- 7U-Evaluation methodology
  - Combines fault-injection experiments and RAS-models and metrics to evaluate systems.
  - Establish a link between the mechanisms and their impact on system goals/constraints.

Reliability Theory Techniques Used

- Continuous Time Markov Chains (CTMCs)
  - Collection of states (S_0, …, S_n) connected by arcs.
  - Arcs between states represent transition rates.
  - State transitions can occur at any instant.
- Markov assumptions
  - $P(X_n = i_n | X_0 = i_0, \ldots, X_{n-1} = i_{n-1}) = P(X_n = i_n | X_{n-1} = i_{n-1})$
- Birth-Death Processes

  - Nearest-neighbor state-transitions only.



- Non-Birth-Death Processes
  - Nearest-neighbor state-transition restriction relaxed.

A: Fault-Free Operation

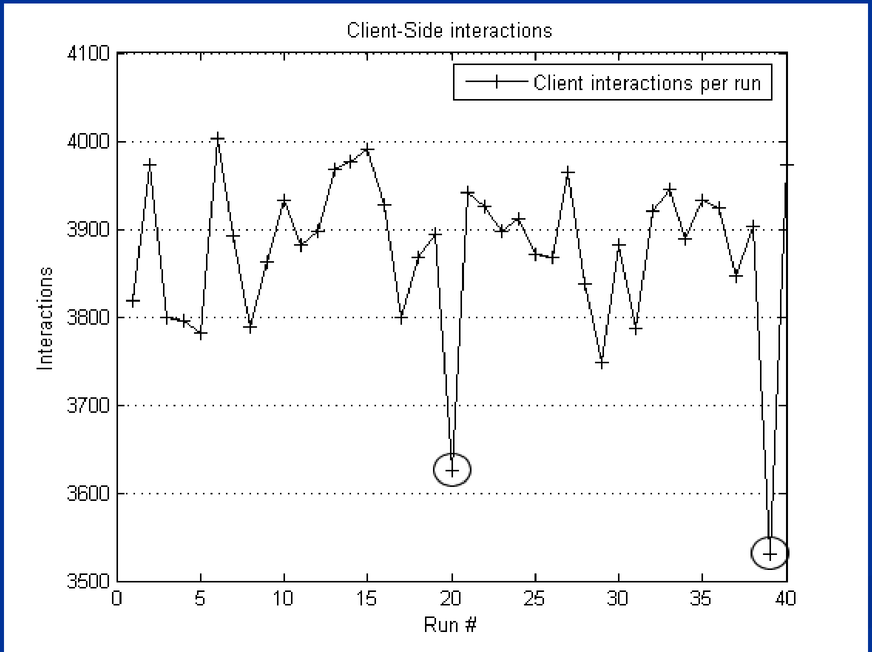
- TPC-W run takes ~24 minutes

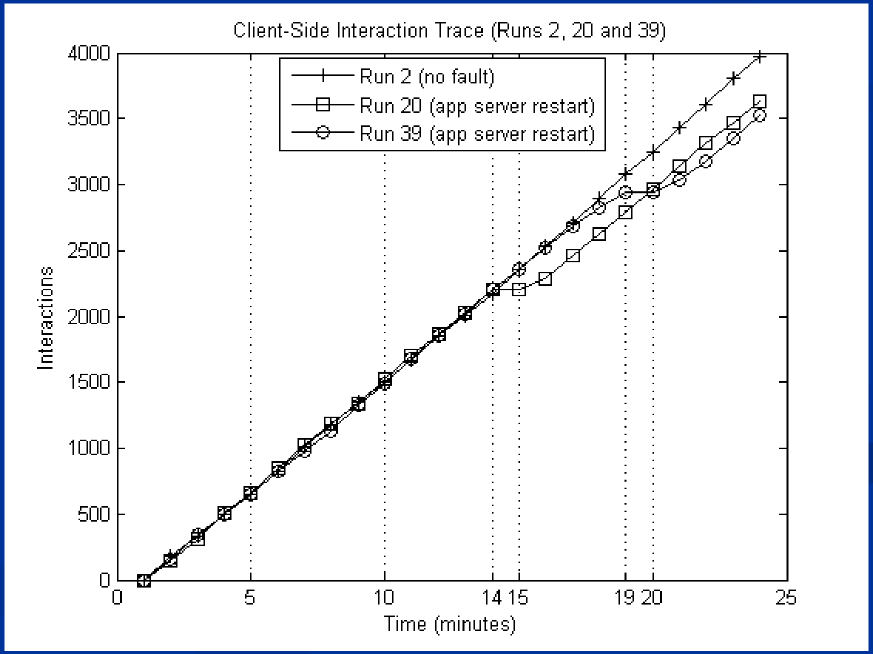
client-side	server-side	success rate
number of interactions: 3973	memory requests : 1848 memory requests granted : 1848	memory : 100%
	fork requests : 0 forks performed : 0	execution : n/a
	read requests : 3,498,678 reads preformed : 3,483,154	reads : 99.5563%
	write requests : 22,369 writes performed : 22,369	writes : 100%
	open requests : 18,476 opens performed : 18,476	opens : 100%
	close requests : 18,560 closes performed : 18,560	closes : 100%

