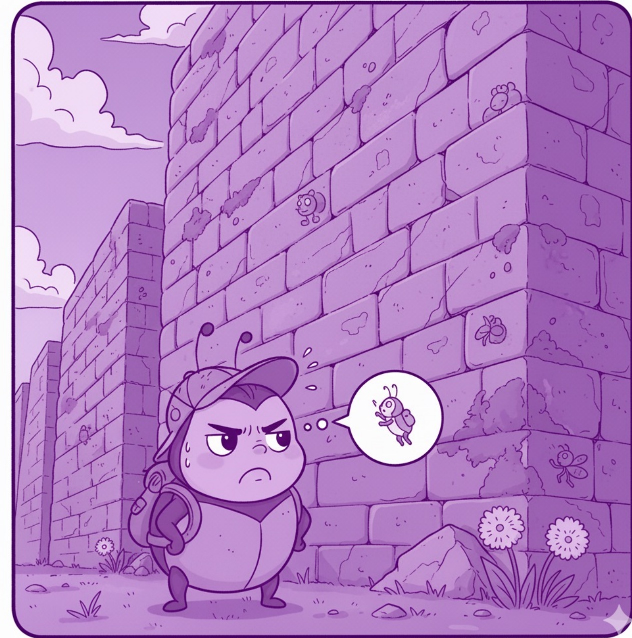


CSE 331

Making Bugs Impossible

James Wilcox

with thanks to Kevin Zatloukal for many slides

Making Bugs Impossible

- Goal to make bugs impossible via
  - clever design and/or
  - type system
- This means no need for tests or reasoning here
  - same is not true for runtime checks (e.g. `checkRep`)
- Worthwhile for common, awful bugs…

Bug 1: Method Call Order

```
public interface A {
  void foo();
  int bar();  // ONLY call this after foo!!
}
```

- Bug if *some* path calls `bar` without `foo` first
  - type checker does not catch this
  - need for this does arise occasionally

    can only happen with mutators

- Not good design
  - someone will eventually make a mistake here

Bug 2: Argument Order

```
void foo(int a, String s);
void bar(int a, int b);

foo("b", 1);  // wrong order: compiler error
bar(2, 1);    // wrong order: no error
```

- Bug if arguments are swapped
  - type checker will not catch if the types are the same

- Hard to remember order of long argument list
  - easy mistake to make

Bug 2: Argument Order

```
// @modifies A
// @effects A[j] = val for 0 <= j < len
void memset(int[] A, int val, int len);
```

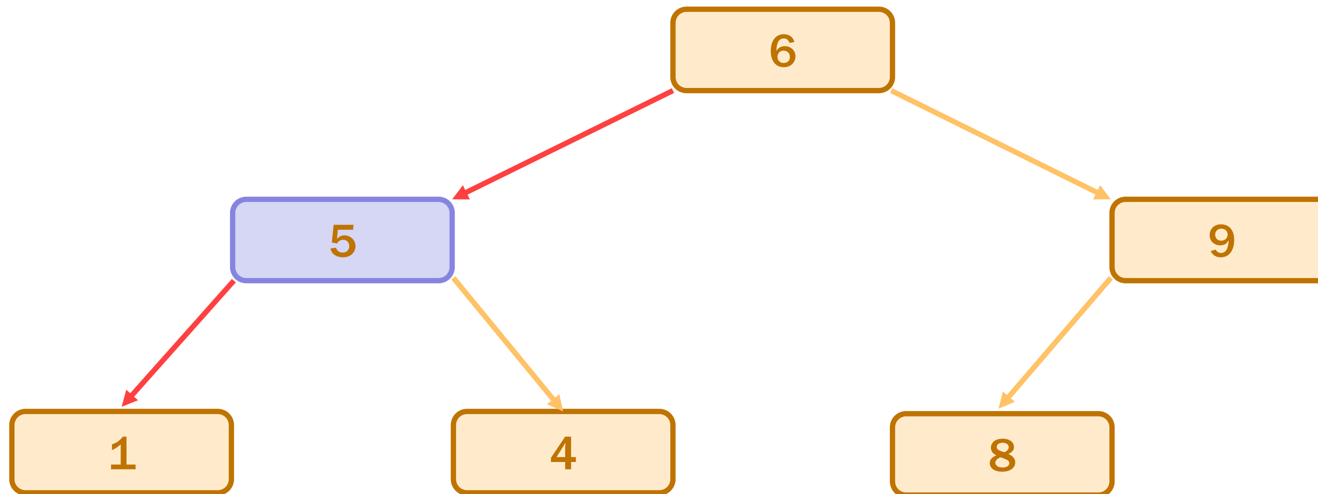
- Famous bug due to mixing up argument order!

```
   memset(A, 0, A.length)   // set A to zeros
vs memset(A, A.length, 0)   // does nothing!
```

