

Software Security

Language-based Security:

'Safe' programming languages

[Chapter 3 of lecture notes on language-based security]

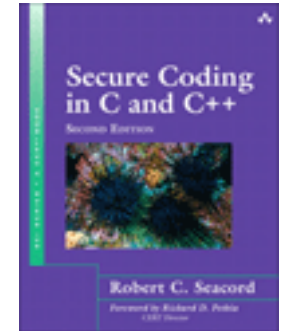
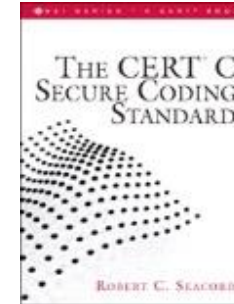
Erik Poll

Producing more secure code

1. You can try to produce more secure C(++) code.

Not just using SAST & DAST tools, but more importantly by reading – or making other people read – books like

- **CERT secure coding guidelines for C and C++** at <http://www.securecoding.cert.org>



2. More structural way to improve security: improve the programming language

- not just to prevent memory corruptions flaws, but other common problems too...

Language-based security

Security features & guarantees provided by programming language

- safety guarantees,
incl. **memory-safety**, **type-safety**, **thread-safety**

There are many flavours & levels of 'safety' here.
Eg. different type systems give different notions of type-safety.
- forms of access control
 - **visibility/access restrictions** with eg. **public**, **private**
 - **sandboxing** mechanisms inside programs
- forms of information flow control

Some features depend on each other, eg

- **type safety** & just about anything else relies on **memory safety**
- **sandboxing** relies on **memory & type safety**

This week: **safety**. See course lecture notes, chapters 2 & 3

Other ways the programming language can help

A programming language can also help security by

- offering good APIs/libraries, eg.
 - APIs with parametrised queries/prepared statements for SQL
 - more secure string libraries for C
- offering convenient language features,
 - esp. **exceptions**, to simplify handling error conditions
- making assurance of the security easier, by
 - being able to understand code in a modular way
 - only having to review the public interface, in a code review

These properties *require* some form of safety

'Safe' programming languages?

You can write insecure programs in ANY programming language.

Eg

- You can **forget or screw up forget input validation** in any language
- **Flaws in the program logic** can never be ruled out

Still...some safety features can be nice:

to *prevent* certain classes of bugs

or at least *mitigate their impact*



General idea behind safety

Under which conditions does
`a[i] = (byte)b`
make sense?

a must be a non-null byte array;
i should be a non-negative integer
less than array length;
b should be (castable to?) a byte

Two approaches

1. the programmer is responsible for ensuring these conditions
“unsafe” approach
2. the language is responsible for checking this
“safe” approach

Heated debates about the pros & cons highlight tension between
flexibility, speed and control vs **safety & security**

But **execution speed** \neq **speed of development of secure code**
and maybe programmers are more expensive than CPU cycles?

Safe programming languages

Safe programming languages

- impose some **discipline or restrictions** on the programmer
- offer some **abstractions** to the programmer, with associated **guarantees**

This takes away some freedom & flexibility from the programmer, but hopefully extra safety and easier understanding makes it worth this.

Attempts at a general definition of safety

A programming language can be considered *safe* if

1. You can trust the abstractions provided by the programming language

The programming language enforces these abstractions and guarantees that they cannot be broken

- Eg a `boolean` is either `true` or `false`, and never `23` or `null`
- Programmer doesn't have to care if `true` is represented as `0x00` and `false` as `0xFF` or vice versa

2. Programs have a precise & well defined semantics (ie. meaning)

- More generally, leaving things **UNDEFINED** in any specification is asking for security trouble

3. You can understand the behaviour of programs in a modular way

'safer' & 'unsafier' languages



Warning: this is overly simplistic, as there are many dimensions of safety

Functional languages such as Haskell are safe because **data is immutable (no side-effects)**

Dimensions & levels of safety

There are many dimensions of safety

memory-safety, type-safety, thread-safety, arithmetic safety;
guarantees about (non)nullness, about immutability, about the
absence of aliasing,...

