Maksym Planeta Björn Döbel

Operating Systems Meet Fault Tolerance

Microkernel-Based Operating Systems // Dresden, 21.01.2020

> *'If there is more than one possible outcome of a job or task, and one of those outcome 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

- 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

Textbook terminology

Dependability threats:

- Failure
- Error
- Fault

Dependability means

- Prevention
- Removal
- Forecasting
- Tolerance

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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?
  - How are they distributed?
  - 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

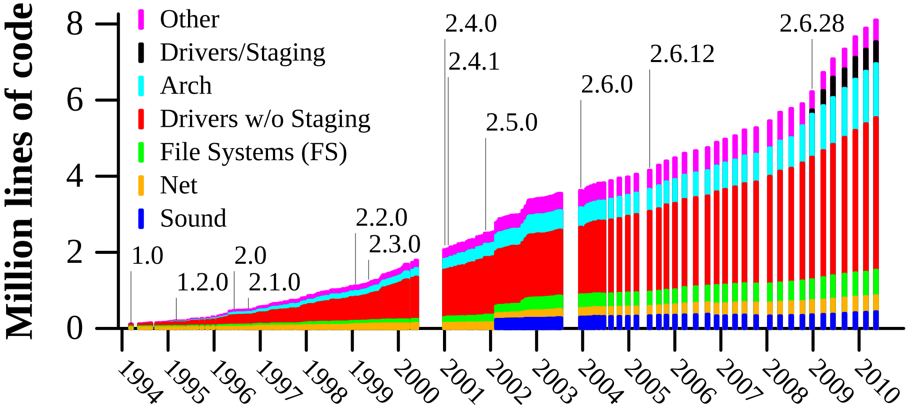

Figure: Linux directory sizes (in MLOC) [13]

Faults per Subdirectory (2001)

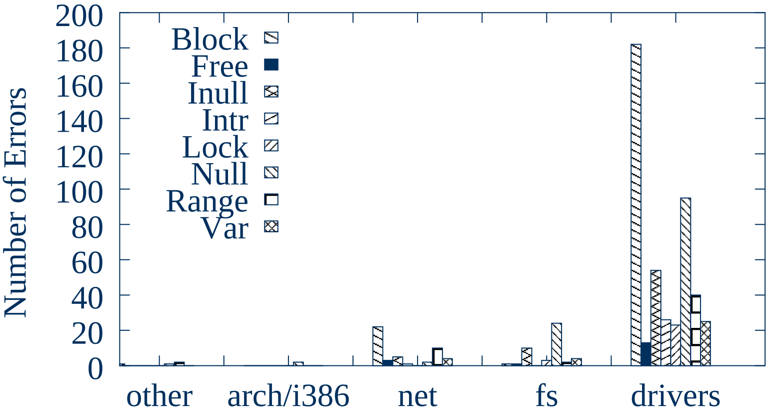

Figure: Number of errors per directory in Linux [2]

Fault Rate per Subdirectory (2001)

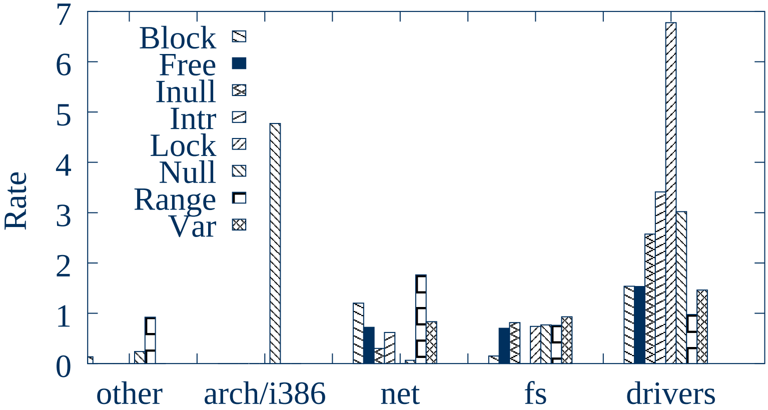

Figure: Rate of errors compared to other directories [2]

