A Practitioner's Guide to
Software-based Soft-Error Mitigation Using AN-Codes

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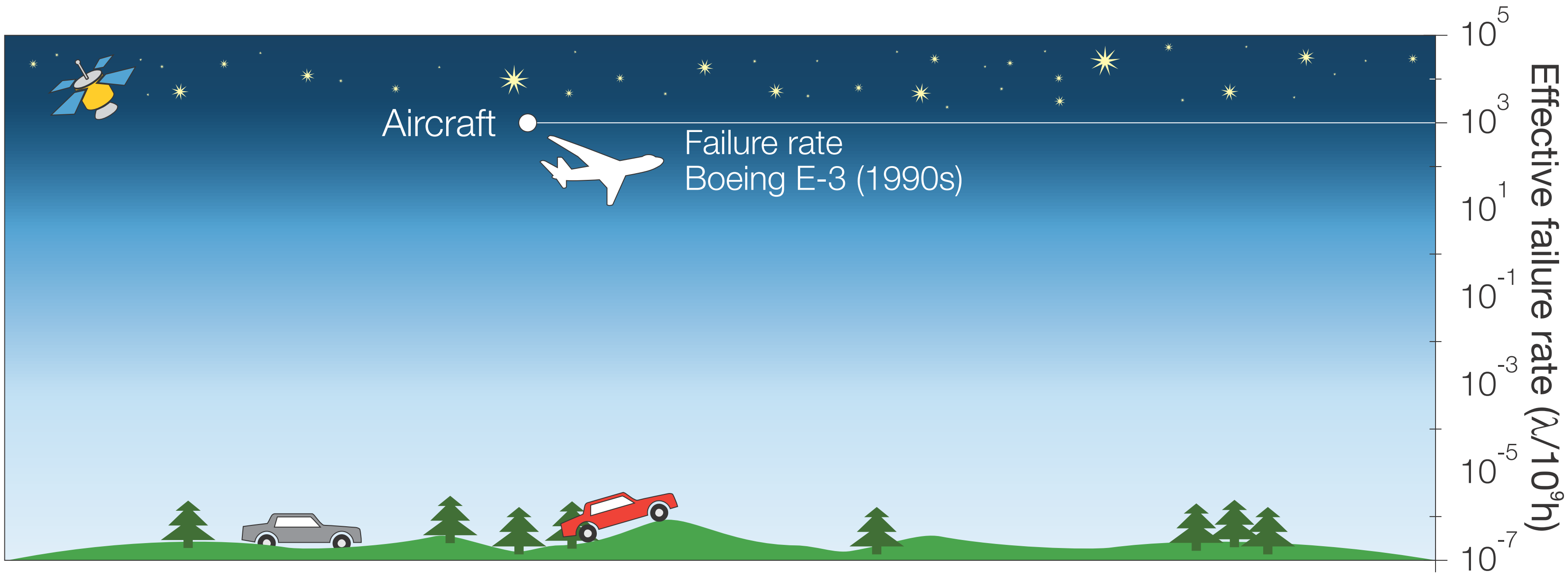
System Software Group

Embedded Systems Initiative

Soft Errors – A Growing Problem



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  - Caused by (cosmic) radiation

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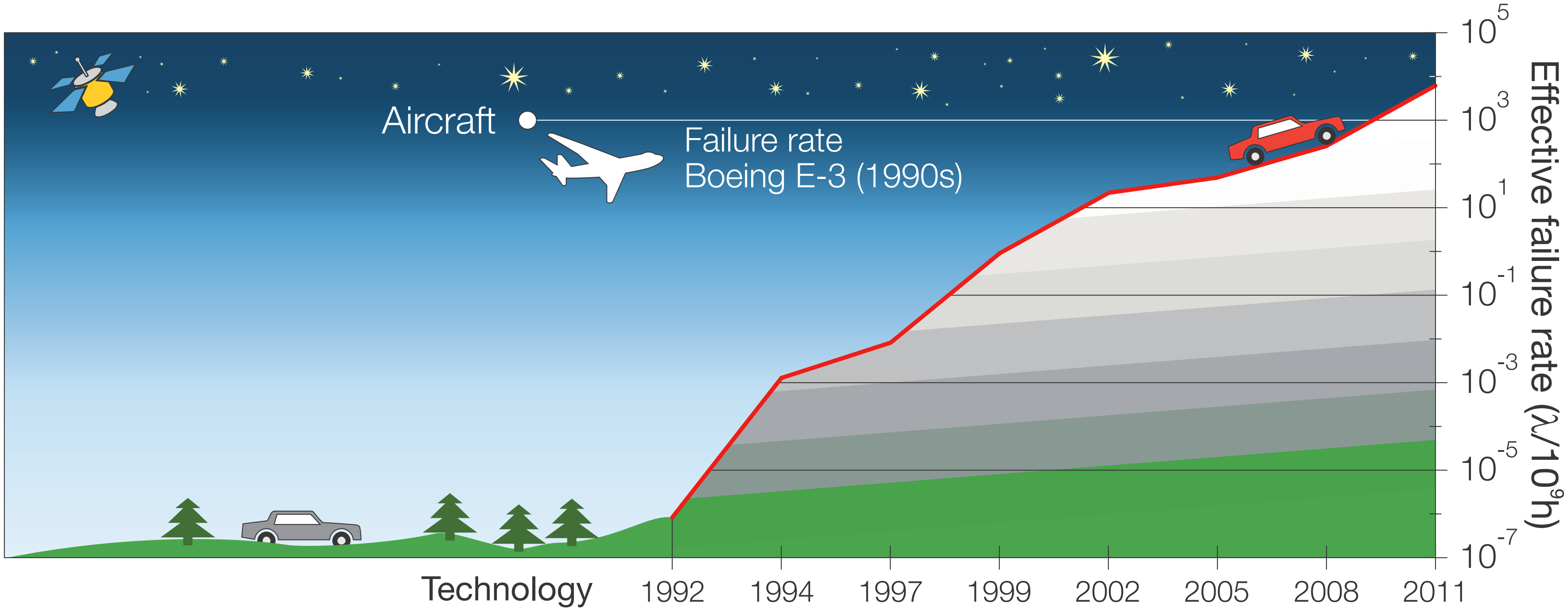

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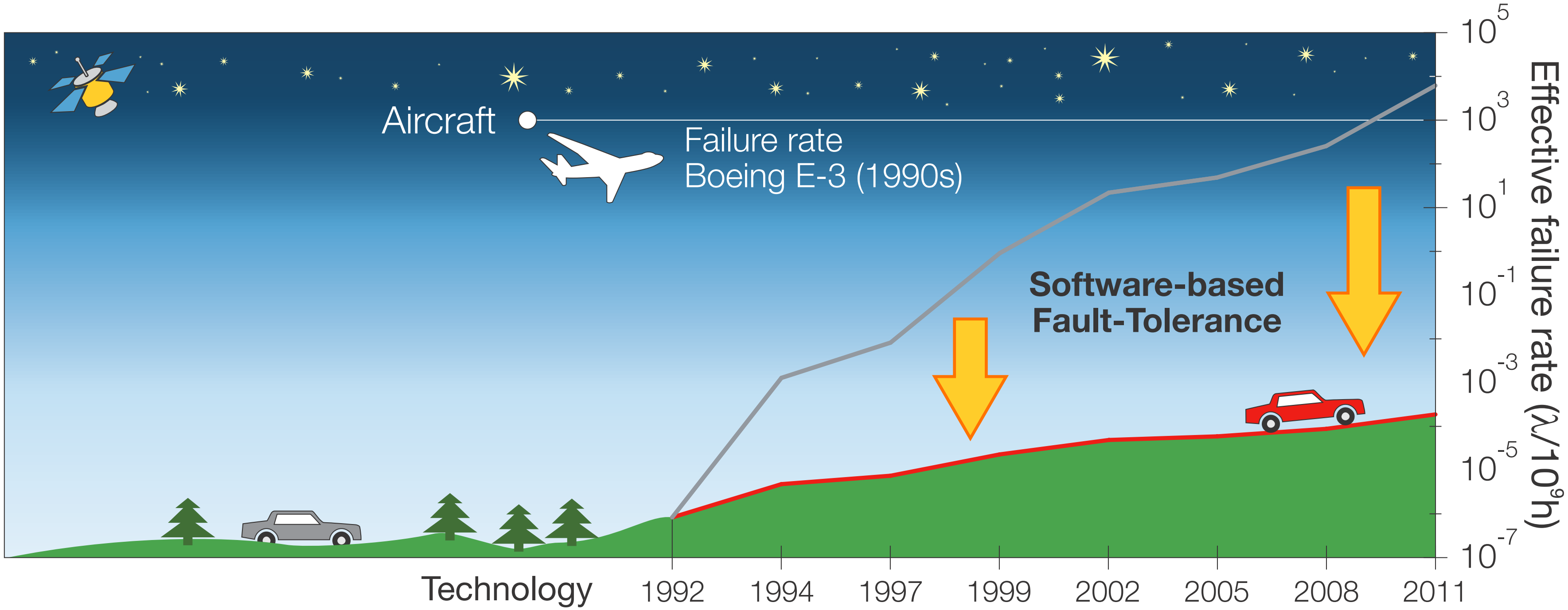
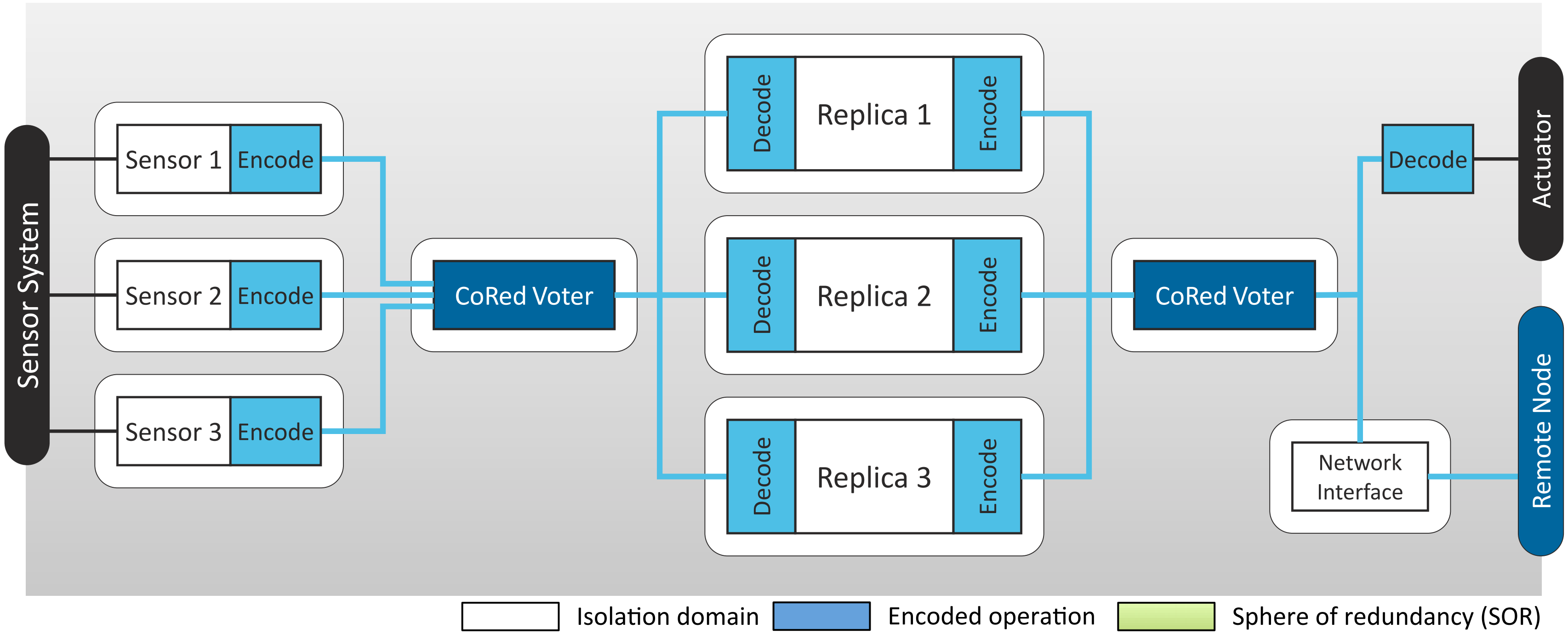


