Using types of rule out bugs: *Python perspective*

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Intermediate Research Software Development Skills In Python for Earth Sciences - Manchester, 19th March 2024

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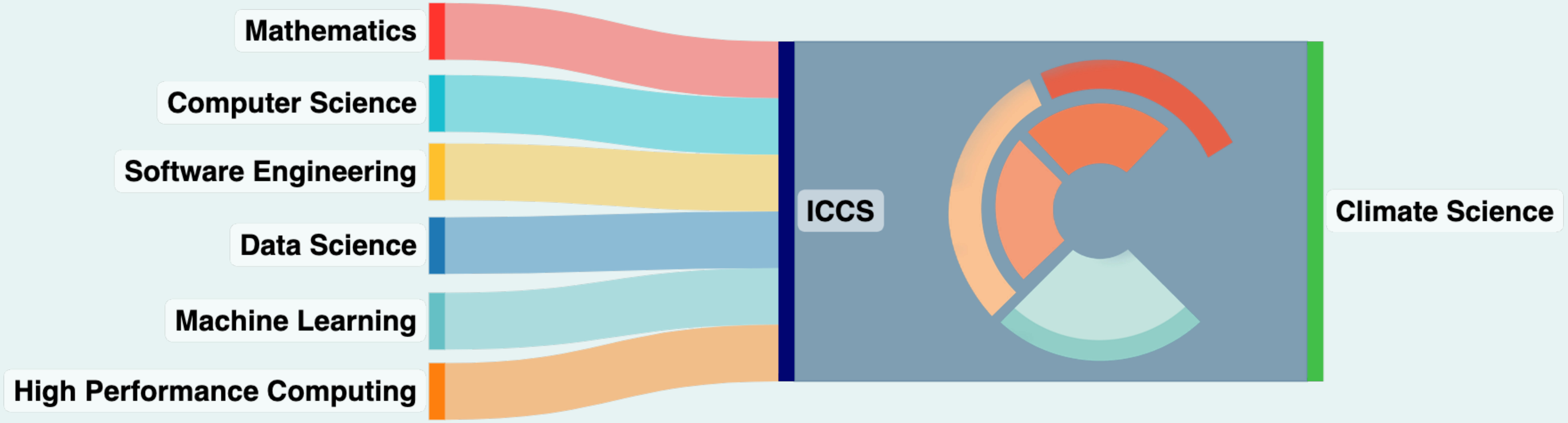

