IKOS: Sound Static Program Analysis

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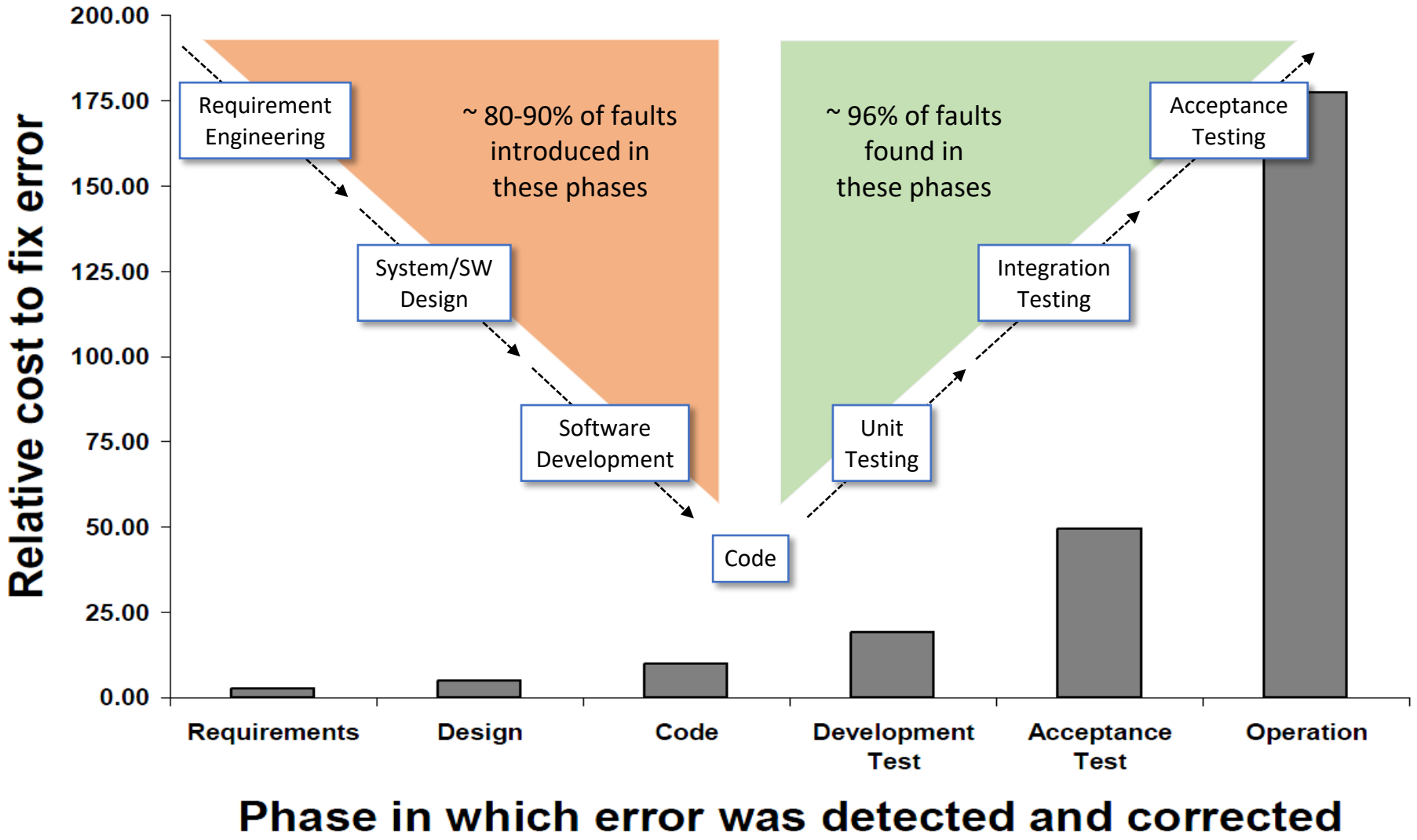
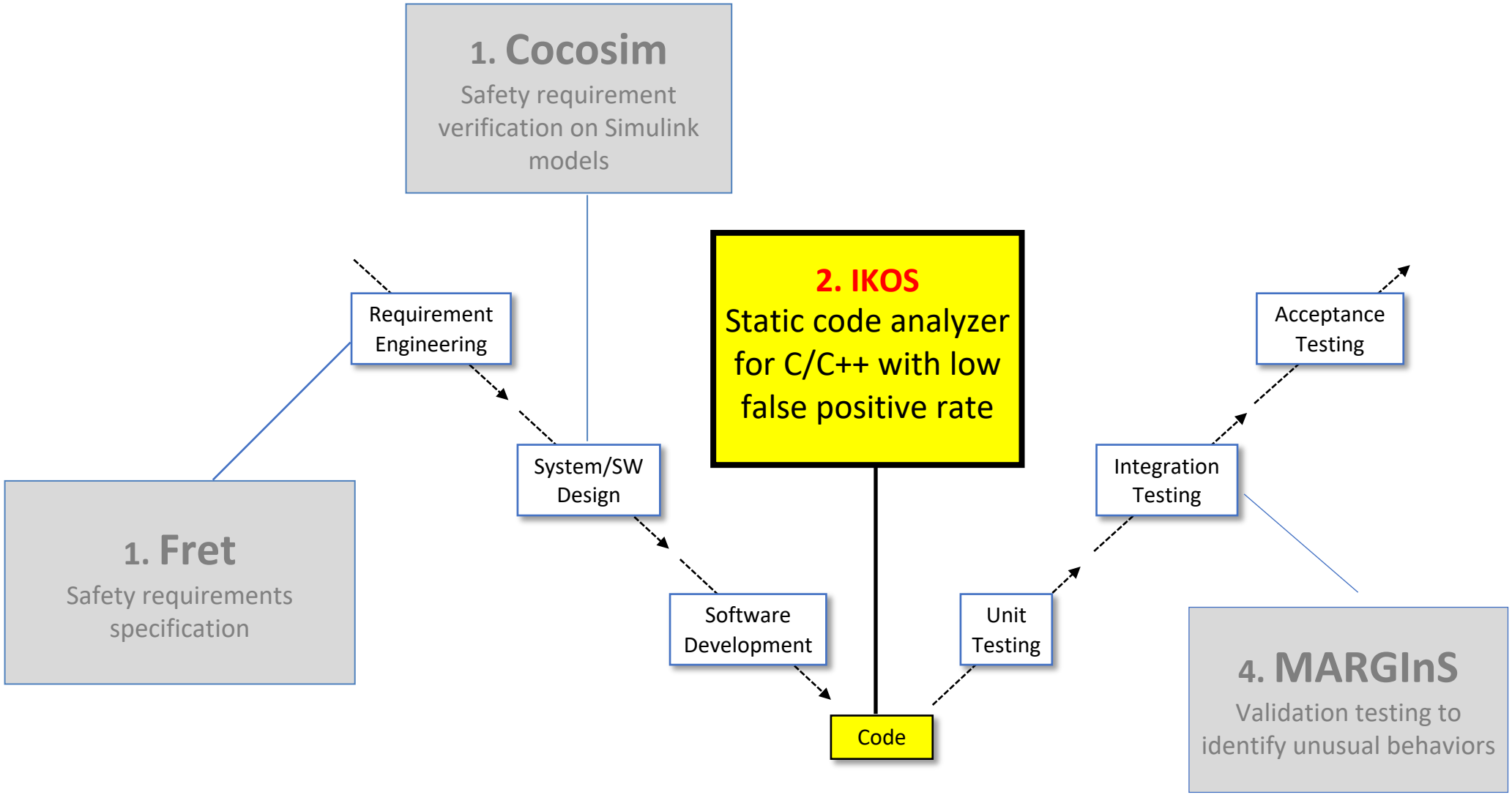
Motivation: V&V Cost Analysis