- **Soft-Errors (Transient hardware faults)**
  - Caused by (cosmic) radiation
  - Performance (technology) vs. reliability
- **Software-based fault-tolerance**
  - Selective and resource-efficient (costs!)
  - Vital component: Arithmetic error coding (AN codes)

Combined Redundancy Approach

CoRed



The Combined Redundancy Approach (***CoRed***) [1]

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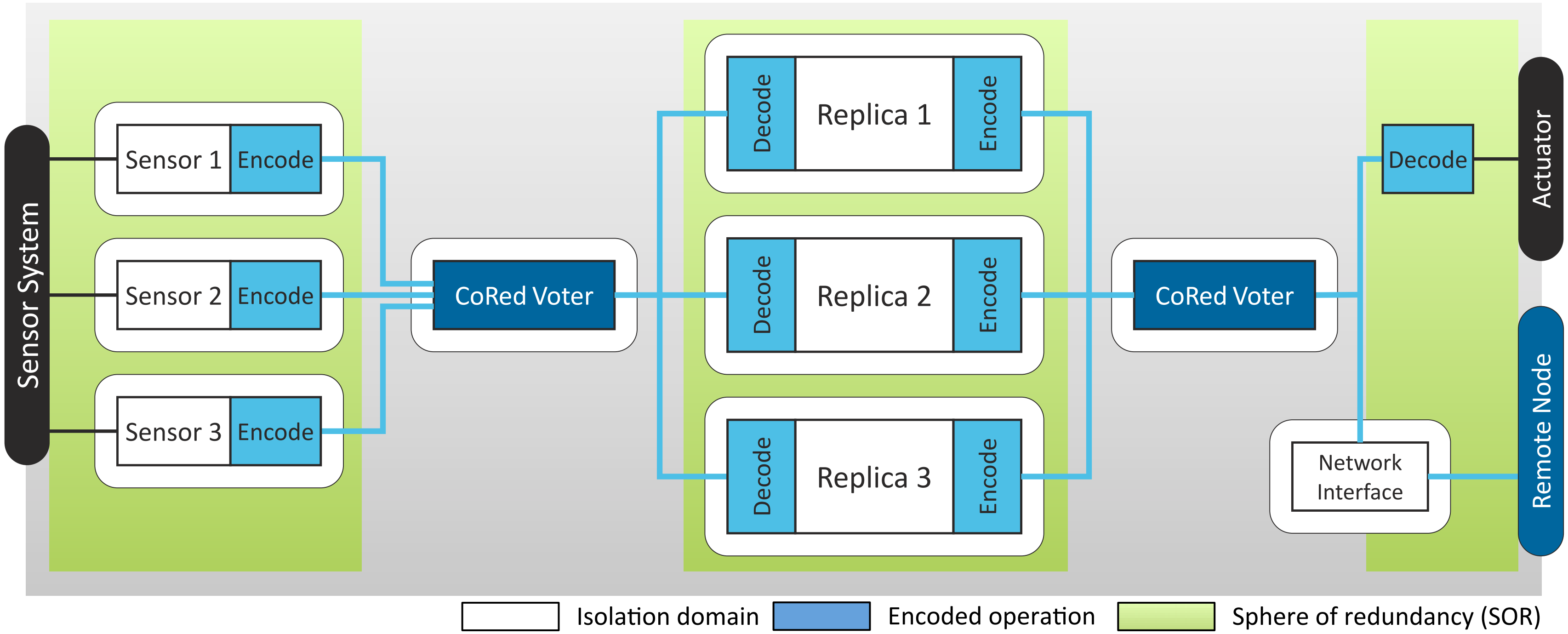

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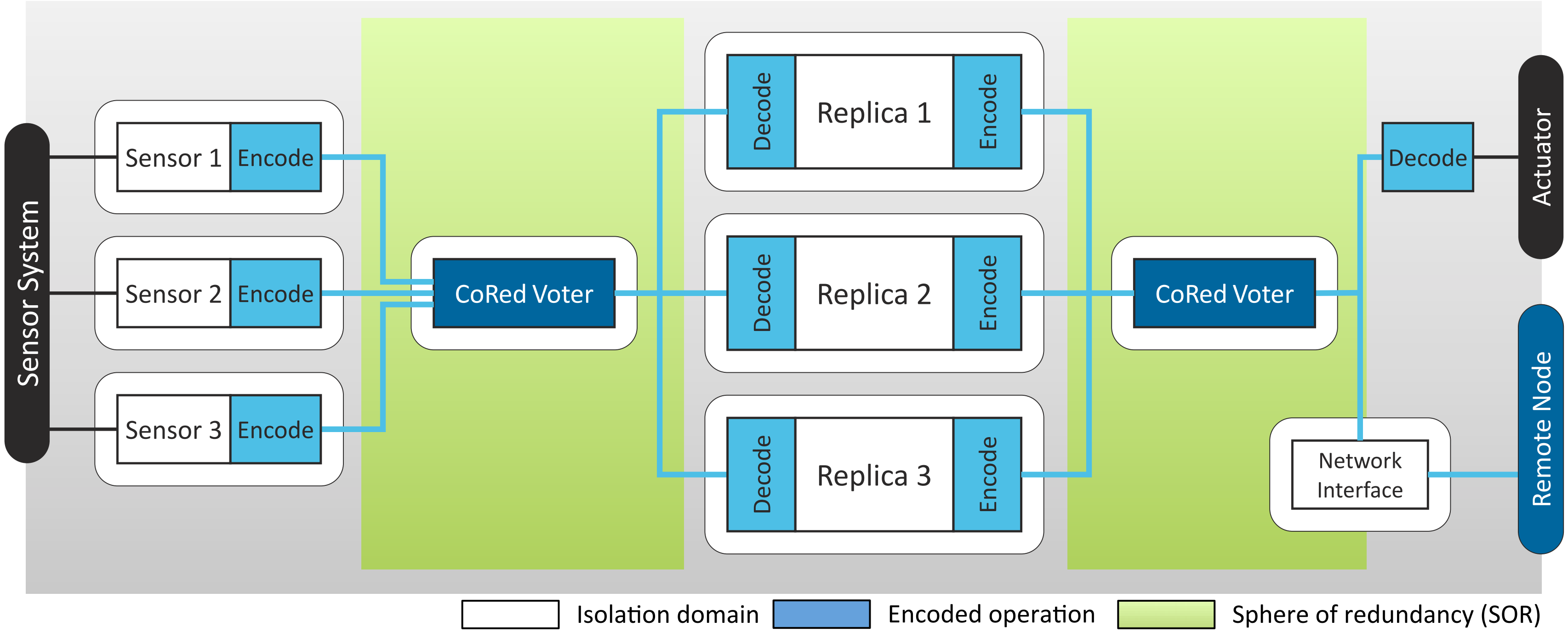

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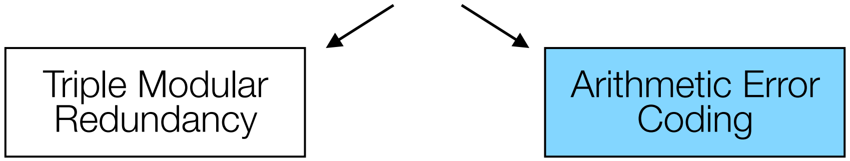

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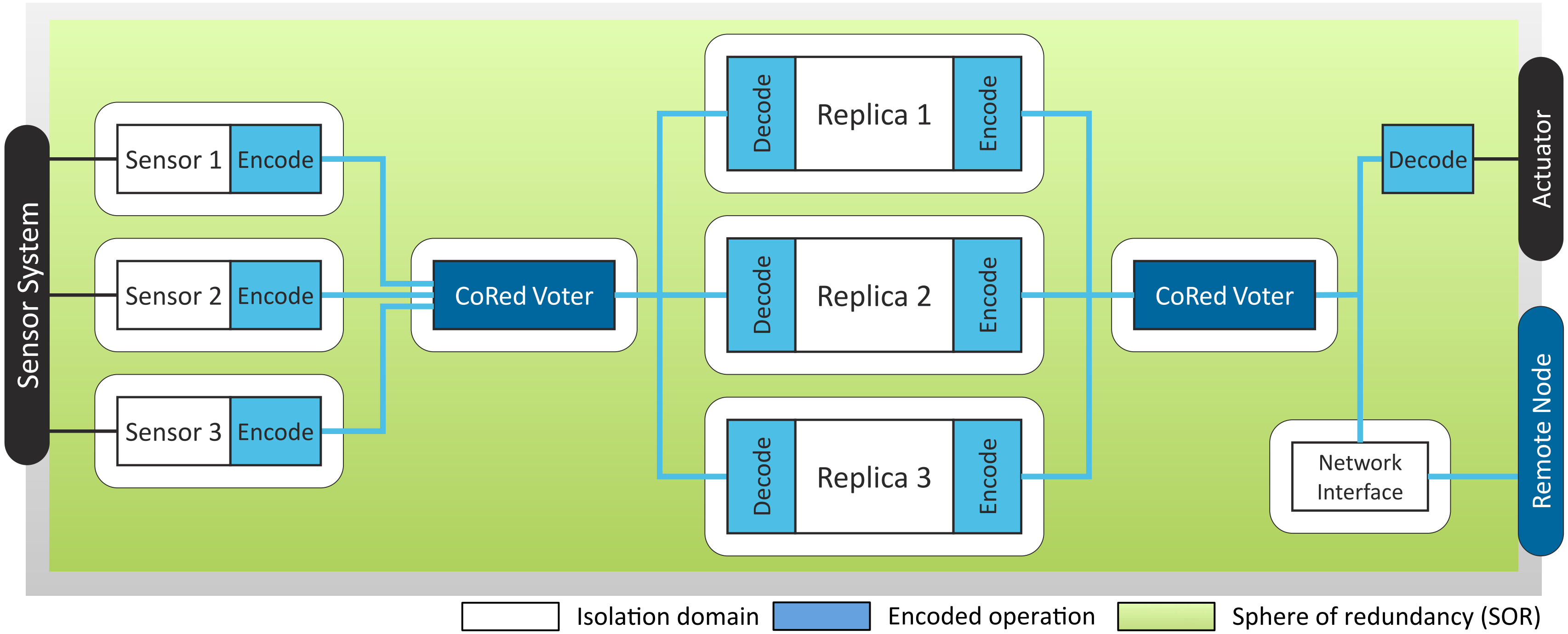

