Software-based Fault Tolerance – Mission (Im)possible?

Peter Ulbrich

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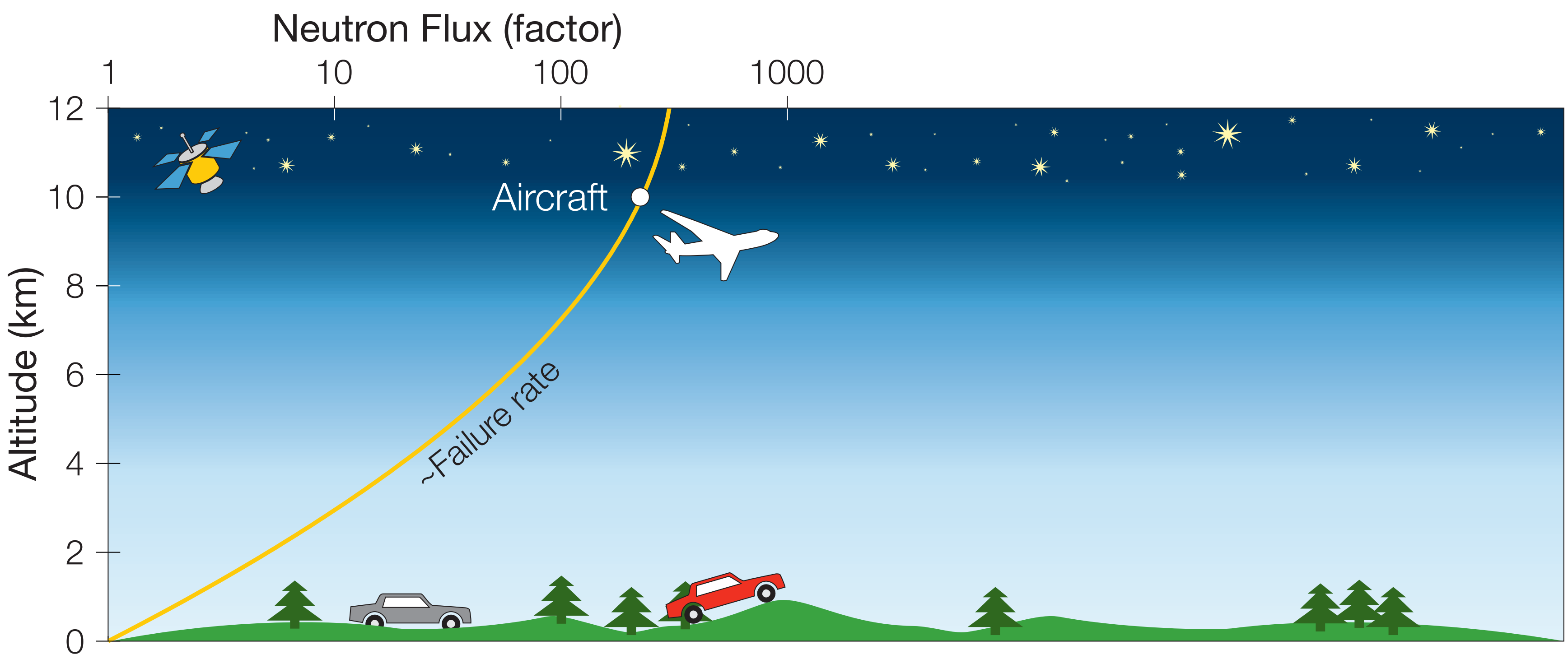
FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

System Software Group

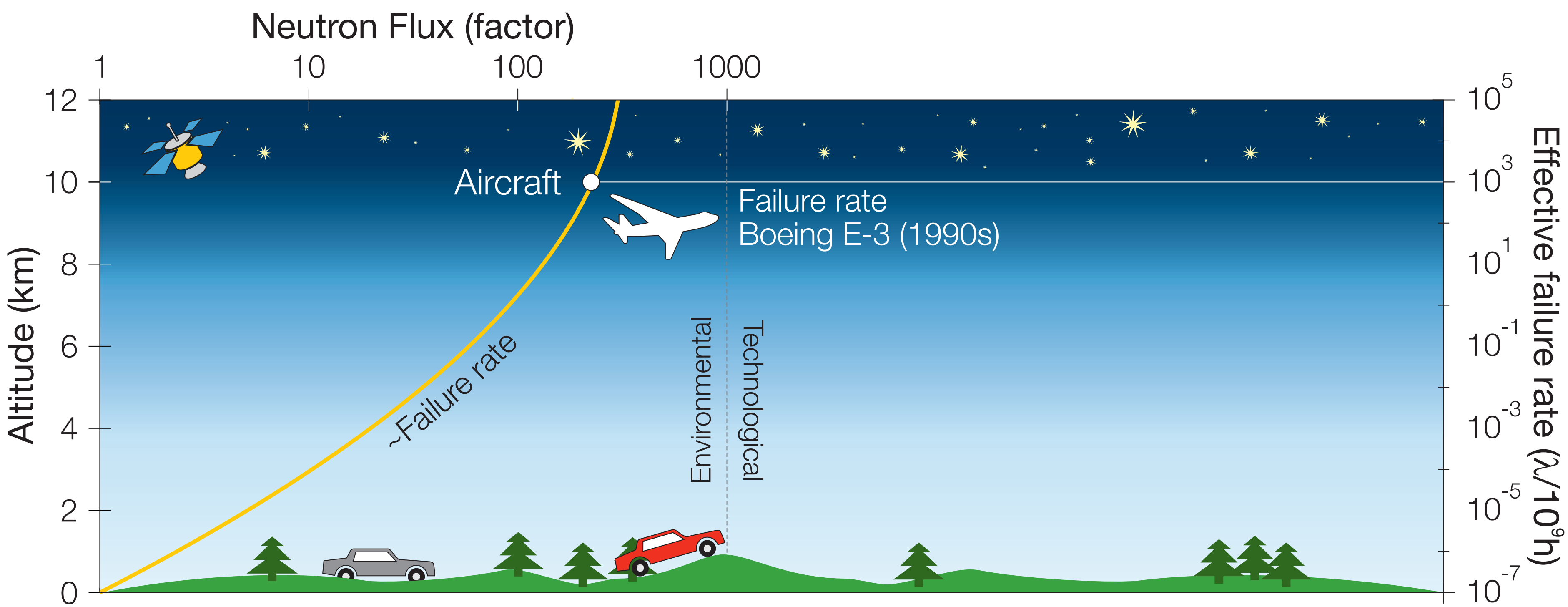
Embedded Systems Initiative

Soft Errors – A Growing Problem



- **Soft-Errors (Transient hardware faults)**
  - Induced by e.g., radiation, glitches, insufficient signal integrity
  - Affecting microcontroller logic

Soft Errors – A Growing Problem



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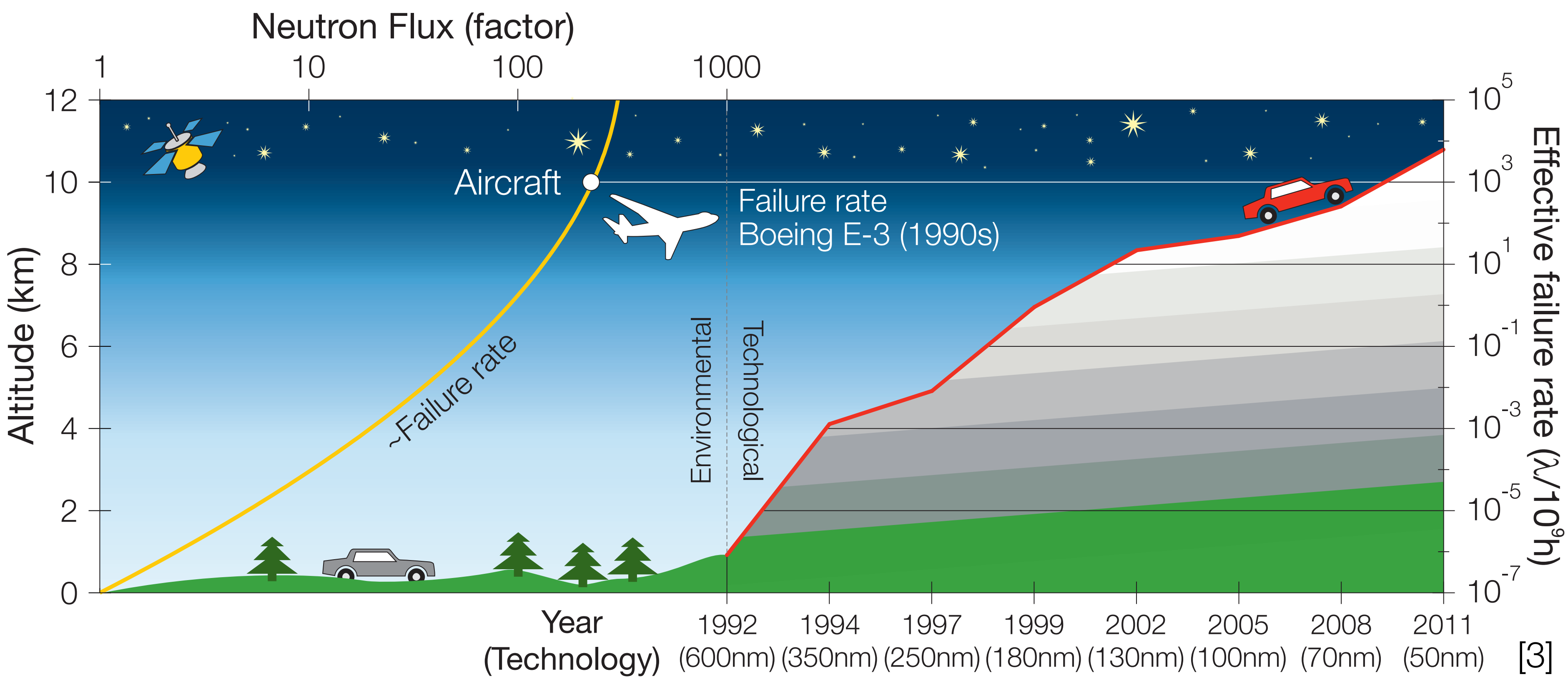

[3]

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  - Induced by e.g., radiation, glitches, insufficient signal integrity
  - Affecting microcontroller logic
- **Future hardware designs: more performance and parallelism**
  → On the price of being less and less reliable

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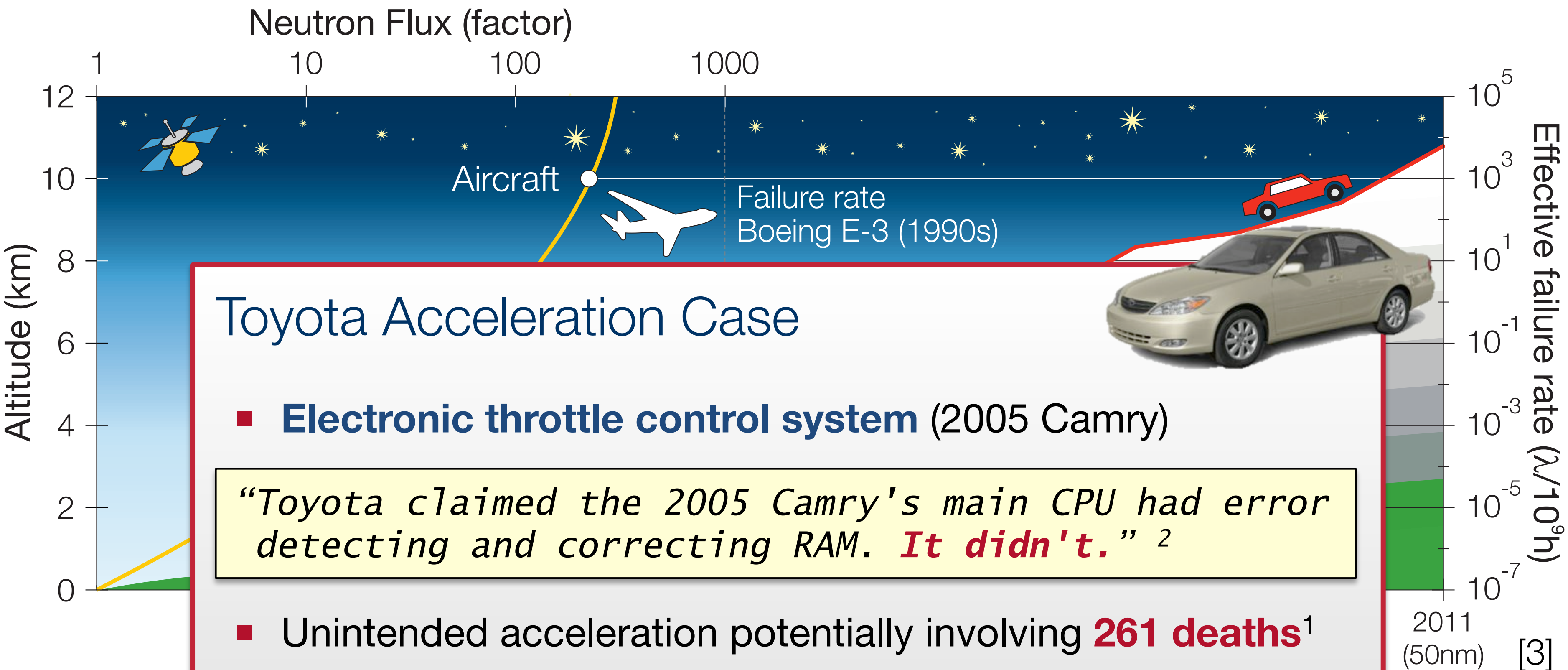


Toyota Acceleration Case

- **Electronic throttle control system** (2005 Camry)

> *"Toyota claimed the 2005 Camry's main CPU had error detecting and correcting RAM. **It didn't.**"* [2]

