Tools and Techniques for Designing and Evaluating Self-Healing Systems

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Overview

- Introduction
- Challenges
- Problem
- Hypothesis
- Experiments
- Conclusion & Future Work

Introduction

- A self-healing system "…automatically detects, diagnoses and repairs localized software and hardware problems" – The Vision of Autonomic Computing 2003 IEEE Computer Society

Challenges

- How do we evaluate the efficacy of a self-healing system and its mechanisms?
  - How do we quantify the impact of the problems these systems should resolve?
  - How can we reason about expected benefits for systems currently lacking self-healing mechanisms?
  - How do we quantify the efficacy of individual and combined self-healing mechanisms and reason about tradeoffs?
  - How do we identify sub-optimal mechanisms?

Motivation

- Performance metrics are not a perfect proxy for “better self-healing capabilities”
  - Faster != “Better at self-healing”
  - Faster != “Has better self-healing facilities”
- Performance metrics provide insights into the feasibility of using a self-healing system with its self-healing mechanisms active
- Performance metrics are still important, but they are not the complete story

Problem

- Evaluating self-healing systems and their mechanisms is non-trivial
  - Studying the failure behavior of systems can be difficult
  - Finding fault-injection tools that exercise the remediation mechanisms available is difficult
  - Multiple styles of healing to consider (reactive, preventative, proactive)
  - Accounting for imperfect repair scenarios
  - Partially automated repairs are possible

Proposed Solutions

- Studying failure behavior
  - “In-situ” observation in deployment environment via dynamic instrumentation tools
- Identifying suitable fault-injection tools
  - “In-vivo” fault-injection at the appropriate granularity via runtime adaptation tools
- Analyzing multiple remediation styles and repair scenarios (perfect vs. imperfect repair, partially automated healing etc.)
  - Mathematical models (Continuous Time Markov Chains, Control Theory models etc.)

Hypotheses

- Runtime adaptation is a reasonable technology for implementing efficient and flexible fault-injection tools
- Mathematical models e.g. Continuous Time Markov Chains (CTMCs), Markov Reward Models and Control Theory models are a reasonable framework for analyzing system failures, remediation mechanisms and their impact on system operation
- Combining runtime adaptation with mathematical models allows us to conduct fault-injection experiments that can be used to investigate the link between the details of a remediation mechanism and the mechanism’s impact on the high-level goals governing the system’s operation, supporting the comparison of individual or combined mechanisms

Runtime Fault-Injection Tools

- Kheiron/JVM (ICAC 2006)
  - Uses byte-code rewriting to inject faults into running Java applications
  - Includes: memory leaks, hangs, delays etc.
  - Two other versions of Kheiron exist (CLR & C)
  - C-version uses Dyninst binary rewriting tool
- Nooks Device-Driver Fault-Injection Tools
  - Developed at UW for Linux 2.4.18 (Swift et. al)
  - Uses the kernel module interface to inject faults
  - Includes: text faults, stack faults, hangs etc.
  - We ported it to Linux 2.6.20 (Summer 07)

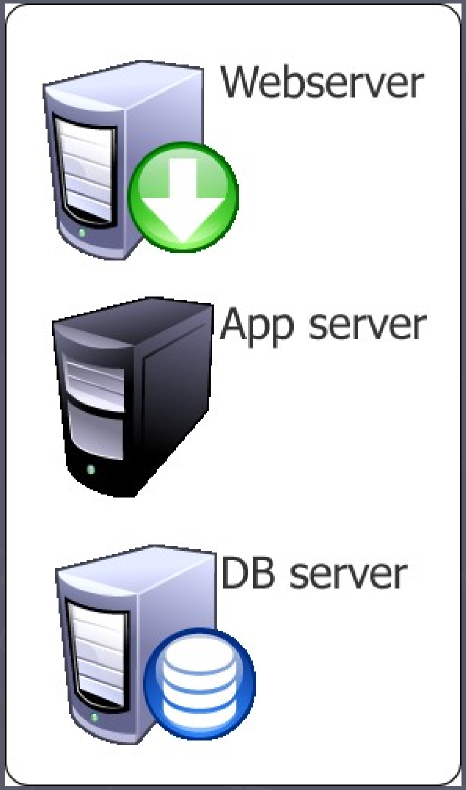
Mathematical Techniques

- Continuous Time Markov Chains (PMCCS-8)
  - Reliability & Availability Analysis
  - Remediation styles
- Markov Reward Networks (PMCCS-8)
  - Failure Impact (SLA penalties, downtime)
  - Remediation Impact (cost, time, labor, production delays)
- Control Theory Models (Preliminary Work)
  - Regulation of Availability/Reliability Objectives
  - Reasoning about Stability

Fault-Injection Experiments

- Objective
  - To inject faults into the components a multi-component n-tier web application – specifically the application server and Operating System components
  - Observe its responses and the responses of any remediation mechanisms available
  - Model and evaluate available mechanisms
  - Identify weaknesses

Experiment Setup



Target: 3-Tier Web Application

TPC-W Web-application
Resin 3.0.22 Web-server and (Java) Application Server
Sun Hotspot JVM v1.5
MySQL 5.0.27
Linux 2.4.18

