Embedded Domain-Specific Languages

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CS141 – Functional Programming
University of Warwick
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Pop quiz

Guess the domain!

Animation

Testing

Web server

Graphics

Web design

Music

```haskell
main :: IO ()
main = hspec $ do
  describe "Prelude.head" $ do
    it "returns the first element of a list" $ do
      head [23 ..] `shouldBe` (23 :: Int)
```

Animation

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```
menu :: Css
menu = header ▷ nav ?
  do background    white
     color         "#04a"
     fontSize      (px 24)
     padding       20 0 20 0
     textTransform uppercase
```

Animation

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```haskell
hilbert :: Int → Trail
hilbert 0 = mempty
hilbert n = hilbert' (n-1) # reflectY <> vrule 1
          <> hilbert  (n-1) <> hrule 1
          <> hilbert  (n-1) <> vrule (-1)
          <> hilbert' (n-1) # reflectX
  where
    hilbert' m = hilbert m # rotateBy (1/4)

diagram :: Diagram B
diagram = strokeT (hilbert 6) # lc silver
                              # opacity 0.3
```

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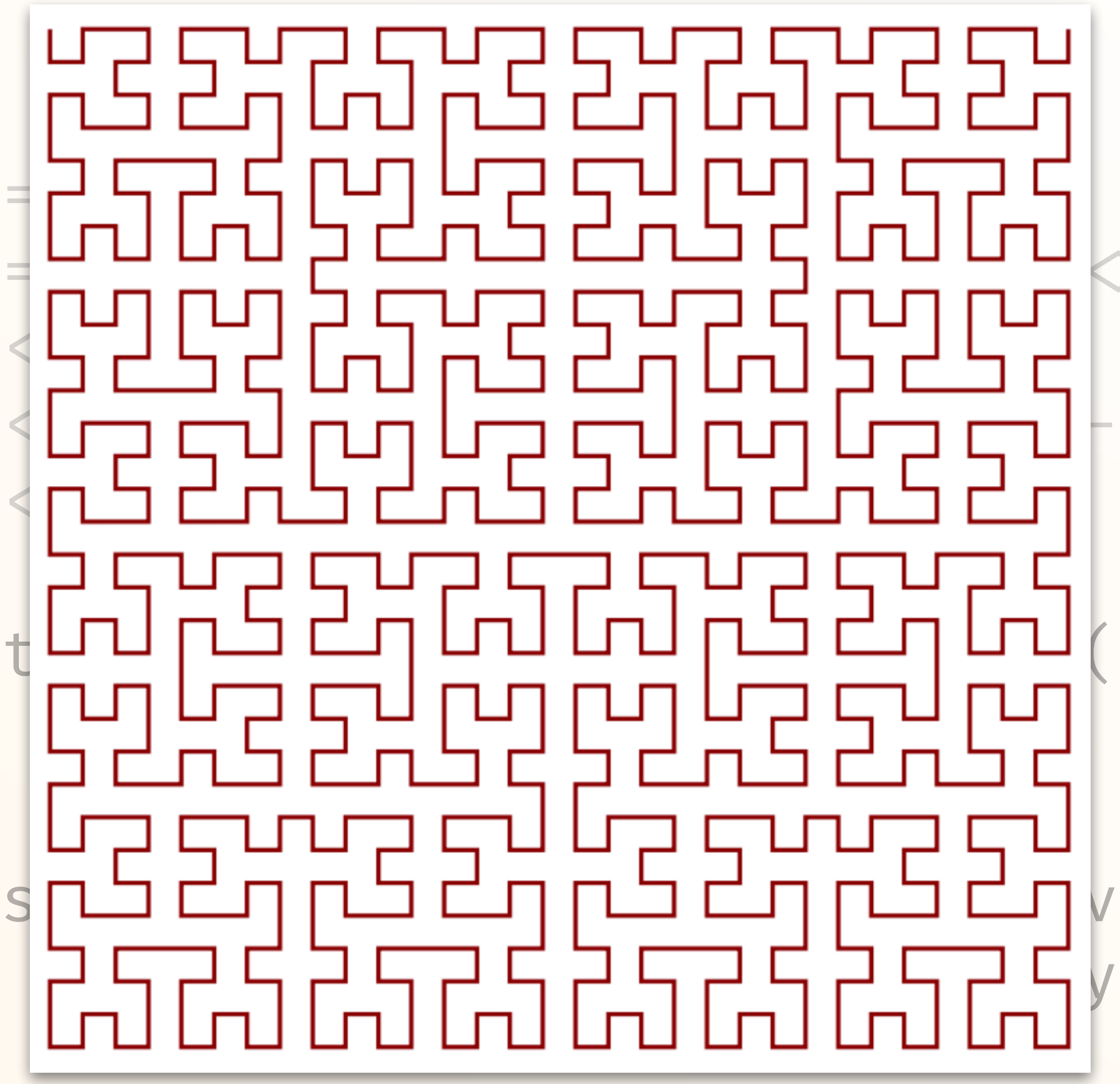
```
hilbert ::
hilbert 0 =
hilbert n =                              <> vrule 1
          <
          <                         -1)
          <

  where
    hilbert                         (1/4)

diagram ::
diagram = s                         ver
                                   y 0.3
```



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```haskell
tricycle :: Behaviour Shape
tricycle u =
  buttonMonitor u `over`
  withColor (cycle3 green yellow red u)
    (stretch (wiggleRange 0.5 1) circle)
  where
  cycle3 c1 c2 c3 u =
    c1 `untilB` nextUser_ lbp u ⟹
    cycle3 c2 c3 c1
```

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```
tricycle :: Behaviour Shape
tricycle u =
  buttonMonitor u `over`
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  cycle3 c1 c2 c3 u =
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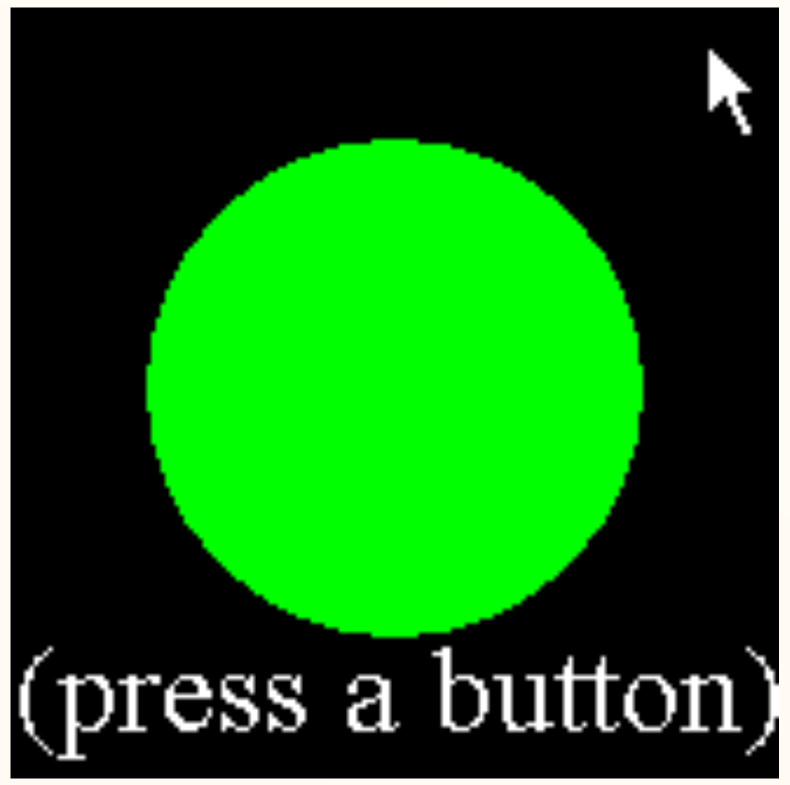

Animation

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Web design

Music

