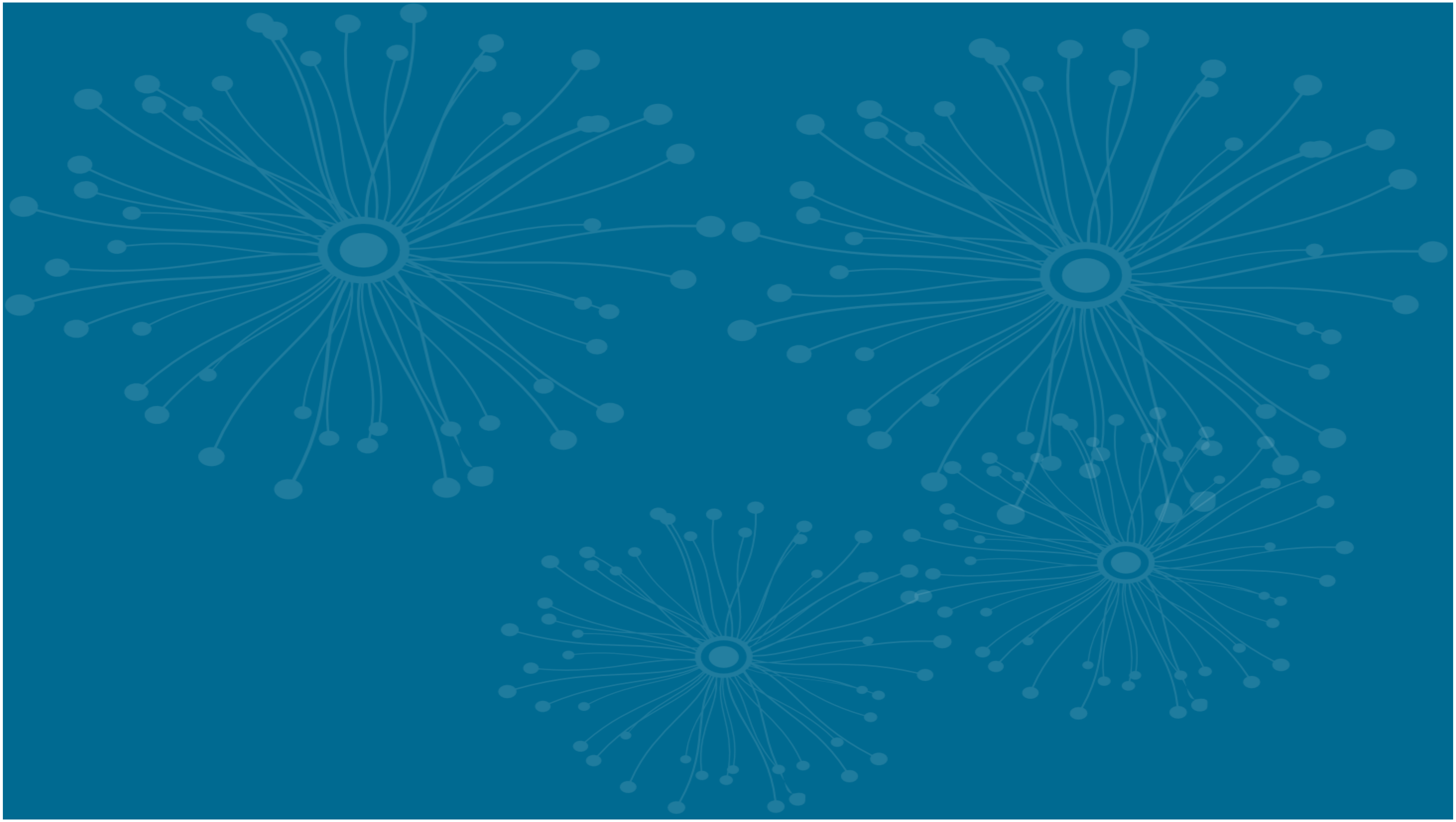


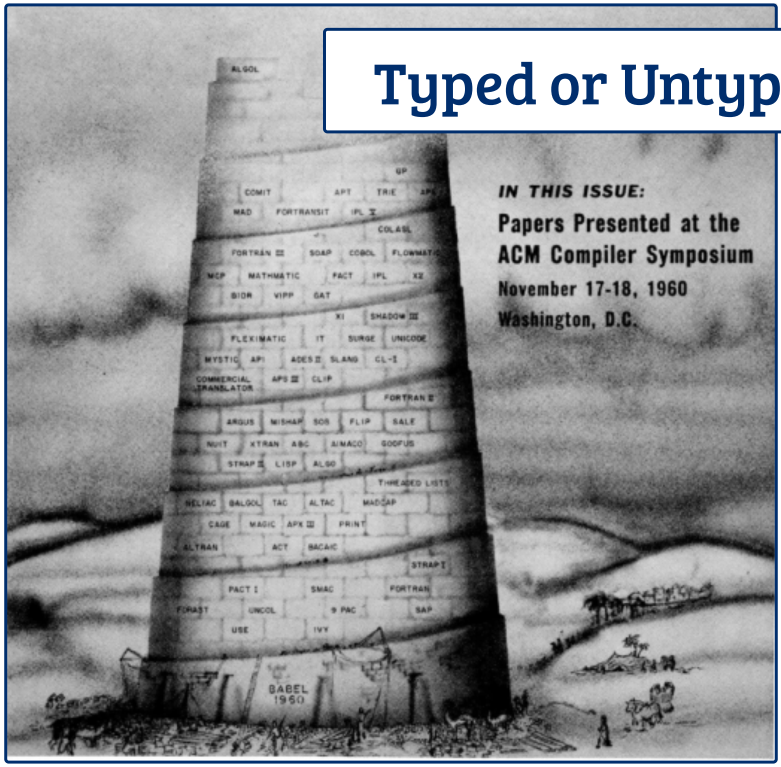
Mixing Typed and Untyped Code

A Tale of Proofs, Performance, and People

Ben Greenman
Spring 2022

BROWN

Typed or Untyped?



IN THIS ISSUE:

Papers Presented at the ACM Compiler Symposium

November 17-18, 1960

Washington, D.C.

Typed or Untyped?

Typed or Untyped?

Java is typed

(statically typed)

```
HashMap<String, Integer> m =
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```

JavaScript is untyped

(dynamically typed)

```
var m = {}
```

Typed or Untyped?

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With types, languages can:

+ Prevent classes of bugs

+ Support tools

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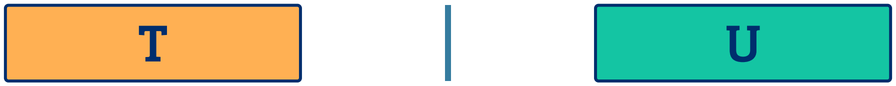
Either way, **long-term implications** for development and maintenance

Typed or Untyped



T

U

Strong support for both sides

Typed or Untyped

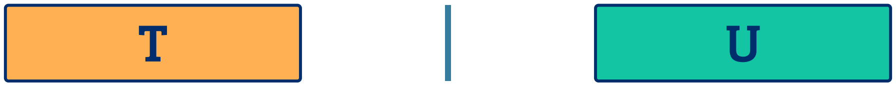
T | **U**

Strong support for both sides

"The advantages of typed PLs are obvious"

Lamport & Paulson, TOPLAS 1999

Typed or Untyped



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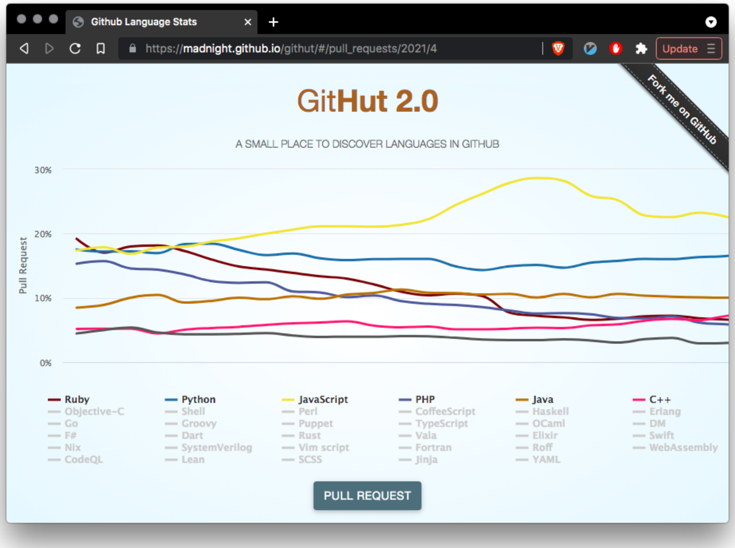

GitHut 2.0

A SMALL PLACE TO DISCOVER LANGUAGES IN GITHUB

s://madnight.github.io/githut/#/pull_requests/2021/4

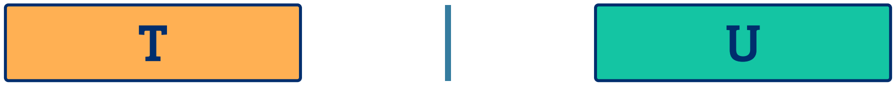
Untyped PLs dominate on GitHub

1. Ruby
2. Python
3. JavaScript
4. PHP
5. Java

✗ Typed or Untyped

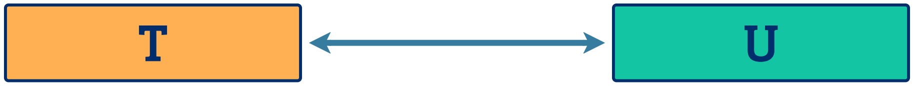
T | U

✗ Typed or Untyped



✓ Typed AND Untyped

Gradual Typing



Gradual Typing

T

U

Key Motivation: **improve stable code** with types

Gradual Typing

T

U

Key Motivation: **improve stable code** with types

```
function parse_lfd_chain(bv, pos, order, max_depth):
  ....
  tag_count = bv_ref(bv, pos, order)
  next_offset = pos + 2 + (* tag_count 12)
  next_pos = bv_ref(bv, next_offset, order)
  pts = parse_tags(tag_count)
  if next_pos == 0:
    return pts
  else:
    return pts ++ parse_lfd_chain(bv, next_pos, order, max_depth - 1)
```

Gradual Typing

Key Motivation: **improve stable code** with types