- If you program long enough, you will see this one
  - easy case to miss in unit tests

Recall: Binary Search Trees

- Suppose someone changed "3" into "5"...
  - now this happens when we search for "4":



  - It can no longer be found!

Bug 3: Key Mutation

```
Map<A, B> map;
```

- Bug if any `A` used as a <u>key</u> in this map is mutated
  - Java type checker will not catch this
  - possible only with aliasing to mutable `A`
- Debugging will be very painful
  - mutation only happen occasionally
  - could take weeks to find it

Impossible By *Design*

Method Call Order

```
public interface A {
  void foo();
  int bar();  // ONLY call this after foo!!
}
```

- Possible to prevent this by better design…

```
public interface A {
  B foo();
}
```

Not possible to call **bar**
(no longer has that method)

```
public interface B extends A {
  int bar();
}
```

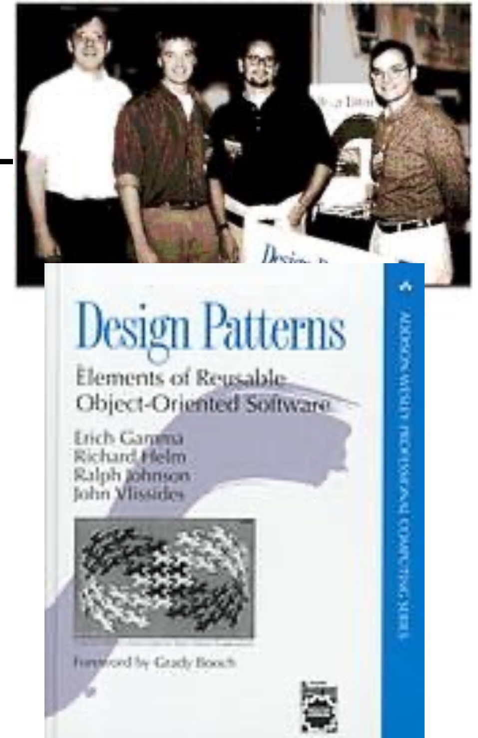
Can only get a B by calling **foo**
(do not provide any other way)

Impossible by Design

- The other bugs can also be prevented by design, but require more complex solutions…

Design Patterns

Design Patterns



- Introduced in the book of that name
  - written by the “Gang of Four”

    Gamma, Helm, Johnson, Vlissides
  - worked in C++ and SmallTalk

- Found that they independently developed many of the same solutions to recurring problems
  - wrote a book about them

- Many are problems with OO languages
  - authors worked in C++ and SmallTalk
  - some things are not easy to do in those languages

Parts of a Design Patterns

Each pattern in the book includes

- **Problem** to be solved
- **Description** of the solution
- **Name** of the pattern

Java Example: Iterator

- Java Collections use the Iterator Design Pattern
  - enumerate a collection while hiding data structure details
  - return another ADT that outputs the items

    that object knows how to walk through the data structure

    operations for retrieving the current item and moving on to the next one

- Clever idea that is now used everywhere
  - Kevin remembers when C++ introduced iterators
  - huge improvement over code we were writing before

Categories of Design Patterns

The book has three categories of patterns

- **Creational**: factory function, factory object, builder, prototype, singleton, ...
- **Structural**: **adapter**, bridge, composite, decorator, façade, flyweight, proxy
- **Behavioral**: command, interpreter, iterator, mediator, observer, state, strategy, visitor, ...
  - green = mentioned already
  - we will just cover a few of these for now...

