Solving Operating-Systems Problems with Probabilistic Model Checking

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Resilience talk
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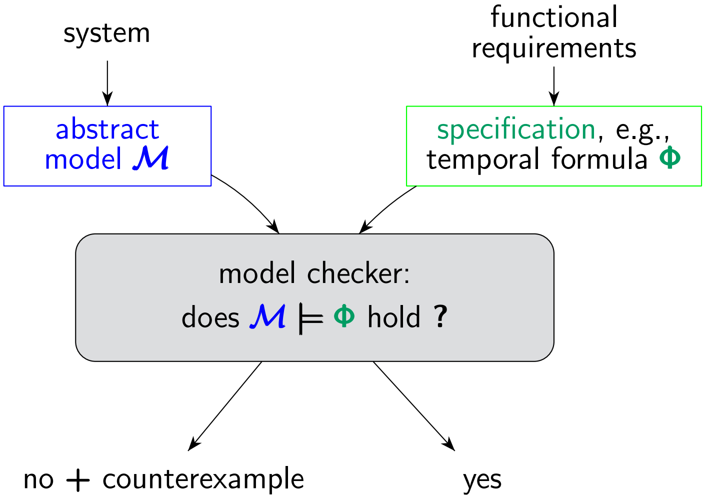
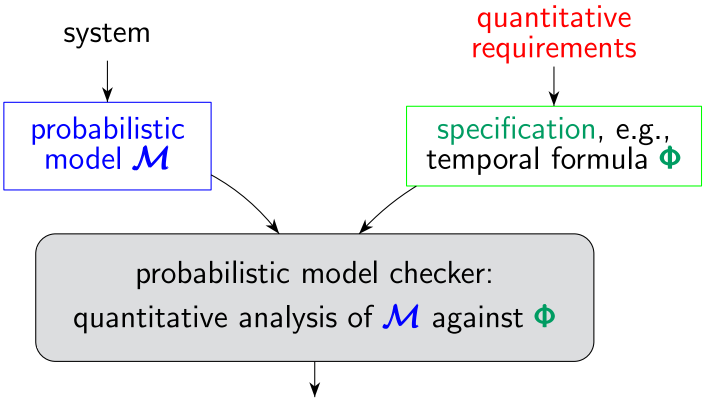
Outline

Model checking



Probabilistic model checking



probability for “bad behaviors” is $< 10^{-6}$
probability for “good behaviors” is **1**
expected costs for ....

Outline

Spinlocks

Problem

- n Processes on n CPU cores
- cooperate to protect a shared resource (OS-kernel ready-queue)
- Contention is rare, the lock is almost always free
- Inter-processor interrupts (IPI's) are far too slow in this case

Solution

- Synchronise over a shared lock variable
- change lock variable with atomic operations (CAS — compare and swap)
- expensive in the contention case

Questions

- Does it scale to 100 cores?
- For which workloads?

Spinlocks

Joint work with Christel Baier, Marcus Daum, Benjamin Engel, Hermann Härtig, Joachim Klein, Sascha Klüppelholz, Steffen Märcker and Marcus Völp

FMICS 2012 **Waiting for locks: How long does it usually take?**, in: M. Stoelinga, R. Pinger (Eds.), 17th International Workshop on Formal Methods for Industrial Critical Systems, Vol. 7437 of Lecture Notes in Computer Science, Springer, 2012, pp. 47–62.

SSV 2012 **Chiefly symmetric: Results on the scalability of probabilistic model checking for operating-system code**, in: F. Cassez, R. Huuck, G. Klein, B. Schlich (Eds.), Proceedings Seventh Conference on Systems Software Verification, Vol. 102 of EPTCS, 2012, pp. 156–166.

Test-And-Test-And-Set Lock

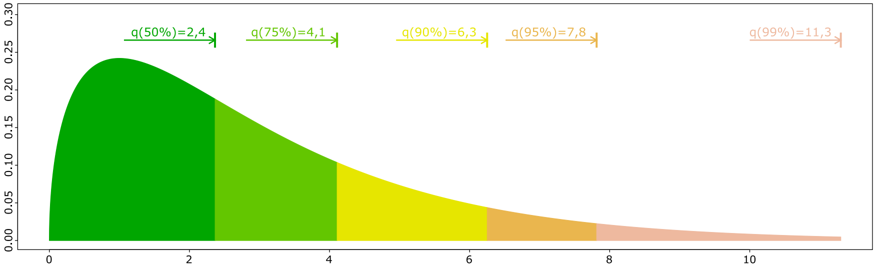
```
volatile bool occupied = false;

volatile void lock(){
  while (atomic_swap(occupied, true)){
      while (occupied){/* spin loop */}
  }
}
void unlock(){
  occupied = false
}
```