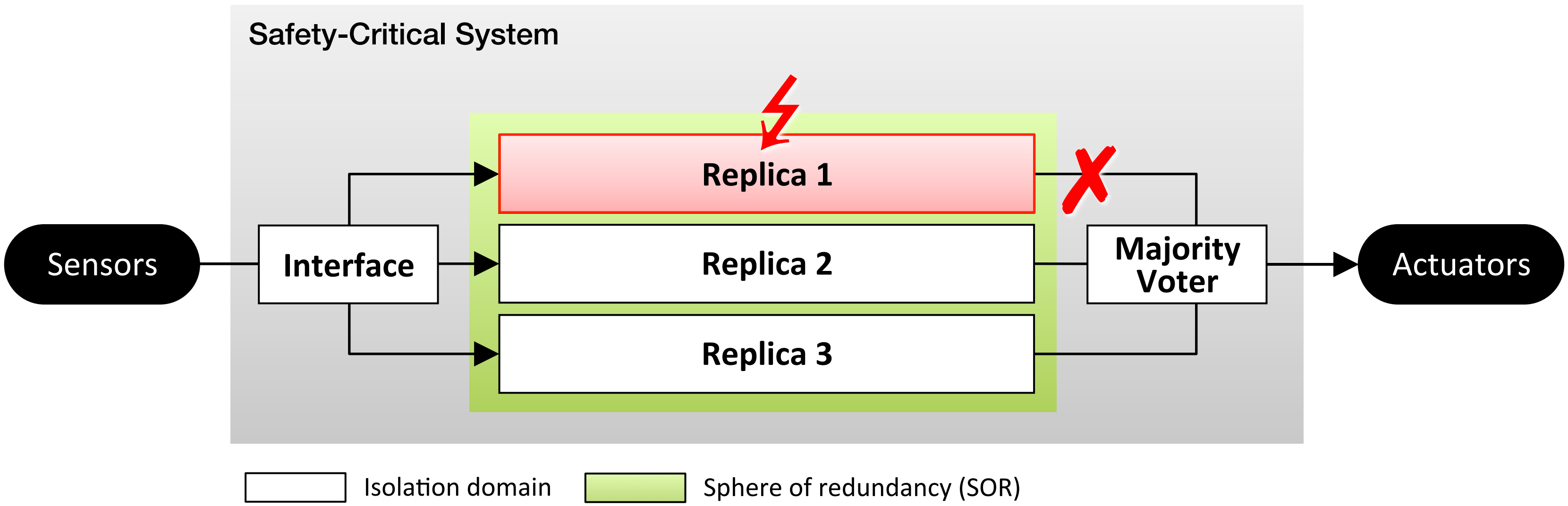
- Unintended acceleration potentially involving **261 deaths**[1]
- Experts identified **soft errors** as possible cause[1]

[1] US News, Mar 17, 2010 [2] Investigation Report, EDN Network, Oct 28, 2013

- So
  - Affecting microcontroller logic

- **Future hardware designs: more performance and parallelism**
  → **On the price of being less and less reliable**

Software-Based Fault Tolerance



- **Software-based redundancy**
  - Triple Modular Redundancy (e.g., recommended by ISO 26262)
  - ✓ Selective and adaptive
  - ✓ Resource efficient

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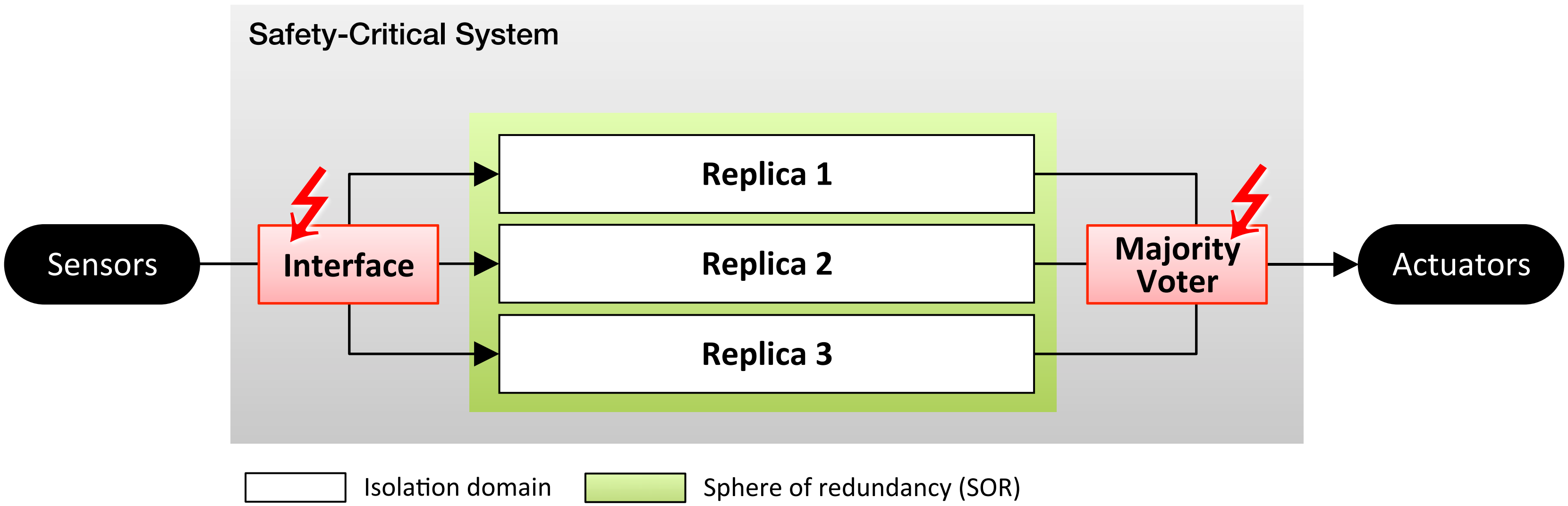
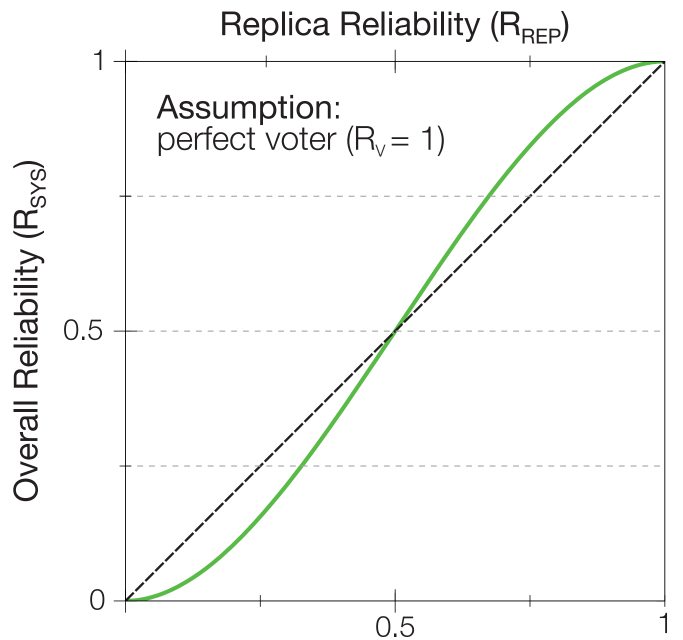


- **Software-based redundancy**
  - Triple Modular Redundancy (e.g., recommended by ISO 26262)
  - ✓ Selective and adaptive
  - ✓ Resource efficient
- **Single points of failure**
  - Interface and Majority Voter
  - Allowing for Silent Data Corruptions (SDC)
  - → Replication is impossible!

Threats to Applicability – Mission failed?



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$$R_{TMR} = R_{Voter} \cdot R_{2-of-3}$$

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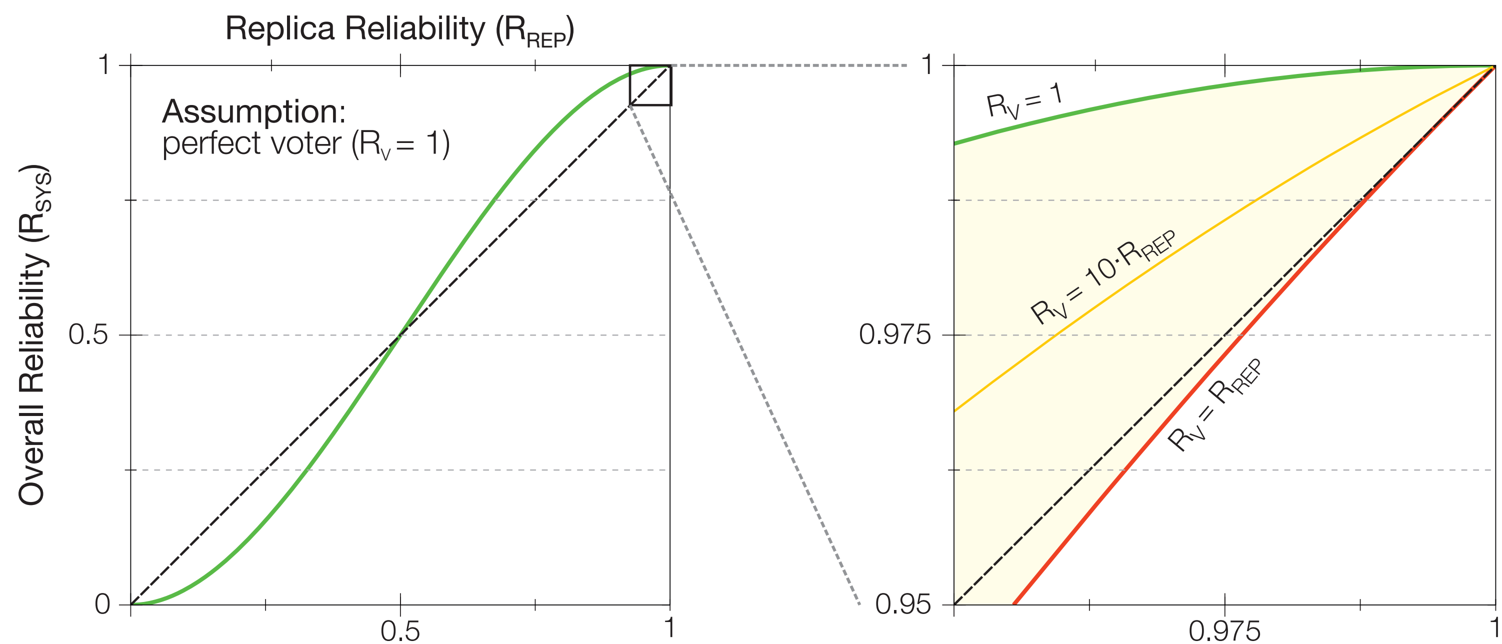

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- **Voting on unreliable hardware?**
  - Very small → residual error probability?
  - Risk analysis → inherently complex (no random error distribution! [4])

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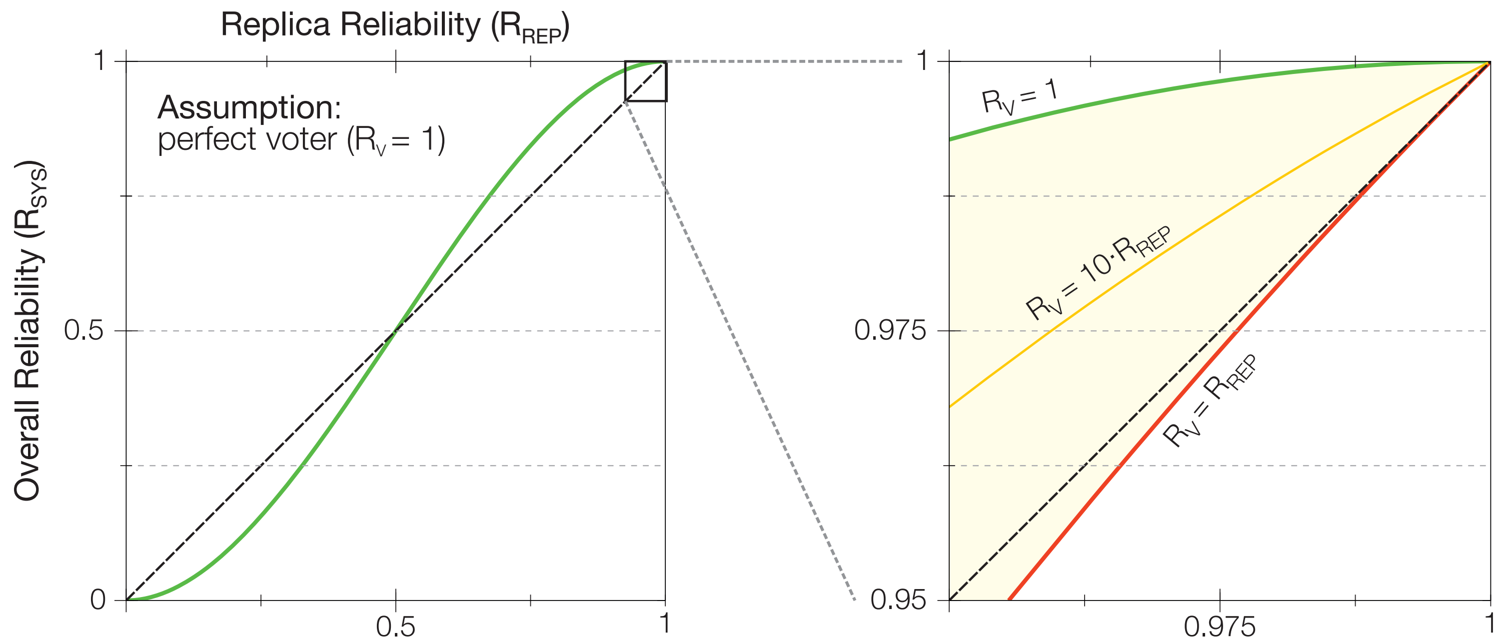

