Maksym Planeta Björn Döbel

Operating Systems Meet Fault Tolerance

Microkernel-Based Operating Systems // Dresden, 02.02.2020

‘If there is more than one possible outcome of a job or task, and one of those outcomes will result in disaster or an undesirable consequence, then somebody will do it that way.’ Edward Murphy jr.

Goal of the Lecture

Dependable Systems

- Problems
- Operating system-related techniques

Dependability[1]

- Availability
  Average fraction of time that a component has been up and running
- Reliability
  Probability that a component has been up and running continuously
- Maintainability
  Time required to repair a faulty component

[1] Algirdas Aviz, Jean-Claude Laprie, and Brian Randell. *Fundamental Concepts of Dependability*. 2001, p. 21.

Textbook terminology

Dependability threats:

- Failure
- Error
- Fault

Dependability means

- Prevention
- Removal
- Forecasting
- Tolerance

Dependable Operating Systems

Faults:

- Software (bugs)
- Hardware

Measures:

- Software Engineering
- Software Architectures

Why Things go Wrong

- Programming in C:

  This pointer is certainly never going to be NULL!

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- Hypocrisy:

  I'm a cool OS hacker. I won't make mistakes, so I don't need to test my code!

A Classic Study

- A. Chou et al.: *An empirical study of operating system errors*, SOSP 2001
- Automated software error detection (today: `https://www.coverity.com`)
- Target: Linux (1.0 - 2.4)
  - Where are the errors?
  - What error types do exist?
  - How long do they survive?
  - Do bugs cluster in certain locations?

Revalidation of Chou's Results

- N. Palix et al.: *Faults in Linux: Ten years later*, ASPLOS 2011
- 10 years of work on tools to decrease error counts - has it worked?
- Repeated Chou's analysis until Linux 2.6.34

Linux: Lines of Code

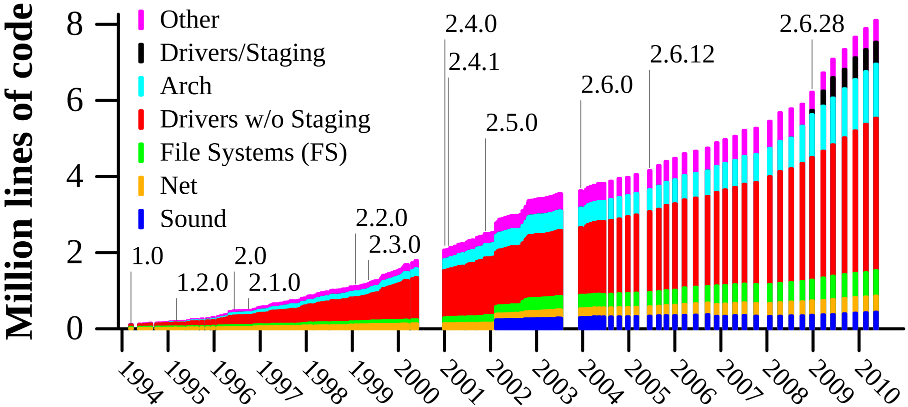


Figure: Linux directory sizes (in MLOC) [19]

Faults per Subdirectory (2001)

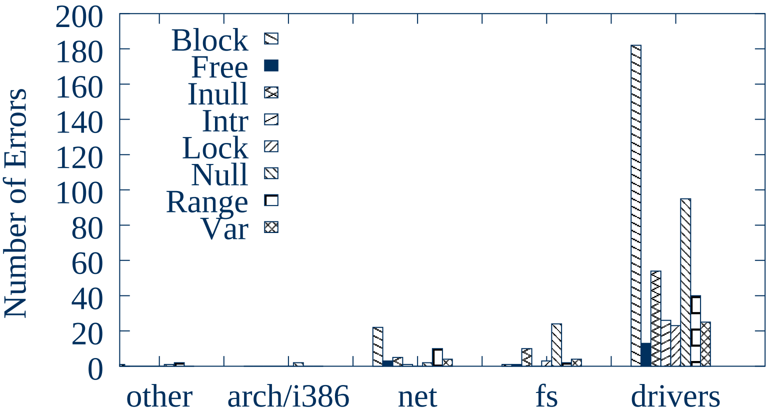


Figure: Number of errors per directory in Linux [4]

Fault Rate per Subdirectory (2001)

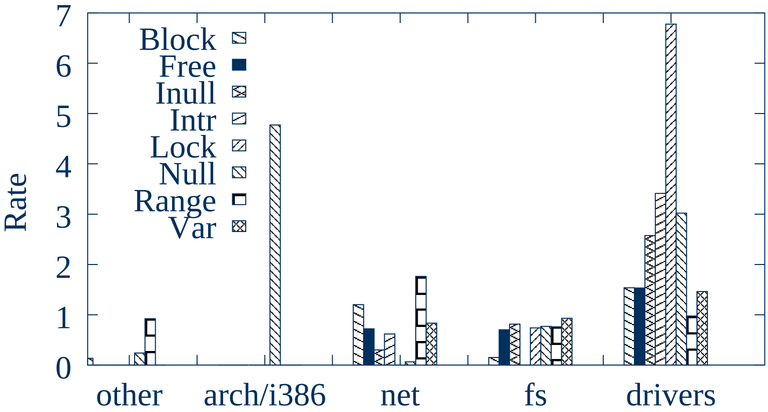
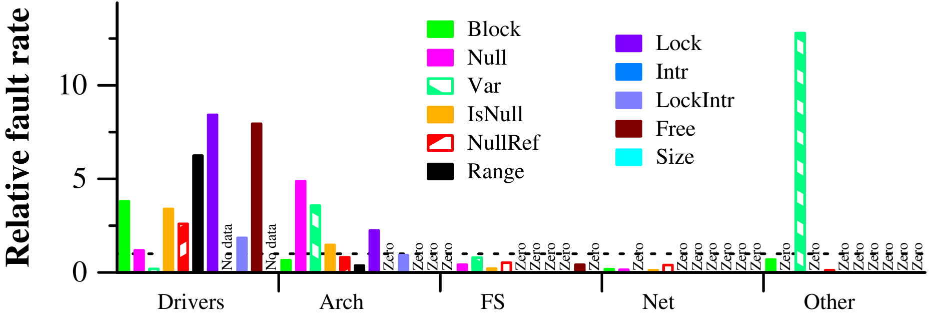


