TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

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# Operating Systems Meet Fault Tolerance

Microkernel-Based Operating Systems // Dresden (online), 16.01.2024

*‘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

OS in critical environments

- Safety
- Security
- Performance

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# 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

# Resilience

*Persistence of dependability when facing changes*

# Dependability vs. Resilience

| Dependability | Technologies for Resilience: Evolvability | Assesability | Usability | Diversity |
|---|---|---|---|---|
| Fault Prevention | ✓ | | ✓ | |
| Fault Tolerance | ✓ | | ✓ | ✓ |
| Fault Removal | ✓ | ✓ | | |
| Fault Forecasting | ✓ | ✓ | | |

# Dependable Operating Systems

Faults:

- Software (bugs)
- Hardware

Measures:

- Software Engineering
- Software Architectures

# 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

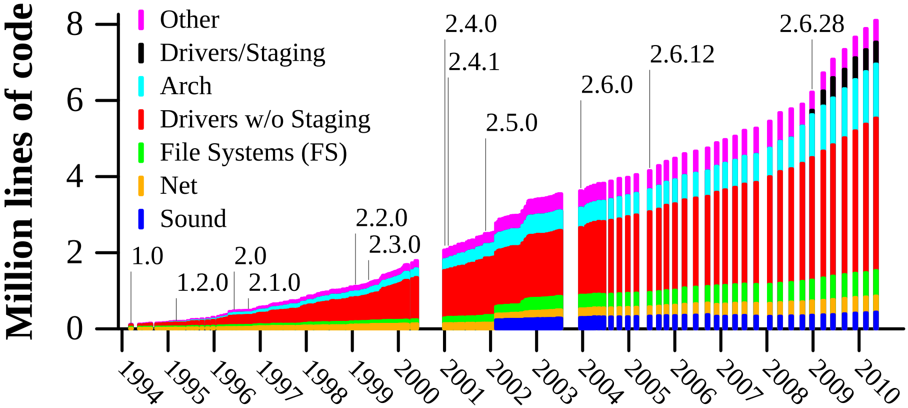


Figure: Linux directory sizes (in MLOC) [19]

# Faults per Subdirectory (2001)

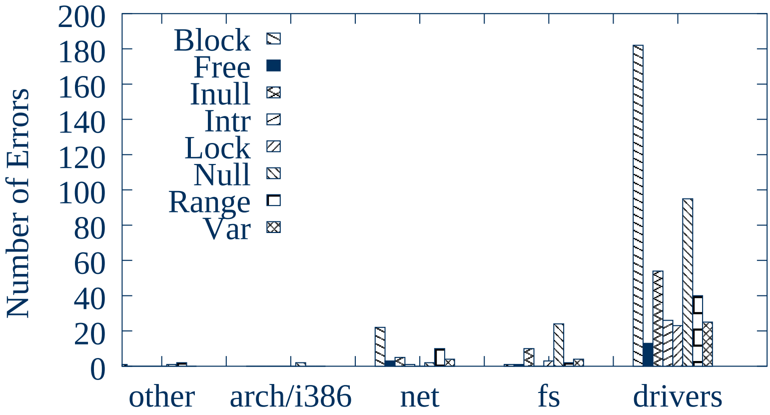


Figure: Number of errors per directory in Linux [4]

# Fault Rate per Subdirectory (2001)

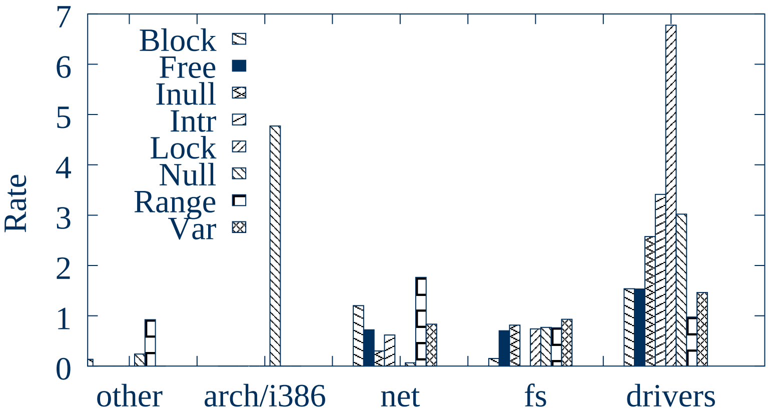


Figure: Rate of errors compared to other directories [4]