Creational Patterns

- One third of the patterns deal with object creation
  - why?

- Because constructors are terrible!

- Already saw factory functions and singleton
  - yet we still need more creational patterns

Constructors

Public Constructors

- Most Java classes have public constructors
  - e.g., create an `ArrayList` with "`new ArrayList<String>()`"
- Constructors have undesirable properties
  - not a good idea to do any real work in them
    - cannot test a method without also testing the constructor
  - surprisingly error-prone
  - several important limitations

Recall: Tight Coupling Example 3

```
class WorkList {
  // RI: len(names) = len(times) and total = sum(times)
  protected ArrayList<String> names;
  protected ArrayList<Integer> times;
  protected int total;

  public addWork(Job job) {
    int time = job.getTime();  // just one call
    total += time;
    addToLists(job.getName(), time);
  }
}
```

RI is not true in method call!

Method Calls from Constructors

- Any method call from a constructor is dangerous!
- Almost always calling with RI false
  - usually, the RI does not hold until all fields are assigned
    - typically, that is the last line of the constructor
  - hence, any methods are called with the RI still false
- Asking for trouble!
  - method needs to know that some parts of RI may be false
  - eventually, someone changing code will mess this up
  - better to avoid method calls in the constructor

Limitations of Constructors

- Constructor is called *after* the object is created
  - can't decide, in the constructor, not to create it
- Limitations of constructors

1. Cannot return an existing object
2. Cannot return a different class
3. Does not have a name!

Factory Functions & Singleton

- Factory functions <u>can</u> return an existing object
- Common case: there is only one instance!
  - called the "singleton" design pattern
- Examples from before…

Recall: Example 2: Point in 2D Space

```
/** Creates a point at the given coordinates. */
public static Point makePoint(double x, double y) {
  if (Runtime.getRuntime().totalMemory() > MIN_MEM) {
    return new PolarPoint(x, y);
  } else {
    return new SimplePoint(x, y);
  }
}
```

Can return instances of different classes in different cases

- This is a "factory function"
  - an example of a design pattern
  - Java SDK includes many, e.g., `Arrays.asList(..)`

Recall: Creator of FastLists

```
public static FastList EMPTY_LIST =
    new FastBackList(null);

/** @return nil */
public static FastList emptyList() {
  return EMPTY_LIST;
}
```

Do not need to create a new object

- This is the "singleton" design pattern
  - **note**: this is only possible since `FastList` is immutable!

Returning a Subtype

- Factory functions can return a subtype
  - declared to return `A` but returns subtype `B` instead
  - allowed since every `B` is an `A`

- Example:

```
// @returns an empty NumberSet that can be used to
//      store numbers between min and max (inclusive)
public NumberSet makeNumberSet(int min, int max) {
  if (0 <= min && max <= 100) {
    return makeArrayNumberSet();  // only supports small sets
  } else {
    return makeSortedNumberSet(); // use a tree instead
  }
}
```

Multiple Constructors

- Java classes allow multiple constructors

```
class HashMap {
  public HashMap() { … }  // initial capacity of 16
  public HashMap(int initialCapacity) { … }
}
```

- Multiple methods with the same name is "overloading"

- Methods are distinguished by the argument types
  - name + arg types is called the "signature" of the method
  - type checker figures out which method you are calling

Constructors Have No Name

- Do not get to name constructors
  - in Java, same name as the class
    - likewise in JavaScript, where it is called “constructor”

- Names are useful!

  1. Let you <u>distinguish</u> between different cases
     - use names to distinguish cases that otherwise look the same

  2. Let you <u>explain</u> what it does
     - the only thing you know the client will read!

Example: Distinguishing Constructors

- JavaScript's Array has multiple constructors

```
new Array()             // creates []
new Array(a1, …, aN)    // creates [a1, …, aN]
new Array(2)            // creates [undefined, undefined]
```

  – what does "`new Array(a1)`" return when `a1` is a number?
  – how to make a 1-element array containing just `a1`

```
const A = new Array(1);
A[0] = a1;
```

  – don't have a name to distinguish these cases!

