# Detecting Pattern-Match Failures in Haskell

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**www.cs.york.ac.uk/~ndm/catch**

# Does this code crash?

```
risers []           = []
risers [x]          = [[x]]
risers (x:y:etc) =
    if x ≤ y then (x:s) : ss else [x] : (s:ss)
    where (s:ss) = risers (y:etc)

> risers [1,2,3,1,2] = [[1,2,3],[1,2]]
```

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Potential crash

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> risers [1,2,3,1,2] = [[1,2,3],[1,2]]
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   where (s:ss) = risers (y:etc)
```

**Property**:
risers (_:_) = (_:_)

Potential crash

```
> risers [1,2,3,1,2] = [[1,2,3],[1,2]]
```

# Overview

- The problem of pattern-matching
- A framework to solve patterns
- Constraint languages for the framework
- The Catch tool
- A case study: HsColour
- Conclusions

# The problem of Pattern-Matching

head (x:xs) = x

head x_xs = **case** x_xs **of**

$\quad$ x:xs → x

$\quad$ [] $\quad$ → error “head []”

- Problem: can we detect calls to error

# Haskell programs “go wrong”

- “Well-typed programs never go wrong”
- But...
  - Incorrect result/actions – requires annotations
  - Non-termination – cannot always be fixed
  - Call error – not much research done

# My Goal

- Write a tool for Haskell 98
  - GHC/Haskell is merely a front-end issue
- Check statically that error is not called
  - Conservative, corresponds to a proof
- Entirely automatic
  - No annotations

= Catch

# Preconditions

- Each function has a precondition
- If the precondition to a function holds, and none of its arguments crash, it will not crash

pre(head x) = x $\in$ {(:) _ _}

pre(assert x y) = x $\in$ {True}

pre(null x) = True

pre(error x) = False

# Properties

- A property states that if a function is called with arguments satisfying a constraint, the result will satisfy a constraint

$$x \in \{(:)\ \_\ \_\} \Rightarrow (\mathrm{null}\ x) \in \{\mathrm{True}\}$$

$$x \in \{(:)\ []\ \_\} \Rightarrow (\mathrm{head}\ x) \in \{[]\}$$

$$x \in \{[]\} \Rightarrow (\mathrm{head}\ x) \in \{\mathrm{True}\}$$

**Calculation direction**

# Checking a Program (Overview)

- Start by calculating the precondition of main
  - If the precondition is True, then program is safe
- Calculate other preconditions and properties as necessary
- Preconditions and properties are defined recursively, so take the fixed point

# Checking risers

```
risers r = case r of
        []     → []
        x:xs → case xs of
                []      → (x:[]) : []
                y:etc → case risers (y:etc) of
                        []     → error "pattern match"
                        s:ss → case x ≤ y of
                                True  → (x:s) : ss
                                False → [x] : (s:ss)
```

# Checking risers

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                       s:ss → case x ≤ y of
                               True  → (x:s) : ss
                               False → [x] : (s:ss)
```

$r \in \{[]\} \vee$

$xs \in \{[]\} \vee$

**risers (y:etc)** $\in$ **{(:) _ _}**

# Checking risers

```
risers r = case r of
      []    → []
      x:xs  → case xs of
          []    → (x:[]) : []
          y:etc → case risers (y:etc) of
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                  True  → (x:s) : ss
                  False → [x] : (s:ss)
```

r ∈ {(:) _ _} ∨
[] ∈ {(:) _ _}

... ∨ (x:[]) : []
∈ {(:) _ _}

... ∨ ⊥
∈ {(:) _ _}

... ∨ (x:s) : ss
∈ {(:) _ _}

... ∨ [x] : (s:ss)
∈ {(:) _ _}

# Checking risers

risers r = **case** r **of**

[] → []

x:xs → **case** xs **of**

[] → (x:[]) : []

y:etc → **case** risers (y:etc) **of**

[] → $\boxed{\text{error “pattern match”}}$

s:ss → **case** x ≤ y **of**

True → (x:s) : ss

False → [x] : (s:ss)

r ∈ {(:) _ _} ∨
[] ∈ {(:) _ _}

... ∨ (x:[]) : []
∈ {(:) _ _}

... ∨ ⊥
∈ {(:) _ _}

... ∨ (x:s) : ss
∈ {(:) _ _}

... ∨ [x] : (s:ss)
∈ {(:) _ _}

**Property**:
r ∈ {(:) _ _} ⇒
risers r ∈ {(:) _ _}

# Checking risers

```
risers r = case r of
    []    → []
    x:xs  → case xs of
        []     → (x:[]) : []
        y:etc  → case risers (y:etc) of
            []    → error "pattern match"
            s:ss  → case x ≤ y of
                True  → (x:s) : ss
                False → [x] : (s:ss)
```