Table 3: *Metrics for Configuration A, Fault-Free Run*

B: Memory Leak Scenario

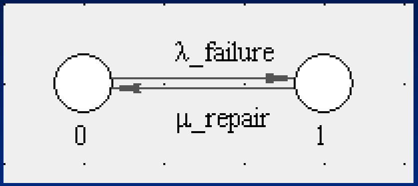
- 1 Failure every 8 hours (40 runs = 16 hours of activity)
- Resin restarts under low memory condition. Restart takes ~47 seconds and resolves the issue each time.





B: Memory Leak Analysis

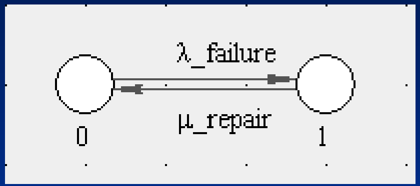
- Birth-Death process with 2 states, 2 parameters:
  - S_0 – UP state, system working
  - S_1 – DOWN state, system restarting
  - $\lambda_{failure}$ = 1/8 hrs
  - μ_{repair} = 47 seconds
- Assumptions
  - Perfect repair
- Results
  - Limiting/steady-state availability = 99.838%
  - Downtime per year = 866 minutes
- Is this good or bad?
  - Two 9's availability



Availability Guarantee	Max Downtime Per Year	Expected Penalties
99.999	~5 mins	(866 - 5)*$p
99.99	~53 mins	(866 - 53)*$p
99.9	~526 mins	(866 - 526)*$p
99	~5256 mins	$0

