DSN 2009 - The 39th Annual IEEE/IFIP International Conference on Dependable Systems and Networks
June 29 – July 2 Estoril, Lisbon Portugal

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Enhancing Fault/Intrusion Tolerance through Design and Configuration Diversity

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29th June 2009, Lisbon, Portugal

FOREVER

CRUTIAL
CRitical UTility InfrastructurAL resilience

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Outline

- Team and motivation
- FOREVER service
- Configuration diversity rules
- Preliminary assessment of the FOREVER service
- Conclusions and future work

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The Team

- FOREVER – a mini-project inside the EU NoE ReSIST http://www.resist-noe.org
- Institutions
  - Universidade de Lisboa (Portugal)
  - City University London (UK)
  - Università di Pisa (Italy)
  - Universidade do Estado de Santa Catarina (Brazil) – Affiliate member
  - Universität Erlangen-Nürnberg (Germany) – Affiliate member
- People
  - Alysson Bessani @ Lisboa
  - Hans Reiser @ Lisboa
  - Paulo Sousa @ Lisboa
  - Ilir Gashi @ City
  - Vladimir Stankovic @ City
  - Alessandro Daidone @ Pisa
  - Rafael Obelheiro @ Santa Catarina
  - Tobias Distler @ Erlangen-Nürnberg
  - Rüdiger Kapitza @ Erlangen-Nürnberg

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Addressing WRAITS Topics

- Topics:
  - automatic recovery and response techniques
  - use of Byzantine fault-tolerant algorithms in IT
  - diversity and failure independence
- *"The workshop will be especially interested in 'practical intrusion-tolerant systems'"*
- *"How to build information systems that are inherently resilient to intrusions"*
- *"Papers can present ongoing work and/or speculative/futuristic ideas"*

Motivations

- Fault/intrusion tolerance is commonly the only viable way of improving the system dependability and (possibly) security.
- Designers are in need of advice about the architectural evolution of fault/intrusion-tolerant systems
  – Many solutions exist, but the current solutions concern (only) a specific snapshot in time, without considering how the system should evolve.
- Fault/intrusion tolerant systems need to counteract the evolution of threats and exploits against a running system.

Motivations (cont.)

- The defensive measures in the current practice are largely *reactive.*
  – E.g. issuance of patches
  – "at-risk-time" is (unnecessarily) long
- Proactive methods are needed to counteract the evolution of faults, threats and vulnerabilities.
  – With proactive methods, design novelty is used as a defence.
- We need a unifying, complementary approach: reactive approaches ought to be enhanced with a more dynamic response to evolving threats and vulnerabilities.

The FOREVER Service

(**F**ault/intrusi**O**n **RE**mo**V**al through **E**volution & **R**ecovery)

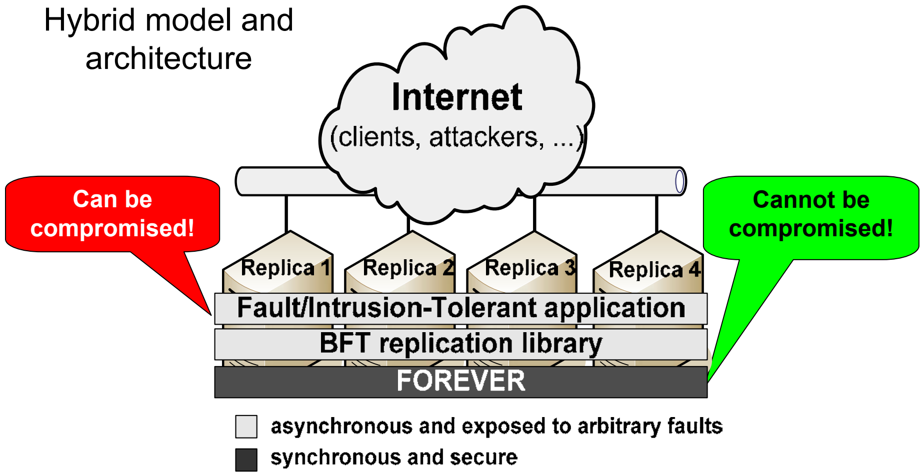
- Byzantine fault-tolerant protocols against arbitrary failures have limited utility
  - They are "only" useful to delay corruptions.
- While a higher number of replicas allows for tolerating more compromised replicas, it also means that there are more individual replicas that need to be different from each other.
  - E.g., 3f+1 and f=1 → 4 (diverse) replicas needed
  - But, 3f+1 and f=2 → 7 (diverse) replicas needed.
- FOREVER's main goal – increasing the number of tolerated arbitrary faults/vulnerabilities, without increasing the number of replicas.

The FOREVER Service (cont.)

- The ambitious goal is to be achieved through
  - Recovery
    - Event-triggered (when malicious behavior is detected or suspected)
    - Time-triggered (every replica is rejuvenated periodically)
  - Evolution
    - Through the use of **configuration diversity rules**
    - Recovered replicas are different from previous incarnations
    - This makes FOREVER *different* from the other recovery services.