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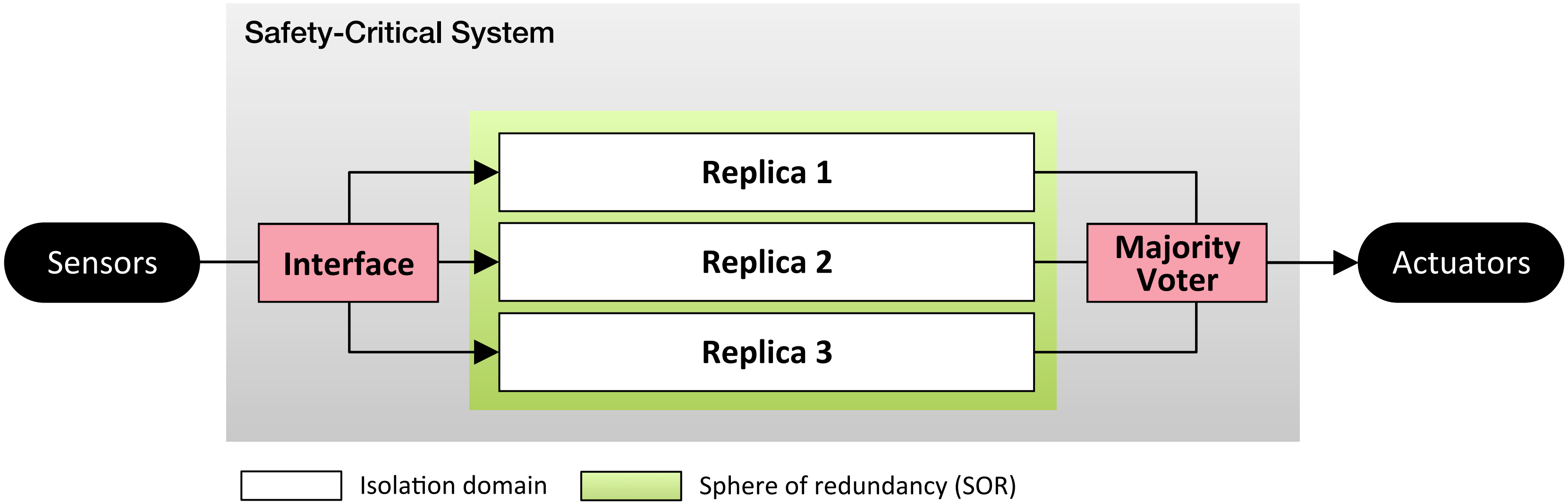
→ Dealbreaker for software-based TMR

Research Aims



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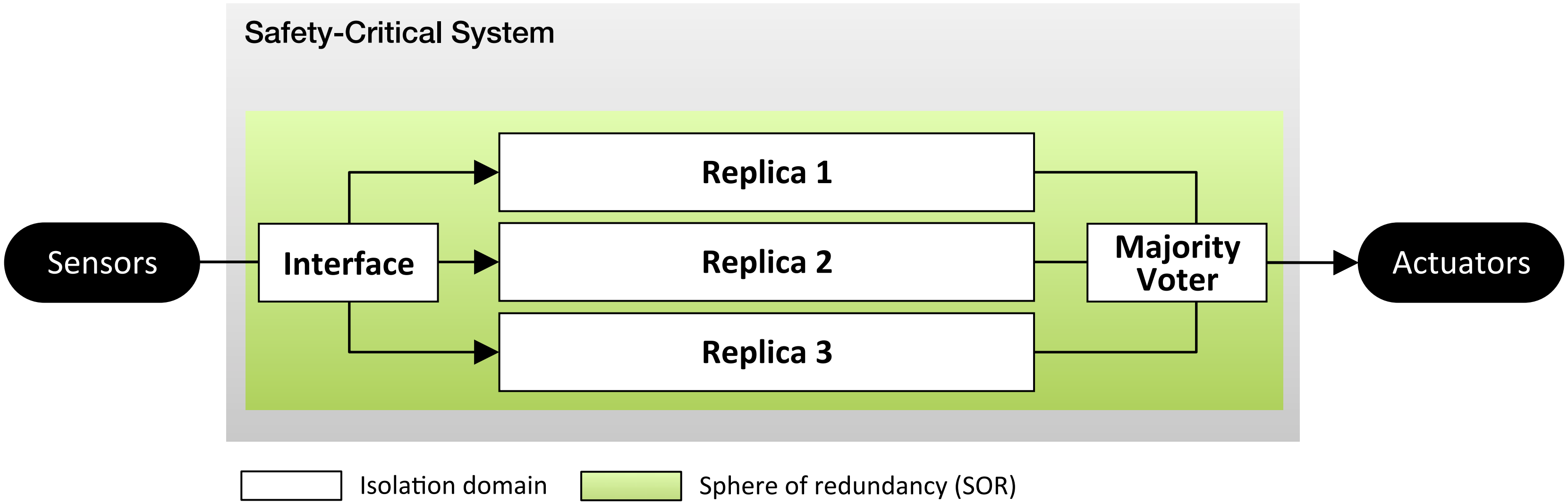

- Eliminate single points of failure
  -
  -

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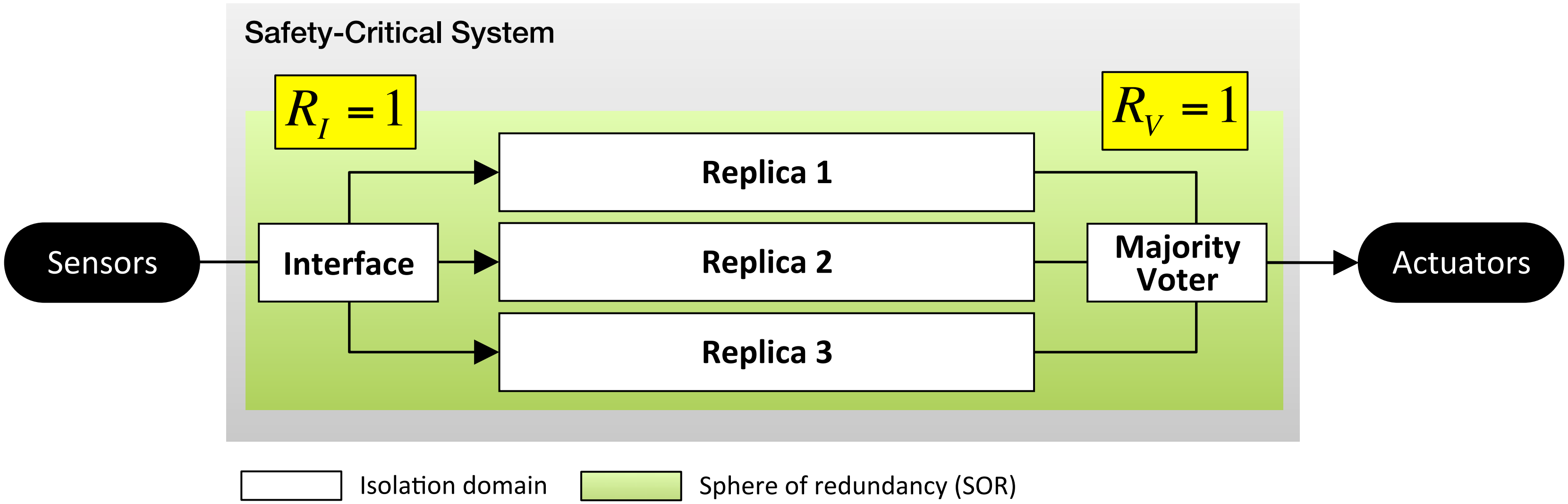

- Eliminate single points of failure
- Constrain residual error probability

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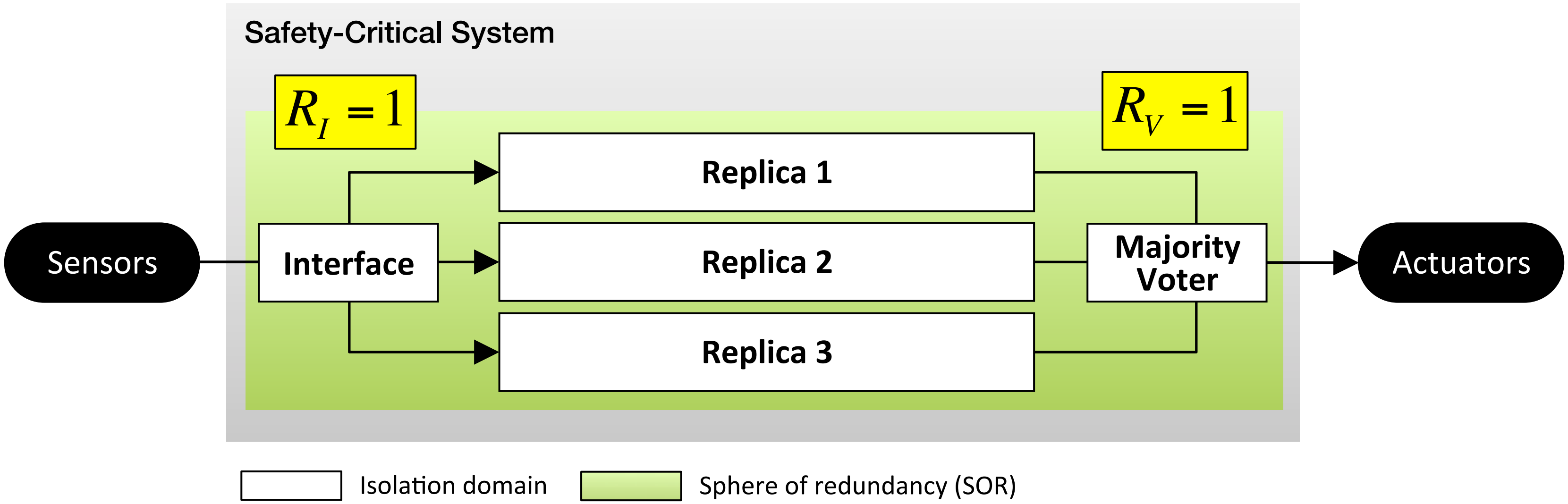

- Eliminate single points of failure
- Constrain residual error probability
- Dependability as a resource efficient option

Agenda

- Introduction
- The Combined Redundancy approach (*CoRed*)
  - Holistic protection – eliminating single points of failure
  - Arithmetic coding
  - Dependable voting
- Constraining residual error probability
  - From coding theory to application – lessons learned
  - Finding appropriate parameters
  - Circumvent implementation pitfalls
- Evaluation
  - Use case
  - Experimental setup
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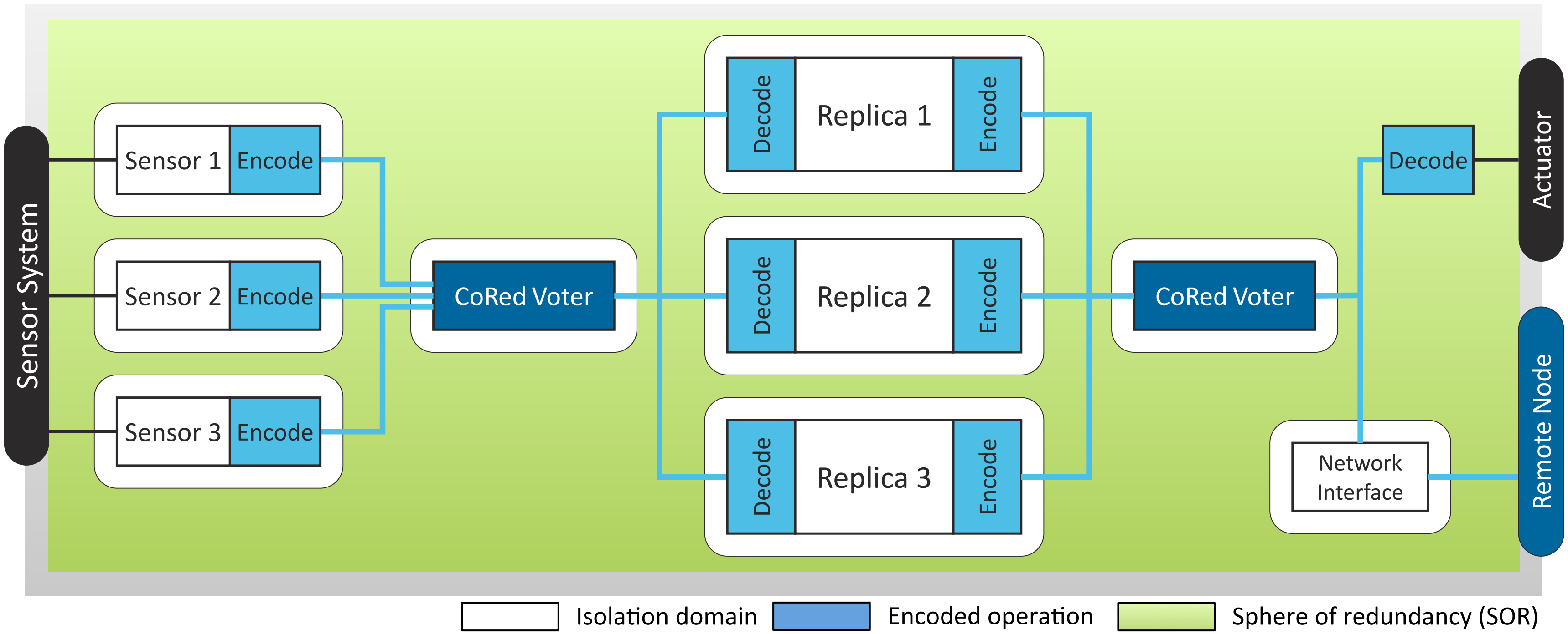
- Conclusion