```
m1 = c' en :|: tripletE g fs g :|:
     start (melody :<  a :| g :~| r :| b :| c')
m2 = c_ majD ec :|: pad3 (r hr) :|:
     g__ dom7 inv inv ec :|: c_ majD ec

comp :: Score
comp = score section   "The end"
             setKeySig c_maj
             setTempo  100
             withMusic $ m1 `hom` m2
```

Animation

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Music

```haskell
main :: IO ()
main = do
  scotty 3000 $ do
    get "/hello/:name" $ do
      name ← param "name"
      text ("Hello " <> name <> "!")
    get "/users/:id" $ do
      id ← param "id"
      json (filter (matchesId id) allUsers)
```

Why was this so easy?

Domain-Specific Languages

Domain-Specific Languages

If in doubt, quote Wikipedia

*A **domain-specific language** (DSL) is a computer language specialised to a particular application domain.* (duh)

*This is in contrast to a **general-purpose language** (GPL), which is broadly applicable across domains.*

GPL ~ Jack of all trades DSL ~ Master of one

Examples of DSLs

Examples of DSLs

Markup languages

HTML, Markdown, LaTeX

```html
<html>
 <body>
  <p>Normal text.</p>
  <p><strong>Bold</strong> text.</p>
 </body>
</html>
```

```markdown
# Heading

+ List with _italic_ text
  - **Bold** text
  - [Link](https://commonmark.org)

> Block quote
```

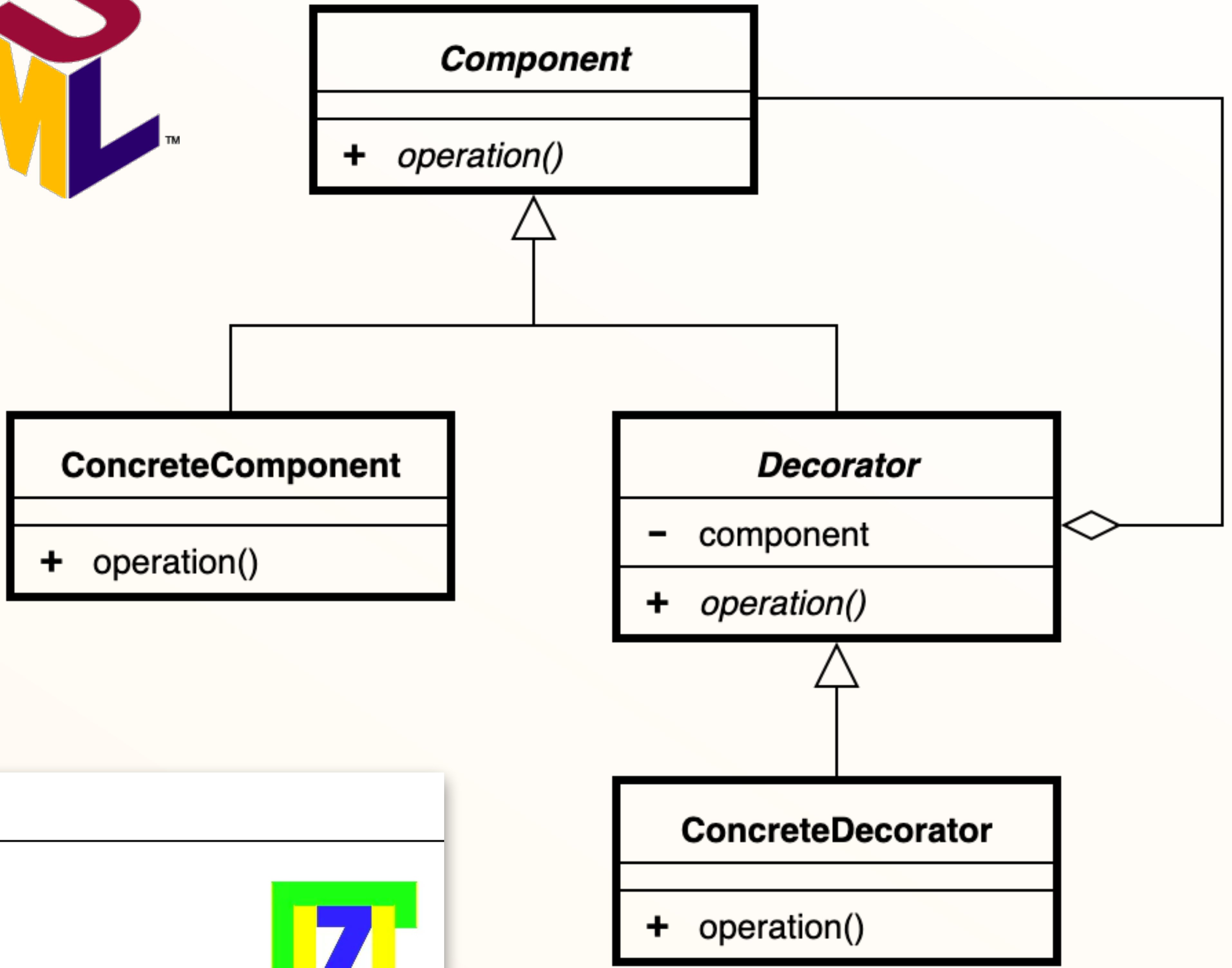
Examples of DSLs

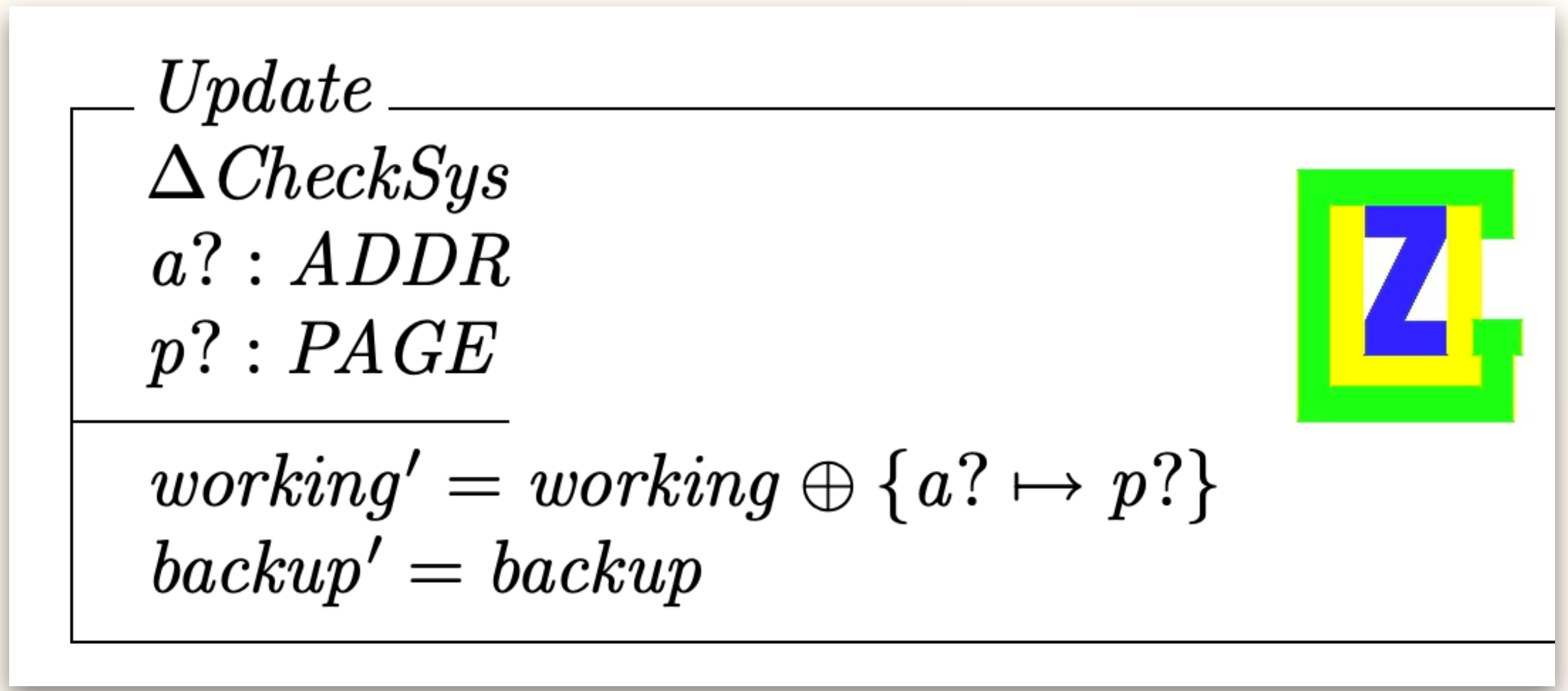
Markup languages

HTML, Markdown, LaTeX

Modelling languages

UML, Z





Update

$\Delta CheckSys$
$a? : ADDR$
$p? : PAGE$

$working' = working \oplus \{a? \mapsto p?\}$
$backup' = backup$

Examples of DSLs

Markup languages

HTML, Markdown, LaTeX

Modelling languages

UML, Z

Description languages

Verilog, PostScript