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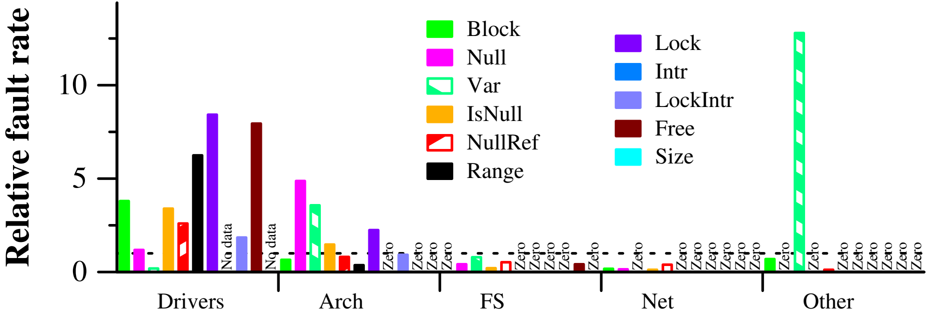

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Bug Lifetimes (2011) [13]

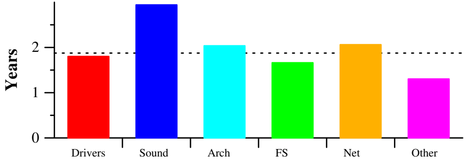

Figure: Per directory

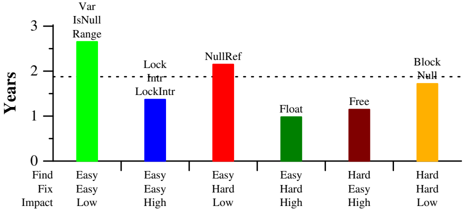

Figure: Per finding and fixing difficulty, and impact likelihood

Software Engineering addressing faults

- 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`.

Writing a kernel in a high-level language[1]

- Biscuit: a monolithic kernel implemented in Go

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

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- Memory or synchronization problems are impossible in *safe* code
- Performance like in C or C++ code
- Some software patterns don't work with (safe) Rust well

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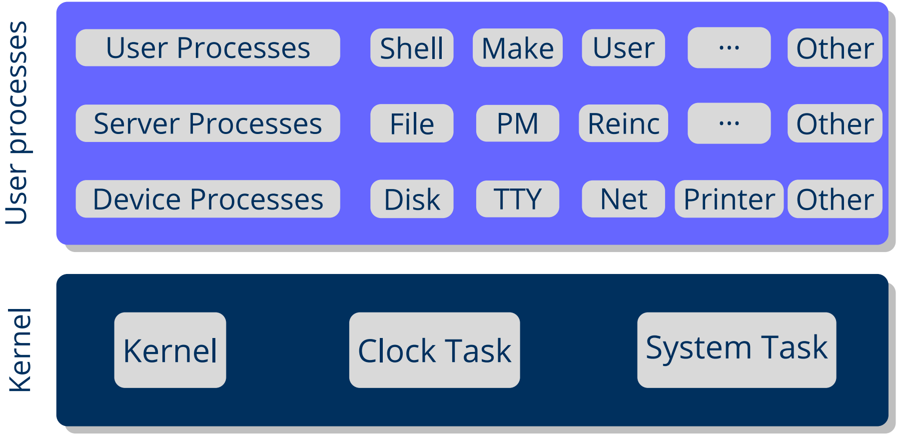
Break

- Faults are an issue.
- Hardware-related stuff is the worst.
- Now what can the OS do about it?

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[3]

- 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)

---

[3] 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[4]

- 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

---

[4] 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[5]

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

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[5] 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.

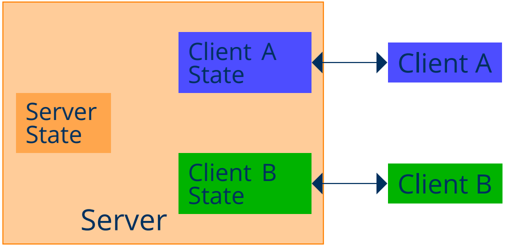
Break

- 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[6]

- 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



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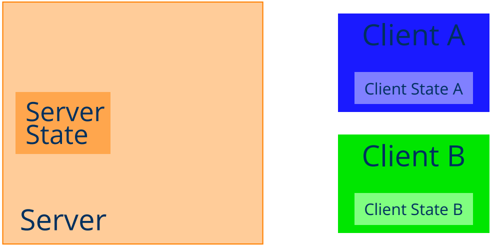
[6] Francis M David et al. 'CuriOS: Improving Reliability through Operating System Structure.'. In: *OSDI*. 2008, pp. 59–72.