CoRed Overview – Holistic Protection Approach



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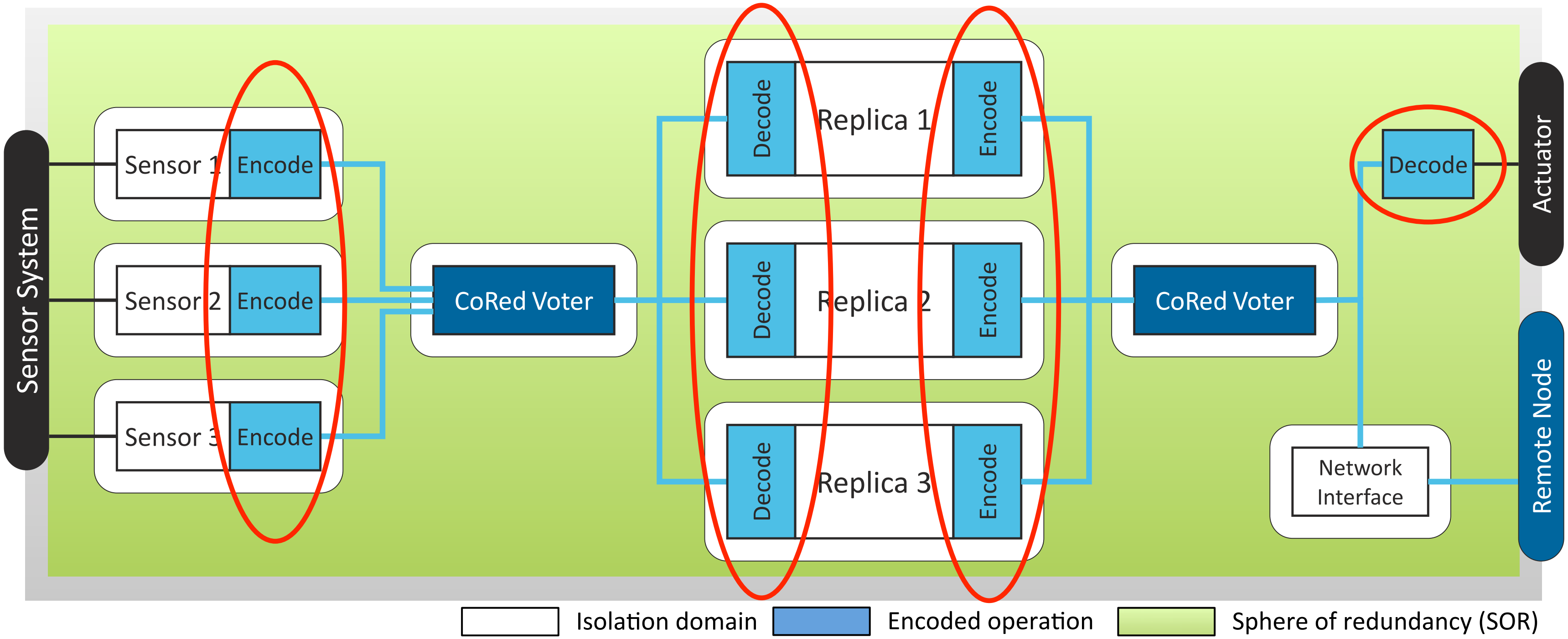
TMR + {

CoRed Overview – Holistic Protection Approach



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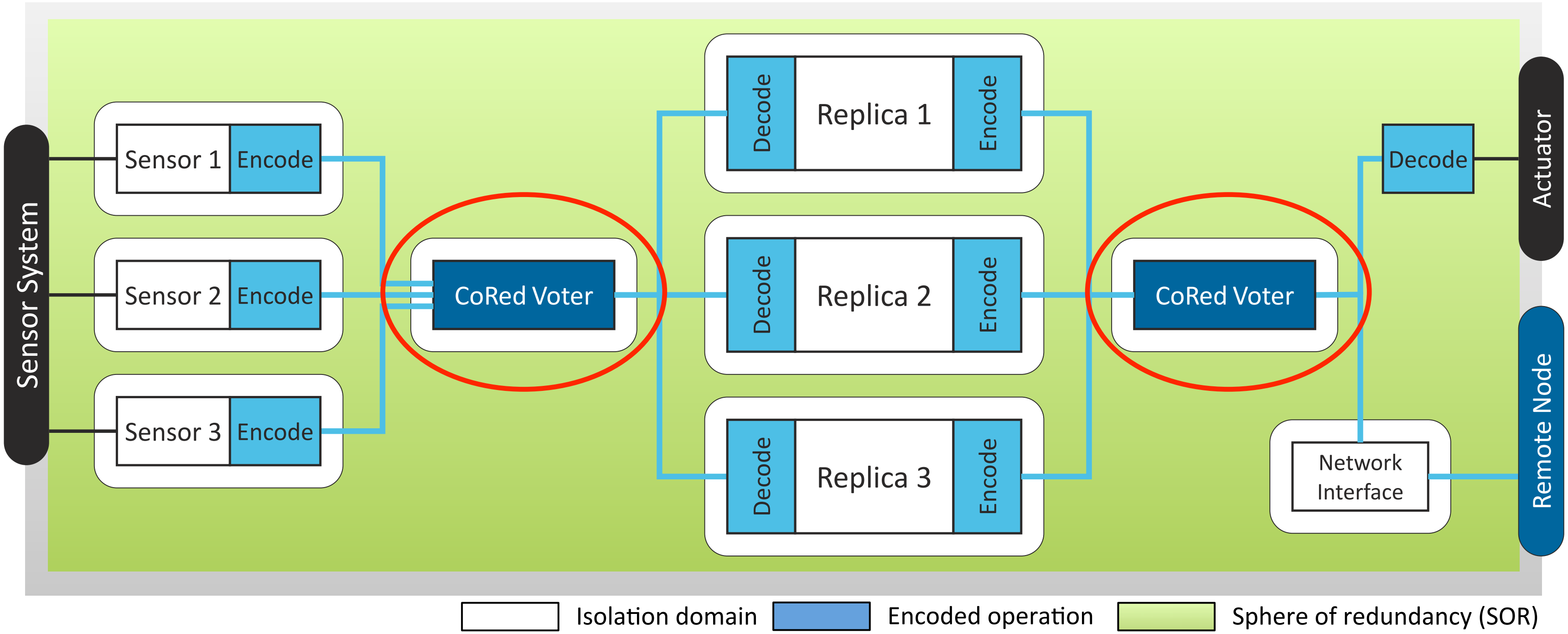

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TMR + { Data-flow encoding, Dependable voters }

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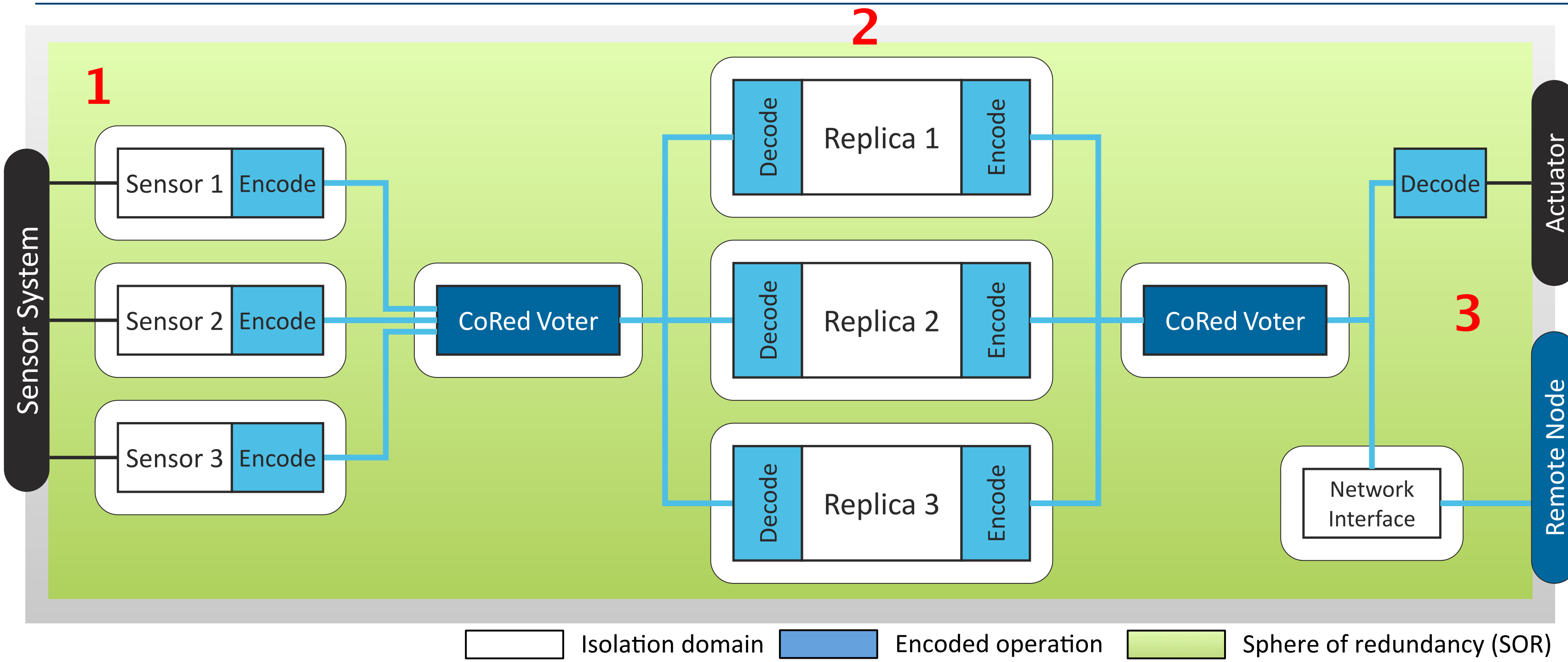


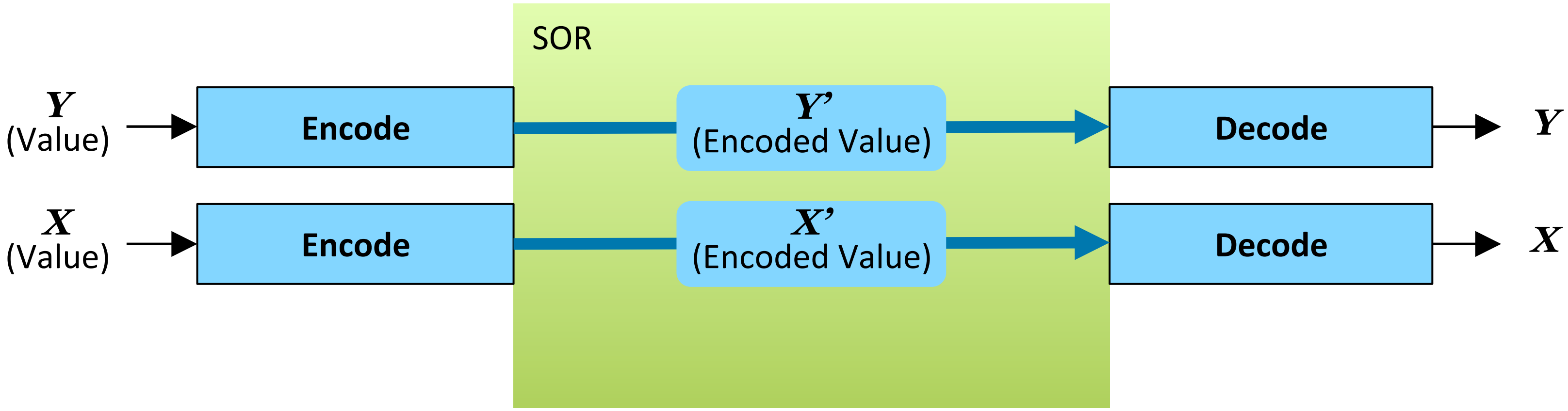
- **The Combined Redundancy Approach (*CoRed*)**

  TMR + { Data-flow encoding / Dependable voters }

- **Holistic protection approach for control applications**
  - Input to output protection

    1 Reading inputs → 2 Processing → 3 Distributing outputs

Eliminating Input and Output Vulnerabilities



- **Arithmetic Codes → ANBD Code**
  - Based on VCP [5]
  - **Data integrity:** Key
  - **Address integrity:** Per variable signature
  - **Outdated data:** Timestamp

$$v' = A \cdot v + B + D$$

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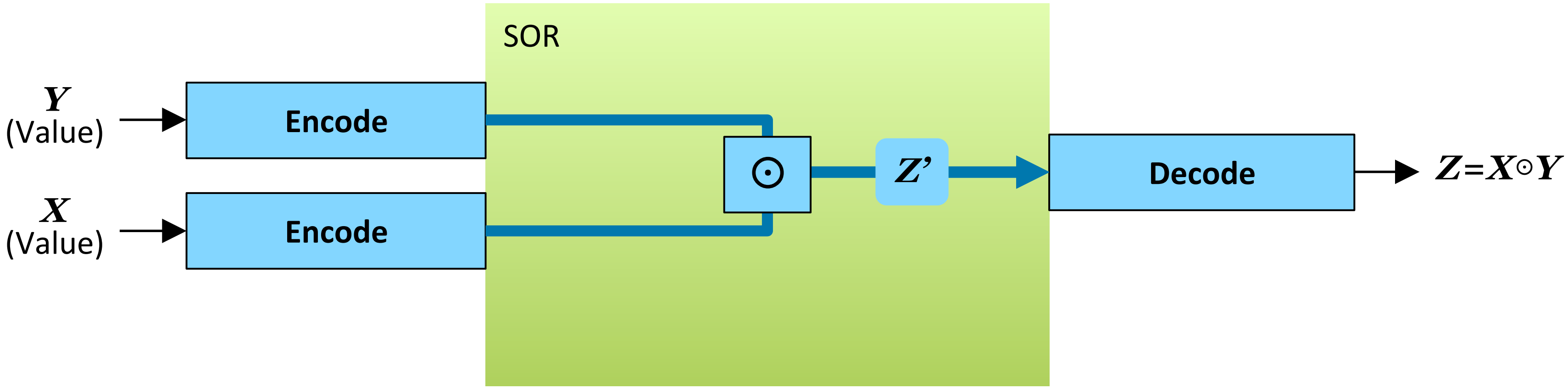