```
module Sign (A, B, Y1, Y2, Y3);
    input [2:0] A, B;
    output [3:0] Y1, Y2, Y3;
    reg [3:0] Y1, Y2, Y3;
    always @(A or B)
    begin Y1=+A/-B;
          Y2=-A+-B;
          Y3=A*-B; end
endmodule
```

```
newpath
100 200 moveto
200 250 lineto
100 300 lineto
closepath
gsave
0.5 setgray
fill
grestore
4 setlinewidth
0.75 setgray
stroke
```

Examples of DSLs

Markup languages

HTML, Markdown, LaTeX

Modelling languages

UML, Z

Description languages

Verilog, PostScript

Special-purpose languages

SQL, Yacc, MATLAB, Sonic Pi

```sql
SELECT Name FROM Customers WHERE EXISTS
  (SELECT Item FROM Orders
   WHERE Customers.ID = Orders.ID
     AND Price < 50)
```

```ruby
with_fx :reverb, mix: 0.2 do
  loop do
    play scale(:Eb2, :major_pentatonic,
               num_octaves: 3).choose,
         release: 0.1, amp: rand
    sleep 0.1
  end
end
```

Examples of DSLs

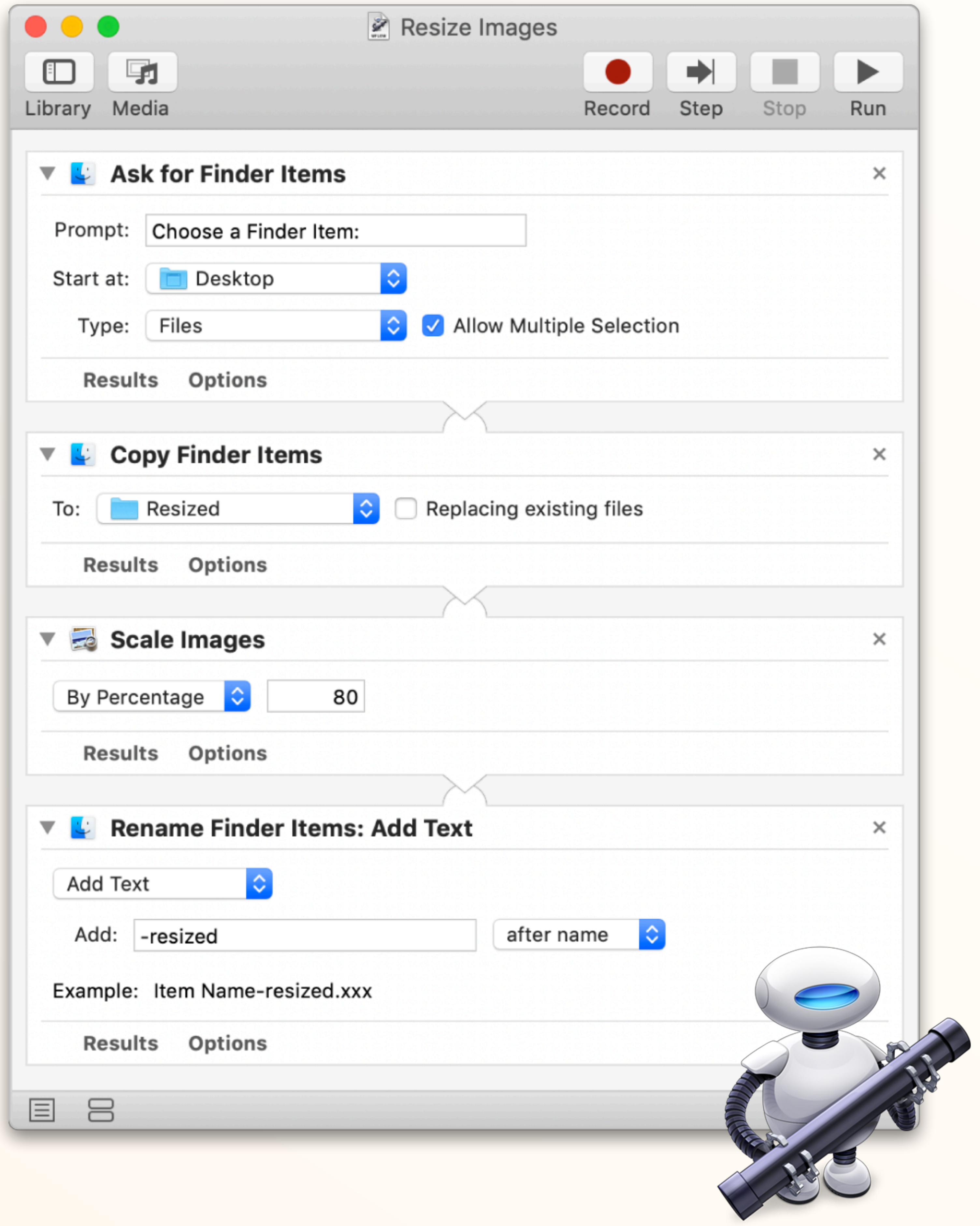
Markup languages
HTML, Markdown, LaTeX

Modelling languages
UML, Z

Description languages
Verilog, PostScript

Special-purpose languages
SQL, Yacc, MATLAB, Sonic Pi

Other?
Automator, Siri, ZORK

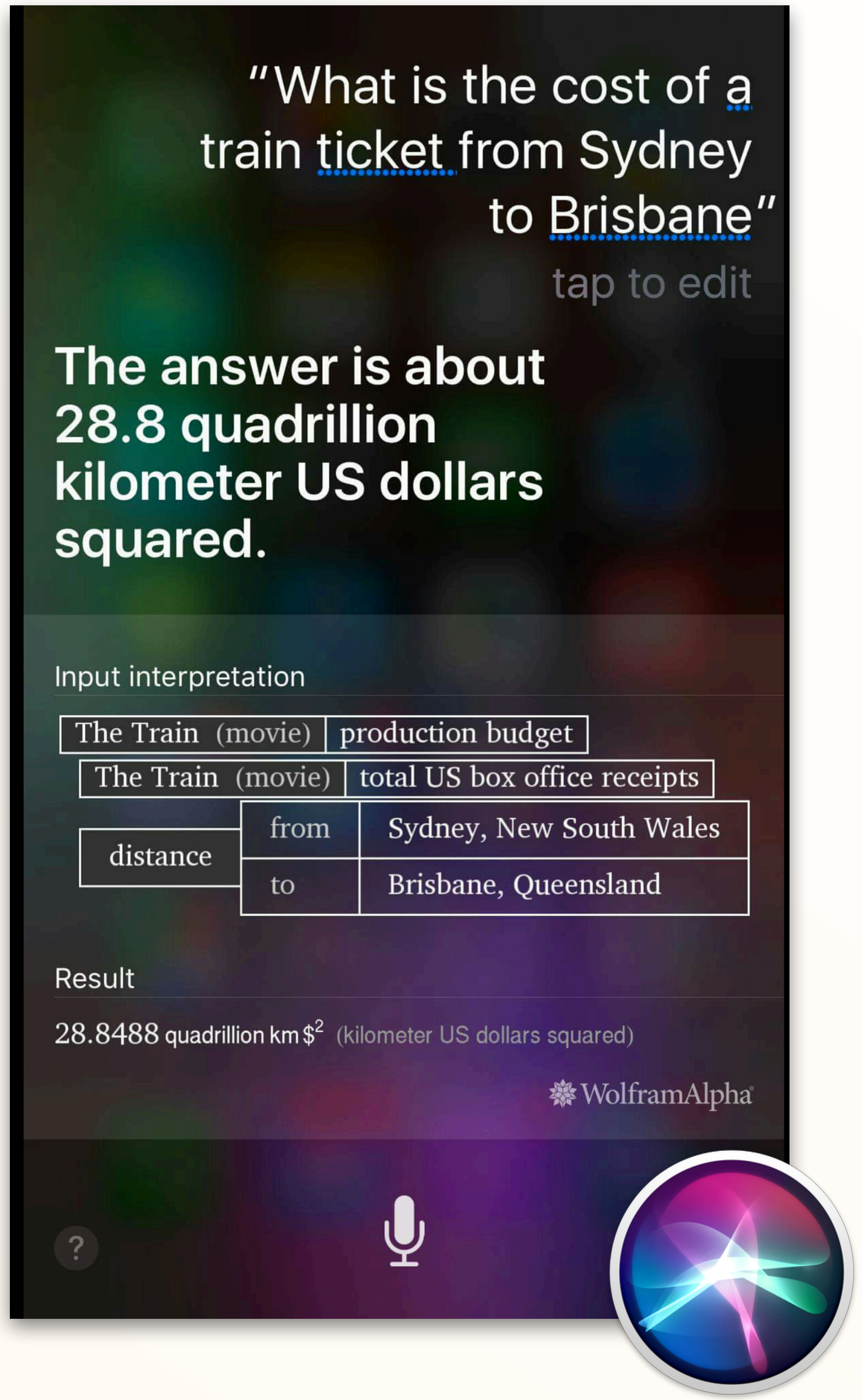


Ask for Finder Items
Prompt: Choose a Finder Item:
Start at: Desktop
Type: Files ✓ Allow Multiple Selection
Results Options

Copy Finder Items
To: Resized ☐ Replacing existing files
Results Options

Scale Images
By Percentage 80
Results Options

Rename Finder Items: Add Text
Add Text
Add: -resized after name
Example: Item Name-resized.xxx
Results Options



"What is the cost of a train ticket from Sydney to Brisbane"
tap to edit

The answer is about 28.8 quadrillion kilometer US dollars squared.

Input interpretation

The Train (movie)	production budget	
The Train (movie)	total US box office receipts	
distance	from	Sydney, New South Wales
	to	Brisbane, Queensland

Result
28.8488 quadrillion km $ ^{2} (kilometer US dollars squared)

