Mica

Automated Differential Testing for OCaml Modules

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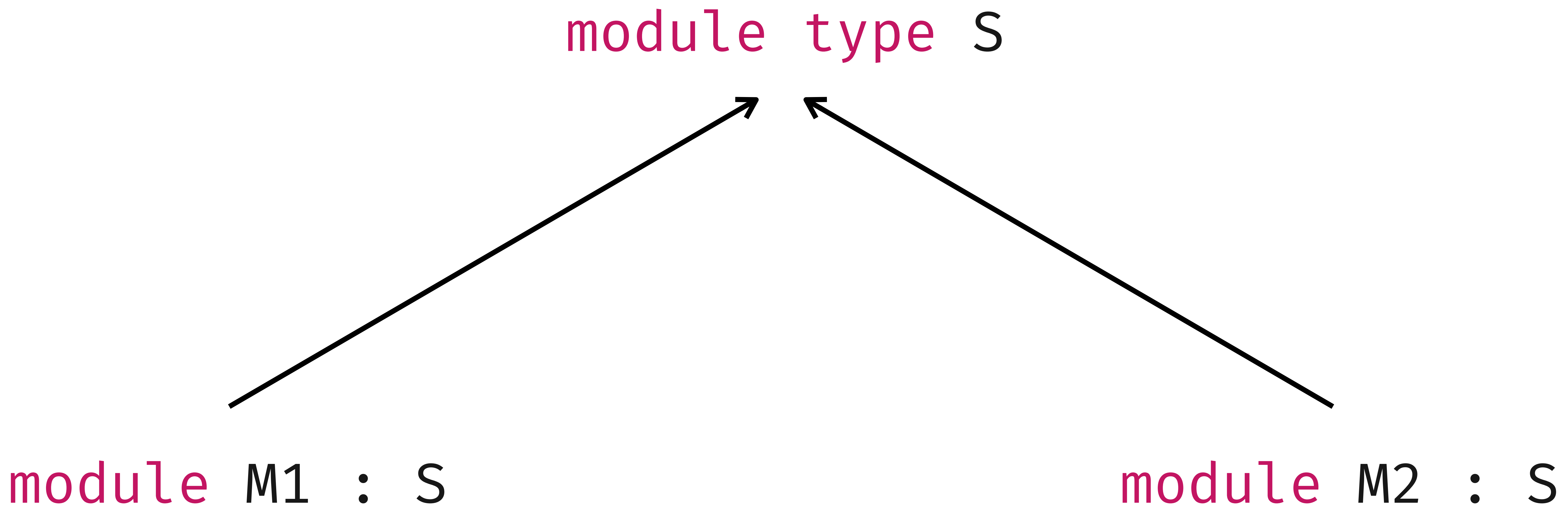
Representation Independence

Two modules can implement the same signature completely differently …



`module type S`

`module M1 : S`

`module M2 : S`

Clients can use S without knowing whether they’re getting `M1` or `M2`!

Example: Finite Sets

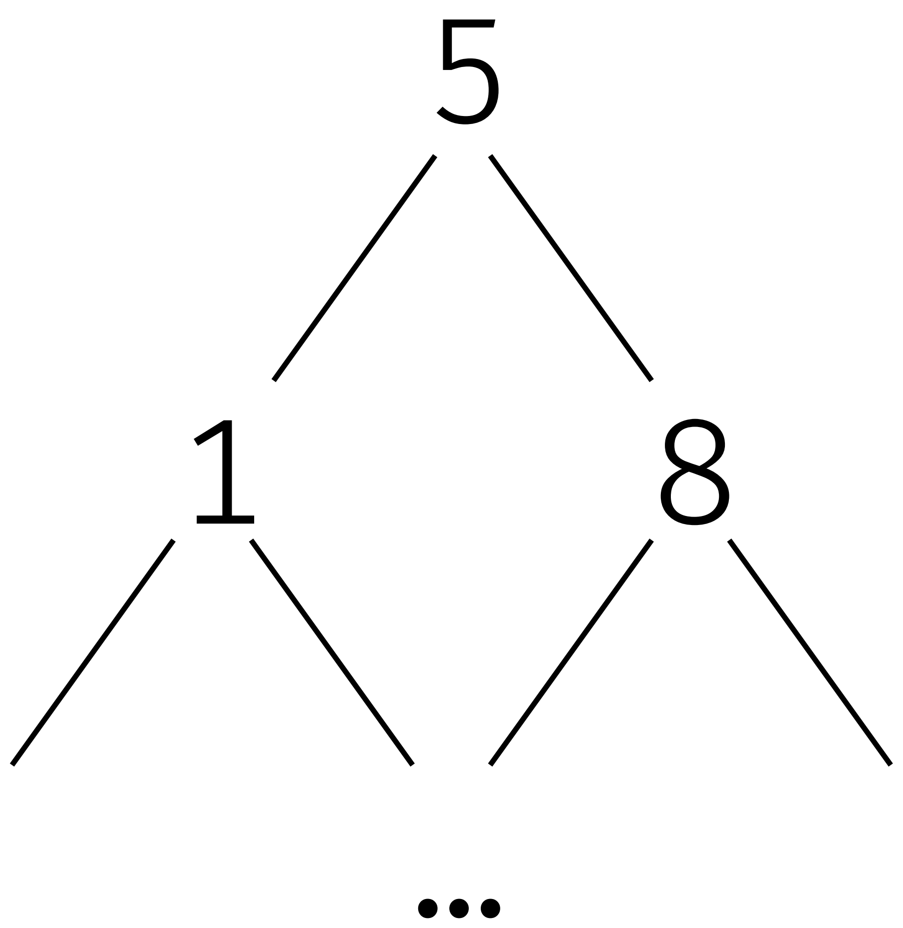
```
module type S = sig
  type 'a t
  val empty  : 'a t
  val insert : 'a -> 'a t -> 'a t
  …
end
```

```
module type S
```

```
{1, 5, 8, …}
```

```
[1; 5; 8; …]
```

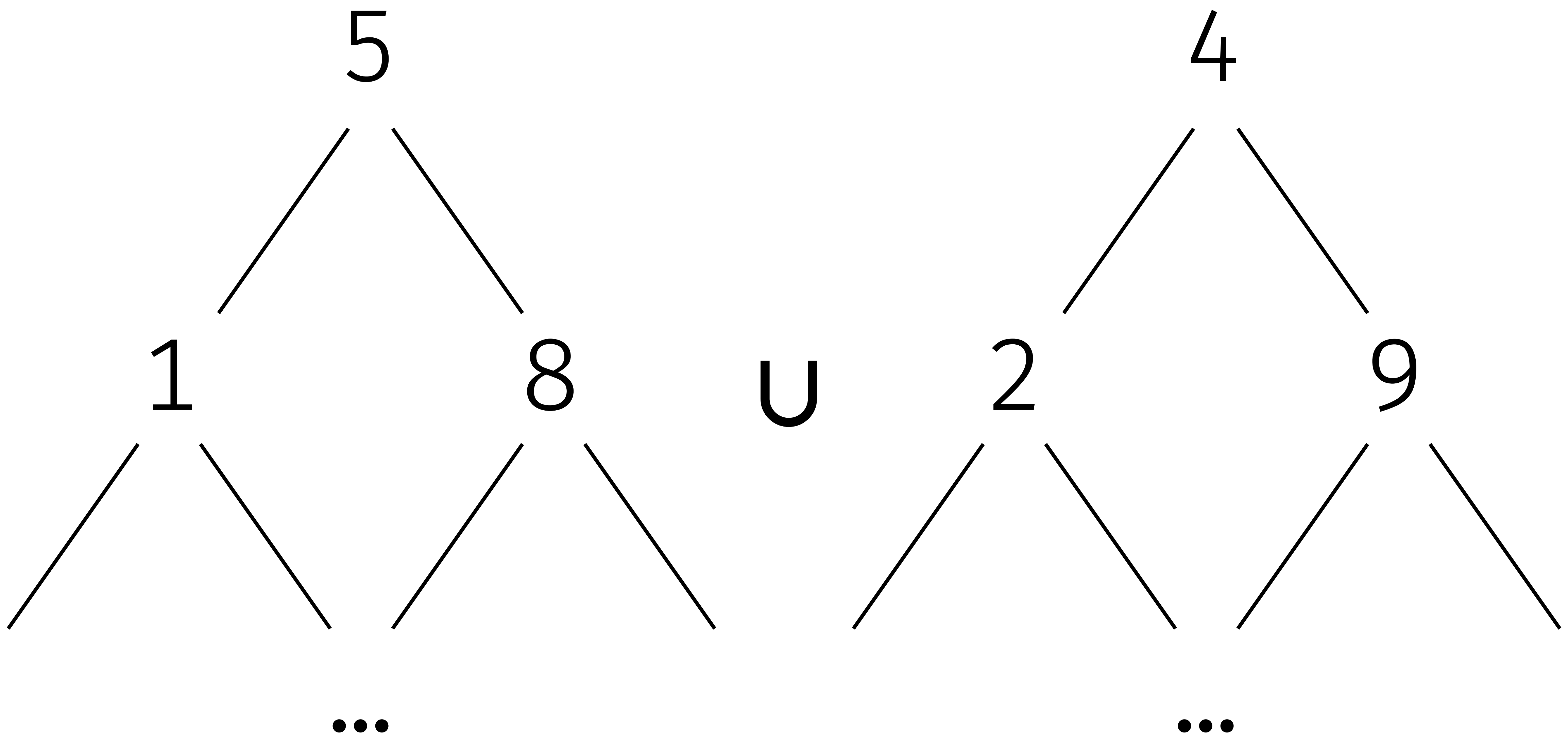
```
module ListSet : S
```



```
module BSTSet : S
```

Are these ***equivalent***?

```
[1; 5; 8] ++ [2; 4; 9]
```



Observational Equivalence

equivalent ***inputs*** $\mapsto$ equivalent ***outputs***

How do we check observational equivalence?

We can use **property-based testing**!

Property-Based Testing

1. Write ***properties***

$\forall x.\ P(x)$

2. Generate ***random inputs***

🏭 $\rightsquigarrow$ x_1 x_2 …

3. Check if inputs satisfy property

Property-Based Testing

Popularised by:

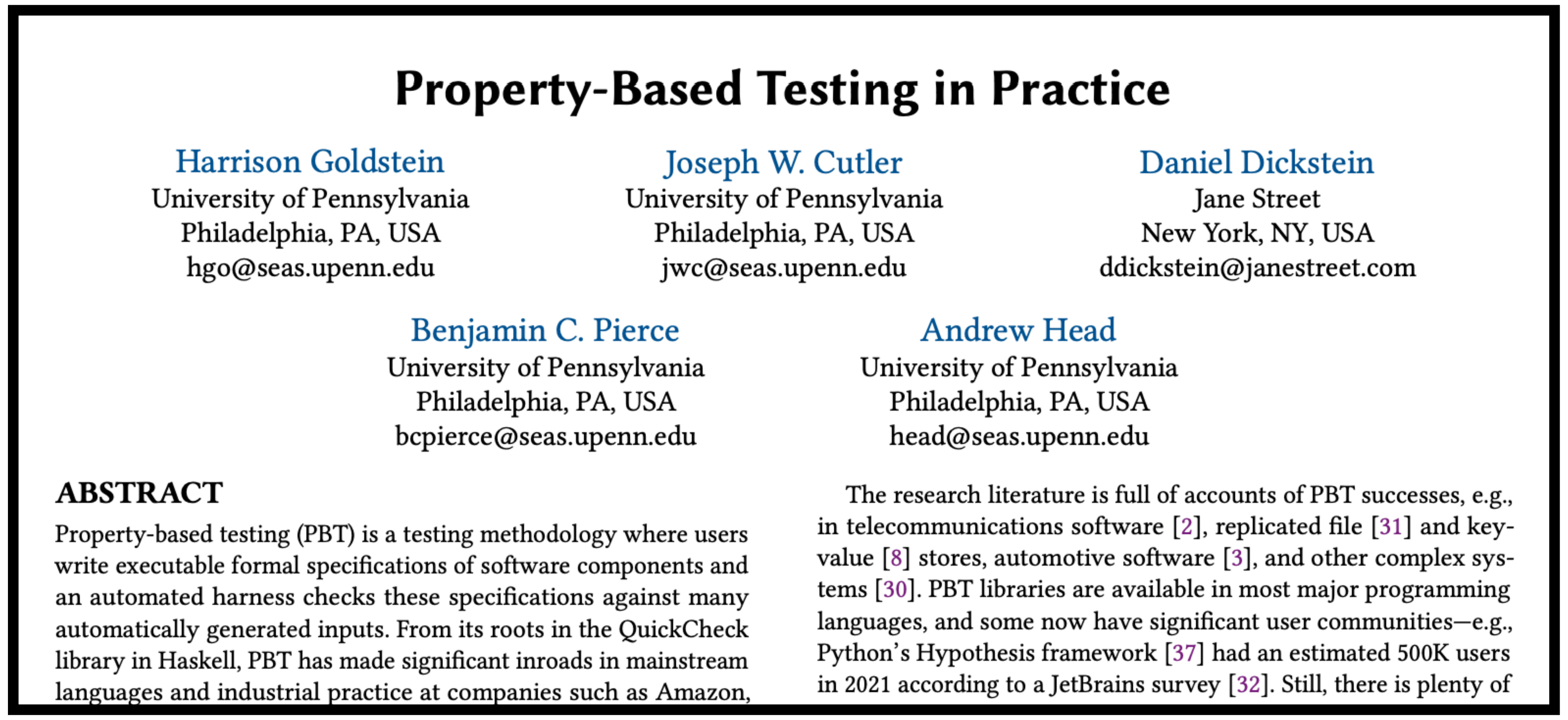
QuickCheck

Claessen & Hughes (ICFP 2000)

Why should we care?

1. Testing observational equivalence requires significant programmer effort

Goldstein et al. (ICSE ’24)



Property-Based Testing in Practice

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ABSTRACT

Property-based testing (PBT) is a testing methodology where users write executable formal specifications of software components and an automated harness checks these specifications against many automatically generated inputs. From its roots in the QuickCheck library in Haskell, PBT has made significant inroads in mainstream languages and industrial practice at companies such as Amazon,

The research literature is full of accounts of PBT successes, e.g., in telecommunications software [2], replicated file [31] and key-value [8] stores, automotive software [3], and other complex systems [30]. PBT libraries are available in most major programming languages, and some now have significant user communities—e.g., Python’s Hypothesis framework [37] had an estimated 500K users in 2021 according to a JetBrains survey [32]. Still, there is plenty of

30 OCaml developers interviewed on their use of PBT

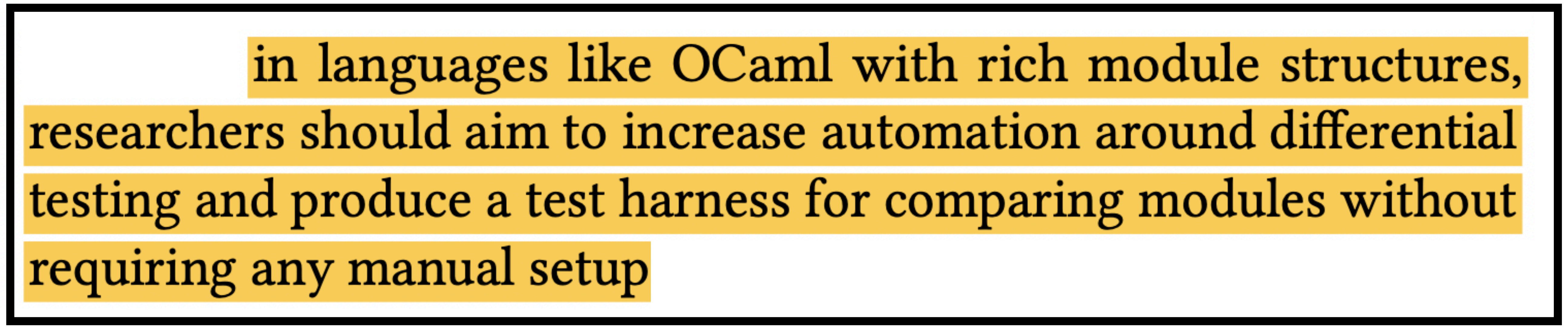
Jane Street

Why should we care?