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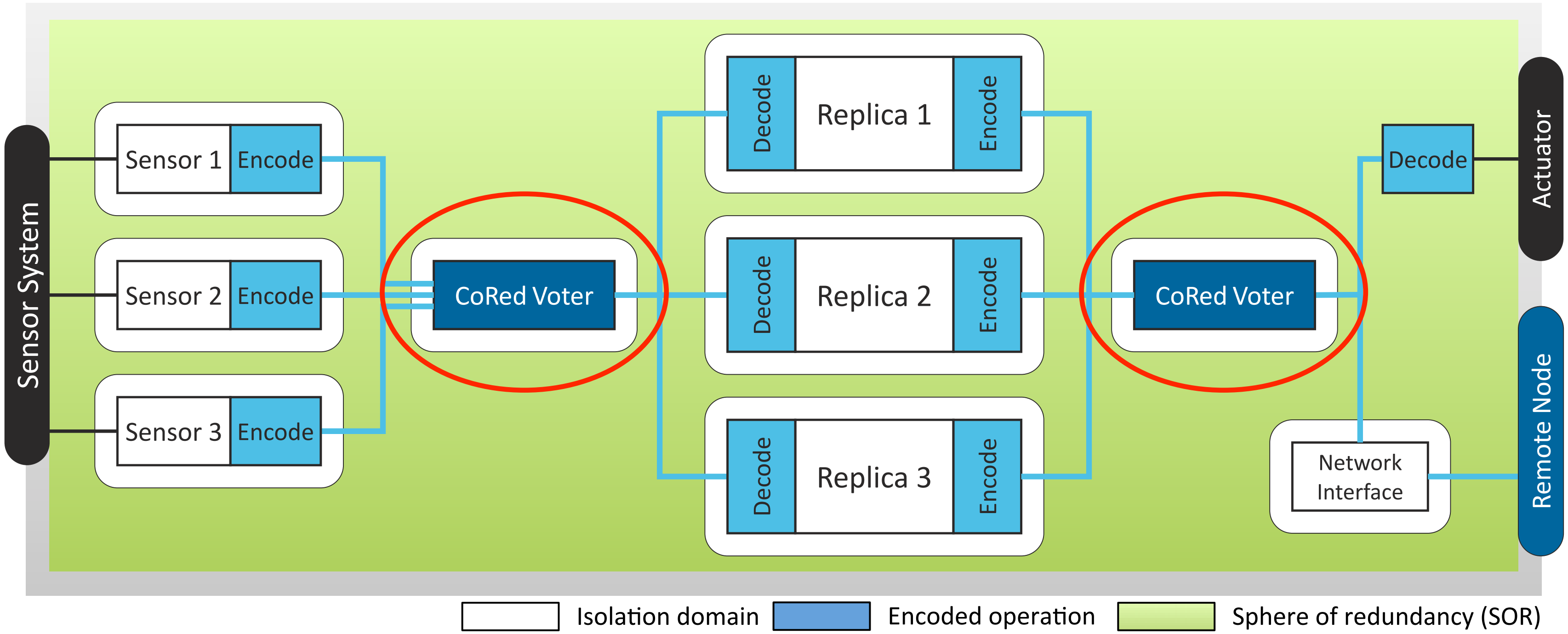

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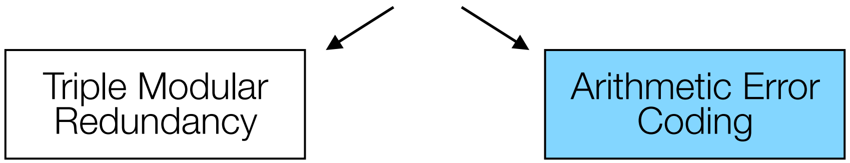

→ Key element: CoRed Dependable Voter

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Problem Statement

Goals:

- Full 1-bit fault coverage
- Get what you're paid for

Implementation:

- UAV Flight-Control
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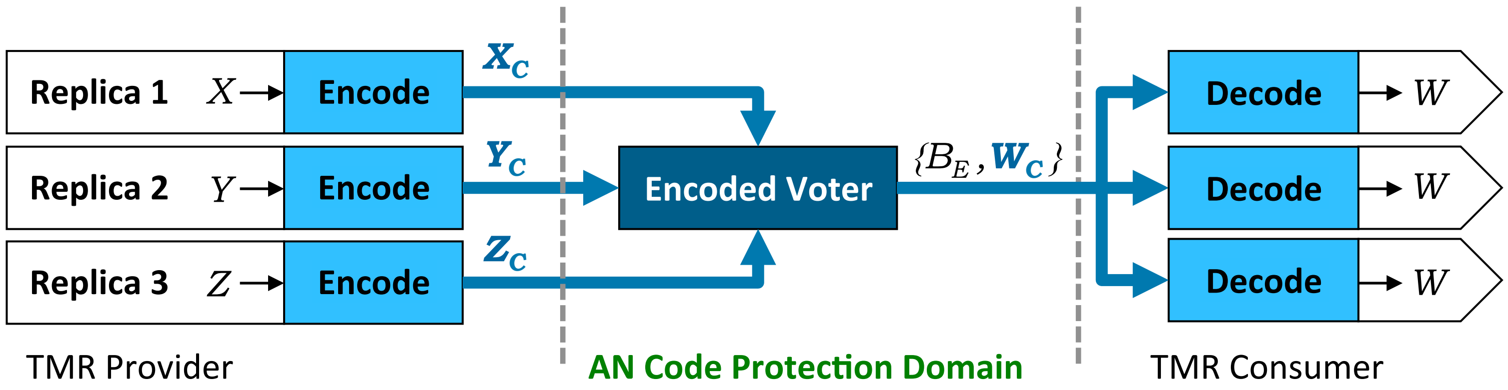
→Practitioners cannot blindly rely on coding theory!

Agenda

- Introduction
- **Background**
  - The *CoRed* Dependable Voter
  - Arithmetic Error Coding
- **Think Binary**
  - Choosing Appropriate Keys
  - Pitfall 1: Mapping Code to Binary
- **Know Your Compiler & Architecture**
  - Pitfall 2: Inter-Instruction State
  - Pitfall 3: Undefined Execution Environment
  - Multi-Bit Faults – A Glimpse
- **Conclusions & Lessons Learned**

The *CoRed* Dependable Voter – Basics



- **Complex encoded comparison operation**
- **Data-flow integrity**
  - Input: Variants (X_C, Y_C, Z_C)
  - Output: Constant signature (B_E) and encoded winner (W_C)
  - Validation: Subsequent check (decode)
- **Control-flow integrity**
  - Static signature (expected value): Compile-time
    → Used as return value E
  - Dynamic signature (actual value): Runtime
    → Applied to winner W_C

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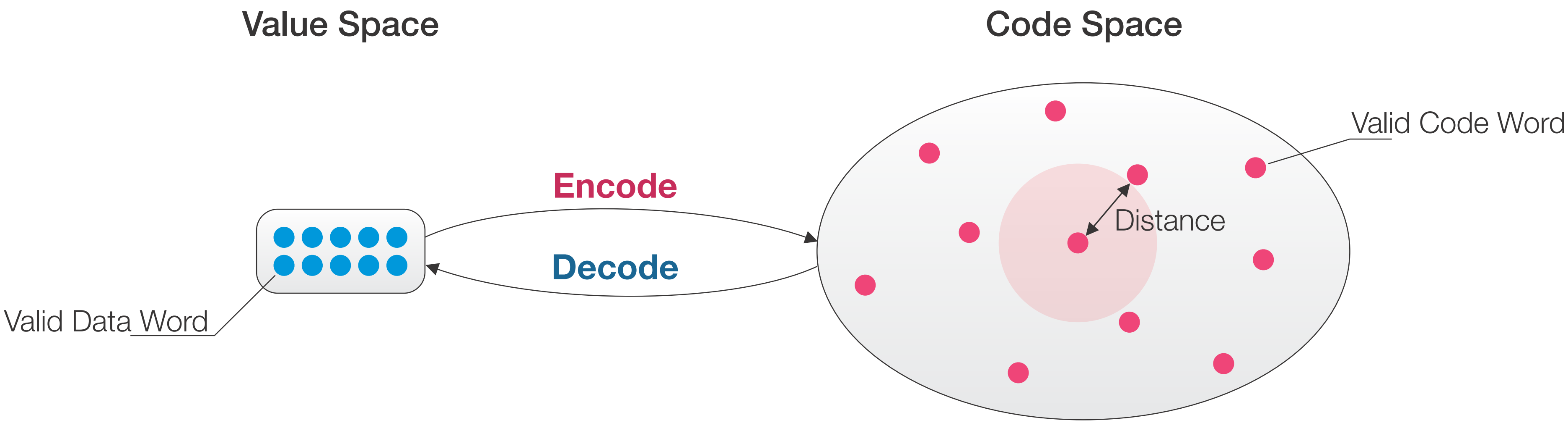

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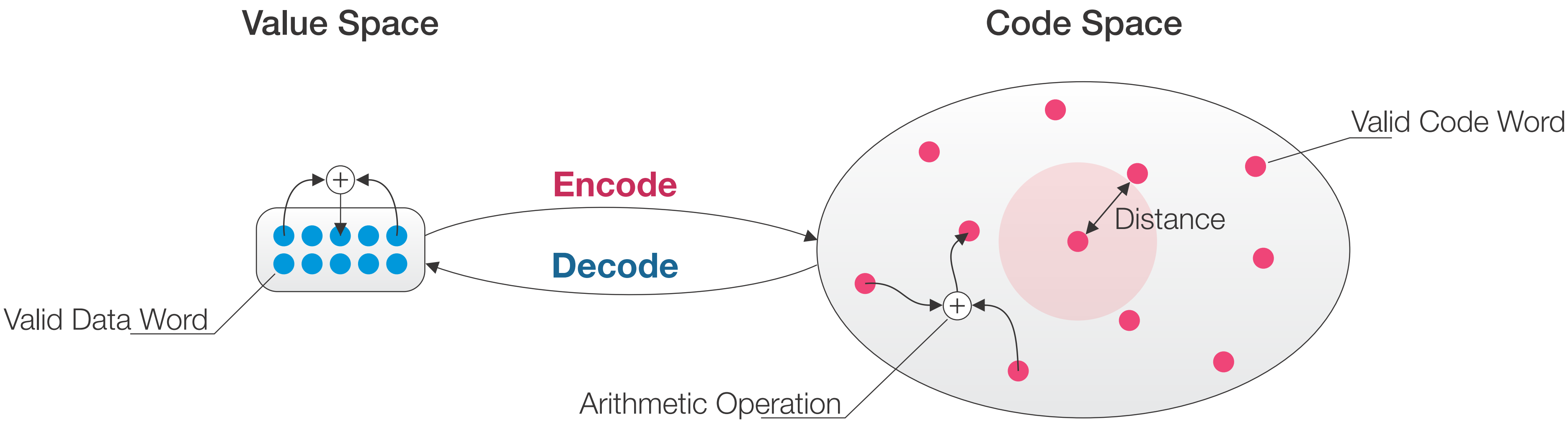

