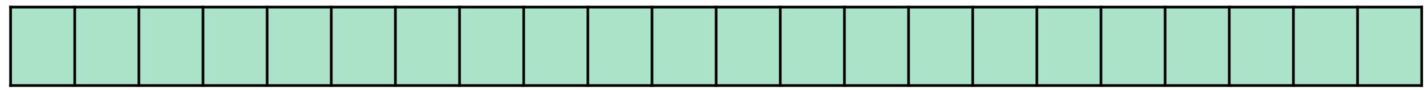
Fuzzing project

Case studies



- **(de)compression**
- **libraries under the hood**
- **CSV**

Generic problems

- **checksums (eg CRC) in the data format**

Last week

(Programming) Language-based security

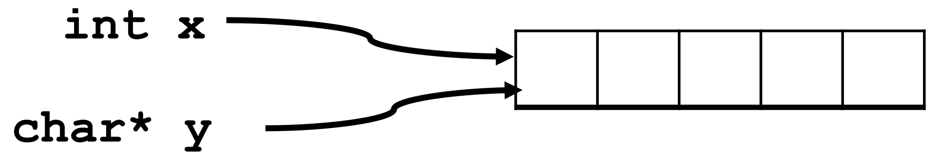
- **memory safety**
  - **just preventing access to un/de-allocated memory or also preventing access to uninitialised memory**
  - **preventing memory corruption bugs**

- **type safety**

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!

Type confusion attacks

```
public class A{
    public Object x;
     ...
}
```

What if we could compile B against A but we run it against A?

We can do pointer arithmetic again!

If Java Virtual Machine would allow such so-called *binary incompatible* classes to be loaded, the whole type system would break.

```
public class A{
  public int x;
  ...
}

public class B{
 void setX(A a) {
  a.x = 12;
 }
}
```

How do we know a type system is sound? (1)

- Representation independence (for booleans)

  it does not matter if we represent `true` as 0 and `false` as 1 (or 0xFF), or vice versa

  - ie. if we execute a given program with either representation, the result is guaranteed to be the same

- We could test this, or try to prove it.

  Given a formal mathematical definition of the programming language, we could prove that it does not matter how `true` *and* `false` *are represented for all programs*

Similar properties should hold for all datatypes.

How do we know type system is sound? (2)

Give two formal definitions of the programming language

- a typed operational semantics, which records and checks type information at runtime
- an untyped operational semantics, which does not

and prove their equivalence for all well-typed programs.

Or, in other words, prove the equivalence of

- a defensive aka paranoid execution engine (which records and checks *all* type information at runtime) and
- a normal execution engine which does not

for any program that passes the type checker.

People have formalised the semantics and type system of eg Java, using theorem provers (Coq, Isabelle/HOL), to prove such results.

Ongoing evolution to richer type systems: non-null vs nullable

Many ways to enrich type systems further, eg

- Distinguish non-null & possibly-null (aka nullable) types

```
public @NonNull String hello = "hello";
```

  - to improve efficiency
  - to prevent null pointer bugs or detect (some/all?) of them earlier, at compile time
- Support for this has become mainstream:
  - C# supports nullable types written as `A?` or `Nullable<A>`
  - In Java you can use type annotations `@Nullable` and `@NonNull`
  - Scala, Rust, Kotlin, Swift, and Ceylon have non-null vs nullable aka option(al) types
- Typically languages then take the approach that references are non-null by default (as PREfast did)

Ongoing evolution to richer type systems: aliasing & information flow

- **Alias control**
  restrict possible interferences between modules due to aliasing.
  - More on the risk of aliasing later this lecture
- **Information flow**
  controlling on the way tainted information flows through an implementation.
  - More on type systems for information flow in later lectures.

Other language-based guarantees

- visibility: public, private, etc
  - eg private fields not accessible from outside a class
- immutability
  - of primitive values (ie constants)
    - in Java : `final int i = 5;`
    - in C(++) : `const int BUF_SIZE = 128;`

    Beware: meaning of `const` is confusing for C(++) pointers & objects!
  - of objects
    - In Java, for example `String` objects are immutable

Scala, Rust, Ceylon, and Kotlin provides a more systematic distinction between mutable and immutable data to promote the use of immutable data structures

Safe arithmetic

What happens if `i=i+1;` overflows?

What would be unsafe or safe(r) approaches?

1. ***Unsafest approach*: leaving this as undefined behavior**
   - **eg C and C++**
2. ***Safer approach*: specifying how over/underflow behaves**
   - **eg based on 32 or 64 bit two-complements behaviour**
   - **eg Java and C#**
3. ***Safer still*: integer overflow results in an exception**
   - **eg checked mode in C#**
4. ***Safest*: have infinite precision integers & reals, so overflow never happens**
   - **Some experiments in functional programming languages**

Thread-safety
&
Aliasing

Problems with threads (ie. lack of thread safety)

- Two concurrent execution threads both execute the statement

```
x = x+1;
```

where **`x`** initially has the value 0.