```
function parse_lfd_chain(bv, pos, order, max_depth):
```

```
function parse_lfd_chain(bv:Bytes, pos:Natural, order:Symbol, max_depth:Natural)
   -> List[PTs]:
  ....
  tag_count = bv_ref(bv, pos, order)
  next_offset = pos + 2 + (* tag_count 12)
  next_pos = bv_ref(bv, next_offset, order)
  pts = parse_tags(tag_count)
  if next_pos == 0:
    return pts
  else:
    return pts ++ parse_lfd_chain(bv, next_pos, order, max_depth - 1)
```

Document the parameters,
benefit from type checks

Gradual Typing

Key Motivation: **improve stable code** with types

Gradual Typing

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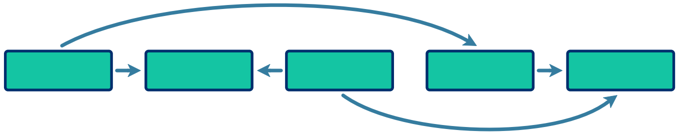

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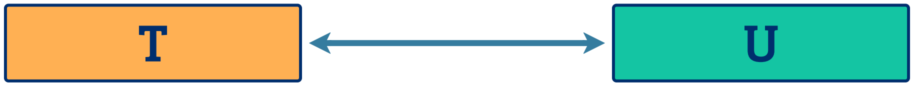

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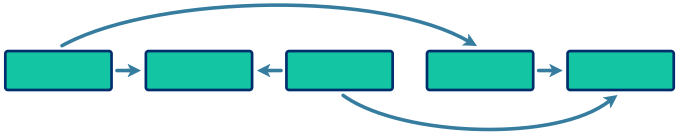
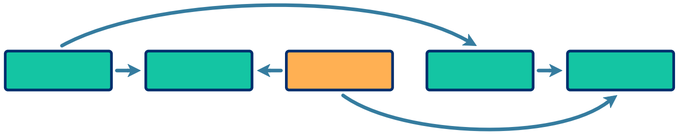


Add types to **one** component,
leave the others **unchanged**

➤



Gradual Typing

T

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Gradual Typing

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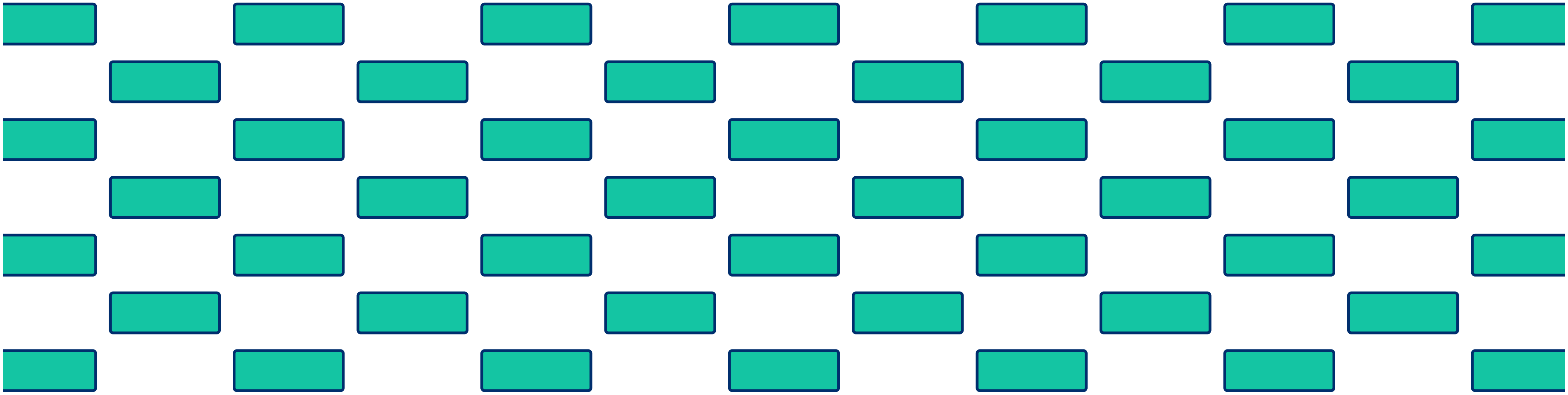

Gradual Typing

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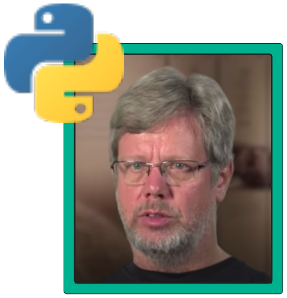


"For **really large codebases**, static languages* have their uses"

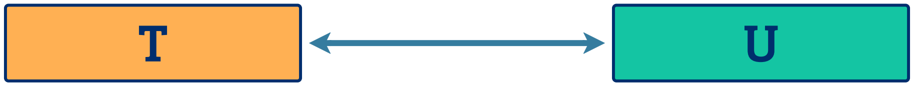
* (despite all their visual overhead and compilation cycles and build tools)

Gradual Typing

T

U

Gradual Typing



T

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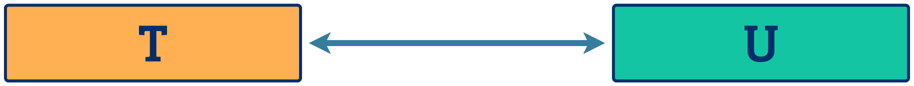
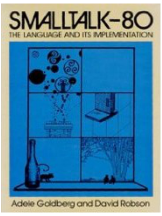
Active space!

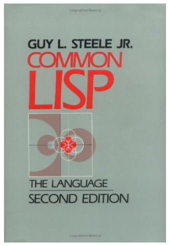
Gradual Typing



Active space!


SMALLTALK-80
THE LANGUAGE AND ITS IMPLEMENTATION
Adele Goldberg and David Robson

StrongTalk
1993



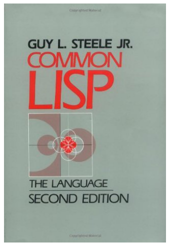
Common Lisp
<1990

Gradual Typing

T

U

Active space!



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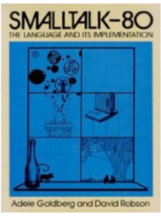
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Gradual Typing
2006

Gradual Typing

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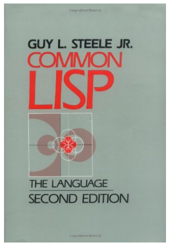

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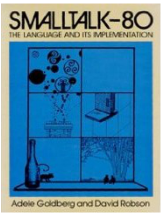
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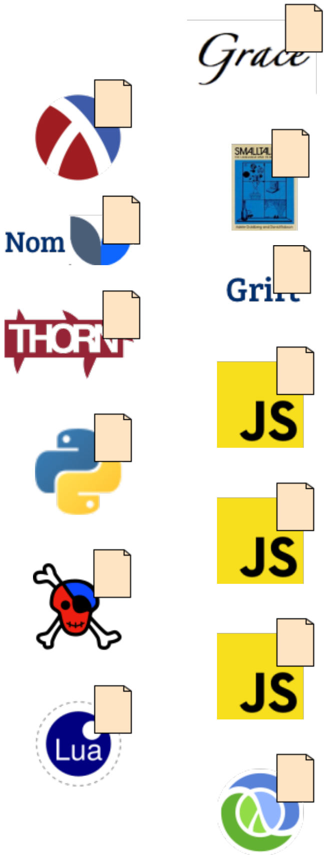

+ Many Research PLs

Gradual Typing

Active space!

Major companies involved

Gradual Typing

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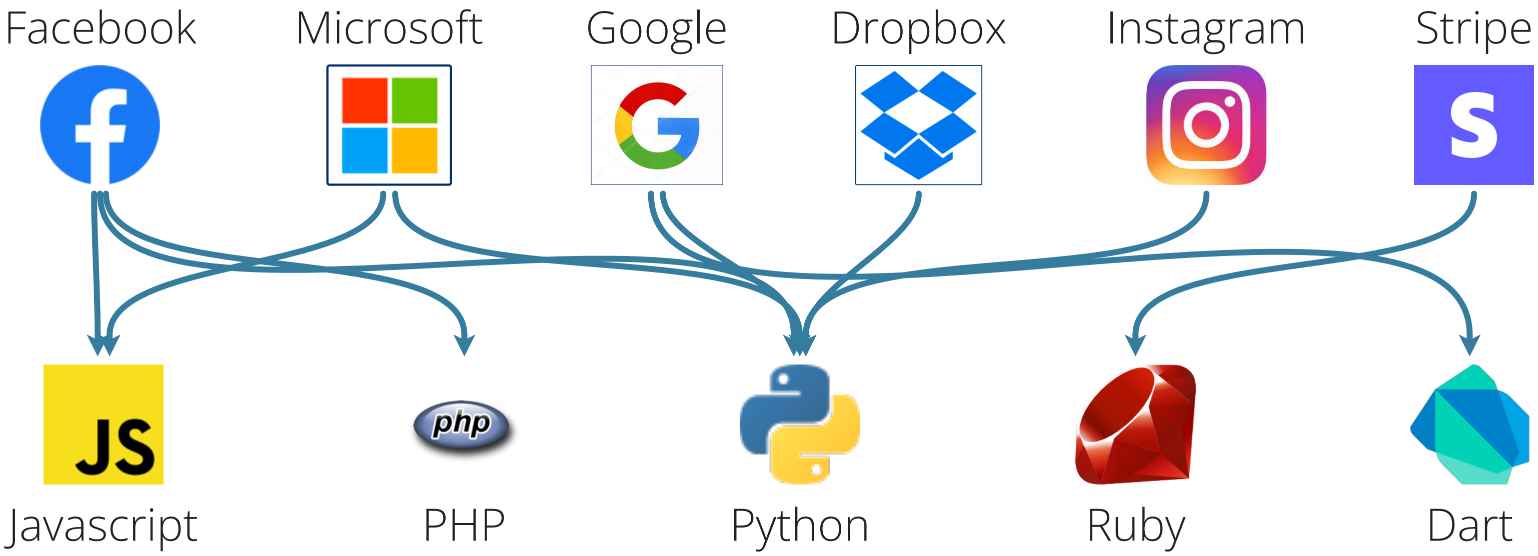
U

Active space!

Major companies involved



Facebook

Microsoft

Google

Dropbox

Instagram

Stripe

Javascript

PHP

Python

Ruby

Dart

Gradual Typing

Active space!

Major companies involved

Growing community interest

Gradual Typing

Active space!

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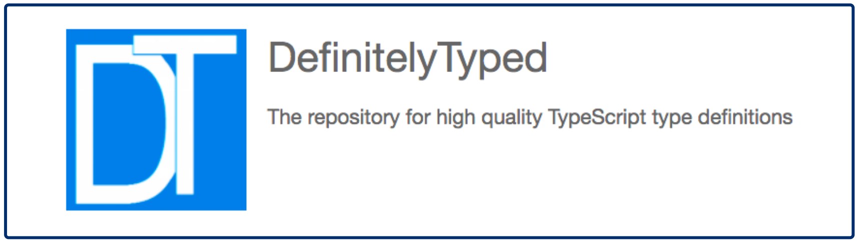
Growing community interest



DefinitelyTyped

The repository for high quality TypeScript type definitions

+ **8k** interfaces

+ **5k** contributors

+ **1 million** clients

Gradual Typing

T

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Active space!

Major companies involved

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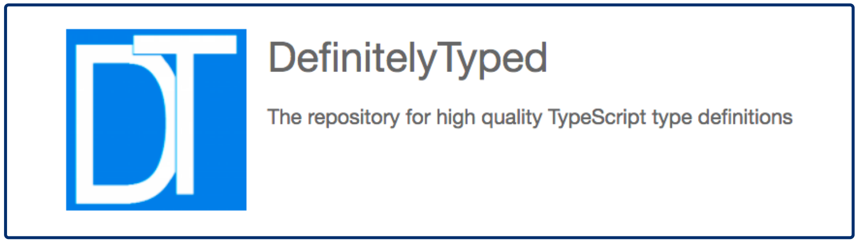

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The repository for high quality TypeScript type definitions

+ **8k** interfaces

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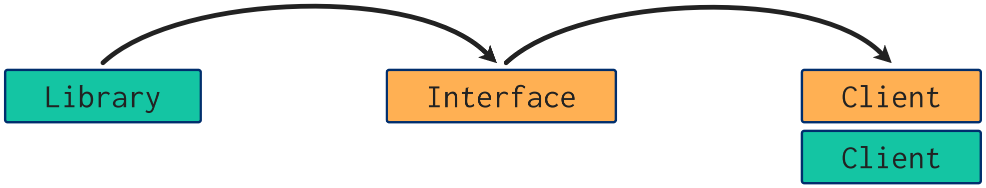
Common case: **new types** for **old libraries**



Library

Interface

Client

Client

Gradual Typing

So what's the **problem**?

Gradual Typing

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So what's the **problem**?

Lots of Languages, but also **Lots of Variety**

Example 1

Typed Function

```
function add1(n : Num)
  n + 1
```

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Q. Is **n** really a number?

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Untyped Caller

```
add1("A")
```

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Example 1

Typed Function

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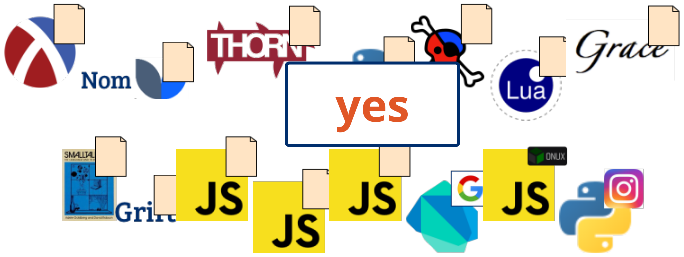
```

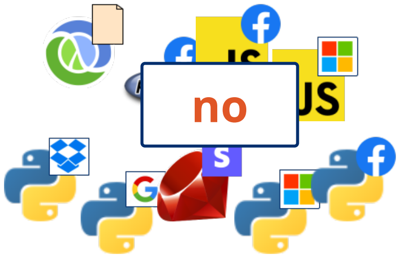
Untyped Caller

```
add1("A")
```

Q. Is **n** really a number?

Some say **yes**, others say **no**





Example 2

Example 2

Untyped Array

```
arr = ["A", 3]
```

Typed Client

```
nums : Array(Num) = arr
nums[0]
```

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Untyped Array

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Typed Client

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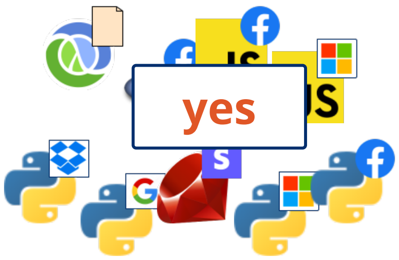
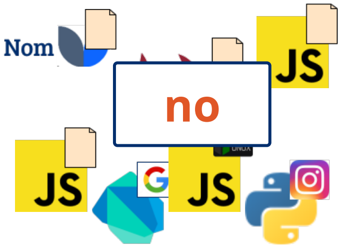
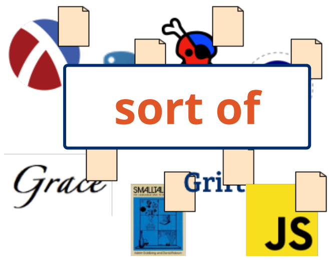
Q. Is **arr** an array of numbers?

Three common answers: **yes**, **no**, and **sort of**







What Should Types Mean?

No consensus on basic questions!

`Num` `Array(Num)`

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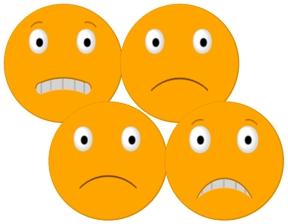
No consensus on basic questions!

`Num` `Array(Num)`

Q. Did anyone **ask** programmers?



What Should Types Mean?

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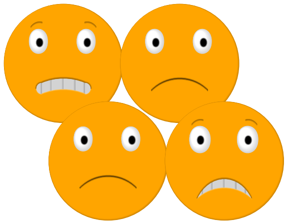

Challenge: How to compare languages?

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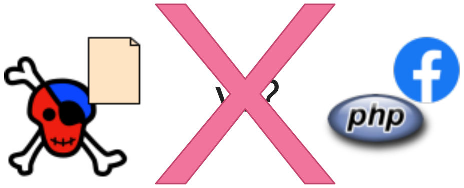


Challenge: How to compare languages?

Don't! Compare **semantics** instead.

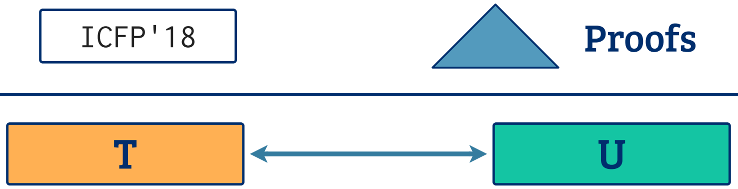
ICFP'18

Proofs

T ↔ **U**

Challenge: How to compare languages?

Don't! Compare **semantics** instead.