Table 3. *Expected SLA Penalties for Configuration B*

C: Driver Faults w/o Nooks – Analysis

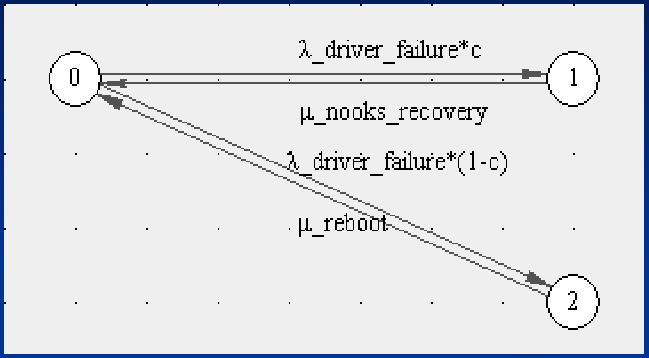


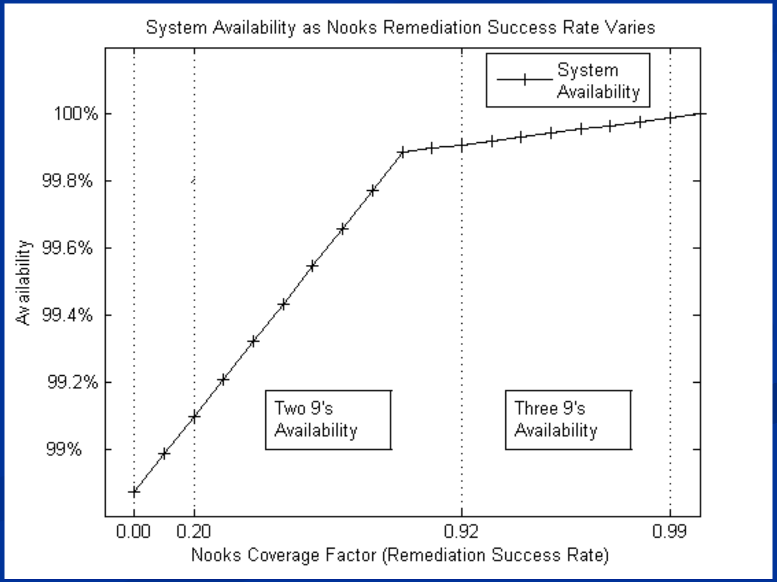
- Birth-Death process with 2 states, 2 parameters:
  - S_0 – UP state, system working
  - S_1 – DOWN state, system restarting
  - $\lambda_{failure}$ = 4/8 hrs
  - μ_{repair} = 82 seconds
- Assumptions
  - Perfect repair
- Results
  - Limiting/steady-state availability = 98.87%
  - Downtime per year = 5924 minutes
- Is this good or bad?
  - Less than Two 9's availability

Availability Guarantee	Max Downtime Per Year
99.999	~5 mins
99.99	~53 mins
99.9	~526 mins
99	~5256 mins

D: Driver Faults w/Nooks – Analysis

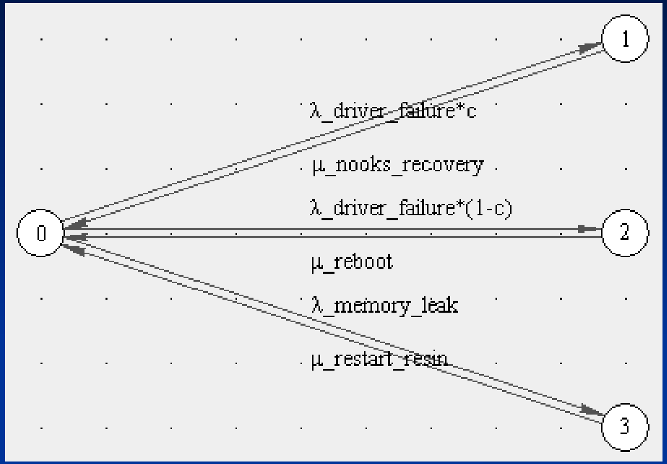
- Birth-Death process with 3 states, 4 parameters:
  - S_0 – UP state, system working
  - S_1 – UP state, recovering failed driver
  - S_2 – DOWN state, system reboot
  - $\lambda_{driver\_failure} = 4/8$
  - $\mu_{nooks\_recovery} = 4{,}093$ microseconds
  - $\mu_{reboot} = 82$ seconds
  - c – coverage factor
- Assumptions
  - Imperfect Repair
- Results
  - Modest Nooks success rates needed to improve system availability.