Remote Browser Emulation clients to simulate user loads

Healing Mechanisms Available

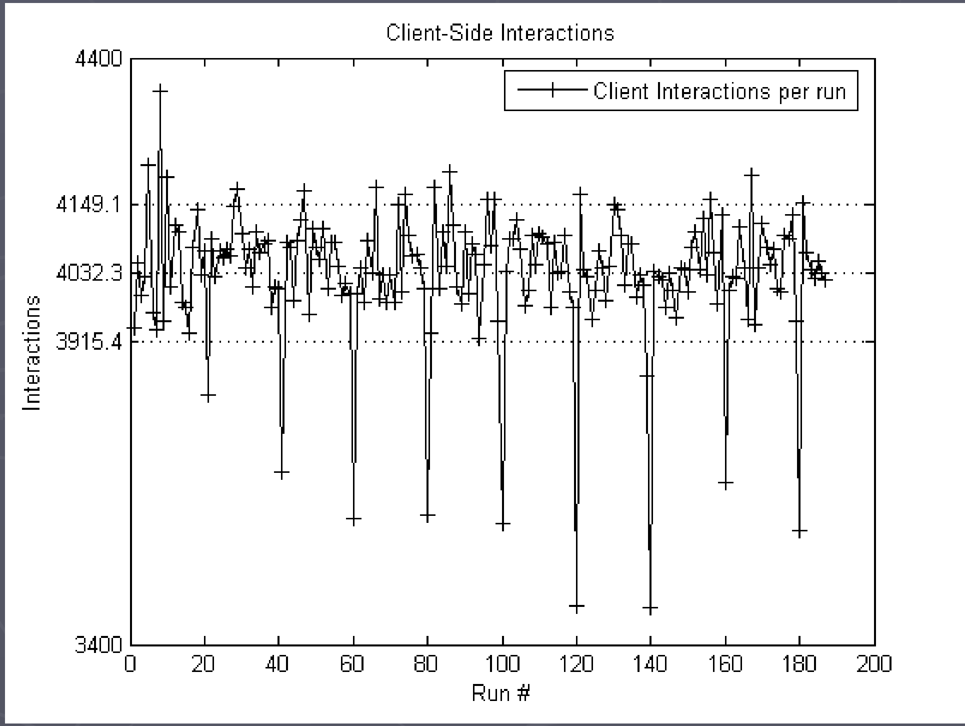
- Application Server
  - Automatic restarts
- Operating System
  - Nooks device driver protection framework
  - Manual system reboot

Metrics

- Continuous Time Markov Chains (CTMCs)
  - Limiting/steady-state availability
  - Yearly downtime
  - Repair success rates (fault-coverage)
  - Repair times
- Markov Reward Networks
  - Downtime costs (time, money, #service visits etc.)
  - Expected SLA penalties

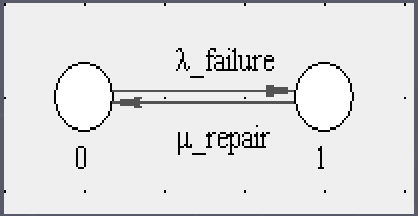
Application Server Memory Leaks

- Memory leak condition causing an automatic application server restart every 8.1593 hours (95% confidence interval)



Resin Memory-Leak Handler Analysis

- Analyzing perfect recovery e.g. mechanisms addressing resource leaks/fatal crashes
  - S_0 – UP state, system working
  - S_1 – DOWN state, system restarting
  - $\lambda_{failure}$ = 1 every 8 hours
  - $\mu_{restart}$ = 47 seconds
- Attaching a value to each state allows us to evaluate the cost/time impact associated with these failures.

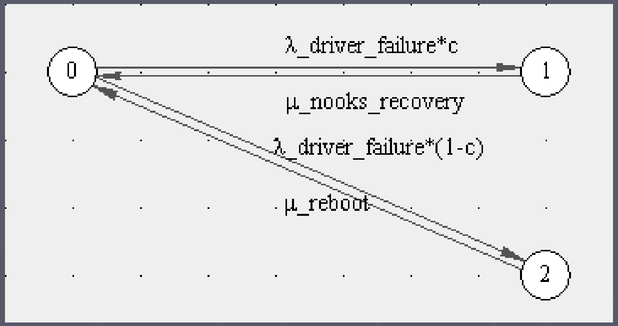


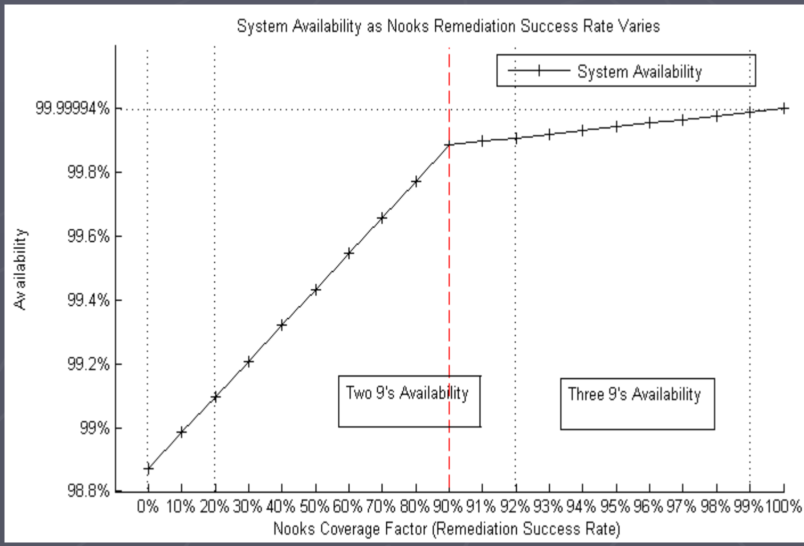
Results:
Steady state availability: 99.838%
Downtime per year: 866 minutes

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

Linux w/Nooks Recovery Analysis

- Analyzing imperfect recovery e.g. device driver recovery using Nooks
  - S_0 – UP state, system working
  - S_1 – UP state, recovering failed driver
  - S_2 – DOWN state, system reboot
  - $\lambda_{driver\_failure}$ = 4 faults every 8 hrs
  - $\mu_{nooks\_recovery}$ = 4,093 mu seconds
  - μ_{reboot} = 82 seconds
  - c – coverage factor/success rate