$r \in \{[]\} \vee$
$xs \in \{[]\} \vee$
**risers (y:etc) $\in$ {(:) _ _}**

**Property**:
$r \in \{(:)\ \_\ \_\} \Rightarrow$
risers $r \in \{(:)\ \_\ \_\}$

# Checking risers

risers r = **case** r **of**

[] → []

x:xs → **case** xs **of**

[] → (x:[]) : []

y:etc → **case** risers (y:etc) **of**

[] → $\boxed{\text{error “pattern match”}}$

s:ss → **case** x ≤ y **of**

True → (x:s) : ss

False → [x] : (s:ss)

r ∈ {[]} ∨

xs ∈ {[]} ∨

**y:etc ∈ {(:) _ _}**

**Property**:

r ∈ {(:) _ _} ⇒

risers r ∈ {(:) _ _}

# Calculating Preconditions

- Variables: pre(x) = True
  - Always True
- Constructors: pre(a:b) = pre(a) $\wedge$ pre(b)
  - Conjunction of the children
- Function calls: pre(f x) = x $\in$ pre(f) $\wedge$ pre(x)
  - Conjunction of the children
  - Plus applying the preconditions of f
  - Note: precondition is recursive

# Calculating Preconditions (case)

$$
\begin{array}{l}
\text{pre(case on of} \\
\qquad\qquad [] \quad\ \to \text{a} \\
\qquad\qquad \text{x:xs} \to \text{b)} \\
= \text{pre(on)} \wedge (\text{on} \notin \{[]\} \qquad\quad \vee \text{pre(a))} \\
\qquad\qquad\quad\ \wedge (\text{on} \notin \{(:)\ \_\ \_\} \vee \text{pre(b))}
\end{array}
$$

- An alternative is safe, or is never reached

# Extending Constraints (↑)

risers r = **case** r **of**

    [] → []
    x:xs → **case** xs **of**
        [] → (x:[]) : []
        y:etc → **...**

xs ∈ {(:) _ _} ∨ ...
r<(:)-2> ∈ {(:) _ _}
r ∈ {(:) _ ((:) _ _)}

<(:)-2> ↑ {(:) _ _}
{(:) _ ((:) _ _)}

<(:)-1> ↑ {True}
{(:) True _}

# Splitting Constraints (↓)

risers r = **case** r **of**
    [] → []
    x:xs → **case** xs **of**
        [] → (x:[]) : []
        y:etc → **...**

(x:[]):[] ∈ {(:) _ _} ∨ ...
True

((:) 1 2) ↓ {(:) _ _}
True

((:) 1 2) ↓ {[]}
False

((:) 1 2) ↓ {(:) True []}
1 ∈ {True} ∧ 2 ∈ {[]}

# Summary so far

- Rules for Preconditions
- How to manipulate constraints
  - Extend (↑) – for locally bound variables
  - Split (↓) – for constructor applications
  - Invoke properties – for function application

- Can change a constraint on expressions, to one on function arguments

# Algorithm for Preconditions

**set** all preconditions to True

**set** error precondition to False

**while** any preconditions change

    recompute every precondition

**end while**

Fixed Point!

- Algorithm for properties is very similar

# Fixed Point

- To ensure a fixed point exists demand only a *finite* number of possible constraints
- At each stage, ($\wedge$) with the previous precondition

- Ensures termination of the algorithm
  - But termination $\neq$ useable speed!

# The Basic Constraints

- These are the basic ones I have introduced
- *Not* finite – but can bound the depth
  - A little arbitrary
  - Can't represent infinite data structures
- But a nice simple introduction!

# A Constraint System

- Finite number of constraints
- Extend operator (↑)
- Split operator (↓)
- notin creation, i.e. $x \notin \{(:)\ \_\ \_\}$
- Optional simplification rules in a predicate

# Regular Expression Constraints

- Based on regular expressions
- $x \in r \rightarrow c$
  - r is a regular expression of paths, i.e. <(:)-1>
  - c is a set of constructors
  - True if all r paths lead to a constructor in c
- Split operator ($\downarrow$) is regular expression differentiation/quotient

# RE-Constraint Examples

- head xs
  - $xs \in (1 \rightarrow \{:\})$
- map head xs
  - $xs \in (<(:)-2>^* \cdot <(:)-1> \rightarrow \{:\})$
- map head (reverse xs)
  - $xs \in (<(:)-2>^* \cdot <(:)-1> \rightarrow \{:\}) \vee$
    $xs \in (<(:)-2>^* \rightarrow \{:\})$

# RE-Constraint Problems

- They are finite (with certain restrictions)
- But there are many of them!
- Some simplification rules
  - Quite a lot (19 so far)
  - Not complete

This fact took 2 years to figure out!