Example: Distinguishing Constructors

- Factory functions have names
  - allow us to distinguish these cases

```
// @returns []
public int[] makeEmptyArray()

// @returns A with A.length = len and
//      A[j] = undefined for any 0 <= j < len
public int[] makeArray(int len)

// @returns [args[0], …, args[N-1]]
public int[] makeArrayContaining(int... args)
```

  - function name is also the one thing you know clients read!

    best chance to tell them how to use it correctly

Example: Distinguishing Constructors

- Factory functions have names
  - allow us to distinguish these cases

```
// @returns []
public int[] makeEmptyArray()

// @returns A with A.length = len and
//      A[j] = undefined for any 0 <= j < len
public int[] makeArray(int len)

// @returns A with A.length = len and
//      A[j] = val for any 0 <= j < len
public int[] makeFilledArray(int len, int val)
```

Be careful...

Creational Pattern: Builder

- **Object that helps with creation of another object**
  - **constructor / factory requires you to give info all at once**
  - **builder lets you describe what you want bit by bit**

- **Example:** `StringBuilder`

```
StringBuilder buf = new StringBuilder();
buf.append("Total distance: ");
buf.append(distance);
buf.append(" meters.");
return buf.toString();
```

  - **each call adds more text / number to the final string**
  - **we can't do this with strings because strings are *immutable***

Creational Pattern: Builder

- Object that helps with creation of another object
  - constructor / factory requires you to give info all at once
  - builder lets you describe what you want bit by bit
- Good pairing: mutable Builder for an immutable type
  - must avoid aliasing with the mutable builder

    e.g., never use it as a key in a BST or Map
  - immutable object can be shared arbitrarily

    no worries about aliasing

Creational Pattern: Builder

- Builder is often written like this:

```
class FooBuilder {
  …
  public FooBuilder setX(int x) {
    this.x = x;
    return this;
  }
  …
  public Foo build() { … }
}
```

  – can then use them like this

```
Foo f = new FooBuilder().setX(1).setY(2).build();
```

avoids worries about argument order

Recall: Argument Order Bugs

```
// @returns A with A.length = len and
//     A[j] = val for any 0 <= j < len
public int[] makeFilledArray(int len, int val)
```

Be careful…

- **Some famous bugs due to mixing up argument order!**
- **If you program long enough, you will see this one**
- **Can fix this with a Builder**

  (in other languages, there is a simpler solution)

Argument Builder

```
// Returns an array with length & value given in args.
public int[] makeFilledArray(Args args)

class Args {
  public int length;
  public int value;
}

Args args = new Args();
args.length = 10;
args.value = 5;
… = makeFilledArray(args);
```

Arguments distinguished by name not by order

– **code using the function is now more verbose…**

  can make this easier by giving them a Builder

Argument Builder

```
// Returns an array with length & value given in args.
public int[] makeFilledArray(Args args) { … }

class ArgsBuilder {
  …
  public ArgsBuilder setLength(int length) {
    this.length = length;
    return this;
  }
  …
  public Args toArgs() { … }
}

… = makeFilledArray(new ArgsBuilder()
    .setLength(10).setValue(5).toArgs());
```

Categories of Design Patterns

The book has three categories of patterns

- **Creational**: factory function, factory object, builder, prototype, singleton, ...
- **Structural**: adapter, bridge, composite, decorator, façade, flyweight, proxy
- **Behavioral**: command, interpreter, iterator, mediator, observer, state, strategy, visitor, ...
  - green = mentioned already

Structural Pattern: Adapter

- In Java, these two classes are not interoperable:

```
interface Duration {
  int getMinutes();
  int getSeconds();
}

interface AmountOfTime {
  int getMinutes();
  int getSeconds();
}
```

  - cannot pass one where the other is expected
  - in Java, different names means they are different

    we say it has a "**nominal**" type system

Structural Pattern: Adapter

- Get around this by creating an adapter

```
class DurationAdapter implements AmountOfTime {
  private Duration d;

  public DurationAdapter(Duration d) {
    this.d = d;
  }

  int getMinutes() { return d.getMinutes(); }
  int getSeconds() { return d.getSeconds(); }
}
```