1. Testing observational equivalence requires significant programmer effort

- Developers described this process as ***"tedious"*** & ***"overwhelming"***
- High ***"overhead"*** associated with writing PBT boilerplate

Goldstein et al. (ICSE '24)



in languages like OCaml with rich module structures, researchers should aim to increase automation around differential testing and produce a test harness for comparing modules without requiring any manual setup

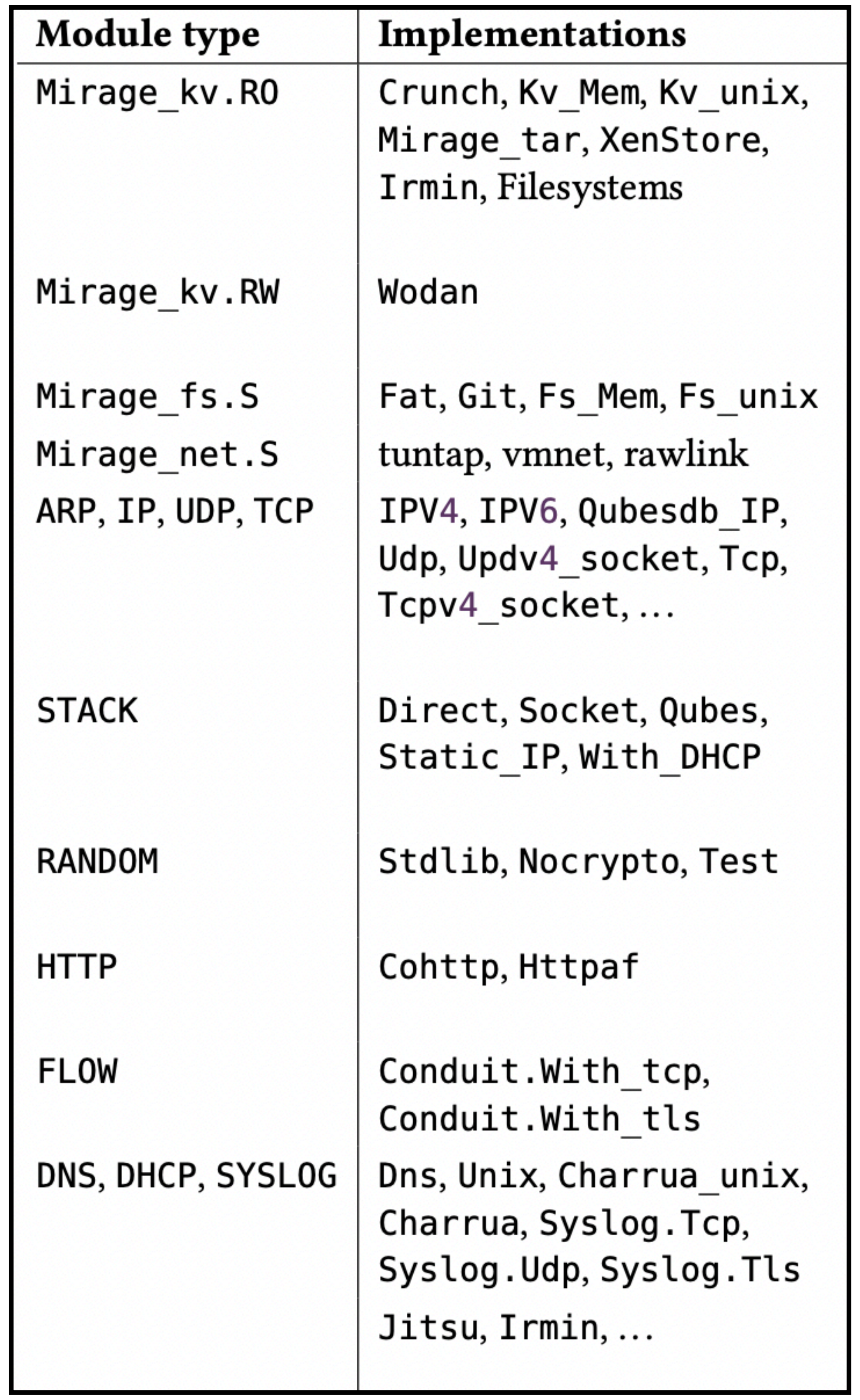
Why should we care?

2. Large OCaml software systems are built using multiple modules that implement the same signature

MirageOS

Module Signatures

Implementations



Module type	Implementations
Mirage_kv.RO	Crunch, Kv_Mem, Kv_unix, Mirage_tar, XenStore, Irmin, Filesystems
Mirage_kv.RW	Wodan
Mirage_fs.S	Fat, Git, Fs_Mem, Fs_unix
Mirage_net.S	tuntap, vmnet, rawlink
ARP, IP, UDP, TCP	IPV4, IPV6, Qubesdb_IP, Udp, Updv4_socket, Tcp, Tcpv4_socket, …
STACK	Direct, Socket, Qubes, Static_IP, With_DHCP
RANDOM	Stdlib, Nocrypto, Test
HTTP	Cohttp, Httpaf
FLOW	Conduit.With_tcp, Conduit.With_tls
DNS, DHCP, SYSLOG	Dns, Unix, Charrua_unix, Charrua, Syslog.Tcp, Syslog.Udp, Syslog.Tls
	Jitsu, Irmin, …

Radanne et al. (2019)

What if I told you …

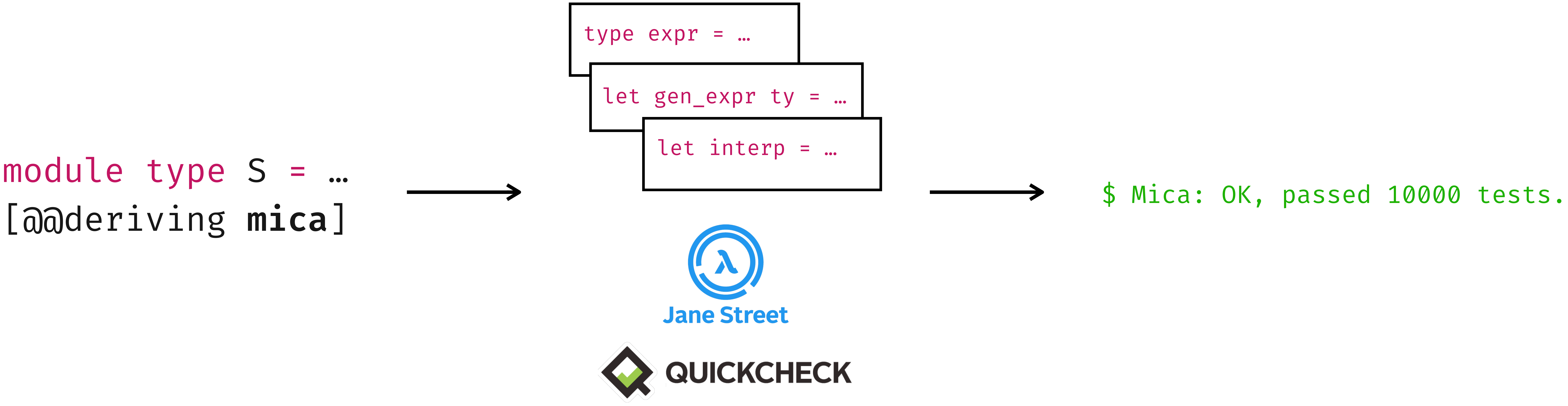
You can take two modules that implement the same signature …

```
module type S

module M1 : S        module M2 : S
```

… and ***automatically*** get PBT code that compares them?

Mica



```
module type S = …
[@@deriving mica]
```

```
type expr = …
```

```
let gen_expr ty = …
```

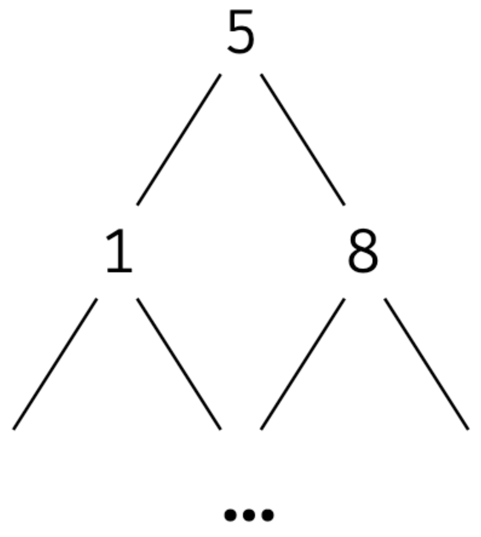
```
let interp = …
```

```
$ Mica: OK, passed 10000 tests.
```

Mica *automatically* generates random S-operations & tests that `M1`, `M2` are observationally equivalent w.r.t. S

```
module M1 : S                                  module M2 : S

  [1; 5; 8; …]
```



```
M1.size (M1.add 2 M1.empty)    ≡    M2.size (M2.add 2 M2.empty)
            ⋮                                  ⋮
M1.is_empty (…)                ≡    M2.is_empty (…)
```

randomly generated

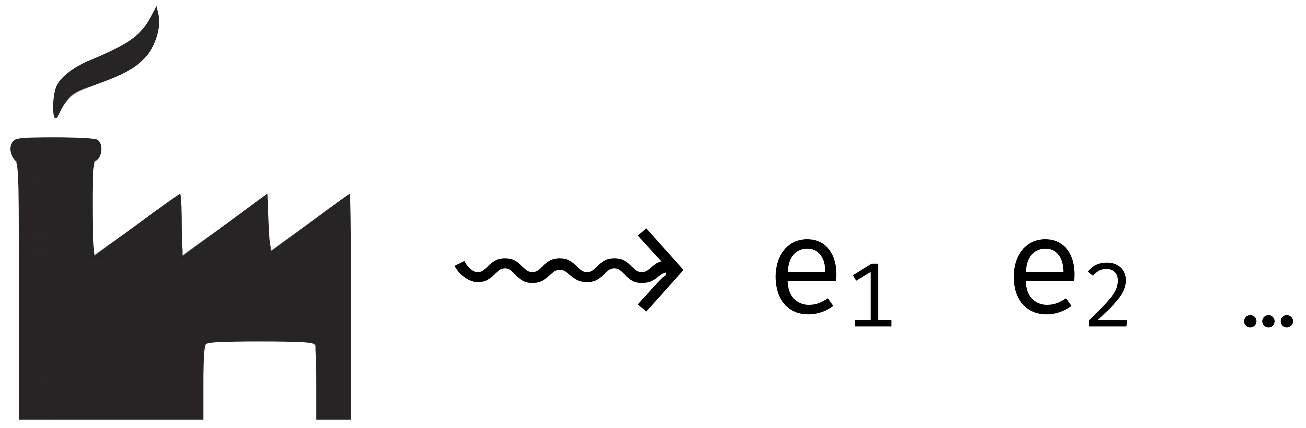
Mica derives the following automatically:

Types

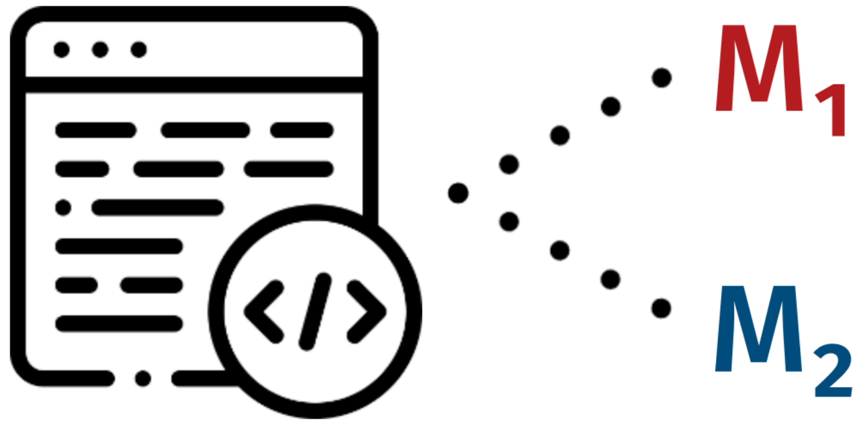
(to be explained later)

```
expr
 ty
value
```

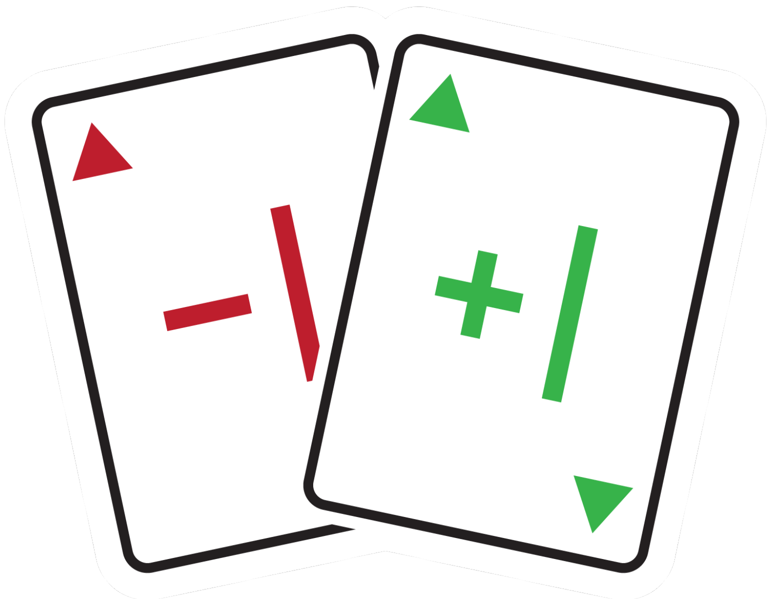
QuickCheck Generator



Interpreter



Test Harness



Symbolic Expressions

Model operations in the module signature using an
inductively-defined algebraic data type

module signature   the **expr** type

```
                                                           type expr =
val empty    : ‘a t                             ⟷            | Empty

val is_empty : ‘a t → bool                      ⟷            | Is_empty of expr

val insert   : ‘a → ‘a t → ‘a t                 ⟷            | Insert of int * expr
…                                                              …
```

Symbolic Expressions

Types

```
type ty = Int | Bool | T
```

Symbolic Expressions

Values

```
type value =
    | ValBool of bool
    | ValIntT of int M.t
    | …
```

Interpretation Functor

```
module Interpret (M : S) = …
```

```
expr                ⟶   value

Insert (2, Empty)   ⟼   M.insert 2 M.empty
```

QuickCheck Generator

randomly generate
symbolic representations of
well-typed expressions

```
gen_expr : ty → expr Generator.t
```

```
Union (Insert (2, Empty), Empty)
```

√

```
Is_empty (Size Empty)
```

X

Test Harness Functor

Checks observational equivalence at ***concrete*** types

(*not* abstract types — they have an abstract notion of equality different from OCaml's polymorphic equality)

```
module TestHarness (M1 : S) (M2 : S) = …
```

`int`	`‘a t`
✓	✗

QuickCheck Generator

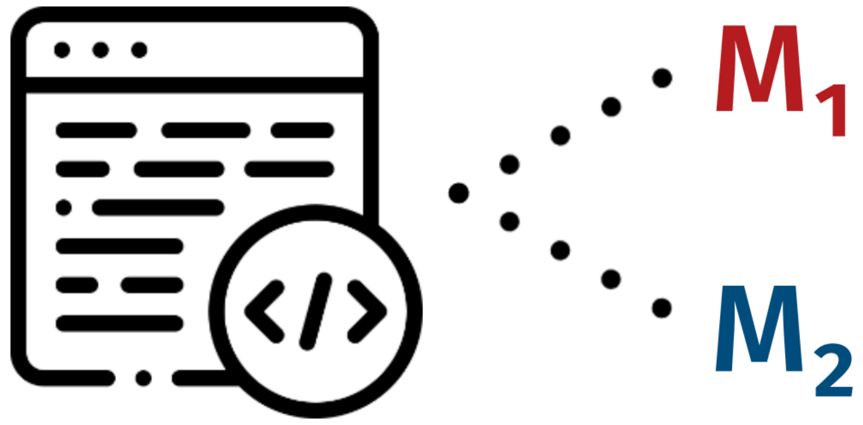
Generates ***random*** symbolic expressions

```
(Size
  (Union (Add 2 Empty) …)
```