# Fault Rate per Subdirectory (2011)

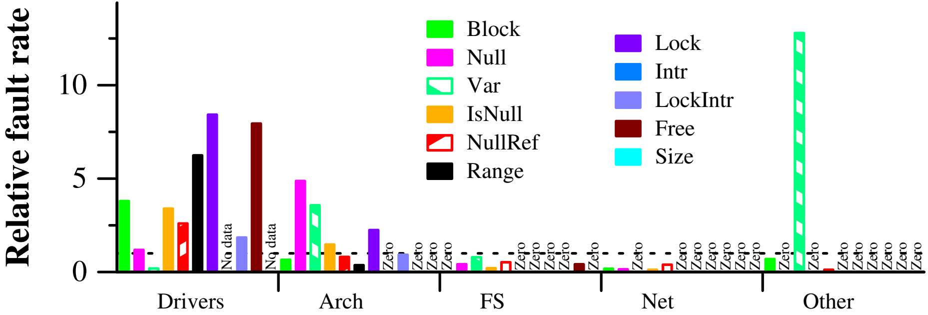


Figure: Rate of errors compared to other directories [19]

# Bug Lifetimes (2011) [19]

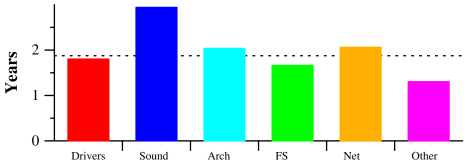


Figure: Per directory

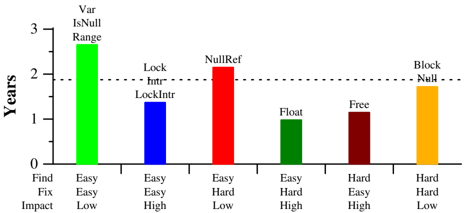


Figure: Per finding and fixing difficulty, and impact likelihood

# 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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The underlying bit representations of floating-point values shall not be used.

# Example: MISRA C++ 2008

| Rule 0-1-7 |
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| Rule 3-9-3 |
|---|
| The underlying bit representations of floating-point values shall not be used. |

| 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#)

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[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

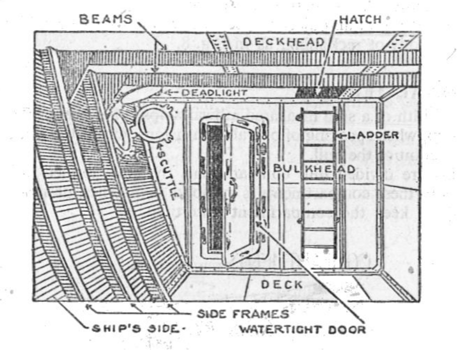


Figure: Ship building

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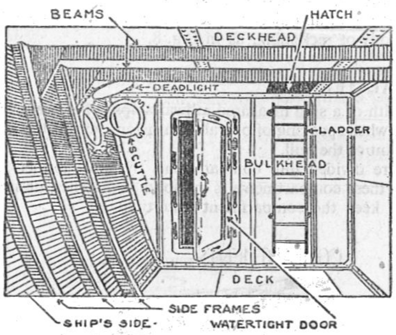


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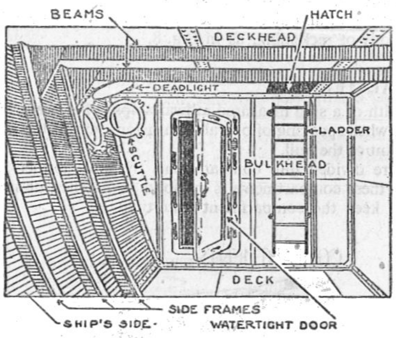
# Software architectures addressing faults

