Eliminating Single Points of Failure in Software-Based Redundancy

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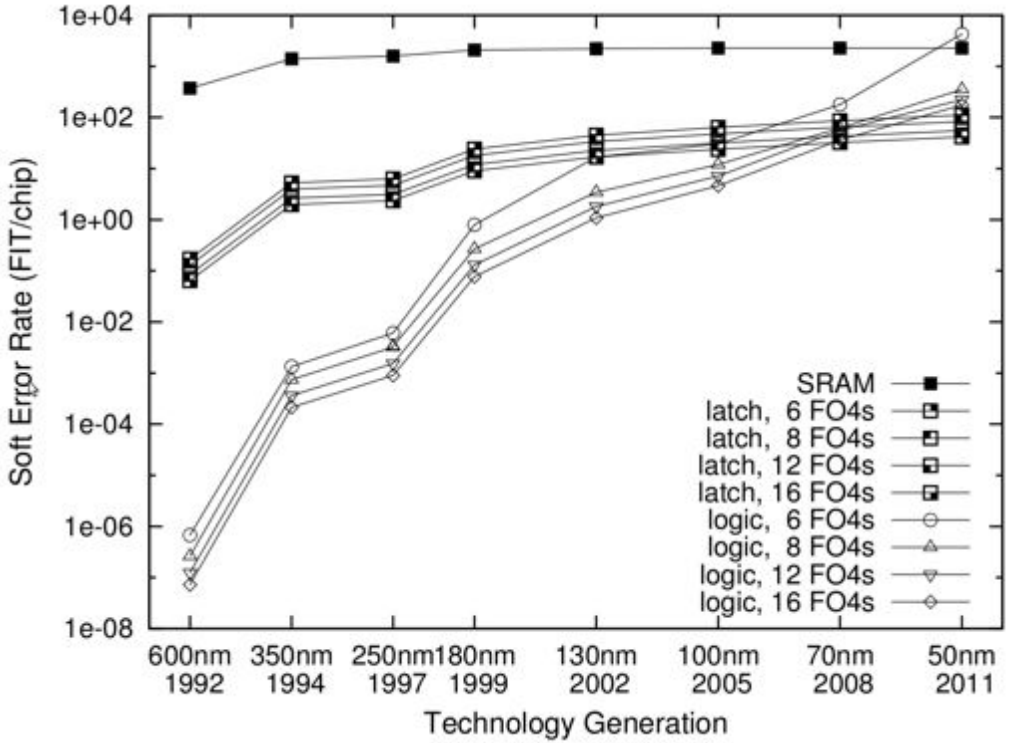
Transient Hardware Faults – A Growing Problem

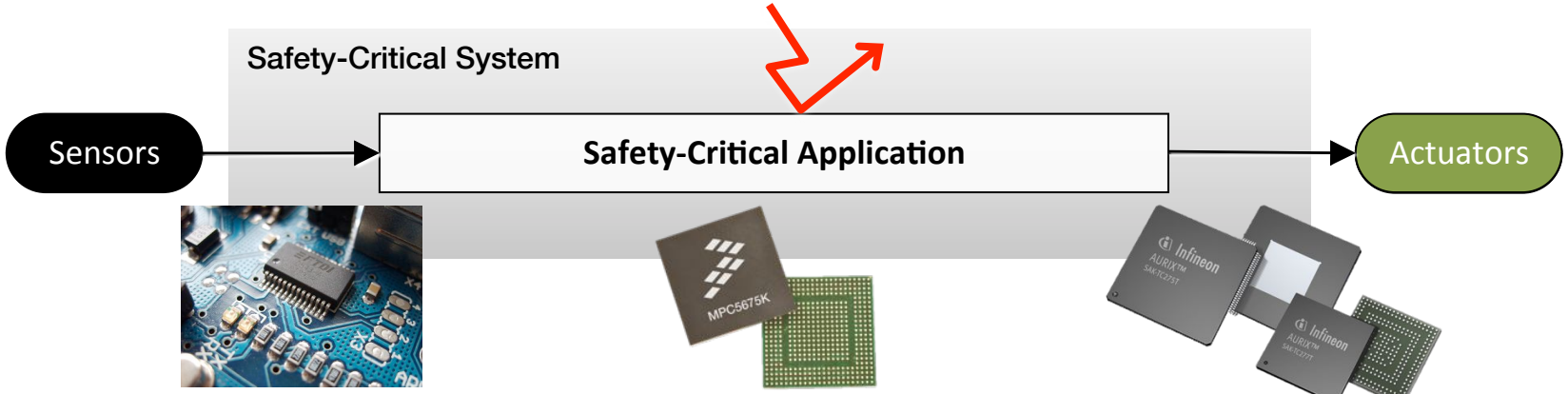


[3] (Shivakumar, 2002)

- **Transient hardware faults (Soft-Errors)**
  - Induced by e.g., radiation, glitches, insufficient signal integrity
  - Increasingly affecting microcontroller logic
- Future hardware designs:
  Even more performance and parallelism
  → **On the price of being less and less reliable**

Countermeasures - Hardware



- Hardware-based countermeasures
  - **Application-specific design** or **specialised hardware**
  - For example ECC, lock-step
  - ✓ **Pragmatic approach** (tackles problem right at source)
  - ✘ **Hardware costs** (e.g., redundancy, checker, …)
  - ✘ **Selectivity** (e.g., multi-application systems)
  - ✘ **Development costs** (diverse safety concepts and HW, (re-)certification)

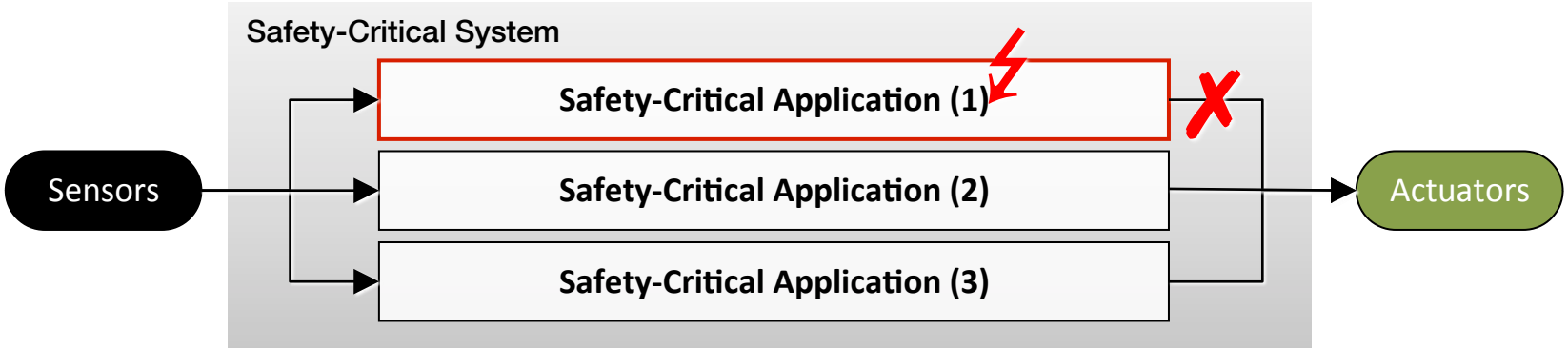
Countermeasures - Software




- Different approaches to address transient hardware faults
  - **Hardware** vs. **software measures**
  - Applicability and costs

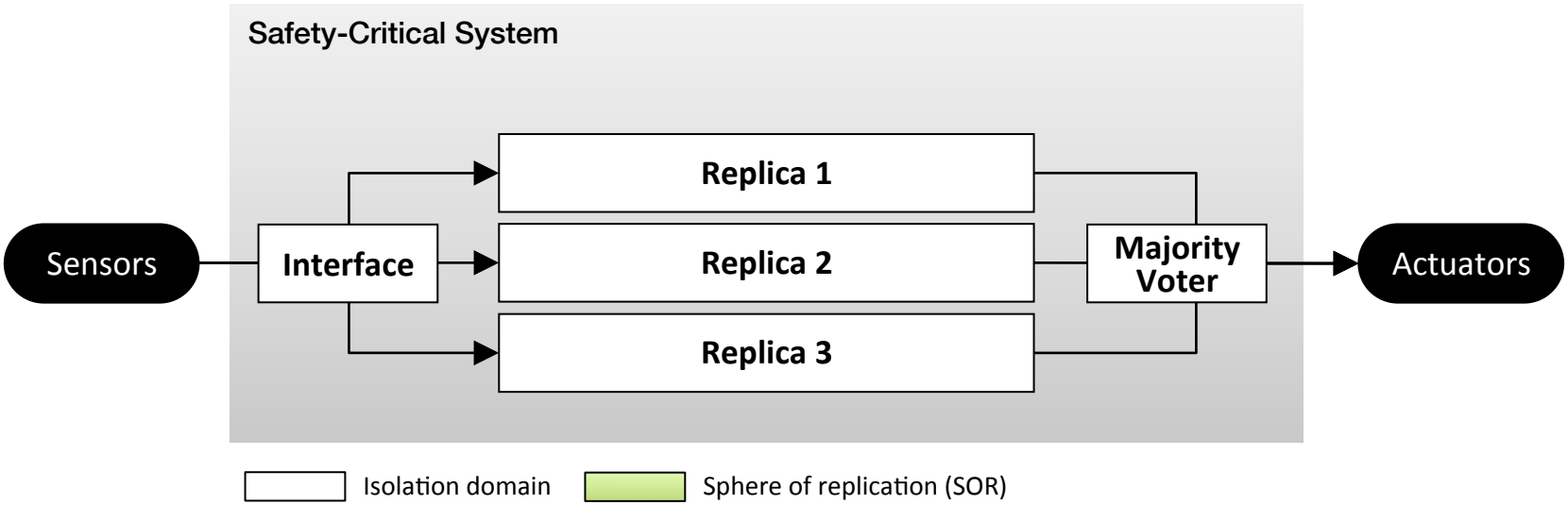
Countermeasures - Software



- Different approaches to address transient hardware faults
  - **Hardware** vs. **software measures**
  - Applicability and costs
- Software-based triple modular redundancy (TMR)
  - **Accepted** and **proven** (e.g., recommended for ASIL D error handling)
  - **Selective** (e.g., multi-application systems)

Software-Based Redundancy in Detail



- **Software-based TMR requires:**
  - **Temporal** and **spatial isolation** (isolation domains)
  - **Interface** and **Majority Voter**

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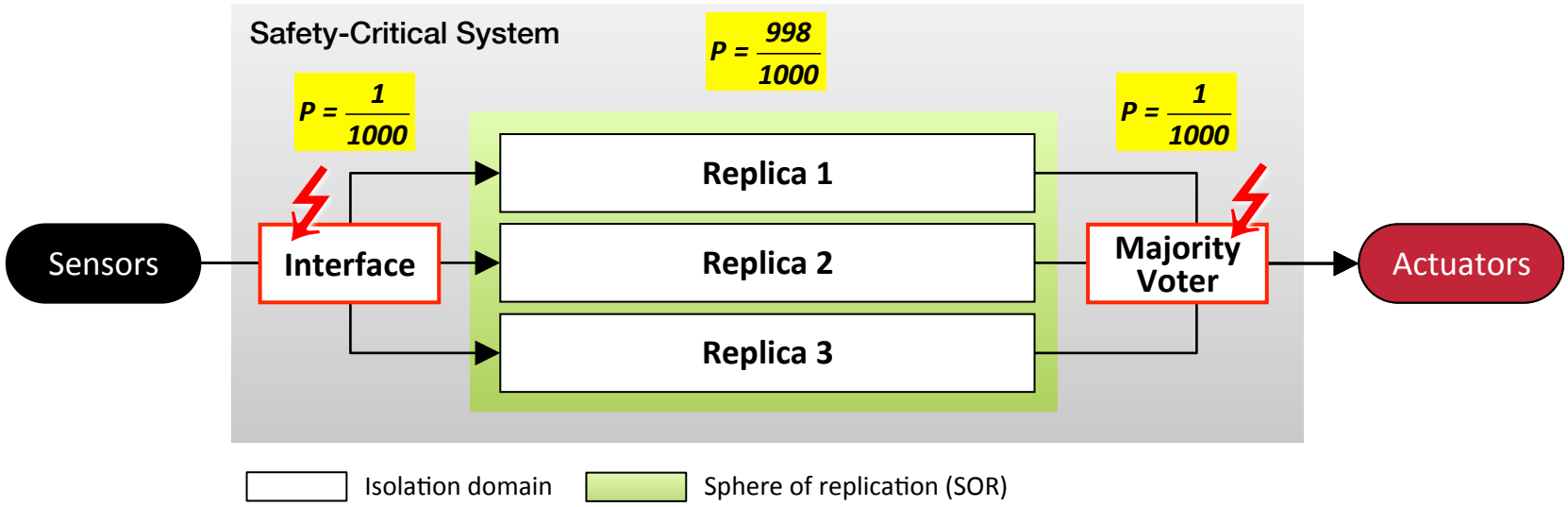

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  - Very small → **Certain probability**