Interpreter

Interprets expressions over modules

```
M.size
  (M.union (M.add 2 M.empty) …)
```



Test Harness

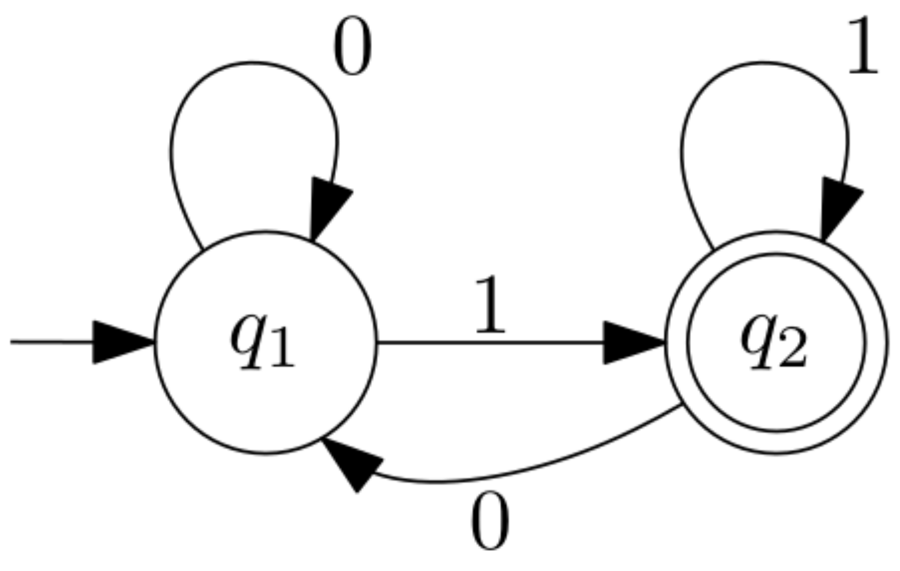
Checks observational equivalence

```
v1 ==? v2
```

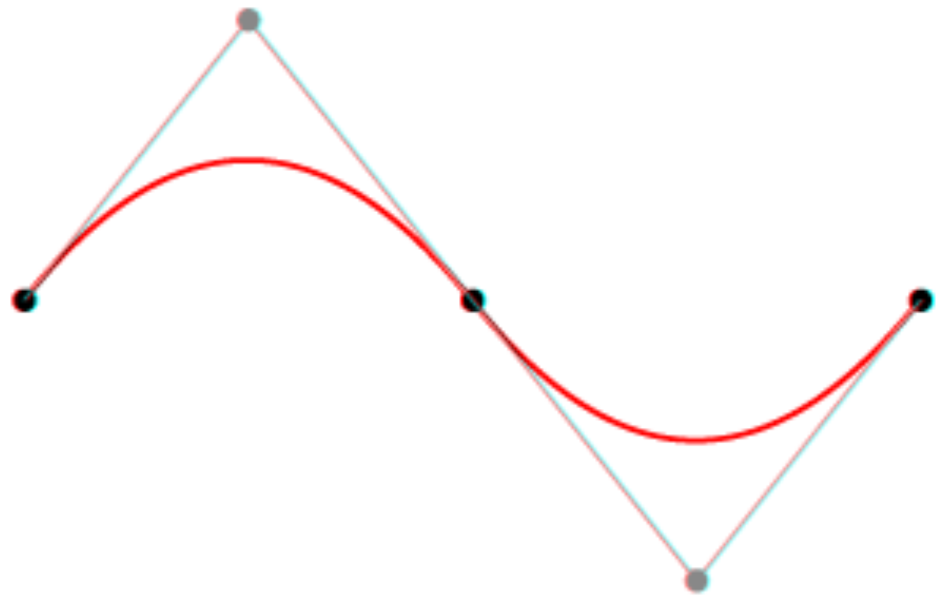
Case Studies

Case Studies

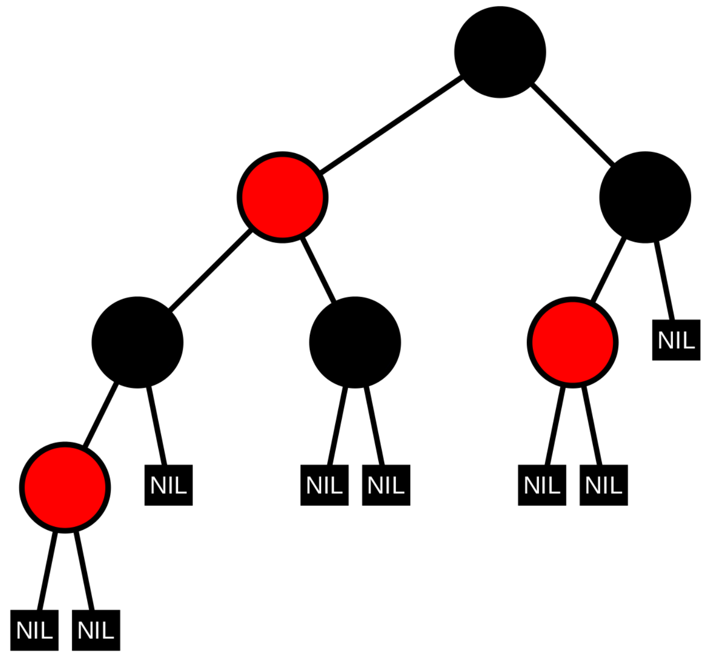
Regex Matchers



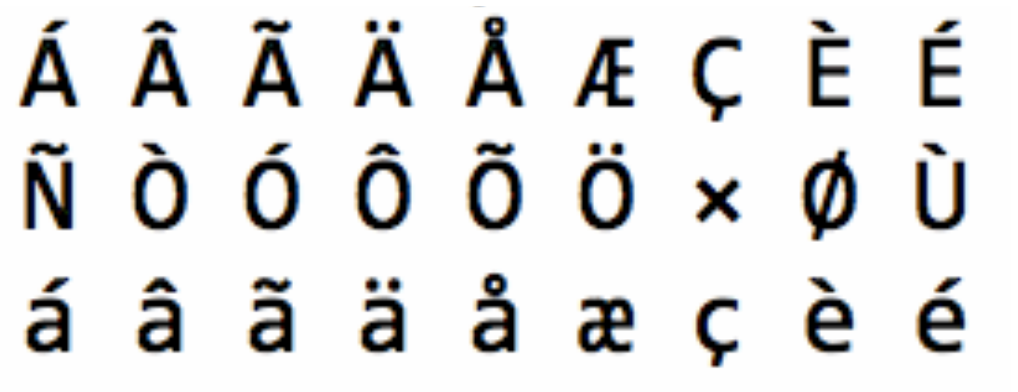
Polynomials



Persistent Maps



Character Sets



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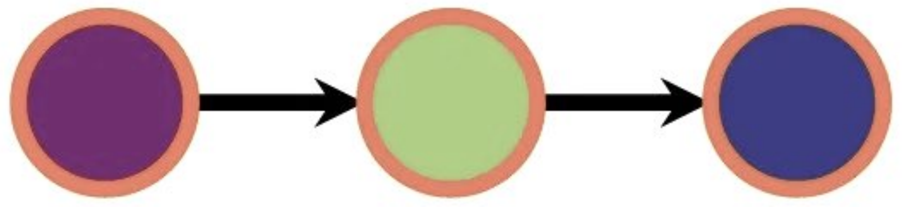
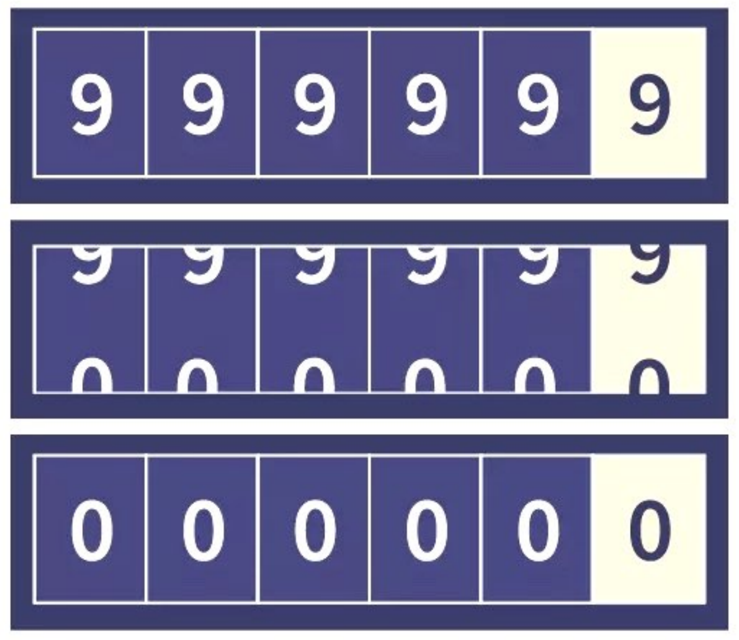
Ephemeral Queues

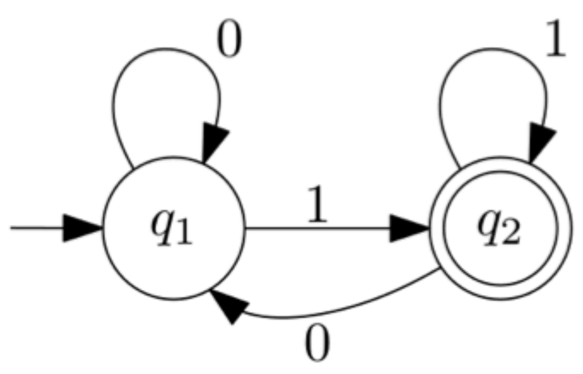


Unsigned Integers

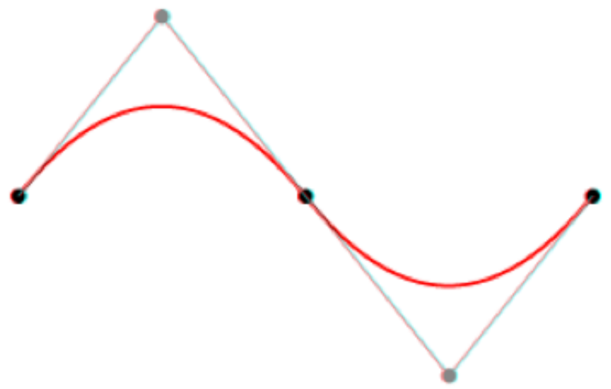


35 manually-inserted bugs caught

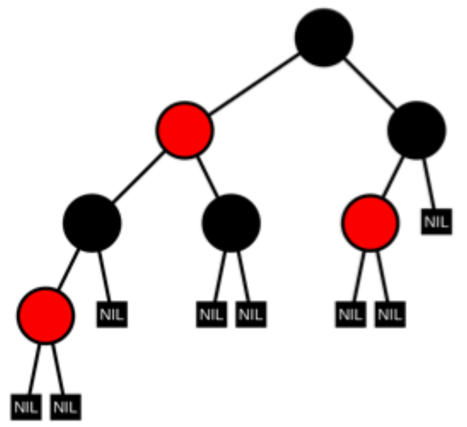
Regex Matchers



Polynomials



Persistent Maps



Character Sets

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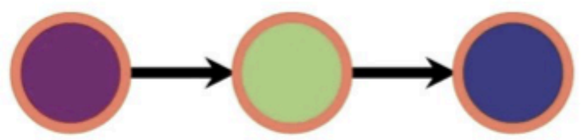
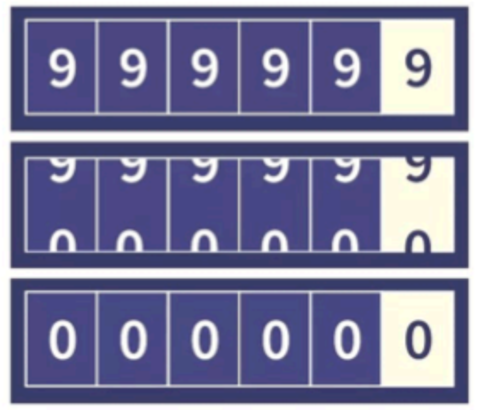
Ephemeral Queues



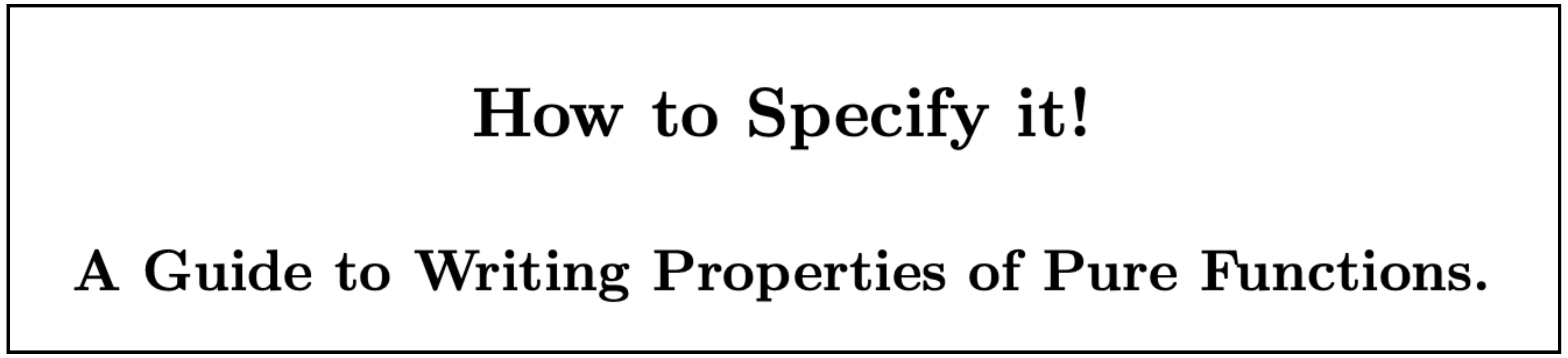
Unsigned Integers



6 real-world OCaml libraries

Case study: ***How to Specify It***

John Hughes

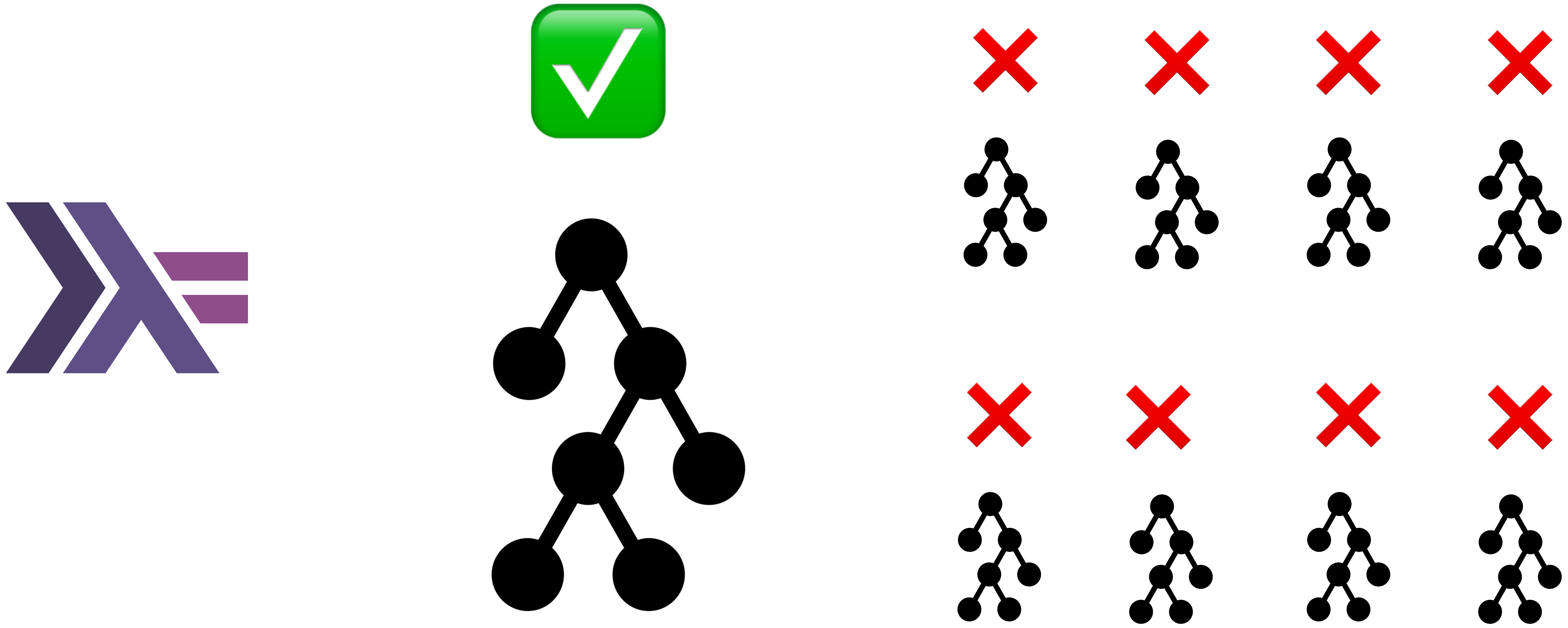


How to Specify it!