Resin + Linux + Nooks Analysis

- Composing Markov chains
  - 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 faults every 8 hrs
  - $\mu_{nooks\_recovery}$ = 4,093 mu seconds
  - μ_{reboot} = 82 seconds
  - c – coverage factor
  - $\lambda_{memory\_leak\_}$ = 1 every 8 hours
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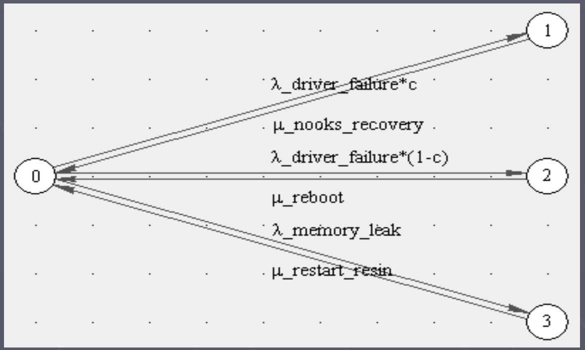
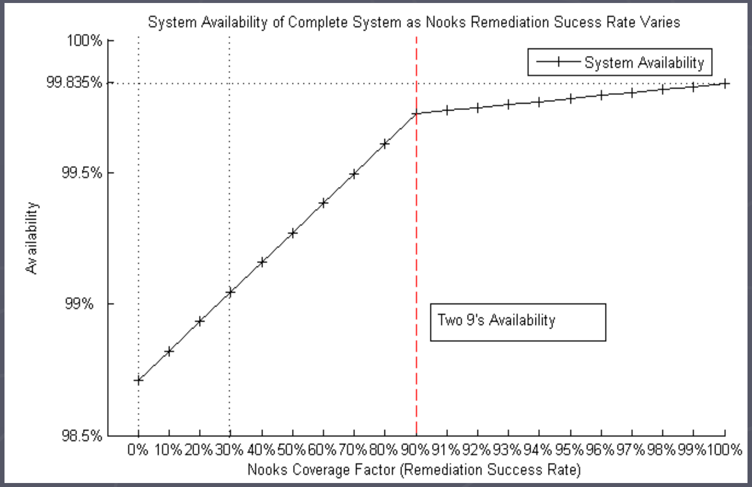
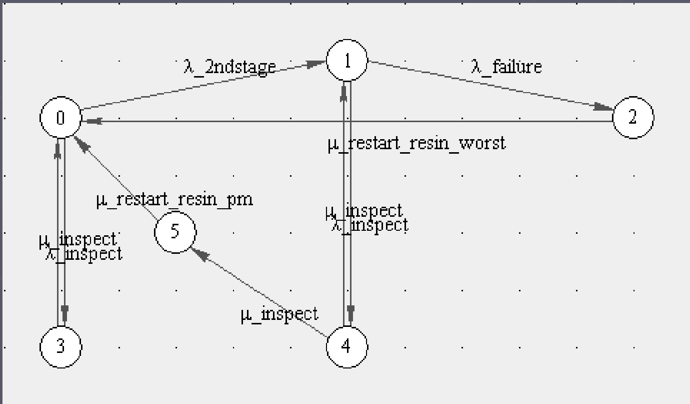


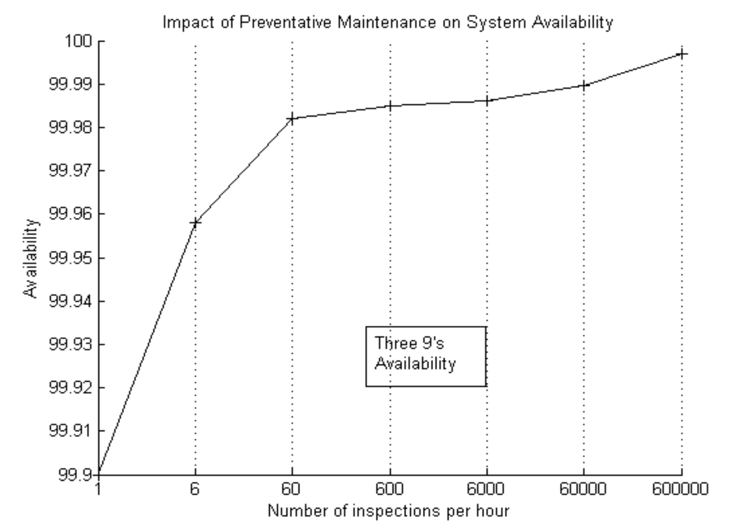


Max availability = 99.835%
Min downtime = 866 minutes

Proposed Preventative Maintenance

- 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
  - $\lambda_{inspect}$ = Memory use inspection rate
  - $\mu_{inspect}$ = 21,627 microseconds
  - $\mu_{restart\_resin\_pm}$ = 3 seconds





Benefits of CTMCs + Fault Injection

- Able to model and analyze different styles of self-healing mechanisms
- Quantifies the impact of mechanism details (success rates, recovery times etc.) on the system’s operational constraints (availability, production targets, production-delay reduction etc.)
  - Engineering view AND Business view
- Able to identify under-performing mechanisms
- Useful at design time as well as post-production
- Able to control the fault-rates

Caveats of CTMCs + Fault-Injection

- CTMCs may not always be the “right” tool
  - Constant hazard-rate assumption
    - May under or overstate the effects/impacts
    - True distribution of faults may be different
  - Fault-independence assumptions
    - Limited to analyzing near-coincident faults
    - Not suitable for analyzing cascading faults (can we model the precipitating event as an approximation?)
- Some failures are harder to replicate/induce than others
  - Better data on faults could improve fault-injection tools
- Getting detailed breakdown of types/rates of failures
  - More data should improve the fault-injection experiments and relevance of the results