Figure: Rate of errors compared to other directories [4]

Fault Rate per Subdirectory (2011)



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Bug Lifetimes (2011) [19]

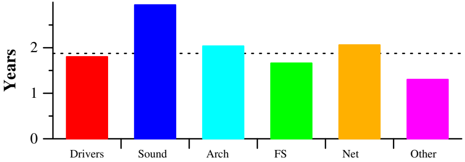

Figure: Per directory

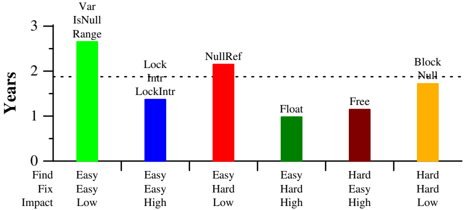

Figure: Per finding and fixing difficulty, and impact likelihood

Software Engineering Measures

- QA
  Examples: Manual testing, automated testing, fuzzing
- Continuous Integration
- Static analysis
- Using safer languages
- Guidelines, best practices, etc.
  Examples: MISRA C++, C++ Guideline Support Library

Example: MISRA C++ 2008

Rule 0-1-7

The value returned by a function having a non-void return type that is not an overloaded operator shall always be used.

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Rule 6-4-6

The final clause of a switch statement shall be the default-clause.

Rule 3-4-1

(Required) An identifier declared to be an object or type shall be defined in a block that minimizes its visibility.

Rationale

Defining variables in the minimum block scope possible reduces the visibility of those variables and therefore reduces the possibility that these identifiers will be used accidentally. A corollary of this is that global objects (including singleton function objects) shall be used in more than one function.

Rule 3-4-1: Example

```
void f(int32_t k)
{
  int32_t j = k * k; // Non-compliant
  {
    int32_t i = j; // Compliant
    std::cout << i << j << std::endl;
  }
}
```

In the above example, the definition of `j` could be moved into the same block as `i`, reducing the possibility that `j` will be incorrectly used later in `f`.

Safer languages

- Garbage collection (Go)
- Memory safety (Rust)
- No unused variables (Go, Rust)
- Check error return codes (Go, Rust)
- No uninitialised memory (Go, Rust)
- etc.

Writing a kernel in a high-level language[2]

- Biscuit: a monolithic kernel implemented in Go

[2] Cody Cutler, M. Frans Kaashoek, and Robert T. Morris. 'The benefits and costs of writing a POSIX kernel in a high-level language.' In: *OSDI*. Oct. 2018. URL: `https://www.usenix.org/conference/osdi18/presentation/cutler`.

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- 5% to 15% slower, up to 600µs latencies for GC

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- Performance like in C or C++ code
- Some software patterns don’t work with (safe) Rust well

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Safe Monoculture Operating Systems

- Safe language for the safe OS
- Maintaining safety guarantees requires using the same language for the subcomponents
- Examples: Theseus[4] (Rust), RedLeaf[5] (Rust), Singularity[6] (C#)

[4] Kevin Boos et al. 'Theseus: an Experiment in Operating System Structure and State Management.' In: OSDI. 2020, pp. 1–19. ISBN: 978-1-939133-19-9. URL: `https://www.usenix.org/conference/osdi20/presentation/boos` (visited on 01/24/2021).

[5] Vikram Narayanan et al. 'RedLeaf: Isolation and Communication in a Safe Operating System.' In: OSDI. 2020, pp. 21–39. ISBN: 978-1-939133-19-9. URL: `https://www.usenix.org/conference/osdi20/presentation/narayanan-vikram` (visited on 01/24/2021).

[6] Gregory M. Kurtzer, Vanessa Sochat, and Michael W. Bauer. 'Singularity: Scientific containers for mobility of compute.' In: *PLOS ONE* 12.5 (May 11, 2017), e0177459. ISSN: 1932-6203. DOI: `10/f969fz`.

Software architectures addressing faults

- Means:
  - Compartmentalisation
  - Redundancy
  - Hardening

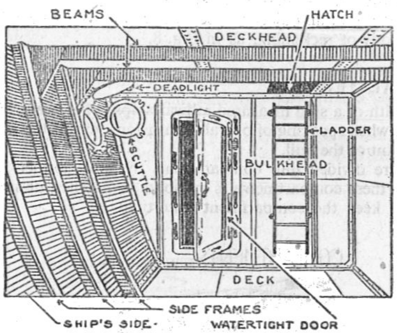

Figure: Ship building

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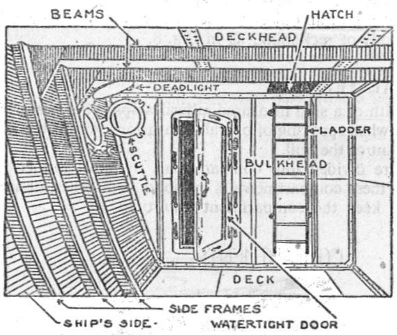

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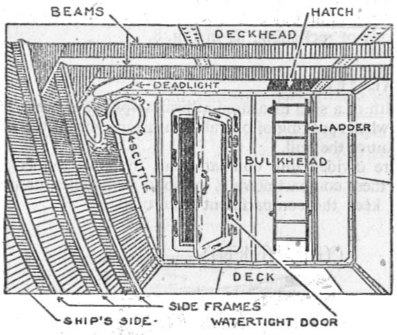
Software architectures addressing faults