ICFP'18

Proofs

Guarded

Types enforce behaviors

Transient

Types enforce top-level shapes

Erasure

Types enforce nothing

Study: Behavior of Gradual Types

DLS'18

People

A **method** to compare semantics

Study: Behavior of Gradual Types

DLS'18

People

A **method** to compare semantics

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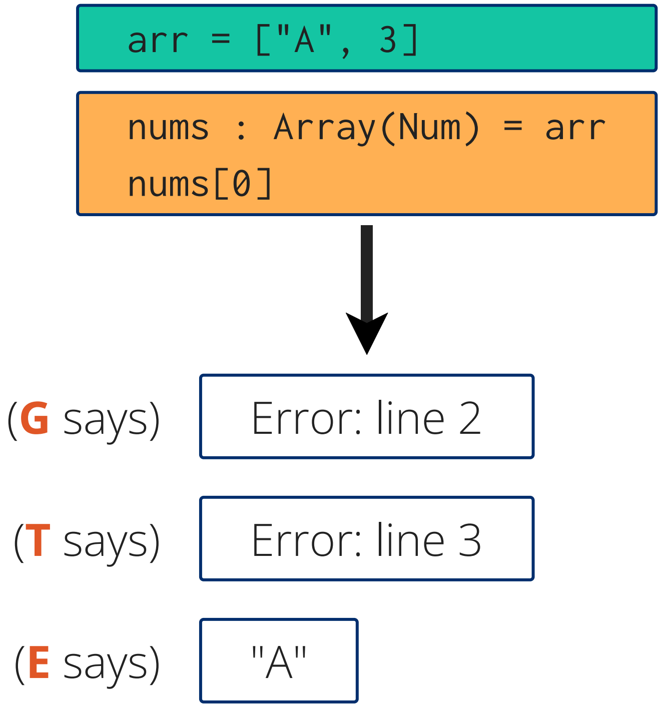
Study: Behavior of Gradual Types

DLS'18 People

A **method** to compare semantics



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(**G** says) Error: line 2

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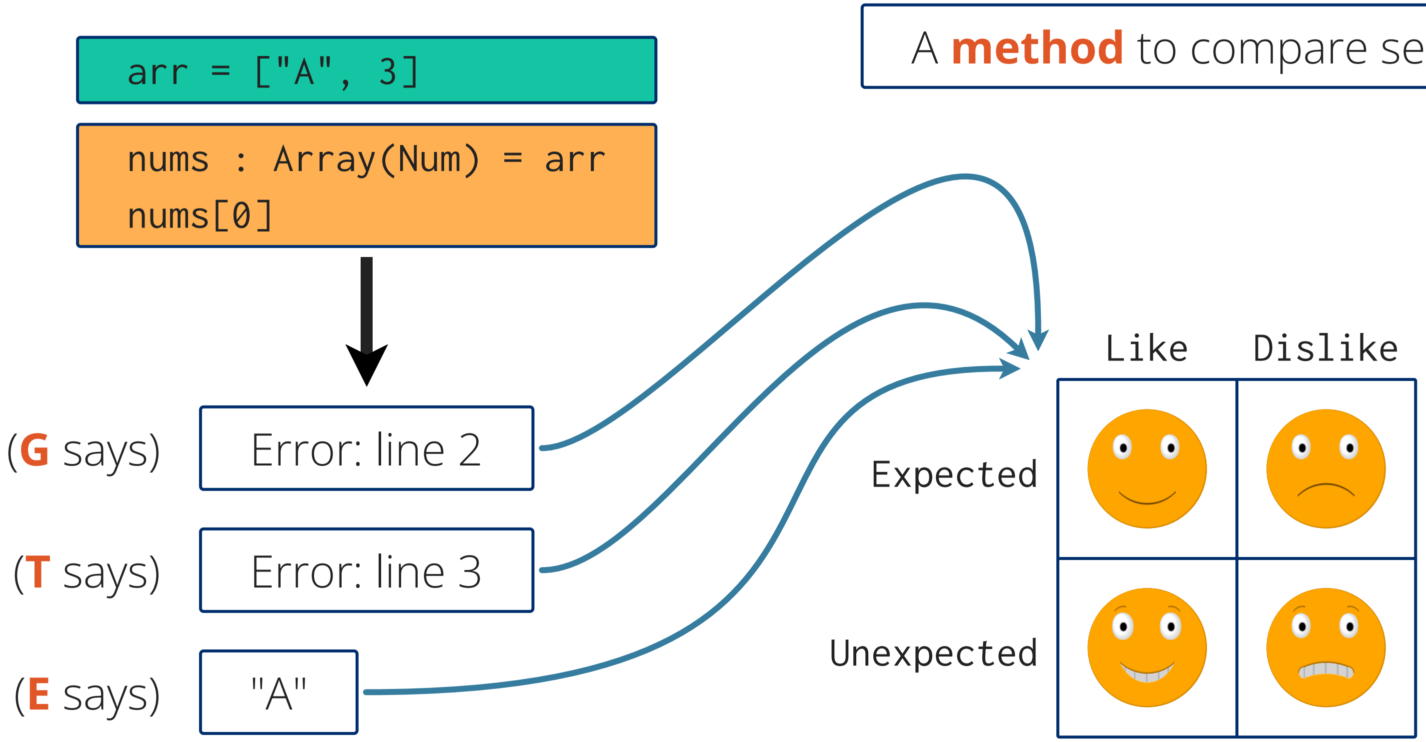
Study: Behavior of Gradual Types

DLS'18 People

A **method** to compare semantics



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Study: Behavior of Gradual Types

DLS'18 People

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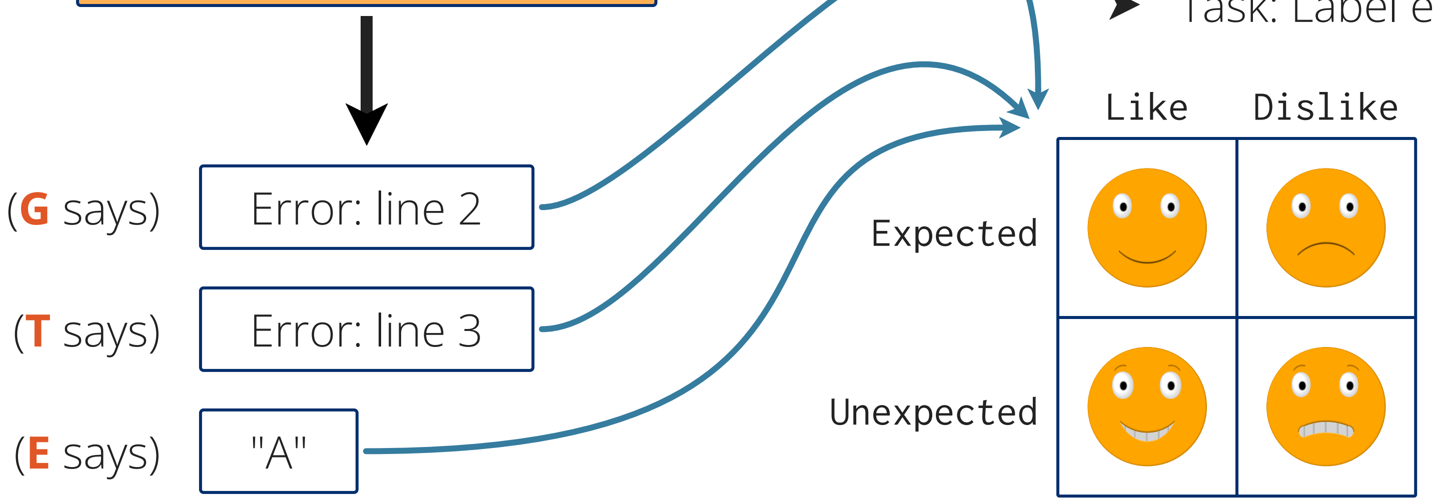

A **method** to compare semantics

- One program
- Distinct results
- Task: Label each result

Study: Behavior of Gradual Types

DLS'18 ▲ People

Company Name
Engineers

Students

amazon mechanical turk beta
Turkers

Study: Behavior of Gradual Types

DLS'18

People

Company Name

Engineers

Students

amazon mechanical turk beta

Turkers

How do the responses relate to the 3 **semantics**?

Guarded

Types enforce behaviors

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Study: Behavior of Gradual Types

DLS'18

People

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amazon mechanical turk

Turkers

Expected & Like

✓ **Guarded**

Types enforce behaviors

Unexpected & Dislike

✗ **Transient**

Types enforce top-level shapes

✗ **Erasure**

Types enforce nothing

Case Closed?

✓ **Guarded**

Types enforce behaviors

✗ **Transient**

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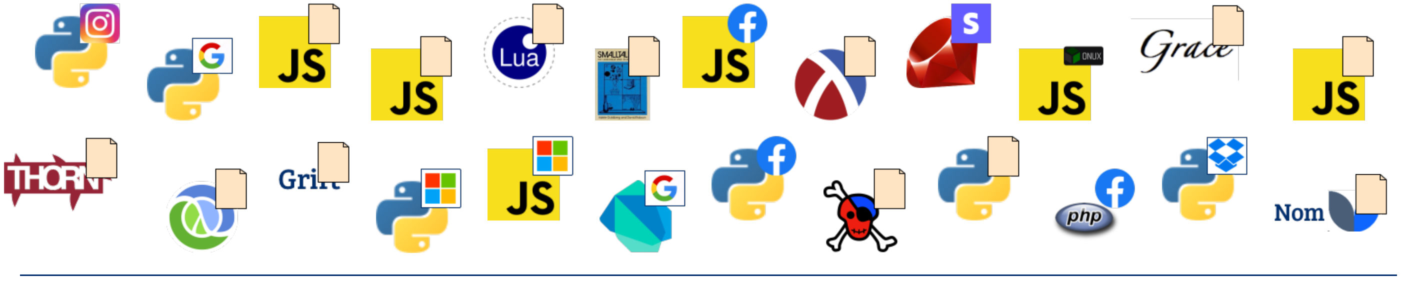
Case Closed?



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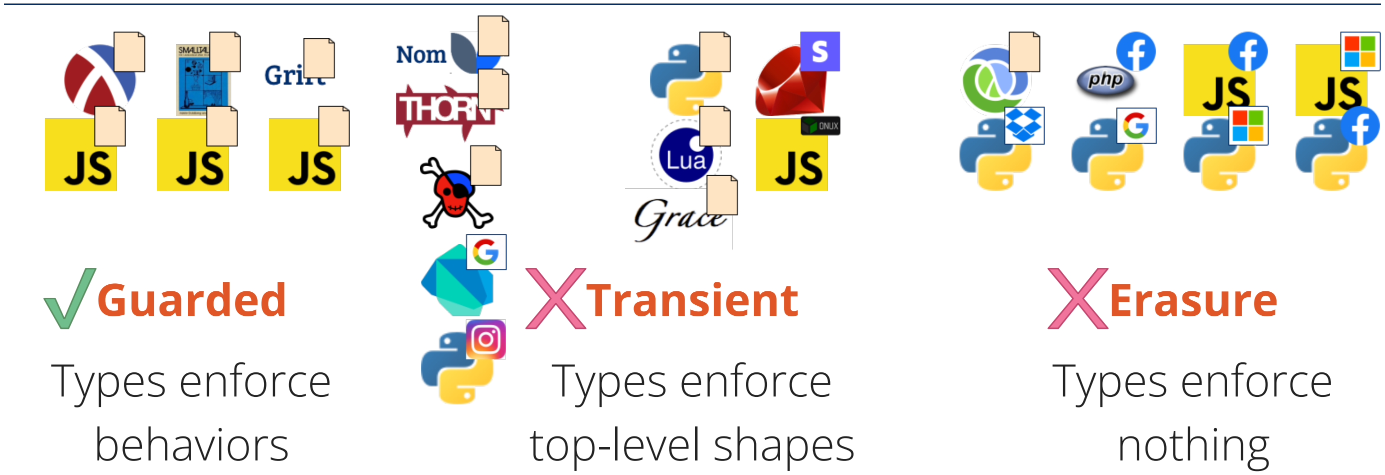
Case Closed? No!

Funny split …



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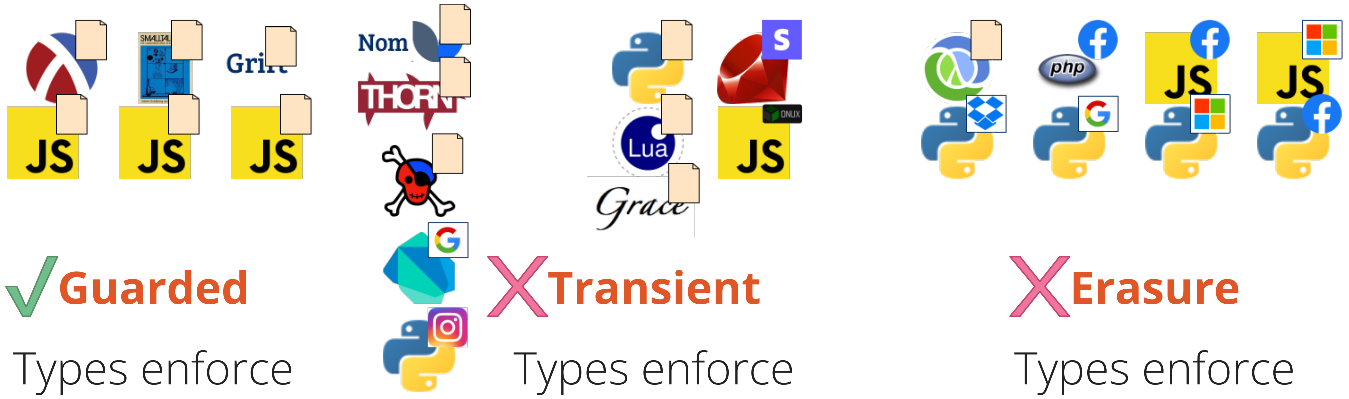
Case Closed? No!