Real-World Downtime Data*

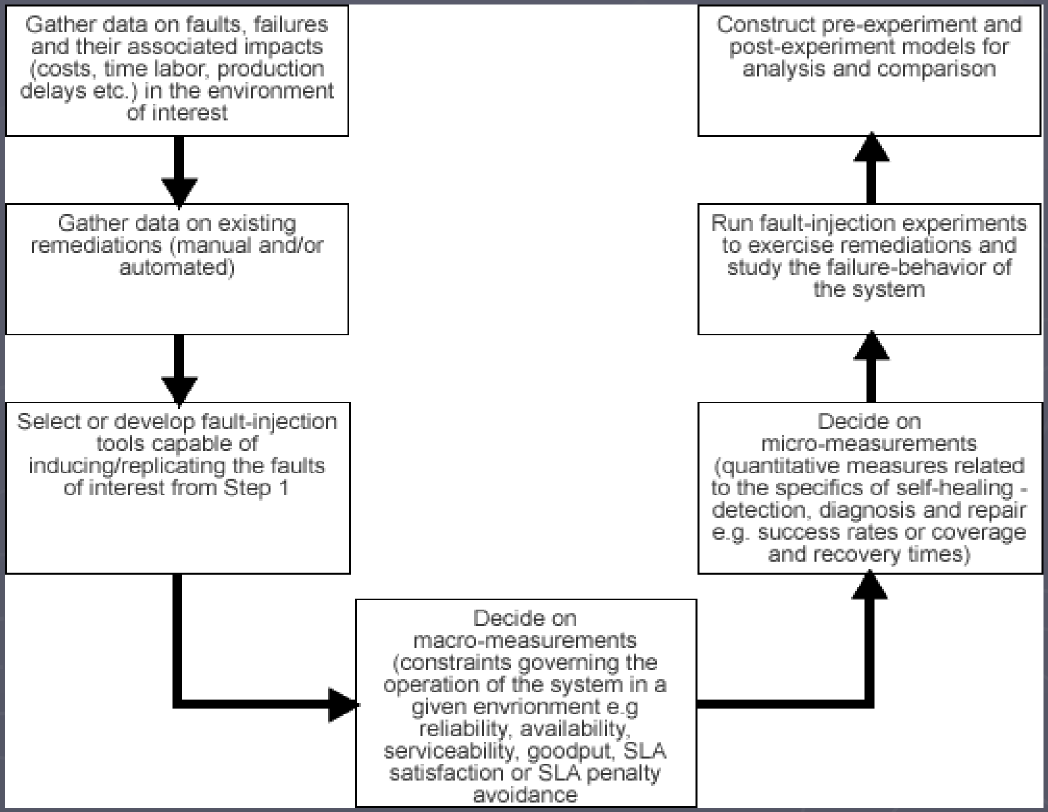
- Mean incidents of unplanned downtime in a year: 14.85 (n-tier web applications)
- Mean cost of unplanned downtime (Lost productivity #IT Hours):
  - 2115 hrs (52.88 40-hour work-weeks)
- Mean cost of unplanned downtime (Lost productivity #Non-IT Hours):
  - 515.7 hrs** (12.89 40-hour work-weeks)

* “IT Ops Research Report: Downtime and Other Top Concerns,” **StackSafe**. July 2007. (Web survey of 400 IT professional panelists, US Only)
** "Revive Systems Buyer Behavior Research," Research Edge, Inc. June 2007

Proposed Data-Driven Evaluation (7U)

- 1. Gather failure data and specify fault-model
- 2. Establish fault-remediation relationship
- 3. Select fault-injection tools to mimic faults in 1
- 4. Identify Macro-measurements
  - Identify environmental constraints governing system-operation (availability, production targets etc.)
- 5. Identify Micro-measurements
  - Identify metrics related to specifics of self-healing mechanisms (success rates, recovery time, fault-coverage)
- 6. Run fault-injection experiments and record observed behavior
- 7. Construct pre-experiment and post-experiment models

