Combining Genetic Algorithms & Simulation to Search for Failure Scenarios in System Models

Kevin Mills, Chris Dabrowski, Jim Filliben and Sandy Ressler
NIST

Cloud Security Working Group
July 17, 2013
Outline

• Motivation & Context
• Method
• Case Study
  — *Koala* IaaS Cloud Simulator
  — Searching for Failure Scenarios
  — Evaluating Method
• Conclusions & Future Work
GROWING GLOBAL DEPENDENCE ON COMPLEX INFO. SYSTEMS

The Cloud Scales: Amazon S3 Growth

Peak Requests: 200,000+ per second

Total Number of Objects Stored in Amazon S3

2.5 Billion
14 Billion
40 Billion
102 Billion
292 Billion

Rackspace Customer Growth

Rackspace Hits 100,000 Customers

Cloud-Based Infrastructure as a Service Comes to Government

Kundra Outlines "Cloud First" Policy for U.S. Government

Netflix Moves Into the Cloud With Amazon Web Services

The Cloud Scales: Amazon S3 Growth

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Rackspace Customer Growth

SAP Exec: Here's Why We Spent $8 Billion On Two Cloud Companies

Amazon cloud accessed daily by a third of all 'Net users

Cloud provider and the Internet becoming one and the same

Microsoft Touts ‘High Tens of Thousands’ of Windows Azure Customers

IBM to battle Amazon in the public cloud

Oracle Transformed - It's Now All about the Cloud

Salesforce Chatterizes 10,000 Of Its Customers First Week After Public Launch

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WE CAN BUILD & DEPLOY SUCH SYSTEMS, BUT CAN WE UNDERSTAND, PREDICT & CONTROL THEM?

Amazon EC2 Outage Explained and Lessons Learned

EC2 OUTAGE REACTIONS SHOWCASE WIDESPREAD IGNORANCE REGARDING THE CLOUD

Rackspace outage was third in two days

SalesForce outages show SaaS customers dependence on providers' DR plans

Google Talk, Twitter, Azure Outages: Bad Cloud Day

How did Amazon have a cloud service outage that was caused by generator failure?

Salesforce.com hit with second major outage in two weeks

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Microsoft's Azure Cloud Suffers Serious Outage

Storms, leap second trigger weekend of outages

AWS outages, bugs and bottlenecks explained by Amazon
Never-before-seen software bug caused flood of requests creating a massive backlog in the system

What's happened to the cloud?
Are major cloud outages in recent times denting confidence?

(Real) Storm Crushes Amazon Cloud, Knocks out Netflix, Pinterest, Instagram

According to the International Working Group on Cloud Computing Resiliency (IWGCR), the total downtime of 13 well-known cloud services since 2007 amounts to 568 hours, which has an economic impact of around $71.7 million dollars.
PAST NIST RESEARCH FROM 2006-2011

How can we understand the influence of distributed control algorithms on global system behavior and user experience?


For more see: [http://www.nist.gov/itl/antd/emergent_behavior.cfm](http://www.nist.gov/itl/antd/emergent_behavior.cfm)
How can we increase the reliability of complex information systems?

- **Research Goals:** (1) develop and evaluate design-time methods that system engineers can use to detect existence and causes of costly failure regimes prior to system deployment and (2) develop and evaluate run-time methods that system managers can use to detect onset of costly failure regimes in deployed systems, prior to collapse.

- **Ongoing:** investigating design-time methods –
  b. Anti-Optimization (AO) + Genetic Algorithm (GA) – TODAY’S PRESENTATION

- **Planned:** investigate run-time methods based on approaches that may provide early warning signals for critical transitions in large systems (e.g., Scheffer et al., “Early-warning signals for critical transitions”, *Nature*, 461, 53-59, 2009).
Method: Genetic Algorithm (GA) steers a population of simulators to search for parameter combinations that lead to system failure.