```
> look under the rug
```

Why use DSLs?

Focus on a particular problem

Higher level of abstraction

Domain-specific expressivity

Optimisation opportunities

Made for domain experts,
not programmers

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Why *not* use DSLs?

Need to learn another language

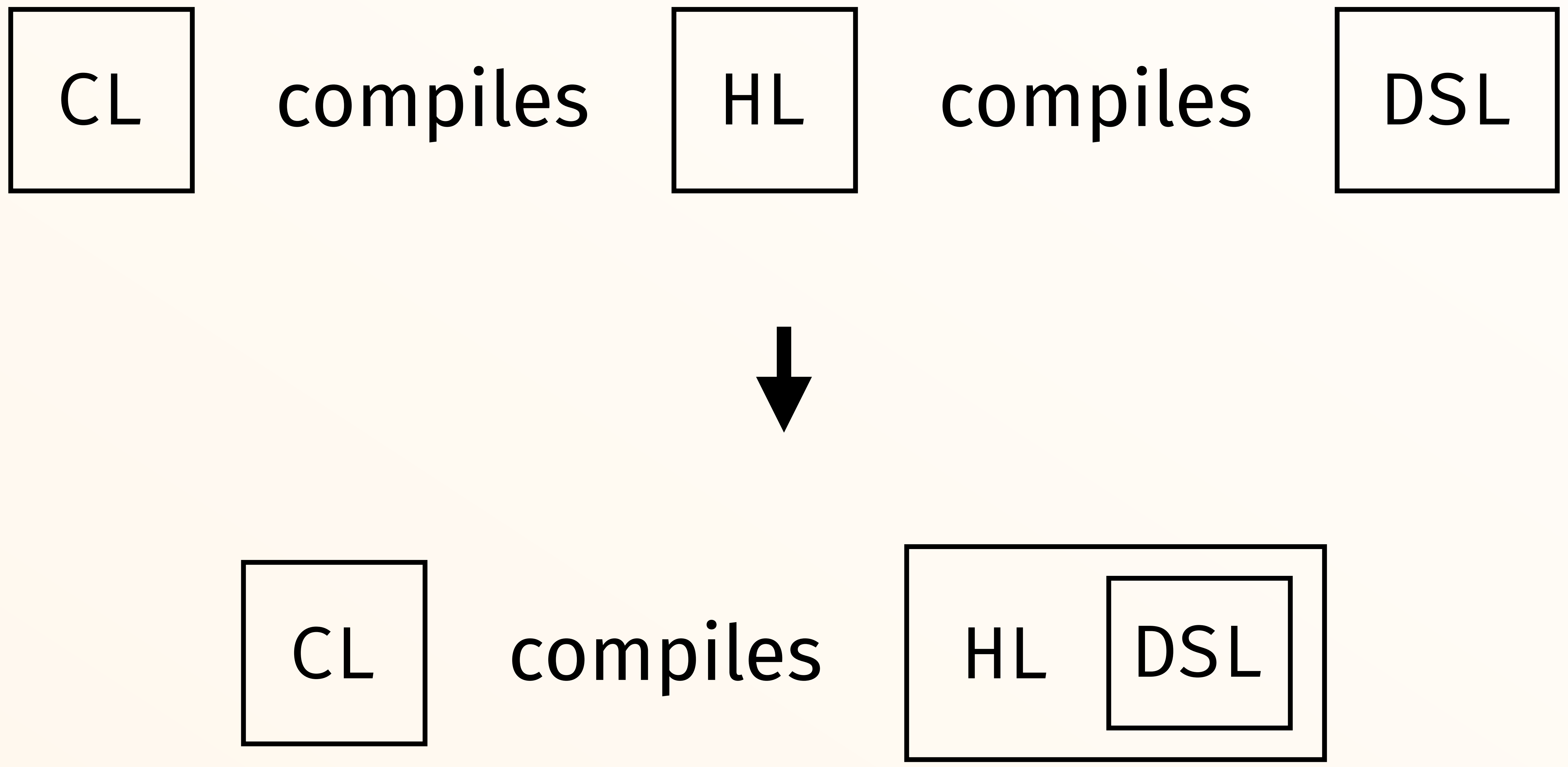
Need compiler, tooling, support

Lose general expressivity

Cutting out the middleman

`CL` compiles `HL` compiles `DSL`

Cutting out the middleman



Domain-Specific Languages

Embedded Domain-Specific Languages

Embedded Domain-Specific Languages

A domain-specific language implemented *inside* some host language

Usually built as a library or a package, so distinction is not always clear

My rules of thumb:

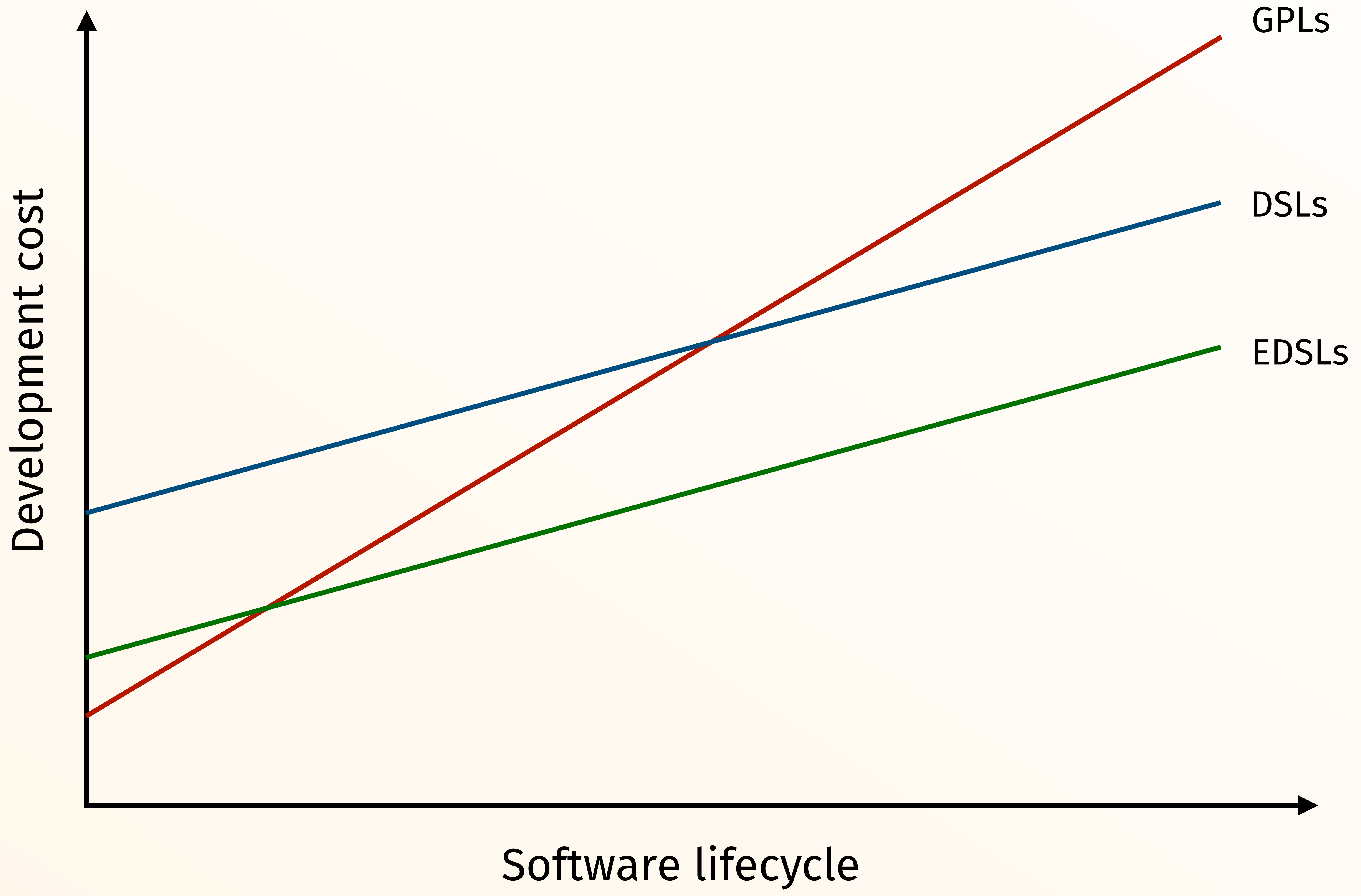
1. *Is the domain recognisable from the syntax?*
2. *Does the syntax hide the complexities of the host language?*

EDSLs vs. DSLs

+	−
Inherit compiler, tooling, and other features of the host language	Constrained by the host language syntax and features
Combine with host language programs and other EDSLs	Possibly less efficient
Easy to extend	
No need to learn another language	
Usable without familiarity with the host language	

The cost argument

(John Hughes)



Examples of EDSLs

The term appears more frequently in the context of functional programming

Closest notion in object-oriented languages: *fluent programming* via *method chaining*

Fluent interfaces

Simulate “English prose” within the syntactic constraints of the language

Often used with the Builder pattern, and testing and mocking frameworks

```
public Person getPerson() {
    return Person.builder()
                 .name("John")
                 .age(27)
                 .occupation("Lawyer")
                 .build();
}
```

Fluent interfaces

Simulate “English prose” within the syntactic constraints of the language

Often used with the Builder pattern, and testing and mocking frameworks

```java
List<Integer> transactionsIds =
    transactions.stream()
                .filter(t -> t.getType() == Transaction.GROCERY)
                .sorted(comparing(Transaction::getValue).reversed())
                .map(Transaction::getId)
                .collect(toList());
```

Fluent interfaces

Simulate “English prose” within the syntactic constraints of the language

Often used with the Builder pattern, and testing and mocking frameworks

```
IEnumerable<string> query = translations
    .Where   (t ⇒ t.Key.Contains("a"))
    .OrderBy (t ⇒ t.Value.Length)
    .Select  (t ⇒ t.Value.ToUpper());
```

Fluent interfaces

Simulate “English prose” within the syntactic constraints of the language

Often used with the Builder pattern, and testing and mocking frameworks