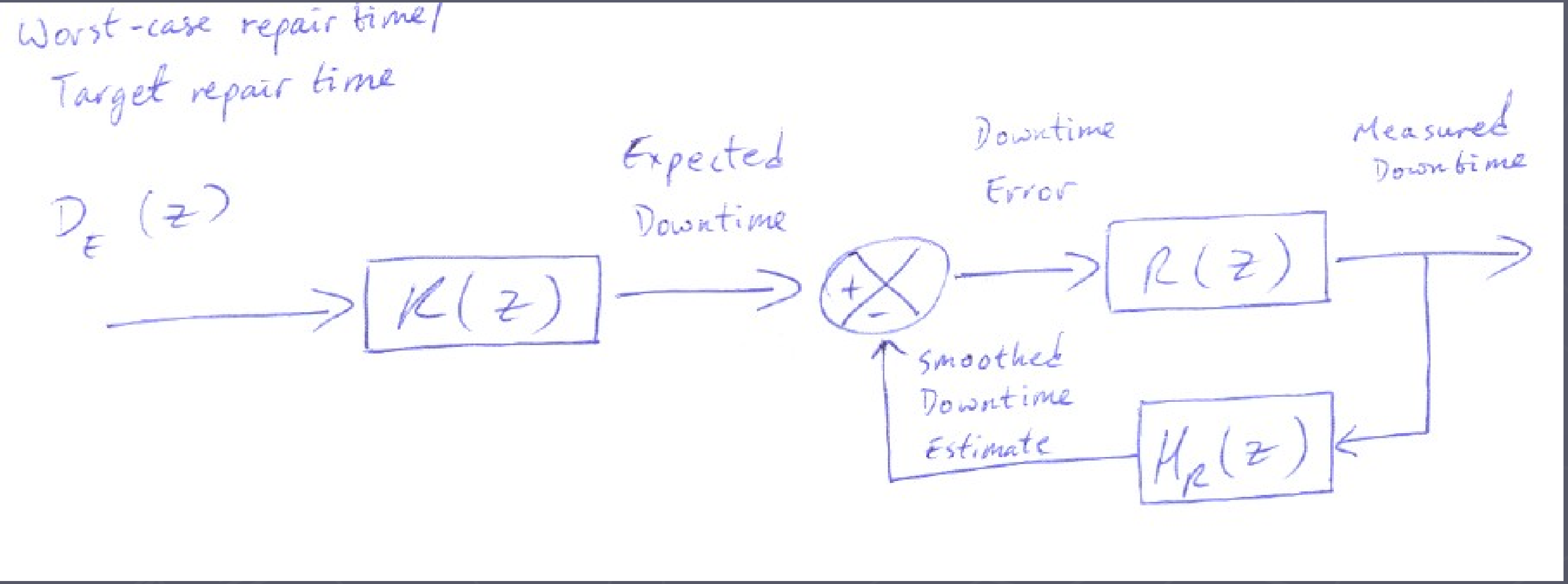
The 7U-Evaluation Method



Preliminary Work – Control Models

- Objective
  - Can we reason about the stability of the system when the system has multiple repair choices for individual faults using Control Theory?
  - Can we regulate availability/reliability objectives?
  - What are the pros & cons of trying to use Control Theory in this context?

Preliminary Work – Control Diagram

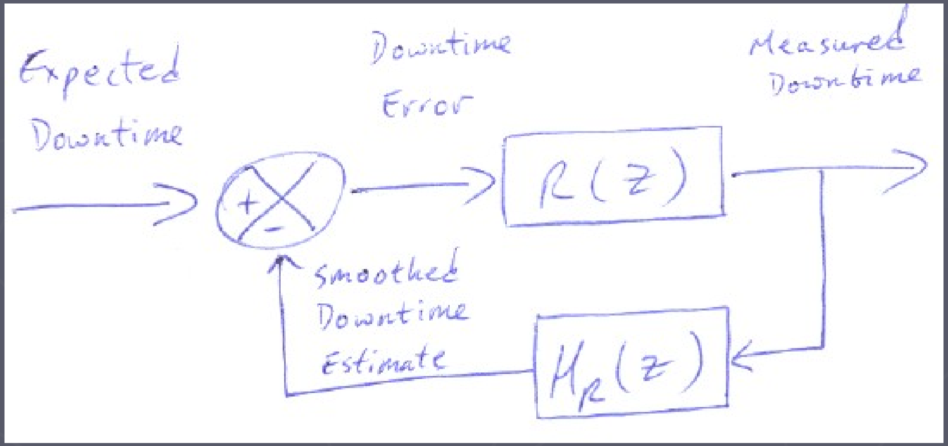


Expected Downtime = f(Reference/Desired Success Rate)
Measured Downtime = f(Actual Success Rate)
Smoothed Downtime Estimate f(Actual Success Rate)

Preliminary Work – Control Parameters

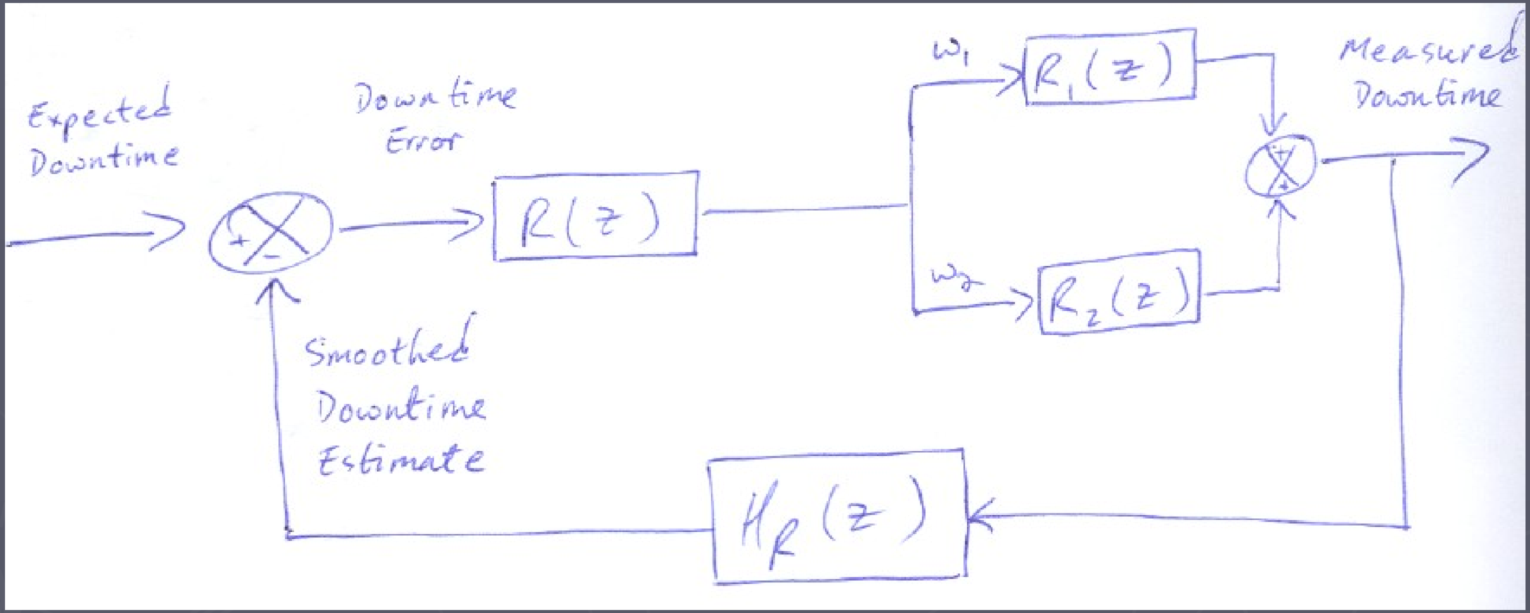
- D_E(z) – represents the occurrence of faults
  - Signal magnitude equals worst case repair time/desired repair time for a fault
- Expected downtime = f(Reference Success Rate)
- Smoothed downtime estimate = f(Actual Success Rate)
- Downtime error – difference between desired downtime and actual downtime incurred
- Measured Downtime – repair time impact on downtime.
  - 0 for transparent repairs or 0 < r <= D_E(k) if not
- Smoothed Downtime Estimate – the result of applying a filter to Measured Downtime

Preliminary Simulations



- Reason about stability of repair selection controller/subsystem, R(z), using the poles of transfer function R(z)/[1+R(z)H_R(z)]
- Show stability properties as expected/reference success rate and actual repair success rate vary
- How long does it take for the system to become unstable/stable

Preliminary Work – Desired Goal



- Can we extend the basic model to reason about repair choice/preferences?