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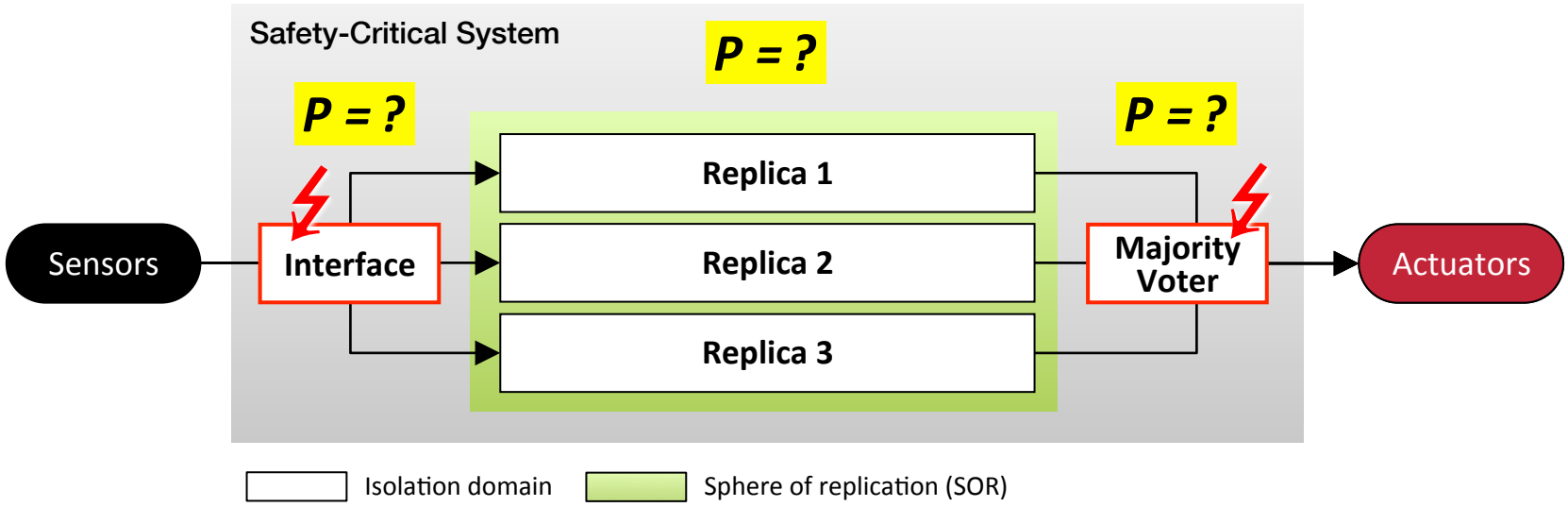

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  - Inherently **complex**
  - Random error distribution? (Nightingale, 2011)

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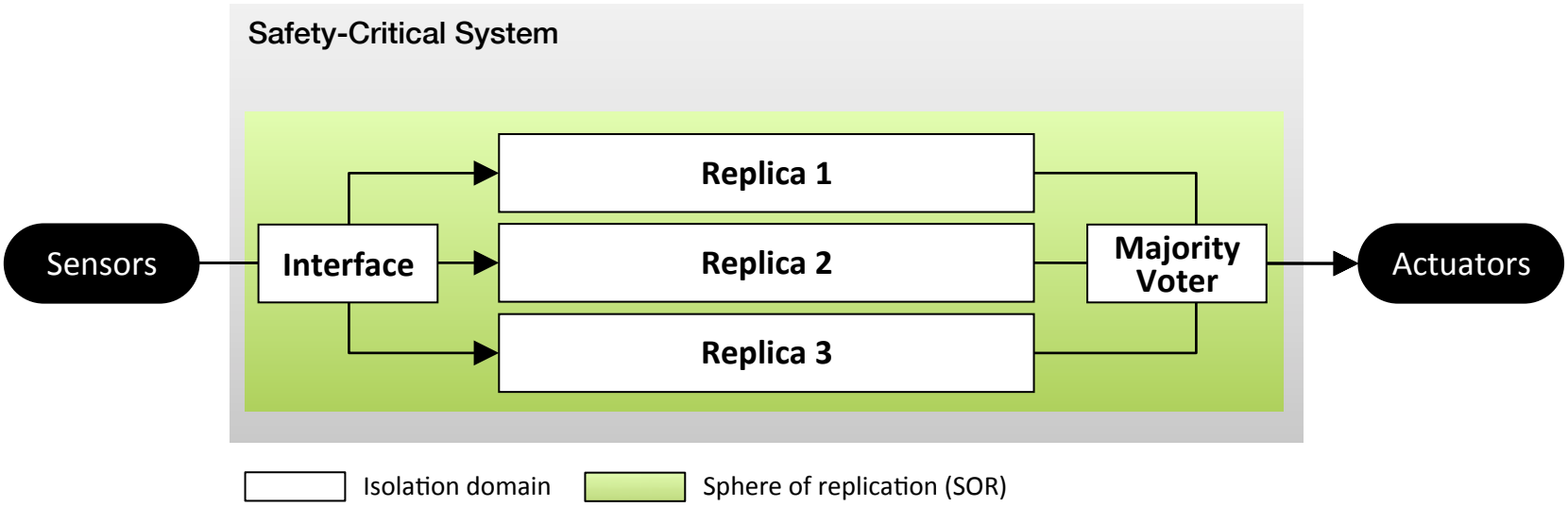

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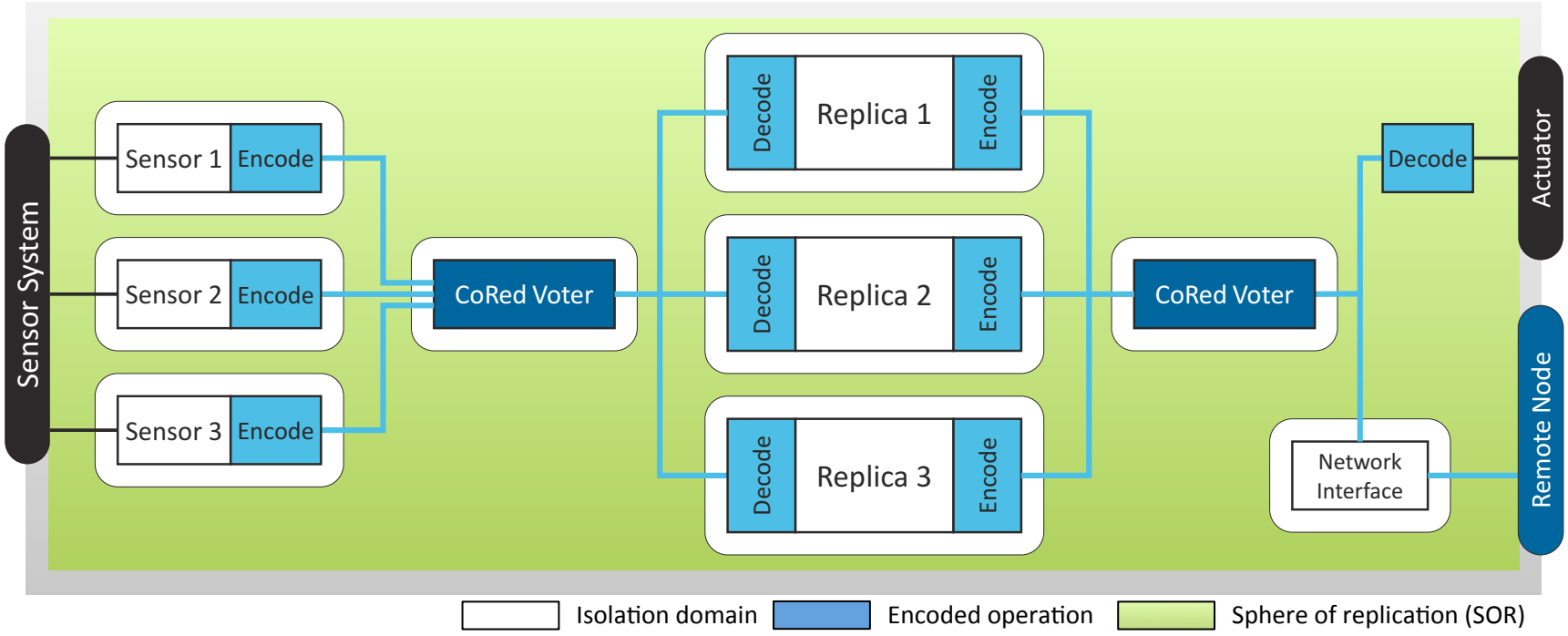
Agenda

- Introduction
- **The Combined Redundancy Approach**
  - Eliminating Vulnerabilities
  - High-Reliability Voters
- **Example: UAV Flight Control**
  - CoRed Implementation
  - Target System: I4*Copter*
- **Evaluation**
  - Experimental Setup
  - Results
- **Conclusion**

CoRed Overview – Holistic Protection Approach



- **The Combined Redundancy Approach (CoRed)**

  TMR +

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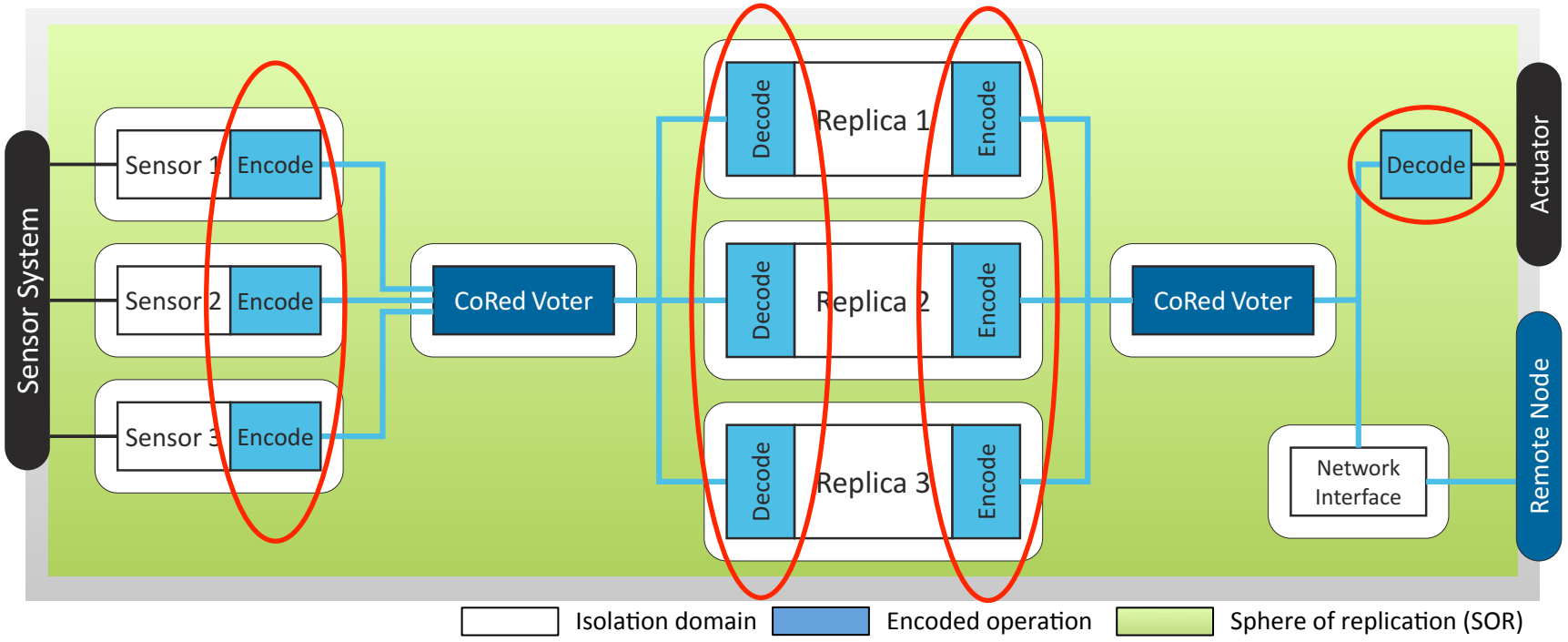

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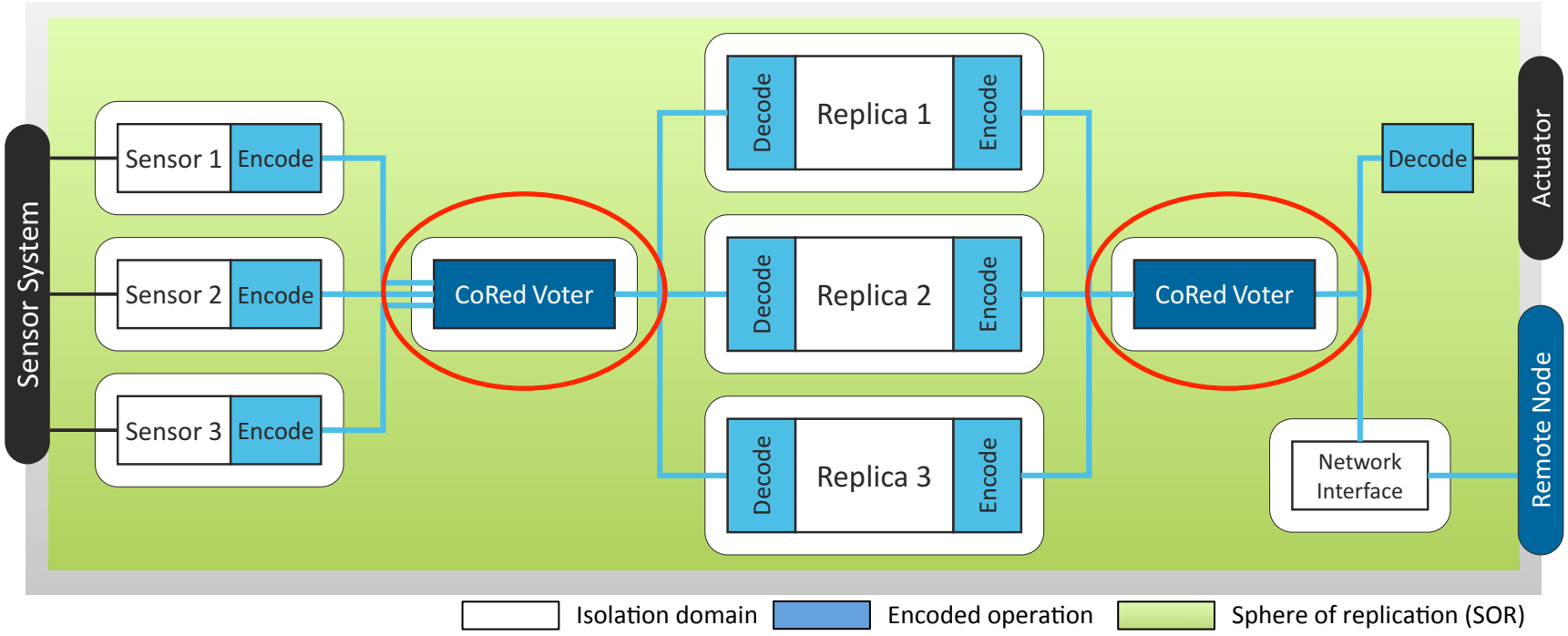