  – makes a `Duration` into an `AmountOfTime`

Alternative Languages

Alternative Languages

- Last time, we looked at ways to prevent bugs by working *within* Java's type system

- Next, we will look at alternative languages
  1. Python
  2. TypeScript
  3. Rust

- Goal is to **understand** how the type system works
  - know which bugs it catches and which it misses
  - we will not be writing any code in this language

Alternative Languages

- Last time, we looked at ways to prevent bugs by working *within* Java's type system

- Next, we will look at alternative languages
  1. Python
  2. TypeScript
  3. Rust

- Java's type system made one set of choices
  - none of these are sacrosanct

    easier to see once you know a few different languages

Python

Background on Python

- By some measures the most popular language

- Sometimes called a "scripting" language
  - for writing "scripts" that call other programs
  - especially easy to call into C libraries

- Designed for ease-of-use not performance
  - python interpreter is *extremely* slow

- Widely used today for AI
  - hard work is done inside of libraries and on GPUs

Background on Python

- Does not require type declarations
  - any variable can store type
  - same variable can switch types during execution

```
x = 1        # I'm an integer
x = "abc"    # I'm a string now!
```

- Called a "dynamically typed" language
  - type checks occur at run-time (in some cases)

    it often tries to convert types that are not correct
  - no type checker means more testing & reasoning

Named Arguments

```
# @modifies A
# @effects A[j] = val for 0 <= j < len
def memset(vals, count, value):
  … # implementation
```

- Can use argument names in calls:

```
memset(A, value=0, count=100)
```

  - latter two arguments are identified by name

    does not matter what order they are in
  - eliminates most argument order bugs

Built-In Dictionary

- Java creates maps like this:

```
Map<Integer, String> m = new HashMap<>();
m.put(3, "foo");
m.put(4, "bar");
```

- Can create the same in Python like this

```
m = {3: "foo", 4: "bar"}
```

  - much more concise
  - can also create records without classes

Built-In Dictionaries

- Can add and remove from dictionaries

```
m = {}
m[1] = "foo"
m["bar"] = 2          # can use strings as keys
```

- But <u>cannot</u> use mutable types as keys:

```
L = [1, 2]
m[L] = "baz"          # runtime type error
```

Built-In Dictionaries

- Cannot use lists as keys:

```
L = [1, 2]
m[L] = "baz"            # runtime type error
```

- Can use tuples (immutable lists) as keys

```
L = (1, 2)
m[L] = "baz"            # okay!
```

- Only immutable keys is less efficient
  - requires extra copying of data in many cases
  - worthwhile for the elimination of key mutation bugs

JavaScript

History of JavaScript

- By some measures, second most popular language
- Incredibly simple language
  - created in 10 days by Brendan Eich in 1995
  - often difficult to use because it is so simple
- Features added later to fix problem areas
  - imports (ES6)
  - classes (ES6)
  - integers (ES2020)

Relationship to Java

- Initially had no relation to Java
  - picked the name because Java was popular then
  - added Java's Math library to JS also
    - e.g., `Math.sqrt` is available in JS, just like Java
  - copied *some* of Java's String functions to JS string

JavaScript Syntax

- Both are in the "C family" of languages

- Much of the syntax is the same
  - most expressions (`+`, `-`, `*`, `/`, `?:`, function calls, etc.)
  - `if`, `for`, `while`, `break`, `continue`, `return`
  - comments with `//` or `/* .. */`

Java vs JavaScript Syntax

- The following code is legal in both languages:
  - assume "`s`" and "`j`" are already declared

```
s = 0;
j = 0;
while (j < 10) {          OR for (j = 0; j < 10; j++)
  s += j;
  j++;
}

// Now s == 45
```

JavaScript Syntax

- Both are in the "C family" of languages

- Much of the syntax is the same
  - most expressions (`+`, `-`, `*`, `/`, `?:`, function calls, etc.)
  - `if`, `for`, `while`, `break`, `continue`, `return`
  - comments with `//` or `/* .. */`

- Different syntax for a few things
  - declaring variables
  - declaring functions
  - equality (`===`)

no declared types (declaring variables, declaring functions)

"==" is not transitive

Differences from Java: Type Declarations

- JavaScript variables have no declared types
  - it is "dynamically typed"

- Declare variables in one of these ways:

```
const x = 1;
let y = "foo";
```

  - "`const`" cannot be changed; "`let`" can be changed
  - use "`const`" whenever possible!