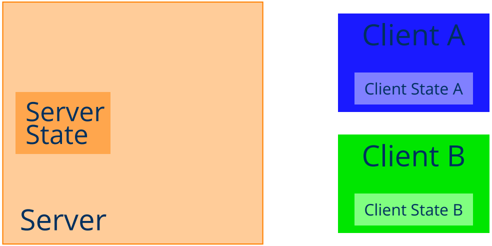
CuriOS: Server State Regions

- 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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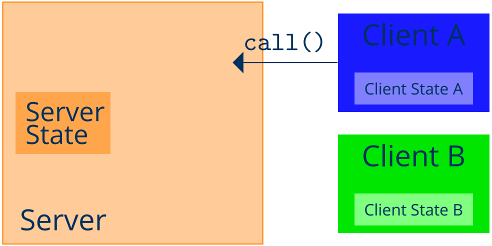

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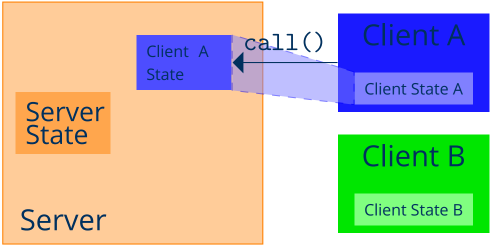

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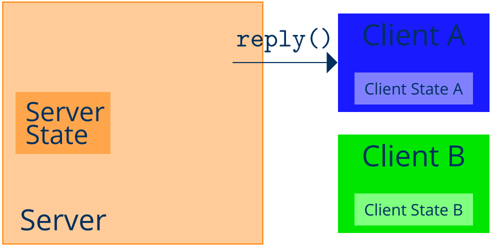

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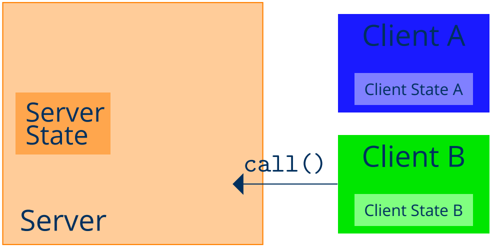

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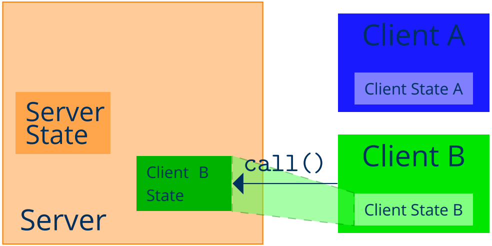

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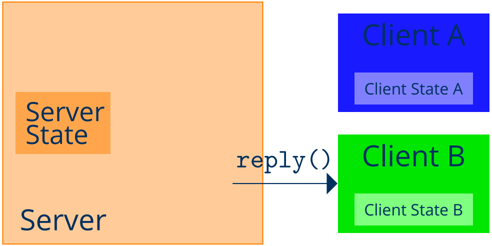


CuriOS: Transparent Restart

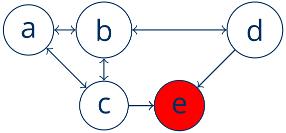
- CuriOS is a *Single-Address-Space OS*:
  - Every application runs on the same page table (with modified access rights)

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

Software verification

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



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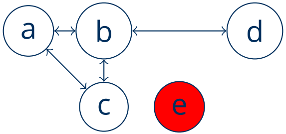

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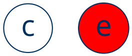

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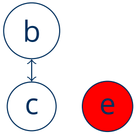

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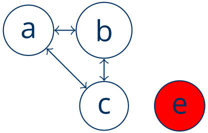

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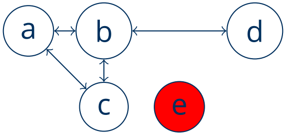

seL4: Formal verification of an OS kernel[7]