Funny split …

Research Languages **vs.** Popular Languages



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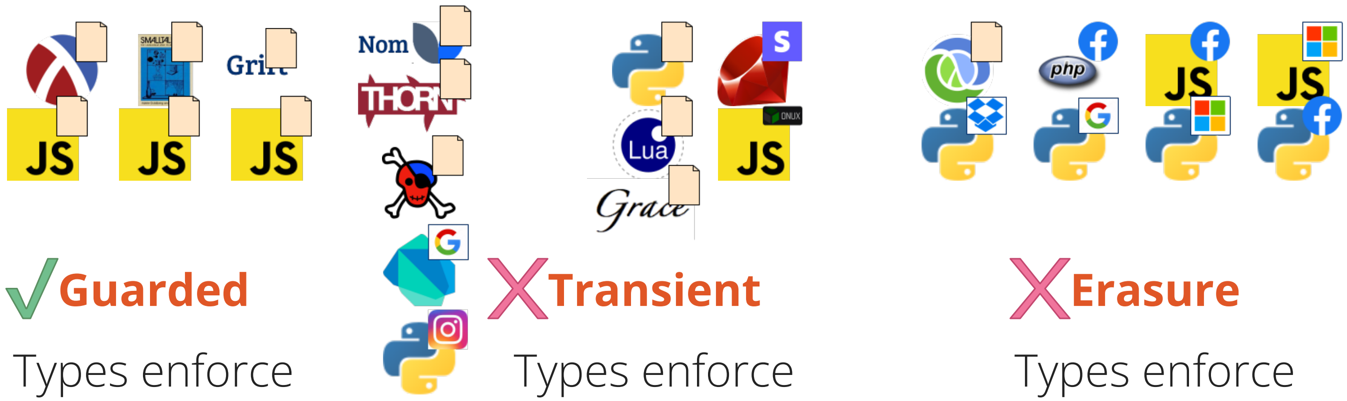

✓Guarded

Types enforce behaviors

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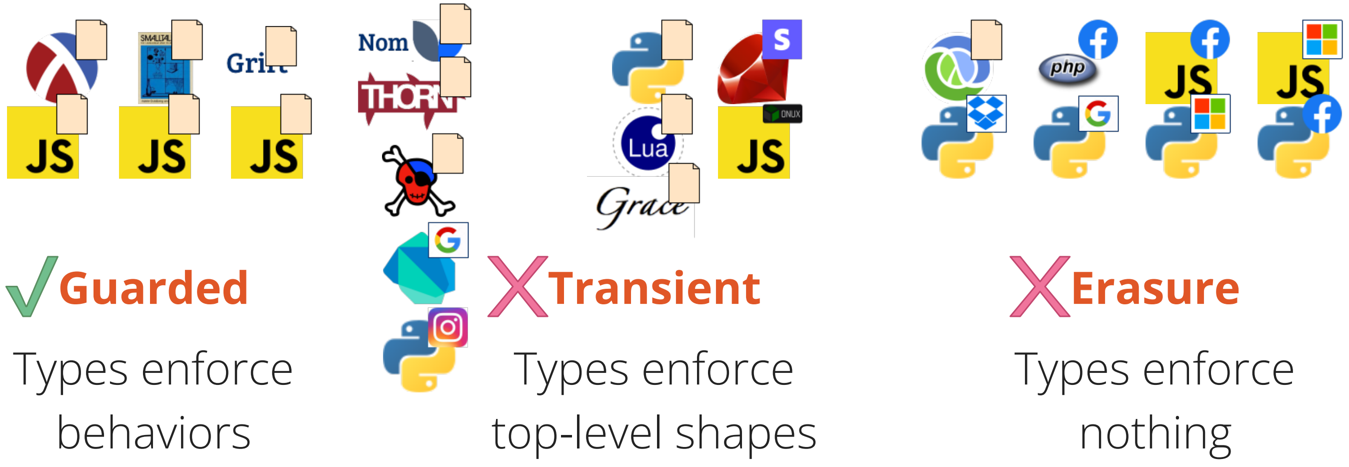
Types enforce nothing

Case Closed? No!

There are **two** problems:

- How should gradual types **behave**?
- What do behaviors **cost**?



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Where Do Costs Come From?

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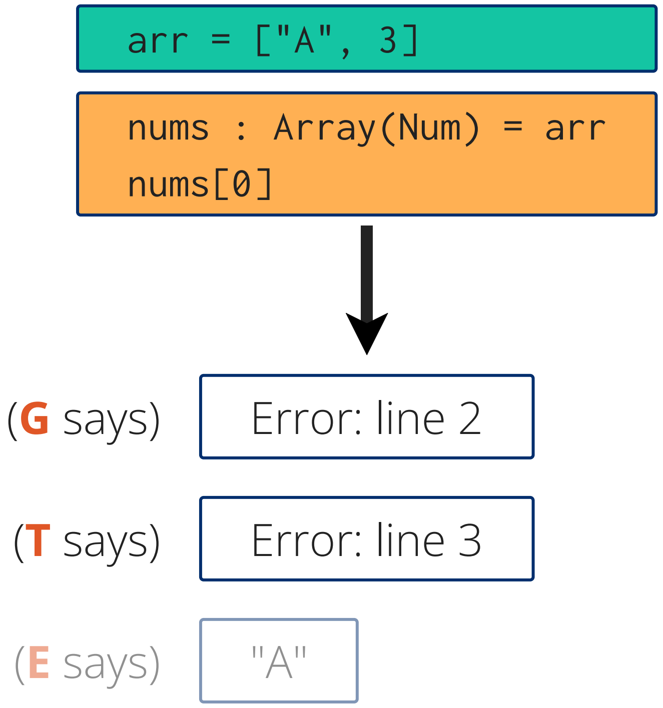

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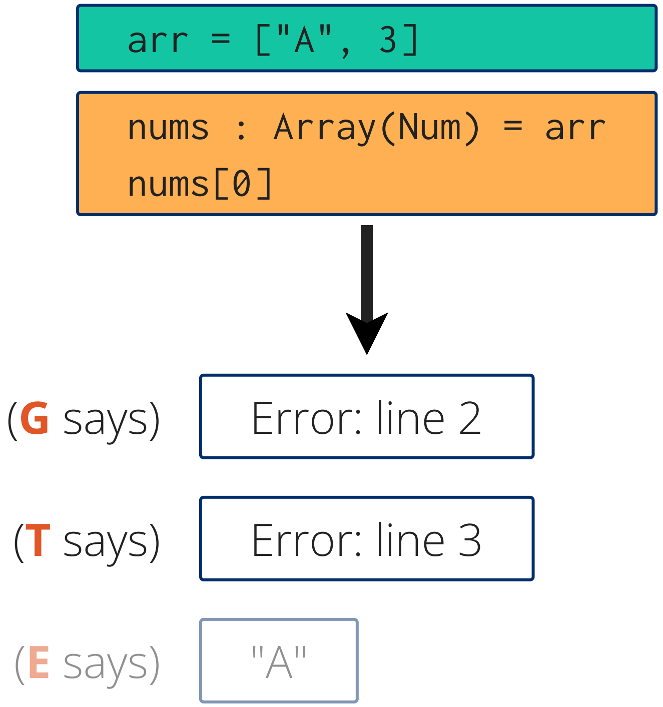
(E says) "A"

Where Do Costs Come From?



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```

```
nums : Array(Num) = arr
nums[0]
```

(**G** says) Error: line 2

(**T** says) Error: line 3

(**E** says) "A"

To detect an Error:

- **traverse** array at boundary
- or **wrap** and delay checks

Cost of **checks** can add up!

Caution: Typed Racket

Guarded type guarantees, but **huge** worst-case costs

25x

180x

1400x

Q. Are bad points common, or rare?

Need a **method** to measure performance

▲ **Performance**

One Program, Many Points

What to Measure = **All** Gradual Possibilities

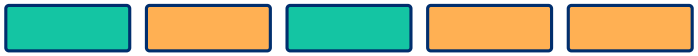
One Program, Many Points

What to Measure = **All** Gradual Possibilities

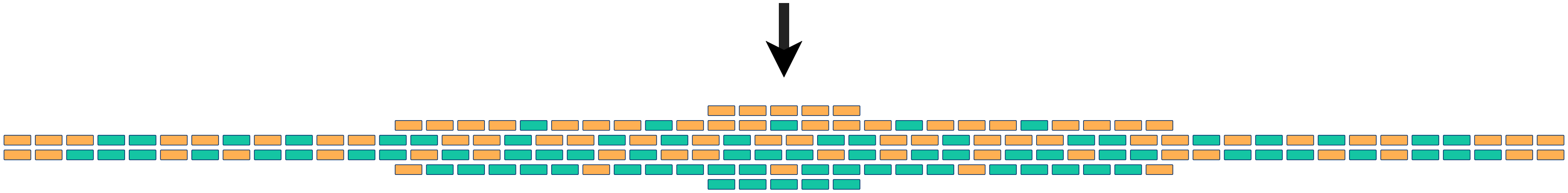
One program with **5** components ...

One Program, Many Points

What to Measure = **All** Gradual Possibilities



One program with **5** components ...



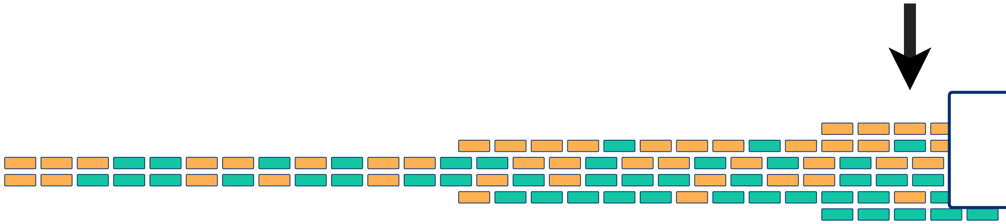
... leads to **32** gradual points

In general, **N** components => **2^N** points

One Program, Many Points

What to Measure = **All** Gradual Possibilities

One program with **5** components ...



Challenge: How to analyze the data?

... leads to **32** gradual points

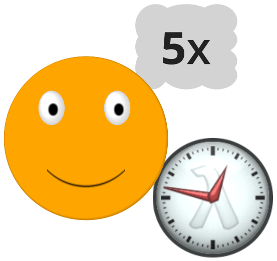
In general, **N** components => **2^N** points

Performance Insight

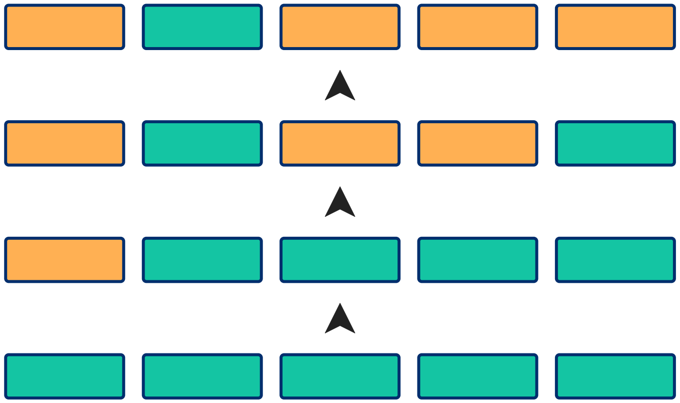
Challenge: How to analyze the data?

Focus on **D-deliverable** configurations

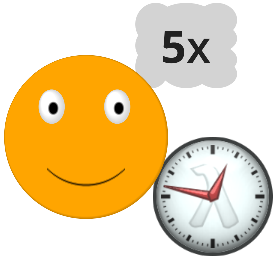
D-deliverable: The Idea



Are we *fast enough*?



D-deliverable: The Idea



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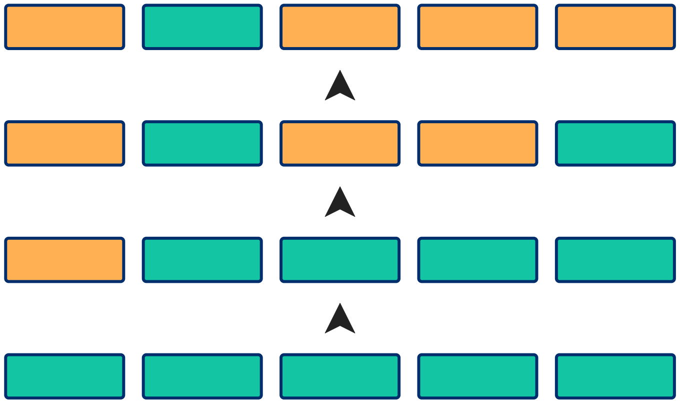
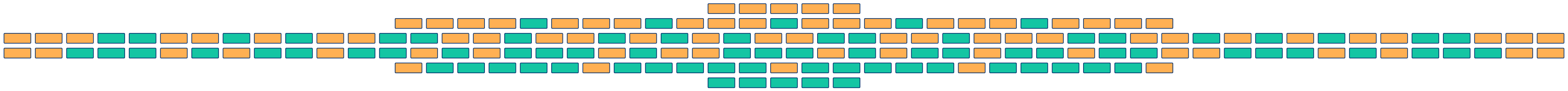


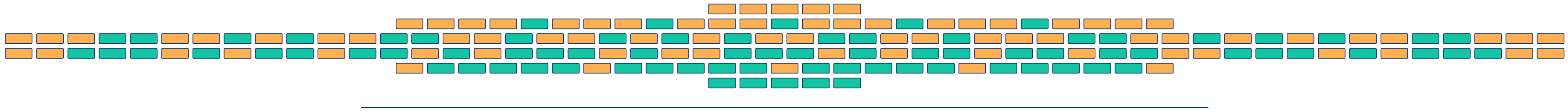
Worst-case overhead is not important

Dx slower is the upper bound

D-deliverable: How to Use



D-deliverable: How to Use



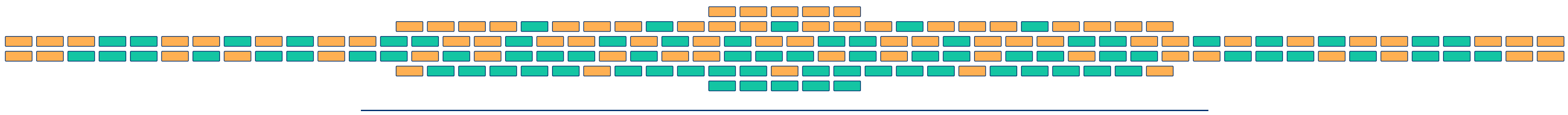
Compress to a **proportion** …

D = 2

➤

50%

D-deliverable: How to Use



Compress to a **proportion** ...