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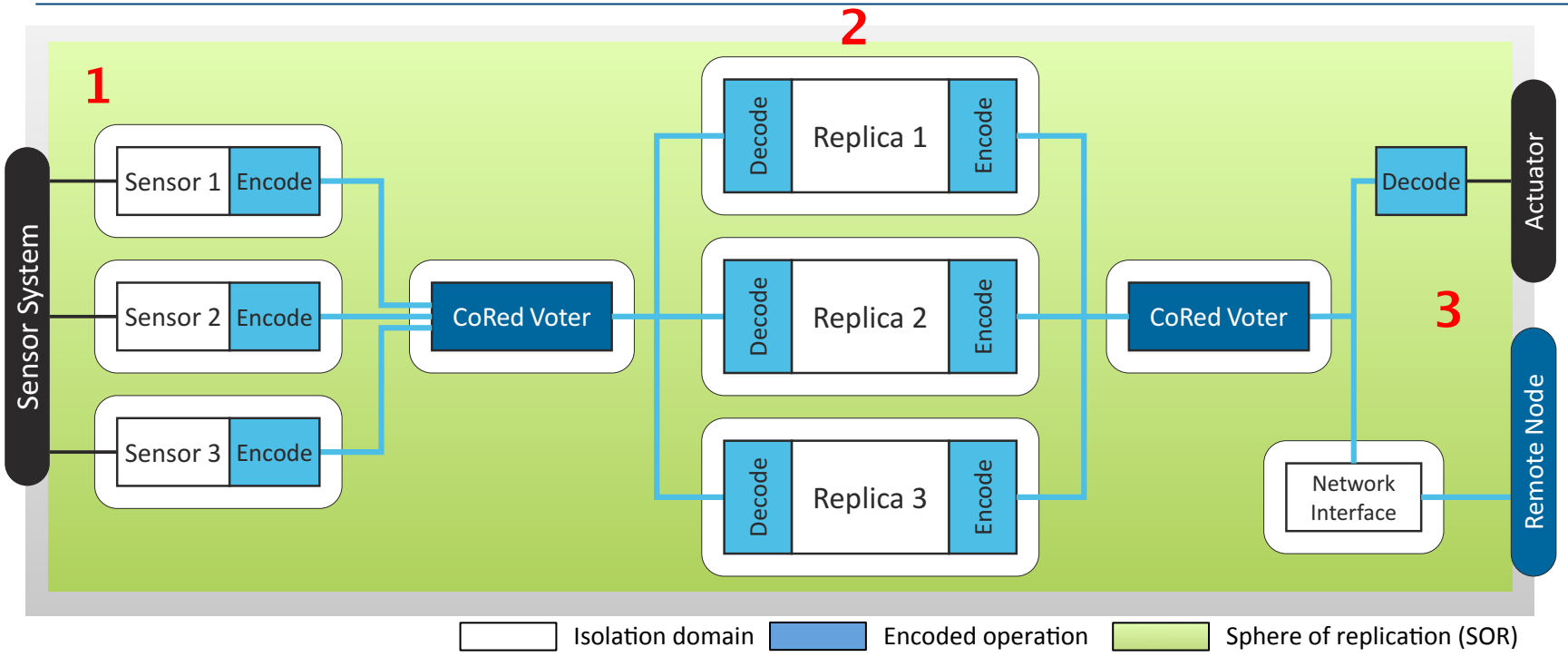


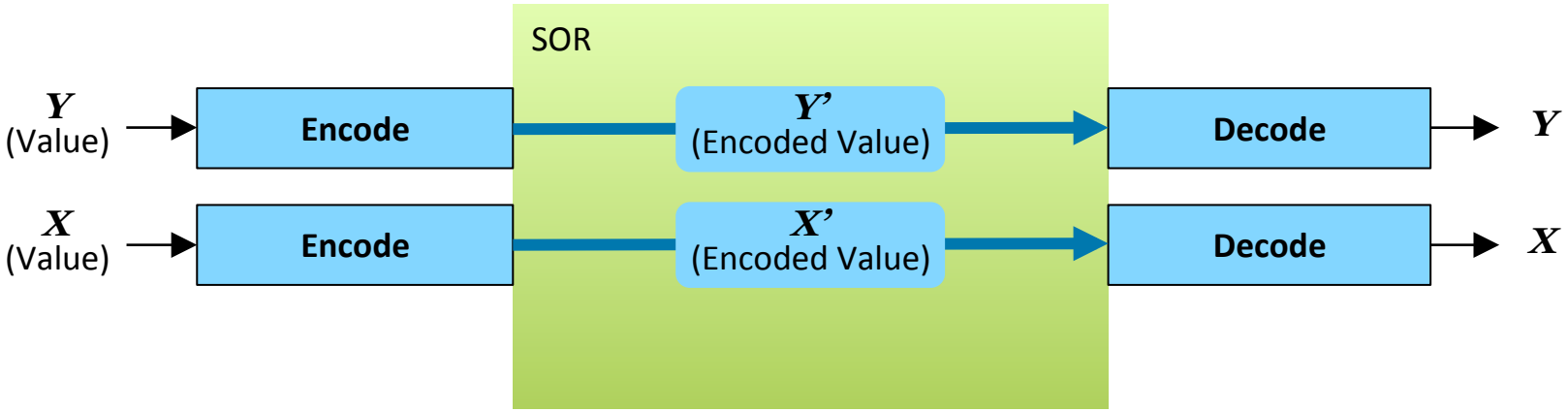
- **The Combined Redundancy Approach (CoRed)**

  TMR + { **Data-flow encoding**, **High-reliability voters** }

- **Holistic Protection Approach**
  - **Input to output protection**

    1 Reading inputs → **2** Processing → **3** Distributing outputs
  - **Composability** → On application and system level

Eliminating Input and Output Vulnerabilities



- Inter-domain data-flow protection
  - **Checksum** vs. **Arithmetic code** (AN code)
  - AN Code → **Encoded data operations**
  - **Enabler for high-reliability voter**

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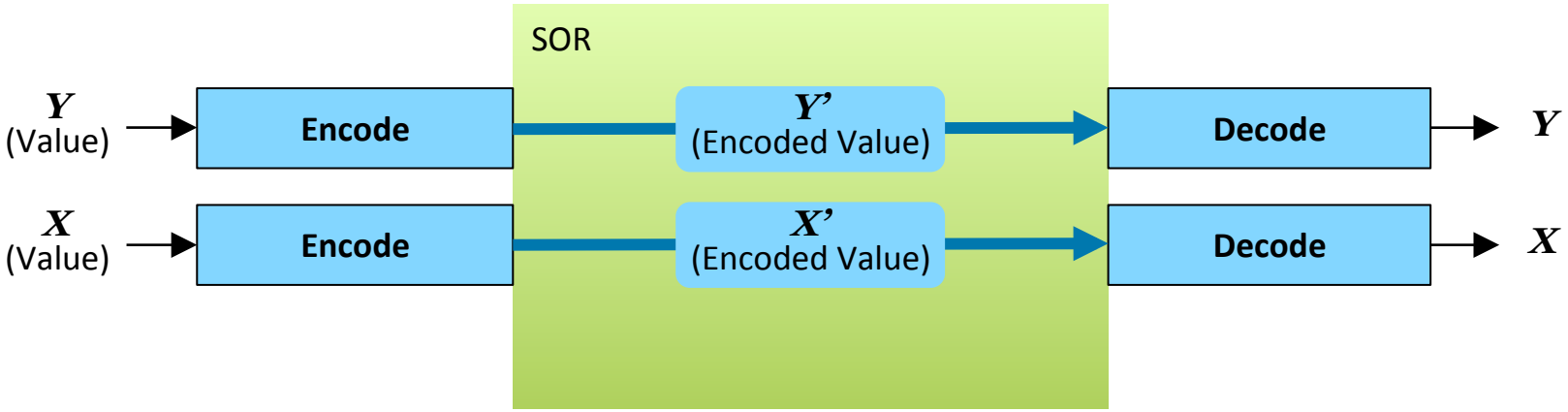

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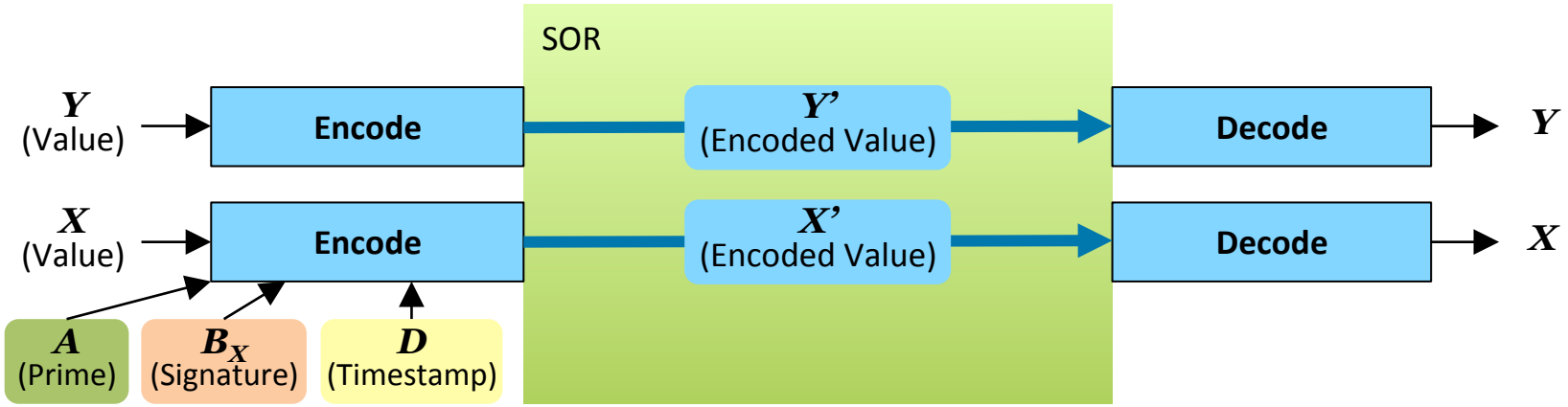

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  - **Outdated data:** Timestamp

$$X' = X \times A + B_X + D$$

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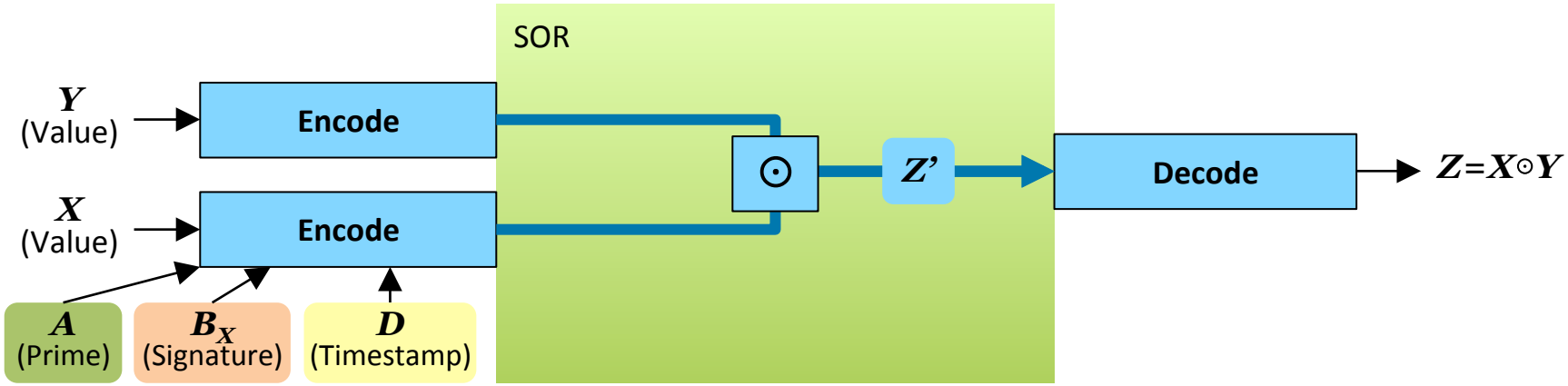