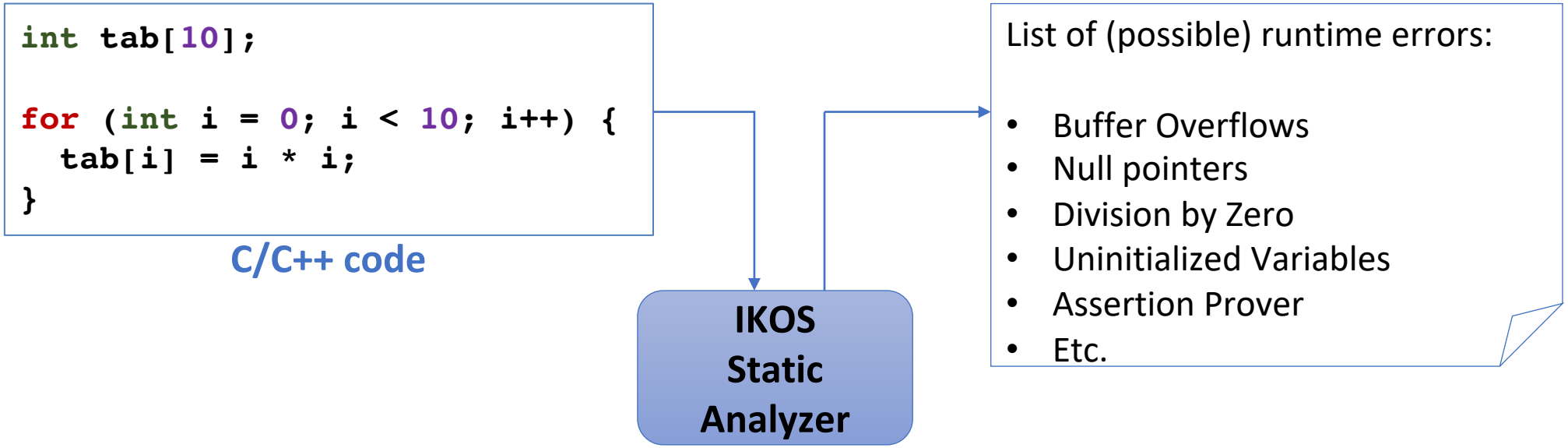
IKOS


1. Cocosim
Safety requirement verification on Simulink models
2. IKOS
Static code analyzer for C/C++ with low false positive rate
1. Fret
Safety requirements specification
Requirement Engineering
System/SW Design
Software Development
Code
Unit Testing
Integration Testing
Acceptance Testing
4. MARGInS
Validation testing to identify unusual behaviors

IKOS

IKOS performs a **compile-time** analysis of a C/C++ source code.

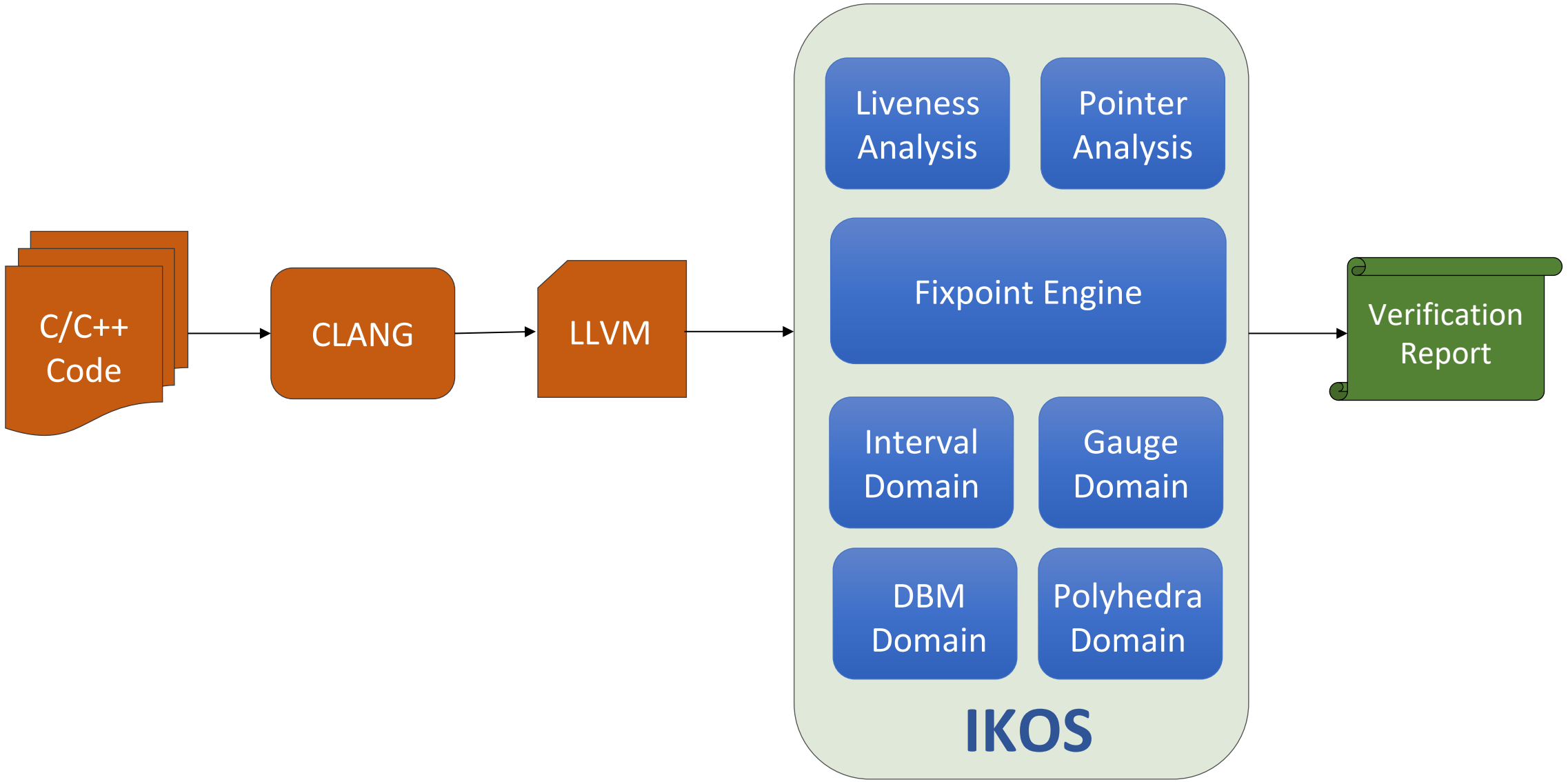
It can **detect** or **prove the absence** of **runtime errors.**