Basic Data Types of JavaScript

- **JavaScript includes the following runtime types**

`number`	
`bigint`	
`string`	
`boolean`	
`undefined`	
`null`	(another undefined)
`Object`	
`Array`	(special subtype of Object)

Checking Types at Run Time

Condition	Code
x is undefined	`x === undefined`
x is null	`x === null`
x is a number	`typeof x === "number"`
x is an integer	`typeof x === "bigint"`
x is a string	`typeof x === "string"`
x is an object or array (or null)	`typeof x === "object"`
x is an array	`Array.isArray(x)`

Programmers must write their own type checks!

TypeScript

TypeScript Adds Declared Types to JavaScript

- TypeScript includes declared types for variables
- Compiler checks that the types are valid
  - produces JS just by *removing* the types

TypeScript Adds Declared Types

- Type is declared after the variable name:

```
const u: bigint = 3n;
const v: bigint = 4n;

function add(x: bigint, y: bigint): bigint {
  return x + y;
};

console.log(add(u, v));  // prints 7n
```

  - return type is declared after the argument list `(…)` and before `{`

- “Where types go” is the main syntax difference vs Java

Literal Types

- Any literal value is also a type:

```
let x: "foo" = "foo";
let y: 16n = 16n;
```

- Variable can only hold that specific value!
  - can assign it again, but only with the same value
  - seems silly, but turns out to be useful…

Ways to Create New Types in TypeScript

- **Union Types** `string | bigint`
  - can be either one of these

- Not possible in Java!
  - TS can describe types of code that Java cannot

Enumerations

- Use unions of literals are "enums"

```
function dist (dir: "left"|"right", amt: bigint): bigint {
  if (dir === "right") {
    return amt;
  } else {
    return -amt;
  }
};
```

- TypeScript ensures that callers will only pass one of those two strings ("left" or "right")
  - impossible to do this in Java

    (must fake it with the enumeration **design pattern**)

Java Enums

- Another design pattern built into Java:

```
enum Dir {
  LEFT, RIGHT
}
```

- `Dir.LEFT` and `Dir.RIGHT` are the only 2 instances

- Cannot pass a `Dir` where `String` is expected
  - must add methods to convert between them

Ways to Create New Types in TypeScript

- **Union Types** `string | bigint`
  - can be either one of these

- How do we work with this code?

```
const x: string | bigint = …;

// how to check if can I call isPrime(x: bigint)?
```

- We can check the type of `x` using "`typeof`"
  - TypeScript understands these expressions
  - will "narrow" the type of `x` to reflect that information

Type Narrowing With "If" Statements

- **Union Types** `string | bigint`
  - can be either one of these

- How do we work with this code?

```
const x: string | bigint = …;

if (typeof x === "bigint") {
  console.log(isPrime(x))    // okay! x is a bigint
} else {
  …                          // x is a string
}
```

Programmer must write type checks only for unions
and the type checker will make sure they do!

Type Narrowing vs Casting

```
const x: string | bigint = …;

if (typeof x === "bigint") {
  console.log(isPrime(x))    // okay! x is a bigint
} else {
  …                          // x is a string
}
```

- Note that this does not require a type cast
  - TypeScript knows x is a `bigint` inside the "if" (narrowing)

- TypeScript has casts but they are completely unsafe!