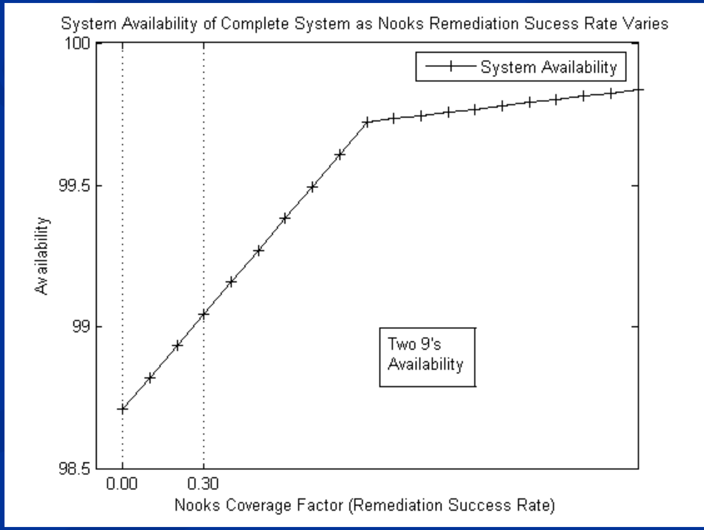




E: Complete Fault Model – Analysis

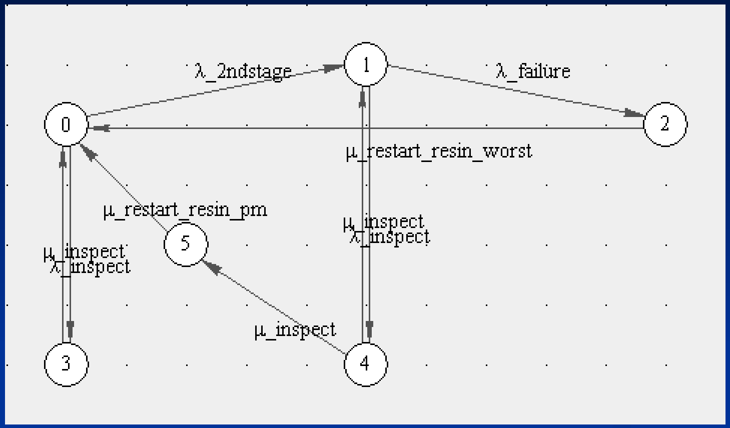
- Birth-Death process with 4 states, 5 parameters:
  - S_0 – UP state, system working
  - S_1 – UP state, recovering failed driver
  - S_2 – DOWN state, system reboot
  - S_3 – DOWN state, Resin reboot
  - $\lambda_{driver\_failure}$ = 4/8 hrs
  - $\mu_{nooks\_recovery}$ = 4,093 microseconds
  - μ_{reboot} = 82 seconds
  - c – coverage factor
  - $\lambda_{memory\_leak\_}$ = 1/8 hours
  - $\mu_{restart\_resin}$ = 47 seconds
- Assumptions
  - Imperfect Repair
- Results
  - Minimum downtime = 866 minutes
  - Availability limited by memory leak handling

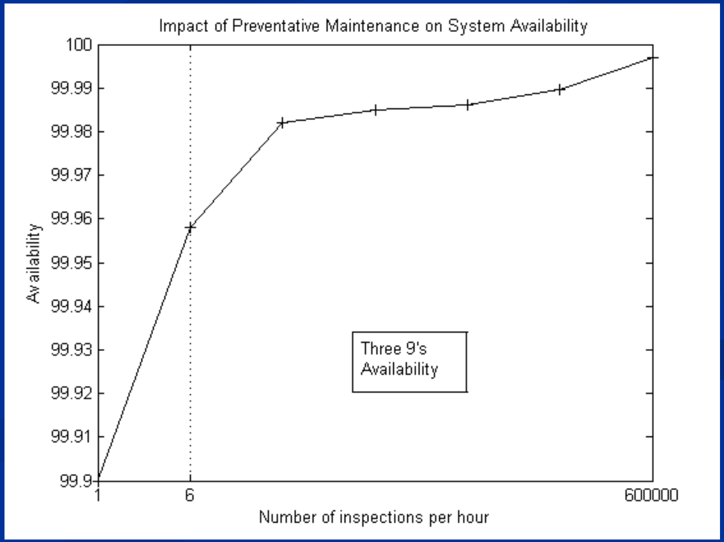




Preventative Maintenance – Analysis

- Non-Birth-Death process with 6 states, 6 parameters:
  - S_0 – UP state, first stage of lifetime
  - S_1 – UP state, second stage of lifetime
  - S_2 – DOWN state, Resin reboot
  - S_3 – UP state, inspecting memory use
  - S_4 – UP state, inspecting memory use
  - S_5 – DOWN state, preventative restart
  - $\lambda_{2ndstage} = 1/6$ hrs
  - $\lambda_{failure} = 1/2$ hrs
  - $\mu_{restart\_resin\_worst} = 47$ seconds
  - $\lambda_{inspect}$ = Rate of memory use inspection
  - $\mu_{inspect} = 21{,}627$ microseconds
  - $\mu_{restart\_resin\_pm} = 3$ seconds
- Results
  - Infrequent checks could have an impact.
  - Only by implementing such a scheme and running experiments would we know for sure.