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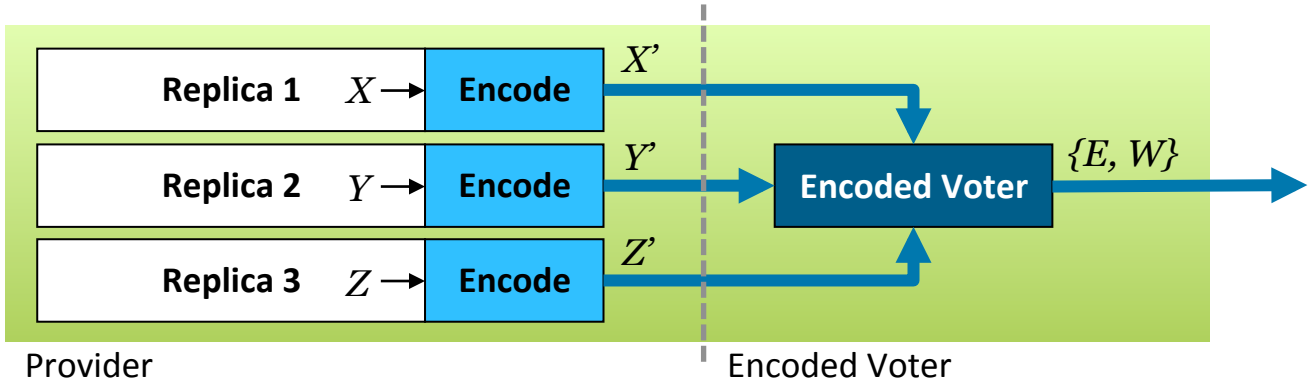
  - **Data integrity:** Prime
  - **Address integrity:** Per variable signature
  - **Outdated data:** Timestamp
  - Set of **arithmetic operands** (+, -, *, =, …)
  - Tailored for **efficient encoded data voting**

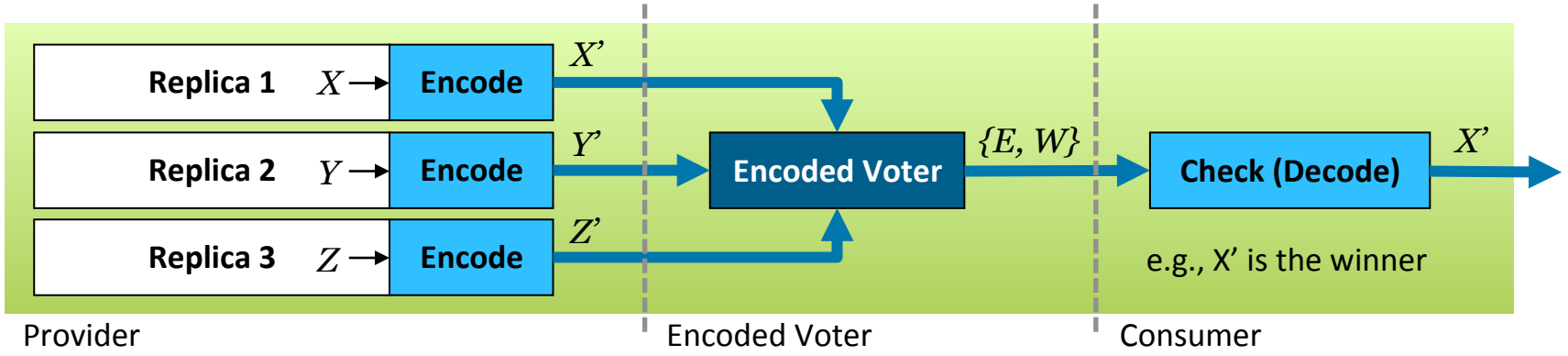
$$X' = X \times A + B_X + D$$

High-Reliability Voter – Basics (1)



- CoRed **Encoded Voter**
  - **Input**: variants (X', Y', Z')
  - **Output**: Equality set (E) and winner (W)
  - Based on EAN operations → **No decoding necessary**
- **Branch decisions (equality) on encoded data**
  - IFF difference of encoded values equals difference of static signatures
    $X = Y \Leftrightarrow X' - Y' = B_X - B_Y$
  - Each branch decision → **Unique signature**

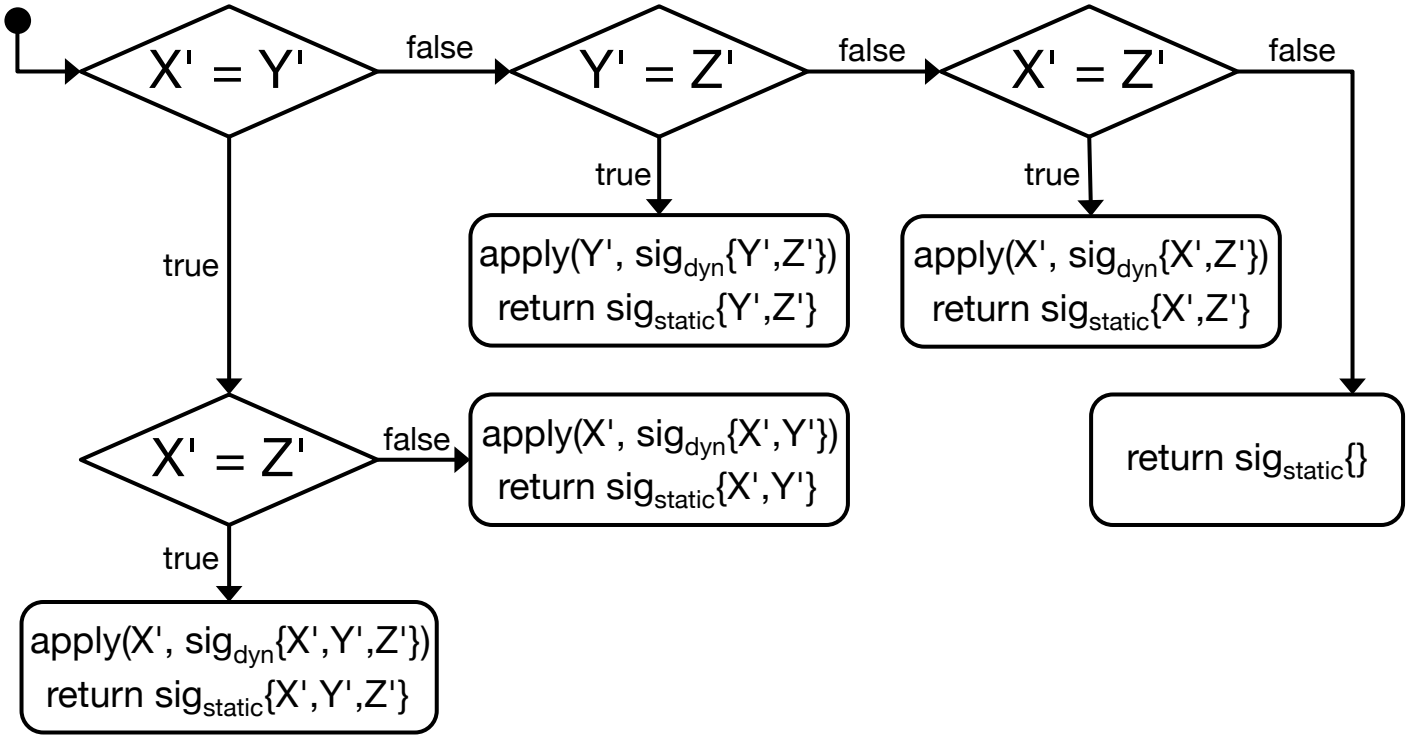
High-Reliability Voter – Basics (2)



- **Correct control-flow**
  - Valid decision → Unique control-flow path
  - Each path → **Unique signature**

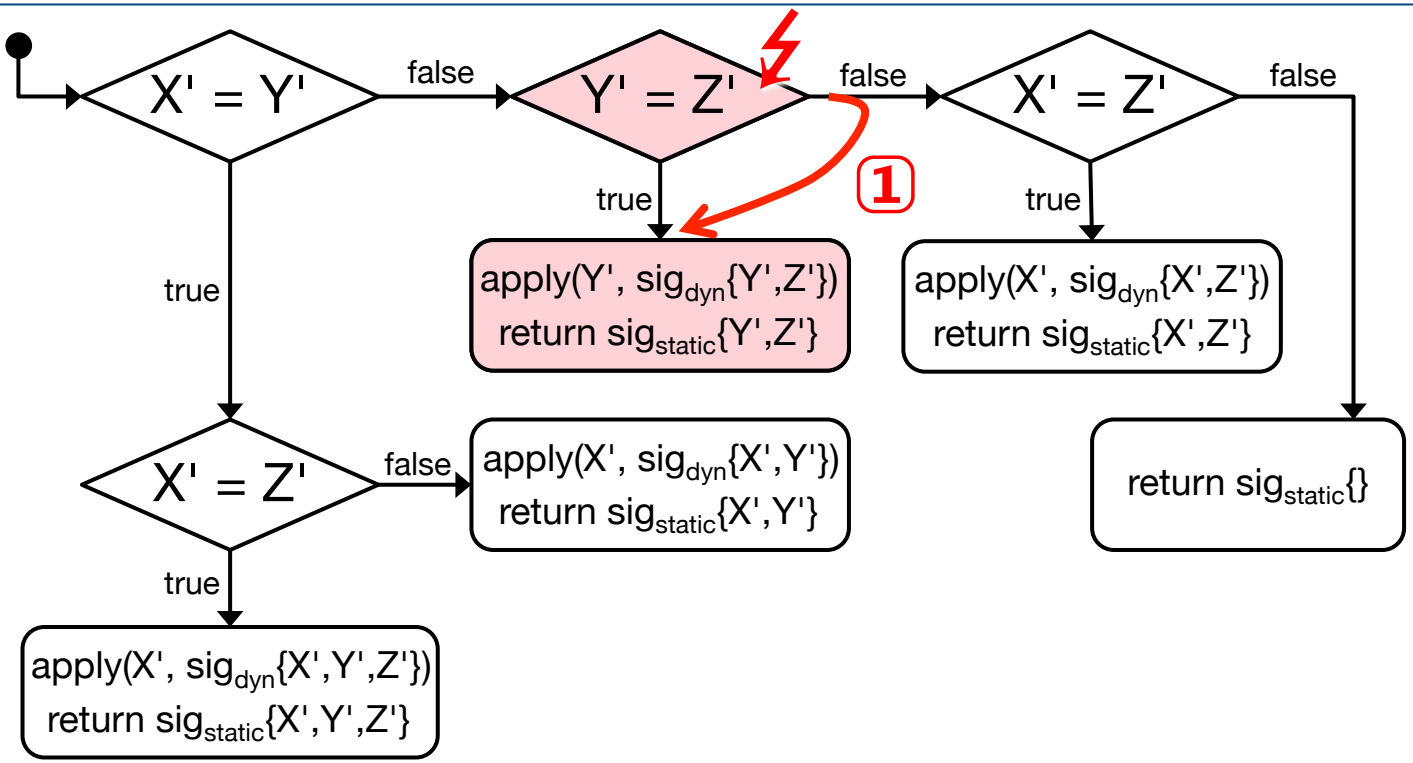
- **Control-flow signatures**
  - **Static signature** (expected value): Compile-time
    → Used as return value E
  - **Dynamic signature** (actual value): Runtime, computed from variants
    → Applied to winner W
  - **Validation**: Subsequent check (decode)

CoRed Encoded Voter – Example



- **Control-flow monitoring**
  - **Finding quorum** → Static signature
  - **Reapply path specific EAN operations** → Sign winner with dynamic signature
  - **Check** → Subsequent decode

CoRed Encoded Voter – Example



1. **Improper branch decision: *Y' ≠ Z'***
   - Voter elects Y' as winner (which is incorrect)
   - Returns E and W correctly
   - **Subsequent decode will fail!** → $sig_{static} \neq sig_{dyn}$

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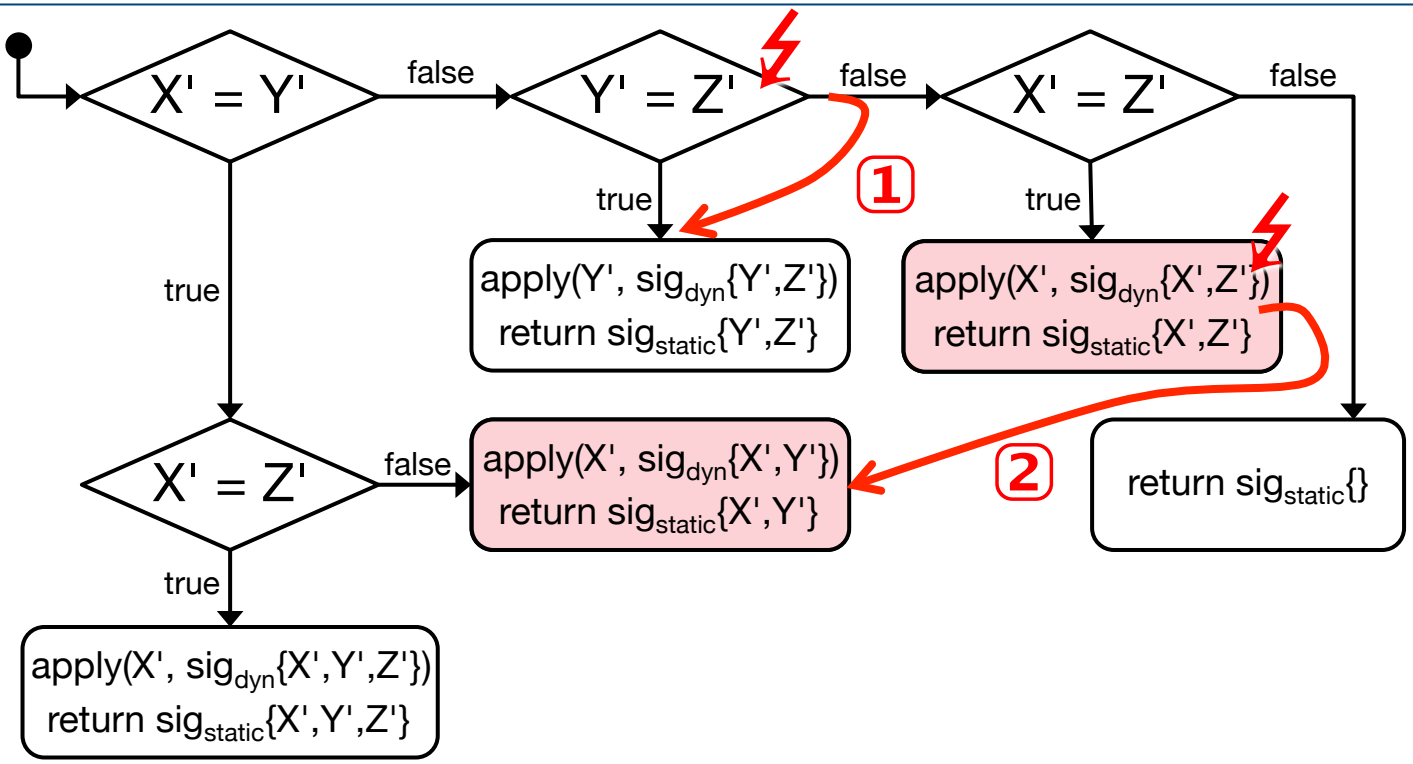