**GENETIC ALGORITHM**

- **Recombination & Mutation**
- **Selection based on Anti-Fitness**

**Model Parameter Specifications**
- List of parameters and for each parameter a MIN, MAX and precision.

**Growing Collection of Tuples:**
- \{Generation, Individual, Fitness, Parameter 1 value, \ldots Parameter N value\}
- \{Generation, Individual, Fitness, Parameter 1 value, \ldots Parameter N value\}
- \ldots
- \{Generation, Individual, Fitness, Parameter 1 value, \ldots Parameter N value\}

**MULTIDIMENSIONAL ANALYSIS TECHNIQUES**

- Principal Components Analysis, Clustering, ...
Case Study Topics

1. *Koala* Simulator
2. *Koala* Parameters & Representation as Chromosomes
3. Genetic Algorithm
4. Population of *Koala* Simulators
5. Dynamics of GA Search
6. Analysis Method
7. Results from Four GA Searches
In our case study we defined **anti-fitness** as the proportion of arriving users not served.
Schematic of *Koala* IaaS Cloud Simulator

Demand and supply layers modeled after Amazon EC2
Internal structure modeled after Eucalyptus v1.6
**Topic 2: Koala Parameters & GA Representation as Chromosomes (i.e., bit strings)**

**Model Parameter Specifications**

- Parallel Execution of Model Simulators
- Population of Model Parameterizations
- Selection based on Anti-Fitness

**Growing Collection of Tuples:**

{Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value}
{Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value}
...
Summary of *Koala* Parameters to Search Over

**Test Case** – Can GA find VM Leakage due to message loss and lack of orphan control?


<table>
<thead>
<tr>
<th>Model Element</th>
<th>Parameter Category</th>
<th>Behavior</th>
<th>Structure</th>
<th>Asymmetry</th>
<th>Failure</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>User</td>
<td></td>
<td>28</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>34</td>
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<tr>
<td>Cloud Controller</td>
<td></td>
<td>21</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td>30</td>
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<tr>
<td>Cluster Controllers</td>
<td></td>
<td>11</td>
<td>5</td>
<td>3</td>
<td>0</td>
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<td>Nodes</td>
<td></td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>Intra-Net/Inter-Net</td>
<td></td>
<td>4</td>
<td>11</td>
<td>2</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td></td>
<td>70</td>
<td>22</td>
<td>14</td>
<td>23</td>
<td>129</td>
</tr>
</tbody>
</table>

Average # values per parameter is about 6, so search space is ≈ $6^{129}$

i.e., ≈ $10^{100}$ scenarios are possible

- adapted 125-parameter Koala IaaS simulator to be GA controllable
- added 4 *Koala* parameters to turn on/off logic to control (a) creation orphans, (b) termination orphans, (c) relocation orphans and (d) administrator actions
## Sample Chromosome Specification

### Koala Parameter Space (Size = $10^{100}$)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MIN</th>
<th>MAX</th>
<th>PRECISION</th>
<th>#VALUES</th>
<th>LOW_BIT</th>
<th>HIGH_BIT</th>
<th>#BITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_CreateOrphanControlOn</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>36</td>
<td>36</td>
<td>1</td>
</tr>
<tr>
<td>P_TerminationOrphanControlOn</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>58</td>
<td>58</td>
<td>1</td>
</tr>
<tr>
<td>P_RelocationOrphanControlOn</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>11</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>P_AdministratorActive</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>330</td>
<td>330</td>
<td>1</td>
</tr>
<tr>
<td>P_clusterAllocationAlgorithm</td>
<td>0</td>
<td>5</td>
<td>1</td>
<td>6</td>
<td>31</td>
<td>33</td>
<td>3</td>
</tr>
<tr>
<td>P_describeResourcesInterval</td>
<td>600</td>
<td>3600</td>
<td>600</td>
<td>6</td>
<td>81</td>
<td>83</td>
<td>3</td>
</tr>
<tr>
<td>P_nodeResponseTimeout</td>
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<td>90</td>
<td>30</td>
<td>3</td>
<td>210</td>
<td>211</td>
<td>2</td>
</tr>
<tr>
<td>P_TerminatedInstancesBackOffThreshold</td>
<td>3</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>56</td>
<td>57</td>
<td>2</td>
</tr>
<tr>
<td>P_TerminationBackOffInterval</td>
<td>180</td>
<td>360</td>
<td>60</td>
<td>4</td>
<td>88</td>
<td>89</td>
<td>2</td>
</tr>
<tr>
<td>P_TerminationRetryPeriod</td>
<td>600</td>
<td>1200</td>
<td>300</td>
<td>3</td>
<td>316</td>
<td>317</td>
<td>2</td>
</tr>
<tr>
<td>P_StaleShadowAllocationPurgeInterval</td>
<td>600</td>
<td>3600</td>
<td>600</td>
<td>6</td>
<td>242</td>
<td>244</td>
<td>3</td>
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<tr>
<td>P_cloudAllocationCriteria</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>321</td>
<td>322</td>
<td>2</td>
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<tr>
<td>P_clusterShadowPurgeLimit</td>
<td>1</td>
<td>21</td>
<td>5</td>
<td>5</td>
<td>290</td>
<td>292</td>
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<tr>
<td>P_instancePurgeDelay</td>
<td>180</td>
<td>600</td>
<td>60</td>
<td>8</td>
<td>98</td>
<td>100</td>
<td>3</td>
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<tr>
<td>P_clusterEvaluationResponseTimeout</td>
<td>60</td>
<td>120</td>
<td>30</td>
<td>3</td>
<td>14</td>
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<td>2</td>
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<tr>
<td>P_MaxPendingRequests</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>72</td>
<td>75</td>
<td>4</td>
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<td>P_CloudTerminatedInstancesBackOffThreshold</td>
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<td>6</td>
<td>1</td>
<td>4</td>
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<td>170</td>
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<td>P_CloudTerminationBackOffInterval</td>
<td>180</td>
<td>360</td>
<td>60</td>
<td>4</td>
<td>40</td>
<td>41</td>
<td>2</td>
</tr>
<tr>
<td>P_CloudTerminationRetryPeriod</td>
<td>3600</td>
<td>10800</td>
<td>1800</td>
<td>5</td>
<td>297</td>
<td>299</td>
<td>3</td>
</tr>
<tr>
<td>P_ClusterShutdownGracePeriod</td>
<td>86400</td>
<td>2.59E+05</td>
<td>43200</td>
<td>5</td>
<td>147</td>
<td>149</td>
<td>3</td>
</tr>
</tbody>
</table>