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  - Can cope with computational flaws
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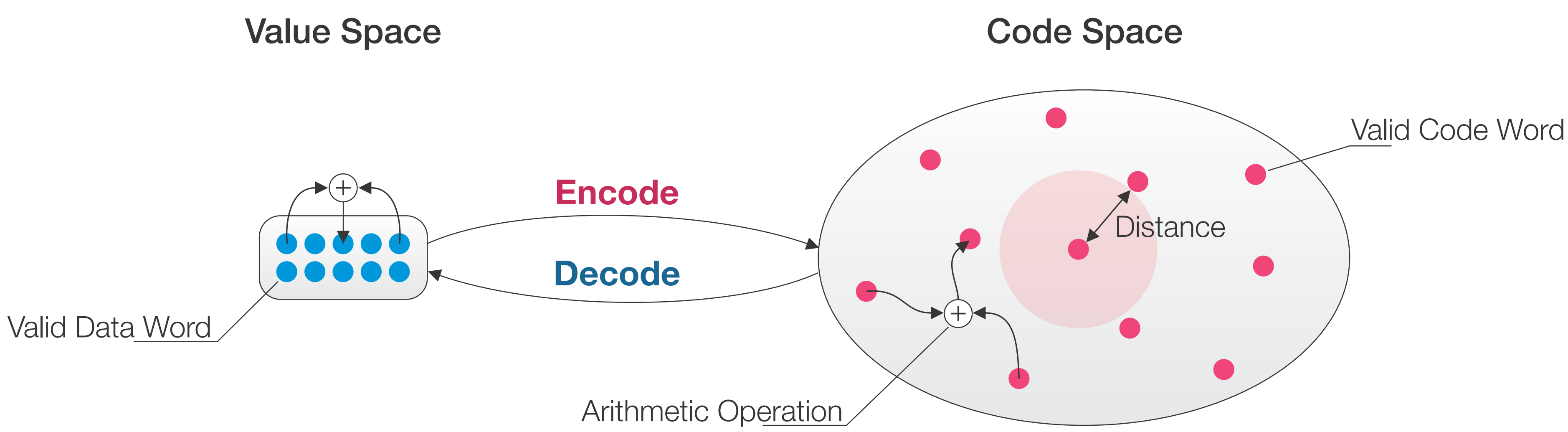

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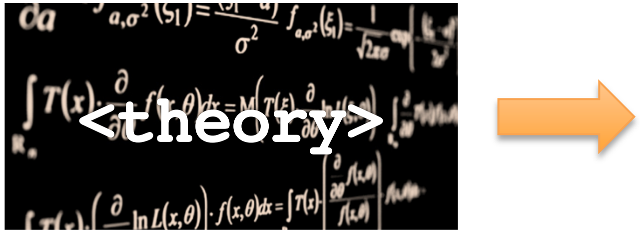
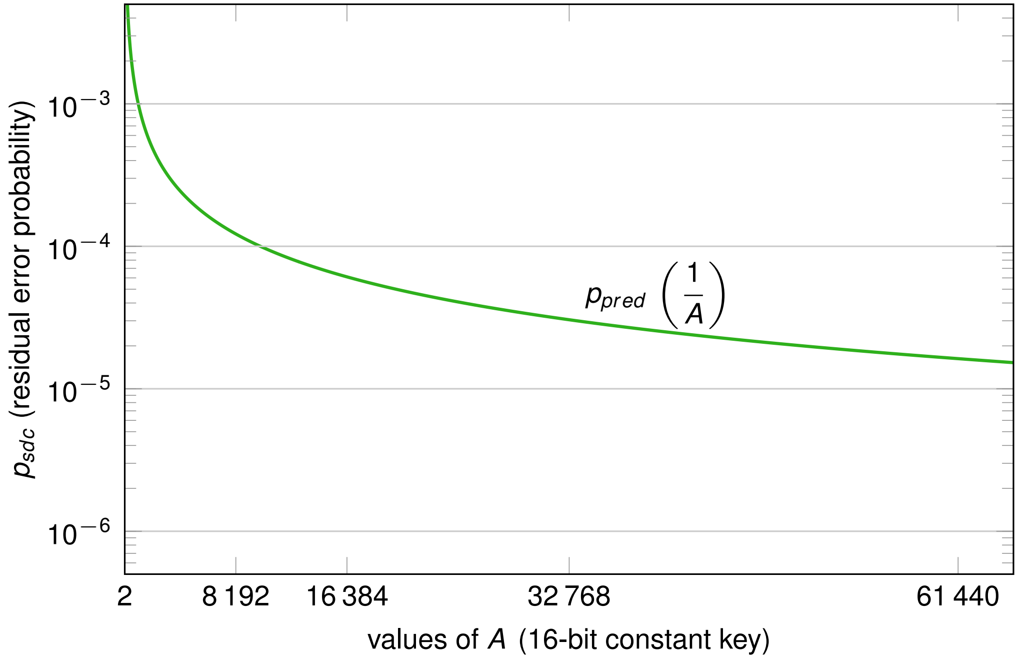
$$v_c = \boxed{A \bullet v} + \boxed{B_v + D}$$

Encoded value — Constant (Key) — Value — Signature — Timestamp

What to Expect? – Residual Error Probability





- **Silent Data Corruption (SDC)**
  - Undetectable code-to-code word mutation
- **Residual error probability**
  - Chance for a SDC
  - Fundamental property for safety assessment

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

→ The bigger key *A*, the better?

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  - Distance (d) between code words (# unequal bits)
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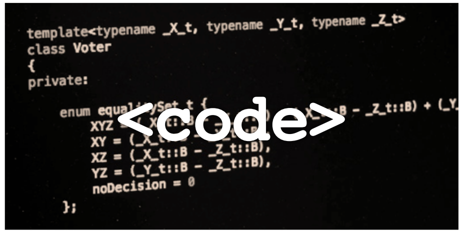
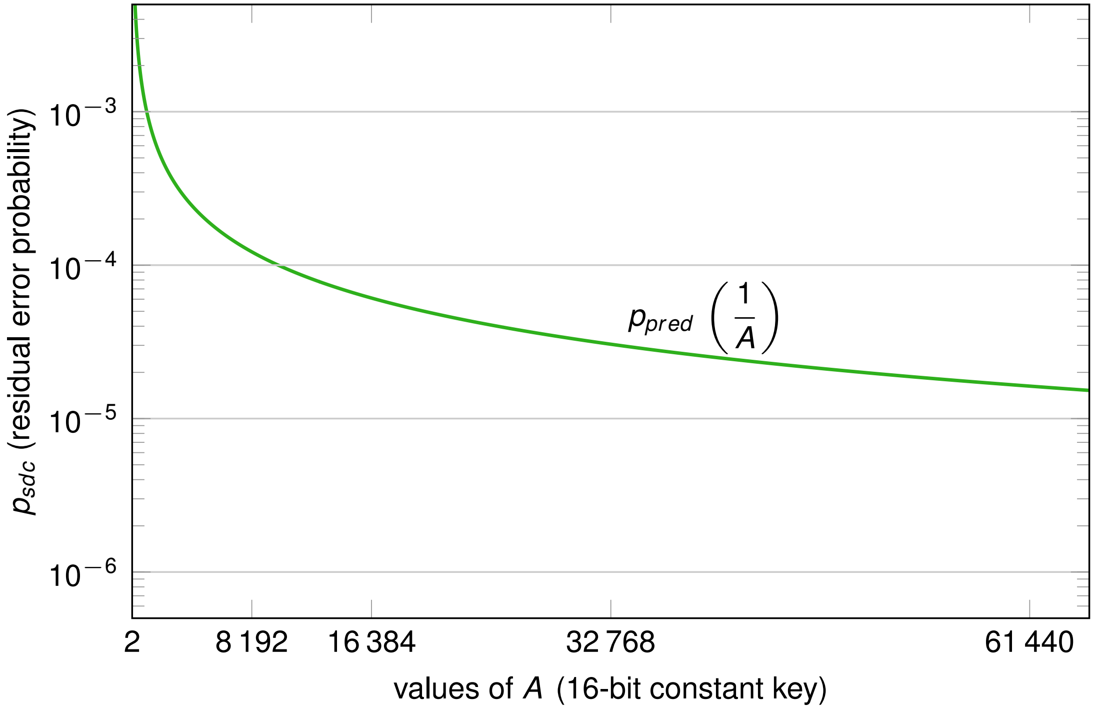
→The bigger the better is misleading!

Double Check – Implementation in the Spotlight





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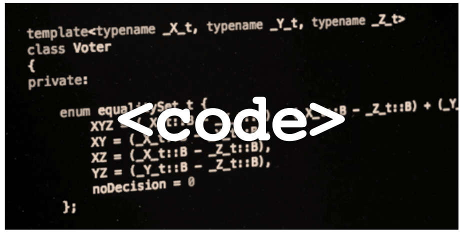