- Means:
  - Compartmentalisation
  - Redundancy
  - Hardening
- Address hardware faults
- Recovery
  - Rollback: return to a previous state
    - Transactions
    - Checkpoint/Restart
  - Roll-forward: everything else
    - Error correcting codes
    - Triple modular redundancy + majority voting



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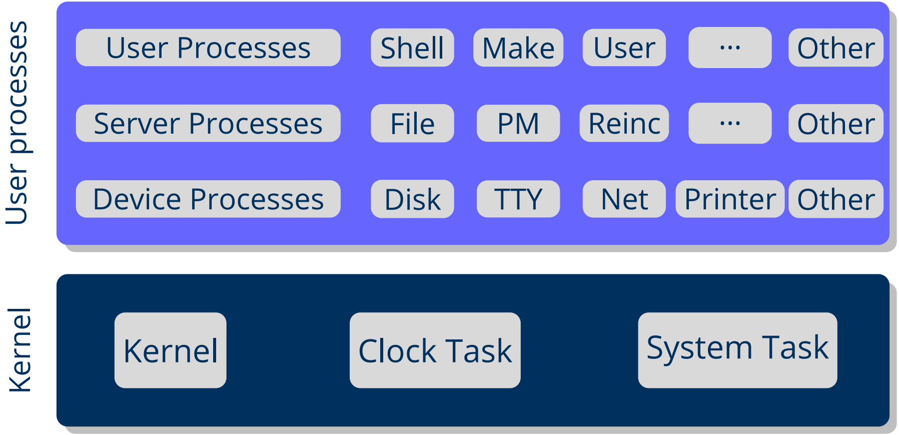
Minix3: A Fault-tolerant OS



User processes

User Processes | Shell | Make | User | ··· | Other

Server Processes | File | PM | Reinc | ··· | Other

Device Processes | Disk | TTY | Net | Printer | Other

Kernel

Kernel | Clock Task | System Task

Minix3: Fault Tolerance[7]

- Address Space Isolation
  - Applications only access private memory
  - Faults do not spread to other components
- User-level OS services
  - Principle of Least Privilege
  - Fine-grain control over resource access
    - e.g., DMA only for specific drivers
- Small components
  - Easy to replace (micro-reboot)

[7] Jorrit N Herder et al. 'Fault isolation for device drivers.' In: *DSN*. 2009, pp. 33–42.

Minix3: Fault Detection

- Fault model: transient errors caused by software bugs
- Fix: Component restart
- *Reincarnation server* monitors components
  - Program termination (crash)
  - CPU exception (div by 0)
  - Heartbeat messages
- Users may also indicate that something is wrong

Repair

- Restarting a component is insufficient:
  - Applications may *depend* on restarted component
  - After restart, *component state* is lost

- Minix3: explicit mechanisms
  - Reincarnation server signals applications about restart
  - Applications store state at data store server
  - In any case: program interaction needed
    - Restarted app: store/recover state
    - User apps: recover server connection

L4ReAnimator: Restart on L4Re[8]

- L4Re Applications
  - Loader component: ned
  - Detects application termination: parent signal
  - Restart: re-execute Lua init script (or parts of it)
  - Problem after restart: capabilities
    - No single component knows everyone owning a capability to an object
    - Minix3 signals won't work

[8] Dirk Vogt, Björn Döbel, and Adam Lackorzynski. 'Stay strong, stay safe: Enhancing reliability of a secure operating system.' In: *Workshop on Isolation and Integration for Dependable Systems*. 2010, pp. 1–10.

L4ReAnimator: Lazy recovery

- Only the application itself can detect that a capability vanished
- Kernel raises *Capability fault*
- Application needs to re-obtain the capability: execute *capability fault handler*
- Capfault handler: application-specific
  - Create new communication channel
  - Restore session state
- Programming model:
  - Capfault handler provided by server implementor
  - Handling transparent for application developer
  - *Semi-transparency*

Distributed snapshots[9]

- Localized checkpoints
- Problem: Unlimited rollbacks
- Solution: Create global snapshot
- No synchronized clock
- No shared memory
- Only point-to-point messages

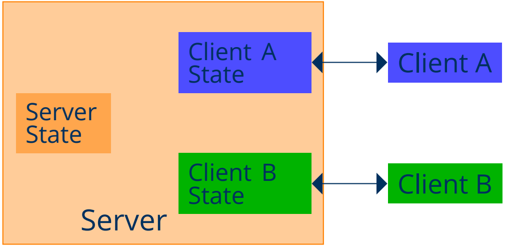
[9] K Mani Chandy and Leslie Lamport. ‘Distributed snapshots: Determining global states of distributed systems.’ In: *ACM Transactions on Computer Systems (TOCS)* 3.1 (1985), pp. 63–75.

Break

- Minix3 fault tolerance
  - Architectural Isolation
  - Explicit monitoring and notifications
- L4ReAnimator
  - semi-transparent restart in a capability-based system
- Next: CuriOS
  - smart session state handling

CuriOS: Servers and Sessions[10]

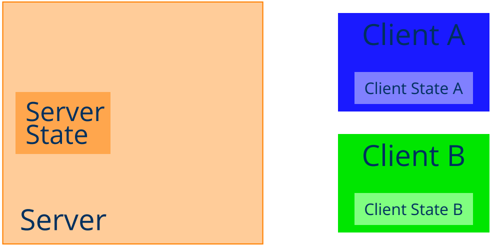
- State recovery is tricky
  - Minix3: Data Store for application data
  - But: applications interact
    - Servers store *session-specific* state
    - Server restart requires potential rollback for every participant



[10] Francis M David et al. 'CuriOS: Improving Reliability through Operating System Structure..' In: *OSDI*. 2008, pp. 59–72.