- model n processes that compete for the lock
- model lock as separate process
- compare results with measurements

Interesting properties

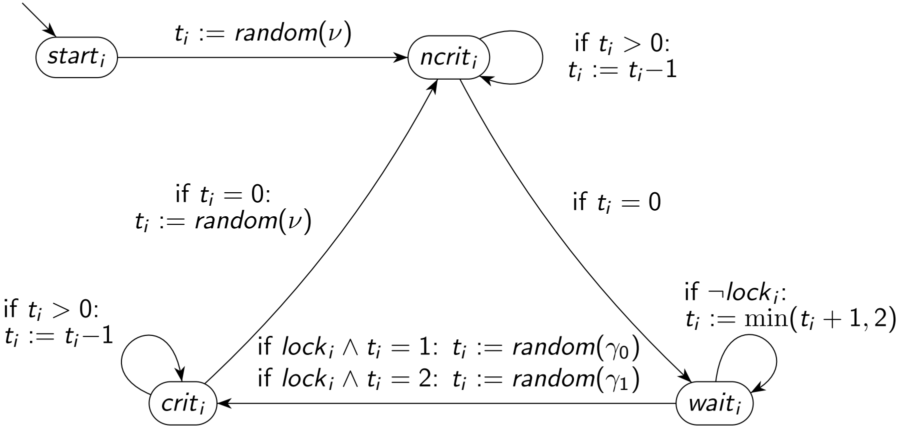
In the long run...

- Probability for finding the lock free
- Probability for getting the lock twice in a row without waiting
- Average waiting time for the lock
  (under the condition that the lock busy)
- the 95% quantile of the waiting time



quantile picture by Rene Schwarz from Wikimedia Commons

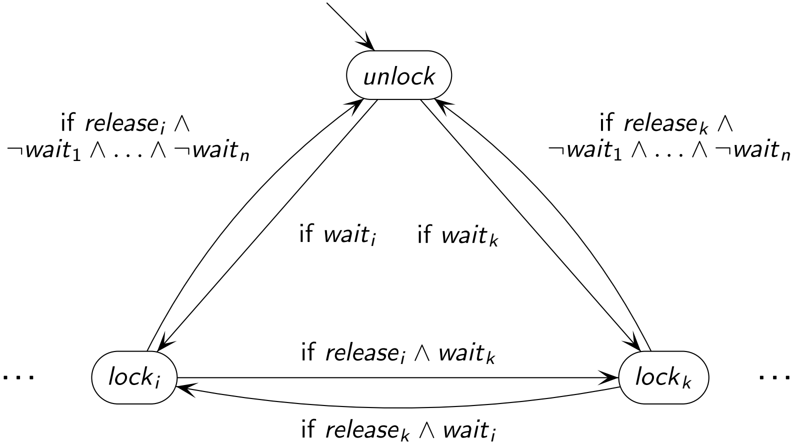
Process i: DTMC Model



Distributions:

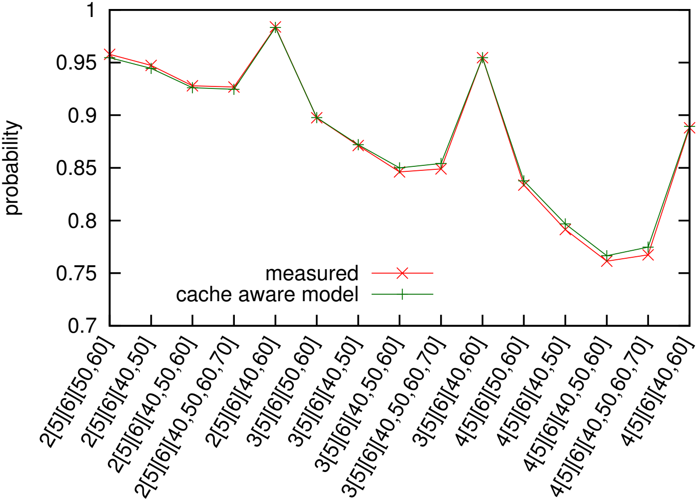
ν	non-critical region
γ_0	critical region (without spinning)
γ_1	critical region (with spinning)