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

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

Verification of a microkernel

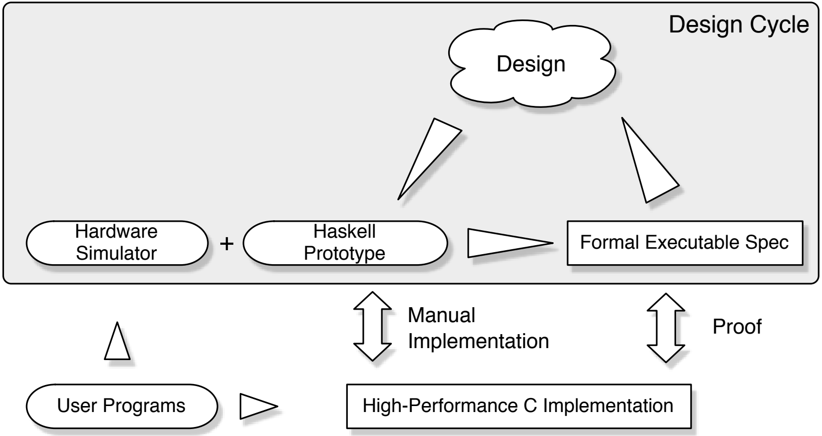


Figure: The seL4 design process [11]

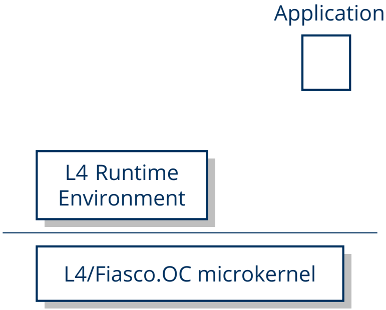
Break

- seL4
  - Assumes correctness of compiler, assembly code, and hardware
  - DMA over IOMMU
  - Architectures: arm, x86
  - Virtualization
  - Future: Verification on multicores
- All these frameworks only deal with software errors.
- What about hardware faults?

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 [14]
  - ECC insufficient [10]
- Decreasing transistor sizes $\rightarrow$ higher rate of errors in CPU functional units [5]

Transparent Replication as OS Service [7, 6]

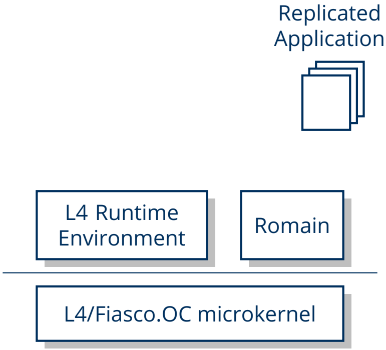


Application

L4 Runtime Environment

L4/Fiasco.OC microkernel

Transparent Replication as OS Service [7, 6]



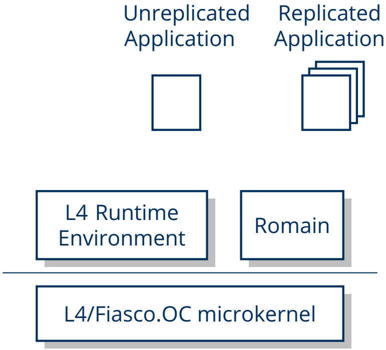
Replicated Application

L4 Runtime Environment

Romain

L4/Fiasco.OC microkernel

Transparent Replication as OS Service [7, 6]



Unreplicated Application

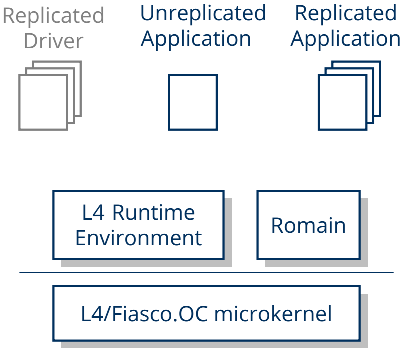
Replicated Application

L4 Runtime Environment

Romain

L4/Fiasco.OC microkernel

Transparent Replication as OS Service [7, 6]