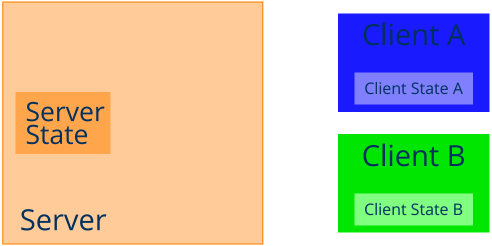
CuriOS: Server State Regions

- CuiK kernel manages dedicated session memory: *Server State Regions*
- SSRs are managed by the kernel and attached to a client-server connection



CuriOS: Protecting Sessions

- SSR gets mapped only when a client actually invokes the server
- Solves another problem: failure while handling A's request will never corrupt B's session state



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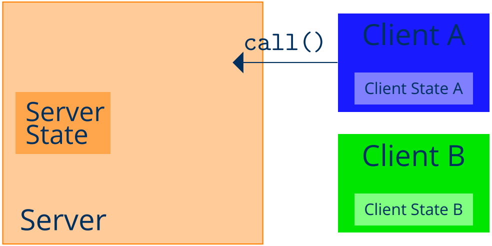

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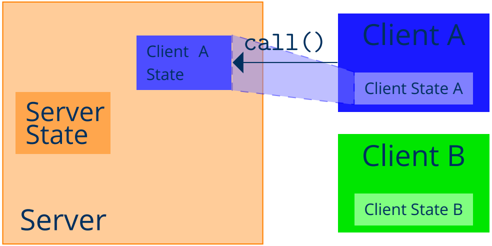

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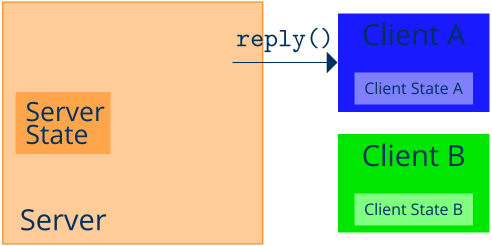

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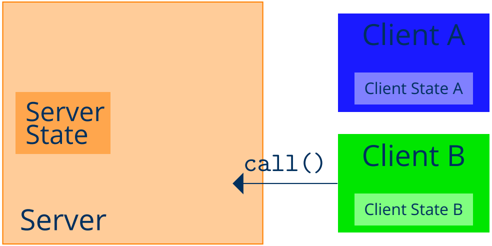

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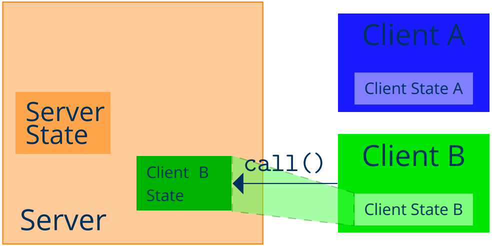

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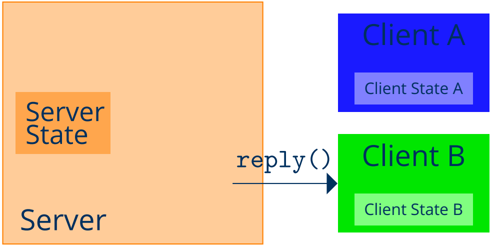
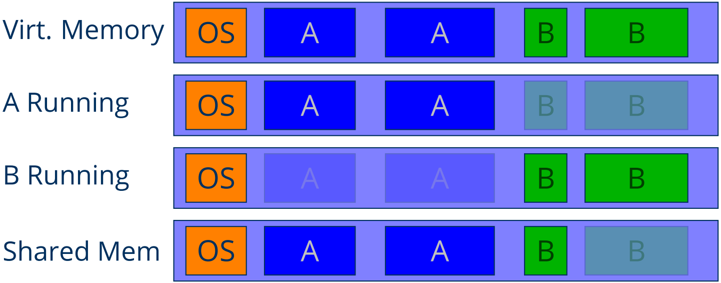


CuriOS: Transparent Restart

- CuriOS is a *Single-Address-Space OS*:
  - Every application runs on the same page table (with modified access rights)



Transparent Restart

- Single Address Space
  - Each object has unique address
  - Identical in all programs
  - Server := C++ object
- Restart
  - Replace old C++ object with new one
  - Reuse previous memory location
  - References in other applications remain valid
  - OS blocks access during restart

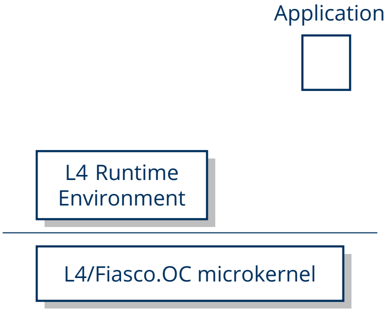
Transient Hardware Faults

- Radiation-induced soft errors
  - Mainly an issue in avionics+space?

- DRAM errors in large data centers
  - Google study: $>$2% failing DRAM DIMMs per year [20]
  - ECC insufficient [12]

- Decreasing transistor sizes $\rightarrow$ higher rate of errors in CPU functional units [7]

Transparent Replication as OS Service [9, 8]



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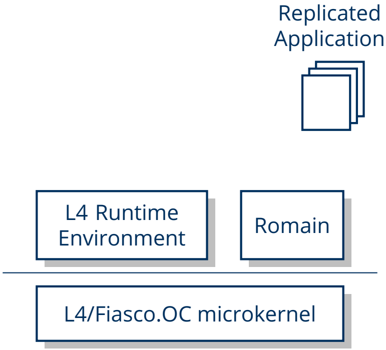

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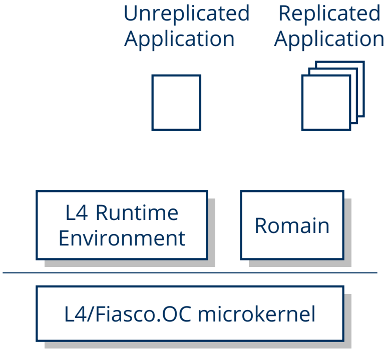