The lock: DTMC Model

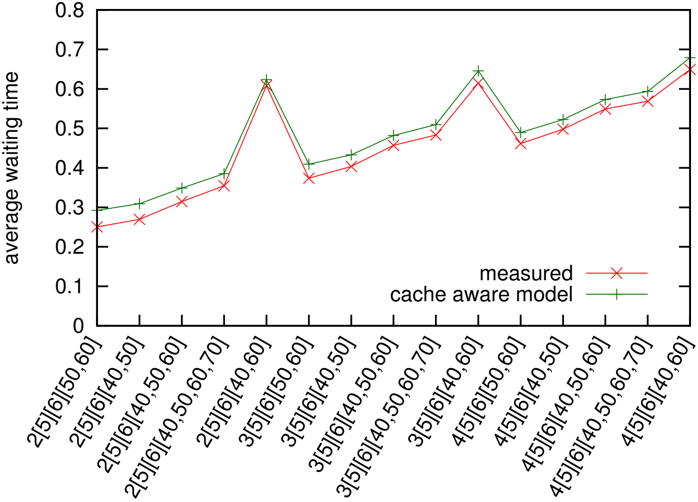


perform uniform probabilistic choice for selecting next lock owner

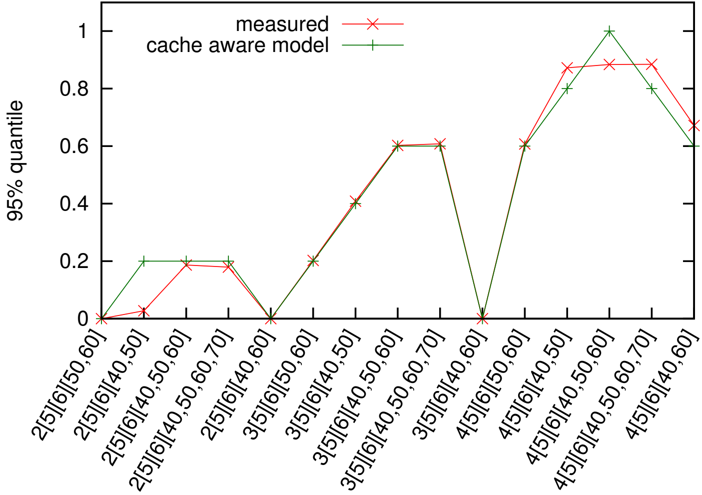
Results: Probability to find the lock free



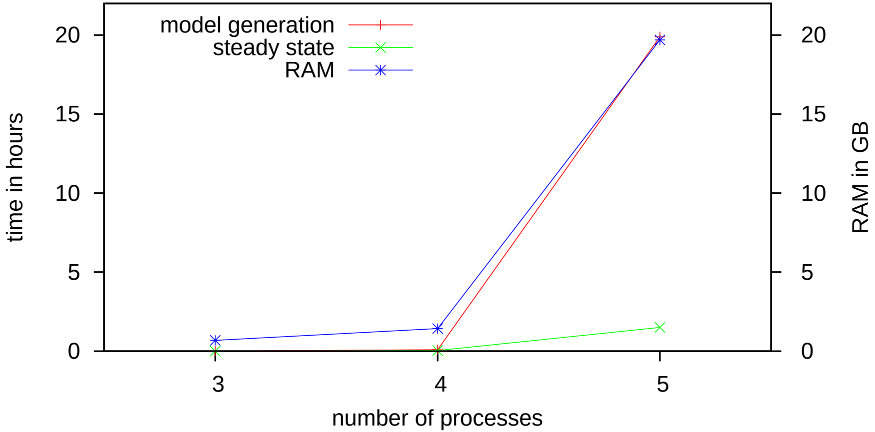
Results: Average waiting time for spinning processes



Results: 95% quantile of the waiting time

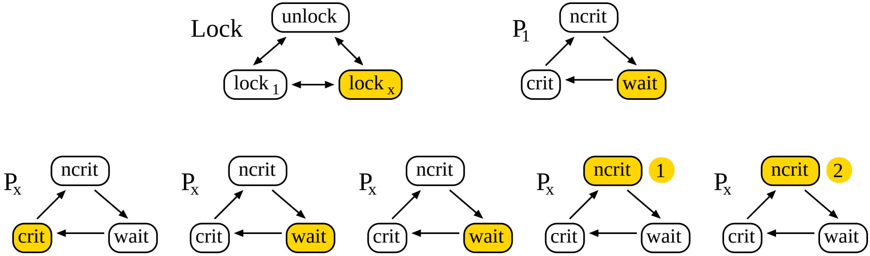


Scalability for PRISM, Distribution [40,50]