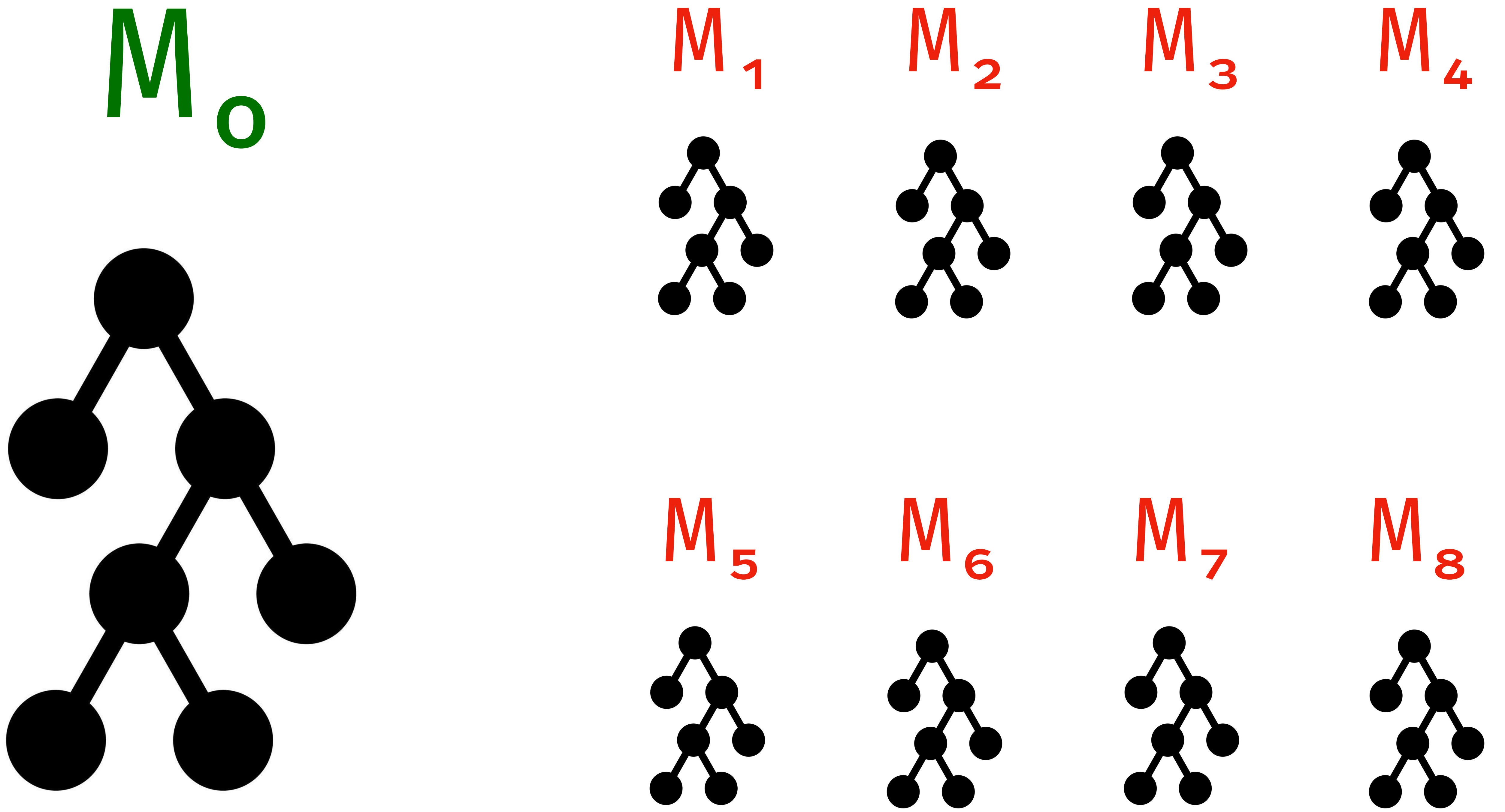
A Guide to Writing Properties of Pure Functions.

(TFP '19)

Case study: **BSTs done 9 ways**



Case study: **BSTs done 9 ways**



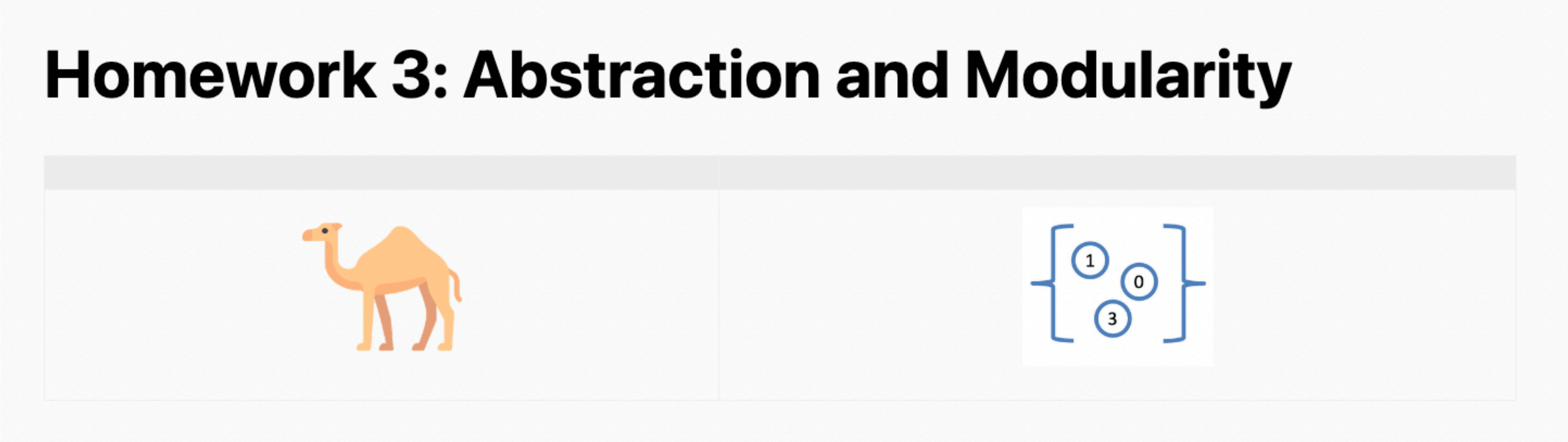
Each bug caught within ~170 randomly generated symbolic expressions

Case study: **Finding bugs in student assignments**

- Penn's undergrad intro OCaml class
  - 400 students every semester

- Natural source of bugs!

Case study: **Sets done 400 ways**



Homework 3: Abstraction and Modularity

Penn CIS 1200, Fall 2023

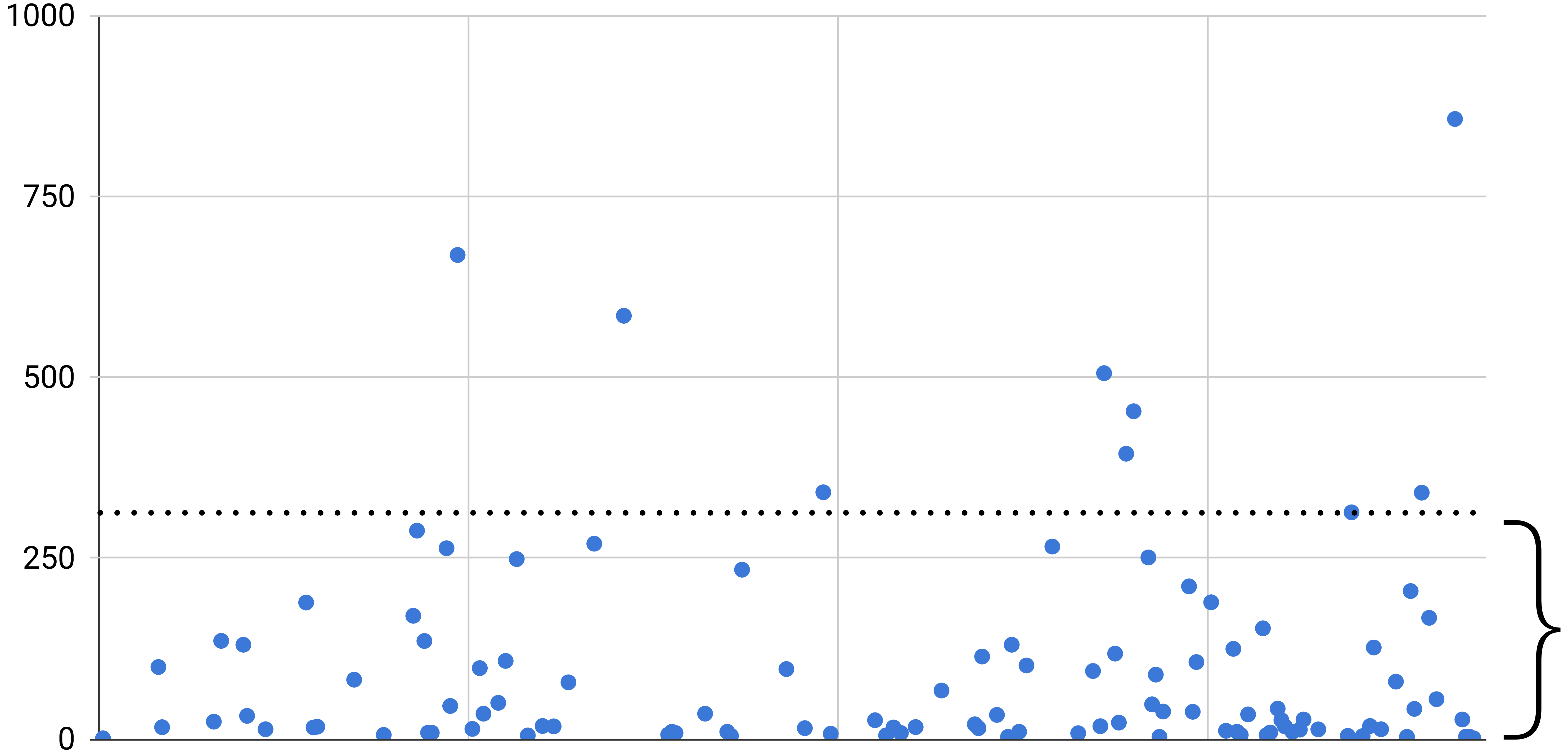
As homework, students were asked to implement sets using lists & BSTs

(we looked at historical data from Fall ’23)

Are students’ implementations observationally equivalent?

Mica caught bugs in 107 students' submissions! (29% of the class)

Average no. of random inputs required to catch bug

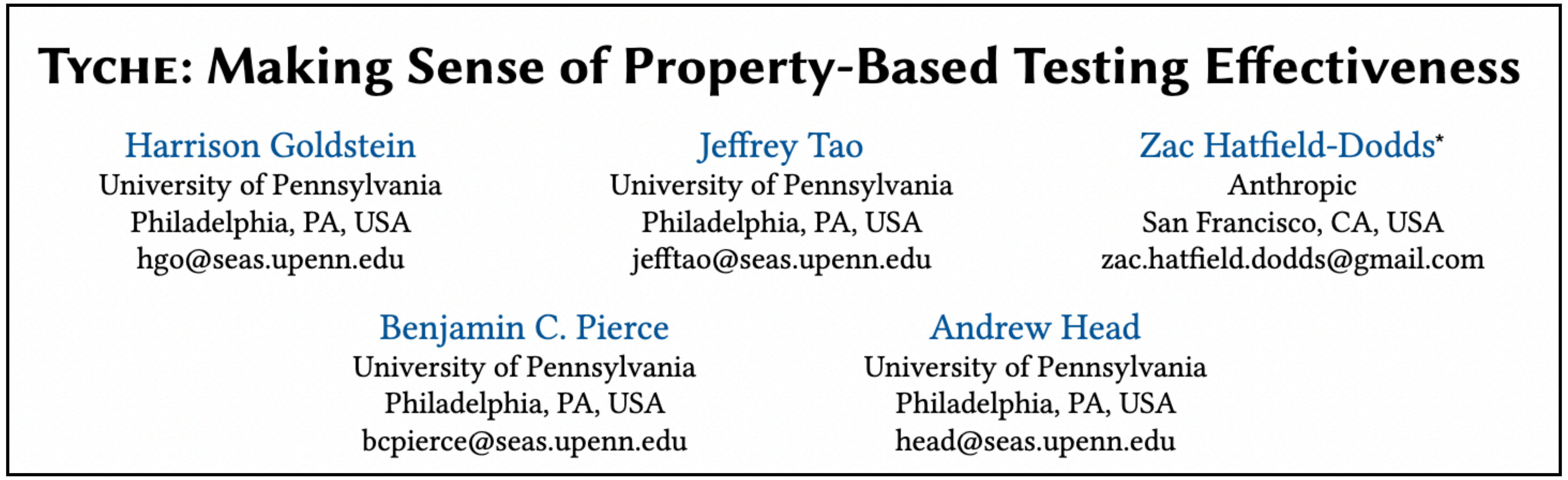


91% of bugs caught within 300 randomly generated symbolic expressions!