```
var foo = 'bar'
var beverages = { tea: [ 'chai', 'matcha', 'oolong' ] };

foo.should.be.a('string');
foo.should.equal('bar');
foo.should.have .lengthOf(3);
beverages.should.have.property('tea').with.lengthOf(3);
```

Embedded DSLs

Functional Embedded DSLs

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Abstractions of functional languages allow for
a more systematic way of embedding DSLs

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a more systematic way of embedding DSLs

Express domain as an *abstract type*

```
type Diagram
```

Functional Embedded DSLs

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a more systematic way of embedding DSLs

Express domain as an *abstract type* and associated operations:

```
type Diagram
```

Functional Embedded DSLs

Abstractions of functional languages allow for
a more systematic way of embedding DSLs

Express domain as an *abstract type* and associated operations:
embedding

```
type Diagram
shape  :: Shape   → Diagram
```

Functional Embedded DSLs

Abstractions of functional languages allow for
a more systematic way of embedding DSLs

Express domain as an *abstract type* and associated operations:
embedding, *combinators*

```
type Diagram
shape  :: Shape   → Diagram
onTop  :: Diagram → Diagram → Diagram
nextTo :: Diagram → Diagram → Diagram
```

Functional Embedded DSLs

Abstractions of functional languages allow for
a more systematic way of embedding DSLs

Express domain as an *abstract type* and associated operations:
embedding, *combinators* and *evaluators*

```
type Diagram
shape  :: Shape   → Diagram
onTop  :: Diagram → Diagram → Diagram
nextTo :: Diagram → Diagram → Diagram
draw   :: Diagram → Svg
```

Deep and shallow embedding

Dual ways of embedding a domain in the host language

Deep	**Shallow**
Intermediate syntactic representation	Interpret as semantics right away
Algebraic data type	**Type synonym**
Embedding: constructor	Embedding: interpreter
Combinators: constructors	Combinators: domain functions
Evaluator: interpreter	Evaluator: identity function

```haskell
type Region
circle   :: Radius → Region
outside  :: Region → Region
inter    :: Region → Region → Region
inRegion :: Point  → Region → Bool
```

Deep

```haskell
data Region = Circle Radius
            | Outside Region
            | Inter Region Region

circle :: Radius → Region
circle = Circle
outside :: Region → Region
outside = Outside
inter :: Region → Region → Region
inter = Inter
```

Shallow

```haskell
type Region = Point → Bool

circle :: Radius → Region
circle r = \p → magnitude p ⩽ r
outside :: Region → Region
outside rg = \p → not (rg p)
inter :: Region → Region → Region
inter rg1 rg2 = \p → rg1 p && rg2 p
```

Deep

```haskell
data Region = Circle Radius
            | Outside Region
            | Inter Region Region

circle :: Radius → Region
circle = Circle
outside :: Region → Region
outside = Outside
inter :: Region → Region → Region
inter = Inter

inRegion :: Point → Region → Bool
inRegion p (Circle r) =
  magnitude p ⩽ r
inRegion p (Outside rg) =
  not (inRegion p rg)
inRegion p (Inter rg1 rg2) =
  inRegion p rg1 && inRegion p rg2
```

Shallow

```haskell
type Region = Point → Bool

circle :: Radius → Region
circle r = \p → magnitude p ⩽ r
outside :: Region → Region
outside rg = \p → not (rg p)
inter :: Region → Region → Region
inter rg1 rg2 = \p → rg1 p && rg2 p

inRegion :: Point → Region → Bool
inRegion p rg = rg p
```

Deep vs. shallow embedding

Two dimensions of extensibility:
adding new *operations*, and adding new *interpretations*

e.g. union of two regions — e.g. area of a region

Deep

Difficult to add a new operation

Extend the data type

Define new combinator

Add new case to every evaluator

Easy to add a new interpreter

Define new evaluator

Pattern-match on the AST

Shallow

Easy to add a new operation

Define new combinator

Difficult to add a new interpreter

Usually need to change
the type representation

Deep vs. shallow embedding

This duality is an instance of the *expression problem*

"The expression problem is a new name for an old problem. The goal is to define a datatype by cases, where one can add new cases to the datatype and new functions over the datatype, without recompiling existing code, and while retaining static type safety (e.g., no casts)."

Phil Wadler

Still a very active area of research!

Functional EDSLs

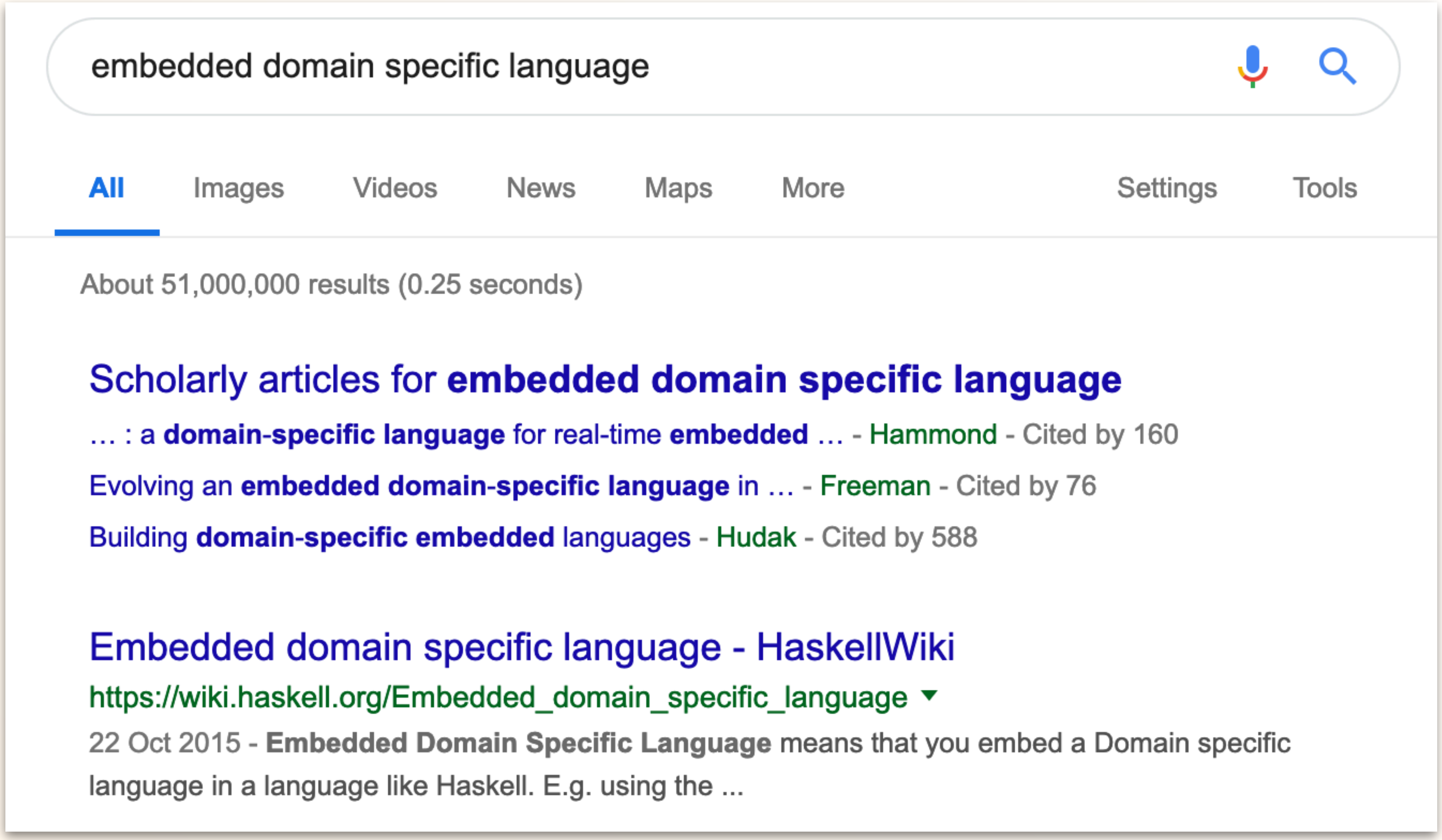
Functional EDSLs in Haskell

Functional EDSLs in Haskell

EDSLs are at the intersection of PL research, industrial applications, and pet projects

And so is Haskell!

Functional EDSLs in Haskell



embedded domain specific language

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About 51,000,000 results (0.25 seconds)

Scholarly articles for embedded domain specific language

… : a **domain-specific language** for real-time **embedded** … - Hammond - Cited by 160

Evolving an **embedded domain-specific language** in … - Freeman - Cited by 76

Building **domain-specific embedded** languages - Hudak - Cited by 588

Embedded domain specific language - HaskellWiki

https://wiki.haskell.org/Embedded_domain_specific_language

22 Oct 2015 - **Embedded Domain Specific Language** means that you embed a Domain specific language in a language like Haskell. E.g. using the ...

Functional EDSLs in Haskell

EDSLs are at the intersection of PL research,
industrial applications, and pet projects

And so is Haskell!

Designing EDSLs is an interesting programming challenge, and
Haskell provides a huge playground for experimentation

Several reasons why Haskell is a great choice for EDSLs

1. Syntactic flexibility

Very minimalistic syntax

- Little boilerplate
- Type inference
- Application by whitespace

Syntactic sugar

- Monadic do-notation
- Infix operators and sections
- Overloading

Flexible source code layout

- Whitespace-insensitive

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```
menu :: Css
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Flexible source code layout

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```
m1 = c' en :|: tripletE g fs g :|:
     start (melody :<  a :| g
                   :~| r :| b :| c')
m2 = c_ majD ec :|: pad3 (r hr) :|:
     g__ dom7 inv inv ec :|: c_ majD ec

comp :: Score
comp = score section    "The end"
             setKeySig c_maj
             setTempo  100
             withMusic $ m1 `hom` m2
```