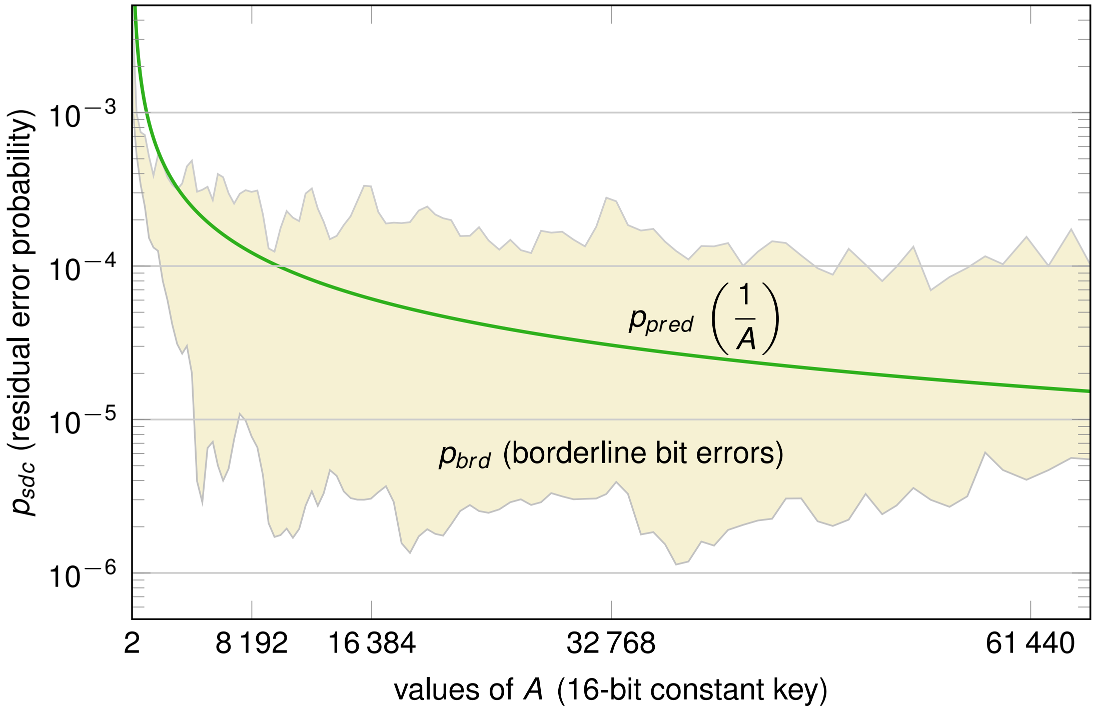

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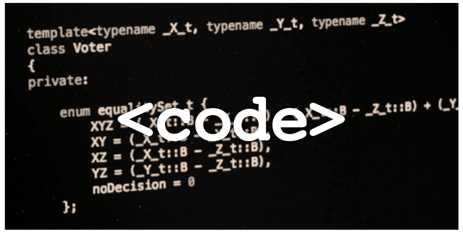

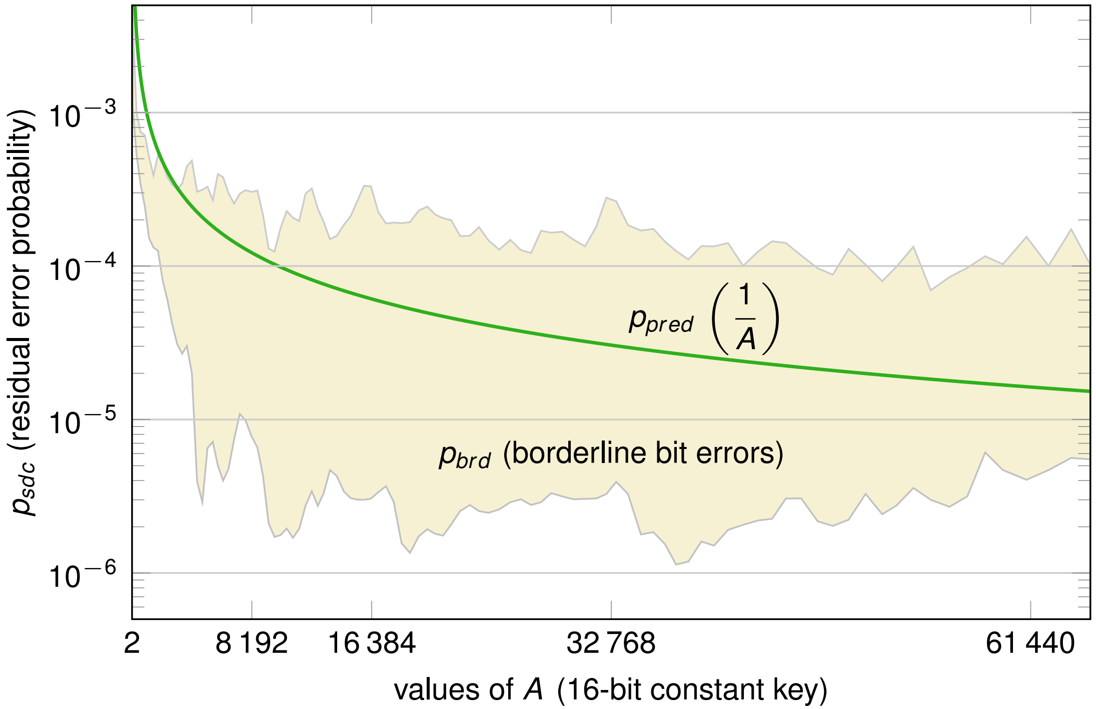

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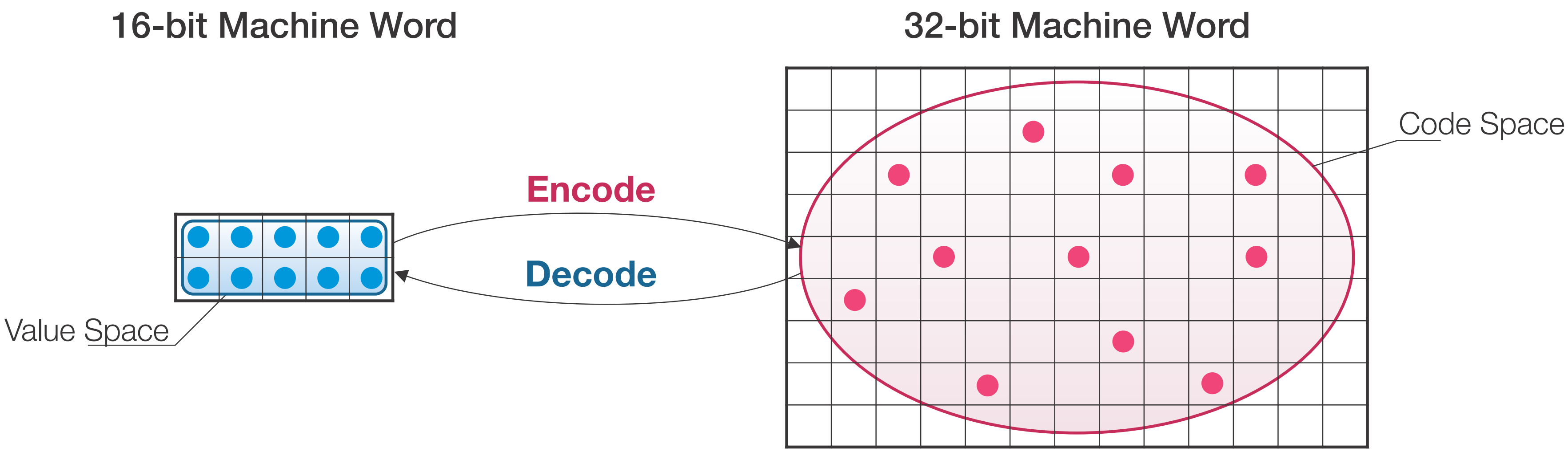

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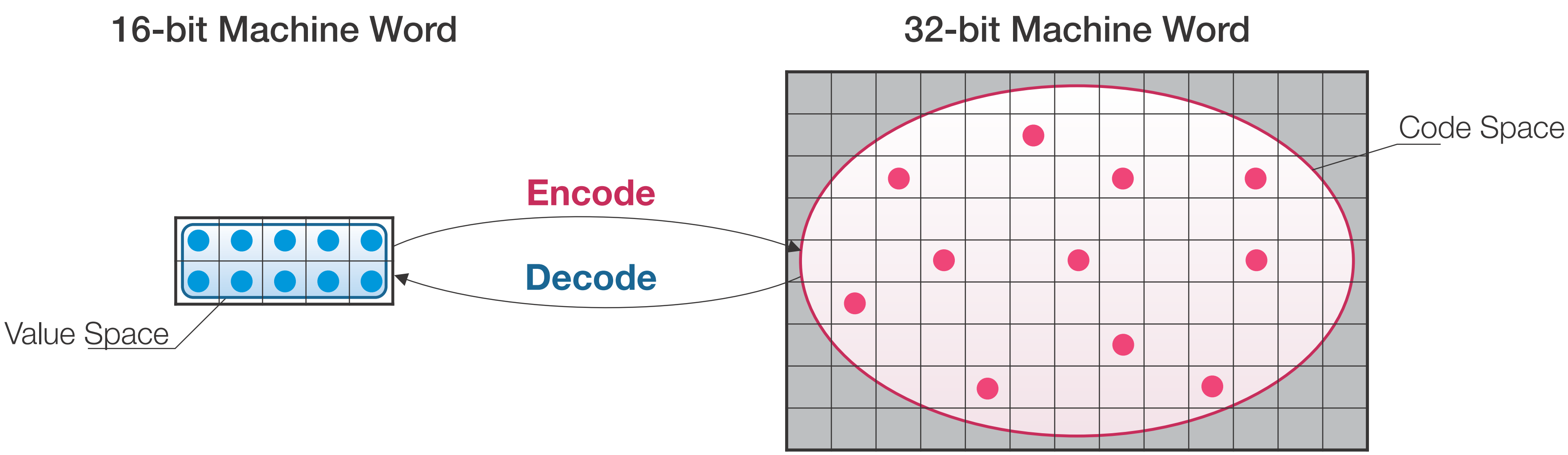

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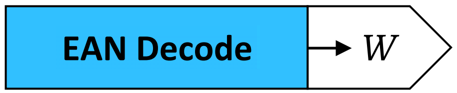
- **EAN Patch:** `decode(`v_C`, A, B, D)`
  - Additional range checks → Prevent code space violation



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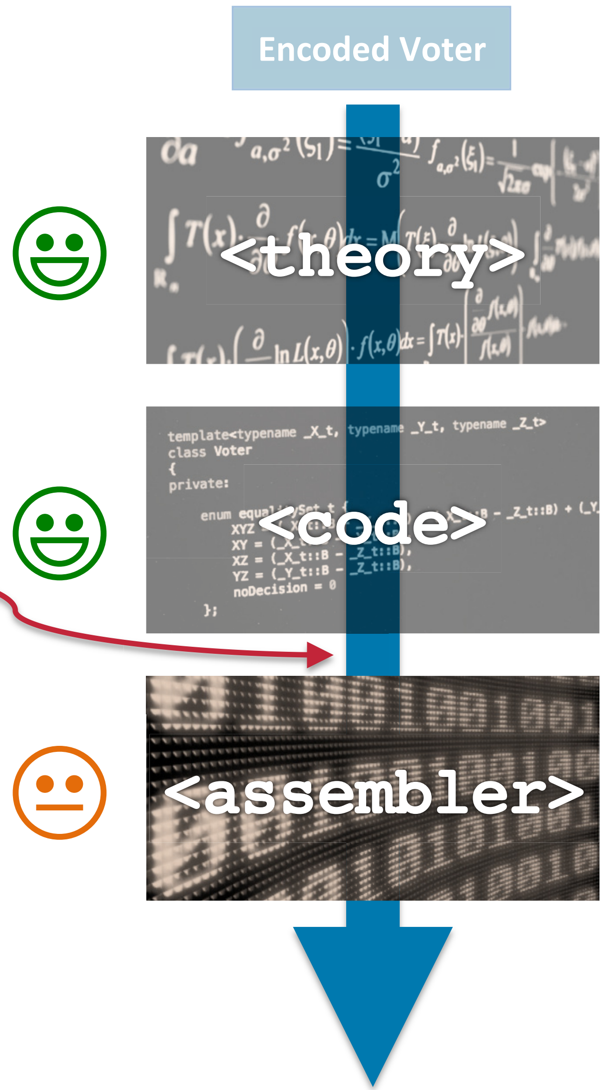