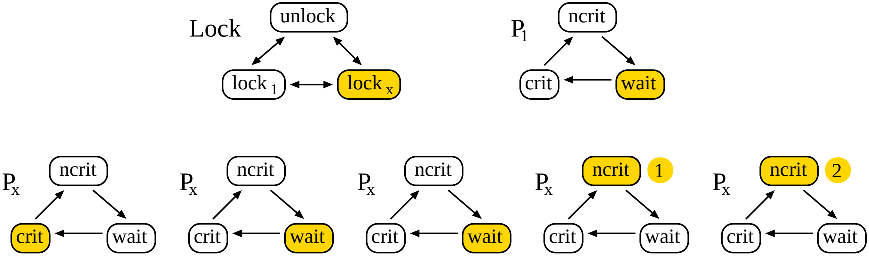


number of states:		
	3 proc.	4,082,808
	4 proc.	198,808,720

Symmetry reduction: Using a generic representative



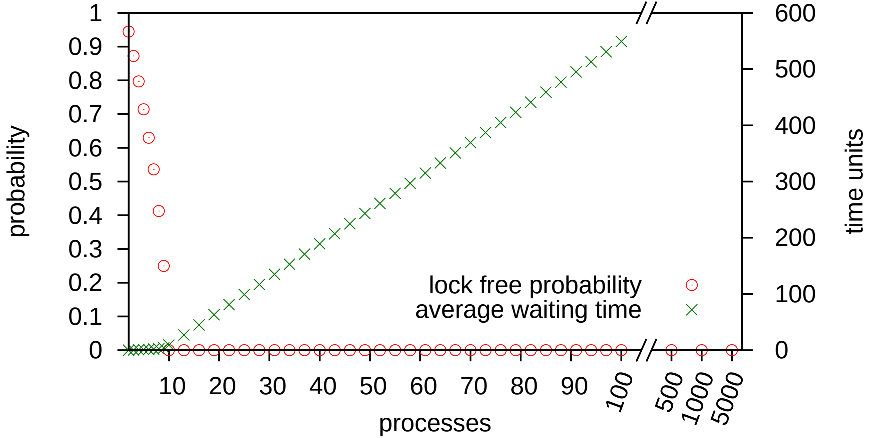
Symmetry reduction: Using a generic representative



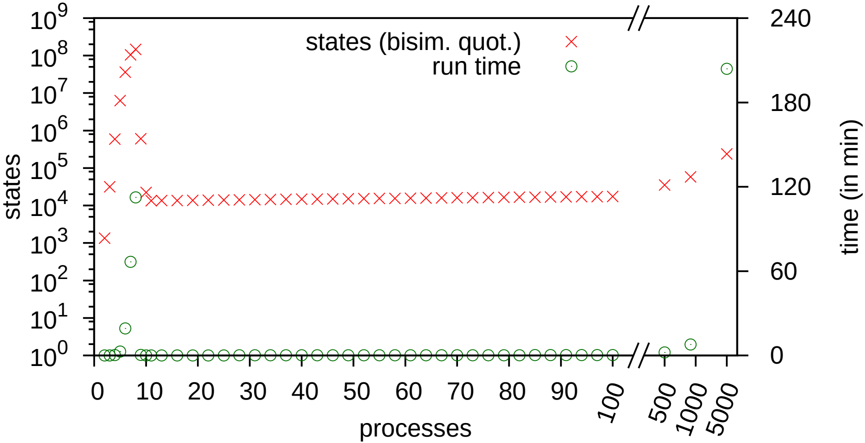
state counters:

crit : 1	ncrit 1 : 1
wait : 2	ncrit 2 : 1

Results for symmetry-reduced model Non-critical Distribution [40, 50]



Scalability for symmetry-reduced model Non-critical Distribution [40, 50]



Why does it scale so extremely well?

Lock is oversaturated

- 1 process is in the critical section
- 6–9 processes are in their non-critical section
- the remaining processes spin
- adding another process only increases the spinning-counter by 1

Processes in non-critical region show a regular pattern

- 1 process releases the lock (circa) every 6 time units
- chooses a non-critical waiting time of 40 or 50 time units
- distance of waiting time is regular

Spinlock Conclusion

Lessons learned

- model checking can be used to predict properties of real systems
- abstract complicated cache behaviour
- impressive scalability with custom symmetry reduction

A spin lock for 10,000 processes?

- certainly nonsense if the lock is saturated for 10 processes already, but
- overbooked services exist
- symmetry reduction will yield similar improvements there

Outline

Scalability with shared ressources

Traditional locking does not scale any more

- atomic operations are slow
  CAS L1 hit $\sim$ 30 cycles
  CAS cache miss $\sim$ 250 cycles
- the speed of light is limited

Reader-writer Lock

- permit multiple readers

Read-copy-update (RCU)

- readers can always proceed
- writers modify private copy and switch atomically
- readers may see outdated version

PWCS

- no locks, no atomic operations
- make inconsistencies detectable

PWCS

Joint work with Christel Baier, Sascha Klüppelholz, Steffen Märcker, Marcus Völp, Benjamin Engel

Nasa FM 2013

A Probabilistic Quantitative Analysis of Probabilistic-Write/Copy-Select, in: Brat, G.; Rungta, N.; Venet, A. (Eds.), 5th International Symposium, NFM 2013, Vol. 7871 of Lecture Notes in Computer Science

