

Software and Safety

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<https://www.woven.toyota>

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Definitions

Definitions

Safety Critical Software

The consequence for failure is injury or loss of life.

Definitions

Software with Safety Consequences

Failure can cause quality-of-life problems for users
— e.g. loss of money, loss of work, loss of trust,
exposure of personal details, identity theft.

Software for Dangerous Devices



Software for Dangerous Devices

- Automotive control software — steering, brakes, engine control



Software for Dangerous Devices

- Automotive control software — steering, brakes, engine control
- Aircraft cockpit software



Software for Dangerous Devices

- Automotive control software — steering, brakes, engine control
- Aircraft cockpit software
- Factory machinery control software



Software for Dangerous Devices

- Automotive control software — steering, brakes, engine control
- Aircraft cockpit software
- Factory machinery control software
- Nuclear power plant control software



Software in Medical Devices



Software in Medical Devices

- Pacemakers



Software in Medical Devices

- Pacemakers
- Defibrilators



Software in Medical Devices

- Pacemakers
- Defibrilators
- Artificial lungs



Software in Medical Devices

- Pacemakers
- Defibrilators
- Artificial lungs
- CT Scanners



Software Designed to Increase Safety



Software Designed to Increase Safety

- Driving assistance software



Software Designed to Increase Safety

- Driving assistance software
- Automatic cut-off on cookers



Software Designed to Increase Safety

- Driving assistance software
- Automatic cut-off on cookers
- Fire alarm and sprinkler systems



Software for Management Tasks



Software for Management Tasks

- Traffic light control software



Software for Management Tasks

- Traffic light control software
- Air traffic management software



Software for Management Tasks

- Traffic light control software
- Air traffic management software
- Railway management software



Personal Data Management



Personal Data Management

- Payment software



Personal Data Management

- Payment software
- Banking software



Personal Data Management

- Payment software
- Banking software
- Phone software



Personal Data Management

- Payment software
- Banking software
- Phone software
- Social Media



Incidental Software



Incidental Software

- Games



Incidental Software

- Games
- Internet-connected devices



Incidental Software

- Games
- Internet-connected devices
- Web browsers



Incidental Software

- Games
- Internet-connected devices
- Web browsers
- Spreadsheets



Software Development Standards

Safety Critical Software has Standards to conform to.

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The “baseline” standard is IEC 61508: “Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems”

Software Development Standards

There are also industry-specific standards:

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- ISO 26262 for automotive software

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- DO-178C for aerospace software

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- IEC 62304 and related standards for medical device software

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- CENELEC EN 50128 for railway software

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- DO-178C for aerospace software
- IEC 62304 and related standards for medical device software
- CENELEC EN 50128 for railway software
- etc.

Software Development Standards

If your software is not “Safety Critical”, then these don’t apply.

Software Development Standards

If your software is not “Safety Critical”, then these don’t apply.

You should still consider “safety”, and the potential impact of failure on your users.

Problem Causes

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A big cause of problems is circumstances the developers didn't expect to happen:

	Knowns	Unknowns
known	known Knowns	known Unknowns
unknown	unknown Knowns	unknown Unknowns

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A big cause of problems is circumstances the developers didn't expect to happen:

- Events they thought “would never happen”

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Problem Causes

A big cause of problems is circumstances the developers didn't expect to happen:

- Events they thought “would never happen”
- Events they **didn't even consider as possibilities**

	Knowns	Unknowns
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Problem Causes

Another big cause is **mistakes**



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The developer **intended** one thing, but the code does something else



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The developer **intended** one thing, but the code does something else

We commonly call these cases **bugs**



Problem Causes

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Problem Causes

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- Hardware failure — sensors, motors, displays, storage, ...
- “Bad” user input — steering off a bridge, entering incorrect drug dosage, ...

From a safety point of view, these are **design** issues.

Can we design the **system** to handle these?

Another Definition

undefined behavior

behavior for which this document imposes no requirements

— C++23 §3.65 [*defns.undefined*]

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behavior for which this document imposes no requirements

— C++23 §3.65 [defns.undefined]

“no requirements” means the code can do **anything at all**.

Undefined Behaviour

*the implemented software unit shall be verified
...to provide evidence for ...confidence in the
absence of unintended functionality*

— ISO 26262

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Code with UB can do **anything at all**. This is likely **unintended functionality**, so must be avoided.