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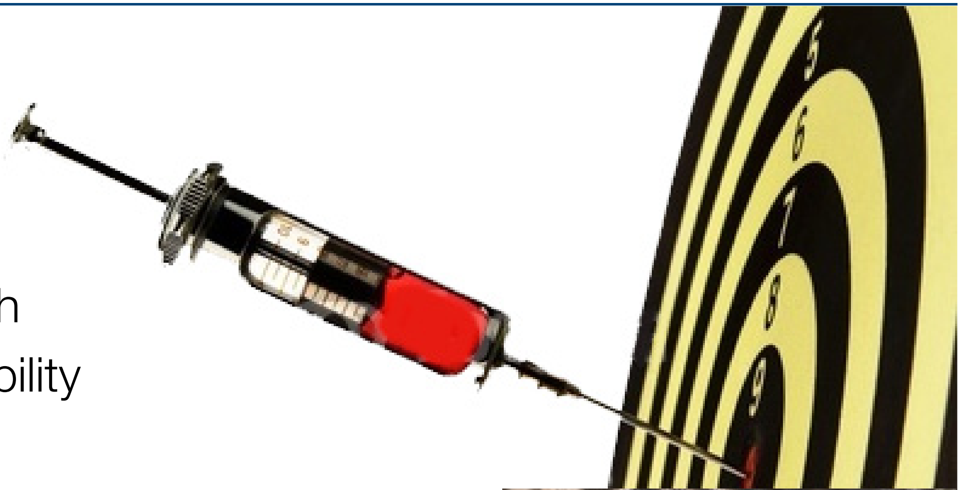
  - Based on Bochs simulator
  - Each and every register, flag, instruction and execution path
  - Fault-space pruning → Feasibility



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  - Footprint:

	CoRed Voter	Simple Voter
Instructions	92	38
Memory (Bytes)	301	112

  - RTOS: Spatial and temporal isolation

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→ **Violation of predicted fault-detection capabilities**

Know your Compiler and Architecture

- Pitfall 2: **Architecture specifics**
  - Example: Absence of compound test-and-branch
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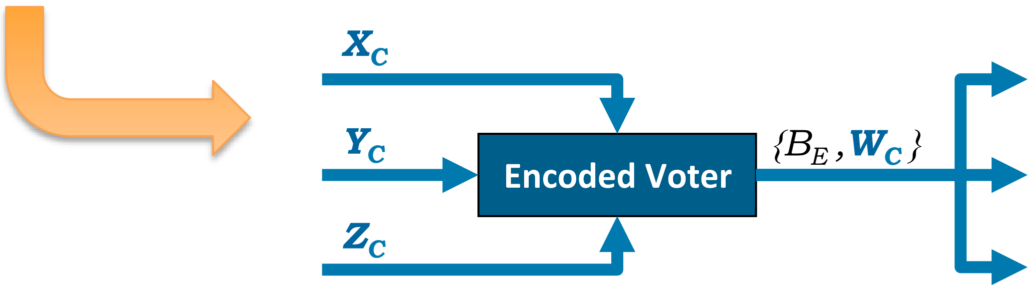

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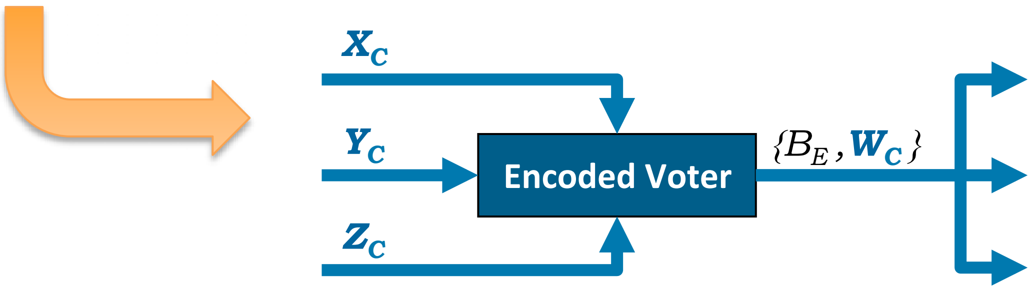

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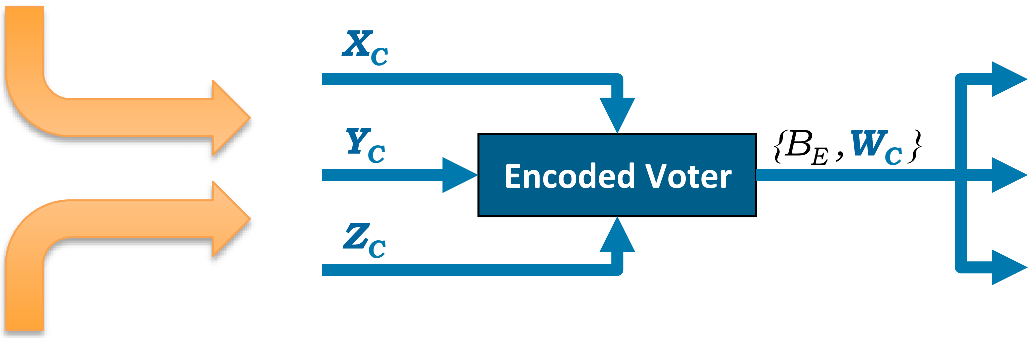

- **EAN Patch:** `vote(`x_C`, `y_C`, `z_C`)`
  - Cleaning the local storage restores isolation

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Fault-Injection Campaigns – Final Results

	Instructions		Registers and Flags		Program Counter	
	Simple	CoRed	Simple	CoRed	Simple	CoRed
OK	784	2772	1040	3204	127	267
Detected (Code)	-	995	-	1435	-	420
Detected (Trap)	93	246	8	41	21	241
Detected (Isolation)	825	1834	1825	3736	2804	6240
Detected (Timeout)	0	1	0	0	0	0
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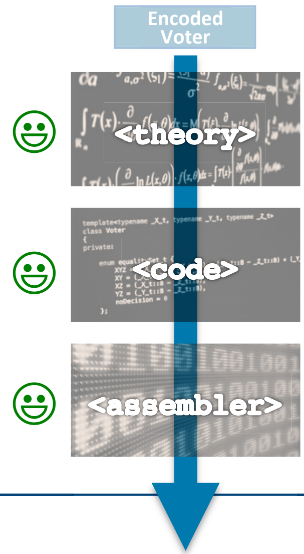
→ **CoRed dependable voter performs as EXPECTED!**



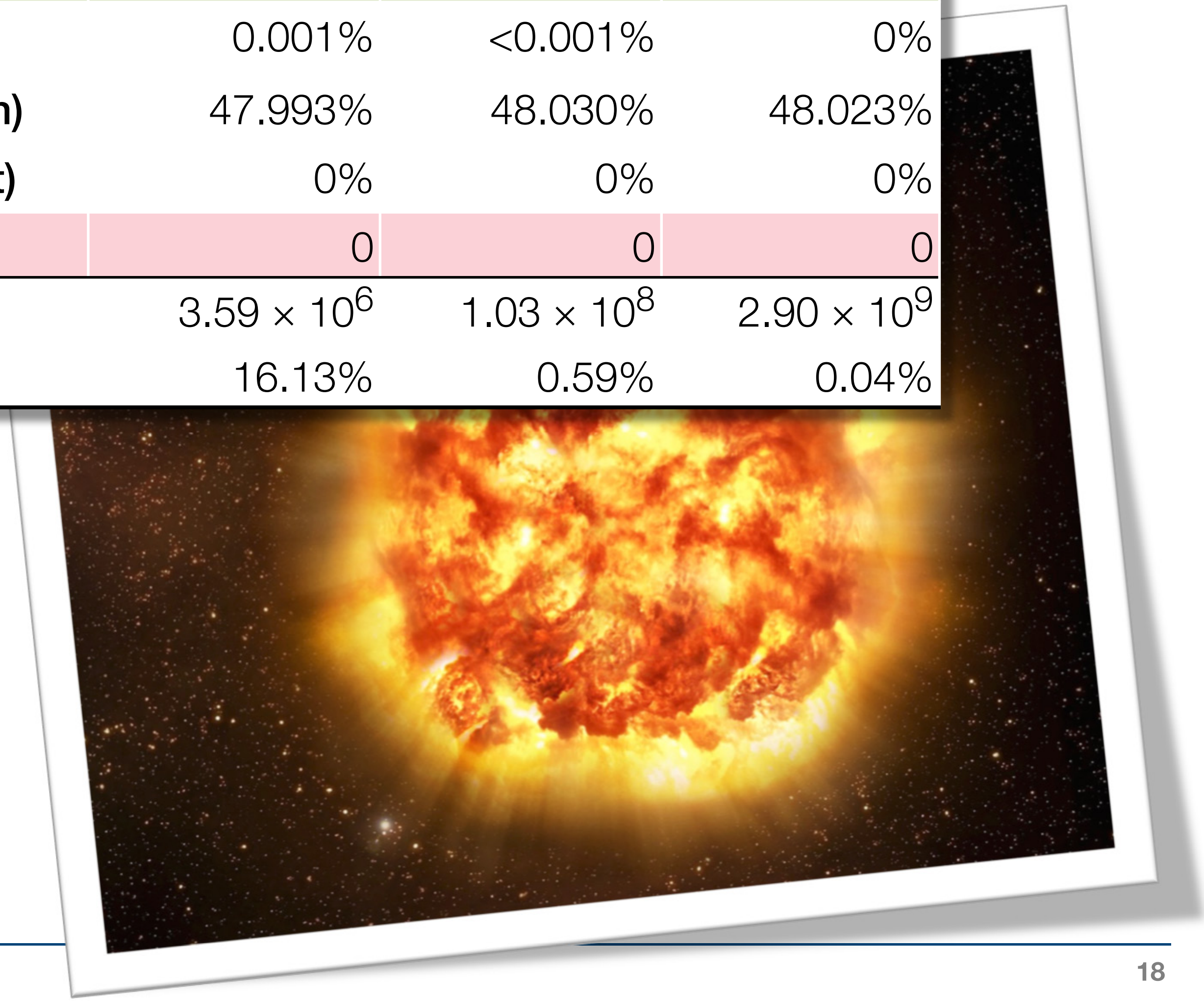
Multi-Bit Faults – The Good, the Bad and the …

	Good A = 58,659	Bad A = 58,368
OK	38639	38639
Detected (Code)	21596	21519
Detected (Trap)	47	47
Detected (Isolation)	60438	60438
Detected (Timeout)	0	0
Undetected	0	**77**

- **2-bit Fault-injection experiments**
  - Full fault space coverage
  - Triple check fault-detection capabilities
- **Distances: d_{good} = 6, d_{bad} = 2**