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   - Voter elects Y' as winner (which is incorrect)
   - Returns E and W correctly
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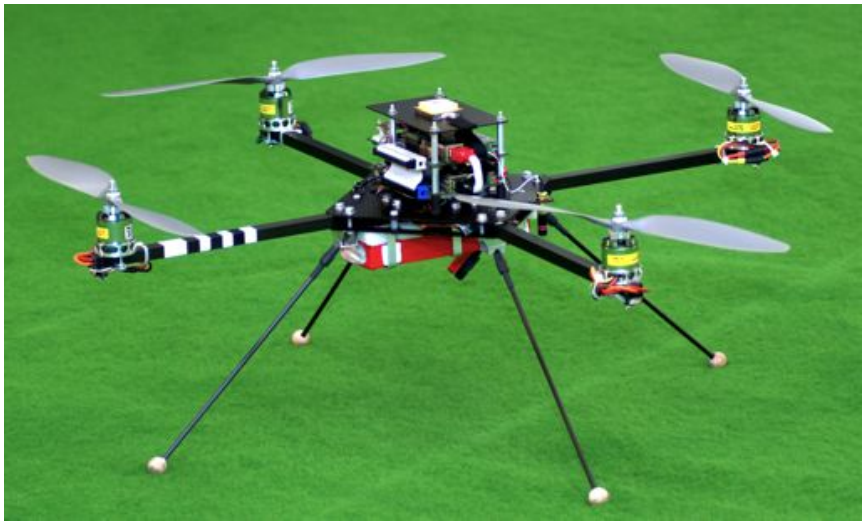
2. **Faulty jump**
   - Voter elects X' and computes W correctly
   - Returns incorrect E → Again **subsequent decode will fail!**

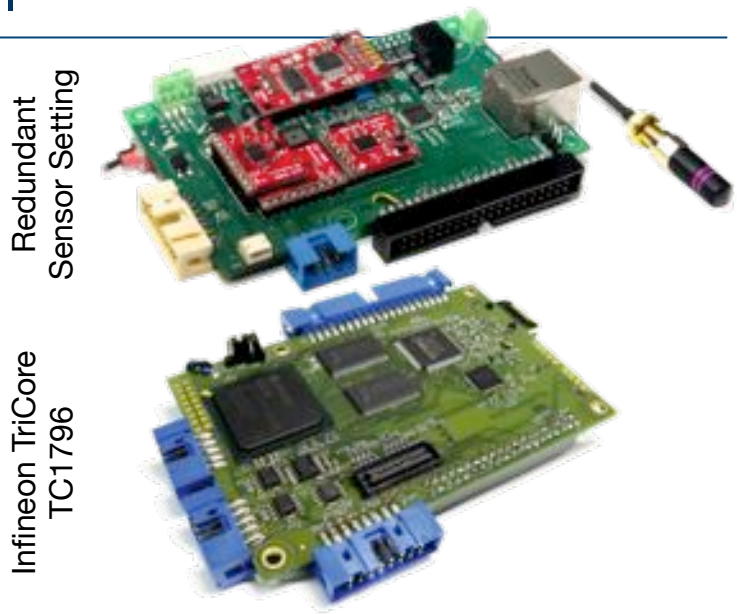
Implementation

- **CoRed implementation**
  - **Easy-to-use C++ templates and libraries**
  - **Hardware independent**: EAN Code and Encoded Voter
  - Thin **OS integration layer**
    - PXROS-HR (Industry-strength commercial RTOS)
    - CiAO (AUTOSAR-OS compatible)
  - CoRed artefacts → Real-time tasks and jobs

- **Runtime-environment requirements**
  - Temporal isolation → static schedule (time triggered)
  - Spatial isolation → HW-based memory protection

CoRed Protected Flight Control

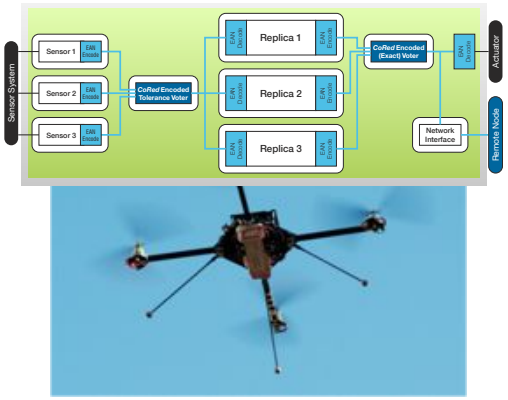




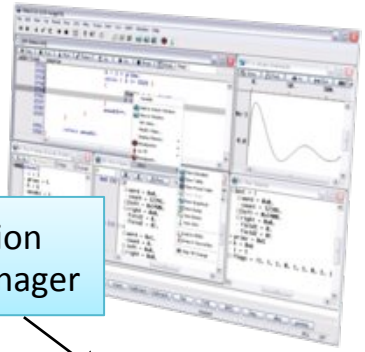
- **Target System:** I4*Copter* quadrotor platform
  - Industry-grade hardware and software
  - Triple **redundant sensor setting**
  - Multi-application system
- **Flight control application**
  - Safety-critical
  - Model-based: MATLAB Simulink
  - Embedded Coder → C++ code

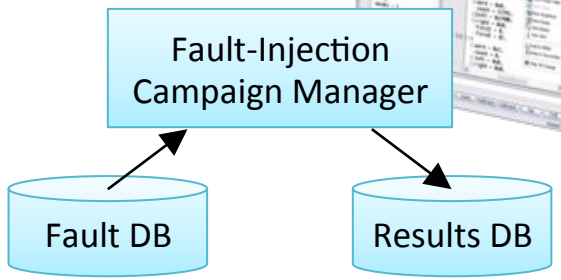
Evaluation – Experimental Setup

Flight-Control Application



[Rebaudengo, 1999]

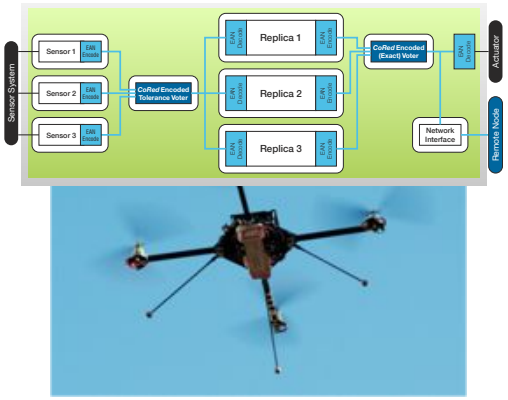




- **Fault injection → Using hardware debugger**
  - Injection of arbitrary fault patterns
  - **Minimal-intrusive** → Minimizing probe effects
- **Fault list generation** (Rebaudengo, 1999)
  - Bits × registers × instructions → Potentially **huge fault space**
  - Vast majority of faults are non-effective → Systematic elimination

Evaluation – Experimental Setup

Flight-Control Application



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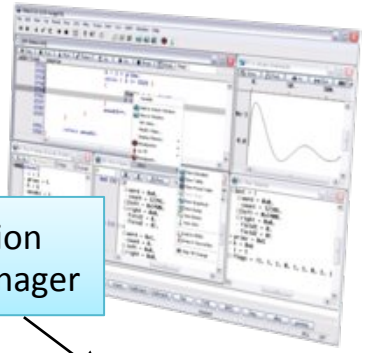

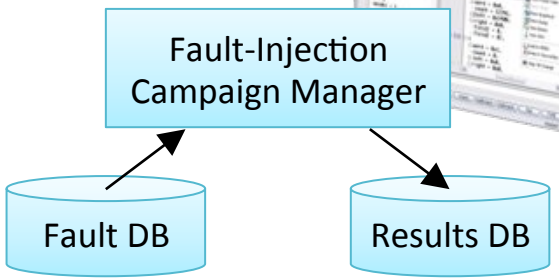

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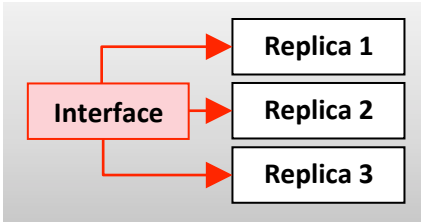
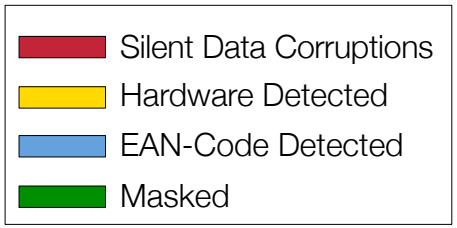
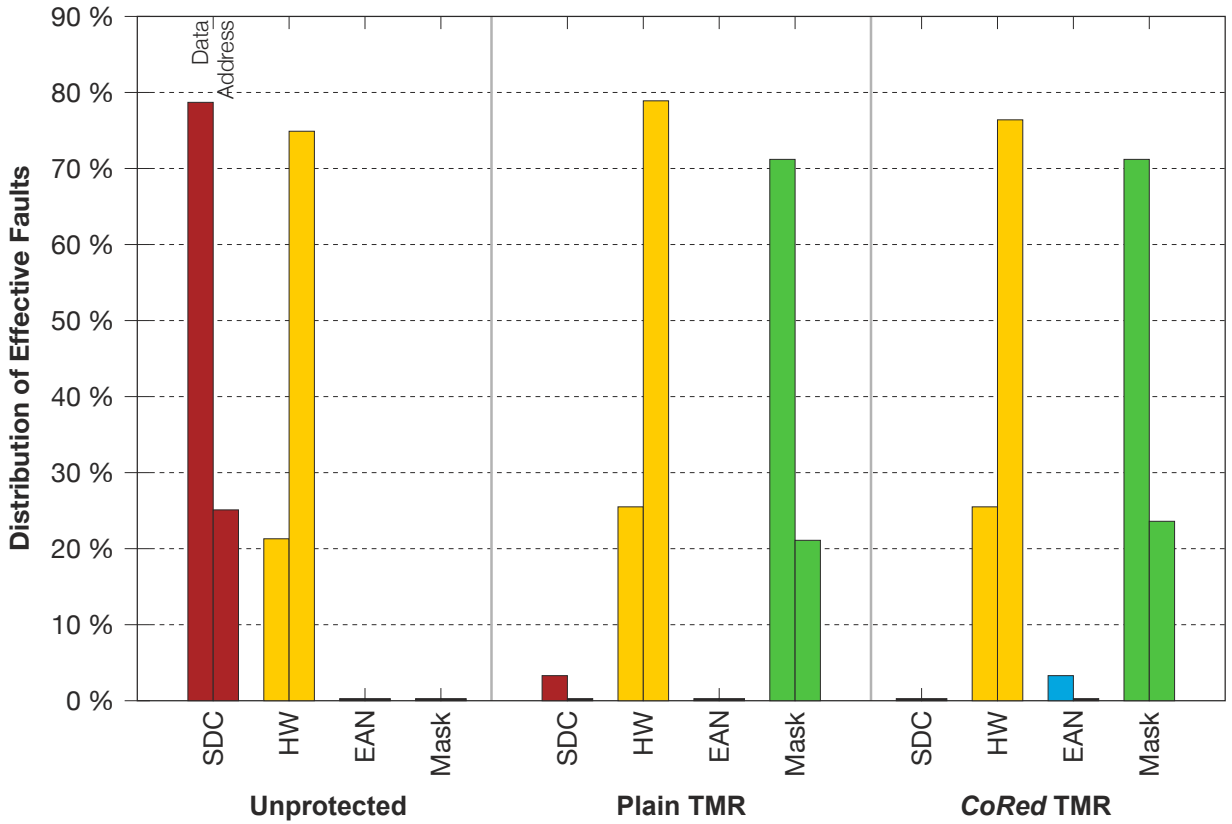
Outcome: **401,592** experiments
Effective: **67,617** errors