IKOS is **NOT** a code style checker

IKOS is **NOT** a compiler: It can detect errors that compilers cannot catch

IKOS Design


C/C++
Code
CLANG
LLVM
Liveness
Analysis
Pointer
Analysis
Fixpoint Engine
Interval
Domain
Gauge
Domain
DBM
Domain
Polyhedra
Domain
IKOS
Verification
Report

Verification Report

- **Safe**: The instruction is **proven free of runtime errors**
- **Error**: The instruction **always produces** a **runtime error**
- **Warning**:
  - The instruction **can produce an error** depending on the input
  - The instruction is **safe** but IKOS could **not prove it** (also called **false positive**)

Example

```
int tab[10];

for (int i = 0; i < 10; i++) {
  tab[i] = i * i;
}
```

- **The analysis discovers program properties:** $0 \leq \mathbf{i} \leq 9$

Example

```
int tab[10];

for (int i = 0; i < 10; i++) {
  tab[i] = i * i;
}
```

- **The analysis discovers program properties:** $0 \leq \mathbf{i} \leq 9$
- **The verification uses the properties discovered:**
  - Array-bound compliance
  - Check that array **tab** has at least 10 elements

IKOS Checks

- Buffer overflow
- Division by zero
- Null pointer dereference
- Assertion prover
- Unaligned pointer
- Uninitialized variable
- Integer overflow (signed, unsigned)
- Invalid bit shift
- Invalid pointer comparison
- Invalid function pointer call
- Dead code
- Double free and Invalid lifetime

IKOS Abstract Domains

Domain	Constraints	Complexity
Interval	$x \in [a, b]$	n
Congruence	$x \in aZ+b$	n
Gauge	$x \in [a*i + b*k + \ldots, a'*i + b'*k + \ldots]$	K*n
Difference Bound Matrices	$x - y \in [a, b]$	n^3
APRON Octagon	$x \pm y \in [a, b]$	n^3
APRON Polka Polyhedra	a*x + b*y + … + c <= 0	Exponential
APRON PPL Polyhedra	a*x + b*y + … + c <= 0	Exponential
Variable Packing of …	…	n

Live demo

IKOS Installation

- Supported platforms:
  - Mac OS
  - Linux
  - Windows (using *MinGW*)
- **Dependencies** can be installed with a **package manager** (`brew`, `apt-get`, `yum`, ..)
- **Installation instructions** for each platform available in: `doc/install/`
- **Bootstrap script** for **non-admin** installations: downloads and compiles all missing dependencies (*slow*)

IKOS Usage

- Analyze a single file: `ikos file.c`
  - Runs the analysis
  - Prints the results
  - Generates an output database containing the analysis results: `output.db`
- Analyze a whole project:
  - `ikos-scan make`
  - `ikos program.bc`
- Generate a report from an output database: `ikos-report output.db`
- Examine the results in a graphical interface: `ikos-view output.db`

IKOS-SCAN

- Analyze a whole project with: `ikos-scan <command>`
- It compiles all executables to LLVM bitcode: `program.bc`
- It runs IKOS on the LLVM bitcode: `ikos program.bc`
- Works with most build systems: Make, CMake, Autoconf, etc...
- Works by overriding environment variables: `CC`, `CXX`, `LD`