Towards a RAS-Benchmark

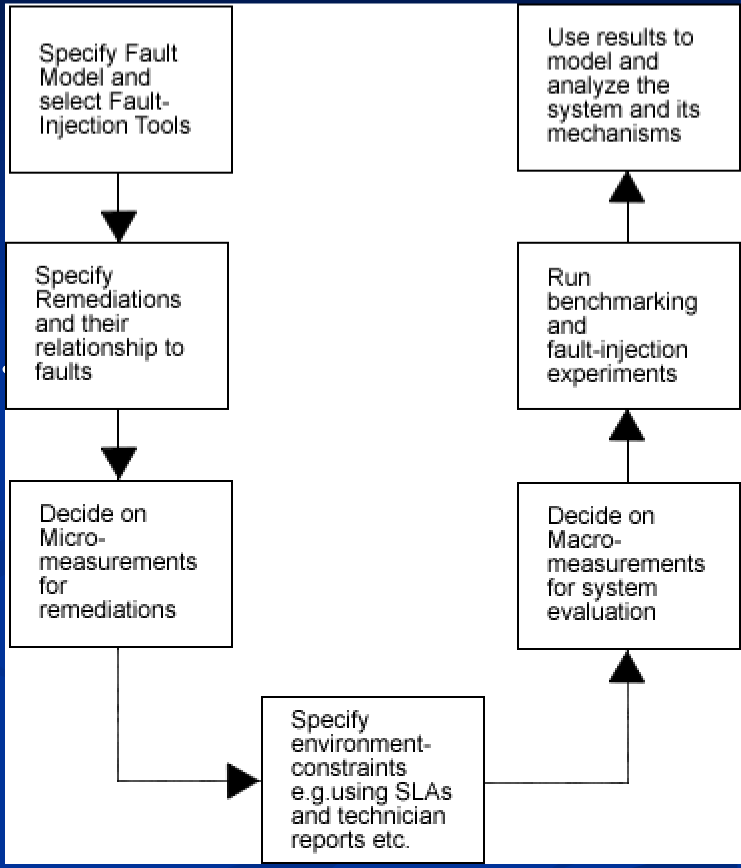
- Thought experiment
  - Type 1 – No detection capabilities.
  - Type 2 – Perfect detection, no diagnosis or repair.
  - Type 3 – Perfect detection and diagnosis, no repair.
  - Type 4 – Perfect detection, diagnosis and repair.
  - Type 5 – Perfect detection, but detectors turned off.
- Expected ranking
  - Type 1 < Type 5 < Type 2 < Type 3 < Type 4

macro-view	goodput	reliability, availability and serviceability	fault-model coverage (expected vs actual)
micro-view	accuracy of detection, diagnosis and repair	speed of detection, diagnosis and repair	

Table 2: *Example Metrics*

7-Step Evaluation "Recipe"

- 7U-Evaluation methodology
  - Combines fault-injection experiments and RAS-models and metrics to evaluate systems.
  - Establish a link between the mechanisms and their impact on system goals/constraints.
  - Highlights the role of the environment in scoring and comparing system.



Part II Summary

- RAS-models are powerful yet flexible tools
  - Able to analyze individual and combined mechanisms.
  - Able to analyze reactive and preventative mechanisms.
  - Capable of linking the details of the mechanisms to their impact on system goals (SLAs, policies etc.)
  - Useful as design-time and post-deployment analysis-tools.
- Limitations
  - Assumption of independence makes it difficult to use them to study cascading/dependent faults.

Accomplishments To Date

- 3 papers on runtime adaptations
  - DEAS 2005 (Kheiron/CLR).
  - ICAC 2006 (Kheiron/JVM, Kheiron/C).
  - Chapter in Handbook on Autonomic Computing.
- Submission to ICAC 2007
  - Using RAS-models and Metrics to evaluate Self-Healing Systems.