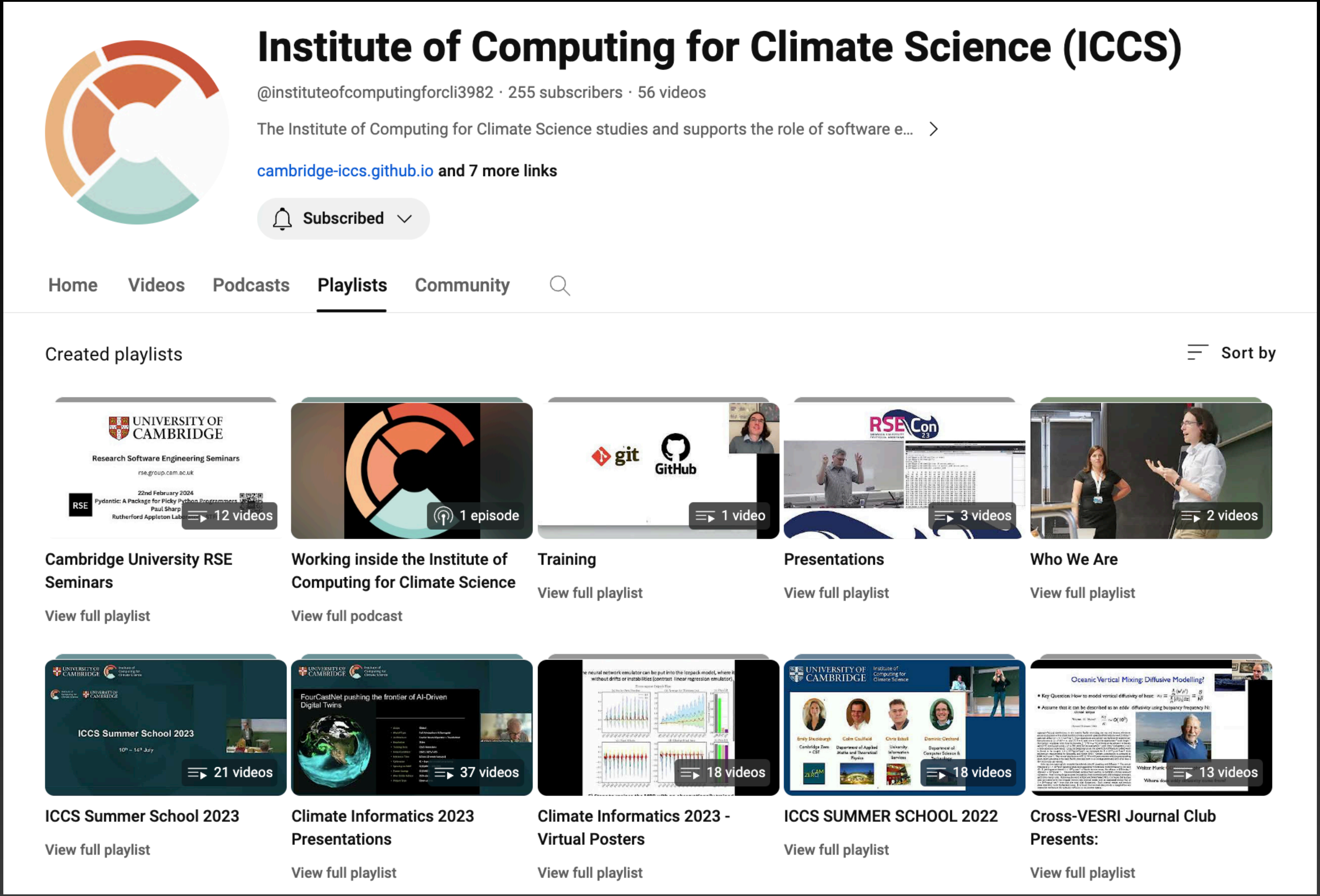

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SCHMIDT **FUTURES**

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Warmup!

```
         1 + 1 = 2

"hello" + 1  =  "hello1"        JS
             =   “iello"        asm
             =   "hellp"        ??!

"hello" * 2  =   "hellohello"   python™

"hello" / 2  =  ??? 🤔
```

Types communicate to us what the computer can do

Learning objectives

- Understand key ideas behind specification and verification
- Understand some key concepts and terminology behind types
- Learn about the mypy tool for typing in Python
- Develop ability to use types to avoid bugs and write code more effectively

Validation

Did we implement the right equations?

vs

Verification

Did we implement the equations right?

Challenge

Telling these two apart when results are not as expected

Terminology: what does "*verified*" mean?

Verification wrt. a specification

i.e. check(implementation, specification)

∴ *validation <u>is</u> verification*

where specification $\triangleq$ $\approx$*observation*

The value of a specification is what we make of it;
it depends on our goals and values

How *much* verification?

- Lots of verification techniques out there:
    - Testing
    - Type systems
    - Deductive verification
    - Static analysis
    - Interactive theorem provers
    - Modelling and model checking
- How much to use?

How *much* verification?

“Lightweight Formal Methods” (Jackson, Wing, 1996)

"...except in safety-critical work, the cost of full verification is prohibitive and early detection of errors is a more realistic goal.

There can be no point embarking on the construction of a specification until it is known exactly what the specification is for; which risks it is intended to mitigate; and in which respects it will inevitably prove inadequate."

