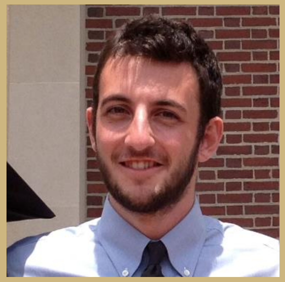
Safe Stream-Based Programming with Refinement Types



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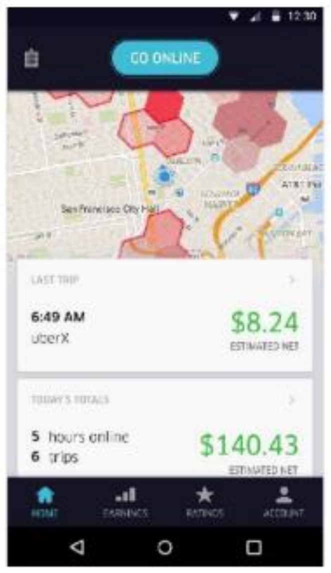
ASE '18
September 6, 2018

Mobile app reliability is *crucial*

UBER

Rider



Driver

Eats

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UBER

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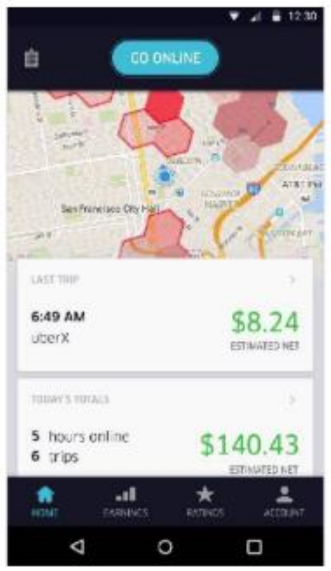

Driver

Eats

- Rider crash: can't get home
- Driver crash: can't earn

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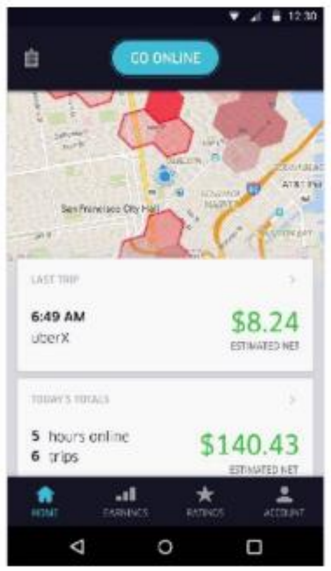

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- Rider crash: can’t get home
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- Whole business depends on mobile apps

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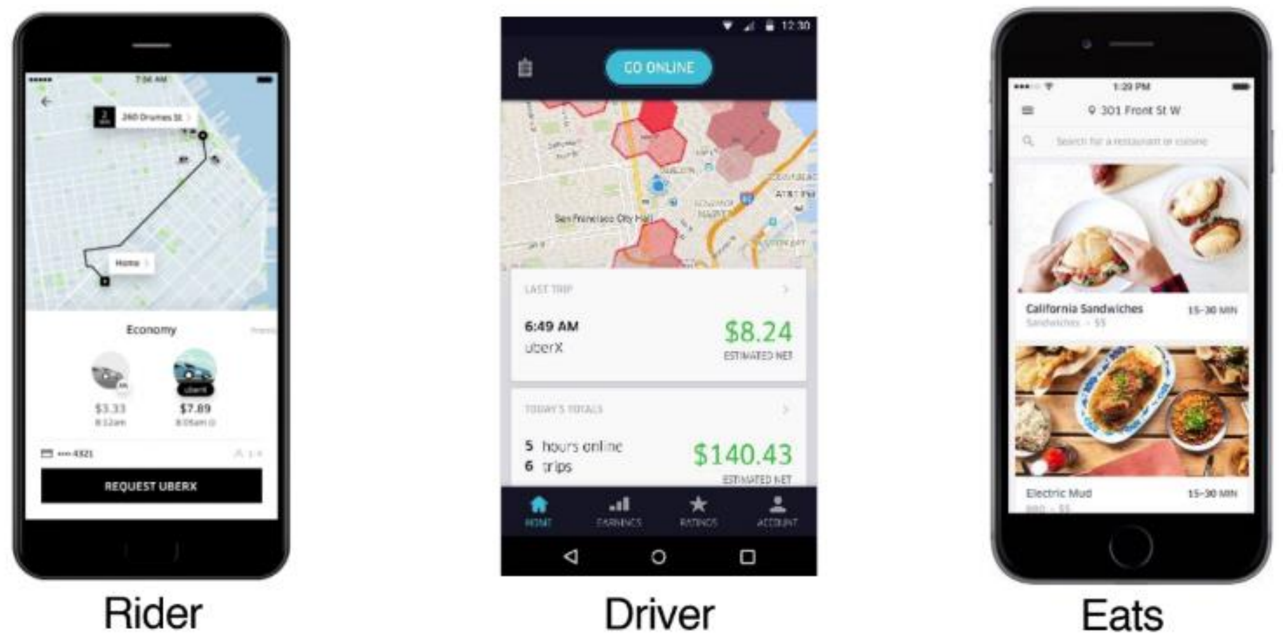

- Rider crash: can't get home
- Driver crash: can't earn
- Whole business depends on mobile apps
- Patching through third-party app stores is *slow*

Apps are fast-moving, large, and complex

- Hundreds of developers working simultaneously
- Millions of lines of code
- Apps depend upon numerous general-purpose libraries

UI Thread Safety

Don't touch the UI from off the main thread. *Easy enough.*

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... not even transitively or through a library.

e.g. `innocuousLookingMethod` calls `foo` calls `bar` calls `uiMethod`

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e.g. `innocuousLookingMethod` calls `foo` calls `bar` calls `uiMethod`

… especially when using stream-based programming libraries with complex threading behavior

→ Stream-Based Programming

→ Effect & Thread Type Refinements

→ UI-Thread Safety

→ Evaluation

Reactive Extensions

ReactiveX

"An API for asynchronous programming with observable streams"

Reactive Extensions

ReactiveX

"An API for asynchronous programming with observable streams"