PWCS Protocol

Writer

```
tag_end++;
write_data();
tag_begin++;
```

Reader

```
ta = tag_begin;
copy_data();
tb = tag_end;
if (ta == tb)
   return data;
```

Use Replication

Writer

```
for (i=0; i<3; i++) {
    r = replica[i];
    r.tag_end++;
    r.write_data();
    r.tag_begin++;
}
```

Reader

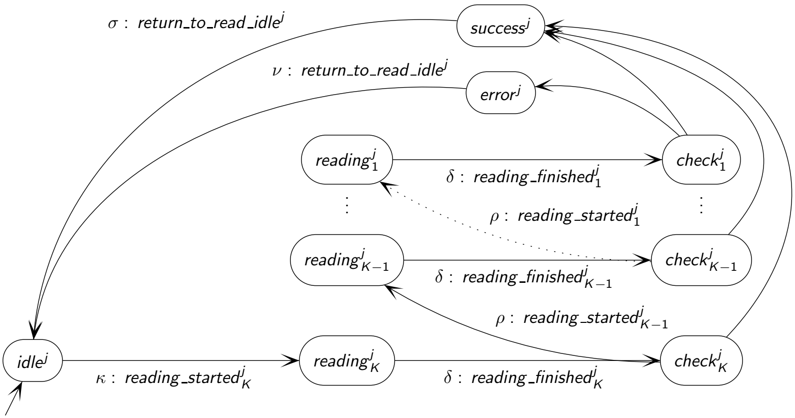
```
for (i=0; i<3; i++) {
    r = replica[i];
    ta = r.tag_begin;
    r.copy_data(&data);
    tb = r.tag_end;
    if (ta == tb)
        return data;
}
// retry/error handling
```

Interesting Properties

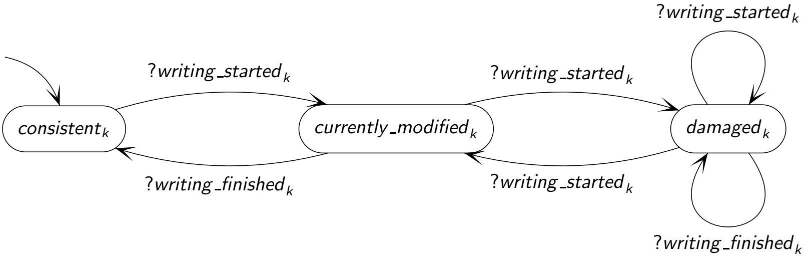
In the long run ...

- Probability to successfully read the data
- the 99% time-quantile for successful reading
- time fraction in which all replicas are damaged
- average time for repairing a damaged replica

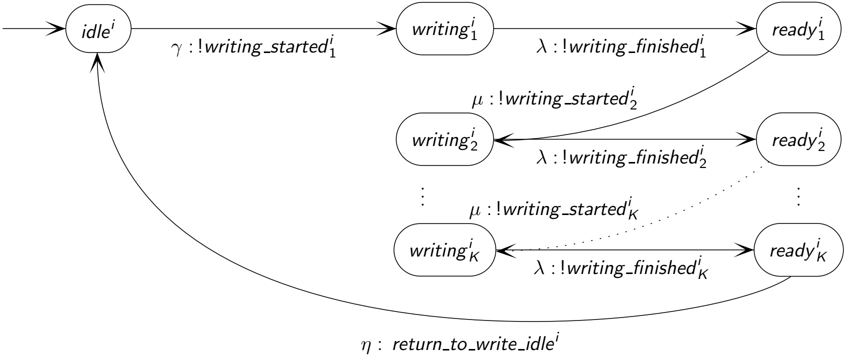
Reader Model



Copies


?writing_started$_k$
?writing_started$_k$
?writing_started$_k$
consistent$_k$
currently_modified$_k$
damaged$_k$
?writing_finished$_k$
?writing_started$_k$
?writing_finished$_k$

Writer Model



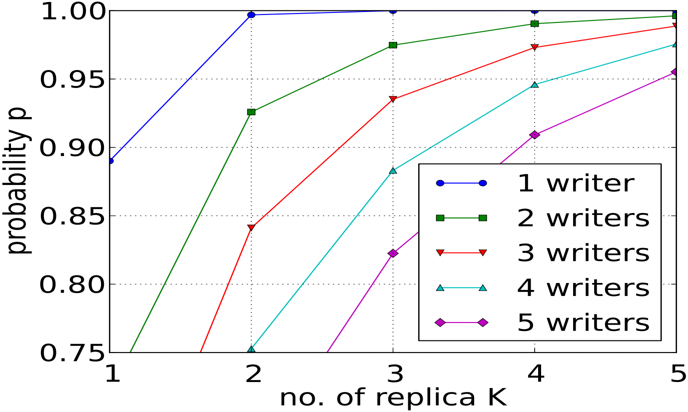
Scenarios

	frequent reads moderate writes		moderate reads moderate writes	
	time	rate	time	rate
idle time (writer)	20	$\gamma = 0.05$	200	$\gamma = 0.005$
idle time (reader)	2	$\kappa = 0.5$	20	$\kappa = 0.05$