Timeline

Timeline	Work	Status
	Develop Initial Kheiron Prototypes	Completed
Jan. 2006	Submitted Kheiron Paper to ICAC	Accepted
Sep. 2006	Build GUI front-end for Kheiron/JVM	Ongoing
Oct. 2006	Build self-healing benchmark simulator	Completed
Nov. 2006	Build Linux-based test-bed for RAS-experiments	Completed
Dec. 2006	Run preliminary RAS-benchmarking experiments	Completed
Jan. 2007	Submit paper on initial results to ICAC 2007	Completed
Feb. 2007	Write Thesis Proposal	Completed
Mar. 2007	Port Linux 2.4 device driver fault tools to Linux 2.6	Ongoing
Mar. 2007	Write device driver fault tool for Windows XP	Ongoing
May. 2007	Write proof of concept database fault injection tool	Ongoing
Jun. 2007	Write or acquire under NDA Solaris 10 fault-injection tools	Ongoing
Jul. 2007	Build test machine for hardware & software fault injection	Ongoing
Aug. 2007	Start next round of RAS-experiments (Solaris,Linux,Win32)	Ongoing
Jan. 2008	Thesis writing	
Aug. 2008	Thesis defense	

Expected Contributions

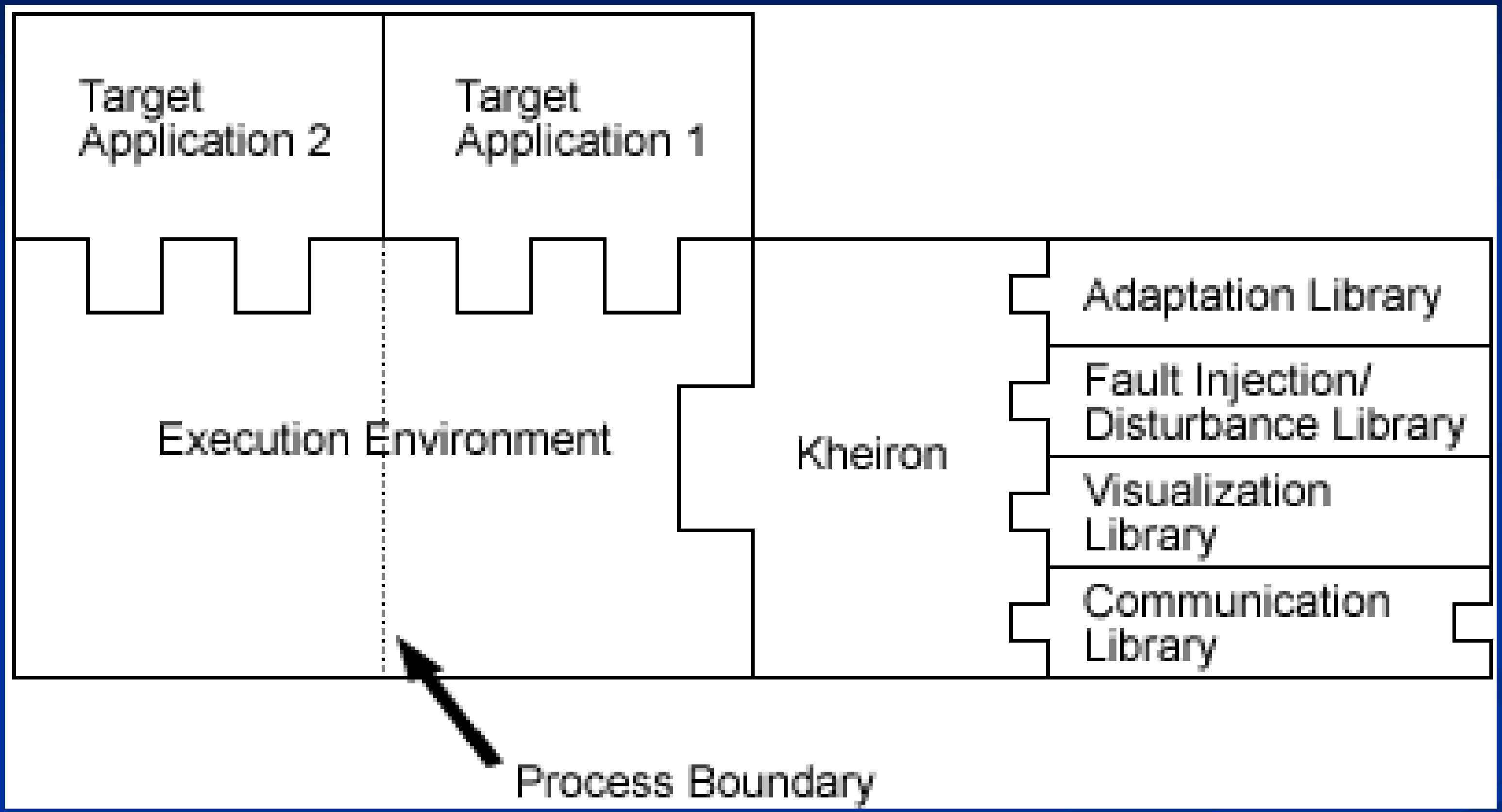
- Contributions towards a representative fault-model for computing systems that can be reproduced using fault-injection tools.
- A suite of runtime fault-injection tools to complement existing software-based and hardware-based fault-injection tools.
- A survey of the RAS-enhancing mechanisms (or lack thereof) in contemporary operating systems and application servers.
- Analytical techniques that can be used at design-time or post-deployment time.
- A RAS-benchmarking methodology based on practical fault-injection tools and rigorous analytical techniques.