IKOS-SCAN

Live demo

Analyzing a library

- The analysis needs an **entry point** (i.e, `main`)
- **Workaround**: create a small program that uses the library
- Extract the LLVM bitcode from an object file: `ikos-scan-extract file.o`
- Analyze a program with a specific entry point: `ikos file.bc –e=MyMain`

IKOS-VIEW

- **Graphical interface** to examine the analysis results
- Starts a **web server** in the terminal, opens the default **browser**
- `ikos-view output.db`

IKOS-VIEW

Live demo

IKOS Abstract Domains Guidelines

- Start with **fast** but **imprecise** domain
- Go towards **slow** but **precise** domain
- Stop when the analysis is too slow for your use case
- Recommended order:
  - Interval: `-d=interval`
  - Gauge + Interval + Congruence: `-d=gauge-interval-congruence`
  - Variable Packing DBM: `-d=var-pack-dbm`
  - Variable Packing Polyhedra: `-d=var-pack-apron-ppl-polyhedra`

IKOS Assumptions

- The source code is compiled with Clang for the **host architecture**
- Clang defines:
  - The data model (size of types)
  - The memory layout (alignments)
  - The endianness
  - The semantic of floating points
  - Etc...

IKOS Assumptions

- The program is **single-threaded**
- The program does **not** receive **signals** or **interrupts**
- **Unknown extern functions**:
  - Do not update global variables
  - Can write on their pointer arguments
  - Do not call user-defined functions (no callbacks)
- **Assembly code** is treated as a call to an unknown extern function
- **Recursive functions** can update any value in memory

False positives

- **False positive**: invalid warning
- Objective: **low rate** of **false positives**
- Common source of false positives:
  - Unknown library functions
  - “Bad” code patterns
  - Imprecision of the analysis

Modeling library functions

- The analyzer does **not** require the **libraries** used by your program
- Unknown library functions will trigger a warning ("ignored call side effect” in `ikos-view`)
- Modeling library functions can **reduce the number of warnings**
- Write “stubs”: fake implementations of library functions

Modeling library functions

```
#include <ikos/analyzer/intrinsic.h>

char* fgets(char* restrict str,
            int size,
            FILE* restrict stream) {
    __ikos_assert(size >= 0);
    __ikos_forget_mem(stream, sizeof(FILE));
    __ikos_abstract_mem(str, size);
    errno = __ikos_nondet_int();
    return __ikos_nondet_int() ? str : NULL;
}
```

IKOS Annotations

- Annotating your source code can **reduce the number of warnings**
- List of intrinsic functions: `analyzer/include/ikos/analyzer/intrinsic.h`
  - `__ikos_assert(condition)`
  - `__ikos_assume(condition)`
  - `__ikos_nondet_int()`
  - `__ikos_check_mem_access(ptr, size)`
  - `__ikos_assume_mem_size(ptr, size)`
  - `__ikos_forget_mem(ptr, size)`
  - `__ikos_abstract_mem(ptr, size)`
  - `__ikos_print_values(description, var)`

IKOS Annotations

```
ret = talg->parse_algoid_params(buf, param_len, param);
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IKOS Annotations

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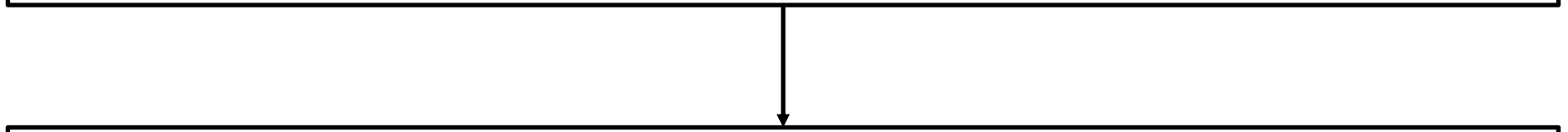


```
int (*fun)(const u8*, u16, alg_param*) =
    talg->parse_algoid_params;
__ikos_assume(fun == parse_algoid_params_generic ||
              fun == parse_algoid_params_ecdsa_with ||
              fun == parse_algoid_params_ecPublicKey ||
              fun == parse_algoid_params_rsa);
ret = fun(buf, param_len, param);
```

Bad code pattern (1)