- Create or receive streams of events and data
- Use expressive operators to compose and transform streams
- Subscribe callbacks to streams to perform side effects

Reactive Extensions

ReactiveX

"An API for asynchronous programming with observable streams"

Used by:

Applied Duality, Microsoft, NETFLIX, GitHub, SOUNDCLOUD, Trello, treehouse, SeatGeek, ooVoo, Couchbase, futurice, O.C.TANNER, UBER, airbnb

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Stream-Based Programming

Reactive Extensions (ReactiveX) example:

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Effects & Refinement Types

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Effect types refine function types by their side-effects:

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e.g. UI access, network I/O, heavy computation

Effects

```
// java.lang.Math
int max(int x, int y) {...}

// android.widget.Button
void setText(String text) {...}

// com.example.MyApp
void foobar() {...}

// some obscure Android library
void poorlyDocumentedMethod() {...}
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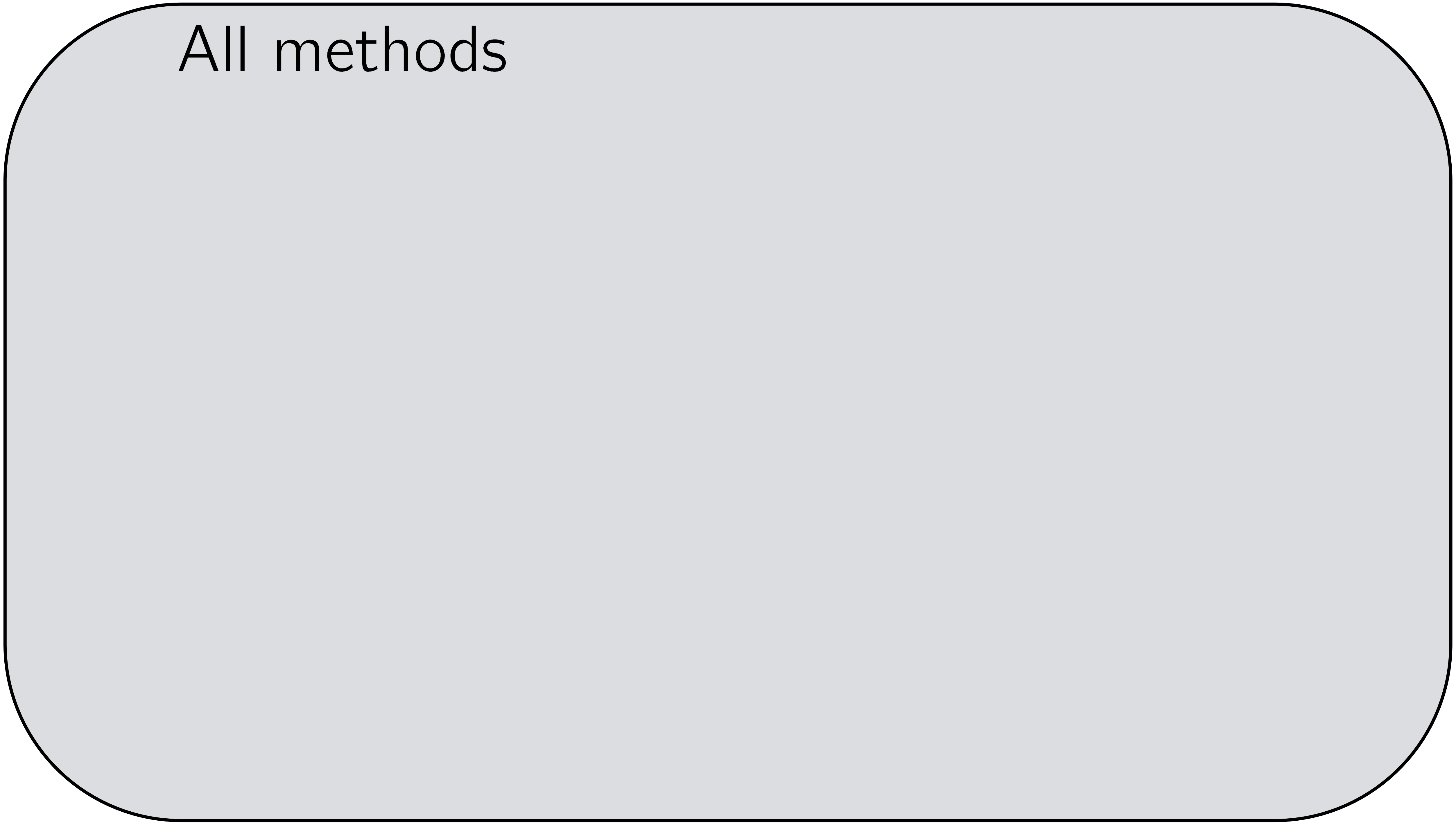
Effect Typing as Call-graph Reachability



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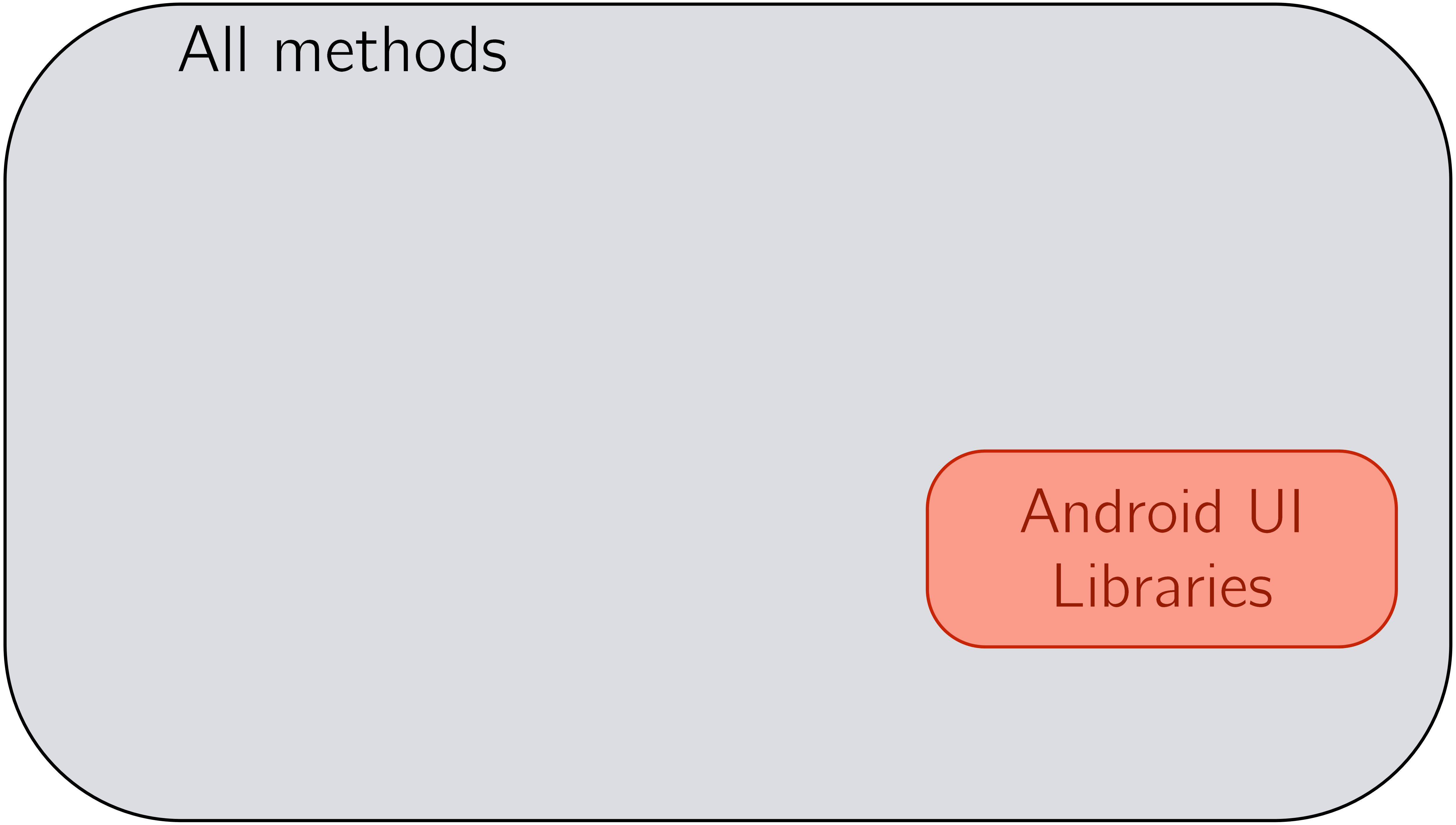