Common parameters

	time	rate
write duration	2	$\lambda = 0.5$
read duration	1	$\delta = 1$
other	0.01	$\mu = \rho = \sigma = \nu = 100$

Results: Successfully read data, frequent reads, moderate writes



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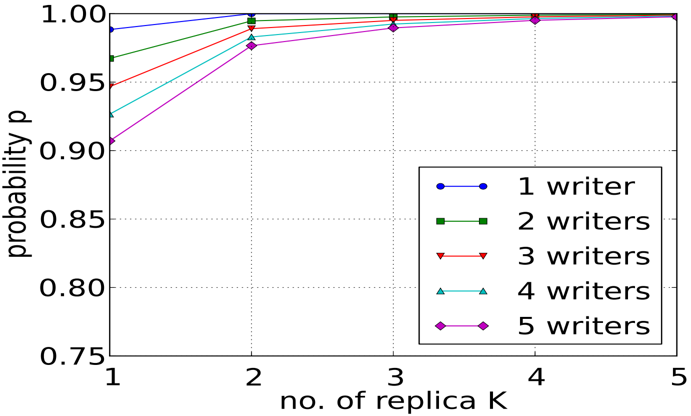
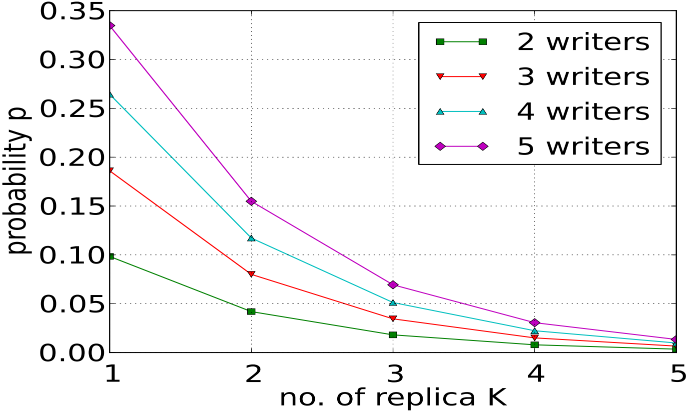


Results: All replicas damaged, frequent reads, moderate writes



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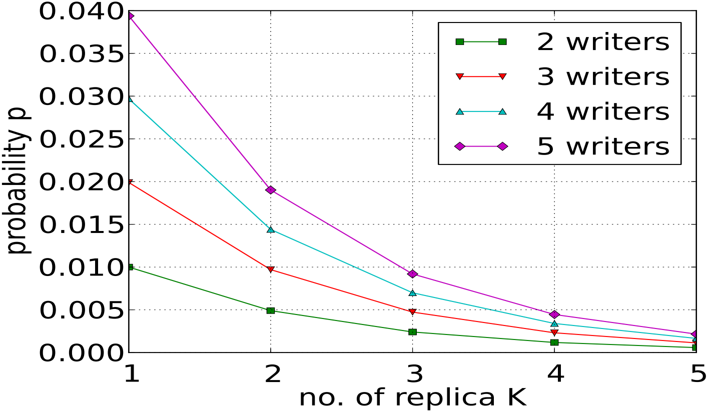


PWCS Conclusion

- investigated different workloads
- PWCS performs surprisingly well
- model contains no error handling
  (read finally failed, replica damaged)
- analysis provides hints for error handling

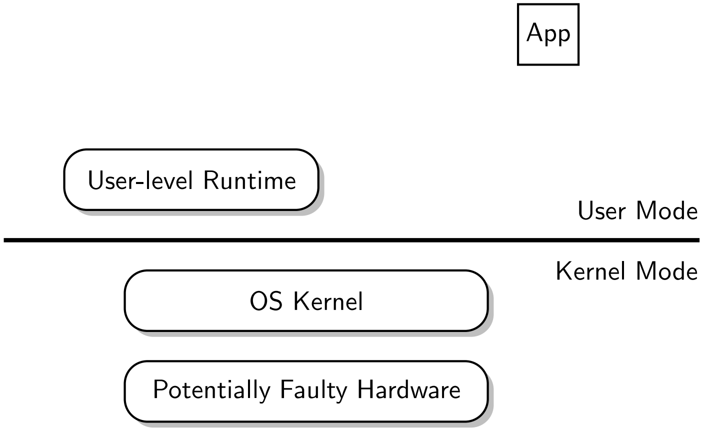
Outline

Romain Case Study

Sketch ideas for model-checking resilience properties

(joint work with Björn Döbel)