Today we will mitigate against data errors

A helpful model: types as sets

- Set defined by its elements (*data*), *e.g.*,
  - $\mathbb{N}$ - Natural numbers $\{1, 2, \ldots\}$ or $\{0, 1, 2, \ldots\}$ depending who you ask!
  - $\mathbb{Z}$ - Integers $\{\ldots, -2, -1, 0, 1, 2, \ldots\}$
  - $\mathbb{R}$ - Real numbers $\{\ldots, 0, 0.1, 0.11, \ldots, e, \ldots, \pi, \ldots\}$
- Sets of pairs of A and B *written* $A \times B$ (Cartesian product)
  - e.g., $\mathbb{N} \times \mathbb{N} = \{(1,1), (1,2), (2,1), (2,2), \ldots\}$
- Functions from A to B *written* $A \to B$
  - e.g. $\mathsf{abs} : \mathbb{Z} \to \mathbb{N}_0$
  - $\sqrt{} : \mathbb{R}_{\geq 0} \to \mathbb{R} \times \mathbb{R}$
  - $+ : \mathbb{N} \times \mathbb{N} \to \mathbb{N}$

Notational convention

$$\textit{expression} : \textit{type}$$

type signature / specification

Static typing vs. Dynamic typing

- Compiler first does type checking
- Ill-typed programs rejected
  - Intrinsic typing - *Ill-typed programs have no meaning* (cannot be run)
- Well-typed programs compiled, using types for optimisation

- No pre-run checks
- Data stored with type information
- Operations check type information
- Errors occur "as it happens"

- Today: we will use mypy to add static typing to Python

Without types?

- E.g., in *assembly languages*
  - *One type* = bits!
  - Everything works / operations may not do what you want
  - *Developer has to track meaning themselves*

Types eliminate a class of bugs

“Well typed programs cannot go wrong”
(Milner, 1978)

(For some definition of wrong!)

mypy

An optional gradual, static type system for Python

- Gradually convert from dynamic to static typing
- Optional $\Longrightarrow$ *extrinsic typing* - ill-typed programs can still run (have meaning)
- Maths-like *type signatures*

```python
flag : bool = True
```

```python
def plus(x : int, y : int) -> int:
    return x + y
```

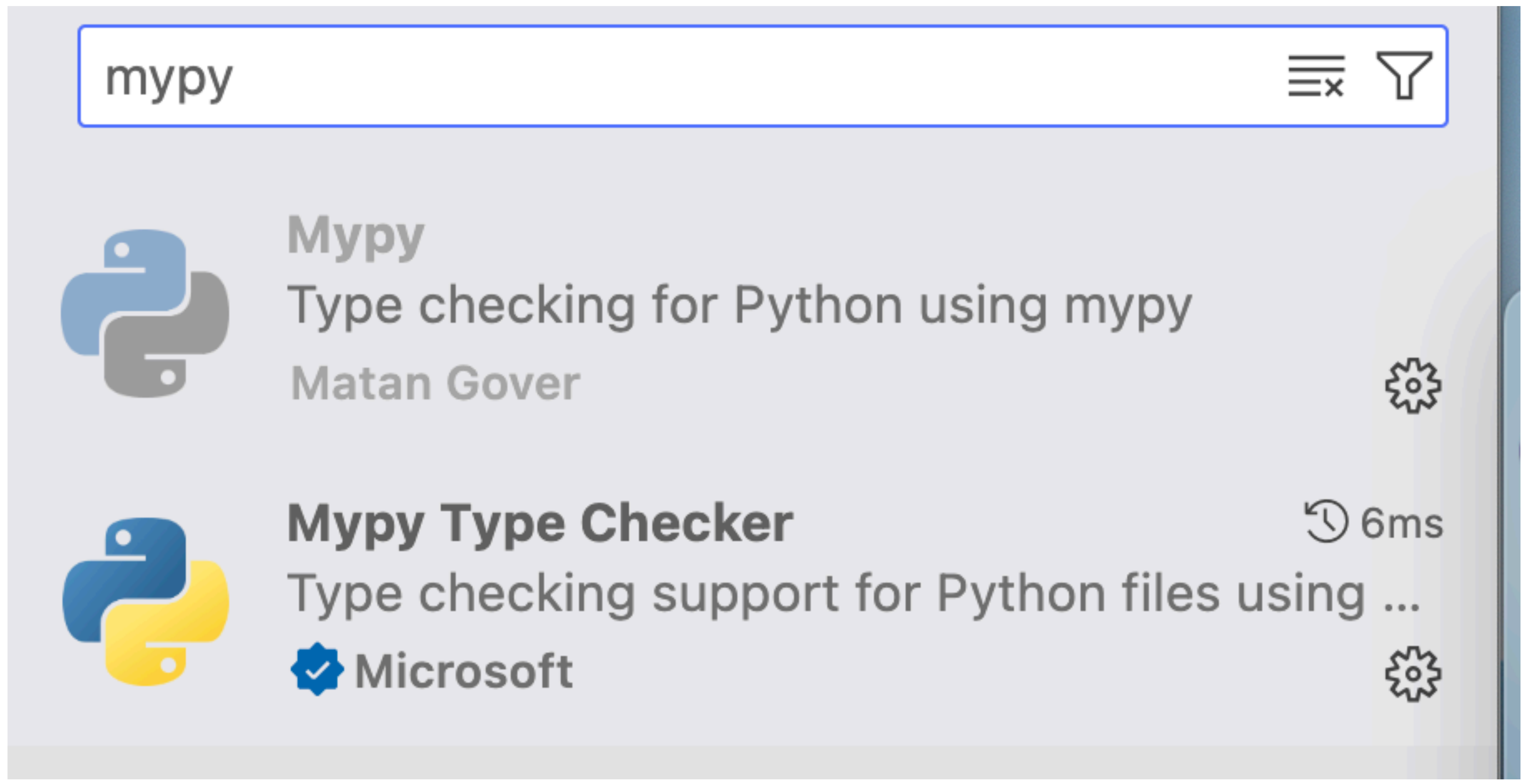
Getting mypy (if you want to 'code along')

```
python3 -m pip install mypy
```