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absence of unintended functionality*

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Code with UB can do **anything at all**. This is likely **unintended functionality**, so must be avoided.

Safety-Critical code **must provide evidence**.

Memory Safety?

There is a lot of publicity about the lack of Memory Safety being a **big** problem.



The Case for Memory Safe Roadmaps

Why Both C-Suite Executives and Technical Experts Need to Take Memory Safe Coding Seriously

Publication: December 2023

United States Cybersecurity and Infrastructure Security Agency
United States National Security Agency
United States Federal Bureau of Investigation
Australian Signals Directorate's Australian Cyber Security Centre
Canadian Centre for Cyber Security
United Kingdom National Cyber Security Centre
New Zealand National Cyber Security Centre
Computer Emergency Response Team New Zealand

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Such problems are often an example of Undefined Behaviour:



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There is a lot of publicity about the lack of Memory Safety being a **big** problem.

Such problems are often an example of Undefined Behaviour:

- Lifetime errors
- Bounds errors



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Undefined Behaviour

Undefined behaviour is often a **consequence of an unexpected event.**

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known	known Knowns	known Unknowns
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Undefined behaviour is often a **consequence of an unexpected event**.

If we are serious about “Safety”, we need to work hard to ensure we **eliminate unexpected events**.

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unknown	unknown Knowns	unknown Unknowns

Consequences

This all impacts how you develop software.

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In particular, it affects how you **specify** that software, and **test** that software.

Validating Input

A tester walks into a bar...



Validating Input

A tester walks into a bar...

- Orders 1 beer



Validating Input

A tester walks into a bar...

- Orders 1 beer
- Orders 99 beers



Validating Input

A tester walks into a bar...

- Orders 1 beer
- Orders 99 beers
- Orders an orange juice



Validating Input

A tester walks into a bar...

- Orders 1 beer
- Orders 99 beers
- Orders an orange juice
- Orders -1 beers



Validating Input

A tester walks into a bar...

- Orders 1 beer
- Orders 99 beers
- Orders an orange juice
- Orders -1 beers
- Orders four candles



Validating Input

A tester walks into a bar...

- Orders 1 beer
- Orders 99 beers
- Orders an orange juice
- Orders -1 beers
- Orders four candles
- Orders a **DROP TABLE DRINKS**



Validating Input

Your software needs to have an **intended** behaviour for **every possible input**.

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Including network traffic, file contents, and interactions with external software or devices.

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Including network traffic, file contents, and interactions with external software or devices.

This is a **design** problem.

Validating Input

Design interactions so input is checkable.

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Design interactions so input is checkable.

Check input for **structure** before **interpreting** values:

Validating Input

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Check input for **structure** before **interpreting** values:

- Use a checksum to validate

Validating Input

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Check input for **structure** before **interpreting** values:

- Use a checksum to validate
- Use a **schema** to check format

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Design interactions so input is checkable.

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- Use a checksum to validate
- Use a **schema** to check format
- Validate sizes and offsets

Validating Input

Design interactions so input is checkable.

Check input for **structure** before **interpreting** values:

- Use a checksum to validate
- Use a **schema** to check format
- Validate sizes and offsets

Decide on behaviour for invalid input.

Validating Input

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- What if the input is valid **on its own**, but not **in the current system state**?

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Choosing appropriate behaviour is the tricky part.

- What if the input is invalid?
- What if the input is valid **on its own**, but not **in the current system state**?
- What if the “input” is that something **external** isn't working as expected?

Validating Input

Choosing appropriate behaviour is the tricky part.

- What if the input is invalid?
- What if the input is valid **on its own**, but not **in the current system state**?
- What if the “input” is that something **external** isn't working as expected?

Can you design the system so these are “expected” and handled gracefully?

Validating Input

Input validation is also a **testing** problem.

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Malformed and invalid inputs can outnumber valid inputs.

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Input validation is also a **testing** problem.

Malformed and invalid inputs can outnumber valid inputs.

Usually it is impractical to test with all possible inputs.

Validating Input

White box analysis of problematic inputs should feed tests.



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Fuzz testing can help fill holes.



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White box analysis of problematic inputs should feed tests.

Fuzz testing can help fill holes.

Test all layers of your end product: low level libraries, middleware, application processes, the whole “system”



Identifying Undefined Behaviour

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One of the **most dangerous** consequences of UB is when **the code does exactly what you naively expected, in testing.**

The UB is still there, and can potentially cause safety issues in production.