D = 2

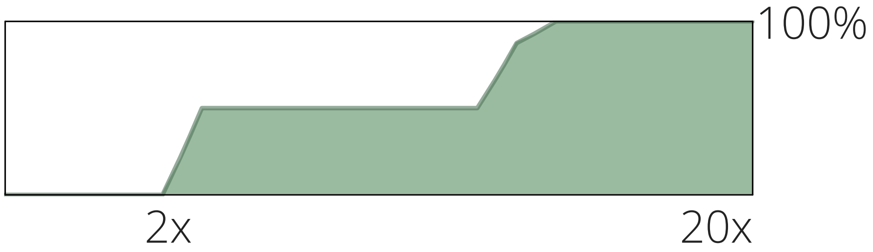
▼

50%

... or to a **CDF**

D ∈ [1, 20]

▼



D-deliverable: How to Scale

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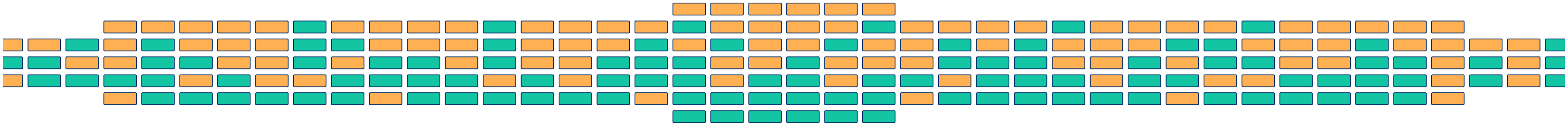
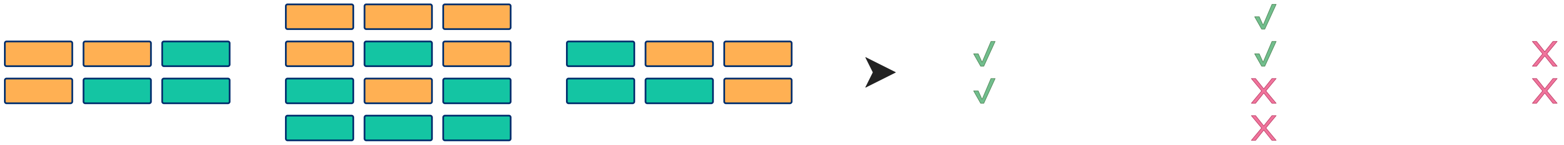


Choosing **D** enables a **Bernoulli random variable**



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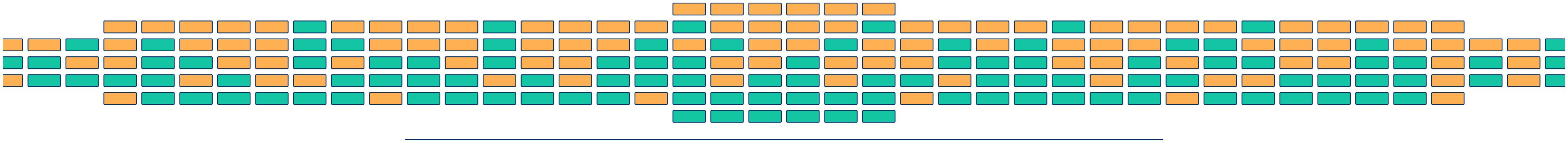

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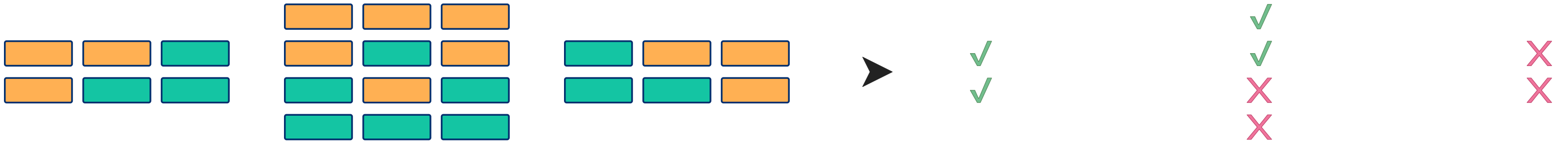
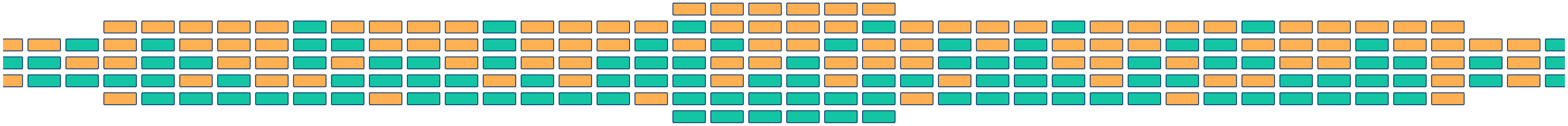


If 50% of **all points** are **D**-deliverable

=>

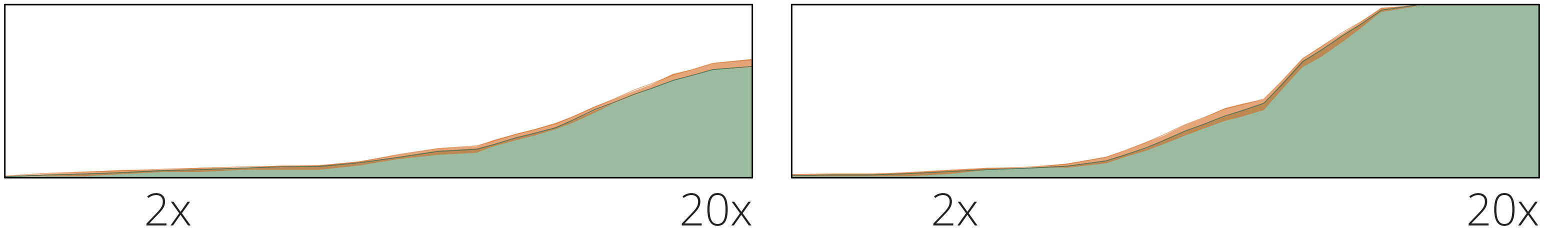
A **random point** has a 50% chance of being fast enough

D-deliverable: How to Scale



Linear sampling has been effective

for **approximating** the **true proportion**



(Orange intervals surround the two green curves)

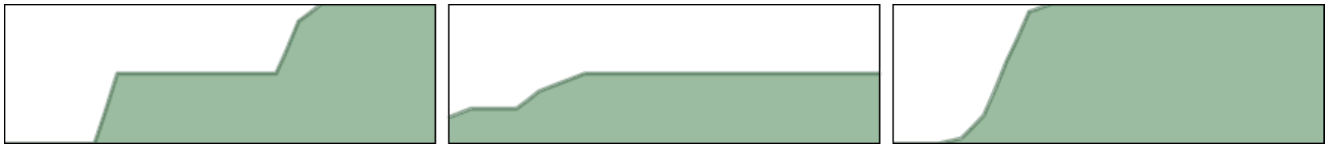
Method

1. Collect benchmark programs

2. Measure all configurations

   or a linear number of samples

3. Focus on the **D-deliverable** configurations



Larger Area = Better Performance

Applications

Typed Racket

POPL'16 JFP'19 OOPSLA'18

Reticulated Python

PEPM'18

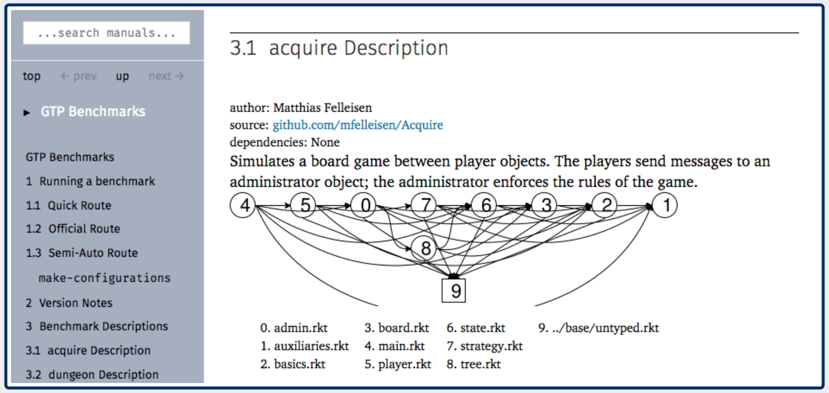
Applications

Curated benchmarks for two languages

Typed Racket

POPL'16 JFP'19

OOPSLA'18



...search manuals...

top ← prev up next →

▸ GTP Benchmarks

GTP Benchmarks

1 Running a benchmark

1.1 Quick Route

1.2 Official Route

1.3 Semi-Auto Route

make-configurations

2 Version Notes

3 Benchmark Descriptions

3.1 acquire Description

3.2 dungeon Description

3.1 acquire Description

author: Matthias Felleisen
source: github.com/mfelleisen/Acquire
dependencies: None

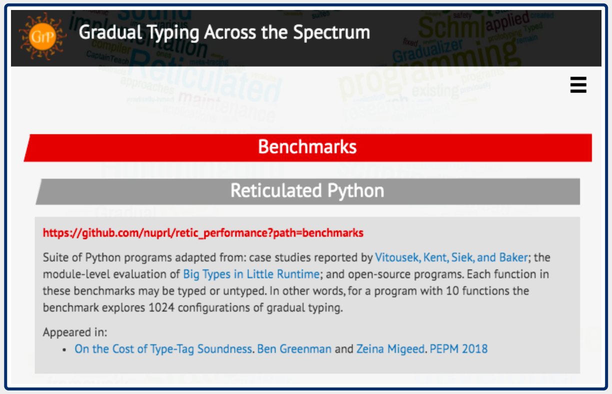
Simulates a board game between player objects. The players send messages to an administrator object; the administrator enforces the rules of the game.

0. admin.rkt
1. auxiliaries.rkt
2. basics.rkt
3. board.rkt
4. main.rkt
5. player.rkt
6. state.rkt
7. strategy.rkt
8. tree.rkt
9. ../base/untyped.rkt

docs.racket-lang.org/gtp-benchmarks

Reticulated Python

PEPM'18



Gradual Typing Across the Spectrum

≡

Benchmarks

Reticulated Python

https://github.com/nuprl/retic_performance?path=benchmarks

Suite of Python programs adapted from: case studies reported by Vitousek, Kent, Siek, and Baker; the module-level evaluation of Big Types in Little Runtime; and open-source programs. Each function in these benchmarks may be typed or untyped. In other words, for a program with 10 functions the benchmark explores 1024 configurations of gradual typing.

Appeared in:

- On the Cost of Type-Tag Soundness. Ben Greenman and Zeina Migeed. PEPM 2018

nuprl.github.io/gtp/benchmarks

from GitHub, Racket packages, Python benchmarks, ... usually without types

Applications

Typed Racket

POPL'16 JFP'19 OOPSLA'18

- **Guarded** semantics
- Bad news! Most **over 20x**
- Better today, but still slow

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PEPM'18

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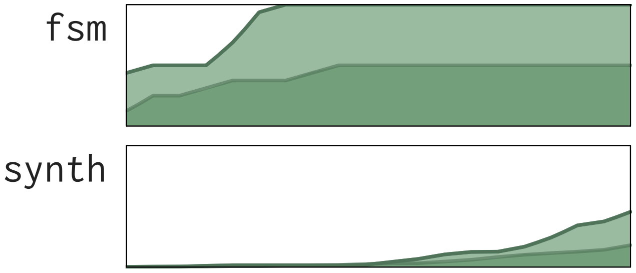
Example: 2015 to 2020



Reticulated Python

PEPM'18

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Q. Are **Guarded** and **Transient** "equally" type-sound?

Applications

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Reticulated Python PEPM'18

- **Transient** semantics
- Not bad! All **under 10x**

Q. Are **Guarded** and **Transient** "equally" type-sound?

Need a **method** to assess type guarantees

Proofs

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"typed code agrees with the types"

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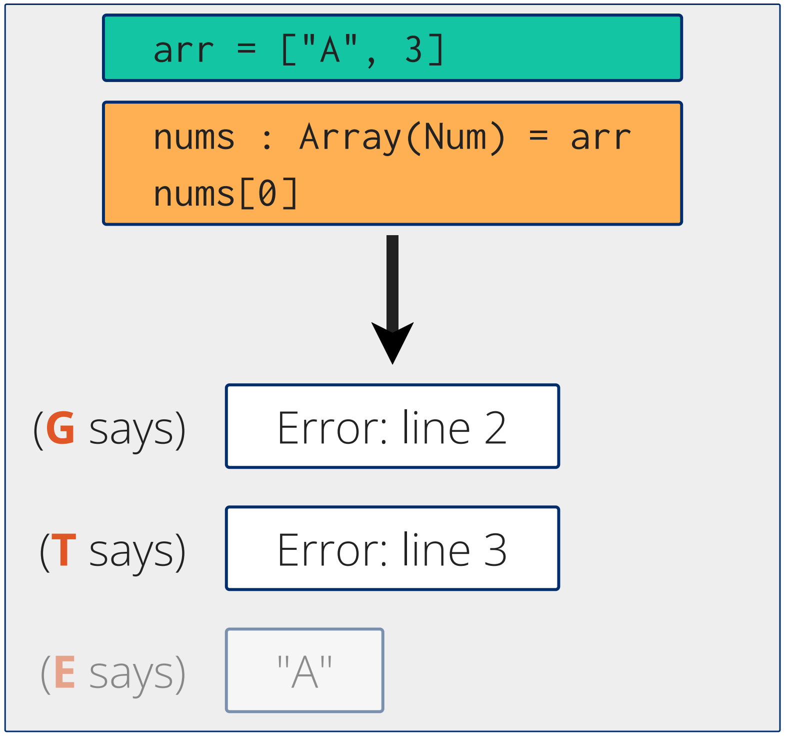

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nums : Array(Num) = arr
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(**G** says) Error: line 2

(**T** says) Error: line 3

(**E** says) "A"

From TS to CM

OOPSLA'19

In Submission'22

Both **Guarded** and **Transient** satisfy **type soundness** (TS)

Only **Guarded** satisfies **complete monitoring** (CM)

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OOPSLA'19

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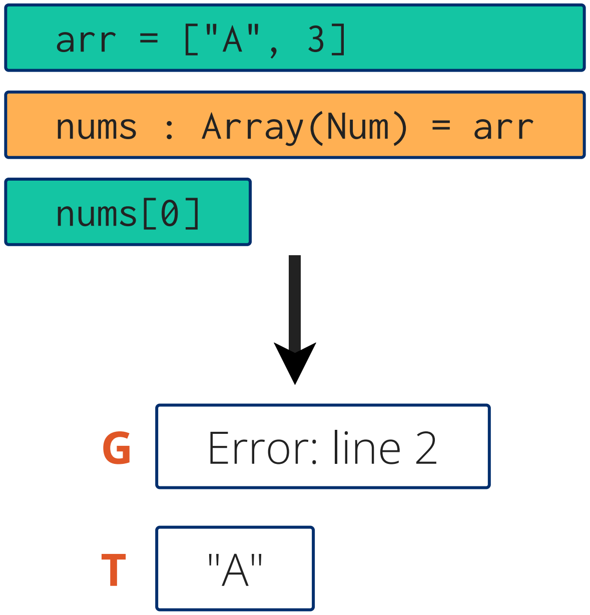