(each dot represents a student, lower is better)

VS Code Integration with **Tyche**

Goldstein et al. (to appear at UIST '24)



Tyche: Making Sense of Property-Based Testing Effectiveness

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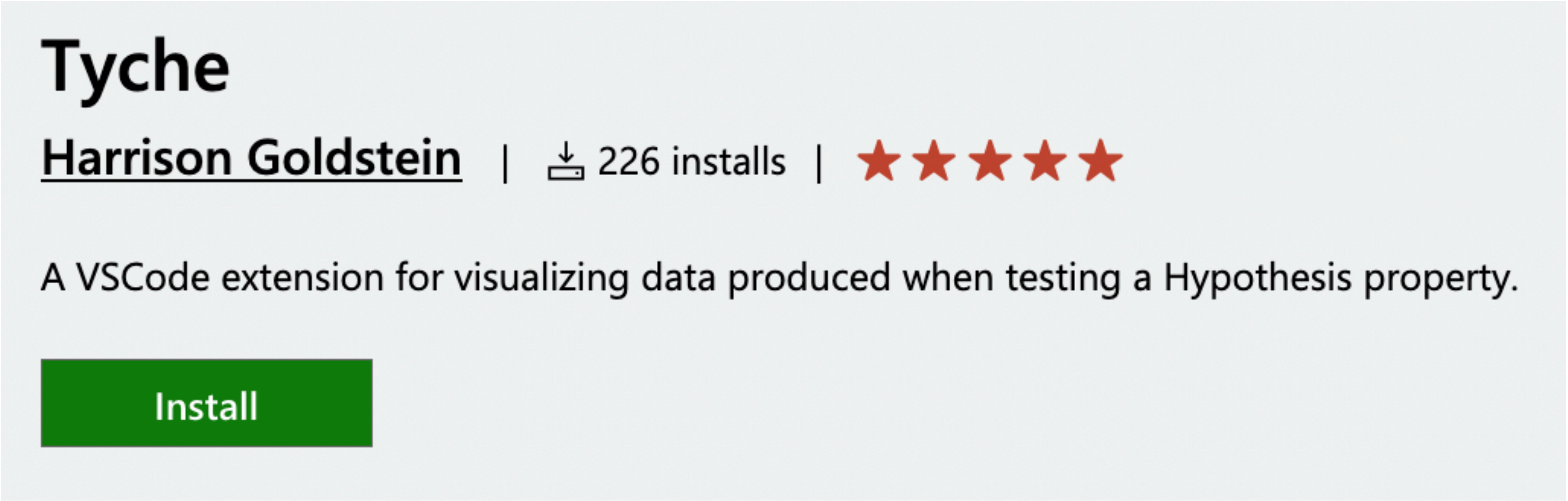


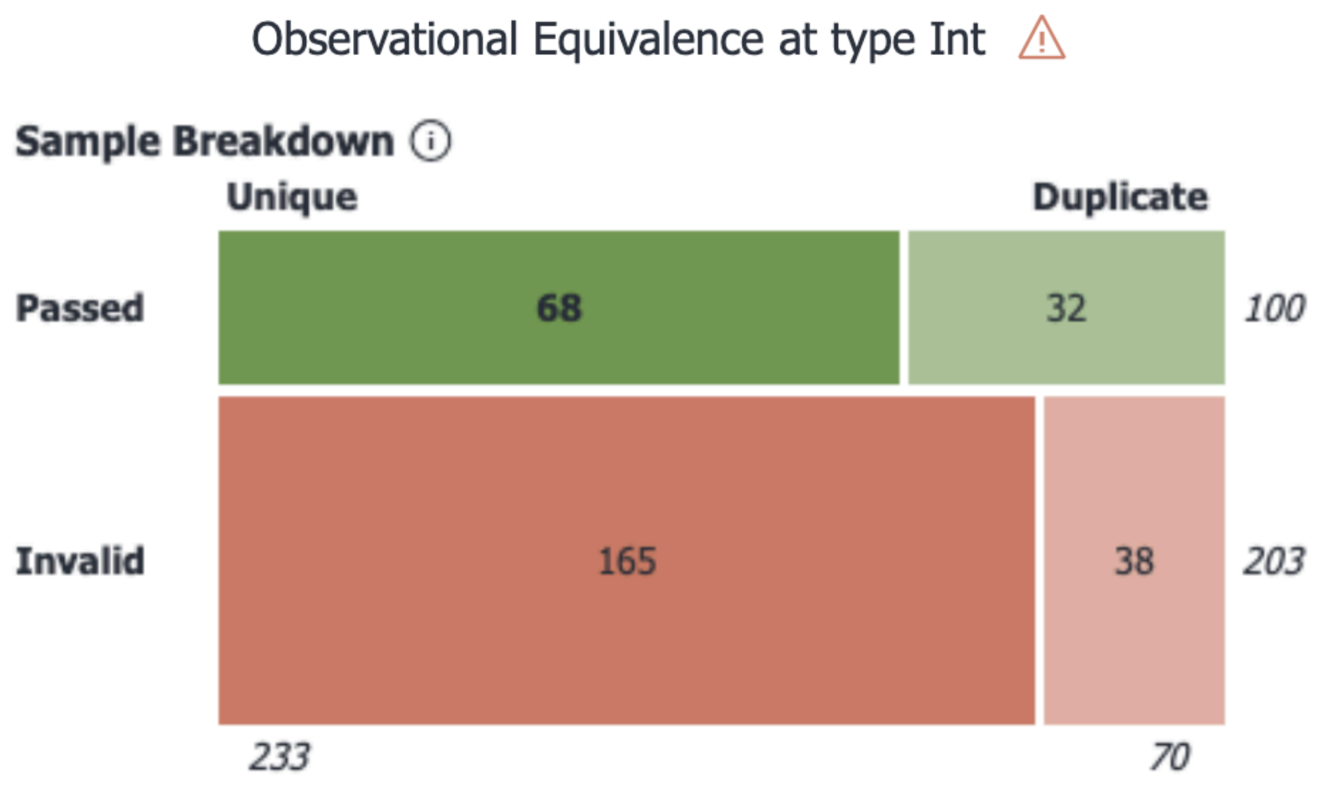
Tyche

Harrison Goldstein | 226 installs | ★★★★★

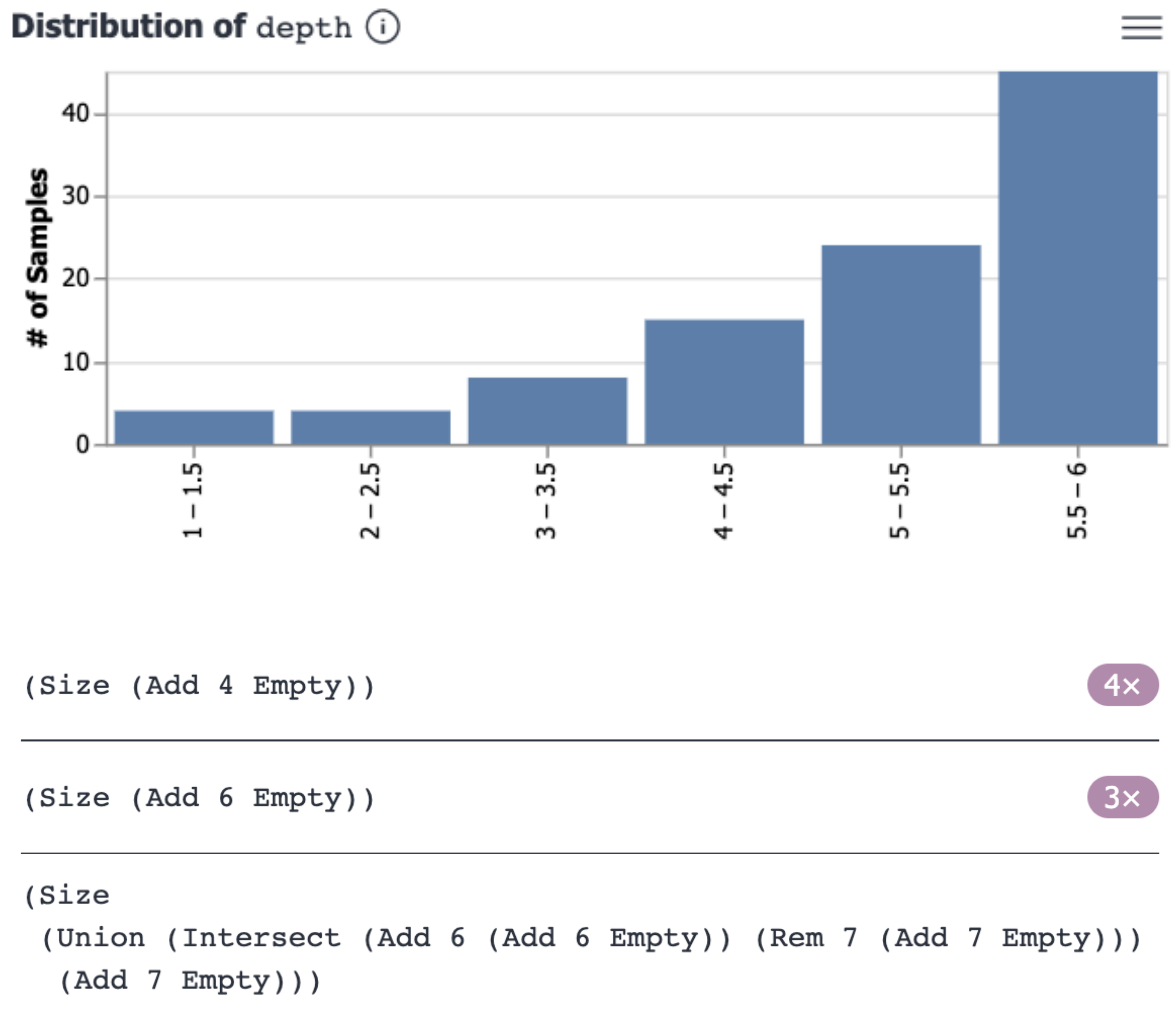
A VSCode extension for visualizing data produced when testing a Hypothesis property.

Using **Tyche** to display **Mica's** test results

Observational equivalence test results



Distribution of symbolic expressions

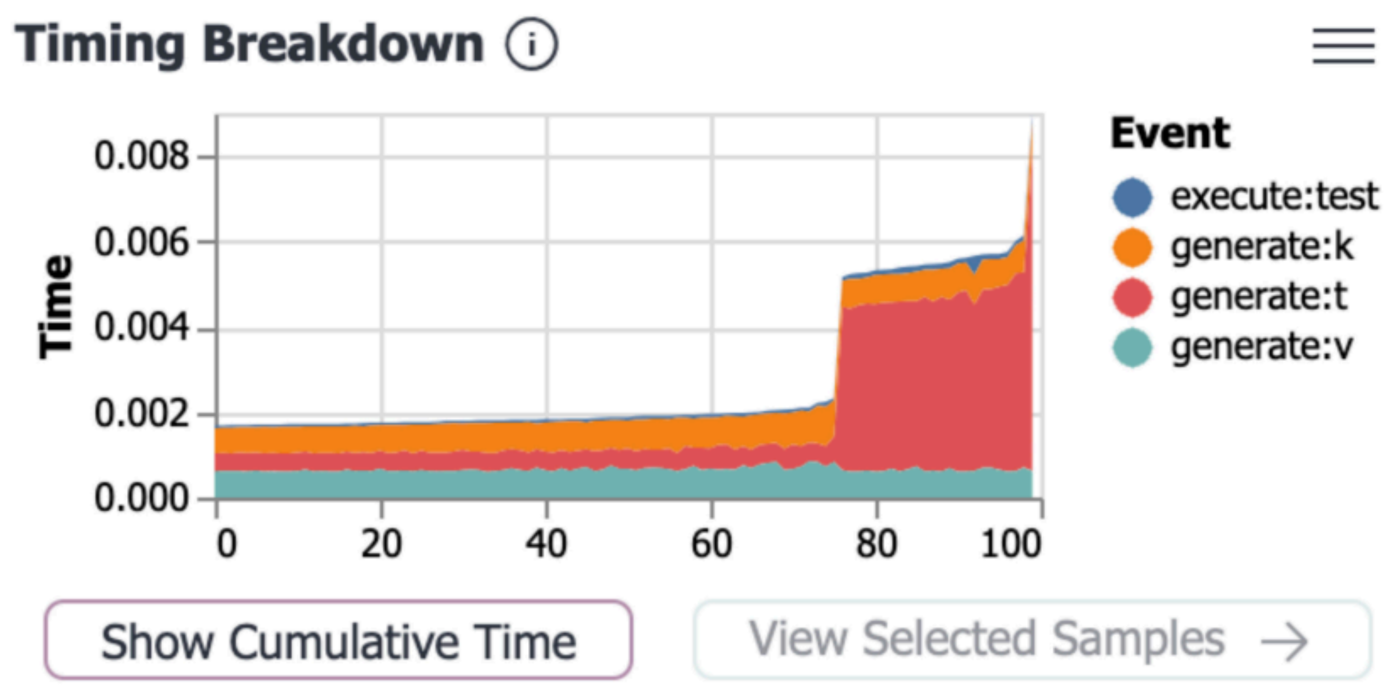


```
(Size (Add 4 Empty))                                        4×
```

```
(Size (Add 6 Empty))                                        3×
```

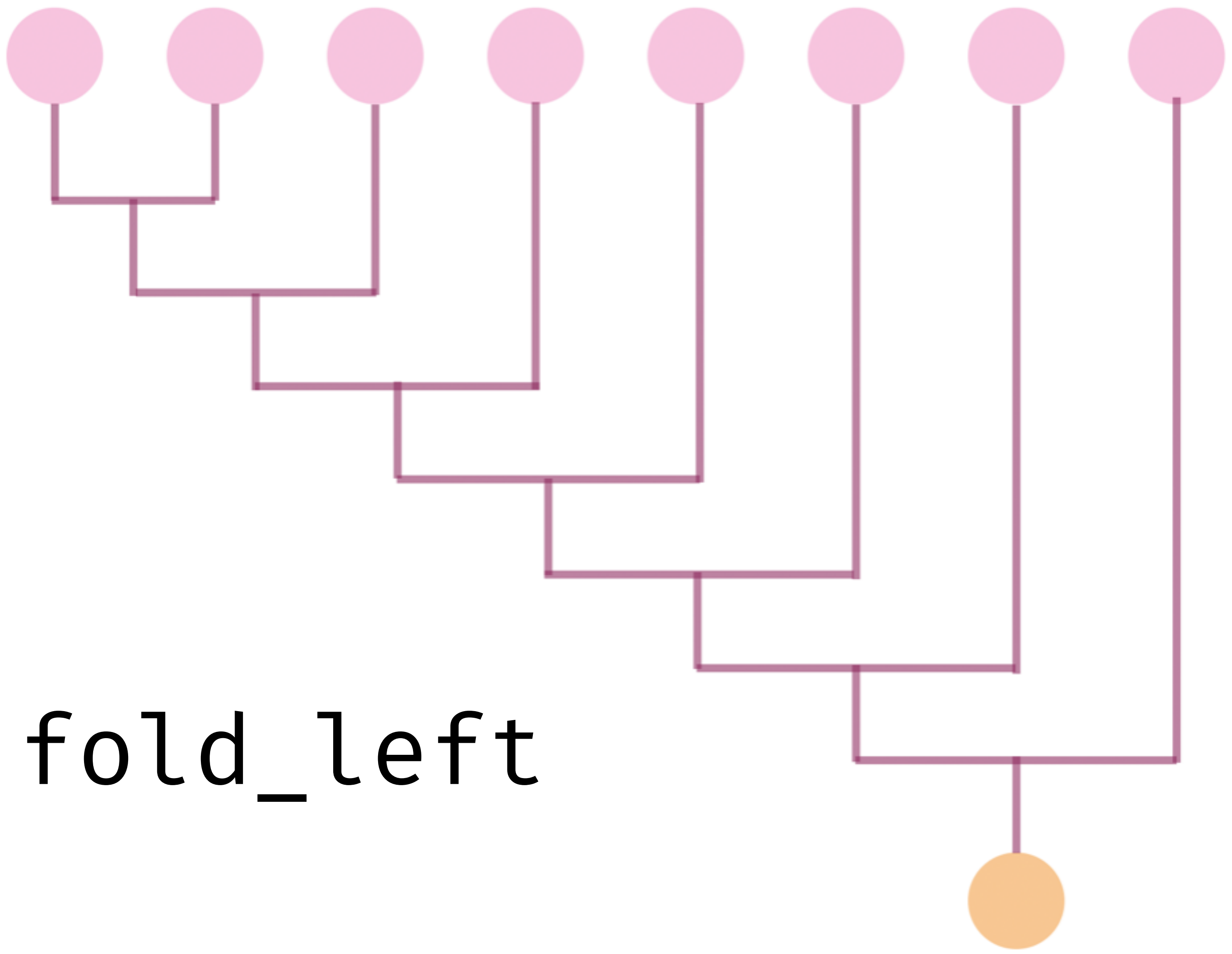
```
(Size
 (Union (Intersect (Add 6 (Add 6 Empty)) (Rem 7 (Add 7 Empty)))
  (Add 7 Empty)))
```