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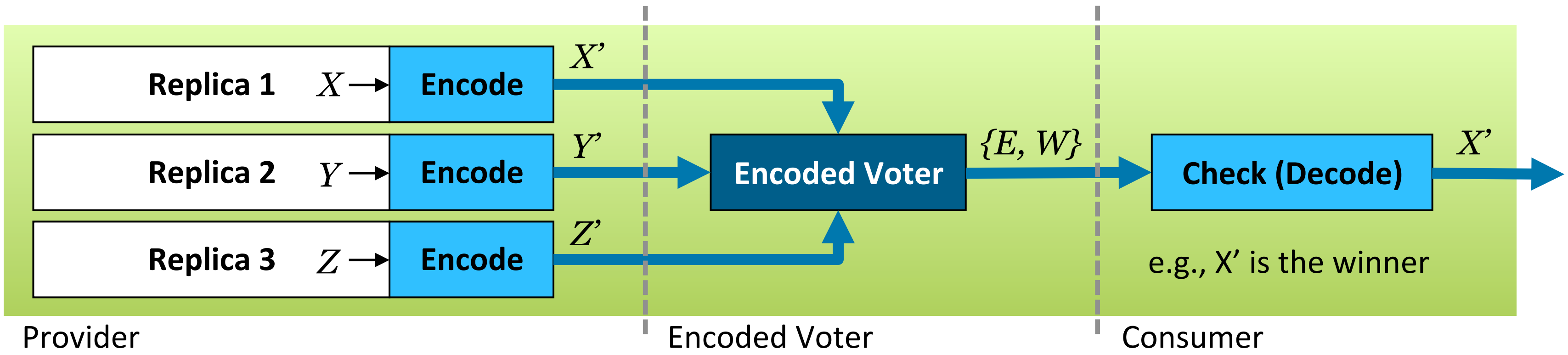
- **Set of arithmetic operators (+, -, *, =, …)**
  - Checksum vs. Arithmetic code (AN code)
  - AN Code → Encoded data operations
  - Enabler for dependable voter

CoRed Dependable Voter – Basics



- CoRed **Dependable Voter**
  - Input: variants (*X'*, *Y'*, *Z'*)
  - Output: Equality set (*E*) and encoded winner (*W*)
  - No decoding necessary

- **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)

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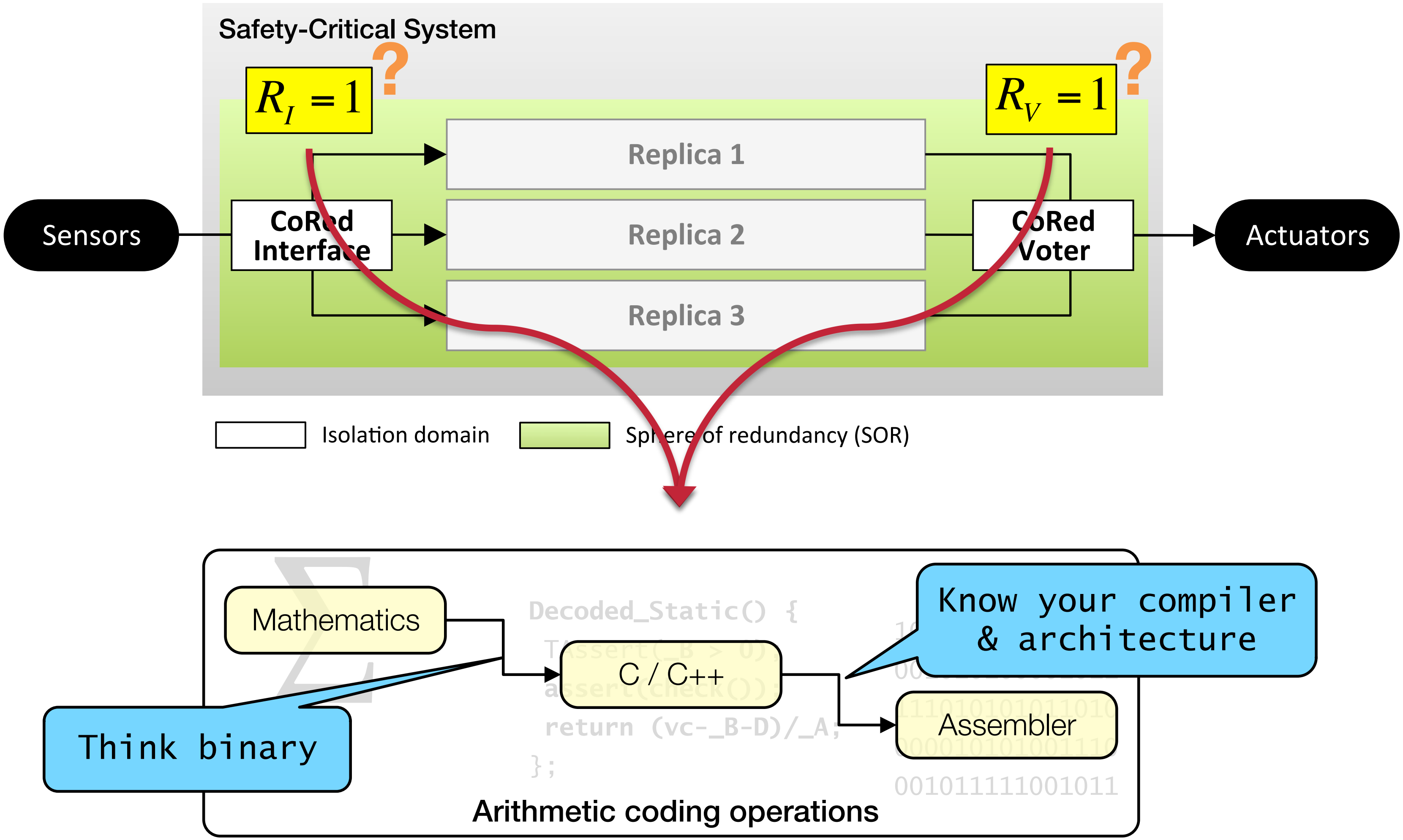
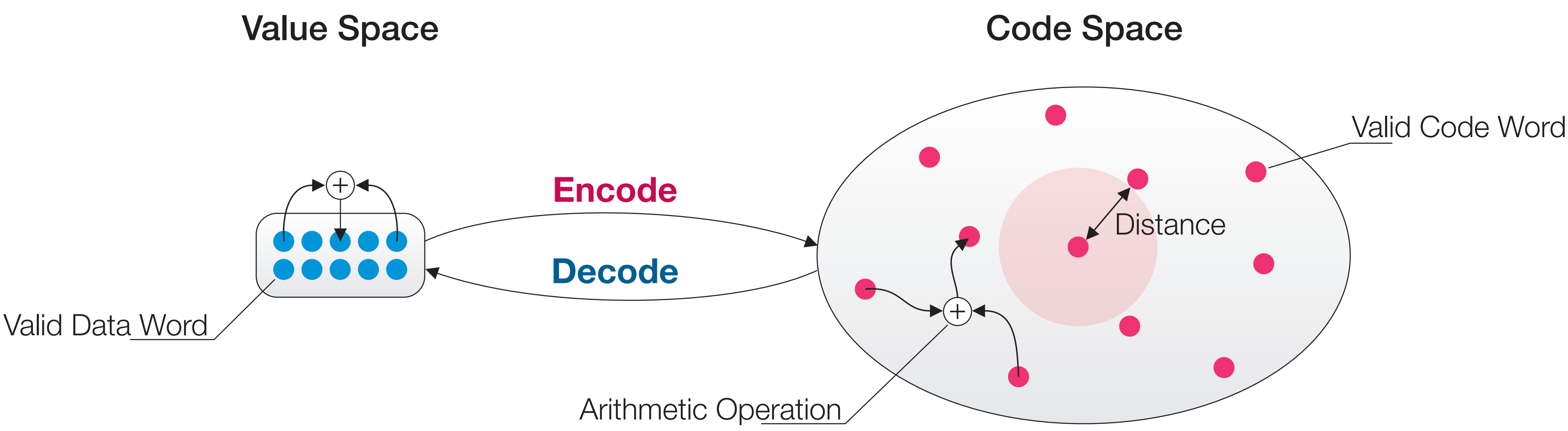
From Coding Theory to Application



Constraining residual error probability



- **Coding theory**
  - Data word + redundant information = code word
  - Fault detection → distance between code words

$$v' = A \cdot v + B + D$$

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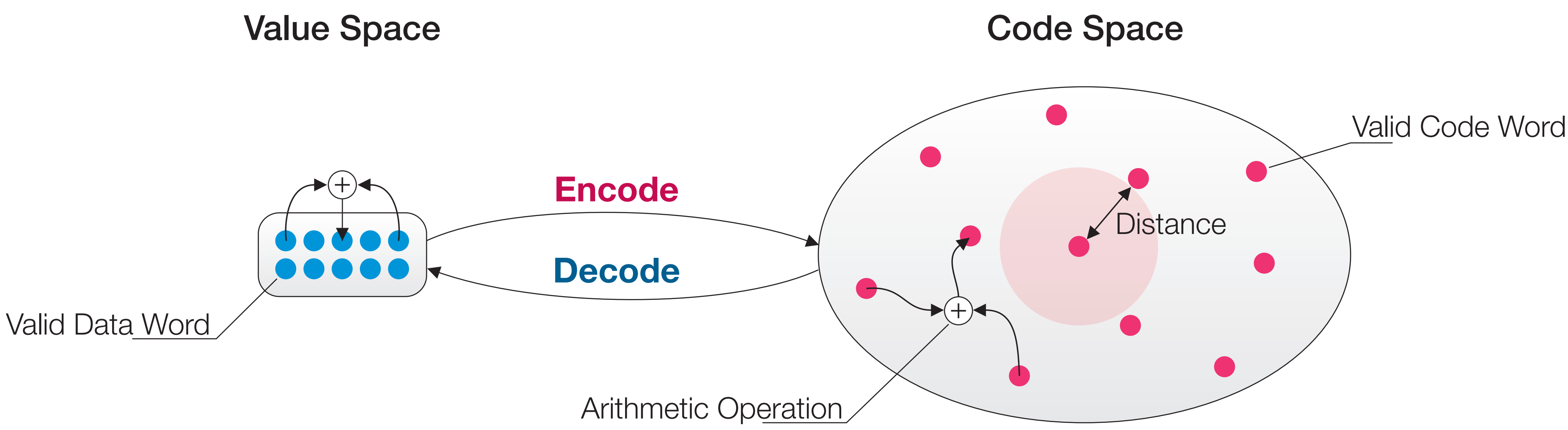

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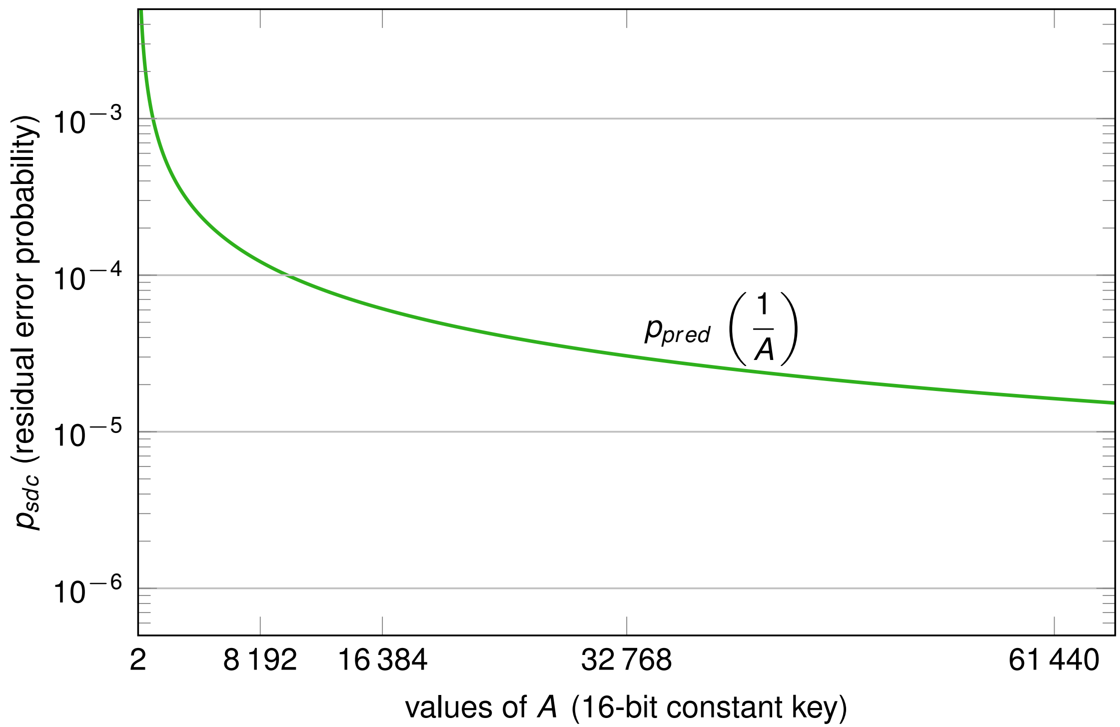
  - Chance for code-to-code word mutation
  - Fundamental property for fault tolerance mathematics

$$p_{sdc} = \frac{\text{valid code words}}{\text{possible code words}} \approx \frac{1}{A}$$

Constraining residual error probability



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Choosing Keys and Signatures

- **Mathematics: prime numbers**
  - Intuitively plausible
  - Literature: little help to find suitable As
- **Practitioner's approach: min. Hamming distance**
  - Distance (d) between code words (# unequal bits)
  - d-1 bit error detection capabilities

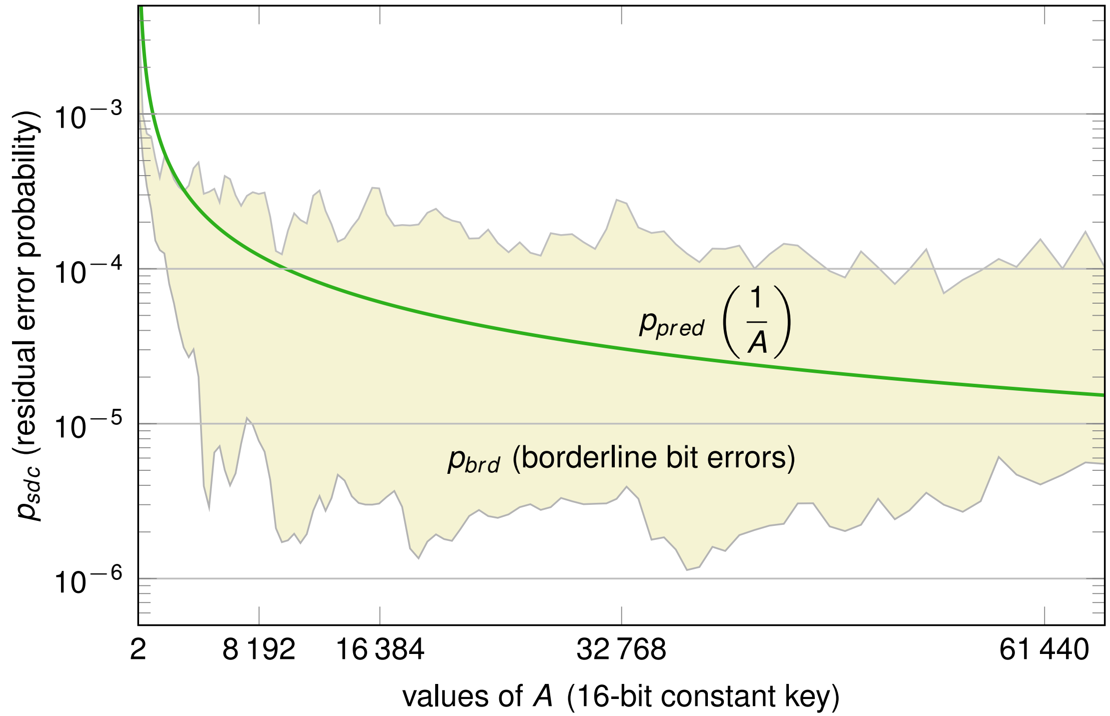
1	0	1	0
1	**1**	**0**	0

- **Brute force**
  - 1.4×10^{14} experiments for all 16 bit As

A =	d_{min} =	#errors detectable =
58,368	2	1
58,831	3	2
58,659	**6**	**5**

→ **The bigger the better is misleading!**

Consistence with Coding Theory – Mission Failed?