The FOREVER Architecture

Hybrid model and architecture



Diversity Management

- **Offline** diversity generation
  - Pool of pre-built OS images (e.g., Linux, OpenBSD)
  - Different OS image started in each recovery
    - Recent studies showed some off-the-shelf sw have **low number of common faults/vulnerabilities**[1].
  - FOREVER selects the OS image that is **less similar** than the OS images running in the remaining replicas.
- **Online** diversity generation
  - FOREVER applies a set of **configuration diversity rules** to the selected OS image.

[1] A. N. Bessani, R. Obelheiro, P. Sousa, and I. Gashi: “*The effects of diversity on intrusion tolerance*”, DI-FCUL TR 08–30, Univ. of Lisbon, Dec. 2008.
I. Gashi, P. Popov, and L. Strigini: “*Fault tolerance via diversity for off-the-shelf products: A study with SQL database servers*”, IEEE TDSC 4(4):280–294, Oct.- Dec.2007.
B. Vandiver: “*Detecting and tolerating byzantine faults in database systems*”, MIT-CSAIL- TR-2008-040, MIT, June 2008.

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Configuration Diversity Rules

- We produced a set of configuration diversity rules, which aim to enhance the resilience of software in between recoveries[1]
- The rules were generated using three approaches
  - *Bottom-up* – scrutinising the implementations of the OSs and applications
  - *Top-down* – exploring reported vulnerabilities
  - *Lateral* – reviewing existing literature of configuration rules for protection against "malicious" behaviour

[1] Full description of rules can be found at http://www.csr.city.ac.uk/people/ilir.gashi/ConfigDiv/

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Configuration Diversity Rules (an excerpt)

ID	Rule name	Design Implication		Security Category
		Impl. intru-siveness	Client notifi-cation re-quired?	
1	Password change	B	Yes	C
2.1	Different authentication protocols	W, B or G	Yes	C
2.2	Different Trusted Third Parties	W, B or G	No	C and A
3	Different "factors" in n-factor authentication methods	W, B or G	Yes	C
4.1	Address Space Layout Randomisation (ASLR)	W	No	I
4.1.1	Pointer obfuscation	W	No	I
4.1.2	Randomisation of global variables and local vari-ables offsets	W	No	I
4.2	Address Space Partition-ing	W, B or G	No	I
4.3	Stack Frame Padding	W, B or G	No	I
4.4	Basic Block reordering	W, B or G	No	I
5.1	Instruction set randomi-sation	W, B or G	No	I
5.2	Instruction set tagging	W, B or G	No	I
5.3	Instruction Reordering	W, B or G	No	I
6.1	Diverse Linux User IDs (UID)	W, B or G	No	I and C
7	Change IP addresses of the hosts	B	Yes	C and A
8	Changing listening port numbers	W, B or G	Yes	C and A
9	Adding or deleting non-functional code	W, B or G	No	I
10.1	Varying dynamic li-braries and system calls	W	No	I
10.2	Varying unique names of system files	W	No	I
10.3	Varying magic numbers in certain files (e.g., ex-ecutables)	W	No	I

FOREVER Service Preliminary Evaluation

- Preliminary assessment of the potential to enhance system resilience.
- Focus on the evaluation of the probability of system failure, through variation of several parameters:
  - The time between recoveries
  - The probability of common vulnerabilities
  - The mean effectiveness of configuration diversity rule-set
- Initial values chosen are pessimistic
  - The common practice when evaluating safety- and reliability-critical systems and/or parameter values are unknown.
- The quantitative evaluation uses a modelling methodology which assumes Multiple Phased Systems.
  - see "I. Mura and A. Bondavalli: "*Markov regenerative stochastic Petri nets to model and evaluate the dependability of phased Missions*", IEEE Transactions on Computers 2001.

System Properties/Assumptions

- n = 4 replicas can tolerate up to f = 1 faults
  - $n \geq 3f+1$
  - Win2k, Linux, Solaris, FreeBSD
- Both "space" (design diversity) and "time" (configuration diversity rules) diversity is considered.
- Arbitrary faults/vulnerabilities; a binary state space: "failed", "OK".
- Common faults/vulnerabilities exist
  - The ratio value used is based on the study[1] using National Vulnerability Database (NVD) data
- Proactive, sequential, fault-free recovery strategy has been assumed.

[1] A. N. Bessani, R. Obelheiro, P. Sousa, and I. Gashi: "*The effects of diversity on intrusion tolerance*", DI-FCUL TR 08–30, Dec. 2008.

Measures of Interest and Parameters

- **p_F** - System failure probability, i.e., probability of having more than f failed replicas.
- **t** - Mission time; we are interested in investigating how system failure probability changes over time.
- **T_P** - Recovery period, based on the waiting time T_W between the recovery of replica *i* and the recovery of replica *i+1*.
  - $T_P = (T_R + T_W) \cdot n$
- **δ_λ** - Base value of the penalty of replica failure rate, if diversity is not applied.
  - Discovery of vulnerabilities is assumed to be progressing
- **δ_{ij}** - Probability of common faults/vulnerabilities among different replicas
  - Since n = 4, the overall system fails as soon as one common fault/vulnerability, affecting a pair of replicas, occurs.
- **δ_x** - Mean value for the effectiveness of the configuration diversity rule-set.