```
CommandResult = XXX();
if (CommandResult == TRUE) {
    FilenameState = YYY();
    if (FilenameState == FM_NAME_IS_INVALID) {
        CommandResult = FALSE;
    }
}
if (CommandResult == TRUE) {
    CommandResult = ZZZ();
}
if (CommandResult == TRUE) {
    // ...
}
return CommandResult;
```

Bad code pattern (1)

- Bad readability
- Prone to errors
- Hard for static analyzers
- Please use “early return on errors”

Bad code pattern (1)

```
CommandResult = XXX();
if (!CommandResult) {
    return FALSE;
}
CommandResult = YYY();
if (CommandResult == FM_NAME_IS_INVALID) {
    return FALSE;
}
CommandResult = ZZZ();
if (!CommandResult) {
    return FALSE;
}
// ...
return TRUE;
```

Bad code pattern (2)

- Single global variable containing everything

```
AppData_t g;

typedef struct {
    PipeId_t CmdPipeId;
    uint16 usCmdPipeDepth;
    char cCmdPipeName[OS_MAX_API_NAME];
    int32 ulfd;
    uint32 uiRunStatus;
    // ...
    uint8 lastCmdBchErrorStatus;
} AppData_t;
```

Bad code pattern (2)

- Makes the buffer overflow analysis harder
- Please split it into different global variables

Bad code pattern (3)

- Small integers for loop counters

```
void f(uint16_t n) {
    for (uint16_t i = 0; i < n; i++) {
        // ...
    }
}
```

Bad code pattern (3)

- Small integers for loop counters

```
void f(uint16_t n) {
    for (uint16_t i = 0; i < n; i++) {
        // ...
    }
}
```

- Integer promotion rules of C

```
void f(uint16_t n) {
    for (uint16_t i = 0;
         (unsigned int)i < (unsigned int)n;
         i = (uint16_t)((unsigned int)i + 1)) {
        // ...
    }
}
```

Bad code pattern (3)

- Creates temporary variables in the LLVM bitcode
- Leads to imprecision of the analysis
- Please use `size_t` (or `int`) for loop indexes

Imprecision

- Initialization functions returning an error code

```
int Init(void) {

    int status = Register();
    if (status != SUCCESS) {
        return status;
    }