Memory Safety issues often fall into this category.

Identifying Undefined Behaviour

Static Analysis can identify some UB at build time.



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Sanitizers and **hardened** libraries can identify some UB at runtime.



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Static Analysis can identify some UB at build time.

Sanitizers and **hardened** libraries can identify some UB at runtime.

Use sanitizers in testing and hardened libraries in testing and production.



Contracts

Preconditions specify what is required to be true when you use a function or class.



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Preconditions specify what is required to be true when you use a function or class.

Postconditions specify what will be true when a function returns.



Checking Contracts: if

You can often check preconditions in code:

```
// precondition: ptr must not be null
void foo(bar* ptr) {
    if(ptr == nullptr) { // contract check
        precondition_violated();
    }
    do_something(*ptr);
}
```


Checking Contracts: macros

You can often check preconditions in code:

```
// precondition: ptr must not be null
void foo(bar* ptr) {
    PRECONDITION(ptr != nullptr);

    do_something(*ptr);
}
```

Checking Contracts: C++26

You can often check preconditions in code:

```
// precondition: ptr must not be null
void foo(bar* ptr)
    pre(ptr != nullptr) { // C++26 syntax

    do_something(*ptr);
}
```

Checking Contracts: Static Analysis

You can often check preconditions in code:

```
// precondition: ptr must not be null
void foo(bar* ptr) {
    /*@ requires @*/           // CodeQL Annotation
    assert(ptr != nullptr);

    do_something(*ptr);
}
```

Checking Contracts: Performance

A checked contract requires evaluating the condition, and branching to the handler on failure.

```
void foo(bar* ptr) {  
    PRECONDITION(ptr != nullptr);  
    do_something(*ptr);  
}
```

```
"foo(bar*)":  
    test rdi, rdi  
    je .L3  
    jmp "do_something(bar&)"  
"foo(bar*) [clone .cold]":  
.L3:  
    push rax  
    call "violation_handler"
```

Checking Contracts: Performance

Compilers are good at optimizing out redundant checks.

```
void baz(bar* ptr){  
    PRECONDITION(ptr!=nullptr);  
    foo(ptr);  
    foo(ptr);  
}
```

```
"baz(bar*)":  
    sub rsp, 24  
    test rdi, rdi  
    je .L9  
    mov QWORD PTR [rsp+8], rdi  
    call "do_something(bar&)"  
    mov rdi, QWORD PTR [rsp+8]  
    add rsp, 24  
    jmp "do_something(bar&)"  
"baz(bar*) [clone .cold]":  
.L9:  
    call "violation_handler"
```

Checking Contracts: Performance

Compilers are good at optimizing out redundant checks.

```
void loop(){
    bar values[10]{};

    for(unsigned i=0;i<10;++i) {
        baz(&values[i]);
    }
}
```

```
"loop()":
    push rbx
    sub rsp, 16
    lea rbx, [rsp+6]
.L12:
    mov rdi, rbx
    call "do_something(bar&)"
    mov rdi, rbx
    add rbx, 1
    call "do_something(bar&)"
    lea rax, [rsp+16]
    cmp rax, rbx
    jne .L12
    add rsp, 16
    pop rbx
    ret
```

If a contract is violated, **you have a bug.**

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```

[ 15.060010] (<018556>) ? find_lock_page+0x56/0x70
[ 15.060010] (<018557>) ? filp_map_page+0x179/0x17d
[ 15.060010] (<018558>) ? do_fault+0x40/0x45
[ 15.060010] (<018559>) ? get_page_from_freelist+0x147/0x360
[ 15.060010] (<018559>) ? handle_mm_fault+0x139/0x390
[ 15.060010] (<018560>) ? do_page_fault+0x10d/0x3a8
[ 15.060010] (<018561>) ? map_in_core+0x38/0x50
[ 15.060010] (<018562>) ? do_page_fault+0x6/0x3a8
[ 15.060010] (<01859303>) ? error_code+0x73/0x80
[ 15.060010] (<0189048>) ? ?_f1919/0x0/0x80
[ 15.060010] (<01893242>) ? copy_to_user+0x10/0x50
[ 15.060010] (<01811475>) ? load_module+0x356/0x70
[ 15.060010] (<018e198b>) ? do_fault+0x3a8/0x490
[ 15.060010] (<01821467>) ? __sysctl_map_capabilities+0x27/0x80
[ 15.060010] (<01827343>) ? security_mmap_capabilities+0x2a/0x30
[ 15.060010] (<0181222d>) ? sysctl_mmap_capabilities+0x210
[ 15.060010] (<01812332>) ? syscall_call+0x7b/0x80
[ 15.060010] Code: 9c 58 84 74 26 05 09 c5 f0 fa 98 84 76 26 04 41 04 9a
c0 b8 84 03 04 00 00 b8 50 10 89 c5 09 c5 b8 74 51 05 50 c4 4b 14 0e
89 10 84 45 f0 50 84 04 74 26 05 09 c5 f0 fa 98 84 76 26 04 41 04 9a
[ 15.060010] RIP: (<0181cf47>) kmem_cache_alloc+0x57/0x120 SS:ESP 0068:0559767
[ 15.060010] GR2: 0000000000000000
[ 15.060010] and trace cdb90857f14b34815 ]--

```



Violated Contracts

If a contract is violated, **you have a bug.**

In testing, notify the developer ASAP, with the maximum information.