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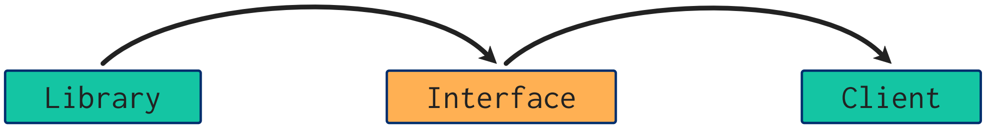

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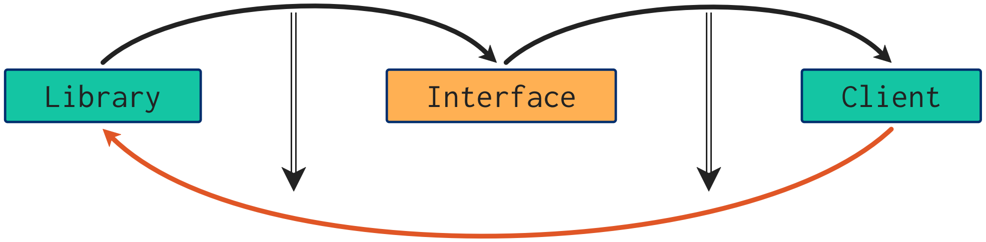

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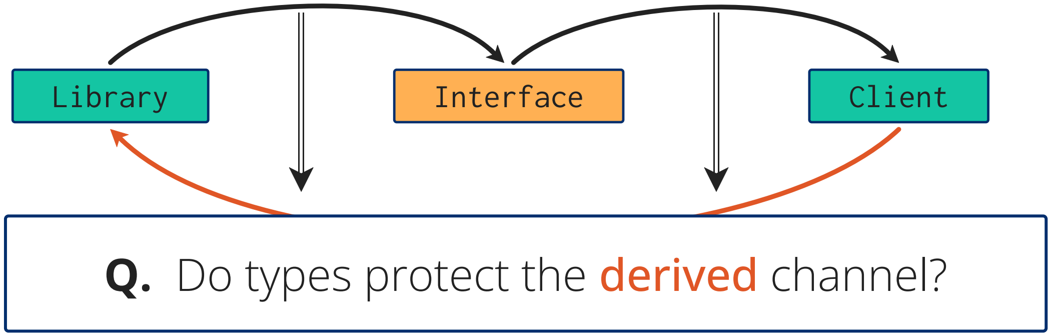

Q. Do types protect the **derived** channel?

From TS to CM

OOPSLA'19 In Submission'22

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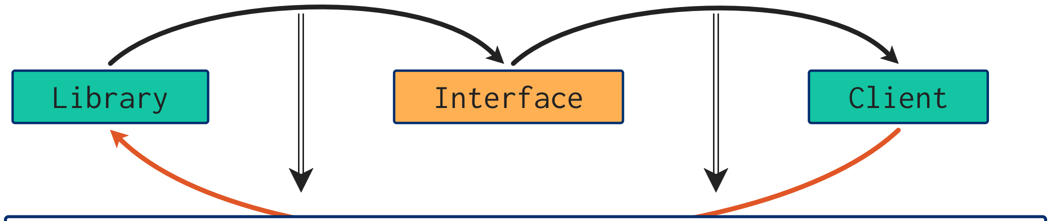

Q. Do types protect the **derived** channel?

Guarded (CM+TS): **Yes**
types made the channel

Transient (TS): **No**
channel is untyped to untyped

Applications

Typed Racket

Reticulated Python

Applications

Typed Racket

Reticulated Python

Q. Are **Guarded** and **Transient** types equally ***strong***?

Applications

Typed Racket

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Applications

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Reticulated Python

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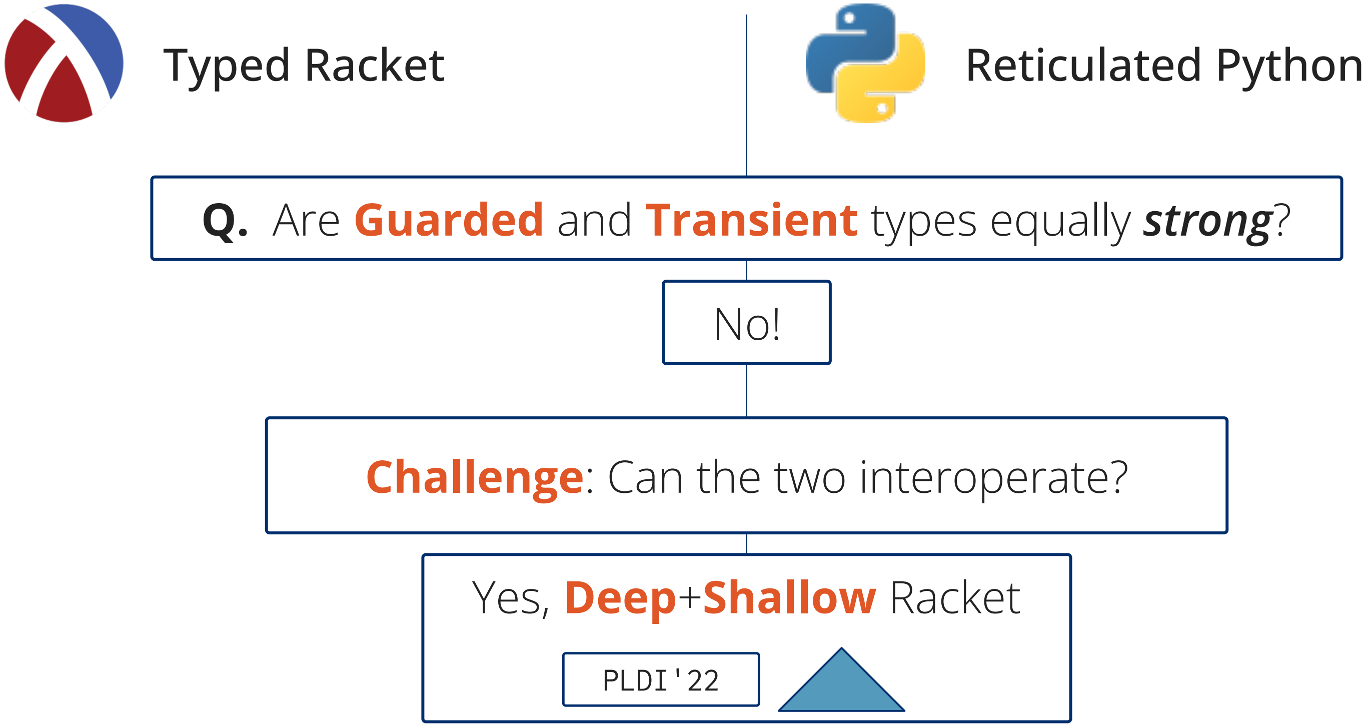
Challenge: Can the two interoperate?

Applications



Typed Racket

Reticulated Python

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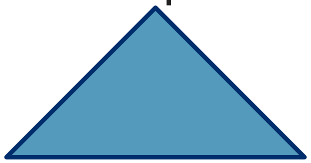
No!

Challenge: Can the two interoperate?

Yes, **Deep**+**Shallow** Racket

PLDI'22

Foundations for Gradual Languages

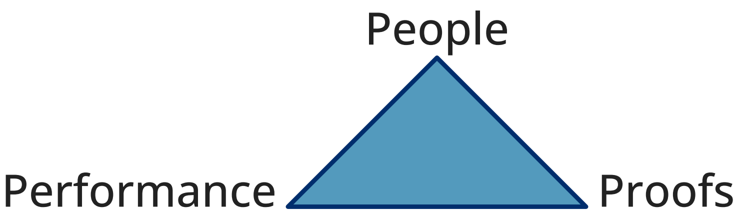


People

Performance

Proofs

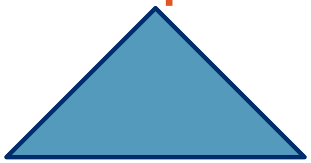
Foundations for Gradual Languages



Research Contributions:

- ➤ Characterizing Designs
- ➤ Directing Improvements
- ➤ Inspiring New Languages

Ongoing Work



People

Performance

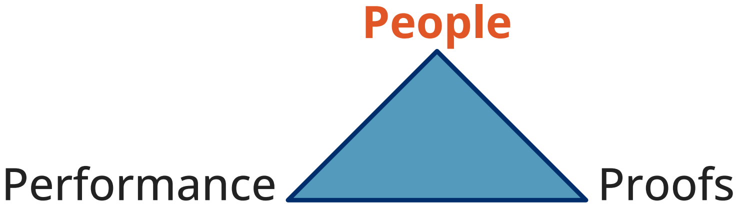
Proofs

Ongoing Work

Static Python at Instagram

Few types, but fast performance

Gradual soundness: type guarantees vs. ease-of-use



People

Performance

Proofs

Ongoing Work

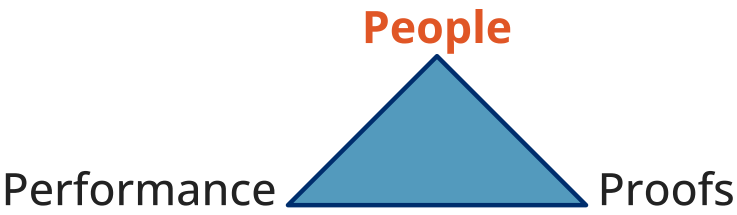
Static Python

Gradual Soundness

Rational Programmer

A method for PL pragmatices

Humans out-of-the-loop



People

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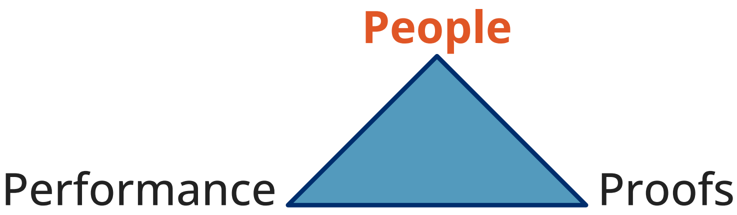
Directly measure pragmatics

Human Factors for Formal Methods:

Language levels for **Alloy**

LTL misconceptions (next slide)



LTL Misconceptions

Linear Temporal Logic

used in: **verification**, **synthesis**, and **robot planning**

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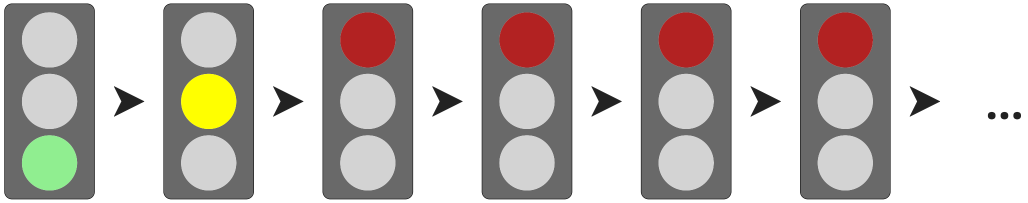

Is Green eventually on?

LTL Misconceptions

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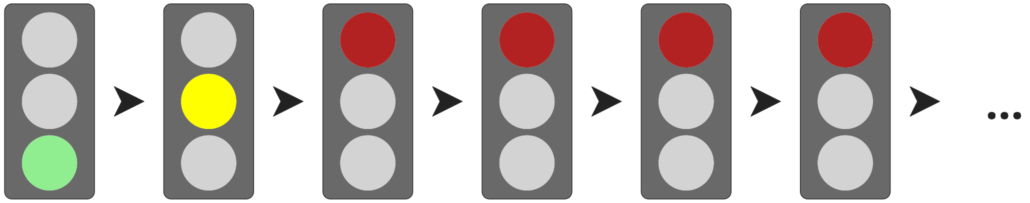

Is Green eventually on?

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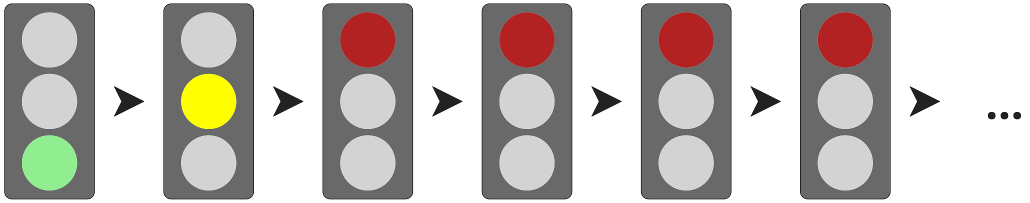

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Q. **In what ways** is LTL tricky, and **what can we do** about it?

Studies with researchers & students

LTL Misconceptions

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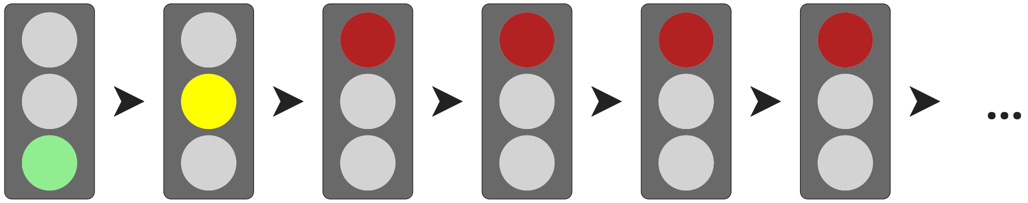

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Studies with researchers & students

Early outcome: **Better syntax** for Alloy 6

Ongoing Work

Static Python

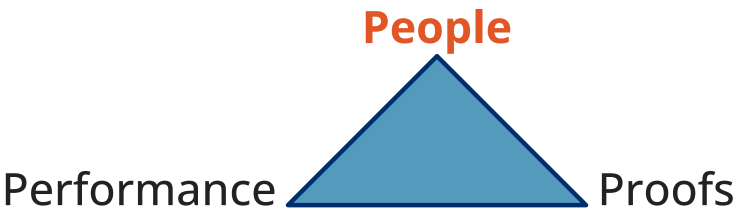
Gradual Soundness

Rational Programmer

Directly measure pragmatics

Human Factors for FM

Alloy and LTL



People

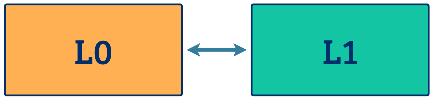
Performance

Proofs

Future Work

Future Work

Typed + Untyped is a multi-language problem



- 2 similar languages
- higher-order interoperability
- strong vs. weak invariants

Future Work

Multi-language systems are everywhere!