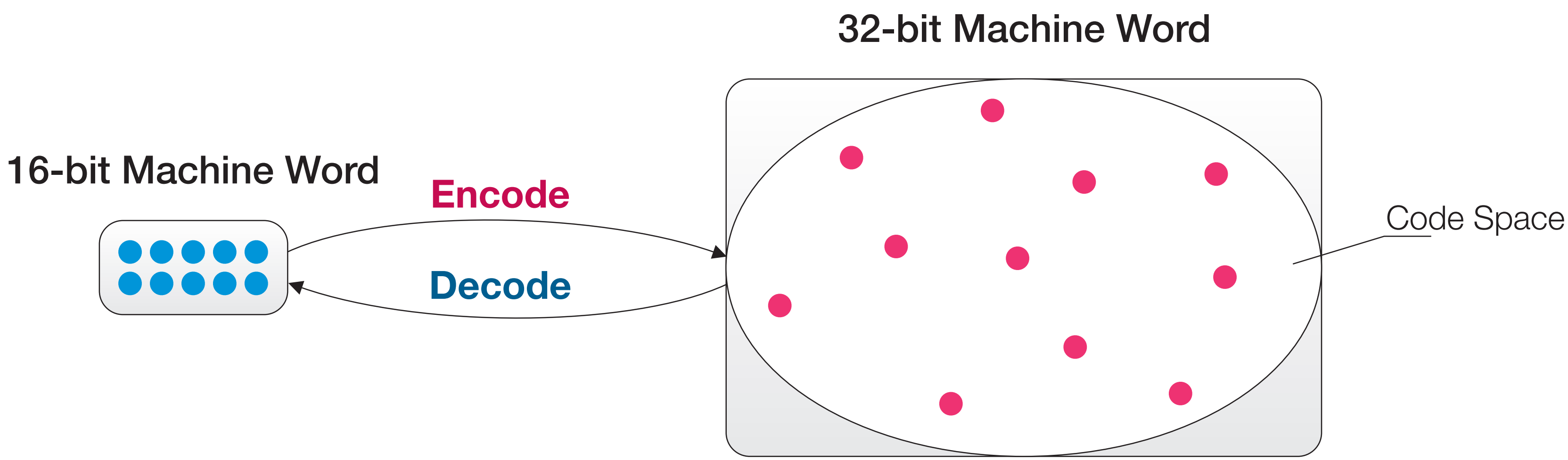


- **Fault-simulation → entire fault-space**
  - Each and every A, v and fault pattern
  - 6.5×10^{16} experiments for 16 bit As and 1-8 bit soft errors

→ Excess of predicted residual error probability

→ Violation of predicted fault-detection capabilities

Think Binary



- **Binary representation of code words**
  - Coding theory is unaware of machine word sizes
  - → Dangerous over- and underflow conditions
  - Extended AN code (EAN) implementation

→ **Compliance with coding theory!**

- **Improved code reliability ($A = 251$)**
  - Predicted 3×10^{-3}
  - Common implementation [4] $\approx 1.3 \times 10^{-2}$
  - EAN implementation $\approx 1.5 \times 10^{-5}$

→ **Improvement by orders of magnitude!**

Know your Compiler and Architecture

- **On target fault-injection → entire fault space**
  - Each and every register, flag, instruction and execution path
  - FAIL* fault injection framework [6]

→ Violation of predicted fault-detection capabilities

- **Architecture specifics**
  - Absence of compound test-and-branch (e.g., IA32 architecture)
  - Control-flow information is stored in single bit
  - → Redundancy is lost
  - → Additional range checks
- **Undefined Execution Environment**
  - Zombie values → leaking from caller to voter function
  - Compiler laziness leaves encoded values in registers
  - → Isolation assumptions violated
  - → Cleaning local storage restores isolation

→ Tight feedback loop with fault-injection experiments

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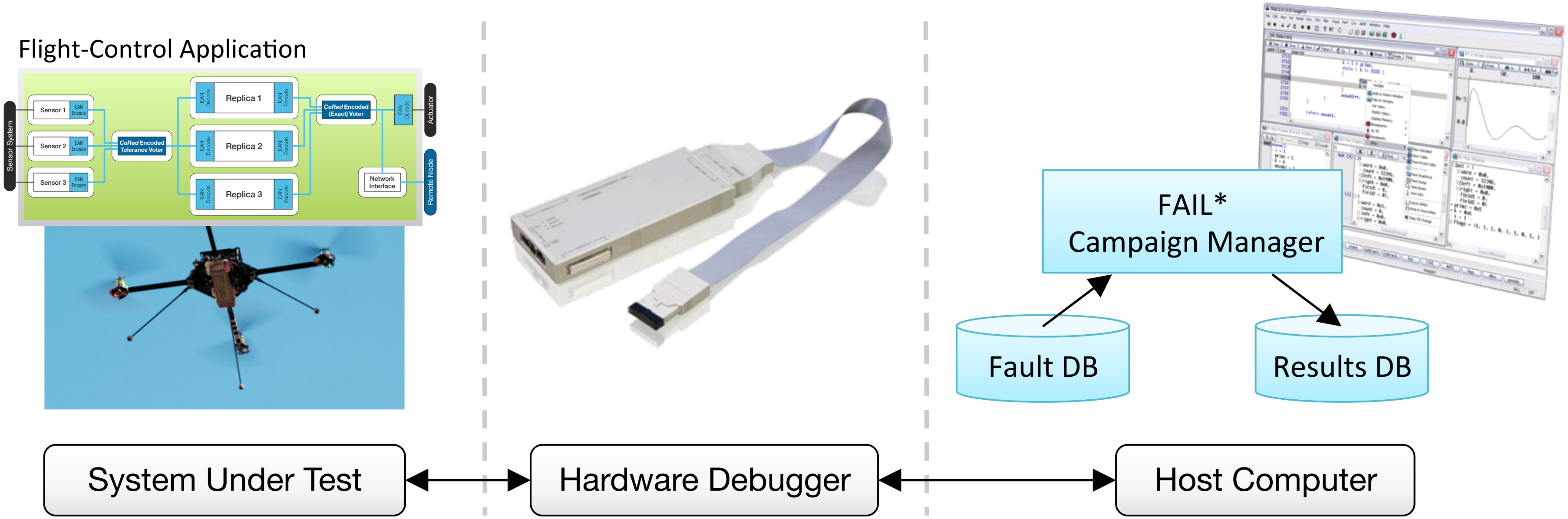
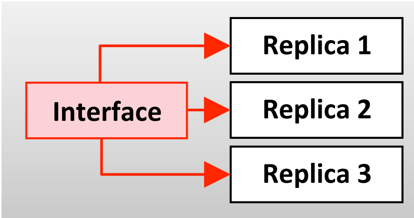
Evaluation – Experimental Setup

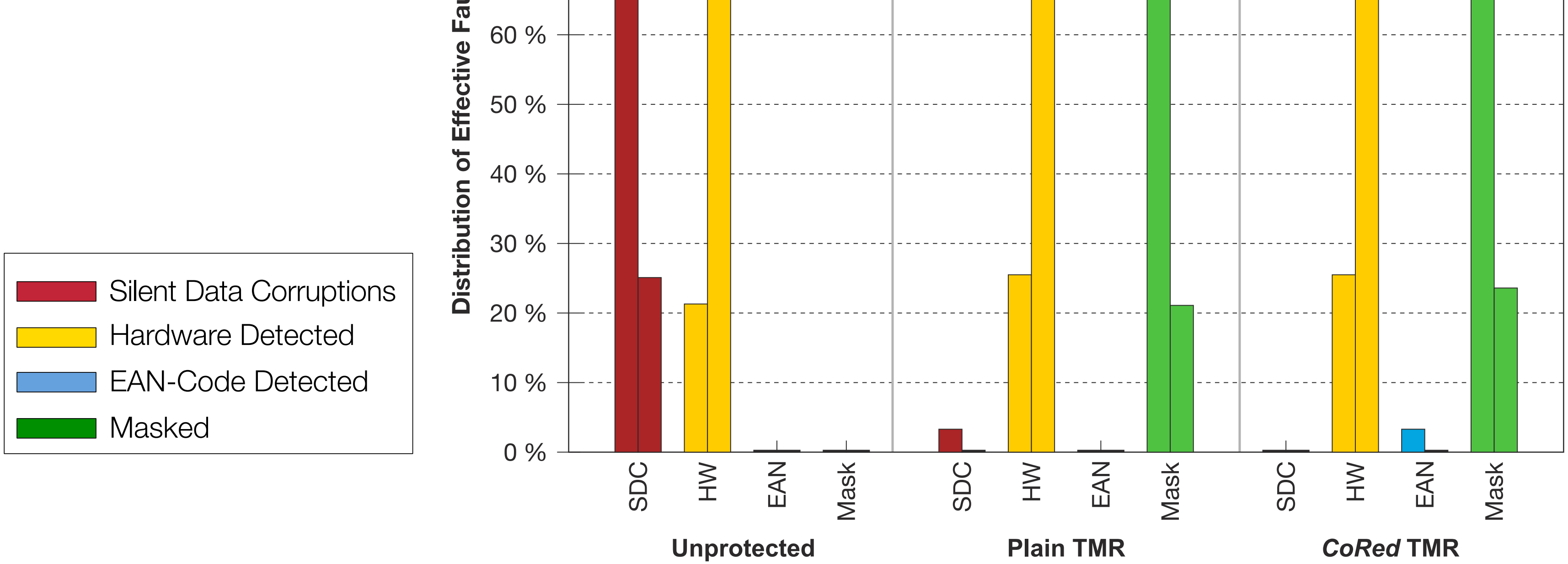


Categories: Fail Silent, Masked,
Hardware Detected, EAN-Code, Control-Flow,
Silent Data Corruption

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

Evaluation – Experimental Results (1)





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

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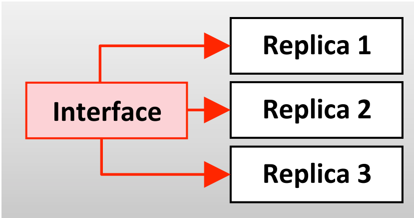

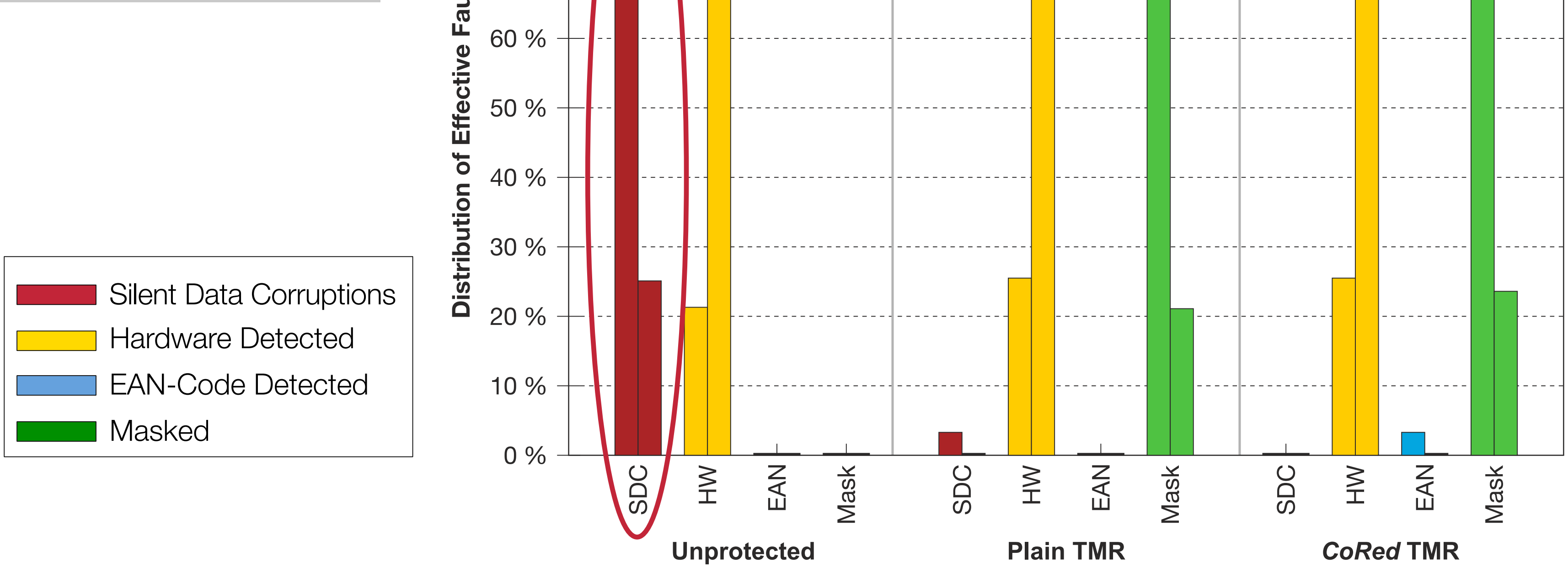

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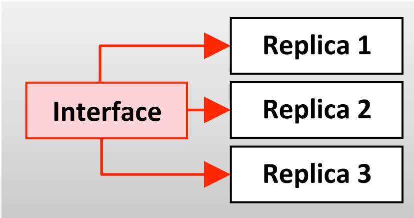