Timing information



Future Work

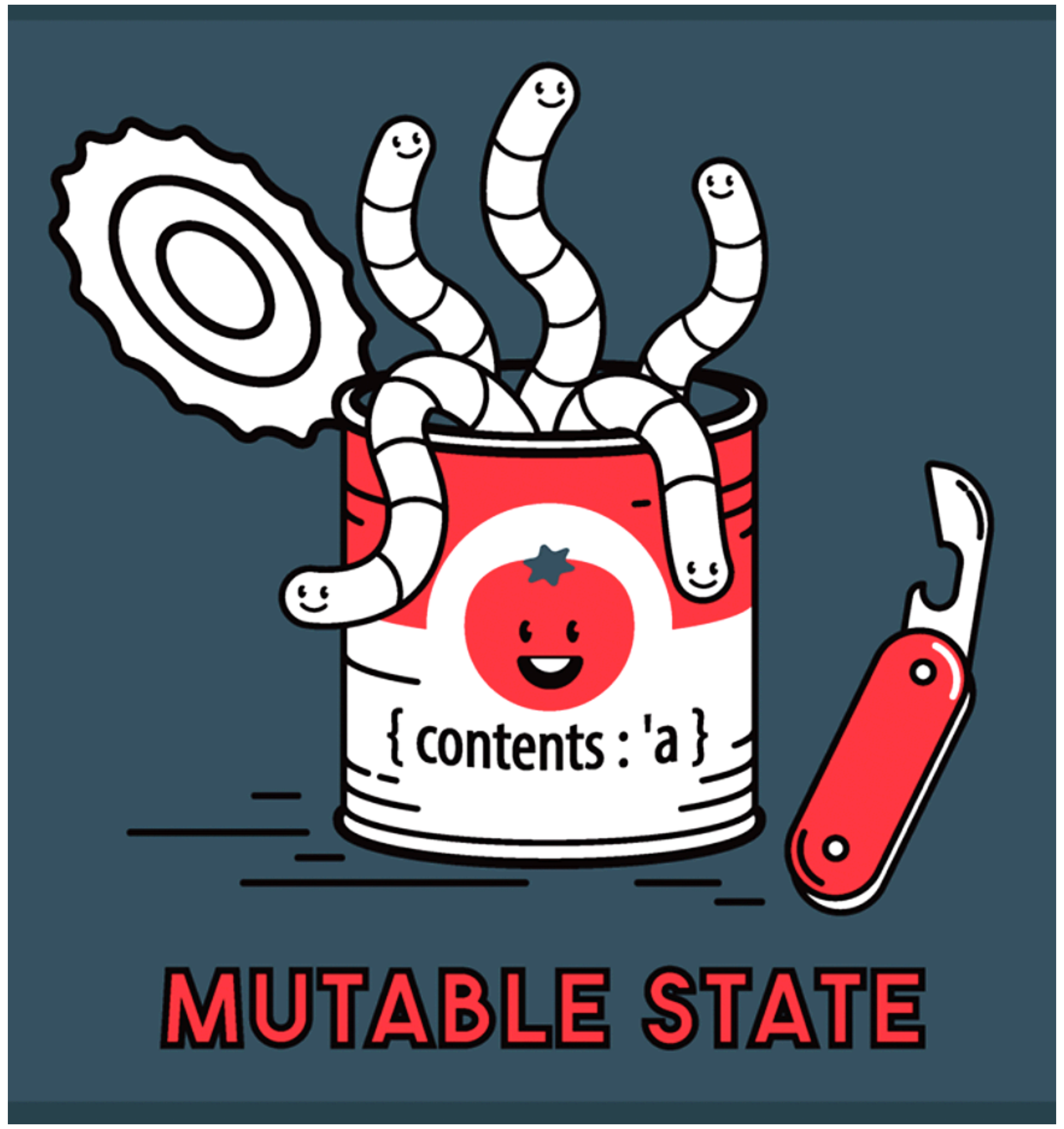
Support more **higher-order functions**



`fold_left`

Future Work

Support **imperative code**



Graphic from Ahrefs

```
type expr = …
  | Seq of expr * expr
```

```
Seq (e1, e2) ≡ e1; e2
```

Future Work

Support differential testing of **functors**

```
module F (M1 : S1) … (Mn : Sn) = …

module G (N1 : S1) … (Nn : Sn) = …
```

Future Work

Use **coverage-guided fuzzing** to guide Mica's QuickCheck generator

Crowbar
(OCaml '17)

Jane Street

FuzzChick
(OOPSLA '19)

PLUM

ParaFuzz
(OCaml '21)

IIT MADRAS

Mica is:

a ***PPX extension***

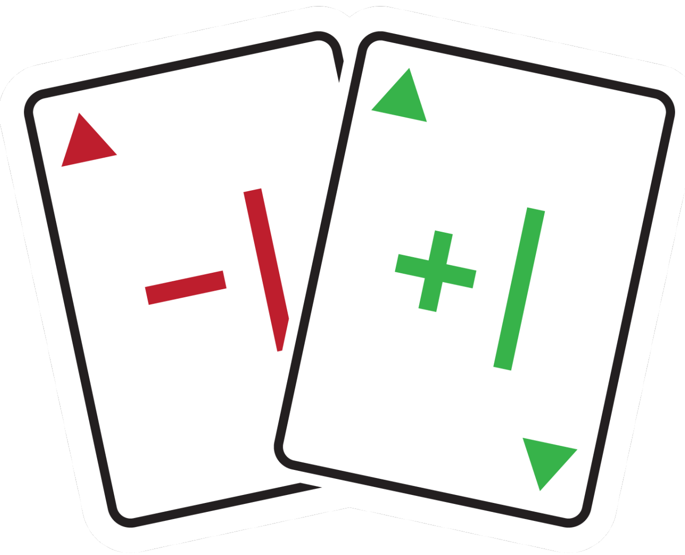
```
[@@deriving mica]
```

that ***automatically*** derives PBT code

QUICKCHECK

for testing

module observational equivalence



Thanks!

`eyn5@cornell.edu`

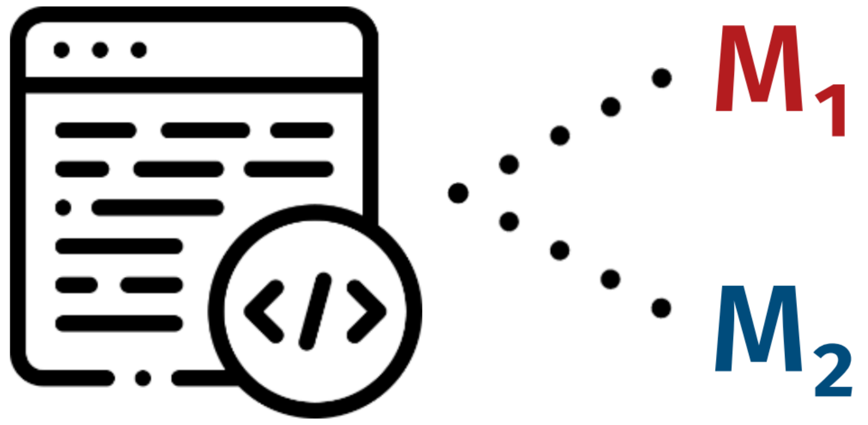
`ngernest/mica`

Preprint on arXiv

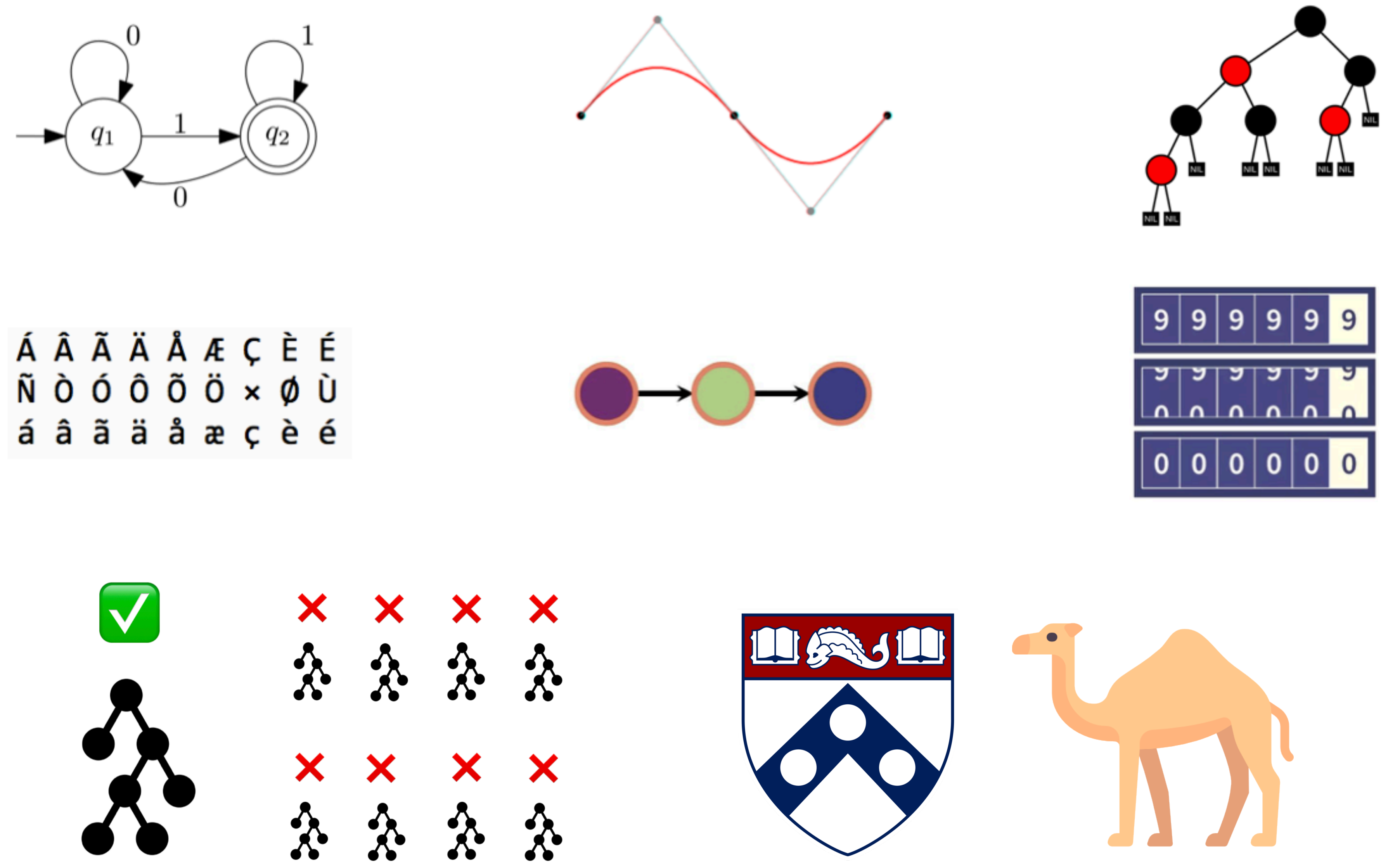
PPX Extension

`[@@deriving mica]`

QUICKCHECK

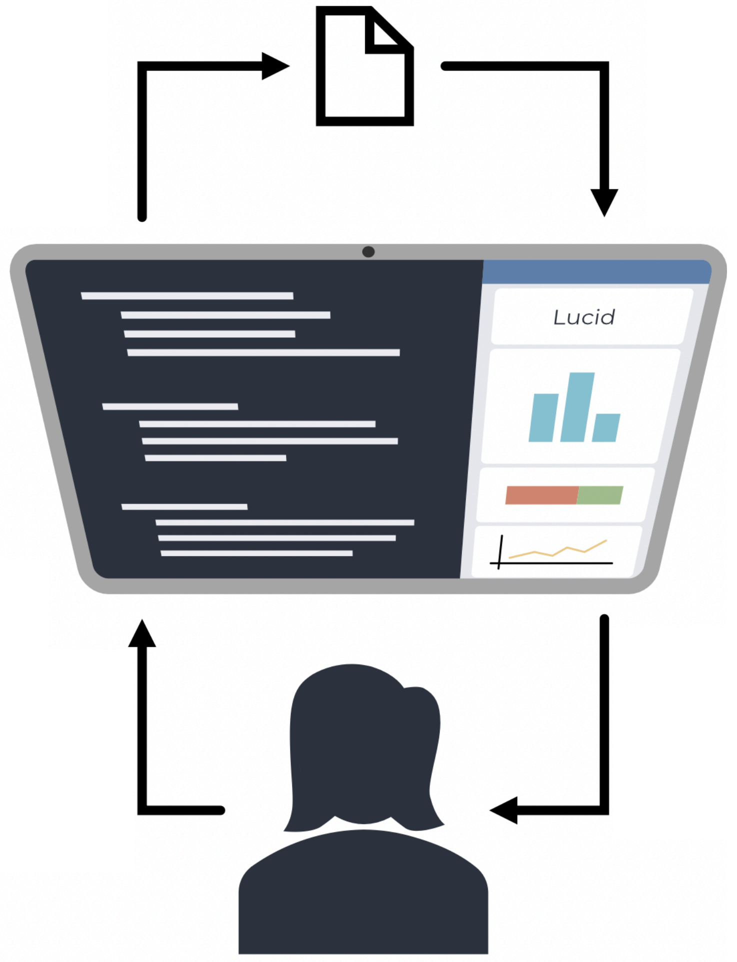


Case Studies



VS Code Integration

Goldstein et al. (UIST '24)