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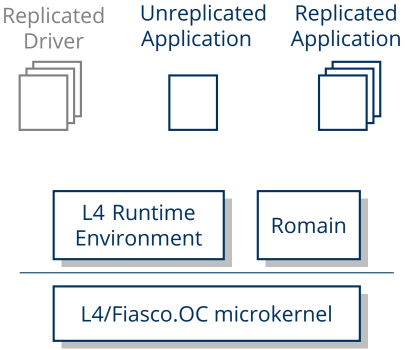


Replicated Driver

Unreplicated Application

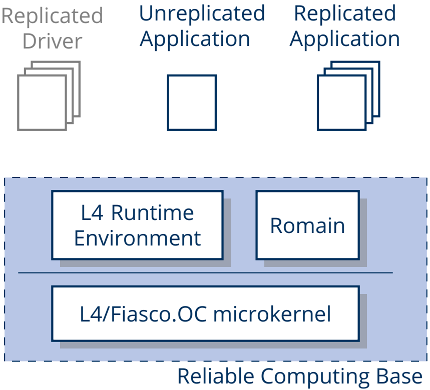
Replicated Application

L4 Runtime Environment

Romain

L4/Fiasco.OC microkernel

Transparent Replication as OS Service [9, 8]



Romain: Structure

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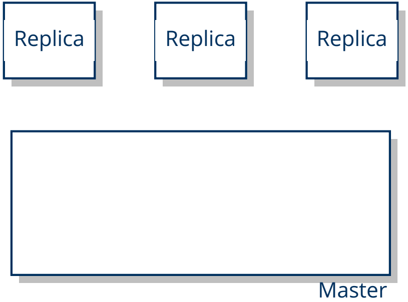

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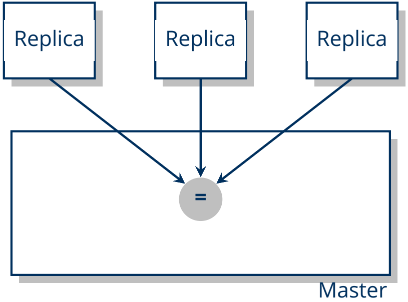

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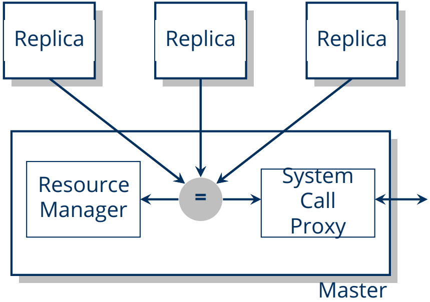
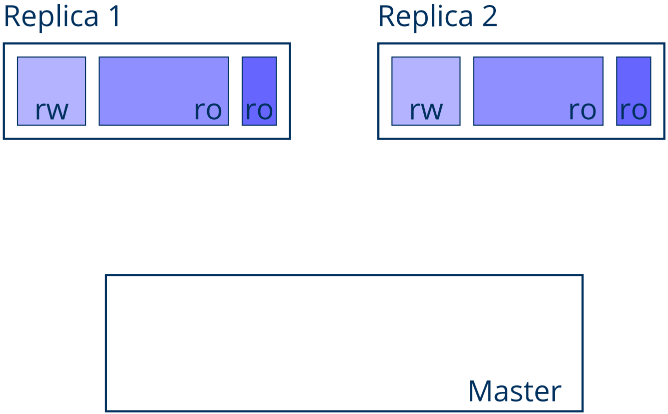


Replica Memory Management



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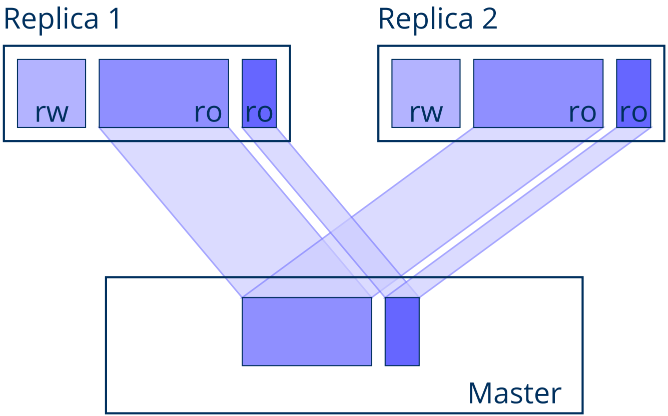
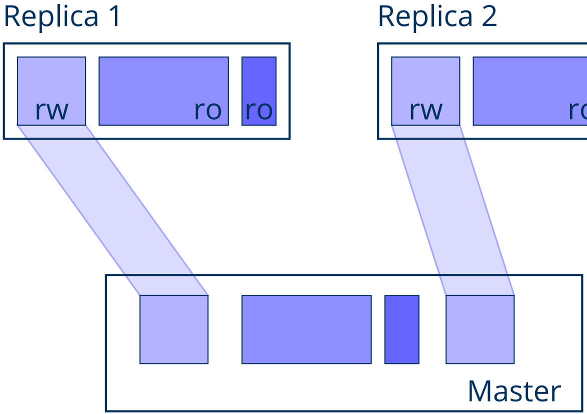
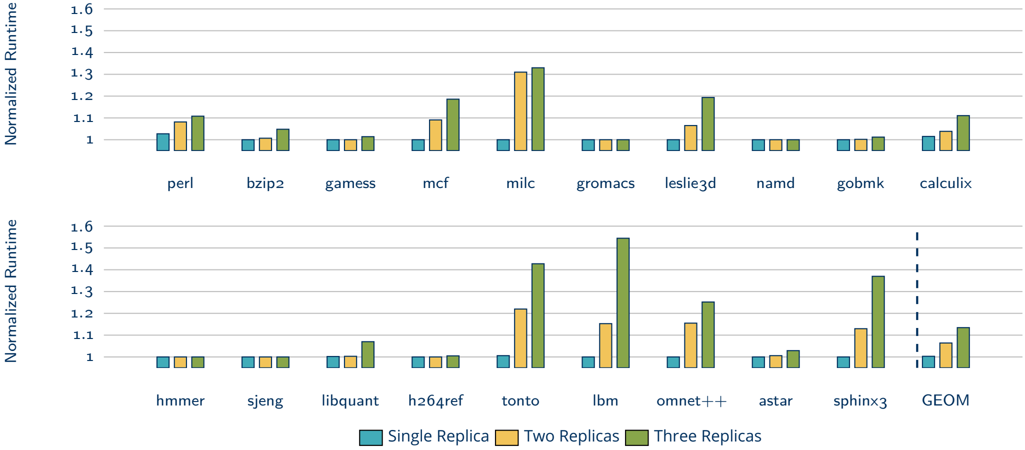