Type Narrowing vs Casting

```
Object x = …;
System.out.println(isPrime((Integer)x))
```

- Java will check this at runtime
  - throws an exception if `x` is not an `Integer`

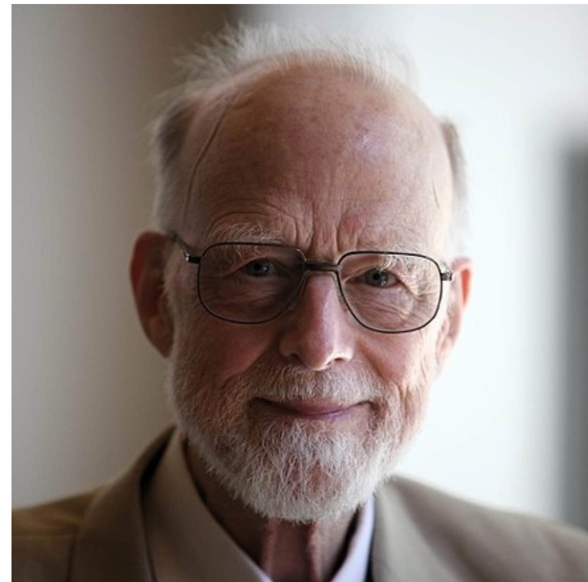
```
const x: string | bigint = …;
console.log(isPrime(<bigint>x))    // trust me!
```

- TypeScript casts are unchecked at runtime!
  - seem designed to create extremely painful debugging

Sir Anthony Hoare

- Recall that Floyd & Hoare invented Floyd Logic
  - won the Turing award in 1980

- Also invented "null"...
  - ... and null pointer exception
  - "billion-dollar mistake"



Tony Hoare

Java Reference Types

- In Java, these type declarations

```
String s;
A x;
```

really mean

```
… s …   // is a String or null
… x …   // is an A or null
```

- All reference types implicitly allow null also!
  - use of fields or methods are checked at runtime

    throws an NPE if it is null
  - no help from the type checker

TypeScript Types

- In Java, these type declarations

```
let s: string;
let x: A;
```

  mean what they say

```
… s …  // is a string
… x …  // is an A
```

- Not possible for these to be null at runtime

TypeScript Types

- Must include null *explicitly*

```
let n: bigint | null;
```

- The type checker will make sure you handle it

```
isPrime(n);     // error: could be null

if (typeof n == "bigint")
  isPrime(n);   // this is okay
```

Ways to Create New Types in TypeScript

- Can create compound types in multiple ways
  - put multiple types together into one larger type

- **Record Types** `{x: bigint, s: string}`
  - anything with *at least* fields "x" and "s"

```
const p: {x: bigint, s: string} = {x: 1n, s: "hi"};
console.log(p.x);  // prints 1n
```

Ways to Create New Types In TypeScript

- Can create compound types in multiple ways
  - put multiple types together into one larger type

- Tuple Types `[bigint, string]`
  - create them like this

```
const p: [bigint, string] = [1n, "hi"];  // an array
```

  - give names to the parts (“destructuring”) to use them

```
const [x, y] = p;
console.log(x);  // prints 1n
```

Use Records for Named Arguments

```
// @modifies A
// @effects A[j] = val for 0 <= j < len
function memset(vals: number[],
    desc: {count: number, value: number})
```

- Client invokes it like this

```
memset(A, {value: 0, count: 100})
```

  - latter two arguments are identified by name

    does not matter what order they are in

  - much easier than Java (less easy than Python)

    Python turns named arguments into a record for you

Type Aliases

- TypeScript lets you give shorthand names for types

```
type Point = {x: bigint, y: bigint};

const p: Point = {x: 1n, y: 2n};
console.log(p.x);  // prints 1n
```

- Usually nicer but not necessary
  - e.g., this does the same thing

```
const p: {x: bigint, y: bigint} = {x: 1n, y: 2n};
console.log(x);  // prints 1n
```

Structural vs Nominal Typing

- Deep difference between TypeScript and Java types

- TypeScript uses "**structural typing**"
  - sometimes called "duck typing"

    "if it walks like a duck and quacks like a duck, it's a duck"

```
type T1 = {a: bigint, b: string};
type T2 = {a: bigint, b: string};

const x: T1 = {a: 1n, b: "two"};
```

  - can pass " `x` " to a function expecting a " `T2` "!