Categories: Fail Silent, Masked, Hardware Detected, EAN-Code, Control-Flow, Silent Data Corruption

Evaluation – Experimental Results (1)







- **Redundant execution campaign (Interface)**
  - Total: ~45,000 Errors

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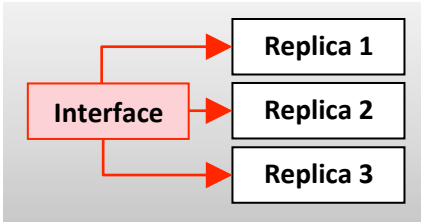

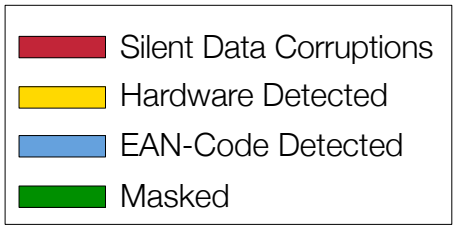

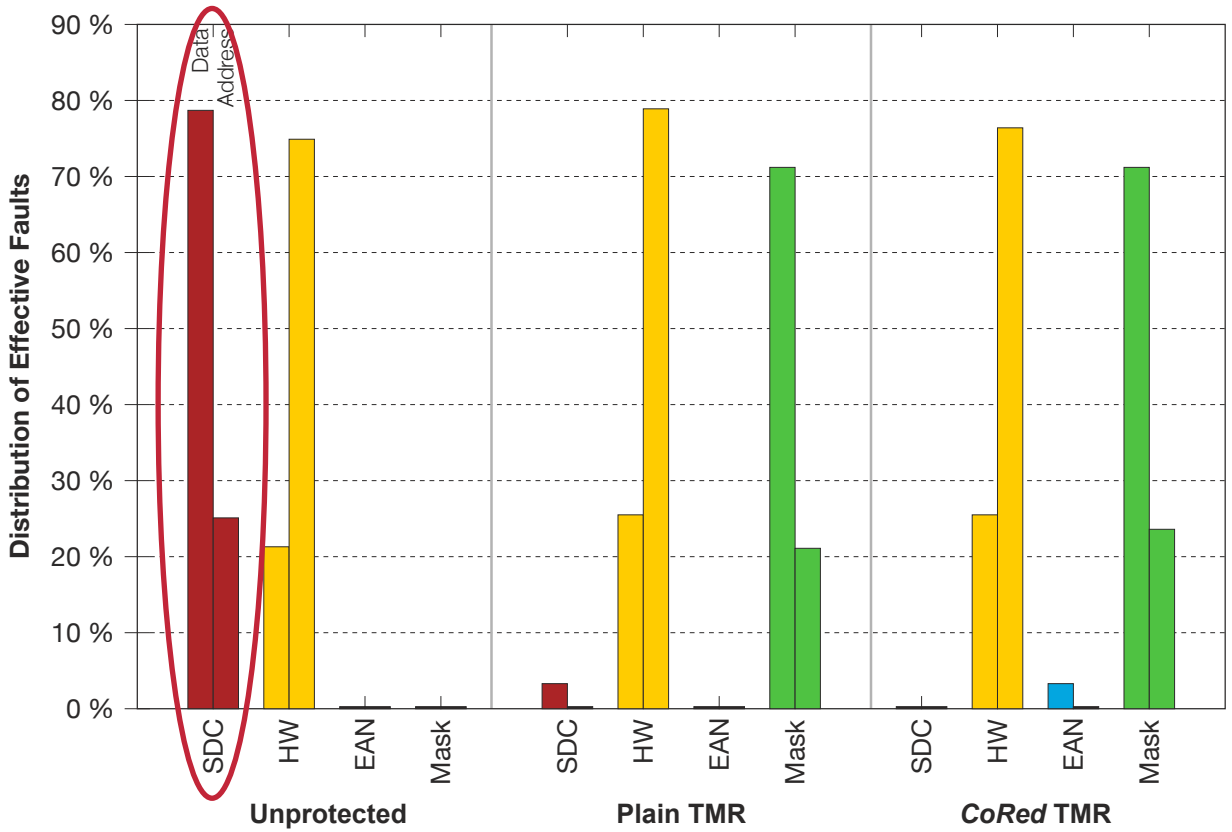

- **Redundant execution campaign (Interface)**
  - Total: ~45,000 Errors
  - **Unprotected**: Suffers from **3,622 corruptions**!

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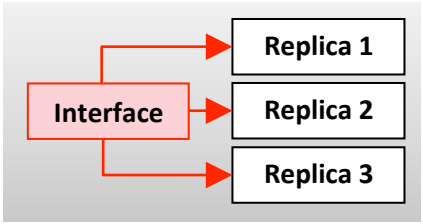

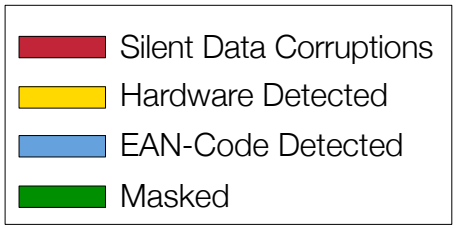

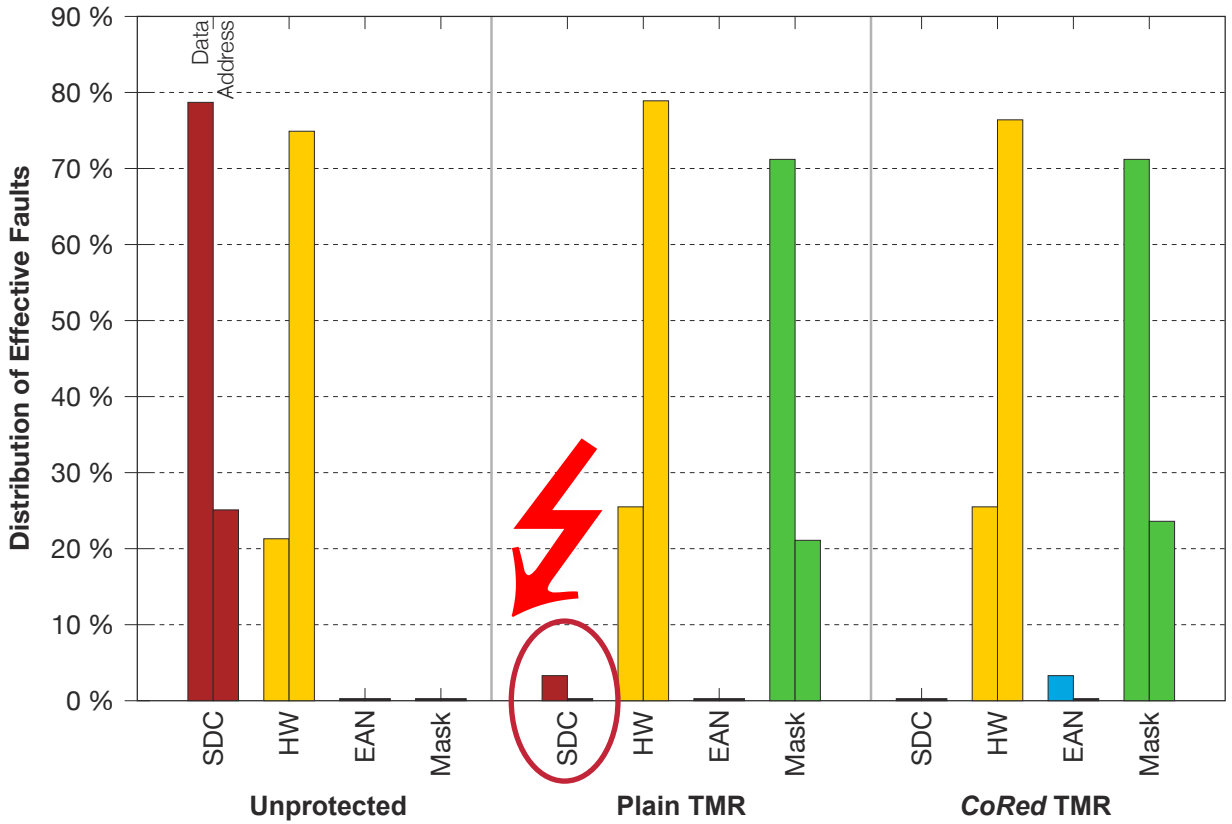

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  - **TMR**: Suffers from **71 corruptions**!

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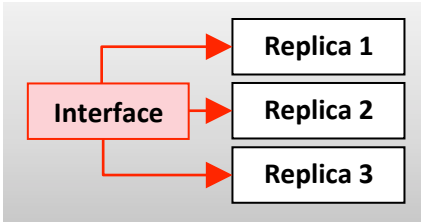