- In practice, too slow for moderate examples

# Multipattern Constraints

- Idea: model the recursive and non-recursive components separately
- Given a list
  - Say something about the first element
  - Say something about all other elements
  - Cannot distinguish between element 3 and 4

# MP-Constraint Examples

- head xs
  - xs $\in$ ({(:) _} $*$ {[], (:) _})

xs must be (:)
xs.<(:)-1> must be _

All recursive tails
are unrestricted

- Use the type's to determine recursive bits

# More MP-Constraint Examples

- map head xs
  - {[], (:) ({(:) _} * {[], (:) _})} *
    {[], (:) ({(:) _} * {[], (:) _})}
- An infinite list
  - {(:) _} * {(:) _}

# MP-Constraint "semantics"

MP = {set Val}

Val = _ | {set Pat} $*$ {set Pat}

Element must satisfy at least one pattern

Each recursive part must satisfy at least one pattern

Pat = Constructor [(non-recursive field, MP)]

# MP-Constraint Split

- $((:)\ 1\ 2) \downarrow \{(:)\ \_\} * \{(:)\ \{True\}\}$
  - An infinite list whose elements (after the first) are all true
- $1 \in \_$
- $2 \in \{(:)\ \{True\}\} * \{(:)\ \{True\}\}$

# MP-Constraint Simplification

- There are 8 rules for simplification
  - Still not complete...
- But!
  - $x \in a \vee x \in b = x \in c$ union of two sets
  - $x \in a \wedge x \in b = x \in c$ cross product of two sets

# MP-Constraint Currying

- We can merge all MP's on one variable
- We can curry all functions – so each has only one variable
- MP-constraint Predicate ≡ MP-constraint

(||) a b $\longrightarrow$ (||) (a, b)

# MP vs RE constraints

- Both have different expressive power
  - Neither is a subset/superset
- RE-constraints grow too quickly
- MP-constraints stay much smaller
- Therefore Catch uses MP-constraints

# Numbers

**data** Int = Neg | Zero | One | Pos

- Checks
  - Is positive? Is natural? Is zero?
- Operations
  - (+1), (-1)
- Work’s very well in practice

# Summary so far

- Rules for Preconditions and Properties
- Can manipulate constraints in terms of three operations
- MP and RE Constraints introduced
- Have picked MP-Constraints