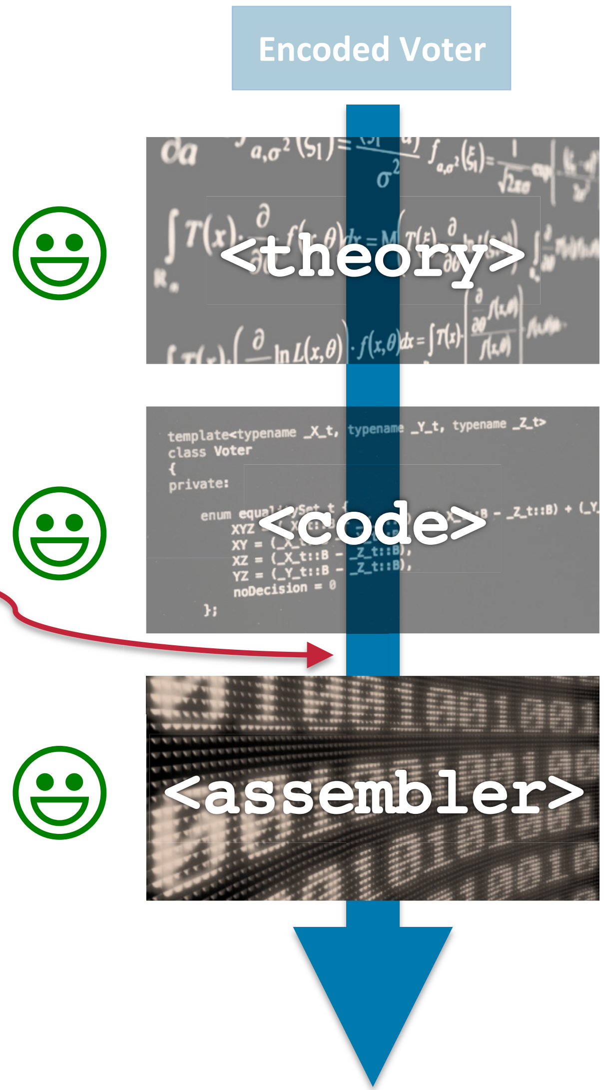
Multi-Bit Faults – Tighten the Rules

	3-bit faults	4-bit faults	5-bit faults
OK	33.742%	33.605%	33.544%
Detected (Code)	18.209%	18.356%	18.431%
Detected (Trap)	0.001%	<0.001%	0%
Detected (Isolation)	47.993%	48.030%	48.023%
Detected (Timeout)	0%	0%	0%
Undetected	0	0	0
Fault Space	3.59×10^6	1.03×10^8	2.90×10^9
Coverage	16.13%	0.59%	0.04%

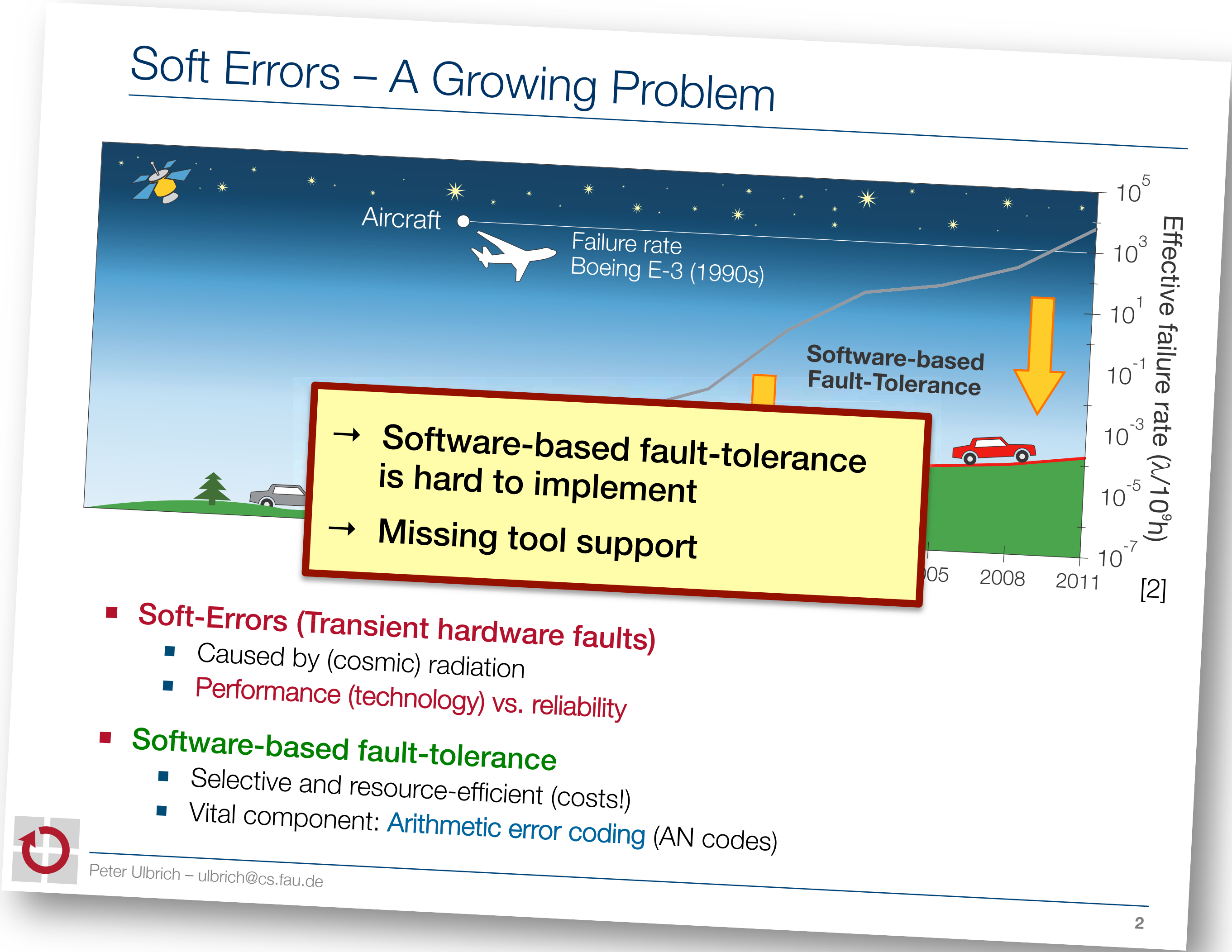


Agenda

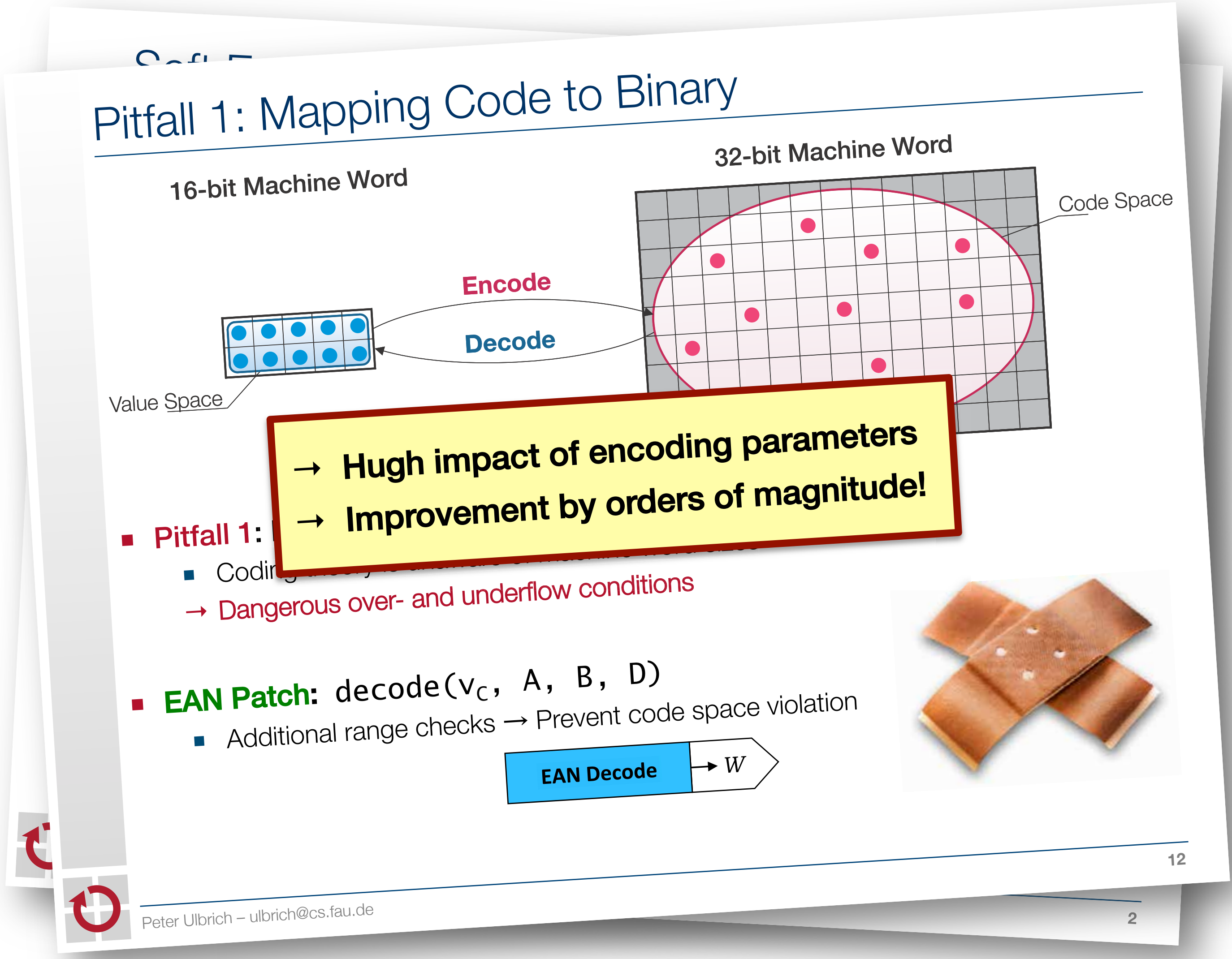
- Introduction
- Background
  - Arithmetic Error Coding
  - The *CoRed* Dependable Voter
- **Think Binary**
  - Choosing Appropriate Keys
  - Pitfall 1: Mapping Code to Binary
- **Know Your Compiler & Architecture**
  - Pitfall 2: Inter-Instruction State
  - Pitfall 3: Undefined Execution Environment
  - Multi-Bit Faults – A Glimpse
- **Conclusions & Lessons Learned**