- 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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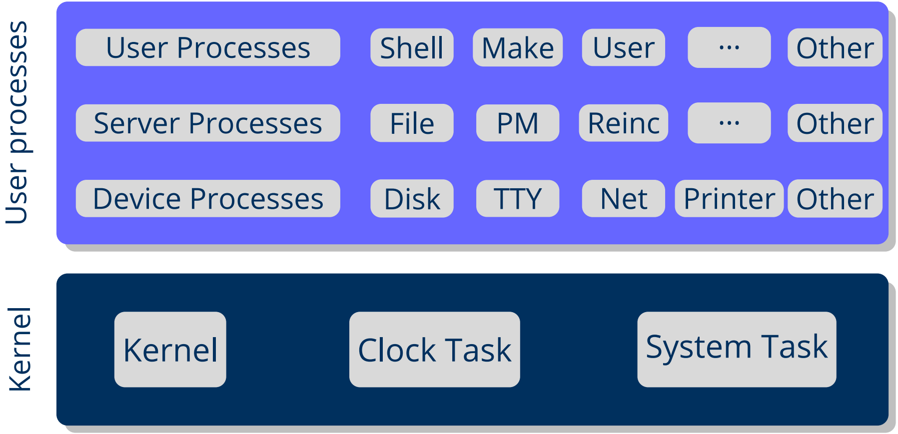
# Minix3: A Fault-tolerant OS



# 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

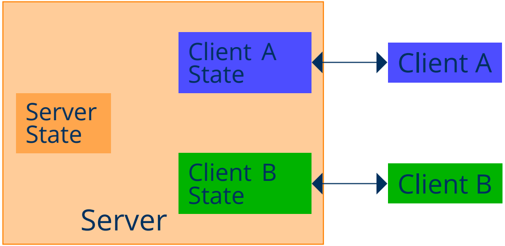
[9] K Mani Chandy and Leslie Lamport. ‘Distributed snapshots: Determining global states of distributed systems.’ In: *ACM Transactions on Computer Systems (TOCS)* 3.1 (1985), pp. 63–75.

# 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]

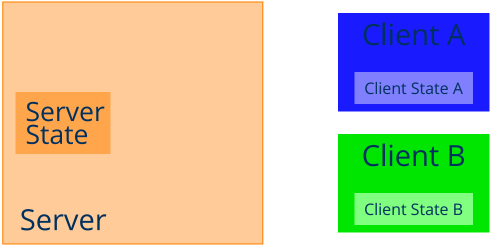
- State recovery is tricky
  - Minix3: Data Store for application data
  - But: applications interact
    - Servers store *session-specific* state
    - Server restart requires potential rollback for every participant




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

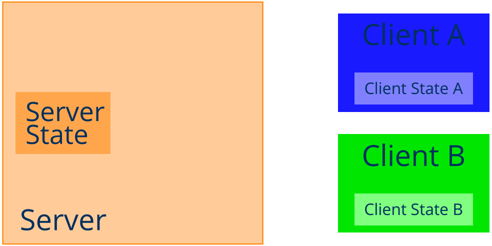
# CuriOS: Server State Regions

- 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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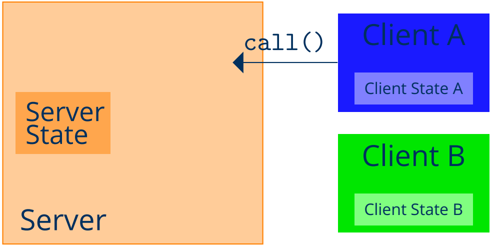

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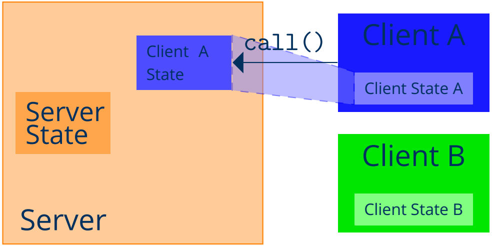

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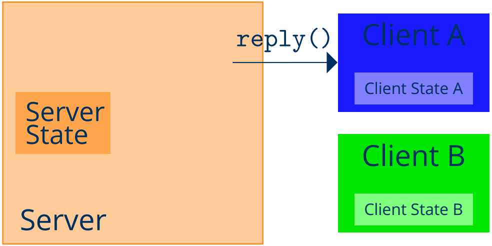

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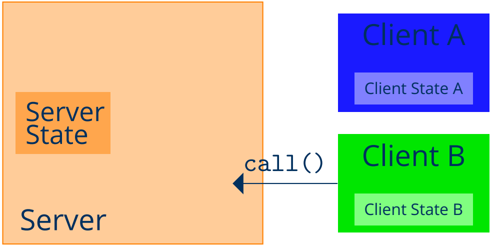