Replicated Driver

Unreplicated Application

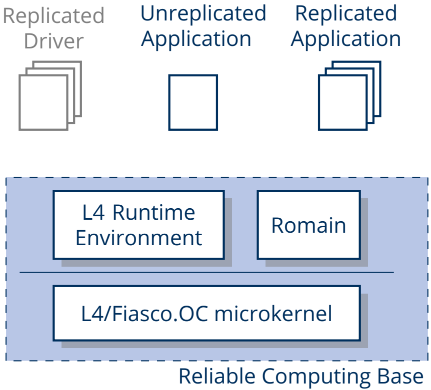
Replicated Application

L4 Runtime Environment

Romain

L4/Fiasco.OC microkernel

Transparent Replication as OS Service [7, 6]



Replicated Driver

Unreplicated Application

Replicated Application

L4 Runtime Environment

Romain

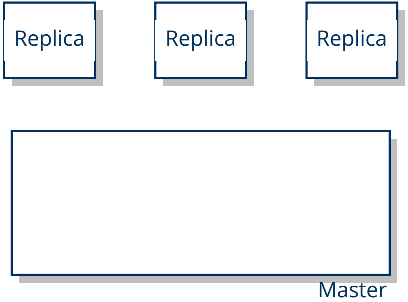
L4/Fiasco.OC microkernel

Reliable Computing Base

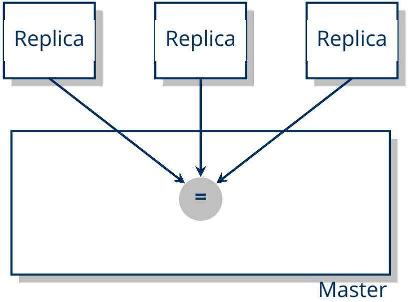
Romain: Structure

Master