Conclusions

- Dynamic instrumentation and fault-injection lets us transparently collect data "in-situ" and replicate problems "in-vivo"
- The CTMC-models are flexible enough to quantitatively analyze various styles and "impacts" of repairs
- We can use them at design-time or post-deployment time
- The math is the "easy" part compared to getting customer data on failures, outages, and their impacts.
  - These details are critical to defining the notions of "better" and "good" for these systems

Future Work

- More experiments on an expanded set of operating systems using more server-applications
  - Linux 2.6
  - OpenSolaris 10
  - Windows XP SP2/Windows 2003 Server
- Modeling and analyzing other self-healing mechanisms
  - Error Virtualization (From STEM to SEAD, Locasto et. al Usenix 2007)
  - Self-Healing in OpenSolaris 10
- Feedback control for policy-driven repair-mechanism selection

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Questions, Comments, Queries?

Thank you for your time and attention

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Extra Slides

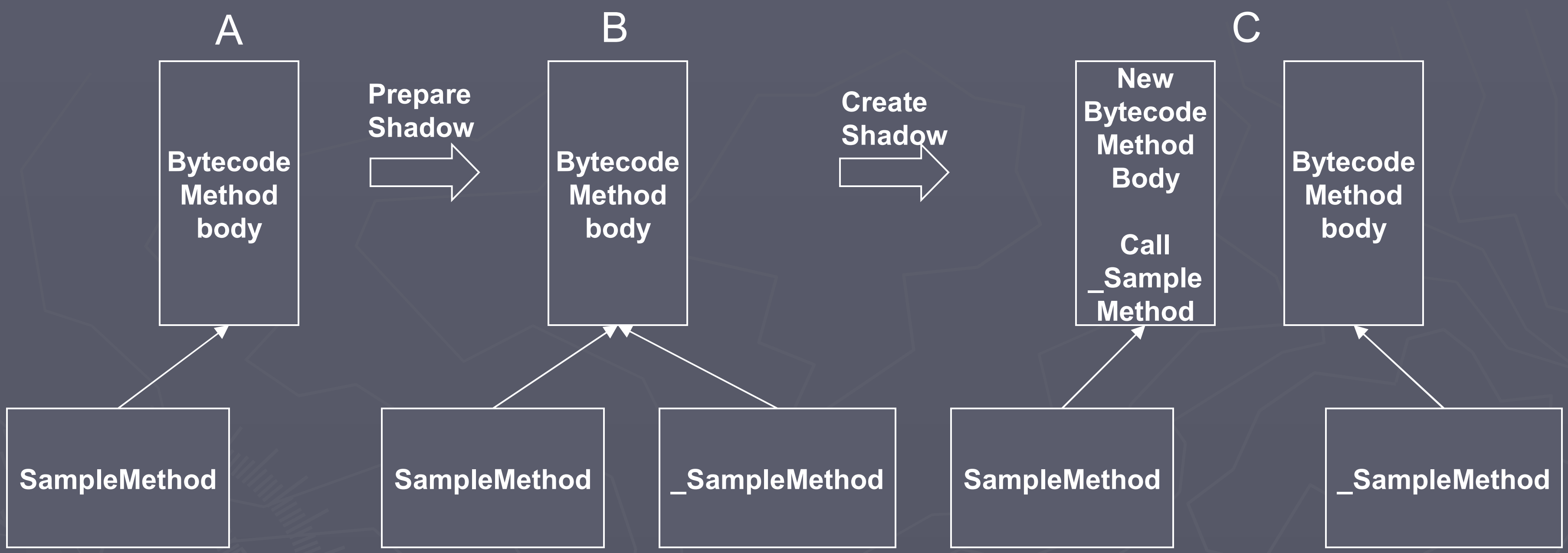
How Kheiron Works

- Key observation
  - All software runs in an execution environment (EE), so use it to facilitate performing adaptations (fault-injection operations) in 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

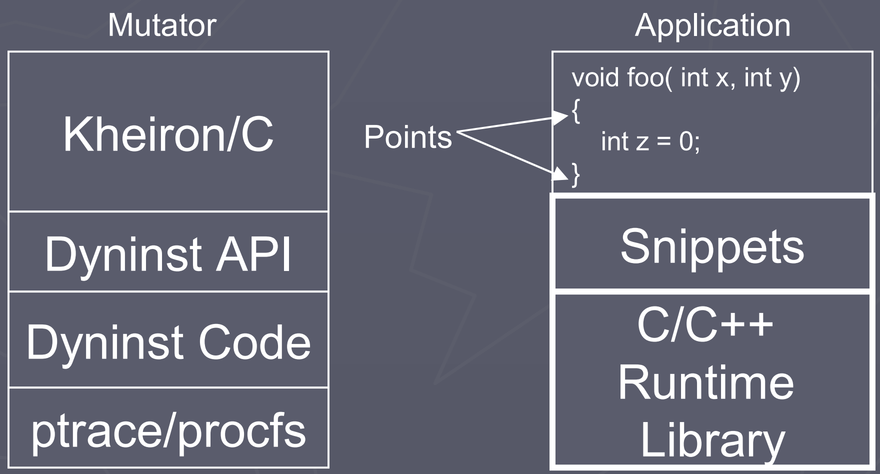


SampleMethod(args) [throws NullPointerException]
<room for prolog>
push args
call _SampleMethod(args) [throws NullPointerException]
{ try{…} catch (IOException ioe){…} } // Source view of _SampleMethod's body
<room for epilog>
return value/void