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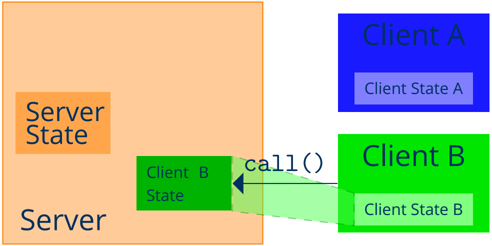

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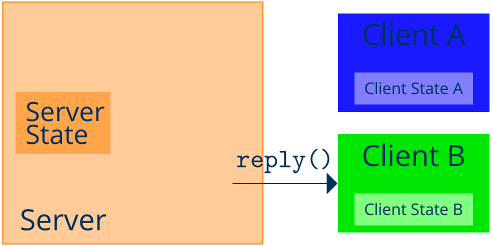


# CuriOS: Transparent Restart

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

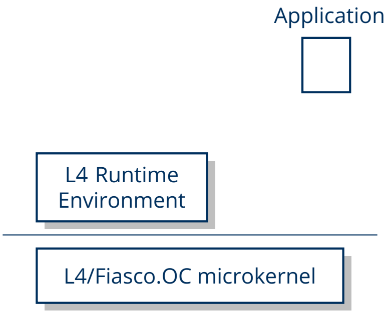
# Transparent Restart

- 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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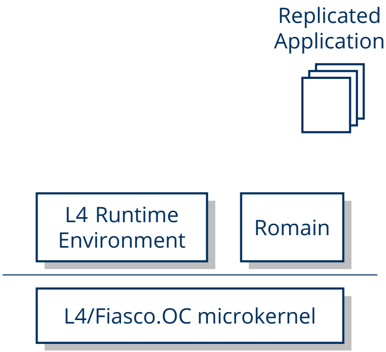

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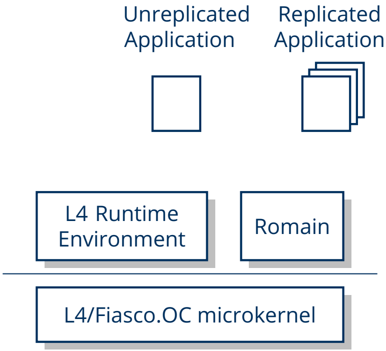

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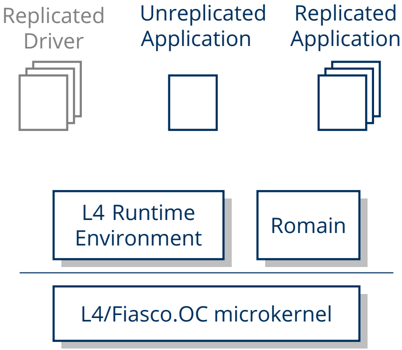

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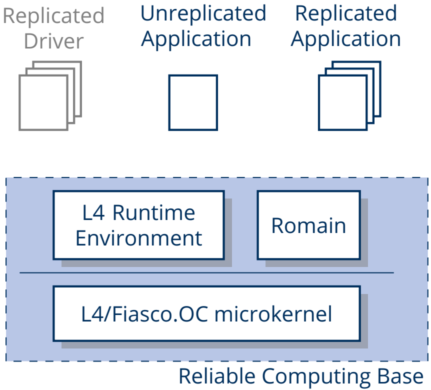

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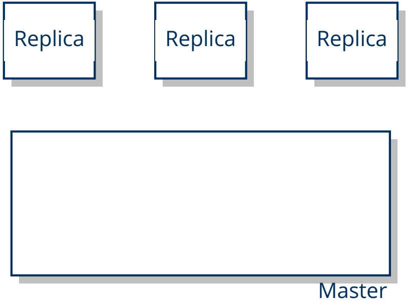

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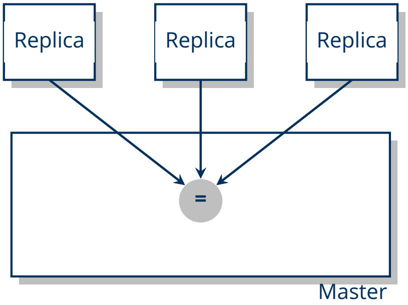