For each dimension, there can be many levels of safety

Eg, in increasing level of safety, going outside array bounds may:

1. **let an attacker inject arbitrary code**
 2. ***possibly* crash the program (or else corrupt some data)**
 3. ***definitely* crash the program**
 4. **throw an exception, which the program can catch to handle the issue gracefully**
 5. **be ruled out at compile-time**
- } 'unsafe';
some undefined semantics
- } 'safe'

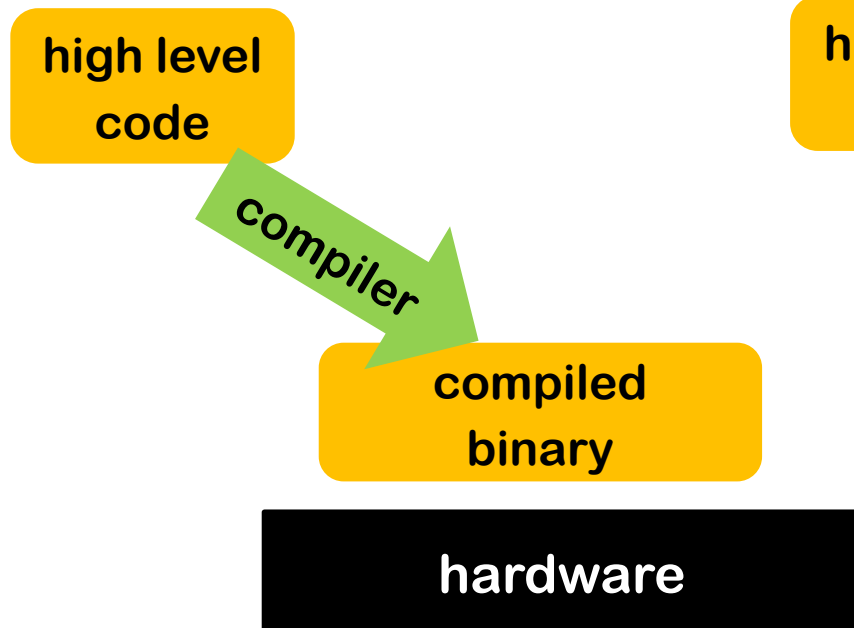
Safety: how?

Mechanisms to provide safety include

- **compile time checks**, eg **type checking**
- **runtime checks**, eg **array bounds checks**, checks for **nullness**, **runtime type checks**, ...
 - for things that cannot be guaranteed by compile time checks
- **automated memory management** using a **garbage collector**
 - so programmer does not have to `free()` heap-allocated data
- using an **execution engine**, to do the things above
 - Eg the **Java Virtual Machine (VM)**, which
 - runs the **bytecode verifier (bcv)** to type-check code,
 - performs some runtime checks
 - periodically invokes the garbage collector