Replica Memory Management



Replicating SPEC CPU 2006 [10]



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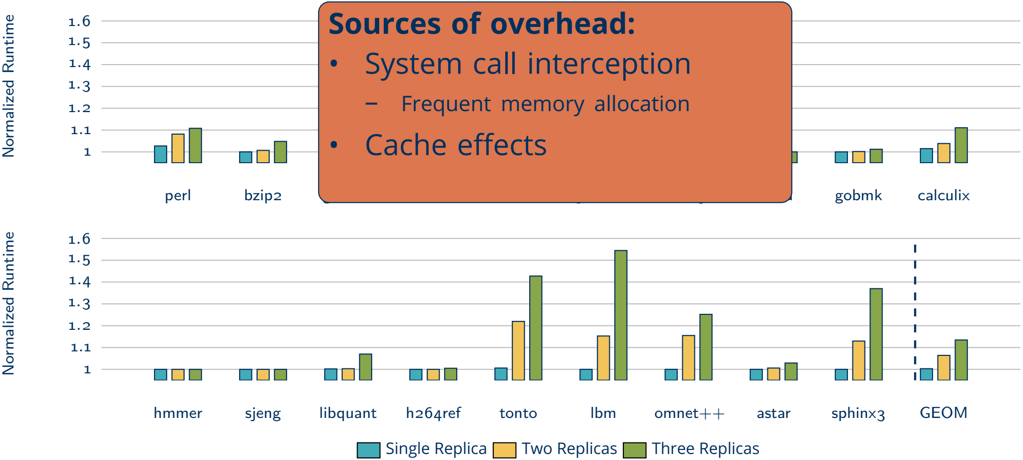
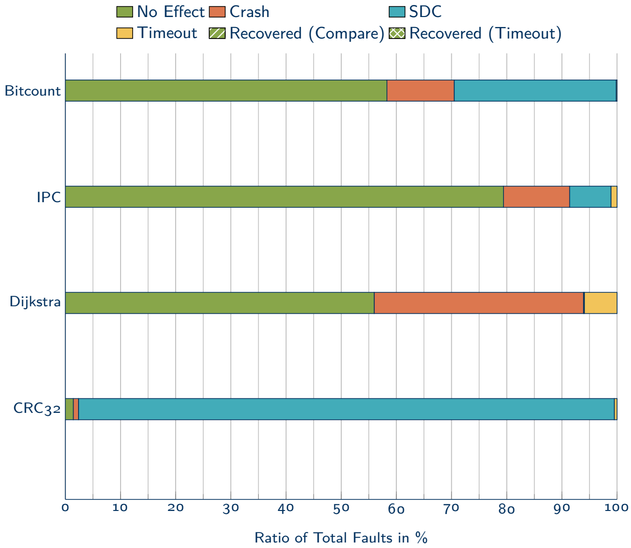


Sources of overhead:

- System call interception
  - Frequent memory allocation
- Cache effects

Error Coverage [10]



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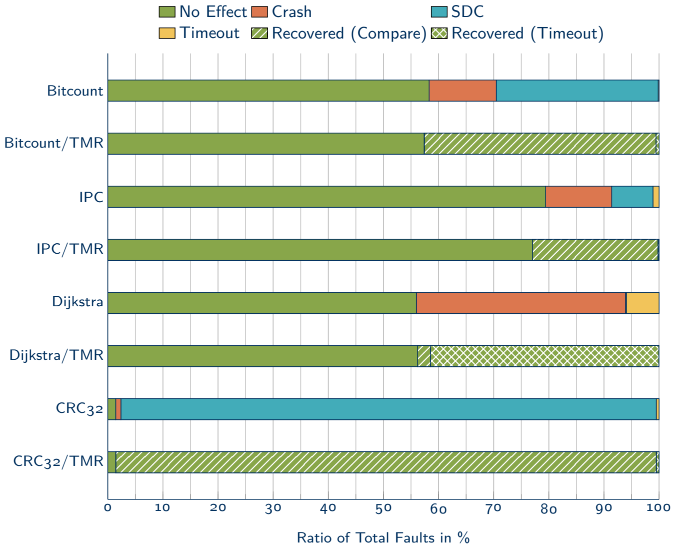


Romain: Summary

- Faults: CPU and memory bit-flips
- Best-effort resilience
- Tripple modular redundancy with small increase in makespan
- Multithreading support with determenistic multithreading[11]

[11] Björn Döbel and Hermann Härtig. 'Can we put concurrency back into redundant multithreading?' In: *EMSOFT*. 2014, pp. 1–10.