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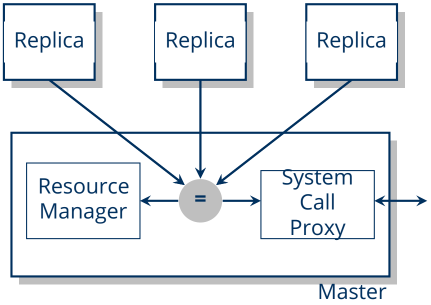
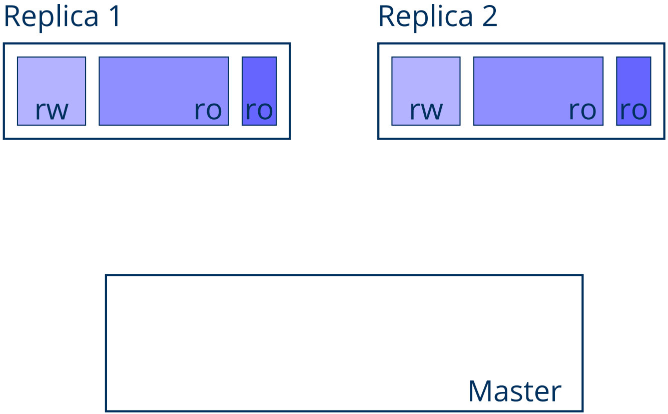


# Replica Memory Management



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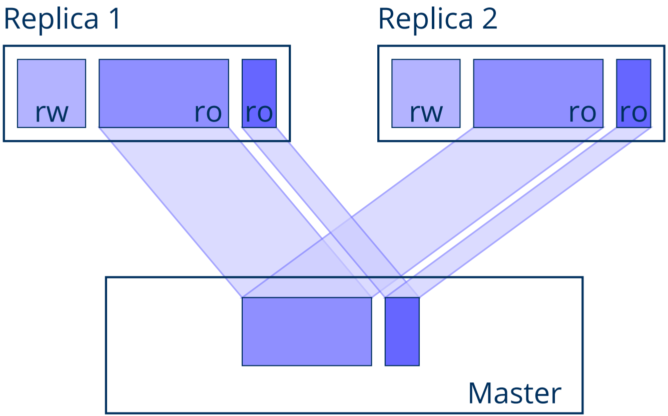

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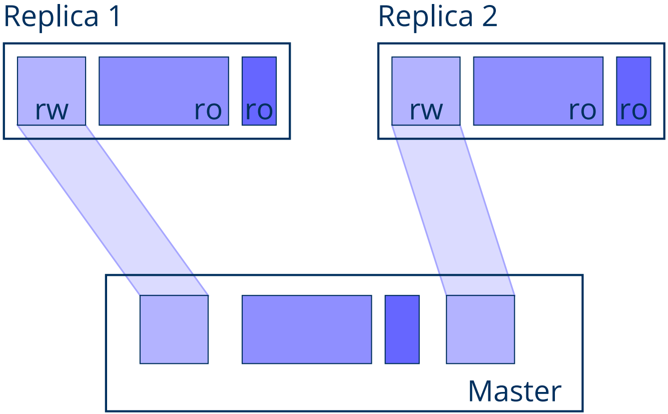
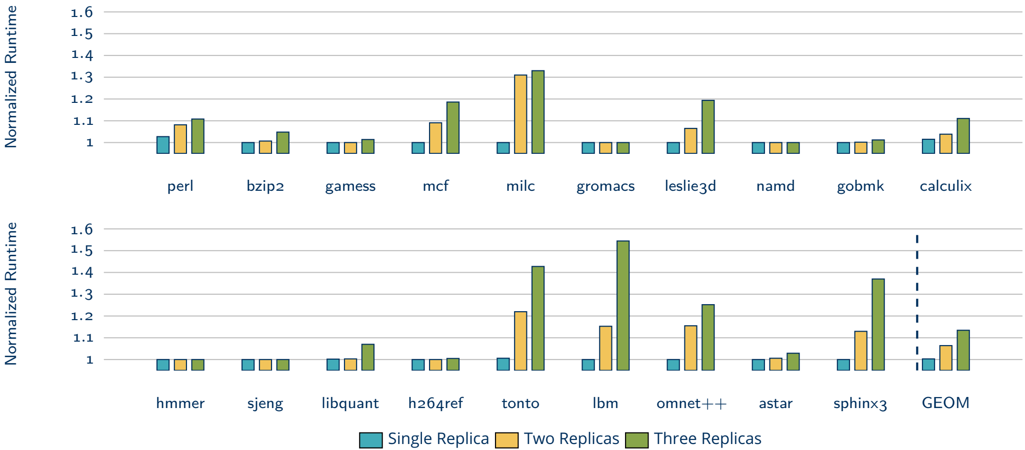