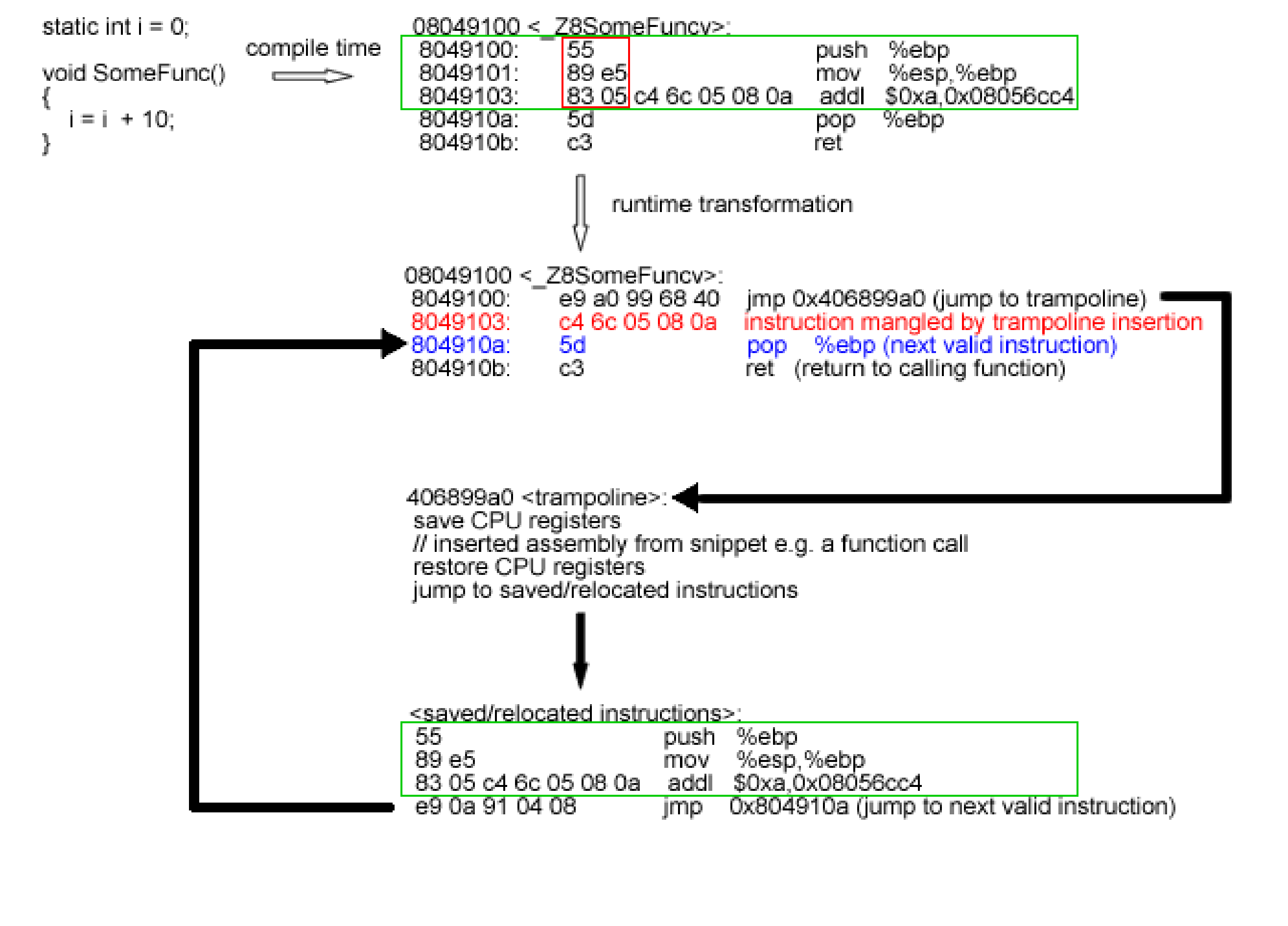
Kheiron/CLR & Kheiron/JVM Fault-Rewrite

```
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
}
```