Future Work

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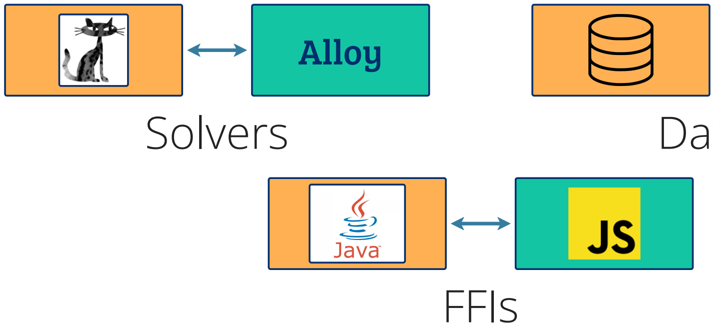

Future Work

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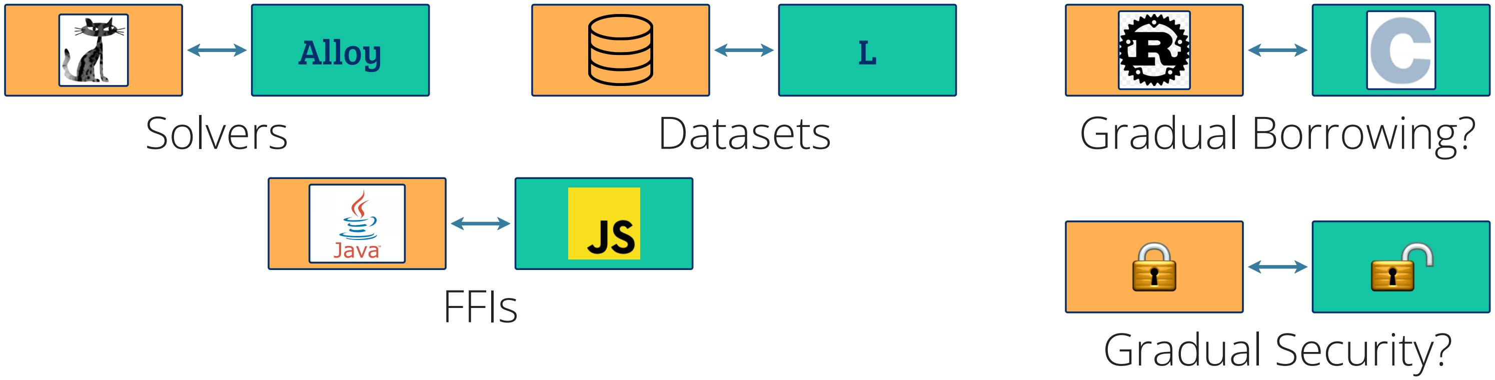


Solvers

Datasets

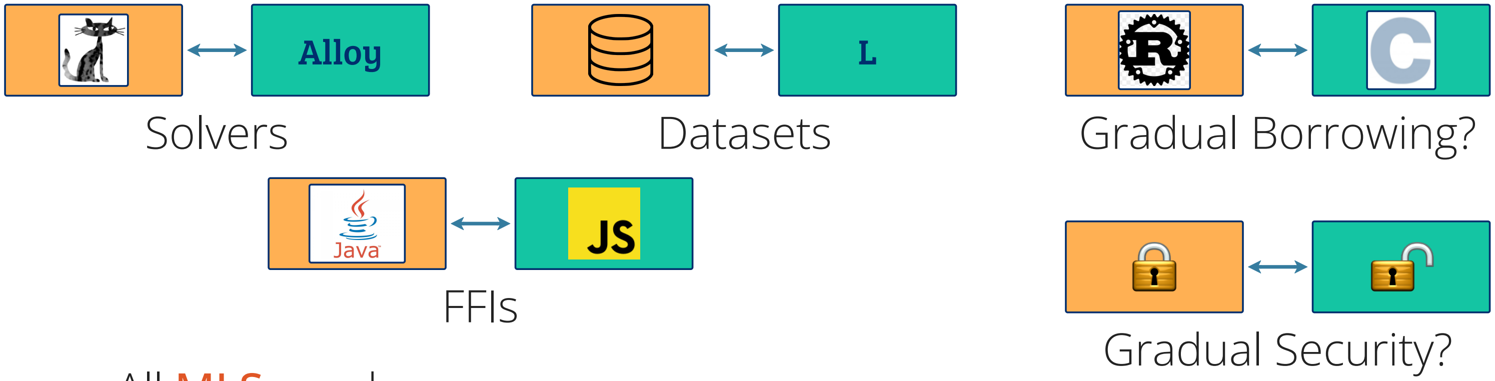
Gradual Borrowing?

FFIs

Gradual Security?

Future Work

Multi-language systems are everywhere!



Solvers

Datasets

Gradual Borrowing?

FFIs

Gradual Security?

All MLS need:

- ➤ Expressive Boundaries
- ➤ Correct & Fast Validation

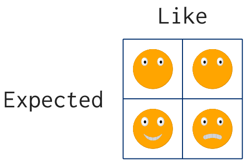
PPP

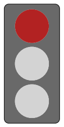
Balanced Foundation

People

Behavior of Gradual Types

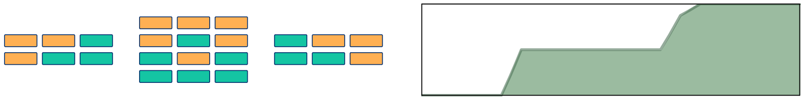
Human Factors for Formal Methods





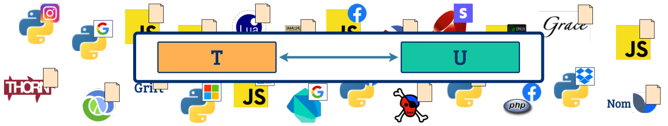
Performance

Measuring Costs at Scale

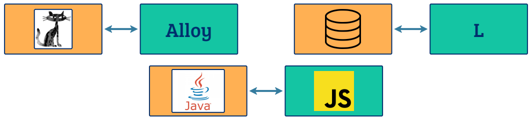


Proofs

Comparing Type Guarantees



Methods for **multi-language systems**



Teaching Alloy

Alloy is a **modeling language** that comes with **two styles**:

Predicate

```
all a, b, c: univ |
  a->b in f and b->c in f
    implies a->c in f
```

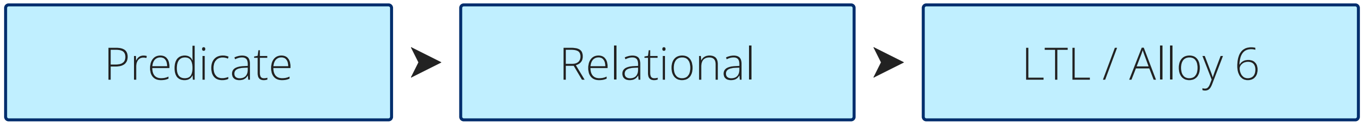
Relational

```
f.f in f
```

(**f** is transitive)

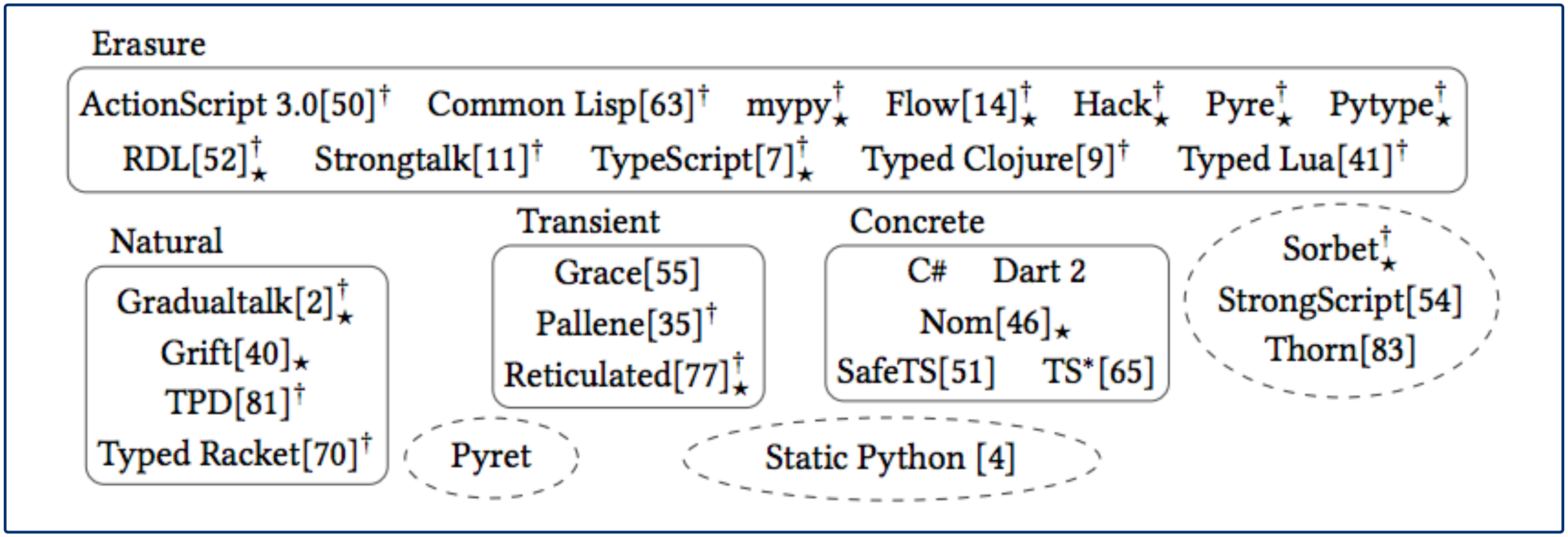
Problem: **errors** assume you know both styles!

Q. Can **language levels** give a smooth introduction?



Predicate ➤ Relational ➤ LTL / Alloy 6

Informal Landscape



Erasure

ActionScript 3.0[50]† Common Lisp[63]† mypy$^{\dagger}_{\star}$ Flow[14]$^{\dagger}_{\star}$ Hack$^{\dagger}_{\star}$ Pyre$^{\dagger}_{\star}$ Pytype$^{\dagger}_{\star}$ RDL[52]$^{\dagger}_{\star}$ Strongtalk[11]† TypeScript[7]$^{\dagger}_{\star}$ Typed Clojure[9]† Typed Lua[41]†

Natural

Gradualtalk[2]$^{\dagger}_{\star}$ Grift[40]$_{\star}$ TPD[81]† Typed Racket[70]†

Transient

Grace[55] Pallene[35]† Reticulated[77]$^{\dagger}_{\star}$

Concrete

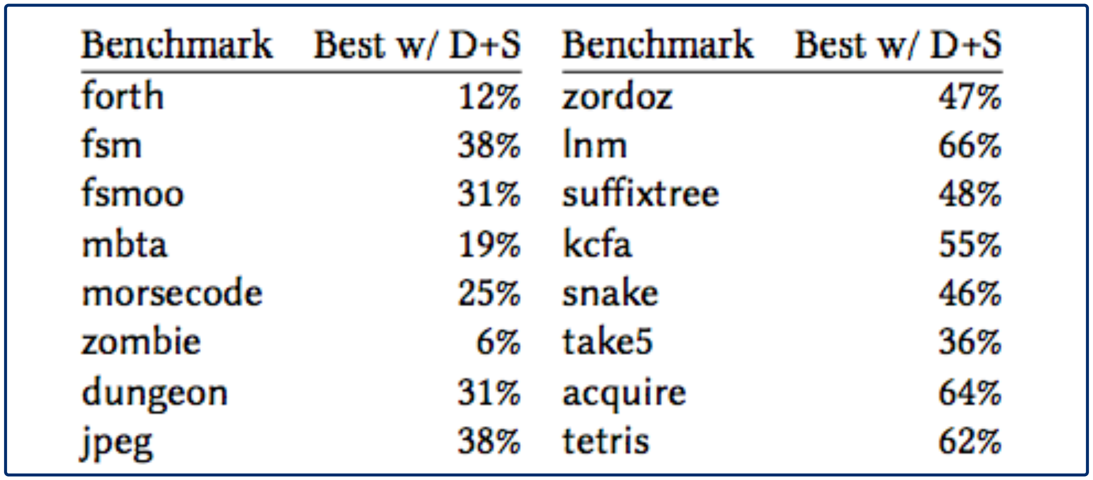
C# Dart 2 Nom[46]$_{\star}$ SafeTS[51] TS*[65]

Sorbet$^{\dagger}_{\star}$ StrongScript[54] Thorn[83]

Pyret

Static Python [4]