Parameter Values and Common Faults Prob.

Study	T_W	δ_λ	δ_x	δ_{ij}
1	{0, 360, 480, 840}	0	0	δ_{ij}
2	0	$\{0, 10^{-6}, 5x10^{-7}, 10^{-7}\}$	0.8	δ_{ij}
3	0	0	0	$\{0, 1, 5, 10\}x\delta_{ij}$
4	0	10^{-6}	{0, 0.2, 0.4, 0.6, 0.8, 1}	δ_{ij}

O.S.	Vulns	Common Vulnerabilities		
		Win2K	Linux	Solaris
FreeBSD	229	3	11	18
Solaris	411	3	5	
Linux	437	3		
Win2K	347			

δ_{ij}		j			
		FreeBSD	Solaris	Linux	Win2K
i	FreeBSD	-	0.029	0.017	0.005
	Solaris	0.029	-	0.006	0.004
	Linux	0.017	0.006	-	0.004
	Win2K	0.005	0.004	0.004	-

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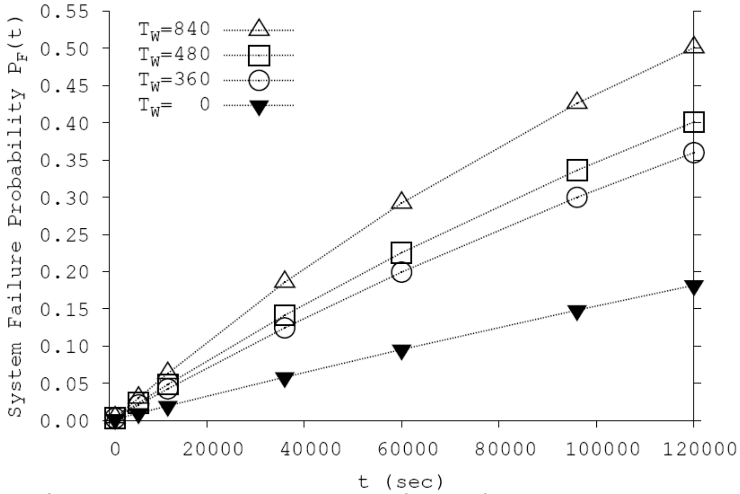
Preliminary Evaluation Results (Study 1)

Waiting Time (T_w) Sensitivity Analysis



$\delta_x = 0$

$\delta_\lambda = 0$

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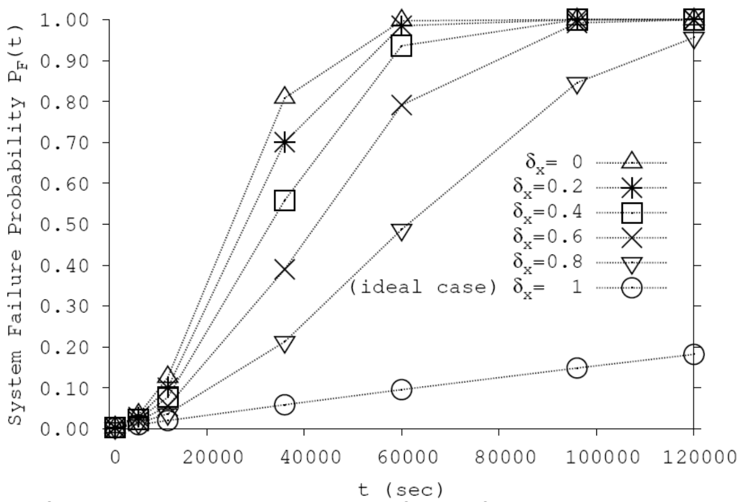
Preliminary Evaluation Results (Study 4)

Rule(s) Effectiveness (δ_x) Sensitivity Analysis



$T_w = 0$

δ_λ NOT changed

Diversity Configuration Rules - Design Implications

- Interface and input language complexity
- Possibility of introducing new faults/vulnerabilities
- Security issues
- Performance issues
- Data consistency issues

Conclusions

- We performed initial study about system evolution wrt. tolerating ever-growing and ever-present threats.
- We defined a set of configuration diversity rules to be used as part of the *“preventive”* FOREVER architecture
  - FOREVER uses both reactive and proactive recovery
- FOREVER uses online and offline diversity generation mechanisms
- Performed *preliminary* evaluation of the FOREVER

Future Work

- Extending configuration diversity rules
  - Possibility of using an alternative categorisation
- Developing proof-of-concept implementations
  - Possibility of using fault-injection
- Extending/improving the evaluation
  - Include the reactive recoveries; and thus e.g. explore trade-off between reactive and proactive strategies.
  - More precise evaluation of the effectiveness of the configuration diversity rules (currently, only a single value represents the effectiveness).
  - Possibility to compare with other (e.g., non-redundant) architecture
- Evaluating the effects on the system performance
  - Aiding the analysis of the "eternal" trade-off between the improvement of dependability/security and performance.

Thank you!