# Replicating SPEC CPU 2006 [10]



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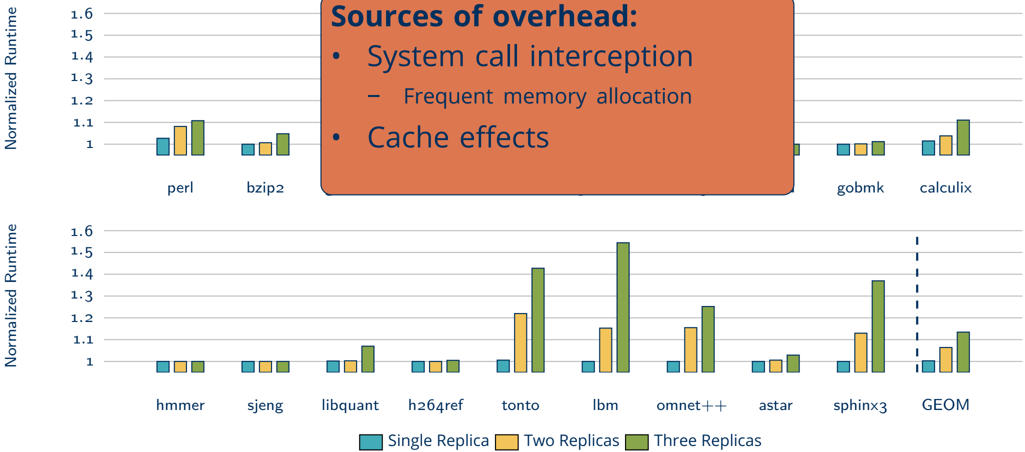
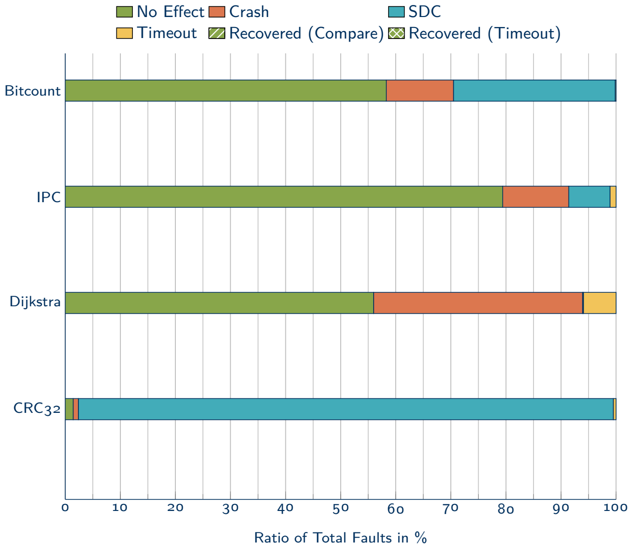



**Sources of overhead:**

- System call interception
  - Frequent memory allocation
- Cache effects

# Error Coverage [10]



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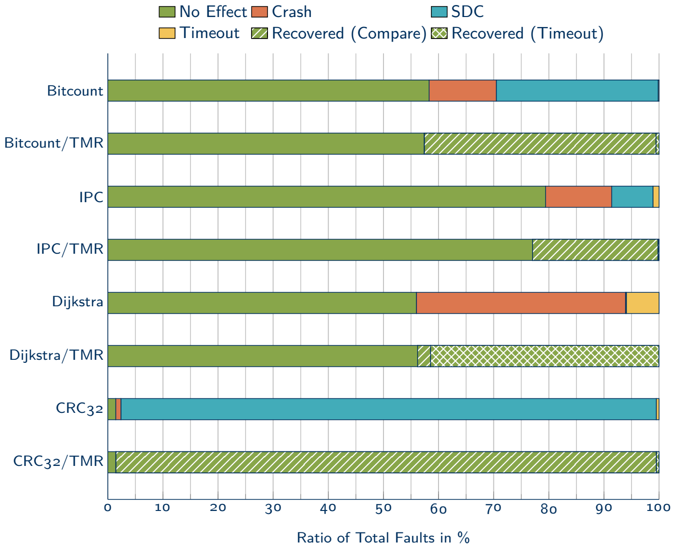