Resilient OS Structure (by Björn Döbel)



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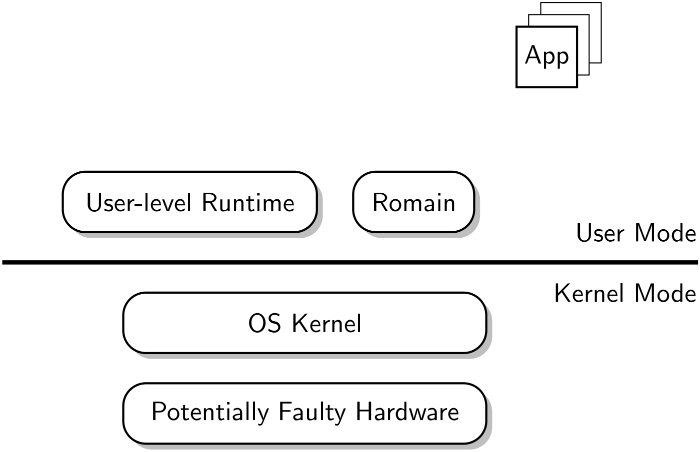

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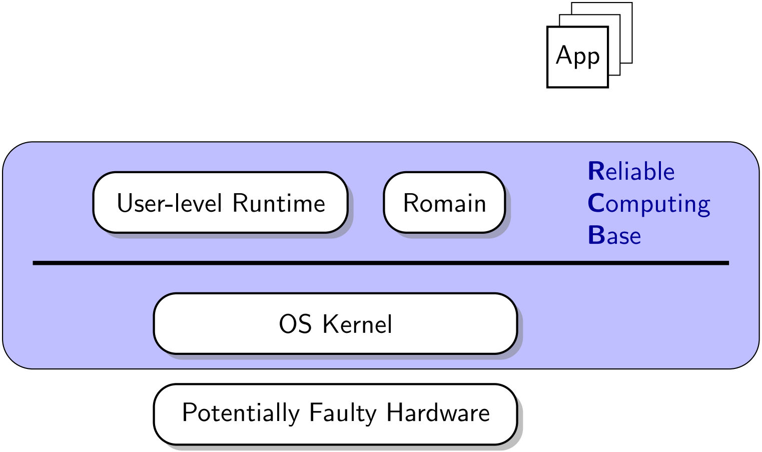

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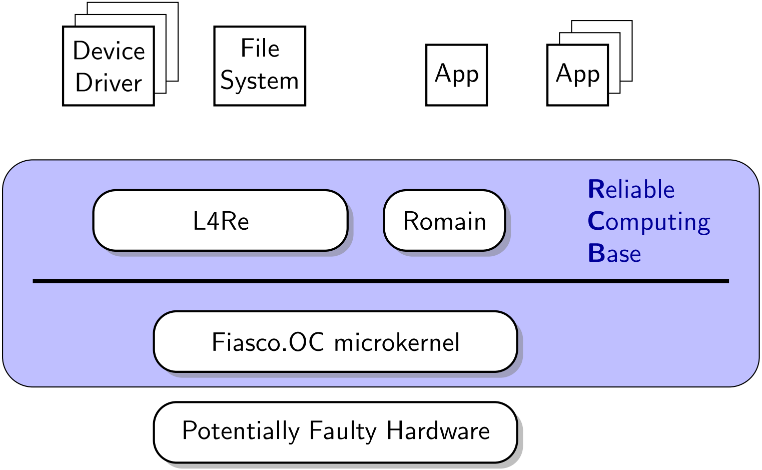
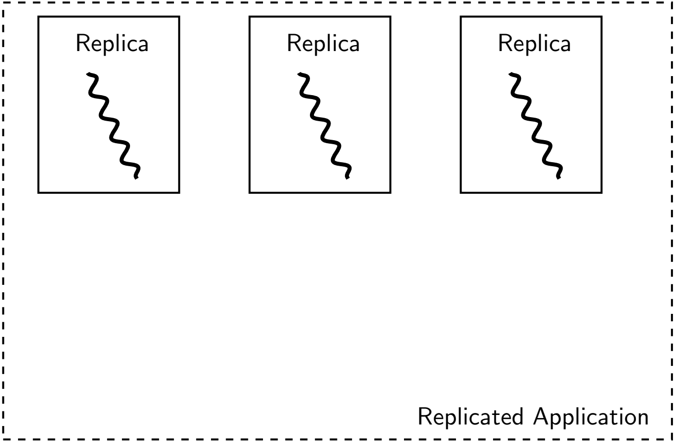
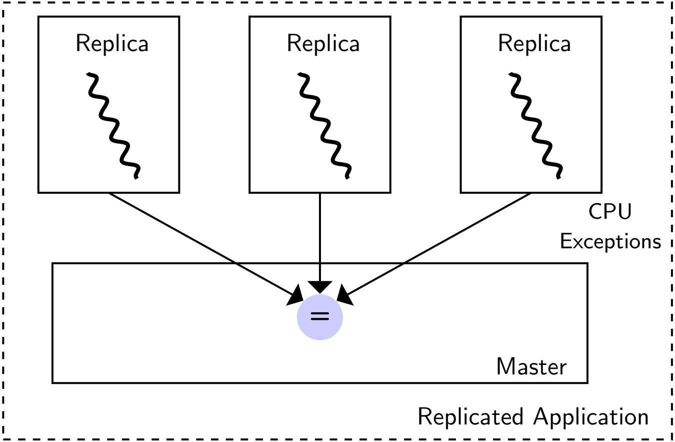