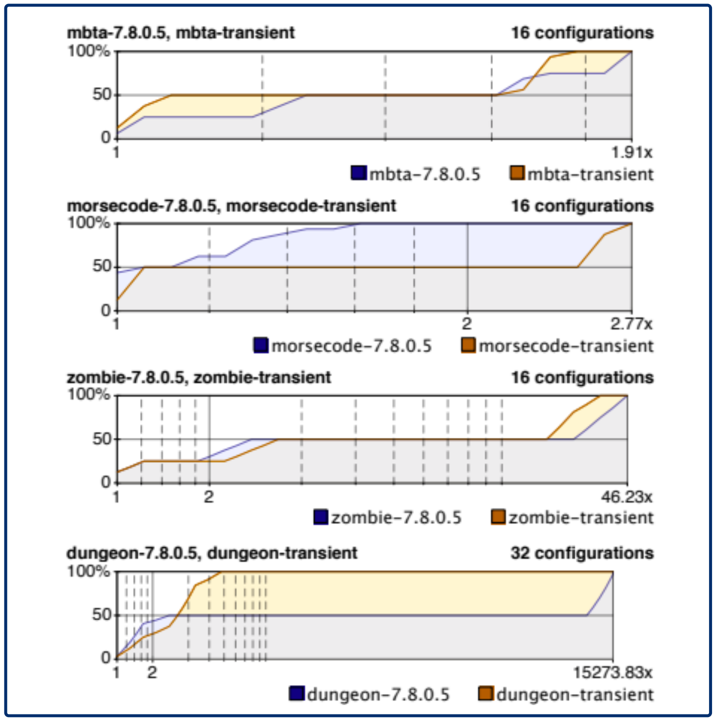
Deep + Shallow

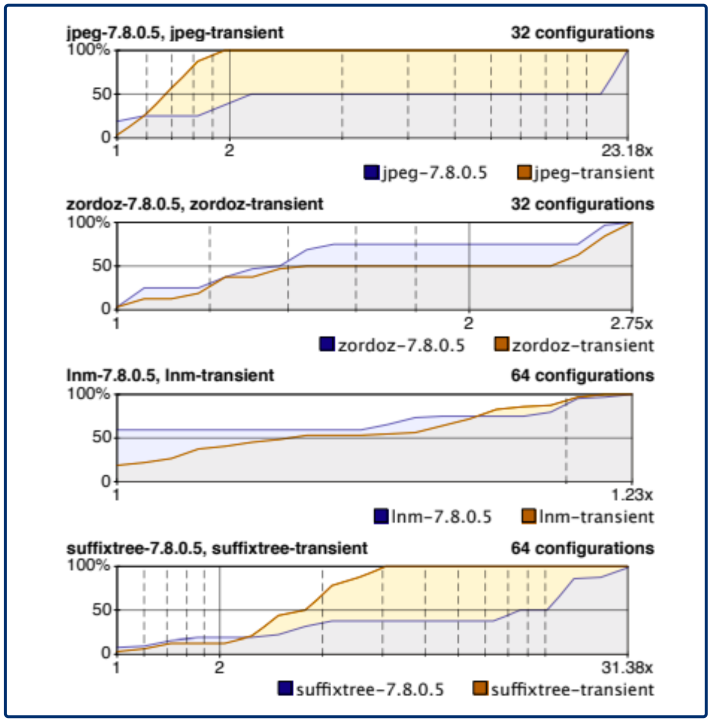


Benchmark	Best w/ D+S	Benchmark	Best w/ D+S
forth	12%	zordoz	47%
fsm	38%	lnm	66%
fsmoo	31%	suffixtree	48%
mbta	19%	kcfa	55%
morsecode	25%	snake	46%
zombie	6%	take5	36%
dungeon	31%	acquire	64%
jpeg	38%	tetris	62%

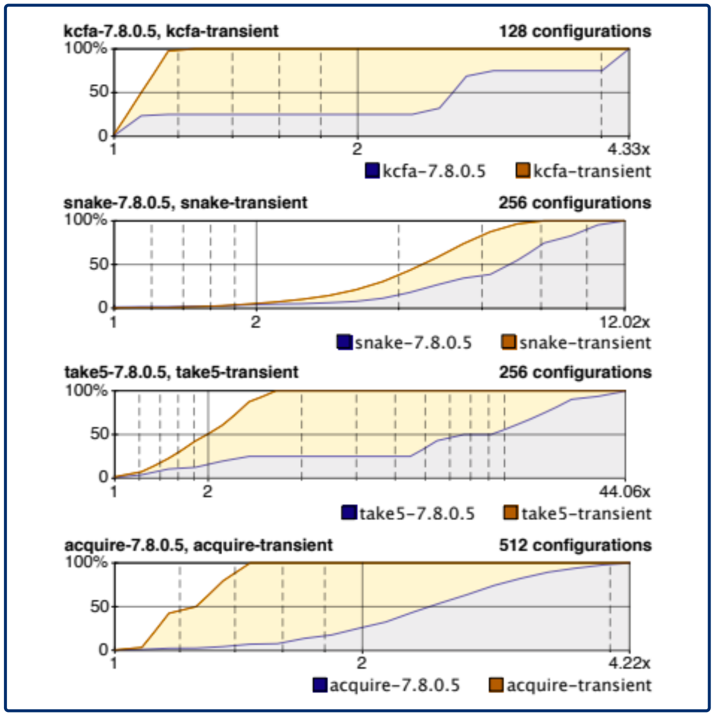
Percent of gradual points that run fastest with a Deep+Shallow mix

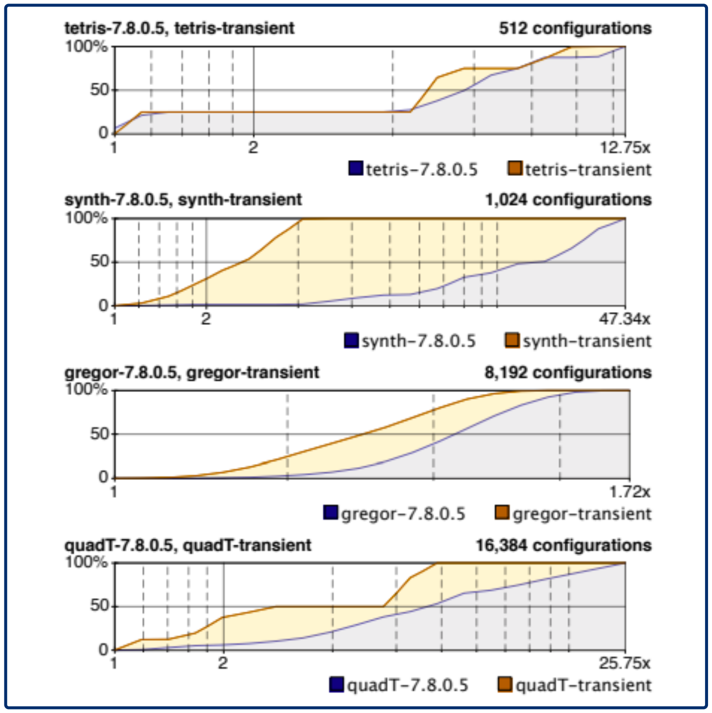
Deep or Shallow (1/2)





Deep or Shallow (2/2)





Prior Work

	Guarded	Transient	Erasure
type soundness			
dyn. gradual guarantee			
blame theorem			

Prior Work

	Guarded	Transient	Erasure
type soundness	✓	✓	✗
dyn. gradual guarantee	✓	✓	✓
blame theorem	✓	✓	✓

Standard tools **do not** tell the difference!

A Toolbox to Measure Type Guarantees

	Guarded	Transient

A Toolbox to Measure Type Guarantees

	Guarded	Transient
complete monitoring	✓	✗

CM: Do types protect all channels?

A Toolbox to Measure Type Guarantees

	Guarded	Transient
complete monitoring	✓	✗
blame soundness	✓	✗
blame completeness	✓	✗

CM: Do types protect all channels?

BS: Do errors point to *only* relevant channels?

BC: Do errors point to *all* relevant channels?

A Toolbox to Measure Type Guarantees

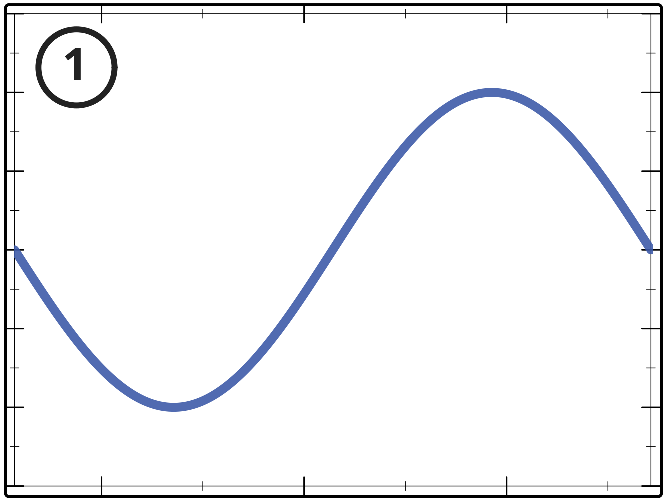
	Guarded	C	F	Transient	A	E
type soundness						
complete monitoring						
blame soundness						
blame completeness						
error preorder						

A Toolbox to Measure Type Guarantees

	Guarded	C	F	Transient	A	E
type soundness	✓	✓	✓	y	✓	✗
complete monitoring	✓	✓	✗	✗	✗	✗
blame soundness	✓	✓	✓	h	✓	0
blame completeness	✓	✓	✓	✗	✓	✗
error preorder	Guarded <	C <	F <	Transient =	A <	E

Example: Clickable Plot

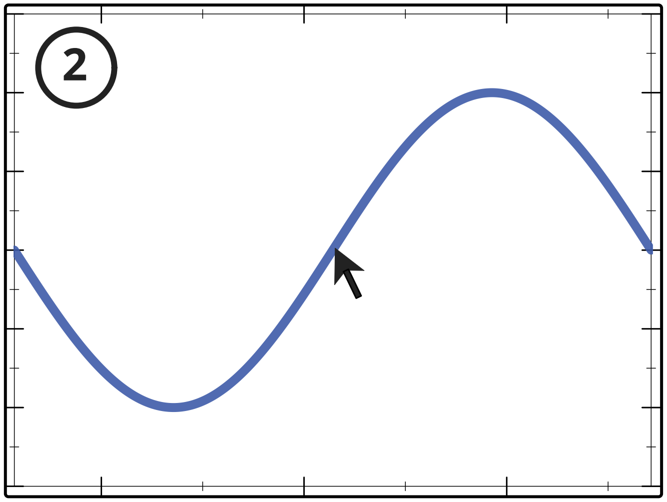
Type Soundness cannot distinguish **Guarded** and **Transient**



1. Plot data
2. Listen for a click
3. Draw an image

Example: Clickable Plot

Type Soundness cannot distinguish **Guarded** and **Transient**



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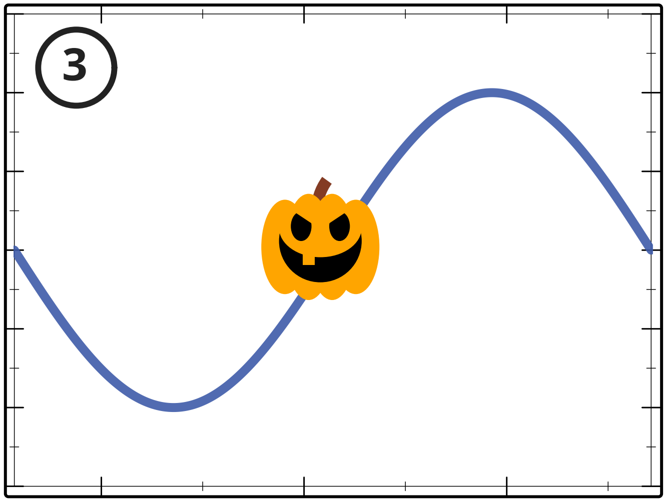

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Example: Clickable Plot

Type Soundness cannot distinguish **Guarded** and **Transient**

Example: Clickable Plot

Type Soundness cannot distinguish **Guarded** and **Transient**

```
type ClickPlot
  init
    Num,Num -> Image

  mouseHandler
    MouseEvt -> Void


  show
    -> Void
```

```
class ClickPlot
  init(onClick)
    # set up

  mouseHandler(evt)
    i = onClick(evt)
    # add image

  show()
    # display
```

Example: Clickable Plot

Type Soundness cannot distinguish **Guarded** and **Transient**

```
function h(x)
  if 0 < fst(x)
    pumpkin
  else
    fish

p = ClickPlot(h)
p.show()
# user clicks
```

```
type ClickPlot
  init
    Num,Num -> Image

  mouseHandler
    MouseEvt -> Void


  show
    -> Void
```

```
class ClickPlot
  init(onClick)
    # set up

  mouseHandler(evt)
    i = onClick(evt)
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  show()
    # display
```

Example: Clickable Plot

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p.show()
# user clic
```

```
type ClickPlot
  init
    Num,Num -> Image
```

```
class ClickPlot
  init(onClick)
    # set up

         ndler(evt)
         nClick(evt)
          image



         play
```

Guarded: error at the **type boundary**

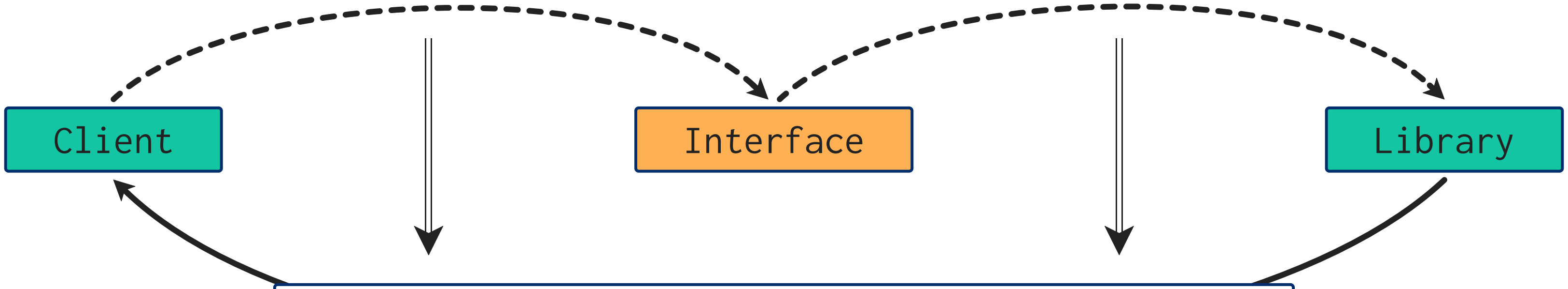
(coordinate pair vs. mouse event)

Transient: error **within** the client

the real issue is **off the stack**!

Example: Clickable Plot

Type Soundness cannot distinguish **Guarded** and **Transient**



Q. Do types protect the **callback** channel?

Guarded: **Yes**

types made the channel

Transient: **No**

the channel is untyped to untyped