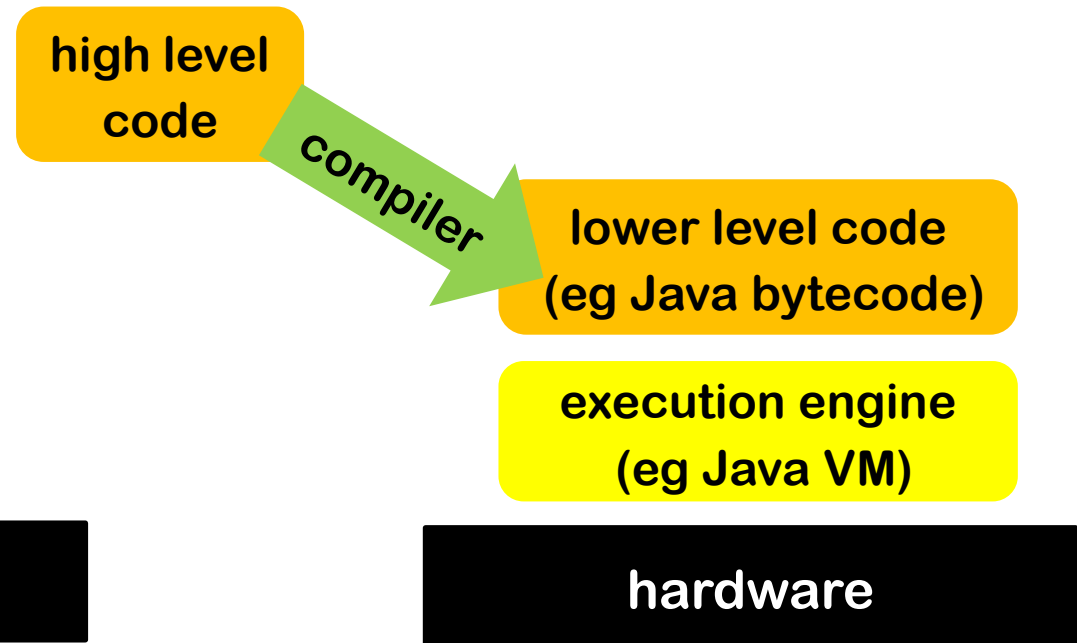
Compiled vs interpreted code

Compiled binary runs on bare hardware



Any defensive measures have to be compiled into the code.

Execution engine (aka 'runtime') isolates code from hardware



The programming language / platform still 'exists' at runtime, and the execution engine can provide checks at runtime

Memory-safety



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

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Exploring Memory Safety in Critical Open Source Projects

Publish Date: June 26, 2024

Rust



Real momentum building behind Rust

as the memory-safe language for low-level 'systems' software



<https://rustnl.org/>

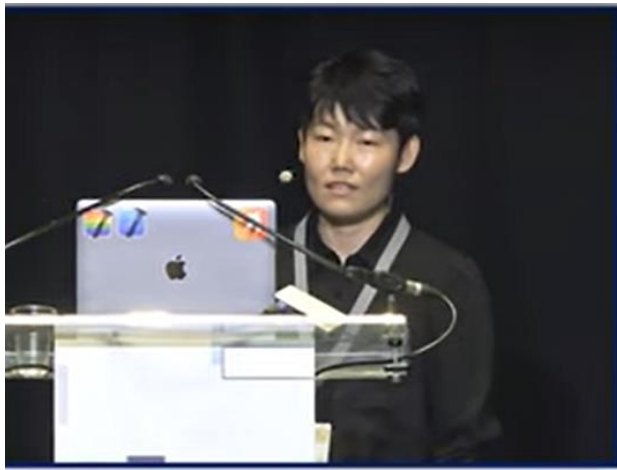
What about Apple?

Apple has started to leave runtime checks for bounds safety in production code, to prevent (some) spatial bugs, but not temporal bugs.

See Yeouul Na's keynote talk at LLVM'23

“-fbounds-safety”: Enforcing bounds safety for production C code

<https://www.youtube.com/watch?v=RK9bfrsMdAM>



Memory-safety – two different flavours

A programming language is **memory-safe** if it guarantees that

1. **programs can never access unallocated or de-allocated memory**
 - hence also: no segmentation faults at runtime
2. **maybe also: program can never access *uninitialised* memory**

Here

1. means we could switch off OS access control to memory.
Assuming there are no bugs in our execution engine...
2. means we don't have to zero out memory before de-allocating it to avoid information leaks (within the same program).
Again, assuming there are no bugs in our execution engine...

Memory safety

Unsafe language features that break memory safety

1. not having array bounds checks
2. allowing pointer arithmetic
3. null pointers, *but only if these cause undefined behaviour*

Null pointers in C

What happens if you dereference a NULL pointer in C?

Common (and incorrect!) folklore:

dereferencing a NULL pointer will crash the program.

But, the C standard only guarantees

the result of dereferencing a null pointer is undefined.

So it *may* crash the program, but **ANYTHING ELSE** *might happen*

See the CERT Secure Coding guidelines for C

<https://www.securecoding.cert.org/confluence/display/c/EXP34-C.+Do+not+dereference+null+pointer>
for discussion of a security vulnerability in a PNG library caused by a null dereference that didn't crash (on ARM processors)

Memory safety

Unsafe language features that break memory safety

1. no array bounds checks
2. pointer arithmetic
3. null pointers, *but only if these cause undefined behaviour*
4. manual memory management with eg. malloc, new & free

Manual memory management can be avoided by

- a) not using the heap at all (eg in MISRA C)
- b) automating it with a garbage collector

Garbage collection first used in LISP in 1959,
and went mainstream with Java in 1995

- c) using ownership type systems, as in Rust

Type-safety

Types

- **Types** assert invariant properties of program elements. Eg
 - This variable will always hold an integer
 - This function will always return an object of class X (or one of its subclasses)
 - This array will never store more than 10 items

NB there is a *wide range of expressivity* in type systems!