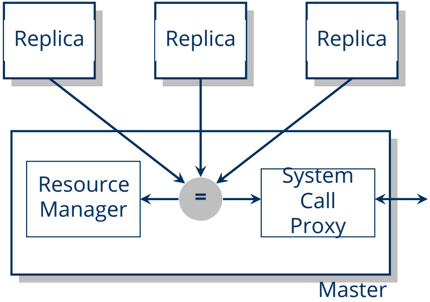
Romain: Structure



Romain: Structure



Romain: Structure


Replica

Replica

Replica

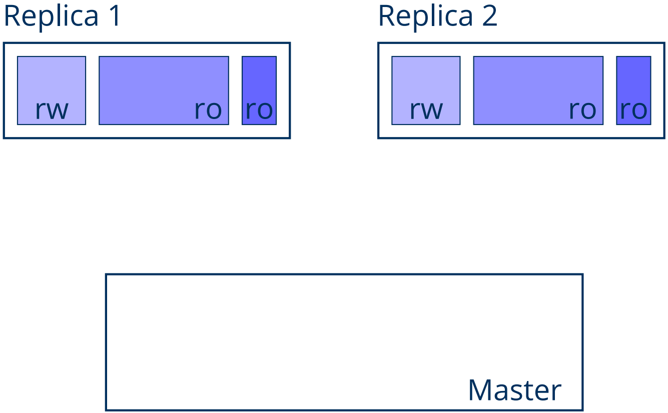
Resource Manager

=

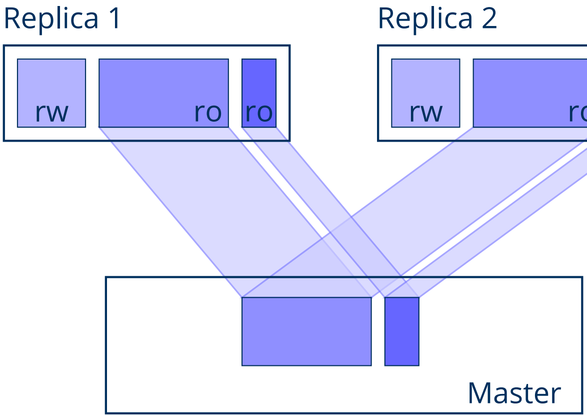
System Call Proxy

Master

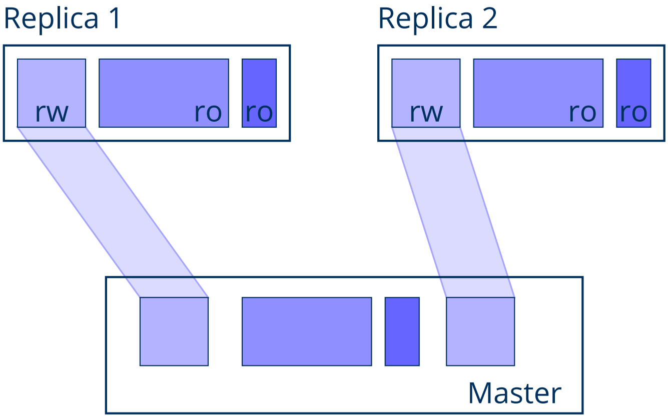
Replica Memory Management



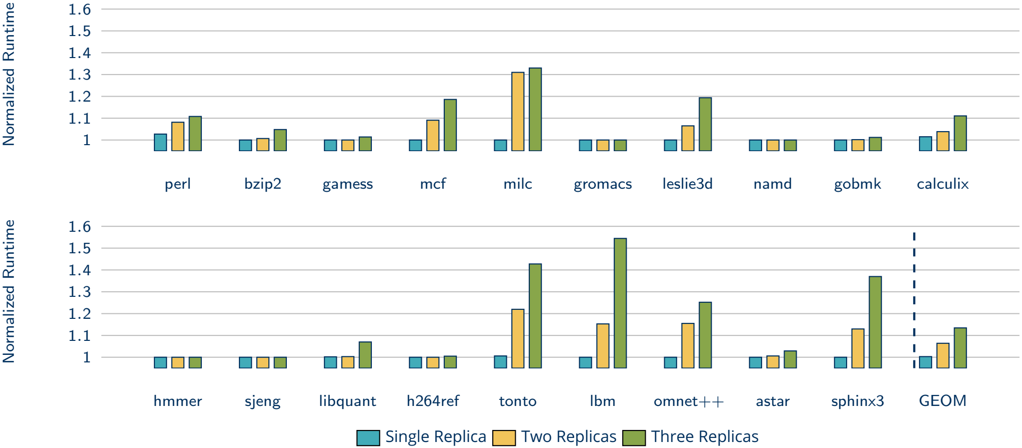
Replica Memory Management



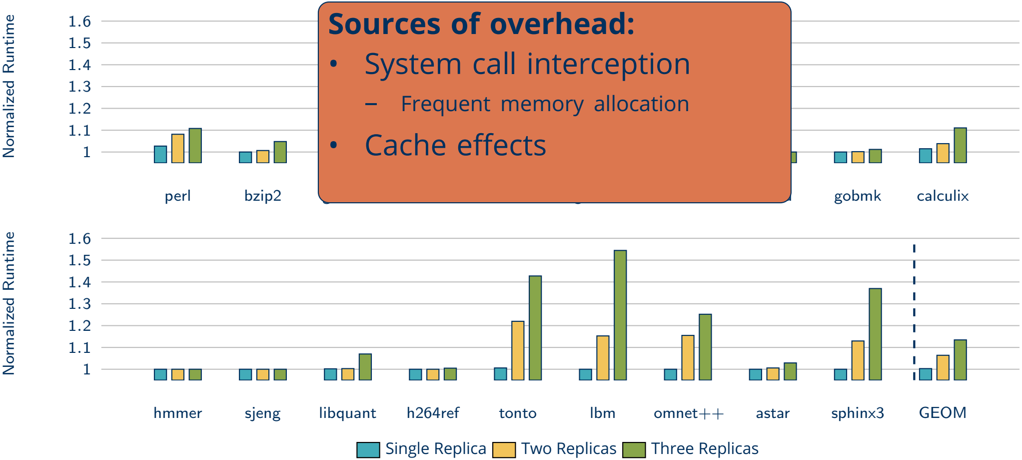
Replica Memory Management



Replicating SPEC CPU 2006 [8]