```
[ 16.060010] [C01f2525] ? find_lock_page+0x56/0x70
[ 16.060010] [C01c0ebc] ? filp_map_page+0x19/0x10
[ 16.060010] [C01efc50] ? __do_fault+0x40/0x40
[ 16.060010] [C01cfe67] ? get_page_from_free_list+0x147/0x360
[ 16.060010] [C01ef253] ? handle_mm_fault+0x139/0x390
[ 16.060010] [C01c0ebd] ? do_page_fault+0x1d/0x3a0
[ 16.060010] [C01cfe30] ? swap_area+0x30/0x50
[ 16.060010] [C01c5600] ? do_page_fault+0x8/0x3a0
[ 16.060010] [C01c5603] ? error_code+0x73/0x00
[ 16.060010] [C01f0080] ? T_1319/0x70/0x00
[ 16.060010] [C01c324d] ? copy_from_user+0x50/0x130
[ 16.060010] [C01b1475] ? load_module+0x55/0x0e70
[ 16.060010] [C01ef490] ? __do_fault+0x3a0/0x490
[ 16.060010] [C0321467] ? apparmor_capable+0x270/0x0
[ 16.060010] [C032146a] ? security_capable+0x2a/0x30
[ 16.060010] [C01b22ae] ? sys_init_module+0x54/0x210
[ 16.060010] [C01b33ce] ? syscalls__call+0x7/0xb
[ 16.060010] CPU: 3c 5d 8d 85 50 65 09 45 f0 7a 90 B4 26 00 d4 1a 40 ea
0b 04 8b 84 00 00 8b 5d 10 25 06 83 0b 38 05 f6 14 b5 50 0c 6b 14 96
09 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
[ 16.060010] RIP: [C01cfdcf] ? kmem_cache_alloc+0x57/0x120 SS:ESP 0068:e0597470
[ 16.060010] CR2: 0000000000000000
[ 16.060010] -- [end trace eb0605714b34016 ]--
```


Violated Contracts

If a contract is violated, **you have a bug.**

In testing, notify the developer ASAP, with the maximum information.

- Break into debugger

```
[ 16.060010] [c01c556c] ? find_lock_page+0x56/0x70
[ 16.060010] [c01c556c] ? filemap_fault+0x139/0x410
[ 16.060010] [c01c556c] ? __do_fault+0x40/0x490
[ 16.060010] [c01c556c] ? get_page_from_freelist+0x147/0x360
[ 16.060010] [c01c556c] ? handle_mm_fault+0x139/0x390
[ 16.060010] [c01c556c] ? do_page_fault+0x104/0x3a0
[ 16.060010] [c01c556c] ? map_vm_area+0x30/0x50
[ 16.060010] [c01c556c] ? do_page_fault+0x8/0x3a0
[ 16.060010] [c01c556c] ? error_code+0x73/0x80
[ 16.060010] [c01c556c] ? ? 319+0x70/0x80
[ 16.060010] [c01c556c] ? copy_from_user+0x5c/0x130
[ 16.060010] [c01c556c] ? load_module+0x55/0x70
[ 16.060010] [c01c556c] ? __do_fault+0x3a0/0x490
[ 16.060010] [c01c556c] ? ? security_capable+0x27/0x80
[ 16.060010] [c01c556c] ? security_capable+0x2a/0x30
[ 16.060010] [c01c556c] ? sys_init_module+0x5a/0x210
[ 16.060010] [c01c556c] ? sysctl ? call+0x7/0x8
[ 16.060010] Code: 9c 50 84 74 26 8889 45 f0 fa 30 8d 74 26 00 64 a1 40 0a 04
c0 0b 04 83 04 00 00 0b 50 10 89 55 e0 0b 30 85 f6 74 51 0b 50 0c <bb> 14 96
09 10 0b 45 f0 50 3d 8d 74 26 00 85 f6 00 85 89 00 00
[ 16.060010] EIP: [c01c556c] kmem_cache_alloc+0x57/0x120 SS:ESP 0068:ed597b7
+
[ 16.060010] CR2: 00000000ffffffff
[ 16.060010] —[ end trace eb9805714b34816 ]—
```

Violated Contracts

If a contract is violated, **you have a bug.**

In testing, notify the developer ASAP, with the maximum information.

- Break into debugger
- Stack trace and core dump

[illegible]

Violated Contracts

If a contract is violated, **you have a bug.**

In testing, notify the developer ASAP, with the maximum information.

- Break into debugger
- Stack trace and core dump
- Custom logging of state