Thank You…

- Questions?
- Comments?
- Queries?

Backup Slides

Kheiron Architecture from 10,000ft



How Kheiron Works

- Attaches to programs while they run or when they load.
- Interacts with programs while they run at various points of their execution.
  - Augments type definitions and/or executable code
  - Needs metadata – rich metadata is better
- Interposes at method granularity, inserting new functionality via method prologues and epilogues.
- Control can be transferred into/out of adaptation library logic
- Control-flow changes can be done/un-done dynamically

System Operation

Time period/ execution event	Unmanaged/Native Applications (C-Programs)	Managed Applications	
		JVM 5.x	CLR 1.1
Application start	Attach Kheiron, augment methods	Load Kheiron/JVM	Load Kheiron/CLR
Module load	No real metadata to manipulate	Augment type definition, augment module metadata, bytecode rewrite	Augment type definition, augment module metadata
Method invoke/entry	Transfer control to adaptation logic	Transfer control to adaptation logic	Transfer control to adaptation logic
Method JIT	n/a	No explicit notifications	Augment module metadata, MSIL rewrite, force re-jit
Method exit	Transfer control to adaptation logic	Transfer control to adaptation logic	Transfer control to adaptation logic

Experiments

- Goal: Measure the feasibility of our approach.
- Look at the impact on execution when no repairs/adaptations are active.
- Selected compute-intensive applications as test subjects (SciMark and Linpack).
- Unmanaged experiments
  - P4 2.4 GHz processor, 1GB RAM, SUSE 9.2, 2.6.8x kernel, Dyninst 4.2.1.
- Managed experiments
  - P3 Mobile 1.2 GHz processor, 1GB RAM, Windows XP SP2, Java HotspotVM v1.5 update 04.

Unmanaged Execution Environment Metadata

Symbol Table Entry

```
typedef struct {
        Elf32_Word      st_name;
        Elf32_Addr      st_value;
        Elf32_Word      st_size;
        unsigned char   st_info;
        unsigned char   st_other;
        Elf32_Half      st_shndx;
} Elf32_Sym;
```

Name	Value
STT_NOTYPE	0
STT_OBJECT	1
STT_FUNC	2
STT_SECTION	3

- Not enough information to support type discovery and/or type relationships.
- No APIs for metadata manipulation.
- In the managed world, units of execution are self-describing.