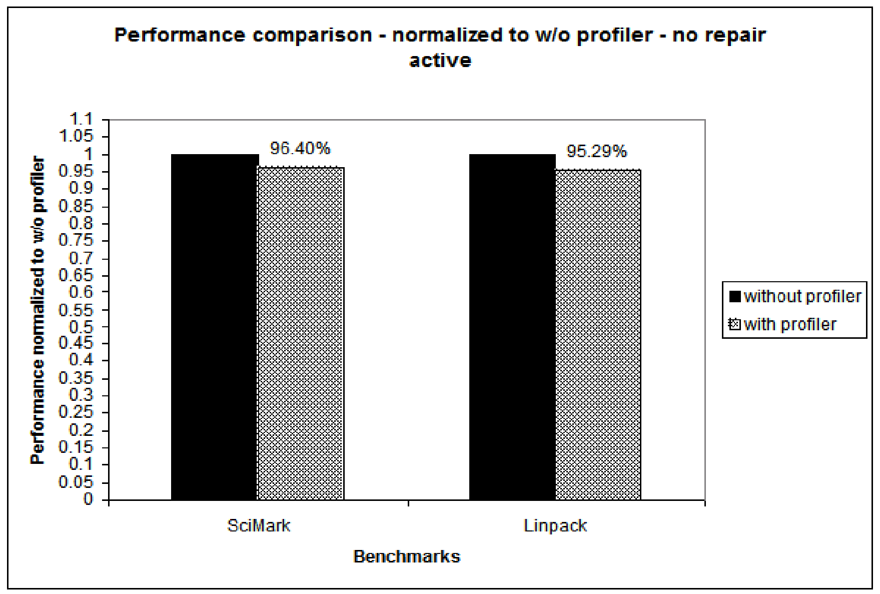
Kheiron/C Operation

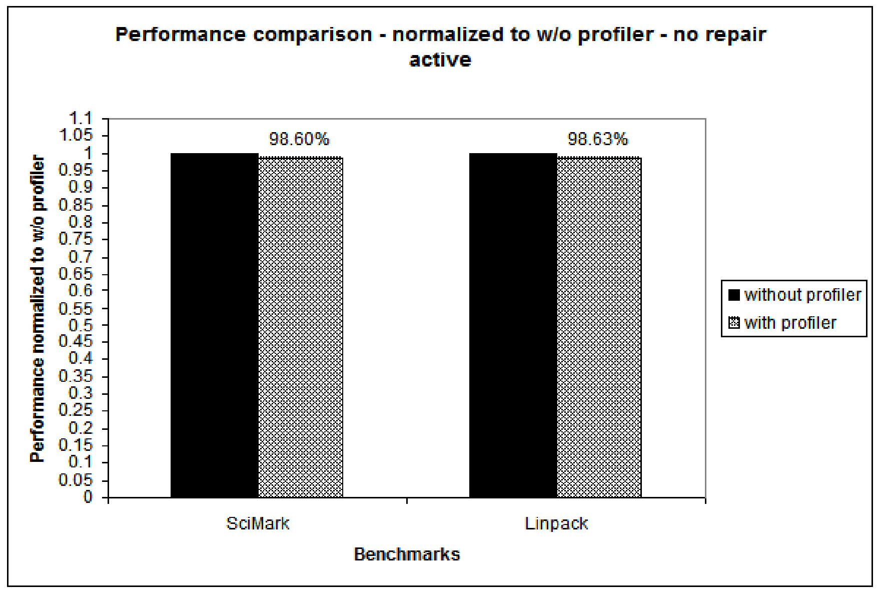


Kheiron/C – Prologue Example



Kheiron/CLR & Kheiron/JVM Feasibility

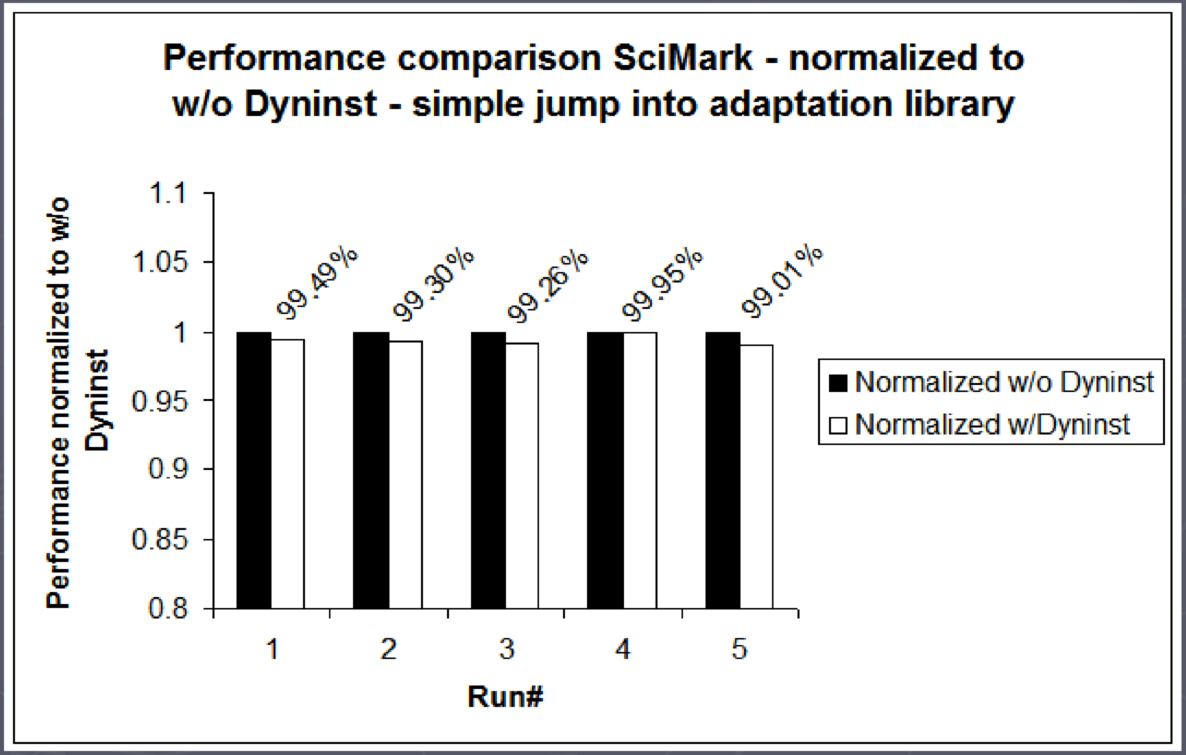




Kheiron/CLR Overheads when no adaptations active

Kheiron/JVM Overheads when no adaptations active

Kheiron/C Feasibility



Kheiron/C Overheads
when no adaptations active

Kheiron 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.

Quick Analysis – End User View

- Unplanned Downtime (Lost productivity Non-IT hrs) per year: 515.7 hrs (30,942 minutes).
- Is this good? (94.11% Availability)

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

- Less than two 9's of availability
  - Decreasing the down time by an order of magnitude could improve system availability by two orders of magnitude