Or possibly:

```
python -m pip install mypy
```

You may want to use the `vscode` extension


mypy

Mypy
Type checking for Python using mypy
Matan Gover

Mypy Type Checker 6ms
Type checking support for Python files using ...
Microsoft

Mypy/Python primitive types

`int`	
`bool`	
`float`	
`str`	
`None`	*(no result type)*
`Any`	*(fall-back, anything)*

```python
def greet(name: str) -> None:
   print("Hi " + name)
```

Type constructors

Like *type functions*: create a type from other types

- For some type `t` then `list[t]` captures lists of elements (all) of type `t`

```
def greet_all(names: list[str]) -> None:
    for name in names:
        print('Hello ' + name)
```

cf. $A \times B$ notation on sets

- `tuple[t1, t2, …]` captures tuples with elements of type t1, t2, etc.

```
some_data : tuple[int, bool, str] = (42, True, “Manchester")
```

Type constructors

Like *type functions*: create a type from other types

- `dict[k, v]` captures records/dictionaries of key k and value v type:

```
x: dict[str, float] = {"field1": 2.0, "field2": 3.0}
```

- `t1 | t2` captures either type t1 or t2 type (Python 3.10 <= `Union[t1, t2]`)

```
def myDiv(x : float, y : float) -> (float | None):
   if y != 0: return x / y
   else:      return None
```

Type constructors and classes

Every class name *is* a type constructor

e.g.,

```
class Complex:
    def __init__(self, realpart, imagpart):
        self.r = realpart
        self.i = imagpart

h : Complex = Complex(3.0, -4.5)
```

Querying mypy

Ask mypy what it thinks the type is:

```
reveal_type(expression)
```

If you need to run too, hide `reveal_type` from runtime:

```
from typing import TYPE_CHECKING

if TYPE_CHECKING:
  reveal_type(d1)
```

Subtyping

- In theory literature, A is a subtype of B written $A :< B$ (*think subsets*)
- Example: `list[t]` is a "subtype" of `Iterable[t]`
- Can pass arguments of a subtype to a function

$$\frac{x : A \qquad f : B \to C \qquad A :< B}{f(x) : C}$$

e.g.

```python
def greet_all(names: Iterable[str]) -> None:
    for name in names:
        print('Hello ' + name)

names = ["Alice", "Brijesh", "Chenxi"]
greet_all(names)   # Ok!
```

Polymorphism

(Also known as *generic types*)

- Consider the function

```
def first(xs : list[str]) -> str:
    return xs[0]
```