What is the value of `x` in the end?

  – Answer: **`x`** can have value 2 or 1

  – But: in some programming languages, incl Java, you can actually end up with a totally random value, as we discuss in the next slides

- The root cause of the problem is a data race:
  `x = x+1` is *not* an atomic operation, but happens in two steps - reading **`x`** and assigning it the new value - which may be interleaved in unexpected ways

- Why can this lead to security problems?

Think of internet banking, and running two simultaneous sessions with the same bank account... *Do try this at home!* ☺

Weird multi-threading behaviour in Java

```
class A {
        private int i ;
        A() { i = 5 ;}
        int geti() { return i; }
}
```

Can geti() ever return something else than 5?

Yes!

Thread 1, initialising x

```
static A x = new A();
```

Thread 2, accessing x

```
j = x.geti();
```

You'd think that here x.geti() returns 5 or throws an exception, depending on whether thread 1 has initialised x

Hence: x.geti() in thread 2 can return 0 instead of 5

Execution of thread 1 takes in 3 steps

1. allocate new object m
2. m.i = 5;
3. x = m;

the compiler or VM is allowed to swap the order of these statements, because they don't affect each other

Weird multi-threading behaviour in Java

```
class A {
    private final int i ;
    A() { i = 5 ;}
    int geti() { return i;}
}
```

Now geti() always return 5.

Declaring a private field as final fixes this particular problem

- due to ad-hoc restrictions on the initialisation of final fields

- A revision of the Java Memory Model specifies how compilers & VM (incl. underlying hardware) can deal with concurrency, in 2004.
- The API implementation of String was only fixed in Java 2 (aka 1.5)

Data races and thread-safety

- A program contains a data race if two execution threads simultaneously access the same variable and at least one of these accesses is a write

  NB data races are highly non-deterministic, and a pain to debug!

- thread-safety = the behaviour of a program consisting of several threads can be understood as an interleaving of those threads
- In Java, the semantics of a program with data races is effectively undefined, i.e. only programs without data races are thread-safe

  Moral of the story:

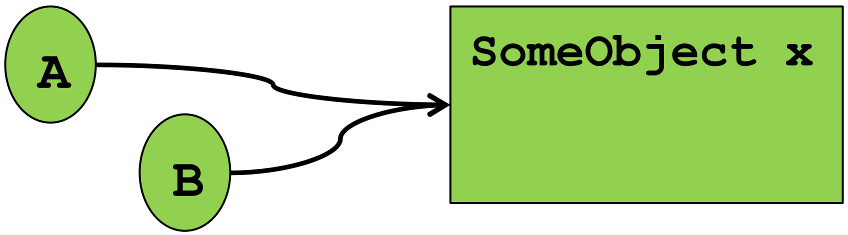
  Even purportedly "safe" programming languages can have very weird behaviour in presence of concurrency

- The programming language Rust aims to guarantee the absence of data races, i.e. thread-safety, at the language level
- Other modern programming language are also introducing features to help with thread safety, e.g. `@ThreadLocal` annotations in Kotlin

Why things often break in C(++), Java, C#, ...

Dangerous combination: **ALIASING** & **MUTATION**

Aliasing: two threads or objects A and B both have a reference to the same object `shared`



This is the root cause of many problems, not just with concurrency

1. in concurrent (aka multi-threaded) context: data races
   - Locking objects (eg `synchronized` methods in Java) can help, but: expensive & risk of deadlock
2. in single-threaded context: dangling pointers
   - Who is responsible for free-ing `shared` ? A or B?
3. in single-threaded context: broken assumptions
   - If `A` changes the shared object `x`, this may break `B`'s code, because `B`'s assumptions about `shared` are broken

References to mutable data are dangerous

In multi-threaded programs, aliasing of mutable data structures can be problematic, as the referenced data can change,

- **even in safe programming languages such as Java or C# !**

```
public void f(char[] x){
  if (x[0] != 'a') { throw new Exception(); }
  // Can we assume that x[0] is the letter 'a'  here?
  // No!! Another concurrent execution thread could
  //       change the content of x at any moment
```

If there is aliasing, another thread can modify the content of the array at any moment.

References to *im*mutable data are *less* dangerous

In a multi-threaded program, aliasing of immutable data structures are safer.

```
public void f(String x){
 if (x.charAt(0) != 'a') { throw new Exception(); }
 // We CAN assume that x[0] is the letter 'a‘ here?
 // Yes, as Java Strings are immutable
   ...
```

Another thread with a reference to the same string *cannot* change the value (or ‘contents’) of the string, as Java strings are immutable.

Kotlin has annotation `@SharedImmutable` to explicitly mark objects as being immutable & (therefore) safe to share