- **Type checking** verifies these assertions. This can be done
 - **at compile time (static typing)** or
 - **at runtime (dynamic typing)**or a combination.
- **Type soundness** (aka **type safety** or **strong typing**)
A language is **type sound** if the assertions are guaranteed to hold at run-time

Type information and – ideally - *guarantees*

```
public class Demo{
    static private string greeting = "Hello";
    final static int CONST = 43;

    static void Main (string[] args){
        foreach (string name in args){
            Console.WriteLine(sayHello(name));
        }
    }

    public static string sayHello(string name){
        return greeting + name;
    }
}
```

greeting only accessible
in class Demo

CONST will *always* be 43

sayHello will always return
a string

sayHello will always be called
with 1 parameter
of type string

Type-safety

Type-safety programming language guarantees that programs that pass the type-checker can only manipulate data in ways allowed by their types

- So you cannot multiply booleans, dereference an integer, take the square root of reference, etc.

NB: this removes lots of room for undefined behaviour

- For OO languages: no “Method not found” errors at runtime

Combinations of memory & type safety

Programming languages can be

- memory-safe, typed, and type sound:
 - Java, C#, Rust, Go
 - though some of these have loopholes to allow unsafety
 - Functional languages such as Haskell, ML, Clean, F#
- memory-safe and untyped
 - LISP, Prolog, many interpreted languages
- memory-unsafe, typed, and type-unsafe
 - C, C++

Not type sound: using pointer arithmetic in C, you can break any guarantees the type system could possibly make

More generally: without any memory safety, ensuring type safety is impossible.

Example – breaking type soundness in C++

```
class DiskQuota {
private:
    int MinBytes;
    int MaxBytes;
};

void EvilCode(DiskQuota* quota) {
    // use pointer arithmetic to access
    // the quota object in any way we like!
    ((int*)quota)[1] = MAX_INT;
}
```

NB For a C(++) program we can make *no guarantees whatsoever* in the presence of untrusted code.

So

- a buffer overflow in some library can be fatal
- in a code review we have to look at *all code* to make guarantees

Ruling out buffer overflows in Java or C#

Ruled out at language-level, by combination of

- **compile-time typechecking** (**static** checks)
 - or at **load-time**, by bytecode verifier (bcv)
- **runtime checks** (**dynamic** checks)

What runtime checks are performed when executing the code below?

```
public class A extends Super{
    protected int[] d;
    private A next;

    public A() { d = new int[3]; }
    public void m(int j) { d[0] = j; }
    public setNext(Object s)
        next = (A)s;
    }
}
```

runtime checks for
1) non-nullness of d,
and 2) array bound

runtime check for
type (down)cast

Remaining buffer overflow issues in Java or C#

Buffer overflows can still exist, namely:

1. in native code
2. for C#, in code blocks declared as `unsafe`
3. through bugs in the Virtual Machine (VM) implementation, which is typically written in C++....
4. through bugs in the implementation of the type checker, or worse, bugs in the type system (unsoundness)

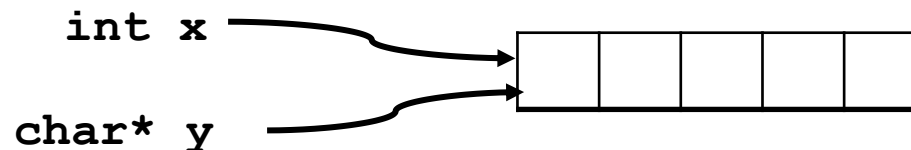
The VM (incl. the type checker aka byte code verifier) is part of the *Trusted Computing Base (TCB) for memory and type-safety*,

Hence 3 & 4: bugs in this TCB can break these properties.

Breaking type safety?

Type safety is an extremely **fragile** property:
one tiny flaw brings the whole type system crashing down

Data values and objects are just blobs of memory. If we can create **type confusion**, by having **two references with different types pointing the same blob of memory**, then *all* type guarantees are gone.



- Example: type confusion attack on Java in Netscape 3.0:

```
public class A[] { ... }
```

Netscape's Java execution engine confused this type **A[]** with the type **array of A**

Root cause: [and] should not be allowed in class names

So this is an **input validation** problem!