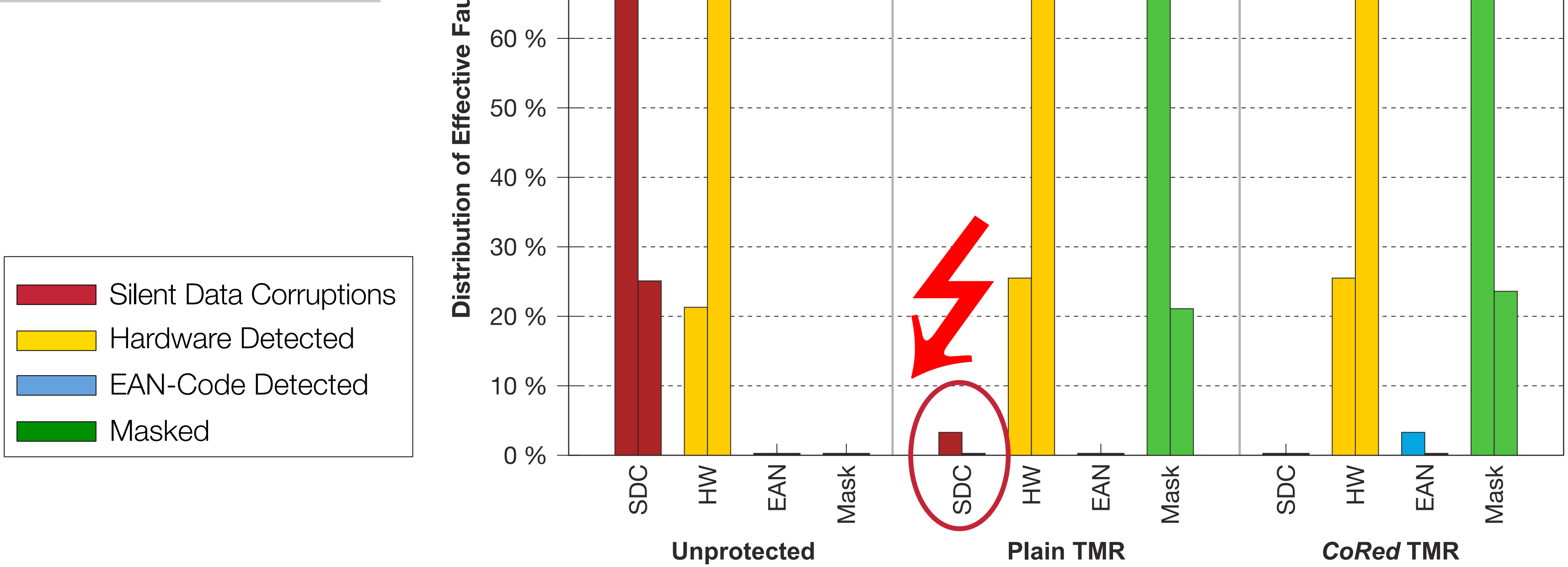

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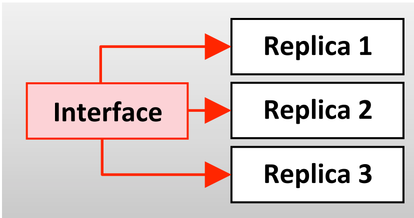

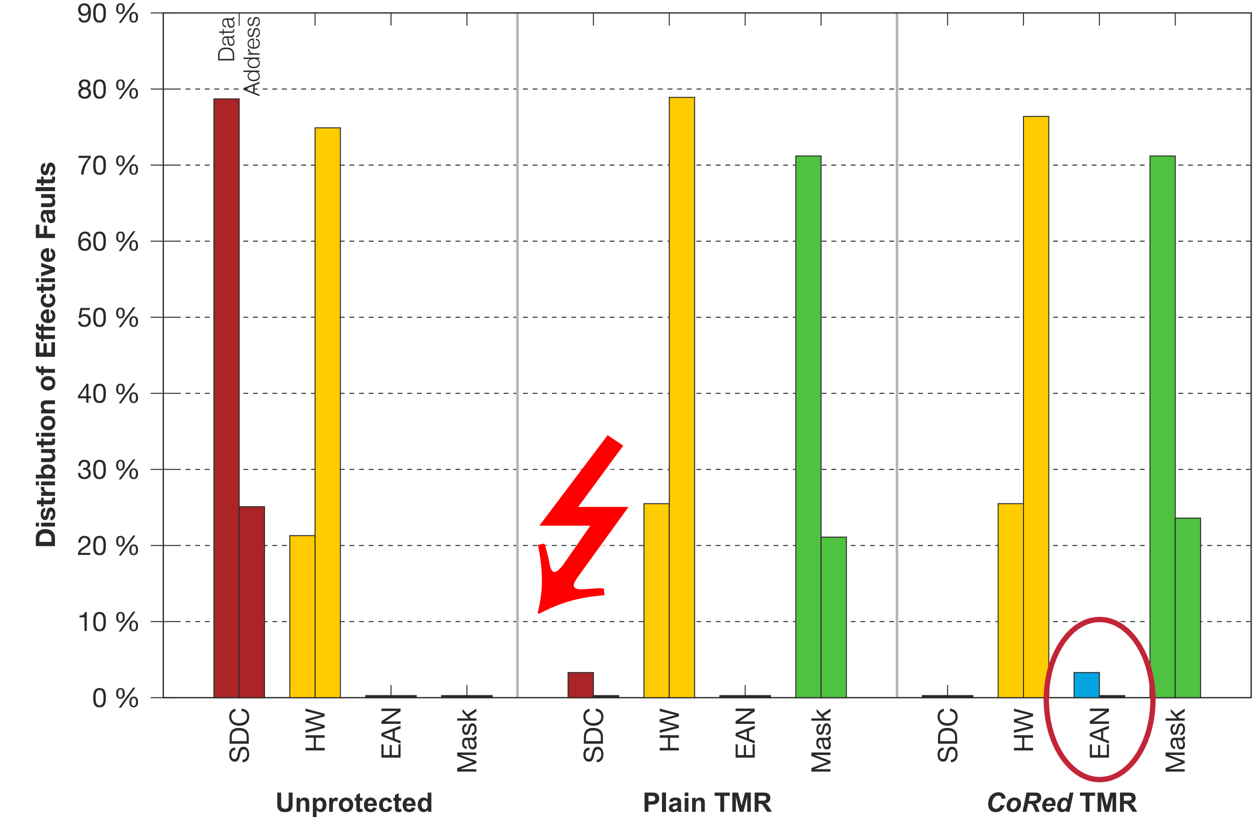

- **Redundant execution campaign (Interface)**
  - Total: ~45,000 Errors
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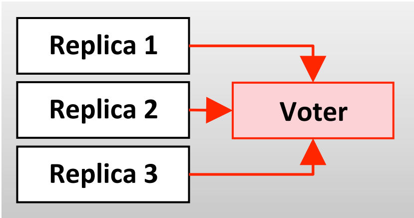
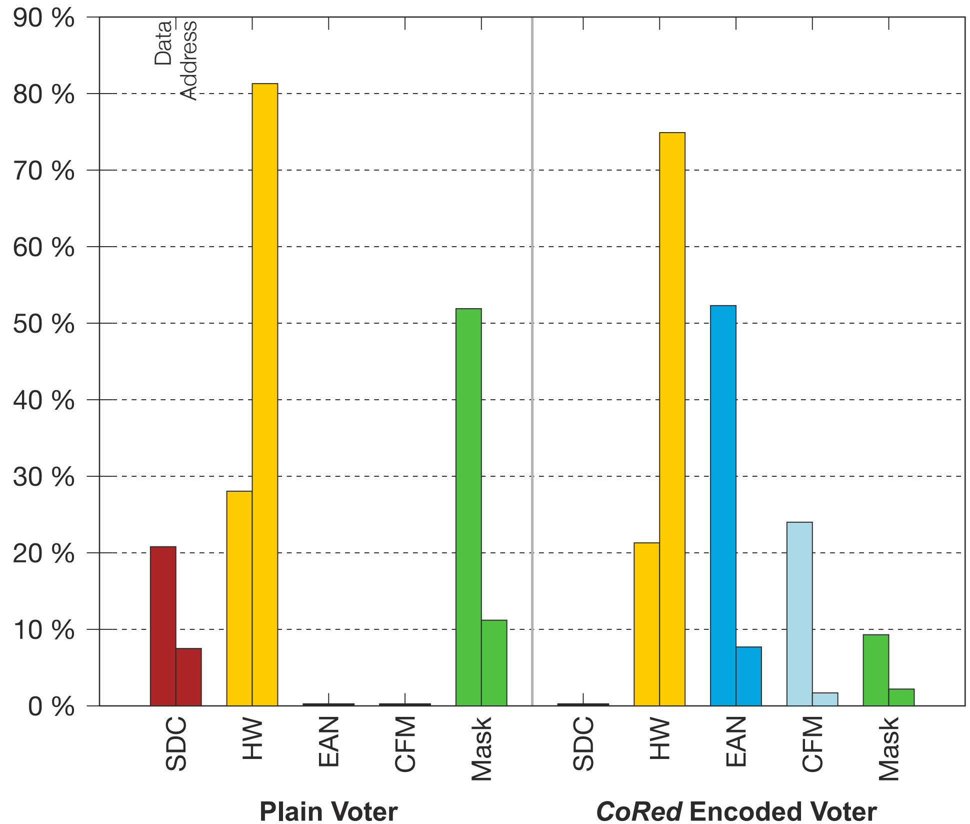
  - TMR: Suffers from 71 corruptions!
  - CoRed: Remaining corruptions are covered → 0 corruptions

Evaluation – Experimental Results (2)





- **Voter campaign**

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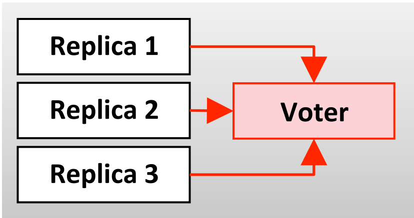

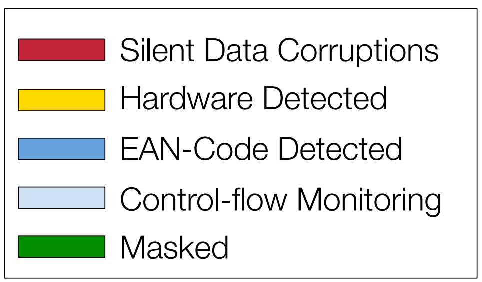

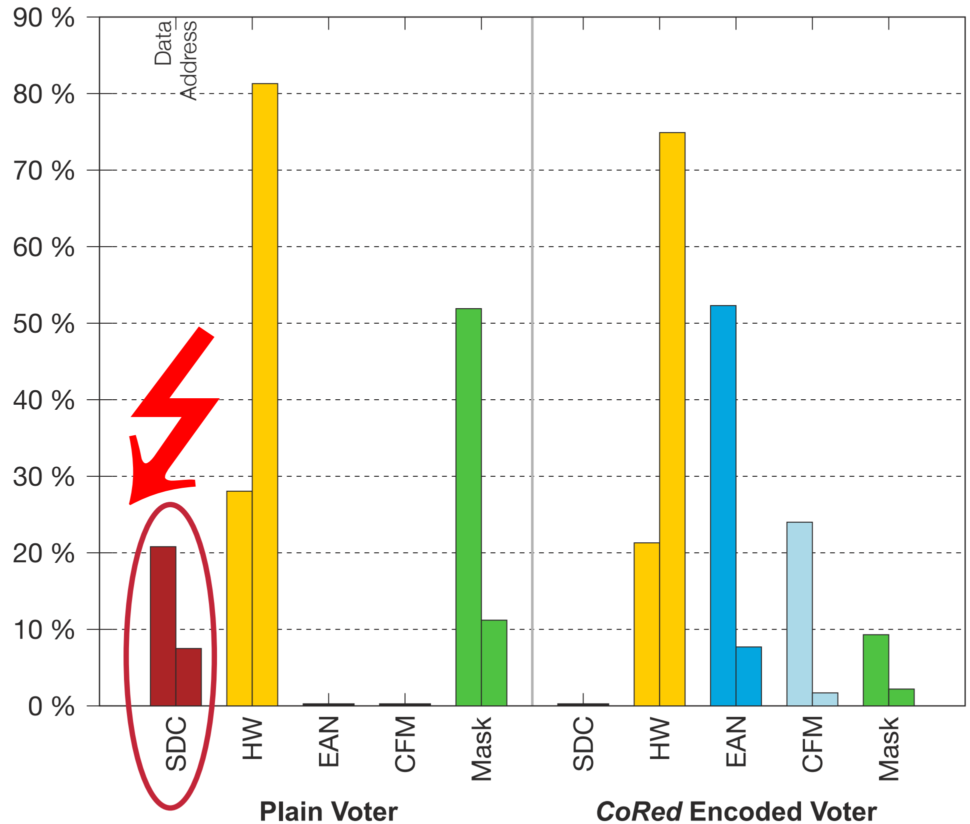

- **Voter campaign**
  - Plain voter:

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

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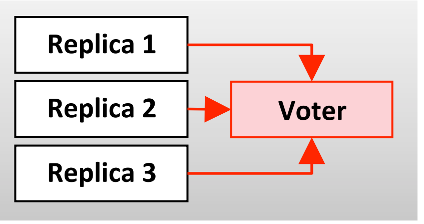

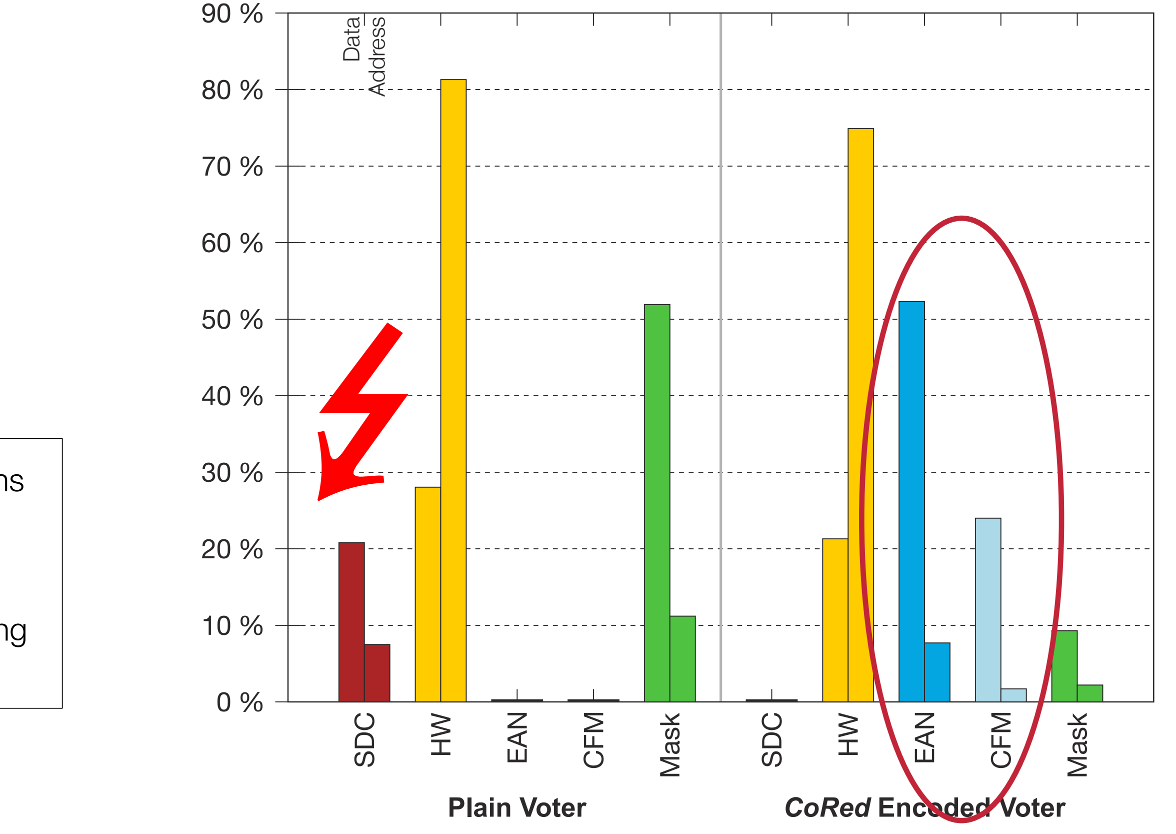

- **Voter campaign**
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  - CoRed Dependable Voter:
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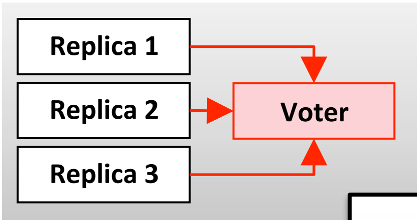

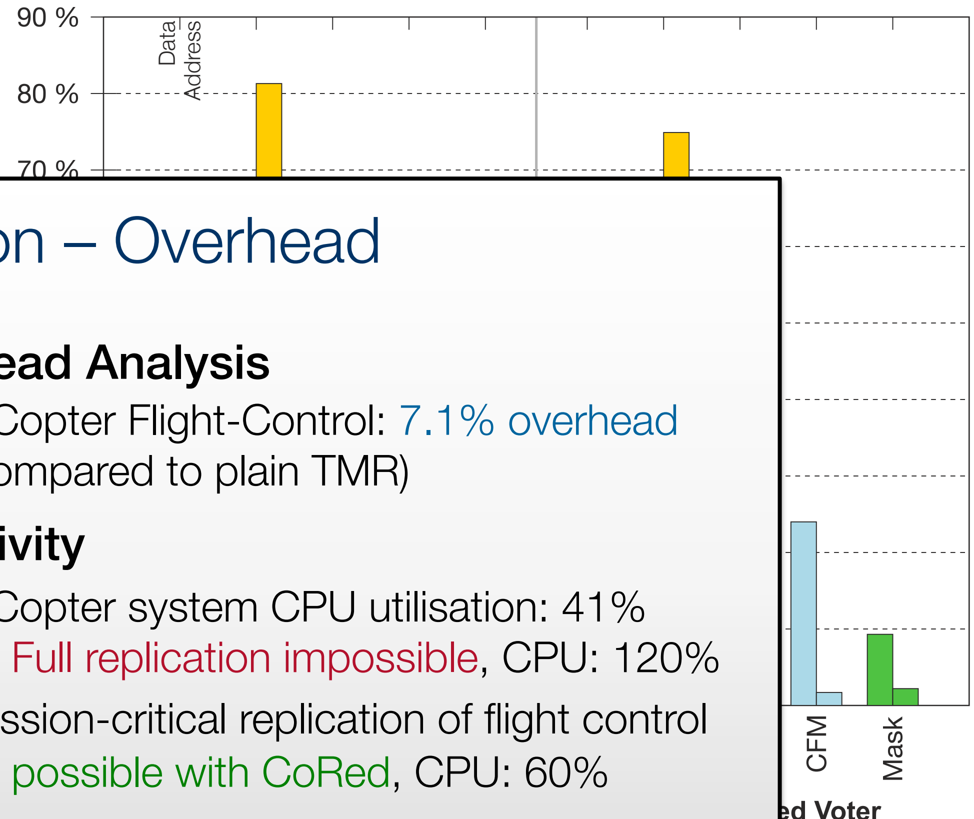

Evaluation – Overhead

- **Overhead Analysis**
  - I4Copter Flight-Control: 7.1% overhead (compared to plain TMR)
- **Selectivity**
  - I4Copter system CPU utilisation: 41%
    → Full replication impossible, CPU: 120%
  - Mission-critical replication of flight control
    → possible with CoRed, CPU: 60%

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☑ **Eliminate single points of failure [1]**

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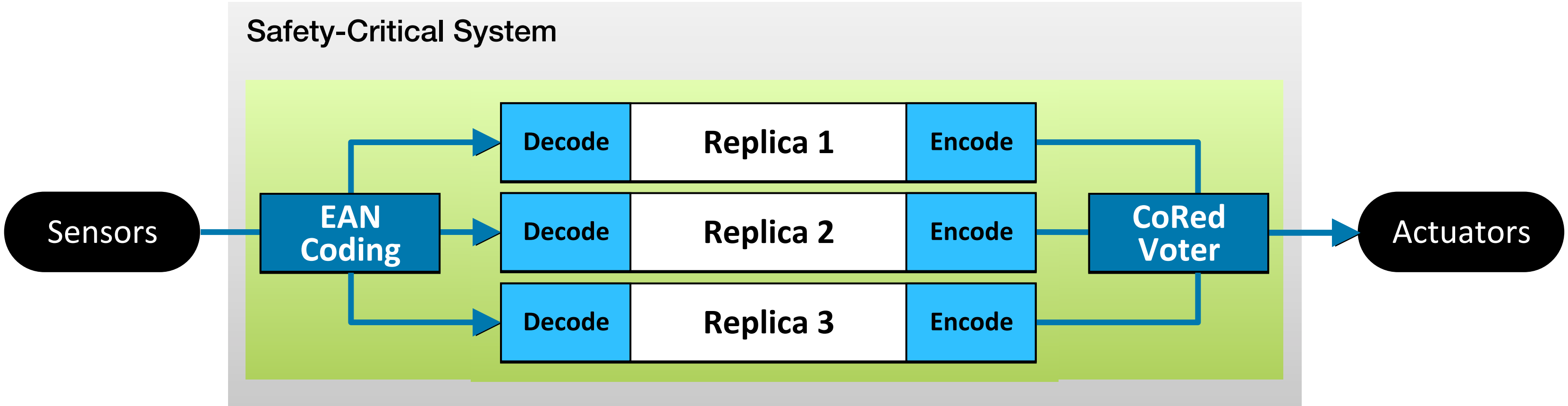

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- TMR + Encoding: Combined Redundancy approach
- Key feature: CoRed Dependable Voter

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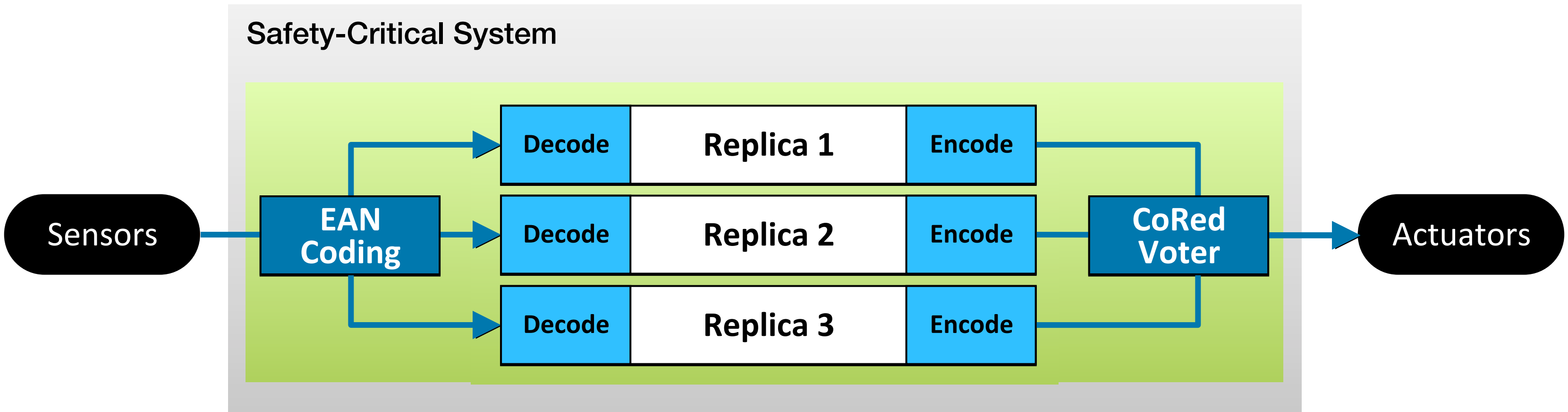

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- TMR + Encoding: Combined Redundancy approach
- Key feature: CoRed Dependable Voter

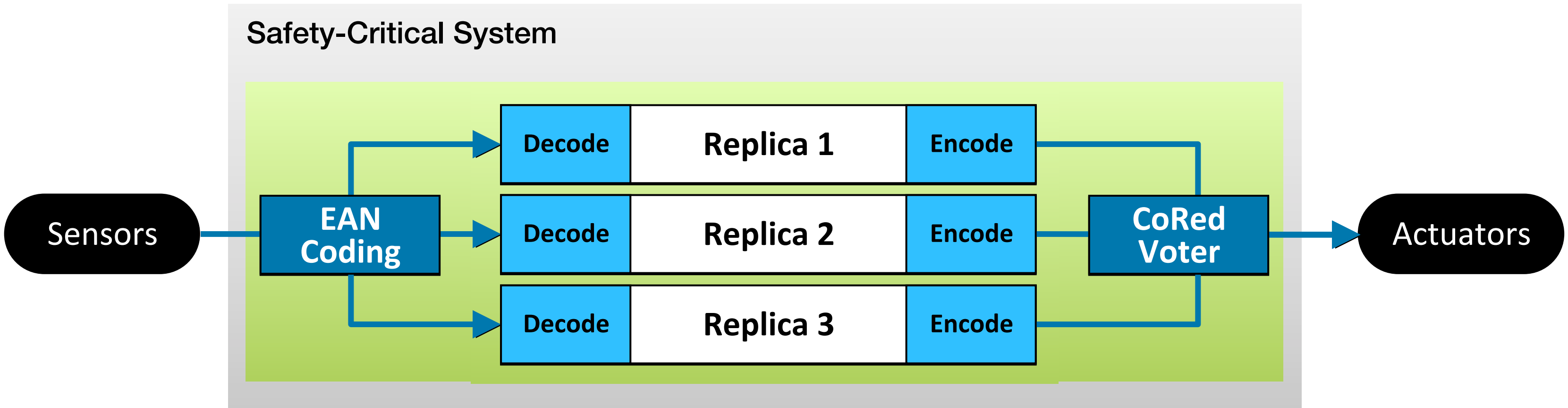
☑ **Constrain residual error probability [2]**

- Parameterisation guidelines: choosing the right A
- Binary aware implementation: complying with coding theory
- Factor 1000 improvement

☑ **Dependability as a resource efficient option**

- Only 7.1% overhead (flight control example)

Conclusion



☑ **Eliminate single points of failure [1]**
- TMR + Encoding: Combined Redundancy approach
- Key feature: CoRed Dependable Voter

☑ **Constrain residual error probability [2]**
- Parameterisation guidelines: choosing the right A
- Binary aware implementation: complying with coding theory
- Factor 1000 improvement

☑ **Dependability as a resource efficient option**
- Only 7.1% overhead (flight control example)

→ Bullet-proof software-based fault tolerance is possible

Thank you!

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