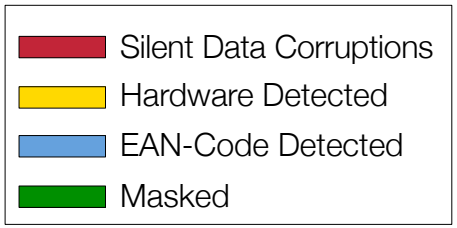

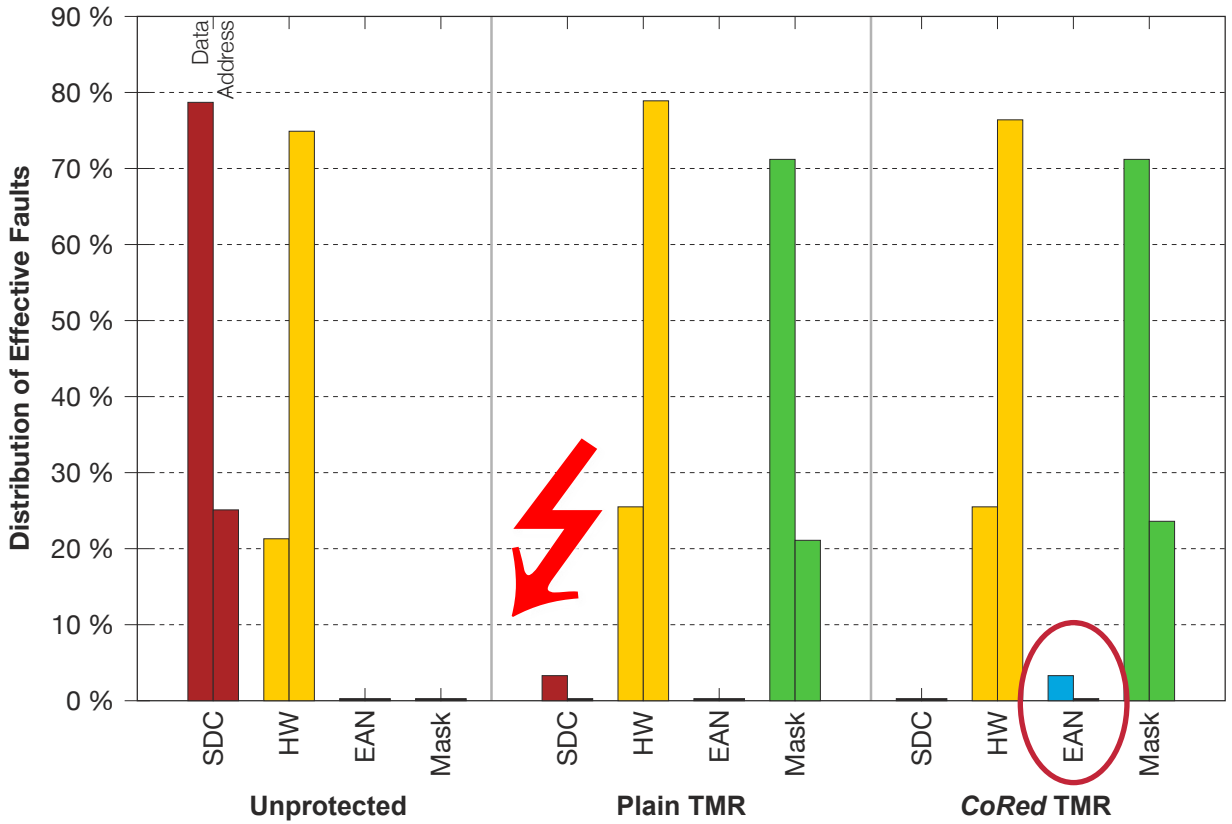

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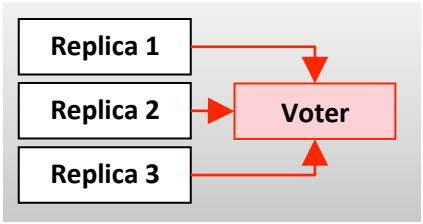
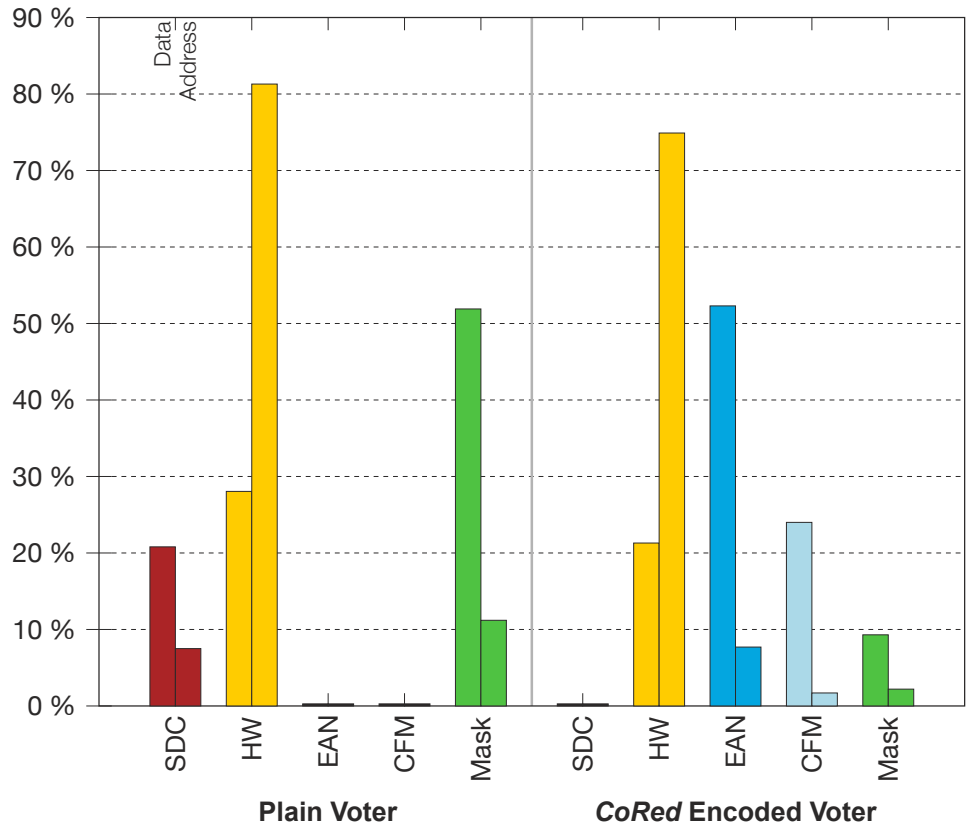
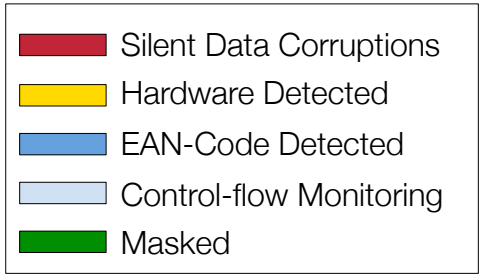
  - **CoRed**: Remaining corruptions are covered → **0 corruptions**

Evaluation – Experimental Results (2)

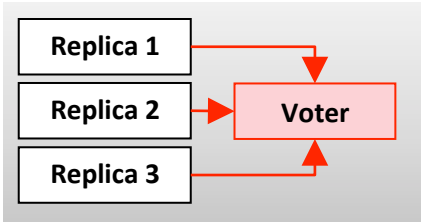


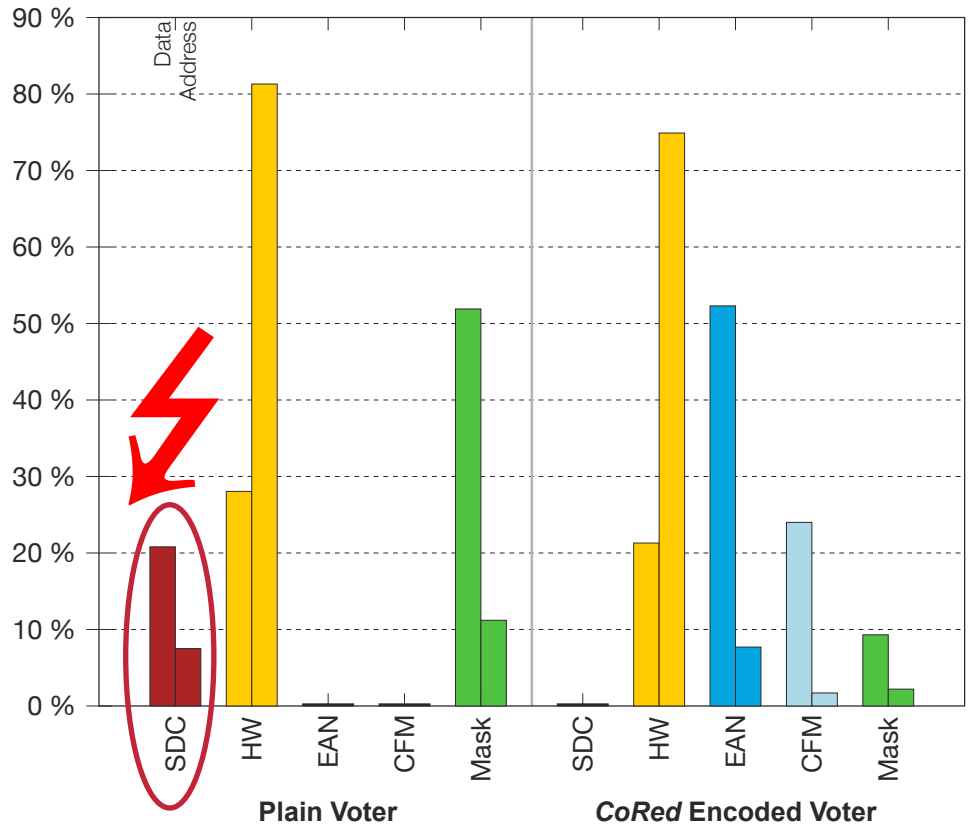


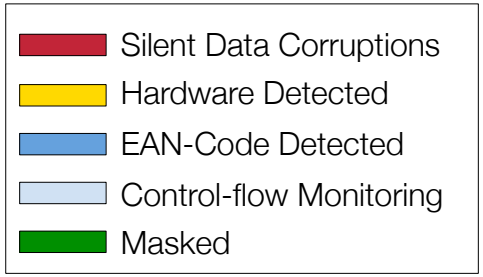


- **Voter campaign**

Evaluation – Experimental Results (2)



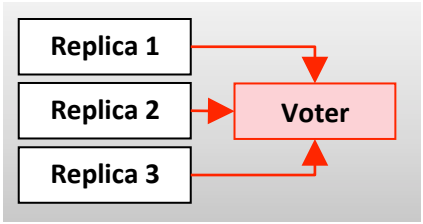


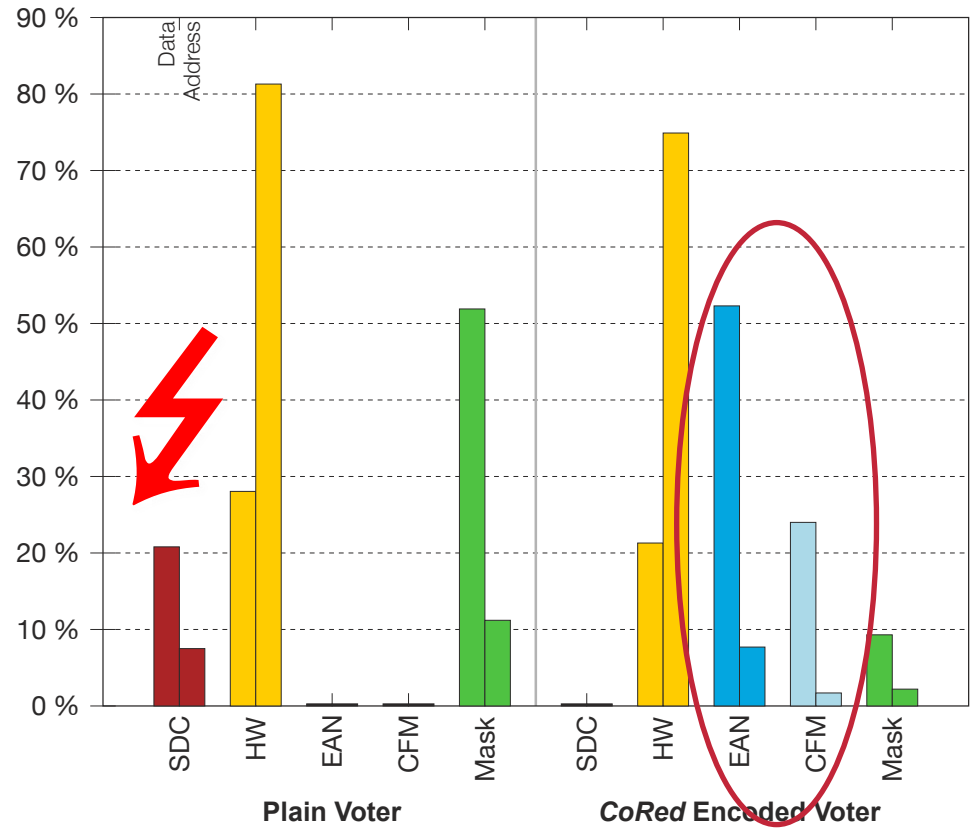


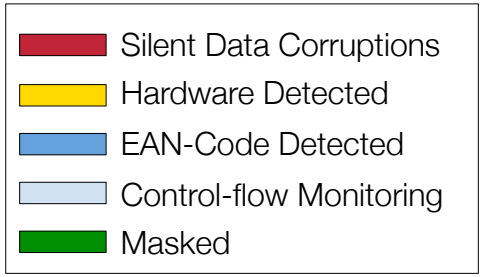
- **Voter campaign**
  - **Plain voter**:

    Total ~11,000 2,465 masked 7,245 retry **1,223 corruptions**

Evaluation – Experimental Results (2)

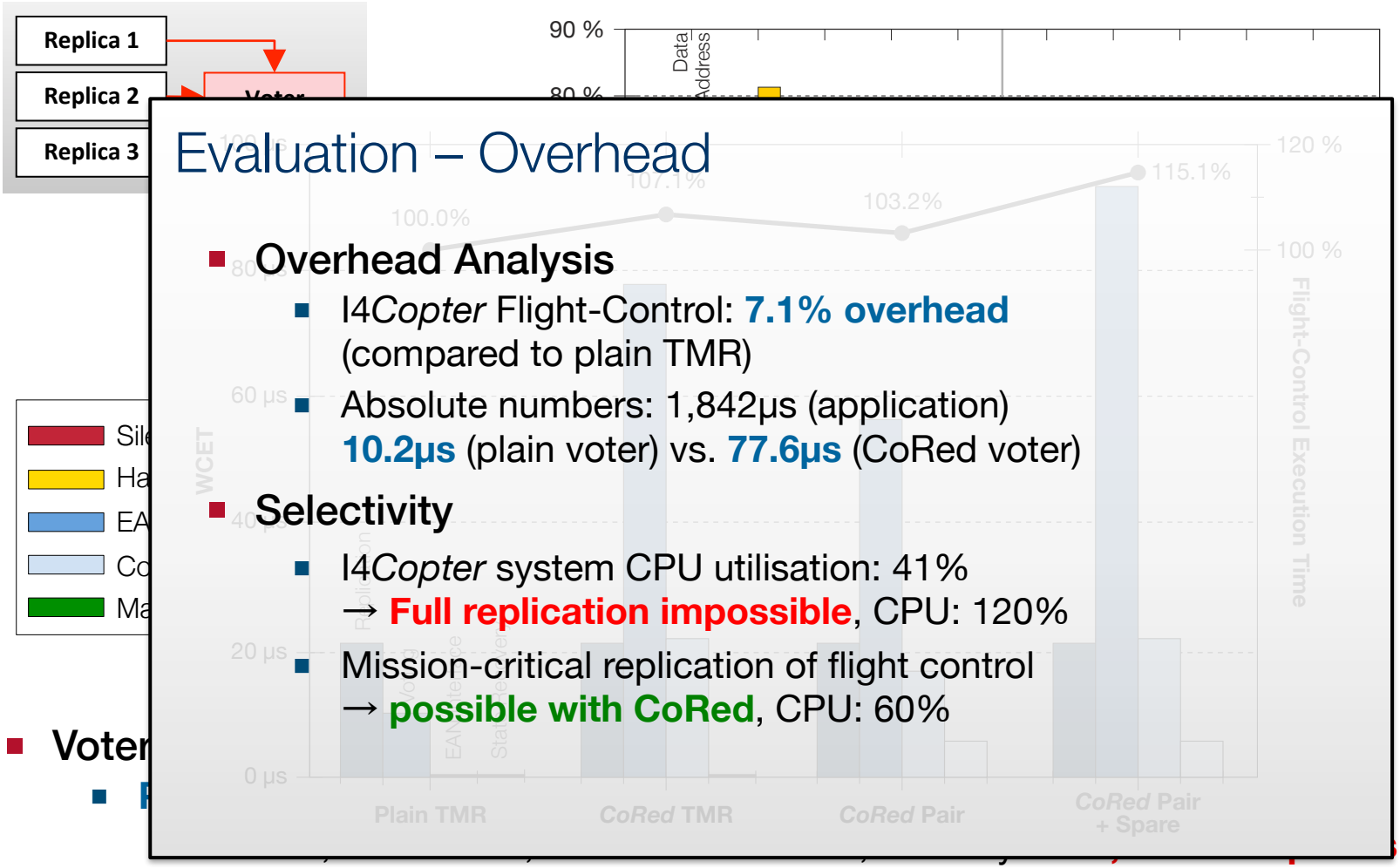






- **Voter campaign**
  - **Plain voter**:
    Total ~11,000 2,465 masked 7,245 retry **1,223 corruptions**
  - **CoRed Encoded Voter**:
    Total ~26,000 1,228 masked 24,682 retry **0 corruptions**

Evaluation – Experimental Results (2)