    status = InitEvent();
    if (status != SUCCESS) {
        return status;
    }

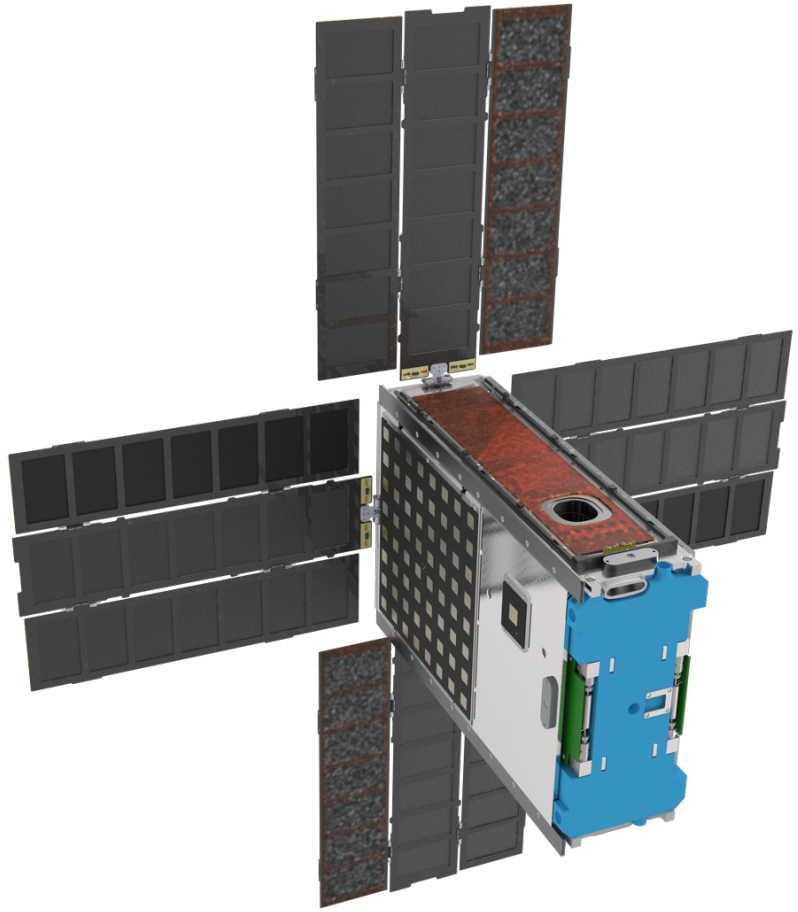
    // ...
```

Imprecision

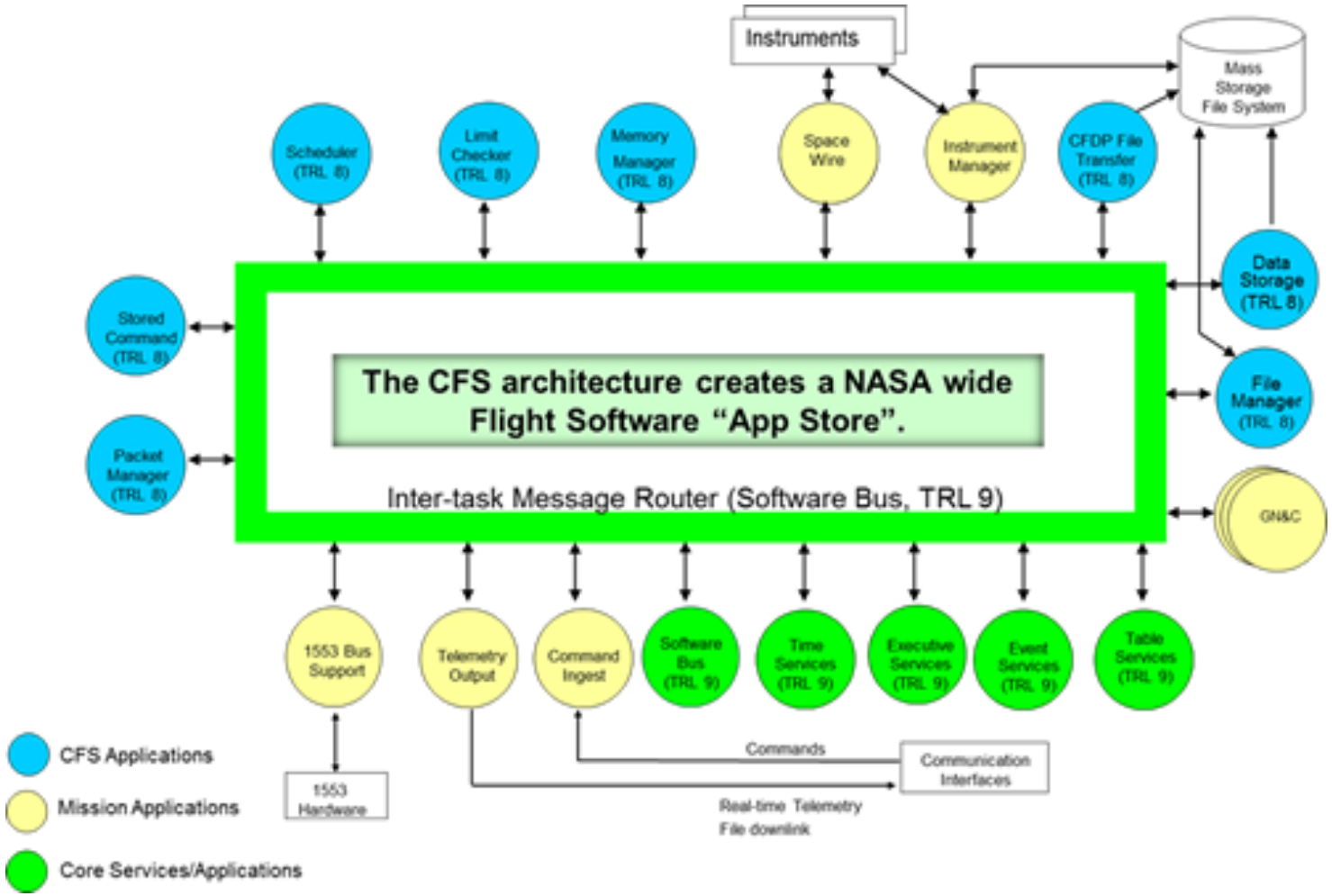
- Imprecision due to the abstract union in the analysis
- Temporary workaround: add `exit(0)` for each failure branch (ugly!)
- Proper fix in the next update – using partitioning

Success Story: BioSentinel

- Space biology mission
- CubeSat spacecraft
- Developed at NASA Ames, in collaboration with JPL, JSC, MSFC
- Flight software built on top of CFS



Success Story: BioSentinel



Success Story: BioSentinel

- Each application was analyzed with IKOS
- The CFE framework was modeled to improve the analysis (~ 1200 LOC)
- Low rate of warnings: 1.31% in average
- Found ~ 17 real bugs

Success Story: BioSentinel

Application	Abstract Domain	Time	Errors	Warnings	Warnings%	Checks
adio	var-pack-dbm	1 min 6.92 sec	0	1	0.07%	1334
brdio	var-pack-dbm	8.02 sec	0	8	0.97%	818
ci	var-pack-dbm	19.98 sec	0	6	0.65%	923
comio	var-pack-dbm	1 min 4.83 sec	0	4	0.26%	1494
epsio	var-pack-dbm	30.64 sec	0	5	0.42%	1181
letio	var-pack-dbm	24.33 sec	0	18	1.64%	1095
ms	interval	0.16 sec	0	0	0%	444
saio	var-pack-dbm	22.35 sec	0	8	0.64%	1246
sensio	var-pack-dbm	4.67 sec	0	79	9.56%	826
spe	interval	0.16 sec	0	0	0%	445
thrio	var-pack-dbm	19.33 sec	0	4	0.38%	1043
to	var-pack-dbm	2 min 18.32 sec	0	33	1.98%	1666
xactio	var-pack-dbm	22.18 sec	0	6	0.51%	1165

BioSentinel Bug (1)