```
[ 16.060010] [c01c556c] ? find_lock_page+0x56/0x70
[ 16.060010] [c01c4ec9] ? filemap_fault+0x179/0x410
[ 16.060010] [c01c4520] ? __do_fault+0x40/0x490
[ 16.060010] [c01c4f77] ? get_page_from_freelist+0x147/0x360
[ 16.060010] [c01c6259] ? handle_mm_fault+0x159/0x390
[ 16.060010] [c05b04b4] ? do_page_fault+0x104/0x3a0
[ 16.060010] [c01c4390] ? map_vm_area+0x30/0x50
[ 16.060010] [c05b0300] ? do_page_fault+0x0/0x3a0
[ 16.060010] [c05b0303] ? error_code+0x73/0x80
[ 16.060010] [c01d004d] ? ? 319+0x70/0x80
[ 16.060010] [c03532de] ? copy_from_user+0x5c/0x130
[ 16.060010] [c0101475] ? load_module+0x55/0xc70
[ 16.060010] [c01c49ab] ? __do_fault+0x3a0/0x490
[ 16.060010] [c0321467] ? __security_capable+0x27/0x80
[ 16.060010] [c02f3f4a] ? security_capable+0x2a/0x30
[ 16.060010] [c01022ca] ? sys_init_module+0x5a/0x210
[ 16.060010] [c01033cc] ? sysctl ? call+0x7/0xb
[ 16.060010] Code: 9c 58 8d 74 26 8889 45 f0 fa 90 8d 74 26 00 64 a1 40 0a 04
c0 0b 04 83 04 00 00 0b 50 10 89 55 e0 0b 30 05 f6 74 51 0b 50 0c <bb> 14 96
09 10 0b 45 f0 5d 8d 74 26 00 05 f6 00 05 09 00 00
[ 16.060010] EIP: [c01c4f77] kmem_cache_alloc+0x57/0x120 SS:ESP 0068:ed597b7
+
[ 16.060010] CR2: 00000000ffffffff
[ 16.060010] —[ end trace eb9805714b34816 ]—
```

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Including continuing.



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Defense in Depth

Use the “Swiss Cheese” approach:



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Software and Safety

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- Use “Swiss Cheese” defense in depth

Announcement

Arene Base Library

Woven by Toyota is releasing our foundation-level C++ library for Safety-Critical Systems as Open Source.

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Woven by Toyota is releasing our foundation-level C++ library for Safety-Critical Systems as Open Source.

It will be released under the Apache License 2.0 with LLVM exception.

Arene Base Library

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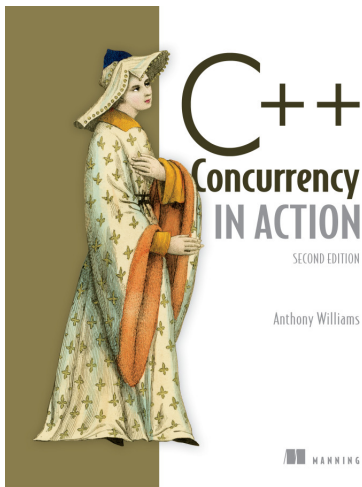
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- Includes enforced preconditions for bounds checks

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