HAFT: Hardware-Assisted Fault Tolerance[12]

- CPU single-event upsets (SEU)
- Instruction-level redundancy for fault detection
- Hardware transaction memory for fault recovery
- *Best-effort* fault tolerance
- Improve efficiency through instruction-level parallelism (ILP) and compiler optimisations

[12] Dmitrii Kuvaiskii et al. 'HAFT: hardware-assisted fault tolerance.' In: *Proceedings of the Eleventh European Conference on Computer Systems*. EuroSys '16: Eleventh EuroSys Conference 2016. London United Kingdom: ACM, Apr. 18, 2016, pp. 1–17. ISBN: 978-1-4503-4240-7. DOI: `10/ghvf8p`.

Instruction-level redundancy

(a) Native

```

z = add x, y




ret z
```

Instruction-level redundancy

(a) Native

```

z = add x, y




ret z
```

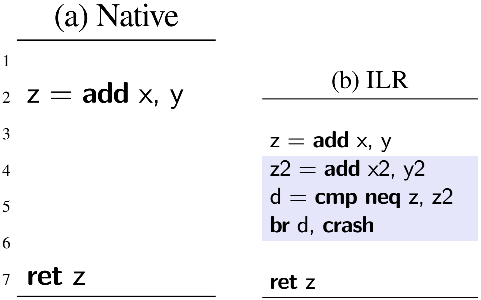
(b) ILR

```
z = add x, y
z2 = add x2, y2
d = cmp neq z, z2
br d, crash

ret z
```

DMR

Instruction-level redundancy



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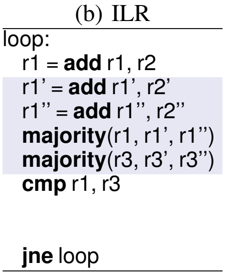
DMR



(b) ILR

```
loop:
   r1 = add r1, r2
   r1' = add r1', r2'
   r1'' = add r1'', r2''
   majority(r1, r1', r1'')
   majority(r3, r3', r3'')
   cmp r1, r3

   jne loop
```

TMR [15]

Instruction-level redundancy

(a) Native

```

z = add x, y




ret z
```

(b) ILR

```

z = add x, y
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br d, crash

ret z
```

DMR

(b) ILR

```
loop:
   r1 = add r1, r2
   r1’ = add r1’, r2’
   r1” = add r1”, r2”
   majority(r1, r1’, r1”)
   majority(r3, r3’, r3”)
   cmp r1, r3


   jne loop
```

TMR [15]

(c) HAFT

```
xbegin
  z = add x, y
  z2 = add x2, y2
  d = cmp neq z, z2
  br d, xabort
xend
ret z
```

HAFT: Performance

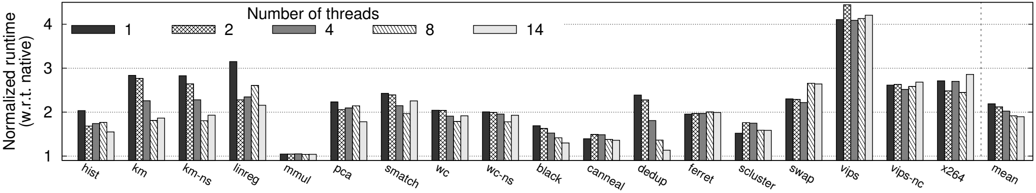


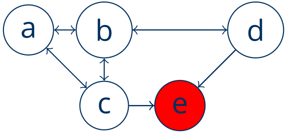
Figure 6: Performance overhead over native execution with the increasing number of threads (on a machine with 14 cores).

Romain vs. HAFT

	Romain	HAFT
Granularity	Syscall	Instruction
Parallelism	Thread-level	Instruction-level
Runtime overhead	≈ 10%	≈ 100%
Resource overhead	≈ 210%	≈ 100%
Faults	CPU & (some) Memory	CPU
Implementation	OS	Compiler & CPU features

Software verification

- Combines software engineering and software architectures
- Define good and bad states
- Define axioms (i.e. initial state is good)
- Prove bad states (i.e. null pointer dereference) are anreachable
- Special theorem prover languages



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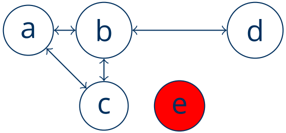

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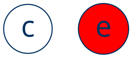

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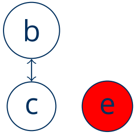

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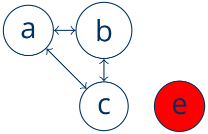

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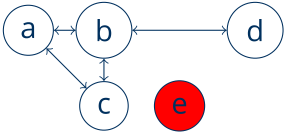


seL4: Formal verification of an OS kernel[13]

- seL4: `https://sel4.systems/`
- Formally verify that system adheres to specification
- Microkernel design allows to separate components easier
- Hence verification process is easier

[13] Gerwin Klein et al. 'seL4: Formal verification of an OS kernel.' In: *SOSP*. 2009, pp. 207–220.

Verification of a microkernel

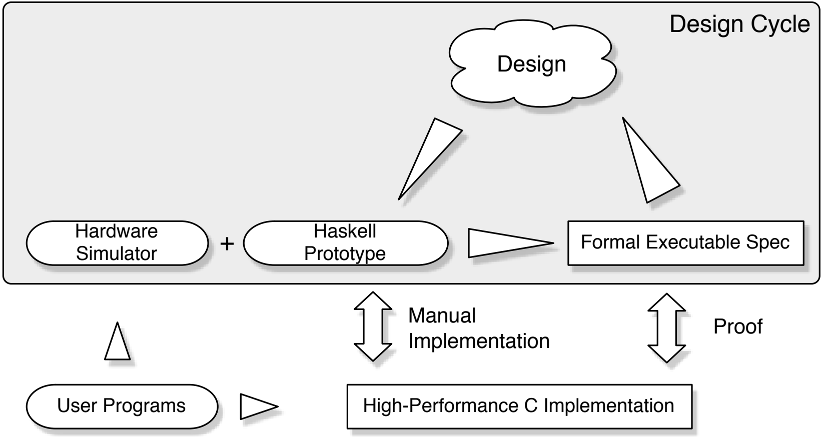


Figure: The seL4 design process [13]