# Romain: Summary

- 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

(a) Native

```
z = add x, y

ret z
```

(b) ILR

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

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  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

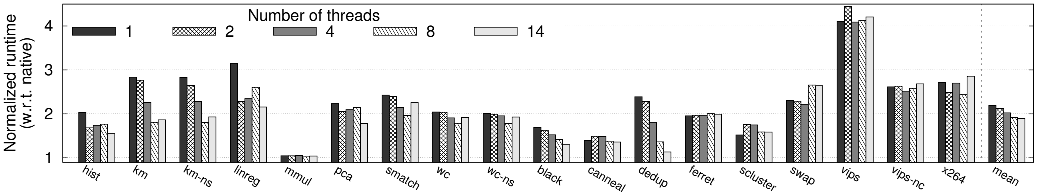


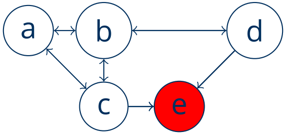

Figure 6: Performance overhead over native execution with the increasing number of threads (on a machine with 14 cores).

# Romain vs. HAFT

| | Romain | HAFT |
|---|---|---|
| Granularity | Syscall | Instruction |
| Parallelism | Thread-level | Instruction-level |
| Runtime overhead | $\approx 10\%$ | $\approx 100\%$ |
| Resource overhead | $\approx 210\%$ | $\approx 100\%$ |
| 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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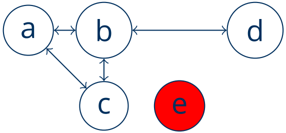

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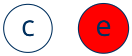

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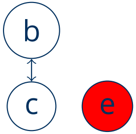

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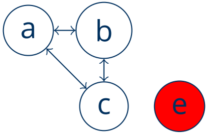

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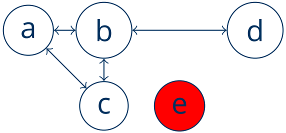


# seL4: Formal verification of an OS kernel[13]

- 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

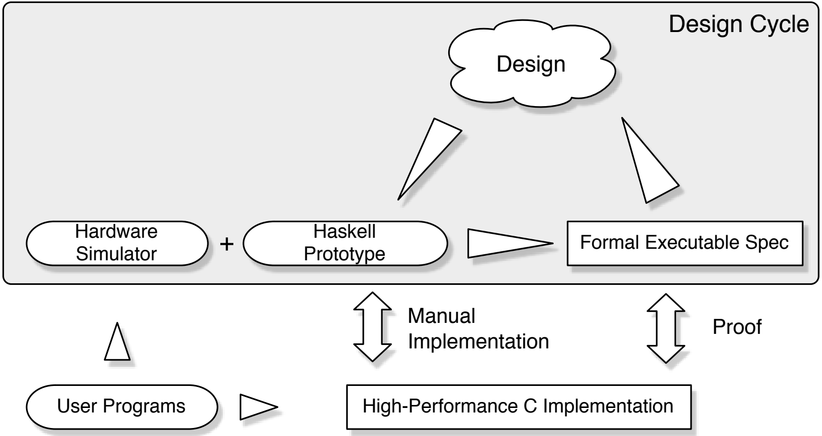



Figure: The seL4 design process [13]

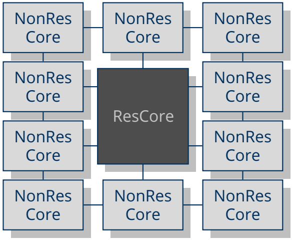
# SeL4: Conclusion

- 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?



# Summary

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- Silent data corruptions are the worst

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Next week (in previous life): Practical exercise starts at 14:50

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