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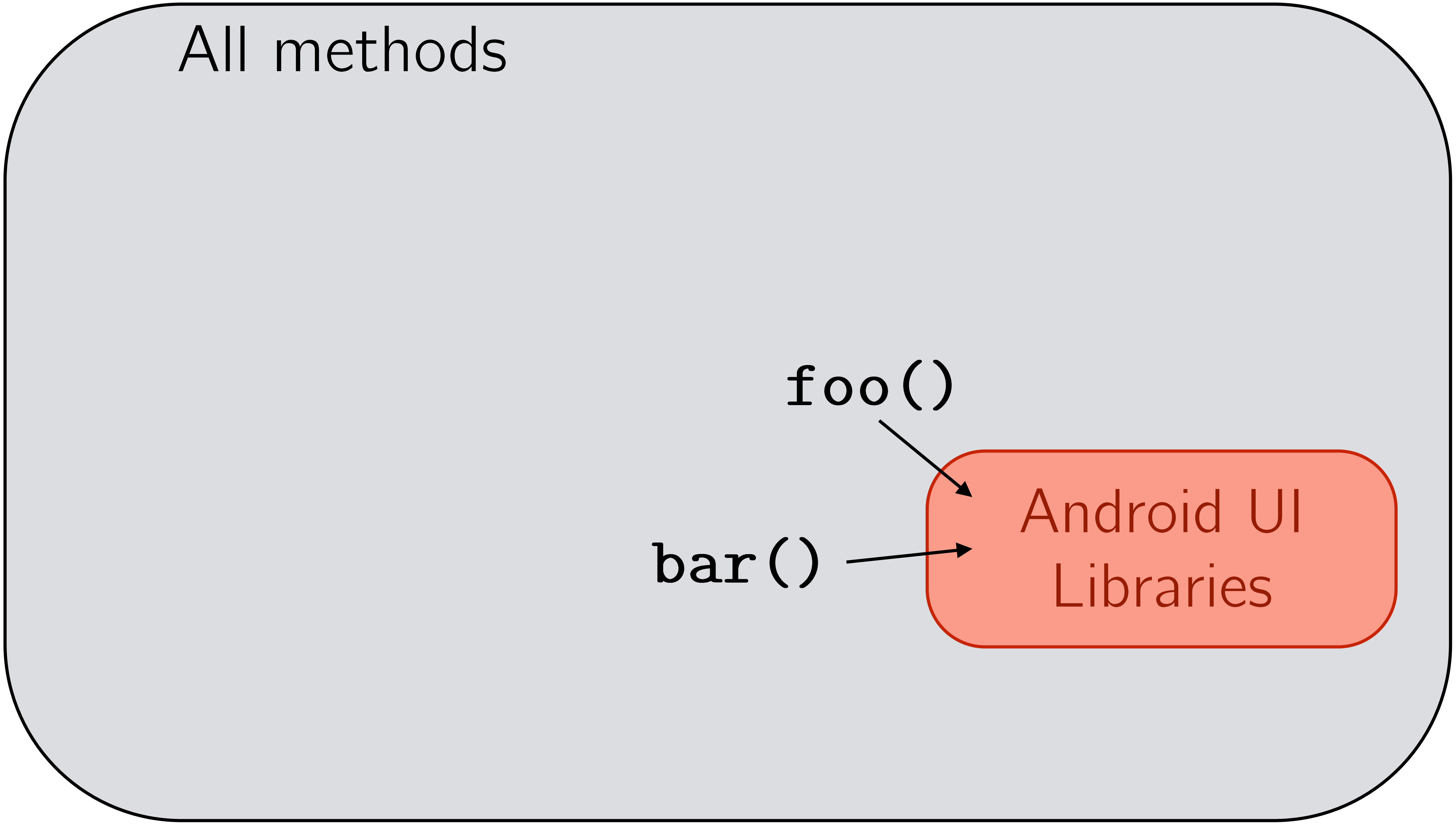

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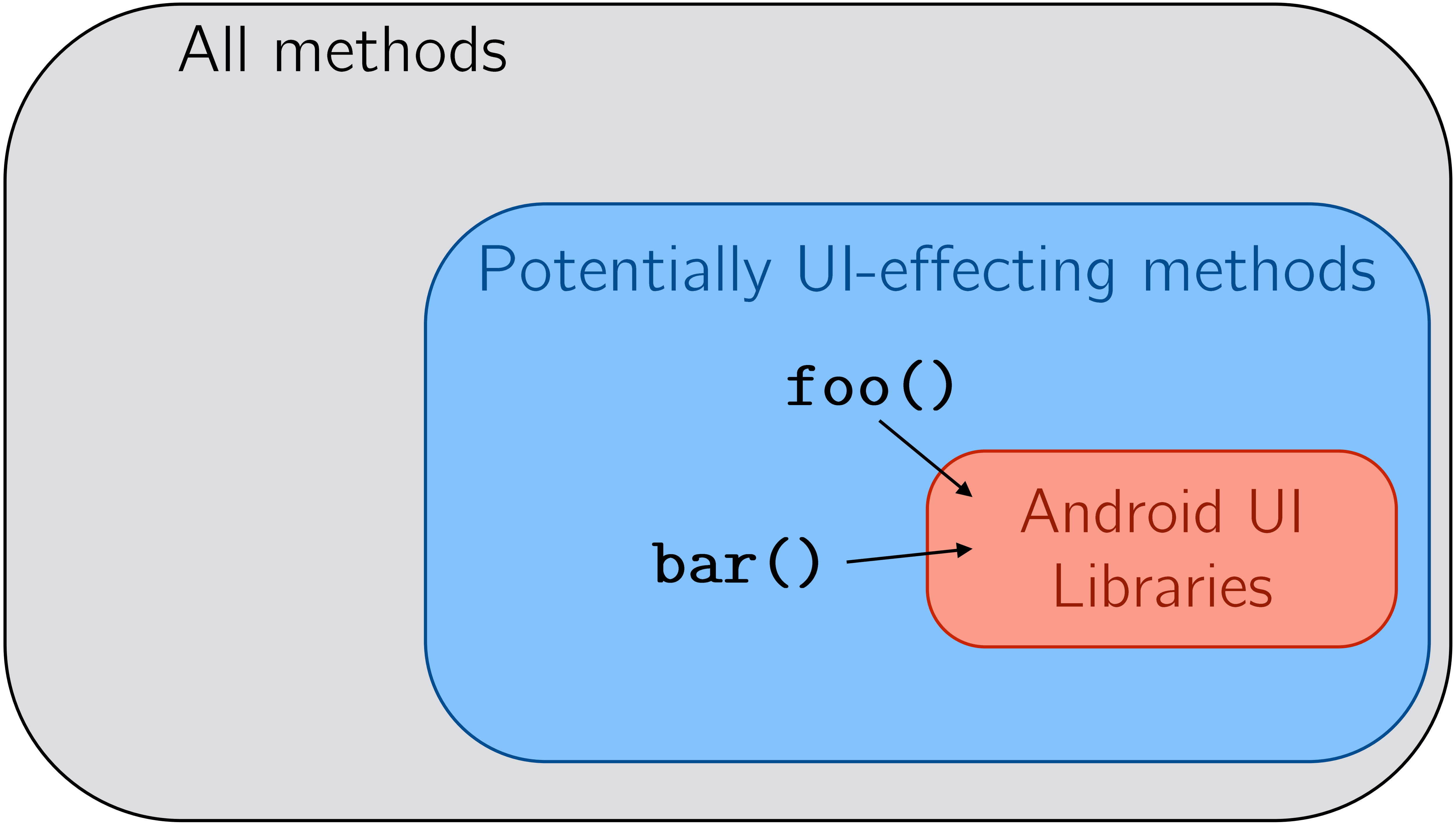

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A method with effect annotation e can **call** a method with effect annotation e' if and only if $e \preccurlyeq e'$

Inheritance:
A method with effect annotation e can **override** a method with effect annotation e' if and only if $e \preccurlyeq e'$

Effects alone are insufficient

Previous work with effect types handles UI library interfaces with *fixed* threading behavior, such as:

```
runOnUiThread : Runnable -> void
```

"Effects for Controlling UI Object Access" Gordon et al., ECOOP '13

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Stream-based interfaces have *dynamic* threading behavior, such as:

```
subscribe : Observable<T> -> Consumer<T> -> void
```

Runs on a thread determined dynamically by the scheduler of the receiver stream

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Thread Type Refinement

Type Lattice:

$$\begin{tikzcd}
 & \texttt{@AnyThread} & \\
\texttt{@UIThread} \arrow[ur] & & \texttt{@CompThread} \arrow[ul] \\
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Example stream function types:

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filter :
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observeOn :
 @AnyThread Observable<T>
  -> @PolyThread Scheduler -> @PolyThread Observable<T>
```

- → Stream-Based Programming
- → Effect & Thread Type Refinements
- → UI Thread Safety
- → Evaluation

UI Thread Safety

A stream-based program is *guaranteed* never to access the UI from a non-UI thread if `@UIEffect` callbacks are only subscribed to `@UIThread` streams.

Example Revisited

```
Observable<...> carLocationData = ... ;

carLocationData

  .filter( car -> /* car has no passenger */ )

  .observeOn(AndroidSchedulers.mainThread())

  .delay(100, TimeUnit.MILLISECONDS)

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    car -> { /* display car on map    */ },

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Example Revisited

@AnyThread

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@SafeEffect

@UIEffect

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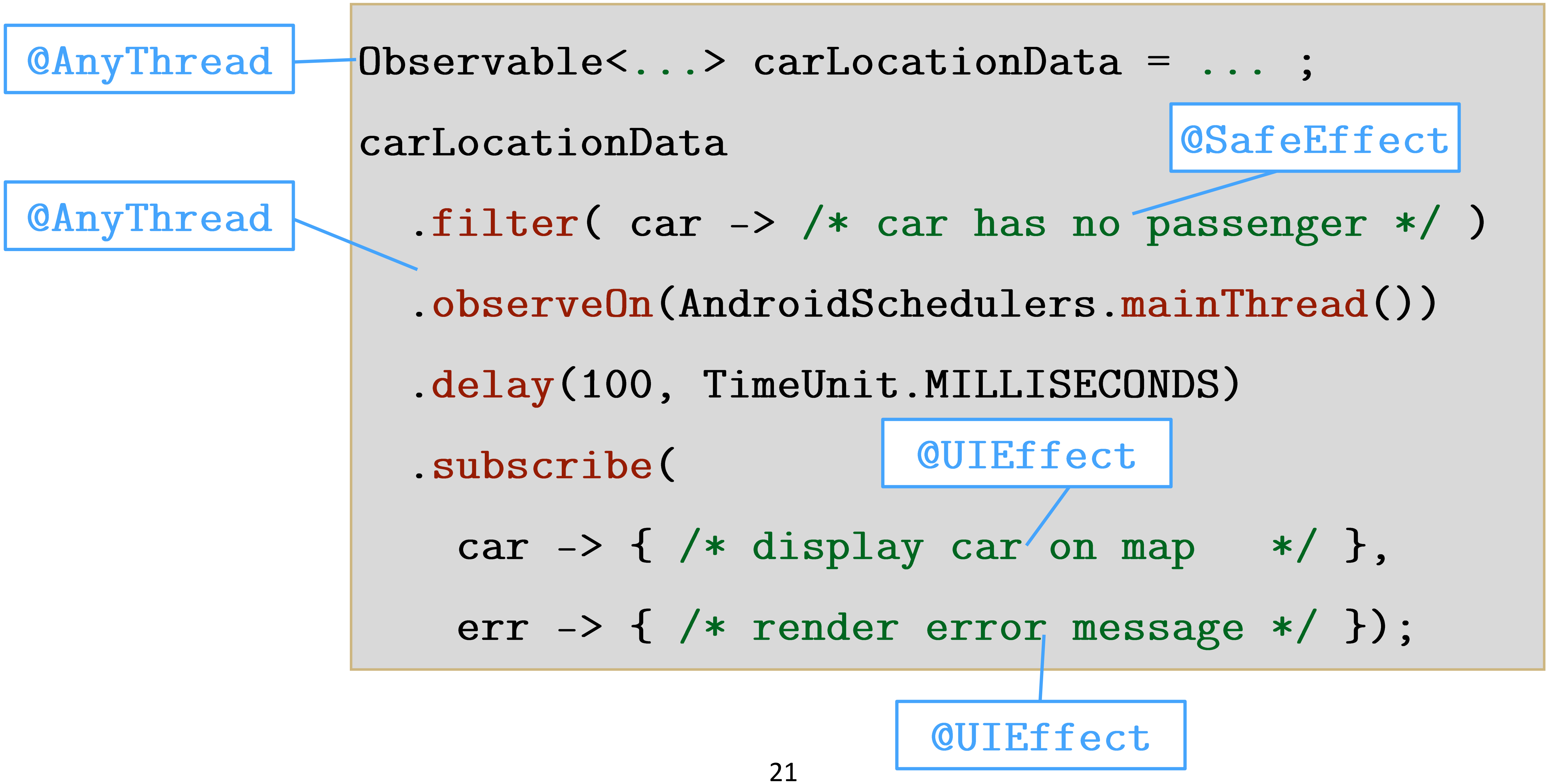

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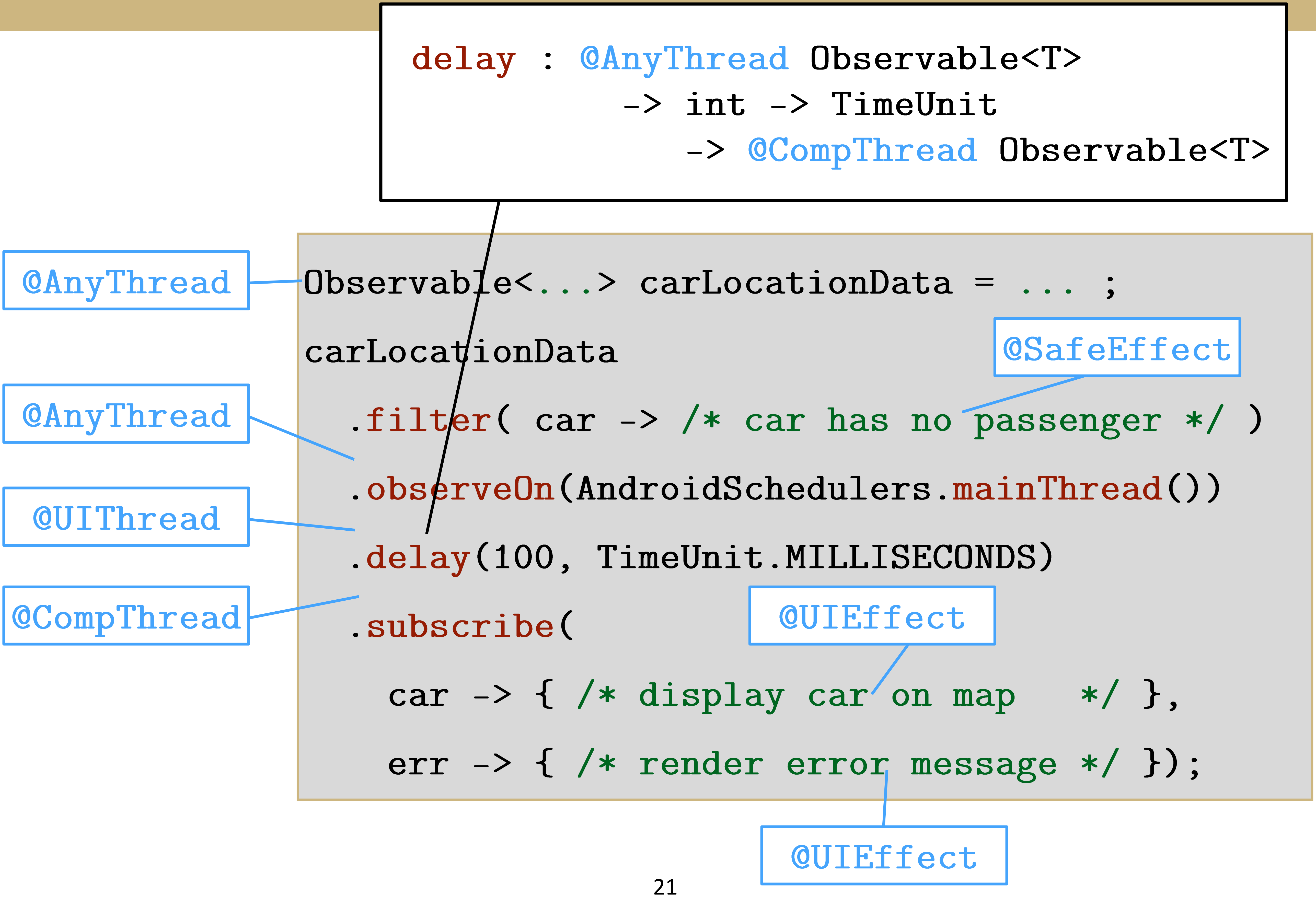

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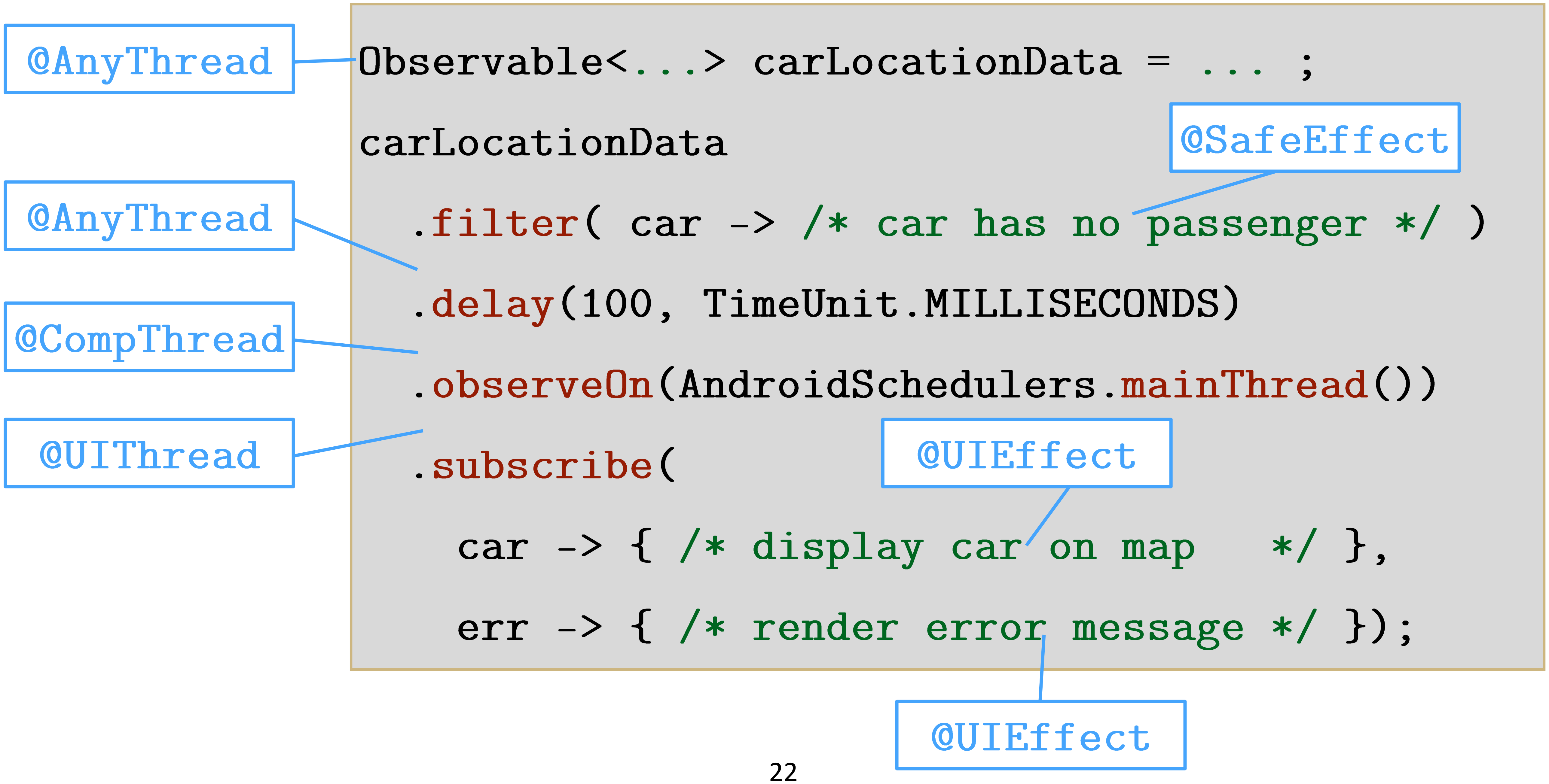

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- $\rightarrow$ Stream-Based Programming
- $\rightarrow$ Effect & Thread Type Refinements
- $\rightarrow$ UI Thread Safety
- $\rightarrow$ Evaluation

Experiments

RQ1: *Is the typechecker practical and easy-to-use?*

- Manual annotation burden is small
- Compile-time performance cost is low