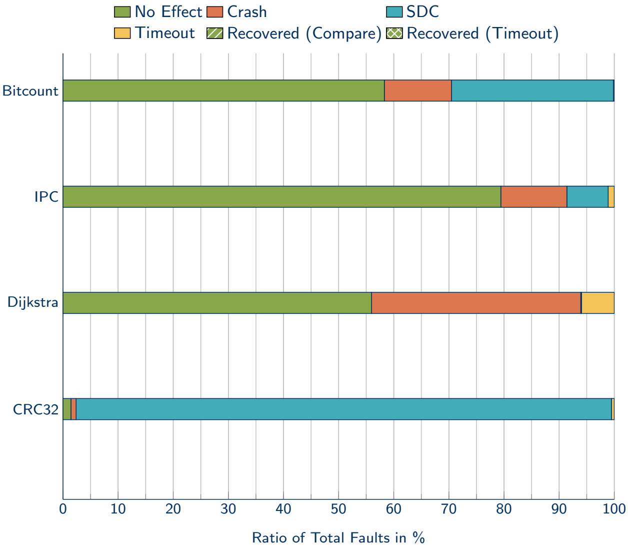
Replicating SPEC CPU 2006 [8]



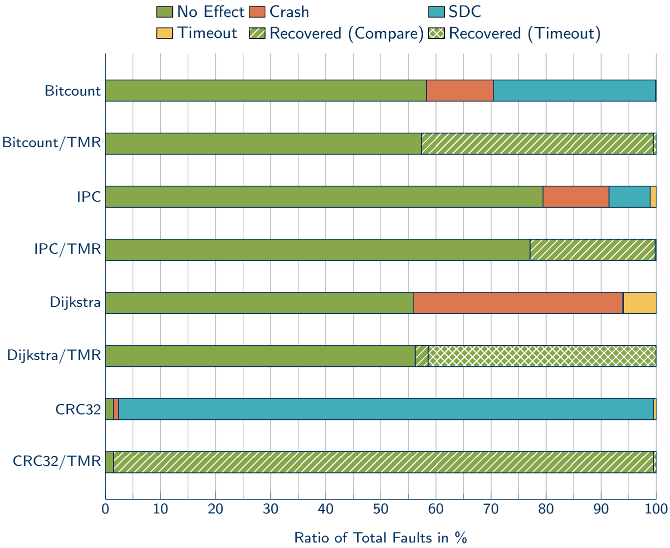
Sources of overhead:

- System call interception
  - Frequent memory allocation
- Cache effects

Error Coverage [8]



Error Coverage [8]



Romain: Summary

- Faults: CPU and memory bit-flips
- Best-effort resilience
- Tripple modular redundancy with small increase in makespan
- Multithreading support with determenistic multithreading[8]

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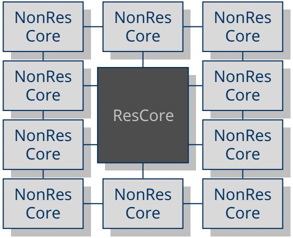
[8] Björn Döbel and Hermann Härtig. 'Can we put concurrency back into redundant multithreading?' In: *EMSOFT*. 2014, pp. 1–10.

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?



Summary

- OS-level techniques to tolerate SW and HW faults
- Address-space isolation
- Microreboots
- Various ways of handling session state
- Replication against hardware errors

Next week: Practical exercise starts at 14:50

Further Reading

- **Minix3**: Jorrit Herder, Ben Gras,, Philip Homburg, Andrew S. Tanenbaum: *Fault Isolation for Device Drivers*, DSN 2009
- **CuriOS**: Francis M. David, Ellick M. Chan, Jeffrey C. Carlyle and Roy H. Campbell *CuriOS: Improving Reliability through Operating System Structure*, OSDI 2008
- **Qmail**: D. Bernstein: *Some thoughts on security after ten years of qmail 1.0*
- **seL4**: Gerwin Klein, Kevin Elphinstone, Gernot Heiser, June Andronick and others *Formal verification of an OS kernel*, SOSP 2009
- **Romain**: Björn Döbel, Hermann Härtig: *Can We Put Concurrency Back Into Redundant Multithreading?*, EMSOFT 2014

Bibliography I

[1] 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.

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

[3] 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`.

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

Bibliography II

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

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

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

[8] Björn Döbel. 'Operating System Support for Redundant Multithreading'. Dissertation. TU Dresden, 2014.

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

Bibliography III

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

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

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

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

[14] 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.

Bibliography IV

[15] 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.