### Genetic Algorithm Computed Chromosome Map (Size = $2^{334}$)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MIN</th>
<th>MAX</th>
<th>PRECISION</th>
<th>#VALUES</th>
<th>LOW_BIT</th>
<th>HIGH_BIT</th>
<th>#BITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_RequestEvaluatorTimeoutWaitProportion</td>
<td>0.1</td>
<td>0.4</td>
<td>0.1</td>
<td>4</td>
<td>145</td>
<td>146</td>
<td>2</td>
</tr>
<tr>
<td>P_RequestEvaluatorClusterMinimumResponse</td>
<td>0.6</td>
<td>0.9</td>
<td>0.1</td>
<td>3</td>
<td>269</td>
<td>270</td>
<td>2</td>
</tr>
<tr>
<td>P_MaxRelocationDurationProportion</td>
<td>0.65</td>
<td>0.95</td>
<td>0.1</td>
<td>4</td>
<td>90</td>
<td>91</td>
<td>2</td>
</tr>
<tr>
<td>P_MaximumRelocateDescribeRetries</td>
<td>4</td>
<td>16</td>
<td>2</td>
<td>7</td>
<td>254</td>
<td>256</td>
<td>3</td>
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<tr>
<td>P_AverageCloudAdministratorAttentionLatency</td>
<td>28800</td>
<td>86400</td>
<td>14400</td>
<td>5</td>
<td>308</td>
<td>310</td>
<td>3</td>
</tr>
<tr>
<td>P_AverageCloudAdministratorShutdownDelay</td>
<td>300</td>
<td>900</td>
<td>300</td>
<td>3</td>
<td>45</td>
<td>46</td>
<td>2</td>
</tr>
<tr>
<td>P_avgTimeToClusterCommunicationCut</td>
<td>2.88E+06</td>
<td>2.88E+07</td>
<td>2.88E+06</td>
<td>10</td>
<td>217</td>
<td>220</td>
<td>4</td>
</tr>
</tbody>
</table>

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**Topic 3: Genetic Algorithm**

**MULTIDIMENSIONAL ANALYSIS TECHNIQUES**

- Principal Components Analysis, Clustering, ...

**GENETIC ALGORITHM**

- **Recombination & Mutation**
- **Selection based on Anti-Fitness**

- Growing Collection of Tuples:
  
  
  [Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value]
  
  [Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value]
  
  [Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value]
  
  [Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value]
  
  [Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value]
  
  [Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value]

- Anti-Fitness Reports

- **MODEL SIMULATORS**

  - Parallel Execution of Model Simulators
  
  - Population of Model Parameterizations
  
  - Model Parameter Specifications

- List of parameters and for each parameter a MIN, MAX and precision.
**Topic 4: Population of Koala Simulators**

**Model Parameter Specifications**

- Parallel Execution of Model Simulators
- Population of Model Parameterizations
  - Selection based on Anti-Fitness
    - Anti-Fitness Reports
- Growing Collection of Tuples:
  
  - (Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)
  - (Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)
  - (Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)
  - (Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)
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**GENETIC ALGORITHM**

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**MULTIDIMENSIONAL ANALYSIS TECHNIQUES**

- Principal Components Analysis, Clustering, ...