2. Powerful abstractions

Type classes

- Exploit the formal structure and properties of the domain
- Overloaded functions that work on all instances of a class
- Syntactic sugar, e.g. do-notation

Denotational design

- Think of the domain in terms of its formal semantics
- Implementation follows the laws of the semantic domain

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Combination ⇝ Monoid

Pretty printers, diagrams, music

```
mconcat [text "foo", space, text "bar"]
        square 1 <> circle 2
```

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Combination $\rightsquigarrow$ `Monoid`

Pretty printers, diagrams, music

Choice $\rightsquigarrow$ `Alternative`

Parser combinators

```
parseString "CS141" <|> many integer
```

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Combination	$\rightsquigarrow$	`Monoid`

Pretty printers, diagrams, music

Choice	$\rightsquigarrow$	`Alternative`

Parser combinators

Composition	$\rightsquigarrow$	`Category`

Lenses

```
("hello",("world","!!!"))^._2._2.to length
```

2. Powerful abstractions

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Combination	⇝	Monoid
Pretty printers, diagrams, music		
Choice	⇝	Alternative
Parser combinators		
Composition	⇝	Category
Lenses		
Sequencing	⇝	Monad
Everything		

```
sat :: (Char → Bool) → Parser Char
sat p = do x ← item
           guard (p x)
           result x
```

2. Powerful abstractions

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Denotational design

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```haskell
hilbert :: Int → Trail
hilbert 0 = mempty
hilbert n = hilbert' (n-1) # reflectY <> vrule 1
            <> hilbert  (n-1) <> hrule 1
            <> hilbert  (n-1) <> vrule (-1)
            <> hilbert' (n-1) # reflectX
  where
    hilbert' m = hilbert m # rotateBy (1/4)

diagram :: Diagram B
diagram = strokeT (hilbert 6) # lc silver
                              # opacity 0.3
```

2. Powerful abstractions

Type classes

Exploit the formal structure and properties of the domain

Overloaded functions that work on all instances of a class

Syntactic sugar, e.g. do-notation

Denotational design

Think of the domain in terms of its formal semantics

Implementation follows the laws of the semantic domain

```
main :: IO ()
main = withSQLite "people.sqlite" $ do
  createTable people
  insert_ people [ … ]

  adultsAndTheirPets ← query $ do
    person ← select people
    restrict (person ! #age .≥ 18)
    return (person ! #name :*: person ! #pet)
  liftIO $ print adultsAndTheirPets
```

3. Type system

Strong typing

- Guide EDSL development and use
- (Sometimes) good documentation
- Error prevention

Domain-specific type systems

- Type-level programming features to precisely model the domain
- Custom compiler errors
- “Logic” programming with type classes
- Term- and type-level embedding

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```
type UserAPI =
        "user"      :> Capture "userid" Integer
                    :> Get '[JSON] User
  :<|> "list-all" :> "users"
                    :> Get '[JSON] [User]
-- equivalent to 'GET /user/:userid'
--              or 'GET /list-all/users'

  userAPI :: Proxy UserAPI
  userAPI = Proxy

  userDocs :: String
  userDocs = markdown $ docs userAPI

  start :: IO ()
  start = do
      run 8000 (serve userAPI userServer)
```

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```
score withMusic $ c qn :-: b qn    ✘

type error:
  • Major sevenths are not permitted
    in harmony: C and B
  • In the expression:
    score withMusic $ c qn :-: b qn