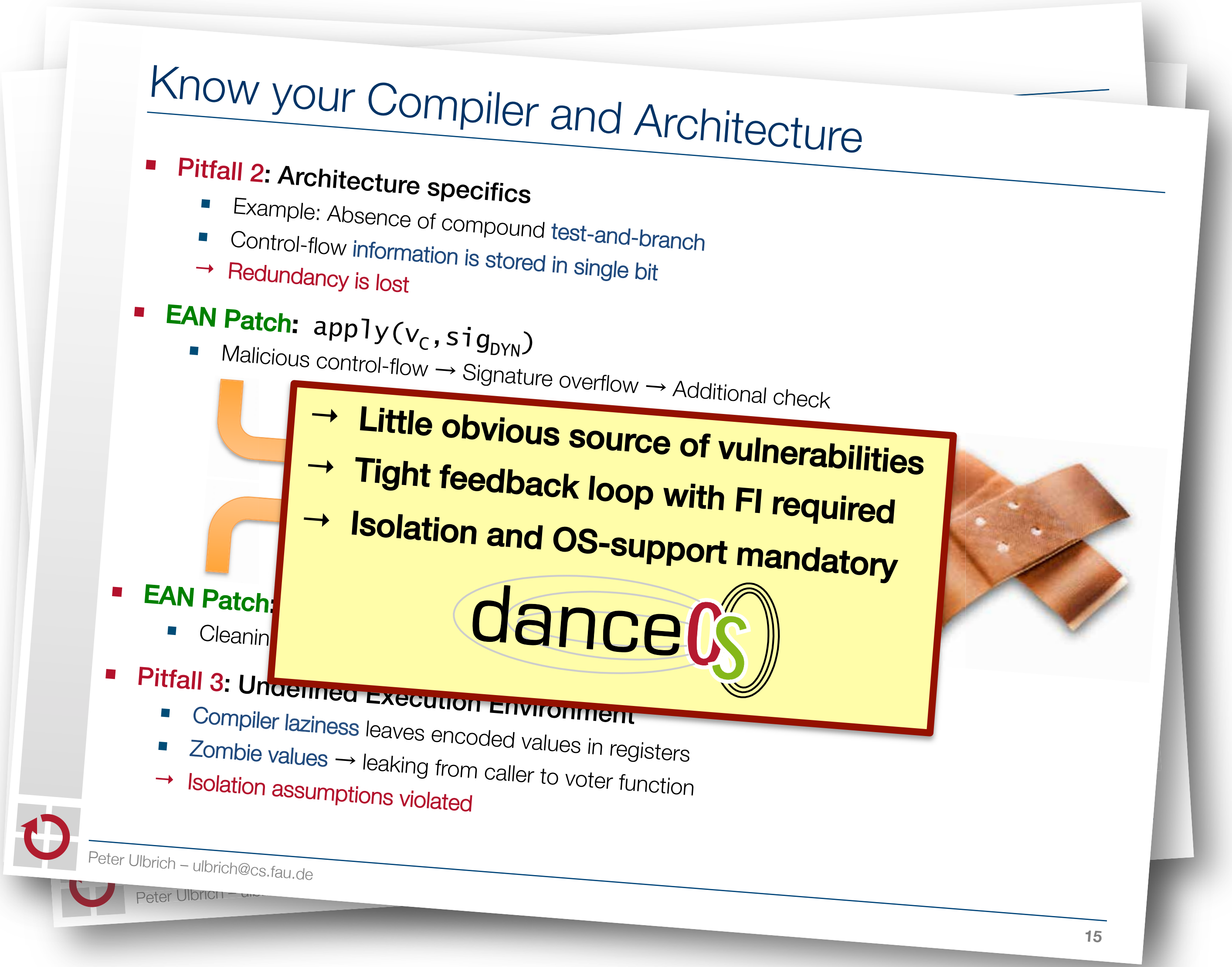
Conclusions & Lessons Learned



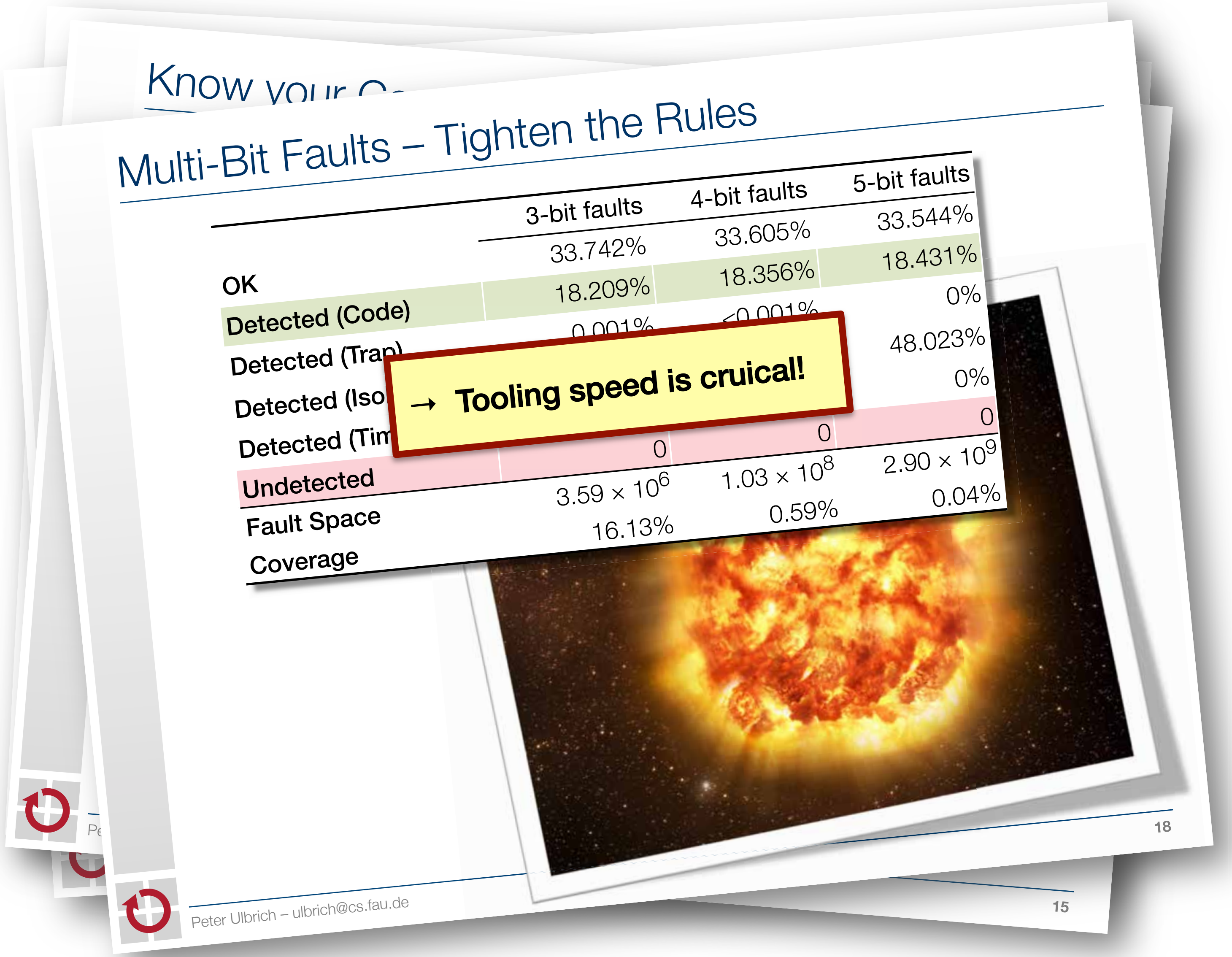
Conclusions & Lessons Learned



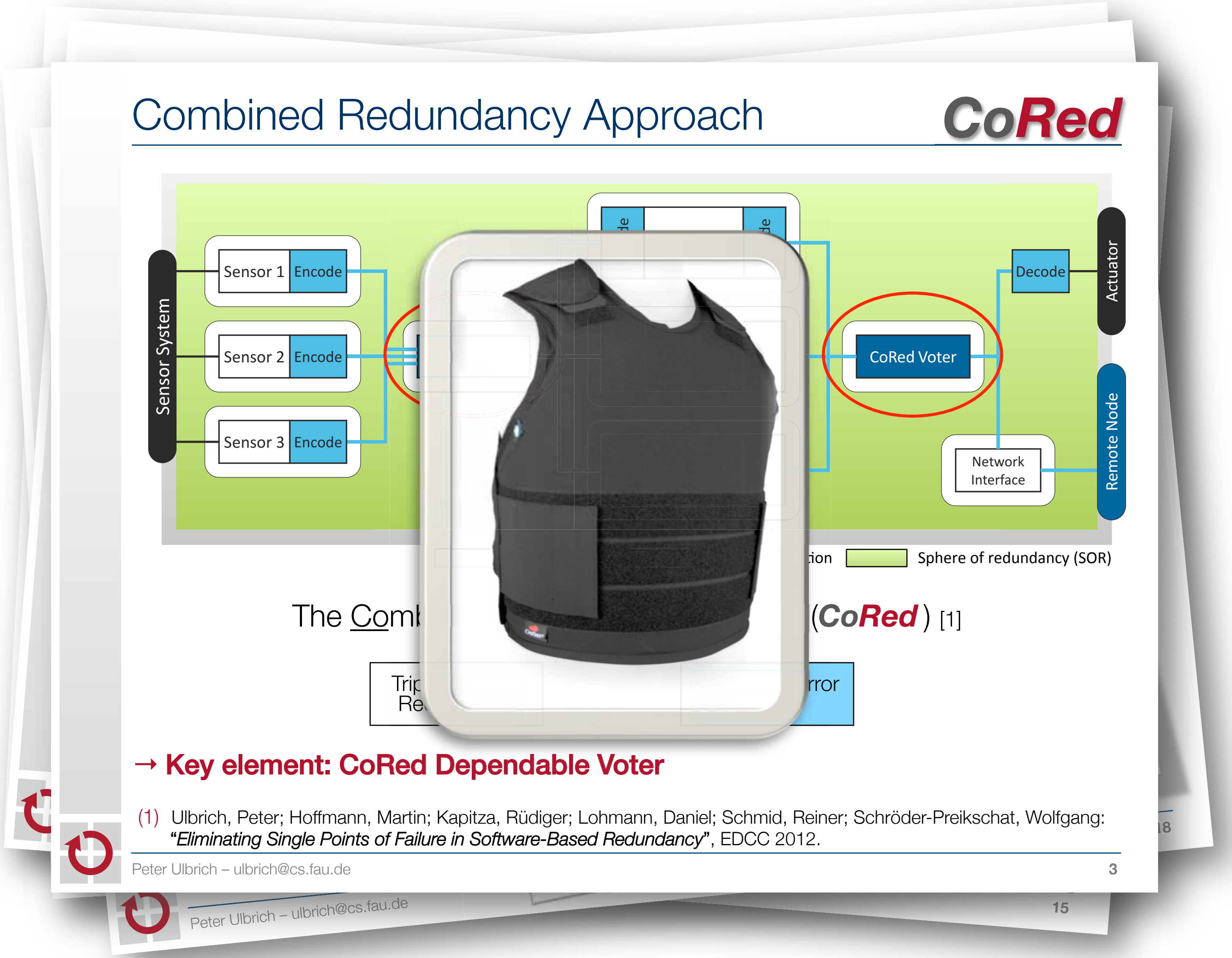
Conclusions & Lessons Learned



Conclusions & Lessons Learned



Conclusions & Lessons Learned



Implementation and further experimental results:

`http://www4.cs.fau.de/Research/CoRed`

Thank you!

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