# Making a Tool (Catch)

- Haskell
- Core
- First-order Core
- Curried
- Analyse

Yhc

In draft paper, see website

This talk

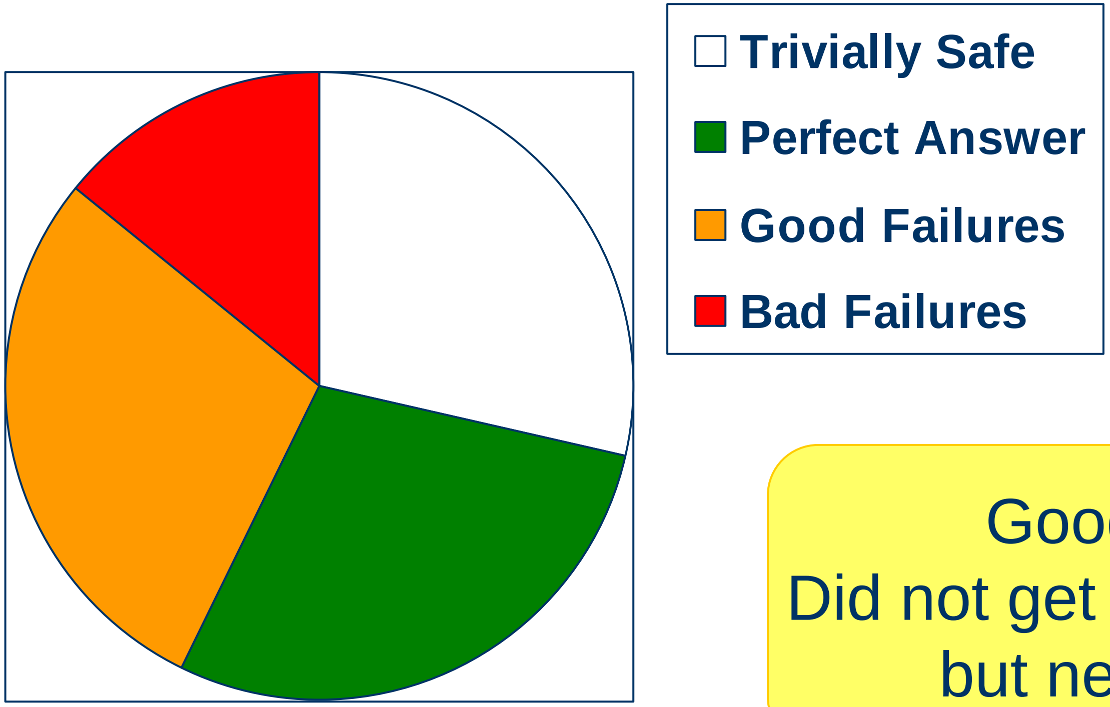
# Testing Catch

- The nofib benchmark suite, but

```
main = do [arg] ← getArgs
          print $ primes !! (read arg)
```

- Benchmarks have no real users
- Programs without real users crash

# Nofib/Imaginary Results (14 tests)




Good failure:
Did not get perfect answer,
but neither did I!

# Bad Failure: Bernouilli

tail (tail x)

- Actual condition: list is at least length 2
- Inferred condition: list must be infinite

drop 2 x

# Bad Failure: Paraffins

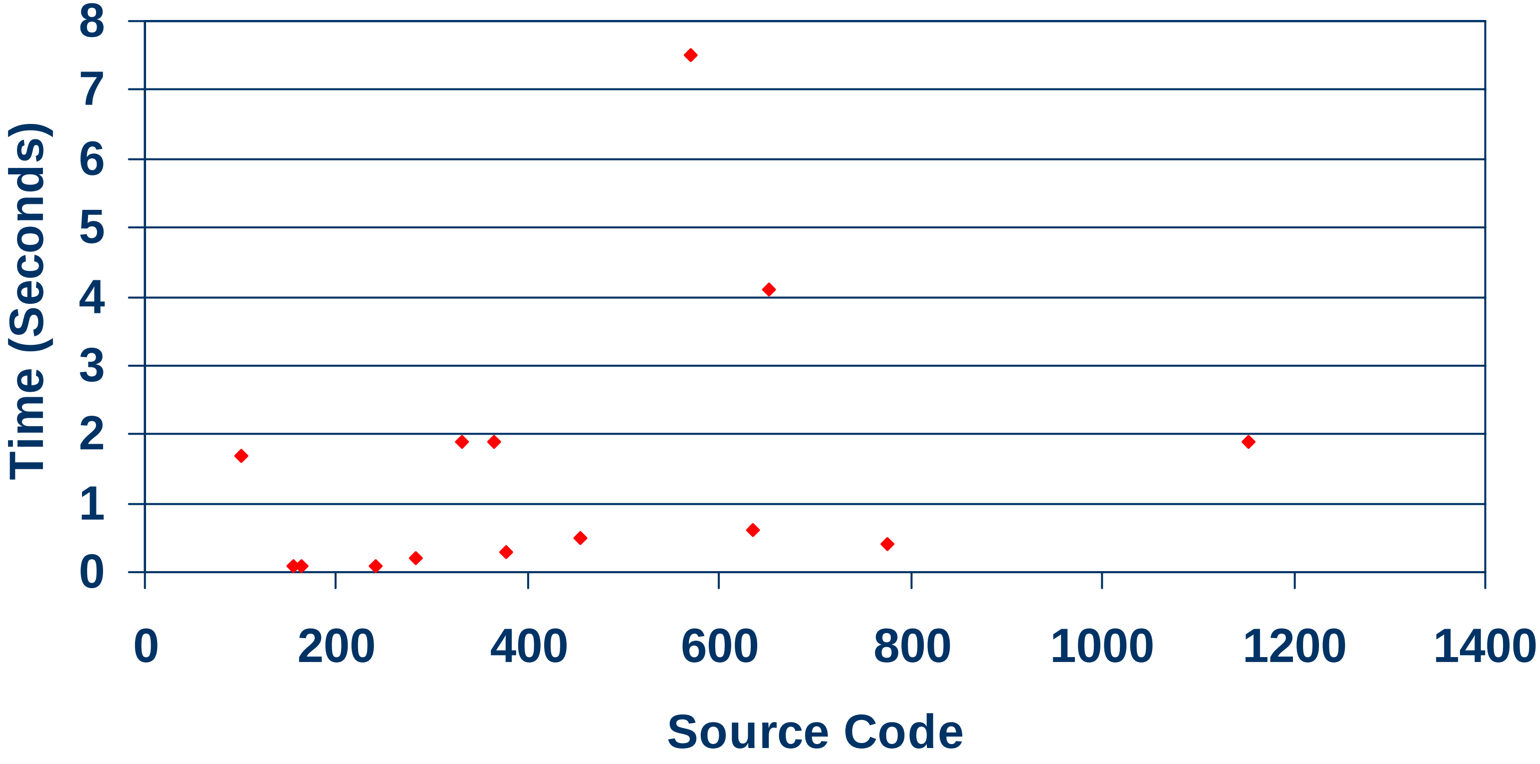
```
radical_generator n = f undefined
    where f unused = big_memory_result
```