Romain: Redundant Replication

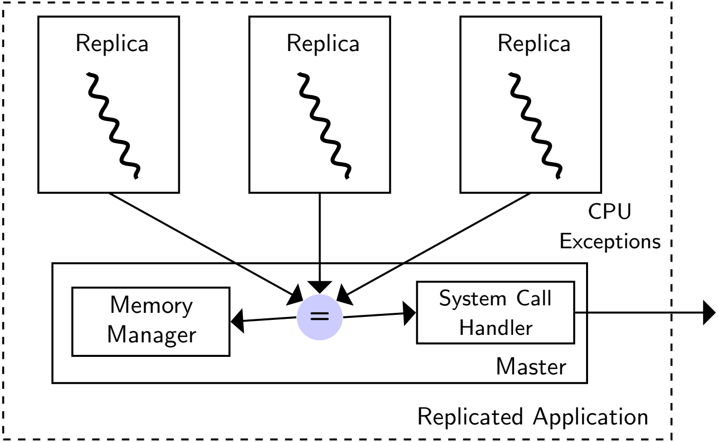


Romain: Redundant Replication



- majority voting
- forward recovery

Romain: Redundant Replication



- majority voting
- forward recovery

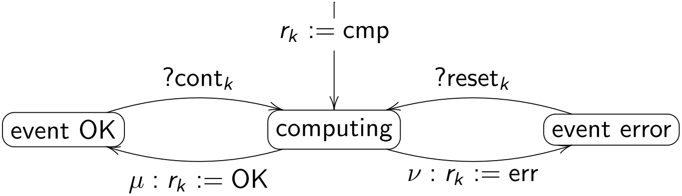
Interesting Properties

In the long run . . .

- reliability depending on the number of replicas
  probability of propagating an error because of biased majority
- resource consumption (trivial: # replicas $\times c$)
- energy consumption depending on reliability
- performance decrease
- probability of non-recoverable errors

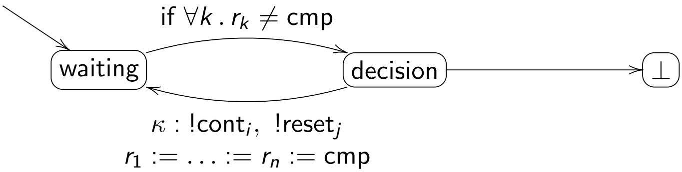
Model for replica k

Replica state $r_k = \text{cmp} \mid \text{OK} \mid \text{err}$



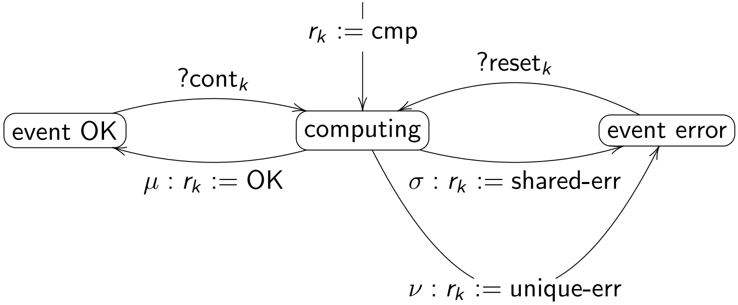
Model of master

Master



Model identical errors in different replicas

Replica state r_k = cmp | OK | unique-err | shared-error



No results yet for Romain

Outline

Conclusion

- probabilistic model checking can compute performance measures
  - energy
  - time
  - quantiles
- model size is always an issue
- model checking is a push-button technology

Conclusion

- probabilistic model checking can compute performance measures
  - energy
  - time
  - quantiles
- model size is always an issue
- model checking is a push-button technology
  - you may need an expert to push the button
  - pushing the button for the first time may take some time