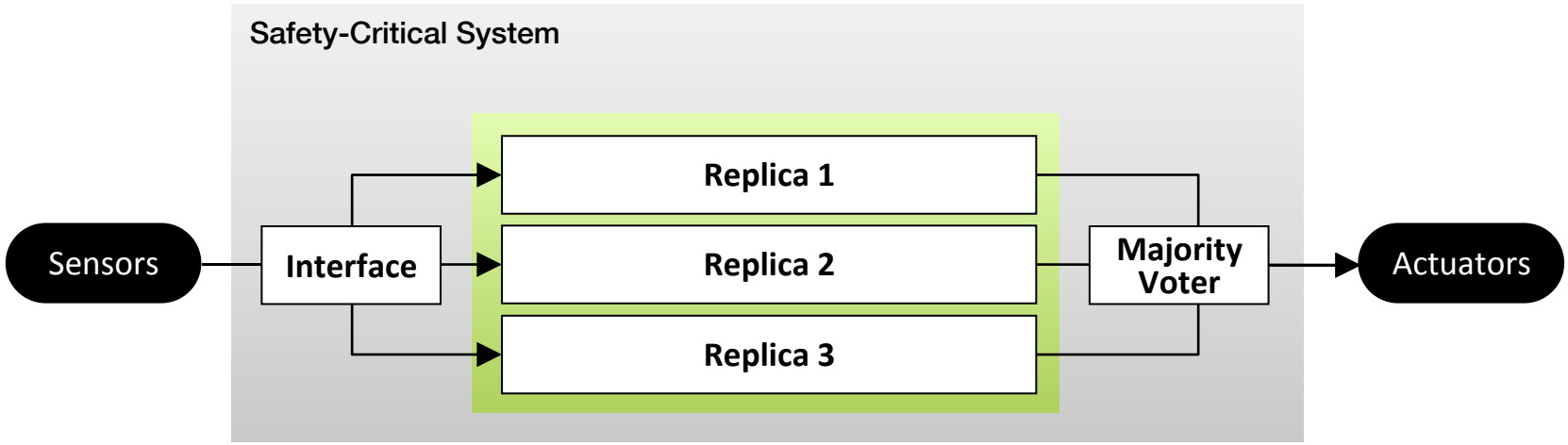


Evaluation – Overhead

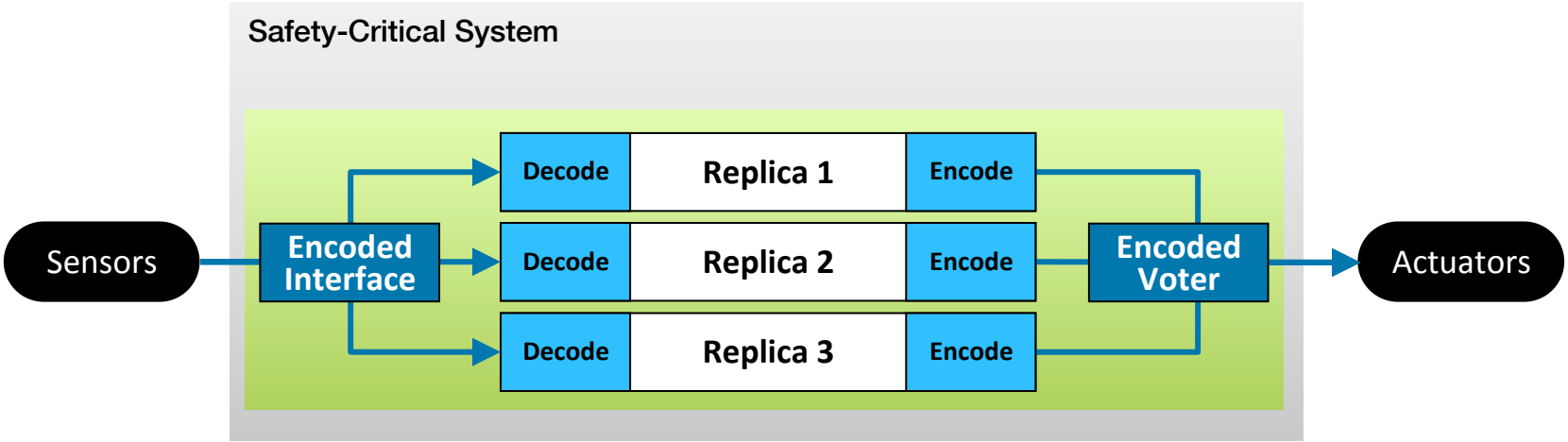
- **Overhead Analysis**
  - I4*Copter* Flight-Control: **7.1% overhead** (compared to plain TMR)
  - Absolute numbers: 1,842µs (application) **10.2µs** (plain voter) vs. **77.6µs** (CoRed voter)
- **Selectivity**
  - I4*Copter* system CPU utilisation: 41% → **Full replication impossible**, CPU: 120%
  - Mission-critical replication of flight control → **possible with CoRed**, CPU: 60%

- **Voter**
  - **CoRed Voter**:
    Total ~26,000 1,228 masked 24,682 retry **0 corruptions**

Conclusion

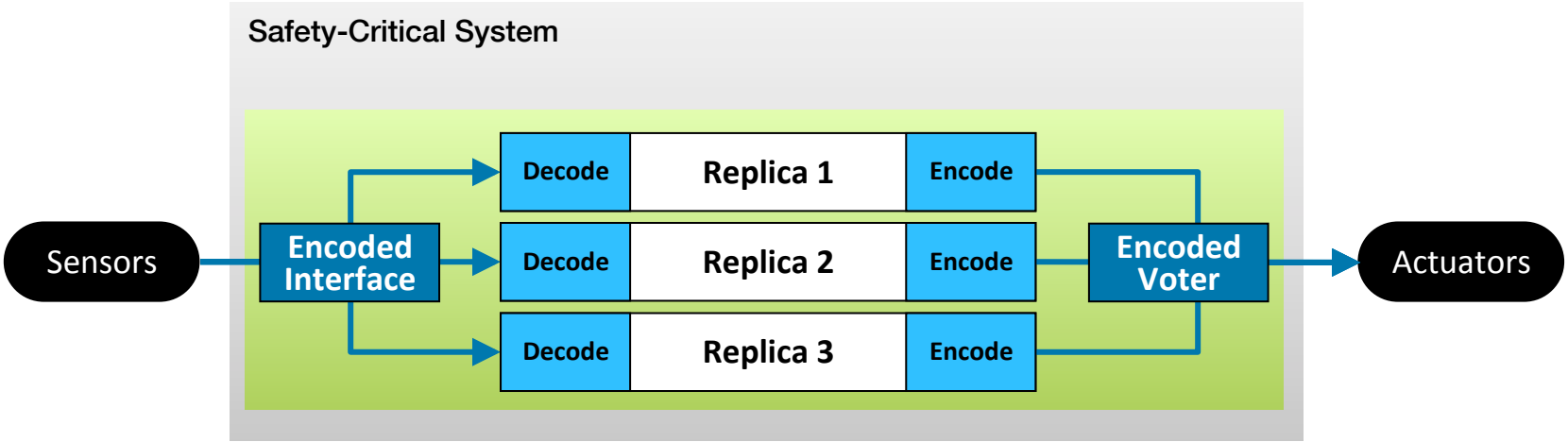

Safety-Critical System
Sensors
Interface
Replica 1
Replica 2
Replica 3
Majority Voter
Actuators

Conclusion



- The Combined Software Redundancy Approach (CoRed)
  - **Eliminate Single Points of Failure** in software-based TMR
  - No specific application knowledge necessary
  - Holistic approach: **input-to-output protection**

Conclusion



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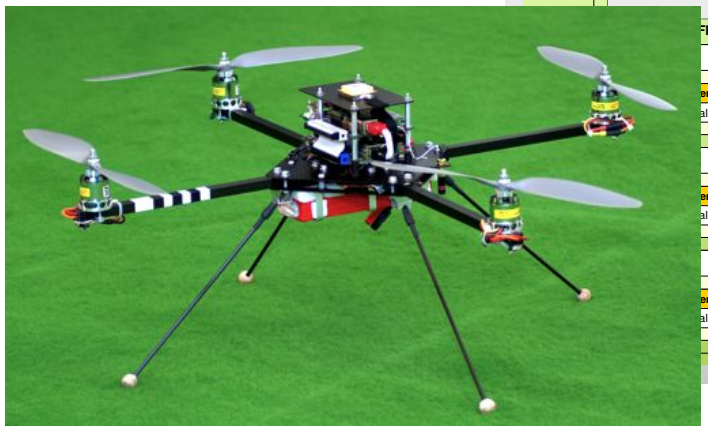

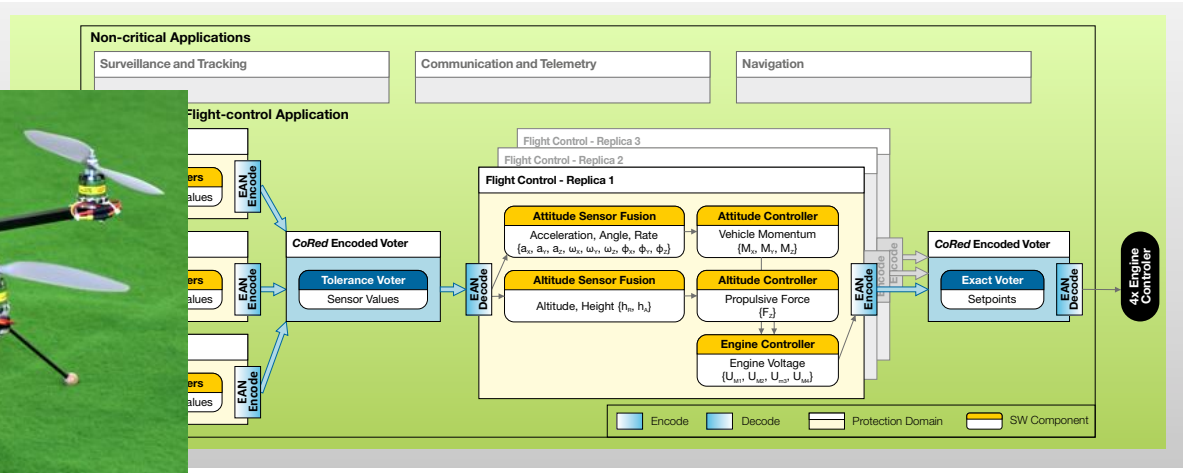

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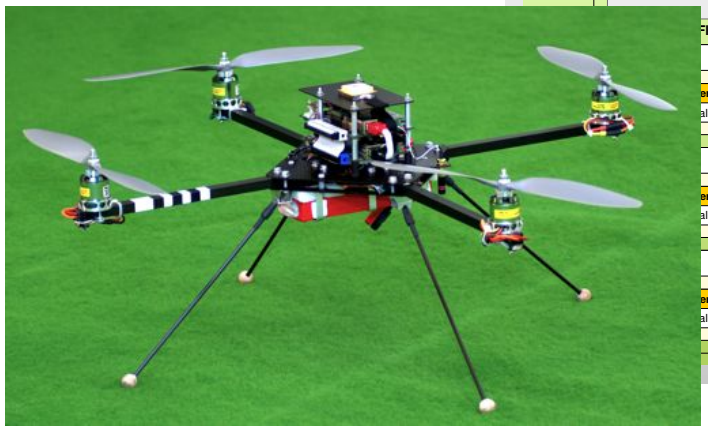
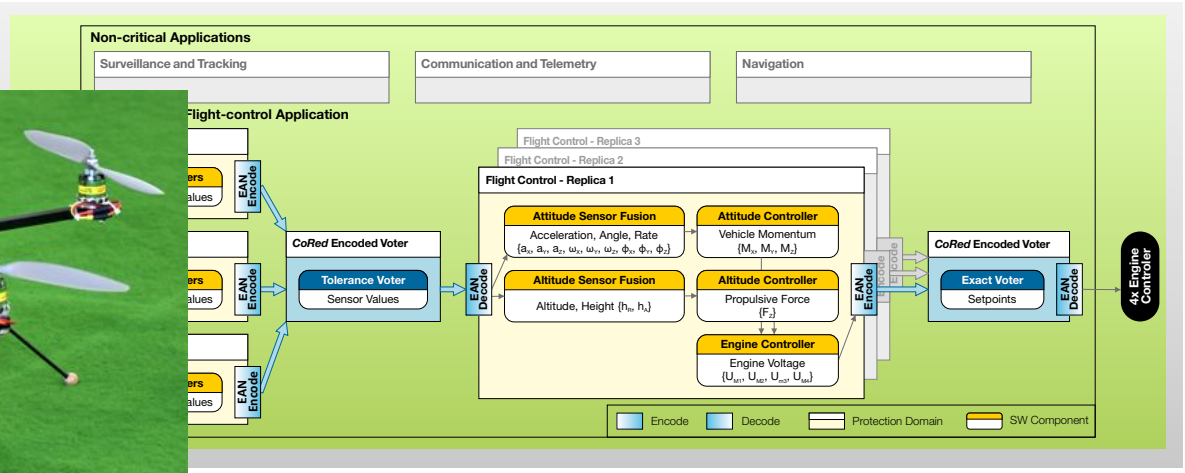
- Applicability: Flight control
  - I4*Copter* MAV
  - **Selective** and **composable**

Conclusion





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  - No specific application knowledge necessary
  - Holistic approach: **input-to-output protection**
- Applicability: Flight control
  - I4*Copter* MAV
  - **Selective** and **composable**
- Experimental Results
  - **CoRed is effective** → Silent data corruptions can be eliminated
  - Only **7.1% overhead** (flight control example)

Thank you!

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ERLANGEN-NÜRNBERG

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