score setRuleSet empty
      withMusic $ c qn :-: b qn    ✓
```

Conclusions

Conclusions

EDSLs are useful, fun to work with and even more fun to work on

Good exercise in programming, using advanced language features and even user experience design

Don't be afraid to experiment, break (monad) rules and try weird hacks – you might end up inventing something cool

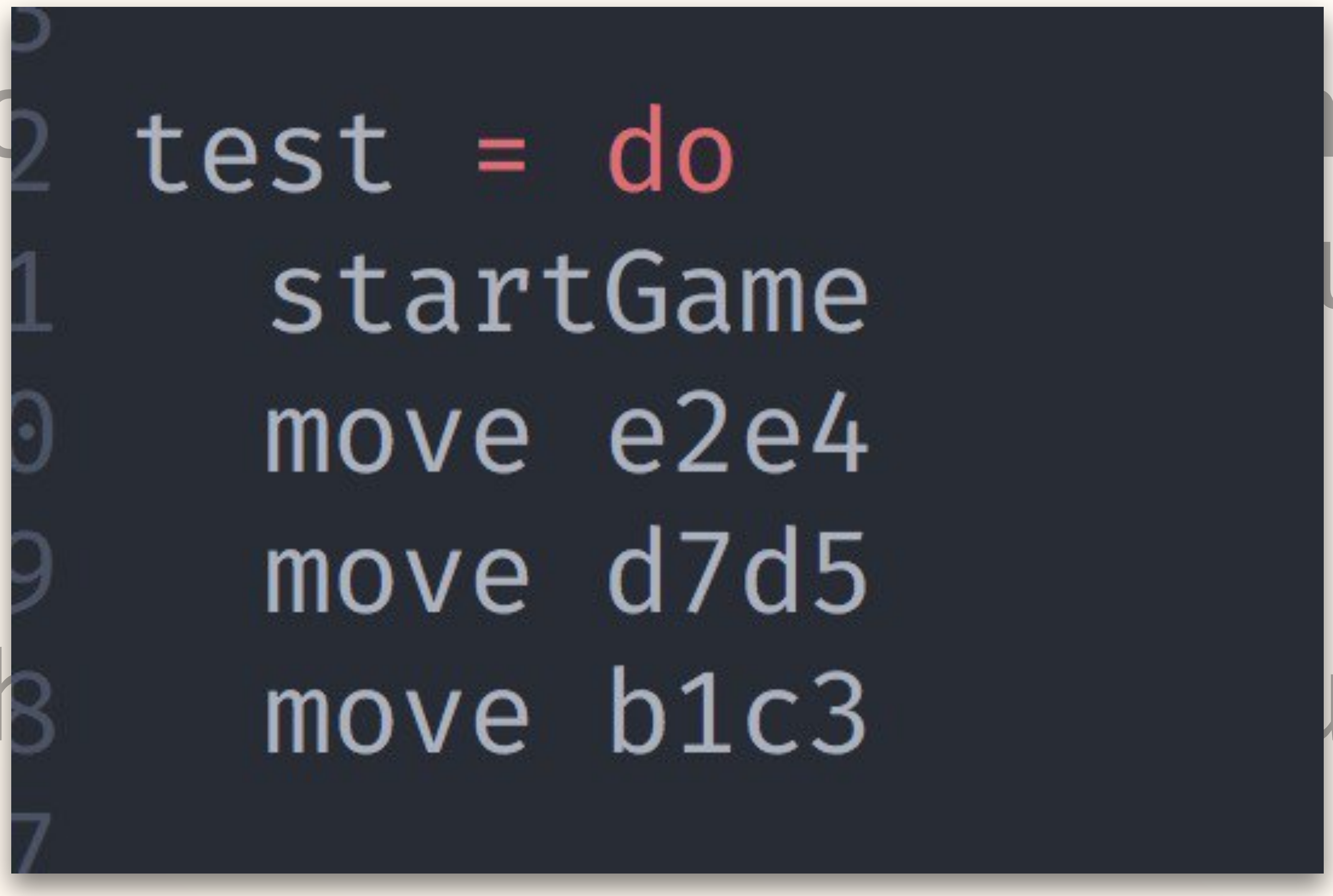
Conclusions

EDSLs are useful, fun to work with a … on

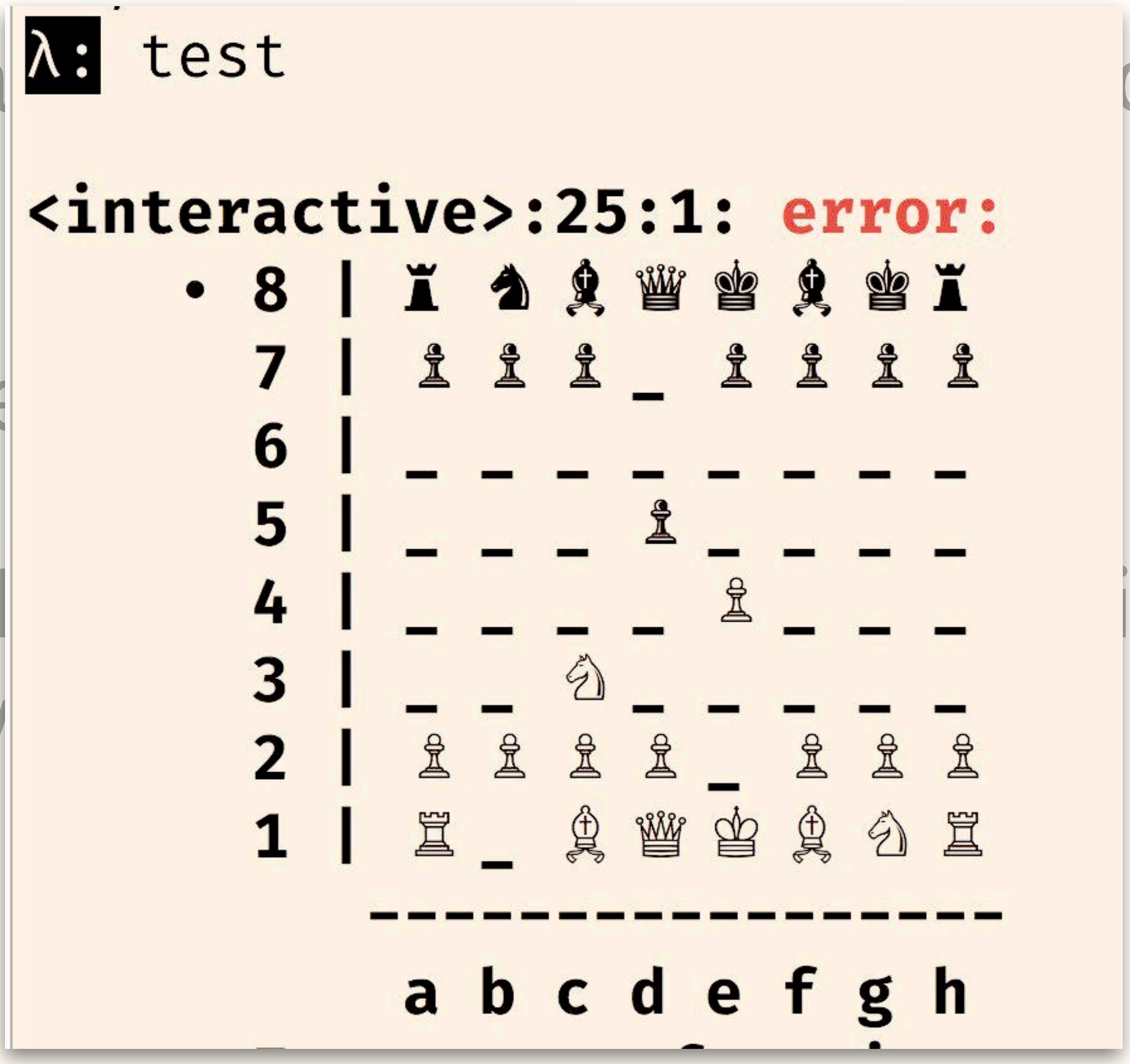
Go… …ning, … user e…

Don't b… …breal… …ird

h… …up inv…



```haskell
test = do
  startGame
  move e2e4
  move d7d5
  move b1c3
```



```
λ: test

<interactive>:25:1: error:
    • 8 | ♜ ♞ ♝ ♛ ♚ ♝ ♚ ♜
      7 | ♟ ♟ ♟ _ ♟ ♟ ♟ ♟
      6 | _ _ _ _ _ _ _ _
      5 | _ _ _ ♟ _ _ _ _
      4 | _ _ _ _ ♙ _ _ _
      3 | _ _ ♘ _ _ _ _ _
      2 | ♙ ♙ ♙ ♙ _ ♙ ♙ ♙
      1 | ♖ _ ♗ ♕ ♔ ♗ ♘ ♖
         -----------------
          a b c d e f g h
```

Conclusions

EDSLs are useful, fun to work with and even more fun to work on

Good exercise in programming, using advanced language features and even user experience design

Don't be afraid to experiment, break (monad) rules and try weird hacks – you might end up inventing something cool

Also a great for third year projects (ask Michael)

Thank you!
Any questions?

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