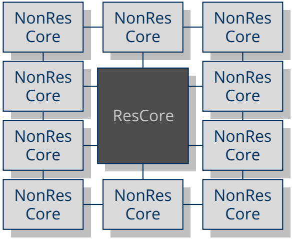
SeL4: Conclusion

- Assumes correctness of compiler, assembly code, and hardware
- DMA over IOMMU
- Architectures: arm, x86
- Virtualization
- Future: Verification on multicores

Hardening the RCB

- **We need:** Dedicated mechanisms to protect the RCB (HW or SW)
- **We have:** Full control over software
- Use FT-encoding compiler?
  - Has not been done for kernel code yet
- RAD-hardened hardware?
  - Too expensive

Why not split cores into resilient and non-resilient ones?



NonRes Core | NonRes Core | NonRes Core

NonRes Core | ResCore | NonRes Core

NonRes Core | | NonRes Core

NonRes Core | NonRes Core | NonRes Core

Summary

- Dependability is robust development practices + reliability techniques
- Do not let failures propagate
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Next week (in previous life): Practical exercise starts at 14:50

Bibliography I

[1] Algirdas Aviz, Jean-Claude Laprie, and Brian Randell. *Fundamental Concepts of Dependability*. 2001, p. 21.

[2] Kevin Boos et al. 'Theseus: an Experiment in Operating System Structure and State Management.' In: OSDI. 2020, pp. 1–19. ISBN: 978-1-939133-19-9. URL: `https://www.usenix.org/conference/osdi20/presentation/boos` (visited on 01/24/2021).

[3] K Mani Chandy and Leslie Lamport. 'Distributed snapshots: Determining global states of distributed systems.' In: *ACM Transactions on Computer Systems (TOCS)* 3.1 (1985), pp. 63–75.

Bibliography II

[4] Andy Chou et al. 'An empirical study of operating systems errors.' In: *SOSP*. 2001, pp. 73–88.

[5] Cody Cutler, M. Frans Kaashoek, and Robert T. Morris. 'The benefits and costs of writing a POSIX kernel in a high-level language.' In: *OSDI*. Oct. 2018. URL: `https://www.usenix.org/conference/osdi18/presentation/cutler`.

[6] Francis M David et al. 'CuriOS: Improving Reliability through Operating System Structure..' In: *OSDI*. 2008, pp. 59–72.

[7] Anand Dixit and Alan Wood. 'The impact of new technology on soft error rates.' In: *International Reliability Physics Symposium (IRPS)*. 2011, 5B–4.

Bibliography III

[8] Björn Döbel and Hermann Härtig. ‘Can we put concurrency back into redundant multithreading?’ In: *EMSOFT*. 2014, pp. 1–10.

[9] Björn Döbel, Hermann Härtig, and Michael Engel. ‘Operating system support for redundant multithreading.’ In: *EMSOFT*. 2012, pp. 83–92.

[10] Björn Döbel. ‘Operating System Support for Redundant Multithreading.’ Dissertation. TU Dresden, 2014.

[11] Jorrit N Herder et al. ‘Fault isolation for device drivers.’ In: *DSN*. 2009, pp. 33–42.

[12] Andy A Hwang, Ioan A Stefanovici, and Bianca Schroeder. ‘Cosmic rays don’t strike twice.’ In: *ASPLOS*. 2012, pp. 111–122.

Bibliography IV

[13] Gerwin Klein et al. ‘seL4: Formal verification of an OS kernel.’ In: *SOSP*. 2009, pp. 207–220.

[14] Gregory M. Kurtzer, Vanessa Sochat, and Michael W. Bauer. ‘Singularity: Scientific containers for mobility of compute.’ In: *PLOS ONE* 12.5 (May 11, 2017), e0177459. ISSN: 1932-6203. DOI: `10/f969fz`.

[15] D. Kuvaiskii et al. ‘ELZAR: Triple Modular Redundancy Using Intel AVX (Practical Experience Report).’ In: *2016 46th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN)*. 2016 46th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN). June 2016, pp. 646–653. DOI: `10/ghvjrb`.

Bibliography V

[16] Dmitrii Kuvaiskii et al. ‘HAFT: hardware-assisted fault tolerance.’ In: *Proceedings of the Eleventh European Conference on Computer Systems*. EuroSys ’16: Eleventh EuroSys Conference 2016. London United Kingdom: ACM, Apr. 18, 2016, pp. 1–17. ISBN: 978-1-4503-4240-7. DOI: `10/ghvf8p`.

[17] Amit Levy et al. ‘Multiprogramming a 64kb computer safely and efficiently.’ In: *SOSP*. 2017.

[18] Vikram Narayanan et al. ‘RedLeaf: Isolation and Communication in a Safe Operating System.’ In: OSDI. 2020, pp. 21–39. ISBN: 978-1-939133-19-9. URL: `https://www.usenix.org/conference/osdi20/presentation/narayanan-vikram` (visited on 01/24/2021).

Bibliography VI

[19] Nicolas Palix et al. ‘Faults in Linux: Ten years later.’ In: *ASPLOS*. 2011, pp. 305–318.

[20] Bianca Schroeder, Eduardo Pinheiro, and Wolf-Dietrich Weber. ‘DRAM errors in the wild: a large-scale field study.’ In: *SIGMETRICS/Performance*. 2009, pp. 193–204.

[21] Dirk Vogt, Björn Döbel, and Adam Lackorzynski. ‘Stay strong, stay safe: Enhancing reliability of a secure operating system.’ In: *Workshop on Isolation and Integration for Dependable Systems*. 2010, pp. 1–10.