**MODEL SIMULATORS**

- Parallel Execution of Model Simulators

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Population of *Koala* Simulators Deployed on a High Performance Computing Cluster

![Diagram of Koala Simulators deployment on a High Performance Computing Cluster.](image_url)
MODEL SIMULATORS

Model Parameter Specifications

Population of Model Parameterizations

Parallel Execution of Model Simulators

Growing Collection of Tuples:
(Generation, Individual, Fitness, Parameter 1 value, …, Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, …, Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, …, Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, …, Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, …, Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, …, Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, …, Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, …, Parameter N value)
...

Anti-Fitness Reports

GENETIC ALGORITHM

Principal Components Analysis, Clustering, ...

Recombination & Mutation

Selection based on Anti-Fitness

MULTIDIMENSIONAL ANALYSIS TECHNIQUES

Topic 5: Dynamics of GA Search

List of parameters and for each parameter a MIN, MAX and precision.

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One GA Search over 500 Generations

GENETIC ALGORITHM CONTROL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generations</td>
<td>500</td>
</tr>
<tr>
<td>Population Size</td>
<td>200 Individuals</td>
</tr>
<tr>
<td>Elite Per Generation</td>
<td>16 Individuals</td>
</tr>
<tr>
<td>Reboot After</td>
<td>200 Generations</td>
</tr>
<tr>
<td>Selection Method</td>
<td>Stochastic Uniform Sampling</td>
</tr>
<tr>
<td># Crossover Points</td>
<td>3</td>
</tr>
<tr>
<td>Mutation Rate</td>
<td>0.001 ≤ Adaptive ≤ 0.01</td>
</tr>
</tbody>
</table>

(a) Average Anti-Fitness

(b) Standard Deviation in Anti-Fitness

(c) Maximum Anti-Fitness Discovered

Graphs showing the evolution of average anti-fitness, standard deviation in anti-fitness, and the maximum anti-fitness discovered over 500 generations.
Assessment of Search Conducted by GA

(based on $10^5$ scenarios, i.e., 200 individuals x 500 generations)

- 84% of scenarios exhibit anti-fitness $\geq 0.50$
- Only 8% of scenarios are duplicate (equals elite-selection percentage)
- For *Koala* simulator, failure scenarios appear within first 100-200 generations
Topic 6: Analysis Method

MULTIDIMENSIONAL ANALYSIS TECHNIQUES

Principal Components Analysis, Clustering, ...

GENETIC ALGORITHM

Recombination & Mutation

Selection based on Anti-Fitness

Growing Collection of Tuples:

(Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)
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(Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)
(Generation, Individual, Fitness, Parameter 1 value, ..., Parameter N value)

Anti-Fitness Reports

MODEL SIMULATORS

Parallel Execution of Model Simulators

Model Parameter Specifications

Population of Model Parameterizations

List of parameters and for each parameter a MIN, MAX and precision.
Differential Probability Analysis

Let $\mathbf{C}$ be the set of collected tuples, each containing a vector of parameter value (PV) pairs and a corresponding anti-fitness value, $f$

Segment $\mathbf{C}$ into high-pass ($H$) and low-pass ($L$) subsets, where:

$H = \{ x \in \mathbf{C} \mid f_x > 0.70 \}$ and $L = \{ x \in \mathbf{C} \mid f_x < 0.15 \}$

For each PV estimate the probability of occurrence in $H$ and $L$:

$P(\text{PV}_i \mid f > 0.70) = \frac{\text{PV}_i \in H}{\text{card}(H)}$ and $P(\text{PV}_i \mid f > 0.15) = \frac{\text{PV}_i \in L}{\text{card}(L)}$

Then compute the estimated differential probability:

$D = P(\text{PV}_i \mid f > 0.70) - P(\text{PV}_i \mid f < 0.15)$

Plot $D$ for each PV pair

Outliers contributing to failure scenarios

PVs exerting little influence on success or failure

Outliers contributing to success scenarios
**Topic 7: Results from Four GA Searches**

**GENETIC ALGORITHM**

- **Selection** based on Anti-Fitness
- **Recombination & Mutation**

**Model Parameter Specifications**

- List of parameters and for each parameter a MIN, MAX and precision.

**Growing Collection of Tuples:**

- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- (Generation, Individual, Fitness, Parameter 1 value,..., Parameter N value)
- ...