- What if we want to use it with list[int] too?

```
def first_int(XS : list[int]) -> int:
    return xs[0]
```

- **Duplication bad for maintenance and understanding**

Polymorphism

(Also known as *generic types*)

- Solution: generalise to <u>any</u> element type T

```
T = TypeVar('T')

def first(xs : list[type[T]]) -> type[T]:
    return xs[0]
```

- (Note: requires an import)

```
from typing import TypeVar, Generic
```

“Free theorems” follow from polymorphic types

- Consider `def someFun(XS : list[type[T]]) -> type[T]`
- “Universality” of `T` tells us we cannot inspect or compute with the `T` elements
- Implies the following (“*naturality*”) property:

```
someFun(list(map(f, x))) = f(someFun(x))
```

$$\begin{tikzcd}
\texttt{list[type[T]]} \arrow[r, "\texttt{someFun}"] \arrow[d, "\texttt{list(map(f,\_))}"'] & \texttt{type[t]} \arrow[d, "\texttt{f}"] \\
\texttt{list[type[S]]} \arrow[r, "\texttt{someFun}"'] & \texttt{type[s]}
\end{tikzcd}$$

Note the right expression applies `f` once, the left applies it `len(x)` times.

∴ Optimisation!

Function types

e.g., for typing higher-order functions

For a function with n-inputs (n-ary) `A1` to `An` and return type `B`:

```
Callable[[A1,... ,An], B]
```

cf. $A \to B$ notation on sets

or $(A_1 \times \ldots \times A_n) \to B$

e.g.,

```
from typing import Callable
S = TypeVar('S')
T = TypeVar('T')
def memo(f : Callable[[S], T], x : S) -> tuple[S,T]:
  return (x, f(x))
```

Escape hatch!

- A type checker *T* is complete if, for all programs *P* then *T(P)* is true
- Most type checkers are *incomplete* $\Longrightarrow$ some valid programs rejected
- Python has an escape hatch:

```
borked = 0 / "hello" # type: ignore
```

Does not raise a type checking error (though it clearly should)

mypy and NumPy

Types for external libraries

Can use the class names already for numpy, e.g.,

```
import numpy as np
myArray : np.ndarray = np.ndarray(shape=(2,2), dtype=float)
```

https://numpy.org/devdocs/reference/typing.html

mypy and NumPy

Types for external libraries

```
import numpy.typing as npt
```

provides

- `ArrayLike` - objects that can be converted to arrays
- `DTypeLike` - objects that can be converted to dtypes
- `NDArray[T]` - numpy arrays of T values

Needs local config, e.g., via `mypy.ini`

```
[mypy]
plugins = numpy.typing.mypy_plugin
```

https://numpy.org/devdocs/reference/typing.html

mypy and NumPy

Types for external libraries

e.g.

```python
import numpy as np
import numpy.typing as npt

def as_array(a: npt.ArrayLike) -> np.ndarray:
    return np.array(a)

def scale_array(a: float, arr: npt.NDArray[np.float64]) -> npt.NDArray[np.float64]:
    return a*arr
```

Coming into land….
What did we learn?

- Understand key ideas behind specification and verification
- Understand some key concepts and terminology behind types
    - “Sets” model
    - Static vs dynamic
    - Extrinsic vs intrinsic
    - Subtyping
    - Polymorphism

Coming into land….
What did we learn?

- Learn about the mypy tool for typing in Python
    - mypy gives us extrinsic static typing
- Develop ability to use types to avoid bugs and write code more effectively
    - Go and practice on your own (**see worksheet!**)
    - Start using in projects

Worksheet

https://dorchard.github.io/types-tutorial/mypy-worksheet.pdf

Thanks- and happy typing!

https://iccs.cam.ac.uk

https://dorchard.github.io

types.pl/@dorchard

@dorchard

VScode mypy plugin woes?

No errors appear

- Check mypy
- Explicitly set path to mypy

```
% which mypy
/opt/homebrew/bin/mypy
```

- Then edit settings.json, adding, e.g.:

```
        "mypy-type-checker.path": ["/opt/homebrew/bin/mypy"]
```