- array :: Ix a $\Rightarrow$ (a, a) $\rightarrow$ [(a, b)] $\rightarrow$ Array a b
  - Each index must be in the given range
  - Array indexing also problematic

# Perfect Answer: Digits of E2

```
e =
   ("2." ++) $
   tail · concat $
   map (show · head) $
   iterate (carryPropagate 2 · map (10*) · tail) $
   2 : [1,1 ..]
```

# Performance of Catch



# Case Study: HsColour

- Takes Haskell source code and prints out a colourised version
- 4 years old, 6 contributors, 12 modules, 800+ lines

- Used by GHC nightly runs to generate docs
- Used online by http://hpaste.org

# HsColour: Bug 1

FIXED

**data** Prefs = ... **deriving** (Read,Show)

- Uses read/show serialisation to a file
- readFile prefs, then read result

- Potential crash if the user has modified the file
- Real crash when Pref's structure changed!

# HsColour: Bug 1 Catch

> Catch HsColour.hs

Check “Prelude.read: no parse”

Partial Prelude.read$252

Partial Language.Haskell.HsColour
    .Colourise.parseColourPrefs

...

Partial Main.main

Full log is recorded
All preconditions
and properties

# HsColour: Bug 2

FIXED

- The latex output mode had:

outToken (‘\”’:xs) = “``” ++ init xs ++ “’’”

- file.hs: “
- hscolour –latex file.hs
- Crash

# HsColour: Bug 3

FIXED

- The html anchor output mode had:

outToken (‘`’:xs) = “<a>” ++ init xs ++ “</a>”

- file.hs: (`)
- hscolour –html –anchor file.hs
- Crash

# HsColour: Problem 4

CHANGED

- A pattern match without a [] case
- A nice refactoring, but not a crash
- Proof was complex, distributed and fragile
  - Based on the length of comment lexemes!
- End result: HsColour cannot crash
  - Or could not at the date I checked it...
- Required 2.1 seconds, 2.7Mb

# Case Study: FiniteMap library

- Over 10 years old, was a standard library
- 14 non-exhaustive patterns, 13 are safe

```
delFromFM (Branch key ..) del_key
    | del_key > key = ...
    | del_key < key = ...
    | del_key ≡ key = ...
```

# Case Study: XMonad

- Haskell Window Manager
- Central module (StackSet)
- Checked by Catch as a library

- No bugs, but suggested refactorings
- Made explicit some assumptions about Num

# Catch's Failings

- Weakest Area: Yhc
  - Conversion from Haskell to Core requires Yhc
  - Can easily move to using GHC Core (once fixed)
- 2nd Weakest Area: First-order transform
  - Still working on this
  - Could use supercompilation

# ??-Constraints

- Could solve more complex problems
- Could retain numeric constraints precisely
- Ideally have a single normal form

- MP-constraints work well, but there is room for improvement

# Alternatives to Catch

- Reach, SmallCheck – Matt Naylor, Colin R
  - Enumerative testing to some depth
- ESC/Haskell - Dana Xu
  - Precondition/postcondition checking
- Dependent types – Epigram, Cayenne
  - Push conditions into the types

# Conclusions

- Pattern matching is an important area that has been overlooked
- Framework separate from constraints
  - Can replace constraints for different power
- Catch is a good step towards the solution
  - Practical tool
  - Has found real bugs

**www.cs.york.ac.uk/~ndm/catch**