**MODEL SIMULATORS**

- Parallel Execution of Model Simulators

**MULTIDIMENSIONAL ANALYSIS TECHNIQUES**

- Principal Components Analysis, Clustering, ...

**Principal Components Analysis, Clustering, ...**

**Anti-Fitness Reports**

- Topic 7: Results from Four GA Searches
Analysis of Results from GA Search 1 – 500 Generations

Seeking Known Failure Scenario – search duration 30 days

CreateOrphanControlOn = FALSE

AvgUserRequestTimeout = 30
AvgThinkTime = 900
NodesPerCluster = 200
UserRestPeriodMultiplier = 32
NodesPerCluster = 400

$D$ (y-axis) for 684 PV pairs (x-axis) for first GA search—outlier PV pairs labeled.
Analysis of Results from GA Search 2 – 205 Generations

Seeking Previously Unknown Failure Scenarios – search duration 14 days

$D$ (y-axis) for 677 PV pairs (x-axis) for first GA search–outlier PV pairs labeled.
Analysis of Results from GA Search 3 – 209 Generations

Nudging up Some Parameter Ranges and Seeking Additional Failure Scenarios - search duration 16 days

NodesPerCluster = 600  UserTypeArraySelector = 4
AvgThinkTime = 1200  AvgUserRequestTimeout = 90
SiteDistanceMultiplier = 7

MinSiteCoordinate = 0  UserRestPeriodMultiplier = 32
StdUserRequestTimeout = 30  AvgInterUserStartDelay = 30
MinReservationRetries = 2  MinClusters = 9
MinIntrasiteDelay = 2x10^-8

MaxSiteCoordinate = 16000  MaxIntrasiteDelay = 1.5x10^-5
MaxPerHopDelay = 0.9  ClusterResponseTimeout = 120
CloudSizeChangeFraction = 0.3  MaxIntersiteLossRate = 10^-7
PlatformTypeArraySelector = 4  ProbabilityImageNotFound = 10^-6

NodeResponseTimeout = 30
MinRestPeriods = 2
RandomizeMinMaxVMsRequested = TRUE
ChoosePlatformTypesRandomly = FALSE

\( D \) (y-axis) for 680 PV pairs (x-axis) for first GA search—outlier PV pairs labeled.
Potential Issue Regarding Estimate of $P(PV_i | f > 0.15) = | PV_i \in L | \setminus | L |$

In scenarios 1-3, $|H| \sim 10^4$, while $|L| \sim 10^3$

To Increase $|L|$:
- use GA to search for success scenarios
- combine those tuples with tuples collected when searching for failures

Conduct differential probability analysis on the combined tuple collection

As an example, we augmented GA search 3 with a 4th GA search looking for success scenarios, and combined the tuple collections from searches 3 and 4 to yield $|L| = 42253$ scenarios and $|H| = 14601$

Next slide, shows the differential probability analysis for the combined tuple collection
Analysis of Results from GA Search 4 – 209+205 Generations

Including additional PV pairs in $L$ discovered by GA searching for success scenarios

- search duration 14 days

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>$AvgUserRequestTimeout$</td>
<td>90</td>
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$D$ (y-axis) for 683 PV pairs (x-axis) for first GA search—outlier PV pairs labeled.
Conclusions

SUMMARY:
• Defined a design-time method, combing GA search with simulation, to seek failure scenarios in system models
• Applied the method in a case study, seeking (and finding) a known failure scenario in an existing cloud simulator
• Iterated search to reveal previously unknown failure scenarios

FINDINGS:
• GA searches explored predominantly non-duplicative scenarios with high anti-fitness
• Uncovered evidence that GA search can reveal insights about optimal parameters settings, while simultaneously searching for failure scenarios
• GA search should be pursued only for systems with sufficient schedule time, and where failure scenarios have high cost
Future Work

• Additional analysis methods need to be explored:
  – Use statistical and information-theoretic techniques to extract features from collected tuples
  – Apply clustering algorithms to suggest specific classes of failure scenarios

• Continue to explore our case study:
  – Uncover parameter subspaces where no failure scenarios can be found
  – Search under alternate definitions of anti-fitness

• Apply method to models of other complex systems:
  – Communication networks
  – Electrical grids
  – Epidemic networks
  – Network attack models

• Investigate run-time methods to provide early warning of incipient failures
QUESTIONS?


Project Team:
Kevin Mills, computer scientist – kmills@nist.gov
Chris Dabrowski, computer scientist – cdabrowski@nist.gov
Jim Filliben, statistician – jfilliben@nist.gov
Sandy Ressler, information visualization specialist – sressler@nist.gov