```
warning: Possible buffer overflow, pointer '&FrameBuffer[0]' with offset 0
bytes points to global variable 'FrameBuffer' of size 4096 bytes
```

```
ssize_t numbytes = read(fd, &FrameBufferRaw[0], 4096);

if (numbytes < 0) {
    return ERROR;
}

// ...

numbytes -= 9; // Integer overflow

memcpy(/*dst*/ FrameBuffer, /*src*/ FrameBufferRaw, /*size*/ numbytes);
^~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

BioSentinel Bug (2)

```
warning: Possible buffer overflow, pointer '&cmd[n + 2]' accesses 1 bytes at
offset between 8 and 16 bytes of local variable 'cmd' of size 16 bytes
```

```
uint8_t  cmd[16];
uint8_t  n;
// ...
switch(cmd_request) {
    case CMD_OPEN:
        n = CMD_OUT + CMD_OPEN; // 6 + 8 = 14
        break;
    // ...
}
// ...
cmd[n + 2] = 0; // 14 + 2 = 16
```

Guidelines

- Use a lightweight static analyzer first: cppcheck, clang-tidy, pvs-studio, etc.
- Use ikos-scan to generate the llvm bitcode (*.bc):* `ikos-scan make`
- Use ikos on the llvm bitcode (.bc): `ikos program.bc`
- Try different abstract domains: `ikos –d=var-pack-dbm program.bc`
- Use ikos-view to examine the results: `ikos-view output.db`
- (Optional) Model key library functions
- (Optional) Annotate the code
- (Optional) Avoid “bad” patterns
- (Optional) Add ikos in your continuous build system?

Comparison: Frama-C EVA

Category	IKOS	Frama-C
Price	**Free**	**Free**
Commercial Support	No	**TrustInSoft**
Rate of false positives	**Similar**	
Execution time	**Similar**	
Warning messages	**Good**	Simple
Analysis features	Few	**Many**
Graphical Interface	**Good**	Simple
Analyze a whole project	**Easy**	Complicated

Comparison: PolySpace

Category	IKOS	PolySpace
Price	**Free**	Expensive
Commercial Support	No	**Yes**
Rate of false positives		???
Execution time		???
Warning messages	**Similar**	
Analysis features	Few	**Many**
Graphical Interface	Good	**Very good**
Analyze a whole project	Easy	???

Comparison: Astrée

Category	IKOS	Astrée
Price	**Free**	Expensive
Commercial Support	No	**Yes**
Rate of false positives		???
Execution time		???
Warning messages		???
Analysis features	Few	???
Graphical Interface	Good	???
Analyze a whole project	Easy	???

IKOS at a glance

- IKOS is a **static analyzer** for **C/C++** targeting **safety critical** software
- IKOS is **open source**: https://github.com/NASA-SW-VnV/ikos
- Contact: ikos@lists.nasa.gov

Thank you.

Questions?