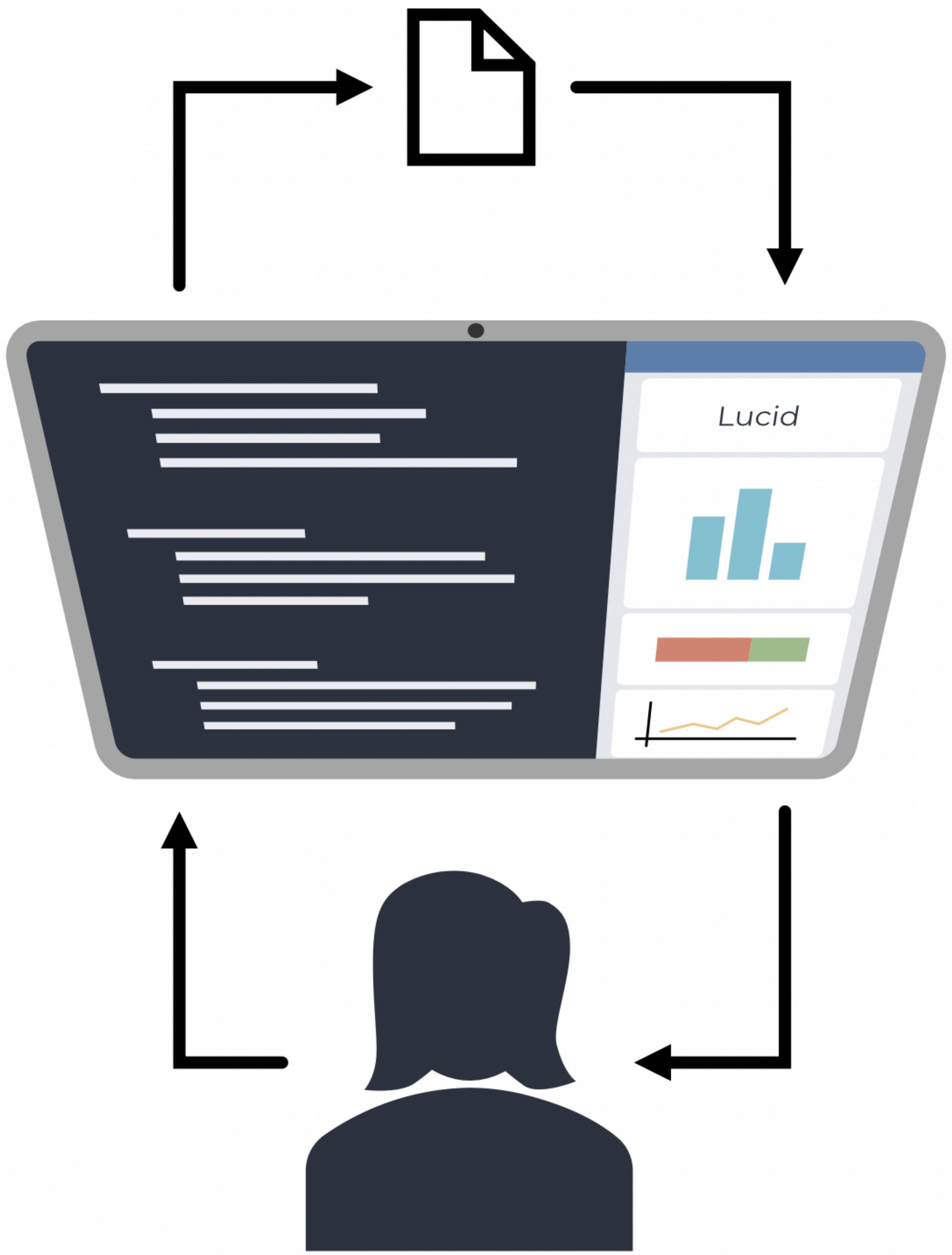


Appendix

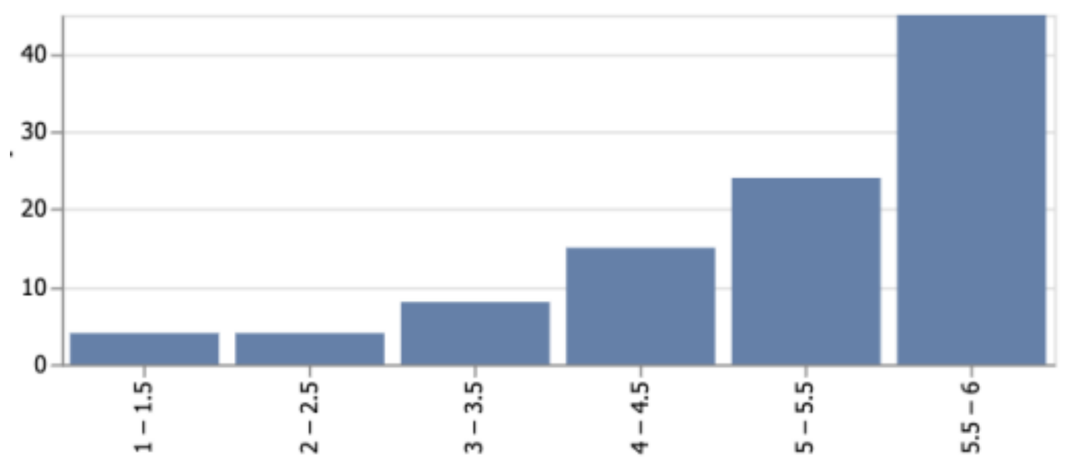
Interacting with **Mica** + **Tyche**

1. Annotate module signature & invoke Mica test harness

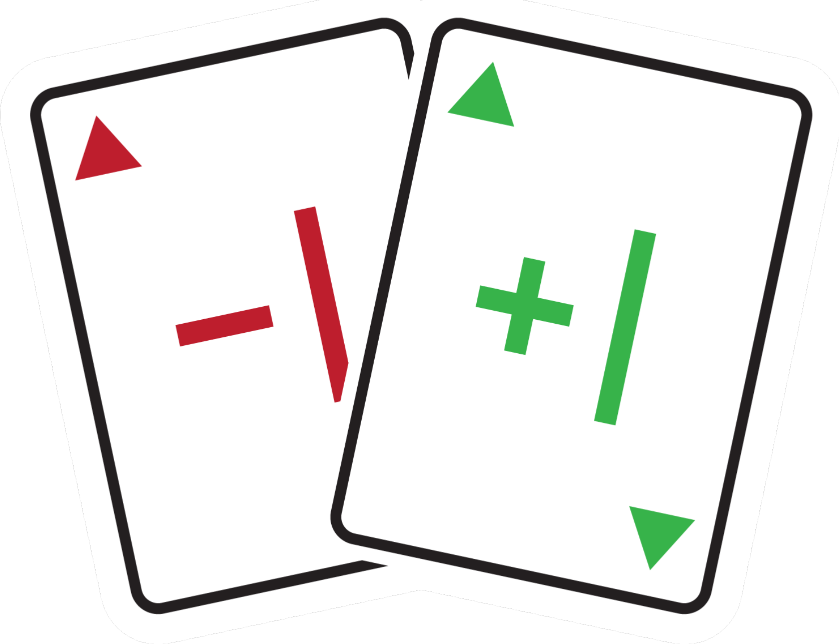
```
module type S = …
[@@deriving mica]
```



2. Tyche visualizes test statistics



3. Examine test results



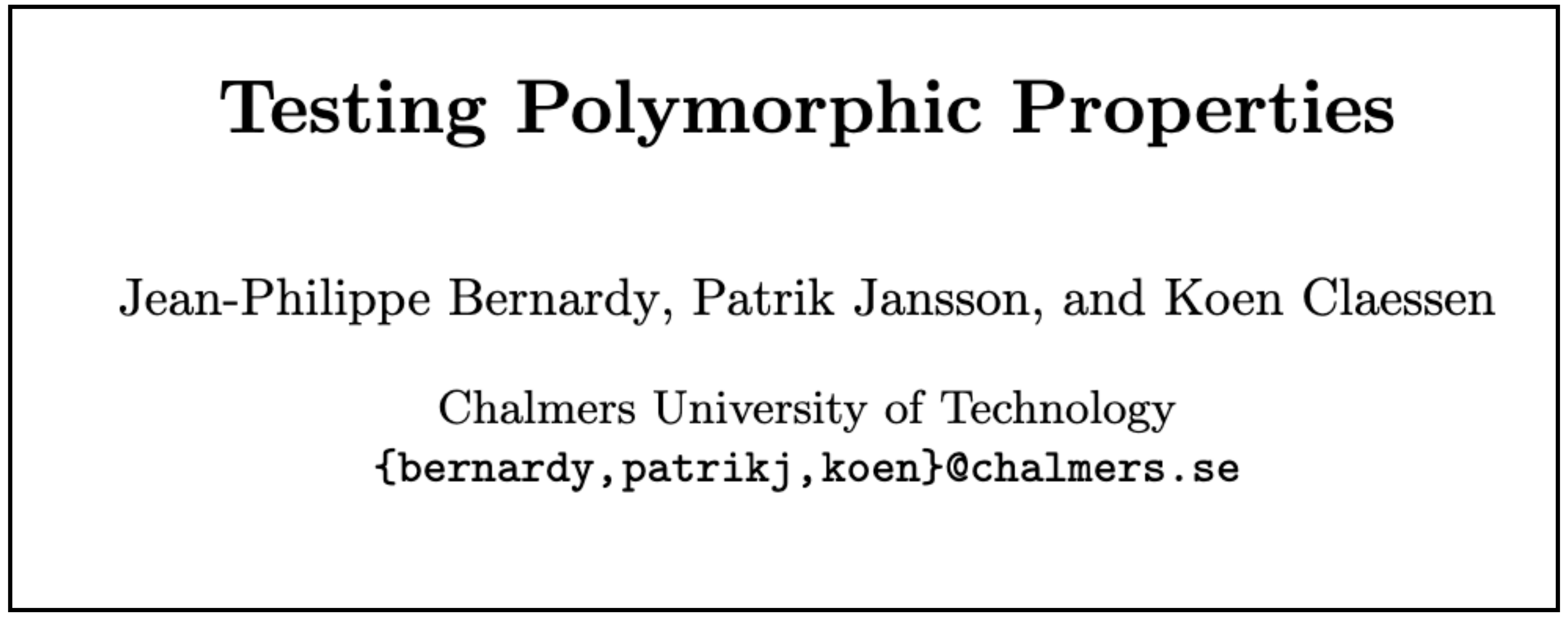
4. Update module implementations

```
module M1 : S = …
module M2 : S = …
```

Monomorphization

Heuristic: `’a` ⇝ `int`

Further reading:

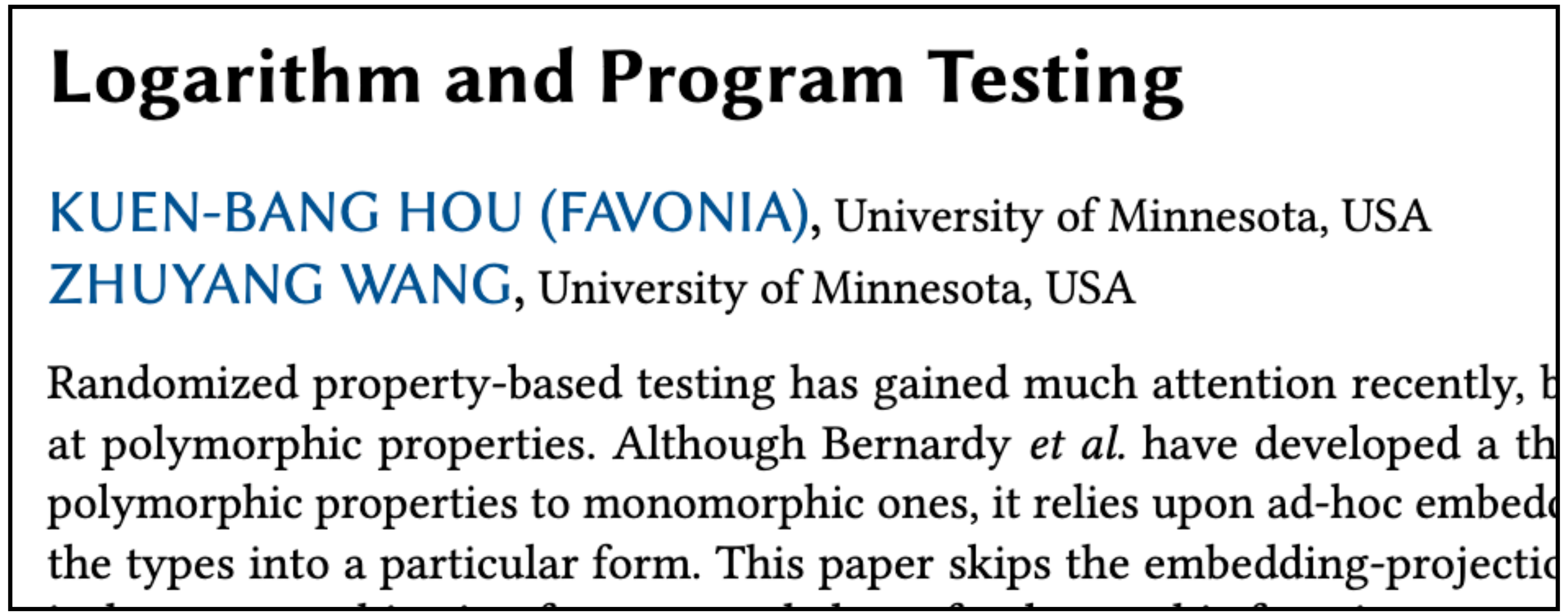


Testing Polymorphic Properties

Jean-Philippe Bernardy, Patrik Jansson, and Koen Claessen

Chalmers University of Technology
{bernardy,patrikj,koen}@chalmers.se

ESOP 2010



Logarithm and Program Testing

KUEN-BANG HOU (FAVONIA), University of Minnesota, USA
ZHUYANG WANG, University of Minnesota, USA

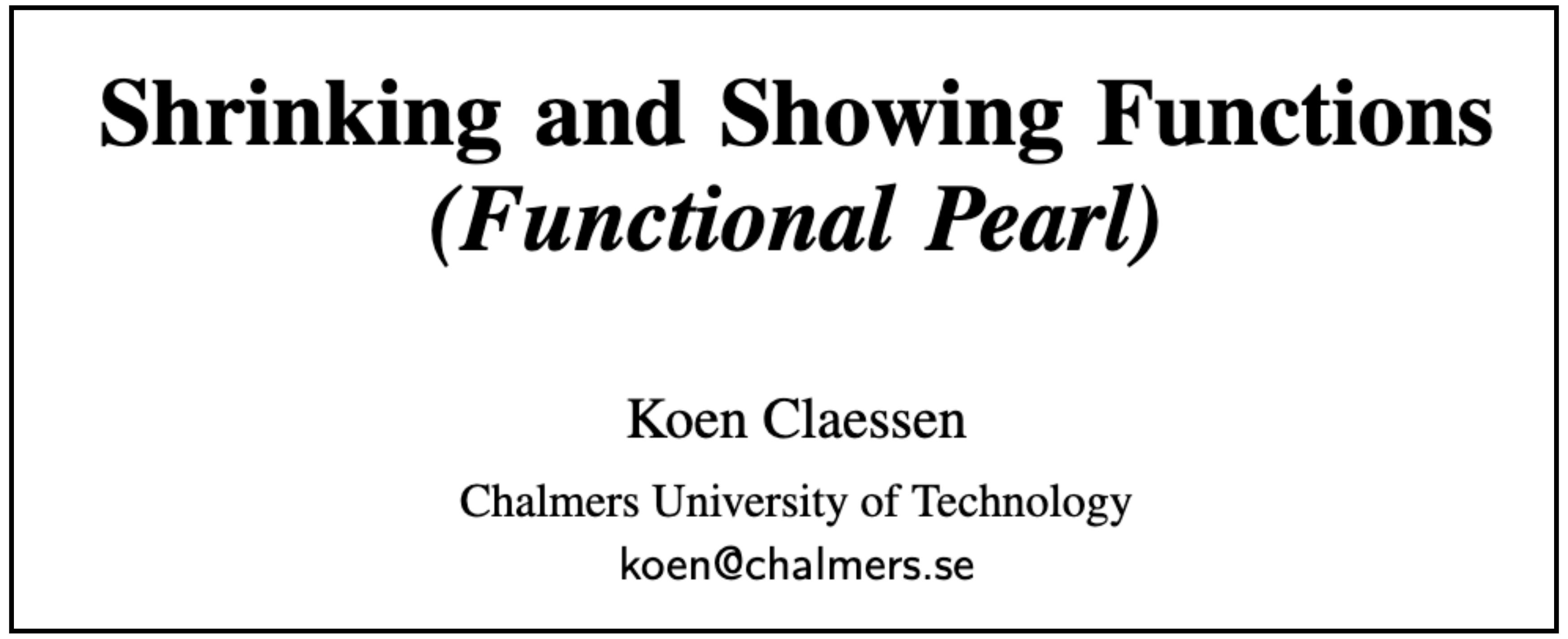
Randomized property-based testing has gained much attention recently, b
at polymorphic properties. Although Bernardy *et al.* have developed a th
polymorphic properties to monomorphic ones, it relies upon ad-hoc embedd
the types into a particular form. This paper skips the embedding-projectio

POPL 2022

Representing Higher-Order Functions Using Symbolic Expressions

```
map : (‘a → ‘b) → ‘a t → ‘b t

type expr = Map of (int → int) * expr | …
```



Shrinking and Showing Functions
(Functional Pearl)