- Error messages and warnings are understandable

RQ2: *Does the typechecker find real bugs and help fix them?*

- Stream-based threading bugs exist in practice
- Typechecker identifies them successfully
- Checked programs are reliably bug-free

Test Corpora

Open Source Android apps:

Java applications on GitHub

… that import ReactiveX `AndroidSchedulers`,

… have at least 15 “stars”

… and had been indexed recently.

Uber Case Study:

- Deployed in production for **Driver** and **Eats** apps.
  - Over 500k LoC in total

Usability

RQ1: *Is the typechecker practical and easy-to-use?*

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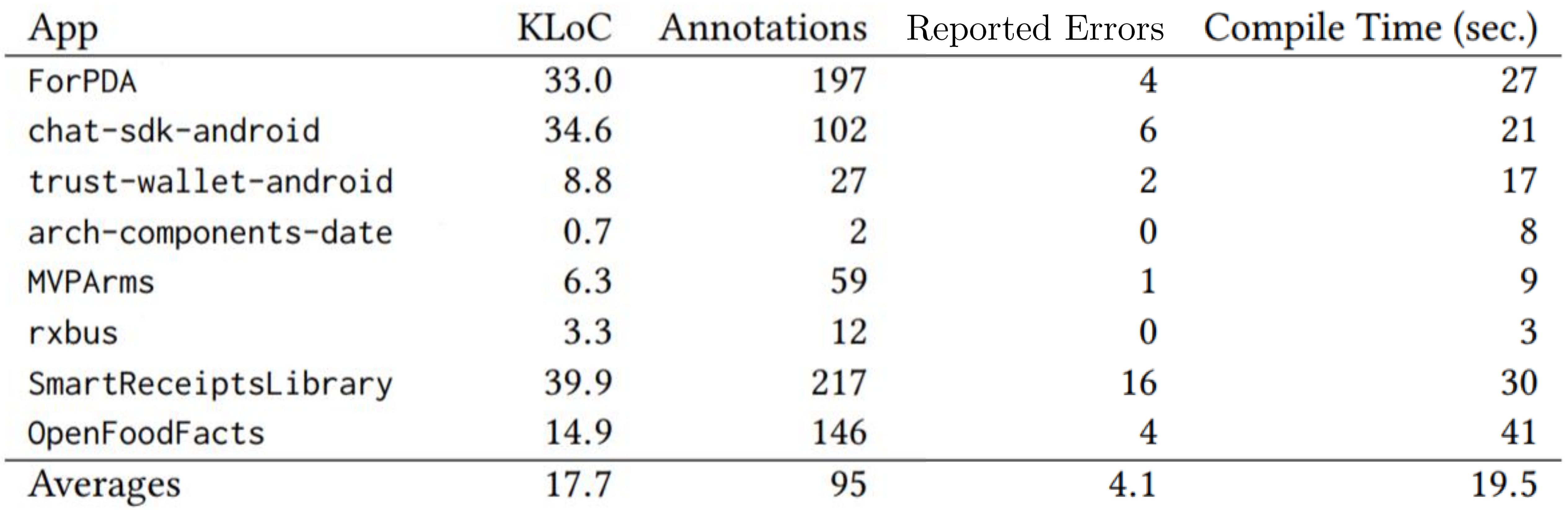

App	KLoC	Annotations	Reported Errors	Compile Time (sec.)
`ForPDA`	33.0	197	4	27
`chat-sdk-android`	34.6	102	6	21
`trust-wallet-android`	8.8	27	2	17
`arch-components-date`	0.7	2	0	8
`MVPArms`	6.3	59	1	9
`rxbus`	3.3	12	0	3
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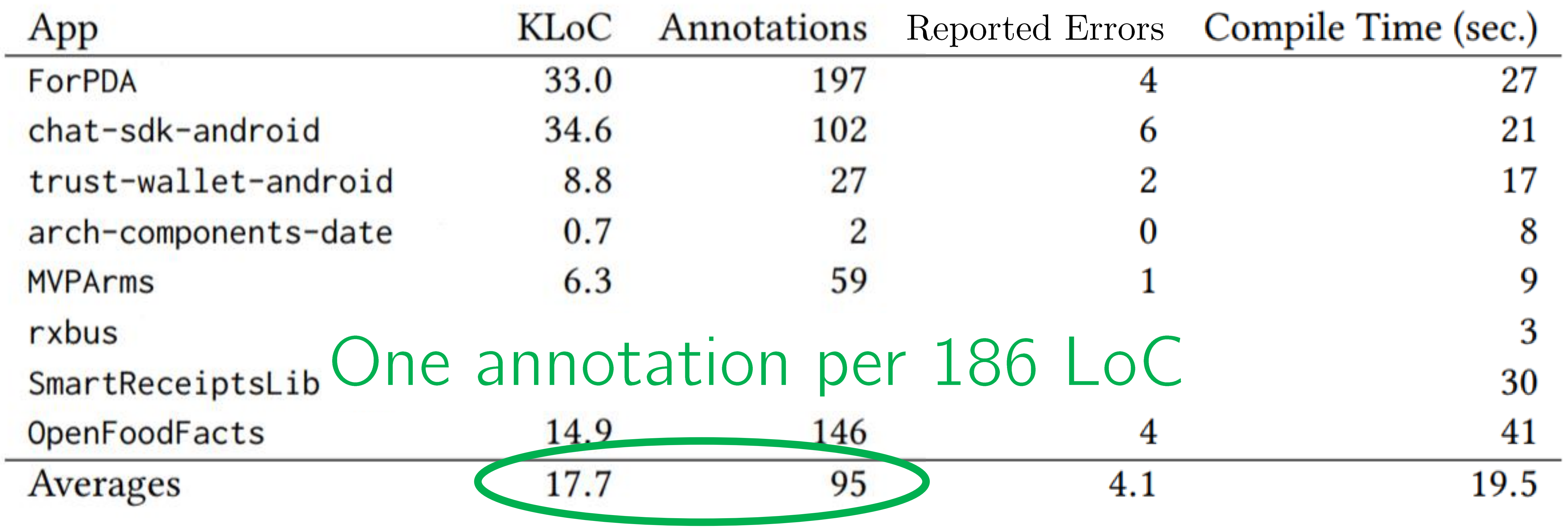

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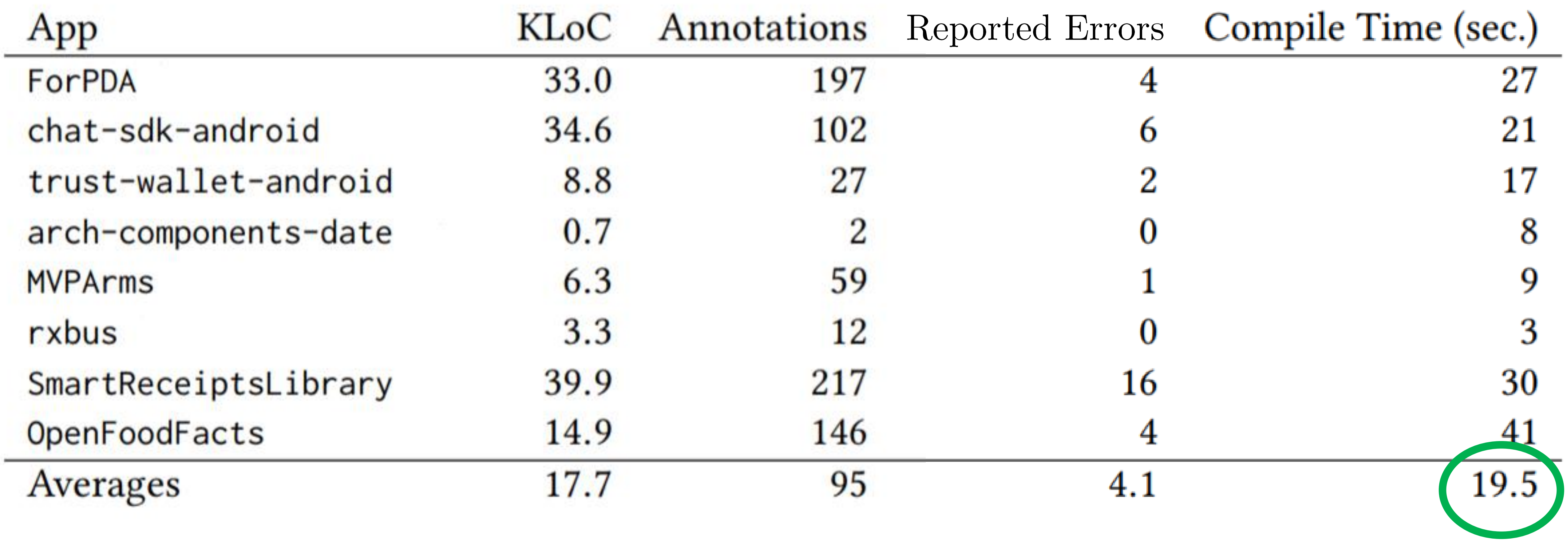

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Uber Case Study:

- Over 4000 commits by 176 Uber developers
- One annotation per 178 LoC by Uber developers

Effectiveness

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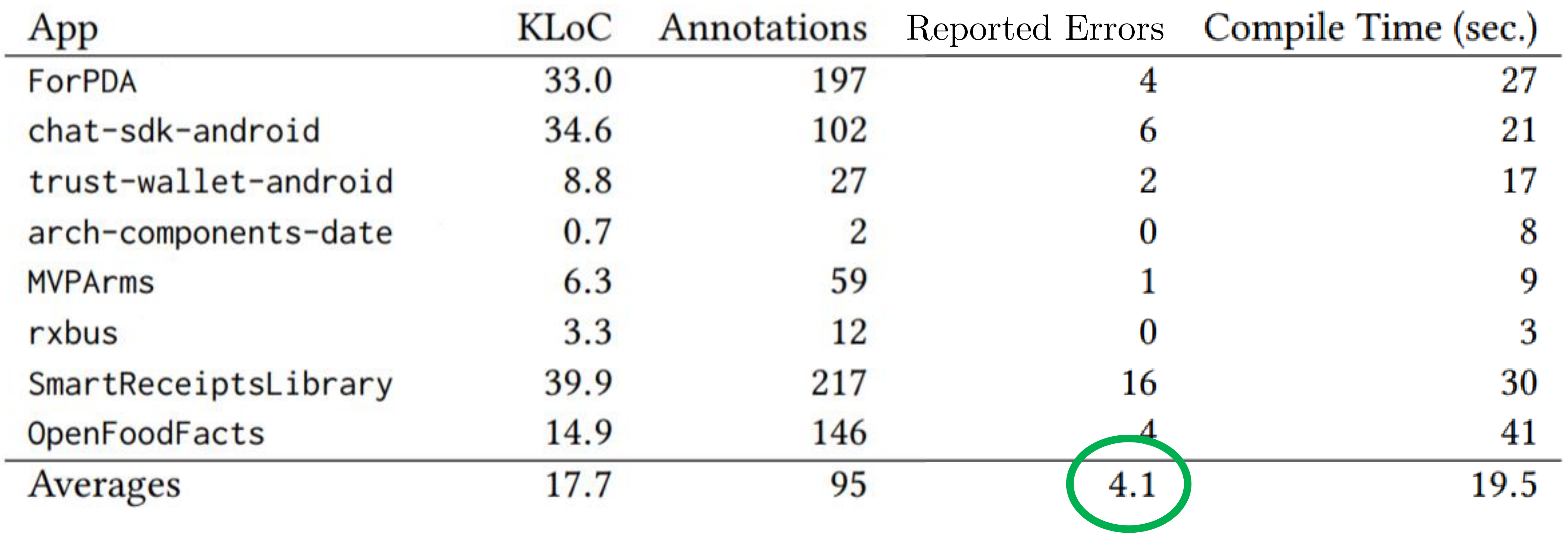

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Uber Case Study:

- 41 changes to threading behavior of stream-processing code during initial setup
- 135 additions of `observeOn(mainThread)` by developers in response to alarms after initial setup

Effectiveness

RQ2: *Does the typechecker find real bugs and help fix them?*

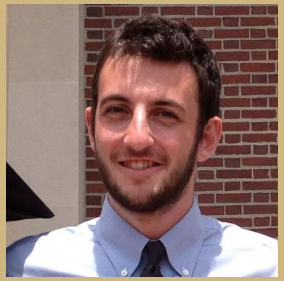
- Stream-based threading bugs exist in practice ✓
- Typechecker identifies them successfully ✓
- Checked programs are reliably bug-free ✓

Uber Case Study:

- Zero `CalledFromWrongThreadException` crashes in production in checked code!
  - monitoring period of one month
  - non-zero crash rates in unchecked apps

Contributions:

- Refinement type system for stream threads
- Typechecker implementation for Android
- Evaluation on open-source and industrial apps



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ASE '18
September 6, 2018