Recall: Structural Pattern: Adapter

- In Java, these two classes are not interoperable:

```
interface Duration {
  int getMinutes();
  int getSeconds();
}

interface AmountOfTime {
  int getMinutes();
  int getSeconds();
}
```

  - cannot pass one where the other is expected
  - in Java, different names means they are different

    we say it has a "**nominal**" type system

Structural vs Nominal Typing

- Adapters are often needed with nominal typing
  - design pattern working around a language issue
- With structural typing, these two interoperate:

```
type Duration = {min: number, sec: number};

type AmountOfTime = {min: number, sec: number};
```

  - can pass either where the other is expected
  - not an issue of fields vs methods

    still interoperable if we have `getMinutes` and `getSeconds` methods

Rust

Rust

- Language for systems programming
  - operating systems
  - real-time systems
  - servers of various kinds
- Type system has extra safety properties
  - regarding aliases, multi-threading, allocation
  - much safer than C or C++
- Only available since 2015

Warnings

- I am not a Rust expert
- Much of the code shown here is illegal
  - ignores additional Rust rules on
    1. multi-threading
    2. memory allocation
  - no time for multi-threading (see 451)
  - memory allocation rules are annoying (more later)

Rust Type System

- Rust ensures every value on the heap has either
  1. a single mutable reference
  2. any number of immutable references

  – cannot have multiple mutable references
  – cannot mix mutable and immutable reference

- Why do this?
  – it prevents the mutable aliases
  – exact same advice we gave earlier about aliases

    these are the two "easy ways" to avoid unsafe aliases

Mutable and Immutable References

- Variables must be declared mutable
  - default is immutable

```
let s = String::from("hello");
s.push_str(", world");  // error!
```

  - requires an explicit declaration to call mutators

```
let mut s = String::from("hello");
s.push_str(", world");  // okay
```

- This is good!
  - but far from perfect (as we will see later)

Mutable References

- Cannot create a second reference:

```
let mut s = String::from("hello");
let mut t = s;
t.push_str(", world");
s.push_str("!");   // error!
```

- Assignment to `t` invalidates `s`
  - ownership "move" from `s` to `t`
  - can no longer use `s`

Function Calls

- Creates problems for function calls:

```
fn add_text(t: mut String) -> {
  t.push_str(", world");
}

let mut s = String::from("hello");
add_text(s);
s.push_str("!");  // error!
```

- Call to `add_text` implicitly assigns "`t = s`"

- So how do we call functions?

Function Calls

- Rust allows a "borrow" by using "&"

```
fn add_text(t: &mut String) -> {
  t.push_str(", world");
}

let mut s = String::from("hello");
add_text(&mut s);
s.push_str("!");  // okay
```

  – ownership is temporarily moved; returned after the call

Function Calls

- If a function attempts to keep an alias, it will cause an error:

```
static ref strs = HashMap::new();

fn add_text(t: &mut String) -> {
  t.push_str(", world");
  strs.insert(t, strs.length());  // error!
}

let mut s = String::from("hello");
add_text(&mut t);
```

  – Rust knows ownership must be returned at the end, so you cannot move ownership into `strs`

Structs (a.k.a. Records)

- Everything above used `String`

- Can declare your own types of records like this:

```
struct MyRecord {
  value: i32;  // 32-bit integer
  count: i32;
}

let r = MyRecord {value: 1, count: 10};
```

  – declares a new record and then instantiates one

Other Thoughts on Rust

- Some parts of Rust are not good for general use

- Notion of immutable is too low-level
  - "mutable" means any change to the fields

- Not every field change is really a mutation
  - only a mutation if it changes the abstract state

    if the abstract state is unchanged, then all methods return the same values, so clients cannot observe any difference

Other Thoughts on Rust

- Some parts of Rust are not good for general use
- Memory allocation is suboptimal
  - uses ownership to avoid garbage collection
- Garbage collection is useful
  - making everyone pay for problems of real-time systems
  - there are type systems that can solve this problem

    see "fully in-place functional programming"
- There is no perfect programming language

Final Thoughts

- Saw language features that prevent bugs
  - Java's choices are not sacrosanct

- Saw variety of type systems
  - TypeScript prevents null pointer exceptions
  - Rust prevents multiple aliases to mutable state
  - structural vs nominal types

- Type systems work well with AI
  - type system can add reliability to LLM codegen
  - very few limits on what can be done (see 311)