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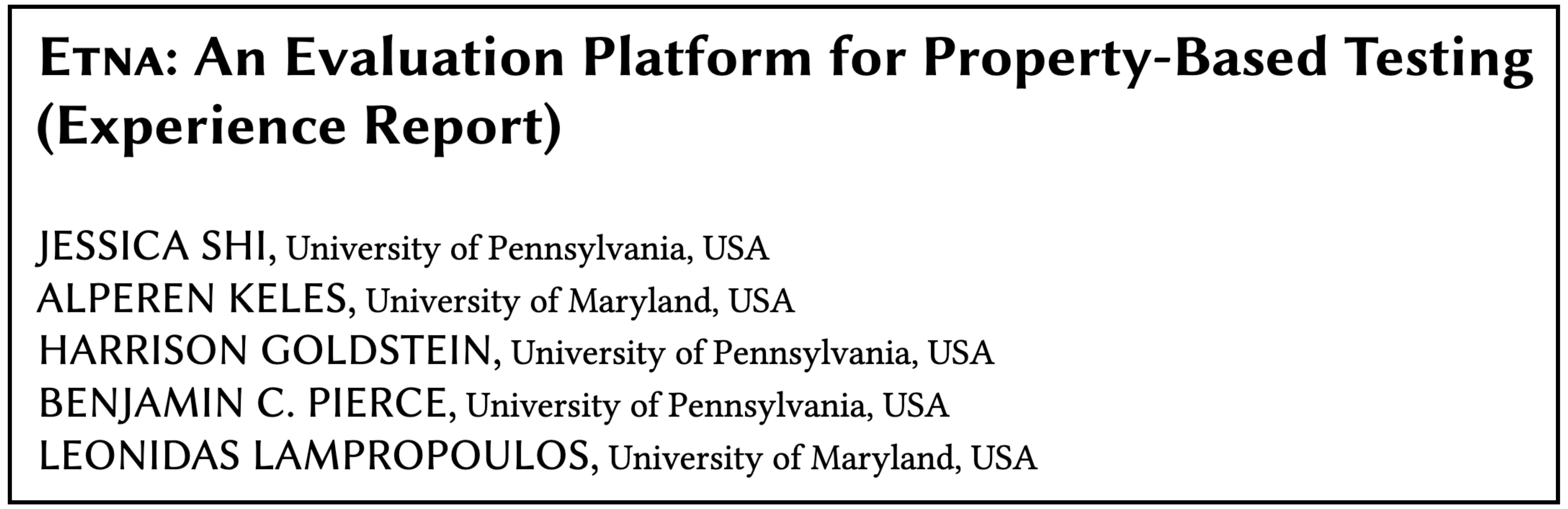
Haskell ‘12

Supporting other PBT libraries besides `Core.Quickcheck`

- Mica's design is ***library-agnostic***: developers can write other backends that support other OCaml PBT libraries (e.g. QCheck, Crowbar, …)
  - (We picked `Core.Quickcheck` just because we were most familiar with it)
- It'd be interesting to build on recent work extending **Etna** (an evaluation platform for different PBT frameworks) for comparing the efficacy of different OCaml PBT libraries



Etna: An Evaluation Platform for Property-Based Testing (Experience Report)

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ALPEREN KELES, University of Maryland, USA
HARRISON GOLDSTEIN, University of Pennsylvania, USA
BENJAMIN C. PIERCE, University of Pennsylvania, USA
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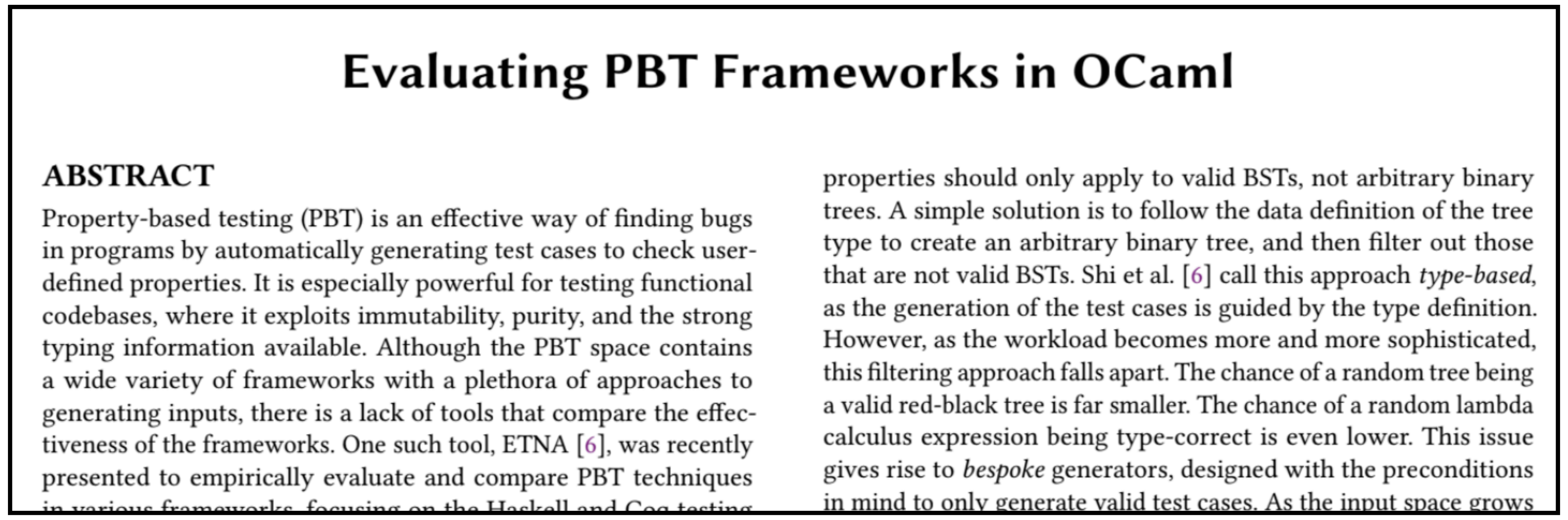
ICFP 2023



Evaluating PBT Frameworks in OCaml

ABSTRACT

Property-based testing (PBT) is an effective way of finding bugs in programs by automatically generating test cases to check user-defined properties. It is especially powerful for testing functional codebases, where it exploits immutability, purity, and the strong typing information available. Although the PBT space contains a wide variety of frameworks with a plethora of approaches to generating inputs, there is a lack of tools that compare the effectiveness of the frameworks. One such tool, ETNA [6], was recently presented to empirically evaluate and compare PBT techniques in various frameworks, focusing on the Haskell and Coq testing

properties should only apply to valid BSTs, not arbitrary binary trees. A simple solution is to follow the data definition of the tree type to create an arbitrary binary tree, and then filter out those that are not valid BSTs. Shi et al. [6] call this approach *type-based*, as the generation of the test cases is guided by the type definition. However, as the workload becomes more and more sophisticated, this filtering approach falls apart. The chance of a random tree being a valid red-black tree is far smaller. The chance of a random lambda calculus expression being type-correct is even lower. This issue gives rise to *bespoke* generators, designed with the preconditions in mind to only generate valid test cases. As the input space grows

(Nikhil Kamath, PLDI '24 SRC)

Compilation Times + How long it takes Mica's tests to run

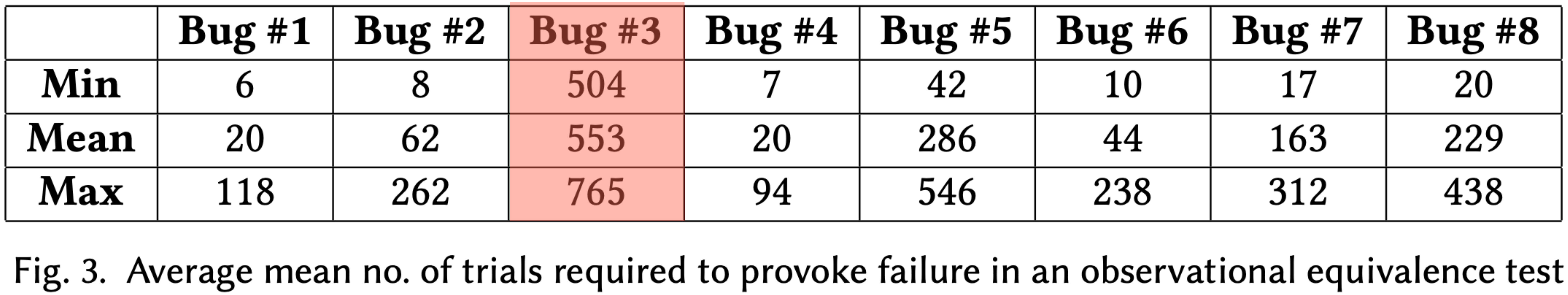
In practice, we haven't found compilation / test runtimes to be an issue!

Module Signature	Compilation Times (using a Mica prototype)	Runtime of PBT test harness
Sets	309.25 μs	2.55 ns
Stacks	361.08 μs	2.54 ns
Polynomials	302.82 μs	2.57 ns
Maps	262.84 μs	2.56 ns
Regexes	266.61 μs	2.57 ns

(Measured using `Core_bench` on an M1 Mac)

How to Specify It (BST Case Study) Stats

Bug revealed only in one branch of a pattern-match:
coverage information would help us here!



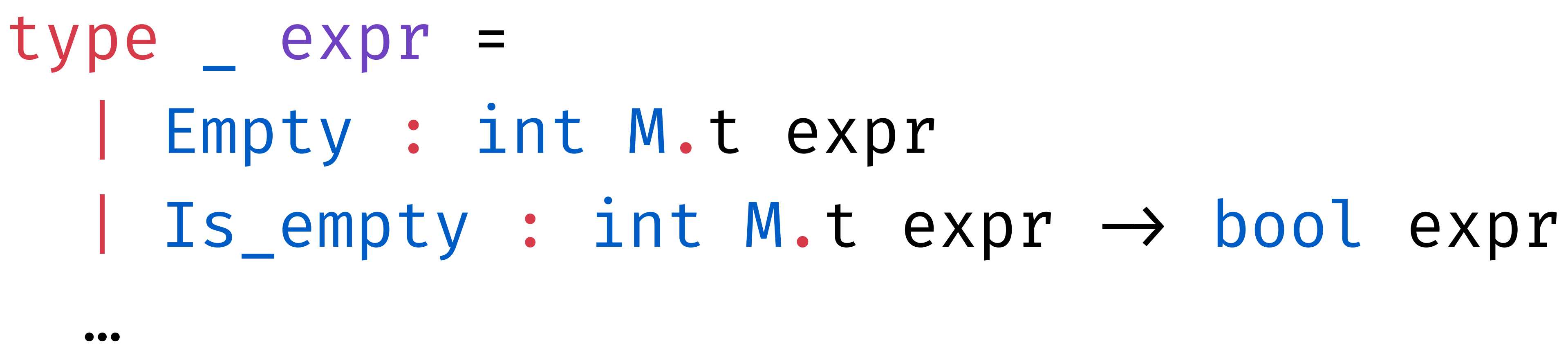
	Bug #1	Bug #2	Bug #3	Bug #4	Bug #5	Bug #6	Bug #7	Bug #8
Min	6	8	504	7	42	10	17	20
Mean	20	62	553	20	286	44	163	229
Max	118	262	765	94	546	238	312	438

Fig. 3. Average mean no. of trials required to provoke failure in an observational equivalence test

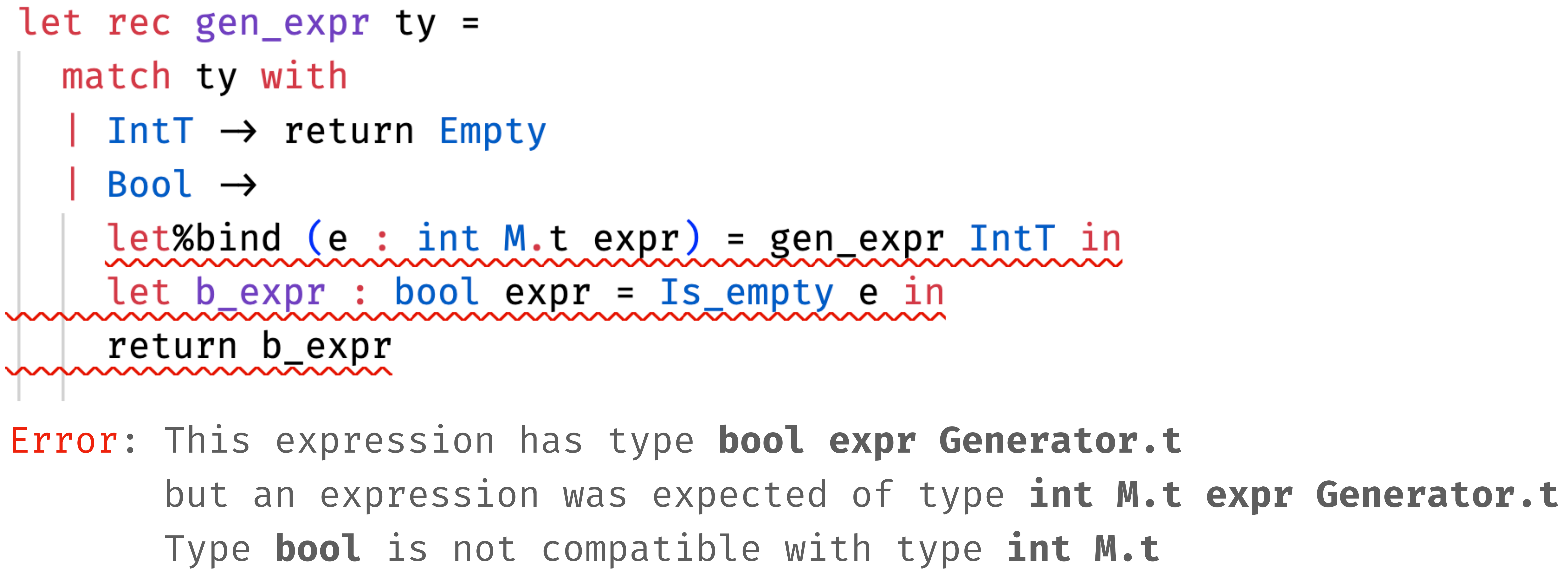
Intrinsically-typed Symbolic Expressions via GADTs

```
module Interpret (M : S) = struct
  (** Both [value] & [expr] are now GADTs *)
  type _ value = …
  type _ expr = …

  (** [a] is a **locally abstract type** – [a] is instantiated
      w/ different concrete types in the function body *)
  let eval_value (type a) (v : a value) : a =
    match v with
    | ValInt x -> x
    | ValIntT intT -> intT
    …

  (** [interp] uses polymorphic recursion *)
  let rec interp : type a. a expr -> a =
   fun expr ->
      match expr with
      | Value v -> eval_value v
      | Empty -> M.empty
      | Is_empty e ->
        let b = M.is_empty (interp e) in
        eval_value (ValBool b) …
```

Intrinsically-typed Symbolic Expressions via GADTs: Attempt



```
type _ expr =
  | Empty : int M.t expr
  | Is_empty : int M.t expr → bool expr
  …
```



```
let rec gen_expr ty =
  match ty with
  | IntT → return Empty
  | Bool →
    let%bind (e : int M.t expr) = gen_expr IntT in
    let b_expr : bool expr = Is_empty e in
    return b_expr
```

```
Error: This expression has type bool expr Generator.t
       but an expression was expected of type int M.t expr Generator.t
       Type bool is not compatible with type int M.t
```

Invoking QuickCheck generators for opaque types

- For any user-defined type `t`, the user should provide a QuickCheck generator called `quickcheck_generator_t`
- Mica will then invoke this generator by calling the appropriate directive from `ppx_quickcheck` in the derived code

```
let rec gen_expr (ty : ty) : expr Generator.t =
  match ty, QC.size with
  | (T, _) → …
    let%bind t = [%quickcheck.generator: t] in …
```

Related Work

Monolith
(Pottier 2021)

Articheck
(Braibant et al. 2014)

- GADT-based DSLs for testing ML modules
- Mutation-based fuzzing
- Mica *automatically* derives the requisite PBT code

Related Work

QCSTM
(Midtgaard 2020)

Model_quickcheck
(Dumont 2020)

- Algebraic data types for representing symbolic expressions
- Mica adds support for binary operations on abstract types

Future Work (Engineering)

Contact us if you're interested in contributing to Mica!

- Shrinking
- Modules with multiple abstract types
- Compute "module coverage" for tests
- Support other OCaml PBT libraries

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